

Merging BSP Trees Yields Polyhedral Set Operations

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Abstract

BSP trees have been shown to provide an effective representation of polyhedra through the use of spatial subdivision, and are an alternative to the topologically based b-reps. While bsp tree algorithms are known for a number of important operations, such as rendering, no previous work on bsp trees has provided the capability of performing boolean set operations between two objects represented by bsp trees, i.e. there has been no closed boolean algebra when using bsp trees. This paper presents the algorithms required to perform such operations. In doing so, a distinction is made between the semantics of polyhedra and the more fundamental mechanism of spatial partitioning. Given a partitioning of a space, a particular semantics is induced on the space by associating attributes required by the desired semantics with the cells of the partitioning. So, for example, polyhedra are obtained simply by associating a boolean attribute with each cell. Set operations on polyhedra are then constructed on top of the operation of merging spatial partitionings. We present then the algorithm for merging two bsp trees independent of any attributes/semantics, and then follow this by the additional algorithmic considerations needed to provide set operations on polyhedra. The result is a simple and numerically robust algorithm for set operations.

Introduction

Methods for representing geometric objects is an issue of considerable importance to disciplines dealing with geometric computation. Several different representations, such as boundary-representations (b-reps), octrees, and csg trees, are currently in use, and a number of new approaches are being explored by various researchers. As in all computation, the data representation/structure determines the algorithms that are needed to provide the operations associated with any semantic domain. And it is the efficiency and simplicity of the algorithms operating on the data structures that determines the attractiveness of a particular representation.

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Constructive solid geometry introduced the explicit use of the paradigm of constructing complex objects from combinations of other usually simpler objects. This methodology is built upon the mathematics of set theoretic expressions. These expressions are analogous to parenthesized boolean expressions, but the variables are instead subsets of a Euclidean D -dimensional space and the operations include, in addition to the analogous regularized boolean set operations, affine transformations. Instantancing, i.e. the utilization of named sub-expressions, is also a part of this method.

These expressions define a value and they can, at least in principal, be evaluated to produce this value. For example, ray-casting evaluates the expressions in a 1D sub-domain of the typically 3D domain, and so solves a simpler problem: classify a line with respect to the expression. When the operands are restricted to polyhedra and are represented by b-reps, then any number of algorithms are known for evaluating such an expression (see for example [Mantyla 88] or [Hoffman 89]).

The methodology underlying b-reps is that of the direct representation of the topology of a polyhedral surface/boundary. The topological approach requires the decomposition of a D -space polytope into connected components of all dimensions d , $0 \leq d \leq D$, and explicitly encodes the connectivity/incidence among these components. Thus, the methodology distinguishes for every d , $0 < d \leq D$, affine subspaces containing sets of d -manifolds (shells), preferably with their relative containment (which shells are inside which other shells), along with their connected set of $d-1$ dimensional boundary elements and the connectivity of these to other elements outside of their affine subspace, and so on recursively in dimension.

B-reps, while widely used, possess a number of inherent difficulties in terms of their representational power. The reliance on the concept of manifolds is at odds with the need for permitting non-manifold boundaries, i.e. the presence of regions on the boundary whose neighborhood is not homeomorphic to an ϵ -ball of some affine subspace. (However, this problem is fixable.) A second is the inability to represent sets whose boundary is unbounded, such as a linear halfspace.

On the algorithmic side, performing set operations with b-reps requires explicit detection of the co-incidence of all $C(D, 2)$ combinations of the variously dimensioned elements (e.g. face-face, face-edge, edge-vertex) along with some appropriate action for each. And the fundamental importance of incidence to the topological methodology exacerbates the already difficult problem of numerical robustness. Additionally, efficiency considerations necessitate some kind of spatial search structure, one that is extrinsic to the representation and is typically an axis-aligned spatial decomposition. Therefore, it does not

transform with the representation and so must be reconstructed after each transformation.

An alternative that has been evolving throughout the decade of the 80's is the *binary space partitioning tree*. The fundamental methodology underlying bsp trees is spatial partitioning. Hyperplanes are used to recursively subdivide D-space to create a disjoint set of D-dimensional cells. Each cell is then designated as either in the interior of the set or in the exterior. The boundary of the set need not be represented explicitly as it is derivable from the cells. The representational power of linear bsp trees is the class of linear sets¹, which includes linear polytopes. The methodology of spatial partitioning ignores all topological properties of the set, and so bsp tree algorithms treat all topologically distinct sets identically, nor is any distinction made between convex and non-convex sets. Thus the entire representational domain is treated uniformly, providing a considerable improvement in the simplicity of the algorithms. In addition, the spatial search structure is intrinsic to the representation and so transforms with it.

I. BSP Trees

The most intuitive way to understand bsp trees is through the process that constructs them, and so we begin our introduction to bsp trees with an example. Figure 1 illustrates the construction of a bsp tree. One begins with a region of space r , chooses some hyperplane h that intersects r , and then uses h to induce a binary partitioning on r that yields two new regions: $r.child^- = r \cap h^-$ and $r.child^+ = r \cap h^+$, where h^- and h^+ are the negative and positive *open* halfspaces of h respectively. Each of these unpartitioned children can in turn be partitioned, and so on, to produce a binary tree of regions.

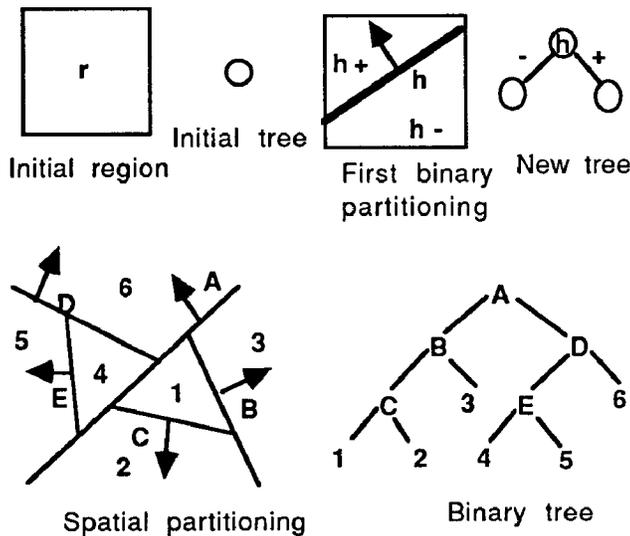


Figure 1 Constructing a bsp tree

A bsp tree is then a hierarchical set of regions of a D-dimension Euclidean space with a relation of parent-child defined on

the set corresponding to "child formed by a binary partitioning of parent". The graph of the relation on the set is a binary tree. The process that builds bsp trees uses a single local operator, viz. *binary partitioning*, which provides the construction: (region, hyperplane) \rightarrow (region⁻, region⁺, binary partitioner). A *binary partitioner* of a d-region R is any $d-1$ subset of R which partitions R into two disjoint subsets, R^- and R^+ , such that any path between two points, $p^- \in R^-$ and $p^+ \in R^+$, must intersect the binary partitioner. Recursively applying this operator produces a bsp tree.

