We Are Born of Stars

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During the spring and summer of 1985 a 10-minute red/blue computer-animated stereo film, called The Universe: We Are Born of Stars, showed to capacity crowds at the Fujitsu Pavilion at Expo 85 in Tsukuba, Japan. The film tells the story of the creation of chemical elements inside stars, their release during supernovae, and their assembly into small molecules, crystals, meteors, planets, DNA, chromosomes, cells, animals, and finally humans.

Because the color dimension of the film was used to provide stereo when

Figure 1. A galaxy, which sets the scene near the beginning of the film.

Figure 2. A planetscape, showing the earth being formed by collisions with meteorites. The surface texture was created by perturbing the surface normals during shading.
viewed through red/blue glasses, the images here, which show one eye from the film, are in black and white.

**Omnimax**

The film was produced for the Omnimax system, which projects a 70mm film through a fisheye lens onto a tilted-dome theater screen. The image extends 180° horizontally, and goes from behind the head of the average viewer to about 22° below the horizon. It thus includes all the peripheral vision, so there is no frame around the screen to destroy the 3D illusion.

The project occupied two teams of computer animators for over a year, using two of the world’s fastest computers. The “L team,” at Toyo Links Corporation, used the Links-1, an array of 265 microprocessors connected together to do parallel-processed ray tracing. (See “About the Cover,” *IEEE CG&A*, April 1985.) The “M team” used a Fujitsu M-380, which has the same scalar unit as Fujitsu’s VP-200 vector processor, and was at the time the world’s fastest scalar general-purpose computer. The scenes in the script were assigned to the team whose hardware and software was most suitable. The L team built galaxies out of hazy ellipsoidal “fireballs” (see Figure 1), planetscapes, seascapes, moons, and meteors, using bump-mapped textures (see Figure 2), and animals and people out of “metaballs” (see Figure 3). The M team built solar prominences out of fireballs (see Figure 4), reacting nuclei out of intersecting spheres (see Figure 5), and molecules out of semitransparent spheres joined by vectors (see Figure 6).

The Omnimax image is magnified onto 2/3 of a hemisphere, 20 meters in diameter. The original frame must be as large and as high-resolution as possible, so that film grain or pixels will not become visible at this huge magnification. To get the largest

![Figure 3. A parade of animals formed from “metaballs,” which are spheres or ellipsoids that melt together when they overlap. The director designed these balloonlike characters after seeing some early, blobby metaball images.](image1)

![Figure 4. A red/blue Omnimax stereo view of prominences on the sun, formed from many partially transparent fireballs.](image2)

![Figure 5. Nuclear reactions inside the sun. Note the motion blur of the rapidly moving particles.](image3)
possible frame using existing movie film stocks, the film runs through the projector horizontally, with the longest dimension of the frame extending 15 perforations along the length of the film. This gives more than three times the film area of a normal five-perforation 70mm frame, and 10 times the area of a normal 35mm movie frame. It requires high pixel resolution and good antialiasing to use this film area effectively. This is one reason we needed such a large amount of computer power.

Another factor was the attempt to use scientifically correct simulations for the nuclear and molecular dynamics. About half of the programming effort and computer time of the M team went into these simulations, which provided the input to the computer graphics rendering algorithms.

The visual appearance of the film was the responsibility of the director, Saburo Yanase, who is an experienced conventional animator. Preliminary versions of the scenes were recorded at video resolution on one-inch videotape. Yanase would look at the videotapes and suggest changes in camera motion, lighting, or simulation dynamics. In the first two cases we could make a new videotape by rerunning only the graphic programs, but if we needed to change the dynamics, we had to rerun the whole simulation program.

We had particular trouble with the solar prominence scene. It took a year's time for a programmer to invent and adjust the parameters in a simulation of particles moving along magnetic field lines. He filled an hour-long videotape with tests to get a scene that finally comprised less than 15 seconds. The videotape saved the expense of recording many versions on 70mm film. The composer also used an edited tape of the test shots to time his music before the 70mm film version was available.

**Handling distortion**

The fisheye lens introduces distortion when the flat film image is projected onto the dome. In live filming, this distortion is exactly counteracted by the fisheye lens in the camera, but in computer animation the distortion must be introduced while rendering the image. The effect of the lens was approximated by a polynomial equation relating the distance on the film from the center of the image circle to the angle on the dome from the center of projection.

For the L team animation, the ray for each pixel was traced through the lens and distorted appropriately before being extended into the simulated environment.

