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Ray tracing for constructive solid modeling

Anju Sharma McCanna

Rochester Institute of Technology
Department of Computer Science

Ray Tracing for Constructive Solid Modeling

by

Anju Sharma McCanna

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Approved by:

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Dr. Andrew T. Kitchen

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Prof. Nan Schaller

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Dr. Peter G. Anderson

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ABSTRACT

This thesis describes a system for the creation and realistic depiction of non-geometric, complex, three dimentional solid models by utilizing a ray tracing algorithm and a graphics relational database. Geometric primitives such as a sphere, cylinder, block, and cone are combined together by using the boolean set operations of union (+), intersection (&), and difference (-). The three dimentional solid models are built based on the concept of constructive solid geometric modeling. The database provides functions for the creation, transformation, and deletion of the primitives and models. A model may be displayed as a wireframe for a fast display or as a shaded solid for a realistic display.

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CHAPTER 1 INTRODUCTION

Solid modeling (SM) systems provide an effective and versatile means for communicating 3-D object information. These systems have received much attention in scientific and engineering applications and have been used in industry and academia by skilled professionals [Gujar]. However, the development of SM systems for the non-professional graphics user has been slow. The reasons for this have been: the high cost of hardware, inadequate operating environments, and the lack of a standard, user friendly interface with the system (such as a graphical window interface). Non-professional graphics users, in the fields of business, communications, art, science, engineering, etc., have been using desktop graphics. The term desktop graphics refers to applications for painting, drawing, making graphs, and using spreadsheets. These tools became available when personal computers were developed [Cline] [McDougal]. Development of SM systems for non-professional graphics users can provide a wide scope of applications in areas such as: desktop presentation, architectural design, advertising, and simulation.

Recently, the cost of high-resolution graphics hardware has decreased and microcomputers have become faster. Contemporary, single processor microcomputers can handle image synthesis of fairly complex 3-D models. In addition, much progress has been made in the development of

multiprocessor systems. These systems allow more complex 3-D models (static or animated) to be processed faster and with more ease.

A solid modeling system for a non-professional graphics user requires a design and implementation that:

(1) is easy to understand and work with;

(2) facilitates the creation and display of realistic, 3-D solid models; and

(3) facilitates the modification and maintenance of these models.

In solid modeling, several methods have been developed for the construction of complex 3-D objects. Most solid modeling systems have used either one or a combination of the following methods: constructive solid geometry (CSG), boundary representation [Mortenson], and sweep techniques [Requicha]. The CSG method is discussed next and the other two methods are discussed in chapter 2, Historical Background, section 2.1.

The CSG method is most appropriate for SM systems for non-professional graphics users, because the concept of CSG is easy to understand. CSG is one of the least complicated methods to implement by using a ray tracing algorithm. Use of a ray tracing algorithm to implement CSG results in the creation of realistic solid models. For modification and maintenance of solid models, CSG is very suitable for integration with a relational database.

CSG modeling is object oriented. In CSG modeling, construction of a complex 3-D object is performed in object

space, by a series of boolean operations on geometric primitives such as spheres, cylinders, cones, blocks, etc. The primitives are used as building blocks. Fig. 1.1 illustrates the boolean operations: union, intersection, and difference.

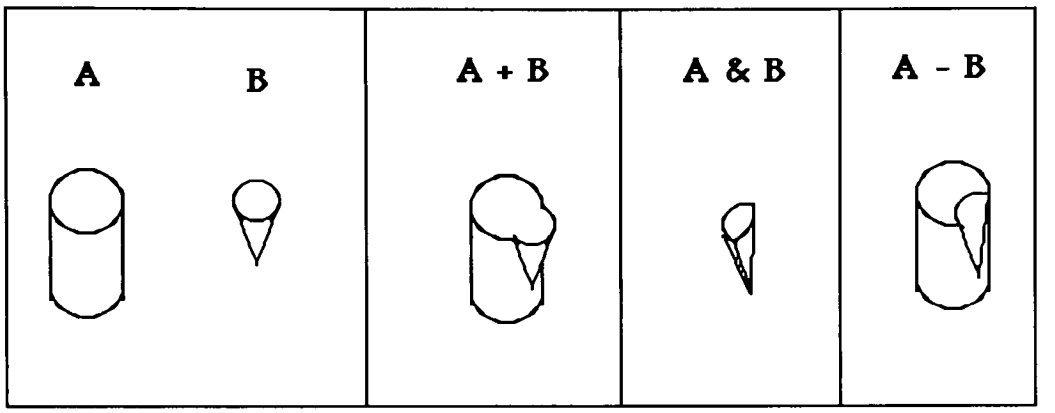
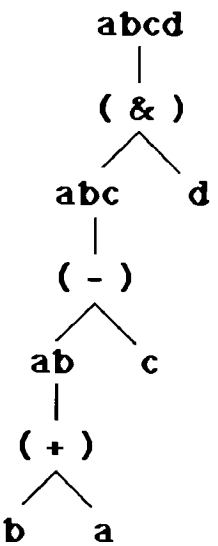


Fig. 1.1 Union (+), Intersection (&), and Difference (-) between a cylinder and a cone.

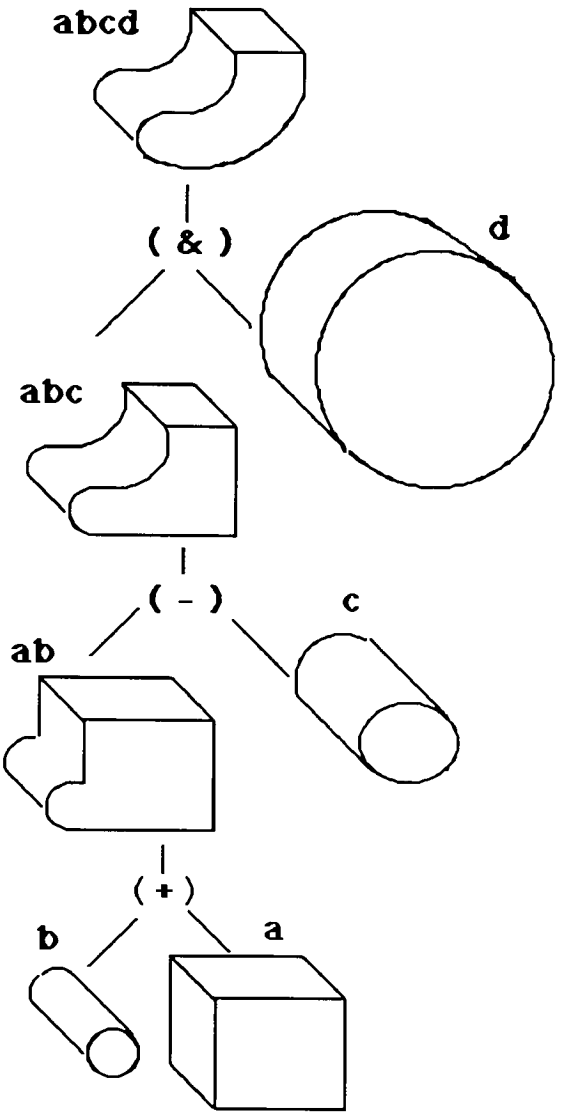
The construction of a composite is processed by using a CSG binary tree. Fig. 1.2 illustrates a CSG binary tree. The binary tree is essentially a parse tree for boolean expression evaluation. In such a tree, the root node represents the entire model, the nonterminal nodes designate the subcomponents combined by using the boolean operators, and the terminal nodes designate the primitives. The nonterminal nodes can also designate transformation operations, such as: translation, scaling, or rotation. Information regarding the location, size, orientation, and color of each primitive is stored in the terminal nodes of the tree. The non-terminal nodes hold information about the left and right solids and the boolean operation that is used to combine them.

Following is the boolean expression evaluation of the parse tree given in Fig. 1.2:

a b c d
=> abc & d
=> (ab - c) & d
=> ((b + a) - c) & d



A parse tree for boolean expression evaluation



Pictorial Version

Fig. 1.2 A CSG binary tree.

1.1 IMPLEMENTATION TECHNIQUES

Two major issues in the constructive solid modeling process are the implementation of the boolean operations: union, intersection, and difference, and the representation of geometric objects. There are several techniques for implementing the boolean operations. These include: the set membership classification method, the triangulation of potentially intersecting faces, a hierarchic boundary representation scheme, the directed loop technique, and the ray tracing (or ray casting) technique.

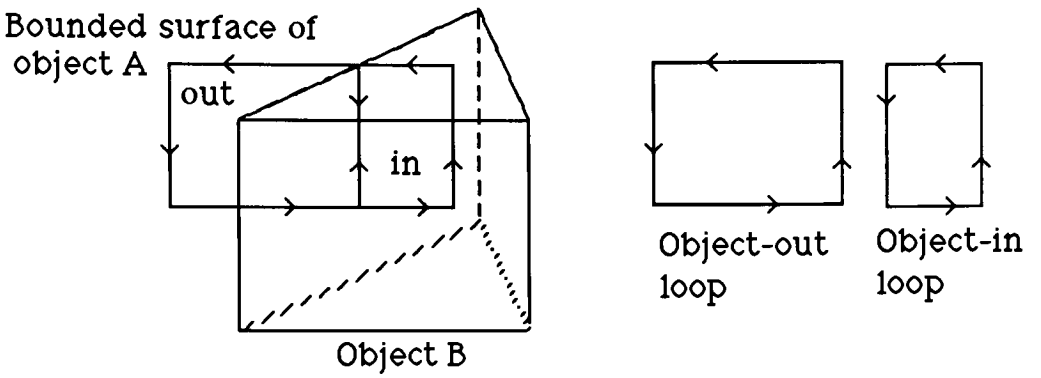
Set membership classification method [Tilove]: A membership classification is a function which operates on a pair of point sets called the reference and candidate sets. The function classifies the candidate into three subsets which are inside, outside, and on the boundary of the reference set. The classification is defined in terms of regular sets and the boolean operations are defined in terms of regularized set operators. Reference sets are represented constructively by combining the primitive regular sets via the regularized set operators. Algorithms based on this method have been used by the Production Automation Project for development of PADL-1 and PADL-2 at the University of Rochester [Tilove].

Triangulation of potentially intersecting faces [Tokieda]: This is an example of the cell decomposition method [Requicha] of solid modeling. Given two polyhedrons, a list of

intersecting face pairs are determined. Each face in the list is triangulated. Next, intersecting triangle pairs are determined. Each triangle pair is processed sequentially. After all the intersecting faces have been processed, they have been marked as inner or outer faces. Based on the boolean operation: union, intersection, or difference, either the inner or outer faces are removed from the polyhedrons. The data structure of the two polyhedrons is reorganized into a single data structure. This method can be applied to curved objects by polygonal approximation of curved surfaces. However, performing polygonal approximation results in less realistic images. This method has been used in the Freedom-II system at Kyushu Institute of Design in Japan [Tokieda].

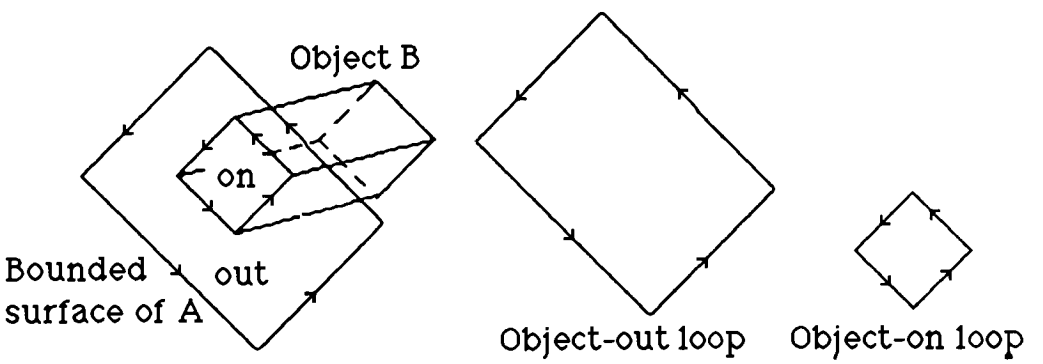
Hierarchic boundary representation scheme [Sun]: This method is based on the study of the boundary properties of objects. The basic concept used is that "a regularized geometric object may be represented by its boundary" and that "a regularized object boundary may be divided into a finite number of bounded surfaces". Given two objects A and B: (1) intersection between bounded surfaces of A and B is determined; (2) loops are formed and classified (a loop can be: object-out, object-in, object-on, out-on, in-on, or on-on. Loop classification is illustrated in Figs. 1.3, 1.4, and 1.5); (3) new bounded surfaces are formed and classified (if S is a new bounded surface on A, then S can be classified with respect to B as: S out B, S in B, etc.); and (4) new object boundaries are formed based on the boolean

operation being performed.



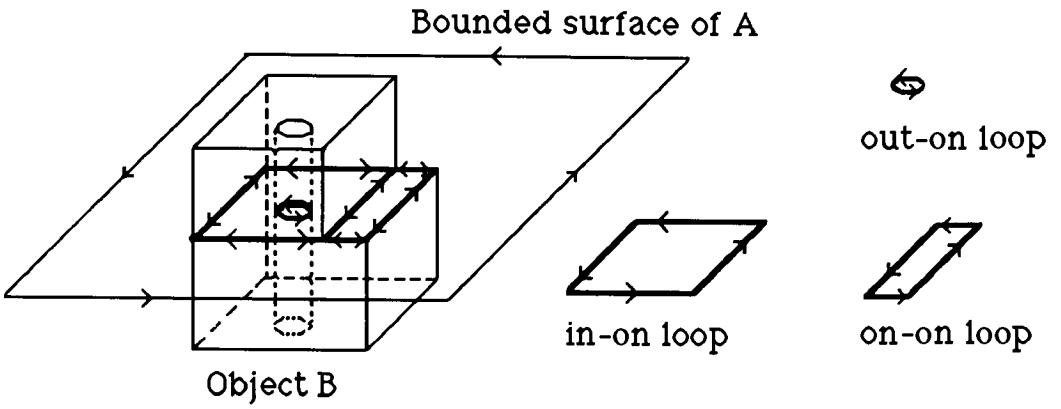
Loop L is an object-out loop on A with respect to B, if there exists at least a point on L which is out of B and all the other points on L are not in B. Loop L is an object-in loop on A with respect to B if there exists at least a point on L which is in B and all the other points on L are not out of B [Sun].

Fig. 1.3 Classification of object-out loop and object-in loop.



Loop L is an object-on loop on A with respect to B if all of the points on L are on the boundary of B [Sun].

Fig. 1.4 Classification of object-on loop.