While the bsp tree is a geometric entity whereas its binary tree is combinatorial, the language of binary trees is often useful for describing certain aspects of the bsp tree. By definition, there is an isomorphism between bsp tree regions and binary tree nodes, and we denote the region of a node V as $V.region$ and conversely the node of a region R as $R.node$. Each internal node V has an associated binary partitioner that partitions $V.region$, while each leaf node corresponds to unpartitioned region. These unpartitioned regions are called *cells*. (In figure 1, the cells are labeled with numbers.) Each edge of the binary tree corresponds to a halfspace: a left edge to the negative halfspace of the parent node's hyperplane and a right edge to the positive halfspace. We can then define any region R as the intersection of open halfspaces corresponding to edges on the path from the root to $R.node$. (In figure 1, cell 3 = $A^- \cap B^+$.) Thus, if the initial region, typically all of D-space, is a convex and open set, it follows that all of the regions of the tree are convex and open sets.

The binary partitioner of a partitioned region R , denoted as $R.bp$, is comprised of a hyperplane, $bp.hp$, a sub-hyperplane (or sub-hp), $bp.shp$, which is the intersection of $R.bp.hp$ with R , and its two halfspaces $bp.hs^-$ and $bp.hs^+$. Every region R is the root region of some bsp tree T , denoted as $R.tree$, and the symmetrical relation is denoted as $T.root_region$ (to unambivalently denote the set of points corresponding to $T.root_region$, as opposed to the data structure, we may also use $T.root_region.domain$). The two subtrees are denoted as $T.neg_subtree$ and $T.pos_subtree$ lying in $T.root_region.bp.hs^-$ and $T.root_region.bp.hs^+$ respectively. The set of cells corresponding to the leaves of T together with the sub-hyperplanes of its internal nodes forms a partitioning of $T.root_region$, and is denoted as $T.partitioning$.

Review of previous work

The original context in which the bsp tree was developed is that of rendering. The linearity of both planes and viewing rays means that if a ray intersects a plane it does so at only one point. And so the plane divides the ray into near and far sections. This permits inducing a visibility priority ordering on the three subspaces formed by the plane: near halfspace \rightarrow plane \rightarrow far halfspace. Given a bsp tree T , determining this ordering at every node of the tree in a recursive manner provides a total ordering of the elements of $T.partitioning$ (see [Schumaker et al 69] or [Sutherland, Sproull, Schumaker 74], and [Fuchs, Kedem, Naylor 80] or [Naylor 81]).

These techniques were extended to ray-tracing polyhedra and non-linear csg-dags in [Naylor and Thibault 86]. This work led to the association of attributes at the cells and the overt idea of bsp trees as a representation of polytopes. In [Thibault and Naylor 87] and [Thibault 87], several new algorithms were introduced. Conversation from a b-rep to a bsp tree and point classification algorithms were derived by extending earlier very similar algorithms. The work with csg-dags led to an algo-

¹ We have only studied bsp trees of finite size (as in number of nodes); but the concept can be extended to trees that are countably infinite.

rithm for evaluating a csg expression in which the primitive objects are polyhedra each represented by a b-rep, to yield a single bsp tree corresponding to the expression's value. An earlier idea of inserting moving objects into a bsp tree led to an algorithm for evaluating a polyhedral set operation between a bsp tree and a b-rep to yield a bsp tree, i.e. $\text{bspt} \langle \text{op} \rangle \text{b-rep} \rightarrow \text{bspt}$. Finally, algorithms were given for generating the polyhedral boundary as either a set of convex polygons represented by a list of vertices or as a set of edges.

In [Bloomberg 86], very similar ideas are developed, and an algorithm for $\text{bspt} \langle \text{op} \rangle \text{bspt} \rightarrow \text{brep}$ is given which classifies faces of one tree with respect to the other; but no subtrees are classified atomically. Even more recent work on bsp trees has provided a means of generating shadows for polyhedral models [Chin and Feiner 89], interactive object design and view volume clipping [Naylor 90a], radiosity [Fussell and Campbell 90], as well as algorithms with asymptotically improved bounds for constructing bsp trees from a set of faces in 3D and edges in 2D (i.e. conversion from b-rep to bsp tree) [Paterson and Yao 89] and [Paterson and Yao 90]. In [Torres 90], a new treatment is given of the original problems addressed in [Schumaker et al 69] of constructing an inter-object bsp tree of moving objects, where the individual objects are represented as bsp trees.

Geometric model as attributes on a space

The motivation for inducing a partitioning on a space S is to provide a means of distinguishing points in S through the association of arbitrary attributes with any of its points; that is to provide the mapping $\text{Model}(X \in S) \rightarrow \text{Attributes}$. We use the bsp tree to implement this general function. We associate with each element of our partitionings (cells and sub-hps) a set of C^0 or higher continuous functions whose domain is considered to be restricted to that element. This provides a quite general mechanism for constructing complex discontinuous functions on S that are piecewise C^0 . However, we will restrict our attention in this paper to the problem of represent regular sets, which requires the simplest possible set of attributes, $\text{Membership} : \{ \text{In}, \text{Out} \}$. Nonetheless, the principal result of this paper is the merging of two independent bsp tree spatial partitionings both defined on S . This merging operation is completely independent of the semantics of any attribute space, and requires only the ability to determine whether the attribute space of two elements can be represented by a single attribute space. Set operations are then constructed on top of this merging operation.

II. Merging Trees

The most primitive operation then is merging two spatial partitionings: given partitionings of the same space, P_1 and P_2 , form a new partitioning $P_3 = P_1 + P_2$ from the pairwise intersection of the cells of P_1 and P_2 , i.e. a cell $c_3 \in P_3 \Leftrightarrow \exists c_1 \in P_1, c_2 \in P_2, \text{ s.t. } c_3 = c_1 \cap c_2, c_3 \neq \emptyset$. Merging can be illustrated by simply overlaying the two partitionings on top of each other, as shown in figure 2.1.

We will then merge two trees $T_1 + T_2 \rightarrow T_3$, s.t. $T_3.\text{partitioning} = T_1.\text{partitioning} + T_2.\text{partitioning}$. However, since bsp trees are a hierarchy of regions, we will need to do somewhat more than merely merge their partitionings. Nonetheless, the algorithm to perform merging of bsp trees is fairly simple and recursive.

