COMPUTER SEARCH FOR NON-ISOMORPHIC CONVEX POLYHEDRA

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13. ABSTRACT

To classify the polyhedra, to survey the polyhedral shapes, and to exhaust their variety by orderly enumeration is a naturally attractive problem, noticed by Euler and Jakob Steiner, to which some mathematicians, especially Max Bruckner, devoted considerable work. With the latest high-speed digital computers decades of manual labor can be compressed into hours. This dissertation is concerned with the solution of the enumeration problem on a digital computer.

A tri- linear polyhedron is one in which each vertex is incident with exactly three edges. Two polyhedra are <u>isomorphic</u> if a one-to-one correspondence can be established between the vertices, edges, and faces of one with those of the other, so that the incidence relations between elements are preserved. Two polyhedra are called <u>equi-surrounded</u> if a one-to-one correspondence can be established between the faces of one and the faces of the other so that each pair of corresponding faces has equivalent surroundings -- i.e. the neighbors of the two faces in question, when taken in cyclic order clockwise, display the same pattern of edge-counts. Isomorphism implies equisurroundedness. A counter-example with 18 faces disproves the converse. However, for polyhedra with up to 17 faces we can apparently equate isomorphism with equisurroundedness.

A polyhedron of F faces can be made from a polyhedron of F-1 faces by <u>partitioning</u> one face into two. Intuitively, this is done by drawing a line segment across a face, creasing the face along the partition line, and popping it outward to retain convexity. If the partition line does not pass through an existing vertex, and the (F-1)-hedron is tri-linear, then the F-hedron created (cont......)

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CHAPTER I

INTRODUCTION AND HISTORICAL REMARKS

Source of the Question.

Serious mathematicians as well as laymen from as far back as Plato and Archimedes have concerned themselves with the study of polyhedra. It is generally believed that the regular polyhedra (those whose faces are regular congruent polygons and whose solid angles are congruent) of four, six, and eight faces were known to the Egyptians, but it remained for the Pythagoreans of about 500 B.C. to discover the other two -- those with twelve and twenty faces. Plato, in his metaphysical approach to things, associated the tetrahedron with fire, the cube with earth, the octahedron with air, the dodecahedron with the universe (possibly because it was discovered last), and the icosahedron with water.

On a more scientific basis, we find references in Euler's work, [22] page 90, that indicate clearly that Euler thought about and posed, though loosely, the general question with which we are here concerned.

> Genera notabiliora, ad quae omnia solida figuris planis inclusa sunt referenda, enumerare nominibusque idoneis denotare.

or,

> Enumerate the more important kinds of polyhedra and give them appropriate names.

In response to this self-posed question he then lists certain polyhedra of up to sixteen faces and makes comments about them. In particular, [22] page 93, states:

> The fourth genus has only one species, which is the triangular prism. The subsequent genera usually have several species, but we cannot go into their enumeration because, for the time being, the other properties of the polyhedra here involved are not sufficiently well known.

This indicates that Euler wondered about the general problem of enumeration of polyhedra but, at that time, was unable to come to any general conclusions.

The nineteenth century mathematician, Jakob Steiner, compactly posed the question, [23] page 227.

> Le nombre des faces d'un polyèdre étant donné, on peut demander, de quelle nature peuvent être ces faces. Quelle est la loi générale?

Other mathematicians who spent considerable time studying polyhedra were The Reverend Thomas P. Kirkman, and Professors Oswald Hermes and Max Brückner. Hermes and Brückner, in particular spent decades enumerating polyhedra by hand. Some of their results are discussed in Chapter II.

In mentioning polyhedra, both Euler and Steiner meant convex polyhedra. The aim of this dissertation is the enumeration of convex polyhedra subject to a restriction which will be stated below (tri-linear convex polyhedra), using a digital computer.

Representation of Polyhedra.

Aside from three-dimensional models, there are many useful ways to represent polyhedra. Some of those which we will have occasion to use later are the following:

1. Straight line nets in a plane, drawn by imagining one face to be expanded until all the other lines of the polyhedron, when projected onto the plane of this face, fall into its interior. For example, the triangular prism represented in this way is shown in Fig. 1.

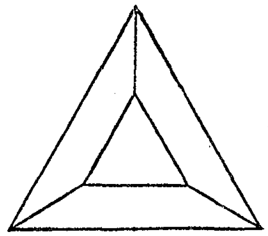


Fig. 1.

2. Curvilinear nets in a plane, topologically equivalent to the straight line nets. For example, the cube is shown in Fig. 2; the diagram contains two concentric circles.

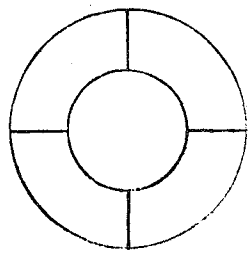


Fig. 2.

3. Curvilinear nets on a sphere, which permit visualization of polyhedra of many faces for which it is difficult to construct an ordinary three-dimensional model.

4. A list of the neighboring faces of each face, in cyclic order,

   a. by name. For example, if the faces of the triangular prism are labelled as shown in Fig. 3, the representation of the polyhedron becomes the following set of "words," one for each face:

      234
      1453
      1254
      1352
      243

   It is understood that these five consecutive "words" correspond to the faces labeled 1, 2, 3, 4, and 5, respectively.

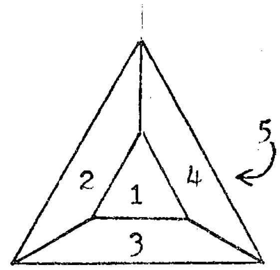


Fig. 3.

b. by edge-count. For example, the same triangular prism would be represented by the following set of words, one for each face, showing the number of edges possessed by each of that face's neighbors, in cyclic order, but without regard to the names of the faces:

444
3434
3434
3434
444

5. Abstract definition. A polyhedron is a system containing three kinds of elements named as follows:

a. "0-dimensional element" or "vertex,"

b. "1-dimensional element" or "edge,"

c. "2-dimensional element" or "face."

There is a relation between unlike elements which we call "incidence"; this relation is symmetric -- if x is incident with y then y is incident with x. The system satisfies the following axioms:

(0) If an edge is incident with both a face and a vertex, then the face is incident with the vertex.

(1) Each edge is incident with two and only two

(a) vertices.

(b) faces.

(2) There can be no more than one edge incident with both of any two given

(a) vertices.

(b) faces.

(3a) Each vertex is incident with at least three edges.

(3b) Each face is incident with at least three edges.

(4) If each of two faces is incident with each of two vertices, there is an edge incident with both faces and both vertices.

Comments:

On (1) and (2). Two faces (vertices) incident with the same edge are called neighbors, and are said to be contiguous, or adjoining to each other.

On (3a). If this axiom is changed to read "exactly three edges," then a special class of polyhedra is defined, called tri-linear polyhedra.

On (4). This axiom is not valid for non-convex polyhedra.

On the whole list of axioms (0), (1a), (1b), (2a), (2b), (3a), (3b), (4). This list does not yield a complete characterization of the concept of polyhedron that we have in view. "Topological" conditions must be added: the system must be connected, simply connected, and orientable, and each face must be simply connected (the neighboring faces must form a single cycle). We omit the axiomatic formulation of these topological conditions -- they are less prominent in our work and we have nothing important to add to Steinitz' work [4,5] in this respect. Yet these topological conditions are essential. They rule out such systems of faces, edges, and vertices as we may find in a pair of disconnected polyhedra, or in a torus-shaped polyhedron, or in a polyhedral Klein bottle, or in a polyhedron with some ring-shaped faces, etc.

Isomorphism.

Polyhedron A is said to be isomorphic with polyhedron B if a one-to-one correspondence can be established between:

a. the vertices of A and the vertices of B,

b. the edges of A and the edges of B, and

c. the faces of A and the faces of B,

such that the incidence relations between elements are preserved. Even if polyhedron A is turned "inside out" in the process of mapping it on polyhedron B, (that is, if the cyclic order of the faces surrounding each face is reversed), A and B are still considered to be isomorphic. In particular, affine mappings with negative determinant are permissible. Since the representation of a polyhedron described in 4a of the preceding section (exhibiting the neighbors by name) lists each face of the polyhedron and shows the identity of each of its neighbors in cyclic order, each edge is completely identified by the two faces which join to form it, and each vertex is identified by a face and two successive neighbors of that face. Hence it is obvious that two polyhedra are isomorphic if and only if their faces can be so labelled (by a permutation of the given labels) that their representations in the manner of 4a are identical.

Equisurrounded.

Two polyhedra whose representations in the manner of paragraph 4b above are identical will be called equisurrounded. We shall see in Chapter IV that equisurroundedness is a necessary but not sufficient condition for isomorphism.

General Theory.

Leonhard Euler (1707-1783) was born in Basel. He was a student of Johann Bernoulli and an associate of Bernoulli's two sons, Daniel and Nicholas. He was a prolific writer and made significant contributions to almost every field of mathematics. He is called the founder of the morphology of polyhedra, having discovered the famous fundamental law for convex polyhedra:

$$V - E + F = 2$$

where V, E, and F, are the numbers of vertices, edges, and faces of the polyhedron. Polyhedra which are not topological spheres always have a value different from 2 on the right side of Euler's equation above, but whatever that value might be, it is called the Euler characteristic. The Euler characteristic of a polyhedron is intimately connected with the topological nature of the polyhedron. For instance, a polyhedron which is a topological torus has Euler characteristic equal to zero. (Imagine cutting the torus at one place and closing the ends. If this figure is then straightened out into a cylindrical shape it becomes a convex polyhedron, with Euler characteristic equal to 2. If the cut was made along existing edges of the original polyhedron, then the cylinder has the same difference, vertices minus edges, but two more faces than the original polyhedron.)

One of the several proofs of Euler's theorem is as follows: Consider the straight line projection of the polyhedron on a plane (representation 1). Ignoring the base face, if we can show that the remaining figure satisfies:

$$V - E + F = 1$$

then, adding the base face we obtain Euler's formula. We proceed by subdividing each face into triangles, by drawing diagonals. For each diagonal added, E and F are increased by one, and V remains the same, so the characteristic $V - E + F$ is unchanged. Finally the figure consists of a set of triangles, some of which are on the outside boundary of the figure and some of which are interior. Of those on the boundary, some have two outside edges and some have only one, where "outside edge" means an edge belonging to no other triangle. Choose any boundary triangle and erase its outside edges. If it has only one, the resulting figure has the same V, but both E and F are reduced by one, hence the characteristic is unchanged. If, on the other hand, the triangle has two outside edges, then we also erase the vertex at their intersection. The result reduces V and F by 1, and E by 2, leaving the characteristic unchanged.

Since there is only a finite number of triangles to start with, we are assured of reaching a state wherein the figure contains only one triangle, which obviously has:

$$V = 3, \quad E = 3, \quad F = 1, \quad \text{with } V-E+F = 1.$$

We conclude that the figure with which we began had characteristic equal to 1, so adding the base face we have Euler's theorem:

$$V - E + F = 2.$$

There are other proofs[1], some of which involve very different ideas. The above proof was not flawlessly presented. Without a more careful elaboration of details, the method could admit an imprudent choice of edges to be erased, by which the figure could be divided into two disconnected nets, each of which has characteristic equal to 1, or lead to other difficulties.

Steinitz' Theorem.

In a polyhedron satisfying axiom (4) every pair of vertices, P and Q, which are each incident with both of two faces, α and β, are joined by an edge PQ which is incident with both α and β. We call such a polyhedron regularly connected, paraphrasing a term introduced by Steinitz, who defines a K-polyhedron as a regularly connected polyhedron with Euler characteristic equal to 2. Steinitz' theorem states that every K-polyhedron is realizable as a convex polyhedron. See [5] pages 227-229. Steinitz' theorem is basically important to our work; it enables us to represent convex polyhedra on a digital computer.

Splitting.

A polyhedron having F+1 faces can be derived from one having F faces by splitting one face into two. There are three types of splits, or partitions of faces; see Fig. 4.

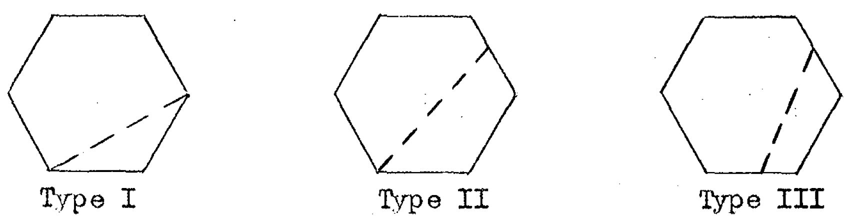


Fig. 4.

[1] See e.g. Polya [8] page 54, exercise 9.

These three types are distinguished by the number of vertices lying on the partition line. A split is accomplished by imagining the face to be scored or creased along the partition line, and pushed outward to form two faces while retaining the convexity of the figure. Steinitz [4] page 192, proved the following theorem.

Theorem 1. Any convex polyhedron of F faces can be derived by starting with the tetrahedron and making partitions of Type I, II, and III.

Diophantine Relations.

By axioms (1b), (2b), and (3b), each face has as many different neighbors as it has edges. No two of its edges can be incident with the same neighbor, hence the maximum number of edges for any face of an F-hedron is F-1. Designating as f_k the number of k-gon faces in a polyhedron, we can add up the faces and edges of the polyhedron and get the following relations:

$$f_3 + f_4 + \dots + f_{F-1} = F$$

$$3f_3 + 4f_4 + \dots + (F-1)f_{F-1} = 2E$$

We also have Euler's relation:

$$V - E + F = 2.$$

Since we are dealing with numbers of things, solutions $(f_3, f_4 \dots f_{F-1})$ of these equations must be in non-negative integers. In general, there are several solutions, looking at the system from a strictly algebraic point of view; however, not every solution of this diophantine system is realizable as a convex polyhedron. Each solution for which there is at least one convex polyhedron defines a Tribe, a non-empty set of convex polyhedra, containing, in general, several members. Regarding the f_k as successive digits, with f_3 in the units position, we obtain a <u>tribe identification number</u> to which we will refer repeatedly below. For clarification, a few examples are shown here:

polyhedron	tribe
tetrahedron	4
triangular prism	32
cube	60
hexagonal prism	2060

CHAPTER II

TRI-LINEAR POLYHEDRA

Definition.

A polyhedron having exclusively trihedral vertices will be called a tri-linear polyhedron. When there is no danger of confusion, just the word polyhedron will be used.

The theory of tri-linear polyhedra has a polar or dual counterpart in the theory of polyhedra having exclusively triangular faces. We will deal only with tri-linear polyhedra.

Euler's Theorem.

By Euler's theorem:

$$V - E + F = 2.$$

Then, since each vertex has three edges leading to it, and since each edge is shared by two vertices, we have, for tri-linear polyhedra:

$$3V = 2E.$$

Combining these relations we get:

$$E = 3(F-2)$$

$$V = 2(F-2).$$

The cube, for instance, is a tri-linear polyhedron with $F = 6$, $E = 12$, and $V = 8$.

Splitting.

Partitions of Types I and II produce non-trilinear polyhedra. Hence we must disallow all but Type III partitions in the creation of tri-linear polyhedra. Since a partition can never reduce the number of edges incident with a given vertex, it follows from Steinitz' theorem (Theorem 1) that any tri-linear polyhedron can be obtained from the tetrahedron by partitions of Type III. However, it is considerably easier to prove this consequence than to prove Steinitz' entire theorem, so we will give a new independent proof. First we must define the inverse process to splitting.

Merging.

We have been talking about creating polyhedra of F+1 faces from F-hedra by splitting faces. Consider the inverse process, which we will call merging. In the sketch, Fig. 5, consider merging faces #1 and #2 by erasing their common edge. The result will be labelled face #1.

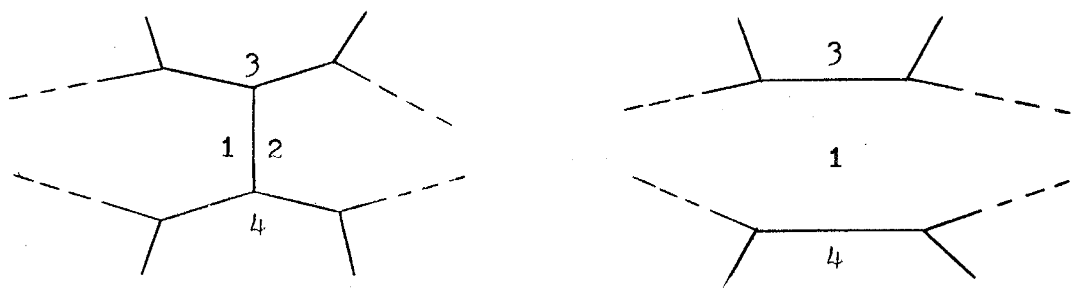


Fig. 5.

If we denote the edge count of face j before merging by e_j, and the same after merging by e'_j, we can make the following general remarks:

$$e'_1 = e_1 + e_2 - 4$$

$$e'_3 = e_3 - 1$$

$$e'_4 = e_4 - 1 .$$

Theorem 2. (Splitting Theorem) We can obtain any convex tri-linear polyhedron by starting with the tetrahedron and making face partitions of Type III (i.e., partitions in which the partition line does not pass through an existing vertex).

In order to prove the splitting theorem, we first need a lemma.

Lemma. If, in a tri-linear polyhedron, there are two triangles incident with the same edge, the polyhedron is, in fact, a tetrahedron.

Proof. Since each vertex of a tri-linear polyhedron is, by definition, a trihedral vertex, Fig. 6 represents the hypothesized pair of adjacent triangles. Vertices C and D are already trihedral, and vertices A and B need another line each.

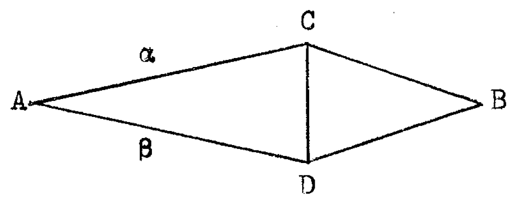


Fig. 6.

Now consider faces α and β, each of which is incident with both vertices A and B, by axiom (0) of the abstract definition of a polyhedron. Then by axiom (4) there must be an edge incident with both vertices, A and B, and both faces, α and β. Hence α and β must be triangular, which proves the lemma.

Proof of Theorem 2: Now, by induction, we can prove the main theorem on splitting. We know that there is only one four-faced polyhedron, the tetrahedron, which happens to be tri-linear. It is trivially derivable from itself, by splittings whose number is zero.

Using the method of mathematical induction, we assume that all tri-linear F-hedra can be made from the tetrahedron by splitting, and we must prove that the same is true for the (F+1)-hedra. For this purpose, we divide the (F+1)-hedra into two classes -- those having some triangular faces, and those having none.

Case I. Some triangles. By the lemma, triangles cannot be neighbors, and so we can find a triangular face with a non-triangular neighbor, and merge the two. Now we must check the axioms. Let us keep a sketch of the situation before us (Fig. 7). We plan to merge faces α and β.

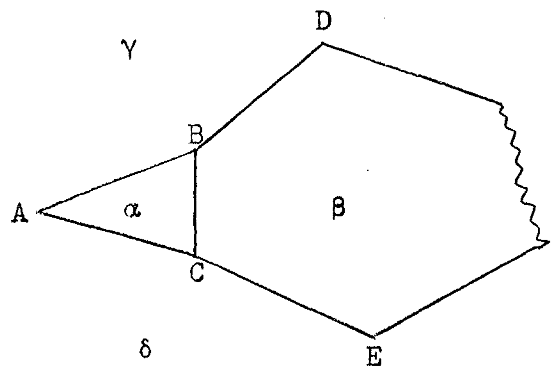


Fig. 7.

Axiom (0). Edges AB and BD become one edge AD after merging. No change in incidence relations of the remaining vertices (different from B and C) takes place. A similar argument holds for edge AE. There is no change in the incidence relations of the elements not emphasized by Fig. 7.

Axiom (1a). The vertex common to both of two merged edges, for instance edges AB and BD, is eliminated, leaving only two vertices incident with the merged edge, AD.

Axiom (1b). On one side of a merged edge, e.g. consisting of AB and BD, lies one face. On the other side lie two faces before merging, and one afterwards. Hence the merged edge, AD, is incident with only two faces.

Axiom (2a). The only way this axiom could be violated would be if a biangle would be created by the merger. This could occur if either β, γ, or δ were triangles. However, by the lemma, this is not possible.

