POLYHEDRA COMPUTATION
UNDER SYMMETRY

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By

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Abstract

The last 15 years have seen significant progress in the development of general purpose algorithms and software for polyhedral computation. Many polytopes of practical interest have enormous output complexity and are often highly degenerate, posing severe difficulties for known general purpose algorithms. They are, however, highly structured and attention has turned to exploiting this structure, particularly symmetry. We focus on polytopes arising from combinatorial optimization problems. In particular, we study the metric polytope associated to the well-known maxcut and multicommodity flow problems, as well as to finite metric spaces. To tackle the huge size of the problem – hundreds of trillions of vertices – a parallel orbitwise enumeration algorithm was implemented and run on Shared Hierarchical Academic Research Computing Network (SHARCNET) clusters. Exploiting the high degree of symmetry, we provide for the first time a description of the highly degenerate metric polytope in dimension 36. The description consists of 1 056 368 orbits and is conjectured to be complete. While the validity of the dominating set conjecture [Laurent-Poljak 1992] is proven for the overwhelming majority of the known vertices of the metric polytope, we disprove the conjecture by exhibiting counterexamples in dimensions 36 and 45.

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Chapter 1

Introduction

Convex polytopes are the d-dimensional analogues of 2-dimensional convex polygons and 3-dimensional convex polyhedra. To a large extent the geometry of polytopes is just that of $\mathbb{R}^d$ itself. These geometric objects of relevant importance in various areas of mathematics and other disciplines have been studied since antiquity (e.g., the platonic solids). Interest in the theory of convex polytopes grew tremendously in the second half of the 20th century due to its relation with linear programming (i.e., optimizing a linear function over the solutions of a system of linear inequalities). DANTZIG's Simplex Algorithm, developed in the late 40's, showed that geometric and combinatorial knowledge of convex polytopes is key for finding and analyzing solution procedures for linear programming problems.

A convex polytope can be defined as the bounded intersection of a finite set $\mathcal{H}$ of halfspaces. The well known theorem of Minkowski-Weyl states that polytopes can also be defined as the convex hull of its set characterization of polytopes give rise to two closely related computational problems: how to compute vertex enumeration problem, and how to compute $\mathcal{H}$ from as the facet enumeration problem. These two problems are essentially equivalent under the point/hyperplane duality.

The vertex/facet enumeration of combinatorial polytopes, i.e. polytopes arising from combinatorial optimization problems, is often trivial for the very first cases and then suddenly the so-called combinatorial explosion occurs even for small instances. While these polytopes turn out to be quickly intractable for enumeration algorithms designed for general polytopes, algorithms using their rich combinatorial features can exhibit surprisingly strong performances. In the last five years different research groups have proposed new enumeration techniques for combinatorial polytopes, in particular the metric polytope, that exploit their large symmetry groups making it possible tackle problems that until now have been intractable.

In this thesis we analyze in detail the vertex enumeration problem applied to the metric polytope. We begin by studying the two main classes of enumeration algorithms designed for general polytopes, namely incremental and pivoting based algorithms. We show how combinatorial polytopes quickly turn intractable for these methods. We then analyze how the rich combinatorial structure of the metric polytope can be exploited to perform enumerations that would otherwise be impossible. Specifically by partitioning its vertices into symmetry groups called orbits and performing an orbitwise enumeration based on adjacency decomposition. A parallel implementation of an orbitwise enumeration algorithm is then developed and experimental computations are carried out on SHARCNET clusters. We perform first-time computation of metric polytope in dimensions 36 and 24 and use its results to determine new combinatorial properties in order to reach tighter relaxations, thereby generating closer approximations. In particular, we exhibit a set of vertices that are counter examples for the dominant set conjecture of Laurent and Poljak obtained from the computation of these two polytopes. We also exhibit a set of vertices that reveal the limitations of certain heuristics used for computing the structure of polyhedra.

1.1 Polytopes

We recall some definitions and elementary properties concerning polyhedra. A complete presentation can be found in BAYER AND LEE [4] BRØNDSTED [5], GRÜNBAUM [23], MCMULLEN AND SHEPHARD [27], and ZIEGLER [32]. A *convex polytope* is an intersection of a finite number of closed half spaces in $I\!R^d$. Since we do not consider non-convex polyhedra, we often omit the term convex. Let P be a d-dimensional polytope, a linear inequality $c \cdot x \leq c_0$ is valid for P if it is satisfied for all points $x \in P$. A face F of P is any set of the form:

$$F = P \cap \{x \in I\!R^d : c \cdot x = c_0\}$$

where $c \cdot x \leq c_0$ is a valid inequality for P. The *dimension* of a face is the dimension of its affine hull. A *proper face* of P is a face F such as $F \neq \emptyset$. The faces of dimension 0, 1, $d-2$ and $d-1$ are respectively called the *vertices*, *edges*, *ridges*) and *facets* of the polytope. One of the earliest results in the field is the generalization by SCHLAFLI in 1852 of EULER's relation stating that the alternating sum of the number of i-faces (including the improper faces $\emptyset$ and P itself) equals zero. For the case $d = 3$, it was discovered by EULER in 1752. The *face lattice* of a convex polytope is the set of all its faces partially ordered by inclusion. Two polytopes are *combinatorially equivalent*, respectively *dual*, if there is a bijection between their faces with preserves, respectively reverses, the inclusion relations.

Figure 1.1: Platonic solids

A d-dimensional polytope with exactly $d+1$ vertices is called a *simplex.* A polytope such that each vertex belongs to exactly d edges is *simple*, and a polytope such that each facet contains exactly d vertices is *simplicial.* A d-dimensional polytope is called k-simplicial if each k-face is a simplex. The dual of a k-simplicial polytope is called k-simple. Figure 1.1 illustrates different types of polytopes in dimension 3, namely the five platonic solids: tetrahedron, cube, octahedron, dodecahedron and isocahedron. We recall some definitions and elementary properties concerning the graph of a polytope. A complete presentation can be found in BRØNDSTED [5] and ZIEGLER [32]. The main reference for the general graph theory is BROUWER, COHEN AND NEUMAIER [6]. The vertices and edges of a d-dimensional polytope P clearly form an undirected graph $G(P)$ called the *skeleton* of P. The *diameter* $\delta(P)$ of a polytope P is the diameter of its skeleton, that is, the smallest number such that any two vertices of P can be connected by a path with at most edges. In this thesis we will consider only non-redundant representation of bounded convex polyhedra. An representation is redundant is removing an hyperplane does not change the polyhedra.

1.2 Thesis Outline

The current Chapter 1 is an introduction to convex polyhedra and some motivation to study the structure of these objects.

Chapter 2 deals the vertex enumeration problem for combinatorial polyhedra and its complexity. We also discuss the strengths and limitations of the two main classes of algorithms for vertex enumeration: pivoting and incremental algorithms.

Chapter 3 introduces the adjacency decomposition method with exploits the large symmetry group of most combinatorial polytopes and enable us to to tackle problems that would be intractable by pivoting or incremental algorithms.

Chapter 4 is devoted to the technical design and development of a software that implements the adjacency decomposition method for vertex enumeration. We also describe how the software was used on large scale SHARCNET parallel clusters, leading to the first time computation of a particulary challenging polytope: the 36-dimensional metric polytope met_9 on 9 nodes.

In Chapter 5 we introduce a theoretical result yielded from the computation met_9: we provide counterexamples in dimension 36 and 45 for the *dominating set conjecture* of MONIQUE LAURENT AND SVATOPLUK POLJAK open since 1992.

Finally, Chapter 6 contains concluding remarks and suggestions for future work.

Appendix A contains some of the most important numerical results obtained from the computation of the 36-dimensional metric polytope met_9.

Appendix B contains the set of orbits of counterexamples for the dominating set conjecture .

Appendix C contains information about the online publication of the software developed in this thesis as well as sample input and output files for computing the metric polytope met_n for $n = 3, \ldots, 9$.

Chapter 2

Polyhedra Computation

2.1 The vertex Enumeration Problem

A d-dimensional convex polyhedron is the intersection of a finite number m of non-redundant halfs-paces $\mathcal{H} = \{H_1, H_2, \ldots, H_{|\mathcal{H}|}\}$ of $I\!R^d$. A bounded polytope P can also be expressed as the convex hull of its vertices $\mathcal{V} = \{v_1, v_2, \ldots, v_{|\mathcal{V}|}\}$. These descriptions of P will be referred to as the *halfspace* and *vertex* descriptions, respectively. In this thesis we consider only non-redundant and bounded convex polyhedra. The size of a polytope, denoted $\text{size}(P) = (|\mathcal{H}| + |\mathcal{V}|)d$, is the space required to store both descriptions of a polytope. There are three closely related computational problems concerning the two descriptions of a polytope:

- The vertex enumeration problem asks to compute $\mathcal{V}$ from $\mathcal{H}$.
- The facet enumeration problem asks to compute $\mathcal{H}$ from $\mathcal{V}$.
- The polytope verification problem asks to decide whether a given vertex description $\mathcal{V}$ and halfspace description $\mathcal{H}$ determine the same polytope.

The first two problems are equivalent under point/hyperplane duality. Either of the first two can be trivially used to solve the third. To solve the vertex enumeration using polytope verification, verify that all vertices have been found for each facet of P. If not, recurse on that facet. In at most $d\ |\mathcal{H}|$ polytope verification calls, the algorithm finds a new vertex. In this thesis we focus on the vertex//facet enumeration problems which are essentially equivalent under point/hyperplane duality. We therefore restricted the discussion to the vertex enumeration problem. When measuring the efficiency of a vertex enumeration algorithm an important factor is the large gap between the upper and lower bound of the output size, i.e., the number of vertices. McMullen [26] upper bound theorem give that the number of vertices of a d-dimensional polytope P defined as the intersection of $|\mathcal{H}|$ halfspaces can be as large as:

$$V_{max} = \binom{|\mathcal{H}|-\lceil \frac{d}{2} \rceil}{\lfloor \frac{d}{2} \rfloor} + \binom{|\mathcal{H}|-1-\lceil \frac{d-1}{2} \rceil}{\lfloor \frac{d-1}{2} \rfloor}$$

Barnette [3] lower bound theorem (for simple polytope) gives that the number of vertices could be as few as:

$$V_{min} = (|\mathcal{H}| - d)(d-1) + 2$$

This large possible gap suggests that the performance of vertex enumeration algorithms be measured not only in terms of input size $d|\mathcal{H}|$ but also in terms of output size $d|\mathcal{V}|$.

The main vertex enumeration algorithms can be viewed as not just generating all vertices of a polytope P but actually the skeleton of P, i.e. the graph formed by its vertices and edges. There are essentially two main classes of algorithms for producing these graphs: graph traversal algorithms and incremental algorithms.

