Space-Time Odyssey

Visualizing the effects of traveling near the speed of light

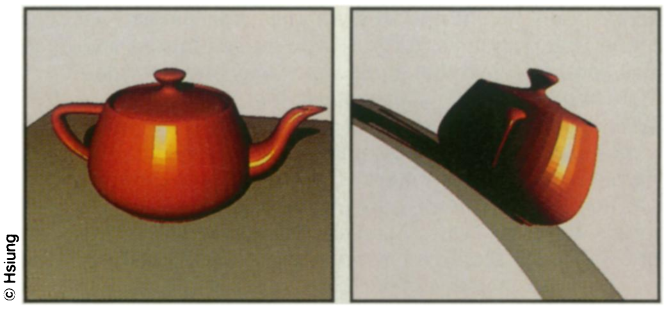
By IVARS PETERSON

To many viewers, the film "2001: A Space Odyssey" reaches its high point with a dazzling sequence of images depicting an astronaut's passage through the Star Gate — a space-twisting trip through a cosmic portal linking distant pieces of the universe.

Two graduate students at Carnegie Mellon University in Pittsburgh have stepped through their own Star Gate, venturing into landscapes no less fantastic and foreign. With the help of an innovative computer-graphics technique and the equations of Einstein's special theory of relativity, Ping-Kang Hsiung and Robert H. P. Dunn are exploring the visual appearance of objects traveling near the speed of light.

Their excursions reveal a variety of startling effects — geometrical distortions, temporal shifts and color changes — that defy intuition. Only when the bare bones of Einstein's equations are clothed in the shape and color of computer-generated images do these effects become evident.

"The visual surprises are wonderful," Dunn says.



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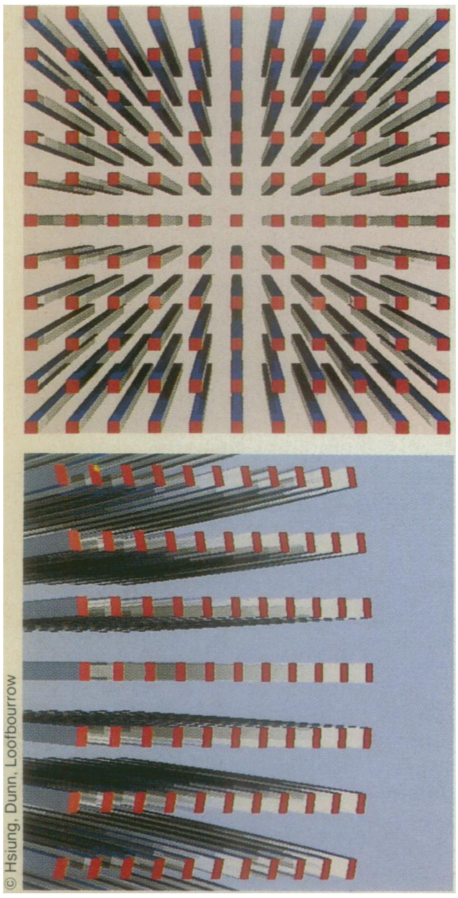
Computer images of a stationary teapot (left) and the same teapot moving to the right at 99 percent the speed of light (right) show how relativistic motion changes an object's appearance by twisting it around to reveal parts not normally visible.



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As an array of rectangular bars seen from above moves sideways, the bars appear to contract in the direction of motion and to rotate about their base so that only the top and rear faces are visible. The cross section of each bar changes from a square to a flattened rectangle. The first image (top) shows the stationary configuration; in the second (bottom), the bars are moving to the right at 0.9 times the speed of light.

In principle, Albert Einstein answered the question of how the world would look if one were traveling at nearly the speed of light when he formulated his special theory of relativity in 1905. His equations reveal, for example, that a body moving at relativistic speeds would appear significantly shorter than if it were at rest.

However, understanding the principles of special relativity doesn't make it easy to imagine how fast-moving objects would actually appear. For instance, for more than 50 years after Einstein's original work, people incorrectly assumed that a photograph of a rapidly moving object would reveal the object's shorter length in a straightforward fashion.

Calculations in 1959 revealed that an optical distortion compensates for much of that contraction. The compensating distortion occurs because a camera records a set of photons that happen to reach the film simultaneously, but the object being photographed may not have emitted all those photons at the same time. For instance, when the shutter clicks, photons from the entire length of an object moving toward the camera enter the lens. But photons from the far end had to be emitted earlier, when the object was farther away. The net effect is to make the object appear longer.