At the M team, where I spent most of my time, we used a different approach. Our scenes were composed of small spheres, ellipsoids, or vectors. Each of these objects can be scan-converted and shaded with a simple image-space algorithm. Therefore we approximated the lens projection by a linear transformation in the neighborhood of each object, so that spheres in the model dome were drawn as ellipses on the film, and vectors in space were drawn as straight lines. (If a vector was too long, it was subdivided into shorter segments to approximate the correct curve on the film.)

**Motion blur**

The objects were sorted in depth, and rendered in order from rear to front into a raster in memory, using a painter's algorithm with transparency. This "2½D" algorithm also made it easy for us to introduce motion blur.

Good motion blur is essential in Omnimax, where rapid camera motion is often employed to add thrill to a scene. With motion-sensitive peripheral vision involved, the viewer gets a realistic feeling of speed through space, so most live Omnimax films include helicopter shots. Even if the camera is aimed in the direction of the helicopter's motion, it is actually panning across the environment at the sides, top, and bottom of the 180° image. The resultant rapid motion of the environment across the frame causes strobing, where a high-contrast edge appears in several different frozen positions instead of moving smoothly.

Until the last two years, computer animation has accentuated this strobing problem because it simulated the environment at a single instant of time. We wanted to introduce motion blur by integrating the moving image during the finite time interval that a simulated shutter is open. In our 2½D algorithm, we could blur each object individually. We also blurred the corresponding transparency mask, which we used to partially
obscure the background before each new object was added.

For small raster images of spheres or atomic nuclei, we assumed a single direction of motion for the whole image, and produced a blurred image in three passes. We first skewed the image so the direction of motion was either horizontal or vertical, then blurred the skewed image, and finally unskewed the result.

Blurring a raster image in a horizontal or vertical direction is particularly simple. The blurred value at a pixel depends only on an integration interval of contiguous input values, all in the same row or column. The blurred values can be computed incrementally, since the integration intervals for two adjacent pixels overlap, except for one pixel at each end.

Vectors were treated differently, because vector endpoints must be able to move independently if a network of connected vectors is to hang together as it changes during the shutter-open time. We therefore wrote a separate program which blurred arbitrarily moving variable-width vectors as it scan-converted them into the raster image. The details of these two motion-blur algorithms are given in the SIGGRAPH 85 conference proceedings.3

**Atoms hit audience**

With these two programs we were able to simulate a rapid, careening flight through a vibrating ice crystal. At several points the camera turns or spins by 90°, and the atoms and bonds blur instead of strobing or doubling. This scene was one of the most exciting in the film. The viewers often tried to touch the atoms, which seemed to be moving just at arm’s reach. People even ducked when they were about to be hit in the head. Ducking doesn’t help; due to the geometry of stereo viewing, you can’t move your head out of the way. But in fact, the hard shiny atom spheres feel soft as they pass right through your face. I had objected to the idea of allowing atoms to hit the viewer, thinking it would destroy the 3D illusion. But the director insisted on doing it, and now I know he was right.

**Making stereo work**

Producing convincing stereo presented another problem, which arises from the 180° field of view. Consider what happens when two Omnimax cameras are placed side by side. It is physically impossible to bring the lenses of two cameras as close as the separation between two human eyes. But one proposal for Omnimax stereo filming of live action was to put two fisheye lenses in front of adjacent frames in the same camera, to give alternate-eye stereo. Figure 7 shows that this will give good stereo separation for objects in front of the lenses, but Figure 8 shows poor stereo separation for objects at the side.

In the dome theater a viewer should be able to turn to the side and still see good stereo, so we needed to simulate different eye positions for each part of the image. In the ray-traced images from the L team, we determined separate simulated eye positions for each vertical scan line, so that the microprocessor assigned to that scan line needed to translate its data only once. For the object-projection images from the M team, we determined eye positions from a head turned to look directly at each object. The object was then projected from one eye onto the dome and finally back from the dome onto the film.

![Figure 7. Two adjacent fisheye lenses recording images of an object in front of them. They view the object at different angles, which produces good stereo separation.](image1)

![Figure 8. Two adjacent fisheye lenses recording images of an object to the side. They view the object at almost the same angle, so the stereo separation is poor.](image2)
We studied 35mm red/blue stereo scenes on a small test dome before we rented the expensive large-format IMAX cameras. Separate lens distortion and dome geometry coefficients were prepared for this test set-up, so that we could simulate the same 3D model that would eventually appear in the theater. Nevertheless, the final images had a completely different feel on the large dome, so we found stereo tests of single frames in 70mm were also necessary.

