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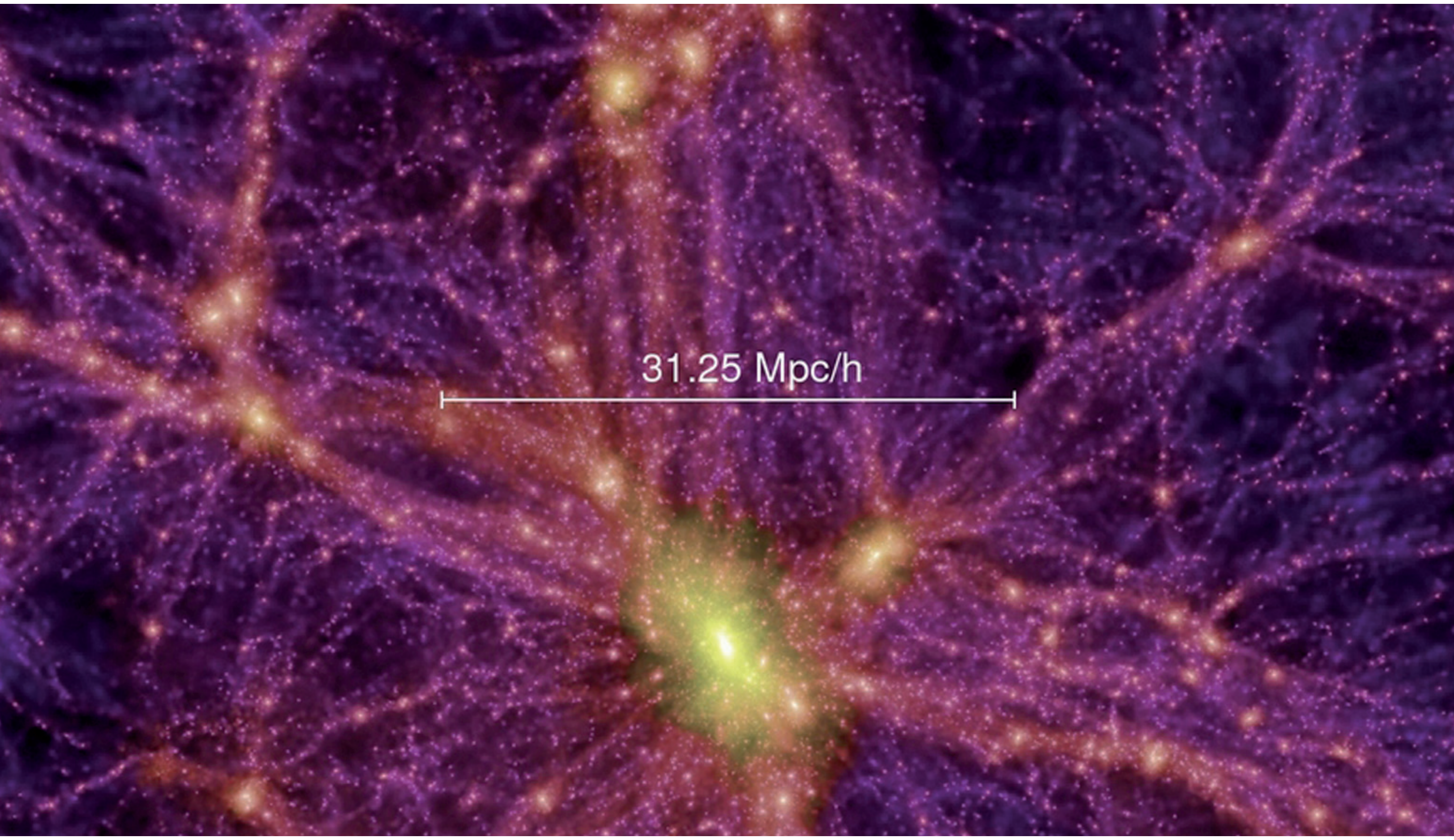

Modeling and Simulation: How Everything Seems to Form and Grow

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Matter and mind can both be viewed as containing packets of energy and information that, in some sense, hide their internal elements from the outside, much like a computer science abstraction or scientific models. As the result of experiment or simulations, these abstractions can be broken down deductively into smaller abstractions or united inductively to form bigger ones.

Lately, there have been reports implying that a brain cell's structure can be viewed as similar to that of the universe's.[1–4] A study published in *Nature*'s Scientific Reports argued that the resemblance between the two could mean that the universe and the brain could have grown in similar ways.[5] A mechanism may be in place in the fabric of the cosmos that guides the growth of systems large and small, from the electrical firing between brain cells and growth of social and computer networks to the expansion of galaxies.[2] It's fascinating to imagine what this universal mechanism might be. Based on some general concepts from computing, cognitive, and natural sciences, this article proposes that the similarities may arise from modeling and simulation, a viewpoint that could have significant impact on computational science education.

