

A User's Guide for LattE integrale v1.7.1*



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1 Introduction

1.1 What is LattE?

The name “**LattE**” is an abbreviation for “**L**attice point **E**numeration.” **LattE** was developed in 2001 to count lattice points contained in convex polyhedra defined by linear equations and inequalities with integer coefficients. The polyhedra can be of any (reasonably small) dimension. In 2007, **LattE macchiato** was released and contained many algorithmic improvements, in particular primal variants of the algorithms. The newest edition, **LattE integrale**, developed in 2010, can compute integrals of polynomials and volumes of rational polytopes. All these algorithms run in polynomial time for fixed dimension. **LattE integrale** was extended in 2012/2013 with a hybrid C++ and **Maple** implementation for computing the top coefficients of weighted Ehrhart quasipolynomials, using the algorithm of [?]. To learn more about the exact details of our implementation for lattice point enumeration, the interested reader can consult [7, 9] and the references listed therein. For learning the algorithmic details of integration, see [2, 8]. Here we give a rather short description of the mathematical objects used by **LattE**. Note that all our computations are done over the integers or the rationals exactly. **LattE** does not accept floating-point numbers as input.

1.1.1 Counting lattice points: Barvinok’s Rational Functions

Given a convex polyhedron $P = \{u \in \mathbb{R}^d : Au \leq b\}$, where A and b are integral, the fundamental object that we compute is a short representation of the infinite power series:

$$f(P; x) = \sum_{\alpha \in P \cap \mathbb{Z}^d} x_1^{\alpha_1} x_2^{\alpha_2} \dots x_d^{\alpha_d}.$$

Here each lattice point is given by one monomial. Note that this can be a rather long sum, in fact for a polyhedral cone it can be infinite, but the good news is that it admits short representations.

Example: Let P be the quadrangle with vertices $V_1 = (0, 0)$, $V_2 = (5, 0)$, $V_3 = (4, 2)$, and $V_4 = (0, 2)$, see Figure 1.

$$f(P; x, y) = x^5 + x^4y + x^4 + x^4y^2 + yx^3 + x^3 + x^3y^2 + yx^2 + x^2 + x^2y^2 + xy + x + xy^2 + y + 1 + y^2$$

The fundamental theorem of Barvinok (circa 1993, see [3]) says that you can write $f(P; x)$ as a sum of short rational functions, in polynomial time when the dimension of the polyhedron is fixed. In our running example we easily see that the 16 monomial polynomial can be written as shorter rational function sum:

$$f(P; x, y) = f(K_{V_1}; x, y) + f(K_{V_2}; x, y) + f(K_{V_3}; x, y) + f(K_{V_4}; x, y)$$

where

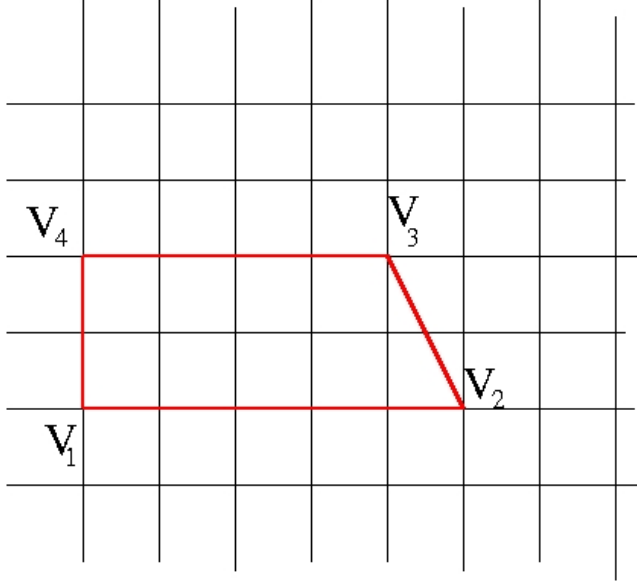


Figure 1: Quadrangle with vertices $V_1 = (0,0)$, $V_2 = (5,0)$, $V_3 = (4,2)$, and $V_4 = (0,2)$.

$$f(K_{V_1}; x, y) = \frac{1}{(1-x)(1-y)} \quad f(K_{V_2}; x, y) = \frac{(x^5 + x^4 y)}{(1-x^{-1})(1-y^2 x^{-1})}$$

$$f(K_{V_3}; x, y) = \frac{(x^4 y^2 + x^4)}{(1-x^{-1})(1-xy^{-2})} \quad f(K_{V_4}; x, y) = \frac{y^2}{(1-y^{-1})(1-x)}$$

$$f(P; 1, 1) = 16$$

Counting the lattice points in convex polyhedra is a powerful tool which allows many applications in areas such as Combinatorics, Statistics, Optimization, and Number Theory.

For details of how the computations are done, see [7, 9] .

1.1.2 Integration

LattE integrale has two different integration algorithms for integrating a rational polynomial $p \in \mathbb{R}[x_1, \dots, x_d]$ over a d dimensional rational polytope. The first one, called the triangulation method, triangulates the polytope into simplices and integrates over each simplex. The other method, called the cone decomposition method, integrates over each tangent cone of the polytope. In order to do this, each tangent cone is triangulated into simple cones. This is the main trade off between the two integration algorithms: you can do one (possibly) large triangulation, or (possibly) many small tangent cone triangulations.

We decompose polynomials into finite sums of powers of linear forms because integrating powers of linear forms can be done in polynomial time [2]. Finding a decomposition of a polynomial as a sum of powers of linear forms is known as the polynomial Waring problem.

See [8] for a detailed explanation on why the next example gives the correct integral.

As an example, let us integrate the polynomial $x_1 + x_2$ over the unit square with vertices $(0, 0)$, $(1, 0)$, $(0, 1)$ and $(1, 1)$. The polynomial is already a power of a linear form so let $\ell = (1, 1)$. To integrate $\int (x_1 + x_2)^M dx$ over the square, we need to compute

$$\frac{M!}{(M+d)!} |\det(u_1, \dots, u_d)| \frac{(\langle \ell, s \rangle)^{M+d}}{\prod_{i=1}^d \langle -\ell, u_i \rangle}$$

at each vertex s where the u_i are the rays from the tangent cone at s , and d is the dimension of the polytope.