2.2 Pivoting Algorithms

Pivoting algorithms, also called graph traversal algorithms, first find one vertex of the skeleton and then attempt to identify all vertices and edges of the graph by traversing it in some fashion. In the case of vertex enumeration each vertex v of a d-polytope P can be identified by a basis, i.e. d facets that contain v and whose spanning hyperplanes are affinely independent. Two simple vertices of P are connected by an edge of P if they have bases that differ in exactly one member. Going from a vertex to an adjacent one during the graph traversal amounts to changing this one member of the basis. This operation is known as pivoting in the simplex algorithm for linear programming. For this reason graph traversal algorithms for vertex enumeration are also known as pivoting algorithms. In the context of facet enumeration going from one facet to a neighboring can be viewed as rotating a supporting hyperplane about the common ridge. Representatives of this class of graph traversal algorithms are the gift wrapping algorithm of CHAND AND KAPUR [7], SEIDEL [31] algorithm and the reverse search algorithm of AVIS AND FUKUDA [2]

2.3 Incremental Algorithms

Incremental algorithms for the vertex enumeration problem compute the vertex description by intersecting the defining halfspaces sequentially. An initial simplex is constructed from a subset of $d + 1$ affinely independent halfspaces and its vertices and skeleton are computed. Additional halfspaces are introduced sequentially and the vertex description and skeleton are updated at each stage. Essentially such an update amounts to identifying and removing all vertices that are not contained in the new halfspace, introducing new vertices for all intersections between edges and the bounding hyperplane of the new halfspace, and generating the new edges between these new vertices. The first explicit description of such an algorithm, now widely known as the double description method, appeared in the pioneering paper of MOTZKIN [?] in 1953. We should mention that so-called Fourier-Motzkin elimination can be viewed just as a dual formulation of the double description method and thus falls in the class of incremental algorithms. All incremental algorithms can use different insertion orders. One can distinguish between static insertion orders, which are determined from the inputs before the actual incremental algorithm is started, and dynamic insertion orders, where the next halfspace to be considered is a function of the current polytope and the remaining halfspaces. Typical static orderings are minindex (process in order as the input happens to be), lexicographic (process halfspaces in lexicographic order of their suitably normalized coefficient vectors), and random. Typical dynamic orderings are maxcut and mincut (as next halfspace choose the one whose complement constrains the most or least vertices of the current polytope). The same algorithm applied to the same input can have vastly different running times when different insertion orders are used. Thus choosing a good insertion order is crucial.

Chapter 3

Polyhedra Computation Under Symmetry

A full d-dimensional bounded polytope P can be defined either by the set $\mathcal{H}$ of its facet-inducing linear inequalities or as the convex hull of its vertex set $\mathcal{V}$. While these two representations are theoretically equivalent, converting one into the other is a difficult computational problem. The computation of $\mathcal{H}$ from $\mathcal{V}$ is the *facet enumeration problem* and the computation of $\mathcal{V}$ from $\mathcal{H}$ is the *vertex enumeration problem.* These two problems being equivalent by the vertex/facet duality, we mainly consider the vertex enumeration problem.

The two main enumerations are: the *pivoting methods* and the *incremental methods.* The basic pivoting method first finds one vertex of P and then identifies all vertices (and edges) by moving from one vertex to an adjacent one. In this method, each vertex v is described by a *basis* - i.e. d affinely independent inequalities containing v. Moving from one vertex to an adjacent one amounts to change one member of the basis in some proper way. The basic insertion method first selects $d + 1$ affinely independent inequalities and computes the vertices and edges of the associated d-simplex. Then at each step k one of the remaining inequalities H_k is inserted and the vertex and edge description is updated by removing the vertices cut off by the newly inserted inequality H_k and adding new vertices (and edges) created by the intersections of edges of the intermediate polytope P_k with the newly inserted inequality H_k. For a detailed presentation of main existing algorithms we refer to AVIS, BREMMER AND SEIDEL [1] and references therein.

Even though these algorithms often perform quite well for many cases - in particular for low dimensional and simple polytopes - and despite the fact that the vertex enumeration problem has been extensively studied by many authors - see for instance [2, 7, 21, 28, 30] - there is no satisfying algorithm for generating the vertices of a general polytope given by its facets. In [1] AVIS, BREMMER AND SEIDEL underlined the main weakness of the pivoting and insertion methods: "...inability to deal with degeneracies or inability to control the sizes of intermediate results". For each main class of algorithms, they exhibited a family of polytopes for which the performances can be very poor. Degeneracy occurs when the incidence Icd_v of a vertex v - i.e. the number of facets containing v - is strictly higher that the dimension d. A highly degenerate vertex might create a very large number of bases and a naive pivoting algorithm would visit each of them. One can deal with degeneracy either by the perturbation technique - which makes the polytope simple but might create a large number of additional vertices, see [1] for details. As for insertion algorithms, they are very sensitive to the order in which the inequalities are inserted. Computing the entire face lattice of P is a computationally extremely expensive approach.

In this thesis we focus on *combinatorial polytopes*, i.e. polytopes arising from combinatorial optimization problems. On one hand, the so-called *combinatorial explosion* occurs even for small instances and these polytopes, often trivial for the very first cases, become quickly intractable by enumeration algorithm designed for solving general polytope. On the other hand, tailor-made algorithms using their rich combinatorial features can exhibit surprisingly strong performances. For example, CHRISTOF AND REINELT [8] computed large instances of the *traveling salesman polytope*, the *linear ordering polytope* and the *cut polytope* using their large symmetry group. In a similar approach, in addition to its large symmetry group, we used a partial knowledge of its combinatorial structure to orbitwise enumerated the vertices of another combinatorial polytope: the *metric polytope* met_n.

3.1 Generating Vertices with Symmetries

3.1.1 Combinatorial Polytopes

We first present some polyhedra with application in combinatorial optimization. In particular we consider polyhedra associated to problems which are symmetric. We recall that the *symmetry group* $Is(P)$ of a polytope P is the group of isometries preserving P. Typical examples of polytopes with large symmetry group are polytopes associated to problems arising from the complete directed graph D_n or the undirected graph K_n on n nodes. Some well know polyhedra are: the *traveling salesman polytope* tsp_n which is the convex hull of all the incidence vectors of all Hamiltonian cycles of K_n and the *linear ordering polytope* lo_n which is the convex hull of the incidence vectors of all acyclic tournaments of D_n. The isometries preserving tsp_n are induced by the $n!$ permutations on $V_n = \{1, 2, \ldots, n\}$, that is, $Is(tsp_n) \simeq Sym(n)$.

In this thesis we consider polytope with even larger symmetry group: the cut and metric polyhedra. The $\binom{n}{2}$-dimensional cut polytope cut_n is usually introduced as the convex hull of the incidence vectors of all the cuts of K_n. More precisely, given a subset S of V_n, the *cut* determined by S consists of the pairs (i,j) of elements of V_n such that exactly one of i,j is in S. By $\delta(S)$ we denote both the cut and its incidence vector in $I\!R^{\binom{n}{2}}$, that is, $\delta(S)_{ij} = 1$ if $|\{i,j\} \cap S| = 1$ and $\delta(S)_{ij} = 0$ otherwise for $1 \leq i < j \leq n$. By abuse of language, we use the term cut for both the cut itself and its incidence vector, so $\delta(S)_{ij}$ are considered as coordinates of a point in $I\!R^{\binom{n}{2}}$. The cut polytope cut_n, which is also called the complete bipartite subgraphs polytope, is the convex hull of all 2^{n-1} cuts, and the cut cone Cut_n is the conic hull of all $2^{n-1}-1$ nonzero cuts.

The cut polytope and one of its relaxation - the metric polytope - can also be defined in terms of finite metric space in the following way. For all 3-sets $\{i,j,k\} \subset \{1,\ldots,n\}$, we consider the following inequalities:

$$x_{ij} - x_{ik} - x_{jk} \leq 0 \qquad (2.1)$$

$$x_{ij} + x_{ik} + x_{jk} \leq 2 \qquad (2.2)$$

The inequalities (2.1) induce the $3\binom{n}{3}$ facets which define the *metric cone.* Then, bounding the latter by the inequalities (2.2) we obtain the *metric polytope* met_n. The $3\binom{n}{3}$ (resp. $\binom{n}{3}$) facets defined by (2.1) (resp. (2.2)) can be seen as triangle (resp. perimeter) inequalities for distance x_{ij} on $\{1,2,\ldots,n\}$. While the cut cone is the conic hull of all, up to a constant multiple, $\{0,1\}$-valued extreme rays of the metric cone, the cut polytope cut_n is the convex hull of all $\{0,1\}$-valued vertices of the metric polytope. The link with finite metric spaces is the following: there is an evident $1-1$ correspondence between the elements of the metric cone and all the semi-metrics on n points, and the elements of the cut cone correspond precisely to the semi-metrics on n points that are isometrically embeddable into some l_1^s.

One of the motivations for the study of these polyhedra comes from their applications in combinatorial optimization, the most important being the max-cut problem. Given a graph $G = (V_n, E)$ and nonnegative weights w_e, $e \in E$, assigned to its edges, the *max-cut* problem consists in finding a cut $\delta(S)$ whose weight $\sum_{e \in \delta(S)} w_e$ is as large as possible. It is a well-known NP-complete problem. By setting $w_e = 0$ if e is not an edge of G, we can consider without loss of generality the complete graph on V_n. Then the max-cut problem can be stated as a linear programming problem over the cut polytope cut_n as follows:

$$\begin{array}{ll} \max & w^T \cdot x \\ \text{subject to} & x \in \mathrm{cut}_n \ . \end{array}$$

Since the metric polytope is a relaxation of the cut polytope, optimizing $w^T \cdot x$ over cut_n instead of met_n provides an upper bound for the max-cut problem.

The polytope cut_n is a $\binom{n}{2}$ dimensional 0–1 polyhedron with 2^{n-1} vertices and met_n is a polytope of same dimension with $4\binom{n}{3}$ facets inscribed in the cube $[0,1]^{\binom{n}{2}}$. We have $\mathrm{cut}_n \subseteq \mathrm{met}_n$ with equality only for $n \leq 4$. Any facet of the metric polytope contains a facet of the cut polytope and the vertices of the cut polytope are vertices of the metric polytope, in fact the cuts are precisely the integral vertices of the metric polytope. Actually the metric polytope met_n wraps the cut polytope cut_n very tightly since, in addition to the vertices, all edges and 2-faces of cut_n are also faces of met_n, for 3-faces it is false for $n \geq 4$, see [10]. Any two cuts are adjacent both on cut_n and on met_n. While the diameter of the dual of the metric polytope met_n^* is 2, the diameters of the dual cut polytope cut_n^* and met_n are respectively conjectured to be 4 and 3, see [9, 25]. We recall that the skeleton of a polytope is the graph formed by its vertices and edges. For a detailed study of those polytopes and their applications in combinatorial optimization we refer to DEZA AND LAURENT [17] and POLJAK AND TUZA [29].

3.1.2 Orbitwise Enumeration Algorithm

As stressed earlier, one important feature of the metric and cut polytopes is their very large symmetry group. More precisely, for $n \geq 5$, we have $Is(\mathrm{met}_n) = Is(\mathrm{cut}_n)$ and both are induced by permutations on $V_n = \{1, \ldots, n\}$ and *switching reflections by a cut* and, for $n \geq 5$, we have $|Is(\mathrm{met}_n)| = 2^{n-1}n!$, see [15]. Given a cut $\delta(S)$, the switching reflection $r_{\delta(S)}$ is defined by $y = r_{\delta(S)}(x)$ where $y_{ij} = 1 - x_{ij}$ if $(i,j) \in \delta(S)$ and $y_{ij} = x_{ij}$ otherwise. As these symmetries preserve the adjacency relations and the linear independency, all faces of met_n are partitioned into orbits of faces equivalent under permutations and switchings.

Proposition 3.1.1 *The vertices of the metric polytope* met_n *are partitioned into orbits of its symmetry group. Let* v_i *be a vertex of* met_n*,* Icd_{v_i} *its incidence,* Adj_{v_i} *its adjacency and* O_i *the orbit generated by the action of* $Is(\mathrm{met}_n)$ *on* v_i*. For any vertex* $v \in O_i$*, we have* $Icd_v = Icd_{v_i}$ *and* $Adj_v = Adj_{v_i}$*.*

In other words, the *neighborhood*, that is, the set of vertices adjacent to a given vertex, is equivalent up to permutations and switchings for all vertices belonging to the same orbit. Proposition 3.1.1 leads to the following *orbitwise enumeration algorithm.* The main two subroutines are the enumeration of the neighborhood N of a vertex v and the computation of the canonical representative $\tilde{v}$ of the orbit O containing v. Starting from an initial vertex v_1 the algorithm computes the canonical representative $\tilde{v}_1$ of the orbit O_1 generated by v_1, computes its neighborhood N_1, identifies new orbits contained in N_1, updates the list L of canonical representatives and then picks up the next canonical representative in L which neighborhood is not yet computed. The algorithm terminates when there is no more such canonical representative in L and outputs L. Since the skeleton of a polytope is connected, this algorithm finds all orbits.

