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# Hyperspace Algorithm for WODERS A

Calculating Shadows in Hyperdimensional Scenes

By Mei-chi Liu, Robert P. Burton and Douglas M. Campbell

-requal ni station the refired and properbe revealed.

tive positions of hyperobjects can

the scene. jection can be selected to present shadows are determined, any prois projected for presentation. Once dimensional space before the scene all calculations in the original ngorithm described here carries out spaces. Therefore, the shadow althemselves to extension to hyperthree-dimensional space do not lend ni awobsha shimreta shadows in use scanning hidden-surface techexisting shadow algorithms that point in two-dimensional space, space may project onto the same

# Dimensional Objects From Lower- to Higher-

sional objects. -nəmib-(1-n) gnibnuod sti yd an n-dimensional object is defined bounding polygons. The surface of ments, and a polyhedron by its a polygon by its bounding line segis defined by two bounding points, jects. For example, a line segment built from lower-dimensional ob-Higher-dimensional objects can be

simply from the direction of each sional object can be determined the illumination of an n-dimenthat is stopletonal objects is that face of an n-dimensional object with The advantage of defining the surwith a vector to the light source. an angle of less than 90 degrees normal to the surface portion forms portion is illuminated only if the portion is illuminated. The surface to determine whether the surface source L for n-space, a test is needed dimensional object X and a light Given a surface portion of an n-

> merical representation. hanced by visual rather than nuutility of such models is often envariables exist simultaneously. The which occur whenever four or more senting hyperdimensional models techniques for meaningfully prefort to develop computer graphics perspace is part of an ongoing efment of a shadow algorithm for hysions and presented. The developquently projected to lower dimenadded to the scene, which is subsesources. Shadows are calculated and together with multiple light great as those of the scene itself, with dimensions that may be as consist of multiple convex objects dimensional scenes. The scenes for calculating shadows in hyper-This paper describes an algorithm

> graphic information. presenting multi-dimensional structive solid geometry scheme for phenomena, and to develop a conhypothesized four-dimensional perspace, to categorize and present hidden-volume algorithm for hyhyperspace; research to develop a perobjects; holograms of objects in cation to the presentation of hystudy of depth cues and their applimoved from hyperobjects; a careful capabilities with hidden lines rerithm and of stereo motion picture velopment of a hidden-line algo-Related efforts include: the de-

scene, information about the relaing shadows in a hyperdimensional tive positions of objects. By includreveal information about the relain a three-dimensional scene, they ploited. When shadows are included tute a cue that remains unexhyperdimensional objects consti-Shadows cast and received by

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Figure 1: The shadow areas of a polyhedron.

normal of its (n-1)-dimensional surfaces. Only the illuminated (n-1)-dimensional surfaces need to be processed by the algorithm, thereby decreasing the computation time.

## **Description of the Algorithm**

The intersecting shadow volume algorithm is an object-space algorithm. It accepts geometrical and topological descriptions of multiple convex objects and the positions of multiple light sources. The viewer is restricted to the near side of all objects which in turn are restricted to the near side of a background plane whose dimension is one less than the dimension of the scene. Shadows are calculated and added to the scene which is then projected for presentation.

In the accompanying figures, parts of the scene are presented in various colors: black for objects; red for the shadow volume of an object formed by a single light source; blue for the shadow volume of a second light source; and green for the intersection of the illuminated portion of the surface of an object and the shadow volume of another object (i.e., the shadow cast upon the illuminated portion of the first object).

Two Three-Dimensional Objects Xand Y and One Light Source L: The algorithm is applied in three steps to determine shadows.

 $\square$  *Step 1:* Use normals to separate the surface polygons of a polyhedron into those illuminated by L and those that are not. The illuminated surface of a polyhedron is defined as consisting of all its illuminated surface polygons. The shadow volume of the polyhedron from the light source is generated

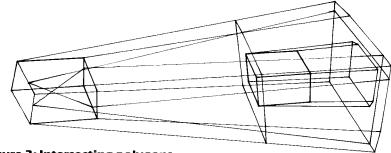
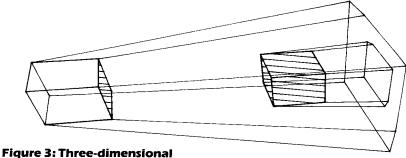


Figure 2: Intersecting polygons attached to the extended surface polygons.



shadows.



Figure 4: The shadow areas of hyperpolyhedra.

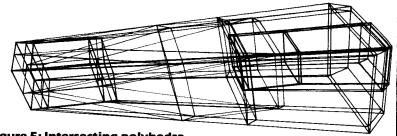


Figure 5: Intersecting polyhedra attached to the extended surface polyhedra.

