The WINSOM solid modeller and its application to data visualization

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The IBM United Kingdom Scientific Centre's WINchester SOlid Modelling system (WINSOM) is a set-theoretic, constructive solid geometry (CSG) modeller based on recursive division techniques. It specializes in handling complex models and provides graphical facilities intended for engineering applications. This paper describes WINSOM and some of the many programs that are linked to it, and gives examples of their application to problems of data visualization.

The WINchester SOlid Modelling system, hereafter referred to as WINSOM, has been under development at the IBM United Kingdom Scientific Centre since 1983.[1] The main feature that differentiates WINSOM from most of the many other solid modelling systems currently available is its ability to handle large models efficiently.

WINSOM is distinguished from other systems in a number of additional respects. First, it is able to represent a wide domain of shapes. A large range of conventional geometric primitives as well as unconventional ones such as numerically defined fields are available in WINSOM. Shape operations such as bends and blends are also supported.

Second, a number of different methods are used to create WINSOM models. WINSOM has its own simple language, but this has recently been supplemented by the ESME (Extensible Solid Model Editor) language, which has special geometric data types and geometric and programming constructs. The language is designed to support interactive graphical editing. These general-purpose input media are further augmented by a number of programs which generate models from databases, Prolog fact bases, and image analysis.

Third, WINSOM is distinguished from other systems by being oriented more toward picture production than most engineering solid modellers; a wide spectrum of different rendering techniques are available in WINSOM and its associated programs. These range from simple approximate wire frames for quick viewing to ray-traced textured pictures.

The range of tasks for which WINSOM has been used is one of the reasons why it has acquired such a wide repertoire of modelling and rendering techniques.

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This extends far beyond the usual engineering component design role—one for which WINSOM is perhaps least well suited, and which we have hardly explored. The applications that have been explored vary from molecular graphics to computer sculpture and from the generation of single images to the production of ten-minute animations. The only obvious link between these applications is that they all include large sets of three-dimensional geometric data, and WINSOM is thus best represented as a *data visualization* modeller.

Modelling techniques

While it does not impinge upon the average user, WINSOM is unusual in being a set-theoretic or CSG (constructive solid geometry) modeller. This means that it represents solids as the set-theoretic combination of simple primitive shapes (Figure 1A to 1D). Thus, shapes such as spheres and cones can be added to or subtracted from one another to create a more complex shape. This contrasts with the majority of today's systems, which represent solids as their boundary surfaces, linked into a coherent whole by topological information. Although many other modellers use the set-theoretic operations as input techniques, they build a boundary model internally; WINSOM does not. Virtues of this approach include numerical stability and compactness; disadvantages include nonuniqueness and the absence of localized surface information, such as edges and vertices.

Recursive division. Historically, the lack of localized information has made computations using set-theoretic models very expensive, since the entire model must be processed to find even the simplest feature, such as part of the surface of the model. WINSOM overcomes this problem by using a technique known as spatial division, which was first implemented in VOLE (VOLume Evaluator).[2] Instead of searching the model to try to find its surface, the *space* that the model occupies is divided into smaller subspaces. For each of these subspaces, new set-theoretic "submodels" are created by replacing those primitives that do not have a surface in the subspace by the empty or universal set and performing elementary simplifications.[3] These new submodels, which are usually smaller and simpler, are only valid in the appropriate subspace.

In the basic WINSOM algorithm for creating pictures, the space occupied by the whole model is a frustum of a pyramid whose apex is at the viewpoint. This is segmented by eight-way division into smaller sections, and this process is repeated recursively. It continues until a subspace is proved to be entirely empty, or until it is the size of a pixel on the screen,

Simple submodels are available just where they are needed to compute parts of the picture.

meaning that the area of the pixel corresponds to the face of the frustum facing the viewpoint. Thus, the simple submodels are available just where they are needed to compute parts of the picture.

To enforce hidden-surface elimination, division proceeds in a front-to-back order, and the current picture is maintained using a quad tree. (For a general discussion of quad-tree structures, see Reference 4.) When a quad has been coloured, the volume behind it is not divided further. By this means, the WINSOM algorithm avoids most of the computation in regions of space that are hidden, even if they contain complex data.

We have improved the original VOLE algorithm in a number of ways, in particular by dealing more efficiently with the small submodels generated by the spatial division process. These small models are represented as truth tables.[5] This speeds membership testing and also automatically ignores redundant and repeated primitives. It greatly improves WINSOM's performance.

Similar techniques are used for other types of rendering. To produce wire frames, or ray-traced pictures, the division is performed on an original cuboid containing the model and does not terminate until a limiting value of complexity is reached. (This topic is discussed further in Reference 6.) At this point, FastDraw[7] generates segments of a wire frame; the ray-tracer stores the divided model and then fires rays into it during picture production.[8–10]

Input to WINSOM

As it was first written, WINSOM included a simple input language. This allowed primitives to be defined, transformed, and combined with the set-theoretic operators. Further commands specified the view to be produced and the lighting required. When WINSOM started being used for large-scale molecular modelling, the shortcomings of this interface emerged. It became necessary to generate models automatically. A programmable interface, connected via a relational database[11–13] or PROLOG,[14,15] extracts molecular information from the Brookhaven databank.[16] The same interface is also applicable to generating WINSOM models from other databases and Prolog fact bases.

A single shape may have more than one definition.

ESME. While the database and image work was very successful, no improvement was made to the *general* usability of WINSOM. In 1986, work started on the ESME (Extensible Solid Model Editor) language.[17] This language includes conveniences such as special geometric data types (e.g., vectors) and operations (e.g., vector products), together with programming facilities such as variables, loops, and subprograms. Other set-theoretic languages such as SML (Solid Modelling Language)[18] and SID (Set-theoretic Input to DORA)[9] have these facilities, but the design of ESME has been taken a stage further by the inclusion of features which are designed to assist the building of interactive graphical editors for particular applications.

Despite the programming excellence of ESME, there are still severe problems that prevent us from writing general graphical editors. These hinge on the non-uniqueness of the set-theoretic model. A single shape may have more than one definition. We have looked at the simplification of set-theoretic models through the elimination of redundant primitives[19] which relieves the designer of some worry about the set-theoretic efficiency of a model.

The set-theoretic definition of a model cannot be deduced from the picture on the screen. Thus, if we try to modify the model by interacting with the picture—for instance by moving a primitive—the effect depends on the original definition and is thus somewhat unpredictable. One tool that we have found to attack this problem is the active zone concept of Rossignac and Voelcker.[20] The active zone of a primitive is the region of the model that can be affected by changing the geometry of the primitives. It depends on the model definition as well as its shape. By displaying the active zone, we get some indication of what a particular change will achieve.[21]

Output from WINSOM

Static pictures. The basic WINSOM algorithm produces coloured and shaded images, which may be lit by multiple light sources, but shadows and reflections cannot be modelled. These pictures are more than adequate for most of the data-visualization applications with which we are involved. As mentioned above, there is also a ray-tracing module in WINSOM, and this is able to produce the shadows and reflections so beloved by computer graphics aficionados. There is a time penalty for this, although in this program the spatially-divided model may be reused for a number of views. At the other extreme, low-resolution pictures are easy to produce quickly using the WINSOM algorithm and are widely used for model and view verification. Wire frames may be generated using the FastDraw program, and these can be animated on a device such as the IBM 5080. Figure 2 shows the different types of rendering produced by WINSOM: Figure 2A shows the central WINSOM algorithm; Figure 2B shows ray-tracing into a divided model; and Figure 2C shows wire-frame generation. This model is made up of 55 planes, 131 spheres, and 340 cylinders. Wire-frame output is about four orders of magnitude cheaper than ray-tracing, with the central WINSOM algorithm positioned between these two extremes. However, these differences are reduced for complex models.

FastDraw sacrifices accuracy to speed. As division progresses, the ratio of model complexity to subspace size is monitored. If it becomes too large, work on that subspace is halted and the submodel is abandoned. This avoids spending time on complex regions that contribute little to the visual impact of the final model. For models containing hundreds of primitives, these wire frames can be computed in under a second on an IBM 3081 processor and are used for verifying input and some view planning. The wires in the wire frame inherit the colours of neighboring surfaces to enhance the legibility of the display. Nevertheless, as with all wire frames, interpreting the picture becomes difficult as model size increases. FastDraw can also prepare a polygon surface from a model. Using polygon sorting or z-buffering (a technique for the removal of hidden surfaces by discarding all but the nearest surface at every pixel) on appropriate hardware, this can give a series of low-quality rendered hidden-surface views close to real time.

Animation. Static WINSOM images can help the researcher to visualize, analyse, and validate the data and support proposed theories. Over the last few years, we have increasingly been drawn into using WINSOM to produce frames for (longer and longer) animation sequences, and we are demonstrating that animation can dramatically enhance visualization. Not only can animation provide structured "tours" in, around, and through our solid models, but it can also convey the evolution of those models in time—a capability which can be of great value in scientific applications.

Our first animation was a "fly-through" of a reconstruction of the Saxon minster in Winchester (shown later in Figure 13), and we have recently undertaken longer animations. Figure 3A to 3C shows frames from an animation for an exhibition of the work of Leonardo da Vinci. These frames illustrate sequences showing the "growth" of a church from the ground plan. Figure 20, shown later, depicts sequences of a computer sculpture in motion.

Nongraphical output. WINSOM is able to compute volume and surface area properties (which traditionally are used to prove that the model really is solid). The ability to obtain nongraphical data interactively is more interesting: A tablet is used to identify a point on a picture. Once the visible object is found, properties such as surface normal (i.e., surface orientation), colour, and location can be identified within the model definition.[22,23]

Low-level detailing. Within the WINSOM environment, there are a number of utilities which, although not associated with modelling, contribute strongly to the system's ability to produce acceptable pictures. One problem encountered early in producing coloured images is that of obtaining shades of colour that have the user's approval. We have extended the Colour Naming System[24] to include names for surface rendering parameters such as glossiness and polish[25] (Figure 4).

The following commands were used to generate the picture in Figure 4:

```
DRAW o at(1,9,0) cnsx(blue)
    U o at(3,9,0) cnsx(green)
    U o at(5,9,0) cnsx(bluish green)
    U o at(7,9,0) cnsx(grayish bluish green)
    U o at(9,9,0) cnsx(medium grayish bluish green)

    U o at(2,6,0) cnsx(yellow)
    U o at(4,6,0) cnsx(glossy yellow)
    U o at(6,6,0) cnsx(very polished glossy yellow)
    U o at(8,6,0) cnsx(plastic matt yellow)
```

The first row in the figure shows control of basic colour. *Blue*, *green*, and *bluish green* control hue, *grayish* controls saturation, and *medium* controls brightness. The second row in the figure shows control of the highlights (specular reflection). *Glossy* and *matt* control the strength of highlight, *very polished* controls the size of the highlight, and *plastic* controls its colour.

Having dealt with colour, we must determine the appropriate lighting for a scene. Positioning and directing lights in the imaginary space of a solid model is known to be difficult. We believe that our SLED (Solid Lighting EDitor) program[26] presents an original solution to this difficulty. WINSOM is able to produce an augmented image type, in which pixels are labelled with depth and surface normal as well as colour. SLED accepts a picture in this form and allows the user to vary the lighting parameters. Because a normal WINSOM run does not produce shadows and reflections, the result of new lighting parameters can be displayed explicitly (Figure 5A). Working at low resolution, the system is fast enough to give an interactive "feel." In Figure 5B, the cursor has identified the target of an alternative light. In Figure 5C, the cursor has set the spread of the spotlight. The final picture, Figure 5D, is the result of adding two more lights.