Orbitwise Enumeration Algorithm

```
begin
    Find an initial vertex $v_1$;
    Compute the canonical representative $\tilde{v}_1$ of the orbit $O_1$ generated by $v_1$;
    Mark $\tilde{v}_1$ with a "$\circ$"; \* neighborhood not yet computed *\
    Initialized the list $L$ of canonical representatives with $\tilde{v}_1$;
    while $L$ contains a vertex $\tilde{v}_i$ marked "$\circ$" do
    begin
      Compute the neighborhood $N_i$ of $\tilde{v}_i$;
      For each vertex $v_k$ adjacent to $\tilde{v}_i$;
        Compute the canonical representative $\tilde{v}_k$ of the orbit $O_k$ generated by $v_k$;
```

```
            If $\tilde{v}_k \in L$, disregard it;
            If $\tilde{v}_k \notin L$, mark it with a "$\circ$" and add it to $L$;
        Mark $\tilde{v}_i$ with a "$\bullet$"; \* neighborhood computed *\
    end
    Output $L$;
end
```

Lemma 3.1.2 *Let I be the number of orbits, Icd_i and Adj_i the incidence and the adjacency of the orbit O_i for $i = 1, \dots, I$. The neighborhood enumeration subroutine is called exactly I times and each neighborhood is generated by Icd_i facets. The canonical representative computation subroutine is called exactly $\sum_{i=1 \dots I} Adj_i$ times.*

Remark 3.1.3

(*i*) *The orbitwise enumeration algorithm performs I classic vertex enumerations for smaller sub-polytopes (one for each orbit of neighborhoods) instead of performing one large classic vertex enumeration (the whole polytope).*

(*ii*) *The computation is independent of the choice of the initial vertex v_1.*

(*iii*) *In case of very high degeneracy, the subroutine computing the canonical representative has to be called a large number of times and some of the neighborhoods might represent a large fraction of the whole polytope.*

For $i = 1, \dots, I$, the algorithm get the orbitwise incidence Icd_i (by simply checking which inequality is satisfied with equality) as input for the neighborhood enumeration subroutine and get the adjacency Adj_i as output of this subroutine. By simply counting the number of times a vertex equivalent to the canonical representative $\tilde{v}_k$ is found in N_i, we get the *orbitwise adjacency table*, that is, the $I \times I$ matrix Adj with $\mathrm{Adj}_{i,j}$ the number of vertices of the orbit O_j adjacent to $v \in O_i$. Assuming we know the size of one orbit, from the matrix Adj we can get the size of the other orbit using the following easy relation: $\mathrm{Adj}_{i,j} \times |O_i| = \mathrm{Adj}_{j,i} \times |O_j|$.

Remark 3.1.4 *The output, that is, the list of canonical representatives $\tilde{v}_i$ for $i = 1, \ldots, I$, is minimally compact. Additionally to the vertex enumeration, the algorithm computes the orbits invariants Adj_i, Icd_i and $|O_i|$. The orbitwise adjacency table Adj reveals the skeleton. The total number of vertices is simply $\sum_{i=1,\ldots,I} |O_i|$ and the full list of vertices can be generated by the action of the symmetry group on each representative $\tilde{v}_i$.*

3.2 Generating Vertices of the Metric Polytope

The adjacency check and the heuristics presented in this section are valid for other combinatorial polytopes but - without theoretical improvement - we restrict ourself to the metric polytope case. Insertion algorithms usually handle better high degeneracy that pivoting algorithms. The metric polytope met_n being extremely degenerate (the cut incidence $\mathrm{Icd}_{\delta(S)} = 3\binom{n}{3}$ is much larger than the dimension $d = \binom{n}{2}$), we choose an insertion algorithm for the neighborhood enumeration subroutine: the *cddlib* implementation of the double description method [20]. In the following, we always assume that the neighborhood enumeration subroutine is performed by an insertion algorithm. Item (*iii*) of Remark 3.1.3 indicates that even the neighborhoods of highly degenerate polytopes might be beyond problems currently solvable by insertion algorithm. In Section 3.2.2, we present heuristics addressing this issue.

3.2.1 Results and Conjectures on the Skeleton of the Metric Polytope

We recall some results on the vertices of the metric polytope and a conjecture which can be seen as complementary to the LAURENT-POLJAK conjecture. The cuts are the only integral vertices of met_n. All other vertices with are not fully fractional are so-called *trivial-extensions* of a vertex of met_{n-1}. In other words, the new vertices are the fully fractional ones. The $(\frac{1}{3}, \frac{2}{3})$-valued fully fractional vertices are well studied and include the anticut orbit formed by the 2^{n-1} *anticuts* $\bar{\delta}(S) = \frac{2}{3}(1, \dots, 1)$-$\frac{1}{3}\delta(S)$. Metric polytopes met_3 and met_4 have, respectively, 4 and 8 vertices made of cuts as $\mathrm{met}_3 = \mathrm{cut}_3$ and $\mathrm{met}_4 = \mathrm{cut}_4$. The 32 vertices of met_5 form 2 orbits: 16 cuts and 16 anticuts. The metric polytope met_6 has 544 vertices (3 orbits), see [25], and met_7 has 275 840 vertices (13 orbits), see [11]. The metric polytope met_8 has 1 550 825 600 vertices partitioned into 533 orbits.

Property 3.2.1 [25] *Let v be a vertex of* met_n, *we have:* $Icd_v \leq Icd_{\delta(S)} = 3\binom{n}{3}$ *with equality only for* $v = \delta(S)$ *and, if v is fully fractional,* $Icd_v \leq Icd_{\bar{\delta}(S)} = \binom{n}{3}$ *with equality only for* $v = \bar{\delta}(S)$.

Conjecture 3.2.2 [25] *Any vertex of the metric polytope is adjacent to a cut.*

Conjecture 3.2.3 [13] *For* $n \geq 6$, *the restriction of the skeleton of the metric polytope* met_n *to the non-cut vertices is connected.*

While Conjecture 3.2.2 underlines the extreme connectivity of the cuts, Conjecture 3.2.3 means that the skeleton remains connected without the cuts. Recall that the cuts form a clique in both the cut and metric polytopes. Therefore, if Conjecture 3.2.2 holds, the cuts would be a dominant clique in the skeleton of met_n implying that its diameter would satisfy $\delta(\text{met}_n) \leq 3$. Conjecture 3.2.2 holds for $n \leq 8$. The computational applications of Conjecture 3.2.3 - which holds for $n \leq 8$ and is strongly believed to be true - are developed in Section 3.2.2.

3.2.2 Heuristic: Skipping High Degeneracy

If Conjecture 3.2.3 holds, all orbits can be found by the following *metric cone skipping* heuristic: disregard $\tilde{v}_k$ if $\tilde{v}_k = \delta(S)$. In other words, disregard the neighborhood of the cuts, that is, essentially the metric cone Met_n. This neighborhood being, far from other, the largest as $\text{Adj}_{\delta(S)} \gg \text{Adj}_{v \neq \delta(S)}$, the heuristic removes the hardest neighborhood enumeration. Note that cuts are very easy to recognize as $\delta(S)$ is uniquely characterised by its incidence: $\text{Icd}_{\delta(S)} = 3\binom{n}{3}$. For the metric on 8 nodes, while $\text{Adj}_{\delta(S)} = 119\,269\,588$ - i.e. 7.7% of the total number of vertices of met_8 - the enumeration of the other 532 neighborhoods generates (with multiplicity) $\sum_{i=1...I}^{v \neq \delta(S)} \text{Adj}_i = 780\,711$ vertices - i.e. less than 0.05% of the total number of vertices. One can easily get the neighborhood of the cut from the orbitwise adjacency table Adj. Taking the column and the row corresponding to the cuts, we have: $\text{Adj}_{\delta(S),i} \times 2^{n-1} = \text{Adj}_{i,\delta(S)} \times |O_i|$ where $\text{Adj}_{i,\delta(S)}$ is the number of cuts adjacent to $v_i \in O_i$.

Proposition 3.2.4 *If true, Conjecture 3.2.3 would be a certificate that the "metric cone skipping heuristic" gives a complete description of the metric poly-*

tope by generating only a very small fraction of the vertices.

One can further decrease the computation time by skipping not only the orbit with the highest incidence (the cuts) but all orbits with arbitrarily high incidence. In this case, a certificate for a complete description is that the restriction of the skeleton of met_n to the low incidence vertices is connected. This heuristic is particularly suitable for partial enumeration purpose and the choice of the initial vertex become an important factor.

Chapter 4

Software Implementation: Parameterization, Design and Parallelization

4.1 Parameterization

Dealing with combinatorial polytope is a major computational challenge due to the usually enormous size and complexity resulting from the high dimensions and degeneracies. In order to perform large scale computations, a particular attention has to be given to the analysis of the combinatorial and geometric properties of the input. The first task is to carefully investigate the behavior, including the adjacency and incidence relationships, for known metric polytopes met_n for $n = 3, \ldots, 8$. Identify potentially easy/hard to compute neighborhoods is a key factor for a successful implementation of the adjacency decomposition method. As stressed earlier, the computation of the neighborhood of highly degenerate vertices with large adjacency can take a considerable amount of resources both in memory and CPU time. Given the usually high correlation between high incidence and high adjacency (and small size orbit), the orbitwise enumeration algorithm developed to compute met_8 used the *skipping high degeneracy* heuristic. The description of met_8 was later proven complete using additional computation of the upper face-lattice. The skipping high degeneracy heuristic consist in simply filtering out potential intractable vertices by checking if their incidence is higher than a fixed threshold value. Checking the incidence is a straightforward computation. This approach was successful for the computation of met_8 as all its 1 550 825 600 can be found using this heuristic. Note that while the number of vertices of met_8 is huge, they are partitioned in 533 orbits which is a relatively small figure. The gap with met_9 is large as this 36-dimensional polytope has an estimate of a hundred billion vertices, partitioned about a million orbits. The heuristic was therefore refined. Fig.4.1 gives an overview of the distribution of orbits by incidence and adjacency for met_8. As it can be observed, the majority of the orbits are of low incidence, and the adjacency distribution through out these orbits is also low but with a small peak: A small subset of low incidence orbits have relatively high adjacency. The higher the incidence, the smaller the group of orbits, and

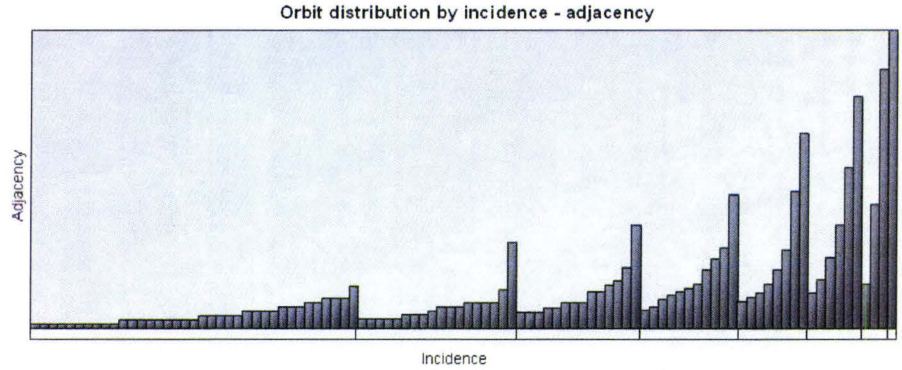

Figure 4.1: Orbit distribution pattern in metric polytope

the taller the peak. This pattern is then repeated through all the orbits until reaching the orbits of very large incidence which constitute the smallest group but have the largest adjacency.