Classifications of object-on loop: Let p be an arbitrary point inside L which is "nearly close to" L, then L is an out-on loop if $p \notin B$, L is an on-on loop if $p \in bB$ (i.e. boundary of B), and L is an in-on loop if $p \in iB$ (i.e. inside of B) [Sun].

Fig. 1.5 Classification of object-on loop into: out-on, on-on, and in-on loops.

For the classification of an object-on loop (i.e. L), an arbitrary point 'p' inside L must be chosen as close to L as possible, otherwise the loop L may be classified incorrectly. In Fig. 1.5, consider the 'out-on-loop' to be called 'L1', and the 'in-on-loop' to be called 'L2'. Any arbitrary point p2 inside L1 also lies inside L2. If L2 is classified with respect to p2, L2 will be incorrectly classified as an out-on-loop. Therfore, to correctly classify L2, the arbitrary point inside L2 must be as close to L2 as possible.

The hierarchic boundary representation method has been realized on a supermicrocomputer (UV68/137T) and can process polygons as well as bivariate parametric Bezier patches [Sun].

Directed loop method [Tang]: In this method the well-established algorithm of realizing boolean operations (union, intersection, and difference) between 2-D configurations has been extended to 3-D solids (when the 3-D solid is represented in the form of a set of bounding faces and loops). In the algorithm for the 2-D case, each contour is composed of directed edges such that the solid object part of the contour always lies on the left-hand side when the edge is traversed in the positive direction. An "in-on-out" set membership classification is used to determine intersection points between two contours. Then, edges are split at the point of intersection. Finally, based on the

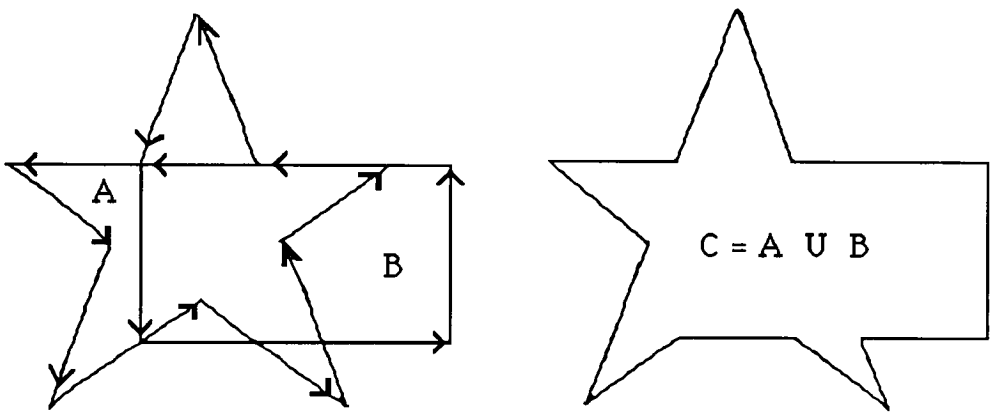


Fig. 1.6 Union of 2-D contours A and B (by using the directed loop method).

boolean operation to be performed, each split part of the edge is either retained or discarded. Fig. 1.6 illustrates an example of the union operation between 2-D contours.

In the 3-D case, contours are replaced with faces. Here four faces meet at a common edge. The "in-on-out" classification of a face is reduced to a 2-D problem by projecting the local normal vector of each face, (in the neighbourhood of the intersecting edge), onto a plane perpendicular to the edge. An example of the 3-D case is illustrated in Fig. 1.7 and Fig. 1.8.

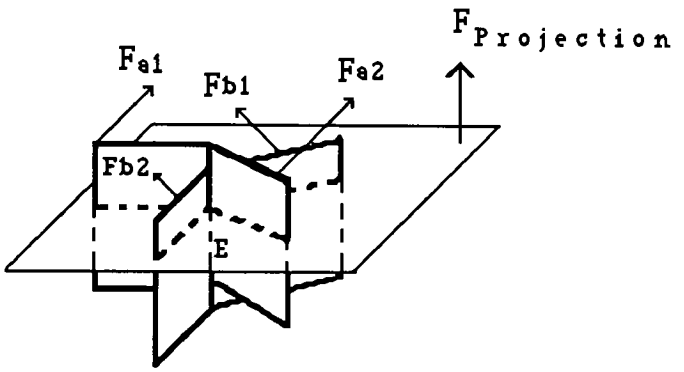


Fig. 1.7
Example of a 3-D case
(using the directed loop method).

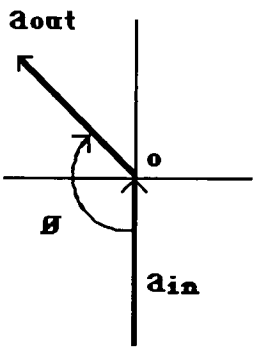


Fig. 1.8
Determination of the angle between intersecting faces.

An incoming vector **ain** is taken as the axis of reference, the angle included between the outcoming vector **aout** and **ain** is computed.

If $\mathbf{a_{in}} \times \mathbf{a_{out}} > 0$, $0 < \phi < 180°$

$\mathbf{a_{in}} \times \mathbf{a_{out}} < 0$, $180° < \phi < 360°$

Similar calculation is repeated for **bin** and **bout**. The normal vectors are then sorted according to their relative angular positions. Finally, based on the boolean operation, the relative angular positions of intersecting faces are compared and each face is either retained or discarded. This method has been used in PANDA-3D [Tang]. This method is useful for planar objects but is inaccurate for curved objects. The authors claim that this technique is computationally more efficient than the set membership classification method.

Ray Tracing [Roth]: The ray tracing technique is well known for rendering highly realistic images. The ray tracing technique can be implemented at different levels of complexity depending on the illumination model used with it. For constructing solid geometric models, a ray tracing technique called **ray casting** is used to realize the boolean operations of union, intersection, and difference.

The observer is assumed to be located along the +ve Z axis. The view plane (also known as the 'image plane' or the 'raster plane') is the X-Y plane at Z = 0. The models are created in object space which is the -ve Z half space. All the objects are assumed to be opaque solids. An object may be either a primitive (such as a sphere, cylinder, block, or cone) or a composite, i.e. a combination of primitives. A single point light source is sufficient to illuminate the object. The light source may be placed by the user any where in 3-D space.

In the ray casting process, rays are cast into object space as probes. A ray originates from the observer's eye, passes through a pixel on the view plane, and continues into the object space. In the object space the ray may or may not intersect with the solid object(s). If the ray does not intersect with any object, the pixel is displayed with the attributes of the background. The same process is repeated by casting another ray through the next pixel, and so on.

Assuming that the ray does intersect with the objects, intersections of the ray with each primitive component of the object are determined. From all the intersection points obtained (for all the primitive components) for a particular ray, one point is selected depending on the boolean operation being performed and depending on which object is closest to the view plane. The algorithm tests to see if the selected point is visible to the observer or not by examining the angle between the normal at the selected point and the sight vector. If the point is visible, the illumination at that point from the light source is determined. Finally, the pixel on the view plane is displayed with the attributes (i.e. color) and illumination of the object at the selected point.

For each primitive at most two ray-primitive intersection points are determined; the point at which the ray enters the primitive's surface and the point at which the ray exits the primitive's surface. Along with the intersection points the normal at each intersection point is also determined. The surface

attributes of the primitive, such as color, are also maintained with each point. After all the intersection points have been determined for a particular ray, the list of points is sorted based on the Z coordinate of the points. From this sorted list, one point is selected. The criteria for selecting one intersection point based on the operations of union, intersection, and difference are explained in section 3.3.2. The ray casting method has been used in the GM solid modeling project.

When a ray is cast, it is more appropriate to consider it as being a vector along the line of sight rather than to consider it as being a reflected light ray (traversed in reverse). After the ray has entered an object's surface, the ray proceeds through the object in a straight line along the line of sight without being refracted. If refraction has to be handled, it must be considered only after a single intersection point has been selected from all the intersection points obtained for the ray. Ray tracing of the refracted ray would then begin from the 'selected point'.

The ray casting method described above can be combined with either a simple illumination model, a global illumination model [Rogers], or no illumination at all. The purpose of an illumination model is to determine the intensity of light reflected towards the observer's eye at each point on the object's surface. With the simple illumination model, the ambient light, the incident light, as well as the light that is reflected diffusely and specularly from the surface of the object can be considered to render a model. When the simple illumination model is used, the

visibility calculations end at the first ray-object intersection point. With the global illumination model, it is possible to process all the effects achieved with the simple illumination model, plus the following: reflection of one object in the surface of another, refraction, transparency, and shadow effects. When the global illumination model is used, the visibility calculations do not end at the first ray-object intersection point. The reflected ray and the transmitted ray generated at the intersection point are traced furthur to determine their intersections with other objects. Finally, for the case when no illumination model is applied, the ray casting technique is useful for displaying just the visible surfaces of a CSG model.

On the whole, a simple illumination model is sufficient to illuminate an object appropriately. More information about the simple illumination model is given in chapter 3, section 3.4.

1.2 REASONS FOR USING RAY TRACING

Among all the methods mentioned in section 1.1, the ray tracing algorithm for realizing the boolean operations in constructive solid geometric modeling is, in some sense, the least complicated and has a wider scope of applicability. Any object for which an intersection routine can be written may be used for constructing 3-D models. Objects in a model may be composed of a mixture of planar polygons, polyhedral volumes, and volumes defined or bounded by quadric or bipolynomial parametric surfaces [Rogers]. The boolean set operations, visible surface processing, and the illumination model, can all be handled simultaneously by the same algorithm. Illumination of the solids can be handled at various levels of complexity by using different illumination equations and techniques. As mentioned in the previous section, Roth has presented ray casting as the basis for a CAD/CAM solid modeling system [Roth]. He has also described how a ray tracing algorithm can be used to generate wireframe line drawings for solid objects and how it can be used to determine the physical properties of a solid.

The use of ray casting in a ray tracing algorithm simplifies determination of ray-object intersection points and the normal vectors at those points, no matter what orientation, size, or position the objects may be in. A single ray-primitive intersection routine is sufficient to process all instances of a primitive.

Compared to the other methods used for realizing the

boolean operations, in the ray tracing method memory usage is fairly low. Memory usage is directly proportional to the complexity of a model.

A drawback to using ray tracing is that the algorithm is slower than many other algorithms when implemented in a single processor environment. However, the ray-object intersection calculations can be processed in parallel. Therefore, a ray tracing algorithm can take advantage of a multiprocessor environment and speed up the ray tracing process considerably. As multiprocessor environments become more common, ray tracing algorithms such as the one proposed become more appropriate for constructive solid modeling implementations.

1.3 PROBLEM STATEMENT

As mentioned in section 1.1, two main problems in constructive solid geometric modeling are the representation of geometric objects, and the implementation of the boolean operations [Sun]. Most algorithms for performing the boolean operations are complicated, slow, and of limited applicability [Tokieda]. Few algorithms have the ability to construct models using solids that have curved surfaces. Functions such as hidden line/surface removal, and illumination of the model, have to be performed by separate algorithms.

In this thesis, a ray tracing algorithm was used to realize the boolean set operations (The reasons for using ray tracing are given in section 1.2). A graphics relational database was designed to facilitate the creation of more complex 3-D solid models and the storage, manipulation, and deletion of these models. For displaying a model, a choice was provided between wireframes for fast display, and shading for displaying a more realistic object. Shading was done by using a simple illumination model in combination with dithering.

The software implemented for this thesis has been named ARTISAN. Software programming was done using the C language. Software development was done on an IBM AT compatible PC using a VGA graphics card and a color graphics monitor. Assembly language routines for using the VGA graphics card were obtained from the "Programmer's Guide To The EGA/VGA" [Sutty].

CHAPTER 2 HISTORICAL BACKGROUND

Evolution of the techniques of solid modeling, ray tracing and dithering are presented below.

2.1 SOLID MODELING

The evolutionary approaches to 3-D object representation are illustrated in Fig. 2.1 [Voelcker]. Interactive computer graphics came into prominence in the decade 1955-64. Interactive computer graphics [Newman] along with projective geometry [Tech.] [Ahuja] and Numerical Control (NC) programming languages [ITT] gave rise to the four independent areas of development: polygonal schemes, sculptured surfaces, wireframes, and solid modeling.

Polygonal Schemes: 3-D modeling systems using polygonal schemes are mainly used for creating visual effects, i.e. for rendering. There is a wide range of systems in this field [Newman]. On one end the emphasis is on achieving highly realistic static image synthesis, while at the other end are real-time animation systems such as flight simulators.

Sculptured Surfaces: This area deals with mathematical methods for defining and representing curves and surfaces. The work of Coons, Bezier, Gordon, and other pioneers dealt with methods for designing multicurved objects such as ships, car bodies, aircrafts, etc. The emphasis in this field has been on: accurate representation of surfaces, and tailoring of such representations to meet functional and esthetic criteria [Coons] [Bezier] [Forrest] [Gordon].