Axiom (2b). To violate this axiom, one must merge two faces which belong to an arrangement we call a "belt" containing three faces. A "three-faced belt" is a set of three mutually contiguous faces which do not have a common vertex; see Fig. 8.

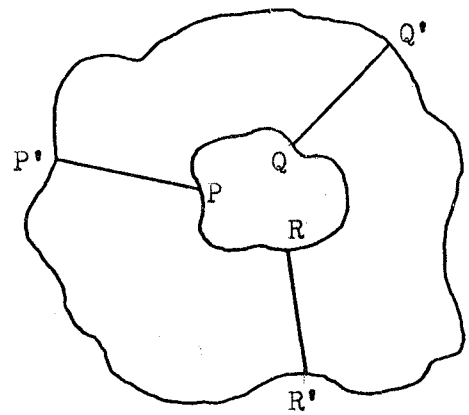


Fig. 8.

Each of the three faces participating in the belt has at least four vertices (P, P', Q and Q', for example); none of the three can be a triangle. And so, in the case of Fig. 7, the faces α and β cannot form a belt with any third face, since α is a triangle.

Axiom (3a). After the merger, vertices B and C in the example are eliminated, and none of the other vertices is changed with regard to its trihedral nature, as we have already mentioned above.

Axiom (3b). The only faces affected by the merger are α, β, γ, and δ. For a face to be incident with less than three edges, a biangle would have to be formed. This was ruled out while we examined axiom (2a).

Axiom (4). The edge required by this axiom is, in the one case, the composite edge ABD, and in the other, ACE. Faces γ and δ have a common edge emanating from vertex A, which is unaffected by the merger. They need not have, and indeed cannot have, any other, since face β cannot be a triangle (hence D and E are distinct vertices).

Case II. No Triangle. The only axioms which require special attention in this case are (2b) and (3b). All others are proved inviolate by the same arguments as in Case I. See Fig. 9.

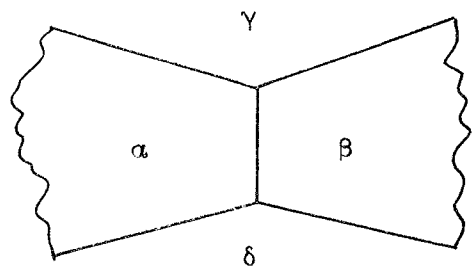


Fig. 9.

Axiom (3b). Each of the four faces affected by the merger has edge-count greater than three, hence after the merger γ and δ will have just one less than before and the merged face, αβ, will have m + n - 4, if α and β had m and n, respectively. No edge-count will be reduced to less than three, hence no biangles will be formed by the merger.

Axiom (2b). This axiom takes a little more discussion, so I left it to the last. First, note how merging can cause two faces to have more than one edge in common. It must be that the two merged faces, α and β, are both neighbors of a third face, ε, so that α, β, and ε form a belt around the polyhedron, as defined above. Erasing the line common to faces α and β would result in the new face, αβ, having two edges in common with the base face, ε.

Examples of three-faced belts are shown in Figs. 10 and 11, where erasing the edge common to faces α and β will violate axiom (2b). Note that in the decahedron of Fig. 11 there exist two belts, αβε and αδε .

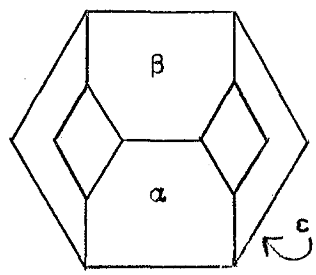


Fig. 10.

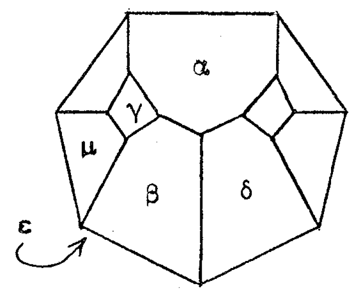


Fig. 11.

What we want to be able to say is that even in a polyhedron not free from belts we can find some edge to erase which will not result in a violation of axiom (2b).

Consider that a belt divides the remaining elements of a net into two parts -- call them the <u>inside</u> and the <u>outside</u> of the belt. If we disregard the outside, and examine just the belt and its inside, we can conclude that there must be at least three faces on the inside. For if there were only one, it would have to be a triangle, and this polyhedron contains no triangles. If there were two faces inside, then one would have to be a triangle (see Fig. 12). Hence there must be at least three faces inside.

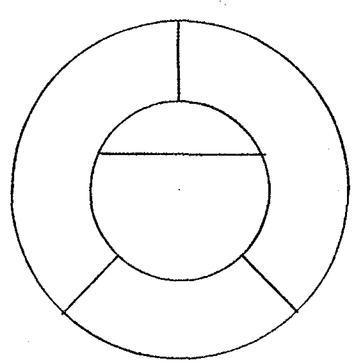


Fig. 12.

Next we should state the obvious fact that no face from the inside can form a belt with a face from the outside of a belt (our polyhedron is simply connected).

If we examine a belt and its inside, we may find that it contains other belts, and they could involve one or two members of the present belt. For ease of communication, let us call the belt we start with B, and such an alternate belt contained partly or totally inside B, B'. (For instance in Fig. 11, α, β, and ε can be considered to form the belt B, and α, δ, and ε to form B'.) Picking such a new belt, B', we can drop the faces which are outside it (there will be at least one to drop), and then proceed to examine B' and its inside. We note in passing that if belt B had b faces inside it, belt B' will have at most b-1 faces inside it. If we continue this process we can be assured of running out of belts ultimately, since we drop at least one face each time. The final belt will contain at least three faces inside it, as we have seen above, and so we can choose any two of them to merge, being sure that they do not form a belt with any one other face.

This completes the proof of the Splitting Theorem for tri-linear polyhedra.

Diophantine Relations for Tri-linear Polyhedra.

Theorem 3. Triangles, quadrilaterals, and pentagons cannot simultaneously be absent from a tri-linear polyhedron.

Proof: Consider the relations below, where f_j still represents the number of j-gon faces of a polyhedron:

$$(1) \qquad f_3 + f_4 + \dots + f_{F-1} = F$$

$$(2) \qquad 3f_3 + 4f_4 + \dots + (F-1)f_{F-1} = 2E = 6(F-2) .$$

In equation (2), $2E = 6(F-2)$ because of Euler's relations for tri-linear polyhedra. Now if we multiply equation (1) by 6 and subtract equation (2) from it, we get:

$$(3) \quad 3f_3 + 2f_4 + f_5 - (f_7 + 2f_8 + \dots + (F-7)f_{F-1}) = 12$$

or, since the f_j are all non-negative, we arrive at the inequality:

$$(4) \qquad 3f_3 + 2f_4 + f_5 \geq 12$$

which says that triangles, quadrilaterals, and pentagons cannot simultaneously be absent. The case of equality is attained in (4) if there is no face with more than six sides. We may also observe that the well-known inequality (4) holds unrestrictedly for convex, not necessarily tri-linear, polyhedra, and so do some of the consequences we shall derive from it.

Now for the special case of F = 6, I should like to investigate the solution of the above diophantine equations, (1) and (2). If we multiply the first equation by 5 and subtract the second, for F = 6, we get:

$$2f_3 + f_4 = 6 .$$

This equation, taken together with

$$f_3 + f_4 + f_5 = 6$$

yields $f_3 = f_5$, and so the system has exactly four solutions in non-negative integers.

f_5	f_4	f_3
3	0	3
2	2	2
1	4	1
0	6	0

Only two of these are realizable as convex tri-linear polyhedra, namely 222 and 060 (see Figs. 13 and 14 respectively).

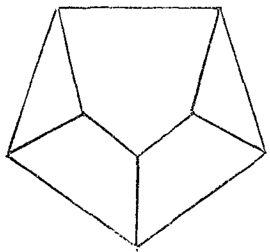


Fig. 13.

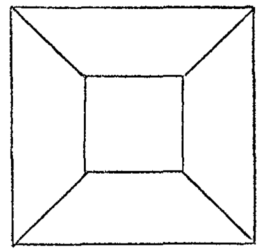


Fig. 14.

The others cannot be drawn in such a way as to satisfy the axioms. This will follow from Theorems 4 and 5 which will be stated here and proved later in this chapter in the section on Kirkman polyhedra.

Theorem 4. In a tri-linear F-hedron containing as base an (F-1)-gonal face, at least two of the remaining faces are triangular.

Theorem 5. In an F-hedron having an (F-1)-gonal face, where $F > 4$, there can be no more than $[\frac{1}{2}(F-1)]$ triangular faces (where $[X]$ denotes the greatest integer contained in X).

Each of the three solutions to the diophantine system, 303, 222, and 141, contains an (F-1)-gon base, where $F = 6$. Hence, invoking Theorems 4 and 5 we have:

$$2 \leq f_3 \leq 2 .$$

That is, since a pentagon is present, the number of triangles must be exactly two. This shows that the solutions 303 and 141 are not realizable as convex tri-linear polyhedra.

Faces with Limited Edge-Count.

It may be of interest to study polyhedra of a large number of faces, none of which has more than, say, M edges. Let us define as the maximum edge-count of a polyhedron the number of sides of the face with the most sides. It would be convenient if we could derive each polyhedron of the subclass for which the maximum edge-count does not exceed a given number M from the tetrahedron by successive splittings without using intermediate polyhedra outside the subclass. It turned out, however, rather surprisingly, that such a derivation is not always possible. The following theorems, 6 and 7, yield substantial information about the cases $M = 5$ and $M = 6$, respectively.

Theorem 6. In a tri-linear polyhedron with F faces and maximum edge-count ≤ 5 there are two adjacent faces which can be merged into one face with no more than 5 sides. This statement is true for $F \leq 11$, but false for $F = 12$.

Theorem 7. In a tri-linear polyhedron with F faces and maximum edge-count ≤ 6 there are two adjacent faces which can be merged into one face with no more than 6 sides. This statement is true for $F \leq 31$, but false for $F = 32$.

Let us recall a simple fact discussed above (in connection with Fig. 5). If two adjacent faces with m and n sides, respectively, are merged, the resulting face has $m + n - 4$ sides. Let us also recall the inequality (4) which goes over into the equation:

$$3f_3 + 2f_4 + f_5 = 12 \qquad (5)$$

when, as in the cases under consideration, the maximum edge-count does not exceed 6. And let us begin with two examples, the first concerned with the case $F = 12$ of Theorem 6, the second with the case $F = 32$ of Theorem 7.

First example. The regular dodecahedron has 12 pentagonal faces. If any two adjacent faces of it are merged, a polygon with $5 + 5 - 4$ faces, that is, a hexagon results. Therefore, the polygon with 11 faces from which our pentagonal dodecahedron is derived by one last splitting must have a hexagonal face. The dodecahedron is a polyhedron of the subclass with maximum edge-count ≤ 5 which we cannot derive from the tetrahedron by successive splittings without going outside this subclass.

Second example. The full page Fig. 15 shows one half of a polyhedron with 32 faces; the other half is identical and fits in with the one half shown by placing the protruding hexagons of one half adjacent to the outside pentagons of the other. (A metrically determined realization of this polyhedron is a "half-regular" or "Archimedean" solid, the "truncated icosahedron." Cut off each of the 12 vertices of a regular icosahedron so that a regular pentagonal face is created at each of the vertices, and a regular hexagon is made of each of the 20 originally triangular faces of the icosahedron.) Our 32-hedron has high symmetry: each pentagonal face is so situated in it as any other pentagonal face, and each hexagonal face as any other hexagonal face. The merger of two adjacent faces of our 32-hedron yields a polygon with

$$5 + 6 - 4$$

or

$$6 + 6 - 4$$

sides, a heptagon or an octagon. We have here a polyhedron with 32 faces of the subclass having maximum edge-count ≤ 6 which we cannot derive by splitting one face of a 31-hedron of the same subclass.

Our examples prove the "negative half" of Theorems 6 and 7. We start proving the positive half with a simple remark: merging a face of n sides with an adjacent quadrilateral or triangle cannot increase is $\leq$ 5 and F $\leq$ 11. Any polyhedron of the subclass S with more than 4 faces can be derived from a polyhedron of the same subclass by splitting one face.

Theorem 9. A convex tri-linear polyhedron with F faces is said to belong to the subclass T if, and only if, its maximum edge-count is $\leq$ 6 and F $\leq$ 31. Any polyhedron of the subclass T with more than 4 faces can be derived from a polyhedron of the same subclass by splitting one face.

Thus, each polyhedron of the subclass S can be connected with the tetrahedron by a chain of polyhedra belonging to the same subclass which are derived from each other by successive splittings (of Type III, of course) and the same holds for the subclass T.

One can prove Theorems 8 and 9 by combining the ideas of the proofs for Theorems 2, 6, and 7. I omit the details whose full presentation seems to be unavoidably long and fussy. Theorem 9 is essential to the appreciation of some of the work that will be presented in Chapter IV.

Kirkman Polyhedra. Dissection of a Polygon into Triangles.

We consider the so-called Kirkman polyhedra -- tri-linear polyhedra with at least one face of F-1 edges, where F is the number of faces in the polyhedron. In any Kirkman polyhedron, we choose a face of F-1 sides as the base; all other faces of the polyhedron are adjacent to the base. We draw a net of the polyhedron (representation 1), on the base. In this net, the vertices not incident with the base and the edges adjacent to, nor identical with, the base. I say that G is a <u>tree</u>, a connected graph containing no loop (no cycle).

Let e and v denote the number of edges and vertices belonging to G, respectively. Recalling that E and V are the number of edges and vertices in the entire polyhedron, we have:

$$\begin{aligned} e &= E - 2(F-1), \\ &= 3(F-2) - 2(F-1) \\ &= F-4. \end{aligned}$$

The number of vertices that do not belong to the base is:

$$\begin{aligned} v &= V - (F-1) \\ &= 2(F-2) - (F-1) \\ &= F-3. \end{aligned}$$

Thus:

$$v = e + 1.$$

It is well known that in a tree the number of vertices exceeds by one the number of edges. An inductive proof of this fact runs so: The simplest tree consists of a single node, has no edge, and so the fact asserted is obvious for a tree with only one node. Then, given that the relation is true for a tree of K nodes, adding another node cannot destroy the relation because the new node must be connected to just one of the existing nodes by just one edge (otherwise a loop would be formed). Thus the relation holds for the K+1 node tree.

Since G contains no loop, as we have observed above, G is the union of a certain number t of distinct trees, and so:

$$v = e + t.$$

Comparing with the above, we see that t = 1. Hence, G is a single tree; G is connected.

Let us digress for a moment and prove Theorems 4 and 5, stated above.

Theorem 4. In a tri-linear F-hedron containing as base an (F-1)-gonal face, at least two of the remaining faces are triangular.

Proof: We have seen that the graph, G, is a tree, a connected graph that contains no cycles. It is enough to consider $F > 4$. Then the tree has at least two extremities, X and Y. Since we are dealing exclusively with tri-linear polyhedra, X must be connected to two successive vertices in the base by two edges, forming a triangular face. Similarly, Y must form a triangular face with two vertices in the base face. Q.E.D.

Theorem 5. In an F-hedron having an (F-1)-gonal face, where $F > 4$, there can be no more than $[\frac{1}{2}(F-1)]$ triangular faces, where $[X]$ denotes the greatest integer contained in X.

Proof: By the lemma which says that the tetrahedron is the only tri-linear polyhedron containing adjacent triangles, the base (F-1)-gon can adjoin triangles only at every other edge, at most. Q.E.D.

Brückner characterized the Kirkman polyhedra as having no "Deckfläche" or crown faces. The "shape" of the tree G, i.e. the pattern of left turns and right turns one makes in traversing the tree, uniquely describes the polyhedron, since there is only one way to connect the tree to the base face. A vertex of G which is incident with only one edge belonging to the tree is connected to two adjacent vertices in the base face by two edges, thereby forming a triangular face. A vertex incident with two edges belonging to the tree is connected to a vertex in the base face by one edge, so placed that all the angles around the crown vertex are less than 180 degrees. A vertex incident with three edges belonging to the tree has no edges leading to the base face, since all vertices are trihedral.

Simply enclosing a tree in a circle is sufficient to permit drawing the entire net of its polyhedron. Take for instance the tree and corresponding polyhedron shown in Fig. 16.

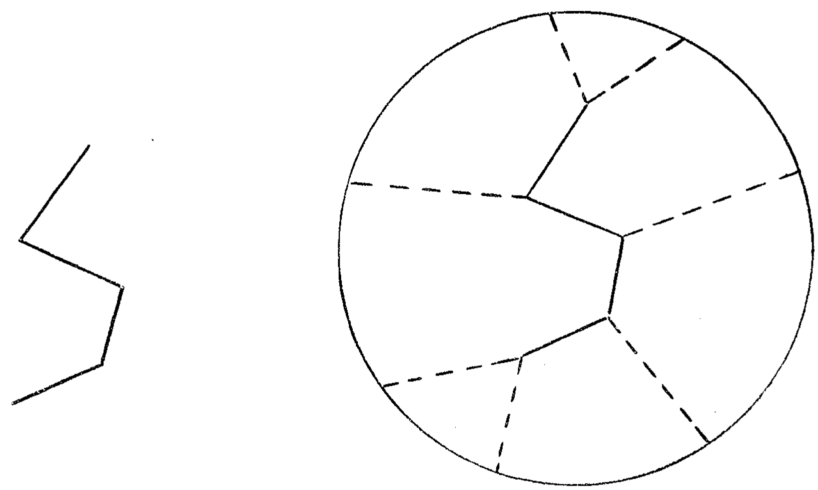


Fig. 16.

As we have seen above, there are v = F-3 vertices and e = F-4 edges in the tree G. Thus, there are five vertices and four edges in the tree of the octahedron of Fig. 16.

Note the combinatorial nature of the structure of a tree. Once a first edge is drawn, one has the choice of "turning left or right" at each succeeding vertex. Weeding out the isomorphisms and including vertices of order three in the tree complicate the enumeration of possible cases. Yet, as observed by Kirkman, the number of such non-isomorphic trees is exactly equal to the number of ways the base polygon can be dissected into triangles, assuming all the edges and angles of the base are equal and indistinguishable. More precisely, the Kirkman polyhedron problem is essentially the dual of the polygon dissection problem, in the sense that faces and vertices are interchanged. (For an exposition on duality, see [8] page 53, exercises 3 and 4, and their solutions.) In Fig. 17 for example, drawing the lines connecting the centroids of the triangles in the hexagon at left we get a tree which corresponds to the polyhedron shown at right.

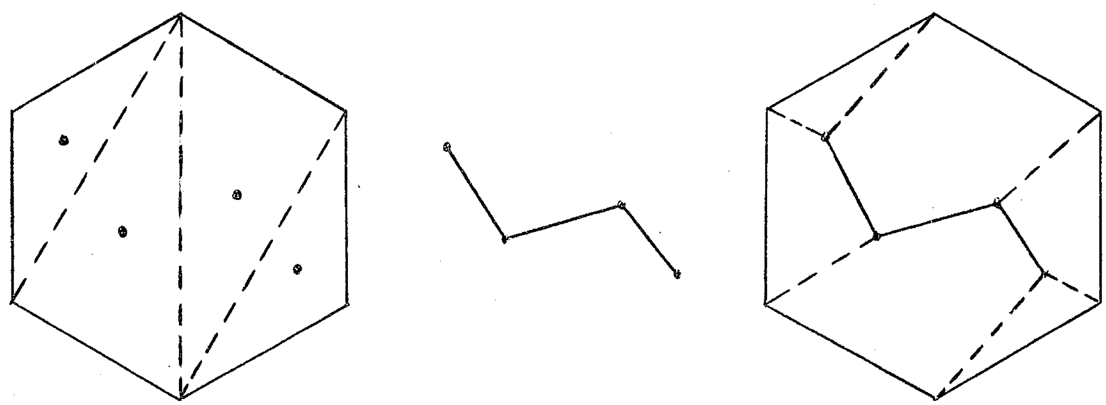


Fig. 17.

