

→ Jones (done)

Edgewise Subdivision of a Simplex *

Herbert Edelsbrunner[†] and Daniel R. Grayson[‡]

Abstract

In this paper we introduce the abacus model of a simplex and use it to subdivide a d -simplex into k^d d -simplices all of the same volume and shape characteristics. The construction is an extension of the subdivision method of Freudenthal [3].

Keywords. Mesh generation, subdivision, simplex shape, symmetry.

1 Introduction

It is easy to subdivide a triangle into four similar triangles all of the same area: cut each edge into equal halves and connect dividing points with lines parallel to the original edges. Since the triangles are similar we can repeat the operation and refine while preserving the triangle shape. Such a construction does not exist in general for tetrahedra and higher-dimensional simplices.

Result. A *subdivision* of a d -simplex is a decomposition into d -simplices such that each pair is either disjoint or meets along a common edge. In other words, the d -simplices and their faces form a simplicial complex. Such complexes are used in engineering and science to represent geometric shapes and domains for the purpose of design, analysis, simulation and visualization. The main result of this paper is a generalization of the

*Research by both authors is partially supported by NSF under grant DMS 98-73945. Research of the first author is also supported by NSF under grant CCR-96-19542, and by ARO under grant DAAG55-98-1-0177.

[†]Department of Computer Science, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, and Raindrop Geomagic, Champaign, Illinois 61820.

[‡]Department of Mathematics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801.

triangle 4-division mentioned above that preserves most of the symmetry found in the two-dimensional case.

MAIN THEOREM. For every integer $k \geq 1$ and every d -simplex σ there is a subdivision into k^d d -simplices σ_i with the following properties:

- (1) all σ_i have the same d -dimensional volume,
- (2) the σ_i fall into at most $\frac{d!}{2}$ congruence classes,
- (3) the faces of σ are subdivided the same way,
- (4) repeated subdivision has the same effect as increasing k ,
- (5) except for boundary effects the neighborhoods of vertices are translates of each other.

Figures 4 through 7 show subdivisions satisfying the Main Theorem. Properties (1) through (5) are statements of symmetry. Observe that the number of congruence classes in Property (2) is independent of k , where two simplices belong to the same class iff one is obtained from the other by a combination of translations, rotations, and reflections. Property (3) means that the effect of the subdivision on a face of σ is exactly the subdivision of that face with the same k and the same method. Property (4) says that instead of subdividing each σ_i into ℓ^d d -simplices we can subdivide σ into $(k\ell)^d$ d -simplices and reach the same result. Property (5) implies that we can think of the subdivision as the intersection of σ with a periodic tiling of \mathbb{R}^d that looks the same from every vertex.

Previous and related work. For $k = 2$, the subdivisions of the Main Theorem have been described by Freudenthal in 1942 [3]. In contrast to our algebraic approach, his construction is geometric and based on Kuhn's triangulation of the d -dimensional cube. The 2-dimensional case of Freudenthal's subdivision is the 4-division of the triangle illustrated in Figure 4. It is frequently used in the generation of 2-dimensional grids (later)

as well as the modeling of surfaces in space. The 3-dimensional case is the 8-division of the tetrahedron; see Figure 5. It was studied by Bey [1] and by Liu and Joe [5] in the context of adaptive mesh refinement for finite element analysis. The work in this paper takes its inspiration from the algebraic constructions of Grayson [4]. He subdivides simplices into Cartesian products of simplices in the context of K-theory. This approach leads to a simple and purely algebraic description of simplices and subdivisions that is amenable to computer implementations.

Apart from mesh refinement for finite element analysis we see applications of our results in computer graphics. The combination of the 4-division of a triangle with a weighted averaging of vertex positions has emerged as a popular tool for surface modeling, see for example DeRose et al. [2]. The generalization of this method to the manipulation and display of 3- and higher-dimensional density distributions requires an easy to compute periodic subdivision that does not suffer from shape deterioration as the simplices get smaller. The Main Theorem offers a solution to this problem.

Outline. Section 2 describes an algorithm that maps a point to a simplex containing the point. Section 3 proves the Main Theorem by collecting the simplices generated by the algorithm. Section 4 illustrates and discusses sample subdivisions in dimensions 2, 3, 4. Section 5 concludes this paper.

