Keith Hengen and Woodrow Shew explore criticality and cognition

The two discuss their evolving views of brain criticality as a central organizing principle of cognition, development and learning.

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This transcript has been lightly edited for clarity; it may contain errors due to the transcription process.

[music]

Woodrow Shew
The reality of real systems is that there are thousands of parameters that control its state. Once you account for all 1000 of them, criticality is no longer a point. It's a large volume in that parameter space.

Keith Hengen
The realization that criticality is not just a statistical fascination, but actually an endpoint of evolution and development and homeostasis, and truly the unifying mathematical principle that allows brains to work.

Woodrow Shew
What Keith is pointing to is a potential, very clear and concrete benefit of criticality that was not explicitly addressed in a lot of the earlier literature, which is learning.

Keith Hengen
There's a lot to be learned from how close you are to criticality and your ability to modulate and move around that space as well.

[music]

Paul Middlebrooks
This is "Brain Inspired", powered by *The Transmitter*. A few episodes ago, on episode 212, I conversed with John Beggs about how criticality might be an important dynamical regime of brain function to optimize our cognition and behavior. Today, we continue and extend that exploration with a few other folks in the criticality world.

Woodrow Shew is a professor and runs the Shew Lab at the University of Arkansas. Keith Hengen is an assistant professor and runs the Hengen Lab at WashU, Washington University in St. Louis, Missouri. Together, they are Hengen and Shew 2025, Neuron. That is, they recently co-authored a review paper in Neuron titled, *Is Criticality a Unified Setpoint of Brain Function?* In the review, they argue that criticality is a homeostatic set point or goal of neural activity, describing multiple properties and signatures of criticality.

They discuss multiple testable predictions of their thesis, and they address the historical and current controversies surrounding criticality in the brain, surveying what Woody thinks is all of the past studies on criticality, which is over 300. In the review, they also offer an account of why many of these past studies did not find criticality, but looking through a modern lens with new analyses, they most likely would find criticality or near-criticality.

We discuss some of the topics in their paper, but we also dance around their current thoughts about things like the nature and implications of being nearer and farther from critical dynamics, the relation between criticality and neural manifolds, and a lot more. It's fun because you get to experience Woody and Keith thinking in real time about these things, which I hope you appreciate. Find all of the relevant links and information in the show notes. There's quite a bit more in the full Patreon version of this episode.

Consider supporting "Brain Inspired" if you want all the full episodes, the full archive as well, or just to express how you value this podcast, bringing you these kinds of thoughtful conversations. Go to patreon.com/braininspired or find the link in the show notes. Here we go.

[transition]

Paul Middlebrooks
Right when Keith logged in here to this podcasting software, you guys just began talking about a shared student or something who's going to be doing insane amounts of research at a very fast clip. I didn't know that you were that intertwined. What is your working relationship, and how far back does it go?

Woodrow Shew
It's pretty intertwined.

Keith Hengen
Yes.

Woodrow Shew
Just this meeting, while Keith was in New Hampshire, I was meeting with three of his students. [laughs] What happened was a year or two ago, Keith contacted me because he was working on a grant that was related to criticality together with Ralf Wessel, who you may also know, Paul, I don't know. He's another guy.

Paul Middlebrooks
I don't know Ralf.

Woodrow Shew
He's been in the criticality community for some time, too. He's also at WashU, who I know him personally. Anyway, they contacted me to see if I wanted to get into this grant they were writing, a big one. I said yes, and also asked Keith if he wanted to help me write that review article that came out in Neuron yesterday.

Paul Middlebrooks
Just yesterday, or two days ago.

Keith Hengen
Two days ago.

Paul Middlebrooks
Two days ago.

Keith Hengen
Then, secondly, I had you come to WashU a few years ago and give a talk. That's when we first met. Then, in working on this very, very cool visionary RM1-- I don't know if you've heard of this mechanism, Paul. It might be dead now in the current climate.

Paul Middlebrooks
I don't know.

Keith Hengen
It's a cool idea from the NIH perspective. It's like, bring together a team of people and just aim for the moon. Literally no specific aims, but your overall aim should be singular. It should not be able to work if you were to break it up into multiple parts. It couldn't work in any one lab.

Paul Middlebrooks
Oh, man. I want to be part of that.

Keith Hengen
It was super fun. We just started nerding out on our own rabbit holes on the side, and we started writing this paper together. Effectively, I've tried to recruit Woody to come from Arkansas to WashU, and he's happy in Fayetteville. And so the next best thing is to just pretend that we're down the hall from each other. We basically have Zoom calls every day.

Woodrow Shew
All the time.

Keith Hengen
Constantly, and sending people back and forth. It's been a lot of fun.

Paul Middlebrooks
This will be like a recorded daily Zoom call for you guys, then.

Keith Hengen
Totally. We have a whole schtick.

Paul Middlebrooks
I recently had John Beggs on the podcast to talk all about criticality, but he wrote the book, *The Critical*-- Now it's escaping me. *The Critical Brain*--

Keith Hengen
The Brain and Cortex, I think?

Paul Middlebrooks
Yes.

Woodrow Shew
Cortex and the Critical Point.

Paul Middlebrooks
That's right. *Cortex and the Critical Point.* Yes. I've been doing a lot of criticality now, poking around in my own research. I've been interested in this. You guys have been part of the criticality community, I guess. It's odd to think about that there does seem to be a criticality community. Am I right with that? Do you feel like you're part of a community or no?

Woodrow Shew
A little bit.

Keith Hengen
No.

Woodrow Shew
Oh, Keith's in it.

Paul Middlebrooks
Oh, good. You're disagreeing already.

Woodrow Shew
Keith's in the community. No, but there is a little bit of an old part of the community that is not-- Keith's new. There's the new guard and the old guard.

Keith Hengen
Let me give you my vision on this, Paul. I came to this from the perspective of homeostatic plasticity, set points, and robust functions. I did my postdoc with Gina Turrigiano who's worked with Eve Marder, who's at Brandeis. That's the epicenter to me of trying to understand how a neuron or a small network of neurons or a brain can, despite the inconsistency of any of its little bits and pieces, continue to do the same thing reliably over time. The idea of criticality is a really attractive endpoint to that.

I just toyed with it and toyed with it, and toyed with it. Once I started my own lab, we did this project with Ralf Wessel on that. Very much felt like I was dipping my toes into this very small and very aggressive community. I want to make fun of them out of total affection for a moment of, it's just a bunch of physicists who love jargon, and they just like to yell at each other about that jargon and specific mathematical nuances that honestly the rest of the world does not care about.

The problem is they're sitting on this incredibly powerful pot of gold. I think maybe we've lacked the data acquisition methods or even the tools to measure criticality in the right contexts. I think it would be really easy in the last 20 years to look at criticality and be like, "That's an interesting mathematical argument," and then walk away from it, and no big deal. I think that the tide is turning. To the extent that I'm part of the community, I'm trying to hitch my wagon to this new direction within the field. I think Woody is the leader of the pack on that.

Paul Middlebrooks
Of the new direction field.

Keith Hengen
Yes. I think of the realization that criticality is not just a statistical fascination, but actually an endpoint of evolution and development and homeostasis, and truly the unifying mathematical principle that allows brains to work, broadly writ.

Paul Middlebrooks
Is that a fair assessment, Woody?

Woodrow Shew
I don't know if I would agree to the leader of the pack.

Paul Middlebrooks
President Shew?

Woodrow Shew
That sounds way bigger than my ego is. I want to give due credit. I trained in Dietmar Plantz's lab just like John did. He's also interested in the big picture. I would say that it's not quite as extreme as the picture Keith just painted, but it's not too far off.

Keith Hengen
Boy, this is coming from somebody who doesn't plan to be a part of that community. When I was trying to understand those early papers in criticality back when I discovered the idea in, say, I don't know, 2013, 2014--

Paul Middlebrooks
What are the early papers? The 2003s, 2004?

Keith Hengen
All straight up to 2014. The arguments about how do you show power law-ishness and what is a universality class? What are the different spike word sequences within these avalanches? I think that there were people at the heart of that research who had a vision and an idea of where it was going, but as somebody who wasn't already in that family, it was not articulated in the way that I got it. It took me 10 years to realize what this might mean.

Woodrow Shew
I get that, especially from the papers themselves, the papers that were written early on, like you said, Paul, in the early 2000s and up to 2014 or so. A lot of the papers at that time period, it faced a lot of resistance because if you try to make these grand claims, you can't do it without backing it up a little bit. Over those years, the last 20 years essentially, I feel like enough support has gradually built up that you can start to make those claims without sounding like a lunatic now.

Keith Hengen
There's also the addition of the machine learning stuff, too, though, Woody, right?

Woodrow Shew
Absolutely.

