SCIENTIFIC COMPUTING

EXTENDING THE MIND

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Almost 150 years ago, the English mathematician John Couch Adams and the French mathematician Urbain Leverrier were separately studying the observed but unexplained perturbations of the orbit of Uranus. Each independently hypothesized a transuranian planet and varied the parameters of the hypothetical planet's orbit until a satisfactory reconstruction of the unexplained perturbations was found. Thus Adams and Leverrier predicted the existence and approximate position of a planet beyond Uranus, which was subsequently found near the predicted position and was given the name Neptune.

When Arno Penzias and Robert Wilson discovered the cosmic background radiation at Bell Laboratories in 1965, it was understood that the radiation would not be completely uniform. To seed the eventual formation of structures, such as the galaxies and galaxy clusters that we see today, there must have been some small inhomogeneity in the mass distribution of the early universe that we would see as small fluctuations in the distribution of the radiation. Since Penzias and Wilson, cosmologists have simulated structure formation under a variety of assumptions, and have determined distributions of initial inhomogeneities that could lead to a universe that looks like the one we live in. Recent observations, first with the COBE satellite, have finally detected the initial fluctuations. The sizes and scales measured are now being combined with the simulations to rule out some theories of the composition of the dark matter in the universe.

◄ SCIENCE COMPUTATION CAN IMITATE NATURE. HERE A LOGARITHMIC FUNCTION YIELDS A SMALL SNAIL SHELL.

The discoveries of Neptune, and of the cosmic-background fluctuations, illustrate how computing brings together theoretical and experimental science. Based on previous observations, theorists develop hypothetical models from which predictions can be made that can be tested by observation or experiment. In the past, this synthetic approach was limited to comparatively simple situations. The availability of high-speed computation has allowed synthetic methods to take their place firmly next to the traditional methods of reductionist analysis.

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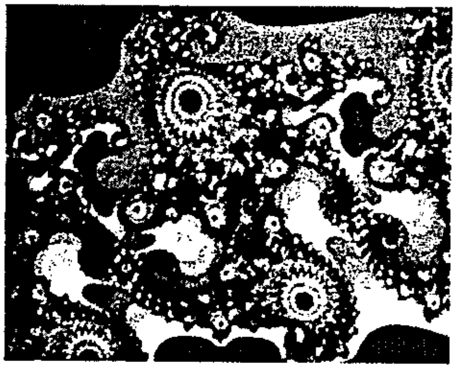
Synthetic computational modeling now plays an important role in diverse areas. Geologists look to computer models to gain insight into tectonic processes and into the origin of the earth's magnetic field. Biologists investigate the consequences of alternative hypotheses of philogenetic trees on the evolutionary history of organisms. Cognitive psychologists now study synthetic computational models in their quest to understand the mechanisms of behavior and language. And economists use synthetic models to understand the consequences of alternative policies.

▶ MANDLEBROT IMAGE



But besides modeling, there are other ways computation is essential. Computation is needed in the acquisition, processing, and interpretation of data. Scientific visualization, including the new field of virtual reality, is an essential tool now at the command of scientists. And with the rapid growth of scientific knowledge, database and network technology have become crucial for access to, and dissemination of, new results.

A great deal of scientific computation is devoted to signal processing. In experimental and observational data the valuable information is often obscured by "noise." We can use powerful mathematical techniques to extract the signal of interest from the confusion of irrelevant signals and noise. For example, in particle physics, huge numbers of events must be filtered in order to find the few that will give us insight into the phenomena of interest. But even after the information is separated from the noise, the data may not be in a useful form. Data must be transformed to make sense of the information produced by instruments like MRI or ultrasound machines, or from an array of radio telescopes (such as the VLA). To support the massive computation required for data acquisition and scientific visualization, signal-processing systems and graphics engines often contain supercomputers.

Many scientific enterprises, such as the Human Genome Project, depend upon the accumulation and correlation of vast amounts of data collected independently by many investigators. Each contributor supplies sequence fragments, which must be pasted together ultimately to form a coherent picture. The task of reconstruction is a massive combinatorial problem, which has required novel algorithms. Computation to support databases and network communication form a foundation for such cooperative enterprises.

The introduction of new tools can revolutionize a field. Galileo's development of the astronomical telescope changed the way we look at, and think about, the universe. But the diversity of application of computers is even more revolutionary.

One way to think about tools is that they are extensions of the human body. A hammer or a pile driver allows one to exert an impulsive force, greatly in excess of what can be achieved with the unaided arm. An astronomical telescope gives the eye a huge aperture. Each of these is a specialized device, designed to extend a particular sense or effector organ. Paper and pencil are extensions of the mind; in particular, of the memory. A computer is different; it is a general tool. Any computer can be configured, by an appropriate program, to implement any information process that can be described formally. This idea was first formulated independently by Alonzo Church at Princeton and Alan Turing at Cambridge: We say that a computer is a Turing-universal machine. The universality of computers explains the diversity of their current applications, and it ensures that new, qualitatively different, and unexpected applications will continue to appear.

The dominant technology of the nineteenth century was mechanical: the control of power for transportation, construction, and manufacturing. The advent of the twentieth century signaled a transition to the dominance of the processing of information, for the new electricity-based communication technologies, such as telephone, radio, and television. The computer revolution of the second half of the twentieth century is the continuation of that trend. We are now seeing the merger of computing with earlier technologies. We find computing engines embedded in other mechanisms, from microwave ovens to smart measuring instruments and adaptive optics. In the twenty-first century we will see the rise of nanotechnology and its close relative biotechnology, eventually leading to real symbiosis between biological and technological beings.

The Digital Universe

Consider an observation of a galaxy by an array of radio telescopes. First, computers are used to point the telescopes and coordinate the reception of the raw data. Then, a computer transforms the raw data into a recognizable image. The picture is cleaned of noise, and foreground stars are subtracted. And finally, the galaxy is isolated and classified according to its essential qualitative and quantitative properties: an Sb galaxy, at a redshift of 0.4, with a rotational velocity of 240 km/s at a distance of 10 kpc from the center, etc.

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Triumph *of* Discovery

A Chronicle of Great Adventures in Science

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Science Advisor to the President of the United States

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