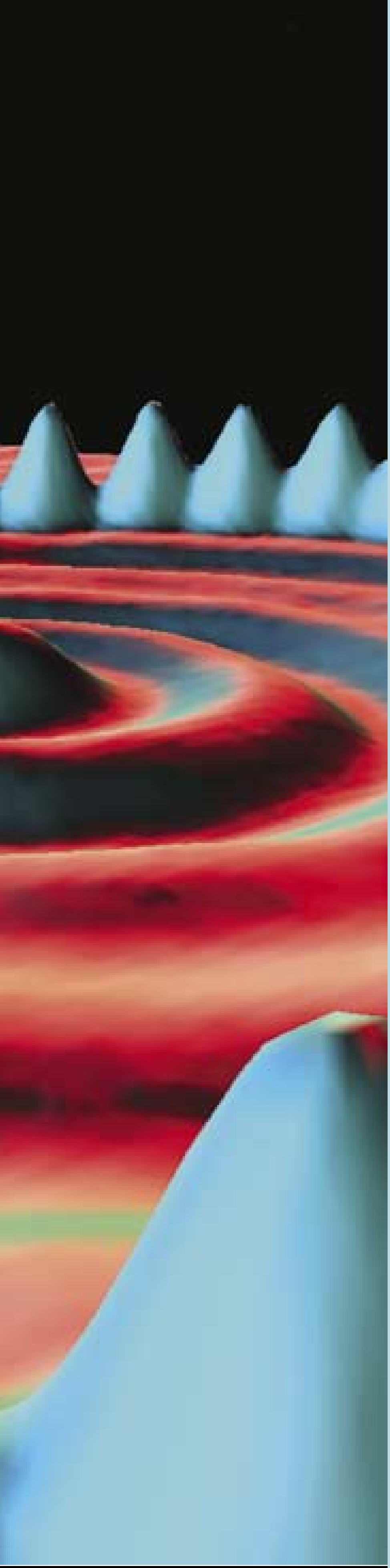


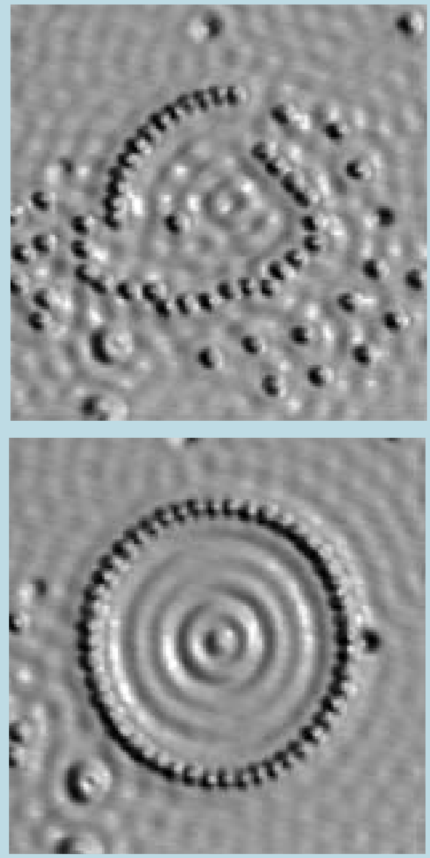
Sightings

Felice Frankel

In this observer's opinion, the "orange and blue quantum corrals" shown in full on pages 262–263 have become contemporary scientific visual icons, in the same category as NASA's "earthrise" image or Doc Edgerton's splashing milk drop. Don Eigler and Dominique Brodbeck were instrumental in developing these images at IBM. Here they discuss the process. The reader should take note that an important visual component of both images is the representation of the electron eigenstates—wavelike structures—within the corrals. The drama of the atomic peaks might distract our eyes, but with such amazing science, does it really matter?

F. F. Don, tell us how you collected the data and then processed that information, turning it into an image.

D. E. We used a scanning tunneling microscope, in which a metal needle under computer control is made to move along the contours of the surface being imaged. The height of the needle at each location on a square grid of points is recorded as a number in the computer. This sequence of numbers representing the height of the surface at each point on the grid is then rendered by the computer to look like a three-dimensional solid.



Scanning tunneling microscope images showing the surface before *(top)* and after the microscope arranged iron atoms into a "corral."