Keith Hengen
That it's sacrosanct. It's just carved in stone that, yes, you need to initiate deep models at critical phase transition or they're not going to learn. That's, I think, the connection to optimal information processing for an unpredictable task. That's what brains have to do. I don't want to come across as accusing those early papers of missing the plot, but suggest that in the last 20 years, as they've developed the science in cell cultures and these simplified neural preparations, there's been a lot of math and CS that's built up along the side. We're at a place now where I think it's much easier to clarify what this means.

Paul Middlebrooks
Things take time for those bigger picture applications.

Keith Totally.

Paul Middlebrooks
Like you said, with the advent of big data, big tools, better recordings, those things can become clearer, I suppose. Keith, you used the word aggressive earlier about the so-called community. I know that there is debate because part of what your review addresses is this historical debate on whether criticality is found or isn't found in various parts of the brains. One of the things that you argue in the paper is that you were just looking at it the wrong way. If you look at it the right way, you actually do indeed find criticality, and so there shouldn't be this debate.

Is the internal debate among what I'm calling a community or whatever, criticality folks, is that hot? Is it aggressive or is it friendly? How would you characterize it, either of you?

Keith Hengen
Woody, I'll let you.

Woodrow Shew
Okay.

Paul Middlebrooks
Without getting yourself into trouble, I'm sure.

Woodrow Shew
No. I'd say it depends where you draw the boundary of the community. I think John mentioned on his chat with you as well that there are some folks who have had a fairly long run of being the critics. There are a few of those groups who have consistently written papers from the critical

point of view on the topic. If you put them inside the boundaries of the community, then you could probably say it was hot at times, but it's also cordial, like John said.

I've had plenty of good conversations with those folks. John was mentioning Alain Destexhe and Jonathan Touboul, who were some of the early critics. More recently, there's been some papers by this group at Emory and Georgia Tech. There's Ilya Nemenman and Audrey Sederberg, and her student, Morel. Audrey was writing this grant with Keith and I that we were just talking about. We're not enemies by any means, and we're very friendly.

Keith Hengen
I think the reconciling factor on this, though, is, every single time we've looked at data, other people said-- Audrey's data, or our collaborator, Jason Maclean. He's at Chicago, right?

Woodrow Shew
Yes.

Keith Hengen
People were maybe a little skeptical. They're not quite drinking the Kool-Aid yet.

Paul Middlebrooks
What are they skeptical about? The grand story or the data?

Keith Hengen
I think the strongest argument against criticality from an empirical perspective is the last 50 years of systems neuroscience, because if you predicate your understanding of a brain on a highly repetitive task and a trial-structured design, objectively, things don't look critical. Say you have a rat pressing a lever 25,000 times, and you look at its motor cortex or wherever you want in the brain--

Paul Middlebrooks
Something with the timing also is important, right?

Keith Hengen
100%. You are going to see something that has a very, very rigid spatio-temporal structure. Both the behavior and the neurobiological dynamics have a lot of scale. They have the same spatial dynamics, the same temporal dynamics. By definition, it's not scale-free, and so it's not critical. That's very simple to conceive of. Does that make sense, Paul? Sorry, I know I just got a little jargony there.

Paul Middlebrooks
No, that's okay because I wanted to actually get into this because I was complaining to Woody the last time I think we had a Zoom that if you have to-- The critical thing to do when measuring criticality is to make your time bins wide enough to have enough data within the time bin to be able to accurately assess criticality. The last whatever 100 years of neuroscience is all about training animals to perform tasks that are very temporally structured. If we want to relate the neural activity to aspects of the task, let's say a lever press, that happens on a millisecond timescale. You just can't measure criticality there.

Keith Hengen
No, I don't even want to get into a technicality like this. Let's just imagine you have an infinitely resolvable tool to tell you where you are with respect to criticality. I think that what we have found with Jason and with Audie and with these tools that Woody's-- We'll get into who Sam Suter is in a few minutes, but a high school kid who's a genius, these new mathematical tools that they're developing, let's just say you had infinite resolution and you say, "This system is not at criticality. I don't think it is on the 25,001st lever press." What we find, though, is as soon as the animal walks away from that lever and it goes back into an extemporaneous, unpredictable world, you're right back at criticality.

Paul Middlebrooks
That's because it's over-trained.

Keith Hengen
It's over-trained, or you can think about it this way. If you're Caitlin Clark and you go up for your 10,000th jump shot, you don't want to be integrating all the scales of information across all the regions of your brain. You don't want to be remembering the fight you had with your mom three days ago. You don't need to be reflecting on where your car is or the emotional state of your-- any of these things. You need to collapse into a very, very simple manifold and repeat that thing.

I think one of the really interesting points that's coming out of the work we're doing right now, and by we, I mean this is a larger collective community and Woody's and my labs working together, is that being near a critical bifurcation gives you a property called marginal stability. In our little review, I don't mean that in a pejorative way, I love this paper, Woody has this incredible analogy that just resonated with me. Marginal stability is the difference between a 747 and an F-16.

The 747 is immensely stable, but it would take a huge amount of force to change direction. An F-16, in contrast, is on the limit of uncontrollable and unflyable. By being one step back from that loss of control, you can flip that thing around on a dime. When Caitlin Clark presumably gets to the line, she can shift that cognitive space and tighten that space so that it is no longer scale-free, and shift into the simple manifold, execute the three-pointer, and then back into this more dynamic range.

It's by virtue of typically tuning the system to that set point that you have that type of flexibility in the first place. We can scratch this out on a chalkboard or the back of a napkin, and we're like, "Oh, that sounds cool." Then when we actually go look in the data and we have Audie there and Jason there, we're like, "Holy shit. It worked better than we could have predicted." It's weird how well this stuff keeps lining up. Back me up on that, Woody.

Woodrow Shew
This is happening a lot recently. Yes, that's true, for sure.

Paul Middlebrooks
That's not good science. You don't want confirmations all the time, you want to falsify stuff. I'm not saying you're not doing good science, by the way. That's not what I meant.

Keith Hengen
No. Sorry, I will shut up in a second. I think that the math of it is that any point has some distance from criticality. Any pursuit.

Paul Middlebrooks
Criticality itself is infinitesimally small. It's a point that can never be achieved.

Keith Hengen
Sure, but it's just like saying every single-- Hold on. Every single point on the globe has some distance from New York City. That's just a fact. We're trying to ask, "Are we proximal to New York? Are we close to New York?" There are certainly cases where we find you are not even close to New York. You have moved away from there. Interestingly, it's in this case of the jump shot, or the lever press, and then you'd actually expect that. If you're going to have these repetitive dynamics that occur trial over trial, over trial, over trial, that shouldn't be near there.

I think that the math of that, the idea that it has an agenda, there's no room for an agenda in there. It is what it is. It's surprising what it keeps showing us about the underlying organization or the system, and that it keeps coming back to these proximal to New York City.

Woodrow Shew
I would add a few comments on here to the last few points you guys have been chatting about, which one of them is that it's one of the misnomers, or not misnomers. One of the misconceptions out there is that criticality is a point, is that it's a singular infinitesimal point. This is one of the ideas that has been on the list of criticisms of the topic for ages is that, how in the world could a sloppy system that's alive and biological be precisely at any mathematical point?

That would be a fair criticism if criticality was a point. It's not. What I mean by that is that when people say that, they've already decided that they know what the important parameters are for the system that control its state, and then they'll tell you for that important parameter, sometimes called a control parameter in physics, it only has one value where it's critical. The reality of real systems is that there are thousands of parameters that control its state. Once you account for all 1000 of them, criticality is no longer a point. It's a large volume in that parameter space of all 1000 parameters.

People don't think of it that way because of the history of the physics behind this kind of topic, where there is a critical point on the phase diagram for water. That's because you're looking at pressure versus temperature, you're not including volume and uncountable other parameters that affect water. They're just not the big, important ones. The fact of the matter is that criticality is not a point. That's one of the really important things.

The other really important point I want to make that's related to this proximity to New York City stuff that Keith was just mentioning, it's almost more important than the fact that it's not a point, actually, is that as you go slightly away from the ideal, perfect, critical-- I won't say point, critical state, as you go slightly away from New York City, all of the--

Paul Middlebrooks
There's still traffic.

Woodrow Shew
There's a lot of traffic, there you go. That doesn't sound right, though. I wanted to talk about the benefits. The bunch of benefits associated with criticality, they don't disappear suddenly as you depart from criticality. As you step further and further away from criticality, those benefits that come from the weird properties of criticality gradually dissipate. They gradually become attenuated.

The system is quite a bit more robust than that old criticism would suggest, that it's such a fragile state to be in. It's not. Especially the benefits of it, they're not fragile. You tune away slightly, and you just have a slightly less large range of scale invariance and things like that. You have a slightly less huge dynamic range.