D_n, the total number of triangular dissections of an n-gon, admitting isomorphic dissections, was known to Euler. See [8] page 102, exercises 7, 8, and 9. Defining $D_2 = 1$, we have for $n \geq 3$,

$$D_n = D_2 D_{n-1} + D_3 D_{n-2} + \cdots + D_{n-1} D_2$$

$$= \frac{2}{2}\,\frac{6}{4}\,\frac{10}{4}\,\frac{14}{5} \cdots \frac{4n-10}{n-1}$$

$$= \frac{(2n-4)!}{(n-2)!(n-1)!}$$

$$= \binom{2n-4}{n-2}\frac{1}{n-1} .$$

To show the connection between these numbers, D_n, and the number of (n+1)-hedra having an n-gon base, suppose the latter is called K(n+1) in honor of Kirkman. We will refer just to K when the number of faces, F = n+1, is understood. Each of the K types has a symmetry group of order S_i, i = 1, 2, 3, ... K. The base in itself admits a group of order 2n, the so-called dihedral group. Then, since edges of the base are considered indistinguishable, we have:

$$D_n = \frac{2n}{S_1} + \frac{2n}{S_2} + \dots + \frac{2n}{S_K}$$

or

$$\frac{D_n}{2n \sum_{i=1}^{K} \frac{1}{S_i}} = 1$$

or

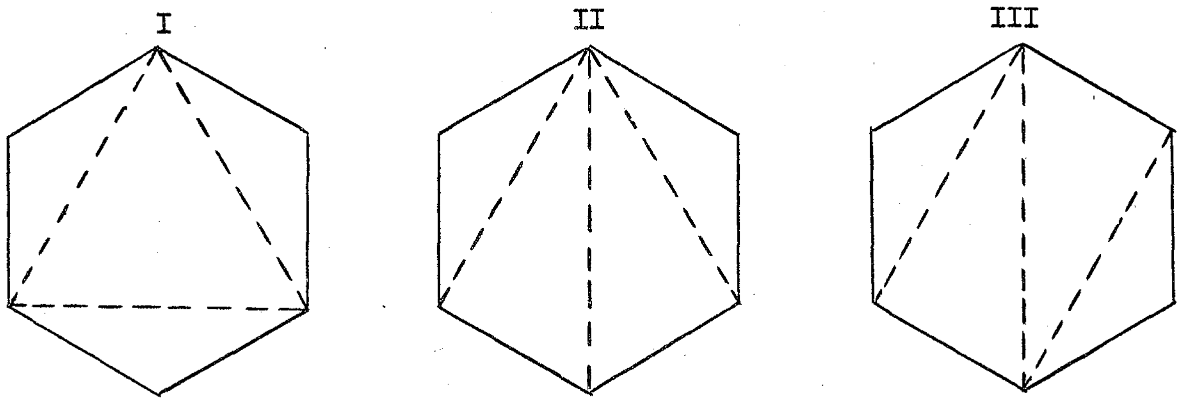
$$K = \frac{D_n}{2n} \cdot \left(\frac{K}{\sum_{i=1}^{K} \frac{1}{S_i}} \right) > \frac{D_n}{2n}$$

because the factor in parentheses, which is dropped to form the last inequality, is the harmonic mean of the S_i, all of which are ≥ 1, and not all of which are equal to 1.

Recalling that n = F-1, and defining L(n) as $D_n/2n$, we have the following table. The numbers for F $\geq$ 12 are Brückner's unverified results. Note that he certainly erred for F = 16, since his K(16) < L(16). See [2].

F	4	5	6	7	8	9	10	11	12	13	14	15	16
L	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{2}$	$1\frac{1}{6}$	3	$8\frac{1}{4}$	$23\frac{5}{6}$	$71\frac{1}{2}$	221	$699\frac{5}{6}$	2261	7429	$24763\frac{1}{3}$
K	1	1	1	3	4	12	27	82	228	731	2282	7531	24312

The foregoing discussion was more intuitive than exhaustive (for more details see [4] pages 50-55, [13], and [16]) so an example is particularly desirable. Consider F = 7, (n = 6). The three types of dissection for the hexagonal base and the operations which map these figures onto themselves are shown in Fig. 18.



I	II	III
I	I	I
M	M	R_{180}
R_{120}		
R_{240}		
MR_{120}		
MR_{240}		

Fig. 18.

Here M designates mirror image, or reflection in the vertical axis, R_j means clockwise rotation through j degrees, and I means identity. Hence the orders of these subgroups are $S_1 = 6$, $S_2 = 2$, and $S_3 = 2$.

$$D_6 = 2n \sum_{i=1}^{3} \frac{1}{S_i} = 12(1/6 + 1/2 + 1/2)$$

$$= 14.$$

These 14 ways of dissecting the hexagon (2 from type I and 6 each from types II and III) are shown in Fig. 19.

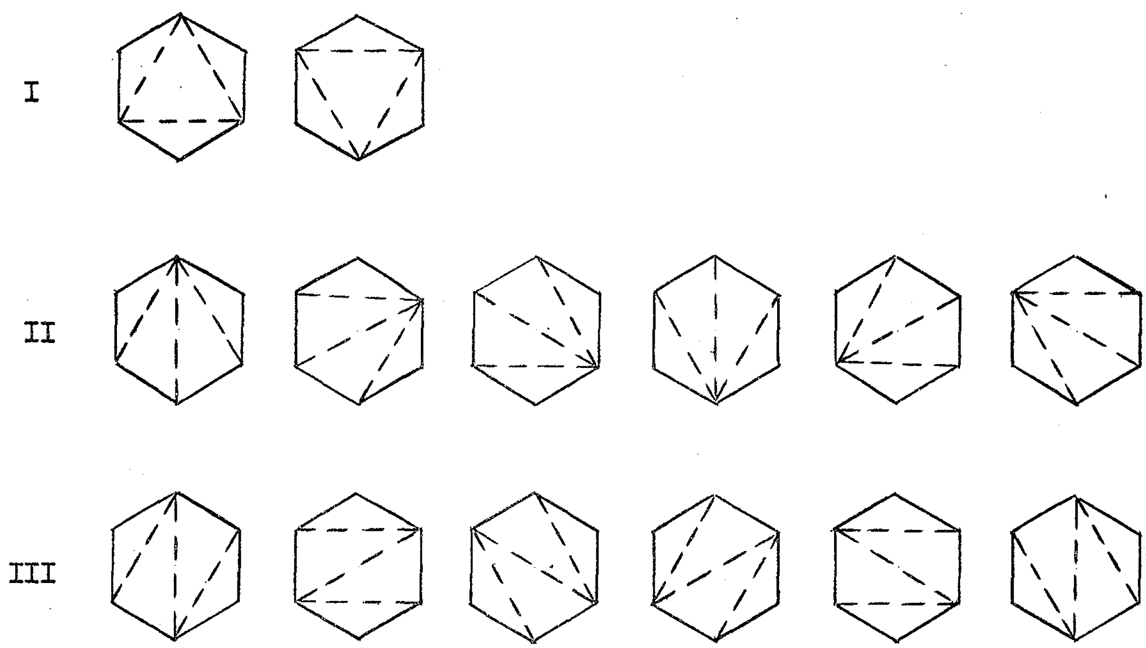


Fig. 19.

Explicit Formulae.

The Reverend Thomas P. Kirkman wrote many papers in the publications of the Philosophical Societies of Manchester and Liverpool, and the Royal Society of London, mostly in the 1850's, on the subject of polyhedra, especially on the "Kirkman polyhedra" discussed in the foregoing section. Kirkman developed a system of rather involved recursion formulas involving f_j (as defined above). There is, however, a particular case in which the formula becomes explicit and rather simple. The number of non-isomorphic polyhedra for which $F \geq 6$, $f_{F-1} = 1$, and $f_3 = 2$ is:

$$2^{\frac{F-8}{2}}\left(2^{\frac{F-6}{2}}+1\right) \qquad \text{(F even)}$$

$$2^{\frac{F-7}{2}}\left(2^{\frac{F-7}{2}}+1\right) \qquad \text{(F odd).}$$

See [17].

Enumeration.

Professor Oswald Hermes and Dr. J. Max Brückner both worked on the extensive enumeration of various subclasses of convex polyhedra. Their work leap-frogged, each having occasion to correct the other's results. Brückner's work culminated in a book, Vielecke und Vielflache, published in 1900, [1]. Subsequently he published papers adding to his results. In particular, at the Congresso Internazionale dei Matematici in Bologna in 1928 he reported certain results, saying in a footnote that the supporting manuscripts would be left to "some German university library." After some amount of correspondence, I finally located them at the University of Heidelberg in eighteen large volumes.[1]

The procedure used by both Hermes and Brückner was to cut off vertices, edges, or even pairs of intersecting edges from polyhedra of F faces to make polyhedra of F+1 faces. Many years of work went into the tabulation of polyhedra by these two men. The most recent results show the following total numbers of non-isomorphic polyhedra of various subclasses (Table 1). The notation is as follows. G stands for Gattung, or tribe, and P stands for polyhedra. The subscript shows the total number of faces, and the superscript shows the number of faces not contiguous with the base face. Since the base face is always chosen so that it has at least as many edges as any other face, $G_{11}^{0} = 30$ means that there are thirty tribes of 11-hedra having at least one 10-gonal face. Generally,

$$P_F \quad \text{and} \quad G_F$$

refer to the set of all non-isomorphic convex polyhedra with F faces,

[1] In the Handschriftenabteilung der Universitätsbibliothek Heidelberg, under the label "Heid. Hs. 964 bis 981."

P_F giving their number, and G_F the number of their tribes, whereas

$$P_F^c \quad \text{and} \quad G_F^c$$

refer only to the subset of those that have a base of F-1-c sides.

TABLE 1

BRÜCKNER'S NUMBERS FOR POLYHEDRA WITH MORE THAN TEN FACES

G_{11}^{0} =	30	P_{11}^{0} =	82
G_{11}^{1} =	51	P_{11}^{1} =	281
G_{11}^{2} =	62	P_{11}^{2} =	508
G_{11}^{3} =	42	P_{11}^{3} =	335
G_{11}^{4} =	14	P_{11}^{4} =	44
G_{11} =	199	P_{11} =	1250

G_{12}^{0} =	50	P_{12}^{0} =	228
G_{12}^{1} =	91	P_{12}^{1} =	991
G_{12}^{2} =	120	P_{12}^{2} =	2264
G_{12}^{3} =	107	P_{12}^{3} =	2826
G_{12}^{4} =	61	P_{12}^{4} =	1232
G_{12}^{5} =	14	P_{12}^{5} =	74
G_{12}^{6} =	1	P_{12}^{6} =	1
G_{12} =	444	P_{12} =	7616

G_{13}^{0} =	88	P_{13}^{0} =	731
G_{13}^{1} =	154	P_{13}^{1} =	3452
G_{13}^{2} =	223	P_{13}^{2} =	9401
G_{13}^{3} =	224	P_{13}^{3} =	16234
G_{13}^{4} =	165	P_{13}^{4} =	15218
G_{13}^{5} =	76	P_{13}^{5} =	4302
G_{13}^{6} =	16	P_{13}^{6} =	115
G_{13} =	946	P_{13} =	49453

G_{14}^{0} =	140	P_{14}^{0} =	2282
G_{14}^{1} =	253	P_{14}^{1} =	12170
G_{14}^{2} =	359	P_{14}^{2} =	37030
G_{14}^{7} =	18	P_{14}^{7} =	178

G_{15}^{0} =	225	P_{15}^{0} =	7531
G_{15}^{1} =	339	P_{15}^{1} =	45232
G_{15}^{8} =	17	P_{15}^{8} =	266

G_{16}^{0} =	350	P_{16}^{0} =	24312

CHAPTER III

COMPUTATION

General Comments.

I have written a computer program in the "Extended Algol" language for the Burroughs B5000 computer [24]. The program starts with the tetrahedron, and performs all possible partitions of faces to form pentahedra, saving only those which are not equisurrounded to one saved previously; see the definition of "equisurrounded" in Chapter I. Then it uses the pentahedra as inputs, partitioning their faces to form hexahedra, then the hexahedra to form heptahedra, and so on. The original program was written to accommodate 11-hedra. Then when Brückner's 1928 paper [2] came to light, I modified the program enough to accommodate larger numbers of faces but of limited edge-count. Hence we have a complete enumeration of convex tri-linear polyhedra of up to 11 faces, and a partial enumeration (maximum edge-count ≤ 6) for $F = 12, 13, 14$, and 15.

Representation.

In partitioning a face of one of the input polyhedra, the representation of the polyhedron is the one labelled 4a in Chapter I, namely a list of the neighboring faces of each face, in cyclic order, by name. For comparing two polyhedra, however, 4b is used -- a list of the neighbors by edge-count rather than by name. To make such a description unique, it was necessary to agree on a canonical form for the latter representation. In my program I permuted the neighbors, retaining the cyclic order, until the resulting word was numerically minimized. Then these words, one for each face, were sorted to make one-to-one matching less laborious a process. Two examples are shown in Fig. 20.

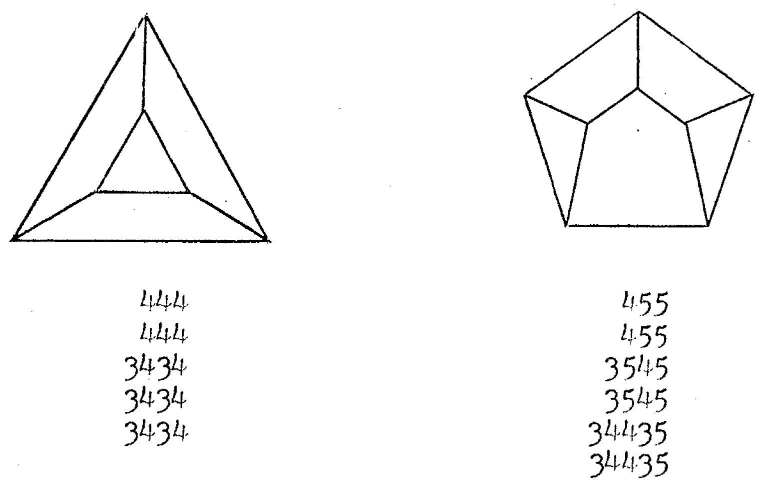


Fig. 20.

Splitting.

Once it is determined which face is to be partitioned, and between which neighbors of that face the partition line is to run, the details of forming the resulting polyhedron simply amount to a great deal of bookkeeping. The procedure by which we assure that all possible partitions are made will be described here. We do the following for each face of each input polyhedron. Assume that the edges (and hence the neighbors) of the face being partitioned are numbered from 1 to N, counterclockwise, as in Fig. 21. We run a partition line from each edge to the next higher numbered edge, including the "wraparound" case from edge N to edge 1. This is referred to as cutting off one vertex.

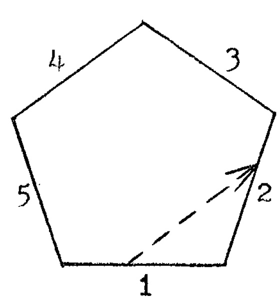


Fig. 21.

Next we run a partition line from each edge to the second higher numbered edge -- e.g. from 1 to 3, 2 to 4, etc., N to 2. This is referred to as cutting off two vertices. For example, in Fig. 22 the partition line runs from edge 4 to edge 1. We continue this process of cutting off

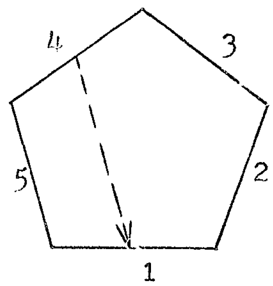


Fig. 22.

V vertices, where V ranges from 1 up to [N/2], the greatest integer contained in N/2. The reason we do not have to go higher is that, because of symmetry, higher values of V simply duplicate partitions that have already been made. For instance, in Fig. 23 the case of V = 3 gives the same partition as the previous one shown above.

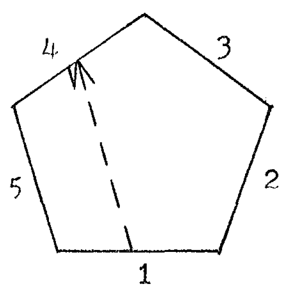


Fig. 23.

The recognition of one other form of symmetry seemed worthwhile in the program. That is, in a face having an even number of edges, N, the partition lines for V = N/2 need begin only at edges numbered from 1 through N/2.

Comparison.

The procedure by which the polyhedra created by the splitting process are checked for equivalence will now be described. First, the tribe number for the newly created polyhedron is formed by counting triangles, quadrilaterals, etc. The tribe is checked against the tribe numbers of each of the polyhedra already formed. If the new one is not found in storage, then no further checking is necessary -- the new one is added to the collection.

If, on the other hand, the new tribe number matches one or more of those in storage, then members of this matching subset of polyhedra are singled out for detailed comparison with the new polyhedron. The detailed comparison entails looking for an exact one-to-one matching of the sets of face "words" of the two polyhedra being compared. That is, they are checked to see if they are equisurrounded, as defined above in Chapter I. At any point in the comparison, if a face word of a polyhedron A is unequal to a face word of polyhedron B, then a new polyhedron from storage is brought out for comparison. Similarly, comparison checking for a new polyhedron can be terminated immediately upon finding a polyhedron in storage with which the new one is equisurrounded. If, however, no such polyhedron is found, then the new one has to be "turned inside out" by reversing the cyclic order of the neighbors of each face, and checking it against the set of polyhedra of the same tribe again. If it survives this test without being rejected as equisurrounded with one in storage, then it is added to the collection. Then the program returns to make another partition.

Thus, in fact, my computer program regards polyhedra as equivalent if, and only if, they are equisurrounded.

Results.

Using the above program on the Stanford University Burroughs B5000 computer, consisting of a 16,384 word core memory, two drums, four tape drives, two card readers, two printers, and a card punch, I created all the tri-linear convex polyhedra of up to eleven faces. This took about twelve hours of computer time. In comparing my results with those published by Brückner [1] enumerated by another method, I found that we agreed, one-for-one, up to the 10-hedra, which is as far as he went at that time. In his 1928 paper [2] he claims to have found 1250 or 1251 11-hedra, these two figures appearing in two different places in the paper. My results showed only 1249 11-hedra, but have not been compared in detail with Brückner's since the supporting manuscripts upon which his paper was based are in Heidelberg. I hope to have the proper pages of the manuscripts duplicated and sent to me, if practicable.

I should like to point out the evidence which gives credence to my results. Brückner and Hermes disagreed quite a bit on their enumeration of polyhedra before the turn of the century. Hermes even found an omission in Brückner's list of 10-hedra, fortunately in time to include the correction in the publication [1].

Another example of a difference with Brückner's results is in the number of 12-hedra with hexagonal base. He claims 74 as against my 76, and there is a provable omission on his part in this case, even without reference to his manuscripts. The number of tribes of this class of polyhedra is 14 according to Brückner, whereas I have found 15. It is sufficient proof of their existence to draw a representative for each tribe, as I have done in Fig. 24.