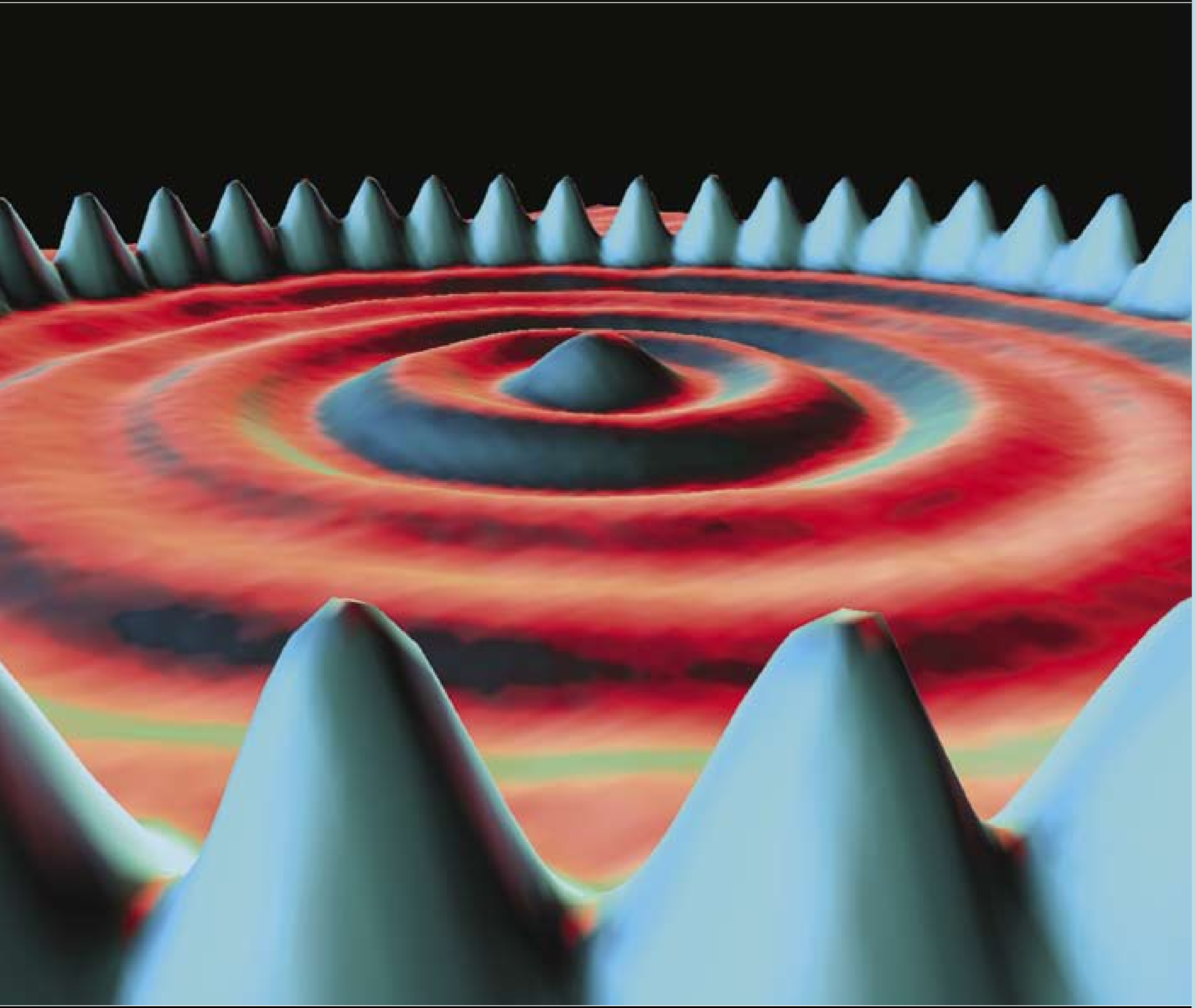
The orange corral was something that I did specifically for the cover of *Science*. I wanted to create an image with as dramatic a perspective as possible to entice the editors into using the image on the cover of the magazine. I chose the colors, "lighting conditions" and point of view of the observer to suit the purpose of the moment. We do rendering of the data during data acquisition, but it is much more rudimentary: just black and white and usually a top-down view of the data, without the benefit of 3-D perspective. During construction of the corral we were looking at data that very much appeared like the images at right.

When Dominique Brodbeck created the blue corral image, we had a more educational or scientific purpose in mind, and so the perspective is one in which you get a much better idea of the shape of the corral and the shape of the waves in the interior of the corral. Nonetheless, Dominique's image appeared on the cover of *Physics Today* (November 1993).

But for the *Science* cover, in a sense, I started with an empty canvas (a black computer screen) and a concept about what I wanted to achieve. I began to apply paint. It was a matter of displaying the corral in 3-D and then searching for the combination of perspective, lighting, surface properties and color that communicated what I wanted to communicate. So the final image came to reveal itself in steps as I worked with computer knob-things.

I wanted others to share in my sense of being an intimate observer of the atoms and the quantum states of the corral. That is why I put the point of view so low and close to the ring of atoms. But it wasn't quite as casual as the preceding statement might imply. I was searching for something and found it.