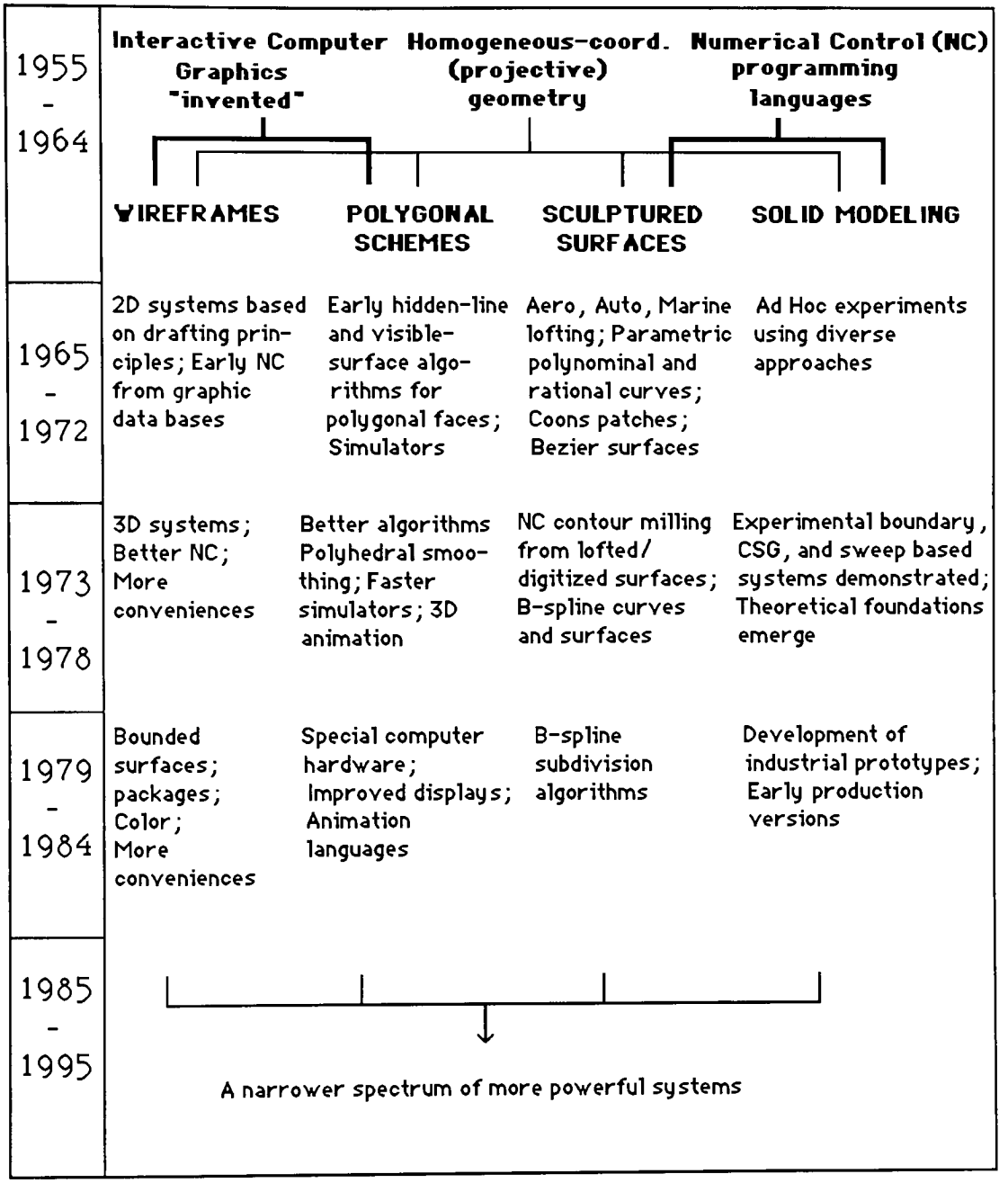


Fig. 2.1 A historical summary of approaches to 3-D object representation (From [Voelcker] page 10).

Wireframes: The wireframe modeling systems first appeared as 2-D interactive systems. In 1970's they evolved into 3-D systems. 3-D wireframe systems have several drawbacks. Two serious deficiencies are: **(1)** they are often ambiguous. Fig. 2.2 illustrates how a wireframe of a cube may represent more than one solid. This is known as the Necker cube illusion [VanDam].

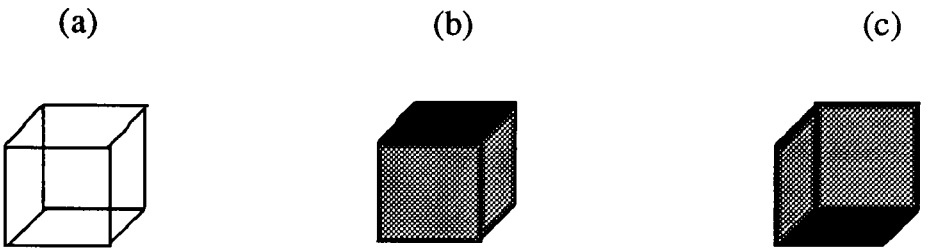


Fig. 2.2 The Necker cube illusion. The cube in (a) can be viewed as the cube in (b) or the cube in (c).
(Necker observed this in 1832).

(2) the viewpoint dependent profile lines that an object with a curved surface requires in its wireframe are often missing. In Fig. 2.3, the dashed lines show the profile lines that are often missing in a wireframe.

Fig. 2.3 Wireframe edges (solid), and viewpoint dependent profile lines (dashed).

To overcome these drawbacks, bounded-surface techniques were used. These in turn led to the use of boundary representation schemes in some solid modeling systems.

Solid Modeling: This area emerged in the 1960's [Roberts]. At that time it had very little theoretical support. In the early 1970's many ad hoc theories were devised to overcome the need for adequate theoretical foundation. The first generation of experimental solid modeling systems were developed in the 1970's. Fig. 2.4 illustrates examples of SM projects that emerged in the mid 1970's. Theoretical foundations based on mathematics emerged in late 1970's [Tilove].

1976 CAM-I organized its Geometric Modeling Project [Okino1][Okino2]
MDSI launched its Design Project [Hakala] [Hillyard].

1977 General Motors began the development of **GMSolid** [Boyse2].

1978 ShapeData's **Romulus** system appeared [Veenman].

1979 Two collaborative university/industry projects were launched:
PADL-2 at University of Rochester [Brown], and the
Geometric Modeling Project at Leeds in the UK.

1980 Evans & Sutherland began to market **Romulus**.

1981 Applicon announced a solid-modeling capability based on
SynthaVision [Nagel] [Goldstein];
ComputerVision announced the **Solidesign** system.

Fig. 2.4 Examples of projects that emerged in the mid 1970's (From [Voelcker] page 13).

In the 1980's a second generation of systems were developed. These were designed for industrial and commercial use. Fig. 2.5 illustrates examples of contemporary CAD/CAM systems.

1988 **ADROS** (Advanced Design Result Oriented System) developed in Mexico, [Siska].

" **SIMAK** developed in USSR, [Klimov].

" **MODEL** developed in Spain at CEIT, [Rodil].

" **PERIS** developed in China in Zhejiang University, [Liang].

Fig. 2.5 Examples of contemporary CAD/CAM systems.

Requicha and Voelcker describe solid modeling as follows [Voelcker]:

> "The term "solid modeling" encompasses an emerging body of theory, techniques, and systems focused on "informationally complete" representations of solids -- representations that permit (at least in principle) any well defined geometrical property of any represented object to be calculated automatically."

Fig. 2.6 illustrates a generic "geometry system", [Voelcker]. This may be considered a depiction of the description of SM given earlier. A typical geometry system has a subsystem called "geometric modeling system" which accepts definitions of objects from users and translates them into internal representations. The subsystem provides facilities for entering, storing, and modifying object representations.

The subsystem is an independant component and it can be combined with a variety of applications. The software implementation for this thesis is an example of the "subsystem". The command translator accepts questions from the users and

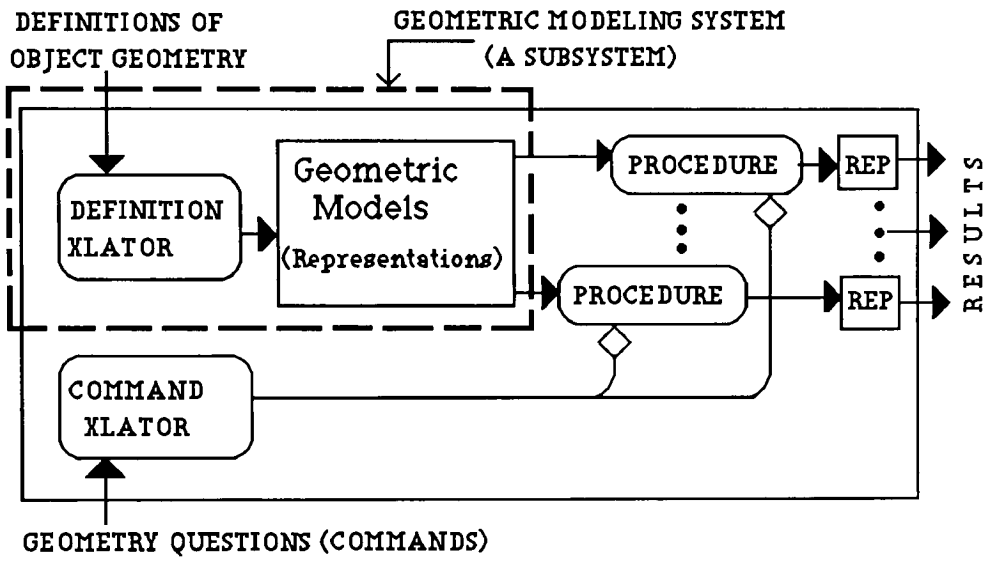


Fig. 2.6 A Geometry System. (From [Voelcker] page 10)

evokes application dependent procedures to answer these questions. For example, questions about the object's volume, surface area, center of gravity, etc.

Several methods for representation of solids are known [Requicha] [Mortenson]. Mortenson classified six methods as: Primitive instancing and/or parametrized shapes, cell decomposition (along with spatial enumeration), wireframe representations, sweep representations, boundary representations, and constructive solid geometry (CSG). Of these six the last three are used in contemporary SM systems.

In **primitive instancing** [Requicha] each member of a group of objects is distinguishable by a few parameters, for example, the family of spike wheels may be described by a type code, the wheel's diameter and the number of spikes. Primitive instancing does not allow creation of new or more complex objects by combining representations. It is also difficult or impossible to determine geometric properties directly from primitive instancing schemes.

Spatial enumeration [Requicha] is a scheme where the occupied space is divided into a 3-D grid of volume elements. A solid is represented by a list of grid blocks that it occupies. This scheme has advantages for performing boolean operations, hidden surface removal or interference detection. However, this representation is difficult to integrate with database techniques [Meier]. Thus this scheme is not used in geometry systems as a fundamental SM method.

The **cell decomposition** [Requicha] method is based on the triangulation theory. A solid is decomposed into disjoint parts of different dimensions. This may be considered a type of spatial enumeration where cells do not have to lie on a fixed grid nor have a prespecified size and shape. Like spatial enumeration this scheme is also difficult to integrate with database techniques [Meier].

Boundary representation (**B-rep**) scheme represents a solid in terms of its boundary. The boundary is viewed as a closed surface or skin around a solid such that it separates the inside from the outside. Fig 2.7 illustrates an example of a B-rep

scheme. The boundaries are represented as unions of faces. Each face is a union of its edges and each edge in turn is bounded by a pair of vertices. Accurate boundary representations are difficult to construct as discontinuity may arise at the juncture of two surfaces. This method is used in combination with other methods in contemporary SM systems.

In the **sweep representations** method, a solid is first represented by a 2-D plot of its cross section which is called an "area set" [Voelcker] or a "generatrix" [Siska]. Then another 2-D plot of the path called the "trajectory set" or the "rail" is described. Interaction between the generatrix and the running rail may be carried out in a parallel, radial, or normal (i.e. perpendicular) way. Using all of this information, the system generates an isometric view of the solid. This method together with other methods has been used in ADROS [Siska]. Fig. 2.8, illustrates some examples of sweep techniques.

CSG and the other SM methods in their embryonic stages of development recognized the importance of boolean operations. (For the CSG method see: chapter 1, Fig. 1.1, Fig. 1.2; and chapter 3, section 3.3.2).

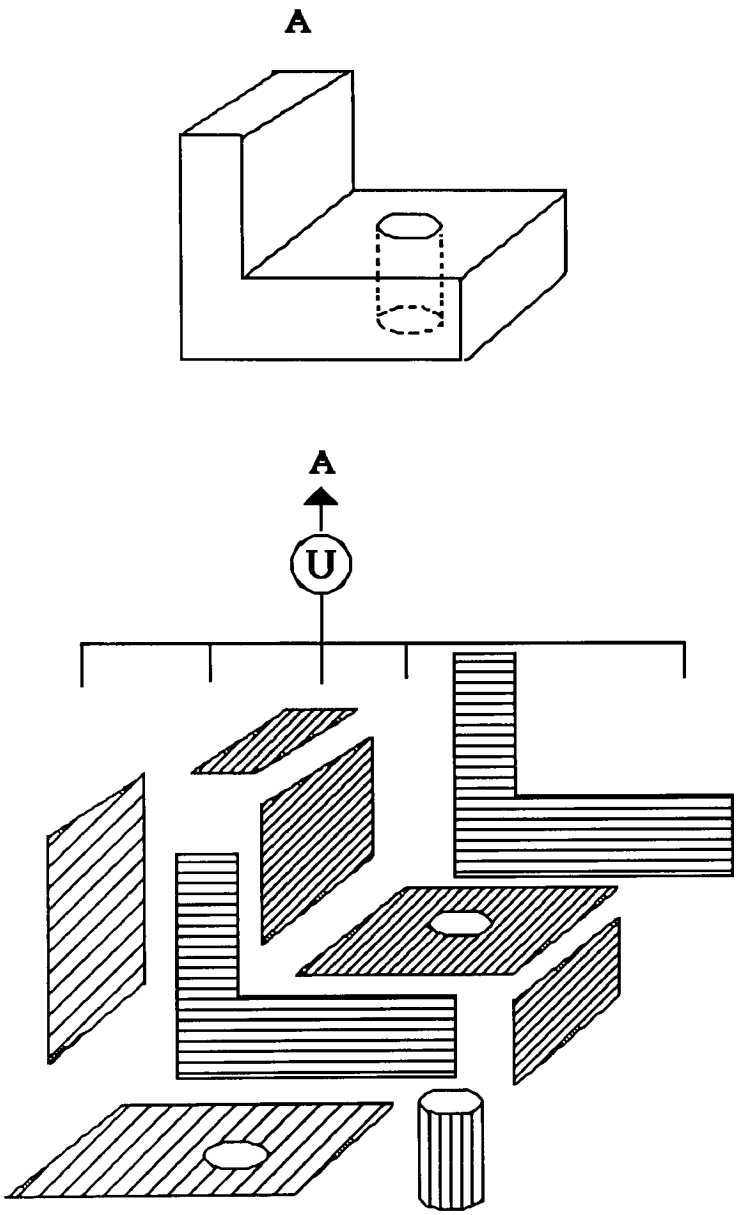


Fig. 2.7 A boundary representation. (From [Voelcker])

