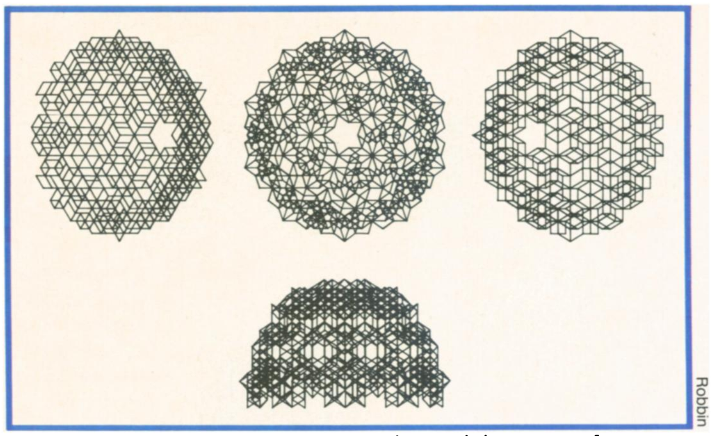
Shadows and Symmetries

Quasicrystal geometry brings a new dimension to art and design

By IVARS PETERSON



Computer plots of the same quasicrystal dome seen from different angles reveal a nonrepeating geometric pattern.

The painted panels and models of architectural structures displayed in artist Tony Robbin's spacious Manhattan studio have a way of catching the eye and teasing the mind. Featuring brightly colored polygons and angular wire frames, these evocative creations respond almost magically to changes in light and an observer's viewing location.

Robbin's designs of domes and vaulted ceilings in particular offer startling geometric perspectives. Constructed from networks of linked rods, with a sprinkling of diamond-shaped faces filled in by tinted, transparent plates, these structures reveal paradoxical patterns that combine orderliness and symmetry with an element of unpredictability.

This visual effect becomes apparent when one imagines standing beneath one of these lacework canopies. Looking straight up, one would see a carousel of overlapping, five-pointed stars. But the view slightly to one side would reveal a dense thicket of squares, while the view to the other side would show a network of triangles and hexagons.

Similarly, as the sun moves across the sky, the shadows cast by a web of rods suspended in the air would shift from one geometric pattern to another at different times during the day. It's as though three different structures lay hidden inside the same object, Robbin remarks.

Equally intriguing, these embedded geometric patterns don't repeat themselves in the same way that a network consisting of rods linked to form solely squares or triangles would repeat itself. Every section of the dome looks a little different from every other section. Yet the structure itself is clearly no crazy quilt of randomly placed polygons (see diagram).

Such a subtle and paradoxical blend of symmetry and irregularity both surprises and delights viewers, Robbin says. From the beginning of time, human beings all over the world have felt compelled to search for and make patterns, he contends, "so when you have a nonrepeating pattern, it's profoundly captivating."

Robbin's creations stem from the discovery nearly a decade ago of a new class of crystalline materials – the so-called quasicrystals – which display evidence of an unconventional atomic arrangement. That discovery focused the attention of crystallographers, physicists, mathematicians and others on the occurrence of nonrepeating patterns in both nature and mathematics. It also opened up the possibility of bringing a new kind of geometry with fascinating visual and structural characteristics into art and architecture.

Quasicrystals first took center stage in late 1984 when Dan Shechtman of the Israel Institute of Technology-Technion and his collaborators reported the discovery of an aluminum alloy that yielded a peculiar diffraction pattern (SN: 3/23/85, p.188). Electrons reflected from the material created an image consisting of concentric rings of well-defined spots arranged so that the overall pattern had a fivefold symmetry. In other words, rotating the pattern through 72 degrees would bring it into a new position in which the pattern looked just as it did in the old position.

The sharpness of the spots indicated that the atoms in the material were organized in some orderly fashion rather than randomly placed. But the pattern's unusual fivefold symmetry suggested that the atoms could not lie in one of the orderly arrangements of repeating units, or building blocks, conventionally assigned to crystals.

Coincidentally, mathematical physicist Roger Penrose of the University of Oxford in England had been studying tilings – ways of perfectly fitting together sets of geometric shapes to cover a flat surface – that also showed a kind of fivefold symmetry. He had been interested in finding the smallest possible set of different tiles that, used together, would cover the surface without forming a regularly repeating pattern.