However, the main feature of SLED is that the lights can be specified both by their position (which can be difficult to fix) and by their effect on the scene. The user specifies the highlights on the displayed object, and the system works backward from these specifications to determine the light position. The angle of the beam and its position can be determined. This is important because the user can indicate the size as well as the position of the desired highlights.

Recently, texturing has been added to WINSOM.[25] This uses "solid texture"[27] which is shaped with pseudo-fractal or bandpassed noise—generated with a minimum of computation from interfering random waveforms—or with regular patterns, such as three-dimensional chess boards. The texture generates values on the surface of an object, which can control all the surface parameters such as hue, gloss, and transparency. (See Figure 6.) Achieving the desired texture is more difficult than determining a colour. We have not found a convincing English-like description of texture and are experimenting with a texture editor (TED) giving real-time control of parameters by dials or a mouse. TED will combine interactive colour definition with the ability to play with texture parameters such as fractal dimension.

The first serious use of WINSOM was to model molecules.

Finally, we have used error diffusion,[28] which exploits shortcomings in the human visual system, to produce pictures on a relatively low-colour-resolution display that are in practice indistinguishable from the high-colour-resolution equivalents. Error diffusion is especially difficult when synthetic images are displayed, because they may have large areas of perfect surface which are not found in real images. Important features of our error-diffusion process[29] are the careful choice of colour levels and the use of smooth-area detection and a randomized Peano diffusion path to prevent detectable error-diffusion pattern regimes. All the pictures in this paper have been error-diffused with a palette of only 252 colours (7 levels—including zero—of green, and 6 levels each of red and blue).

Applications

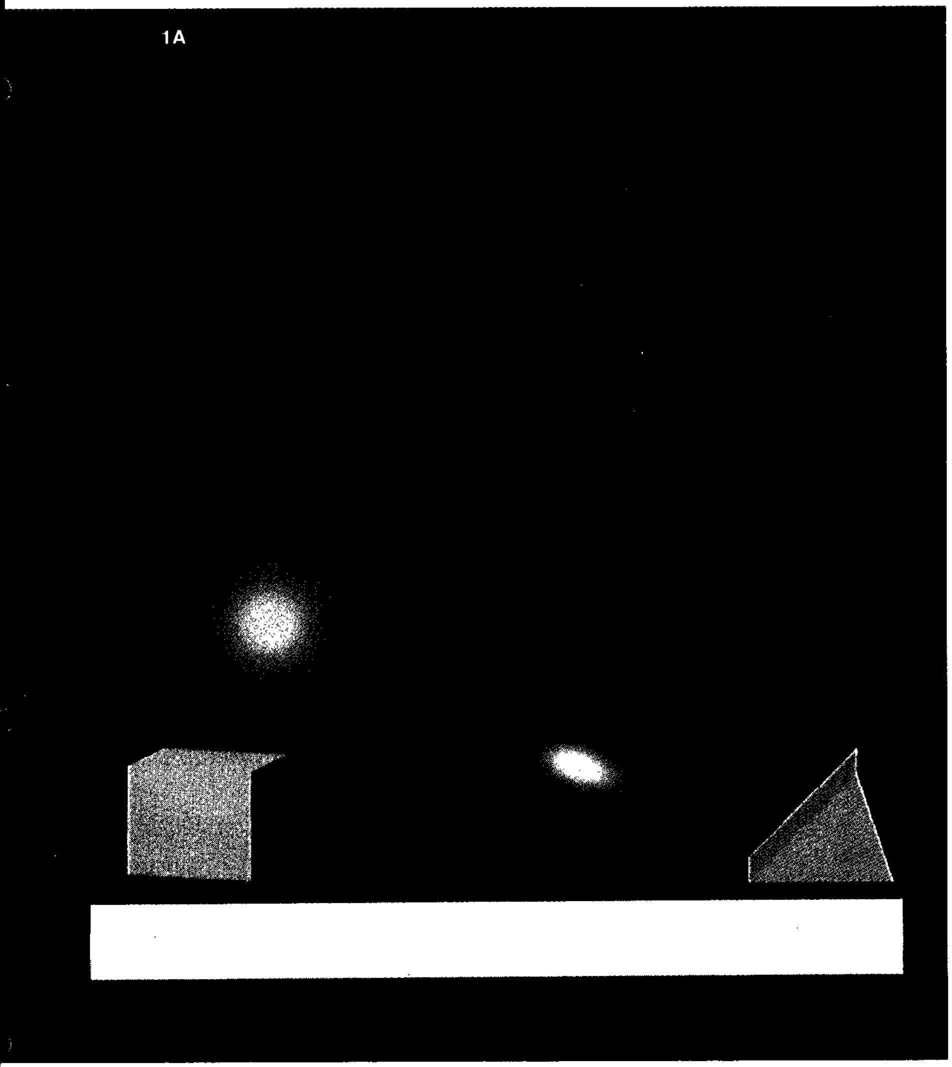
Molecular modelling. The first serious use of WINSOM was to model molecules. There are many programs which can generate ball-and-stick representations of molecules, and this simple geometry can be displayed quickly by special algorithms or in real time on vector displays. Our programs[30] are more flexible, since they use the database to collect and structure the data required for a picture, resulting in the generation of an appropriately coloured mixture of atom, ball-and-stick, and backbone representations.

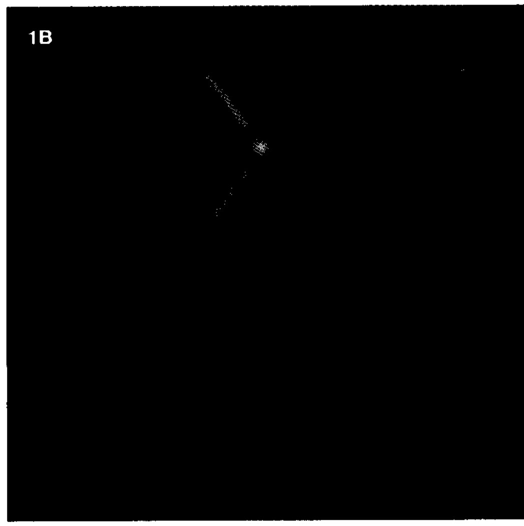
WINSOM primitives for cylinder and helix are particularly useful for an *abstraction* of molecules to be drawn showing the secondary structure. The application programs require some geometry code to fit these primitives to sets of atoms, when a wide range of representations of molecules becomes possible. In Figure 7A, the representation traces the course of the polypeptide chain through each of the six monomeric units, as white folded "string." The second representation (Figure 7B) highlights areas where the polypeptide chain folds into regular, stable, helical structures known as alpha-helices. The alpha-helices are shown as yellow spirals. The central zinc atom is shown as a sphere. In the third image (Figure 7C), alpha-helices are shown as yellow cylinders. Spheres are again used for the zinc atom and the atoms directly involved in bonding between the insulin hexamer and the coordinating central zinc atom. Finally (Figure 7D), we see an entirely space-filling model, with electron clouds represented by spheres of prescribed radii. The spheres are colour-coded to distinguish different atoms.

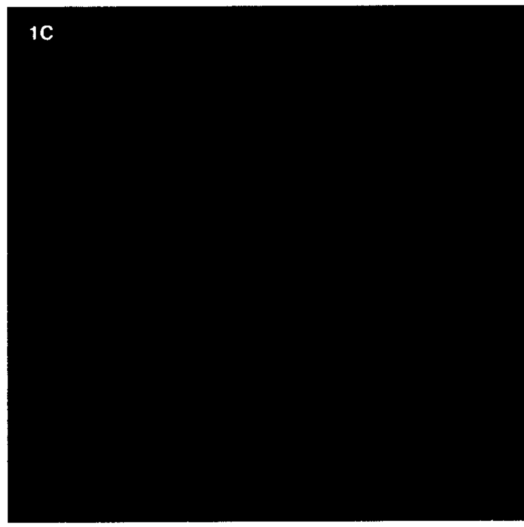
All our programs that generate WINSOM models from a molecular database have the option of generating a simple wire-frame equivalent first, as shown in Figure 8. This permits the user to make a quick check of the picture to see that it has the expected content, and the user can choose a view interactively.[31]

Crystals. All crystal structures—from elements in the solid state, through simple metallic salts, to complex minerals—are uniquely described by the positions of the constituent atoms in a unit cell. The unit cell can be thought of as the smallest building block of atoms which, when tessellated indefinitely in three dimensions, yields the repetitive, infinite structures characteristic of crystals.

If the basic unit cell is described using WINSOM primitives (spheres for atoms and planes for the anion coordination polyhedra around cations), then the large-scale repetitive crystal structure can easily be generated. This approach has been used to great effect in the illustration of the structural relationships between some of the recently discovered high-tem-







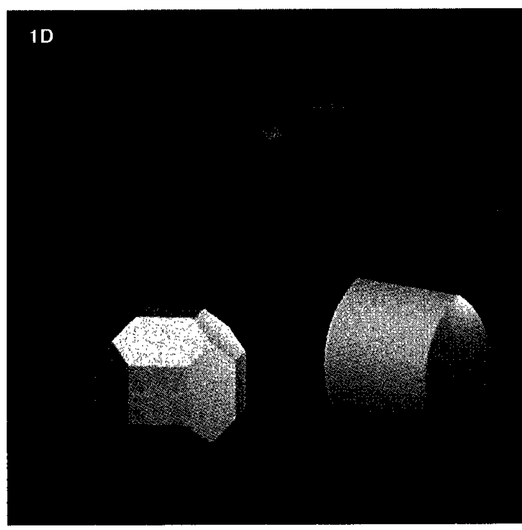
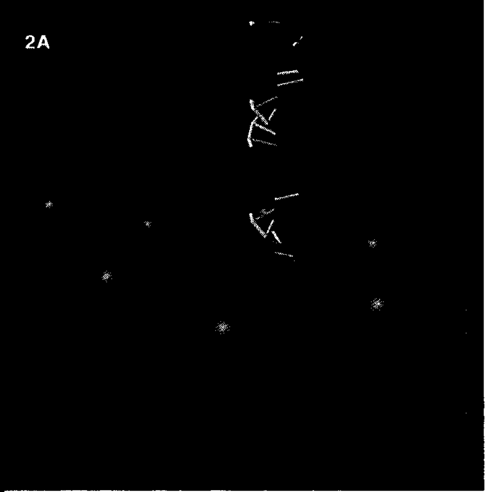


Figure 1 **WINSOM basics: (A) the geometric primitives available in WINSOM; (B) examples of the union, (C) difference, and (D) intersection operators**