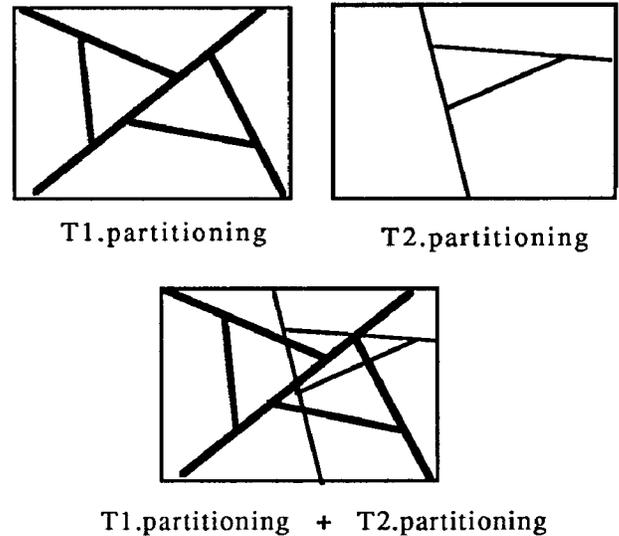


Figure 2.1 Merging partitionings

As with most bsp tree algorithms, we can understand tree merging in terms of the paradigm of inserting an object into a tree; in this case, the object is a tree as well. (Below, we will relax this asymmetrical view). As always, we need the two basic bsp tree operations: performing a binary partitioning of the object if at a partitioning node and executing a cell $\langle \text{op} \rangle$ object when at a leaf.

Performing a binary partitioning of a bsp tree by the binary partitioner of a node provides $(\text{Bspt}, \text{Bp}) \rightarrow (\text{inNegHs}, \text{inPosHs} : \text{Bspt})$; that is, a tree is split by a binary partitioner to yield two trees $T^- = T \cap \text{bp.hs}^-$ and $T^+ = T \cap \text{bp.hs}^+$. A Cell $\langle \text{op} \rangle$ Tree routine is imported by the tree merging routine, and it is this routine that embodies the semantics of the application. Its function is to merge the single set of attributes of a cell with the attributes of a tree. When the semantics is that of set operations on polyhedra, the spatial structure of the result will be either that of the cell or the tree (the specifics are discussed below in section V).

Given these two operations, the algorithm partitions one tree, say T_2 , by the binary partitioner at the root of the other, T_1 . The two resulting trees, T_2^- and T_2^+ , are defined on exactly the same region (domain) as $T_1.\text{neg_subtree}$ and $T_1.\text{pos_subtree}$ respectively. Thus, we have created two new sub-problems, each identical in form to the original problem: merge two trees each of which partition the same subspace. When a cell is reached, the semantics-dependent Cell $\langle \text{op} \rangle$ Tree routine is called. The basic algorithm is given in Figure 2.2. An illustration of tree merging appears in Figure 2.3. As one can see, each cell of T_1 is replaced with that subset of T_2 that lies in that cell.

While figure 2.2 provides the essentials of the merging algorithm, there remain a number of secondary issues. The first of these arises from the fact that the algorithm is completely symmetric with respect to its two operands, so one has the option of choosing at each recursive invocation of $\text{Merge_Bspt}()$, whether to partition the first tree by the second or the second by the first. A method $\text{Choose_Partitioner}()$ can be provided to $\text{Merge_Bspt}()$ for this purpose, and may enforce whatever policy is appropriate for the current usage. (Note that since the merge operations may be used to provide a non-commutative operator, the order of the operands must be preserved by having two distinct CASEs, one with T_1 as the partitioner and one for T_2 .)

```

Merge_Bspts : ( T1, T2 : Bspt ) -> Bspt
 ::=
Types
PartitionedBspt : ( inNegHs, inPosHs : Bspt )

Imports
Merge_Tree_With_Cell : ( T1, T2 : Bspt ) -> Bspt      User defined semantics.
Partition_Bspt : ( Bspt, Bp ) -> PartitionedBspt

Definition
IF T1.is_a_cell OR T2.is_a_cell
THEN
  VAL := Merge_Tree_With_Cell( T1, T2 )
ELSE
  Partition_Bspt( T2, T1.root_region.bp ) -> T2_partitioned
  VAL.neg_subtree :=
    Merge_Bspts( T1.neg_subtree, T2_partitioned.inNegHs )
  VAL.pos_subtree:=
    Merge_Bspts( T1.pos_subtree, T2_partitioned.inPosHs )
  VAL.root_region := T1.root_region
END IF
RETURN VAL
END Merge_Bspts
  
```

Figure 2.2 Merging BSP Trees Algorithm

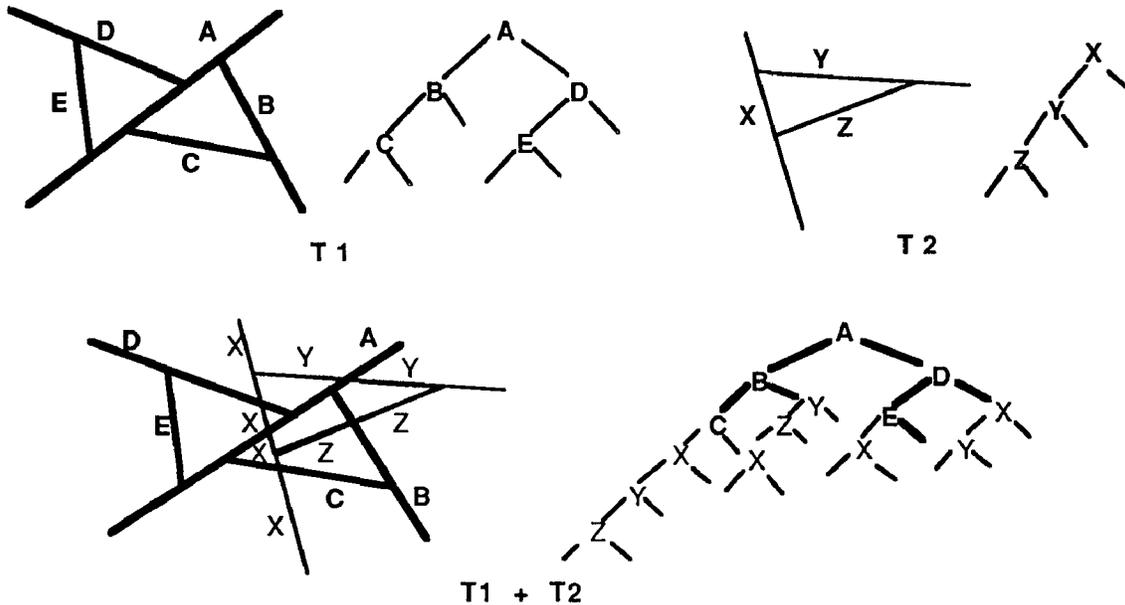


Figure 2.3 Merging two trees

Secondly, it may be necessary to perform merging of attributes in the sub-hp of the bp that is used as the partitioner. This can be handled by a Merge_Bp_Attributes() method. For representing polyhedra, these attributes are the faces of the polyhedra and the requisite routines are discussed below in section VI.