Due to the large number of orbits met_9, the skipping highest degeneracy heuristic was refined to take in account the adjacency and computation-time in addition to incidence. The intractability is a result mostly of the adjacency witch is only estimated by the incidence. As illustrated by the incidence-adjacency distribution graph, some orbits with high incidence have with relatively moderate adjacency and could be computed. Incidence and adjacency upper and lower bounds were therefore added into the design of the software as parameter These bounds create a *computation window* as shown in Fig.4.2. The computation window allow us to introduce a new termination criteria: the enumeration will be considered complete when the set of orbits that are found within the computation window have all been computed. At the initial state of the vertex enumeration process, the computation window can be set to include only the set of orbits with the lowest known incidence (which have the low

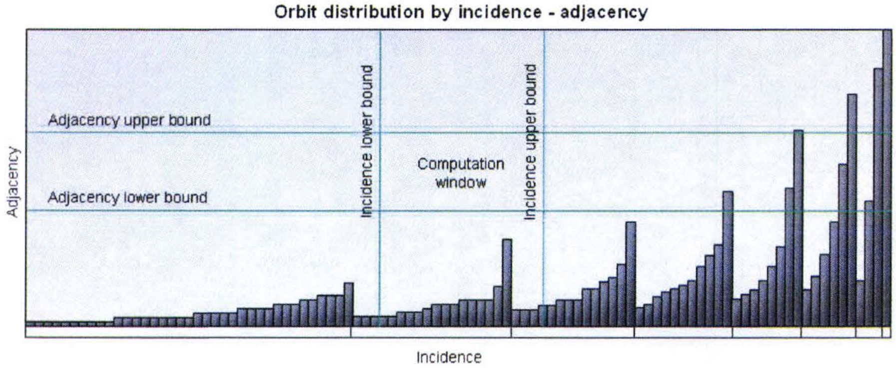

Figure 4.2: Computation window

adjacency). This will ensure that the computation can be completed since all such orbits to be computed are tractable. This is shown in Fig.4.3. In this figure we can see how the computation of a small set of low incidence orbits can reveal a large amount of information about the rest of the structure of the polytope. The key idea is to turn the enumeration incremental: Once a set of orbits has been computed, resume the computation from that point, so no orbit has to be computed twice. The information obtained within each computation can be used to fine tune the next one, given that at each stage new orbits will be discovered, toward a complete description of the polytope. Once the first computation has been completed, the computation window can be set to include the next cluster of tractable orbits, as shown in Fig.4.4. Every time a new computation window is set, additional tractable orbits are computed, inducing the discovery of additional orbits. Intractable orbits can be detected in time and properly skipped. This process is then repeated till all tractable orbits have been computed as shown in Fig.4.5.

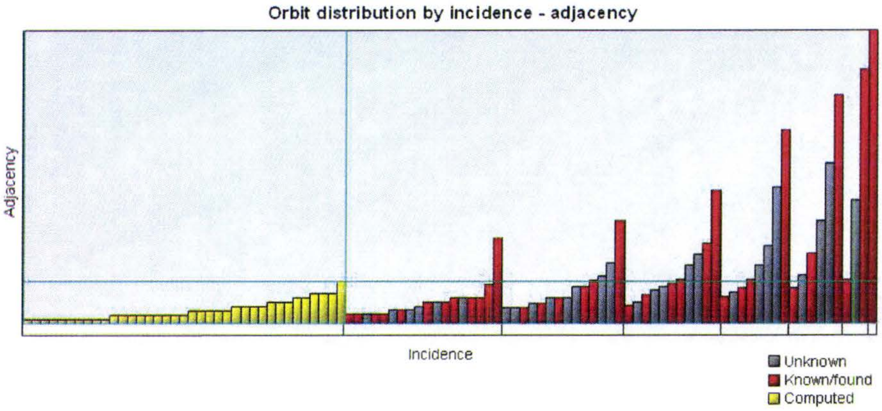

Figure 4.3: Lowest incidence initial orbit set computation

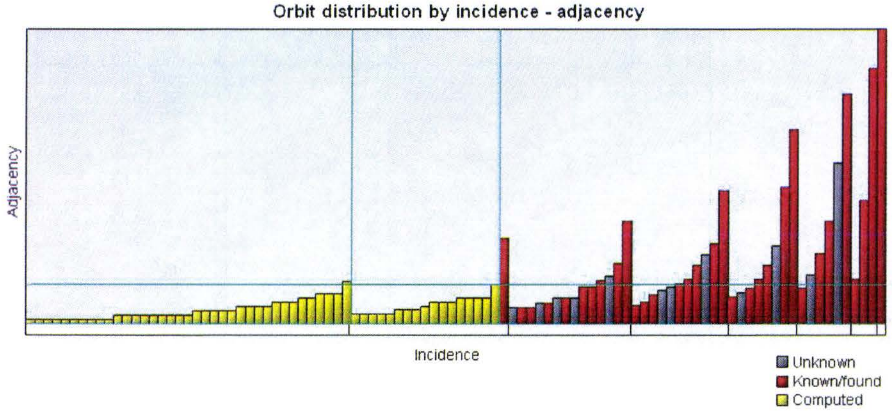

Figure 4.4: Targeting the next cluster of tractable orbits

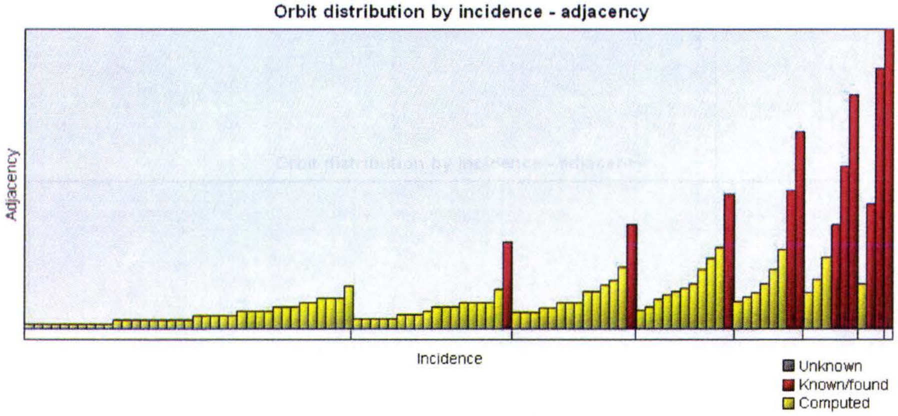

Figure 4.5: Orbit computation distribution

4.2 Design

An object oriented design approach was adopted for the implementation of the orbitwise enumeration algorithm. For this, a set of entities (objects) were defined, each one with its set of responsibilities. These objects are described next.

4.2.1 Orbit Database

This object's responsibility is to store in memory the set of orbits under computation, as well as saving and retrieving them from a secondary storage device, such as a hard disk drive. Also, this object will be responsible for keeping track of the status of each orbit, whether it has been computed or not, found or unknown.

4.2.2 Orbitwise Adjacency Calculator

This object's responsibility is to compute orbits. This is, given the coordinate of a vertex, obtain the set of adjacent vertices and return the canonical representative of the orbits they belong to. This is performed by utilizing TCDDLib, a n enhanced version of the Double Description Method Library which includes tools for incidence and adjacency control as well as time-out mechanisms.

4.2.3 Enumeration Controller

This object's responsibility is to coordinate the other objects in the process. This includes initializing the Orbit database, extracting the orbits to be computed from it and feeding them into the Orbitwise adjacency calculator. This object is also responsible for program initialization and termination.

The interaction between these three main objects is detailed in Fig.4.6.

4.3 Parallelization

It is important to observe that throughout the enumeration, the computation of an orbit requires only the coordinates of one of its vertices. This provides the

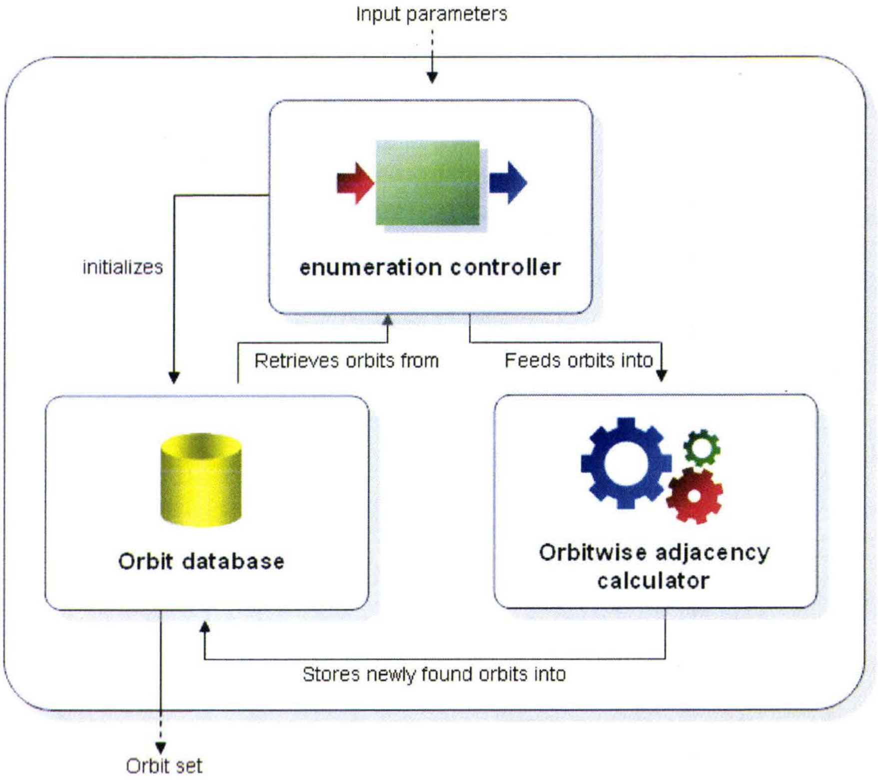

Figure 4.6: Orbitwise enumeration main modules

ideal setting to parallelize the system given that multiple orbits could be computed concurrently as there is no need to share data in between their computations. For this, we first separate the main process introduced in the preceding section into sub processes: a master process that will contain the enumeration controller and orbit database objects, and a variable number of slave processes, each containing an instance of the orbitwise adjacency calculator object. This is shown in Fig.4.7.