Keith Hengen
Woody, the fact that this is even a point of concern is what I'm talking about, about the last 20 years of these involuted, navel-gazy arguments, because to anybody else in the world, it's like body temperature. Yes, we say 98.6, but we don't worry if you're at 98.7. We just say, "Yes, there's a point. Biology tunes to that, and we're fine with it." Nobody's sitting here arguing that, "No, because biology can't tune to a point, that there is no body temperature regulation." That's crazy.

Woodrow Shew
No, that's true. That's true.

Keith Hengen
I think that intuitively, the further you are from an optimal set point, the worse things are going to get. I think a lot of people accept that. The questions that are more relevant to the world in terms of criticality is, does a disease state pull you further from that? Does sleep deprivation pull you further from that? IQ, is it inversely correlated with proximity to criticality? Things like this, rather than pulling up phase diagrams.

Woodrow Shew
Yes.

Paul Middlebrooks
Go ahead, Woody, sorry.

Woodrow Shew
As just one last little point, part of the reason for that historical mess that that second half or the last third of our paper talked about was there. It was because people didn't pose their scientific questions in this correct way that Keith is saying. Instead of asking, "How far from New York City are you?" they were asking, "Are you at New York City or not at New York City?" That's how the questions were asked initially, just because, I don't know, that's how people thought of it initially, but it's a misguided way to go about it because the answer is always going to be no. You're never going to be precisely there where you are.

Paul Middlebrooks
The whole concept of what was at criticality was always fuzzy to me from those earlier papers. I guess what you're saying is that's what you're trying to address. That's the new fun in criticality research is-- Let me back up. My audience offered up some questions, and a recurring theme in people thinking about criticality is, "Okay, fine, fine, if you're subcritical, the signal dampens out, obviously. That's not good. You're super critical, everything goes berserk, and you're epileptic. That's not good."

Then the question really is, within the pretty good, close to New York, maybe you're in the suburbs zone of criticality, one of the benefits of criticality is information processing. That's a fuzzy thing. You either have great information processing or not, but is that what you're starting to try to address is when you deviate because of one thing, the nature of the information processing, its capacity, deviates in a certain way? Is that what you're trying to start to get at?

Woodrow Shew
Yes, to some extent. Also, yes, and information processing is not a zero or one thing. You're not either able to process or not able to process information. There's a huge range from not to able. As you tune closer away, it's going to modulate that in some way.

Keith Hengen
Yes, Paul, I think the thing that felt like a light bulb for me a couple of years ago, maybe as Woody and I were starting to work on this RM1 project, is the realization that if not everything, the vast majority of what a brain has to do is unpredictable. You could not have known, your genetic code could not have anticipated podcasting. You don't have a hardwired circuit for almost anything you do other than really basic cardiorespiratory function and maybe bipedal motion.

Paul Middlebrooks
Did you just say that I'm not born to do this? Come on.

Keith Hengen
Good. Well played. The point here, though, is that whether you're born into a cave, fighting leopards in prehistoric wherever, or you're born flying jet packs in Tokyo in the future, you effectively have the same brain, and it has to optimize itself to either environment. You can't know which pairs of neurons, pairs obviously being a very, very small network, are going to become relevant, and at what time likes, you'll need to learn information.

If you think about a-- I don't want to make this concrete because it's extremely abstract, but just imagine a simple grid network of nodes or neurons as you're building a model, you need to be able to somehow reliably drive co-variation between any arbitrary pair of those neurons in there, because you don't know the solution. The only place where you can explore the entire solution space is if you start out very close to New York City.

The point about Caitlin Clark is that once you've learned that solution, if that's all you need going forward, you don't need criticality. You just need to replay that solution over and over. It's a much simpler manifold. Given that every time you wake up and walk out your door, it's a new world, you might need to modify what you have learned. You might need to add things to it. It would make sense, again, from an axiomatic perspective, that you'd like to return the resting state of that network back to something near New York City so that you could continue to make these unpredictable connections and optimize your behavior and information processing for the future.

Paul Middlebrooks
This seems directly related to explore-exploit dichotomy.

Woodrow Shew
Absolutely. Actually, that's one of my favorite things I would like to do an experiment on in a very direct and explicit way with a mouse that's exploring-

Paul Middlebrooks
Oh, that's interesting.

Woodrow Shew
-or not. That's one of my pet hypotheses that I would like to test right now, but I don't have the experiment going right now to say, "Does criticality benefit foraging and exploration?" I think it does. I think it will because of a bunch of reasons that I'm not going to go through, but it's a good idea.

Keith Hengen
Woody, I want to shout out Steve Van Hooser's data here that you analyzed. I feel like that's such an incredible-- To give you an example of one of these experiments where we take somebody else's experimental data a couple of years after the fact, and then run this analysis and walk away going, "Well, that worked better than we could have hoped."

Paul Middlebrooks
Let me just pause there because criticality is one of those things where you have so many resources because there's so much experimental data just sitting there. You could just take it from anywhere. It's almost limitless, but anyway, it's a good field to be in for that very reason. It's such an open field. It seems like a fun spot to be in.

Keith Hengen
Totally agreed. Steve Van Hooser is a visual cortical physiologist at Brandeis, and he was a de facto mentor of mine during my postdoc. I don't know if there's any trainees listening to this, but Steve is just an incredible mentor and a really, really good, humble guy. He worked with ferrets. He studies the experience-dependent emergence of orientation and direction selectivity in the visual cortex because those aren't hardwired in the ferrets. It has to be driven by experience.

There's decades and decades of research on things like monocular deprivation and dark rearing and GABAergic treatments to delay or advance the critical periods, et cetera, et cetera. If we are right, though, you would predict that before the animal is exposed to visual experience, the further it is from criticality, the less effective that experience should be in driving these plastic changes. Does that make sense?

Paul Middlebrooks
Sure.

Keith Hengen
Steve did these beautiful eight or 12-hour-long recordings where he puts the ferret into a head mount, and he's doing calcium imaging and displays, repeatedly, the same orientation and direction just [onomatopoeia] for hours and hours and hours on end. Then, before he does that and after he does that, he measures the selectivity of the neurons in the visual cortex. Surprise, surprise, if you play a 45-degree angle and repeat for 12 hours into this animal's eyes, into the retina, you see a major shift towards that orientation after the thing.

If you regress the amount of change that you drove, so the efficacy of that plasticity, against that animal's distance from New York City before the experiment started, the R-squared was 0.99. It was bonkers. Just to restate that, the further animals were from critical, the less effective this plastic paradigm was. That was our first hint about this-- I would say our first empirical wet lab neurobiological hint that these rules really do set the brain up for-

Woodrow Shew
Learning,

Keith Hengen
-modeling itself on the world.

Paul Middlebrooks
I was going to say that's not really a learning paradigm, but it's like an entrainment paradigm or something, but it is related. It directly would apply to learning.

Keith Hengen
Now Woody and I have developed a protocol in my lab where we actually-- We think that the organizing principle, the end point of sleep across phylogeny, is to restore critical dynamics--

Paul Middlebrooks
That's a big claim.

Keith Hengen
It's a big claim, but I will back it up. I will die on this hill right now. I will. I'm open to counter-evidence, but I have yet to find it convincingly. Anyway, rather than just pushing animals away from criticality with pharmacology or sleep deprivation or drugs, we have found a way to structure sleep and drive a homeostatic super compensation, the same way like when you lift weights a bunch, you get hypertrophy. We can enrich the robustness of the near-critical regime. When we do that, these animals learn complex tasks in about one-fifth the time that a normal mouse does.

Paul Middlebrooks
You do that while they're sleeping?

Keith Hengen
I won't get into some of the entire details of this because I don't want to throw my postdoc, James McGregor, under the bus and preclude him from publishing it. He has found a way to manipulate the efficacy of sleep. We'll just leave it at that. [laughs] They're super mice.

Woodrow Shew
They're super mice, and this is not an entrainment task. This is a learning how to hunt cockroaches task. Super cool [laughs].

Paul Middlebrooks
Oh yes. I think, Keith, I've heard you say that you've gone through thousands of cockroaches or something.

Keith Hengen
Yes. My grad student, Jacob Amis, realized that for a period of time, he was the world's number one commercial consumer of Turkestan Red Runner cockroaches. Just if there's any experimentalists listening to this, Chris Neil did really beautiful work back in, I think, 2015 or something, showing mice capturing crickets. He demonstrates that it's a visually-guided behavior, and it's very cool. It's a neat visual motor spatial, interceptive integration task. The problem we were having is that crickets have a third dimension of movement. They can jump.

That makes the trial-to-trial variance just huge in an already complicated task. An ecology collaborator of ours, this guy John Grady, said, "Hey, you should switch over to this fast, small cockroach."

Paul Middlebrooks
2d.