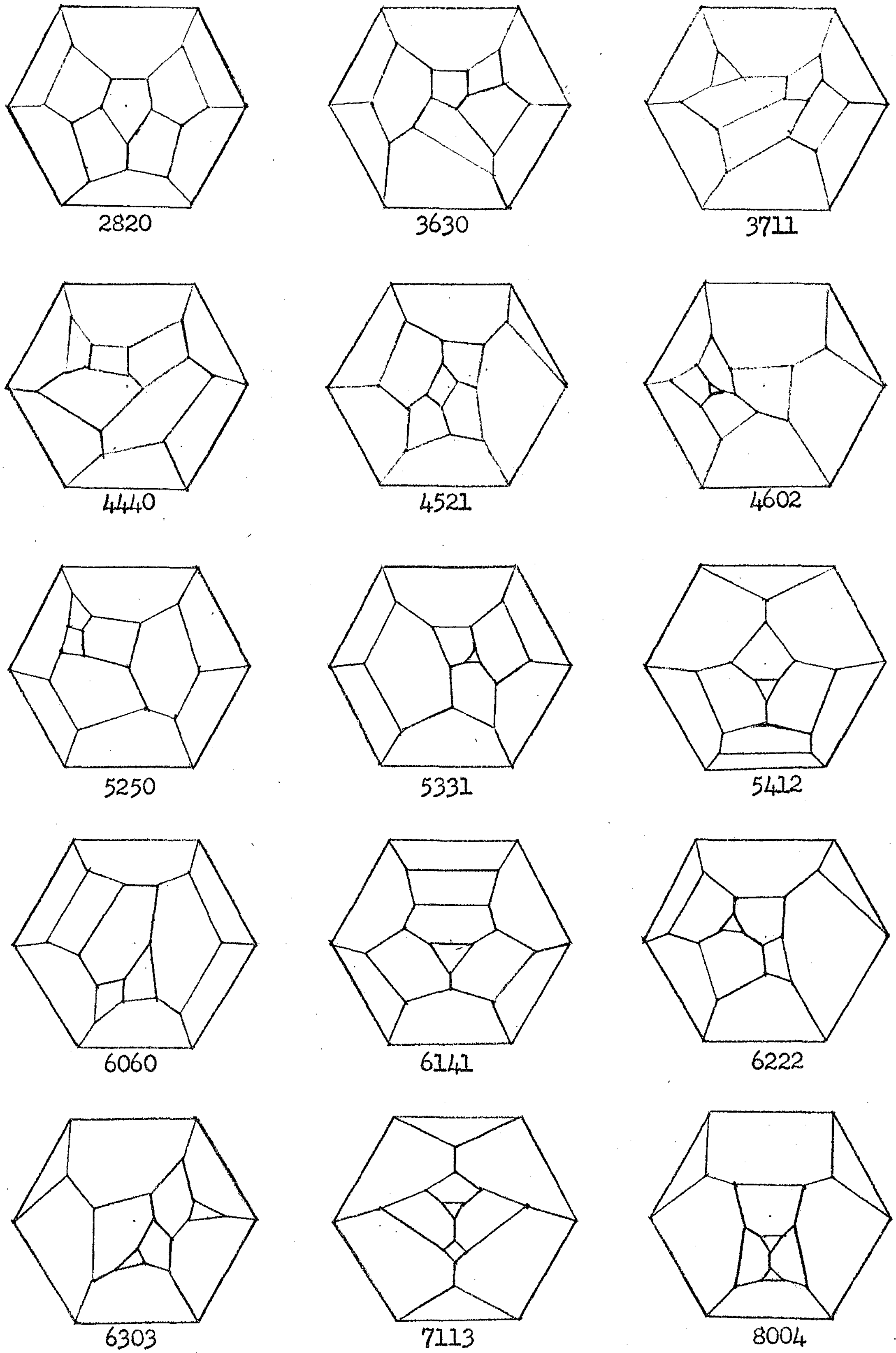


Fig. 24. Fifteen tribes of 12-hedra with maximum edge-count = 6.

In the section above called, "Kirkman polyhedra. Dissection of a Polygon into Triangles," we proved another error in Brückner's results, analytically rather than empirically.

Regarding the difference in the number of 11-hedra, the net difference of 1 between Brückner's 1250 and my 1249 polyhedra is a composite of two errors in certain subsets. For the number of 11-hedra with an octagonal base face (two faces in the polyhedron not contiguous with the base face) Brückner had 508 and I had 509. On the other hand, Brückner had 335 with a heptagonal base, whereas I had 333. These errors are in opposite directions, making a net discrepancy of 1.

As will be explained in Chapter IV, Testing Isomorphism, the criterion of equisurroundedness is a necessary but not sufficient condition for isomorphism of two polyhedra. If I had consistently found fewer polyhedra than Brückner then I would suspect that I had discarded some equisurrounded polyhedra which were, in fact, non-isomorphic. But the fact is that, except in the last cited case of the preceding paragraph, I consistently found more polyhedra than Brückner.

For purposes of comparison with the hand-work of Brückner and Hermes, I shall itemize my specific results in Table 2 and repeat theirs, where they differ from mine.

Recall that G stands for Gattung, or tribe, and P for polyhedra. The subscript shows the total number of faces, and the superscript shows the number of faces not contiguous with the base face. My results are shown, followed by Brückner's in parentheses where his differ from mine.

TABLE 2

SOME OF MY RESULTS COMPARED WITH THOSE OF BRÜCKNER

G_{11}^{0}	= 30	P_{11}^{0}	= 82
G_{11}^{1}	= 51	P_{11}^{1}	= 281
G_{11}^{2}	= 62	P_{11}^{2}	= 509 (508)
G_{11}^{3}	= 42	P_{11}^{3}	= 333 (335)
G_{11}^{4}	= 14	P_{11}^{4}	= 44
G_{11}	= 199	P_{11}	= 1249 (1250)
G_{12}^{5}	= 15 (14)	P_{12}^{5}	= 76 (74)
G_{12}^{6}	= 1	P_{12}^{6}	= 1 (reg. dodecahedron)
G_{13}^{6}	= 16	P_{13}^{6}	= 115
G_{14}^{7}	= 18	P_{14}^{7}	= 184 (178)
G_{15}^{8}	= 17	P_{15}^{8}	= 267 (266)

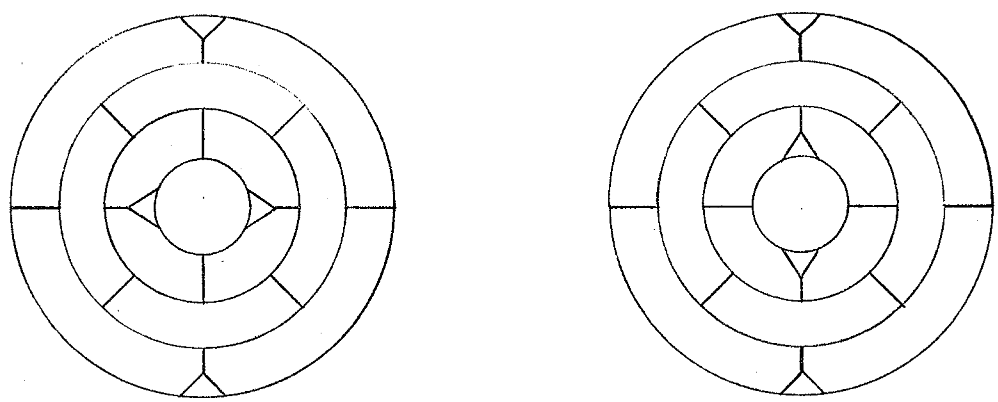
CHAPTER IV

TESTING ISOMORPHISM

The results of this work were obtained using "equisurroundedness" as the criterion for the equivalence of polyhedra. In the course of the work it turned out, however, that the following is true:

<u>Theorem 10. Equisurroundedness is a necessary but not a sufficient condition for isomorphism.</u>

The necessity is obvious, and the insufficiency is demonstrated by a counter-example. In a polyhedron having a large number of faces it is possible to isolate a symmetrical subset of faces in such a way that a perturbation can be made which does not alter the "surroundings" of the individual faces. The best example derived heretofore from this general idea is represented by Fig. 25. Each of the two polyhedra R and S has



Polyhedron R

Polyhedron S

Fig. 25.

eighteen faces deployed as follows: there are four hexagons forming a belt around the "equator" and two "polar caps" which look like the net of Fig. 26. In polyhedron S, the orientation of the two polar caps is "parallel," but in polyhedron R, one is rotated through 90 degrees with respect to the other, about the pole.

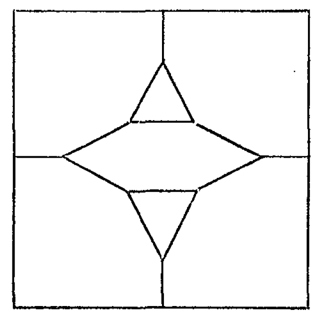


Fig. 26.

The present computer work includes only polyhedra of less than eighteen faces, yet we have no assurance that the criterion of equi-surroundedness is sufficient for isomorphism even for such polyhedra. A counter-example of fewer faces could possibly be found. The experimental evidence makes this seem unlikely since I found more of the higher polyhedra than Brückner in some cases, and never less. However, unless an analytical proof were found, a complete test for isomorphism would be necessary even for those polyhedra already generated, and certainly for those with more faces. Such a test is considerably more time-consuming than the test for equisurroundedness since face labels can be interchanged in so many ways, in general. However, it is not quite as bad as it might seem, since only like faces need be interchanged. That is, we can make tests for necessary conditions, thereby making it possible to reject the hypothesis of isomorphism early, and proceed to the detailed exhaustive isomorphism test only in a relatively small number of cases.

If two polyhedra, R and S, are isomorphic, their faces must match with respect to certain properties. For instance, if face R_1 is to correspond to face S_1, then they must not only have the same number of edges, but also must adjoin like polygons -- i.e. be equisurrounded as faces. Therefore it is not necessary to form all possible permutations of the labels of the faces, but only permutations of like faces. The number of permutations becomes very much smaller in a hurry. For example, 18! might become 2!4!4!8!.

We want to devise a list of necessary conditions for faces which will lead us to a conclusion of non-isomorphism quickly, leaving very few polyhedra to be checked completely. First, the tribes of the two polyhedra must of course be the same. Secondly, they must be equisurrounded. Thirdly, a face pair, one from each of the polyhedra being compared, must have equisurrounded neighbors also. A decision to be made here is whether to use the separate edge-counts of each of these neighbors' neighbors, or just the total of same.

Suppose we have such a list of necessary conditions for two polyhedra, A and B. This classifies the faces of A and B into subsets having like properties. Assume that the correspondence, by properties, is as shown in the following property list:

Polyhedron A	Property	Polyhedron B
(1,2)	1	(3,5)
(4,6,7)	2	(1,2,4,7)
(3)	3	(6)
(5,8)	4	(8)

We can conclude immediately that the two polyhedra are non-isomorphic since the numbers of faces in the above subsets do not correspond. However, if such a list does have equal numbers of faces in the corresponding subsets, we would have to test further in a manner like this: Choose a small subset and assume a correspondence between one face of A and one face of B. For example, under property 1 above, assume face A_1 maps into face B_3. This changes the property list. Then further extensions of the face properties (e.g. neighbors' neighbors) being evaluated are made, thereby refining the property list still further. This leads either to a contradiction, proof of isomorphism, or no further refinement. In the case of a contradiction, non-isomorphism is proved. Proof of isomorphism comes when the property list contains only subsets of one element each. In the last case, when there is no further refinement, we make a further assumption of correspondence and repeat.

Note that, regardless of whether two polyhedra are equisurrounded in their original form, or when one is turned inside out, the labels on the faces might not correspond unless one is turned inside out. For example, without relabeling the faces we ought to be able to determine that the two tetrahedra of Fig. 27 are isomorphic. In both tetrahedra, the base face is face #1.

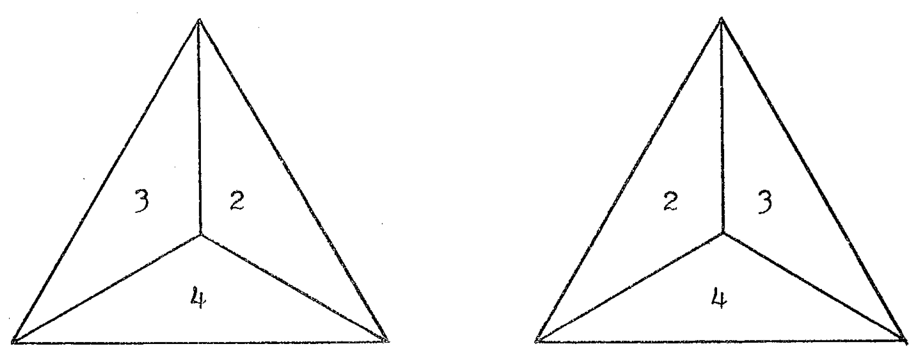


Fig. 27.

Now let us consider the eighteen-faced counter-example of Fig. 25, above, showing two polyhedra, R and S, which are equisurrounded but not isomorphic. Suppose we label the South Pole caps the same for the two polyhedra, as shown in Fig. 28. The numbers outside the cap are the labels of the adjoining faces -- the four hexagons around the equator.

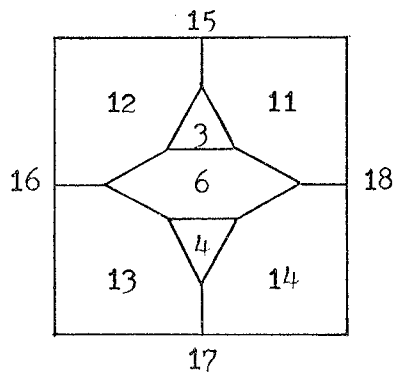


Fig. 28. Common South Pole.

For the North Pole caps, suppose we label the faces as shown in Fig. 29 for polyhedron R and polyhedron S. For this arrangement, the neighbors' edge-counts, listed under "Surroundings," and the neighbors' labels are shown in Table 3.

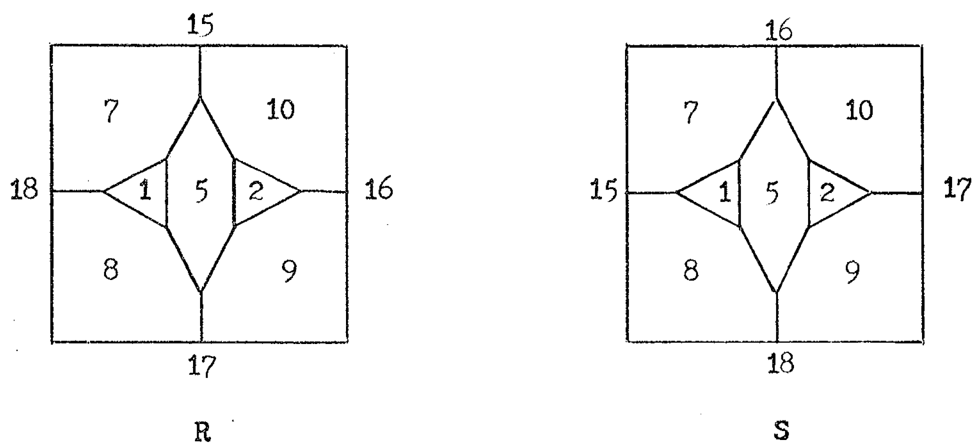


Fig. 29. North Poles.

TABLE 3

COMPUTER REPRESENTATION OF TWO SPECIAL 18-HEDRA

Face	Surroundings	R						S					
1	666				5	7	8				5	7	8
2	666				5	9	10				5	9	10
3	666				6	11	12				6	11	12
4	666				6	13	14				6	13	14
5	366366	1	8	9	2	10	7	1	8	9	2	10	7
6	"	3	12	13	4	14	11	3	12	13	4	14	11
7	366666	1	5	10	15	18	8	1	5	10	16	15	8
8	"	1	7	18	17	9	5	1	7	15	18	9	5
9	"	2	5	8	17	16	10	2	5	8	18	17	10
10	"	2	9	16	15	7	5	2	9	17	16	7	5
11	"	3	6	14	18	15	12	3	6	14	18	15	12
12	"	3	11	15	16	13	6	3	11	15	16	13	6
13	"	4	6	12	16	17	14	4	6	12	16	17	14
14	"	4	13	17	18	11	6	4	13	17	18	11	6
15	666666	7	10	16	12	11	18	7	16	12	11	18	8
16	"	9	17	13	12	15	10	7	10	17	13	12	15
17	"	8	18	14	13	16	9	9	18	14	13	16	10
18	"	7	15	11	14	17	8	8	15	11	14	17	9

For complete isomorphism testing, we need to permute the labels on one of the polyhedra and see if the result is identical with the other. Those with the same "surroundings" in the table are the ones which need to be permuted. Thus, we have to permute the labels on the faces within the subsets: (1,2,3,4); (5,6); (7,8,...13,14); and (15,16,17,18). There are 24.2.40320.24 ways to do this -- about 45 million. Even for smaller polyhedra, e.g. nine faces, the heptagonal prism requires 7!2! = 10,080 permutations. Because of the symmetry, the cardinality of the subsets is not reduced by most of the extensions of properties described above.

To be feasible, perhaps such a complete isomorphism test must wait for the next generation of computers.

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APPENDIX

Explanation of Appendix.

The appendix consists of two parts -- the listing of the computer program in Burroughs B5000 Extended Algol, followed by the enumeration of polyhedra produced by the computer. Because of the large volume of output it was necessary to code the list of polyhedra rather cryptically. A word of explanation is in order. Maximum edge-count is abbreviated MEC.

Each line of print in the list represents one polyhedron. The line bears the identification number (they are numbered serially) of the polyhedron, followed by one coded word for each face of the polyhedron, in order, beginning with face #1. Each word consists of n digits, where n is the number of sides of that face. The digits identify the adjoining faces in clockwise order. For polyhedra having more than 9 faces, the character "A" stands for 10, B for 11, etc. An example will help clarify the coding. Take polyhedron #1 from the list of 11-hedra on page 86. A clearer listing of its 11 faces is shown in Table 4.

TABLE 4

FIRST 11-HEDRON

Face Number	Number of Sides	Identification of Neighbors in Clockwise Order
1	8	4 3 8 6 9 10 11 2
2	8	10 9 6 5 3 4 1 11
3	5	4 2 5 8 1
4	3	3 1 2
5	5	7 8 3 2 6
6	6	7 5 2 9 1 8
7	3	8 5 6
8	5	7 6 1 3 5
9	4	10 1 6 2
10	4	9 2 11 1
11	3	10 2 1