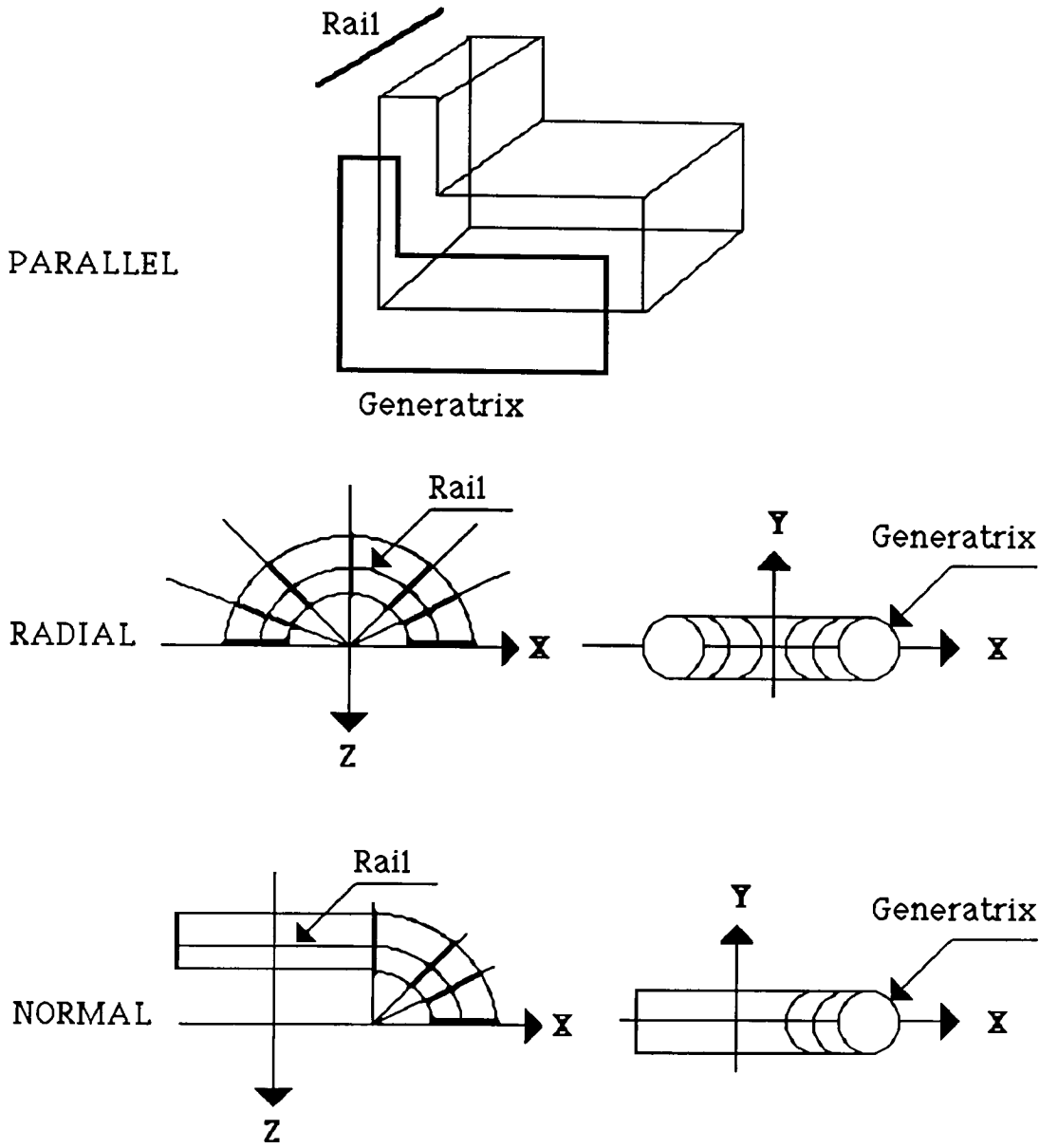


Fig. 2.8 Parallel, radial, and normal sweep representations.
(From [Siska])

2.2 RAY TRACING

Ray tracing was first described by Appel in 1967-68, [Appel]. Initially in the MAGI (Mathematics Applications Group, Inc.) implementation, the algorithm was used for visible surface processing of opaque surfaces only, [Nagel]. To make shaded pictures of solids, the photographic process is simulated in reverse. The observer is assumed to be on the positive Z axis. For each pixel in the screen, a light ray is cast from the observer, through the pixel, into the object space to identify the visible surface of the object. The first surface intersected by the ray is the visible one. The surface normal at the ray-surface intersection point is computed and, knowing the coordinates of the light source, the brightness of the pixel in the screen is computed.

This algorithm was later improved so that global illumination effects such as reflections, refractions, transparency and shadows could be achieved naturally without implementing complicated algorithms, [Kay] and [Whitted]. The algorithm used by most ray tracing programs is described by Whitted. Roth presented ray tracing as the basic method for a solid modeling system [Roth]. The research reported by Roth, "Ray Casting for Modeling Solids", was conducted at the Computer Science Department of the GM Research Laboratories. This research was used in the GMSolid modeling project which was developed in 1977-78 for internal use at General Motors [Boyse].

Recently, ray tracing has been used for rendering

parametric patches [Kajiya2] and algebraic surfaces [Hanrahan]. Cook, Porter, and Carpenter have presented a technique of distributed ray tracing which further enhances realism [Cook]. A new two-way ray tracing technique has been used in PERIS to enhance realism [Liang]. In this technique there are two phases. The first phase is a view-independent process in which rays emitted from the light source are traced. The second phase is a view-dependent process in which rays that originate from the eye are traced.

Since ray tracing consumes a large amount of computer time, most people are discouraged from using this otherwise powerful technique. Much work has been done to speed up the image generation process. Roth has described a screen-space solution in which minimum bounding boxes are used around the solids in the CSG composition tree. If it is determined that the ray does not intersect the bounding box, it is unnecessary to traverse recursively down the composite's subtrees. Ullner has described hardware solutions that involve multiple microprocessors in various configurations [Ullner]. Each processor manages either a subset of rays or a subset of objects.

The screen-space and hardware solutions, do not completely solve the problem of slow speed in the image generation process. Kajiya has shown that doubling the number of objects in a scene almost doubles the rendering time. Doubling both the objects and the rays takes four times longer to render the image [Kajiya1]. To overcome this problem, Glassner presented a new method in which the number of ray-object

intersections (that must be made to fully trace a given ray) is considerably reduced [Glassner1]. In this method the octree technique is used to dynamically subdivide 3-D space into cubes, called voxels, of decreasing volume until each cube/voxel containes less than a maximum number of objects. Each cell of the octree holds a list of objects that have a piece of their surface in that cell. In this method, all the voxels in an octree do not need to be processed. The intersection of a ray is tested for only those objects that have a piece of their surface in the voxel being processed. This method reduces the number of ray-object intersections to a large extent.

In addition to its use for rendering and solid modeling, ray tracing can be used in animation. Glassner recently presented a technique for ray tracing animated scenes using spacetime ray tracing [Glassner2]. He has shown that it is possible to ray trace large animations much faster with spacetime ray tracing using hierarchies of bounding volumes, than with the usual frame-by-frame rendering.

2.3 DITHERING

Dithering has been derived from halftoning (also known as gray scaling). The halftoning technique uses a minimum number of intensity levels, usually black and white, for increasing visual resolution [Rogers] [VanDam]. Visual resolution, which is also known as intensity resolution, is used for making the fine details in a picture more visible. Originally the halftoning technique was used in the weaving of silk pictures and textiles. Modern halftone printing was invented by Stephen Hargon in 1880 [Rogers]. Halftone printing is a screen or cellular process in which cells can be of variable sizes. Screens with 50 to 90 dots per inch are used for newspaper photographs. Screens with 100 to 300 dots per inch are used in books and magazines.

In computer generated images a technique called patterning has been used to increase visual resolution. In patterning, fixed size cells are used. A pattern

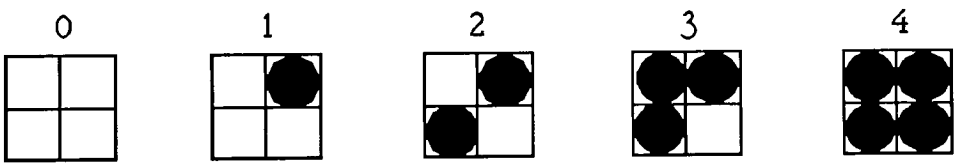


Fig. 2.9 2 x 2 bilevel pattern cells (From [Rogers] page 102).

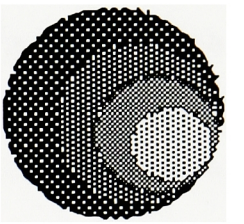
cell is formed by combining several pixels. Fig. 2.9 illustrates patterning using four pixels for each cell. The figure shows five possible intensity levels. For a bilevel display the number of possible intensities is one more than the number of pixels in a

is a tradeoff between spatial resolution and visual resolution. Spatial resolution is the spatial integration that our eyes perform. In [VanDam] it has been explained as follows:

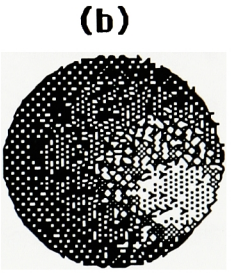
> "If we view a very small area (say a 0.02 x 0.02 inch square) from a normal viewing distance, the eye will integrate fine detail within the small area and record only the overall intensity of the area."

The tradeoff between spatial and visual resolution is illustrated in Fig. 2.10.

When a smaller cell size is used, intensity (i.e. visual) resolution decreases and spatial resolution increases. Increase in spatial resolution can result in contouring. Contouring occurs when transitions between adjacent intensity levels become conspicuous.



As the cell size increases, more intensity levels become available and spatial resolution decreases. Here there is a balance between intensity resolution and spatial resolution. Transitions between intensity levels are more gradual.



Excess intensity resolution causes a loss of spatial resolution. Loss of spatial resolution makes it difficult for the eyes to record the overall intensity of a small area of the image. Transitions between adjacent intensity levels almost disappear.

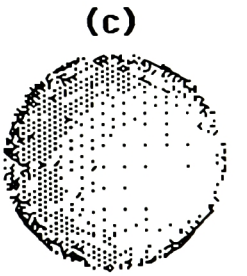


Fig. 2.10 Tradeoff between spatial resolution and intensity (i.e. visual) resolution in patterning.

Visual resolution can be increased by increasing the cell size but that results in the loss of spatial resolution. On the other hand, increase of spatial resolution can result in contouring. To overcome this, new methods were developed which maintained spatial resolution while visual resolution was improved.

In the new methods, a fixed threshold was used for each pixel. If the image intensity was more than the threshold value, the pixel was white, otherwise it was black. In a simple thresholding technique, a relatively large amount of error was generated which resulted in loss of a lot of fine detail in the image. Floyd and Steinberg developed a technique which distributed the error to surrounding pixels [Rogers]. The error was added to the image intensity of each pixel "after" comparison with the selected threshold value.

Dithering was another improvement of the thresholding techinque. In dithering, a random error was added to the image intensity of each pixel "before" comparison with the threshold value. Bayer in 1973 [Rogers] developed an optimum additive error pattern which was added to the image in a repeating checker board pattern. This method was known as ordered dither.

The smallest optimum 2 x 2 matrix, given below, was developed by Limb around 1969 [Rogers].

$$[D_2] = \begin{bmatrix} 0 & 2 \\ 3 & 1 \end{bmatrix}$$

Larger ordered dither patterns were obtained recursively by using the following:

$$[D_n] = \begin{bmatrix} 4D_{n/2} & 4D_{n/2} + 2U_{n/2} \\ 4D_{n/2} + 3U_{n/2} & 4D_{n/2} + U_{n/2} \end{bmatrix}$$

where, $n >= 4$, and represents the matrix size; and

$$[U_n] = \begin{bmatrix} 1 & 1 & \ldots & 1 \\ 1 & 1 & \ldots & 1 \\ : & : & \ldots & : \\ 1 & 1 & \ldots & 1 \end{bmatrix} = \textbf{Unity matrix}$$

$(n)^2$ intensities can be produced from a dither matrix D_n.

The Floyd-Steinberg algorithm, ordered dither, and patterning techniques can be used with color. (The dither algorithm is explained briefly in section 3.4 and in [VanDam] on page 601).

CHAPTER 3 IMPLEMENTATION DETAILS

The software implemented for this thesis has been named ARTISAN. The major components of ARTISAN are:

(1) The relational database;

(2) The graphic application functions;

(3) The ray tracing algorithm that performs addition, subtraction, and intersection to build models;

(4) The simple illumination model; and

(5) The graphics display program.

The first four components work together to realize the concept of constructive solid geometric (CSG) modeling. The relational database was specially designed and implemented for ARTISAN. In the second and third components, the techniques used are similar to the ray casting method used by Roth [Roth]. The fourth component was incorporated within the ray tracing algorithm and deals mainly with shading the models. The overall function of the first four components is to do all the required calculations and generate display data. The combination of the first four components is called "Build", and may be referred to as the "calculations program".

The fifth component, called "Paint", is a separate program that uses graphics display routines to display models. The graphics display (GD) program uses the display data generated by the calculations program. Since the fifth component uses machine dependent display routines, it is not a portable component. There are several advantages to separating the calculation and image

display functions into separate programs:

- Each program can be run separately so that MS-DOS systems with limited memory can be utilized.

  The calculation program does not use any system and machine dependant functions therefore it can be easily ported to any environment that supports the C language.

- Generation of display data can be done on inexpensive systems, (i.e. systems that do not have expensive display hardware and software). The display data generated can be used by a display program on the target display machine.

3.1 THE RELATIONAL DATABASE

The relational database uses three types of relations (a relation is a group or class of similar objects). The three types of relations are described below.

(1) Type I relations: In the database, the primitives (i.e. geometric solids) which have the same characteristics are grouped into one relation. For example, all instances of spherical objects are classified as the primitive-type "sphere" and are stored in the relation called SPHERE. All instances of cylindrical objects are classified as the primitive-type "cylinder" and are stored in the relation called CYLINDER.

(2) Type II relation: All the models (i.e. composites) are stored in the relation called MODEL. The MODEL relation is different from the relations for the primitives. The MODEL relation is used for storing and manipulating the nonterminal nodes of the CSG tree in the database, whereas, the relations for primitives are used for storing the terminal nodes (or leaves) of the CSG tree.

(3) Type III relation: All the transformation factors for transforming models (i.e. composites) are stored in the relation called XFORMS.

Each relation has a DATA file and an INDEX file. Fig. 3.1 (a) and (b) illustrate datafile records for type I relations: sphere and cylinder. In Fig. 3.1, the NAME field is the key field (i.e. the name of a primitive is used to distinguish one primitive instance from another). The fields CX, CY, and CZ are the x, y, and z coordinates

of the center of the primitive. The field RAD is the radius. The fields HT and DEP hold information about the height and depth of the primitive. The ORDER field holds the order in which the object is rotated about the X, Y, and Z axes. The fields RX, RY, and RZ are the angles of rotation about the x, y, and z axes respectively. For example, if the value in ORDER is "ZXY", it means that the primitive is first rotated about the Z axis by the angle RZ, then it is rotated about the X axis by the angle RX, and finally it is rotated about the Y axis by the angle RY. The field CAPPED is a flag that is true when the cylinder has both the top and bottom lids closed, otherwise the flag is false. Currently the cylinder cannot be capped at just one end. The USAGE field is a counter which gives the number of times an object has been used as a part in one or more models that exist in the database.

Name	Cx	Cy	Cz	Rad	Ht	Dep	Order	Rx	Ry	Rz	Color	Usage

(a) Template of a record in the datafile SPHERE.DTA

Name	Cx	Cy	Cz	Rad	Ht	Dep	Order	Rx	Ry	Rz	Color	Capped	Usage

(b) Template of a record in the datafile CYLINDER.DTA

Fig. 3.1 Datafile records for the primitives: sphere and cylinder.