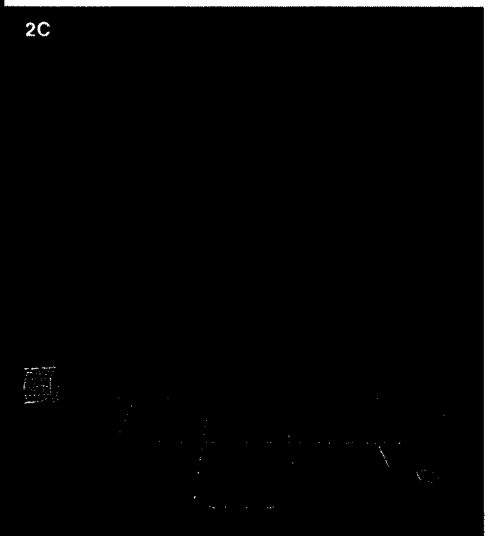


Figure 2 Different types of rendering produced by WINSOM

Figure 3 Three frames from the animation of Leonardo da Vinci's work

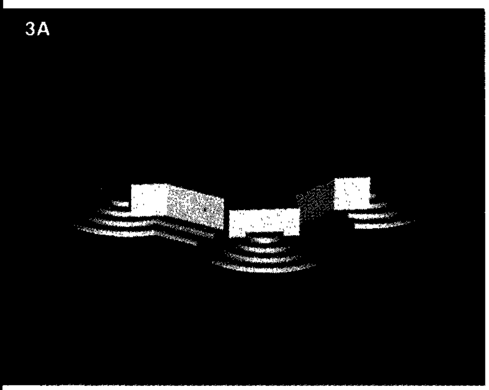
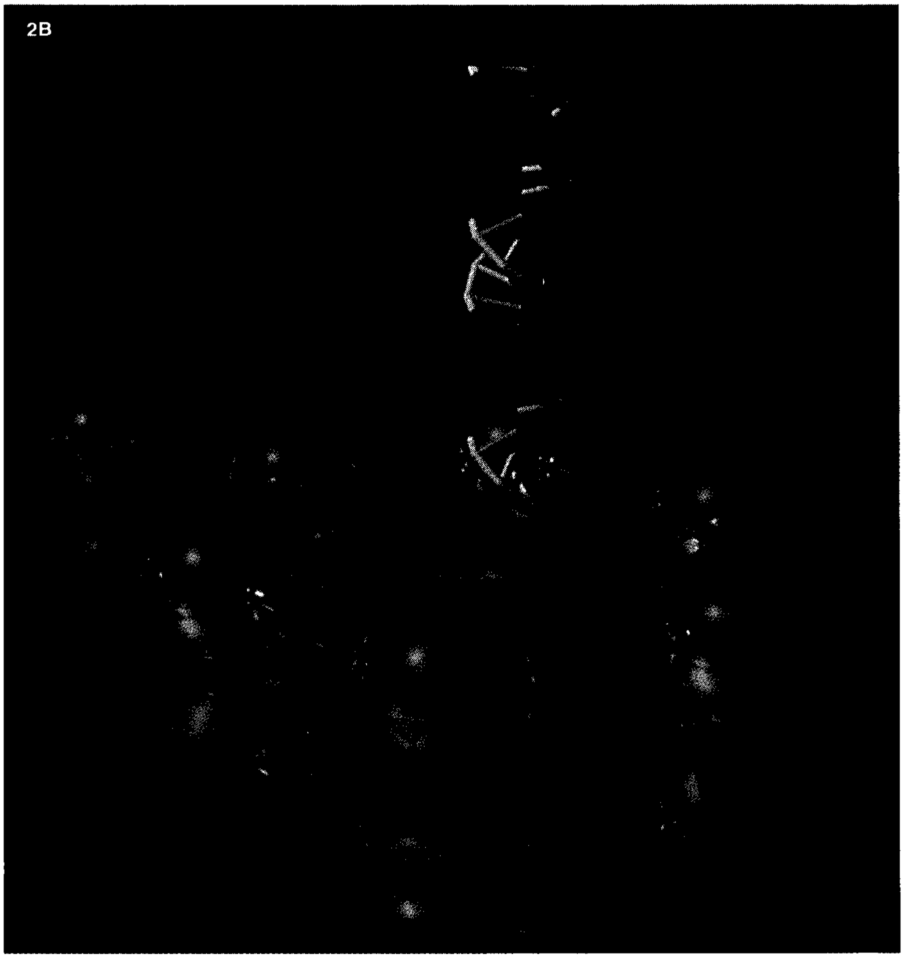
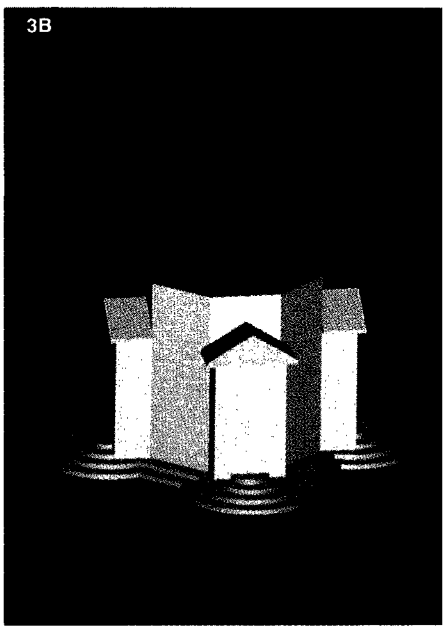


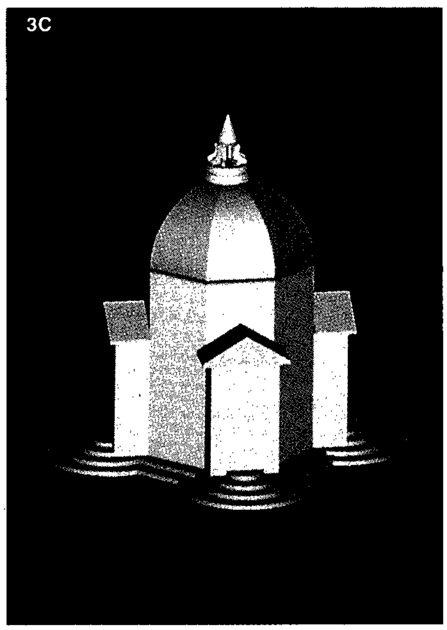
Figure 4 Surface properties in WINSOM

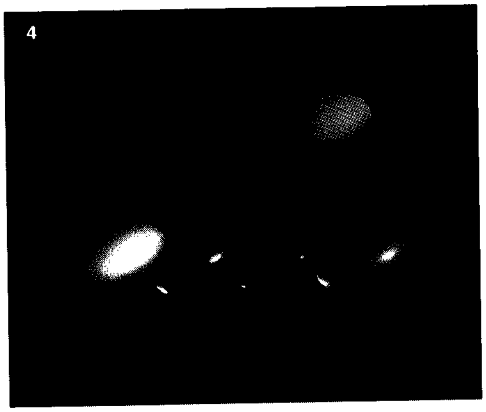
Figure 5 The SLED lighting editor

Figure 6 Solid textures used by WINSOM





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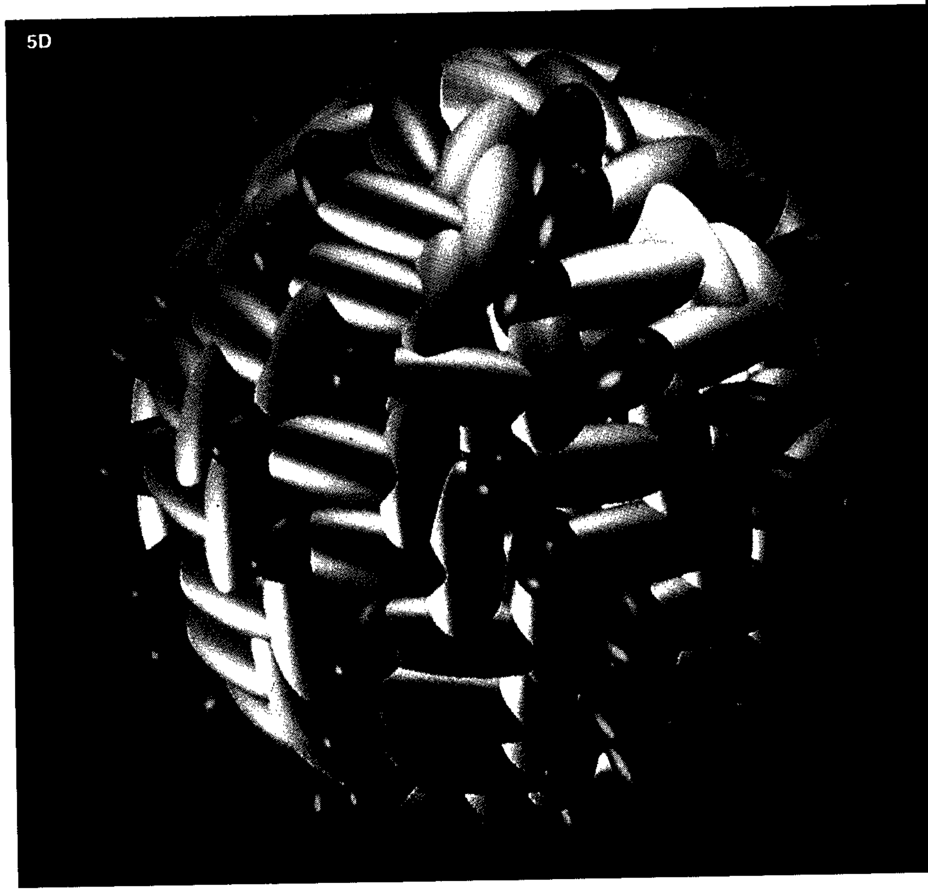
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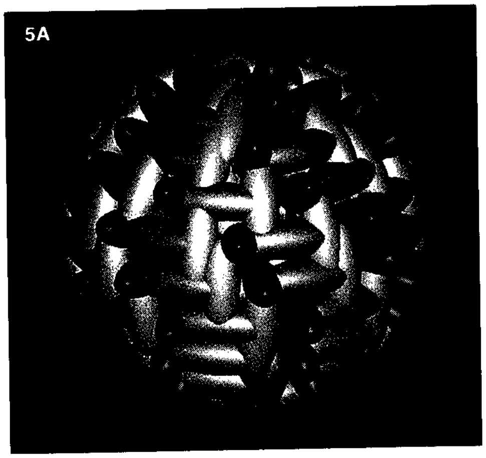
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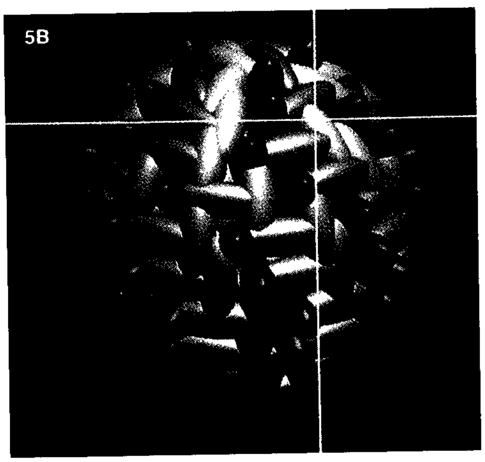
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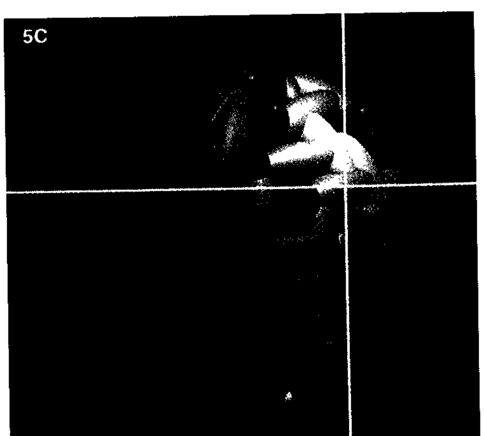
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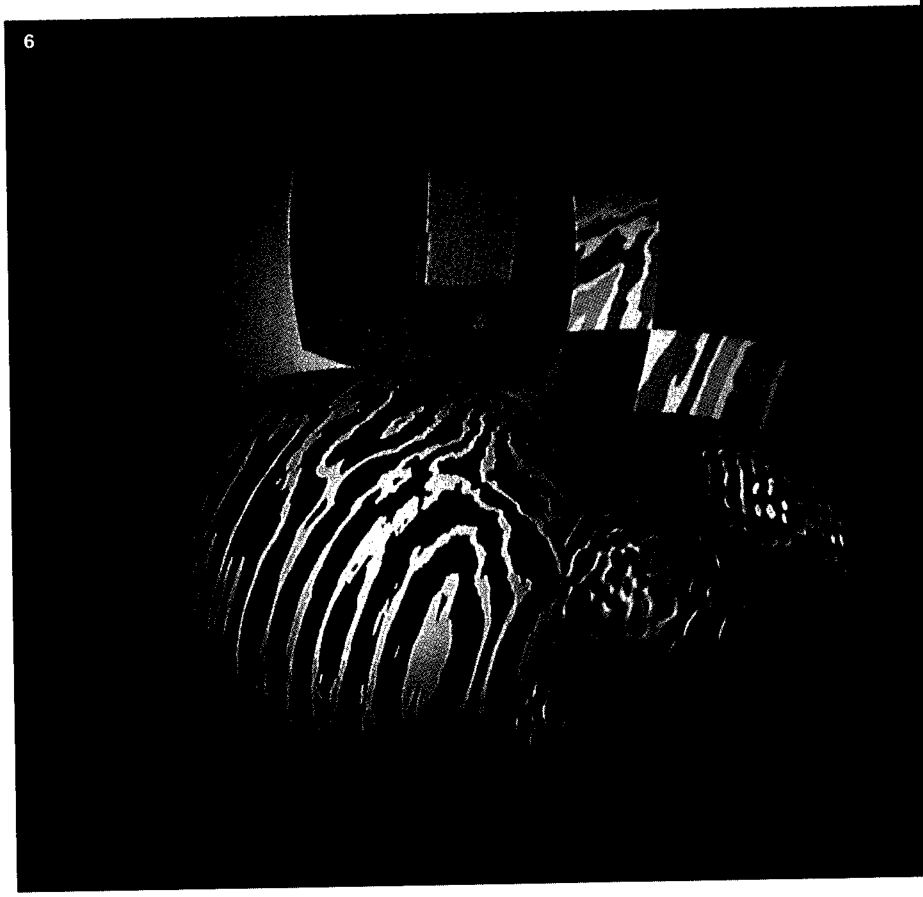
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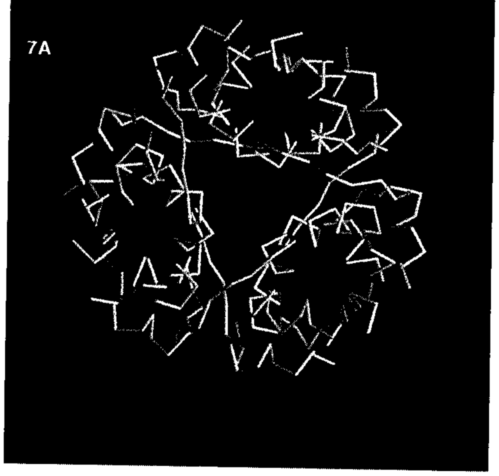
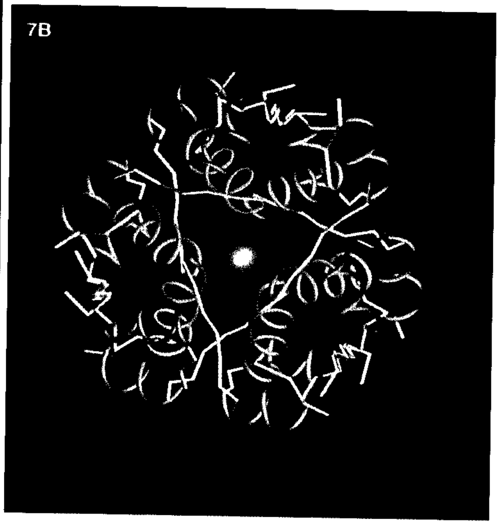
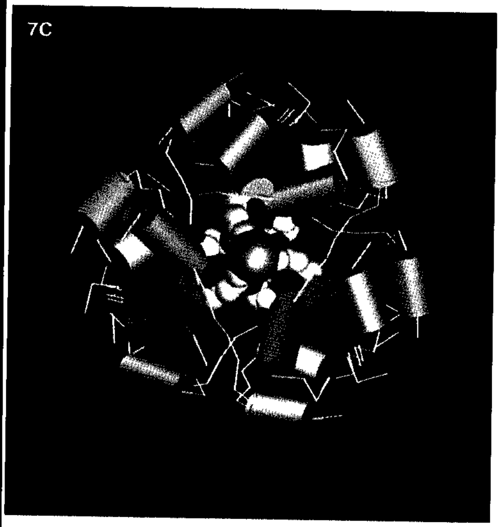