Keith Hengen
Yes. It worked beautifully. To Woody's point, when you first introduce-- These mice have been raised their entire lives in a laboratory environment, at Charles River, or Jackson, or wherever they're from. They've only seen chow. You throw a cockroach in and they're terrified. They go to the other side of the cage, and then you can see them start to calculate, "Maybe I can eat that." They have no idea what they're doing. They walk towards it, it takes them off, and they get scared again.

It takes them hours. It takes them multiple trials. They're fumbling it. After a couple of days, they become little killers. We'll call them the mice that are ultra-critical, right in downtown Manhattan, they figure it out after one or two trials. The very first trial, there's no difference. They're scared. I think James has done 20 or 30 animals at this point, and it is a beyond-robust effect. It's startling.

Woodrow Shew
Yes [chuckles].

Paul Middlebrooks
Sorry, Woody, I was waiting if you wanted to jump in there. I couldn't tell if you wanted to say something.

Woodrow Shew
Let me just summarize this last five minutes here, which is that what Keith is pointing to is a potential, very clear and concrete benefit of criticality that was not explicitly addressed in a lot of the earlier literature, which is learning. Let me just hit that with a little bit of a-- underline that point here, punctuate the end of that long bit there, that is criticality, I think is important for learning, which is very similar to what we were saying. Learning is when your brain encounters something that it hasn't had to deal with before. You've got to come up with a new solution.

That open-ended computation, or performance, is where I think criticality is really most important. That's where I think this data Keith's describing is going to be cool. It's going to open up a pretty new, interesting result.

Keith Hengen
In terms of just immediate value application, James has been running this paradigm in multiple mechanistically distinct animal models of degenerative diseases. It provides an immediate cognitive benefit to them and extends the effective, by that I mean no gross symptoms. It extends their effective lifespan.

Paul Middlebrooks
I'm about to back us way up, but before I do that, I've recently been to a few conferences in the neurotech world, neuromodulation, implantable devices to treat disorders, and people in those fields are very excited. I've seen some really cool stuff. It made me wonder, are we going to be building devices as a mental hygiene, get you back to criticality, external, either transcranial direct current stimulation stuff, mild electroshock therapy to invoke critical states? Is that in the near future?

Woodrow Shew
I would say it is to some extent in the near future. I think that using criticality as a clinically relevant guide is a yes in the near future. Exactly how one pushes the brain around to get it closer or not is a little less obvious. Keith mentioned an idea that's pretty cool that has to do with messing with patterns of sleep in order to do that, which we think we can do in mice anyway, but whether or not it's going to happen by drugs or by electrical zappers or whatever, I don't know. My suspicion is that it will be useful. There's a lot of ways it could be super useful clinically.

Paul Middlebrooks
Go ahead.

Keith Hengen
Oh, I was just going to say, I think that before we jump to the sci-fi--

Paul Middlebrooks
Yes, I didn't need--

Keith Hengen
I don't know. Let me just philosophically say, this human desire to just have a device or a pill that makes you better, if we just forget that for a moment, simply having an effective readout of where you are in terms of these dynamics would be immensely valuable without trying to manipulate it externally at all.

Woodrow Shew
What you need is a quantitative and objective measure of cognition. That's something that every--

Keith Hengen
A biomarker for cognition, perhaps.

Paul Middlebrooks
So you're saying that criticality measurements could be that biomarker, is it?

Woodrow Shew
Yes.

Paul Middlebrooks
I'm going to bring us way back here. Scale-freeness is everywhere. Per box sandpiles, critical. I know you're going to disagree with me on that, but you know what I'm pointing at. I was in my basement two days ago waiting for the washing machine to finish, and it has a drain that goes into a big sink. It's on spin, and I see the water spitting out, sometimes a couple of drops, then a little squirt. I'm thinking, "If I measured that, it would be at criticality." It had a branching ratio of one, which I know is not the right way to assess criticality, but it looked very scale-free.

Criticality is not just in brains, but Woody, you were just talking about having a good metric for criticality, essentially, in brains. I guess it's a two-part question. If criticality is not something that is specific only to brains, it's in other processes as well, why do we care about it in brains? Then, do we define criticality differently in a brain than we do a washing machine drip or whatever? Do they need to be defined differently? How do we clearly define criticality? Sorry, that was a lot, I know.

Woodrow Shew
No, that's my wheelhouse. How do you define criticality? I can give you what I think of as a hard and fast definition of criticality. This definition applies to things that are more general than the brain, more things than the brain. I'm sure about your washer, maybe [laughs].

Paul Middlebrooks
I'll measure it.

Woodrow Shew
The definition of criticality, from my point of view, which is almost-- It's coming from physics, really, but I think it's important to advance beyond some of the original places that criticality was studied in physics were not living systems. I think John mentioned this, too. They're equilibrium systems, and they're not alive. In some ways, dynamics is unimportant in those systems. Whereas the brain, dynamics is at least half the story [chuckles]. Space and time are both very important.

Anyway, what's the definition of criticality? It has two pieces. It has two necessary and sufficient conditions. One of them is not going to surprise anyone who knows a little bit about criticality, which is that the system's dynamics have to be scale-invariant if you're at criticality. This is this peculiar property where many, many, many, many, many scales are important in the dynamics of the system, and those scales are arranged in a very peculiar way that's arranged according to a power law. That's scale invariance.

Sounds like a very technical thing, but from the point of view of brain function, it's, again, like your brain needs to have lots of scales of interactions, both in time and space, in order to do all the stuff that it does. It should be very plausible at a very basic level like that. Anyway, condition A is that scale invariance.

Paul Middlebrooks
Can we just pause there? Can I ask a question about--

Woodrow Shew
Absolutely.

Paul Middlebrooks
It's scale-invariant across a couple of what are called decades. The more decades it scales, whatever, it just means across different orders of magnitude. I asked John about this also, and it's still lingering, that it seems that different behaviors, different neural processing, function best within different spatial-temporal scale. One brain area, let's say, keep it simple, like the early visual cortex-- I'll bring this up later. One brain area might be doing something that affects things on very short time scales, whereas another brain area might be doing something that affects things on longer time scales.

Would you then expect that scale invariance, the set in which there's a nice parallel, there's a scale invariance, would that be then shifted, or do they all have to be the same? Does that make sense?

Woodrow Shew
Yes, it's a very good question. It's a very interesting and important question, I think, that's being addressed right now in a lot of research. I would say, coming back to a point Keith made earlier, if an animal is doing some very repetitive task, say, they're repeating the task every half second, I bet you if you take a look at their motor cortex, you're going to see dynamics in there that's dominated by a one-second time scale. That is an example where at least some neurons in there, in the motor cortex, are not going to be scale-invariant in their dynamics.

That's the example Keith was talking about, this long tradition in computational systems neuroscience. That will be a counterexample to criticality, apparently. Whereas if you are doing a working memory task and you look in prefrontal cortex neurons where the monkey's got to keep something in mind for the last three or four or five or six or 10 seconds, now you're talking about this persistent activity that has very long time scales that are important, as well as short time scales that are probably important.

The monkey had to see a brief stimulus and catch it, and keep it in mind, and maybe do something impressive with it. Most tasks, they don't have to do too much impressive with it, but just got to keep it in mind. That's a very basic example where you need short time scales and long time scales at the same time. That's a case where you probably are going to need criticality. The short answer to your question is, I think absolutely, depending on the brain region and what it's doing, it may need to be closer to criticality, where it has a wider range of time scales and spatial scales, or it may need to be further from criticality where it has a narrower range.

That close and far that I'm talking about here is still like you're either in the center of New York or you're in the suburbs. You're not in Milwaukee. Sorry, Milwaukee. I've got nothing against Milwaukee.

Keith Hengen
I like Milwaukee.

Paul Middlebrooks
I like Milwaukee.

Woodrow Shew
I didn't ever give my second criterion.

Paul Middlebrooks
No, we're still coming back to it, I promise, or you can do it now. I haven't lost it.

Woodrow Shew
Let me just throw it in there. The second criterion is that you're at a boundary in your phase diagram of your system. That means, if you tune the parameters that control the system, and you're at a boundary, that means you're at some point where the dynamics change abruptly.

Paul Middlebrooks
Just to recap, scale invariance and at a boundary.

Woodrow Shew
Exactly. Those are the two necessary and sufficient conditions, in my opinion, for criticality. Both of those conditions are met by most of those bifurcation-type models. Part of the reason I said this is to come back to Keith's point here about temporal criticality or spatial criticality, that is, if you're talking about a one-dimensional time series model, or a low-dimensional time series model, like most people who study bifurcations, you're talking about time domain only.