Vertex $s_1 = (0, 0)$: Because $\langle \ell, s_1 \rangle^{1+2} = 0$ the valuation on this cone is zero.

Vertex $s_2 = (1, 1)$:

$$\frac{M!}{(M+d)!} |\det(u_1, \dots, u_d)| \frac{(2)^{1+2}}{(-1)(-1)} = \frac{1!}{(1+2)!} \times 1 \times 8 = 4/3$$

Vertex $s_3 = (1, 0)$:

$$\frac{M!}{(M+d)!} |\det(u_1, \dots, u_d)| \frac{(1)^{1+2}}{(1)(-1)} = \frac{1!}{(1+2)!} \times 1 \times -1 = -1/6$$

Vertex $s_4 = (0, 1)$:

$$\frac{M!}{(M+d)!} |\det(u_1, \dots, u_d)| \frac{(1)^{1+2}}{(1)(-1)} = \frac{1!}{(1+2)!} \times 1 \times -1 = -1/6$$

The integral $\int_{x_1=0}^{x_1=1} \int_{x_2=0}^{x_2=1} x_1 + x_2 dx_1 dx_2 = 0 + 4/3 - 1/6 - 1/6 = 1$ as it should be.

1.1.3 Weighted Ehrhart Polynomials

LattE integrale can also compute the weighted Ehrhart quasipolynomials where the weight function is a polynomial or a sum of powers of linear forms. However, the polytope must be a simplicial polytope and **Maple** must be installed on your computer.

1.1.4 Ehrhart Polynomials of Knapsack polytopes

LattE integrale can compute the Ehrhart quasipolynomials as function of t of polytopes in the form

$$\{x \in \mathbb{R}_{\geq 0}^n \mid \alpha_1 x_1 + \cdots + \alpha_n x_n = t\}.$$

These polytopes are also related to Sylvester's denominator.

1.2 Which programs of LattE compute what?

LattE contains three key executables:

count counts lattice points, computes Ehrhart polynomials and Ehrhart series of polytopes. This executable has replaced **ehrhart**, but **ehrhart** is still included for backwards compatibility.

integrate integrates polynomials, powers of linear forms, and products of powers of linear forms over polytopes. Integrate can also compute weighted Ehrhart quasipolynomials.

top-ehrhart-knapsack Computes the Ehrhart quasipolynomials for knapsack-type polytopes.

max/minimize perform linear integer optimization.

The other executables in **latte** are drivers, converters, and other small utility functions.

2 Input Files

A polytope can be defined from a list of vertices (a v-representation) or a list of hyperplane inequalities (h-representation) and so **LattE** can start from either representation in different formats. Here are four common file formats:

1. **LattE** style vertex file
2. **LattE** style hyperplane file
3. CDD style vertex file
4. CDD style hyperplane file

Users of **Polymake** will notice that **Polymake**'s facets and vertices are printed in a format that is easily converted to a **LattE** style h- or v-representation.

We now explore the file syntax of each.

2.1 LattE h-representation

2.1.1 Inequality Description

Let P be a polytope described by a system of inequalities $Ax \leq b$, where $A \in \mathbb{Z}^{m \times d}$, $A = (a_{ij})$, and $b \in \mathbb{Z}^m$. Note that any hyperplane representation with rational coefficients can be brought into this form; for example $x + 1/2y \leq 5/9$ should be written as $18x + 9y \leq 10$. With $P = \{x : Ax \leq b\}$, the input file is;

```
m d+1
b -A
```

Example: Let $P = \{(x, y) : x \leq 1, y \leq 1, x + y \leq 1, x \geq 0, y \geq 0\}$. Thus

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \\ -1 & 0 \\ 0 & -1 \end{pmatrix}, \quad b = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

and the LattE input file would be

```
5 3
1 -1 0
1 0 -1
1 -1 -1
0 1 0
0 0 1
```

2.1.2 Equality Constraints

By default, a constraint is an inequality of type $a^T x \leq b$. But to input an equality constraint $a^T x = b$ we need to add a keyword.

Example: Let P be as in the previous example, but require $x + y = 1$ instead of $x + y \leq 1$, thus, $P = \{(x, y) : x \leq 1, y \leq 1, x + y = 1, x \geq 0, y \geq 0\}$. Then the LattE input file that describes P would be as such:

```
5 3
1 -1 0
1 0 -1
1 -1 -1
0 1 0
0 0 1
linearity 1 3
```


The last line states that among the 5 inequalities one is to be considered an equality, the third one.

In general, the linearity syntax is :

```
linearity <number of equations> <row index of constraint, start counting from 1>
```

2.1.3 Nonnegativity Constraints

For bigger examples it quickly becomes cumbersome to state all nonnegativity constraints for the variables one by one. Instead, you may use another shorthand.

Example: Let P be as in the previous example, then the **LatTE** input file that describes P could also be described as such:

```
3 3
1 -1 0
1 0 -1
1 -1 -1
linearity 1 3
nonnegative 2 1 2
```

The last line states that there are two nonnegativity constraints and that the first and second variables are required to be nonnegative. **NOTE** that the first line reads “3 3” and not “5 3” as above!

In general, the nonnegative syntax is :

```
nonnegative <number of variables in list> <variable index, start counting from 1>
```

2.1.4 Cost Vector

The functions maximize and minimize solve the integer linear programs

$$\max\{c^T x : x \in P \cap \mathbb{Z}^d\}$$

and

$$\min\{c^T x : x \in P \cap \mathbb{Z}^d\}.$$

Besides a description of the polyhedron P , these functions need a linear objective function given by a certain cost vector $c \in \mathbb{Z}^d$, where the input style is very similar to a **LatTE** h-representation file.