(continued)



Electrons are confined in a "quantum corral"—a circle of 48 iron atoms *(blue peaks)*, just 143 ängstroms in diameter, that have been arranged on a copper surface with the tip of a scanning tunneling microscope (STM). The circular oscillations reveal the density distribution of electrons occupying quantum states of the corral, also measured by the STM, and show that they form standing waves, a phenomenon not directly observed before this experiment in 1993. Corrals shape the spatial distribution of surface-state electrons so that the properties of electrons in reduced-dimension systems can be studied. (Image courtesy of the American Association for the Advancement of Science and IBM Almaden Research Center. It accompanied Crommie, M. F., C. P. Lutz and D. M. Eigler, 1993, Confinement of electrons to quantum corrals on a metal surface, *Science* 262:218–220.)

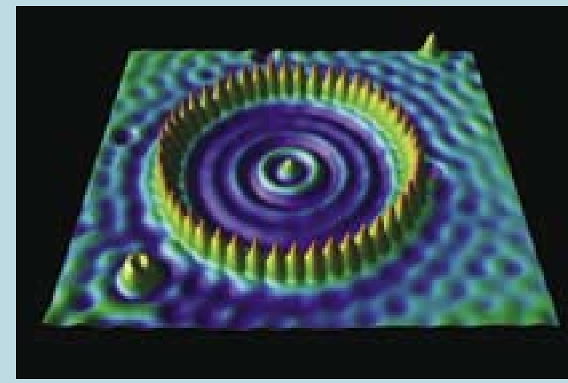
F. F. Do you remember your response when you finally finished the process?

D. E. There definitely was a response on my part when I looked at the completed structure for the first time. I don't have an exact recollection, but I'm fairly confident it was something like "Cool! There is quantum mechanics!" The symmetry and simplicity of the waves in the interior of the corral have a special meaning to a physicist. These things were entirely predictable, and we routinely work them out in our problem sets when we take courses in quantum mechanics. We knew of them in a purely cerebral way. But here they are, alive to our eyes and responsive to our hands ... quantum mechanics made visceral! The realization that you can build a quantum state of your own design, see the result, and change and shape the quantum state like a lump of clay ... well that's just candy to a physicist. The corrals evoke a delectable intimacy between us and the quantum world.

F. F. Dominique, describe to us the differences between the two images.

D. B. Both images try to visually separate the ring of atoms from the wavy surface, but there is a significant difference in how this is achieved. In the orange corral, the separation is achieved by using a clever combination of different-colored light sources (turquoise from the left, red from the front directly into the camera) and surface-reflection properties. This is quite tricky and takes a lot of trial and error in practice. I guess this was only really feasible because Don's workstation is equipped with a special dial-and-knob box that maps all these parameters to hardware controls and allows a very direct way of interaction. (It would actually be interesting to study how the haptic experience influences the interaction.) Plus the rendering is fast enough to show the changes in real time. I think interaction is key here.

For the blue corral, on the other hand, the separation effect was achieved by coloring the surface by height, using a color map that assigns a single color to a particular height above ground. There are far fewer degrees of freedom to handle compared to the technique described above. The lighting setup then just uses a white light coming from behind left, at a polar angle that maximizes the sense of shape of the subtle wave pattern outside of the corral.



"Blue corral" image, published on the cover of *Physics Today* in November 1993, displays the full quantum corral using a different perspective and coloring scheme.

From an image creator's point of view, what I always liked about working with STM data was the fact that the surfaces are very similar to landscapes, and that you can apply the same design guidelines and intuition as you do in landscape photography.

F. F. Don, can you briefly give the history of this technology?

D. E. It happened in five distinct steps.

Step 1: Invention of the scanning tunneling microscope and its ability to create atomic-resolution images (Gerd Binnig and Heinrich Rohrer, the 1986 Nobel Prize in Physics with Ernst Ruska)

Step 2: The design, construction and operation of a low-temperature (4 degrees Kelvin) ultra-high-vacuum STM that would allow the study of atomically clean, well-characterized surfaces at temperatures low enough to stop the thermal diffusion of atoms on a surface (Eigler)

Step 3: The demonstration of the ability to manipulate individual atoms with atomic precision using a low-temperature STM (Eigler and Schweizer 1990, *Nature* 344:524–526)

Step 4: The discovery that the standing waves due to surface-state electrons could be imaged with the STM (Crommie, Lutz and Eigler 1993, *Nature* 363:524–527)

Step 5: Confinement of the surface-state electrons into quantum corrals made from individually placed atoms (Crommie, Lutz and Eigler, the article that accompanied the quantum corral image)

The steps are sequential and linked in the sense that each step was not possible without the previous step, and each step was motivated by the previous one.

Felice Frankel is a science photographer and research scientist at the Massachusetts Institute of Technology. Sightings *looks at all categories of visual representation of scientific ideas and information. This is the 13th in the series. Address: c/o* American Scien*tist, P. O. Box 13975, Research Triangle Park, NC 27709-3975. Internet: felicef@mit.edu*

Resource: Making Science and Engineering Pictures: A Practical Guide to Presenting Your Work
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