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The semiregular polytopes

G. BLIND AND R. BLIND

Abstract. A convex d-polytype in E^d is called semiregular, if its facets are regular and its vertices equivalent. A list of semiregular polytopes for $d \ge 4$ is known since 1900. Recently it has been proved by Π . B. Макаров [сб. Вопр. дискр. геом., Мат. исслед. ИМ АН Молд. ССР вып. 103, С. 139–150, Кишинев 1988], that this list is complete for d=4. We present here a simple proof for that this list is complete in any dimension.

1. Introduction

Let P be a convex d-polytope in E^d . P is called **regular-faced**, if all its facets are regular. P is called **semiregular**, if its facets are regular and if its vertices are equivalent (i.e. the group of symmetries of P acts transitively on the vertices of P). Clearly, every semiregular polytope is regular-faced.

For d=3 the semiregular polytopes coincide with the Archimedean solids. For $d \ge 4$ Gosset established a list of semiregular polytopes in [6]. Various constructions of semiregular polytopes have been described since, but all the time it stayed open whether Gosset's enumeration is complete (see [7, p. 413]). Only in 1988 there is published a proof [8], that Gosset indeed found all the semiregular d-polytopes for d=4. This proof uses the complete enumeration of regular-faced 3-polytopes in [9]; the vertex-figure of a semiregular polytope is then carefully examined.

In [1], [2] and [3] we completely enumerated the regular-faced d-polytopes for $d \ge 4$; a wide class of them, however, is only given by a method how to construct them. We shall show, how to deduce from this list of all regular-faced polytopes

THEOREM 1. Gosset's list of semiregular d-polytopes is complete for $d \ge 4$.

2. Gosset' list of semiregular d-polytopes for $d \ge 4$

Besides the regular polytopes Gosset found 7 semiregular polytopes, namely 3 for d = 4 and always one for $d = 5, \ldots, 8$. They are described in [6] by the sets of

d	name in [6]	sets of facets	a $(d-3)$ -face is contained in
4	tetroctahedric	5 octahedra 5 tetrahedra	2 octahedra 1 tetrahedron
	tetricosahedric	24 icosahedra 120 tetrahedra	2 icosahedra or {1 icosahedron tetrahedron} or {3 tetrahedra
	octicosahedric	120 icosahedra 600 octahedra	1 icosahedron 2 octahedra
5, , 8		(d-1)-crosspolytopes $(d-1)$ -simplices	2 $(d-1)$ -crosspolytopes 1 $(d-1)$ -simplex

their facets together with some incidence properties of the following type

3. Regular-faced d-polytopes for $d \ge 4$

In [1], [2] and [3] we showed, that for $d \ge 4$ the following list of regular-faced d-polytopes is complete:

for $d \ge 5$: the regular polytopes,

the polytopes of Gosset's list,

the pyramid with basis a regular (d-1)-crosspolytope, and

the bipyramid with basis a regular (d-1)-simplex.

for d = 4: the regular polytopes,

the polytopes of Gosset's list,

the pyramid with basis an octahedron,

the bipyramid with basis a tetrahedron,

the pyramid and the bipyramid with basis an icosahedron,

the union of a tetroctahedron (see Gosset's list) and of a pyramid, whose

basis is an octahedric facet of the tetroctahedron, and

the set \mathcal{A} of polytopes arising from the regular 600-cell by cutting off vertices in the following way:

Let Z be the 600-cell and let $\{E_i\}_{i=1}^k$ be a set of vertices of Z, such that no two vertices of $\{E_i\}_{i=1}^k$ are adjacent, i.e. joined by an edge of Z. Since Z is regular, for every E_i the vertices adjacent to E_i are contained in a hyperplane, which determines a closed halfspace $H(E_i)$ not containing E_i . Then $Z \cap \bigcap_{i=1}^k H(E_i)$ is a convex polytope, which is regular-faced, because Z is simplicial and no two vertices of $\{E_i\}_{i=1}^k$ are adjacent. We say that $Z \cap \bigcap_{i=1}^k H(E_i)$ arises from Z by maximally cutting off the vertices of $\{E_i\}_{i=1}^k$. Thus the set $\mathscr A$ is the set of those regular-faced polytopes which arise from the 600-cell by maximally cutting off a set of vertices, where every two vertices are non-adjacent.