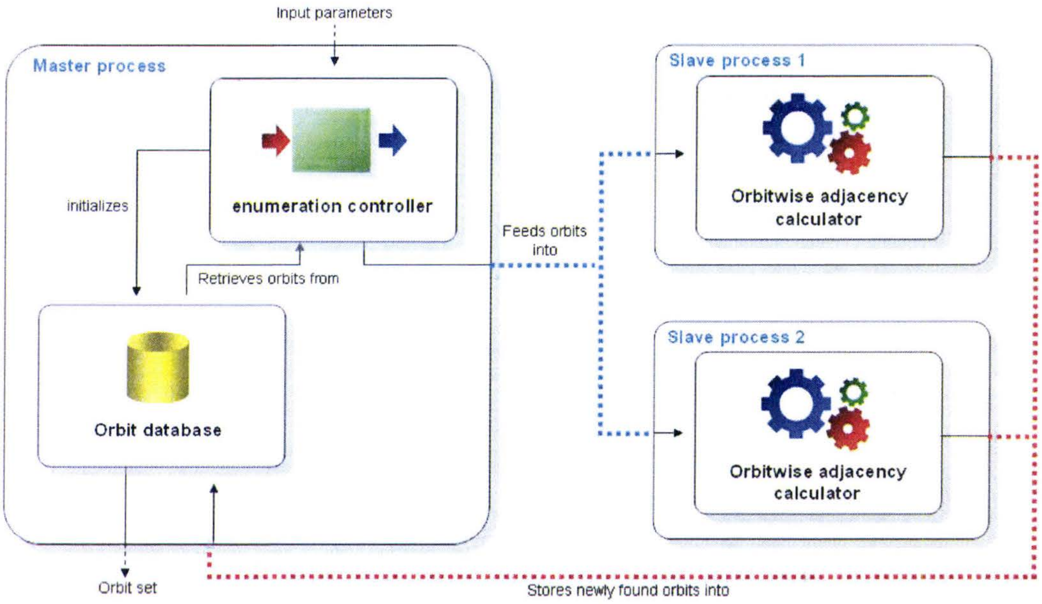

Figure 4.7: Process parallelization

4.4 Computation

The computation of the 36 dimensional metric polytope met_9 was performed on SHARCNET clusters. Established in 2001, SHARCNET is consortium of colleges and universities in a *cluster of clusters* of high performance computers, linked by advanced fibre optics. It is aimed to:

- Accelerate the production of research results to meet the needs of researchers and industry partners in today's competitive fast-paced business environments

- Unite students, researchers and companies by providing cutting edge computational expertise and hardware

Name	silky	Name	wobbe
Make	Silicon Graphics	Make	Hewkett Packard
Class	Shared memory	Class	Distributed cluster
Architecture	Intel Itanium 2	Architecture	AMD Opteron
CPUs	128	CPUs	208
OS	Linux 2.4.21	OS	Fedora Core 3
Location	UWO	Location	McMaster University

Table 4.1: Clusters used in the computation

- Link academic researchers and corporate partners in a search for new business opportunities

SHARCNET was founded by McMaster University, University of Guelph, University of Windsor, Wilfrid Laurier University, The University of Western Ontario, Fanshawe College and Sheridan College. In 2003 it was expanded with the University of Waterloo, Brock University, York University, The University of Western Ontario and the Institute of Technology. Finally, it gather some more new members in 2005, with the inclusion of Trent University, Laurentian University and Lakehead University.

The details of the two SHARCNET clusters used for this project are summarized in Table 4.1.

The computation was performed through 33 incremental steps, each including a greater variety of orbits by adjusting the computation window based on previous computations. The overall computation time was two months. The progress of the computation is presented in Fig.4.8.

Conjecture 4.4.1 *The current description of metric polytope* met_9 *is complete, i.e. the vertices of* met_9 *are partitioned into the 1 056 368 orbits.*

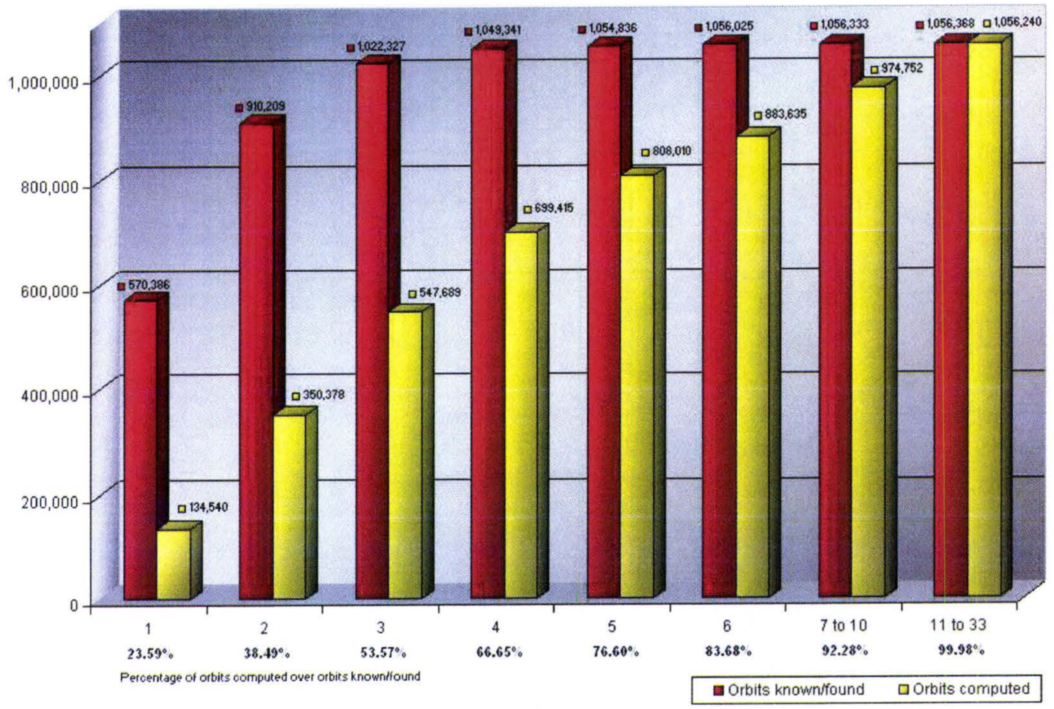

Figure 4.8: Incremental computation of the metric polytope

Chapter 5

Counterexamples to the Dominating Set Conjecture

5.1 Counterexamples to the Dominating Set Conjecture

Laurent and Poljak [25] conjectured that every fractional vertex of the metric polytope met_n is adjacent to some integral vertex, i.e., to a cut. Since we have $\mathrm{met}_3 = \mathrm{cut}_3$ and $\mathrm{met}_4 = \mathrm{cut}_4$, the conjecture, which is commonly called the dominating set conjecture, is obviously true for the 4 vertices of met_3 and for the 8 vertices of met_4. The conjecture holds for the 32 vertices of met_5 and the 544 vertices of met_6 as well as for several classes of vertices of met_n, see [24]. The conjecture was further substantiated by the computation of met_7 and met_8. The 275 840 vertices of met_7 and the 1 550 825 600 vertices of met_8 are adjacent to a cut, see [11, 13].

While the overwhelming majority of the known vertices of met_9 satisfy the dominating set conjecture, we found few counterexamples. In particular, we exhibit the following fractional vertex not adjacent to any integral vertex.

Proposition 5.1.1 *The neighbors of the fractional vertex* $\frac{1}{9}(2, 2, 3, 3, 4, 4, 5, 5, 4, 3, 5, 6, 6, 3, 3, 5, 5, 2, 4, 3, 5, 6, 3, 3, 6, 6, 5, 3, 2, 6, 6, 3, 3, 5, 3, 4)$ *of the metric polytope* met_9 *are all fractional.*

The vertex given in Proposition 5.1.1, as well as other vertices not adjacent to any cut, were found by an extensive computer search of the vertices of the 36-dimensional metric polytope met_9. Note that while finding a vertex providing a counterexample to the dominating set conjecture is computationally challenging, to verify that a given vertex is indeed not adjacent to a cut is easy if the vertex is quasi-simple, i.e., if the incidence of the given vertex is equal to the dimension plus one. For example, one can easily check, see Section 5.3, that the vertex given in Proposition 5.1.1 satisfies with equalities 37 of the 336 inequalities defining met_9 and is adjacent to 37 vertices which are all fractional.

5.2 Related Questions

5.2.1 The Diameter of the Metric Polytope

Since any pair of cuts forms an edge of met_n, the dominating set conjecture would imply that the diameter $\delta(\mathrm{met}_n)$ of the metric polytope satisfies $\delta(\mathrm{met}_n) \leq 3$. We recall that the diameter of a polytope P is the smallest number $\delta(P)$ such that any two vertices of P can be connected by a path with at most $\delta(P)$ edges. We have $\delta(\mathrm{met}_3) = \delta(\mathrm{met}_4) = 1$, $\delta(\mathrm{met}_5) = \delta(\mathrm{met}_6) = 2$ and $\delta(\mathrm{met}_7) = \delta(\mathrm{met}_8) = 3$. While the diameter of the restriction of met_9 to its known vertices appears to be less than 3, it is not clear that the diameter of met_n is bounded by a constant.

5.2.2 The No-cut Set Conjecture

Conjecture 3.2.3 can be seen as complementary to the dominating set conjecture both graphically and computationally: For any pair of vertices, while the dominating set conjecture implies that there is a path made of cuts joining them, i.e., the cut vertices form a dominating set, Conjecture 3.2.3 means that there is a path made of non-cut vertices joining them, i.e., the cut vertices do not form a cut-set. On the other hand, while the dominating set conjecture means that the enumeration of the extreme rays of the metric cone Met_n is enough to obtain the vertices of the metric polytope met_n, Conjecture 3.2.3 means that we can obtain the vertices of met_n without enumerating the extreme rays of Met_n.

5.3 Counterexample Generation and Verification

One important feature of the metric and cut polyhedra is their very large symmetry group. We recall that the symmetry group $Is(P)$ of a polyhedron P is the group of isometries preserving P and that an isometry is a linear transformation preserving the Euclidean distance. For $n \geq 5$, the symmetry groups of the polytopes met_n and cut_n are isomorphic and induced by permutations on V_n and *switching reflections by a cut*, see [15], and the symmetry groups of the cones Met_n and Cut_n are isomorphic to $Sym(n)$. Given a cut $\delta(S)$, the switching reflection $r_{\delta(S)}$ is defined by $y = r_{\delta(S)}(x)$ where $y_{ij} = 1 - x_{ij}$ if $(i, j) \in \delta(S)$ and $y_{ij} = x_{ij}$ otherwise.

5.3.1 Counterexample Generation

The vertices of met_n are partitioned into orbits under the action of the symmetry group $Is(\mathrm{met}_n)$. Using a parallel implementation of an orbitwise enumeration algorithm, 1 056 368 orbits of vertices of met_9 were computed on Shared Hierarchical Academic Research Computing Network (SHARCNET) clusters. Among these 1 056 368 orbits, 1 221 provide counterexamples to the dominating set conjecture, including 483 made of quasi-simplicial vertices. As the dimension of met_9 is 36, these quasi-simplicial counterexamples satisfy with equality exactly 37 inequalities. The remaining 738 orbits providing counterexamples to the dominating set conjecture are made of vertices satisfying with equality at least 38 inequalities. Some of these counterexamples have a relatively large incidence and adjacency: For example, the vertex $\frac{1}{9}$(1, 2, 3, 3, 4, 4, 4, 6, 3, 4, 4, 3 3, 5, 7, 5, 5, 6, 6, 2, 4, 6, 3, 3, 3, 3, 3, 3, 3, 3, 6, 6, 4, 6, 4, 2) satisfies with equality 44 inequalities and has 84 fractional adjacent vertices, and the vertex $\frac{1}{12}$(3, 3, 3, 6, 7, 7, 7, 7, 6, 6, 3, 4, 4, 4, 4, 6, 3, 4, 4, 4, 4, 9, 4, 4, 8, 8, 7, 7, 7, 7, 8, 4, 4, 4, 4, 8) satisfies with equality 43 inequalities and has 202 fractional adjacent vertices. See Appendix B for a complete list of the known counterexamples.

5.3.2 Counterexample Verification

For a given quasi-simple vertex, one can easily verify that all the adjacent vertices are fractional by performing 3 simple computations which we illustrate using the vertex given in Proposition 5.1.1.

(*i*) Check which of the 336 inequalities of met_9 are satisfied with equality by the given vertex. For the vertex given in Proposition 5.1.1, we obtain the

37 inequalities given in Section 5.3.3.

(*ii*) Compute the pointed cone formed by the active inequalities identified in (*i*). For the vertex given in Proposition 5.1.1, we obtain a quasi-simplicial cone with 37 extreme rays.