Finally, it is desirable to perform *condensation*. When the attributes defined on Tree.root_region.domain are homogeneous, there is no reason to maintain a partitioning of the domain, and so we will condense the tree into a single cell. Under the recursive assumption that the two subtrees are already condensed, determining homogeneity requires first that they both be singular, i.e. comprised of a single node, and then that their attributes be identical. If attributes defined on the domain of the

binary partitioner are independent of those of the subtree, then this subspace must be taken into account as well when determining homogeneity. Note that in the case of polyhedra, binary partitioner attributes, i.e. the faces of the polyhedra, are *not* independent; they are a function of their neighborhood of cells.

III. Binary Partitioning of a BSP Tree

We now address the problem of partitioning a bsp tree. Given a bsp tree T and a binary partitioner P defined on the same region of space, we want to form two trees, T⁻ and T⁺ such that T⁻ = T

$\cap P.hs^-$ and $T^+ = T \cap P.hs^+$, where $Regions(T^-) = \{ r^- \mid r^- = r \cap P.hs^-, r \in Regions(T), \text{ and } r^- \neq \emptyset \}$ and similarly for $Regions(T^+)$.

To compute the two trees resulting from this operation, we will once again use the notion of inserting a geometric entity into the tree; in this case, the entity is a binary partitioner. This insertion process will identify which regions of T lie entirely in $P.hs^-$, or entirely in $P.hs^+$, or are intersected by P . (Note that insertion visits exactly those regions that are intersected by P). Accomplishing this requires determining the relative spatial relationships of two bp's and, when they intersect, splitting each bp by the hyperplane of the other. This operation as well as the representation and generation of sub-hp's is discussed below in section IV.

We have the usual form of first distinguishing between cell and partitioning nodes (singular and non-singular trees), and in the case of a partitioning node, performing a binary partitioning of the inserted entity, i.e. the partitioning bp. Partitioning a cell is trivial: one needs only to return two copies of that cell. For a partitioning node, however, the issue is more involved.

The first step is to perform a *bi-partitioning* between P and T 's bp; that is, each bp is classified with respect to the other into the standard binary partitioning cases:

Location : { InNegHs, InPosHs, InBoth, On }.

Figure 3.1 shows the four possible geometric configurations. (Not shown are InNegHs/InPosHs, InPosHs/InPosHs, and On-parallel, since they have the same geometry but with one normal flipped.) The routine to perform this operation, `Bi-Partition_Bps()` is discussed in section IV.

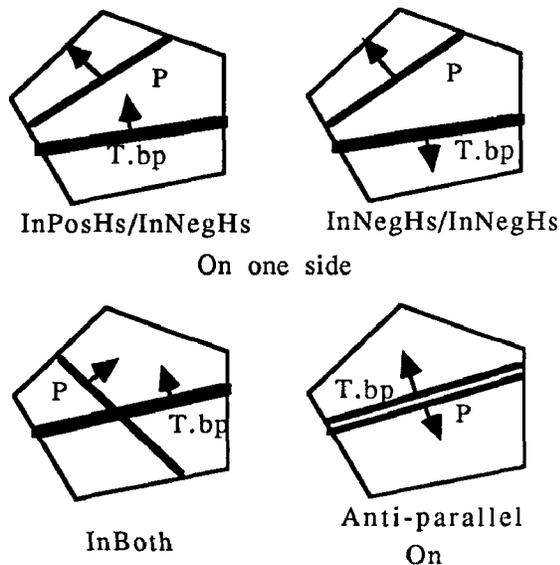


Figure 3.1 Spatial relationships between two binary partitioners

While each of the seven cases are treated separately, they all share the basic premise that any subtree containing the partitioner will need to be partitioned, and any that does not will need no modification. So, the case where P 's location = InNegHs results in $T.neg_subtree$ being partitioned but not $T.pos_subtree$, and InPosHs requires the opposite action, InBoth entails partitioning both, and On neither. The parts of subtrees resulting from this recursive partitioning are then pieced together to form the two trees which are the return values of this operation.

To see this more clearly, figure 3.2 attempts to illustrate what is taking place for the InBoth case in which four subtrees are generated, two from each subtree of T . During the process of inserting the bp P into the tree, one views the activity primarily in terms of the two halfspaces of T .root region: we construct $P^- = P \cap T.hs^-$ and $P^+ = P \cap T.hs^+$. In contrast, the result, which is formed after any required subtree partitioning, is instead in terms of the halfspaces of P : $T^+ = T \cap P.hs^+$ and $T^- = T \cap P.hs^-$, which also entails computing $T.bp^- = T.bp \cap P.hs^-$ and $T.bp^+ = T.bp \cap P.hs^+$. So we have T^- being formed out of pieces from both of T 's two subtrees :

```

T-.neg_subtree := T's_neg_subtree.inNegHs
T-.pos_subtree := T's_pos_subtree.inNegHs
T-.root_region.bp := T's_bp.inNegHs
    
```

and similarly for T^+ .

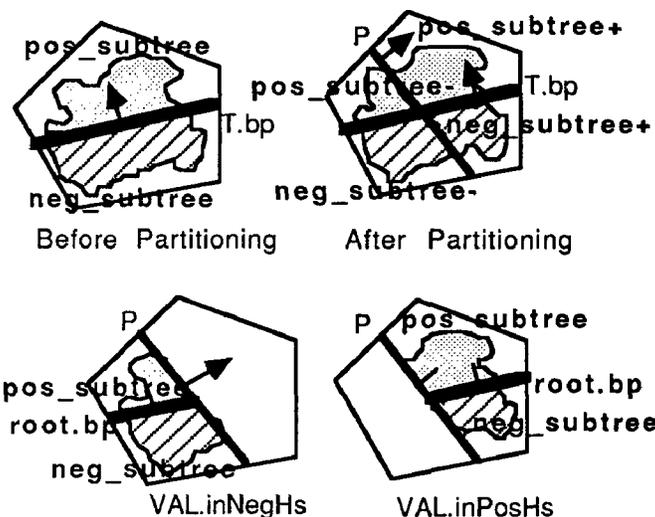


Figure 3.2 Partitioning a tree for InBoth case

The cases in which P is entirely to one side of $T.bp$ is illustrated in figure 3.3. There are four instances of this case obtained by flipping normals; only one is shown here. For this case $T.bp$ and $T.neg_subtree$ remain intact; only $T.pos_subtree$ is partitioned. The return values are:

```

T-.neg_subtree := T.neg_subtree
T-.pos_subtree := T's_pos_subtree.inNegHs
T-.root_region.bp := T.bp
and
T+ := T's_pos_subtree.inPosHs.
    
```

Analogous assignments yield the other three instances.