2 Abacus Model of a Simplex

We think of a d -simplex primarily as a sequence of $d+1$ numbers in the unit interval. With the introduction of this idea we prepare an algebraic interpretation of a simplex that frees us from depending on our geometric intuition.

Colored rectangle. Let P_0, P_1, \dots, P_d be affinely independent points that span a simplex σ in \mathbb{R}^d . The ordering of the points is important, as it affects the following construction. If b_0, b_1, \dots, b_d are non-negative real numbers that sum to 1 then

$$X = \sum_{i=0}^d b_i \cdot P_i$$

is a point in σ . The b_i are the *barycentric coordinates* of X . We may portray them graphically by drawing the unit interval as a rectangle with regions colored from 0 through d , making sure to arrange

the colors from left to right, so that b_i is the fraction of points with color i . Figure 1 illustrates this for $d = 7$ and the point with barycentric coordinates $(0.26, 0.11, 0.07, 0.11, 0.19, 0.08, 0.04, 0.14)$. The coordi-

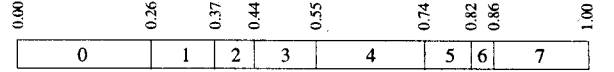


Figure 1: The rectangle represents the unit interval with points colored from 0 through 7.

nates of the dividing lines are displayed above the rectangle. They are provided by the partial sums $0 = B_0, B_1, \dots, B_d, B_{d+1} = 1$ with $B_i = b_0 + b_1 + \dots + b_{i-1}$. B_1 through B_d can be any non-decreasing sequence in the unit interval.

Stack of rectangles. Suppose we chop the rectangle in Figure 1 into k pieces of equal width, stack them on top of each other, and expand the scale by a factor of k in the horizontal direction for clarity; see Figure 2. The coordinates of the dividing lines are obtained by

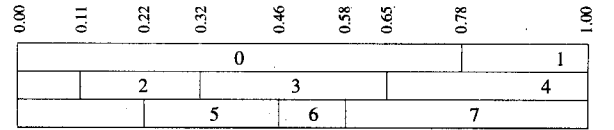


Figure 2: The rectangle in Figure 1 is chopped into three pieces, which are stacked and expanded.

multiplying the coordinates of the earlier dividing lines by k and discarding the integer part, keeping only the fractional part. We discard any duplicates, letting $j+2$ be the number of distinct values remaining. Call these numbers $0 = C_0, C_1, \dots, C_j, C_{j+1} = 1$, making sure to sort them in increasing order. We extend the dividing lines vertically until they span the entire stack and label each region by its color; see Figure 3. The widths of the regions in the stack are $c_i = C_{i+1} - C_i$, for $0 \leq i \leq j$.

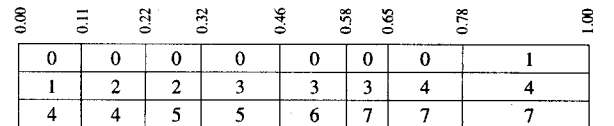


Figure 3: Each rectangle is cut into equally many regions, and each region keeps the original color of its points.

Color scheme. The number of regions in each row of the stack is $j + 1$. Forgetting the positions of the vertical dividing lines we get a matrix

$$\chi = \begin{pmatrix} \chi_{1,0} & \chi_{1,1} & \cdots & \chi_{1,j} \\ \chi_{2,0} & \chi_{2,1} & \cdots & \chi_{2,j} \\ \vdots & \vdots & \ddots & \vdots \\ \chi_{k,0} & \chi_{k,1} & \cdots & \chi_{k,j} \end{pmatrix}$$

of $k(j + 1)$ colors. We call χ a *color scheme* because it determines the combinatorics but not the geometry of the coloring. The matrices that may occur are those whose entries are drawn from the set $\{0, 1, \dots, d\}$, whose entries are in non-decreasing order when read like text:

$$\chi_{1,0} \leq \chi_{1,1} \leq \cdots \leq \chi_{1,j} \leq \chi_{2,0} \leq \cdots \leq \chi_{k,j},$$

and whose columns are pairwise different.