Of the several examples of these tiles that Penrose discovered and investigated in the 1970s, one set consisted of a pair of diamond-shaped (rhombic) tiles, one fatter than the other. Normally, rhombic tiles can be laid down to form a repeating, or periodic, pattern. But by working out rules that specify which edges of one tile can fit with certain edges of another, Penrose could force the tiles into a nonrepeating pattern.

His "matching" rules forbid juxtapositions that lead to periodic arrangements. Remarkably, the resulting patterns have an approximate fivefold symmetry.

Other investigators later found three-dimensional analogs of the Penrose tilings. In this case, the basic building blocks are not tiles but polyhedrons – three-dimensional figures bounded by flat, polygonal faces. For example, it's possible to build up a nonrepeating pattern in three dimensions simply by using two types of rhombohedrons, which resemble skewed cubes.

It was natural for physicists and others to turn to the Penrose tilings and their three-dimensional analogs as reasonable models of the basic units that might fit together to produce a quasicrystal. Indeed, even before the discovery of quasicrystals, crystallographer Alan L. Mackay of Birkbeck College in London, England, had speculated that Penrose patterns could have a counterpart among crystal structures.

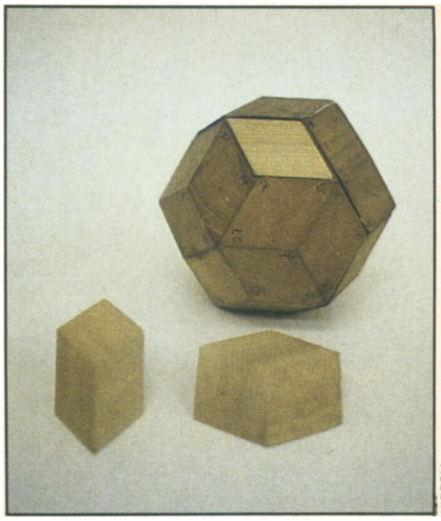
In their attempts to elucidate the physics underlying quasicrystals, many researchers have studied a variety of models based on the existence of particular types of structural units or tiles. Paul J. Steinhardt of the University of Pennsylvania in Philadelphia and his collaborators, for instance, have expended considerable effort working out rules specifying how Penrose tiles could, step by step, automatically join together to create the kind of large-scale, nonrepeating structures that presumably form the basis of quasicrystals (SN: 7/16/88, p.42).

However, such investigations have yet to settle the issue of precisely where the atoms in a quasicrystal lie and what causes such materials to grow into these particular atomic patterns. Although Penrose tilings and their three-dimensional analogs serve as convenient models, no one has established a clear connection between these mathematically derived forms and the physical reality of quasicrystals.

At the same time, the discovery of quasicrystals has prompted a reevaluation of what constitutes a crystal. Scientists in the past generally defined crystals as materials whose atoms are arranged in periodic patterns, as if the atoms were locked into specific positions on a regular grid. Many researchers are now beginning to think of a crystal as simply any solid that yields a diffraction pattern consisting largely of well-defined, bright spots, as recorded on a photographic plate when X-rays or electrons pass through the material.

This new definition greatly enlarges the number of geometric arrangements that can be considered crystalline. It also raises a host of subtle and difficult mathematical questions concerning the relationship between specific geometries in abstract mathematical models of crystals and the positions and intensities of spots in diffraction patterns.

"Tilings have nothing to do with real quasicrystals," says mathematician Marjorie Senechal of Smith College in Northampton, Mass. "But they are a useful tool for studying the geometry of nonperiodicity."


Robbin

Sets of two types of rhombohedrons fit together to form a solid polyhedron.

Mathematicians and physicists are not the only ones interested in nonperiodic patterns. A handful of artists, architects and tinkerers, often quite independently, have explored the possibilities of using the flexibility afforded by such novel building-block schemes in their own designs.