And finally, the third case of On requires no further partitioning and is given simply by selecting the appropriate subtrees:

```

IF normals are parallel
THEN
    T- := T.neg_subtree
    T+ := T.pos_subtree
ELSE
    T+ := T.neg_subtree
    T- := T.pos_subtree
END
    
```

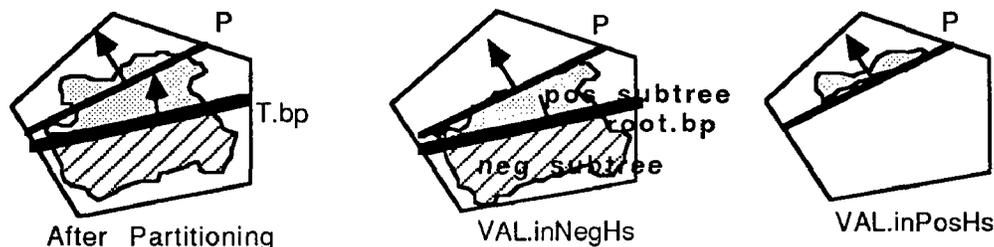


Figure 3.3 Partitioning a tree for InPosHs case

It is important to note that any newly formed tree should have the condensation operation applied to it. While not needed for correctness, this can have a significant impact on performance. Consider figure 3.4 in which two complex objects are each contained inside their bounding simplex. If T2 is inserted into T1, then T2 will be partitioned by X then Y and then Z. At this point, the fragment of T2 inside T1's bounding simplex will be condensed to a single out-cell, and

so the merging operation will be complete. Neither of the subtrees inside the bounding simplices will be visited during this process.

With the description of Partition_Bspt complete, we make the following observation : to merge T1 with T2, we can insert T2 into T1, which entails the apparent paradox of inserting T1 into T2 (actually, T1's bp's), but one piece at a time.

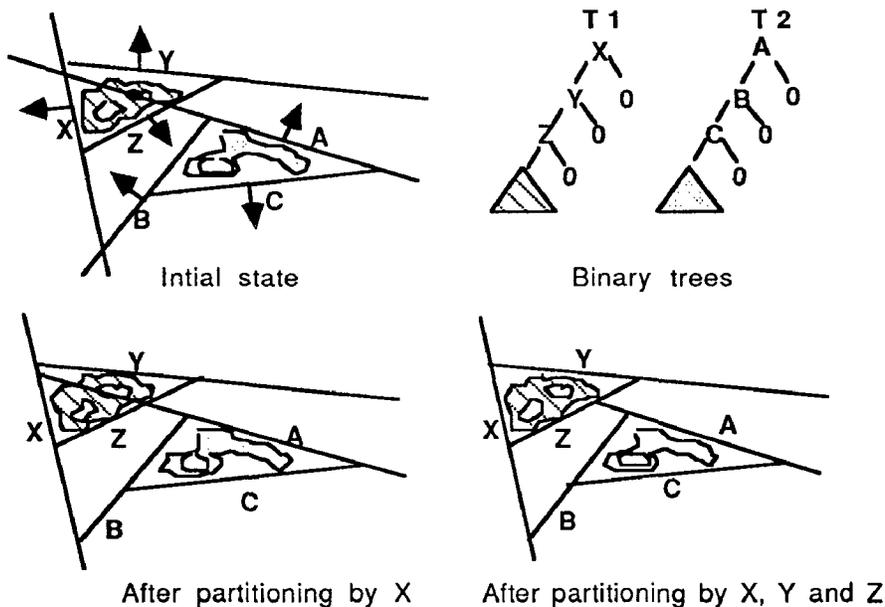


Figure 3.4 Effect of condensing during partitioning

IV. Representation and partitioning of binary partitioners

Partition_Bspt relies upon Bi-Partition_Bps as the basic operation for determining the relative location of two Bps and for splitting them when the location is InBoth halfspaces. To provide this, we will need an explicit representation of the domain of a bp, i.e. of its sub-hp. This is unlike all previous operations on bsp trees, which require only hyperplane equations and possibly a single "representative point" in the interior of a sub-hp (as in the set operations in [Thibault and Naylor 87]). Determining the respective locations of two binary partitioners that partition the same region R can be based on computing their intersection :

$$\begin{aligned}
 P1.shp \cap P2.shp &= (R \cap P1.hp) \cap (R \cap P2.hp) \\
 &= P1.shp \cap P2.hp.
 \end{aligned}$$

As the value of R must appear in the expression, we "encode" it into a sub-hp. However, when there is no intersection, we need to know in which halfspace the sub-hp lies, and in this case the routine that computes $P1.shp \cap P2.hp$ can tell us only the location of P1 with respect to P2.hp. Therefore, we will need to either use the representative point method or perform the complementary operation $P2.shp \cap P1.hp$.

In the current implementation, a sub-hp is represented by a b-rep, and for the sake of simplicity we restrict the embedding space to be 3-dimensional so that the sub-hps are polygons. Since sub-hps are convex, we can represent them using the simplest representation: a list of vertices.

Given explicit sub-hps, the bi-partitioning operation is comprised of two applications of the same operation: partition a polygon by a plane. First P1.shp is partitioned by P2.hp. We then performing the same operation for P2.shp with respect to P1.hp

There is a one problem with using b-reps: sub-hps may be unbounded sets and b-reps can not represent unbounded sets (e.g. the sub-hp of `T.root_region.bp` when `T.root_region.domain = 3-space` is a hyperplane). Our solution to this is to represent 3-space as a bounded set, in particular as a box centered at the origin whose size is sufficiently large to accommodate the geometric model. We call this the *universe-box*. Since geometric models typically require no more than 7 orders of magnitude (e.g. from 1 mm. to 1 km), constructing a sufficiently large box is easily done without compromising numerical robustness appreciably, especially when using double precision.

To generate a representation of the sub-hp for the bp at some tree node v , we need to first construct a polygonal representation of the bp's hp [Thibault 87]. This is done by projecting one of the sides of the universe-box onto the hyperplane. The side chosen is the one whose the ratio of its area to that of its projection is closest to unity. To achieve this, we choosing the side whose normal makes the smallest angle with that of the hyperplane.

Given this "hyperplane as bounded polygon", we insert it into the tree, partitioning it at each node as usual, but following only the path that leads to the target node v . Thus, when our incipient sub-hp is `InBoth`, we retain only that half which is in the region of the next node on the path. When we reach v , we have the desired sub-hp. Given any bsp tree containing no explicit sub-hp's, we will perform this operation for every node in the tree. (Rather than following a path from the root to the "current" node, we actually follow the path in the opposite direction, from the node to the root via parent links. This of course is a unique path and avoids the issue in the root-to-node order of knowing whether to follow the left or right child.)

Anytime an affine transformation is applied to a tree, those sub-hp's which are "unbounded" will need to be recomputed since they will no longer correspond to the intersection of their hyperplane with the universe-box. To facilitate this, each sub-hp is tagged to indicate whether it is unbounded, and if so, then regenerated when transformed. (If one uses the first $D+1$ nodes to construct a bounding simplex, then only the first D sub-hps of this simplex are unbounded, i.e intersect the universe box.) All other sub-hp's can be transformed normally (by their vertices), since they will remain bounded (under the assumption that the universe-box is sufficiently large).