Combination of points. The numbers c_i sum to 1 and can therefore be used as barycentric coordinates to express our original point X in terms of other points. For k not necessarily distinct colors χ_1 through χ_k we introduce the notation

$$P_{\chi_1 \chi_2 \dots \chi_k} = (P_{\chi_1} + P_{\chi_2} + \dots + P_{\chi_k})/k.$$

This way we obtain exactly all points in our d -simplex σ whose barycentric coordinates are integer multiples of $1/k$. Each column in a color scheme corresponds to such a point. We now show that the c_i are the barycentric coordinates of X with respect to the points that correspond to the columns of the color scheme $\chi = \chi(X, k)$.

COMBINATION LEMMA. $X = \sum_{i=0}^j c_i \cdot P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}}$.

PROOF. The product $k \cdot b_i$ is the total width of regions with color i . It follows that the sum, over all entries of the color scheme, of P_i/k times the width of the corresponding region is the sum of $b_i \cdot P_i$. By definition this is our original point X . Now consider

$$\begin{aligned} Y &= \sum_{i=0}^j c_i \cdot P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}} \\ &= \frac{1}{k} \cdot \sum_{i=0}^j c_i \cdot (P_{\chi_{1,i}} + P_{\chi_{2,i}} + \dots + P_{\chi_{k,i}}), \end{aligned}$$

which is a sum over all entries of the same color scheme. Each term corresponds to a column, and the contribution of an entry with color i is again P_i/k times the width of the corresponding region. Hence $X = Y$. \square

Independence of points. We prove that the points in the Combination Lemma are affinely independent. This implies that a color scheme with $j + 1$ columns specifies a j -simplex. The color scheme depends on the sequence in which the vertices of σ are presented. This sequence defines a directed path obtained by concatenating the *shape vectors* $V_i = P_i - P_{i-1}$ for $1 \leq i \leq d$. Since σ is non-degenerate, the d shape vectors are linearly independent. *Sorry ok*

INDEPENDENCE LEMMA. The points $P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}}$ defined by the columns of a color scheme χ are affinely independent.

PROOF. Assume first that χ has $d + 1$ columns and consider the vectors connecting points of adjacent columns:

$$V'_i = P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}} - P_{\chi_{1,i-1} \chi_{2,i-1} \dots \chi_{k,i-1}}.$$

In the transition from column $i - 1$ to column i only a single color changes, and that color increases by 1. Suppose for example that the color increases in row ℓ . We define a permutation π of $\{1, 2, \dots, d\}$ by setting $\pi(i) = \chi_{\ell,i} = \chi_{\ell,i-1} + 1$. π is indeed a permutation because the transition to $\pi(i)$ occurs exactly once in the matrix χ . We find that

$$\begin{aligned} V'_i &= \frac{1}{k} \cdot (P_{\pi(i)} - P_{\pi(i)-1}) \\ &= \frac{1}{k} \cdot V_{\pi(i)}. \end{aligned}$$

The linear independence of the V_i thus implies the linear independence of the V'_i . A color scheme with $j + 1$ columns is obtained by removing $d - j$ of the $d + 1$ columns of a full color scheme. The corresponding operation for the vectors is addition. Specifically, the d linearly independent vectors are grouped into j sums, which are again linearly independent vectors and thus define a j -simplex. \square

3 Subdivision of a Simplex

Section 2 described an algorithm which takes a point of σ and produces a smaller simplex within σ that contains the point. We use that algorithm to construct a subdivision of σ .

Edgewise subdivision. Each point $X \in \sigma$ defines a unique color scheme $\chi = \chi(X, k)$ with k rows. This color scheme defines a unique simplex σ_χ , namely the one spanned by the points $P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}}$ that correspond

to the columns of χ . The *edgewise subdivision* of σ consists of all simplices defined this way by points of σ :

$$\text{Esd}_k \sigma = \{\sigma_\chi \mid \chi = \chi(X, k), X \in \sigma\}.$$

A set of simplices is a subdivision of σ iff the interiors of the simplices are pairwise disjoint and the union of interiors is σ . We establish this property for $\text{Esd}_k \sigma$.

SUBDIVISION LEMMA. For each $k \geq 1$, $\text{Esd}_k \sigma$ is a subdivision of σ .