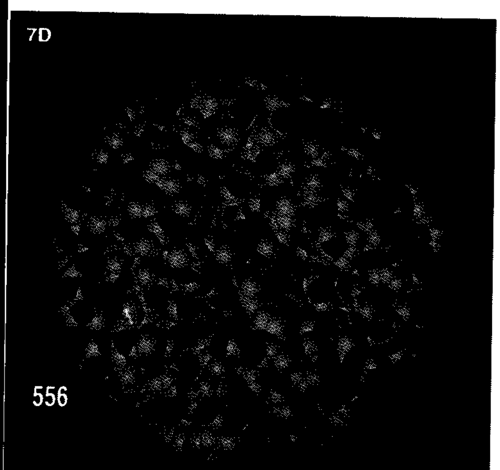
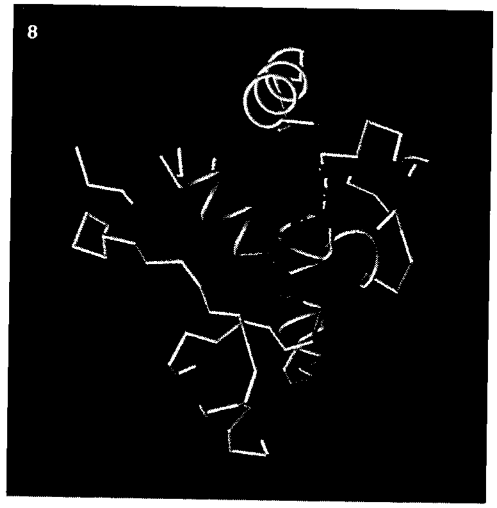
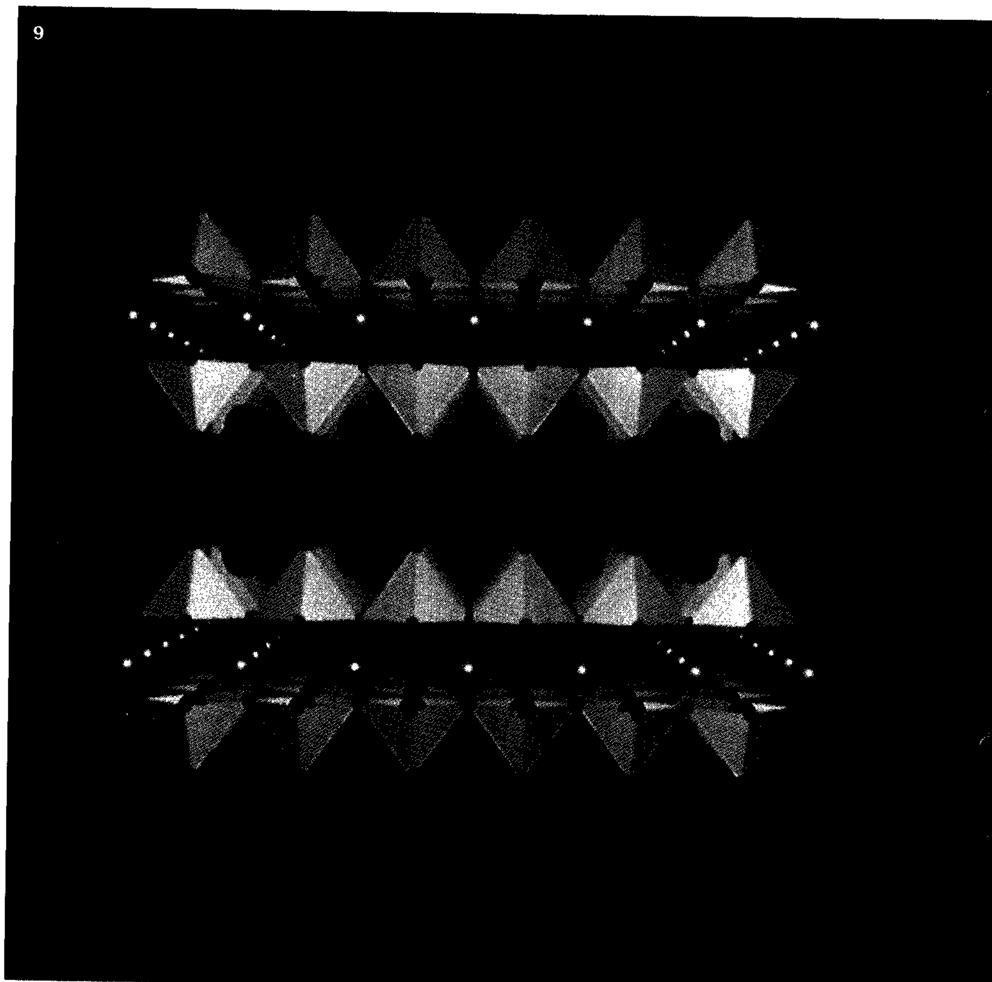


Figure 7 Four views of the insulin hexamer

Figure 8 Secondary structures.
Stick and sheet models of Dihydrofolate Reductase (DHFR) from the bacterium Lactobacillus Casei.





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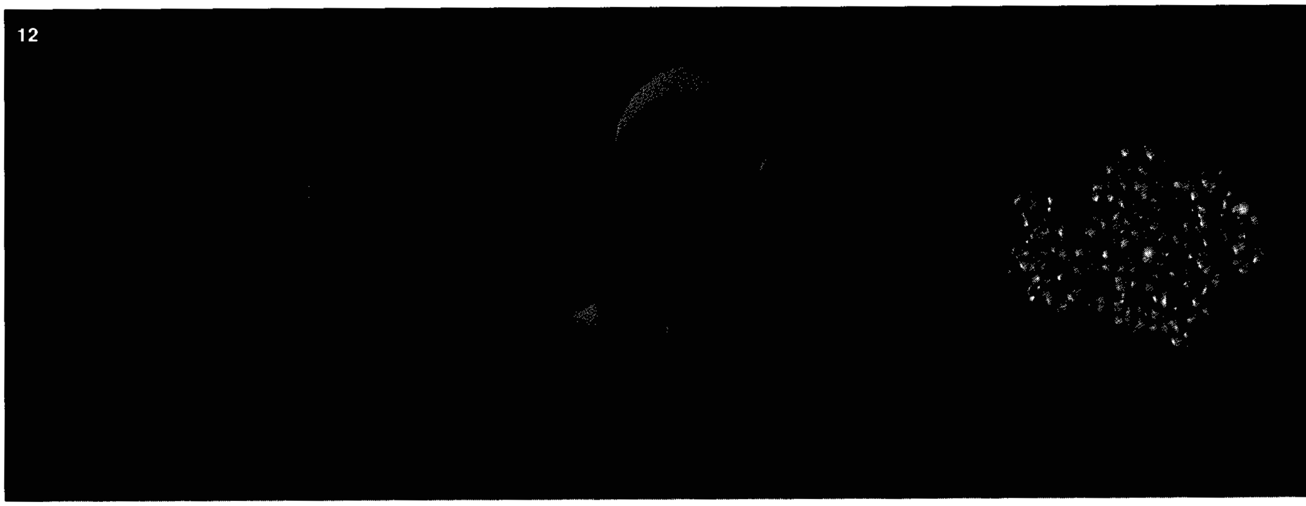