Let us remark that analogously we may maximally cut off a suitable set of vertices from the icosahedron.

4. Proof of the Theorem

Let P be a semiregular polytope, which is not regular and not contained in Gosset's list. Since P is regular-faced and since the vertices of P are equivalent, we immediately deduce from the list of all regular-faced polytopes that P is 4-dimensional and that $P \in \mathcal{A}$.

Now let P be any semiregular polytope with $P \in \mathcal{A}$. Let P arise from Z by maximally cutting off k > 0 vertices of Z. Then, since Z has 120 vertices, the number e of vertices of P is given by

(*)
$$e + k = 120$$
.

The set of facets of P is a set of tetrahedra and exactly k icosahedra. Let a vertex E of P be incident with $m \ge 0$ icosahedric facets. Then the vertex-figure of P at E is a 3-polytope arising from an icosahedron by maximally cutting off m vertices where every two are non-adjacent. But such 3-polytopes exist only if $m \le 3$. We remark that for m = 3 there exists only one such 3-polytope: its 3 pentagonal faces do not have a common vertex, but every two of them have a common edge; so in case m = 3 the 3 icosahedral facets through E do not have a common edge, but every two of them have a common 2-face.

The vertices of P are equivalent, hence every vertex of P is contained in m icosahedric facets; thus $m \ge 1$. Moreover, every icosahedric facet contains 12 vertices of P, so e = 12k/m. From this and (*) follows

$$\frac{12+m}{m}k = 120, \qquad 1 \le m \le 3.$$

The only integer solution of this equality is m = 3, k = 24; so we have m = 3.

Now let E be a given vertex of P and let I, I_1 , I_2 be the m=3 icosahedric facets through E. Then by the previous remark $I \cap I_1 \cap I_2$ is not an edge of I, but $I \cap I_1$ and $I \cap I_2$ are 2-faces of I. Thus, if \mathscr{F} is the set of those 2-faces of I, which are also contained in another icosahedric facet, then no two elements of \mathscr{F} have a common edge, but every vertex of I is contained in exactly two elements of \mathscr{F} . From this it is easily seen that \mathscr{F} is uniquely determined for given $I \cap I_1$ and $I \cap I_2$, and so are the facets intersecting I in a 2-face. Proceeding in this way we see that P is uniquely determined for given I, I_1 and I_2 .

Three icosahedric facets through a vertex correspond to vertices of Z, which are uniquely determined up to isometries of Z by the previous remark. So there exists at most one semiregular polytope in \mathcal{A} .

The tetricosahedric polytope of Gosset's list is known to be in \mathscr{A} (see e.g. [5, p. 152f.]). Hence it is the only semiregular polytope in \mathscr{A} , which concludes the proof.

5. Concluding remarks

- 1. We tried to make the proof as self-contained as possible. The result would also follow immediately from k = 24 using Theorem 2 in [4].
- 2. It is well known (see e.g. [7, p. 413]) that if the definition of semi-regularity is slightly changed by substituting 'all vertex figures are congruent' for the transitivity of the symmetry group, then the Archimedean solids are no more the only 3-polytopes allowed, but there exists exactly one additional polytope. Further additional 3-polytopes exist, if instead of the congruence of the vertex figures we assume only, that every vertex is contained in the same number of facets (see [9]*). This is in contrast to the situation in higher dimensions:

In the proof of our Theorem we did not really use the transitivity of the symmetry group of a semiregular polytope, but only the fact that every vertex is contained in the same number of facets. Thus we have

THEOREM 2. A regular-faced d-polytope, where every vertex is contained in the same number of facets, is semiregular for $d \ge 4$.

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^{*} e.g. $M_6 + M_9$ is such a polytope; note that thus it may happen, that some vertices of such a polytope are contained in a quadrangle and others are not.

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