Example: If the polyhedron is given in the file “fileName”

```

4 4
1 -1 0 0
1 0 -1 0
1 0 0 -1
1 -1 -1 -1
linearity 1 4
nonnegative 3 1 2 3

```

the cost vector must be given in the file “fileName.cost”, as for example in the following three-dimensional problem:

```

1 3
2 4 7

```

The first two entries state the size of a $1 \times n$ matrix (encoding the cost vector), followed by the $1 \times n$ matrix itself. Assuming that we call maximize, this whole data encodes the integer program

$$\max\{2x_1 + 4x_2 + 7x_3 : x_1 + x_2 + x_3 = 1, x_1, x_2, x_3 \in \{0, 1\}\}.$$

2.2 LattE v-representation

LattE can start from a homogenized v-representation of the polytope. To homogenize a vertex, simply add an leading 1 to the vertex. This has the effect of lifting the polytope to a cone in one dimension higher such that the original polytope can be extracted by intersecting the cone with the $x_1 = 1$ plane. For example, take a triangle in the plane, then Figure 2 shows the resulting cone.

Let v_1, \dots, v_k be the vertices of a polytope $P \subseteq \mathbb{R}^n$, then the **LattE** v-representation file format is:

```

k (n + 1)
1 v1
⋮
1 vk

```

Example: Note, like **LattE** h-representations files, a rational-vertex polytope with can be written with integer data by scaling each homogenized vertex. Below are the vertices of a rectangle $(0, 0), (2/3, 0), (0, 1/4), (2/3, 1/4)$:

```

4 3
1 0 0
3 2 0
4 0 1
12 8 3

```

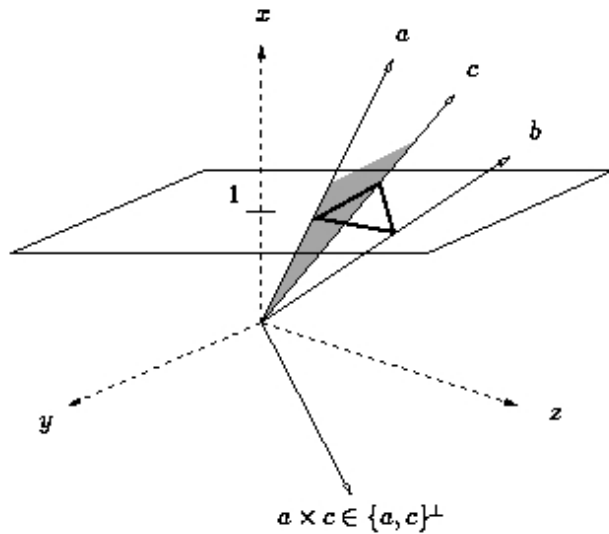


Figure 2: Homogenized triangle.

2.3 CDD Input Files

In addition to the formats described above, **LattE** can also accept input files in standard CDD format. Below is an example of CDD input that is readable into **LattE**.

```
H-representation
begin
4 4 integer
2 -2 4 -1
3 -2 -2 3
6 2 -4 -3
1 2 2 1
end
```

For a complete description of CDD file syntax, see the CDD manual [6].

2.4 Non-full dimensional polytopes

When the input polytope is not full dimensional, **LattE** projects that polytope such that it becomes full dimensional. This transformation preserves the lattice point count of the input polytope.

Note, however, that the integration routines do not currently support non-full dimensional polytopes.

2.5 LattE vs. CDD file formats

There are a few key differences between LattE and CDD file formats.

1. CDD used the file extension *.ine for h-representation files, and *.ext for v-representation files. However, LattE makes no assumption on the file extensions of files. We recommend *.vrep.latte and *.hrep.latte for LattE style files, but you are free to name your files anything.
2. CDD also requires “H-representation” or “V-representation” keywords in the file. Forgetting about the “linearity” and “nonnegative” keywords, there is no difference between a LattE v- and h-representation file.

2.6 Polynomials and linear forms

LattE `integrale` can also integrate polynomials and in particular sums of powers of linear forms over polytopes. Powers of linear forms are the fundamental structure used to integrate. Next, we describe the syntax of polynomials and linear forms

- A polynomial is represented as a list of its monomials in the form

$[monomial_1, monomial_2, \dots],$

where $monomial_i$ is represented by

$[coefficient, [exponent-vector]].$

For example, $3x_0^2x_1^4x_2^6 + 7x_1^3x_2^5$ is input as $[[3, [2, 4, 6]], [7, [0, 3, 5]]]$.

- To deal directly with sums of powers of linear forms, a fundamental data structure in LattE `integrale`, the input format is

$[linear-term_1, linear-term_2, \dots],$

where $linear-term_i$ is represented by

$[coefficient, [power, [coefficient-vector]]].$

For example, $3(2x_0 + 4x_1 + 6x_2)^{10} + 7(3x_1 + 5x_2)^{12}$ is input as $[[3, [10, [2, 4, 6]]], [7, [12, [0, 3, 5]]]]$.

The reason this is useful is because any polynomial can be written as a sum of powers of linear forms, see [2].

2.7 Products of linear forms

LattE integrale can integrate a product of linear forms over a simplex or a triangulation of a polytope.

The input format for a sum of products of linear forms is

```
[ [coefficient, [[power1, [coefficient-vector1]], [power2,
[coefficient-vector2]], ...]], ...].
```

For example, the integrand

$$(1x_1 + 2x_2)^3(4x_1 + 5x_2)^6 + 7(8x_1 + 9x_2)^{10}(11x_1 + 12x_2)^{13}(14x_1 + 15x_2)^{16}$$

is written as

```
[[1, [ [3, [1, 2]], [6, [4, 5]] ]], [7, [ [10, [8, 9]], [13, [11, 12]],
[16, [14, 15]] ]]
```

3 Running LattE

The executables of **LattE integrale** are installed in the “bin/” subdirectory of the installation tree. The standard distribution of **LattE integrale** sets the installation tree to be the “dest/” subdirectory of the source tree. Thus, to invoke the **count** executable, you would type

```
dest/bin/count
```

3.1 How to use count

count has a nice help menu, to view it, run

```
count --help
```

The following options control what **count** computes.