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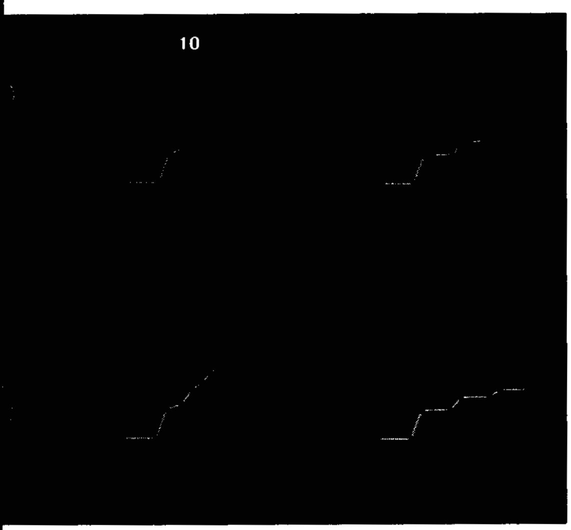

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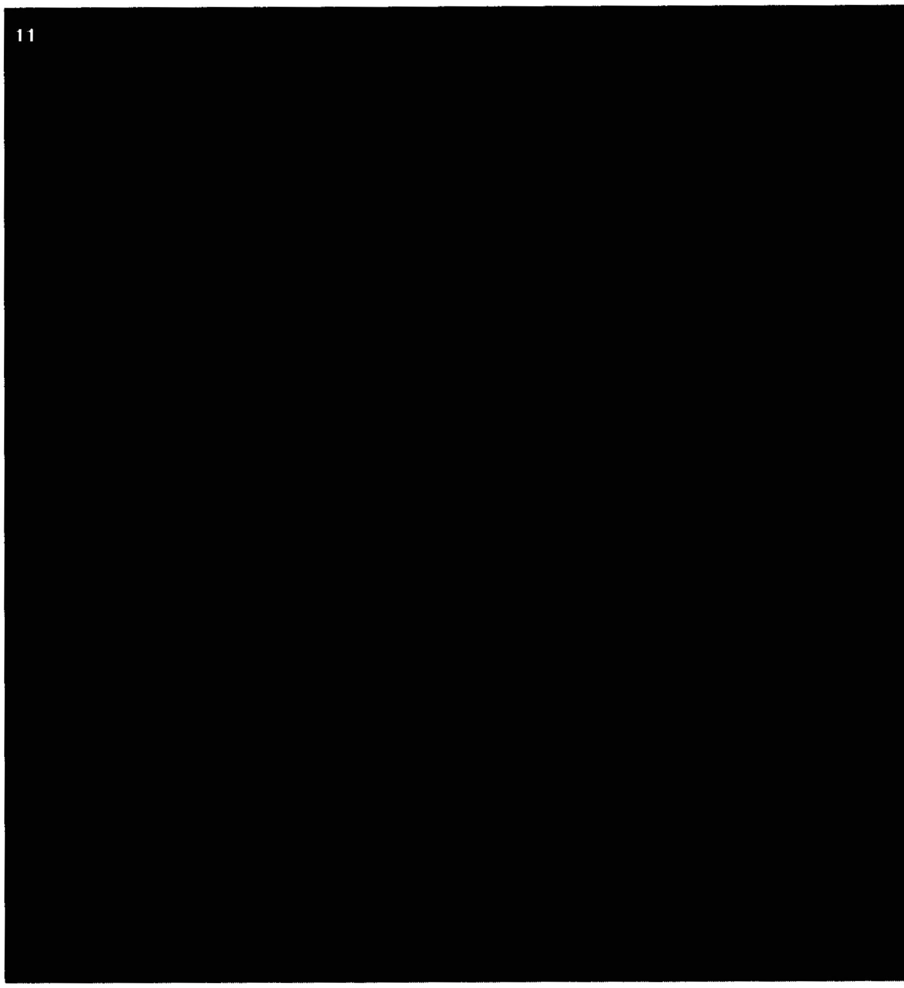
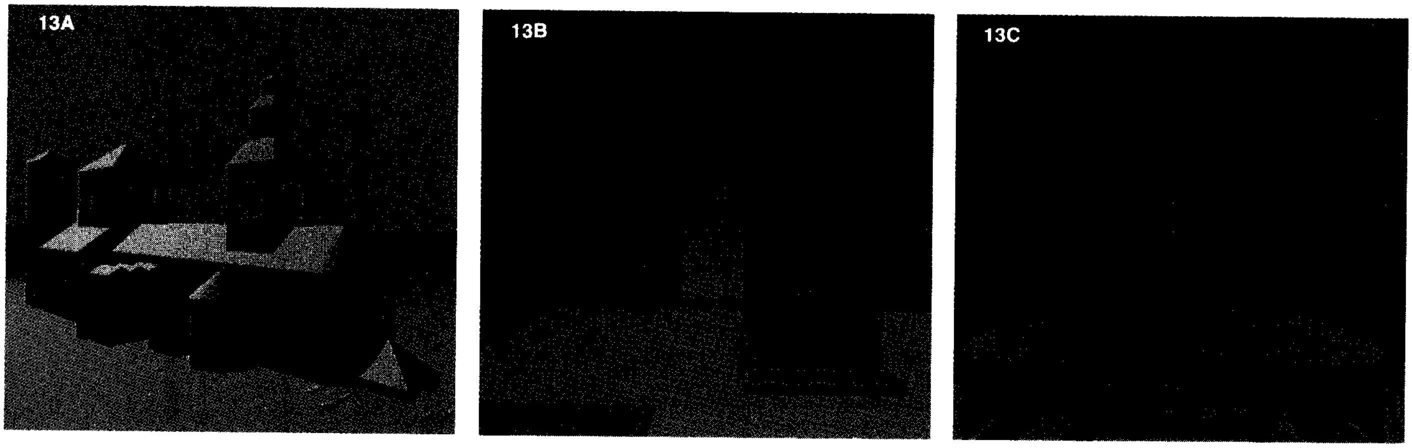


Figure 9 Crystal representations. Yttrium barium copper oxide, a high-temperature superconductor.

Figure 10 Theoretical predictions of average shapes in flexible liquid crystals

Figure 11 Micelles

Figure 12 Fields around an object



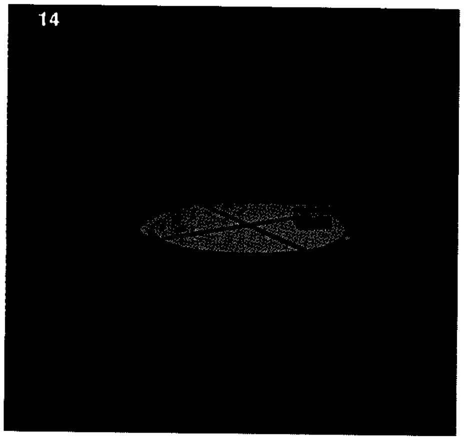


Figure 13 Frames from the animation of the Anglo-Saxon minster in Winchester

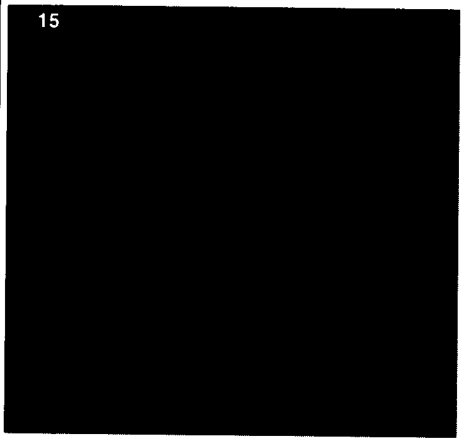
Figure 14 WINSOM archaeological reconstruction of an early Christian Manx cemetery

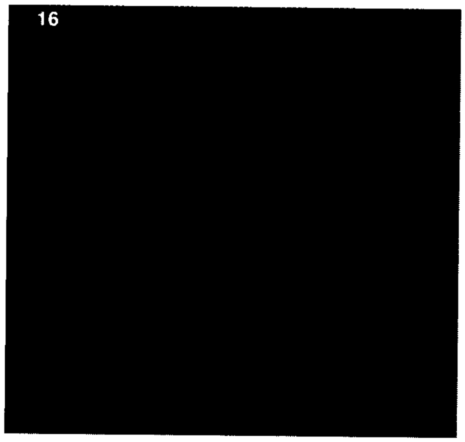
Figure 15 The coronary arteries modelled from X-ray data, constructed from the union of 395 cylinders and spheres

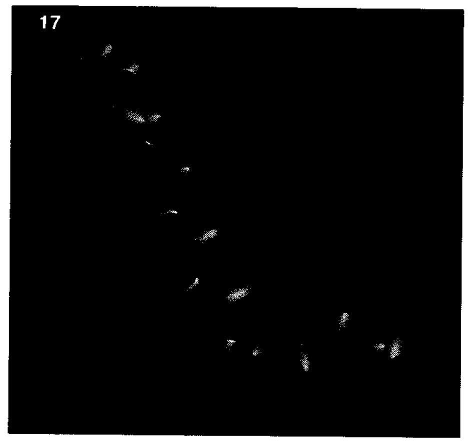
Figure 16 A hippocampal neuron, formed by the union of 1149 spheres and 1134 frusta of cones

Figure 17 Proteo-glycan assembly; one possible configuration

Figure 18 Simulating molecular beam epitaxy; three frames from the educational animation