If you're talking about a one-dimensional Hopf bifurcation or something like that, there's no population of neurons per se in that model. You might think of it as representing some population or something like that, but there's no explicit representation of multiple neurons in there. Yet, if you tune one of those models to be right at its tipping point, right at its boundary in a certain part of its phase space, and it has scale-invariant dynamics, then that's a type of criticality. It's a type of--

Keith Hengen
John Beggs had a grad student, Leandro Fosque, and he's now a postdoc in my lab, working also with a dynamical systems guy, ShiNung Qing, and he's putting together a paper now where he actually solves for criticality, basically using Woody's definitions, in dynamical systems that don't have space. Purely, are they temporal? This is an agnostic space.

Paul Middlebrooks
Activation-based.

Keith Hengen
Yes, because the history of neuroscience is the Hodgkin-Huxley stuff. It starts out as a series of differential equations or a dynamical model that then predicts so much of what we've then gone on to discover experimentally. We can go back now, or Leandro can do this, go back and show that all of those models come from the family of critical bifurcations.

Woodrow Shew
Yes. This conversation that can be had about whether you're talking about temporal or spatial criticality, it's getting into the weeds. That's a disclaimer, a little bit. What I would point out is that most of the ways that people have assessed criticality in real experimental data from brains is on the temporal side. That is, you end up looking at a time series of fluctuations and looking at the nature of those fluctuations and asking if they're scale-invariant. Most ways of studying criticality do that when you get down to the brass tacks.

Paul Middlebrooks
Those original or first few studies, the Beggs and Plenz stuff, that was spatial, right?

Woodrow Shew
It looks spatial at first glance, but the first step in avalanche analysis is to take all the spikes from a population, turn it into one population sum.

Keith Hengen
Woody, this is where-

Woodrow Shew
Count spikes in one time bin.

Paul Middlebrooks
That was across electrodes in that case, I think.

Woodrow Shew
It is, it is, but you turn it into a single time series.

Keith Hengen
Woody, this is where--

Woodrow Shew
That first step eliminates spatial correlations entirely from the picture.

Keith Hengen
Let's get to what you were calling reticulotemporal in the supplemental section versus purely temporal. This is like the avalanche versus D2, because I think that's an important point.

Woodrow Shew
No, avalanches is not assessing spatial correlations at all. It works better if you have lots of neurons, which requires a spatial-- It requires a recording system that covers space.

Paul Middlebrooks
Why would we care about space? Why would we even care about the spatial aspect?

Keith Hengen
Because it's like an Ising model, right? You would expect that if you look at the correlation constant, that it basically approaches, what, infinity in a purely critical system, that you can move information across any size. If you were to, say, do a whole-brain voltage imaging experiment, you would expect to see fractals. You'd expect to see spatial fractals. If you ignore the time series, you'd expect to see very, very, very small patterns that are self-similar to medium patterns and large patterns, and whole brain patterns. That's not what we're doing. Woody, I guess what I'm trying to get at here is, even though avalanches are intrinsically temporal, there's still the-- I'm trying to set you up for this, man.

Paul Middlebrooks
He's not taking it.

Keith Hengen
The gap between avalanches thing, right? This is where we actually see a divergence of these two ways of thinking about criticality.

Woodrow Shew
That's true. Yes. The new method that's being described a couple times here, D2, is a way of assessing temporal scale invariance. That is, it's really the most direct and most-- It's taking temporal scale invariance head-on and not stepping around it, going at it from weird angles. That's the whole basis of this new analysis is that it is assessing temporal scale invariance in a time series. Now, avalanche analysis, like Keith was just saying, is this long tradition. It's almost from the beginning of this whole field. Like he said, by definition, avalanches, they chop out the quiet periods of activity.

Therefore, you've disrupted the full time series is not there. You've cut out the silent periods, and you're just analyzing the periods where you have a lot of activity. That gives a different answer slightly than what you'll get from this new method, D2, that assesses the full temporal scale invariance of the whole time series.

Keith Hengen
What's interesting is that they usually point in the same direction. When we take the same data, and we analyze them with D2, or with the avalanche phase measure that Zhengyu Ma, a grad student I worked with, she came up with. It's called DCC. It's based on avalanches. D2 and DCC typically point to the same thing, for example, during disease.

Woodrow Shew
In most cases, like in awake animals, they're almost always identical. Not identical, but there's no discrepancies.

Speaker 3: When we look at certain situations that are punctuated by regular silent periods, D2 will go away from criticality, because by definition, it's losing some of that richness of timescale. This is things like non-REM sleep when you're doing single-unit recordings. When Woody looks at non-REM with D2, he says, "Oh, D2 bumps up." He still sees the same trend, that sleep is pulling the system back towards critical. Sleep itself looks further from criticality than wake. We don't see that with DCC, because when you just look at the distribution of those bursts of activity, you still have this beautiful scaling relation. We saw recently the same thing in another collaborator, Gordon Smith, who's at Minnesota, also works in the ferret visual cortex. These animals are born-- Are you familiar with ferret development, Paul?

Paul Middlebrooks
No.

Keith Hengen
Are you a connoisseur?

Paul Middlebrooks
Of course I am. No, I don't know.

Keith Hengen
Of course not. It's amazing. They're born at the equip-- When they come out, they're like a second-trimester human or like a G18 rat. They still have layer two, three neurons migrating while they're postnatal.

Paul Middlebrooks
Oh, wow.

Keith Hengen
Yes, so you can record postnatally in animals and be getting retinal waves and a lot of stuff that's typically happening in utero. You have these really, really long off periods where the system is just silent, and then it's just punctuated by really beautiful spreading bursts of activity, and then long silences again. If you look at D2, it's not critical. Right before the eyes open, all of a sudden, something changes, and it was this emergence of temporal scale freeness. In those early punctuated periods, those bursts of activity are scale-free. They still show that same scaling relation.

I'm not sure. To me, this is a really, really fascinating question of how do you make that conversion and what's the switch? We think it might have to do with inhibitory neurons and inhibitory strength, and Woody's been modeling a bunch of this. When you get back to this question of which parts of the brain are closer to criticality or further? I suspect that-- Woody, would you call these different types of critical? How would you--?

Woodrow Shew
Yes, I think so. I think so. That's the thing is that general definition that I offered you, Paul, over the past half hour is it's sort of an umbrella definition. You were asking, how's the definition of criticality in the brain different from the one in sand piles or your washing machine or whatever? The definition that I just gave is one of these umbrella definitions that covers quite a few things and a lot of different types of criticality.

Paul Middlebrooks
Expand on what you mean by types of criticality because it's tricky.

Woodrow Shew
Yes. Keith just went through this one. This one example is a pretty good example where early in development, the activity of cortex looks very different than later in development for an awake animal. It goes from this type of dynamics that looks like quiet periods punctuated by large bursts. That's what we see in these very young animals, whereas in awake adults, you see this more constant fluctuating spike rates that don't ever shut up. The brain never quiets down to-- like quiet, there's no activity.

Paul Middlebrooks
You could say that those are two different manifestations of a single thing, a.k.a. criticality, or you could say that those are two different types of criticality?

Woodrow Shew
Yes. From our data analysis, they both satisfy those two criteria I mentioned. Here's how they're different and why I would say they might be different types, is that the precise scale invariance that we would say each of those two states has is different.

Paul Middlebrooks
Okay.

Woodrow Shew
In one case, it's this temporal scale invariance where you have all the time scales embedded together. That's the adult awake brain. In the other case, you don't have all the time scales. You have this very weird thing happening in time where it's perfectly quiet, and then a big burst of activity, and then quiet. In time, it's very disrupted and choppy, and weird. If you just cut out the active bits and throw away the silent periods and analyze those things like neuronal avalanches, then those things are power-law distributed, and that is a type of scale invariance.

Keith Hengen
Woody, I want to say something. I'm going to dumb this down, and just tell me if I'm wrong.

Woodrow Shew
Okay.

Keith Hengen
Paul, what he was talking about, all of these thousands of parameters that can influence a brain, and the definition of criticality is basically that if you were to take one of those knobs and just turn it, it would have very, very little effect. Just turn it, turn it, turn it, no effect, no effect. Then all of a sudden, you make a small nudge, and the system changes dramatically. That's this discontinuity.

Paul Middlebrooks
Oh, well, that's like an emergent bifurcation, et cetera.

Keith Hengen
It's like heating a pot of water. Water is water. Yes, sure, it's getting warmer, but it's still liquid. It still has the same specific gravity. Then all of a sudden, you go from 50 degrees to 99, and then you cross this little line, and all of a sudden, it becomes a gas. There are presumably multiple boundaries that you can cross. You can turn other parameters and find a different boundary. As long as you're at one of these boundaries, and it

supports some form of scale-free brain activity, that is a critical point that should be capable of producing all of the different solution space, pairwise connectivity of neurons, and things that you need for computation, et cetera. Is that a too simplified way of saying, like--

Woodrow Shew
No, I agree with everything you just said, but maybe the last sentence, I would modify a little bit.

Keith Hengen
Go for it.