- Count the number of lattice points in polytope P , where P is given in a file named “fileName.hrep.latte” in different file formats.

```
count fileName.hrep.latte
count --vrep fileName.vrep.latte
count --cdd fileName.ine
```

- Count the number of lattice points in nP , the dilation of P by the integer factor n .

```
count --dilation=n fileName.hrep.latte
```

- Use the homogenized Barvinok algorithm [5] to count the number of lattice points in the polytope P . Use if number of vertices of P is big compared to the number of constraints.

```
count --homog fileName.hrep.latte
```

- Compute the number of lattice points (default)

```
count --count-lattice-points fileName.hrep.latte
```

- Compute the multivariate generating function of the set of lattice points of the polyhedron

```
count --multivariate-generating-function  
      fileName.hrep.latte
```

For unbounded polyhedra, one needs to combine this with the option `--compute-vertex-cones=4ti2` (now the default when 4ti2 is available), as other methods in `LatTE` currently refuse to handle unbounded polyhedra. For example,

```
count --compute-vertex-cones=4ti2  
      --multivariate-generating-function fileName.hrep.latte
```

writes the multivariate generating function (in Maple notation) to “file-Name.rat.”

- Compute the Ehrhart polynomial of a lattice polytope

```
count --ehrhart-polynomial fileName.hrep.latte
```

Note: For the computation of weighted Ehrhart quasipolynomials of rational polytopes, or their top coefficients, see section 3.2.1 below.

- Compute the unsimplified Ehrhart series as a univariate rational function

```
count --ehrhart-series fileName.hrep.latte
```

- Compute the simplified Ehrhart series as a univariate rational function (needs **Maple**).

```
count --simplified-ehrhart-series fileName.hrep.latte
```

- Compute the first N terms of the Ehrhart series

```
count --ehrhart-taylor=N fileName.hrep.latte
```

The following options relate to the Barvinok algorithm and were introduced by Matthias Köppe in **LattE macchiato**, see [7]. Not all modes of operation support all options.

- Triangulate and signed-decompose in the dual space (traditional method, default)

```
count --dual fileName.hrep.latte
```

- Triangulate in the dual space, signed-decompose in the primal space using irrationalization

```
count --irrational-primal fileName.hrep.latte
```

- Triangulate and signed-decompose in the primal space using irrationalization

```
count --irrational-all-primal fileName.hrep.latte
```

- Decompose cones down to an index (determinant) of N instead down to unimodular cones (which have an index of 1).

```
count --maxdet=N fileName.hrep.latte
```

- Do not signed-decompose simplicial cones

```
count --no-decomposition fileName.hrep.latte
```

- Use polynomial substitution for specialization (traditional method, default)

```
count --polynomial fileName.hrep.latte
```

- Use exponential substitution for specialization (recommended for maxdet larger than 1)

```
count --exponential fileName.hrep.latte
```

REMARK The functionality of the LattE v1.2 `ehrhart` command has been merged into `count`:

```
count --ehrhart-series FILENAME
```

```
(replaces: ehrhart FILENAME)
```

```
count --simplified-ehrhart-series FILENAME
```

```
(replaces: ehrhart simplify FILENAME)
```

```
count --ehrhart-taylor=N FILENAME
```

```
(replaces: ehrhart N FILENAME)
```

The `ehrhart` program is still available, but it does not accept the new command-line options of `count`.

3.2 How to use integrate

Like `count`, `integrate` has a help menu. To view the menu, run

```
integrate --help
```

There are two different integration (and volume) algorithms. The triangulation method triangulates the entire polytope and integrates over each simplex. In the cone decomposition method we integrate over each cone, possibly triangulating it first. Unlike other integration software, LattE integrates polynomials and powers of linear forms in exact arithmetic.

`integrate` is also able to compute weighted Ehrhart quasi-polynomials, see the next subsection.

- Integrates using the cone-decomposition method.

`--cone-decompose`

- Integrates using the triangulation method.

`--triangulate`

- Sets what you want to compute: a volume or an integral.

`--valuation=integrate`

`--valuation=volume`

- Sets the file that contains the polynomial, powers of linear forms, or products of powers of linear forms. If this option is not set, and the valuation is integration, the integrand will be read from stdin.

`--monomials=FILE`

`--linear-forms=FILE`

`--product-linear-forms=FILE`

If the integrand is a polynomial or a power of a linear form, there are two integration and volume algorithms available: a polytope triangulation based method and a tangent cone based method. If the integrand is a product of powers of linear forms, there is only one algorithm available and it is a polytope triangulation based method.

Example: Let us view a few examples of the above options

- Integrates a polynomial in file “FILE” using the triangulation method.

```
integrate --valuation=integral --triangulate
--monomials=FILE fileName.hrep.latte
```

- Find a volume using the cone decomposition method from a LattE v-representation file.

```
integrate --valuation=volume --cone-decompose
--vrep fileName.vrep.latte
```

- If an integration method is not given, LattE `integrale` computes the integral with *both* methods. This can also be done by the `--all` option. The next two commands do the same thing: find a volume using both methods from a LattE v-representation file.

```
integrate --valuation=volume --vrep fileName.vrep.latte
```

```
integrate --valuation=volume --all  
--vrep fileName.vrep.latte
```

3.2.1 How to use integrate for computing weighted Ehrhart quasipolynomials

This option currently requires **Maple**. For non-lattice polytopes, the coefficients of the Ehrhart quasipolynomials are computed as step functions. The triangulation of vertex cones is performed in the dual space; command line options to do otherwise are ignored.

By default, **LattE integrale** computes the coefficients incrementally, starting from the highest coefficient, which is the easiest to compute. You can interrupt the computation at any time if you don't need any further coefficients. If you know in advance, how many coefficients from the top you need, use the option `--num-coefficients=K`.

