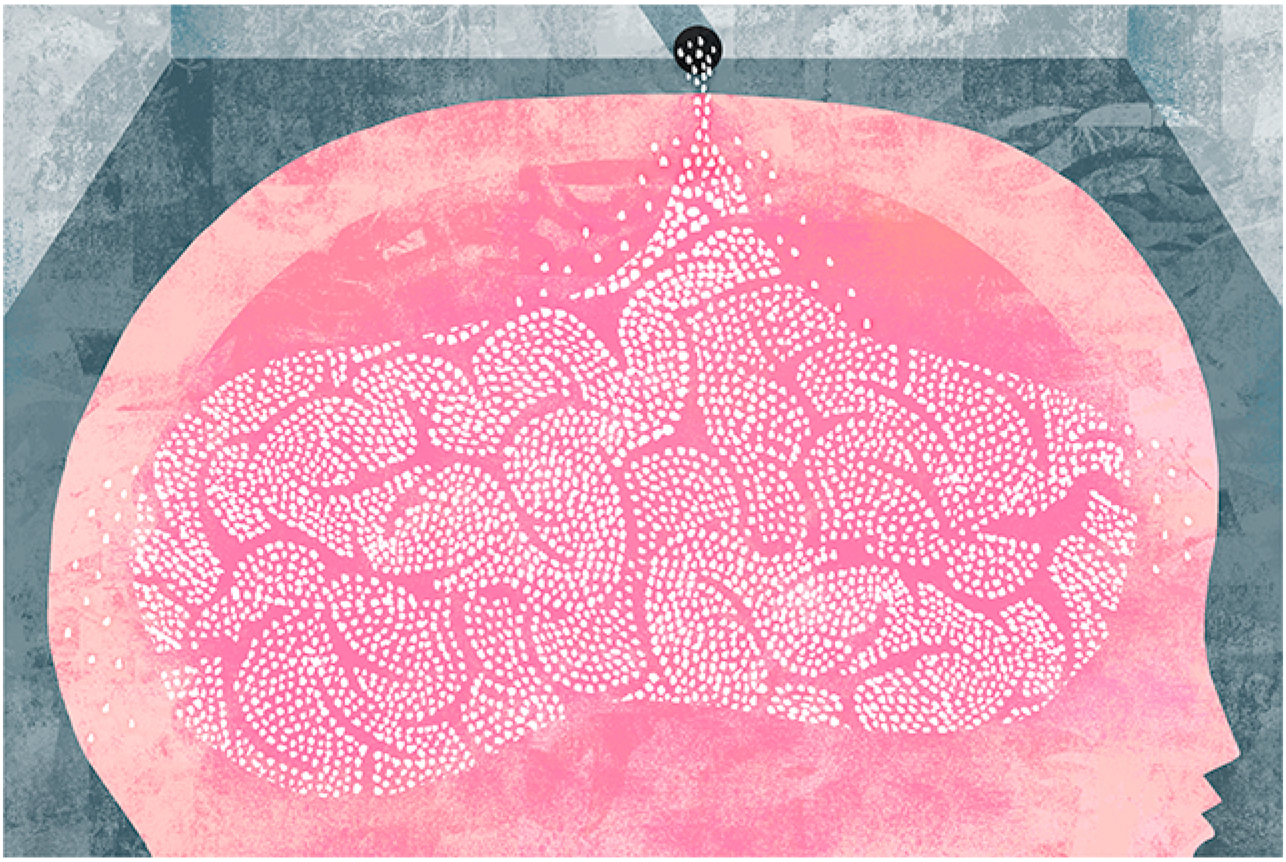
A Fundamental Theory to Model the Mind

By Jennifer Ouellette


Mounting evidence suggests that localized episodes of disordered brain activity, like avalanches in a sand pile, help keep the overall system in healthy balance.

In 1999, the Danish physicist Per Bak proclaimed to a group of neuroscientists that it had taken him only 10 minutes to determine where the field had gone wrong. Perhaps the brain was less complicated than they thought, he said. Perhaps, he said, the brain worked on the same fundamental principles as a simple sand pile, in which avalanches of various sizes help keep the entire system stable overall — a process he dubbed "self-organized criticality."

As much as scientists in other fields adore outspoken, know-it-all physicists, Bak's audacious idea — that the brain's ordered complexity and thinking ability arise spontaneously from the disordered electrical activity of neurons — did not meet with immediate acceptance.