Woodrow Shew
I'm not sure that every one of those different types of criticality is good for all kinds of computation. That early development stuff, it's scale-invariant, and it's doing something, but it's probably not good for processing visual input or something. These long periods of silence seem like a brain that is not quite working yet. It's doing something. It's wiring up and--

Paul Middlebrooks
This is--

Keith Hengen
No, no, you're completely right.

Woodrow Shew
Yes. It's very-- Sorry, go ahead, Paul.

Paul Middlebrooks
No, no, this is orthogonal, but this is-- I told you guys that I've been using Woody's new measurement, D2, classic neural avalanche measurements, et cetera, to look at criticality in brain activity that is recorded in my lab. There's a certain amount of frustration at, you get the numbers and then you're left with like, all right, well, what does that mean? How to interpret. You can come up with a just so story, if you want to, but then I guess what I'm wondering is like, how far away are we from being able to definitively make claims about as you move from the center of New York out to the suburbs, like when you're at the third stoplight, what does that mean? Versus when you're all the way out in the suburbs, how far away are we from that?

Keith Hengen
Paul, you just knocked it out of the park. You just defined to me the transition from 15 or 20 years ago in the field to where I think it's going now, which is to sort of have these abstract sounding like, yes, there's a power law. We're in New York, or we're near it.

Paul Middlebrooks
Look, it has a slope.

Keith Hengen
There you go?

Paul Middlebrooks
It's near, it's like within some range, but it's on the upper end of that range. Is it more? There's always--

Keith Hengen
Three decades, five decades of power law. I think that the more interesting question is to say, well, what if you should compare in conditions? If you have a motor learning paradigm to say, do animals that learn more tend to have a lower D2 value? Or they're after extensive experience and learning before they sleep. Does D2 drift up? Can we start to actually make predictions about the function of the system based on this measure? Because it has direct explanatory power in terms of information reach. In dynamical systems where they call it empowerment and reach.

Those things go up at a critical bifurcation. I think you need to make comparisons. You need to look at different animals that have different intrinsic IQ and the capacity for learning. You need to look at disease. You need to look at a well-rested versus fatigued. All of a sudden, I think you're going to be sitting on a measure that can predict these things and actually make an accounting for them. One of the things that leaves me wanting more in a lot of neuroscience is, say, like LFP spectral power. We can say, for example, during slow wave sleep, ah, delta power goes up and it's more restorative. But--

Paul Middlebrooks
You're pointing to another thing that has had years and years of controversy of whether--

Keith Hengen
It's very clear, statistically speaking, that if you fatigue an animal, it's going to have more slow wave energy. My point is, it doesn't mean anything. You could literally invert it and say, ah, as animals are more fatigued, you have less slow wave power, and it would be just as useful. It is a totally

abstract, effectively arbitrary correlate that's reliable. It's like the sound of a heartbeat. I can listen to it. I know you're alive. It is an effective reporter. If I don't understand the fundamental idea of valves and pumps, and blood, it doesn't teach me anything.

Whereas criticality, whether you like it or not, it makes a very specific prediction. I would have to close up shop on these projects if you could show me that kids with higher IQ are further from criticality than kids with low IQ. Because you make a direct prediction ahead of time. That's the point. It's not just an abstracted correlate.

Paul Middlebrooks
Wait, but you could do the same thing with, let's say, well, whatever, gamma oscillations or something. How does it differ? You could use gamma oscillations in a predictive way like that.

Keith Hengen
Yes, but my point is, what is it about gamma that would tell, like fundamentally, mathematically speaking, don't pay this on prior knowledge of what people have seen in the past, but why should a system with more or less gamma be cognitively better or worse?

Paul Middlebrooks
Because it correlates with spikes. More high gamma means higher spiking correlation.

Keith Hengen
It doesn't have to. It doesn't in every situation. I could design a different system that doesn't have that quality. That's just a by-product of-- it's an epiphenomenon. That's it.

Paul Middlebrooks
Okay. You just showed your hand and what you think of oscillations, but it's also a top-down causal, but we can't go down this road.

Keith Hengen
There are species that don't have theta, for example, and they still do just fine when it comes to 3D mapping.

Paul Middlebrooks
That doesn't mean that theta doesn't contribute anything in species that do have theta, just because you can do it without theta.

Keith Hengen
Sure. Here's my point here. I don't think that a system-- any system that's far from criticality can learn unpredictably complex tasks. I think it's a mathematical necessity, and so therefore you have-- this is Occam's razor. You can either come up with all these situations, well, that species has it and it matters there, but those guys didn't because they follow a different set of rules and they've evolved a different thing. I'm saying, or we can just go to one rule. It's a simple rule.

Paul Middlebrooks
What about species that don't spike, C. elegans?

Keith Hengen
You can still be critical in a non-spiking network.

Paul Middlebrooks
Plants.

Keith Hengen
No idea. I don't think so. No, actually, let's go out on a limb here. In a system that can't do meaningfully adaptive learning, that can't do things that aren't genetically pre-programmed. I'm like, I'm not prepared for this at all. I'm thinking on the seat of my pants. There's no evidence that there's been a selective pressure for them to adapt a flexible computational regime. Ergo, there should be no reason to expect those things to be critical.

Woodrow Shew
Let me just-- I'm going to push back.

Paul Middlebrooks
Did you drop acid right before we hit record, and is it just now kicking in? Just kidding. I'm sorry, Woody.

Woodrow Shew
Here's an interesting one for you that I've been thinking about is that we had somebody came and gave a talk in my department recently about bacteria, and bacteria obviously do not have neurons. Yet one of the things that bacteria do are like, they're pretty simple as you know, but they do have sensory apparatus. Yes. They have certain receptors for chemical agents--

Paul Middlebrooks
Specifically, E coli. Yes.

Woodrow Shew
E coli. Yes. It's these guys that have a flagella that they use to swim around. They have a motor system, they have a sensory system, and they have a weird chemical network inside their single cell body that does some computation. It takes some sensory input and turns it into motor output. They swim up the gradient to get food and stuff like that. Importantly, here's where I'm going with this is that in the absence of a food gradient, what these things do is they swim around according to a path that has power loss statistics.

Paul Middlebrooks
This is their random tumbling thing?

Woodrow Shew
Yes. The run and tumble thing they do is, yes, they move around according to what's called a levee flight. It has these little path links that are in random directions, but the lengths of them are drawn from a power law. In a sense, their behavior is scale invariant, and the computation that their simple little body is doing is actually another example of criticality. I'm pretty sure I'm putting that at 95% certainty because there's a chemical interaction network inside their body that has dynamics, and those dynamics are generating these scale-invariant motions. I would put a lot of money on the gamble that says that the dynamical system that turns sensory input into motor action for E. coli is that criticality.

Paul Middlebrooks
Okay. You almost can't not be at near criticality because if you're not, you're not going to have any information transformation. It's almost like defining.

Woodrow Shew
No, no, no.

Paul Middlebrooks
This is good.

Woodrow Shew
Viola Priesemann is awesome, and she has a really beautiful paper showing that when you take a neuromorphic chip and you're doing really simple things, and let's say two plus two, there's no need to be near critical. You don't need multiple time scales. You don't need multiple spatial patterns for very simple computations. There is absolutely no benefit to criticality, and it might be costly. There might be a reason that when Caitlin Clark takes a jump shot, you actually collapse onto a simpler manifold. It's an easier situation.

Paul Middlebrooks
Then why would E. coli be at criticality to do this very simple repetitive?

Woodrow Shew
Here's why. I've got an answer for you. It's because when there's no sensory signal and that's when their system turns to criticality and starts doing critical dynamics, that critical dynamics in their movement about the--

Paul Middlebrooks
Maximizes the range.

Woodrow Shew
That maximizes their foraging efficacy.

Paul Middlebrooks
I know, but it's only one thing they have to do to do that. I'm trying to have what Keith was saying gel with what you're saying, Woody. The E. coli is Caitlin Clark. That's all they do is run and tumble when they're not--

Woodrow Shew
No, no, I think it would be Caitlin Clark if that's all she ever had to do was take a jump shot. No, that's not a good analogy. That's a whole nothing. Cut it.

Keith Hengen
They're not. The E. coli have to take some strategy where they're sampling a large space, and it's physical. If they just had to always just move 10 microns to the left, then yes, they would not need to be--

Woodrow Shew
If they always had a food-rich environment, they would never need this behavior that they have. They would never need to even go anywhere, so

they wouldn't need that, and they wouldn't have evolved it if they were somehow always in food. They evolved this critical sensory motor system so that they can find food when there's not much in their nearby environment.

Paul Middlebrooks
I guess so. Here's one of my issues that-- With the advent of dynamical systems, studying dynamical systems and doing low-dimensional transitions on high-dimensional data, and then everything, absolutely everything, is all of a sudden a manifold, and manifolds are everywhere. It gets to the point, well, it's almost meaningless if-- It felt special at the beginning, and now everything's--

Keith Hengen
Manifolds are stupid.