- Sets what you want to compute: weighted Ehrhart quasipolynomials.

```
--valuation=top-ehrhart
```

- Sets the weight function from a file.

```
--monomials=FILE  
--linear-forms=FILE
```

- Sets the weight function to 1 (unweighted). This is the default.

```
--top-ehrhart-unweighted
```

- Only compute the top K coefficients. The quasipolynomial's coefficients are not computed incrementally. Use this option if you know in advance you can wait for the software to finish or have low memory requirements. When this option is missing, the entire quasipolynomial's coefficients are computed incrementally which takes more memory but you may manually stop the computation at any time.

```
--num-coefficients=K
```

- Save the quasipolynomial to a file. If “--num-coefficients=K” is used, the file write is done after the quasipolynomial is computed. If “--num-coefficients=K” is missing, the quasipolynomial’s coefficients are saved as they are computed.

`--top-ehrhart-save=FILE`

- Compute the weighted Ehrhart polynomial that is valid for non-integer dilations, rather than integer dilations only. The formulas for the coefficients will usually be more complicated. Even for lattice polytopes, one obtains Ehrhart quasipolynomials rather than Ehrhart polynomials.

`--real-dilations`

- Sets interactive mode if you want to manually type a polynomial or a sum of linear forms. You cannot compute a weighted Ehrhart quasipolynomial where the weight is a product of linear forms.

`--interactive-mode`

Example: Let us view a few examples of the above options.

- Compute the unweighted Ehrhart quasipolynomial that is valid for real dilations, rather than integer dilations only.

```
integrate --valuation=top-ehrhart --real-dilations
      fileName.hrep.latte
```

- Compute weighted Ehrhart quasipolynomial where the weight is a polynomial.

```
integrate --valuation=top-ehrhart --monomials=FILE
      fileName.hrep.latte
```

- Find only the two largest degree terms of the linear form weighted Ehrhart quasipolynomial

```
integrate --valuation=top-ehrhart --linear-forms=FILE
      --num-coefficients=2 fileName.hrep.latte
```

- Manually enter a weight function and save the Ehrhart quasipolynomial to a file

```
integrate --valuation=top-ehrhart --interactive-mode
      --top-ehrhart-save=FILE fileName.hrep.latte
```

3.3 Options common to both count and integrate

A common subproblem in counting lattice points and integration requires finding triangulations and tangent cones. Also, there are many different software tools available to do this. Instead of reinventing the wheel, **LattE** links with other software tools to compute these basic objects. In this section, we describe how you can control which software tool is used.

- The **4ti2** program can be used instead of **cddlib** to compute the vertex cones of polytopes, triangulations, and duals of cones. In many cases, **4ti2** is faster, which is why it is now the default when it is available.

```
--compute-vertex-cones={cdd,4ti2}  
--triangulation={cddlib,4ti2}  
--dualization={cdd,4ti2}
```

- By default, **LattE** assumes the h-representation may contain redundant hyperplanes and tries to find and remove them. You can control how much more **LattE** should spend checking the input h-representation with the following option.

```
--redundancy-check={none,cddlib,full-cddlib}.
```

- “full-cddlib” (the default) uses **cddlib** to compute an irredundant system of linear equations and inequalities describing the polyhedron. This corresponds to the traditional **LattE** behavior; it can be expensive.
- “cddlib” (used to be the default in the 1.2+mk-0.9.x series) uses **cddlib** to compute some implicit linearities only; it often fails but is faster than full-cddlib.
- “none” does nothing, the input description of the polytope should be irredundant.

3.4 How to use top-ehrhart-knapsack

To view the help menu, run

```
top-ehrhart-knapsack --help
```

A knapsack is a polytope in the form $\{x \in \mathbb{R}^d \mid \alpha_1 x_1 + \cdots + \alpha_d x_d = t; x_i \geq 0\}$, which we identify by the coefficients $\alpha = [\alpha_1, \dots, \alpha_d]$. **top-ehrhart-knapsack** can compute the largest k degree terms in the Ehrhart quasi-polynomial $E(\alpha, t)$

as a function of t . We assume the greatest common divisor of the α_i is one, because if g is the greatest common divisor of the α_i and $g \neq 1$, then $E(\alpha/g, t) = E(\alpha, gt)$. There are only a few command line parameters:

- file, -f FILENAME** FILENAME contains the knapsack file in a special format (see below). Required parameter.
- out, -o FILENAME2** Saves the result to a file. This is an optional parameter, but is recommended to always save the result to a file as the output can be large.
- k n** Computes the n^{th} term of the Ehrhart polynomial. This or “-all-k” is required.
- all-k n** Computes the largest n^{th} terms of the Ehrhart polynomial.
- gcd-polynomial (0 | 1)** If 1, uses a polynomial time algorithm to find the coefficients of the Ehrhart quasi-polynomial. The default is 1. See note below.

top-ehrhart-knapsack uses a special file format to input the knapsack coefficients. For a the knapsack α , the input file contains one line: the number of coefficients in the knapsack followed by each coefficient separated by spaces.

The two main computation options are best illustrated with an example. Consider the knapsack $\alpha := [1, 2, 3, 4, 5]$. Notice that the greatest common divisor is one. Save this knapsack in a file called knap1.txt:

```
5 1 2 3 4 5
```

To compute the 2^{nd} coefficient of the Ehrhart polynomial, use the command

```
top-ehrhart-knapsack --file knap1.txt -k 2 --out results.mpl
```

which gives the result

```
coeff4minus1:= (1/96);
```

and hence the 2nd term is $t^2/96$.

Next, we can compute the largest 5 terms (because the dimension of this knapsack is 4, this means we are computing the full Ehrhart polynomial), with the command

```
top-ehrhart-knapsack --file knap1.txt --all-k 5 --out results.mpl
```

which gives the result

```
coeff4minus0:= (1/2880);
coeff4minus1:= (((((-1/48) + (((((((1)*((Frac( T * (1/3) ) )*(3))) + <and so on>;
coeff4minus2:= <another large expression>;
coeff4minus3:= <another large expression>;
coeff4minus4:= <another large expression>;

topKPolynomial:=(coeff4minus0)*T^(4) + (coeff4minus1)*T^(3)
+ (coeff4minus2)*T^(2) + (coeff4minus3)*T^(1) + (coeff4minus4)*T^(0);
```

Notice that the expressions for each coefficient might be very long. It is recommended that you always save the results in an output file, and use a computer algebra system to simplify the expressions. Also note that the output can be parsed by **Maple**. In fact, using **Maple** to simplify the expressions, “coeff4minus1” is $1/96$. Finally, the $\text{Frac}(x)$ function represents the fractional part of x and is equal to $x - \lfloor x \rfloor \in [0, 1)$, where $\lfloor x \rfloor$ is the largest integer smaller or equal to x .