But over time, in fits and starts, Bak's radical argument has grown into a legitimate scientific discipline. Now, about 150 scientists worldwide investigate so-called "critical" phenomena in the brain, the topic of at least three focused workshops in 2013 alone. Add the ongoing efforts to found a journal devoted to such studies, and you have all the hallmarks of a field moving from the fringes of disciplinary boundaries to the mainstream.

In the 1980s, Bak first wondered how the exquisite order seen in nature arises out of the disordered mix of particles that constitute the building blocks of matter. He found an answer in phase transition, the process by which a material transforms from one phase of matter to another. The change can be sudden, like water evaporating into steam, or gradual, like a material becoming superconductive. The precise moment of transition — when the system is halfway between one phase and the other — is called the critical point, or, more colloquially, the "tipping point."

Classical phase transitions require what is known as precise tuning: in the case of water evaporating into vapor, the critical point can only be reached if the temperature and pressure are just right. But Bak proposed a means by which simple, local interactions between the elements of a system could spontaneously reach that critical point — hence the term self-organized criticality.

Think of sand running from the top of an hourglass to the bottom. Grain by grain, the sand accumulates. Eventually, the growing pile reaches a point where it is so unstable that the next grain to fall may cause it to collapse in an avalanche. When a collapse occurs, the base widens, and the sand starts to pile up again — until the mound once again hits the critical point and founders. It is through this series of avalanches of various sizes that the sand pile — a complex system of millions of tiny elements — maintains overall stability.

While these small instabilities paradoxically keep the sand pile stable, once the pile reaches the critical point, there is no way to tell whether the next grain to drop will cause an avalanche — or just how big any given avalanche will be. All one can say for sure is that smaller avalanches will occur more frequently than larger ones, following what is known as a power law.

Bak introduced self-organized criticality in a landmark 1987 paper — one of the most highly cited physics papers of the last 30 years. Bak began to see the stabilizing role of frequent smaller collapses wherever he looked. His 1996 book, "How Nature Works," extended the concept beyond simple sand piles to other complex systems: earthquakes, financial markets, traffic jams, biological evolution, the distribution of galaxies in the universe — and the brain. Bak's hypothesis implies that most of the time, the brain teeters on the edge of a phase transition, hovering between order and disorder.

The brain is an incredibly complex machine. Each of its tens of billions of neurons is connected to thousands of others, and their interactions give rise to the emergent process we call "thinking." According to Bak, the electrical activity of brain cells shift back and forth between calm periods and avalanches — just like the grains of sand in his sand pile — so that the brain is always balanced precariously right at that the critical point.

A better understanding of these critical dynamics could shed light on what happens when the brain malfunctions. Self-organized criticality also holds promise as a unifying theoretical framework. According to the neurophysiologist Dante Chialvo, most of the current models in neuroscience apply only to single experiments; to replicate the results from other experiments, scientists must change the parameters — tune the system — or use a different model entirely.


Per Bak at Rockefeller University in 1998.

Self-organized criticality has a certain intuitive appeal. But a good scientific theory must be more than elegant and beautiful. Bak's notion has had its share of critics, in part because his approach strikes many as ridiculously broad: He saw nothing strange about leaping across disciplinary boundaries and using self-organized criticality to link the dynamics of forest fires, measles and the large-scale structure of the universe — often in a single talk. Nor was he one to mince words. His abrasive personality did not endear him to his critics, although Lee Smolin, a physicist at the Perimeter Institute for Theoretical Physics, in Canada, has chalked this up to "childlike simplicity," rather than arrogance. "It would not have occurred to him that there was any other way to be," Smolin wrote in a remembrance after Bak's death in 2002. "Science is hard, and we have to say what we think."

Nonetheless, Bak's ideas found fertile ground in a handful of like-minded scientists. Chialvo, now with the University of California, Los Angeles, and with the National Scientific and Technical Research Council in Argentina, met Bak at Brookhaven National Laboratory around 1990 and became convinced that self-organized criticality could explain brain activity. He, too, encountered considerable resistance. "I had to put up with a number of critics because we didn't have enough data," Chialvo said. Dietmar Plenz, a neuroscientist with the National Institute of Mental Health, recalled that it was impossible to win a grant in neuroscience to work on self-organized criticality at the time, given the lack of experimental evidence.