COMPUTER PROGRAM

```
BEGIN COMMENT            D. W. GRACE             BIN 141
     EXT. 4425,       POLYHEDRON PARTITIONING PROBLEM
THINGS TO REMEMBER TO CHANGE BEFORE RUNNING
     THE DATA CARD CONTAINING F, PMAX, I, MS, AND ML.
     THE GMAX ASSIGNMENT STATEMENT -- THE FIRST EXECUTED STATEMENT.   ;
LABEL B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, FINALEND, GENESIS, ILOOP,
      MSMT, MLMT, MSZERO, MLZERO, POK, RESTART, READALL, START;
SWITCH SW6 ← B1, B2, B3, B4, B5, B6, B7, B8, B9, B10;
BOOLEAN BOOLIO, BOOL;
INTEGER A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, ALF, BAD, BAM, CNTL,
      DEL, DIM, F, FREQ, G, GMAX, I, J, JOE, K, LIXO, LIXM, MCH, ML, MS,
      N, PATJS, PATJT, PMAX, PRMINDEX, QINDEX, S, SAM, SIXO, SIXM, T,
      T1, TOTCOUNT, U, V, VM, VMAX, W, X, Y, Z;
REAL ARRAY COUNT[0:10], DELSAVE[0:11], DELTA[0:11],FREQL[0:1,0:700],
      FREQS[0:1022], MATCH[0:200], P[0:10], PRM[0:9], Q[0:11],
      QL[0:225,0:10],QS[0:125,0:10],QLD[0:14, 0:1013],QSD[0:12, 0:1013];
SAVE ARRAY INQ[0:11], PAT[0:11, 0:16],  QAT[0:11, 0:11];
ALPHA ARRAY CHAR[0:15];
FILE LP(2,15), PFIL 2(1,15,SAVE 099), QLDFIL 2(1,15,SAVE 099),
      QSDFIL 2(1, 15, SAVE 099);
FORMAT FMT1("FACE J =",I3,"NOT FOUND AS NABOR IN FACE WORD ",2A6);
FORMAT FMT2("TRIBE ", 11A1);
FORMAT FMT4 ("START TO MAKE ",I3,"-HEDRA FROM ",I3,"-HEDRA.");
FORMAT FMT6(X12, I1, X16, I2, X11, I2, X6, 10(A1, "-", A1, X2) ) ;
FORMAT FMT9(X5, "ELAPSED EXECUTION TIME IS", F8.2, " MINUTES. RESTART PA
RAMETER I IS NOW", I4, ".");
FORMAT FMT10(X5, "L POLY NO. FOLLOWED BY ITS QLD.",I4,X2,  11(A6,X1));
FORMAT FMT11(X5, "S POLY NO. FOLLOWED BY ITS QSD.",I4,X2,  11(A6,X1));
FORMAT FMT12(X5, "PERMUTE RIGHT    NUMBER OF SIDES    FACE    CLOCKWISE
NEIGHBORS (ID. NO.)-(NO. OF SIDES)     NOTE: #=10, @=11.");
FORMAT FMT13(X5, "POLY", I4, " FACE", I2, " WITH V =", I2, " AND S =",
I3, ".   RESTART PARAMETERS F, PMAX, I, MS, AND ML ARE",I3,I4,I4,I5,I5);
FORMAT FMT15(/"EXECUTION TIME EXCLUSIVE OF COMPILATION WAS ",F9.2,
      " MINUTES.");
FORMAT FMT16("RESTART USING PARAMETERS F =",I3," PMAX =",I4,  "  I =",
     I4, "  MS =", I5, "  AND ML =", I5);
FORMAT FMT17("PFIL MESSED UP.  I =", I4, " NOT EQUAL TO P[0] =",I4);
FORMAT FMT91(I5, X1,93A1);
FORMAT FMT92(X99, I3, I4, I4, I5, I5);
PROCEDURE PARTITION     ;
BEGIN
    LABEL ERR1, ENDPART, END8, END10, END11, BIGT, STNEXT;
    T ← V+S ; COMMENT T = SUBSCRIPT OF TERMINAL NABOR BUT NOT MOD N. ;
    COMMENT S = SUBSCRIPT OF STARTING NABOR, AND V = NO. VERTS CUT OFF.;
    FOR Y ← 1 STEP 1 UNTIL F DO
    BEGIN JOE ← PAT[Y,0];
      FOR Z ← 0 STEP 1 UNTIL JOE DO QAT[Y,Z] ← PAT[Y,Z];
    END; COMMENT NOW MAKE CORRECTIONS TO QAT CAUSED BY PARTITION.   ;
    QAT[G,0] ← V + 2;  COMMENT NEW FACE HAS V + 2 EDGES.   ;
    QAT[G,1] ← J;
    FOR Z ← 0 STEP 1 UNTIL V DO QAT[G,Z+2] ← PAT[J,Z + S];
    BAM ← V - 2;
    JOE ← QAT [J, 0] ← N - BAM;
```

```
COMMENT  CUT FACE HAS N-V+2 EDGES.
IF N < 1 THEN GO TO BIGT;
QAT [J, S + 1] ← G;   COMMENT  THE FIRST S NABORS ARE UNCHANGED.;
FOR Z ← S + 2 STEP 1 UNTIL JOE DO QAT [J, Z] ← PAT [J, BAM + Z];
GO TO STNEXT;
COMMENT  GO AHEAD AND ADJUST NABORS S AND T NEXT.   ;
BIGT: COMMENT                                  BIGT: ;
QAT [J, 1] ← G;
BAM ← (T MOD N) - 2;
FOR Z ← 2 STEP 1 UNTIL JOE DO QAT [J, Z] ← PAT [J, BAM + Z];
COMMENT NEW FACE, G, REPLACED ALL NABORS OF CUT FACE ENTRE S AND T.;
STNEXT: COMMENT                                        STNEXT: ;
PATJS ← PAT [J, S];
COMMENT  PATJS = NABOR NUMBER S OF FACE J.   ;
JOE ← PAT [PATJS, 0];
QAT [PATJS, 0] ← JOE + 1;
FOR Z ← 1 STEP 1 UNTIL JOE DO IF QAT [PATJS, Z] = J THEN
BEGIN FOR Y←JOE STEP -1 UNTIL Z DO QAT[PATJS,Y+1]←QAT[PATJS,Y];
   GO TO END11;
END;
END11: COMMENT                                        END11:;
QAT [PATJS, Z] ← G;
COMMENT  QAT[PATJS,0] = DIMENSION OF NABOR S.          NOTICE THAT
T MAY BE BIGGER THAN N BECAUSE OF THE WRAP-AROUND FEATURE. ;
PATJT ← PAT [J, T]; COMMENT   PATJT = NABOR NUMBER T OF FACE J.    ;
JOE ← PAT [PATJT, 0]; COMMENT  DIMENSION OF NABOR T.    ;
QAT [PATJT, 0] ← JOE + 1;
FOR Z ← 1 STEP 1 UNTIL JOE DO IF QAT [PATJT, Z] = J THEN
BEGIN FOR Y ← JOE - 1 STEP - 1 UNTIL Z DO QAT [PATJT, Y + 2] ←
   QAT[PATJT, Y + 1];
   GO TO END10;
END;
END10: COMMENT                                         END10: ;
QAT [PATJT, Z + 1] ← G;  COMMENT  EDGE/COUNT OF NEIGHBOR T.  ;
FOR Z ← 2 STEP 1 UNTIL V DO
BEGIN U ← PAT [J, S + Z - 1];
   COMMENT  U = ID OF NABOR NO. S+Z-1 OF FACE J.    ;
   COMMENT   THAT IS, WE DO THIS FOR NABOR NO. S+1, S+2,...T-1. ;
   FOR Y ← 1 STEP 1 UNTIL QAT [U, 0] DO IF QAT [U, Y] = J THEN
   BEGIN QAT [U, Y] ← G; GO TO END8; END;
   BAD ← QAT [U, Y];
   ERR1: WRITE (LP, FMT1, J, BAD . [4 : 20], BAD . [24 : 24]);
END8:   END;   COMMENT                                     END8: ;
ENDPART: END;    COMMENT END OF PROCEDURE PARTITION.          ENDPART:;
PROCEDURE ISOCHECK;
BEGIN
   LABEL CANON, E3, E4, E5, E6, E7, E8, E9, E10,ENDISO,END5, FILLQSD,
      L3, L4, L5, L6, L7, L8, L9, L10, MAKEPRM, PICKPRM, STARTPRM,SORT;
   SWITCH SW2 ← L3, L4, L5, L6, L7, L8, L9, L10;
   SWITCH SW7 ← E3, E4, E5, E6, E7, E8, E9, E10;
   FORMAT FMT14 ("TCTCOUNT ERROR.", I2, X5, 15 (I2, X1));
   BOOL10 ← FALSE;
   LIXD ← (ML+1) DIV 92;
   LIXM ← ((ML+1) MOD 92) × 11;
   SIXD ← (MS+1) DIV 92;
```

```
SIXM ← ((MS+1) MOD 92) × 11;
FOR Z ← 3 STEP 1 UNTIL F DO COUNT [Z] ← 0;
FOR Z ← 1 STEP 1 UNTIL G DO COMMENT    FOR EACH FACE.      ;
BEGIN DIM ← QAT [Z, 0];
   COUNT [DIM] ← COUNT [DIM] + 1;
END;
TOTCOUNT ← 0;
FOR Z ← 3 STEP 1 UNTIL F DO TOTCOUNT ← TOTCOUNT + COUNT [Z];
IF TOTCOUNT = G THEN GO TO CANON;
WRITE (LP, FMT14, TOTCOUNT, FOR Z ← 1 STEP 1 UNTIL 15 DO COUNT [Z]);
CANON: COMMENT                                          CANON:;
CNTL ← COUNT[F] + COUNT[F-1];
COMMENT  NOW WE FORM ALL POSSIBLE PERMUTATIONS OF THE NABORS EDGE-
COUNTS AND PICK THE NUMERICALLY SMALLEST FOR OUR CANONICAL FORM. ;
STARTPRM: COMMENT                                    STARTPRM:;
FOR Z ← 1 STEP 1 UNTIL G DO COMMENT      FOR EACH FACE.     ;
BEGIN DIM ← QAT [Z, 0];
   PRMINDEX ← DIM - 1;
   IF BOOLIO THEN GO TO SW7 [DIM - 2]; COMMENT E3, ..., E10. ;
   A10 ← QAT [QAT [Z, 10], 0];
   A9 ← QAT [QAT [Z, 9], 0];
   A8 ← QAT [QAT [Z, 8], 0];
   A7 ← QAT [QAT [Z, 7], 0];
   A6 ← QAT [QAT [Z, 6], 0];
   A5 ← QAT [QAT [Z, 5], 0];
   A4 ← QAT [QAT [Z, 4], 0];
   A3 ← QAT [QAT [Z, 3], 0];
   A2 ← QAT [QAT [Z, 2], 0];
   A1 ← QAT [QAT [Z, 1], 0];
   GO TO MAKEPRM;
   E10: A10 ← QAT [QAT [Z, DIM - 9], 0];
   E9: A9 ← QAT [QAT [Z, DIM - 8], 0];
   E8: A8 ← QAT [QAT [Z, DIM - 7], 0];
   E7: A7 ← QAT [QAT [Z, DIM - 6], 0];
   E6: A6 ← QAT [QAT [Z, DIM - 5], 0];
   E5: A5 ← QAT [QAT [Z, DIM - 4], 0];
   E4: A4 ← QAT [QAT [Z, DIM - 3], 0];
   E3: A3 ← QAT [QAT [Z, DIM - 2], 0];
   A2 ← QAT [QAT [Z, DIM - 1], 0];
   A1 ← QAT [QAT [Z, DIM], 0];
   DELSAVE [Z] ← DELTA [Z];
   COMMENT   MUST SAVE THE DELTAS WHILE DOING INSIDE-OUT CHECK.   ;
   MAKEPRM: COMMENT                                  MAKEPRM:;
   GO TO SW2 [DIM - 2];
   L10: COMMENT                                           L10:;
   PRM [0] ← 0 & A10 [8 : 44 : 4] & A9 [12 : 44 : 4] & A8 [16 : 44
   : 4] & A7 [20 : 44 : 4] & A6 [24 : 44 : 4] & A5 [28 : 44 : 4] &
   A4[32 : 44 : 4] & A3[36 : 44 : 4] & A2[40 : 44 :4] & A1[44:44:4]];
   PRM [1] ← 0 & A1 [8 : 44 : 4] & A10 [12 : 44 : 4] & A9 [16 : 44
   : 4] & A8 [20 : 44 : 4] & A7 [24 : 44 : 4] & A6 [28 : 44 : 4] &
   A5[32 : 44 : 4] & A4[36 : 44 : 4] & A3[40 : 44 :4] & A2[44:44:4]];
   PRM [2] ← 0 & A2 [8 : 44 : 4] & A1 [12 : 44 : 4] & A10 [16 : 44
   : 4] & A9 [20 : 44 : 4] & A8 [24 : 44 : 4] & A7 [28 : 44 : 4] &
   A6[32 : 44 : 4] & A5[36 : 44 : 4] & A4[40 : 44 :4] & A3[44:44:4]];
   PRM [3] ← 0 & A3 [8 : 44 : 4] & A2 [12 : 44 : 4] & A1 [16 : 44
```

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: 4] & A10 [20 : 44 : 4] & A9 [24 : 44 : 4] & A8 [28 : 44 : 4]
& A7[32 : 44 :4] & A6[36 : 44: 4] & A5[40 : 44 :4] & A4[44:44:4];
PRM [4] ← 0 & A4 [8 : 44 : 4] & A3 [12 : 44 : 4] & A2 [16 : 44
: 4] & A1 [20 : 44 : 4] & A10 [24 : 44 : 4] & A9 [28 : 44 : 4]
& A8[32 : 44 :4] & A7[36 : 44: 4] & A6[40 : 44 :4] & A5[44:44:4];
PRM [5] ← 0 & A5 [8 : 44 : 4] & A4 [12 : 44 : 4] & A3 [16 : 44
: 4] & A2 [20 : 44 : 4] & A1 [24 : 44 : 4] & A10 [28 : 44 : 4]
& A9[32 : 44 :4] & A8[36 : 44: 4] & A7[40 : 44 :4] & A6[44:44:4];
PRM [6] ← 0 & A6 [8 : 44 : 4] & A5 [12 : 44 : 4] & A4 [16 : 44
: 4] & A3 [20 : 44 : 4] & A2 [24 : 44 : 4] & A1 [28 : 44 : 4]
& A10[32: 44 :4] & A9[36 : 44: 4] & A8[40 : 44 :4] & A7[44:44:4];
PRM [7] ← 0 & A7 [8 : 44 : 4] & A6 [12 : 44 : 4] & A5 [16 : 44
: 4] & A4 [20 : 44 : 4] & A3 [24 : 44 : 4] & A2 [28 : 44 : 4] &
A1 [32: 44 :4] & A10[36: 44: 4] & A9[40 : 44 :4] & A8[44:44:4];
PRM [8] ← 0 & A8 [8 : 44 : 4] & A7 [12 : 44 : 4] & A6 [16 : 44
: 4] & A5 [20 : 44 : 4] & A4 [24 : 44 : 4] & A3 [28 : 44 : 4] &
A2 [32: 44 :4] & A1 [36: 44: 4] & A10[40: 44 :4] & A9[44:44:4];
PRM [9] ← 0 & A9 [8 : 44 : 4] & A8 [12 : 44 : 4] & A7 [16 : 44
: 4] & A6 [20 : 44 : 4] & A5 [24 : 44 : 4] & A4 [28 : 44 : 4] &
A3 [32: 44 :4] & A2 [36: 44: 4] & A1 [40: 44 :4] & A10[44:44:4];
GO TO PICKPRM;
L9: COMMENT                                                 L9:;
PRM [0] ← 0 & A9 [12 : 44 : 4] & A8 [16 : 44 : 4] & A7 [20 : 44
: 4] & A6 [24 : 44 : 4] & A5 [28 : 44 : 4] & A4 [32 : 44 : 4] &
A3 [36 : 44 : 4] & A2 [40 : 44 : 4] & A1 [44 : 44 : 4];
PRM [1] ← 0 & A1 [12 : 44 : 4] & A9 [16 : 44 : 4] & A8 [20 : 44
: 4] & A7 [24 : 44 : 4] & A6 [28 : 44 : 4] & A5 [32 : 44 : 4] &
A4 [36 : 44 : 4] & A3 [40 : 44 : 4] & A2 [44 : 44 : 4];
PRM [2] ← 0 & A2 [12 : 44 : 4] & A1 [16 : 44 : 4] & A9 [20 : 44
: 4] & A8 [24 : 44 : 4] & A7 [28 : 44 : 4] & A6 [32 : 44 : 4] &
A5 [36 : 44 : 4] & A4 [40 : 44 : 4] & A3 [44 : 44 : 4];
PRM [3] ← 0 & A3 [12 : 44 : 4] & A2 [16 : 44 : 4] & A1 [20 : 44
: 4] & A9 [24 : 44 : 4] & A8 [28 : 44 : 4] & A7 [32 : 44 : 4] &
A6 [36 : 44 : 4] & A5 [40 : 44 : 4] & A4 [44 : 44 : 4];
PRM [4] ← 0 & A4 [12 : 44 : 4] & A3 [16 : 44 : 4] & A2 [20 : 44
: 4] & A1 [24 : 44 : 4] & A9 [28 : 44 : 4] & A8 [32 : 44 : 4] &
A7 [36 : 44 : 4] & A6 [40 : 44 : 4] & A5 [44 : 44 : 4];
PRM [5] ← 0 & A5 [12 : 44 : 4] & A4 [16 : 44 : 4] & A3 [20 : 44
: 4] & A2 [24 : 44 : 4] & A1 [28 : 44 : 4] & A9 [32 : 44 : 4] &
A8 [36 : 44 : 4] & A7 [40 : 44 : 4] & A6 [44 : 44 : 4];
PRM [6] ← 0 & A6 [12 : 44 : 4] & A5 [16 : 44 : 4] & A4 [20 : 44
: 4] & A3 [24 : 44 : 4] & A2 [28 : 44 : 4] & A1 [32 : 44 : 4] &
A9 [36 : 44 : 4] & A8 [40 : 44 : 4] & A7 [44 : 44 : 4];
PRM [7] ← 0 & A7 [12 : 44 : 4] & A6 [16 : 44 : 4] & A5 [20 : 44
: 4] & A4 [24 : 44 : 4] & A3 [28 : 44 : 4] & A2 [32 : 44 : 4] &
A1 [36 : 44 : 4] & A9 [40 : 44 : 4] & A8 [44 : 44 : 4];
PRM [8] ← 0 & A8 [12 : 44 : 4] & A7 [16 : 44 : 4] & A6 [20 : 44
: 4] & A5 [24 : 44 : 4] & A4 [28 : 44 : 4] & A3 [32 : 44 : 4] &
A2 [36 : 44 : 4] & A1 [40 : 44 : 4] & A9 [44 : 44 : 4];
GO TO PICKPRM;
L8: COMMENT                                                 L8:;
PRM [0] ← 0 & A8 [16 : 44 : 4] & A7 [20 : 44 : 4] & A6 [24 : 44
: 4] & A5 [28 : 44 : 4] & A4 [32 : 44 : 4] & A3 [36 : 44 : 4] &
A2 [40 : 44 : 4] & A1 [44 : 44 : 4];
PRM [1] ← 0 & A1 [16 : 44 : 4] & A8 [20 : 44 : 4] & A7 [24 : 44
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: 4] & A6 [28 : 44 : 4] & A5 [32 : 44 : 4] & A4 [36 : 44 : 4] &
A3 [40 : 44 : 4] & A2 [44 : 44 : 4];
PRM [2] ← 0 & A2 [16 : 44 : 4] & A1 [20 : 44 : 4] & A8 [24 : 44
: 4] & A7 [28 : 44 : 4] & A6 [32 : 44 : 4] & A5 [36 : 44 : 4] &
A4 [40 : 44 : 4] & A3 [44 : 44 : 4];
PRM [3] ← 0 & A3 [16 : 44 : 4] & A2 [20 : 44 : 4] & A1 [24 : 44
: 4] & A8 [28 : 44 : 4] & A7 [32 : 44 : 4] & A6 [36 : 44 : 4] &
A5 [40 : 44 : 4] & A4 [44 : 44 : 4];
PRM [4] ← 0 & A4 [16 : 44 : 4] & A3 [20 : 44 : 4] & A2 [24 : 44
: 4] & A1 [28 : 44 : 4] & A8 [32 : 44 : 4] & A7 [36 : 44 : 4] &
A6 [40 : 44 : 4] & A5 [44 : 44 : 4];
PRM [5] ← 0 & A5 [16 : 44 : 4] & A4 [20 : 44 : 4] & A3 [24 : 44
: 4] & A2 [28 : 44 : 4] & A1 [32 : 44 : 4] & A8 [36 : 44 : 4] &
A7 [40 : 44 : 4] & A6 [44 : 44 : 4];
PRM [6] ← 0 & A6 [16 : 44 : 4] & A5 [20 : 44 : 4] & A4 [24 : 44
: 4] & A3 [28 : 44 : 4] & A2 [32 : 44 : 4] & A1 [36 : 44 : 4] &
A8 [40 : 44 : 4] & A7 [44 : 44 : 4];
PRM [7] ← 0 & A7 [16 : 44 : 4] & A6 [20 : 44 : 4] & A5 [24 : 44
: 4] & A4 [28 : 44 : 4] & A3 [32 : 44 : 4] & A2 [36 : 44 : 4] &
A1 [40 : 44 : 4] & A8 [44 : 44 : 4];
GO TO PICKPRM;
L7: COMMENT                                                 L7:;
PRM [0] ← 0 & A7 [20 : 44 : 4] & A6 [24 : 44 : 4] & A5 [28 : 44
: 4] & A4 [32 : 44 : 4] & A3 [36 : 44 : 4] & A2 [40 : 44 : 4] &
A1 [44 : 44 : 4];
PRM [1] ← 0 & A1 [20 : 44 : 4] & A7 [24 : 44 : 4] & A6 [28 : 44
: 4] & A5 [32 : 44 : 4] & A4 [36 : 44 : 4] & A3 [40 : 44 : 4] &
A2 [44 : 44 : 4];
PRM [2] ← 0 & A2 [20 : 44 : 4] & A1 [24 : 44 : 4] & A7 [28 : 44
: 4] & A6 [32 : 44 : 4] & A5 [36 : 44 : 4] & A4 [40 : 44 : 4] &
A3 [44 : 44 : 4];
PRM [3] ← 0 & A3 [20 : 44 : 4] & A2 [24 : 44 : 4] & A1 [28 : 44
: 4] & A7 [32 : 44 : 4] & A6 [36 : 44 : 4] & A5 [40 : 44 : 4] &
A4 [44 : 44 : 4];
PRM [4] ← 0 & A4 [20 : 44 : 4] & A3 [24 : 44 : 4] & A2 [28 : 44
: 4] & A1 [32 : 44 : 4] & A7 [36 : 44 : 4] & A6 [40 : 44 : 4] &
A5 [44 : 44 : 4]:
PRM [5] ← 0 & A5 [20 : 44 : 4] & A4 [24 : 44 : 4] & A3 [28 : 44
: 4] & A2 [32 : 44 : 4] & A1 [36 : 44 : 4] & A7 [40 : 44 : 4] &
A6 [44 : 44 : 4];
PRM [6] ← 0 & A6 [20 : 44 : 4] & A5 [24 : 44 : 4] & A4 [28 : 44
: 4] & A3 [32 : 44 : 4] & A2 [36 : 44 : 4] & A1 [40 : 44 : 4] &
A7 [44 : 44 : 4];
GO TO PICKPRM;
L6: COMMENT                                                 L6:;
PRM [0] ← 0 & A6 [24 : 44 : 4] & A5 [28 : 44 : 4] & A4 [32 : 44
: 4] & A3 [36 : 44 : 4] & A2 [40 : 44 : 4] & A1 [44 : 44 : 4];
PRM [1] ← 0 & A1 [24 : 44 : 4] & A6 [28 : 44 : 4] & A5 [32 : 44
: 4] & A4 [36 : 44 : 4] & A3 [40 : 44 : 4] & A2 [44 : 44 : 4];
PRM [2] ← 0 & A2 [24 : 44 : 4] & A1 [28 : 44 : 4] & A6 [32 : 44
: 4] & A5 [36 : 44 : 4] & A4 [40 : 44 : 4] & A3 [44 : 44 : 4];
PRM [3] ← 0 & A3 [24 : 44 : 4] & A2 [28 : 44 : 4] & A1 [32 : 44
: 4] & A6 [36 : 44 : 4] & A5 [40 : 44 : 4] & A4 [44 : 44 : 4];
PRM [4] ← 0 & A4 [24 : 44 : 4] & A3 [28 : 44 : 4] & A2 [32 : 44
: 4] & A1 [36 : 44 : 4] & A6 [40 : 44 : 4] & A5 [44 : 44 : 4];
```