The option `--gcd-polynomial` controls how poles are computed, which is given by the greatest common divisor of subsets of $\{\alpha_1, \dots, \alpha_d\}$. For example, the options `--gcd-polynomial 1 -k 5` will require finding all $\binom{d}{5} + \binom{d}{4} + \dots + \binom{d}{1}$ subsets of size at most 5 and compute the greatest common divisor of each one. However, `--gcd-polynomial 0 -k 5` will use a dynamic programming technique to compute the greatest common divisor of every subset of $\{\alpha_1, \dots, \alpha_d\}$. If the number of unique greatest common divisors from subsets is much smaller than 2^d , and d is large, `--gcd-polynomial 0` should be much faster.

3.5 Optimization

Latte can also optimize over the integer points of a polytope. However, this part of the software is not as stable as the rest of the code. The optimization executables **require** a cost vector specified in “fileName.cost” if the polytope file is named “fileName.”

- Maximizes/Minimizes a given linear cost function over the lattice points in the polytope. The Digging algorithm [5] is used. Optimal point and optimal value is returned.

```
./latte-maximize fileName
./latte-minimize fileName
```

- Maximizes/Minimizes a given linear cost function over the lattice points in the polytope. The Binary search algorithm is used. Only optimal value is returned.

```
./latte-maximize bbs fileName
./latte-minimize bbs fileName
```

4 Downloading and Installing LattE

LattE is downloadable from the following website:

<http://www.math.ucdavis.edu/~latte/>

LattE uses the GNU Autoconf, Automake, Libtool tools. The following README file provides detailed instructions.

This is LattE integrale, the official new version of LattE.

In addition to the traditional LattE function of counting lattice points in polytopes by variants of Barvinok's algorithm, LattE integrale can also compute volumes and integrate polynomial functions over polytopes. It supersedes LattE macchiato, an improved version of LattE.

LattE requires the following programs and libraries:

- * GMP, compiled with `--enable-cxx`
- * NTL, version 5.4 or newer
- * cddlib
- * (optional) LRS
- * (optional) LiDIA
- * (optional) 4ti2

If you do not have these libraries installed yet, follow the instructions below to install them. However, we also package a source code distribution called

`"latte-integrale"`

that includes all of these libraries and will build them automatically. You can get it at the same place where you got LattE integrale,

<http://www.math.ucdavis.edu/~latte/>

Building and installing LattE

It is STRONGLY RECOMMENDED to use the source code distribution called `"latte-integrale"`. It contains all prerequisite libraries and also PATCHES for some of the libraries that fix configuration and build problems that are not yet included in upstream releases of the library.

If you do not wish to use `"latte-integrale"`, follow the instructions below. The instructions assume you want to install LattE and all its prerequisites into your home directory, namely into a hierarchy rooted at the directory `$HOME/latte`.

1. Install the GNU Multiple Precision Library

Download it from <http://www.swox.com/gmp/>
Unpack it, then in the source directory do:

```
./configure --prefix=$HOME/latte --enable-cxx
make
make install
```

2. Install Victor Shoup's Number Theoretic Library

Obtain it from <http://www.shoup.net/ntl/>
Unpack it, then in the source directory do:

```
cd src
./configure PREFIX=$HOME/latte GMP_PREFIX=$HOME/latte NTL_GMP_LIP=on
make
make install
```

3. Install Komei Fukuda's package cddlib

Obtain then from http://www.ifor.math.ethz.ch/~fukuda/cdd_home

4. Put \$HOME/latte/bin into your \$PATH
and \$HOME/latte/lib into your LD_LIBRARY_PATH.

5. Optionally, install the non-free library LiDIA.

If you are using LiDIA 2.2.0, note that it installs the directory
include/lidia but expects its header files in include/LiDIA. We
advise to put a symbolic link after installation of LiDIA.

6. Optionally, install 4ti2.

N. Build and install LattE

From the source directory of LattE:

```
./configure --prefix=$HOME/latte --with-default=$HOME/latte
make
make install
```

Now the LattE executables (count, integrate, latte-minimize, latte-maximize, ...) should be available in \$HOME/latte/bin.

More information

* License: GNU General Public License, see COPYING

- * Authors: see AUTHORS
- * Documentation: See the LattE manual (file ‘doc/manual.pdf’) to get started.
- * Changes since the official release 1.2: see NEWS and ChangeLog
- * Website: <http://www.math.ucdavis.edu/~latte>

5 A Brief Tutorial

In this section we invite the reader to follow along a few examples that show how to use **LattE** and also how to counter-check results.

5.1 Counting Magic Squares

Our first example deals with counting magic 4×4 squares. We call a 4×4 array of nonnegative numbers a magic square if the sums of the 4 entries along each row, along each column and along the two main diagonals equals the same number s , the magic constant. Let us start with counting magic 4×4 squares that have the magic constant 1. Associating variables x_1, \dots, x_{16} with the 16 entries, the conditions of a magic 4×4 square of magic sum 1 can be encoded into the following input file “EXAMPLES/magic4x4” for **LattE**.

```
10 17
1 -1 -1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0
1 0 0 0 0 -1 -1 -1 -1 0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0 0 -1 -1 -1 -1 0 0 0 0
1 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 -1 -1
1 -1 0 0 0 -1 0 0 0 -1 0 0 0 -1 0 0 0
1 0 -1 0 0 0 -1 0 0 0 -1 0 0 0 -1 0 0
1 0 0 -1 0 0 0 -1 0 0 0 -1 0 0 0 -1 0
1 0 0 0 -1 0 0 0 -1 0 0 0 -1 0 0 0 -1
1 -1 0 0 0 0 -1 0 0 0 0 -1 0 0 0 0 -1
1 0 0 0 -1 0 0 -1 0 0 -1 0 0 -1 0 0 0
linearity 10 1 2 3 4 5 6 7 8 9 10
nonnegative 16 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
```