The domain of the NAME field is "character" strings which can be up to thirty characters long. The fields COLOR, CAPPED, and USAGE hold "integer" values. The ORDER field is a character string, three characters long. The data values in the rest of the fields are of type "double".

The USAGE field is significant for the DELETE RECORD function. When the usage is greater than one, the value (usage 1) is the number of times that object has been used as a part in models. An object is deletable, if the object is not a part of any model, or if the object is a part of a model which has recently been deleted. Whenever an object is deleted, its usage is decremented by one. When the usage is equal to zero, it means that the object has been marked "deleted". The record marked deleted is physically removed from the data file later on. When usage is equal to one, it means that the object exists in the database but is not part of any model, and can be deleted if the user wants to do so.

Associated with each DATA file is an INDEX file. The purpose of the index file is to provide fast search and retrieval of data and to maintain the records in a sorted order at all times. The records in the index file represent a binary sequence tree [McFadden]. In a binary sequence tree, the left branch of an element (i.e. node) leads to elements with key values less than the key for the given element, and the right branch leads to elements with key values greater than the given element. In this document the binary sequence tree is referred to as the index tree. The key of the first record that is entered in the data file is used to form

the root of the index tree. Fig. 3.2 is a template of an index record.

LEFT FILE TYPE	LEFT BYTE OFFSET	KEY (NAME)	RIGHT FILE TYPE	RIGHT BYTE OFFSET

Fig. 3.2 Template of an index record in an index file.

The object's name is stored in the KEY field. The name in the KEY field can be a "character" string not more than thirty characters long. All the rest of the fields hold "integer" values. The file type and byte offset together represent the left or right branch of a node.

The LEFT FILE TYPE can be either "data" or "index", whereas, the RIGHT FILE TYPE can be either "data", "index", or "null". When either of the file types is "index", it means that the associated byte offset leads to the location of another index record in the same index file. When the RIGHT FILE TYPE is "data", the RIGHT BYTE OFFSET is the location of a data record in the data file. When the RIGHT FILE TYPE is "null", it means that there are no data records that have a key name greater than the current key.

The indexing scheme used here is known as **dense indexing**. Dense indexing means that the location of a data record (in the data file) for each index key is directly available from the index record itself. In indexing schemes that do not use dense indexing, the data record's location corresponding to an index key has to be calculated and/or searched. In the scheme

used in this implementation, when the LEFT FILE TYPE is "data", the LEFT BYTE OFFSET always refers to the location of the data record for the current key. This type of indexing produces a skewed tree structure as opposed to a balanced tree structure.

In the type II relation, i.e. in the MODEL relation, each record represents a non-terminal node of a CSG tree. Fig. 3.3 is an example of a record in the data file MODEL.DTA. The field OPERATION is either for, (1) the boolean set operations: union (i.e. addition), difference (i.e. subtraction), and intersection, or (2) the transformation of a model. When a model is transformed, the transformation of the whole model is performed with respect to the center of any one of its primitive subcomponents. When the OPERATION is transformation, the LEFT SOLID INFORMATION leads to the model that is transformed. The RIGHT SOLID INFORMATION leads to a primitive component (of the model) with respect to the center of which the model is transformed. MODEL NAME is the name of the resultant model after transformation. The transformation factors for translation, scaling, and rotation of the model are stored in the XFORMS relation. When the OPERATION is a boolean operation, the LEFT SOLID represents the first selected object and the RIGHT SOLID represents the second selected object.

The fields MODEL NAME, SOLID'S NAME, SOLID'S RELATION, and DATAFILE hold "character" strings. The maximum length of the field SOLID'S RELATION can be up to eight characters. The DATAFILE name can be up to twelve characters long. The data file name is formed by appending

".DTA" to the SOLID'S RELATION name. All other strings can be at most thirty characters long.

MODEL NAME	OPERATION	LEFT SOLID INFORMATION	RIGHT SOLID INFORMATION	USAGE

Expansion of LEFT and RIGHT SOLID INFORMATION fields:

SOLID'S NAME	SOLID'S RELATION	DATAFILE NAME	OFFSET IN FILE	RECORD LENGTH

Fig. 3.3 Template in the datafile MODEL.DTA.

In the type III relation, i.e. in the XFORMS relation, each record holds all the information required to transform a particular model. Fig. 3.4 illustrates a record in the data file XFORMS.DTA. The field NAME, is the key field. It holds the name of the resultant model (i.e. the model that results from the transformation operation). The field OBJ, is the name of the primitive component with respect to which the transformation is done. The REL field, is the relation to which the primitive component belongs (i.e. cylinder, sphere, etc.). The fields DX, DY, and DZ are the translation factors. The fields SX, SY, and SZ are the scaling factors. The fields RX, RY, and RZ are the rotation factors. The fields NAME, OBJ, REL, and ORDER are character strings (they have the same maximum lengths as mentioned before). The USAGE field holds "integer" values. The values in rest of the fields are of type "double".

NAME	OBJ	REL	DX	DY	DZ	SX	SY	SZ	ORDER	RX	RY	RZ	USAGE

Fig. 3.4 Datafile record in XFORMS.DTA.

The index files for the MODEL and the XFORMS relations are processed exactly the same way as that for the primitives.

Besides the relations the database has two system files called RELATION.SYS and ATTRIBUTE.SYS.

RELATION NAME	DATAFILE NAME	INDEXFILE NAME	FIELD COUNT	KEY FIELD	RECORD COUNT	RECORD SIZE	. . .

Fig. 3.5 Example of some fields in a record in the system file RELATION.SYS.

1. The RELATION file has a definition record for every relation in the database. Fig. 3.5 is an example of a record in RELATION.SYS.
2. The ATTRIBUTE file has a definition record for every field of each relation. Attribute is another term used for "field". Fig. 3.6 is an example of a record in ATTRIBUTE.SYS.

RELATION NAME	ATTRIBUTE NAME	ATTRIBUTE TYPE	KEY FLAG	ATTRIBUTE LENGTH	IS-A

Fig. 3.6 Template of a record in system file ATTRIBUTE.SYS.

The field ATTRIBUTE TYPE holds a character which can have one of the three following values: N for numeric (i.e. integer), C for character, or D for decimal (i.e. real). The value in field KEY FLAG is true if the field is a key field, otherwise it is false. The field IS-A holds an internal code which gives information about what the field name means (i.e. information about what the field represents). The internal code in this field is used by the graphics application functions. The IS-A field works as a link between the database and the graphic application functions.

The very first time the ARTISAN system is started, it goes through an initialization phase. In the initialization phase, the system files, RELATION.SYS and ATTRIBUTE.SYS, are created and opened for reading and writing. These system files remain open throughout the execution of ARTISAN. Next, the MODEL relation is defined. The definition is composed of information such as the relation name, field names, field types, field lengths, etc. (as given in Fig. 3.6). This information is saved in the system files. Similarly, the relations for primitive-types SPHERE and CYLINDER are defined and saved in the system files. The data and index files for each relation are created as each relation is defined. For each of the primitive-type relations, SPHERE and CYLINDER, the first primitive is created and its data record is saved in the relation's data file. The definition is composed of the following: the coordinates of the center, radius, height (if applicable), color, the angles of rotation about the x, y, and z axes, etc. (as given in Fig. 3.1). The first primitive created is referred to as the

"local/parent primitive" (The concept of the local primitive is explained later in section 3.2). The key (i.e. the name) of the local primitive is used to create the first index record which is saved in the relation's index file. The first index record is used as the root of the index tree.

Currently, the database has definitions and ray-object intersection routines for the sphere, cylinder, block, and cone. The definitions and ray-object intersection routines for other geometric primitives can be installed into the implementation later. The issues and complexities regarding installation of definitions and ray-object intersection routines for new primitive objects are discussed in section 3.6.

3.1.1 USER INTERFACE FUNCTIONS

The relational database is not built on a standard package, it was specially developed for this system. The relational database provides user interface through menu driven functions such as:

ADD
BEGIN SESSION
CHANGE VARIABLES
COPY
DELETE
DELETE ALL
DELETE CONTENTS
DESCRIBE
DISPLAY
DISPLAY RECORDS
INTERSECT
MODIFY
PRINT TREE
REMOVE DELETED RECORDS
SELECT
SUBSTRACT
TRACE ONE OBJECT
TRANSFORM

Following is a brief description of the functions:

ADD -

This command is used to perform the boolean operation of union (+) between the two selected objects. The ray tracing algorithm is used to realize the boolean operation. The resultant object is saved in the MODEL relation after the object has been displayed and approved by the user.

BEGIN SESSION

This command first makes the user select an object by automatically evoking the SELECT command, then it presents the user with a second menu of commands. The second menu

contains the following commands: SELECT, TRANSFORM, MODIFY, DELETE, ADD, SUBTRACT, INTERSECT, DISPLAY, COPY, PRINT TREE, and TRACE ONE OBJECT. All the commands in the second menu require pre-selection of one or two objects.

CHANGE VARIABLES

This command allows the user to change: the position of the eye (i.e. the center of projection) along the Z axis, the position of the point light source, and other illumination variables.

COPY -

This makes a copy of the selected object and saves it under a new name. In other words this command is used for creating duplicates of an object.

DELETE -

This command is used to delete the data and index records of a selected object. The object may be a primitive or a composite. This command is useful for removing unwanted objects that may result from commands such as: COPY, TRANSFORM, ADD, INTERSECT, and SUBTRACT.

DELETE ALL -

The purpose of this command is not only to delete all the contents of the data and the index files but also to delete the field definitions from the system's attribute file and the relation definition from the system's relation file.

DELETE CONTENTS -

This is used to delete all the contents of the data and index files for a specified relation (including the data for the local primitive).

DESCRIBE

This is used either to display the relation descriptions in the entire database, or to display the record description of a particular relation. To describe the database, all the pertinent information about each relation is displayed. To describe a particular relation, all the information about the fields of that relation is displayed.

DISPLAY -

This displays either a wireframe or an illuminated image of the selected object. The illuminated image is displayed only if either ADD, SUBTRACT, INTERSECT, or TRACE ONE OBJECT was the latest command performed.

DISPLAY RECORDS -

This displays all the data records of a specified relation. The data records are displayed sorted based on the name of the objects in the relation. After this, the user is provided with an option to see the index records in the associated index file.

INTERSECT

This command is similar to the ADD command except that it is

used to perform the boolean operation of intersection (&) between the two selected objects.

MODIFY -

This command operates on one selected object. It allows the user to change the data record of the object. This command does not result in the creation of a new object. The TRANSFORM or COPY commands should be used to create new objects.

PRINT TREE-

This command prints the objects that are present in the CSG tree of a selected object. It prints the names of the objects and the relations to which they belong. This command is useful if the selected object is a model composed of several sub-models and primitives.

REMOVE DELETED RECORDS -

The purpose of this command is to physically remove data and index records of objects that have been marked deleted. This command operates on the data and index files of all the relations in the database. The data and index files are re-created for the undeleted objects. Therefore, it is expected that this command will be used infrequently, i.e. when there are several records marked deleted as opposed to just one or two.

SELECT -

This command is used to retrieve a particular object (primitive or composite) from the database to perform further functions. This function builds the CSG tree for the selected object in memory. Some of the commands that are provided after a SELECT command are: TRANSFORM, MODIFY, COPY, DELETE RECORD, TRACE ONE OBJECT, or DISPLAY. These commands are used to operate on one selected object. (To perform the ADD, INTERSECT, and SUBTRACT commands, two objects are required, thus the SELECT command must be used twice to select two objects before these commands are used).

SUBTRACT

This command is similar to the ADD command except that it is used to perform the boolean operation of difference (-) between the two selected objects. The second object is always subtracted from the first object.

TRACE ONE OBJECT -

This command is used to create a solid, shaded image of a selected object. The boolean operations of union, intersection, and difference are binary operations which require the selection of two objects (i.e. components). In order to construct a complex model, components of the model must be built first. The components must exist in the database before they can be combined with other objects. Often it is useful to see what a sub-component looks like before it is combined with anything

else. A wireframe of a component just gives a rough idea about the component's position, size, and orientation but this command enables the user to see the realistic version of the component. Thus, this command is used to recreate a solid, shaded version of any model or primitive that exists in the database.

TRANSFORM -

This command is used for creating new instances of primitives or new composites. This command allows the user to translate, scale, and rotate a selected object. The transformed object is saved under a new name. Transformation of a composite object is performed with respect to a user specified primitive component (of the composite object).

3.2 THE GRAPHIC APPLICATION FUNCTIONS

The graphic application functions, such as: DISPLAY, TRANSFORM, ADD, SUBTRACT, and INTERSECT, use three kinds of cartesian coordinate systems:

(1) the screen coordinate system,

(2) the global coordinate system, and

(3) the local coordinate system.

Following is a description of each system.

(1) In the screen coordinate system, the screen (or view plane) is in the X-Y plane. The plane equation of the view plane is Z = 0. The 3-D primitives and models are built in the -Z half space and the eye of the observer is in the +Z half space at (0, 0, Z). The +Z axis is perpendicular to the screen and points out from the screen.

For the ray tracing process, a ray originates from the observer's eye, passes through a pixel on the view plane, and continues into the -Z half space where the ray may or may not intersect with the object(s).

(2) The global coordinate system (also known as the scene or model coordinate system) is the main system the user is aware of. The user has the option to position the point light source anywhere in this system. The models are created by the user in the -Z half space behind the view plane, preferably in the quadrant defined by the +X, +Y, and -Z axes.

In this coordinate system the user has the options to:

- move the solid object around by translation and/or rotation;
- change the size of the object by scaling;
- combine two objects to form models by applying the operations: addition, intersection, and subtraction;
- change the position of the observer (i.e. the center of projection, COP) to see the object from a different distance;
- change the position of the light source to see how that effects the illumination of the object;
- change the intensities of the light source and the ambient light;
- change the coefficients for ambient reflection, diffuse reflection, and specular reflection, and other variables used in the shading equation given in section 3.4.