During the 1960s, those calculations initiated a burst of interest in the geometry and optics of relativistic motion. But the complexity of the problem and the lack of tools for visualizing the results forced physicists to stick to extremely simple objects, such as rectangles, cubes, spheres and two-dimensional grids of squares. Without shadows, color and depth, such representations offered at best crude sketches of a rich and complex landscape.

To achieve realistic images of relativistic scenes, Hsiung and Dunn introduced the element of time into a standard computer-graphics technique known as ray tracing. Ray tracing is a kind of simulated photography in reverse, Hsiung says. To create an image, a computer program tracks the path each light ray would follow if it traveled backward from the display screen through a pinhole or lens to the light source. That computed path traces all the reflections and other optical effects a particular light ray encounters as it makes its way through a given three-dimensional scene.

In general, ray-tracing computations assume that light propagates with infinite speed, so that all light rays, no matter how long or convoluted their paths, arrive at the image location at the same time. By keeping track of how long it takes a given light ray to pass from source to image and by introducing the appropriate mathematical corrections for relativistic effects, Hsiung and Dunn bring the finite speed of light to ray tracing.

"From this one change, the diverse

effects of special relativity follow automatically," report Hsiung, Dunn and supervisor Robert H. Thibadeau in the January-February PIXEL.

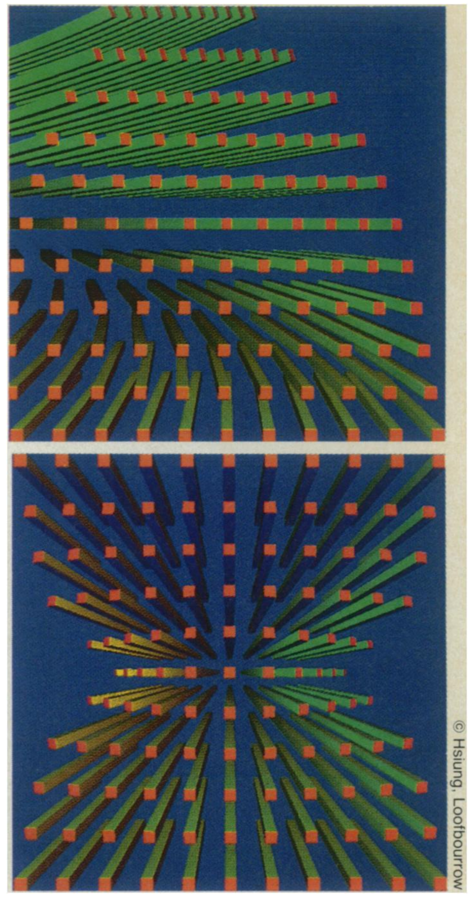
The ray-tracing method also allows for a more experimental or exploratory approach to the study of relativity. "When drawing a diagram by hand, you must understand in advance everything that you intend to show," the team writes. "An image created by ray tracing, however, may very well hold surprises even for its creators."

Using a computer program they call REST-frame, Hsiung and Dunn have created sets of vivid images depicting a number of different moving objects seen from various viewpoints. "It's a very interesting tool, almost like a piece of lab equipment," Hsiung says. "The rules are embedded in the program. We set up our model, and the program constructs the images."

In one set of simulations, the viewer looks down on a set of upright rectangular bars arranged on a square grid, resembling a particularly monotonous city landscape made up of identical office towers seen from directly overhead. When this array slides sideways under the viewer at a speed near that of light, the image appears distorted. The bars contract along the direction of motion and appear to rotate around their base so that only the top and rear faces are visible. At the same time, the cross section of each bar changes from a square to a narrow rectangle.

Another set of images depicts the altered appearance of a cubic lattice, which resembles a Tinkertoy assembly of rods and balls. Moving directly toward an observer at relativistic speeds, the lattice appears to bend back on itself until it looks almost spherical. Interestingly, receding objects show considerably less distortion than approaching objects.

Hsiung and Dunn also obtain surprising effects when they vary their point of view – for example, by glancing sideways as a speeding lattice approaches. "You can look off your direction of motion. That's something no one has done before," Dunn says. "Once you can change your angle smoothly from moment to moment, you see really amazing things."