V. Set Operations on Polyhedra

Once the mechanism for merging spatial partitionings is in place, performing set operations on polyhedra is a relatively simple matter. The merging process recurses until one of the two operands is homogeneous, i.e. is a cell, at which point we use a routine for merging cell attributes with those of some arbitrary tree (which may also be a cell). For set operations, this amounts to simply selecting either the cell or the tree, possibly complemented, as a function of the membership attribute (Figure 5.1). Complementation of a tree involves simply the boolean complementation of the membership attribute. Figure 5.2 illustrates the union of two bsp tree objects.

In general, there is more to do than this. If there are other attributes, such as color, index of refraction, density, or whatever, these will need to be merged in some appropriate way as well. And so the above routine will need to be augmented to handle these. (Exactly how a particular attribute, such as color or transparency, should be merged in a union for instance, is currently an unsettled issue). Note that this additional merging of attributes may generate condensable subtrees.

```
Cell_SetOp_Tree: ( T1, T2 : Bspt ) -> Bspt
::=
  VAL :=
    IF T1.is_an_InCell
    THEN
      CASE operation
      Union -> T1
      Intersection -> T2
      Difference -> Complement_Bspt( T2 )

      Symmetric_Difference ->
        Complement_Bspt( T2 )
    END
    ELSEIF T1.is_an_OutCell
    THEN
      CASE operation
      Union -> T2
      Intersection -> T1
      Difference -> T1
      Symmetric_Difference -> T2
    END
  ELSE Repeat the above with T1 and T2 swapped.
END Cell_SetOp_Tree
```

Figure 5.1 Cell_SetOp_Tree for Set Operations

VI. Polyhedral Faces

While the above routine covers "attribute maintenance" for D -dimensional cells, there remains the same issue for the $D-1$ domains of the binary partitioners. For polyhedra, the entire boundary of the set lies in the sub-hps, and while the boundary is wholly derivable from the D -cells, one may wish to explicitly represent the set of boundary faces. The primary motivation for doing so is to provide the input required by rendering systems that are based on polygon drawing. Using the bsp tree, one can provide a visibility priority ordering of the faces to such a system. (Note that if instead one uses ray-tracing, the explicit representation of the boundary is unnecessary.)

The boundary of a set is precisely those points whose ϵ -neighborhood contains both interior and exterior points for all ϵ . Thus, any subset of a sub-hp which has an in-cell on one side and an out-cell on the other will be on the boundary of the polyhedra. In figure 6, we illustrate this idea by showing the boundary along with normals to the faces oriented to "point" to the exterior. Note that a sub-hp may contain more than one face and that the face orientations may be either parallel to the hyperplane orientation or anti-parallel.

There are two possible approaches to face generation: either in every tree maintain faces as an intrinsic component of the representation, or delay creation of any faces until after an entire expression has been evaluated. Both approaches utilize a *neighborhood operation* that finds those cells in the neighborhood of a sub-hp, or equivalently, those cells whose boundary intersects a sub-hp. Consider any subtree T . If we insert the sub-hp at `T.root_region` into `T.neg_subtree` and then into `T.pos_subtree`, the cells that are reached are precisely those in the sub-hp's neighborhood. These cells can be naturally grouped into those in the positive subtree and those in the negative subtree. In addition, the search of a subtree will partition the sub-hp into subsets that bound a single cell, and so will classify the sub-hp into "in" and "out" subsets.

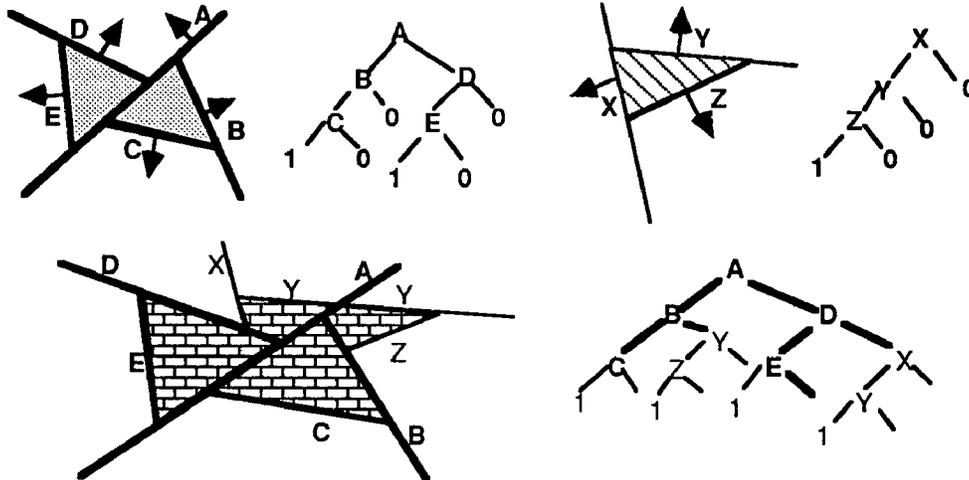


Figure 5.2 Union of two objects

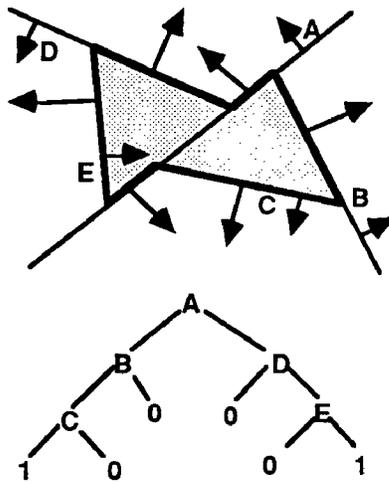


Figure 6 Faces of a polytope

So with this, generation of faces from a sub-hp is straightforward [Thibault 87]. First, classify the sub-hp with respect to one of T 's subtrees, say the negative subtree, and then classify the resulting fragments with respect to the positive subtree. This yields fragments whose neighborhood is "homogeneous", i.e. is the same for all points in the fragment. With this information, we can generate the following classifications:

neg_subtree	pos_subtree	classification
in	in	in
in	out	on (parallel)
out	in	on (anti-parallel)
out	out	out

Retaining the *on* fragments, separated into parallel and anti-parallel lists, as part of each binary partitioner provides the polyhedral faces. These faces, in fact, provide only a partial classification of the partitioner's domain. There are two kinds of *on*-regions, parallel and anti-parallel, but *in*-regions and *out*-regions are lumped together implicitly as *not-on*. Note that these face fragments are convex, since they are generated by the intersection of halfspaces with their supporting hyper-

plane. To generate all of the faces of a tree that contains explicit sub-hps but not explicit faces, one simply performs this neighborhood operation for every binary partitioner in the tree.