PROOF. The algorithm in Section 2 is deterministic and maps a point $X \in \sigma$ to a set of barycentric coordinates that express X in terms of the vertices of a j -simplex $\sigma_\chi \subseteq \sigma$. These coordinates are positive, which implies that X lies in the interior of σ_χ . It follows that the union of interiors of simplices in $\text{Esd}_k \sigma$ is σ .

What happens if we start at the other end? Suppose we take a j -simplex $\sigma_\chi \in \text{Esd}_k \sigma$, choose non-zero barycentric coordinates $c_0 + c_1 + \dots + c_j = 1$ and define

$$Y = \sum_{i=0}^j c_i \cdot P_{\chi_{1,i} \chi_{2,i} \dots \chi_{k,i}}.$$

Applying our algorithm to this point Y will lead to the same c_i and σ_χ because each step in the algorithm is uniquely reversible. It follows that the interiors of the simplices in $\text{Esd}_k \sigma$ are pairwise disjoint. \square

Number of simplices. To count simplices we exploit the one-to-one correspondence between simplices and color schemes. For simplices of maximum dimension this is straightforward.

COUNTING LEMMA. If the dimension of σ is d then the number of d -simplices in $\text{Esd}_k \sigma$ is k^d .

PROOF. We may count the simplices in $\text{Esd}_k \sigma$ by looking at the vertical dividing lines as illustrated in Figure 2. The color schemes are completely determined by working from left to right, and selecting for each dividing line the row in which it appears. For a d -simplex there are d dividing lines, and each one may appear in one of k rows, so there are k^d possibilities. \square

To count simplices of dimension $j < d$ is similar but more complicated. Now we have j dividing lines and each may be multiply defined. Furthermore, the right ending line of the stack may also be multiply defined. The number of j -simplices in $\text{Esd}_k \sigma$ is therefore equal

to the number of ways we can draw d not necessarily distinct rows from $\{1, 2, \dots, k\}$ and distribute them over the j dividing lines plus one right ending line in such a way that each dividing line receives at least one row.

Volume. For a simplex σ with vertices P_0, P_1, \dots, P_d in \mathbb{R}^d it is known that the d -dimensional volume is

$$\text{vol } \sigma = \frac{1}{d!} \cdot |\det(P_1 - P_0, P_2 - P_0, \dots, P_d - P_0)|.$$

We prove Property (1) of the Main Theorem, which claims that all d -simplices in the edgewise subdivision have the same volume.

MEASURING LEMMA. The d -dimensional volume of every d -simplex $\sigma_\chi \in \text{Esd}_k \sigma$ is $\text{vol } \sigma_\chi = \text{vol } \sigma / k^d$.

PROOF. By definition of the shape vectors we have $P_i - P_0 = V_i + V_{i-1} + \dots + V_1$. Using elementary column operations we find that volume can also be expressed using shape vectors:

$$\text{vol } \sigma = \frac{1}{d!} \cdot |\det(V_1, V_2, \dots, V_d)|.$$

Permuting the vectors does not affect the absolute value of the determinant, and shrinking them to $1/k$ -th their original lengths decreases the determinant by a factor of $1/k^d$. \square

Simplex types. We have seen in the proof of the Independence Lemma that the shape vectors of a d -simplex in the edgewise subdivision are obtained by permuting and shrinking the shape vectors of σ . We use this to prove Property (2) of the Main Theorem.

CONGRUENCE LEMMA. If the dimension of σ is d then the number of pairwise non-congruent d -simplices in $\text{Esd}_k \sigma$ is at most $d!/2$.

PROOF. $\text{Esd}_k \sigma$ contains at most $d!$ types of d -simplices, each defined by a permutation of the d shape vectors of σ . Reversing the sequence (without reversing the directions of the vectors) effectively reflects the d -simplex through the origin. Reflected simplices are congruent, which implies the claimed upper bound. \square

In general the upper bound is tight. For sufficiently large k all permutations occur, and for generic shape vectors two permutations define congruent d -simplices only if the permutations are equal or the reverse of each

other. For special d -simplices σ the congruence classes may further collapse. For example if every permutation of the d shape vectors can be geometrically realized by an orthogonal transformation then we have only one congruence class. Such shape vectors are determined by their common length and the single angle between any two vectors. It follows that, \mathbb{R}^d can be tiled by congruent copies of σ . Compare this with results on tiling \mathbb{R}^3 with copies of a single tetrahedron [6].