Figure 1 shows how matter and mind can form and grow. Here, we call every packet of distinguishable stuff around us, be it information or matter, a model. An apple, an orange, an atom, a neuron, or an electron can each be considered as a model of matter. Likewise, a word, a sentence, a summary, or a book can be considered as a model of information. Each colored circle in the figure is a model that contains internal details hidden from the outside world. Models can unite to form bigger models or break

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down into smaller models. This two-way traffic is illustrated by deductive (top down) and inductive (bottom up) arrows in the figure.

A Universal Process

We can apply this structure to the matter in our universe by having the highest level contain all of space and by having the lower levels, respectively, contain galaxies, stars, visible matter, molecules, atoms, protons, neutrons, electrons, and other smaller fundamental particles. The space and time scales for interactions (such as collisions) among models at each level depend on the physical sizes and intensity of the models at that level. There is a vast difference (say, 10^{-15} versus 10^{+15}) between space scales and time scales of events occurring at the high and at the low interatomic ones. The higher the level, the larger the scales. The tremendous difference between scales creates a disconnect or screening between levels that can be pierced through the use of technology such as telescopes and microscopes. So, while at the microscopic level, matter is made of atoms and smaller particles, at the macroscopic level, we see only their unions and generalized forms. A beneficial consequence of this is that we can focus on the natural world's general features without thinking about its microscopic constituents.

If we apply these concepts to information processing by our minds, the lowest level would contain the tiniest details. As we move up, each level would contain unions of the details below it, with the highest level containing the most general information. The space-time scales discussed earlier would also apply here. The tiniest information packet, such as the letter A, would take less space for storage and less time for processing than those larger packets, such as a word, with this trend continuing all the way to a sentence, paragraph, chapter, book, and so on. Thus, both storage and processing of information involve the distributive (top down) and associative (bottom up) characteristics[6] shown in Figure 1.

In life, we're bombarded with information from all directions, and we deal with it through abstraction, with the higher the level of abstraction, the wider its applicability and validity.[7] Abstraction is a form of inductive thinking that helps our cognitive development by simplifying, categorizing, and registering key information and knowledge for quicker retrieval and processing.[8] Edsger Dijkstra, an early pioneer in programming, regarded abstraction as the most vital activity of a competent programmer.[9]

As humans grow, they deal with detailed and generalized information. In the process of doing so, the details our brain can register and store, the hierarchical connections it establishes between them, and the generalizations, conclusions, and principles it forms through abstractions build over time. There results a pyramid or tree structure, an operational mechanism that we call brain software, or mind.[7] The brain attempts to interpret every new concept and piece of information that it encounters in terms of previously registered models, that is, objects, faces, scenarios, and so on.[8] As we grow older, the relationships among registered information lead to an interplay of various combinations and scenarios that end up inductively clustering related details into conclusions, generalizations, and more inclusive models of information.

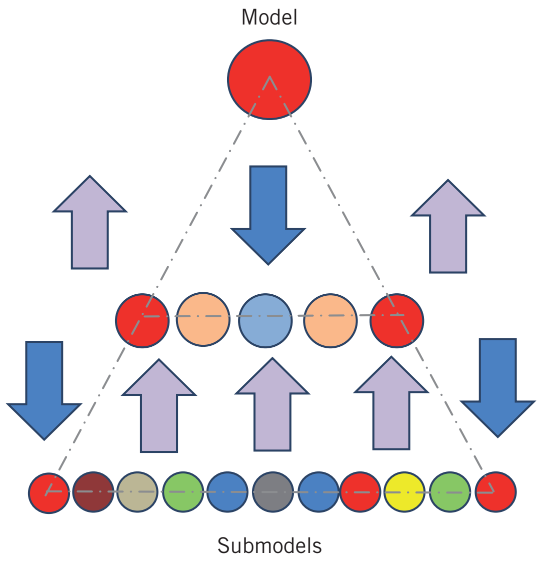

Figure 1. A mechanism of formation and change. Each colored circle in the figure is a model that contains internal details hidden from the outside world. Models can unite to form bigger models or break down into smaller models. This two-way traffic is illustrated by deductive (top down) and inductive (bottom up) arrows.

For example, before the age of 10 to 12 months, babies don't grasp that items falling from their mouths still exist. But as a result of what-if scenarios (simulations) played by their brains and repeated experiences, babies eventually conclude that the item has just fallen out of their reach.[10,11]

Perhaps we've developed abstract thinking as a survival skill to overcome our limited resources of time, memory, and attention.[11] This would explain our tendency to summarize and generalize information before storing it. Likewise, having a limited ability for multitasking might be the reason for our tendency to bring closure to a subject and thus be able to move on to the next one. However, recent findings indicate that both the storage and processing of information in our brains involve a synchronized distributed participation of all neurons in related regions of the brain.[6] Accordingly, abstraction could also be related to the storage mechanism within our brains.