In the first image (top), each row of bars moves sideways to the right at a different speed. The speeds increase progressively from the bottom row to the top. In the second image (bottom), each row of bars moves toward the observer at a different fraction of the speed of light. The speed is highest in the middle row and diminishes above and below that row.

To add more realism to their visualizations, Hsiung and Dunn have recently tackled the issue of color. Because relativistic motion alters the frequency of light, approaching objects actually would appear more blue (signifying higher frequency) and receding objects more red. Moreover, at sufficiently high speeds, infrared radiation would shift from the invisible part of the spectrum to the visible range. And by shifting into ultraviolet frequencies, rapidly approaching objects could become practically invisible. The team has managed to simulate these color effects for a variety of simple objects.

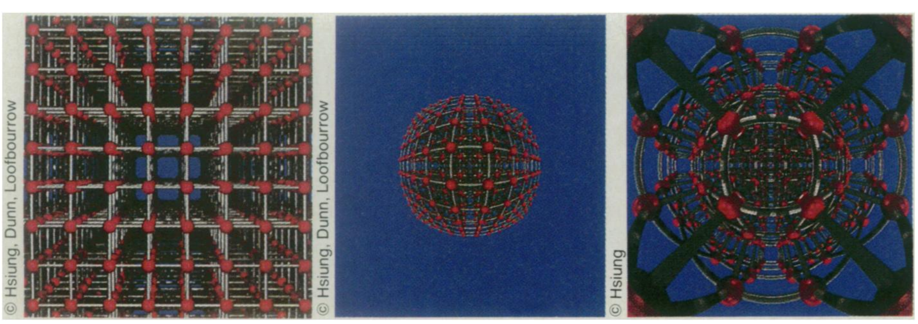
What about flashing lights on a speeding spaceship? Hsiung and Dunn say they can now simulate the way in which relativistic motion alters the rate at which moving clocks keep time. Thus, lights will flash at different rates and in different colors depending on their relative motion and that of the observer.

"We have all three elements – geometric, temporal and spectral – in the program," Hsiung says. "We're now trying to make the computations more efficient and the program more streamlined." He described some of these developments in February at the Association for Computing Machinery's computer science conference, held in Washington, D.C.

Hsiung and Dunn also must watch for errors in their program. Initially, they could check their results against previous calculations by others. But now the scenes are so complex that it's sometimes difficult to distinguish between a genuinely strange effect and a bug in the computer program.

"Sometimes the program produces images we don't understand," Hsiung says. "Usually, when we investigate further, we either find a bug or, more often, discover something that actually makes sense."

"We're working at a level where you can't really anticipate the results," Dunn adds.



When an object in the form of a cubic lattice made up of balls connected by straight rods (left) moves toward the observer at a significant fraction of the speed of light, its edges seem to recede and the rods become curved. The middle image shows the approaching lattice's appearance when moving at 0.99 times the speed of light. As the lattice gets closer, the image becomes even more distorted (right).

Accurate simulations of relativistic effects could play an important educational role not only for physics students at all levels but also for researchers in a variety of disciplines. Astrophysicists in particular may be interested in the appearance of rapidly moving celestial objects as an aid in interpreting their observations of, say, particles swirling at relativistic speeds around objects such as black holes.

Even objects moving at only one-hundredth the speed of light can show subtle but important distortions in shape. By studying computer simulations of astronomical objects moving at modest relativistic speeds, astrophysicists could bet-

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ter appreciate the actual appearance of, for instance, gas jets and outflows from newly formed stars.

"What you see [in any observation] is a kind of illusion," Dunn says. "We're thinking about how to recover reality – how to recreate the original structure [from the illusion] so you can get a more accurate sense of what the object is."

Moreover, the notion of time-dependent ray tracing may have applications beyond visualizing relativistic effects. For example, Hsiung can modify his basic program to keep track of a wave's phase – the location of its troughs and crests. The extra information is sufficient for creating striking simulations of the way light waves sometimes cancel each other out and sometimes reinforce each other to generate the bright and dark bands characteristic of optical interference patterns.

That capability is useful for simulating many kinds of wave phenomena, including the behavior of sound waves. Hsiung thinks the technique holds potential for simulating how radar and sonar signals behave in particular environments.

The innovation's most immediate use, however, may be in video games and advertising, Hsiung and Dunn concede. Imagine a flying saucer zooming past a futuristic skyline at relativistic speeds – in search of the perfect burger. □