The alternative is to maintain explicit faces at all times. So the result of a single set operation, $T3 := T1 <op> T2$, will entail generating all of the polyhedral faces of $T3$ before $T3$ is used in any subsequent set operations. The objective is the same as before, to know the classification of all sub-hps, but the approach is less direct. Instead of classifying sub-hps, we employ the fact that the faces of $T3$ are a subset of those of $T1$ and $T2$ combined, and in effect classify only the subsets of sub-hps "covered" by the faces. Note that the addition of faces to the representation will require extending both `Complement_Bspt()` to swap parallel and anti-parallel face lists and `Bi-Partition_Bp()` to partition any faces lying in a binary partitioner (this will be needed only if its sub-hp is `InBoth`, and thus the sub-hp provides a "convex hull" test for the faces).

We will use a combination of two techniques already introduced: cell `<op>` tree and the neighborhood operation. The first is employed under two circumstances. When, during the recursive process of tree merging, one of the two arguments is a cell, the routine `Cell_SetOp_Tree()` is called. This executes the set operation by returning one of the two arguments (possibly complemented), and so implicitly classifies any faces in the process. The second circumstance occurs during `Partition_Bspt()` whenever the partitioning `bp` reaches a cell. Its face fragments can then have the same rules applied to them. The only remaining case is that of *on*-faces. Whenever the *On* case in `Partition_Bspt()` occurs we will need to use the neighborhood operation in lieu of direct classification by cells. *On*-faces from $T1$ ($T2$) will need to be classified with respect to the subtrees of $T2$ ($T1$) (see [Thibault and Naylor 87] and [Naylor 90a]).

VII. Numerical Robustness

The occurrence of numerical errors due to finite arithmetic has been a nemesis of geometric computing since its inception. Its negative impact is greatest when the result of a numerical computation is used to discriminate logical alternatives in an algorithm. This can lead to arbitrarily "discontinuous" behavior; that is, the output of the algorithm can be highly sensitive to

small random perturbations of the discriminators (the program may fail as well). While a number of schemes have been devised to ameliorate the problem, the simplest and most common is the use of ϵ -intervals. For example, a discrimination based on whether a real value X is less than, greater than, or equal to 0 can be replaced with one that determines whether a $X < -\epsilon$, $X > +\epsilon$, or in $[-\epsilon + \epsilon]$ respectively. More sophisticated methods enforce the intended semantics through a variety of schemes (see e.g. [Karasick 89]).

The only numerical computation in this work is the partitioning of a polygon by a plane. Its primitive operation is the dot product of a point and a plane to determine the location of that point with respect to the plane. The specific algorithm we use assumes the semantics of *planar, convex* polygons, and we rely on the epsilon method just described to attain robustness (to dampen the noise). Thus, the hyperplanes are in effect slabs 2ϵ thick. Any failure of this technique is detected, but no correction strategy is evident other than using larger epsilons (this has been in use since [Naylor 81]).

Unfortunately, this approach is insufficient to achieve a robust bi-partitioning operation. In fact, larger epsilon exacerbate the problem. Recall that there is a correlation between the location of the two bps: $P1's\ location = InBoth \Leftrightarrow P2's\ location = InBoth$, and similarly $On \Leftrightarrow On$, and $NotInBoth \Leftrightarrow NotInBoth$. Numerically this does not always hold. Our approach is to detect inconsistencies and induce a mapping to one of the consistent result. When one location is *InBoth* and the other is *InNegHs* or *InPosHs*, we can force the the former to be either *InNegHs* or *InPosHs* by selecting the "half" which contain vertices farthest from the partitioning plane, or we can force the second to the *InBoth* condition by extracting "on" vertices. If only one bp is *On*, we force it to a value consistent with the other bp. While we believe that forcing semantic consistency is essential, our current choices for enforcing this are at this point only tentative.

Numerical problems also affect attaining the semantics of the neighborhood operation. The method used for constructing bsp trees, defined in the continuum, implies that any sets lying in *T.root_region.bp.shp* will not be *On* any sub-hp in either of *T's* subtrees; however, numerically this does not always hold. We employ the following defense. When a face fragment from node *V* is classified as *On* during the neighborhood operation at a descendant node *U*, we essentially treat that node as if it were contained in the face's sub-hp, i.e. as if it did not exist. We then choose the subtree of *U* that is "not adjacent" to *V*, and continue the search.

The combination of these techniques has led to a robust set operation algorithm in the sense that the program will not fail and its output is in the neighborhood of the ideal output over a large numerical range. For example, the standard test in which a set operation is performed between a cube and a second cube that has been rotated successively about each of its three principal axes by an angle α has been executed successfully with $\alpha = 10^{-9}$ with $\epsilon < 10^{-11}$, including $\epsilon = 0$, using 64-bit floating point numbers. For $10^{-9} > \alpha > 10^{-14}$, union continued to give the same results, while intersection and difference found some sides to be equivalent. As the value of ϵ approaches α , more equivalences are produced until the two objects are computationally considered identical.

While using a small epsilon is interesting for testing the numerical limits, large epsilons are much more desirable (thicker hyperplanes) since they limit the size of the smallest fragments and so avoid representing features far below any

viewing resolution. An upper bound to the thickness is the point at which the affect of treating faces as being co-planar, when in fact they are not, becomes visible to a viewer.

VIII. Complexity

A simple worst case lower bound of $\Omega(n^2)$ is obtained by noting that a checker board can be constructed from the symmetric difference of two trees, the first composed of n horizontal strips with alternating boolean values and the second composed of n similiar vertical strips.

As for an upper bound, the binary partitioner of each node of one tree is compared with the bp of each node of the second tree at most once, giving $O(|T1| * |T2|)$ or more simply $O(n^2)$. This analysis would be sufficient if each comparison was guaranteed to be $O(1)$. However, it is possible for a sub-hp to be of size $O(n)$, e.g. the base of an n sided cone. If this were true for every sub-hp, Partition_Bspt could take $O(n^2)$ per call, giving a total time of $O(n^3)$.

To show that this is not the case, we first observe that each sub-hp vertex is compared to a hyperplane of the other tree at most once per node. So if we can show that the total number of sub-hp vertices is $O(n)$, we will have $O(n^2)$ total work. To prove this we use arrangements of hyperplanes. An arrangement comprised of n d-cells can be represented by a bsp tree with an isomorphism from arrangement cells to bsp tree cells (leaf nodes) [Naylor 81]. Since it is known that the number of vertices of an arrangement is $O(n)$ and the sub-hp vertices are a subset of these, it can be shown that despite the fact that there are multiple instances of some vertices, the number of sub-hp vertices of an arrangement is also $O(n)$. Any bsp tree can be converted to its corresponding arrangement by replacing each cell/leaf with a tree representing the partitioning of that cell by all hyperplanes of the tree that intersect it. If we now remove any sub-hp separating two of the newly created cells, the new number of vertices will be:

$$n * O(1) - \Omega(1) < (n-1) * O(1).$$

If this is repeated, one node at a time, until the original tree is recreated, we will have $O(|T|)$ vertices. We then have that merging bsp trees is worst case optimal $\Theta(n^2)$.