The purpose of the stereo tests was to determine the stereo magnification factor, which was a constant, multiplying all the coordinates in the scene. The coordinate origin was at the viewer's head, so if all coordinates were multiplied by two, everything would become twice as far away and twice as large. This would have no effect on the composition of a mono view, but would change the apparent size of everything when the scene was viewed in stereo. For example, in the scenes showing Saturn or the sun, we could make everything of astronomical size, extending beyond the dome towards infinity. This would decrease the 3D, because the stereo separation of distant objects is minimal. On the other hand, we could bring the rings of Saturn or the solar prominences close to the viewer, to make the stereo interesting. But then we would give the feeling of a toy planet or sun. There were some interesting arguments between groups supporting these two alternatives.

The DNA molecule

The scene that was my personal responsibility showed a DNA molecule, starting at the level of single atoms and ending up as a whole chromosome. This scene lasted over two minutes and contained smooth transitions between many levels of detail, with different representation styles, geometries of coiling, and dynamic simulations.

There was a tremendous change of scale during the scene, which was accomplished by gradually moving the viewpoint away, while continuously adjusting the stereo magnification factor to shrink the size of the chromosome and keep it inside the dome. Objects faded with distance, and became invisible beyond a certain limiting distance. During the animation we gradually increased this distance to show more and more of the chromosome.

Figure 9 shows a ball-and-stick model of a DNA double helix, gradually winding around hazy histone protein spheres. The atoms vibrated according to a molecular dynamics simulation, which calculated the atomic positions using Newton's law of motion, taking into account the attractive and repulsive forces between each atom and all the others. In Figure 10 the histones have joined together in groups of eight, and the DNA that coils around them is drawn as a ladder. The transition between the ball-and-stick and the ladder form was a continuous one, controlled by the distance from the camera. In a transition zone of distances, atoms gradually moved from their positions, as predicted by the simulation, towards one of the vertices of the ladder, and one bond in each base pair stretched to form a ladder rung.

At the top of Figure 10, and also on the cover, you can see the next
Figure 10. Histone-DNA units arranging themselves into a chromatin fiber.

level of coiling, where the histone-DNA units are organized in a spiral called a chromatin fiber. It would have been very difficult to make a simulation that formed such an ordered structure naturally. Instead, we started with the ordered spiral, and pulled on the DNA at the bottom to unwind it. Then we used the simulation data in reverse order to make the animation. (We used the same trick when showing water freezing to the ice crystal: We simulated ice melting and then filmed it in reverse.)

In the next level of coiling, the chromatin fiber spirals outward from a central protein scaffold, and then bends and follows an interwound spiral back again. This forms a collection of horizontal prongs, shown in stereo in Figure 11. During the animation I applied a twist to the chromatin fiber, which caused the prongs to spin and grow outwards, and also to rotate at different rates about a vertical axis. This is the same behavior you will see if you twist a stiff rope or electric cord. The axis curve followed by the fiber was defined by piecewise cubic arcs, and it took some complicated differential geometry to figure out how much twist was present in a given curve. At the level of detail in Figure 11, the DNA is represented as a single thick curve, and the eight histone spheres in each group have been replaced by a single larger sphere.

Figure 12 shows the final level of coiling in progress, with motion blur evident near the top, where the prongs are rotating rapidly. One arm of the chromosome is formed by wrapping the vertical axis, to which the prongs are attached, around another spiral, while keeping the prongs horizontal. At the end of the scene, a second arm moves in from the side of the dome, and the camera pulls back to reveal the familiar chromosome shape.

The chromatin fiber is now represented by a single shiny tube. Instead of using polygons or some other surface representation, I built the tube out of many overlapping “cylinder” spheres. I shaded each sphere as if it were part of a straight cylinder, whose axis was tangent to the axis curve for the tube, and used soft-edged spheres, so that the shading and highlights melted together where the spheres overlapped. But I clipped each sphere to a smaller width by lines parallel to the cylinder axis, so that the tube itself would not have a soft profile. For the transition frames between the representations in Figures 11 and 12, I sorted the cylinder spheres for Figure 12 slightly in front of the corresponding histone spheres and DNA vectors for Figure 11, and made the transparency of the cylinder spheres a decreasing function of distance. So as the camera pulled back, it appeared as if the chromatin structure became covered by a transparent glassy sheath, which gradually grew opaque.