Symmetry of dimension. Each face τ of σ is a simplex which is subdivided as a consequence of the subdivision of σ . We prove Property (3) of the Main Theorem.

FACE LEMMA. Let τ be a face of σ and assume the vertices of τ are ordered as specified by the ordering of the vertices of σ . Then $\text{Esd}_k \tau \subseteq \text{Esd}_k \sigma$.

PROOF. Let $\Sigma = \{0, 1, \dots, d\}$ and $T \subset \Sigma$ such that P_i is a vertex of τ iff $i \in T$. A point $X = \sum b_i \cdot P_i \in \sigma$ belongs to τ iff $b_i = 0$ for all $i \in \Sigma - T$. As a consequence, the color scheme χ defined by X contains only colors in T . Every color scheme with colors drawn from T can be obtained from a color scheme with colors drawn from Σ by dropping all columns that contain colors from $\Sigma - T$. \square

Symmetry of scale. It is plausible that a finer edge-wise subdivision of σ is a subdivision of a coarser edge-wise subdivision provided this is true for the edges of σ . We prove Property (4) of the Main Theorem.

REFINEMENT LEMMA. $\text{Esd}_\ell \text{Esd}_k \sigma = \text{Esd}_{k\ell} \sigma$.

PROOF. We show that every simplex in $\text{Esd}_{k\ell} \sigma$ belongs to Esd_ℓ of a simplex in $\text{Esd}_k \sigma$. Since $\text{Esd}_{k\ell} \sigma$ and $\text{Esd}_\ell \text{Esd}_k \sigma$ both subdivide σ this implies that the two subdivisions are the same.

Let $X = \sum b_i \cdot P_i$ be a point in σ , and let B_i be the sum of the first i barycentric coordinates, as usual. Let $\chi = \chi(X, k)$ and $\chi' = \chi(X, k\ell)$ be the corresponding color schemes. The coordinates of the dividing lines in the corresponding stacks are $k \cdot B_i \bmod 1$ and $k\ell \cdot B_i \bmod 1$. Equivalently, if C is a dividing line for χ then $\ell \cdot C \bmod 1$ is a dividing line for χ' . In other words, the stack of χ' is obtained from that of χ by chopping each rectangle into ℓ pieces, stacking the pieces, and expanding by ℓ in the horizontal direction for clarity. It follows that $\sigma_{\chi'} \in \text{Esd}_\ell \sigma_\chi$. \square

Symmetry of location. Ignoring boundary effects, the neighborhoods of any two vertices in an edgewise subdivision are the same. We prove Property (5) of the Main Theorem.

TRANSLATION LEMMA. Let P, P' be vertices in $\text{Esd}_k \sigma$ and σ' a simplex in $\text{Esd}_k \sigma$. Then $\sigma' + (P - P')$ either belongs to $\text{Esd}_k \sigma$ or lies outside σ .

PROOF. Consider a point X in the interior of σ' and assume $Y = X + (P - P')$ lies within σ . The coordinates of $P - P'$ are integer multiples of $1/k$. It follows that the vertical dividing lines of the stacks defined by X and Y are the same, but the rows defining the dividing lines may be different. Specifically, the row indices increase or decrease depending on the coordinates of $P - P'$. The color scheme $\chi = \chi(Y, k)$ differs from $\chi' = \chi(X, k)$ by increasing or decreasing colors accordingly. Since all points X in the interior of σ' define the same color scheme, all $Y = X + (P - P')$ define the same transformed color scheme and therefore belong to the interior of the same simplex in the edgewise subdivision. This simplex is $\sigma' + (P - P')$. \square

4 Examples

This section presents examples of the edgewise subdivision for simplices of dimension 2, 3, 4.