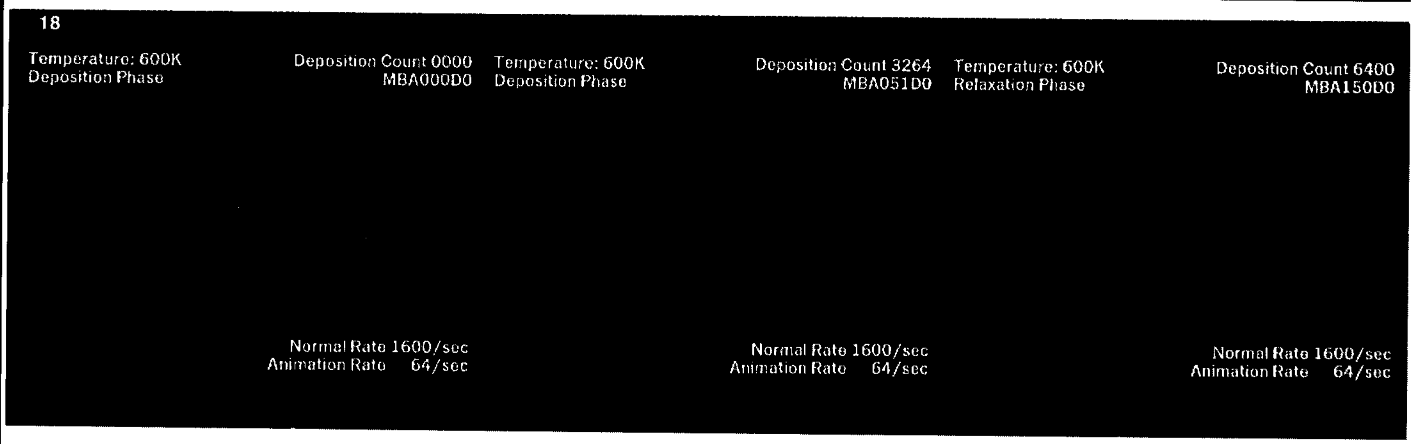
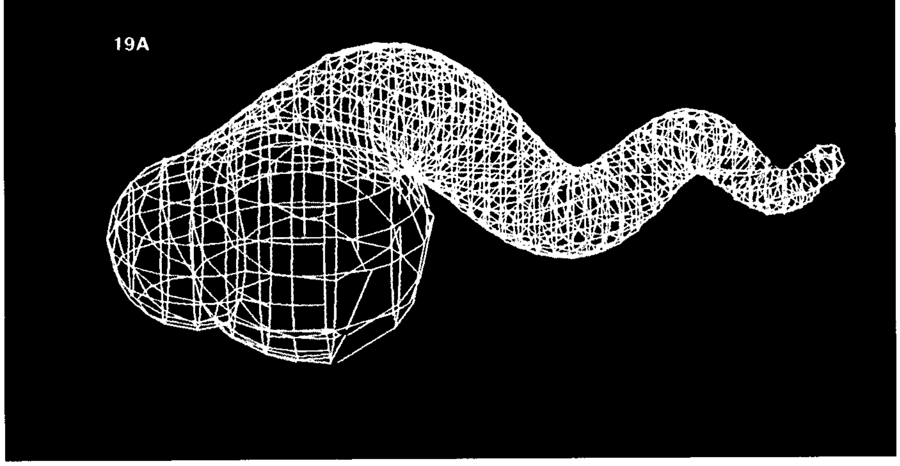
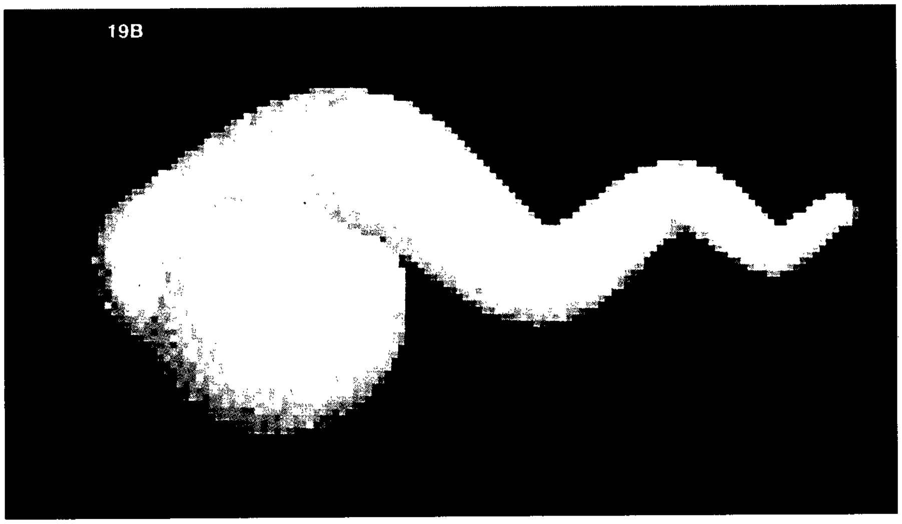
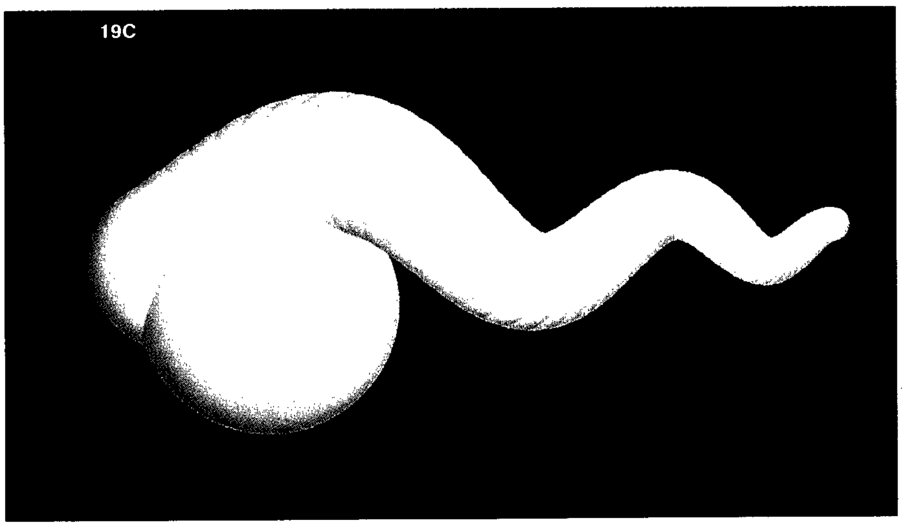


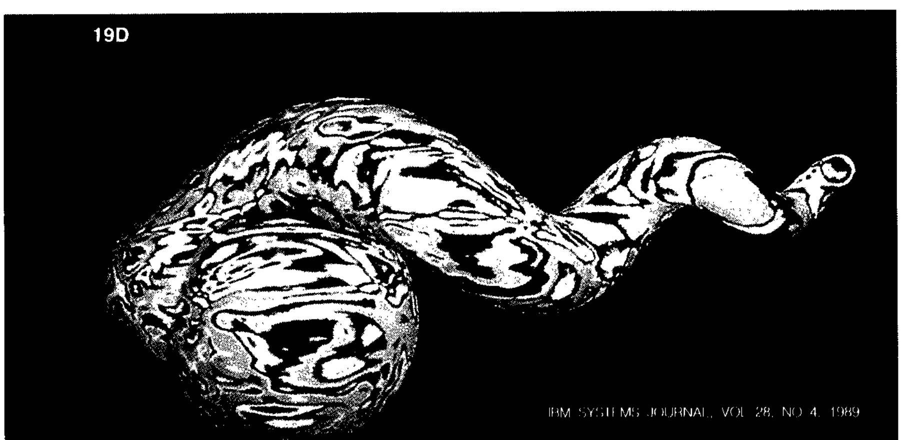
Figure 19 Levels of detail in a sculpture

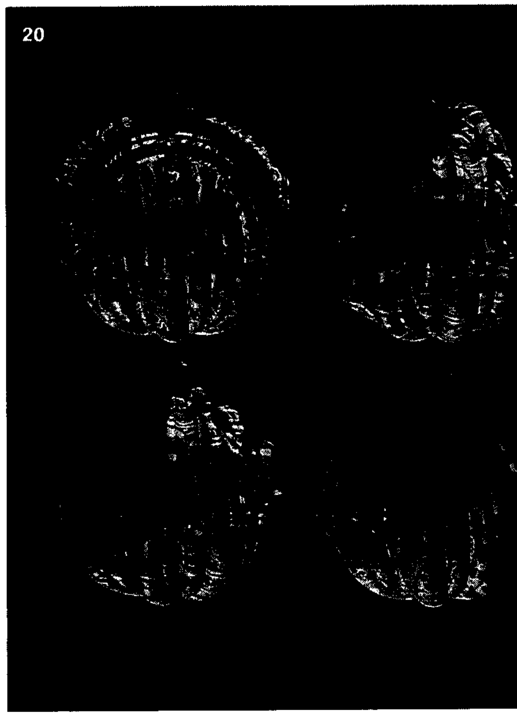
Figure 20 A sequence of frames from an animation

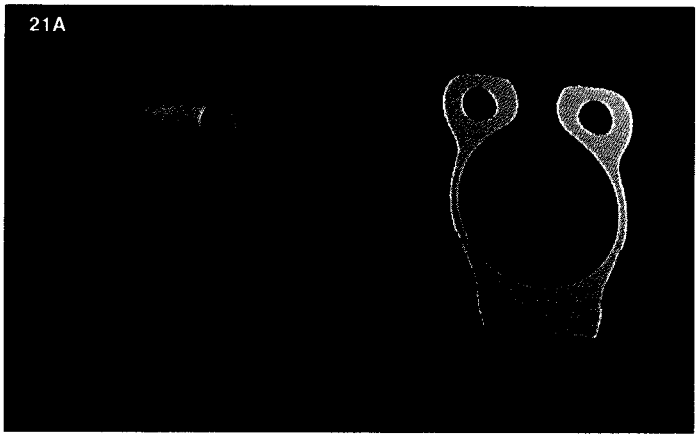












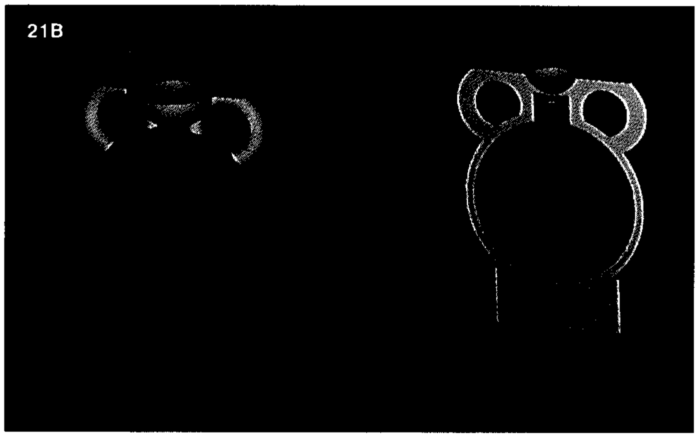
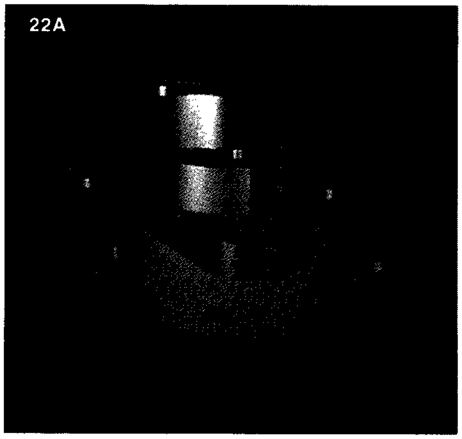
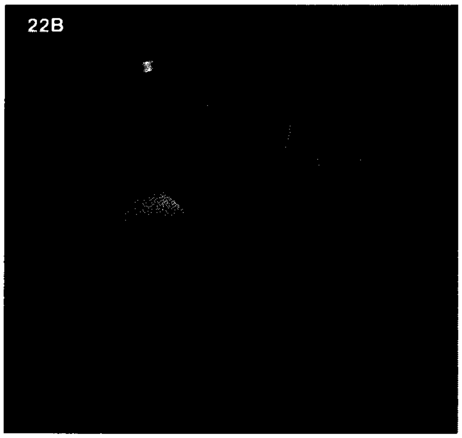


Figure 21 Simple primitives blended to give a complex shape: (A) Greek urn constructed by (B) blending a very crude initial model