In the late 1960s, inventor Stephen C. Baer of Zomeworks Corp. in Albuquerque, N.M., discovered that rods sprouting from nodes in the shape of dodecahedrons – three-dimensional forms having 12 pentagonal faces – could be assembled into polyhedral building units, which in turn could be combined to create an array of larger structures displaying a fivefold symmetry. This idea became the basis of his patented "zome" building system.

That endeavor led to a book describing the system, a toy construction kit and various structural designs. "We have playground climbers made with fivefold symmetry [at various locations] in Albuquerque," Baer says.

Somewhat later, Koji Miyazaki of Kobe University in Japan, working with assemblies of fat and skinny rhombohedral blocks, discovered that these assemblies could be stacked and fitted together to make perfect space-filling, three-dimensional structures – examples of the three-dimensional analogs of Penrose tilings applied to architecture.

Other designers took a more mathematical approach. Motivated by a fascination with projections—in effect, the two- or three-dimensional "shadows" – of higher-dimensional geometric forms, Haresh Lalvani, a member of the architecture faculty at the Pratt Institute in Brooklyn, investigated the use of various mathematical procedures for transforming lattices in a particular dimension into new geometric patterns, including nonperiodic arrangements, in a lower dimension.

Using this approach, Lalvani not only created a variety of ingenious designs but also anticipated a number of mathematical discoveries concerning the intriguing properties of Penrose tilings. In some cases, he even went beyond what mathematicians had succeeded in working out.

"But I have no [mathematical] proofs," Lalvani notes. "I have demonstrations [in computer and architectural models]."

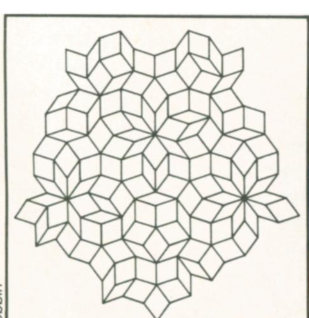
Designers aim to create pleasing or provocative structures, so their designs are governed by aesthetic considerations rather than by matching or growth rules and other mathematical niceties.

Nonperiodic structures built from just a few basic types of building blocks offer a number of striking features. In particular, such modular systems introduce the possibility of constructing truly unique structures that are both spatially and visually interesting, Lalvani insists.

"The same system allows many possibilities," he says. "It allows nonrepetitiveness. It allows repetitiveness – if needed – because the same basic units can be laid out periodically." Lalvani holds several architectural-design patents based on these concepts.

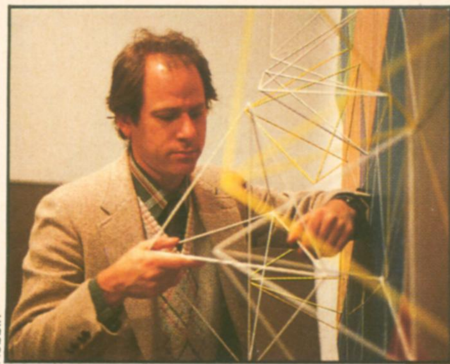
Tony Robbin started out as a painter, creating complex works filled with interwoven patterns and ambiguous figures to create the illusion of seeing more than one object in the same place at the same time. "I was interested in ways of experiencing and depicting space – complex spaces, multiple spaces, paradoxical spaces," he recalls.

That fascination inexorably pulled Robbin into the realm of four-dimensional geometry. In his typical fashion, he set out to learn everything he could about the fourth dimension (SN: 5/27/89, p.328), even hiring a tutor to introduce him to


Robbin


Quilt: Aline McKenzie; Photo: Linda "Sip" Siperstein

Sets of two different types of diamond-shaped tiles fit together nonperiodically to create a Penrose tiling, which forms the basis for a quilt design.



Robbin

Artist Tony Robbin (left) uses models to illustrate what a dome based on quasicrystal geometry would look like. His structures feature rods sprouting from dodecahedral nodes and faces filled in by plastic plates (below).

space-time and Einstein's general theory of relativity.

But it was a visit in 1979 to Brown University in Providence, R.I., during which he saw mathematician Thomas F. Banchoff's computer-generated images of four-dimensional hypercubes, that really persuaded him that mathematics could serve as his gateway to higher-dimensional spaces. He also took away an appreciation of what a computer could do to help visualize complicated forms.