Triangle. Figure 4 shows the edgewise subdivisions Esd_2 and Esd_3 of a triangle. The three vertices are la-

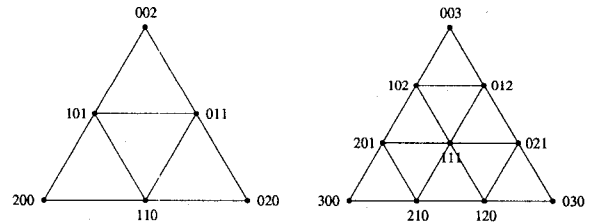


Figure 4: 4-division to the left and 9-division to the right.

beled $k00, 0k0, 00k$ indicating the sequence used in the construction of the subdivisions. Note that the sequence matters, however, since all $6 = 3!$ permutations lead to the same subdivision consisting of k^2 similar triangles. The vertex labels encode barycentric coordinates:

$$xyz = \frac{x}{k} \cdot k00 + \frac{y}{k} \cdot 0k0 + \frac{z}{k} \cdot 00k.$$

8-division of tetrahedron. The smallest non-trivial edgewise subdivision of a tetrahedron σ is the 8-division illustrated in Figure 5. The tetrahedra adjacent to the

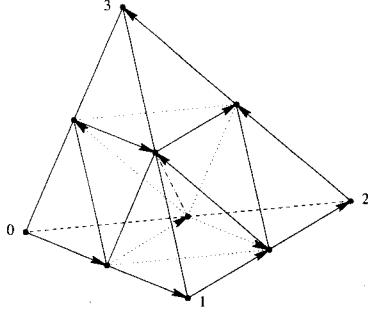


Figure 5: The octahedron in the center of the 8-division is decomposed into four tetrahedra surrounding the space diagonal.

four vertices are similar to σ . The four tetrahedra subdividing the center octahedron are generally not similar to σ because their shape vectors come in a different sequence. Observe that exactly one diagonal of the octahedron belongs to the 8-division. Every proper subset $T \subset \{0, 1, 2, 3\}$ defines a non-trivial partition into two sets and a *halfway plane* of points with barycentric coordinates $\sum_{i \in T} b_i = \sum_{i \notin T} b_i$. There are 7 halfway planes, and the 8-division can be defined by cutting σ with 6 of them. The only halfway plane not used is defined by $T = \{0, 2\}$ and crosses the diagonal that belongs to the subdivision.

27-division of tetrahedron. The 27-division of σ shares many of the features of the 8-division; see Figure 6. It embeds four 8-divisions, one adjacent to every

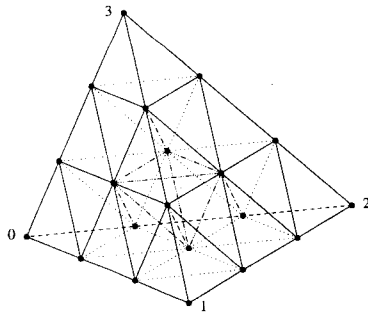


Figure 6: The 27-division contains four octahedra arranged around the tetrahedron in the center, each decomposed into four tetrahedra around parallel space diagonals.

vertex of σ . Any two such 8-divisions overlap in a single

tetrahedron adjacent to the middle of the edge joining the two vertices. We have $4 \cdot 8 - \binom{4}{2} = 26$, which shows that the four 8-divisions cover all tetrahedra except the one in the center of the 27-division.

16-division of 4-simplex. We are not able to draw the entire 16-division, but we can draw the 4-simplex σ and argue about its 16-division. A 3-simplex is usually drawn as a convex quadrilateral in \mathbb{R}^2 simultaneously subdivided into two triangles in the two ways possible. Two of the triangles are in the back and the other two are in the front. By analogy we think of a 4-simplex as a convex double tetrahedron in \mathbb{R}^3 simultaneously subdivided into two tetrahedra and into three tetrahedra. Maybe the two tetrahedra are in the back and the three are in the front. Figure 7 shows two 4-simplices, each with a different subset of edges in the 16-division. For $k = 2$ the color scheme of an edge is a 2-by-2 ma-

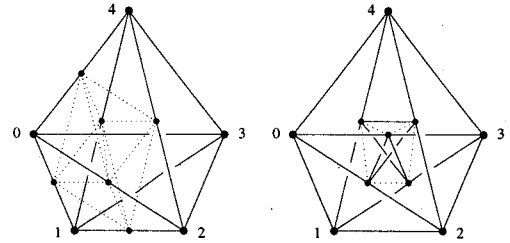


Figure 7: Sketches of two 4-simplices. To the left the dotted lines show the 8-division of one tetrahedral face. To the right the dotted lines decompose a Möbius strip in the interior of the 4-simplex into five triangles.

trix with entries from $\{0, 1, 2, 3, 4\}$. At least one of the colors is not used, which implies that all edges in the 16-division belong to the subdivisions of proper faces. We can therefore draw all edges by superimposing the edges of the five 8-divisions in the boundary of σ .