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Figure 6: Four-dimensional shadows.

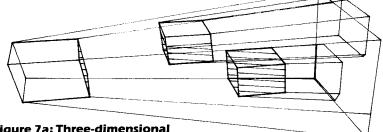
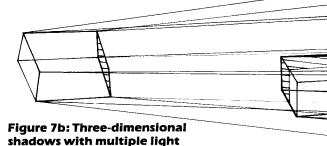


Figure 7a: Three-dimensional shadows with multiple objects.



shadows with multiple light sources.

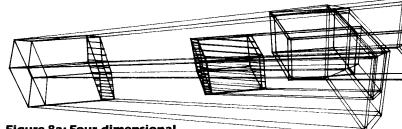
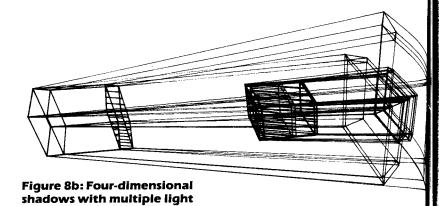


Figure 8a: Four-dimensional shadows with multiple objects.

sources.



by projecting the illuminated surface from the polyhedron toward the background plane. The shadow volume is itself a three-dimensional polyhedron bounded on the ends by the illuminated surface and the projection of the illuminated surface onto the background plane (Figure 1). This is computationally equivalent to projecting each illuminated surface polygon onto the background plane.

 $\square$  Step 2: Intersect the shadow volume of polyhedron Y with each illuminated surface polygon of polyhedron X. If the intersection is nonempty, the intersection is a shadow polygon, line, or point and is added to the list of shadows in

the scene. Repeat, interchanging the roles of polyhedra X and Y (Figures 2 and 3).

☐ Step 3: Project and present the illuminated surfaces and shadows (polygons, lines, and points).

Two Four-Dimensional Objects Xand Y and One Light Source L: The algorithm is extended to determine shadows in four-dimensional space in three steps.

☐ *Step 1*: Use normals to separate the surface polyhedra of the hyperpolyhedron into those illuminated by L and those that are not. The illuminated surface of a hyperpolyhedron is defined as consisting of all its illuminated surface polyhedra. The shadow hypervolume of the hyperpolyhedron from the light source is generated by projecting the illuminated surface from the hyperpolyhedron toward the background hyperplane. The shadow hypervolume is itself a four-dimensional hyperpolyhedron bounded on the ends by the illuminated surface and the projection of the illuminated surface onto the back-

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ground hyperplane (Figure 4). This is computationally equivalent to projecting each illuminated surface polyhedron onto the back-

ground hyperplane.

☐ Step 2: Intersect the shadow hypervolume of a hyperpolyhedron Y with each illuminated surface polyhedron of hyperpolyhedron X. If the intersection is nonempty, the intersection is a shadow entity of dimension less than four and is added to the list of shadows in the scene. Repeat, interchanging the roles of hyperpolyhedra X and Y (Figures 5 and 6).

 $\square$  *Step 3:* Project and present the illuminated surfaces and shadows (polyhedra, polygons, lines, and

points).

Two n-Dimensional Objects X and Y and One Light Source L: The algorithm is applied to determine shadows in n-dimensional space in three steps.

☐ *Step 1*: Use normals to separate the (n-1)-dimensional surface elements of the n-dimensional convex object into those illuminated by L and those that are not. The illuminated (n-1)- dimensional surface of the object is the union of its illuminated (n-1)-dimensional surface elements. The shadow hypervolume of the object from the light source is generated by projecting the illuminated surface of the object toward the background hyperplane. The shadow hypervolume is itself an n-dimensional hyperpolyhedron bounded on the ends by the illuminated surface and the projection of the illuminated surface onto background hyperplane.

☐ Step 2: Intersect the n-dimensional shadow hypervolume of the object Y with each illuminated

surface element of the object X. If the intersection is nonempty, the intersection is a shadow entity and is added to the list of shadows in the scene. Since the shadow hypervolume is of dimension n and the illuminated surface element is of dimension n-1, the dimension of a shadow entity is at most n-1. Repeat, interchanging the roles of

## **Determining Object Surface** Illumination

An n-dimensional convex object Y is defined by a finite set of linear equations  $E_1,...,E_m$  as follows. A point  $X + (x_1,...x_n)$  of n-space is strictly in Y only if  $E_i(x)*0$  for i=1,...,m, (i.e., if the point x is strictly "inside" every hyperplane which defines Y). A point is inside, or on, Y only if  $E_i(x) \dagger 0$  for i = 1, ..., m.