Of even greater interest is the expected case. This requires a definition of "good" trees, which we have developed but do not have space here to explore. If, for now, we simply take good to mean balanced, then merging two balanced trees of size n can produce, at worst, a tree with maximum depth of $2 \log n$. Or more generally speaking, merging two good trees should yield a reasonably good tree. Note that the use of a bounding simplex as in figure 3.4 can lead to $O(d)$ time to merge two trees whose bounding simplices are disjoint and the interior of one simplex is not intersected by a sub-hp of the other.

Concluding remarks

It is worth comparing this algorithm to the method in [Thibault and Naylor 87]. One of the two methods in that work performs a set operation between a bsp tree represented polyhedron and a b-rep represented polyhedron. The inserted entity is the b-rep polyhedron, represented as a list of polygons. In this work, we have instead a bsp tree, clearly a more complex structure than a list, although not necessarily more complex than the more general b-rep structure as a hierarchy of lists (not used in [Thibault and Naylor 87]). However, there are at least two ways in which one gains from the using a bsp tree.

The first advantage arises from the efficiency of a hierarchical search structure: entire subtrees can be classified without examining their contents. In the average case, this can lead to $O(\log n)$ behavior instead of $O(n)$. The second is algorithmic simplicity. Besides the obvious advantage of having only the bsp tree data type to deal with, it is difficult to determine with a b-rep the relative spatial classification of some other entity. The algorithms in [Thibault and Naylor 87] require, when the faces of the b-rep object are entirely to one side of a partitioning hyperplane, the determination of whether the corresponding sub-hp is inside or outside of the polyhedron. While [Thibault and Naylor 87] gives the simplest solutions for this in 2D and 3D, the method is cumbersome and does not easily generalize to arbitrary dimensions (so much so that we have not seriously attempted to do so). In our new setting, while we still need this classification of the sub-hp with respect to the inserted object, its spatial structure being a bsp tree makes this straightforward, and in fact occurs as part of the partitioning operation itself, thereby necessitating no additional consideration and so solves the problem for arbitrary dimensions.

This work remains a hybrid approach, since b-reps are used for polygons, both as sub-hps and faces. However, prior to implementing this scheme, we devised an "all bsp tree" representation which dispenses with b-reps entirely (see [Naylor 90b] for a brief description). Thus, the sub-hps and the faces of a d-dimensional tree are represented by d-1 dimensional trees, and so on recursing in dimension until $d = 0$. This representation has many advantages including dimension independence as well as obviating the problem encountered here with b-reps not being able to represent unbounded sets. We chose to implement the hybrid approach described here to provide a more easily attainable intermediate step, since many techniques have been developed using polygons as b-reps that must be provided in the new scheme. Nonetheless, the routines Merge_Bspts and Partition_Bspt are essentially the same in both schemes, the difference being limited primarily to Bi-Partition_Bps; and forming the boundary requires only the capabilities already provided by these routines.

References

- [Bloomberg 86]
Sandra H. Bloomberg, "A Representation of Solid Objects for Performing Boolean Operations", U.N.C. Computer Science Technical Report 86-006 (1986).
- [Chin and Feiner 89]
N. Chin and S. Feiner, "Near Real-Time Shadow Generation Using BSP Trees", *Computer Graphics* Vol. 23(3), pp. 99-106, (Aug. 1989).
- [Fuchs, Kedem, and Naylor 80]
H. Fuchs, Z. Kedem, and B. Naylor, "On Visible Surface Generation by a Priori Tree Structures," *Computer Graphics* Vol. 14(3), pp. 124-133, (June 1980).
- [Fussell and Campbell 90]
Donald Fussell and A.T. Campbell, "Adaptive Mesh Generation for Global Diffuse Illumination," *Computer Graphics* Vol. 24(3), (Aug. 1990).
- [Hoffmann 89]
Christoph M. Hoffmann, *Geometric and Solid Modelling*, Morgan Kaufmann, 1989.
- [Karasick 89]
Michael Karasick, "On the Representation and Manipulation of Rigid Solids," Ph.D. Thesis, Cornell University (March 1989).
- [Mantyla 88]
Matti Mantyla, *Solid Modeling*, Computer Science Press, 1988.
- [Naylor 81]
Bruce F. Naylor, "A Priori Based Techniques for Determining Visibility Priority for 3-D Scenes," Ph.D. Thesis, University of Texas at Dallas (May 1981).
- [Naylor 90a]
Bruce F. Naylor, "SCULPT : An Interactive Solid Modeling Tool", *Proc. of Graphics Interface*, (May 1990).
- [Naylor 90b]
Bruce F. Naylor, "Binary Space Partitioning Trees as an Alternative Representation of Polytopes", *Computer Aided Design*, Vol 22(4), (May 1990).
- [Naylor and Thibault 86]
Bruce F. Naylor and William C. Thibault, "Application of BSP Trees to Ray-Tracing and CSG Evaluation," Technical Report GIT-ICS 86/03, School of Information and Computer Science, Georgia Institute of Technology, Atlanta, Georgia 30332 (February 1986).
- [Paterson and Yao 89]
M.S. Paterson and F.F. Yao, "Binary partitions with applications to hidden-surface removal and solid modeling", *Proceedings of Fifth Symp. on Computational Geometry*, pp. 23-32, (1989).
- [Paterson and Yao 90]
M.S. Paterson and F.F. Yao, "Optimal Binary Space Partitions for Orthogonal Objects", *Proceedings of 1st Symp. on Discrete Algorithms*, pp. 100-106, (Jan. 1990).
- [Schumaker et al 69]
R. A. Schumacker, R. Brand, M. Gilliland, and W. Sharp, "Study for Applying Computer-Generated Images to Visual Simulation," AFHRL-TR-69-14, U.S. Air Force Human Resources Laboratory (1969).
- [Sutherland, Sproull and Schumaker 74]
I.E. Sutherland, R.F. Sproull and R. A. Schumacker, "A Characterization of Ten hidden Surface Algorithms," *ACM Computing Surveys* Vol 6(1), (1974).
- [Thibault and Naylor 87]
W. Thibault and B. Naylor, "Set Operations On Polyhedra Using Binary Space Partitioning Trees," *Computer Graphics* Vol. 21(4), (July 1987).
- [Thibault 87]
William C. Thibault, "Application of Binary Space Partitioning Trees to Geometric Modeling and Ray-Tracing", Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, Georgia, (1987).
- [Torres 90]
Enric Torres, "Optimization of the Binary Space Partition Algorithm (BSP) for the Visualization of Dynamic Scenes" *Eurographics '90* (Sept. 1990).