The simplices that decompose the interior of σ correspond to color schemes that use all five colors. There are only 5 triangles because there are only that many 2-by-3 matrices with five colors:

$$\begin{pmatrix} 0 & 0 & 1 \\ 2 & 3 & 4 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 1 \\ 2 & 3 & 4 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 2 \\ 2 & 3 & 4 \end{pmatrix}, \\ \begin{pmatrix} 0 & 1 & 2 \\ 3 & 3 & 4 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 2 \\ 3 & 4 & 4 \end{pmatrix}.$$

As illustrated in Figure 7, the triangles form a Möbius strip one time around the center of σ . The five solid edges form the boundary of the strip and the five dotted edges cut it into five triangles. Similarly we find 20 tetrahedra that do not lie in the boundary and decompose σ into $2^4 = 16$ 4-simplices.

5 Discussion

This paper introduces the edgewise subdivision of a d -simplex and proves it is symmetric in dimension, in scale, and in location. The main ingredient in the construction is the abacus model of a simplex, which leads to a mechanical description of the subdivision amenable to computer implementations.

Variation. The abacus model can also be used to decompose a d -simplex into Cartesian products of simplices. Such decompositions are by-products of edgewise subdivisions. We return to the stack of rectangles as illustrated in Figure 2. Each rectangle contains dividers which are allowed to move freely between the left and the right end, except they cannot switch places. Each rectangle represents a simplex, and the stack represents the Cartesian product of these simplices. In \mathbb{R}^3 we have three types of 3-dimensional Cartesian products: tetrahedra, triangular prisms, and parallelepipeds. Figure 8 illustrates the decomposition for $k = 3$, which is the smallest integer for which all three types arise. Compare this with the 27-division in Figure 6.

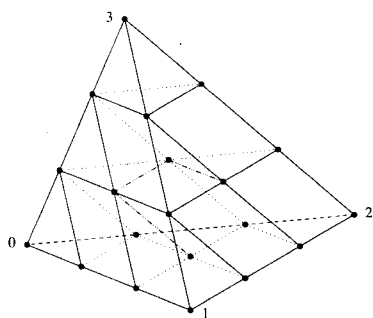


Figure 8: The tetrahedron is decomposed into three tetrahedra, six triangular prisms, and one parallelepiped. Each bounding triangle is decomposed into three triangles and three rhombi.

Questions. For $d = 2$ there is only one edgewise subdivision per triangle and per integer $k \geq 1$. For $d = 3$ there are three different edgewise subdivisions, each one defined by the cyclic rotations and reversals of a permutation of the 4 vertices. How many edgewise subdivisions are there for general $d > 3$? A related question is the identification of the best edgewise subdivision for a given measure of simplex shape. More formally, which permutation of the vertices of a d -simplex defines the

edgewise subdivision that maximizes the minimum or the average shape measure of its simplices?

References

- [1] J. BEY. Tetrahedral grid refinement. *Computing* **55** (1995), 355-378.
- [2] T. DEROSE, M. KASS AND T. TRUONG. Subdivision surfaces in character animation. *Computer Graphics, Proc. SIGGRAPH 1998*, 85-94.
- [3] H. FREUDENTHAL. Simplicialzerlegung von beschränkter Flachheit. *Ann. Math.* **43** (1942), 580-582.
- [4] D. R. GRAYSON. Exterior power operations in higher K-theory. *K-Theory* **3** (1989), 247-260.
- [5] A. LIU AND B. JOE. Quality local refinement of tetrahedral meshes based on 8-subtetrahedron subdivision. *Math. Comput.* **65** (1996), 1183-1200.
- [6] M. SENECHAL. Which tetrahedra fill space? *Math. Mag.* **54** (1981), 227-243.