The convex object Y defined by  $E_1,...,E_m$  has m (n-1)-dimensional boundary surfaces, each of which lies in one of the m hyperplanes  $E_i(x) = 0$ . If E<sub>i</sub> is the linear equation that defines the i-th (n-1)-dimensional surface element, then the element is illuminated by a light source at the point X only if  $E_i(x) > 0$  (i.e., if X is 'outside" the boundary hyperplane used to define object Y).

A hyperplane E is defined by first choosing n points p1,...,pn which do not lie in (n-2)-dimensional space. Each point p<sub>i</sub> can be written in terms of its n coordinates as  $p_i = (p_{i1},...,p_in)$ , where p<sub>i</sub> j denotes the projection of p<sub>i</sub> on the j-th axis. The  $n \times n$  matrix  $M = (m_{ij})$ is found next where

 $\begin{array}{ll} X_{_{j}}-P_{_{1j}} & if \ i=1, \ 1{\leqslant}j{\leqslant}n \\ m_{_{ij}}=&P_{_{ij}}-P_{_{1j}} \ if \ 2{\leqslant}i{\leqslant}n, \ 1{\leqslant}j{\leqslant}n \end{array}$ 

The linear equation E is the determinant of the matrix M. It can be given in the ordinary linear form

 $\mathbf{E}(\mathbf{x}) = \mathbf{C}_{i}\mathbf{x}_{i} - \mathbf{C}_{i}\mathbf{P}_{1}\mathbf{i},$ where C<sub>i</sub> is the cofactor of the element in the first row and i-th column of the matrix M.

the n-dimensional objects X and ☐ Step 3: Project and present t illuminated surfaces and shado (which are at most (n-1)mensional).

Multiple Objects and Light Source If there are m n-dimensional jects X<sub>1</sub>, X<sub>2</sub>, ..., X<sub>m</sub> in the scen with  $V_1$ ,  $V_2$ , ...,  $V_m$  illuminat surface elements respectively, th Step 2 of the algorithm is repeat for each illuminated surface h perpolyhedron for each of the m n-dimensional shadow volume Assuming the average number visible surface polyhedra to be the computational time of the gorithm is increased by a factor (m-1)V.

If there are k light sources L<sub>1</sub>,  $L_k$ , then Step 2 of the algorith must be repeated k times. This creases the computation time of algorithm by a factor of k.

Assuming k light sources and objects with the same avera number of illuminated surfaces, total computation time—incli ing transformations, hidden-si face elimination, calculation shadow volumes, intersections a shadows cast upon objects $kn(n-1)t_av$ , where  $t_av$  is the av age computation time to calcula shadows cast upon one object fr another.

Running on a VAX 11/750, computation time to calculate to ical three- and four-dimension shadows is listed in Table 1.

## Conclusion

The shadow algorithm present here has been successfully imp mented to determine shadows three- and four-dimensional space Multiple objects (Figures 7a and 8 and multiple light sources (F Calculation of the Point(s) of Intersection of a Line and an m-dimensional Subspace in n-space, m<n

To determine what parts of an illuminated (n-1)-dimensional surface lie in an ndimensional shadow volume, it is necessary to break down the illuminated surface into its line elements and then determine the intersection of the line elements of the illuminated surface and the (n-1)-dimensional boundaries of the shadow volume. Thus, the problem of the intersection of a line and an m-dimensional space where m < n needs to be solved.

A line L (a one-dimensional space) is defined by two points  $1_1$  and  $1_2$  where  $(1_{i1},$  $\mathbf{1}_{i2},...,\mathbf{1}_{in}$ ) are the n-space coordinates of the point  $\mathbf{1}_i.$  A point  $\mathbf{x}=(x_1,...,x_n)$  is on Lonly if  $x_i = t(1_{ij} - 1_{2i}) + 1_{2i}$  for some real number t and for all i,  $1 \le i \le n$ .

An m-dimensional space S is defined by m+1 points  $s_1,...,s_m+1$ . By an appropriate change of coordinates, it is assumed, without loss of generality, that the 1-dimensional space L and the m-dimensional space S lie in a space spanned by the first (m+1)-coordinate axis of n-space. Since S is confined to the (m+1)dimensional subspace in the first (m + 1) space coordinates, the space S may be given as the solution of S(x) = 0 where

(1)  $S(x) = B_j(x_j - s_{1j}),$ 

where  $B_i$  is the determinant of the  $m \times m$  matrix

$$b_{11}$$
 ...  $b_1 j - 1 b_1 j + 1$  ...  $b_1 m + 1$ 

$$B_j \, = \, b_{i1} \quad ... \quad b_i \, j + 1 \, b_i \, j + 1 \quad ... \quad b_i \, m + 1$$

Since L is confined to an (m+1)-dimensional space in the first (m+1) space coordinates, the previous remark can be refined to state that  $\boldsymbol{x}$  belongs to L only if  $x_i = t(1_{1i} - 1_{2i}) + 1_{2i}$  for some real number t for all j,  $1 \le j \le m + 1$  and  $x_i = 1_{2i} = 1_{1i}$  for all  $j, m+2 \le j \le n$ .