(*iii*) From the given vertex, follow each extreme ray of the cone computed in (*ii*) until at least one of the inequalities defining met_9 is violated. The obtained points are the adjacent vertices. For the vertex given in Proposition 5.1.1, we obtain the 37 adjacent vertices given in Section 5.3.3. As these 37 adjacent vertices are all fractional, the vertex given in Proposition 5.1.1 is indeed a counterexample.

Note that, while the computation (*ii*) can be extremely expensive for a highly degenerate vertex in high dimension, it can be done efficiently if the given vertex is quasi-simple. It takes less than a second of CPU time for the vertex given in Proposition 5.1.1 using enumeration packages such as *lrs* or *cdd*. Computations (*i*) and (*iii*) are straightforward and take less than a second of CPU time.

5.3.3 Counterexample Incidence and Adjacency Lists

Incidence List

The vertex given in Proposition 5.1.1 satisfies with equalities the following 37 inequalities of met_9: $\Delta_{6,7,\bar{9}}$, $\Delta_{5,\bar{8},9}$, $\Delta_{5,\bar{7},9}$, $\Delta_{\bar{5},7,8}$, $\Delta_{5,6,\bar{8}}$, $\Delta_{4,\bar{7},9}$, $\Delta_{4,\bar{6},9}$, $\Delta_{4,\bar{6},8}$, $\Delta_{\bar{4},6,7}$, $\Delta_{4,5,9}$, $\Delta_{4,5,\bar{7}}$, $\Delta_{3,\bar{6},9}$, $\Delta_{\bar{3},6,7}$, $\Delta_{3,5,\bar{8}}$, $\Delta_{3,4,\bar{6}}$, $\Delta_{2,7,\bar{9}}$, $\Delta_{2,6,\bar{9}}$, $\Delta_{2,6,\bar{8}}$, $\Delta_{2,6,7}$, $\Delta_{2,5,\bar{8}}$, $\Delta_{\bar{2},4,9}$, $\Delta_{\bar{2},4,8}$, $\Delta_{2,\bar{4},7}$, $\Delta_{2,\bar{4},6}$, $\Delta_{2,\bar{3},6}$, $\Delta_{1,\bar{5},8}$, $\Delta_{\bar{1},4,5}$, $\Delta_{1,\bar{3},8}$, $\Delta_{1,\bar{3},6}$, $\Delta_{\bar{1},3,5}$, $\Delta_{\bar{1},3,4}$, $\Delta_{1,\bar{2},9}$, $\Delta_{1,\bar{2},8}$, $\Delta_{\bar{1},2,7}$, $\Delta_{\bar{1},2,6}$, $\Delta_{\bar{1},2,5}$, $\Delta_{\bar{1},2,3}$ where the triangle inequality (2.1) and the perimeter inequality (2.2) are respectively denoted by $\Delta_{i,j,\bar{k}}$ and

$\Delta_{i,j,k}$.

Adjacency List

The vertex given in Proposition 5.1.1 is adjacent to the following 37 fractional vertices of met_9:

$$\tfrac{1}{3}(0,1,1,1,2,2,1,1,1,1,1,2,2,1,1,2,0,1,1,0,2,2,1,1,2,2,1,1,0,2,2,1,1,1,1,2)$$

$$\tfrac{1}{3}(0,1,1,1,2,2,1,1,1,1,1,2,2,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,0,2,2,1,1,1,1,2)$$

$$\tfrac{1}{3}(1,0,2,0,1,1,0,2,1,1,1,2,2,1,1,2,0,1,1,0,2,2,1,1,2,2,1,1,0,2,2,1,1,1,1,2)$$

$$\tfrac{1}{3}(1,1,0,1,1,1,2,2,2,1,2,2,2,1,1,1,2,0,2,1,1,1,1,1,2,2,2,0,1,1,2,1,1,1,1,0)$$

$$\tfrac{1}{3}(1,1,0,1,1,1,2,2,2,1,2,2,2,1,1,1,2,0,2,1,1,1,1,1,2,2,2,2,1,3,2,1,1,3,1,2)$$

$$\tfrac{1}{3}(1,1,1,1,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,2,1,1)$$

$$\tfrac{1}{3}(1,1,1,1,1,1,2,2,2,1,2,2,2,1,1,1,2,0,2,1,1,2,1,1,2,2,2,1,1,2,2,1,1,2,1,1)$$

$$\tfrac{1}{3}(1,1,1,1,1,1,2,2,2,1,2,2,2,1,1,2,2,1,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,2,1,1)$$

$$\tfrac{1}{3}(1,1,1,1,2,1,2,2,1,1,2,2,2,1,1,2,2,1,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,2,1,1)$$

$$\tfrac{1}{3}(1,1,1,1,2,1,2,2,2,1,2,2,2,1,1,2,2,1,1,1,2,2,1,1,2,2,2,1,1,2,2,1,1,2,1,1)$$

$$\tfrac{1}{4}(1,1,1,1,1,2,2,2,2,2,2,2,3,1,1,2,2,0,3,1,1,2,2,1,3,3,2,1,1,3,3,1,1,2,2,2)$$

$$\tfrac{1}{4}(1,1,1,1,2,2,2,2,2,2,2,3,3,1,1,2,2,1,1,1,3,2,1,1,3,3,3,1,1,3,2,2,2,2,2,2)$$

$$\tfrac{1}{6}(1,1,2,2,3,3,3,3,2,2,3,4,4,2,2,3,3,2,2,2,4,4,2,2,4,4,3,2,1,4,4,2,2,3,2,3)$$

$$\tfrac{1}{6}(1,1,3,1,3,3,2,3,2,2,2,4,4,1,2,4,2,2,2,1,4,4,2,2,3,4,4,2,1,4,4,3,2,3,2,3)$$

$$\tfrac{1}{6}(1,1,3,2,3,3,3,3,2,2,3,4,4,2,2,4,3,2,2,2,4,4,2,2,4,4,3,2,1,4,4,2,2,3,2,3)$$

$$\tfrac{1}{6}(1,1,3,2,3,3,3,3,2,2,3,4,4,2,2,4,3,2,2,2,4,5,2,2,4,4,3,3,1,3,4,2,2,4,2,2)$$

$$\tfrac{1}{6}(2,1,2,2,2,2,4,4,3,2,4,4,4,2,2,3,3,1,3,3,3,4,2,2,4,4,4,2,2,4,4,2,2,4,2,2)$$

$\frac{1}{7}(1,1,3,2,3,3,3,3,2,2,3,4,4,2,2,4,3,2,2,2,4,5,2,2,4,4,3,3,1,5,4,2,2,4,2,4)$

$\frac{1}{7}(1,1,3,2,3,4,3,3,2,2,3,4,5,2,2,4,3,2,3,2,4,5,2,3,4,4,3,2,1,5,5,2,2,3,3,4)$

$\frac{1}{7}(1,1,3,2,3,4,3,4,2,2,3,4,5,2,3,4,3,2,3,2,5,5,2,3,4,5,3,2,1,4,5,2,3,3,2,3)$

$\frac{1}{7}(2,2,2,3,3,2,5,4,4,2,5,5,4,3,2,4,5,1,4,3,4,5,3,2,5,4,4,3,2,5,5,2,3,5,2,3)$

$\frac{1}{7}(2,2,2,3,3,3,5,5,4,2,5,5,5,3,3,4,5,1,3,3,3,5,3,3,5,5,4,2,2,4,4,2,2,4,2,2)$

$\frac{1}{9}(1,2,4,2,5,5,4,4,3,3,3,6,6,3,3,6,4,3,3,2,6,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(2,2,3,3,4,4,5,3,4,3,5,6,6,3,3,5,5,2,4,3,5,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(2,2,3,3,4,4,5,5,4,3,5,6,6,3,3,5,5,2,4,3,3,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(2,2,3,3,4,4,5,5,4,3,5,6,6,3,3,5,5,2,4,3,5,6,3,3,6,6,5,3,2,6,6,3,3,5,3,6)$

$\frac{1}{9}(2,2,3,3,4,4,5,5,4,3,5,6,6,3,3,5,5,2,4,3,5,6,3,3,6,6,3,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(2,2,3,3,4,4,5,5,4,3,5,6,6,3,3,5,5,2,4,3,5,6,3,3,6,6,5,3,2,6,6,3,3,3,3,4)$

$\frac{1}{9}(2,2,3,3,4,4,5,5,4,3,5,6,6,3,3,5,5,2,6,3,5,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(2,2,3,3,4,6,5,5,4,3,5,6,6,3,3,5,5,2,4,3,5,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{9}(3,2,2,4,3,3,6,6,5,3,5,6,6,3,3,4,6,1,5,4,4,6,3,3,6,6,5,3,2,6,6,3,3,5,3,4)$

$\frac{1}{10}(2,2,4,3,5,4,5,5,4,4,5,7,6,3,3,6,5,3,4,3,7,7,3,4,7,7,6,3,2,6,7,4,4,5,3,4)$

$\frac{1}{10}(2,2,4,3,5,5,5,6,4,4,5,7,7,3,4,6,5,3,3,3,6,7,3,3,7,6,6,4,2,7,6,4,3,6,3,5)$

$\frac{1}{10}(3,3,2,4,4,3,7,7,6,3,7,7,6,4,4,5,7,1,6,4,4,6,4,3,7,7,6,3,3,7,7,3,3,6,4,4)$

$\frac{1}{12}(3,3,3,5,5,5,7,7,6,4,8,8,8,4,4,6,8,2,6,4,6,8,4,4,8,8,8,4,4,8,8,4,4,8,4,4)$

$\frac{1}{12}(3,3,3,5,5,5,8,7,6,4,8,8,8,5,4,6,8,2,6,5,6,8,4,4,7,8,6,4,3,8,8,3,4,7,4,5)$

$\frac{1}{12}(3,3,3,5,5,5,8,7,6,4,8,8,8,5,4,6,8,2,6,5,6,8,4,4,9,8,8,4,3,8,8,5,4,7,4,5)$

5.3.4 Computationally Challenging Orbits

Some vertices are extremely hard to find by the adjacency decomposition method. For example, for met_9 the hardest to find vertex is $v^* = \frac{1}{7}(1, 2, 2,3,3, 3, 3,4,3,3,2,2,4,4,3,4,3,3,1, 5, 4, 3, 5, 3, 5, 2, 4, 4, 2,1,2,2,3,4,5,3)$. The vertex v^* is moderately degenerate as its incidence is 42 (i.e dimension plus 6) but its adjacency is minimal as $\text{Adj}_{v^*} = \text{Icd}_{v^*} = 42$. All the 42 neighbors of v^* are highly degenerate (their incidence ranges from 57 to 252) and have a very large adjacency: the smallest being 48 969. In other words, this relatively small (incidence and adjacency wise) vertex v^* is surrounded by very large vertices. This phenomenon reveals the limitations of the skipping highest degeneracy heuristic: a vertex surrounded by a wall of highly degenerate vertices may not be find. While this phenomenon is not surprising as polytopes of large dimension are known to be odd, the vertex v^* is, to the best of our knowledge, the first known example.