Now we simply invoke the counting function of **LattE** by typing:

```
count EXAMPLES/magic4x4
```

The last couple of lines that **LattE** prints to the screen look as follows:

```
Total Unimodular Cones: 418
Maximum number of simplicial cones in memory at once: 27
```

```
***** Total number of lattice points: 8 *****
```

```
Computation done.
Time: 1.24219 sec
```

Therefore, there are exactly 8 magic 4×4 squares that have the magic constant 1. This is not yet impressive, as we could have done that by hand. Therefore, let us try and find the corresponding number for the magic constant 12. Since this problem is a dilation (by factor 12) of the original problem, we do not have to create a new file. Instead, we use the option “dilation” to indicate that we want to count the number of lattice points of a dilation of the given polytope:

```
count --dilation=12 EXAMPLES/magic4x4
```

The last couple of lines that `LattE` prints to the screen look as follows:

```
Total Unimodular Cones: 418
Maximum number of simplicial cones in memory at once: 27
```

```
***** Total number of lattice points: 225351 *****
```

```
Computation done.
Time: 1.22656 sec
```

Therefore, there are exactly 225351 magic 4×4 squares that have the magic constant 12. (We would NOT want to do THAT one by hand, would we?!)

Here is some amazing observation: the running time of `LattE` is roughly the same for counting magic squares of sum 1 and of sum 12. This phenomenon is due to the fact that the main part of the computation, the creation of the generating function that encodes all lattice points in the polytope, is nearly identical in both cases.

Although we may be already happy with these simple counting results, let us be a bit more ambitious and let us find a counting formula that, for given magic sum s , returns the number of magic 4×4 squares that have the magic constant s .

For this, simply type (note that `LattE` invokes `Maple` to simplify intermediate expressions):

```
count --simplified-ehrhart-series EXAMPLES/magic4x4
```

The last couple of lines that `LattE` prints to the screen looks as follows:

Rational function written to EXAMPLES/magic4x4.rat

Computation done.

Time: 0.724609 sec

We are informed that this call created a file “EXAMPLES/magic4x4.rat” containing the Ehrhart series as a rational function:

$$(t^8 + 4t^7 + 18t^6 + 36t^5 + 50t^4 + 36t^3 + 18t^2 + 4t + 1) / (-1+t)^4 / (-1+t^2)^4$$

Now we could use **Maple** (or your favorite computer algebra software) to find a series expansion of this expression.

$$\begin{aligned} & \frac{t^8 + 4t^7 + 18t^6 + 36t^5 + 50t^4 + 36t^3 + 18t^2 + 4t + 1}{(-1+t)^4(-1+t^2)^4} \\ = & 1 + 8t^1 + 48t^2 + 200t^3 + 675t^4 + 1904t^5 + 4736t^6 + 10608t^7 + 21925t^8 + \\ & 42328t^9 + 77328t^{10} + 134680t^{11} + 225351t^{12} + 364000t^{13} + 570368t^{14} + \\ & 869856t^{15} + O(t^{16}) \end{aligned}$$

The summands $8t$ and $225351t^{12}$ reconfirm our previous counts.

Although this rational function encodes the full Ehrhart series, it is not always as easy to compute as for magic 4×4 squares. As it turns out, adding and simplifying rational functions, although in just one variable t , can be extremely costly due to the high powers in t and due to long integer coefficients that appear.

However, even if we cannot compute the full Ehrhart series, we can at least try and find the first couple of terms of it.

```
count --ehrhart-taylor=15 EXAMPLES/magic4x4
```

The last couple of lines that **LattE** prints to the screen look as follows:

Memory Save Mode: Taylor Expansion:

```
1
8t^1
48t^2
200t^3
675t^4
1904t^5
4736t^6
10608t^7
21925t^8
42328t^9
```

```

77328t^10
134680t^11
225351t^12
364000t^13
570368t^14
869856t^15
Computation done.
Time: 1.83789 sec

```

Again, our previous counts are reconfirmed.

Nice, but the more terms we want to compute the more time-consuming this task becomes. Clearly, if we could find sufficiently many terms, we could compute the full Ehrhart series expansion in terms of a rational function by interpolation.

5.2 Counting Lattice Points in the 24-Cell

Our next example deals with a well-known combinatorial object, the 24-cell. Its description is given in the file “EXAMPLES/24_cell”:

```

24 5
2 -1 1 -1 -1
1 0 0 -1 0
2 -1 1 -1 1
2 -1 1 1 1
1 0 0 0 1
1 0 1 0 0
2 1 -1 1 -1
2 1 1 -1 1
2 1 1 1 1
1 1 0 0 0
2 1 1 1 -1
2 1 1 -1 -1
2 1 -1 1 1
2 1 -1 -1 1
2 1 -1 -1 -1
1 0 0 1 0
2 -1 1 1 -1
1 0 0 0 -1
2 -1 -1 1 -1
1 0 -1 0 0
2 -1 -1 1 1
2 -1 -1 -1 1
2 -1 -1 -1 -1
1 -1 0 0 0

```

Now we invoke the counting function of `Latte` by typing:

```
count EXAMPLES/24_cell
```

The last couple of lines that `Latte` prints to the screen look as follows:

```
Total Unimodular Cones: 240
Maximum number of simplicial cones in memory at once: 30

***** Total number of lattice points: 33 *****

Computation done.
Time: 0.429686 sec
```

Therefore, there are exactly 33 lattice points in the 24-cell. We get the same result by using the homogenized Barvinok algorithm:

```
count --homog EXAMPLES/24_cell
```

The last couple of lines that `Latte` prints to the screen look as follows:

```
Memory Save Mode: Taylor Expansion:

***** Total number of lattice points is: 33 *****

Computation done.
Time: 0.957031 sec
```

5.3 Integrating over a polytope

Let us integrate the polynomial $w^2x^2y^4z^8 - 3/8x^2$ and the power of a linear form $3(w + 2x + 4y + 6z)^{10}$ over the 24-cell.