(3) The local coordinate system is used to simplify the determination of ray-object intersections. Its main purpose is to help in ray tracing objects that may have been rotated, scaled, and/or translated in the global coordinate system. The relation for each primitive-type has the first primitive defined in the local coordinate system. This primitive is called the local primitive. By rule the name of the local primitive is formed by concatenating the letter "A" with the primitive-type's name. For example, for the primitive-type SPHERE the local primitive is named ASPHERE and for the primitive-type CYLINDER the local primitive is named

ACYLINDER. Fig. 3.7 illustrates local primitives for the sphere and the cylinder. The local primitive always has a fixed center, radius,

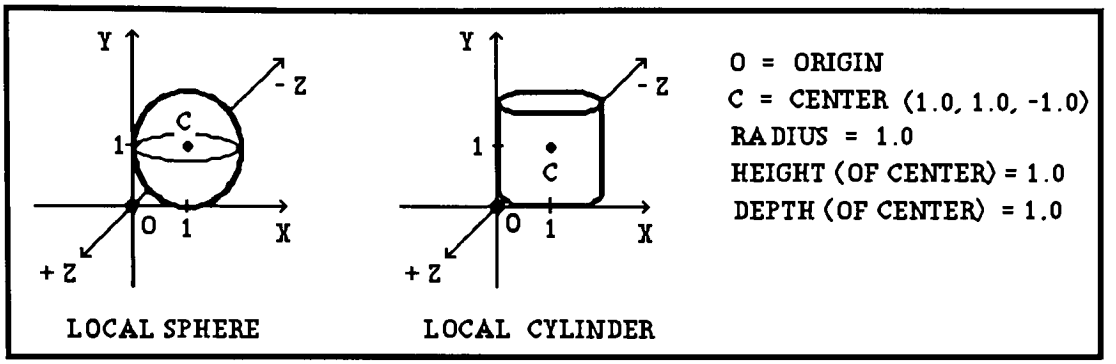


Fig. 3.7 ASPHERE and ACYLINDER, defined in the local coordinate system.

height (of center), depth (of center), and the angles of rotation about the three axes. Currently the local primitives for all the primitive-types are defined as follows:

Center (x, y, z) = (1.0, 1.0, -1.0);
Radius = 1.0;
Height of center = 1.0 (Therefore, total height = 2.0 units);
Depth of center = 1.0 (Therefore, total depth = 2.0 units);
Order of rotation = "XYZ";
Rotation about x axis, alpha = 0.0;
Rotation about y axis, beta = 0.0; and
Rotation about z axis, gamma = 0.0;

In effect, the local primitive of every primitive-type is used as a kind of parent primitive from which all other instances of primitives are derived. The local/parent primitive cannot be deleted or modified by the user. The local primitive for each relation is created automatically in the initialization phase when ARTISAN is started for the first time. When the user first creates

a new instance of a primitive, the location, size and orientation of the new primitive is the same in both, local and global, coordinate systems. When the user translates, scales, and/or rotates the new primitive, all the transformations on the new primitive take place in the global coordinate system only. In the local coordinate system the new primitive remains constant and equivalent to the parent primitive.

Whenever the user SELECTs a primitive object, the transformation factors are determined from the datafile and two transformation matrices, called LtoM and MtoL, are computed. These matrices are saved in memory along with other information about the object. MtoL is a 4 x 4 linear transformation matrix that transforms the object from the model (i.e. global) to the local coordinate system. LtoM is a 4 x 4 linear transformation matrix that transforms the object from the local to the model coordinate system.

The reason why the local primitive is required for each primitive-type is because it simplifies the problem of calculating ray-object intersections during the raytracing process. No matter what location, size, or orientation the primitive object may have in the model (i.e. global) coordinate system, a single ray-object intersection routine (for the local primitive) is sufficient to handle the raytracing of all the primitive objects of that primitive-type.

The ray-object intersection routine is specially designed to determine ray-object intersection points for the local primitive. To raytrace a primitive object the routine uses the object's MtoL transformation to transform the ray from the model to the local

coordinate system. The effect of translating, scaling, and rotating a solid is achieved by translating, scaling, and rotating the rays [Roth]. Since, the equation of a ray is the same as the equation of a line in 3-D space, a ray is transformed by transforming its fixed point and its direction vector. Consider the ray equation:

$$\begin{aligned} rx &= cpx + (px - cpx)\,T &&= cpx + aT \\ ry &= cpy + (py - cpy)\,T &&= cpy + bT \\ rz &= cpz + (pz - cpz)\,T &&= cpz + cT \end{aligned}$$

Here, rx, ry, and rz are the x, y, and z components of the ray; cpx, cpy, and cpz are the x, y, and z components of the center of projection, COP (i.e. the eye); px, py, and pz are the coordinates of the pixel on the screen; a, b, and c are the x, y, and z components of the direction vector of the ray; and T is the ray (or line) parameter. In the given ray equation, the fixed point is the COP (i.e. cpx, cpy, and cpz) and the ray's direction vector is given by a, b, and c. The fixed point is transformed as follows:

$$(cpx', cpy', cpz', 1) = (cpx, cpy, cpz, 1) * MtoL$$

Where, (cpx', cpy', cpz') is the transformed point. The direction vector is transformed as follows:

$$(a', b', c', 0) = (a, b, c, 0) * MtoL$$

where (a', b', c') is the transformed vector. When the ray is transformed in this way, the ray parameter T remains constant in both, local and model, coordinate systems. The equation of the

transformed ray is obtained as follows:

```
rx' = cpx' + (a' * T)
ry' = cpy' + (b' * T)
rz' = cpz' + (c' * T)
```

Consider a point corresponding to parameter T on a ray in the model coordinate system. After the ray is transformed to the local coordinate system, the point (now transformed) still corresponds to the same T on the transformed ray [Roth]. This implies that neither the parameters nor the points need to be transformed, only the ray needs to be transformed between the local and model coordinate systems.

When the ray is in the local coordinate system, it is not necessary to find and transform the actual points where the ray enters and exits the object but it is sufficient to determine the ray parameters that designate those points.

3.3 Ray Tracing Algorithm for Processing a CSG Tree:

Data structures used in this algorithm are given in section 3.3.1. The criteria for selecting an intersection point are given in section 3.3.2. Input to TraceObject are: a pointer to solid node of binary tree, the operation, and the ray equation. Output from TraceObject are: 'Xpts' the intersection point(s), and 'Norm' the normal to each intersection point. 'Xpts' is an array of type POINTNODE.

```
TraceObject(SolidNodePtr, Operation, Xpts, Norm)  {
   if (Operation is for a Composite solid)  {
      TraceObject(L_SolidPtr, ... );          /*  These two calls could be
      TraceObject(R_SolidPtr, ... );                executed in parallel  */

      /* Select one ray-object intersection point based on the boolean
         operation being performed.  */
      SelectXpt(Xpts, ... );
      Return;
      }
   else if (Operation is for a Primitive solid)  {
      Based on ( PrimitivePtr->Type)  {

      /*    Transform ray to primitive's local coordinate system
            using the primitive's MtoL_Xformation.
         -  Determine ray parameters with respect to primitive's
            surface equation in its local coordinate system.

            Determine if ray intersects with the object at atleast one
            point.
            If (ray intersects with the object)
               Determine outward normal at each intersection point.
               Calculate intersection points for the model in object
               space (i.e. the global coordinate system) using ray
               parameters.
         -  Save information in:  Xpts, and Norm.      */
         }
      }
   }
```

3.3.1 DATA STRUCTURES

Following are the minimal data structures that were used for the CSG tree:

```
PRIMITIVE NODE:     /* leaf node of the CSG tree                    */
   Name-of-primitive
   Type             /* sphere, cylinder, block, cone, etc.          */
   LtoM-Xformation  /* 4 x 4 transformation matrix                  */
   MtoL-Xformation  /*  "        "        "                         */

SOLIDNODE:          /* nonterminal/terminal node of the CSG tree */
   Name-of-solid
   Operation        /* +, &, -, or no-operation                     */
   L_SolidPtr       /* pointer to left solid node                   */
   R_SolidPtr       /* pointer to right solid node                  */
   PrimitivePtr     /* pointer to terminal/primitive node */
```

When **Operation == no-operation**, SOLIDNODE represents a primitive. In this case, the pointers L_SolidPtr and R_SolidPtr are both NULL. PrimitivePtr leads to the node for the primitive.

When **Operation == boolean operation**, SOLIDNODE represents a composite. In this case, the pointer PrimitivePtr is NULL. L_SolidPtr leads to information of the left solid and R_SolidPtr leads to information of the right solid.

When **Operation == xformation**, L_SolidPtr leads to the object that is to be transformed. R_SolidPtr leads to the reference primitive with respect to which the object is to be transformed and PrimitivePtr leads to the transformation factors required to perform the operation.

```
POINT NODE:     /* structure for intersection points and normals */
   x, y, z      /* components along x, y, and z axes             */
   solidnodePtr /* pointer for solid through which ray passed    */
```

3.3.2 SELECTION OF INTERSECTION POINTS

Selection of intersection points is based on the boolean operations: union, intersection, and difference. The selection process for each operation is explained below with the aid of Fig. 3.8.

INTERSECTION: abc (&) d => abcd
All the intersection points are sorted with respect to their z coordinates. Each point is tested one by one. The first point that satisfies the following condition is the selected point. The point must lie on or within **(d and (a or b or c))**.

DIFFERENCE: ab (-) c => abc
c1 = point where ray enters cylinder **c**, in object **abc**.
c2 = point where ray exits cylinder **c**, in object **abc**.
ab1 = point where ray enters object **ab** in object **abc**.
ab2 = point where ray exits object **ab** in object **abc**.

Consider object **c** to be invisible. Any part of another object within **c** also becomes invisible. Only the boundary of **c** that lies within **ab** or touches the boundary of **ab** is visible. Point **c2** is visible and is closest to the eye. Therefore, **c2** is the selected point. The normal at **c2** will be the inward normal determined with respect to the center of object **c**.

UNION: a (+) b => ab
In object ab , point b1 is closest to the eye. Therefore, the selected ray-object intersection point is **b1**.

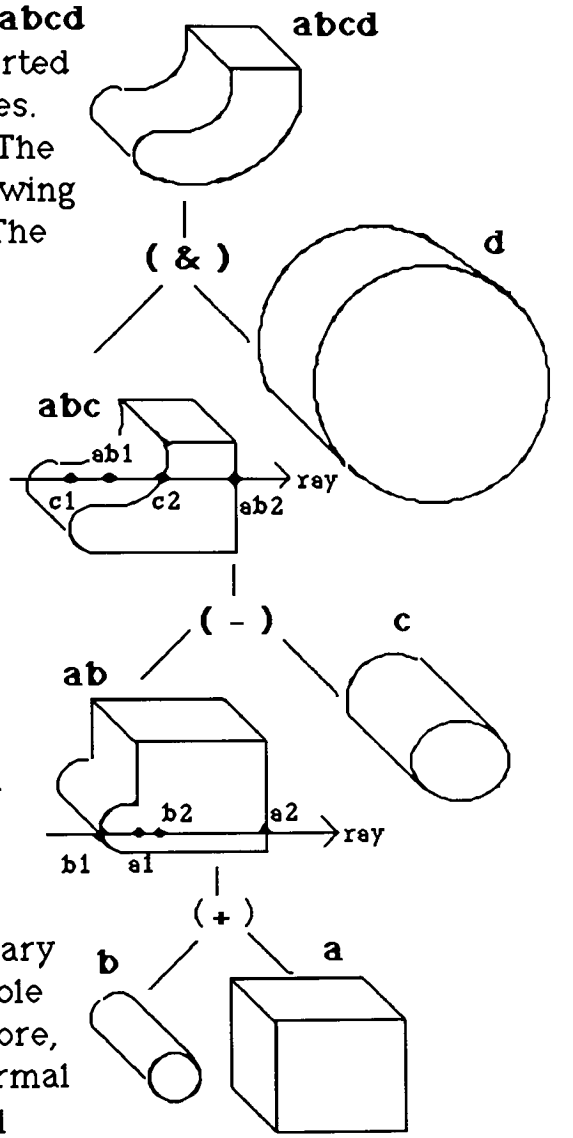


Fig. 3.8
Illustration of the method used in procedure **SelectXpt** for selection of an intersection point based on the boolean operation being performed.

The difference operation requires a more in-depth examination of the intersection points, in contrast to the other two operations. The possible cases of the difference operation are discussed below. Consider two objects to be object1 and object2. For the difference (-) operation it is assumed that object2 is subtracted from object1. Consider the following intersection points for the two objects:

enter1	=	point at which ray enters object1's surface
exit1	=	" " " " exits " "
enter2	=	" " " " enters object2's surface
exit2	=	" " " " exits " "

The outcome of the difference operation between object1 and object2 can be any of the following cases:

Case 1: If the sequence of ray-object intersection points is either (enter2 exit2 enter1 exit1) or (enter1 enter2 exit1 exit2), the point enter1 which belongs to the first object is the selected point since it is the first visible point in the line of sight.

Case 2: If the sequence of intersection points is (enter2 enter1 exit2 exit1), object2 lies partially within object1. This is the case explained before with the help of fig 3.8. Point exit2 is the selected point and the normal at that point is the inward normal determined with respect to the second object. The color associated with the point is changed to the color of the first object.

Case 3: If the sequence of points is (enter2 enter1 exit1 exit2), the second object passes through the first object such that the background is visible to the observer. In this case, the point exit2 is the selected point and its color is changed to the color of the background.

Case 4: Consider the first object to be a composite solid made up of two primitives, primitive1 and primitive3.

enter3 = point at which ray enters primitive3's surface
exit3 = " " " " exits " "

The points enter1, exit1, enter3, and exit3 all belong to the first object as a whole. The points enter2 and exit2 belong to the second object. If the sequence of points is (enter2 enter1 exit1 exit2 enter3 exit3), it implies that object2 passes through primitive1 but lies ahead of primitive3. Therefore, in this case, primitive3 is visible to the observer and the selected point is enter3.

To be able to examine all the intersection points obtained with a ray for the difference operation, arrays called 'Zbuf' and 'Znorm' were utilized. 'Zbuf' is an array of intersection points of type POINTNODE and can hold more points than the 'Xpts' array. 'Znorm' is a parallel array that holds the normal at each point in 'Zbuf'. In procedure SelectXpt, first 'Zbuf' was sorted based on the Z-coordinates of the points, then the sequence of points was examined in the manner explained for the cases given above.

3.3.3 BOUNDING VOLUMES

The algorithm in section 3.3 gives an idea of how much time is consumed in transforming the ray from model to local coordinate system, determining intersections, selecting an intersection point, etc. All this time is a waste if the ray clearly misses the solid object. Therefore, both an object-space and a screen-space solution [Roth] were used to detect if the ray clearly missed the solid. For the object-space solution, bounding volumes such as bounding sphere or bounding box were used. A bounding box (or box enclosure) is a tight rectangular parallelopiped around the solid in the model coordinate system. The box for an object was computed at the time when the user SELECTed the object. The box is defined by six points: xmin, xmax, ymin, ymax, zmin, and zmax. These coordinates were saved, along with other information about the object, in the object's CSG tree in memory. For the screen-space solution, the projection of the box enclosure on the view plane was used to detect if a ray missed an object.

