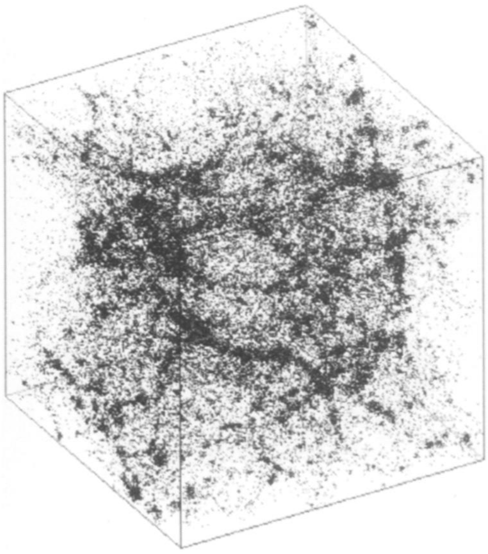
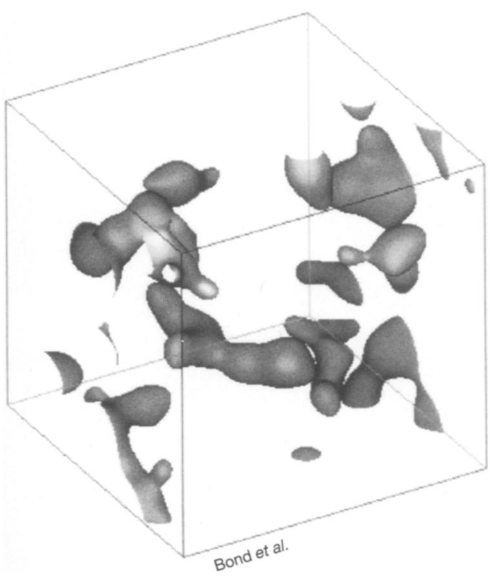
Weaving the Cosmic Web

Bottom up or top down? Now the twain shall meet

By RON COWEN





Top: Computer simulation of structure in the present-day universe. Simulation depicts both large-scale and small-scale features. Bottom: Another perspective on structure in the modern universe smooths over small-scale features and focuses attention on large structures.

When astronomers peer into space, they see a spidery network—galaxies bunched along walls and filaments separated by huge voids. But after decades of theoretical and observational work, cosmologists still understand only poorly how the smooth, soupy consistency of the infant universe evolved into the lumpy patchwork of the modern universe.

In a simplified view, this riddle has two parts. First, tiny lumps that appeared randomly in the primordial mix of hot gas and particles enlarged dramatically during the first minuscule fraction of a second in the life of the cosmos, a period known as inflation (SN: 5/8/93, p.296). Then gravity finished the job, slowly pulling these expanded but still randomly scattered lumps into the patchwork of large-scale structures evident today.

"At some level, it couldn't be a simpler physics problem to understand," notes cosmologist J. Richard Bond of the Canadian Institute for Theoretical Astrophysics at the University of Toronto. "You start with some theory of random perturbations [lumps] and then gravity defines how they evolve."

But in several current cosmological theories, gravity must act in a complex, highly nonlinear fashion in order to faithfully reproduce what Bond and his colleagues now call the web structure. New studies, however, suggest that instead of weaving the structure of the universe out of whole cloth, gravity fills out the shape of an established pattern. The blueprint was already in place.

Like primitive strands of DNA, the tiny lumps in the primordial universe seem to have encoded the master plan for the web structure. The patterns "were there in nascent form from the beginning," says Bond. "They were laid out in the initial conditions [for the universe] in quite a simple way; gravity just expanded them."

That understanding emerges from new work which combines two theories about the evolution of the universe. At a meeting of the American Astronomical Society in Pittsburgh last June, Lev A. Kofman of the University of Hawaii in Honolulu, who collaborates with Bond and Canadian Institute colleague Dmitri Y. Pogosyan, outlined how these once mutually exclusive theories have been married. He said it appears that gravity simultaneously promotes the merger of small objects into bigger ones and guides these merged objects into the larger, weblike pattern.