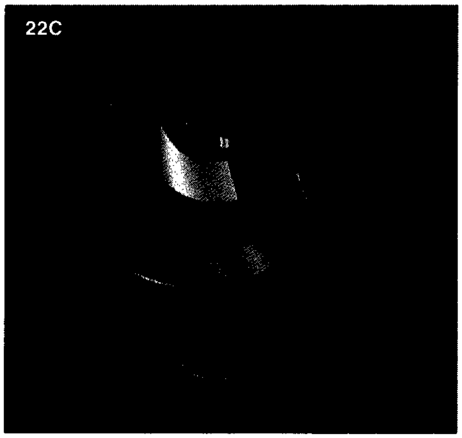
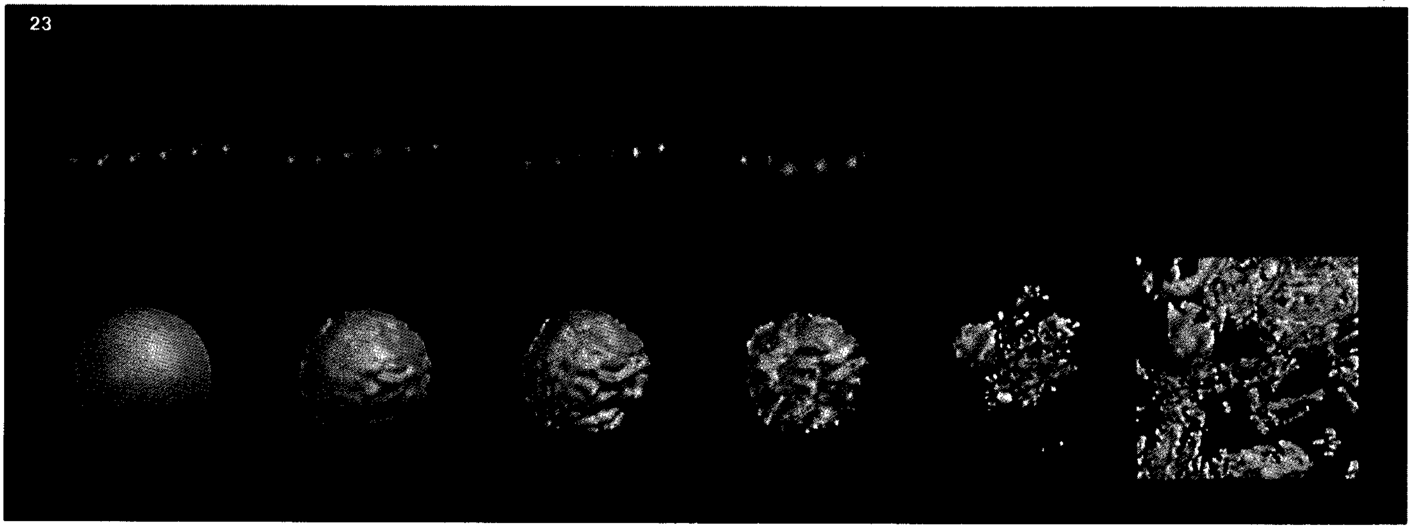


Figure 22 Bending and twisting a set-theoretic model: (A) pump cover plate is (B) first bent, then (C) twisted

Figure 23 Continuous deformation between two set-theoretic models



perature superconductors. The effect of chains and sheets of copper atoms on T_c (the temperature below which the superconducting behavior appears) can be demonstrated. Figure 9 shows a high-temperature superconductor (yttrium barium copper oxide).

Liquid crystals. *Flexible liquid crystals* are liquid crystals of the kind found in electronic displays and are composed of elongated particles with a rigid core

WINSOM has facilities to display potential and other scalar fields from a regular grid of sample measurements over the region of interest.

section. Flexible hydrocarbon chains attached to the rigid core of the molecule enhance its liquid crystalline properties. In Figure 10 we show the results of theoretical calculations on these chains. The rigid core is represented by the red cylinders, while the average position of each of the carbon atoms in the chain is represented by the small blue spheres joined by yellow cylinders. The ellipsoids in the top row represent the extent of thermal fluctuation of the atomic positions away from their average location.

Lyotropic liquid crystals are surfactants which include detergents and are composed of molecules with a water-attracting or *hydrophilic* group and a water-repelling or *hydrophobic* group. The hydrophilic group is happy to be surrounded by water molecules, the hydrophobic group is not. As a direct consequence, the surfactant molecules tend to arrange in aggregates such that the hydrophobic groups are protected from the water by a shell of hydrophilic groups.

These aggregates of molecules are called *micelles.* The simplest shape they take up is a sphere. Ellipsoidal, cylindrical, and bilayer structures are also known. In living organisms, cell membranes are known to be composed of a bilayer of surfactants; Figure 11 shows idealized representations of these aggregates. We have represented the hydrophilic part of the molecule as a red sphere and the hydrophobic part as a blue worm-like chain.

In Figure 11, the micelles are idealized representations of several different surfactant aggregates in an aqueous solution. The red sphere represents an atomic group which is water-attracting (hydrophilic); the blue chain represents a hydrophobic hydrocarbon chain. The spherical micelle (top left) is an aggregate of detergent-like molecules as found in solution in water. A cut-away view of this is shown on the bottom left. The planar micelle (top right) depicts so-called "bilayers" which form the cell-membranes in living organisms. The cylindrical micelle (bottom right) is another aggregate of detergent-like molecules.

Potential fields. Shape is not the only consideration with molecules, which are surrounded by a cloud of electrons that govern interaction with other molecules. In applications such as the study of the chemistry of biological processes, and in the computer-aided design of new drugs, the electronic shape is as important as the conventional shape.

WINSOM has facilities to display potential and other scalar fields from a regular grid of sample measurements over the region of interest. There are two basic facilities provided, allowing either the value or the shape of the field to be displayed.[32] The simpler option is probably to display field values using colour. WINSOM allows any surface to be coloured from the value of a field. This technique is well-suited to cases when the field value is of most interest on a particular surface (as, for example, a molecular surface). However, it is not restricted to this case and can be used to show the values of a field either within an object or in the space around it. In the first case, the object must be sectioned, which is of course easy to do in solid modelling. To display the field outside an object, a surface must be extended into the region of interest. In Figure 12, the first picture (left) shows an enalpryl molecule coloured by field strength, with a disk through the molecule, as the added surface.

To provide for the display of field shape, WINSOM has a primitive which is defined by a three-dimensional contour of a field. Such equipotential primitives act in exactly the same way as geometrically defined objects; they can participate in set-theoretic expressions; their surface colour and characteristics can be defined, and they are rendered accordingly.

The central picture in Figure 12 shows a series of equipotential contours surrounding an enalapryl molecule. The inner ones are exposed by subtracting a sphere. (The third picture [right] shows yet another way to display the shape of the field. The electric field, around the main chain of the enzyme adenylkinase, is displayed by solid arrows positioned along paths of steepest descent.)

Solid modelling also has a major role to play in archaeological reconstruction.

Archaeological reconstructions. Recent work has demonstrated that solid modelling also has a major role to play in archaeological reconstruction. This is especially true where it is not normally feasible to generate the resources necessary to build physical reconstructions, as in the cases of the Minoan palace of Knossos on Crete and the Viking settlement of Jorvik in York. The first application of WINSOM in an archaeological context was the reconstruction of the Saxon minster of Winchester, which was demolished at the end of the eleventh century. The archaeologists involved in the project employed a combination of documentary and archaeological evidence, as well as analogies drawn from other Saxon churches, to suggest how the Old Minster may have looked. These ideas were then transformed into a WINSOM model. A full animated tour of the Old Minster model was created and exhibited at the British Museum's 1987 *Archaeology in Britain* exhibition. Figure 13 shows sequences from this animation. Figure 13A shows an exterior view of the minster, Figure 13B shows the tomb of St. Swithin in the nave, and Figure 13C shows the elaborate altar.

WINSOM also proved useful in the analysis of an early Christian chapel and burial ground from the Isle of Man.[33] It was possible to deduce the presence of certain structural features within this complex from a variety of data-collection techniques, including geophysical methods such as resistivity and topographic surveys. The solid model shown in Figure 14 exposed several ambiguities in the sequence of constructional events at the site, which had previously been overlooked.

Another project involved the famous temple site of Navan in Armagh, Northern Ireland. All that now remains of the so-called temple are positions of a series of holes which formerly held posts. WINSOM "posts" were planted in the post holes. Their heights were computed on the basis of assumptions regarding a possible roof structure. By this means, we enabled the archaeological investigators to explore the possibility of alignments within the structure.

We have recently used a variant of WINSOM fields for the terrain mapping of a medieval site at Mathrafal in Wales, with a reconstructed castle. A picture of the WINSOM terrain model of this motte-and-bailey castle may be seen in another paper in this issue.[34]

Such models clearly have a major role to play in presenting archaeology to the public. More importantly, in creating them it is necessary to think more deeply about how the various archaeological components relate to one another. One quickly becomes acutely aware of the deficiencies in the data upon which the model is to be based. Even simple insights help the archaeologist to isolate and examine more closely those areas where evidence lurks unnoticed. It is possible then to think about other ways of testing the theory or confirming the observation.

Biological applications. If a pair of X-ray pictures are taken from different angles and one can find corresponding details in each view, it is possible to reconstruct the exact three-dimensional position of these details. In X-ray pictures of the chest, one can identify details on the arteries surrounding the heart—in particular the positions where they divide—and thus determine where these arterial bifurcations are as three-dimensional positions within the living body. One can also estimate the widths of the arteries and so build a model of the arterial system surrounding the heart. This is most simply represented by a number of connected cylinders and cones. Repeating this with each frame from a cinematic X-ray film produces an animated model of the arteries in action during the heartbeat. Figure 15 shows two frames from such an animation overlayed, showing the left ventricle in its most contracted state (in red) and in its largest state (in blue). This method offers considerable potential for the diagnosis of heart diseases.

In a project concerned with gaining a greater understanding of the operation of the Hippocampus region of the rat's brain,[35] WINSOM is used to display a solid model of a single neuron. Photographs of optical sections of the entire cell volume, obtained utilizing the small depth of field of a microscope, are image-processed to find the centre line and width of the "in focus" parts of the dendrite structure and its topography in three dimensions.[36] This geometric information is used to construct a WINSOM model as a union of spheres and frusta of cones. The picture shows one view of the three-dimensional dendritic structure of a typical cell. The measured volume and surface area of the structure are used in theoretical predictions, which are then compared with electrophysiological measurements on each cell, with the aim of broadening the theory of cell operation (Figure 16).

Another biological application is the study of proteoglycan assemblies. These are very large molecules whose approximate chemistry is known, but the only evidence for their shape comes from electron microscope pictures. We have used the programming power of ESME to produce a range of possible shapes based on available statistical information. One configuration of a proteo-glycan assembly is shown in Figure 17. Probably none of these is a "correct" picture of a proteo-glycan assembly, but each gave the researchers a much clearer idea of the three-dimensional nature of the molecule.

Physics. Recent work on the simulation of molecular beam epitaxy illustrates how theory can explain the growth of semiconductor substrate surfaces under the influence of directed atomic and molecular beams. The theory was known to be consistent with gross experimental observations, but a WINSOM animation (see Figure 18) of the time-dependent processes immediately yielded much information on the nature of individual growth mechanisms, which was fundamental to the understanding of the epitaxial process.

Another recent scientific animation addresses even more fundamental issues—those of quantum chromodynamics, a discipline which attempts to comprehend the basic forces of nature. Earlier work in this area[37] has used WINSOM to visualize the energy fields surrounding t'Hooft-Polyakov magnetic monopoles, a concept predicted by recent theories. The animation combines this work with results stemming from mathematical topology to show how the shape, motion, and even basic nature of a monopole can change in the presence of another monopole.

Sculpture. Although WINSOM was not designed with artists in mind, William Latham has used it to produce a wide range of sculptures.[38] For this application, the ability of WINSOM to handle models with a large number of primitives is crucial. The programming power of ESME permits a few simple programs to create a wide range of branching horn forms, and the artist concentrates on choosing and combining contrasting forms to make novel three-dimensional computer sculptures. The addition of texture increases the visual impact of the result.

As with so many of our applications, preparation of a sculpture begins with wire-frame pictures. As satisfactory forms are designed, the work proceeds to more complete renderings as illustrated in Figure 19. This figure shows a sculpture in wire-frame form (Figure 19A), low-resolution rendered (Figure 19B), high-resolution rendered (Figure 19C), and textured (Figure 19D). The final form of the sculptures is large high-resolution photographs and animations in which the viewer seems to move around (or through) the sculpture, or during which the sculpture itself grows, as shown in Figure 20.