Since 2003, however, the body of evidence showing that the brain exhibits key properties of criticality has grown, from examinations of slices of cortical tissue and electroencephalography (EEG) recordings of the interactions between individual neurons to large-scale studies comparing the predictions of computer models with data from functional magnetic resonance (fMRI) imaging. "Now the field is mature enough to stand up to any fair criticism," Chialvo said.

One of the first empirical tests of Bak's sand pile model took place in 1992, in the physics department of the University of Oslo. The physicists confined piles of rice between glass plates and added grains one at a time, capturing the resulting avalanche dynamics on camera. They found that the piles of elongated grains of rice behaved much like Bak's simplified model.

Most notably, the smaller avalanches were more frequent than the larger ones, following the expected power law distribution. That is, if there were 100 small avalanches involving only 10 grains during a given time frame, there would be 10 avalanches involving 100 grains in the same period, but only a single large avalanche involving 1,000 grains. (The same pattern had been observed in earthquakes and their aftershocks. If there are 100 quakes measuring 6.0 on the Gutenberg-Richter scale in a given year, there will be 10 7.0 quakes and one 8.0 quake.)

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Ten years later, Plenz and a colleague, John Beggs, now a biophysicist at Indiana University, observed the same pattern of avalanches in the electrical activity of neurons in cortical slices — the first key piece of evidence that the brain functions at criticality. “It was something that no one believed the brain would do,” Plenz said. “The surprise is that is exactly what happens.” Studies using magnetoencephalography (MEG) and Chialvo’s own work comparing computer simulations with fMRI imaging data of the brain’s resting state have since added to the evidence that the brain exhibits these key avalanche dynamics.

But perhaps it is not so surprising. There can be no phase transitions without a critical point, and without transitions, a complex system — like Bak’s sand pile, or the brain — cannot adapt. That is why avalanches only show up at criticality, a “sweet spot” where a system is perfectly balanced between order and disorder, according to Plenz. They typically occur when the brain is in its normal resting state. Avalanches are a mechanism by which a complex system avoids becoming trapped, or “phase-locked,” in one of two extreme cases. At one extreme, there is too much order, such as during an epileptic seizure; the interactions among elements are too strong and rigid, so the system cannot adapt to changing conditions. At the other, there is too much disorder; the neurons aren’t communicating as much, or aren’t as broadly interconnected throughout the brain, so information can’t spread as efficiently and, once again, the system is unable to adapt.

A complex system that hovers between “boring randomness and boring regularity” is surprisingly stable overall, said Olaf Sporns, a cognitive neuroscientist at Indiana University. “Boring is bad,” he said, at least for a critical system. In fact, “if you try to avoid ever sparking an avalanche, eventually when one does occur, it is likely to be really large,” said Raissa D’Souza, a complex systems scientist at the University of California, Davis, who simulated just such a generic system last year. “If you spark avalanches all the time, you’ve used up all the fuel, so to speak, and so there is no opportunity for large avalanches.”

D’Souza’s research applies these dynamics to better understand power outages across the electrical grid. The brain, too, needs sufficient order to function properly, but also enough flexibility to adapt to changing conditions; otherwise, the organism could not survive. This could be one reason that the brain exhibits hallmarks of self-organized criticality: It confers an evolutionary advantage. “A brain that is not critical is a brain that does exactly the same thing every minute, or, in the other extreme, is so chaotic that it does a completely random thing, no matter what the circumstances,” Chialvo said. “That is the brain of an idiot.”