In the Jan. 1, 1996 ASTROPHYSICAL JOURNAL, a team that includes Adrian L. Melott of the University of Kansas in Lawrence details a related story.

Once upon a time, not so very long ago, cosmologists had two distinct ideas about the way the universe evolved. In the top-down theory, developed by Russian physicist Yakov Zel'dovich and his Soviet collaborators during the 1970s, giant sheets and pancakelike structures formed first. These flat structures later fragmented into smaller objects, such as galaxies and clusters of galaxies.

In the early 1980s, a competing theory gained popularity in the West. It argued that structure evolved from the bottom up. Small objects formed and congregated into increasingly bigger structures as the universe matured. Eventually, this process constructed massive clusters of galaxies.

Neither theory was perfect. Zel'dovich's top-down scenario had difficulty accounting for the emergence of individual galaxies early in the cosmos. And in tightly confining galaxies to thin walls and filaments, it couldn't explain why any galaxies existed at all in the voids in between.

The original bottom-up theory, on the other hand, accounted for small-scale structure extremely well but couldn't reproduce the giant walls, filaments, and voids that telescope surveys began revealing in the 1980s. Indeed, the existence of a Great Wall of galaxies, reported by cosmological cartographers in 1985, shocked many purveyors of the bottom-up scenario.

In 1983, Melott, Sergei F. Shandarin, a protégé of Zel'dovich now at the University of Kansas, and their colleagues proposed a new version of the bottom-up theory. Their proposal, which invoked a type of invisible, hypothetical mass known as cold dark matter, seemed to reproduce some of the filamentary structure and gave bottom-up models the upper hand.

"Many cosmologists feared that the elegant Zel'dovich theory would decline together with the Soviet Union," Kofman wrote in a summary of his new work.

But since the early 1980s, cosmologists have mapped the distribution of thousands of galaxies that lie as far away as 1 billion light-years—roughly one-tenth of the distance to the observable edge of the universe. These observations show that the cosmos exhibits both the large-scale structure indicated by the original top-down theory and the small-scale structure, in which little merges into big, favored by bottom-up models. Computer simulations reveal the same duality.

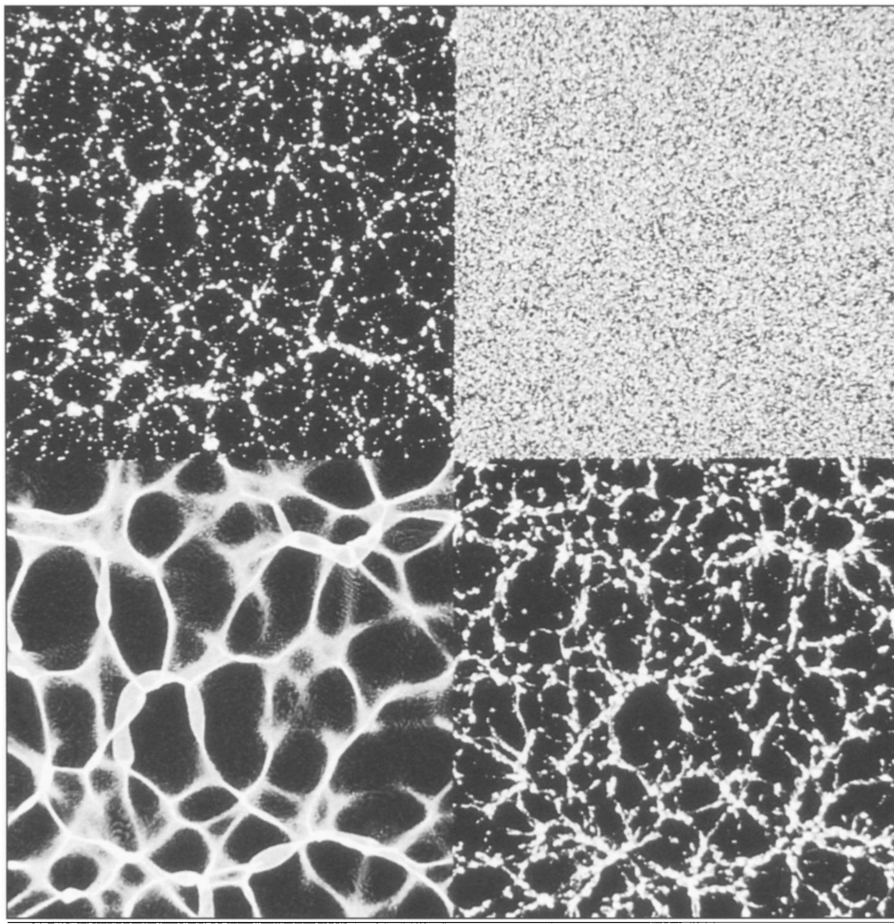
"The real universe is kind of combining the two," explains Melott. "If you want to describe the way structure progresses, you need the mathematics of both."