Further developments of WINSOM

Much effort is put into helping potential users of WINSOM get the best from their system. This time is rarely wasted, as applications often lead to important developments. In addition to such fortuitous advances, we are currently focusing on a number of facets of the system.

WINSOM II. Various special applications of WINSOM caused us to extend the conventional set-theoretic modelling capabilities in new directions. We now realize that many of these extensions can be combined under a single umbrella of algebraic modelling. WINSOM II is an experimental system that implements some of these ideas.

Attempts to use WINSOM in design (as opposed to science or engineering) led to the implementation of a blend system similar to that of Ricci[39] (Figure 21), and thus to several operations generalized beyond the usual set operations. Design applications also required perspective and then more complex viewing projections. We found these could be used to distort the objects themselves, as well as our views of them. This permitted blending and bending operations on solid objects (Figure 22) similar to those of Barr.[40]

The introduction of contoured potential fields[32] described elsewhere in this paper (see also Figure 12) was the key to the integration of these concepts. In WINSOM II, *all* objects are considered as fields. No longer does a primitive sphere just have an inside and an outside, but rather every point in space has a potential that gives some measure of *how far* inside or outside the sphere it is. To make a solid, we contour the potential: points with a negative potential are inside the sphere, and points with a positive potential are outside the sphere.

The operations of union and intersection of solids are replaced by the minimum and maximum of potentials. As a potential defines a *number* at each point in space, we can also apply the standard arithmetic operations to add and subtract potentials, or even to take sines and logarithms. This permits us to generate complex blend functions based on potentials. Using the weighted average of the potential functions for two objects permits us to define a continuous deformation from one to the other (Figure 23).

In Figure 23, the upper sequence shows a line of spheres averaged with a cube in increasing proportion (left to right) of the latter. The lower sequence shows a sphere averaged with pseudo-fractal solid texture in a similar way. The ability to see solid texture as a solid may not yet have many applications but illustrates our desire to harmonize intuitively different types of modelled entity.

The basic potential fields X, Y, and Z have as their values the value of the x, y, and z coordinates of a point, respectively. These can be used to generate an object from any algebraically defined function in three dimensions. In this respect, WINSOM II is similar to earlier work done at the University of Bath[41] and its derivatives[42,43] which use complex polynomial expressions to generate primitives for blending. Following the work at Bath, WINSOM II is currently implemented using interval-arithmetic techniques. In the future we feel that algebra-system techniques will make models of this type both quicker and more reliable to evaluate. We are collaborating on the construction of an algebra system specifically aimed at geometric problems.[44]

Animation. Despite having produced several successful animations, we are aware of shortcomings in our animation capability. WINSOM does not utilize any interframe coherence, since we currently know no way to exploit this reliably.[45,46] We are, however, exploring the possibilities for running WINSOM on parallel processors, and we are collaborating on an implementation that runs on an array of Transputers™.[47]

In any case, raw frame-generation times are not the only problem. The difficulty is that of planning and choreographing an animation effectively. Shortcomings in this respect often *surface* at frame-generation time, when sequences need to be repeated! We currently plan to make animation less painful by designing a computerized storyboard system compatible with WINSOM and, more importantly, with ESME.

It has been exciting and rewarding to develop solid modelling techniques suitable for areas outside engineering and actually to apply them.

Conclusion

WINSOM's ability to render complex shapes at reasonable cost has put it in the vanguard of the application of shape modelling techniques to data visualization, a topic which is getting so much notice today. It has been exciting and rewarding to develop solid modelling techniques suitable for areas outside engineering and actually to apply them. One lesson we have learned is that we could never have done this without the help of the many subject specialists who have collaborated with us over the last ten years.

Acknowledgments

We are grateful to everyone who worked with us on the WINSOM projects, both those from non-IBM institutions and research Fellows at the IBM United Kingdom Scientific Centre (UKSC). In particular, we would like to mention collaboration with the following: on the static modelling of magnetic monopoles—A. J. G. Hey and J. H. Merlin (Southampton University) and M. T. Vaughan (Northeastern University, Boston); on the dynamic modelling of magnetic monopoles—M. F. Atiyah and N. J. Hitchin

(Oxford University), J. H. Merlin (Southampton University), and D. L. Pottinger (UKSC Fellow); on molecular beam epitaxy—D. D. Vvedensky and S. Clarke (Imperial College, London); on the reconstruction of hippocampal neurons—H. V. Wheal (Southampton University) and H. M. Cole (UKSC Fellow); on the modelling of liquid crystals—G. R. Luckhurst and D. J. Tildesley (Southampton University); on geometric algebra systems—J. H. Davenport and A. Bowyer (Bath University); on the parallel-processing version of WINSOM—P. M. Dew and D. Morris (Leeds University); on the reconstruction of the Saxon minster—B. Kølbye-Biddle (Wessex Archaeological Trust); on the Mathrafal project—C. J. Arnold, J. W. Huggett, and C. J. Springham; on the Leonardo exhibition animations—P. Steadman (Open University); on the modelling of proteo-glycan assemblies—K. Parker and P. Winlove (Imperial Cancer Research Institute) and M. Bayliss and T. Hardingham (Kennedy Institute); on all of the UKSC projects—students from various universities and polytechnics.

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Thomas R. Heywood *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Tom Heywood joined IBM in 1963 at the IBM UK Laboratory at Hursley. While there he held both technical and management posts in PL/I, VTAM, CICS, and graphics products. In 1983, Dr. Heywood joined the UK Scientific Centre as first manager of the graphics research group. The group's scope of research includes most aspects of data visualization and parallel processing for high-speed visualization. In 1989, Dr. Heywood returned to the laboratory as manager of strategic projects.

William H. Latham *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* William Latham initially trained as a printmaker, sculptor, and animator and obtained a B.F.A. in fine art from Oxford University, UK, and an M.A. from the Royal College of Art in London. In 1987, Mr. Latham became a Research Fellow in the Graphics Applications group at the IBM UK Scientific Centre in Winchester. There he has specialized in using three-dimensional solid modeling and computer photo-realist techniques to create computer sculptures. An exhibition of Mr. Latham's work is currently touring the UK, and his animations have appeared internationally on television and at film festivals. His recent film, *The Conquest of Form*, was shown at the 1989 SIGGRAPH Computer Graphics Theater.

Robert W. Phippen *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Robert Phippen has been working at the IBM UK Scientific Centre since 1986 as a Research Fellow attached to the graphics group. Dr. Phippen has been working on data visualization applied to theoretical studies of liquid crystals. His research has concentrated on molecular dynamics and Monte-Carlo simulations of model liquid crystalline systems, coupled to development of theoretical techniques to predict the results of these simulations. Dr. Phippen obtained a B.Sc. in chemistry at Southampton University, UK, in 1983. He remained there to do research in liquid crystals and statistical mechanics. Dr. Phippen was awarded his Ph.D. degree in 1988. He is a member of the British Liquid Crystal Society.

Peter Quarendon *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Peter Quarendon graduated in natural sciences at Cambridge University, UK. He joined the IBM Laboratory at Hursley in 1968 as a programmer. Dr. Quarendon worked on PL/I compilers and other topics related to programming languages, including a precursor to Prolog. In 1973, he went to Newcastle University under the Advanced Education Scheme to continue this research. After obtaining a Ph.D. degree there, he returned to IBM Hursley and began work on low-cost graphics. This eventually resulted in the GDDM program product and the availability of a graphics feature on all IBM mainframe terminals. Dr. Quarendon moved to the IBM UK Scientific Centre in 1983, where he initiated work on the WINSOM solid modeler and its application. After a period as manager of the graphics research group, he assumed responsibility for technical aspects of graphics research.

Paul Reilly *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Dr. Reilly received a B.A. Honours degree in archaeology and history at the University of Leeds, UK, and the Ph.D. degree in computer-based archaeological research at the Research Centre for Computer Archaeology in Staffordshire Polytechnic, UK. He has worked on many archaeological excavation and field survey projects in Britain and elsewhere in Europe. During the period 1986-1989, Dr. Reilly was a Research Fellow at the IBM UK Scientific Centre and became an IBM Research Scientist in 1989. He has written over 20 papers and a book relating to computer applications in archaeological research.

M. William Ricketts *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Mr. Ricketts graduated in mathematics at Oxford University, UK, in 1969. In the same year, he joined the IBM UK Laboratory at Hursley. Mr. Ricketts worked on the PL/I checkout compiler until 1977, at which time he moved into work in character graphics (later to become GDDM) where he specialized in system environments. In 1986, Mr, Ricketts joined the graphics systems research group at the IBM UK Scientific Centre. Initially, he investigated the applicability of parallel processing to graphics systems. More recently, Mr. Ricketts has focused on data visualization activities and is now working on new implementations of the WINSOM concepts.

John Simmons *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Dr. Simmons received the B.Sc. and Ph.D. degrees in physics at the University of Birmingham, England. He worked for many years on pattern recognition techniques as applied to the evaluation of bubble chamber experiments in the field of high-energy physics. He joined the IBM UK Laboratory at Hursley in 1974 and has been associated with workstation development since that time. Following an initial design study at Hursley, Dr. Simmons spent two years at the Vimercate Plant in Italy, working on the detailed design and prototyping of the IBM 7350 Image Processing System. On returning to Hursley, he worked on a number of graphics projects culminating in the display graphics system for PC systems. Dr. Simmons joined the IBM UK Scientific Centre in 1988, where he has been involved with the application of three-dimensional graphics techniques to the visualization of biological structures.

Stephen J. P. Todd *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Professor Todd studied mathematics at Oxford University, UK, from 1965-1971. In 1971, he joined the IBM UK Scientific Centre at Peterlee. He developed the Peterlee Relational Test Vehicle, one of the first relational database systems. He was also involved in research in image processing. He spent 1979 to 1981 at the IBM Research Laboratory in San Jose, California, where he worked in text processing and coding theory. He rejoined the UK Scientific Centre in 1981. Since then, Professor Todd has researched a number of graphics areas, including picture generation from databases, languages to create solid models for a variety of applications, and the realistic rendering of these solid models.

Andrew G. N. Walter *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Andrew Walter read engineering science at Oxford, University, UK. He worked for ten years in industry, specializing in real-time microprocessor control systems, loosely coupled parallel processing, and two-dimensional, real-time pattern recognition systems. He joined the IBM Scientific Centre in Winchester five years ago, and has since been working on computer graphics applications and animation. He was responsible for producing *The Old Minster, Winchester*, which was the first movie produced using the WINSOM solid modeler.

John R. Woodwark *IBM UK Scientific Centre, Athelstan House, St. Clement Street, Winchester, Hampshire SO23 9DR, United Kingdom.* Dr. Woodwark joined IBM in 1985 and now manages the graphics research group at the UK Scientific Centre. Before joining IBM, he was a lecturer in manufacturing engineering at Bath University, UK, where he was involved in projects with industry ranging from display technology to robotics. His work on modeling and graphics concentrated on improving the computability of the set-theoretic solid model. Applications included a reconstruction of the Roman baths at Bath which was shown on BBC television in 1984. His publications include *A Programmer's Geometry* coauthored with Dr. Adrian Bowyer, first published in 1983 and now being reprinted for the second time, and *Computing Shape*, published in 1986. He obtained his B.Sc. at Leeds University, UK, as a Rolls-Royce university apprentice. Subsequently he returned to Leeds to do research in computer-aided manufacture and received a Ph.D. in 1978.

Reprint Order No. G321-5374.