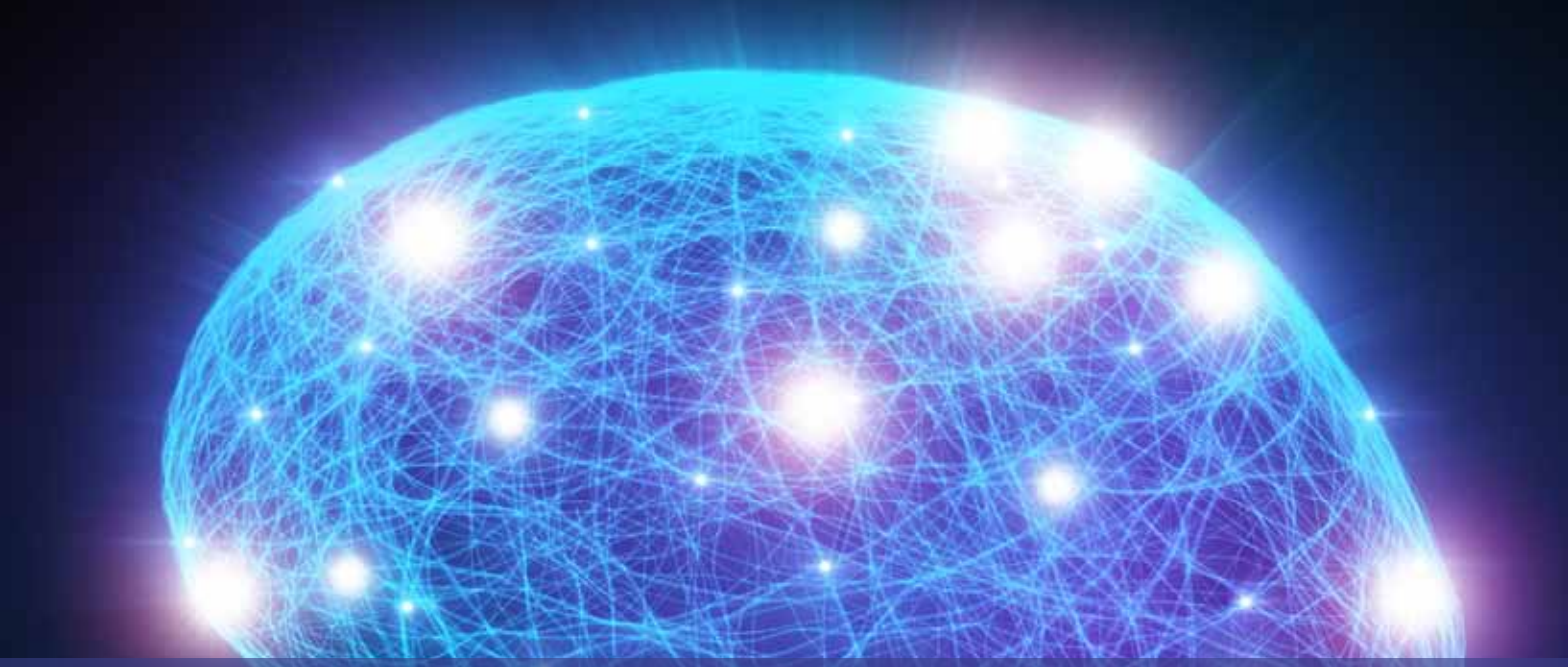


Finding Common Links *for* HUMAN BRAIN, INTERNET, *and* COSMOLOGY

The structure of the universe and the laws that govern its growth may be more similar than previously thought to the structure and growth of the human brain and other complex networks, such as the Internet or a social network of trust relationships between people, according to a paper published last year in the science journal *Nature's Scientific Reports*.

"By no means do we claim that the universe is a global brain or a computer," said Dmitri Krioukov, co-author of the paper, published by the Cooperative Association for Internet Data Analysis (CAIDA), based SDSC. "But the discovered equivalence between the growth of the universe and complex networks strongly suggests that unexpectedly similar laws govern the dynamics of these very different complex systems."

Having the ability to predict—let alone trying to control—the dynamics of complex networks remains a central challenge throughout network science. Structural and dynamical similarities among different real networks suggest that some universal laws might be in action, although the nature and common origin of such laws remain elusive.