Melding the theories "*is* paradoxical," he says. "That's why it took a very long time to get accepted."

By way of analogy, Melott recollects that earlier in this century, quantum physicists debated whether electrons and photons were waves or particles.

"Some experiments provided evidence that electrons and photons were particles, others indicated they were waves," notes Melott. "Each is a justifiable way of understanding [the phenomena], but both were incomplete.

"In some sense we're saying that the description of gravitational clustering is incomplete when you use either picture [top-down or bottom-up] in isolation."



Melott, Pauls, Sathyaprakash, Sahni/National Center for Supercomputing Research

Top left: Full computer simulation of the formation of structure in the universe, showing stringy features. Top right: Structure formation in the old bottom-up theory. Bottom right: Top-down theory indicates placement of superclusters of galaxies. Bottom left: Combining the bottom-up and top-down models shows remarkable agreement with the complete computer simulation at top left.

At first glance, structure in the new models seems to develop according to the standard bottom-up protocol. Galaxies coalesce to form bigger galaxies, and these build into clusters. But elements of the top-down model coexist, systematically guiding the path of these massive structures and determining which partners they will merge with next. The net effect is that gravity shuttles the clusters into the familiar patterns of filaments and sheets.

"It's like a flock of ducks moving toward another flock," says Melott. "Together, they form a bigger flock, but with a V-shaped pattern."

Even before two clusters separated by several hundred million light-years have fully formed, says Bond, they behave as if they were aligned. That correlation apparently emerged from conditions present within the tiny lumps at the birth of the universe that later gave rise to galaxies and galaxy clusters. Gravity merely acts to amplify that correlation. Previous versions of the bottom-up theory, he says, hadn't taken into account this linkage, which drives galaxies into the filamentary patterns seen in the sky.

"What we're trying to do is develop the language and the physical understanding" of how computer simulations generate large-scale patterns from particular initial conditions, Bond explains. Such simulations, turning gravity loose on a sea of particles representing the early universe, have indeed done a reasonable job of reproducing the web structure.

But the new work "is much more satisfying than saying, 'Well, I stuck this in my computer and this is what came out,'" adds cosmologist Simon D.M. White, director of the Max Planck Institute for Astrophysics in Garching, Germany.

While it may amount only to semantics, Melott and Bond don't agree on which theory—top-down or bottom-up—plays the leading role in their new models. Melott suggests that top-down dominates because it acts as the organizer of large-scale structure, pushing and prodding the merging galaxies. And in the July 3 PHYSICAL REVIEW LETTERS, Shandarin, Melott, and their University of Kansas colleagues argue that the very first structures to collapse gravitationally in the universe were indeed the pancakelike objects suggested by Zel'dovich.

Bond concurs. But he asserts that the bottom-up mechanism is the key player in forming structure—it just needs a little guidance in moving things around.

Bond notes that he and his colleagues hadn't completely compared their work and detailed computer simulations when they presented their findings at the June astronomy meeting. Now, he says, the team "has nailed it. Unless you can actually go one-on-one with the simulations and say, 'Look at this match,' you haven't done the complete proof.

"My view is that this is now incontrovertible. I'm expecting people will say, 'You've got it, this is it.'" □