The following vertices corresponds to some extremal (maximal) values found among the 1 056 368 orbits of met_9:

- Adjacency ($\text{Adj}_{max} = 197\,339$):

  $\frac{1}{3}(1, 1, 1, 1, 1, 1, 2, 2, 1, 1, 1, 2, 2, 1, 1, 2, 2, 1, 1, 1, 2, 2, 1, 1, 1, 2, 1, 1, 2, 1, 2, 1, 1, 2, 1, 1)$

- Incidence ($\text{Icd}_{max} = 88$):

  $\frac{1}{6}(0, 0, 1, 2, 2, 2, 2, 4, 0, 1, 2, 2, 2, 2, 4, 1, 2, 2, 2, 2, 4, 1, 3, 3, 3, 3, 2, 2, 4, 2, 4, 4, 2, 4, 2, 2)$

  $\frac{1}{7}(0, 0, 1, 2, 2, 4, 4, 4, 0, 1, 2, 2, 4, 4, 4, 1, 2, 2, 4, 4, 4, 3, 3, 3, 5, 5, 4, 2, 2, 2, 2, 2, 2, 2, 2, 4)$

- Denominator (maximum denominator 43):

$$\tfrac{1}{43}(10,10,10,16,19,20,20,26,14,16,26,29,16,30,16,20,14,29,30,16,16,26,13,\\ 10,14,16,15,16,12,10,13,27,13,14,26,14)$$

$$\tfrac{1}{43}(10,10,10,16,19,20,24,26,14,16,26,29,16,30,16,20,14,29,30,16,16,26,13,\\ 10,14,16,15,16,12,10,13,27,13,14,26,14)$$

5.3.5 Counterexample for the Metric Polytope on 10 Nodes

The computation of the 45 dimensional metric polytope met_{10} was started and more than a quarter of a million of orbits were found. These orbits include 992 counterexamples to the dominating set conjecture in dimension 45. Preliminary investigations indicate that a significant fraction of the vertices of met_{10} provide counterexamples to the dominating set conjecture.

The following two vertices with incidence and adjacency equal to 46 are counterexamples to the dominating set conjecture for met_{10}:

$$\tfrac{1}{10}(2,2,3,3,4,4,5,6,6,3,2,5,6,6,4,4,5,5,4,3,6,7,6,4,6,7,4,3,6,3,7,4,3,6,3,3,4,3,\\ 4,5,2,2,7,3,4)$$

$$\tfrac{1}{75}(17,17,18,31,31,36,48,48,49,34,29,20,48,19,31,31,38,35,48,48,53,31,53,44,49,\\ 19,48,36,30,31,30,39,17,35,18,29,17,17,48,22,44,53,22,31,53)$$

Chapter 6

Conclusions

This thesis deals with the vertex enumeration problem for convex polytope in general dimension. We focus on polytopes arising from combinatorial optimization problems. In particular, we study the metric polytope associated to the well-known maxcut and multicommodity flow problems, as well as to finite metric spaces. To tackle the huge size of the problem – hundreds of trillions of vertices – a parallel orbitwise enumeration algorithm was implemented and run on Shared Hierarchical Academic Research Computing Network (SHARCNET) clusters. Considerable effort were put into the implementation in order to develop an efficient portable and scalable ANSI C software based on the MPI (Message Passing Interface) specification which was run on parallel clusters, both distributed and shared memory architectures. Exploiting the high degree of symmetry, we provide for the first time a description of the highly degenerate metric polytope in dimension 36. The description consists of 1 056 368 orbits and is conjectured to be complete. While the validity of the dominating set conjecture [Laurent-Poljak 1992] is proven for the overwhelming majority of the known vertices of the metric polytope, we disprove the conjecture by exhibiting counterexamples in dimensions 36 and 45.

Appendix A

Metric Polytope met_9 Orbitwise Description

inc	min adj	max adj	count
37	37	45	148192
38	38	233	207111
39	39	458	193507
40	40	862	150846
41	41	1763	108418
42	42	3558	75583
43	46	13163	53203
44	48	15676	37903
45	51	26913	26065
46	54	75046	17473
47	57	125066	11487
48	60	193529	7655
49	80	192128	5035
50	72	189986	3554
51	101	174988	2191
52	104	174403	1699
53	166	116747	1193
54	207	197339	966
55	251	156126	856
56	193	145496	737
57	296	175729	558
58	273	127651	440
59	382	164277	338
60	314	137709	273
61	1057	159418	185
62	409	160000	175
63	617	196626	127
64	1315	158163	81
65	3024	195111	89
66	5160	191206	63
67	4987	131633	54
68	8786	126734	36
69	10127	152956	24
70	15770	162887	38
71	17652	166487	19
72	32176	134949	8
73	20088	136570	10
74	23780	130824	11
75	48100	119709	5
76	8703	148374	3
77	5935	77523	4
78	8694	189323	5
79	112206	188726	4
80	20631	107055	5
81	29290	175032	3
82	54711	176274	2
84	28713	122478	2
86	95055	137259	2
88	147990	151206	2

Table A.1: Orbits of met_9 by incidence with minimum and maximum adjacency

inc	min den	max den	count
37	3	43	148192
38	3	38	207111
39	3	40	193507
40	3	35	150846
41	3	38	108418
42	3	31	75583
43	3	31	53203
44	3	27	37903
45	3	29	26065
46	3	25	17473
47	3	21	11487
48	3	23	7656
49	3	19	5038
50	3	17	3557
51	3	17	2196
52	3	15	1704
53	3	15	1197
54	3	15	970
55	3	15	860
56	3	15	740
57	3	14	561
58	3	15	442
59	3	14	339
60	3	12	275
61	3	12	187
62	3	12	175
63	3	11	131
64	3	12	85
65	3	11	90
66	3	11	63
67	3	11	57
68	3	9	39
69	3	9	25
70	3	9	52
71	3	7	20
72	5	7	9
73	3	7	10
74	3	6	16
75	3	7	6
76	3	6	5
77	3	6	6
78	3	7	5
79	4	7	8
80	3	6	16
81	3	7	3
82	3	7	3
83	3	5	2
84	3	5	4
85	4	5	3
86	5	7	2
88	6	7	2
89	3	4	3
90	4	4	2
91	3	5	2
93	4	4	1
97	4	4	2
98	3	3	1
104	3	3	1
105	3	3	1
111	3	3	1
112	3	3	1
118	3	3	1
122	3	3	1
124	3	3	1
129	3	3	1
144	3	3	1
252	1	1	1

Table A.2: Orbits of met_9 by incidence with minimum and maximum denominator

den	min icd	max icd	min adj	max adj	count
3	37	84	45	197339	854
4	41	70	48	98739	485
5	40	86	42	196626	891
6	37	88	37	195111	22511
7	37	88	37	188726	16104
8	37	70	37	31493	45482
9	37	70	37	32612	111245
10	37	65	37	20260	108904
11	37	67	37	7640	99223
12	37	64	37	3689	143409
13	37	57	37	2842	123678
14	37	59	37	1720	74339
15	37	58	37	1394	88949
16	37	50	37	685	59258
17	37	51	37	528	39031
18	37	49	37	483	35960
19	37	49	37	408	27957
20	37	46	37	381	15243
21	37	47	37	467	15442
22	37	46	37	190	7586
23	37	48	37	210	6389
24	37	44	37	120	4236
25	37	46	37	118	3020
26	37	42	37	96	1819
27	37	45	37	122	1948
28	37	42	37	101	620
29	37	45	37	72	509
30	37	43	37	75	413
31	37	43	37	64	229
32	37	41	37	100	165
33	37	40	37	49	158
34	37	40	37	46	48
35	37	40	37	46	57
36	37	39	37	40	28
37	37	39	37	40	22
38	38	41	38	45	2
39	37	37	37	37	17
40	39	39	40	40	1
41	37	37	37	37	2
42	37	37	37	37	4
43	37	37	37	37	2

Table A.3: Orbits of met_9 by denominator with minimum and maximum incidence and adjacency

Appendix B

Dominating Set Conjecture Counterexamples for Metric Polytope met_9

Incidence	Adjacency	Count
37	37	483
38	38	18
38	39	368
38	46	1
38	62	6
39	42	85
39	48	104
39	55	44
39	75	3
39	88	1
40	42	12
40	44	18
40	45	2
40	48	1
40	68	1
40	75	31
40	83	6
40	100	1
40	120	1
41	49	3
41	51	5
41	58	2
41	60	3
41	80	2
41	87	2
41	108	1
41	112	1
41	116	2
41	136	4
41	142	1
42	60	1
42	158	2
43	51	1
43	74	3
43	202	1
44	84	1

Table B.1: Counterexamples for met_9

$\frac{1}{15}(3, 4, 5, 5, 5, 6, 7, 10, 7, 8, 8, 8, 5, 4, 9, 5, 5, 7, 10, 11, 6, 10, 10, 9, 6, 5, 10, 9, 6, 5, 9, 4, 5, 9, 4, 5)$

$\frac{1}{15}(3, 4, 4, 5, 8, 8, 8, 9, 5, 7, 8, 5, 5, 11, 10, 6, 5, 10, 10, 6, 5, 9, 4, 10, 4, 5, 5, 5, 5, 4, 10, 6, 5, 6, 5, 9)$

$\frac{1}{15}(3, 4, 4, 5, 8, 8, 8, 9, 5, 7, 8, 5, 5, 11, 10, 6, 5, 10, 10, 6, 5, 9, 4, 6, 4, 5, 5, 5, 5, 4, 10, 6, 5, 10, 5, 9)$

$\frac{1}{27}(6, 6, 9, 9, 9, 13, 15, 18, 12, 7, 15, 15, 7, 9, 16, 15, 9, 11, 19, 19, 12, 18, 18, 14, 16, 9, 18, 10, 10, 9, 8, 8, 9, 16, 9, 7)$

$\frac{1}{18}(3, 5, 6, 6, 8, 8, 10, 11, 8, 7, 7, 5, 11, 7, 12, 11, 11, 13, 7, 5, 6, 6, 6, 12, 6, 5, 12, 6, 12, 5, 6, 12, 7, 6, 11, 7)$

$\frac{1}{15}(3, 4, 5, 5, 8, 8, 8, 8, 7, 8, 8, 5, 5, 5, 11, 9, 9, 4, 10, 10, 4, 10, 5, 5, 5, 5, 5, 5, 5, 5, 10, 10, 6, 10, 6, 6)$

$\frac{1}{27}(6, 6, 9, 9, 13, 13, 18, 18, 12, 7, 15, 7, 9, 16, 16, 9, 11, 19, 19, 12, 12, 18, 10, 10, 9, 9, 8, 8, 9, 9, 16, 9, 9, 7, 17, 18)$

$\frac{1}{12}(3, 3, 3, 4, 5, 6, 7, 7, 4, 6, 5, 4, 7, 4, 8, 6, 5, 8, 9, 8, 4, 7, 4, 3, 4, 4, 3, 4, 5, 3, 7, 8, 4, 3, 7, 4)$

$\frac{1}{12}(3, 3, 3, 4, 5, 5, 6, 7, 4, 6, 5, 4, 8, 9, 4, 6, 7, 8, 4, 5, 8, 7, 4, 4, 3, 4, 7, 3, 4, 3, 4, 5, 8, 7, 4, 7)$

$\frac{1}{12}(3, 3, 3, 4, 5, 6, 7, 7, 4, 6, 5, 8, 5, 4, 8, 6, 7, 4, 9, 8, 4, 7, 4, 3, 4, 4, 5, 4, 3, 3, 5, 4, 8, 7, 5, 4)$

$\frac{1}{12}(3, 3, 4, 4, 4, 6, 7, 8, 6, 7, 7, 7, 3, 4, 5, 7, 7, 7, 9, 4, 5, 4, 4, 8, 3, 4, 8, 4, 5, 8, 4, 7, 8, 7, 4, 3)$

$\frac{1}{25}(4, 6, 7, 9, 13, 14, 15, 16, 10, 9, 9, 17, 10, 17, 16, 9, 7, 7, 16, 9, 14, 16, 8, 7, 8, 9, 10, 9, 16, 7, 9, 16, 17, 7, 16, 17)$

$\frac{1}{27}(6, 6, 9, 9, 9, 13, 15, 18, 12, 7, 11, 15, 7, 9, 16, 15, 9, 11, 19, 19, 12, 18, 18, 10, 16, 9, 18, 10, 10, 9, 8, 8, 9, 16, 9, 7)$