We know from our experiences with parallel computing that efficient utilization of distributed hardware necessitates scatter and gather operations, and that seems to be true for brains as well.[12] A newborn's brain contains 100 billion neurons that get connected to each other in various ways. Information is stored in the memory in the form of a specific pattern of neurons placed on a pathway and fired together.[6] An increase in the number and strength of such pathways improves information storage and retrieval. Accordingly, recording an event's memory could be a combination of previously formed memories, each of which might also involve neural maps of concepts and details. When new information arrives, it appears to activate related neurons and pathways in a distributive process similar to the top-down action in Figure 1, where a model is decomposed into related pieces.

Although obviously related to recording the memory of an event, memory retrieval appears to be a reassembly of its original pattern of neurons and pathways in an associative process similar to the bottom-up action in Figure 1. Remembering is often regarded as an act of creative re-imagination, and what is retrieved probably isn't the original pattern but one with some holes or extra bits. Some neuroscientists argue that there's no distinction between the act of remembering and thinking in the brain.[6] This reminds us of another analogy with the computing world: in computing's early days, data and instructions were stored distinctly, but when the distinction was removed, computing became much easier and more powerful.

Computational Modeling and Simulation

Our view of how the mind learns is somewhat analogous to the scientific method for research, also described in Figure 1. Scientists often start with a model based on their existing understanding and then inductively build a new model or reject the old one based on experiment or simulation. If the new and old models are sufficiently different, then we can say that a conceptual change has taken place.[13]

A new framework[14] for the national K–12 science standards suggests that students learn better if they're engaged in activities closely resembling the way scientists think and work. While this is easier said than done, recent technologies now make it possible to put in the hands of students the tools used by scientists. With its increasing power and ease of use, computational modeling and simulation technology (CMST) has become a common tool.

Over the past decade, I've trained more than 700 pre- and in-service teachers about the methodology and principles of CMST, and my findings indicate that CMST tools are effective in both teaching and learning science and mathematics.[15] Because students learn well with the help of CMST tools, we infer that these tools must be feeding the mind in the manner that the mind actually works, at least as suggested here. CMST tools enabled students to conduct complex science experiments using ready-made models, thereby eliminating the need for some of the usual prerequisite STEM knowledge in math, computing, and science. Students were exposed to STEM concepts in an incremental way as they demonstrated better skills and higher interest. Such a deductive approach created an effective remedy to raise STEM interest among thousands of students in various settings both at urban and suburban school districts.

In addition, students who became proficient in the use of these tools took it a step further by creating their own models and conducting controlled simulations with them. For some, this led to discovery of the underlying mathematical, computational and scientific principles either on their own or with help from teachers or peers. This final step is essentially the inductive process as used by scientists.

Discussion and Key Recommendations

It appears that the brain's distributed neural structure enables it to store, process, and retrieve information in a scatter/gather fashion that matches the distributive and associative characteristics of matter and information.[6–13] Such a harmony among basic gears of a system offers many potential benefits, but we might not be using it to the fullest extent possible. There are many lessons to extract from the universality of such a structure and dynamism.

One problem in education is that students form many misconceptions and preconceptions before they reach school age, which becomes a major challenge to teaching and learning.[8] It's important to provide students with skills and tools and teach them to examine their knowledge, assumptions, concepts, and beliefs by breaking them down to their constitutive details, testing them under various conditions, and finally rebuilding those concepts inductively using newly collected data and facts. This matches the recommendations of recent national K–12 standards to teach early graders decomposition (distributive) and abstraction (associative) skills as part of the computational thinking (CT) skill set.[16] Scientists have already been using CT skills, and it's time to teach everyone, as there are now easy-to-use modeling and simulation tools to foster them at a young age.

The ideas in this article resulted from many years of research in engineering, physics, computer, and cognitive sciences, as well as teaching experience in college and secondary schools. While its main purpose was to discuss the universality of modeling and simulation process and its pedagogical use in teaching, there are several conclusions we can draw.

First, it appears that discrete formation is key to the dynamics around us. If quantifiable (discrete) stuff can form various patterns to make up atomic and cellular structures as well as instructions and thoughts, then everything is computable.[11] Furthermore, basic computable behavior (addition and subtraction) of discrete forms is what leads to inductive (associative) and deductive (distributive) processing. We have come to call this high-level processing "modeling and simulation" in the context of computational processing of information constructs, but it is commonly applicable to natural dynamism of all other discrete forms. Second, it appears that the emergence of a discrete form (model) is an outcome of an inductive process driven by a collective behavior of its submodels as well as relationships and bonds among them. In computational research and education, this process is driven by a researcher or a teacher. In cognition, it's driven by a self-aware brain, and in the case of matter, it's driven by acting forces and fields. While the second thesis applies to all levels, we don't know if that's the same process that led to the formation of the smallest matter units at the very bottom in Figure 1. Our final conclusion is that a model's evolution has a bi-directional orientation, which in the present case would be substantiated if you contacted me with your comments or suggestions. ■

Acknowledgments

The cover image, known as the "millennium simulation" of the universe, is courtesy of the Virgo Consortium for Cosmological Simulations (*Nature*, vol. 435, no. 629, 2005). The author also acknowledges support by the National Science Foundation.

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