```
    PRM [5] ← 0 & A5 [24 : 44 : 4] & A4 [28 : 44 : 4] & A3 [32 : 44   .
    : 4] & A2 [36 : 44 : 4] & A1 [40 : 44 : 4] & A6 [44 : 44 : 4];     .
    GO TO PICKPRM;                                                     .
    L5: COMMENT                                         L5:;           .
    PRM [0] ← 0 & A5 [28 : 44 : 4] & A4 [32 : 44 : 4] & A3 [36 : 44   .
    : 4] & A2 [40 : 44 : 4] & A1 [44 : 44 : 4];                        .
    PRM [1] ← 0 & A1 [28 : 44 : 4] & A5 [32 : 44 : 4] & A4 [36 : 44   .
    : 4] & A3 [40 : 44 : 4] & A2 [44 : 44 : 4];                        .
    PRM [2] ← 0 & A2 [28 : 44 : 4] & A1 [32 : 44 : 4] & A5 [36 : 44   .
    : 4] & A4 [40 : 44 : 4] & A3 [44 : 44 : 4];                        .
    PRM [3] ← 0 & A3 [28 : 44 : 4] & A2 [32 : 44 : 4] & A1 [36 : 44   .
    : 4] & A5 [40 : 44 : 4] & A4 [44 : 44 : 4];                        .
    PRM [4] ← 0 & A4 [28 : 44 : 4] & A3 [32 : 44 : 4] & A2 [36 : 44   .
    : 4] & A1 [40 : 44 : 4] & A5 [44 : 44 : 4];                        .
    GO TO PICKPRM;                                                     .
    L4: COMMENT                                         L4:;           .
    PRM [0] ← 0 & A4 [32 : 44 : 4] & A3 [36 : 44 : 4] & A2 [40 : 44   .
    : 4] & A1 [44 : 44 : 4];                                           .
    PRM [1] ← 0 & A1 [32 : 44 : 4] & A4 [36 : 44 : 4] & A3 [40 : 44   .
    : 4] & A2 [44 : 44 : 4];                                           .
    PRM [2] ← 0 & A2 [32 : 44 : 4] & A1 [36 : 44 : 4] & A4 [40 : 44   .
    : 4] & A3 [44 : 44 : 4];                                           .
    PRM [3] ← 0 & A3 [32 : 44 : 4] & A2 [36 : 44 : 4] & A1 [40 : 44   .
    : 4] & A4 [44 : 44 : 4];                                           .
    GO TO PICKPRM;                                                     .
    L3: COMMENT                                         L3:;           .
    PRM [0] ← 0 & A3 [36 : 44 : 4] & A2 [40 : 44 : 4] & A1 [44:44:4];.
    PRM [1] ← 0 & A1 [36 : 44 : 4] & A3 [40 : 44 : 4] & A2 [44:44:4];.
    PRM [2] ← 0 & A2 [36 : 44 : 4] & A1 [40 : 44 : 4] & A3 [44:44:4];.
    GO TO PICKPRM;                                                     .
    PICKPRM: COMMENT                                PICKPRM:;          .
    DELTA [Z] ← 0;                                                     .
    FOR Y ← 1 STEP 1 UNTIL PRMINDEX DO COMMENT  PRMINDEX=QAT[Z,0]-1.;.
       IF PRM[Y] < PRM[DELTA[Z]] THEN  DELTA[Z] ← Y;                   .
    COMMENT  RECALL THAT WE SET DELTA TO ZERO ABOVE.                   .
    NOW DELTA CONTAINS THE PHASE SHIFT NEEDED IN THE PERMUTATION TO    .
    PUT THESE FACES IN CANONICAL FORM,  AND PRM[DELTA] CONTAINS THE    .
    NEIGHBORS EDGE-COUNTS IN CANONICAL FORM. THE LATTER MUST BE        .
    STUFFED INTO THE QLD OR QSD ARRAYS FOR COMPARISON WITH OTHERS. ;  .
    Q[Z] ← 0 & PRM[DELTA[Z]][1:5 :43] & DIM[44:44: 4];                 .
END;     COMMENT    END OF Z LOOP WHICH BEGAN AT STARTPRM.        ;    .
Y ← G;                                                                 .
SORT:          COMMENT                                     SORT:;      .
BOOL ← FALSE;                                                          .
FOR Z ← 2 STEP 1 UNTIL Y DO IF Q[Z] > Q[(X+Z-1)] THEN                  .
BEGIN DOUBLE (Q[Z], Q[X], ←, Q[X], Q[Z]);          ,                   .
   BOOL ← TRUE;                                                        .
END;                                                                   .
IF BOOL THEN BEGIN Y ← Y-1;     GO TO SORT;     END;                   .
IF CNIL = 0 THEN GO TO FILLQSD;COMMENT  SEE CANON: + 1        ;        .
FOR Z ← 1 STEP 1 UNTIL G DO QLD[LIXD,Z+LIXM] ← Q[Z];                   .
GO TO END5;                                                            .
FILLQSD:     COMMENT                                     FILLQSD;      .
FOR Z ← 1 STEP 1 UNTIL G DO QSD[SIXD,Z+SIXM] ← Q[Z];                   .
END5:                   COMMENT                          END5: ;       .
```

```
BEGIN LABEL C3, C4, C5, C6, C7, C8, C9, C10, COMPL, COMPS, D3, D4,
   D5, D6, D7, D8, D9, D10, DETAILL, DETAILS, END1,        END3,
   END4,        END7, M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, N1,
   N2, N3, N4, N5, N6, N7, N8, N9, N10, NEQL, NEQS, NEWL, NEWS,
   PACKFREQL, PACKFREQS, PRINTPOLY;
   SWITCH SW1 ← C4, C5, C6, C7, C8, C9, C10;
   SWITCH SW3 ← D4, D5, D6, D7, D8, D8, D8;
   SWITCH SW4 ← N3, N4, N5, N6, N7, N8, N9, N10;
   SWITCH SW5 ← M3, M4, M5, M6, M7, M8, M9, M10;
   IF BOOLIO THEN
   BEGIN IF CNTL = 0 THEN GO TO DETAILS;
      GO TO DETAILL;
   END;
   COMMENT  WE HAVE TWO SETS OF ARRAYS FOR THE POLYHEDRA FOUND THUS
   FAR. WE HAVE ARBITRARILY SEPARATED THEM ACCORDING TO WHETHER THEY
   HAVE ANY FACES OF EDGE-COUNT F OR F-L, OR NOT. WE HAVE TWO SETS
   OF PARALLEL CODE TO TREAT THESE TWO CLASSES OF POLYHEDRA, S AND
   L. THE LATTER BEGINS HERE.  FOR EACH STORED POLYHEDRON WE HAVE A
   CODE WORD, FREQL[], SHOWING IN THE LOW-ORDER  4 BITS THE NUMBER
   OF TRIANGLES, IN THE NEXT 4 BITS THE NUMBER OF QUADRILATERALS,
   AND SO FORTH.  IF THE NEW POLYHEDRON FORMED BY THE PRESENT PARTI-
   TION HAS A DIFFERENT TRIBE NUMBER FROM ALL THOSE POLYHEDRA FOUND
   AND STORED THUS FAR,  THEN WE CAN BE SURE THAT THE NEW ONE IS NOT
   ISOMORPHIC WITH ANY OF THE OLD ONES.  THUS WE CAN ADD THE NEW ONE
   TO THE LIST WITHOUT FURTHER CHECKING.  ON THE OTHER HAND, IF WE
   DO FIND A MATCH OF FREQUENCY WORDS, WE STILL CANNOT BE SURE THAT
   WE HAVE AN ISOMORPHIC POLYHEDRON BUT MUST NOW CHECK THE SO-CALLED
   QLD[] WORDS (QSD[] FOR S POLYS), WHICH CONTAIN THE INFORMATION
   AS TO DEPLOYMENT OF FACES, BY DIMENSION,  IN THE POLYHEDRON.
   NOTE THAT MATCH[] CONTAINS THE SUBSCRIPTS OF STORED POLYHEDRA
   HAVING THE SAME FREQUENCY WORD AS THE NEW ONE BEING TESTED.
   MCH IS THE NUMBER OF SUCH MATCHES FOUND.   ;
   MCH ← 0;
   IF CNTL = 0 THEN GO TO COMPS;
   COMPL: COMMENT                                                COMPL:;
   FOR Y ← 1 STEP 1 UNTIL ML DO
   BEGIN FREQ ← FREQL [Y DIV 700, Y MOD 700];
      GO TO SW1 [F - 3]; COMMENT    C4, C5,....C10.     ;
      C10: IF COUNT [10] ≠ FREQ . [16 : 4] THEN GO TO END1;
      C9: IF COUNT [9] ≠ FREQ . [20 : 4] THEN GO TO END1;
      C8: IF COUNT [8] ≠ FREQ . [24 : 4] THEN GO TO END1;
      C7: IF COUNT [7] ≠ FREQ . [28 : 4] THEN GO TO END1;
      C6: IF COUNT [6] ≠ FREQ . [32 : 4] THEN GO TO END1;
      C5: IF COUNT [5] ≠ FREQ . [36 : 4] THEN GO TO END1;
      C4: IF COUNT [4] ≠ FREQ . [40 : 4] THEN GO TO END1;
      C3: IF COUNT [3] ≠ FREQ . [44 : 4] THEN GO TO END1;
      MCH ← MCH + 1;
      MATCH [MCH] ← Y;
   END1:   END;  COMMENT  END OF Y LOOP.                         END1:;
   IF MCH = 0 THEN GO TO NEWL; COMMENT ADD NEW POLY TO THE LIST.  ;
   COMMENT NOW OUR NEW POLYHEDRON IS DESIGNATED BY A LIST OF F+1 = G
   WORDS, EACH WORD DESIGNATING ONE FACE, AND EACH WORD SHOWING THE
   EDGE-COUNT OF THE FACE AND THE EDGE-COUNTS OF ITS NEIGHBORS, IN
   CANONICAL FORM.  NOW WE HAVE TO COMPARE THE NEW POLYHEDRON WITH
   THE SET OF POLYHEDRA HAVING THE SAME TRIBE NUMBER, AND ARRAYED
```

```
BY FACES IN QLD[MATCH[Z],Y] ISOLATED ABOVE.      SINCE, IN THE          .
COMPARISON OF QLD WORDS, REJECTION OF THE NEW POLYHEDRON OCCURS         .
UPON FINDING AN ISOMORPHISM, AND ISOMORPHISMS OCCUR MORE OFTEN          .
THAN NOT, IT IS BEST TO COMPARE THE NEW POLYHEDRON COMPLETELY           .
WITH THE FIRST POLYHEDRON IN STORAGE BEFORE PROCEEDING TO THE           .
NEXT, REJECTING THE NEW ONE IF IT IS MATCHED BY ANY POLYHEDRON IN.
STORAGE, AND ADDING IT TO THE COLLECTION OTHERWISE.    ;                .
DETAILL: COMMENT                               DETAILL:;                .
FOR Z ← 1 STEP 1 UNTIL MCH DO COMMENT    FOR EACH MATCH IN FREQ.;.
BEGIN W ← MATCH [Z] DIV 92;                                             .
   X ← (MATCH [Z] MOD 92) × 11;                                         .
  FOR Y ← 1 STEP 1 UNTIL G DO IF QLD[LIXD,Y+LIXM] ≠ QLD[W,Y+X]          .
     THEN GO TO END3;   COMMENT  SOME FACE NOT EQUAL.     ;             .
  GO TO ENDISO;                                                         .
END3:    END;    COMMENT   END OF Z LOOP.                 END3:;        .
IF BOOLIO THEN                                                          .
BEGIN FOR Z ← 1 STEP 1 UNTIL G DO DELTA [Z] ← DELSAVE [Z];              .
   GO TO NEWL;                                                          .
END;                                                                    .
COMMENT  IF WE COME OUT THE BOTTOM OF THE Z LOOP, WE HAVE CHECKED.
 ALL THE STORED POLYHEDRA AND HAVE NOT FOUND AN ISOMORPHISM. NOW .
WE MUST TURN   THE NEW POLYHEDRON "INSIDE OUT" BY REVERSING THE         .
CYCLIC ORDER OF ITS    NABORS ,  AND THEN GO BACK AND CHECK IT          .
AGAIN FOR ISOMORPHISM.    ;                                             .
BOOLIO ← TRUE;                                                          .
GO TO STARTPRM;                                                         .
NEWL: COMMENT                                                   NEWL;.
ML ← ML + 1;                                                            .
COMMENT  ONE MORE POLY HAS BEEN ADDED TO THE OUTPUT LIST. ;             .
IF G = GMAX THEN GO TO PACKFREQL;                                       .
COMMENT  NO NEED TO MAKE QL ARRAY.    ;                                 .
FOR Z ← 1 STEP 1 UNTIL G DO COMMENT     FOR EACH FACE.      ;           .
BEGIN DEL ← DELTA [Z];                                                  .
   QL [ML, Z] ← DIM ← QAT [Z, 0];                                       .
   GO TO SW4 [DIM - 2];                                                 .
   N10: QL [ML, Z] . [4 : 4] ← QAT [Z, (((DEL + 9) MOD DIM) +1)];.
   N9: QL [ML, Z] . [8 : 4] ← QAT [Z, (((DEL + 8) MOD DIM) + 1)];.
   N8: QL [ML, Z] . [12 : 4] ← QAT [Z, (((DEL + 7) MOD DIM) +1)];.
   N7: QL [ML, Z] . [16 : 4] ← QAT [Z, (((DEL + 6) MOD DIM) +1)];.
   N6: QL [ML, Z] . [20 : 4] ← QAT [Z, (((DEL + 5) MOD DIM) +1)];.
   N5: QL [ML, Z] . [24 : 4] ← QAT [Z, (((DEL + 4) MOD DIM) +1)];.
   N4: QL [ML, Z] . [28 : 4] ← QAT [Z, (((DEL + 3) MOD DIM) +1)];.
   N3: QL [ML, Z] . [32 : 4] ← QAT [Z, (((DEL + 2) MOD DIM) +1)];.
   N2: QL [ML, Z] . [36 : 4] ← QAT [Z, (((DEL + 1) MOD DIM) +1)];.
   N1: QL [ML, Z] . [40 : 4] ← QAT [Z, (DEL + 1)];                      .
END;                                                                    .
WRITE (QLDFIL, *, FOR Z ← 1 STEP 1 UNTIL G DO QL [ML, Z]);              .
PACKFREQL: COMMENT                                  PACKFREQL:;         .
FREQL[ML DIV 700, ML MOD 700] ←                                         .
     COUNT[3] & COUNT[4][40:44:4] & COUNT[5][36:44:4] &                 .
     COUNT[6][32:44:4] & COUNT[7][28:44:4] & COUNT[8][24:44:4] & .
     COUNT[9][20:44:4] & COUNT[10][16:44:4]; COMMENT  TRIBE NO. ;.
IF F < 7 THEN GO TO PRINTPOLY;                                          .
WRITE (QLDFIL, *, FREQL [ML DIV 700, ML MOD 700], FOR Z ← 1             .
   STEP 1 UNTIL G DO QLD [LIXD, Z + LIXM]);                             .
```

```
GO TO PRINTPOLY;
COMPS: COMMENT                                                   COMPS:;
FOR Z ← 1 STEP 1 UNTIL MS DO
BEGIN FREQ ← FREQS [Z];
   GO TO SW3 [F - 3]; COMMENT D4, D5, ...D8, D8, D8.    ;
   D8: IF COUNT [8] ≠ FREQ . [24 : 4] THEN GO TO END4;
   D7: IF COUNT [7] ≠ FREQ . [28 : 4] THEN GO TO END4;
   D6: IF COUNT [6] ≠ FREQ . [32 : 4] THEN GO TO END4;
   D5: IF COUNT [5] ≠ FREQ . [36 : 4] THEN GO TO END4;
   D4: IF COUNT [4] ≠ FREQ . [40 : 4] THEN GO TO END4;
   D3: IF COUNT [3] ≠ FREQ . [44 : 4] THEN GO TO END4;
   MCH ← MCH + 1;
   MATCH [MCH] ← Z;
END4:  END;  COMMENT   END OF  Z LOOP.                    END4:  ;
IF MCH = 0 THEN GO TO NEWS;
DETAILS: COMMENT                                   DETAILS:;
FOR Z ← 1 STEP 1 UNTIL MCH DO COMMENT  FOR EACH MATCH IN FREQ. ;
BEGIN W ← MATCH [Z] DIV 92;
   X ← (MATCH [Z] MOD 92) × 11;
   FOR Y ← 1 STEP 1 UNTIL G DO
   IF QSD[SIXD,Y+SIXM] ≠ QSD[W,Y+X] THEN GO TO END7;
   GO TO ENDISO;
END7:   END;   COMMENT END OF Z LOOP.                       END7: ;
IF BOOLIO THEN
BEGIN FOR Z ← 1 STEP 1 UNTIL G DO DELTA [Z] ← DELSAVE [Z];
   GO TO NEWS;
END;
BOOLIO ← TRUE;
GO TO STARTPRM;
NEWS: COMMENT                                                     NEWS:;
MS ← MS + 1;
IF G = GMAX THEN GO TO PACKFREQS;
FOR Z ← 1 STEP 1 UNTIL G DO COMMENT    FOR EACH FACE.      ;
BEGIN DEL ← DELTA [Z];
   QS [MS, Z] ← DIM ← QAT [Z, 0];
   GO TO SW5 [DIM - 2];
   M10: QS [MS, Z] . [4 : 4] ← QAT [Z, (((DEL + 9) MOD DIM) +1)]];
   M9: QS [MS, Z] . [8 : 4] ← QAT [Z, (((DEL + 8) MOD DIM) + 1)]];
   M8: QS [MS, Z] . [12 : 4] ← QAT [Z, (((DEL + 7) MOD DIM) +1)]];
   M7: QS [MS, Z] . [16 : 4] ← QAT [Z, (((DEL + 6) MOD DIM) +1)]];
   M6: QS [MS, Z] . [20 : 4] ← QAT [Z, (((DEL + 5) MOD DIM) +1)]];
   M5: QS [MS, Z] . [24 : 4] ← QAT [Z, (((DEL + 4) MOD DIM) +1)]];
   M4: QS [MS, Z] . [28 : 4] ← QAT [Z, (((DEL + 3) MOD DIM) +1)]];
   M3: QS [MS, Z] . [32 : 4] ← QAT [Z, (((DEL + 2) MOD DIM) +1)]];
   M2: QS [MS, Z] . [36 : 4] ← QAT [Z, (((DEL + 1) MOD DIM) +1)]];
   M1: QS [MS, Z] . [40 : 4] ← QAT [Z, (DEL + 1)]];
END;
WRITE (QSDFIL, *, FOR Z ← 1 STEP 1 UNTIL G DO QS [MS, Z]);
PACKFREQS: COMMENT                                  PACKFREQS:;
     FREQS[MS] ←COUNT[3] & COUNT[4][40:44:4] & COUNT[5][36:44:4].
   & COUNT[6][32:44:4] & COUNT[7][28:44:4] & COUNT[8][24:44:4] ;
IF F < 7 THEN GO TO PRINTPOLY;
WRITE (QSDFIL, *, FREQS [MS], FOR Z ← 1 STEP 1 UNTIL G DO QSD [
   SIXD, Z + SIXM]);
PRINTPOLY: COMMENT                                  PRINTPOLY:;
```