By performing complex supercomputer simulations of the universe and using a variety of other calculations, researchers have now proved that the causal network representing the large-scale structure of space and time in our accelerating universe is a graph that shows remarkable similarity to many complex networks such as the Internet, social, or even biological networks.

"These findings have key implications for both network science and cosmology," noted Krioukov. "We discovered that the large-scale growth dynamics of complex networks and causal networks are asymptotically (at large times) the same, explaining the structural similarity between these networks."

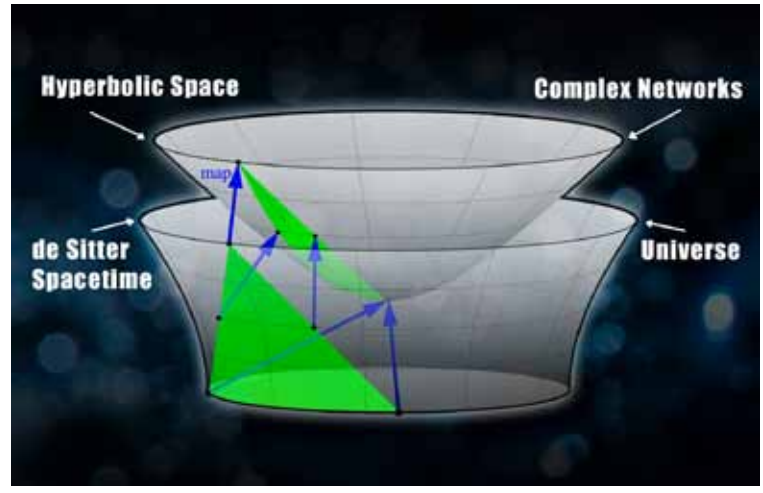
"This is a perfect example of interdisciplinary research combining math, physics, and computer science in totally unexpected ways," said SDSC Director Michael Norman. "Who would have guessed that the emergence of our universe's four-dimensional spacetime from the quantum vacuum would have anything to do with the growth of the Internet? Causality is at the heart of both, so perhaps the similarity Krioukov and his collaborators found is to be expected."

Of course the network representing the structure of the universe is astronomically huge—in fact it can be infinite. But even if it is finite, researchers' best guess is that it is no smaller than 10^{250} atoms of space and time. (That's the digit 1 followed by 250 zeros.) For comparison, the number of water molecules in all the oceans of the world has been estimated to be 4.4×10^{46}.

Yet the researchers found a way to downscale this humongous network while preserving its vital properties, by proving mathematically that these properties do not depend on the network size in a certain range of parameters, such as the curvature and age of our universe.

After the downscaling, the research team turned to *Trestles*, one of SDSC's data-intensive supercomputers, to perform simulations of the universe's growing causal network. By parallelizing and optimizing the application, Robert Sinkovits, director of SDSC's Scientific Applications Group, was able to complete in just over one day a computation that was originally projected to require three to four years.

"In addition to being able to complete these simulations much faster than previously ever imagined, the results perfectly matched the theoretical predictions of the researchers," said Sinkovits.



Simple mapping between the two surfaces representing the geometries of the universe and complex networks proves that their large-scale growth dynamics and structures are similar. Image courtesy of CAIDA/SDSC

The most frequent question that people may ask is whether the discovered asymptotic equivalence between complex networks and the universe could be a coincidence," said Krioukov. "Of course it could be, but the probability of such a coincidence is extremely low. Coincidences in physics are extremely rare, and almost never happen. There is always an explanation, which may be not immediately obvious."

"Such an explanation could one day lead to a discovery of common fundamental laws whose two different consequences or limiting regimes are the laws of gravity (Einstein's equations in general relativity) describing the dynamics of the universe, and some yet-unknown equations describing the dynamics of complex networks," added Marián Boguñá, a member of the research team from the Departament de Física Fonamental at the Universitat de Barcelona, Spain.

Other researchers who worked on this project are Maksim Kitsak, CAIDA/SDSC/UC San Diego; and David Rideout and David Meyer, Department of Mathematics at UC San Diego.

kc claffy is head of SDSC's CAIDA group, and has played a leading role in Internet research for more than a decade responding to industry, government, and academic needs in providing tools and analyses to promote a scalable global Internet infrastructure.