Paul Middlebrooks
Manifolds are everywhere, but I worry that criticality could go down that road in my head.

Keith Hengen
Okay, Paul, do you want to do acid for a moment as a group? I think we can explain everything in existence by the fundamental principle of what criticality is. Do you want to do that real fast?

Paul Middlebrooks
See, you're going to-- Oh, wait, are you-- I'm about to talk about how acid resets our critical point.

Keith Hengen
Yes. No, no. Somebody was asleep at the wheel and invited me to give a TEDx talk in Boston last year. This guy, Mike Wong, was talking about this idea of functional information, which he thinks is the third law of thermodynamics. The idea is that even though the systems have increasing entropy constantly, they will always evolve towards more and more and more complicated informationally dense phenomena within them. This got me to thinking, if you start out with nothing but simple particles in the universe, why do we end up with complicated systems like we have?

You can say, well, what exists persists and what persists exists by definition. Imagine an infinite amount of time and an infinite amount of iterations. Now, you could say, okay, well, if we just have a bunch of sand on a planet, let's start there. The planet's self-organized. We just have a bunch of sand. It's flat. There's nothing happening. You're never going to get sandcastles. You're never going to build anything. You add some wind to it. You have some activation energy to this thing.

If there's too much wind, it'll destroy anything that starts to build. It'll just rip it down. If there's too little wind, you'll just move one particle a little bit here and there. What you need is wind at some threshold where you can push all of the different sizes of sand. Sometimes you move one grain, sometimes you move hundreds of grains. If you do that infinitely, eventually, and those sand grains can interact with each other, they're a little bit sticky, by definition, probability one, you would generate every possible sandcastle out there of all scales.

Paul Middlebrooks
Far out man!

Keith Hengen
Hold on. If there's any selective pressure, if there's any selective pressure for one of those sandcastles over others, then that's going to fucking persist. You'll start to see more of those things. Then the same thing applies to that. Now all of a sudden, if those sandcastles can interact, you can build this out. Is it so surprising that you start to see these power law signatures throughout the universe? Not every system has them. Obviously, you could look at 8 billion people. You'll never find someone with 400 fingers. We have a lot of definite scale in a lot of the universe. Don't get me wrong. The fact that we see people have criticized criticality by saying, "Oh, there's power laws everywhere." I'm saying, yes, no shit. We wouldn't be here if there weren't.

Paul Middlebrooks
What I'm saying is, how can you not be a criticality to exist? Maybe that's the point you're making.

Keith Hengen
We can predict kids' IQs by looking at how close they are to criticality on the day that they're born. It's not that-- I shit you not. Sorry, I'm starting to swear.

Paul Middlebrooks
It's kicking in, man. It's really--

Keith Hengen
I can't even. You guys just said ocean. This is data from Deanna Barch and Joan Luby at WashU. It's amazing. They scanned 250 babies at the moment of birth and then tracked them prospectively for the next six years. I guess what I'm trying to say and what Woody was getting at is none of these systems, neurobiologically speaking, will work if they're not somewhere near New York. That's not the question. The question is, are there moments when you deviate from-- when you go out to Staten Island, you go out to New Jersey, and why would you need to go there?

Then if you can't really get into Manhattan, does the-- as you were saying, the number of stops that you are out on that train, does that predict something? Can that tell us when you're going to have a disease? Does that tell us how quickly you'll be able to learn something? I think the answer to this resoundingly is yes. To your point, yes, if you're not even close to critical, if you're way off in Nebraska, you're dead. It's just not going to work. There's a lot to be learned from how close you are to criticality and your ability to modulate and move around that space as well.

Paul Middlebrooks
Woody?

Keith Hengen
Sorry, I just monologued at you.

Paul Middlebrooks
No, no, I just--

Woodrow Shew
Yes, I like that. I like that trajectory. That was a big avalanche, Keith. That was like-- went way out to outer space and then back to the very practical. [laughter] I like it. One of the things that I'm really excited about right now in terms of the theory side of what my lab does-- my lab actually does do experiments, but we do theory too. One of the theory projects going on in my lab right now is about-- I really would like to connect the dots here between people who are taking the high-dimensional brain and breaking it into all these different manifolds, and what I've been thinking about for the last 15 years, criticality.

What we find in these, the computational models that lots of people use, is that one brain or one model that's high-dimensional can do lots of different things simultaneously. That is, it can have a manifold that's critical. It can have another manifold that's completely desynchronized and stable. It can have another manifold simultaneously that is oscillating with gamma oscillations.

Paul Middlebrooks
In different subspaces?

Woodrow Shew
Yes. You can break everything down. We had a paper in 2024 about subspaces, but we barely scratched the surface on the topic, really, in that paper. It's blowing my mind a little bit right now that, I don't know, at least from my point of view, a large fraction of the debates in computational neuroscience center around questions of the type, what is the dynamical state of the brain? Obviously, Keith and I are sitting here promoting this notion that criticality is the dynamical state of the brain. There are other folks who would promote the idea that some asynchronous regime is the most important state the brain is in when an animal's awake or inactive, and stuff like that.

There are others. Oscillations. There's many. People argue about them forever. Are they epiphenomenal? Which one's the real one? Which one's the most important one? I think they all coexist at the same time. At certain times, one of them dominates over the other. That's why there's support for all of them in the experimental data. One experiment has a case where the critical subspace dominates. That's what we see. Another case has a case where some oscillatory mode dominates.

Paul Middlebrooks
How does one mode come to in and out of dominance?

Woodrow Shew
It all has to do with how you wire up the network, the interactions network between the neurons. That question, though, that you just asked is a deep question. It's hard to answer that with-- there's a lot of theory out there. There's this random matrix theory stuff that is all about that thing kind of thing really.

Paul Middlebrooks
Going back to some of the early recurrent neural network modeling from Monte and Cicillo, where they emulated a decision-making task that had two different contexts. If they put the contexts as inputs to the system, given one context, then the system would form a low-dimensional line attractor state or whatever. Given another context, its dynamics would form a different low-dimensional state. These were actually trained in as the inputs.

Woodrow Shew
That's a different question. That's an interesting question, but it's a different question of like, how could you control which mode?

Paul Middlebrooks
In that sense, they control it by-- It's just the input. It's a different input.

Woodrow Shew
That could be a big part of it, actually, is the input determines which mode is dominant. Part of the reason I brought that up was just because you mentioned manifolds. The other reason I brought it up was that this notion that Keith was going off about just a second ago, it's like the

inevitability of criticality in some ways. It comes up in this context, too. That is, if you want to have any mode in a neural system or subspace in a neural system that has long timescales, that has persistence of any kind, that's not just-- Yes, you could have it come in dictated by some input that's slow. If you have some input to the system that's driving it at a slow fluctuation, then that will trivially cause a slow--

Paul Middlebrooks
Let's say intrinsic activity.

Woodrow Shew
If you want an intrinsic generated mode that has long timescales, it has to be a critical mode. This is what this theory will tell you. To me, that's profound because there's tons of--The list of things that the brain does that are intrinsically generated and have persistence is, you can't, that list would be hundreds of things. It's like emotions. It's everything. Almost everything we do has persistence in long time scales in it.

I saw a talk at Cosine last spring where they were talking about-- they had these really cool experiments. This was, who is this David Anderson's group. They had these really cool experiments where they're trying to get to the bottom of aggression in mice and they found a manifold. They found a manifold in a certain nucleus in the mouse's brain where there is persistent activity. They found this slow mode that ramps up when the mouse gets angry and slowly goes down when they cool off, and they have some cool methods that they have for identifying what is this slow manifold.

Paul Middlebrooks
Was that in Lisbon? I saw that talk, I believe, but I'm not sure if it was at Cosine or not, this is the most recent one. Yes. Sorry. All right.

Woodrow Shew
He's pinpointed a slow mode, a slow manifold. I'm telling you, a brain cannot create such slow manifolds without being close to criticality.

Keith Hengen
The other point that I want to tack on your point that you tacked on my weird monologue, is this idea that like, we got critiqued on something we wrote that learning only requires very fast pairing of stimuli. That's just crazy. So much of everything that we do, you would think like rage and aggression is a fast, hot, immediate response to a thing. There are slow modes to, that's what he was saying, almost every aspect of what we're doing. Even with immediate sensory processing, when you close your eyes, those systems don't just-- your vision doesn't just stop. There's persistence, there is continuity, and there is reverberation through all of this.

I think the baseline fabric to that is a system self-organized around one of these-- what did you call that discontinuity? What did you call it, Woody?

Woodrow Shew
The boundaries?