```
        WRITE(LP[NO],FMT91, (MS + ML), FOR Z ← 1 STEP 1 UNTIL G DO
        [FOR Y ← QAT[Z,0] STEP -1 UNTIL 1 DO CHAR[QAT[Z,Y]], 48]);
        WRITE(LP,     FM192, F, PMAX, I, MS, ML);
        IF (MS + ML) MOD 50= 0 THEN WRITE (LP [PAGE]);
     END;
ENDISO: END; COMMENT END OF PROCEDURE ISOCHECK.              ENDISO:  ;
COMMENT *******************  EXECUTION  ********************EXECUTION ;
GMAX ← 11;
T1 ← TIME(1);     COMMENT   START THE CLOCK.         ;
FILL CHAR[*] WITH "0","1","2","3","4","5","6","7","8","9","A","B","C",
      "D","E","F" ;
READ(F, PMAX, I, MS, ML); COMMENT  PUNCH THIS NEW DATA CARD TO RESTART.;
COMMENT F = NUMBER OF FACES IN POLYHEDRON TO BE PARTITIONED.
        PMAX = MAX NUMBER OF INPUT POLYHEDRA, INDEXED ON I.
         MS AND ML ARE THE NUMBERS OF S AND L POLY STORED AWAY.   ;
P[0] ← 1;  P[1] ← 17187;  P[2] ← 13331;  P[3] ← 16915;  P[4] ← 8979;
IF MS + ML = 0 THEN GO TO GENESIS; COMMENT THIS IS NOT A RESTART.     ;
WRITE(LP[DBL], FMT16, F, PMAX, I, MS, ML);
SPACE (PFIL, I-1); COMMENT PREPARE TO READ THE ITH INPUT POLYHEDRON.   ;
IF F+1 < GMAX THEN GO TO READALL; COMMENT QL AND QS ARE ALSO ON TAPE.  ;
IF MS = 0 THEN GO TO MSZERO;
FOR Z ← 1 STEP 1 UNTIL MS-1 DO
BEGIN W ← Z DIV 92;
     X ← (Z MOD 92) × 11;
     READ (QSDFIL, 12, INQ [*]);
     FREQS [Z] ← INQ [0];
     FOR Y ← 1 STEP 1 UNTIL 11 DO QSD [W, Y + X] ← INQ [Y];
END;
Z ← MS;
W ← Z DIV 92;
X ← (Z MOD 92) × 11;
READ(QSDFIL[NO],12,INQ[*]);
FREQS[Z] ← INQ[0];
FOR Y ← 1 STEP 1 UNTIL 11 DO QSD[W, Y+X] ← INQ[Y];
WRITE(QSDFIL, 12, INQ[*]);
MSZERO:                       COMMENT                          MSZERO:;
IF ML = 0 THEN GO TO MLZERO;
FOR Z ← 1 STEP 1 UNTIL ML-1 DO
BEGIN W ← Z DIV 92;
     X ← (Z MOD 92) × 11;
     READ (QLDFIL, 12, INQ [*]);
     FREQL [Z DIV 700, Z MOD 700] ← INQ [0];
     FOR Y ← 1 STEP 1 UNTIL 11 DO QLD [W, Y + X] ← INQ [Y];
END;
Z ← ML;
W ← Z DIV 92;
X ← (Z MOD 92) × 11;
READ(QLDFIL[NO],12,INQ[*]);
FREQL[Z DIV 700, Z MOD 700] ← INQ[0];
FOR Y ← 1 STEP 1 UNTIL 11 DO QLD[W, Y+X] ← INQ[Y];
WRITE(QLDFIL, 12, INQ[*]);
MLZERO:                       COMMENT                          MLZERO:;
FOR Z ← 1 STEP 1 UNTIL MS DO
BEGIN W ← Z DIV 92;
     X ← (Z MOD 92) × 11;
```

```
    WRITE (LP, FMT11, Z, FOR Y ← 1 STEP 1 UNTIL 11 DO QSD [W, Y + X]);    .
END;                                                                       .
FOR Z ← 1 STEP 1 UNTIL ML DO                                               .
BEGIN W ← Z DIV 92;                                                        .
    X ← (Z MOD 92) × 11;                                                   .
    WRITE (LP, FMT10, Z, FOR Y ← 1 STEP 1 UNTIL 11 DO QLD [W, Y + X]);    .
END;                                                                       .
WRITE(LP[PAGE]);                                                           .
GO TO RESTART;                                                             .
READALL:                       COMMENT                            READALL: ;.
IF MS = 0 THEN GO TO MSMT;                                                 .
FOR Z ← 1 STEP 1 UNTIL MS-1 DO                                             .
BEGIN W ← Z DIV 92;                                                        .
    X ← (Z MOD 92) × 11;                                                   .
    READ (QSDFIL, *, FOR Y ← 1 STEP 1 UNTIL F + 1 DO QS [Z, Y]);          .
    READ (QSDFIL, *, FREQS [Z], FOR Y ← 1 STEP 1 UNTIL F + 1 DO QSD [W    .
    , Y + X]);                                                             .
END;                                                                       .
Z←MS;                                                                      .
W ← Z DIV 92;                                                              .
X ← (Z MOD 92) × 11;                                                       .
READ(QSDFIL,      *,            FOR Y ← 1 STEP 1 UNTIL F+1 DO QS[Z,Y]);   .
READ(QSDFIL[NO], *, FREQS[Z], FOR Y ← 1 STEP 1 UNTIL F+1 DO QSD[W,Y+X]);.
WRITE(QSDFIL    , *, FREQS[Z], FOR Y ← 1 STEP 1 UNTIL F+1 DO QSD[W,Y+X]);.
MSMT:                          COMMENT                               MSMT: ;.
IF ML = 0 THEN GO TO MLMT;                                                 .
FOR Z ← 1 STEP 1 UNTIL ML-1 DO                                             .
BEGIN W ← Z DIV 92;                                                        .
    X ← (Z MOD 92) × 11;                                                   .
    READ (QLDFIL, *, FOR Y ← 1 STEP 1 UNTIL F + 1 DO QL [Z, Y]);          .
    READ (QLDFIL, *, FREQL [Z DIV 700, Z MOD 700], FOR Y ← 1 STEP 1       .
       UNTIL F + 1 DO QLD [W, Y + X]);                                     .
END;                                                                       .
Z←ML;                                                                      .
W ← Z DIV 92;                                                              .
X ← (Z MOD 92) × 11;                                                       .
READ (QLDFIL, *, FOR Y ← 1 STEP 1 UNTIL F + 1 DO QL [Z, Y]);              .
READ(QLDFIL[NO], *, FREQL[Z DIV 700, Z MOD 700],                           .
   FOR Y ← 1 STEP 1 UNTIL F+1 DO QLD[W,Y+X]);                              .
WRITE(QLDFIL    , *, FREQL[Z DIV 700, Z MOD 700],                          .
   FOR Y ← 1 STEP 1 UNTIL F+1 DO QLD[W,Y+X]);                              .
MLMT:                          COMMENT                               MLMT: ;.
GO TO RESTART;                                                             .
GENESIS:                  COMMENT                                 GENESIS: ;.
WRITE(PFIL, *, FOR J ← 0 STEP 1 UNTIL 4 DO P[J], 8888888);                 .
REWIND(PFIL);                                                              .
START:                   COMMENT                                    START:;.
WRITE(LP[PAGE]);   COMMENT  SKIP TO THE NEXT PAGE.   ;                     .
RESTART:                     COMMENT                              RESTART;.
G ← F + 1   ;  COMMENT NEW POLYHEDRON WILL HAVE G FACES.    ;              .
WRITE(LP[PAGE], FMT4, F+1, F); COMMENT WRITE STARTING MESSAGE;             .
ILOOP:                       COMMENT                                ILOOP:;.
READ(PFIL, *, FOR Y ← 0 STEP 1 UNTIL F DO P[Y]);  COMMENT I IS IN P[0].;.
IF P[0] = I THEN GO TO POK; COMMENT WE GOT THE RIGHT INPUT POLYHEDRON. ;.
WRITE (LP, FMT17, I, P[0]);  COMMENT  WE DID NOT.    ;                     .
```

```
GO TO FINALEND;
POK:                              COMMENT                                          POK;
FOR J ← 1 STEP 1 UNTIL F  DO   COMMENT   FOR EACH FACE.   ;
BEGIN PAT[J,0] ← P[J].[44:4];
    GO TO SW6 [PAT [J, 0]];
    B10: PAT [J, 10] ← P [J] . [4 : 4];
    B9: PAT [J, 9] ← P [J] . [8 : 4];
    B8: PAT [J, 8] ← P [J] . [12 : 4];
    B7: PAT [J, 7] ← P [J] . [16 : 4];
    B6: PAT [J, 6] ← P [J] . [20 : 4];
    B5: PAT [J, 5] ← P [J] . [24 : 4];
    B4: PAT [J, 4] ← P [J] . [28 : 4];
    B3: PAT [J, 3] ← P [J] . [32 : 4];
    B2: PAT [J, 2] ← P [J] . [36 : 4];
    B1: PAT [J, 1] ← P [J] . [40 : 4];
END;   COMMENT    END OF J LOOP.   ;
COMMENT  NOW THE POLYHEDRON NUMBER I IS DECOMPOSED INTO ATOMIC ELEMENTS,
 PAT[J,K], FOR K = 0, 1, ...,PAT[J,0].  THE DIMENSION OF THE FACE IS IN
PAT[J,0] AND THE KTH NABOR IS IN PAT[J,K].    ;
COMMENT  FOR EACH FACE, INDEXED ON J, DO THE FOLLOWING VERY BIG LOOP.  ;
FOR J ← 1 STEP 1 UNTIL F DO
BEGIN N ← PAT[J,0]; COMMENT FACE J HAS N EDGES.     ;
    VMAX ← N DIV 2;
    COMMENT    VMAX = MAX NUMBER OF VERTICES TO BE CUT OFF.  ;
    FOR Z ← 1 STEP 1 UNTIL VMAX DO PAT [J, Z + N] ← PAT [J, Z];
    VM ← VMAX - 1;
    FOR V ← 1 STEP 1 UNTIL VM DO FOR S ← 1 STEP 1 UNTIL N DO
    BEGIN PARTITION;
       ISOCHECK;
    END;
    IF N MOD 2 = 0 THEN SAM ← VMAX ELSE SAM ← N;
    COMMENT   SOME PARTITIONS CAN BE AVOIDED WHEN V = N/2.     ;
    V ← VMAX;
    FOR S ← 1 STEP 1 UNTIL SAM DO
    BEGIN PARTITION;
       ISOCHECK;
    END;
    COMMENT  END 2ND S LOOP. ALL CUTS DONE. ;
END;    COMMENT  END OF J LOOP.  ALL FACES OF POLY I HAVE BEEN CUT.    ;
I ← I + 1;  COMMENT  CUT UP NEXT POLYHEDRON.      ;
IF I ≤ PMAX THEN GO TO ILOOP;
WRITE(LP[PAGE]);
FOR Z ← 1 STEP 1 UNTIL MS DO
BEGIN W ← Z DIV 92;
      X ← (Z MOD 92)×11;
      WRITE(LP,FMT11, Z, FOR Y ← 1 STEP 1 UNTIL 11 DO,QSO[W,Y+X]);
END;
WRITE(LP[PAGE]);
FOR Z ← 1 STEP 1 UNTIL ML DO
BEGIN W ← Z DIV 92;
      X ← (Z MOD 92)×11;
      WRITE(LP,FMT10, Z, FOR Y ← 1 STEP 1 UNTIL 11 DO QLO[W,Y+X]);
END;
IF G = GMAX THEN GO TO FINALEND;  COMMENT GMAX IS ASSIGNED FIRST.    ;
REWIND(PFIL);
```