During the raytracing process, the pixels on the screen are usually scanned from left to right and from top to bottom. Before beginning the raytracing process it is necessary to determine the area of pixels that should be scanned so that the entire solid in object space gets ray traced. The area of pixels to be scanned is determined by using the box enclosures mentioned earlier. Before the ray tracing process was started, a special procedure recursively descended the CSG tree from the root node to the leaves. At the

terminal nodes it determined the 2-D projection of the bounding box upon the view plane. The projected vertices were saved in an array called ScanList and were used later for the screen-space solution in the ray tracing algorithm. As the procedure returned up the tree, at each node it combined the projected areas of the left and right subtrees. When the procedure returned to the root node, it had the whole area to be traced for the entire object. Tracing started at pixel (xmin, ymax), and ended at pixel (xmax, ymin).

For the screen-space solution, in the ray tracing algorithm, if it was determined that the pixel (px,py) under consideration did not lie within the projected area for a particular node, then it was unnecessary to traverse down the subtrees of that node. For the object-space solution, after the ray equation was determined, a ray-box intersection test was performed. If this test failed for a primitive in the CSG tree, it meant that the ray clearly missed the primitive and that it was not necessary to perform the ray-primitive intersection test.

3.4 THE ILLUMINATION MODEL

In ARTISAN, the light is assumed to be a single point light source. All the objects are assumed to be opaque (i.e. non-transparent) solids having smooth surfaces. The only variable surface attribute for all primitives is color. The illumination model used in ARTISAN, is invoked locally. That means, only the light from the light source and the object's surface orientation are taken into consideration to determine the intensity of the light reflected to the observer's eye. This illumination model is also known as the simple illumination model. The equation used by the simple illumination model to determine intensity, takes into consideration the ambient light, incident light, and light reflected diffusely and specularly from the object's surface. The following equation was used to calculate the intensity at a point.

$$I = I_a . K_a + \frac{I_l}{d + K}\left[K_d . \cos(\theta) + K_s . \cos^n(\alpha)\right]$$

where I = reflected intensity,
I_a = incident ambient light intensity,
I_l = incident intensity from a point light source,
K_a = ambient reflection constant ($0 \leq K_a \leq 1$),
K_d = diffuse reflection constant ($0 \leq K_d \leq 1$),
K_s = specular reflection constant,

K = an arbitrary constant,
d = distance from perspective viewpoint to the object,
θ = angle between the light direction and the surface normal ($0 \leq \theta \leq \pi/2$),
α = angle between the reflected ray and the line of sight ($-\pi/2 \leq \alpha \leq \pi/2$), and
n = a power that approximates the spatial distribution of the specularly reflected light.

This equation can be reduced to the Lambertian diffuse reflection illumination equation which uses just the intensity of incident light, the diffuse reflection constant, and cosine of the angle of incidence. The Lambertian diffuse reflection equation was sufficient to produce good results. After the reflected intensity was determined, an ordered dither algorithm was used to determine the final display value for the pixel. For more information about dithering see section 2.3. In the dither algorithm, position (i, j) in the dither matrix is determined first.

```
i = Px MOD n;
j = Py MOD n;
```

Then, the pixel display value is determined as follows:

```
if I(Px, Py) < DMAT(i, j) then
      Value = I2;
else Value = I(Px,Py);
```

where MOD is a function that returns the modulo value of its arguments,
(Px, Py) designate the pixel on the raster (i.e. viewplane),
DMAT is the ordered dither matrix of dimension n x n,
I(Px, Py) is the reflected intensity at the pixel (Px, Py),
Value is the final intensity for the pixel, and
I2 is a reflected intensity slightly lower than I(Px,Py).

3.5 GRAPHICS DISPLAY PROGRAM

The graphics display (**GD**) program can run on systems that have a CGA (Color Graphics Adapter), EGA (Enhanced Graphics Adapter), or VGA (Video Graphics Array) graphics adapter and display hardware.

In ARTISAN, as the ray tracing algorithm determines and selects the ray-object intersection points, it writes the following information to an output file: the coordinates (Px, Py) of the pixel through which the ray passed, the color of the solid to which the intersection point belonged, and the intensity at that point. When the GD program is evoked it simply opens the output file and displays each pixel with an appropriate shade of a color depending on the given intensity at each pixel.

Similarly, for displaying a wireframe of a solid object, all the calculations are done in ARTISAN and the points and lines to be displayed are written to the output file (along with the color at each point). The GD program processes the points read from the output file in the same manner as mentioned above. Different and small size versions of the GD program can be easily written to facilitate the presentation of image data on displays supported by Sun windows, X windows, or any other windowing system or display technology.

3.6 HELPFUL HINTS

Following are a few helpful things to keep in mind while building a model:

1. If the object that is to be subtracted has the option to be either capped or open, such as a cylinder or a cone, the user must make it capped rather than open.
2. Often either one or both components of a model need to be modified before a boolean operation can be performed on them. The best way to handle this is to evoke the operation command ADD, SUBTRACT, or INTERSECT, see what the combined components look like in a wireframe display and return to the menu without saving the combination as a model. The components can be modified and the above procedure can be repeated until the model is correct.
3. A complex model should be built with all its components in a particular orientation. The whole model should be transformed only after all the components have been combined together.
4. The size of an object can be changed in two ways. One way is to use scaling to make an object bigger or smaller. The other way is to translate the object closer to the view plane or further away from the view plane. (Due to perspective projection objects that are closer to the view plane appear to be larger than objects of the same size that are far away from the view plane). Changing the position of the

observer along the +Z axis does not have the same effect on the size of the object. As the observer moves away from the view plane the projection of the object on the view plane becomes parallel in appearance rather than perspective. As the observer moves toward the viewplane the projection becomes more and more perspective in appearance.

5. When an object is created care must be taken to see that it is completely behind the view plane (unless the user purposely wants the view plane to cut through the object).

6. The position of the point light source plays an important role in the shading of the model. Best results were obtained when the point light source was placed fairly close to the model (about 100 to 200 units away from the model).

3.7 INSTALLATION OF NEW PRIMITIVE TYPES

Installation of new primitive types into the database cannot be done interactively by the user. New primitive types have to be installed into the database by a software programmer. Installation of new primitive types has no effect on the definitions and routines for primitives that already exist in the database. For example, the following steps were taken to install block and cone into the database. The highlighted items are the new statements that were added to the existing code.

1. In the file "globals.h", the block and cone definitions were added as follows:

```
/*  In the include file "globals.h"  */
. . .
#define        MODEL        10
#define        SPHERE       20
#define        CYLINDER     30
#define        BLOCK        40
#define        CONE         50
. . .
```

2. In the file "get_type.c", there are two procedures called GetObjtype and GetPrmtype. Procedure GetObjtype examines the given relation name to determine if the object belongs to the COMPOSITE (i.e. MODEL), PRIMITIVE, or XFORMS relations. Procedure GetPrmtype examines the given relation name to determine if the primitive object is a SPHERE, CYLINDER, BLOCK, or CONE. The statements for block and cone were added to these procedures as follows:

```
/*  In the source file "get_type.c"  */

GetObjtype(srelation,solidtype)
char    srelation[];
int     *solidtype;
{
   if (strcmp(srelation,"MODEL") == 0)
      *solidtype = COMPOSITE;
   else if (strcmp(srelation,"SPHERE") == 0)
      *solidtype = PRIMITIVE;
   else if (strcmp(srelation,"CYLINDER") == 0)
      *solidtype = PRIMITIVE;
   else if (strcmp(srelation,"BLOCK") == 0)
      *solidtype = PRIMITIVE;
   else if (strcmp(srelation,"CONE") == 0)
      *solidtype = PRIMITIVE;
   . . .
 }
```

```
/*  In the source file "get_type.c"  */

GetPrmtype(srelation,prmtype)
char    srelation[];
int     *prmtype;
{
   if (strcmp(srelation,"SPHERE") == 0)
      *solidtype = SPHERE;
   else if (strcmp(srelation,"CYLINDER") == 0)
      *solidtype = CYLINDER;
   else if (strcmp(srelation,"BLOCK") == 0)
      *solidtype = BLOCK;
   else if (strcmp(srelation,"CONE") == 0)
      *solidtype = CONE;
   . . .
 }
```

3. Each field required by a primitive type must have a predefined field name code. All the field name codes are defined in a file called "is_a.h" as follows:

```
#define     OBJNAME     1
#define     OBJTYPE     2
#define     DX          3
#define     DY          4
#define     DZ          5
#define     SX          6
#define     SY          7
#define     SZ          8
#define     RX          9
#define     RY          10
#define     RZ          11
#define     COLOR       12
#define     CAPPED      13
#define     USAGE       26
#define     ORDER       27
```

No new information was added in "is_a.h" because the field name codes required to define sphere and cylinder can be used to define block and cone too.

In the procedure GetList (in the source file "chklist.c"), the case statements for block and cone were added after the case statements for sphere and cylinder. The fields that a primitive type requires were put into an array called "Clist" (also referred to as "CheckList"). A primitive type (or relation) can have at most fifteen fields. Clist/CheckList is a list used by procedure DefineRel and MakePr.

```
GetList(rname,Clist,fnum)          /* In the source file "chklist.c" */
char    rname[];
int     Clist[], *fnum;
{
 . . .
 switch (ptype)
  {
   case SPHERE   : . . .                                          break;
   case CYLINDER : . . .                                          break;
    case  BLOCK  :  i = 0;
                    Clist[++i] = OBJNAME;
                    Clist[++i] = DX;
                    Clist[++i] = DY;
                    Clist[++i] = DZ;
                    Clist[++i] = SX;
                    Clist[++i] = SY;
                    Clist[++i] = SZ;
                    Clist[++i] = ORDER;
                    Clist[++i] = RX;
                    Clist[++i] = RY;
                    Clist[++i] = RZ;
                    Clist[++i] = COLOR;
                    Clist[++i] = USAGE;
                   *fnum = i;                                     break;
    case  CONE   :  i = 0;
                    Clist[++i] = OBJNAME;
                    Clist[++i] = DX;
                    Clist[++i] = DY;
                    Clist[++i] = DZ;
                    Clist[++i] = SX;
                    Clist[++i] = SY;
                    Clist[++i] = SZ;
                    Clist[++i] = ORDER;
                    Clist[++i] = RX;
                    Clist[++i] = RY;
                    Clist[++i] = RZ;
                    Clist[++i] = COLOR;
                    Clist[++i] = CAPPED;
                    Clist[++i] = USAGE;
                   *fnum = i;                                     break;
  default          :                                             break;
  }
. . .
}
```

DefineRel used CheckList to formulate the definitions of the new primitive type. The definitons were then saved in the system files: relation.sys and attribute.sys. Every field in CheckList must have a case statement for it in the procedure DefineRel. The procedure DefineRel is in the source file "define_p.c". In the procedure DefineRel the fields were defined as follows:

```
DefineRel(relname)        /*  In the source file "define_p.c"  */
char  relname[];
{
  . . .
/* Creates data and index files. For block the files created are BLOCK.DTA and BLOCK.NDX */
    Mk_data_index();
    GetList(rname,CheckList,&items);                    /* Gets the list of field name codes */
    . . .
    /*  Builds the definition of each field one by one and writes it into the attribute.sys file */
    switch  (CheckList[a_count])
        {
        /* NOTE:  Each field name code in CheckList must have a case statement here */

        case OBJNAME :  Scopy(abuffer.aname,"NAME");
                        abuffer.atype = CHARACTER;
                        abuffer.alen = NAMELEN;
                        abuffer.akey = TRUE;
                        . . .                                          break;
        case DX      :  Scopy(abuffer.aname,"CX");
                        abuffer.atype = DECIMAL;
                        abuffer.alen = sizeof(double);
                        abuffer.akey = FALSE;
                        . . .                                          break;
        case DY      :  Scopy(abuffer.aname,"CY");
                        . . .                                          break;
        case DZ      :  Scopy(abuffer.aname,"CZ");
                        . . .                                          break;

        case SX      :  Scopy(abuffer.aname,"RAD");
                        abuffer.atype = DECIMAL;
                        abuffer.alen = sizeof(double);
                        abuffer.akey = FALSE;
                        . . .                                          break;
        . . .
        default      :  . . .                                          break;
        }
    . . .       /* Writes definition of the primitive type's relation into the relation.sys file */
    . . .
    }
```

The definition of each field requires a name, a field type, a field size, and a key flag. The name is specified so that the user can understand what the field is. The type can be either CHARACTER (for text), NUMERIC (for integers), or DECIMAL (for real numbers). The size is the maximum size the data in a field could have. The key flag is true for the name field and false for all the other fields. The procedure MakePr used CheckList to create the first primitive (i.e. the local primitive) for the new primitive type. (Procedure MakePr is in the source file "makepr.c"). For the block, MakePr created the first block called ABLOCK, and for the cone, MakePr created the first cone called ACONE. Every field in CheckList must have a case statement for it in the procedure MakePr. MakePr uses standard data predefined for the local primitive. The local primitive data is defined in LocalPrm (in the source file "main.c"). LocalPrm is a structure of type PR_BUFFER. For each field there must be a member (or holder) in the PR_BUFFER structure. LocalPrm must have a default value initialized for each field. PR_BUFFER and LocalPrm are defined as follows:

```
typedef  struct  _prbuffer          /* In the file "structs2.h"  */
  {
     char     pname[PNAME];         /* Name of the primitive object */
    char      relation[FNAME];      /* Primitive type: block, cone, etc.  */
    char      rname[PNAME];         /* Used for XFORMS:  name of object to the right */
    char      r_rel[PNAME];         /* Used for XFORMS:  relation of right object  */
    double    dx;                   /* X-coordinate of object's center */
    double    dy;                   /* Y-coordinate of object's center */
    double    dz;                   /* Z-coordinate of object's center */
    double    sx;                   /* Half of object's width  */
    double    sy;                   /* Half of object's height  */
    double    sz;                   /* Half of object's depth  */
    double    rx;                   /* Angle of rotation about X-axis */
    double    ry;                   /* Angle of rotation about Y-axis */
    double    rz;                   /* Angle of rotation about Z-axis */
    char      order[OLEN];          /* Order of rotation.  OLEN = 3    */
    int       color;                /* Color of the object    */
    int       capped;               /* TRUE if object is capped, FALSE otherwise */
    int       usage;                /* Number of times the primitive is used        */
    }   PR_BUFFER;


/* LocalPrm is initialized in the file "main.c" as follows */

PR_BUFFER  LocalPrm =  {
                       " ",   " ",   " ",   " ",
                       1.0,   1.0,   -1.0,
                       1.0,   1.0,   1.0,
                       0.0,   0.0,   0.0,
                       { 'X',   'Y',   'Z',   '\0' },
                       2,     1,  1
                       };
```

4. In the main procedure, procedure calls to DefineRel and MakePr were added for block and cone as follows:

```
main( )
{
   . . .
   DefineRel("SPHERE");
   MakePr("SPHERE");
   DefineRel("CYLINDER");
   MakePr("CYLINDER");
   DefineRel("BLOCK");
   MakePr("BLOCK");
   DefineRel("CONE");
   MakePr("CONE");
   . . .
}
```

5. In procedure MakeTree (in the source file "activate.c"), if the flag "capped" is irrelevant for a primitive type, then the flag must always be set to TRUE when an object is selected. The primitives such as sphere and block always have the flag "capped" set to TRUE. Whereas, primitives that have lid(s), such as cylinder and cone, may have the flag "capped" set to TRUE or FALSE.