Keith Hengen
Yes. Some boundary in parameter space. To make it concrete-- Woody, when you showed me that you could separate out these modes, the first thing to point out is that it's very easy to build, to take a data set, shuffle things. You will not have a critical mode. You can't. It's an inevitability. You can't just shake a bunch of spikes and be like, "Aha, I can select a subset that look critical." That's not true. That's like, let's lead with that. It's not a foregone conclusion.

When Woody showed me the critical subspace and we looked at the avalanche power laws, they were the most beautiful linear, like long-stretched power laws I've ever seen in real data. I think that this layering of modes on the backbone of this reverberating critical framework is, I think it's getting somewhere.

Woodrow Shew
At the risk of sounding like, Paul, you object, like sometimes to being like, we're always going to find what we're looking for. This is going to sound like that, but I think it's actually correct, which is that I think the brain is, it's got a bunch of mixed-up modes. It's not always the case that one single mode is going to dominate such that it's clean and looks like its own thing. Most often what you're going to have is a mix of modes that are apparent, and any given neuron, actually, each neuron participates in multiple modes.

Keith Hengen
Maybe this is what it means to get it right though. Paul, like you're saying, you try to falsify yourself over and over and you could throw up your hands and be like, "Oh, we see this here all the time," but it's not like we just see criticality power laws and that's it, walk away, case closed. You start to realize, oh, there are times when it looks muddier. Why is that? Then you start to say, "Oh, there's different modes," and you're shifting between this and you have quick flexibility around these things in a context-dependent fashion. You see drift as a function of waking time, for example.

I think that John Beggs and Dietmar and all those guys were-- they were right. I think that they were right axiomatically and on first principles. I think they were right in terms of their data. A lot of the controversy has arisen around figuring out the more effective high-resolution ways to look at this, and then the contexts. I don't know. I think that it's-- I'm rambling now. I think you're right.

Paul Middlebrooks
Is there anything that-- We're getting close, and I'm not going to spend all of your day here. It sounds very exciting. Wait, but before I do this, what do you think, based on what you're saying, so is criticality necessary for the mixed modes? Was that the claim?

Woodrow Shew
No, but it's necessary to have slow modes. The closer to criticality you get, the longer the timescales you'll get. In order to get the scale invariance that we sometimes see in the experiments, it requires a mode to be very close to.

Paul Middlebrooks
Okay. Got it.

Keith Hengen
Paul, what I was trying to say is that, even things that people classically assume do not involve a slow mode, I don't necessarily agree with that. Even fast social interactions, even learning and stimulus-driven responses, I think, have slow modes in a real brain.

Woodrow Shew
Yes. Maybe I should be more specific, by slow I mean seconds. Slow compared to the timescale of neural interactions.

Paul Middlebrooks
Neural firings. Yes.

Woodrow Shew
Yes. Slow compared to 10 milliseconds or 5 milliseconds.

Paul Middlebrooks
What's holding you guys back these days? What do you worry about when you're approaching these problems? What--

Woodrow Shew
The NIH?

Paul Middlebrooks
Okay. All right. That's a given. That's a given.

Woodrow Shew
Yes. That's number one.

Paul Middlebrooks
Keith, it's certainly not access to drugs. We can tell that. I like this theme, though. That's fine. I don't know.

Keith Hengen
No, it's good. I think that the thing that I want more than anything now is to really aggressively validate D2 in human data sets because all of this, again, as we said, started out with just observational statistical descriptions. Now, Woody, I again say you're driving the field towards these really interesting predictions and comparisons of conditions. It's still all-- maybe I'm shallow. I want to see this play out in people. It's been hard. Without D2, is it Meisel or Meisel? Do you know how to say his last name? Christian Meisel.

That's like really beautiful work with like-- and what is it? Gustavo Deco, like these long-range temporal correlations, but all of these things are just ever so slightly adjacent to getting at the core of it. To be able to measure proximity to criticality in a mathematically rigorous fashion on a fast timescale in human data, I think that's going to move us forward like a freight train.

Paul Middlebrooks
We think of humans as smarter than mice, their brains are different. Is it a different criticality? What I'm asking about is how criticality differs between species, because it seems like a universal single thing, even though it's not a set point, but it seems like a principle that is required for brains to function the way they do. There are differences amongst brains between species.

Keith Hengen
Simplistically speaking, I think it's the same thing. Think about like building a convolutional network with 1,000 neurons versus 10,000 neurons. In either case, tuning them to a transition, a phase transition or bifurcation in the small network and large network is going to maximize information processing in that network. You're just going to be able to do bigger, more complicated tests. We did a really cool study with Audie Cederberg showing that in, what are they called? The networks we use for--

Woodrow Shew
Reservoir computers.

Keith Hengen
Reservoir computers, that if you took a network and tuned it to criticality, but you gave it a task that was just way beyond it, it didn't matter. It didn't do a better job. It just failed. That'd be like trying to teach a bullfrog to speak Latin. It doesn't have the machinery. It doesn't matter if it's near criticality. Then we replicated what Viola showed, that for a really, really trivial task, it didn't need to be near criticality. It could still solve it short, but when you-- When you match the complexity of a task for the size of that network, you will maximize your performance at critical. I think that fundamental principle, wait, people have seen this in leeches, right?

Woodrow Shew
There's some evidence of scale-invariant fluctuations in leech neural systems. Yes. Okay.

Keith Hengen
Leeches all the way up there, there's evidence of it there, but to make those fundamental predictions about cognition and disease and et cetera, in people is yes, that's where we got to do it.

Woodrow Shew
I'll go ahead and just send a brief plug out there. If you ask what's holding my lab back the most, is I need some better grad students. If there's anybody listening--

Paul Middlebrooks
Oh my God, you just threw your own grad students under the bus, huh? You need some better.

Woodrow Shew
I should have said more, actually.

Paul Middlebrooks
He said better. laughs]

Woodrow Shew
I didn't mean better. **[inaudible 01:30:03]** I need more manpower. Yes. I feel like I'm drowning in the projects that I need to finish.

Paul Middlebrooks
Oh, okay.

Woodrow Shew
There's so many more on the docket that are all exciting.

Keith Hengen
I can vouch for the people in Woody's lab are awesome. It's a cool culture. Those guys, you have a smart team.

Paul Middlebrooks
Yes. Okay. I actually have to run to meet with-- we're going to say goodbye here. You can log off, too. Woody and I can finish up as well, if that's fine. I was just going to ask if there was anything that we didn't cover that you guys wanted to highlight. We didn't really even talk about like all the stuff in the review, which is crazy since, but I'll talk about that in the intro and I'll point people to it. Is there anything, Woody or Keith, if you have to go, go for it.

Keith Hengen
Paul, I just want to quickly say thank you so much. This was a blast, and I really appreciate the chance.

Paul Middlebrooks
Okay. Thanks. Thanks, Keith. I just wanted to ask if there were things that you wanted to highlight or discuss that we haven't.

Woodrow Shew
I think we hit most of the ones that I had emailed you, and I'm more or less. I would maybe mention that if you're going to talk about the review, like one of the things I'm proud of, this was my sabbatical project, where I did this. What I am pretty sure is an exhaustive search for experimental.

Paul Middlebrooks
Over 300 papers, right?

Woodrow Shew
Yes. I did this in a systematic way, where I had a couple of search criteria and got 3,000 papers and then excluded them one by one, down to 320 or something like that. I'm pretty sure I have every paper that reports experimental evidence for criticality, and they're not. I couldn't, of course, talk about 320 papers.

Paul Middlebrooks
But you graphed them. They're in that beautiful figure.

Woodrow Shew
They're in the graph. More importantly, this is something I would like to point to. Maybe it's not appropriate for your podcast, but how about just for you, if you want to? It's that there's a downloadable spreadsheet of all 300 papers.

Paul Middlebrooks
That's great. Yes. Okay.

Woodrow Shew
Which is, I really want people to make use of it. Because it's like, if you need to cite something-

Paul Middlebrooks
That's a great resource.

Woodrow Shew
The spreadsheet has--

Paul Middlebrooks
You did like that huge lead leg work that someone would be frustrated attempting to do if they're searching for something related to the criticality that they're interested in. Right. That's awesome.

Woodrow Shew
It's like, I hope that people will use it and are like, "Oh, and now I can be sure I'm not missing things.

Paul Middlebrooks
I'm going to directly go and download that myself. Thank you for doing that work. The review is great also, and I'll mention again in the intro, but I had read it a long time ago before it was published. All right, well, I will be in touch with you in the near future. Thanks, Woody. I appreciate the time. This was fun. We were all over the place, but it was fun.

Woodrow Shew
That was a little chaotic. I feel like John is more in control.

Paul Middlebrooks
We had two people, too, which was good. Okay. This has been fun. Thanks. Have a wonderful weekend, sir.

Woodrow Shew
You too. See you.

Paul Middlebrooks
Bye.

[music]

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