"I realized that real mathematics was more liberating and richer, more complicated and more exhilarating, than my ignorant artist's fantasies about it," he says. "I was dissatisfied with using artists' tricks to depict spaces. I decided to take the plunge."

Robbin's immersion in mathematics led to the creation of a series of works in which welded steel frames protruded from painted canvas panels to represent sections of hypercubes. Because the painted lines remain fixed and the relative positions of the rods change as a viewer walks past, such a work recreates in a novel fashion the experience of seeing the multiple faces of a three-dimensional shadow cast by a rotating hypercube.

Robbin became interested in quasicrystals and the mathematics associated with them when he learned that nonperiodic patterns can be understood mathematically as slices or projections of periodic lattices in higher dimensions. In other words, regular patterns in six-dimensional space — when seen in three dimensions — could under certain circumstances appear as nonperiodic geometric structures matching those that scientists sometimes use as models of quasicrystals.

Robbin obtained a computer program from Steinhardt that enabled him to generate such three-dimensional quasicrystal lattices on a computer screen. That program was based on earlier work by mathematician N.G. deBruijn, now retired and living in Nuenen, the Netherlands, who had discovered a way to generate Penrose tilings by drawing certain grids of intersecting lines and putting a tile at each point of intersection.

Adapting Steinhardt's computer program to his own needs, Robbin added a repertoire of features that enabled him to visually explore a variety of designs based on quasicrystal geometries. Without a computer to generate and manipulate these intricate, three-dimensional forms, Robbin says, "it is truly difficult to understand the aesthetic potential of quasicrystal structures."

Visitors next summer to the newly established Center of Art, Science and Technology at the Technical University of Denmark in Lyngby may be the first to experience one of his quasicrystal designs in its full-scale splendor. Center officials have commissioned Robbin to construct a large model and to conduct feasibility studies for erecting a quasicrystal canopy and climbing structure enveloping one end of the center.

The Denmark project raises a number of intriguing engineering issues — the kind that come up whenever a novel design makes the transition from concept to real world. For instance, no one really knows how strong or stable a full-scale quasicrystal structure would be.

"To my knowledge, nothing is known about its static behavior," Lalvani says. At the same time, there's no hard evidence that a quasicrystal structure would have any unusual structural characteristics, "but you intuitively feel there would be a difference," he adds.

"Because they are nonrepeating patterns, quasicrystals are structurally different from anything yet built," Robbin argues. From his experience with models, he suspects that quasicrystal structures might be somewhat spongy — able to absorb shock and spring back.

But neither intuition nor tabletop models can substitute for a full engineering analysis of how such a structure would behave. If it proceeds as planned, the Denmark project will provide the first opportunity to investigate the structural characteristics of a quasicrystal-based design.

In quasicrystal geometry, mathematicians, physicists, artists and architects share the experience of seeing in its complexity a pattern that is subtle, yet powerful, and a symmetry that is elusive, yet enthralling.

Mathematicians enjoy the opportunity to explore the diversity of forms arising from simple rules and principles. They look for links between these patterns and other types of mathematics. They try to enumerate the geometric possibilities in any given situation. They sense the mystery.

Physicists see in these patterns hints of how nature may organize matter under certain circumstances. They invent and invoke special rules to create models that appear to mimic the behavior of real-life quasicrystals.

Artists and architects gain an aesthetically and structurally challenging way of dividing and organizing space — even though they generally use only arbitrary fragments of quasicrystals. "Normally, we work with repetitive grids and lattices," Lalvani says. "A different underlying grid — a different way of organizing space — changes things radically."

More than most artists, Robbin seeks inspiration in mathematics and science. He tries to weave together mathematical, physical and aesthetic threads into compelling works of art.

"If you want to be creative, it's essential for an artist to know about geometries and space," Robbin says.

At the same time, scientists and mathematicians benefit from new modes of expression created by artists, he insists. With their highly developed capabilities of visualization, artists introduce new viewpoints that contribute to the development of science and culture as a whole.

While artists mine the territory and exploit the riches that mathematicians stake out, Robbin says, they also serve as the provisioners and bankers of these prospector mathematicians. □