```
FOR Z ← 1 STEP 1 UNTIL MS DO
     WRITE(PFIL, *, Z, FOR Y ← 1 STEP 1 UNTIL G DO QS[Z,Y]);
FOR Z ← 1 STEP 1 UNTIL ML DO
     WRITE(PFIL, *, Z+MS, FOR Y ← 1 STEP 1 UNTIL G DO QL[Z,Y]);
WRITE(PFIL, *, 8888888);
REWIND(PFIL);
F ← G;  COMMENT INPUT POLYHEDRA ARE NOW G-FACED.      ;
PMAX ← MS + ML;   COMMENT THE NUMBER OF INPUT POLYHEDRA IS ML+MS.   ;
I ← 1;   COMMENT   START CUTTING THE FIRST INPUT POLYHEDRON.    ;
ML ← MS ← 0;   COMMENT   INITIALIZE MAX INDICES ON STORED RESULTS.     ;
WRITE(QSOFIL, *, F);  WRITE(QLOFIL, *, F);
REWIND(QSOFIL);
REWIND(QLOFIL);
GO TO START;  COMMENT   SO NOW WE GO BACK AND CUT UP THESE POLYHEDRA.  ;
FINALEND:      COMMENT   END OF ENTIRE PROGRAM.                FINALEND:;
WRITE(LP[DBL],FMT15, (TIME(1) - T1) / 3600); COMMENT TIME IN MINUTES.  ;
END.
```

LIST OF POLYHEDRA

TRI-LINEAR POLYHEDRA

OF

5 THROUGH 8 FACES

1 4352 3415 4251 231 321

1 43562 53416 4251 231 3261 521
2 4652 5341 4256 2361 3216 4351

1 435672 653417 4251 312 6132 5271 621
2 435762 65341 4251 312 67132 5217 561
3 437562 65341 42571 312 61732 521 351
4 43762 65341 42571 312 6732 5217 3561
5 43567 65347 4251 3172 6132 5271 6241

1 4356782 7653418 4251 312 6132 7152 6281 721
2 4356872 765341 4251 312 6132 78152 6218 671
3 4358672 765341 4251 312 68132 71852 621 561
4 435872 765341 4251 312 68132 7852 6218 5671
5 438672 765341 42581 312 6832 71852 621 3561
6 435678 765348 4251 3182 6132 7152 6281 7241
7 43582 7653418 4251 312 68132 7852 628 56721
8 43872 765341 42581 312 6832 7852 6218 35671
9 435862 41653 4251 312 781326 75218 685 5761
10 43862 41653 42581 312 78326 75218 685 35761
11 48762 41653 4258 3812 78326 7521·6185 43571
12 435762 416583 42851 312 713826 7521 615 532
13 435762 41683 42851 312 71386 75821 615 6532
14 437562 658341 428571 231 738261 521 351 532

TRI-LINEAR POLYHEDRA

OF

9 FACES

1	438692	419653	42581	312	78326	752918	685	76135	621
2	493862	41653	425819	3912	78326	75218	685	76135	431
3	43892	419653	42581	312	78326	75298	685	769135	8621
4	49862	41653	42589	3912	78326	75218	685	761935	4381
5	762498	34165	4258	38912	67832	7521	6185	435719	481
6	76298	349165	4258	3892	67832	7521	6185	435719	2481
7	76948	34965	4258	38192	67832	75291	6185	43571	6241
8	79248	341965	4258	3812	67832	7529	69185	43571	7621
9	43567892	87653419	4251	312	6132	7152	8162	7291	821
10	43567982	8765341	4251	312	6132	7152	89162	7219	781
11	43569782	8765341	4251	312	6132	79152	81962	721	671
12	43596782	8765341	4251	312	69132	71952	8162	721	561
13	4356982	8765341	4251	312	6132	79152	8962	7219	6781
14	4359782	8765341	4251	312	69132	7952	81962	721	5671
15	4356789	8765349	4251	3192	6132	7152	8162	7291	8241
16	435692	87653419	4251	312	6132	79152	8962	729	67821
17	435982	8765341	4251	312	69132	7952	8962	7219	56781
18	439782	8765341	42591	312	6932	7952	81962	721	35671
19	356789	8765349	42519	392	6132	7152	8162	7291	82431
20	43569872	417653	4251	312	3261	891527	8621	7196	681
21	43596872	417653	4251	312	32691	819527	8621	716	561
22	43956872	417653	42591	312	32619	81527	8621	716	351
23	49356872	417653	42519	3912	3261	81527	8621	716	431
24	4356972	417653	4251	312	3261	891527	86219	796	6871
25	4396872	417653	42591	312	3269	819527	8621	716	3561
26	4956872	417653	4259	3912	32619	81527	8621	716	4351
27	3568729	4917653	42519	392	3261	81527	8621	716	2431
28	496872	417653	4259	3912	3269	819527	8621	716	43561
29	568729	4917653	4259	392	32619	81527	8621	716	24351
30	4356872	4176593	42951	312	39261	81527	8621	716	532
31	4356872	4176953	4251	312	32961	815927	8621	716	652
32	4356872	4179653	4251	312	3261	815297	86921	716	762
33	4356872	417953	4251	312	32961	81597	86921	716	7652
34	4356872	41793	42951	312	3961	81597	86921	716	76532
35	43568792	41953	4251	312	32961	81597	8691	716	17652
36	43589672	765341	4251	312	81326	852719	621	5691	861
37	43958672	765341	42591	312	819326	85271	621	561	351
38	4359672	765341	4251	312	891326	852719	621	569	5861
39	4958672	765341	4259	3912	819326	85271	621	561	4351
40	435972	765341	4251	312	891326	85279	6219	569	58671
41	586729	7653491	4259	392	819326	85271	621	561	24351
42	435869	765349	4251	3192	81326	852791	629	561	67241
43	4358672	7659341	42951	312	813926	85271	621	561	532
44	4358672	7695341	4251	312	813296	859271	621	561	652
45	4358672	769341	42951	312	81396	859271	621	561	6532
46	495872	417653	4259	3912	681932	7852	8621	6715	4351
47	439672	765341	425891	312	8326	719852	621	5693	3861
48	435982	7653410	4251	312	689132	7852	628	721956	581
49	435829	765918	4951	319	681392	7852	628	72156	53412
50	769435	83965	492851	319	826713	75291	615	325	34162

TRI-LINEAR POLYHEDRA

OF

10 FACES

1	43869A2	41A9653	42581	312	78326	752918	856	76135	62A1	921
2	4386A92	419653	42581	312	78326	7529A18	856	76135	621A	691
3	438A692	419653	42581	312	78326	75291A8	856	76A135	621	861
4	43A8692	419653	4258A1	312	78326	752918	856	761A35	621	381
5	4A38692	419653	42581A	3A12	78326	752918	856	76135	621	431
6	438692A	4A19653	42581	31A2	78326	752918	856	76135	621	241
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TRI-LINEAR POLYHEDRA

OF

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1208 43596A2 876B5341A 4251 312 9132B6 95B27A1 8A62 72A 561 82167 652
1209 4359A2 876B5341A 4251 312 9132B6 95B27A 8A62 72A 56A1 821967 652
1210 43596782A 8765BA1 4A51 31A 913AB26 95271 8162 721 615 412B53 5A2
1211 43596782BA 876B1 4A51 31A 913AB6 95B271 8162 721 615 41B53 65A12
1212 435682 8765341B9 4251 312 3261 AB15279 8962 729 A6782B 69B 6A921
1213 56A92B 876534B19 425B 3B2 3261B A15279 8962 729 A67821 691 24351
1214 4356A92 87653419B 4251 312 3261 A1527B9 8B62 72B A6B21 691 67829
1215 98724356 A53417B6 4251 312 A6132 A2B78915 86B21 9671 816 526 762
1216 98724356 A534176B 4251 312 A6132 AB278915 8621 9671 816 52B6 6A2
1217 435A96B72 417653 4251 312 A13269 8B19527 8621B 7B6 A561 915 6871
1218 435A96872 41765B3 42B51 312 A13B269 819527 8621 716 A561 915 532
1219 435A96872 4176B53 4251 312 A132B69 8195B27 8621 716 A561 915 652
1220 87243BA596 417653 425AB1 312 A32691 952781 8621 716 561 351B 3A1
1221 8724B3A596 417653 425A1B 3B12 A32691 952781 8621 716 561 351 431
1222 87243A5B6 417653 425A1 312 A3269B1 952781B 8621 716 56B 351 5961
1223 87243B596 417653 425AB1 312 A32691B 952781 8621 716 561 35B 3A51
1224 872B3A596 4B17653 425A1B 3B2 A32691 952781 8621 716 561 351 2431
1225 7243A596B 417653 425A1 312 A32691 95278B1 8621B 7B6 561 351 6871
1226 87243A596 41765B3 42B5A1 312 A3B2691 952781 8621 716 561 351 532
1227 87243A596 4176B53 425A1 312 A32B691 95B2781 8621 716 561 351 652
1228 87243A596 417B653 425A1 312 A32691 952B781 86B21 716 561 351 762
1229 8724A35B6 765341 A4251 A123 9B1326 952781B 8621 716 56B 431 5961
1230 8724B3596 765341 A4251B AB123 91326 952781 8621 716 561 43B 4A31
1231 724A3596B 765341 A4251 A123 91326 95278B1 8621B 7B6 561 431 6871
1232 8724A3596 7653B41 A4B251 A12B3 91326 952781 8621 716 561 431 342
1233 8724A3596 765B341 A42B51 A123 913B26 952781 8621 716 561 431 532
1234 8724A3596 76B5341 A4251 A123 9132B6 95B2781 8621 716 561 431 652
1235 8724A3596 7B65341 A4251 A123 91326 952B781 86B21 716 561 431 762
1236 8724A3596 765B41 A4B51 A12B3 913B26 952781 8621 716 561 431 5342
1237 43596A7B2 41B53 4251 312 9132B6 8A195B7 86B1A A67 561 8716 17652
1238 87B2435A6 41B53 4251 312 9A132B6 95B781A 86B1 716 A56 9615 17652
1239 872A3596 4A1765B3 42B51A A23 913B26 952781 8621 716 561 4312 532
1240 87B2A3596 4A1B53 4251A A23 9132B6 95B781 86B1 716 561 4312 17652
1241 87B243596 A341B5 A5142 312 A2B6913 95B781 86B1 716 561 325 17652
1242 43596872 A53417B6 4251 312 A69132 95A2B781 86B21 716 561 526 762
1243 43596872 A534176B 4251 312 A69132 95AB2781 8621 716 561 52B6 6A2
1244 43596872B A5B176 4B51 31B A6913B2 95A2781 8621 716 561 526 53412
1245 43596872B A65B17 4B51 31B 913B26 A781952 86A21 716 561 762 53412
1246 87A243596 41AB53 4251 312 9132BA6 95A781 86A1 716 561 765B21 A52
1247 872A3956 4A176B53 42591A A23 932B61 815B27 8621 716 513 4312 652
1248 87249356 A34176B5 942A51 9123 A2B613 815B27 8621 716 431 532 652
1249 86724395 76B5A341 42A591 312 93A2B681 85B271 621 615 351 325 652

TRI-LINEAR POLYHEDRA

OF

8 AND 9 FACES

WITH

MEC $\leq$ 6

1 46782 534187 4256 1236 3276 43571 81652 721
2 4682 534187 4256 1236 3276 435781 8652 6721
3 4872 53417 4256 81236 3276 43578 18652 4671
4 724685 75341 6425 3612 718632 43581 521 651
5 724865 75341 6425 36812 71632 43518 521 461
6 782465 753418 6425 3612 71632 4351 5281 721
7 72465 75341 68425 38612 71632 48351 521 643
8 435862 41653 4251 312 781326 75218 685 5761
9 435762 416583 42851 312 713826 7521 615 532
10 437562 658341 428571 231 738261 521 351 532

1 4982 534187 4256 91236 3276 435789 8652 19672 4681
2 4689 53497 4256 19236 3276 435781 86529 1679 41872
3 87294 534917 5642 819236 3276 35784 18652 1467 241
4 89724 53417 5642 81236 3276 35784 198652 91467 871
5 87294 53917 56492 81936 3276 35784 18652 1467 3412
6 824697 875341 5642 3612 3276 435791 819652 172 671
7 824967 875341 5642 36912 3276 435719 81652 172 461
8 824679 875341 5642 3612 3276 43571 891652 1972 781
9 82467 875341 56942 39612 3276 493571 81652 172 643
10 724685 753941 49256 36129 863271 81435 215 651 342
11 724965 75341 6425 891236 71632 843519 521 469 4861
12 724865 753941 64925 812936 71632 84351 521 461 342
13 824659 875341 6425 3612 632791 4351 8952 7219 5781
14 824657 875341 69425 39612 63271 49351 8152 721 643
15 358629 491653 42519 392 781326 75218 856 7615 2431

TRI-LINEAR POLYHEDRA

OF

10 FACES

WITH

MEC $\leq$ 6

1	9A824	753418	5642	91236	3276	357894	5286	1A9672	A1468	981
2	98A4	7534A8	5642	91A236	3276	357894	5286	A19672	1468	8241
3	982A4	753A18	564A2	91A36	3276	357894	5286	19672	1468	3412
4	9824	75A418	564A	912A36	3A276	357894	5286	19672	1468	5342
5	9824	7A3418	5642A	91236	3A76	357894	5A286	19672	1468	7532
6	98A4	753A8	564A2	91A36	3276	357894	5286	19672A	1468	34182
7	982A4	75A18	564A	91A36	3A276	357894	5286	19672	1468	53412
8	89A46	53497	5642	1A9236	3276	814357	52986	1679	A18724	941
9	8A946	53497	5642	19236	3276	814357	52986	A1679	1A8724	891
10	8946	5349A7	5642	19236	3276	814357	52A986	1679	187A24	972
11	894A6	53497	5A42	1923A	3276A	81A57	52986	1679	18724	14356
12	9487A2	5391A7	92564	81936	3276	57843	8652A1	1467	3412	721
13	948A72	53917	92564	81936	3276	57843	86521A	A1467	3412	871
14	94A872	53917	92564	841936	3276	57843	86521	14467	3412	431
15	982465	875341	6A425	3A612	632791	4A351	8952	9721	7815	643
16	948A72	917534	5642	923681	3276	35784	86521A	67A14	124	871
17	94872	917534	5A642	923681	A3276	3A5784	86521	6714	124	563
18	94872	917534	5642	923681	327A6	35A784	86A521	6714	124	765
19	94872	917534	5642	923681	3276	357A84	8A6521	6A714	124	786
20	9724A8	53417	5642	368A12	3276	35784	986521	91A467	187	481
21	97248A	53417	5642	36812	3276	35784	986521	9A1467	1A87	891
22	97248	5A3417	5642A	36812	3A276	35784	986521	91467	187	532
23	982467	534187	56A42	3A612	3276	4A3571	916528	9721	817	643
24	857246	41753A	9A2564	93612A	863271	81435	215	651	34A	3942
25	857246	941753	9256A4	93A612	863271	814A35	215	651	342	643
26	24965A	75341A	2564	891236	7A1632	843519	52A	946	8614	5721
27	865724	753941	925A64	936812	716A32	843A51	521	614	342	563
28	824657	875341	9A4256	96123A	71632	93514	8152	721	64A3	943
29	824657	875341	94256A	96123	71632	9A3514	8152	721	643A	693
30	935862	91653A	4A2519	9A3	781326	75218	856	7615	4312A	3492

TRI-LINEAR POLYHEDRA

OF

11 FACES

WITH

MEC ≤ 6

1	98A4	7534A8	5642	91A236	3276	357894	5286	AB9672	81468	18824	98A1
2	98A4	753BA8	564B2	91AB36	3276	357894	5286	A19672	1468	18284	34A2
3	98A4	75BA8	564B	91AB36	3B276	357894	5286	A19672	1468	18284	534A2
4	A49882	753A18	A2564	91A36	7632	578943	5286	96721B	8B146	3412	981
5	A4B982	753A18	A2564	9B1A36	7632	578943	5286	96721	81B46	3412	491
6	AB982	753A18	A2564	9BA36	7632	578943	5286	96721	81B46	34B12	A491
7	A4982	75BA18	AB564	91A36	763R2	578943	5286	96721	8146	3412B	53A2
8	A4982	7B3A18	A2B564	91A36	763B	578943	5B286	96721	8146	3412	7532
9	A498B2	753A18	A2564	91A36	7632	578943	52B86	967B1	8146	3412	1872
10	A4982	7BA18	AB564	91A36	763B	578943	5B286	96721	8146	3412B	753A2
11	9B824	1875A4	A564	912A36	3A276	357894	5286	1B9672	B1468	3425	981
12	9824	18B5A4	A564	912A36	3A2B76	357894	5B86	1967B2	1468	3425	8752
13	98824	187A34	A5642	91236	A763	943578	5A286	1B9672	81468	5327	981
14	9824	187B4	A564B	912B36	A763	943578	5AB286	19672	1468	53B7	7A342
15	98AB4	753A8	564A2	91BA36	7632	578943	5286	19672A	1468	818234	A41
16	98A4B	753A8	564A2	9B1A36	7632	578943	5286	19672A	1B468	18234	491
17	98A4	753BA8	564AB2	91A36	7632	578943	5286	19672A	1468	182B34	3A2
18	982AB4	75A18	4A56	91BA36	3A276	357894	5286	72196	8146	34B125	A41
19	982BA4	75AB18	4A56	91A36	3A276	357894	5286	72196	8146	341B25	2A1
20	9B82A4	75A18	4A56	91A36	3A276	357894	5286	721B96	8B146	34125	981
21	894AB6	34975	5A42	3A192	3276A	81BA57	86529	1679	87241	356B14	A61
22	8894A6	34975	5A42	3A192	3276A	81A57	86529	B1679	87241B	35614	891
23	A824B9	753418	5642	369B12	3276	357894	5286	A96721	A1B468	198	491
24	A8249B	753418	5642	36912	3276	357894	5286	A96721	AB1468	1898	9A1
25	A4689	5B3497	56428	A92361	3B276	357814	52986	1679	A13724	194	532
26	A4689	53497B	5642	A92361	32B76	357814	5B2986	1679	A13724	194	752
27	A9468B	53497	5642	36192	3276	357814	52986	AB1679	A87241	1B89	8A1
28	A9468	5B3497	5642B	36192	3B276	357814	52986	A1679	A87241	189	532
29	A29487	A75391	564B92	9B3681	6327	84357	A18652	4671	3B412	721	493
30	A29487	A75391	56B492	93B681	6327	84B357	A18652	4671	3412	721	643
31	A72948	53B917	9B2564	93681	6327	57843	A86521	A1467	2B341	871	392
32	A72948	53917	925B64	93681	6B327	57843B	A86521	A1467	2341	871	563
33	A72948	53917	92564	936B81	6327	578B43	A86521	A14B67	2341	871	684
34	A87294	53B917	982564	A19368	3276	57843	52186	A4671	2B341	814	392
35	A87294	5B3917	92B564	A19368	3B276	57843	52186	A4671	2341	814	532
36	A87294	53917	92564	A19368	3276	57B843	521886	A46B71	2341	814	786
37	982465	875341	AB4256	A6123B	791632	A3514	8952	9721	7815	64B3	A43
38	982465	875341	A4256	A6123	791632	A3514	88952	98721	78815	643	897
39	948A72	917534	5B642	923681	B3276	385784	A86521	A1467	124	871	563
40	94872	917534	A6425B	923681	AB3276	A57843	86521	7146	124	3856	5A3
41	A89724	5B3417	5642B	A12368	3B276	35784	986521	91A467	187	481	532
42	A97248	5B3417	5642B	36812	3B276	35784	521986	A14679	A871	918	532
43	982467	534187	AB4256	A6123B	3276	A35714	916528	9721	817	4B36	A43
44	862935	A91653	A2519B	AB9	781326	75218	856	7615	4B312A	4923B	94A3

TRI-LINEAR POLYHEDRA

OF

12 FACES

WITH

MEC ≤ 6

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 1 BCA49 7534A8 5642 1A2369 3276 357894 5286 B9672A B1468 1CB824 C198A BA1
 2 BAC9 7534A8 5642 CA2369 3276 357894 5286 B9672A B1C468 C1B824 198A A491
 3 BA49 753CA8 564C2 1AC369 3276 357894 5286 B9672A B1468 1B82C4 198A 34A2
 4 BA49 7C34A8 5642C 1A2369 3C76 357894 5C286 B9672A B1468 1B824 198A 7532
 5 BA49 75CA8 564C 1AC369 3C276 357894 5286 B9672A B1468 1B82C4 198A 534A2
 6 BAC49 753CA8 564C2 1C369 3276 357894 5286 B9672A B1468 1B82C 198A 1A234
 7 98A4 753CA8 BC2564 91AB36 7632 578943 5286 19672A 1468 B4182C 34AC 38A2
 8 98A4 75CBA8 BC564 91AB36 763C2 578943 5286 19672A 1468 B4182 34A2C 53B2
 9 98A4 753BAC B2564 91AB36 7632 578943 52C86 1967CA 1468 B418C2 34A2 A872
10 98A4 75CA8 BC564 91AB36 763C2 578943 5286 19672A 1468 B4182C 34AC 53BA2
11 98A4 753BA8 B2564 91AB36 7632 57C943 528C6 19C72A 146C8 B4182 34A2 7896
12 98A4 753BA8 B2564 91AB36 7C632 5C943 528C 19C72A 146C8 B4182 34A2 57896
13 98A4 75BCA8 B564 91AB36 3B276 357894 5286 19672A 1468 182C84 34AC25 BA2
14 98A4 75CBA8 B564 91AB36 3BC276 357894 5286 19672A 1468 18284 34A2C5 5B2
15 98A4 7C5BA8 B564 91AB36 3B2C76 357894 5C286 19672A 1468 18284 34A25 752
16 98AC4 75BA8 B564 91CB36 3B276 357894 5286 19672A 1468 1828C 34CA25 1AB4
17 98AC4 75BA8 B564C 91C36 3B276 357894 5286 19672A 1468 1828C 3CA25 1AB34
18 98AC 75BA8 B564 9CB36 3B276 357894 5286 19672A 1C468 1828C 34CA25 91AB4
19 98A4 75BA8 B564 91AB36 3B27C6 35C94 528C 19C72A 146C8 182B4 34A25 57896
20 B9C82A 753A18 564A2 BA369 7632 578943 5286 721C96 B468C1 B1234 A491 981
21 BC982A 753A18 564A2 BA369 7632 578943 5286 72196 B4681C B1234 A49C1 891
22 B982AC 753A18 564A2 BA369 7632 578943 5286 72196 B4681 BC1234 A491C AB1
23 982AC 753A18 564A2 BA369 7632 578943 5286 72196 B4681C BC1234 A49C AB91
24 B982A 7C3A18 564A2C BA369 763C 578943 5C286 72196 B4681 B1234 A491 7532
25 B982CA 75C18 564AC BA369 763C2 578943 5286 72196 B4681 B1C34 A491 53A12
26 982AC4 75BA18 B564A 91CA36 B2763 789435 5286 96721 8146 B34C12 53A2 A41
27 9C82A4 75BA18 B564A 91A36 B2763 789435 5286 96721C 8C146 B3412 53A2 981
28 982A4C 75BA18 B564A 9C1A36 B2763 789435 5286 96721 81C46 B3412 53A2 491
29 A49C82 A187B3 B564A2 91A36 B763 578943 5B286 96721C 8C146 4123 5327 981
30 A4C982 A187B3 B564A2 9C1A36 B763 578943 5B286 96721 81C46 4123 5327 491
31 AC4982 A187B3 B564A2 91CA36 B763 578943 5B286 96721 8146 4C123 5327 A41
32 A4982 A18CB3 B564A2 91A36 B763 578943 5BC86 967C21 8146 4123 532C7 8782
33 A4982 A187B3 B564A2 91A36 BC763 578943 5CB286 96721 8146 4123 C5327 B75
34 A4982 A187B3 B564A2 91A36 B7C63 5C8943 5B28C 96C721 8146 4123 5327 5786
35 A49882 B753A1 A2564C AC3691 7632 578943 B8652 B1967 8146 3C412 8721 4A3
36 982AC4 7BA18 564AB 91CA36 3876 578943 5B286 96721 8146 34C12B 53A27 A41
37 982CA4 7BAC18 564AB 91A36 3876 578943 5B286 96721 8146 341C2B 53A27 2A1
38 9C82A4 7BA18 564AB 91A36 3B76 578943 5B286 96721C 8C146 3412B 53A27 981
39 982A4 7BA18C 564AB 91A36 3B76 578943 5B2C86 967C21 8146 3412B 53427 872
40 982A4 7BA18 564AB 91A36 3B7C6 5C943 5B28C 9C721 8146C 3412B 53A27 57896
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41 98C24 1C87B4 A564B 912B36 A763 943578 5AB286 C19672 1468 5387 A3427 821
42 9C824 187B4 A564B 912B36 A763 943578 5AB286 1C9672 C1468 5387 A3427 981
43 9C24 1C87B4 A564B 912B36 A763 943578 5AB286 C9672 C1468 5387 A3427 9821
44 B82A49 753A18 A2564C AC3691 7632 578943 5286 B96721 B1468 3C412 981 4A3
45 B8249C 75A418 A564 A36912 3A276 357894 5286 B96721 BC1468 3425 1C98 9B1
46 B8249 75A418 AC564 A36912 3CA276 357894 5286 B96721 B1468 C3425 198 A53
47 B824C9 A34187 A5642 9C1236 A763 578943 5A286 B96721 B1C468 5327 198 491
48 B8249C A34187 A5642 91236 A763 578943 5A286 B96721 BC1468 5327 1C98 9B1
49 B8249 A34187 AC5642 91236 A763C 578943 5A286 B96721 B1468 5C327 198 A53
50 B8249 A34187 A5642 91236 AC763 578943 5CA286 B96721 B1468 C5327 198 A75
51 B498A 75C3A8 564A2C BA3691 763C2 578943 5286 72A196 1468 B18234 1A4 532
52 B498A 7C53A8 564A2 BA3691 7632C 578943 5C286 72A196 1468 B18234 1A4 752
53 BC98A4 753A8 564A2 B1A369 7632 578943 5286 72A196 B4681C 23418 9C14 B91
54 B98A4 753CA8 564AC2 B1A369 7632 578943 5286 72A196 B4681 2C3418 914 3A2
55 B98A4 7C53A8 564A2 B1A369 7632C 578943 5C286 72A196 B4681 23418 914 752
56 B4982A 7C5A18 564A B43691 763A2C 357894 5C286 72196 B146 B12534 A41 752
57 B82A49 7C5A18 4A56 3691A 3A2C76 357894 5C286 B96721 B1468 34125 981 752
58 B82A49 75A18 4AC56 3691A 3CA276 357894 5286 B96721 B1468 C34125 981 A53
59 B6894A 3497C5 425A 3A192 32C76A BA5781 865C29 7916 87241 B14356 A61 752
60 B6894A 349C75 425A 3A192 3276A BA5781 8652C9 7916 87C241 B14356 A61 972
61 B6894A 3C4975 4C25A 3A192C 3276A BA5781 86529 7916 87241 B14356 A61 342
62 B6894A 34975 425A 3A192 3276A BA5781 86529C 7C916 8C7241 B14356 A61 987
63 B94A68 3C4975 5A4C2 3A192C 3276A A5781 86529 B1679 B87241 35614 891 342
64 B94A68 34975C 5A42C 3A192 3C276A A5781 86529 B1679 B87241 35614 891 532
65 B94A68 34975 5A42 3A192 3276A A57C81 8C6529 B16C79 B87241 35614 891 786
66 A4689 34975C B5642C A92361 BC2763 814357 86529 1679 A18724 194 53C 5B32
67 BA9468 5C3497 5642C 36192 3C276 357814 52986 B1679A A87241 B891 A18 532
68 A72948 B91753 B25649 6C8193 6327 578C43 A86521 A14C67 B3412 871 923 684
69 A87294 B91753 B25649 A19368 7C632 5C7843 C52186 A4671 B3412 814 923 765
70 A87294 B91753 B25649 A19368 7632 57C843 5218C6 A46C71 B3412 814 923 786
71 982465 875341 B4256C BA6123 791632 AC3514 8952 9721 7815 BC64 A43C 6A83
72 982465 875341 B4256A BA6123 791632 A3514 8C952 9C721 7C815 B364 A43 897
73 948A72 917534 B6425C 923681 BC3276 B57843 A86521 A1467 124 871 3C56 5B3
74 A89724 34175C B5642C A12368 BC2763 35784 986521 91A467 187 481 53C 5B32
75 A89724 B34175 B5C642 A12368 B276C3 3C5784 986521 91A467 187 481 532 563
76 A97248 34175C B5642C 36812 BC2763 43578 986521 A14679 A871 918 53C 5B32
77 862935 A91653 BA2519 B9AC 781326 75218 856 7615 4B312A C4923B 4CA39 AB4

TRI-LINEAR POLYHEDRA

OF

13 FACES

WITH

MEC ≤ 6

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 1 BDC9 7534A8 5642 CA2369 3276 357894 5286 B9672A B1C468 CDB824 D198A 1DA49 BAC1
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TRI-LINEAR POLYHEDRA

OF

14 FACES

WITH

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TRI-LINEAR POLYHEDRA

OF

15 FACES

WITH

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