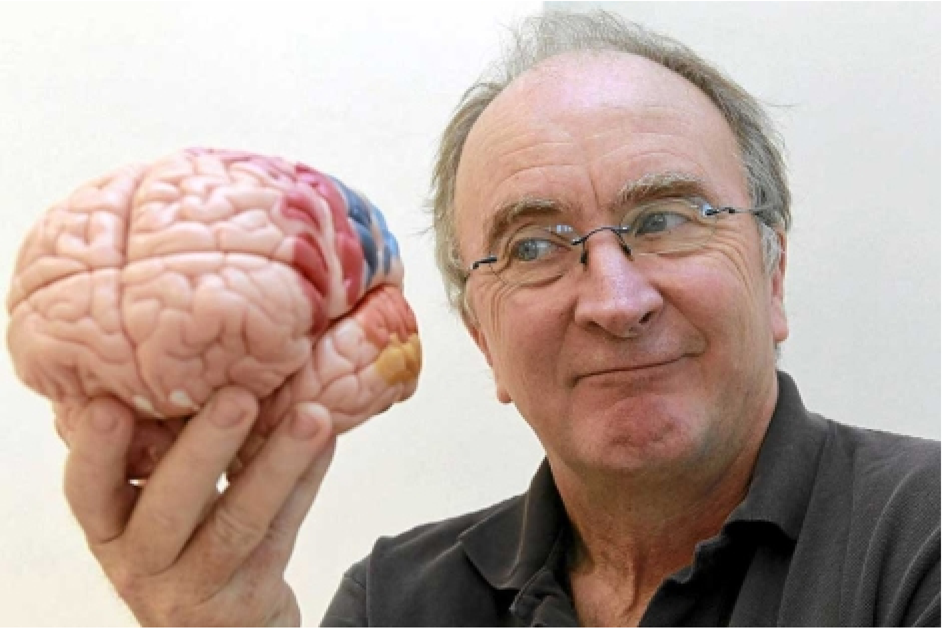

From left: Kim Christensen, Dante Chialvo, Per Bak and Zeev Olami at Brookhaven National Laboratory in the early 1990s.

When the brain veers away from criticality, information can no longer percolate through the system as efficiently. One study (not yet published) examined sleep deprivation; subjects remained awake for 36 hours and then took a reaction time test while an EEG monitored their brain activity. The more sleep-deprived the subject, the more the person's brain activity veered away from the critical balance point and the worse the performance on the test.

Another study collected data from epileptic subjects during seizures. The EEG recordings revealed that mid-seizure, the telltale avalanches of criticality vanished. There was too much synchronization among neurons, and then, Plenz said, "information processing breaks down, people lose consciousness, and they don't remember what happened until they recover."

Chialvo envisions self-organized criticality providing a broader, more fundamental theory for neuroscientists, like those found in physics. He believes it could be used to model the mind in all its possible states: awake, asleep, under anesthesia, suffering a seizure, and under the influence of a psychedelic drug, among many others.

This is especially relevant as neuroscience moves deeper into the realm of big data. The latest advanced imaging techniques are capable of mapping synapses and monitoring brain activity at unprecedented resolutions, with a corresponding explosion in the size of data sets. Billions of dollars in research funding has launched the Human Connectome Project — which aims to build a "network map" of neural pathways in the brain — and the Brain Research Through Advancing Innovative Neurotechnologies (BRAIN), dedicated to developing new technological tools for recording signals from cells. There is also Europe's Human Brain Project, working to simulate the complete human brain on a supercomputer, and China's Brainnetome project to integrate data collected from every level of the brain's hierarchy of complex networks.


Dante Chialvo during an interview with the Spanish newspaper El Mundo in 2011.

But without an underlying theory, it will be difficult to glean all the potential insights hidden in the data. “It is fine to build maps and it is fine to catalog pieces and how they are related, so long as you don’t lose track of the fact that when the system you map actually functions, it is in an integrated system and it is dynamic,” Sporns said.

“The structure of the brain — the precise map of who connects with whom — is almost irrelevant by itself,” Chialvo said — or rather, it is necessary but not sufficient to decipher how cognition and behavior are generated in the brain. “What is relevant is the dynamics,” Chialvo said. He then compared the brain with a street map of Los Angeles containing details of all the connections at every scale, from private driveways to public freeways. The map tells us only about the structural connections; it does not help predict how traffic moves along those connections or where (and when) a traffic jam is likely to form. The map is static; traffic is dynamic. So, too, is the activity of the brain. In recent work, Chialvo said, researchers have demonstrated that both traffic dynamics and brain dynamics exhibit criticality.

Sporns emphasizes that it remains to be seen just how robust this phenomenon might be in the brain, pointing out that more evidence is needed beyond the observation of power laws in brain dynamics. In particular, the theory still lacks a clear description for how criticality arises from neurobiological mechanisms — the signaling of neurons in local and distributed circuits. But he admits that he is rooting for the theory to succeed. “It makes so much sense,” he said. “If you were to design a brain, you would probably want criticality in the mix. But ultimately, it is an empirical question.”

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