$\frac{1}{15}(3, 4, 5, 5, 6, 8, 8, 8, 7, 8, 8, 5, 5, 5, 11, 9, 9, 10, 4, 10, 4, 10, 5, 5, 5, 5, 5, 5, 5, 5, 10, 10, 6, 10, 8, 6)$

$\frac{1}{15}(3, 4, 5, 5, 8, 9, 9, 9, 7, 6, 8, 11, 6, 6, 10, 9, 9, 4, 5, 5, 5, 5, 5, 10, 10, 4, 10, 5, 5, 4, 5, 5, 9, 10, 9, 9)$

$\frac{1}{12}(3, 3, 4, 4, 4, 6, 7, 8, 6, 5, 7, 7, 9, 4, 7, 7, 7, 7, 3, 4, 7, 4, 8, 4, 5, 8, 4, 8, 3, 4, 4, 7, 8, 5, 4, 3)$

$\frac{1}{12}(3, 3, 3, 4, 5, 5, 6, 7, 4, 6, 5, 8, 8, 9, 4, 6, 7, 4, 4, 5, 8, 7, 4, 6, 3, 4, 3, 5, 4, 3, 8, 7, 4, 3, 4, 7)$

$\frac{1}{12}(3, 3, 4, 4, 4, 6, 7, 8, 6, 5, 7, 7, 9, 4, 5, 7, 7, 7, 3, 4, 5, 4, 8, 4, 7, 8, 4, 8, 3, 4, 4, 5, 8, 7, 4, 3)$

$\frac{1}{12}(3, 3, 4, 4, 4, 4, 6, 7, 6, 5, 7, 7, 7, 3, 4, 7, 5, 7, 7, 9, 4, 4, 4, 8, 8, 7, 8, 4, 4, 5, 4, 4, 3, 8, 7, 5)$

$\frac{1}{12}(3, 3, 4, 4, 4, 4, 6, 7, 6, 4, 7, 7, 7, 9, 4, 5, 7, 7, 7, 3, 4, 4, 4, 8, 8, 8, 8, 4, 4, 4, 4, 4, 4, 8, 3, 5)$

$\frac{1}{11}(2, 3, 4, 4, 5, 6, 6, 7, 5, 4, 4, 7, 4, 8, 7, 5, 7, 6, 3, 3, 4, 4, 5, 8, 4, 3, 3, 4, 4, 3, 3, 7, 6, 4, 7, 7)$

$\frac{1}{15}(3, 4, 5, 5, 8, 8, 8, 8, 7, 6, 8, 5, 5, 5, 11, 9, 9, 4, 10, 10, 4, 10, 5, 5, 5, 5, 5, 5, 5, 5, 10, 10, 8, 10, 6, 6)$

$\frac{1}{15}(3, 4, 5, 5, 8, 8, 8, 8, 7, 6, 6, 5, 5, 5, 11, 9, 9, 4, 10, 10, 4, 10, 5, 5, 5, 5, 5, 5, 5, 5, 10, 10, 6, 10, 6, 6)$

$\frac{1}{12}(3, 3, 3, 4, 6, 7, 7, 7, 4, 6, 4, 5, 4, 8, 8, 6, 5, 9, 8, 4, 4, 7, 3, 4, 4, 4, 4, 3, 4, 4, 7, 5, 5, 4, 4, 8)$

$\frac{1}{33}(6, 8, 11, 11, 16, 17, 19, 22, 14, 11, 11, 10, 23, 13, 20, 11, 11, 22, 9, 11, 14, 22, 11, 12, 22, 11, 11, 12, 22, 11, 13, 11, 10, 10, 23, 21)$

$\frac{1}{19}(4, 5, 6, 7, 10, 11, 11, 11, 9, 10, 11, 14, 7, 7, 13, 11, 12, 5, 6, 12, 6, 7, 6, 11, 5, 5, 13, 6, 12, 6, 7, 7, 11, 6, 12, 6)$

$\frac{1}{15}(3, 4, 5, 8, 8, 8, 8, 9, 7, 8, 5, 5, 5, 11, 10, 9, 4, 6, 6, 4, 5, 5, 5, 5, 5, 4, 10, 10, 6, 5, 10, 6, 5, 10, 5, 9)$

$\frac{1}{11}(2, 3, 4, 4, 6, 6, 7, 7, 5, 4, 4, 4, 8, 7, 7, 5, 7, 3, 3, 4, 6, 4, 8, 4, 3, 5, 4, 4, 3, 3, 4, 7, 3, 7, 7, 4)$

$\frac{1}{12}(3, 3, 3, 4, 5, 6, 7, 7, 4, 4, 7, 4, 5, 4, 8, 6, 5, 8, 9, 8, 4, 7, 4, 3, 6, 4, 3, 4, 5, 3, 7, 8, 4, 3, 7, 4)$

$\frac{1}{12}(2, 3, 4, 6, 6, 6, 8, 8, 5, 4, 4, 4, 8, 6, 6, 7, 3, 7, 3, 7, 7, 8, 8, 4, 4, 4, 8, 6, 4, 4, 4, 4, 4, 4, 4, 8)$

$\frac{1}{15}(3, 4, 5, 5, 8, 9, 9, 9, 7, 6, 8, 11, 6, 6, 10, 9, 9, 4, 5, 5, 5, 5, 5, 10, 10, 4, 10, 5, 5, 4, 5, 5, 9, 10, 6, 9)$

$\frac{1}{15}(3, 4, 5, 7, 8, 8, 8, 9, 7, 6, 10, 5, 5, 11, 10, 9, 5, 4, 6, 4, 5, 10, 5, 5, 5, 4, 5, 5, 5, 10, 10, 6, 5, 6, 5, 9)$

$\frac{1}{12}(3, 3, 4, 4, 4, 6, 6, 7, 6, 5, 7, 7, 3, 9, 4, 7, 7, 7, 5, 3, 4, 4, 8, 4, 4, 7, 4, 8, 8, 3, 4, 4, 7, 8, 7, 5)$

$\frac{1}{21}(4, 6, 6, 7, 8, 11, 12, 13, 8, 10, 7, 6, 15, 14, 9, 12, 13, 14, 7, 6, 7, 7, 14, 5, 14, 7, 7, 8, 7, 14, 9, 14, 7, 13, 6, 7)$

$\frac{1}{33}(6, 8, 11, 11, 14, 17, 19, 22, 14, 11, 11, 10, 23, 13, 20, 11, 11, 22, 9, 11, 14, 22, 11, 12, 22, 11, 11, 12, 22, 11, 13, 11, 10, 10, 23, 21)$

$\frac{1}{27}(6, 6, 9, 9, 9, 13, 15, 18, 12, 7, 11, 15, 7, 9, 16, 9, 9, 11, 19, 19, 12, 18, 18, 14, 16, 9, 18, 10, 10, 9, 8, 8, 9, 16, 9, 7)$

$\frac{1}{21}(4, 6, 6, 8, 10, 11, 13, 13, 8, 10, 6, 14, 15, 9, 13, 12, 14, 6, 7, 13, 7, 14, 14, 5, 7, 7, 14, 9, 7, 7, 13, 7, 7, 6, 12, 14)$

$\frac{1}{22}(4, 6, 7, 8, 12, 13, 14, 14, 10, 11, 8, 16, 9, 10, 14, 7, 14, 6, 7, 8, 8, 13, 7, 14, 15, 7, 8, 9, 6, 6, 7, 8, 14, 15, 7, 8)$

$\frac{1}{15}(3, 4, 5, 5, 6, 7, 10, 10, 7, 8, 8, 5, 4, 7, 9, 5, 7, 10, 11, 6, 6, 10, 5, 6, 5, 5, 5, 4, 5, 5, 9, 6, 4, 9, 5, 10)$

$\frac{1}{12}(2, 3, 4, 6, 6, 8, 8, 8, 5, 4, 4, 8, 6, 8, 8, 7, 3, 3, 5, 7, 7, 8, 4, 4, 4, 4, 6, 4, 4, 4, 8, 4, 4, 4, 4, 8)$

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$\frac{1}{16}(3, 4, 6, 6, 6, 8, 11, 11, 7, 5, 5, 9, 11, 10, 10, 4, 10, 6, 4, 9, 9, 10, 10, 6, 5, 5, 4, 6, 5, 9, 10, 5, 5, 11, 5, 10)$

$\frac{1}{21}(4, 6, 6, 7, 8, 10, 11, 13, 8, 10, 7, 6, 14, 15, 9, 12, 13, 14, 6, 7, 7, 7, 14, 14, 5, 7, 7, 7, 8, 14, 14, 9, 7, 13, 7, 6)$

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$\frac{1}{21}(4, 6, 6, 8, 10, 11, 11, 13, 8, 10, 6, 14, 7, 15, 9, 12, 14, 6, 13, 7, 7, 14, 14, 7, 5, 7, 14, 7, 9, 7, 7, 13, 7, 8, 14, 6)$

$\frac{1}{27}(6, 6, 9, 9, 13, 15, 18, 18, 12, 7, 15, 7, 9, 16, 16, 9, 11, 19, 19, 12, 12, 18, 10, 10, 9, 9, 8, 8, 9, 9, 16, 9, 9, 7, 11, 18)$

$\frac{1}{24}(5, 6, 8, 8, 8, 12, 12, 16, 11, 7, 9, 13, 7, 17, 15, 6, 10, 10, 16, 6, 10, 16, 16, 10, 12, 8, 16, 16, 8, 8, 6, 16, 8, 10, 8, 16)$

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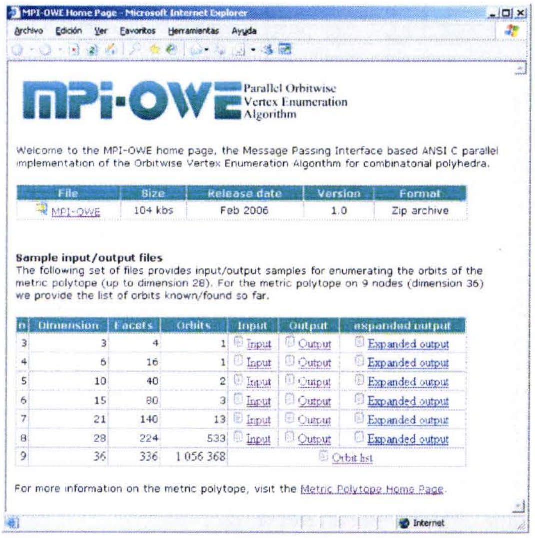
Appendix C

Software Publication

The source code of the ANSI C software implementation of the orbitwise vertex enumeration algorithm based on the Message Passing Interface (MPI) was made available online at: `http://www.cas.mcmaster.ca/~deza/mpiowe.html` . The input and output of metric polytopes met_n is provided for further testing and benchmarking of the software.



Welcome to the MPI-OWE home page, the Message Passing Interface based ANSI C parallel implementation of the Orbitwise Vertex Enumeration Algorithm for combinatorial polyhedra.

File	Size	Release date	Version	Format
MPI-OWE	104 kbs	Feb 2006	1.0	Zip archive

Sample input/output files
The following set of files provides input/output samples for enumerating the orbits of the metric polytope (up to dimension 28). For the metric polytope on 9 nodes (dimension 36) we provide the list of orbits known/found so far.

n	Dimension	Facets	Orbits	Input	Output	expanded output
3	3	4	1	Input	Output	Expanded output
4	6	16	1	Input	Output	Expanded output
5	10	40	2	Input	Output	Expanded output
6	15	80	3	Input	Output	Expanded output
7	21	140	13	Input	Output	Expanded output
8	28	224	533	Input	Output	Expanded output
9	36	336	1 056 368	Orbit list		

For more information on the metric polytope, visit the Metric Polytope Home Page.

Figure C.1: MPI-OWE Home Page

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