Let  $A_i = 1_{1i} - 1_{2i}$ ,  $1 \le j \le m + 1$ . Since  $1_1 \ne 1_2$ , there is an index, say i, such that  $A_i \ne 0$ . The equation  $x_i = tA_i + 1_{2i}$  is multiplied by  $A_i$ , and the equation  $x_i = tA_i + 1_{2i}$  is multiplied by A<sub>j</sub> and then subtracted. Then

$$A_{j}\mathbf{x}_{i} - A_{i}\mathbf{x}_{j} = A_{j}\mathbf{1}_{2i} - A_{i}\mathbf{1}_{2j}\mathbf{f}_{j},$$

$$\mathbf{x}_{i} = (\mathbf{A}_{i}\mathbf{x}_{i} - \mathbf{f}_{i})/\mathbf{A}_{i}.$$

Thus, a point 
$$x = (x_1,...,x_n)$$
 belongs to L only if

$$\mathbf{x}_{i} = (\mathbf{A}_{i}\mathbf{x}_{i} - \mathbf{f}_{i})/\mathbf{A}_{i} \quad 1 \leq j \leq i-1$$

$$\mathbf{x}_{i} = \mathbf{t}\mathbf{A}_{i} + \mathbf{1}_{2i} \quad \mathbf{j} = \mathbf{i}$$

$$x_{_{j}}=(A_{_{j}}x_{_{i}}-f_{_{j}})/A_{_{i}}\quad i+1{\leqslant}j{\leqslant}m+1$$

$$x_i = 1_{2i} = 1_{1i} \quad m+1 \le i \le n.$$

 $x_j = 1_{2j} = 1_{1j}$   $m+1 \le j \le n$ . Assume that L and S intersect. Let x be a point both on L and in S. Since x is on L, x satisfies (2). Since x is in S, S(x) = 0. Using (1),

(3) 
$$B_i(x_i - s_{1i}) = 0$$
.

Then (3) is rewritten as

$$(4)\; B_{_{j}}x_{_{j}} = \; B_{_{j}}s_{_{1j}}$$

$$(5) B_i x_i + B_j (A_j x_i - f_j) / A_i = B_j s_{1j}.$$

Multiplying by A<sub>i</sub>, equation (5) becomes

(6)  $(B_iA_i)x_i = A_i B_is_{ij} + B_if_i$ .

If  $B_i A_i = 0$ , then there is no restriction on  $x_i$  and the entire line L in in the subspace. If  $B_i A_i \neq 0$ , then the point  $x_i$  is uniquely defined by

(7)  $\mathbf{x}_{i} = [\mathbf{A}_{i} \ \mathbf{B}_{i}\mathbf{s}_{1i} + \mathbf{B}_{i}\mathbf{f}_{i}]/(\mathbf{B}_{i}\mathbf{A}_{i}).$ 

Since  $x_i$  is uniquely defined by (7), then all the other coordinates of x are uniquely defined by (2). In this case, the point of intersection has been computed.

ures 7b and 8b) have been includ in scenes. The objects used in thr dimensional scenes are cubes; t objects used in four-dimension scenes are hypercubes.

When the shadows in a fourmensional scene overlap each oth it has been difficult to tell who each shadow is actually located. a means of increasing the reali of the scene, depth cues to achie realism in a three-dimension scene should be considered. The might include rotation, hiddenment elimination, interaction a stereoscopy. It is still difficult predict that a profound feeling hyperspace will be gained. New theless, the development of a shad algorithm for hyperspace rep sents one more step toward threshold beyond which an int tive feeling for hyperdimension scenes will be realized.

Some of the numerical al rithms needed for the implem tation of the shadow algorithm accompany this article. A compl description of the numerical al rithms is available in Mei-chi Li Master's Thesis (see References

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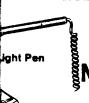
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University of Utah in 1973. ceived a Ph.D. in Computer Science from the Science at Brigham Young University. He re-

University of Morth Carolina in 1971. He received a Ph.D. in Mathematics from the puter Science at Brigham Young University. Douglas Campbell is a Professor of Com-

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Versity in 1982. Computer Science from Brigham Young Uni-Research Institute. She received an M.S. in Mei-chi Liu is a programmer/analyst at Eyring

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