The different structures in Figures 9 through 12 have all been observed by electron microscopy, but no one has seen the transitions between them. Therefore, except for the atomic vibrations at the beginning, all the dynamics in the scene are a plausible fiction. Nevertheless, the sequence is being requested for use in medical school classes, because it explains how a piece of DNA many times longer than a cell is packaged.

Figure 11. A twisted chromatin fiber. To view this stereo pair, you must relax your eyes so that they converge near infinity, with the right eye looking at the right image, and the left eye at the left. At the same time, you must focus on the page. This is difficult, since the focus and convergence controls are linked in your brain. You may be able to obtain a stereo viewer with lenses to help you focus on the page. If you wear glasses for nearsightedness, it also helps to remove them.
into a compact chromosome during cell division.

Figure 12. One arm of a chromosome. The tube representing the chromatin fiber is formed from many overlapping hazy spheres.

The hard part

I am sometimes asked what was the most difficult aspect of the film production. I answer that in my opinion it was the quality control of color in the film recording, processing, and post-production optical effects. Because the red and blue layers in color film respond differently, we made two different exposure translation tables for the two eyes' views. We needed to maintain consistent film-processing chemistry and temperature, and printing lights and exposures, to insure that the final print was exposed in the same way as the samples used to prepare the translation tables. This was a difficult task, because of the many steps in the printing process.

We needed a splice-free color printing negative, containing all such optical effects as cuts, fades, dissolves, and superimposed titles and credits. To allow greater flexibility for color correction in producing this negative, and to provide for the future possibility of making a black-and-white mono version of the film, we decided to record each eye's image.

Figure 13. Members of the production team viewing a test print in the Fujitsu Cosmos Dome. Note red-blue glasses, plastic covers on the newly-installed seats, and warm clothing. (This was January, and the theater had no heat, since it was designed for only one summer's use.) In the front row are (left to right) Nelson Max, the computing director, and Koichi Omura, who designed the Links-I computer. Above and between them is Kojo Ichihashi, the technical director.
on a separate negative in black and white. From these negatives, two separate prints were made. A specially modified Omnimax-format optical printer exposed both these prints through colored filters, to produce the composite printing negative. This in turn was used to make the final "release" prints. Thus there were a total of four generations of film, and we tried to compensate for the nonlinearities in all the recording and printing steps by measuring the density of the final release print to prepare our translation tables. This meant that each iteration in our tables took at least a week of printing and processing.

We found that the dynamic range of the blue was much smaller than that of the red. This meant that the blue image was darker than the red, and could show less contrast. Now the apparent size of a smoothly shaded object, especially one with a hazy edge, seems to be determined from a contour where the contrast changes most rapidly. So if the contrast were different in the red and blue images, an object would appear a different size to each eye.

To further complicate matters, we were using two different film recorders: a recorder built specially for the Links-1 by Osaka University, and a Dicom D48 used with the Fujitsu equipment. These two recorders had different phosphors of different colors. There is no black-and-white film stock available in 65mm or 70mm, so even the black-and-white images had to be recorded on color film, which picked up the phosphor color. So we had additional problems color-balancing the scenes from the two teams.

We did not have enough disks, nor want to handle enough tapes, to store all our raster data, so we could not easily change the color tables after our scenes were recorded. We had to rely on what little flexibility remained in the printing process. Needless to say, the color control was quite a task for the team at Far East Laboratories, which did our post-production work.

All the hard work on The Universe seems to have paid off. Journalists rated the Fujitsu Pavilion as the most popular at the World's Fair, or else as tied with a Japanese government pavilion where robots walked and played the piano. Now that Expo 85 has closed, the film is being distributed internationally by IMAX Systems, and it should be possible to see it in a theater closer to home.

References


Nelson Max is a computer scientist in the Computer Graphics Group at Lawrence Livermore National Laboratory. He has taught mathematics and computer graphics at the University of California at Berkeley, the University of California at Davis, Carnegie Mellon University, and Case Western Reserve University. He was also director of the NSF-sponsored Topology Films Project, which produced computer-animated educational films. Max's research interests are in achieving realism in high-resolution raster images and in efficiently generating computer animation. He spent more than a year working on The Universe at Toyo Links in Japan.

Max received a BA from Johns Hopkins University and a PhD from Harvard University, both in mathematics. He is a member of the ACM and IEEE Computer Society.

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