6. In procedure TraceObject (in the source file "raytrace.c"), case statements for block and cone were added as follows:

```
TraceObject( . . . )
{
. . .
    switch (ptype)
        {
        case SPHERE     :   . . .                   break;
        case CYLINDER   :   . .                     break;
        case BLOCK      :   TraceBlock(. . .);
                            . . .                   break;
        case CONE       :   TraceCone(. . .);
                            . . .                   break;
        default         :   . . .                   break;
        }
. . .
}
```

TraceBlock is a routine (in the source file "trcblock.c") that was implemented to determine ray-block intersections. In TraceBlock, the interseciton of the ray with each face of the block was tested one by one. The normal at each point was also determined. The procedure returned the ray parameters for the points at which the ray entered the block's surface and the point at which the ray exit the block's surface. The normal at these points were also returned.

TraceCone is a routine (in the source file "trccone.c"), that was implemented to determine ray-cone intersections. In TraceCone, mainly two intersection tests were required. Intersection of the ray with the quadric surface of the cone and intersection of the ray with the base of the cone were determined. The procedure returned the ray parameters and normals at the intersection points.

7. In the procedure DoFrame (in the source file "wirefram.c"), case statements for the block and cone were added as follows:

```
DoFrame()
{
 . . .
 switch (ptype)
    {
    case SPHERE      :  SphrFrame( );        break;
    case CYLINDER    :  CylnFrame( );        break;
    case BLOCK       :  BlockFrame( );       break;
    case CONE        :  ConeFrame( );        break;
    default          :  . . .                break;
    }
 . . .
 }
```

The procedure BlockFrame was implemented to process the wire frame for blocks. The procedure ConeFrame was implemented to process the wire frame for cones.

8. All new source files that were created were included in the "makefile" to be compiled and linked with the rest of the implementation.

3.8 INSTALLATION OF NEW FIELDS

This section discusses the steps required to install a new field into a primitive's definition in the database. (Refer to step 3 of section 3.6 for files, procedures, and structures mentioned in the following explanation).

Consider the hypothetical situation, where a new field for 'transparency' was to be installed for the primitive type cone. The new field would function as a flag which would be true if the object was transparent, and false if the object was opaque.

1. First, the field name code TRANSP must be defined in the file, "is_a.h".
2. In the case statement for cone, in procedure GetList, the additional field name code TRANSP must be included in the array Clist.
3. In procedure DefineRel, an additional case statement must be inserted for TRANSP. The case statement must specify the field name to be "TRANSPARENT", the type to be NUMERIC, the field length to be the size of an integer, and the key flag to be FALSE.
4. In the structure PR_BUFFER, a new member called "transp" of type int must be defined.
5. In LocalPrm a default value (false, i.e. 0) for the new field must be initialized.
6. In procedure MakePr, a case statement for TRANSP must be inserted. In the case statement for TRANSP, the default value

(for transparency) in LocalPrm must be assigned to the data structure used for creating the first primitive for cone.

7. In the procedure CopyBuffer, a statement for the new field is required. In CopyBuffer, contents of the second buffer are copied to the first buffer. Both buffers are structures of type PR_BUFFER.

```
CopyBuffer(buf1,buf2)
PR_BUFFER   *buf1, *buf2;
{
   . . .
   buf1->color = buf2->color;
   buf1->capped = buf2->capped;
   buf1->transp  =  buf2->transp;
   .   .
}
```

8. In procedure ShowBuf, the value assigned to the field for transparency must be displayed along with the value assigned for color, etc.
9. In procedure Process, first the new transparency option must be included in the menu for options that the user can change. Then, a case statement must be inserted for the transparency option similar to the case statement for the "capped" option.
10. In procedures CopyPrData and CopyPdata, case statements for TRANSP must be included. In CopyPrData, contents of a buffer (of type PR_BUFFER) are copied to another data structure. In CopyPdata, contents from another data structure are copied to a buffer (of type PR_BUFFER).
11. Wherever a structure of type PR_BUFFER is used, code statements to handle the new field must be included.

12. The old definition of cone, along with the contents of the data and index files for cone, can be removed from the database by using the DELETE ALL command in ARTISAN.

After recompilation and execution of ARTISAN, the new definition of cone will get installed into the database and the local primitive called "ACONE" will be created automatically.

CHAPTER 4 CONCLUSIONS

4.1 SUMMARY

The main function of the system implemented is to facilitate the creation and depiction of non-geometric, complex, realistic, three dimentional solid models. The system implemented includes its own graphics relational database which provides a means of creating, storing, manipulating, modifying, and deleting the 3-D models. The process of building a 3-D model is based on the concept of constructive solid geometric modeling (CSG). Geometric primitives such as a sphere, cylinder, block, and cone are used as building blocks. The geometric primitives are combined together by using the boolean operations of union (+), intersection (&), and difference (-). A ray tracing algorithm is used to realize the boolean operations. In the ray tracing algorithm, the technique of ray casting is used to determine the ray-object intersections. A simple illumination model, using a point light source, is used to shade the models. The technique of ordered dithering is used in combination with the simple illumination model to improve the shading of a model.

The system provides the user with the options to move the solid model around by translation and/or rotation, change the size of the model by scaling, change the position of the observer (i.e. the center of projection, COP) to see the model from a different distance, change the position of the light source to see how that effects the illumination of the model, and change the intensity of the light source and other illumination variables. While creating

and editing the models the user has the option to view the model either as a wireframe for fast display or as a shaded solid for a realistic display.

The ray tracing algorithm handles the boolean set operations, visible surface processing, and the illumination of the model simultaneously. Since the ray-object intersection calculations can be processed in parallel, the ray tracing technique becomes more appropriate for constructive solid modeling compared with the other implementation techniques mentioned in section 1.1, given a multiprocessor environment.

Software implementation was done in the C language, on an IBM AT compatible PC using a MS-DOS operating system, a VGA graphics card, a color graphics monitor, and a math co-processor. The whole implementation, which is known as ARTISAN, is composed of two programs. One program, "Build", performs the calculations and generates display data, and the other, "Paint", uses the data generated to display the image. The calculation program does not use any system or machine dependent functions, whereas the graphics display program uses machine dependent display routines. The calculation program has a menu driven user interface which may not be as user friendly as a graphical user interface but it preserves the portability of the program.

The process of building a model that has several sub-components can be time consuming if the ray tracing algorithm is used every time two components are combined together. So the ADD, SUBTRACT, and INTERSECT commands allow the user to see wireframe representations of the components, and

save the resultant model in the database without actually ray tracing the resultant model. The wireframes give the user a rough idea about the placement, size, and orientation of the components. Thus, the time utilized in building a complex model can be greatly reduced by using the wireframe displays for viewing the progress of the model building process. Once the entire model has been built, it can be ray traced.

4.2 SOLUTIONS TO PROBLEMS ENCOUNTERED

1) **Internal meaning:** In order for the graphic application functions to interpret the fields in a record, an extra field called IS-A was added to each field's definition, in the system file ATTRIBUTE.SYS. For example, for the application functions, internally the LENGTH of a block means the same as twice the RADIUS of a sphere. Both LENGTH and RADIUS give information about the dimensions of the objects along the x-axis. Thus, both LENGTH and RADIUS have identical IS-A fields. Another use of IS-A is that it makes the field's meaning independent of the field's position in the record. That means, the position of a field could be first, last, or anywhere in between in a record. Without the IS-A field, it would be harder for the application functions to interpret information in the database.

2) **Deletion of a subcomponent:** For the function DELETE RECORD, an object could not be deleted and physically removed from the database if the object was being used as a part of other solid models. This problem could be solved by adding a field called PART-OF to each object's record. The information in PART-OF would lead to a list of models of which the object is a part. Instead of using this scheme a simpler method was used. Instead of PART-OF, a field called USAGE was used with each object's definition. USAGE holds the number of times the object has been used as a part of other models in the database. When a model (i.e. composite)

is deleted, the USAGE of its subcomponents (i.e. submodels and primitives) is decremented by one. When a model is created, the USAGE of its subcomponents is incremented by one. More information about the USAGE field is given in section 3.1.

4.3 DEFICIENCIES

1) Currently ARTISAN has definitions and ray-object intersection routines for the primitive types cylinder, sphere, block and cone. Installation of new primitive types, such as the torus, into the database cannot be done directly by the user. Installation of new primitive types can be done only by a software programmer, as explained in section 3.6.

2) The display data that results from the ray tracing algorithm or the wireframe function is stored in the output file, called "outfile". This output file is then used by the graphics display program to display the image. Output files are often quite large, therefore to conserve disk storage the software currently reuses a single data file to store display data. By reusing the output file its previous contents are lost. If it is required that the display data for a particular session be saved, the user must manually copy the data file to a file with a different name.

3) The simple illumination model, discussed in section 3.4, does not take into consideration the light that reaches an object's surface by reflection from, or transmission through, other objects. The simple illumination model does not process shadows. To incorporate these illumination

effects, a global illumination model would be required. A brief description of a global illumination model is given, along with an explanation of the ray tracing technique, in section 1.1. In a global illumination model shadows are processed by default. A global illumination model is computationally more expensive than a simple illumination model. For more information about the global illumination model refer to [Rogers].

4.4 FUTURE EXTENSIONS

1) Currently ARTISAN has a single point light source which the user may place anywhere in 3-D space. Additional light sources could be added to improve quality of images. For multiple light sources, the illumination effects get added linearly. The shading function given in section 3.4, for calculating the reflected intensity becomes:

$$I = I_a . K_a + \sum_{j=1}^{m} \frac{I_{l_j}}{d + K} \left[K_d . \cos(\theta_j) + K_s . \cos_j^n(\alpha_j) \right]$$

The additional light source(s) would first be defined in the file "constant.h", similar to the point light source already defined. In the procedure ChangeLight, the user is given

an option to change the position of the light source. Code statements could be inserted in procedure ChangeLight to give the user options to change the additional light source(s). Then, in the procedure Shade (in the source file "shadec.c"), the angle of incidence (i.e. the angle between the surface normal and the light vector), would have to be tested for each light source. Those light sources for which the angle of incidence is not in the range of 0° to 90°, must be ignored. The other valid light sources would have to be taken into consideration. In the procedures Shade (in the source file "shadec.c") and Dither (in the source file "dither.c"), the reflected intensity would have to be calculated (using the equation given above) for each valid light source.

2) ARTISAN assumes that all objects are opaque and have smooth surfaces. However, objects could have the option to be transparent. It is possible to process objects that have a semitransparent, nonrefractive surface, by using the simple illumination model. If the first object that a ray intersects is transparent, it implies that:

- both the outer and inner surfaces of the first object are visible to the observer, and
- any objects that lie behind the first object are also visible to the observer.

Therefore, for the first object, all the ray-object

intersection points are tested for visibility using the outward surface normal as well as the inward surface normal. All visible points are taken into consideration. The objects that lie behind the transparent object are processed the same way depending on whether they are opaque or transparent. To process refractive transparent objects, implementation of the global illumination model would be more appropriate. For more information on transparency see [Rogers].

If objects had the option to be transparent, a new field would have to be installed in the primitive's definition in the database. The procedure for installing a new field in the primitive's definition is given in section 3.7.

3) When a global illumination model is implemented, shadow effects get processed automatically. However, a special procedure to process shadows could be added to the simple illumination model. The test to see if an intersection point is in shadow, is performed only if the point is visible to the observer. If the point lies in shadow, there is no need to calculate the reflected intensity at that point. The general procedure for processing shadows is as follows: At each visible ray-object intersection point, a shadow feeler is generated in the direction of the light source. If a shadow feeler intersects with an object before reaching the light,

then the intersection point lies in shadow with respect to that light. Since all objects are assumed to be opaque, no light reachs the intersection point that lies in the shadow.

4) Currently in ARTISAN, a cylinder may or may not have its top and bottom lids (or caps) closed. When the flag "capped" is true, both the top and bottom lids are closed. When "capped" is false, both the lids are open. It would be possible to provide the user with an option to have just one of the lids closed. Instead of using the field "capped" as a flag, it could be used as a code, such that when:

capped == 0, both lids are open;
capped == 1, only the top lid is closed;
capped == 2, only the bottom lid is closed; and
capped == 3; both top and bottom lids are closed.

In the ray-object intersection routine for cylinder, intersection of the ray with the top and bottom lids would then have to be performed based on the code value in "capped".

A similar scheme could be implemented for blocks. The user could be given the option to have any one of the six sides of a block open. Thus, for a block, the field "capped" could have code values ranging from 1 to 7. Each side (or face) could be assigned a value from 1 to 6. A code value of 7 would mean that all the sides of the block are closed. If the user requires more than one side of a block

to be open, the bits in the "capped" field may be used to encode the information.

5) The display data in the output file could be compressed so that output of previous ray tracings could be saved.

6) ARTISAN could be more naturally written in an object oriented language like C++ because CSG solid modeling is an object oriented concept.

4.5 RELATED THESIS TOPICS

The most important feature of ARTISAN is the use of a ray tracing algorithm to realize the boolean operations: union, intersection, and difference. However, on the whole, ARTISAN is a graphics database that represents the "subsystem" of the "geometry system" that was explained in chapter 2. This suggests that additional application layers can be built over ARTISAN. The additional application layers could be for simulation, object information, interference analysis, etc. Any additional application layer built upon ARTISAN could be considered a thesis topic.

A related thesis topic could be, replacement of ARTISAN's menu driven user interface with a natural language (or graphics) user interface along with an artificial intelligence application layer. Installation of new primitive objects into the database, by the user could be a possible project.

Utilization of ray tracing algorithms to simulate motion blur and animation are other related thesis topics. Glassner has done considerable work on these topics. His research could be used to study and implement motion blur and/or animation using ray tracing algorithms.

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