Create a file named “even.polynomial” that has on its first line the polynomial. See Section 2.6 for a review of the syntax.

```
[[1,[2,2,4,8]], [-3/8,[0,2,0,0]]]
```

After running the integration command using the triangulation method

```
integrate --valuation=integrate --triangulate --monomials=even.polynomial 24_cell
```

we see that the two monomials were decomposed into 406 powers of linear forms and the answer is

starting to integrate 406 linear forms.

```
Integration (using the triangulation method)
  Answer: -110535307/170059500
  Decimal: -0.64998019516698567266162725399052
  Time: 1.92 sec
Computational time (algorithms + processing + program control)
  Total time: 2.00 sec
```

Now create a new file named “power10.linearforms” that has in its first line the power of a linear form:

```
[[3,[10,[1,2,4,6]]]]
```

Then integrate this power of a linear form over the 24_cell using the cone decomposition method with the following command:

```
integrate --cone-decompose --linear-forms=power10.linearforms 24_cell
```

We see the answer is computed very quickly.

```
Integration (using the cone decomposition method)
  Answer: 59555515086/77
  Decimal: 773448247.87012987012987012987013
  Time: 0.02 sec
Computational time (algorithms + processing + program control)
  Total time: 0.07 sec
```

For the next example, consider the truncated cube in Figure 3

The vertices are

```
24 4
1 3 1 1
1 3 1 -1
1 3 -1 1
1 3 -1 -1
1 -3 1 1
1 -3 1 -1
```

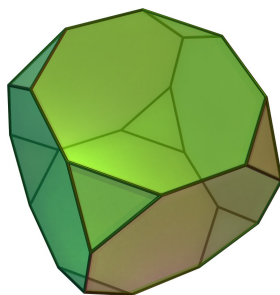


Figure 3: The truncated cube.

```

1 -3 -1 1
1 -3 -1 -1
1 1 3 1
1 1 3 -1
1 1 -3 1
1 1 -3 -1
1 -1 3 1
1 -1 3 -1
1 -1 -3 1
1 -1 -3 -1
1 1 1 3
1 1 1 -3
1 1 -1 3
1 1 -1 -3
1 -1 1 3
1 -1 1 -3
1 -1 -1 3
1 -1 -1 -3

```

This time, let us enter the polynomial $x^{40}y^{40}z^{40}$ from stdin, which will be decomposed into 68,920 powers of linear forms. Run

```

integrate --cone-decompose --triangulation=4ti2
--vrep truncatedCube.vrep.latte

```

and type

```
p [[1,[40,40,40]]]
```

We see the exact answer is

```

93991283632941965714919247928639002510318209692293688827363993265109276641003769553256
2795239135836124463932439643671211584534957465679791608181565

```

This answer displays the power of using exact rational arithmetic!

5.4 Computing the Weighted Ehrhart Polynomial

Again, `LatTE integrale` can (currently) only compute weighted Ehrhart polynomial functions if the user has `Maple`.

Consider the standard 0/1 square, which we represent in v-representation format as the file “square.vrep.latte”:

```
4 3
1 0 0
1 1 0
1 0 1
1 1 1
```

Let’s first compute the unweighted Ehrhart polynomial of the square:

```
integrate --valuation=top-ehrhart --vrep square.vrep.latte
```

and we get the answer $N^2 + 2N + 1$.

Note: For the case of the unweighted Ehrhart polynomial of a lattice polytope, when all coefficients are to be computed, it is faster to use `count --ehrhart-polynomial` instead. The benefit of `integrate --valuation=top-ehrhart` lies in the greater generality (polynomial weights, rational polytopes) and the ability to compute the top few coefficients, when the computation of the full Ehrhart polynomial is computationally intractable [?].

Next, compute the Ehrhart polynomial with weight $x_1^2 x_2^4$ where we enter the polynomial on the terminal:

```
integrate --valuation=top-ehrhart --interactive-mode
--vrep square.vrep.latte
```

and then type

```
p
[[1,[2,4]]]
```


The answer is $\frac{1}{15} * N^8 + \frac{4}{15} * N^7 + \frac{71}{180} * N^6 + \frac{1}{4} * N^5 + \frac{2}{45} * N^4 - \frac{1}{60} * N^3 - \frac{1}{180} * N^2$.

Finally, repeat the above commands, but find the polynomial that is correct if N is any real dilation factor and save the answer to a file called “bigAnswer”. That is, add `--real-dilations --top-ehrhart-save=bigAnswer` to the command line and use the same polynomial.

Open the file “bigAnswer.” To evaluate the polynomial at a point $a \in \mathbb{R}$, first open the file “compute-top-ehrhart.mpl” that was made by **LatTE integrale** and copy the same load path “compute-top-ehrhart.mpl” uses into “bigAnswer”. Make your “bigAnswer” file look something like this (your file path might be different):

```
read("/home/latte/dest/share/latte-int/Conebyconeapproximations_08_11_2010.mpl");

epoly:= ‘‘something big’’;

eval(subs({N=a,n=a, MOD=latteMod},epoly);
```

Note that you had to set both n and N to the point $a \in \mathbb{R}$ and the “latteMod” function is defined in the **Maple** script. If you then run this **Maple** file with the point $a = 2.5$ you will get 85.00000031.

5.5 Example of Optimization with LatTE

Next, let us solve the problem “cuww1” [4, 5]. Its description is given in the file “EXAMPLES/cuww1”:

```
1 6
89643482 -12223 -12224 -36674 -61119 -85569
linearity 1 1
nonnegative 5 1 2 3 4 5
```

The cost function can be found in the file “EXAMPLES/cuww1.cost”:

```
1 5
213 -1928 -11111 -2345 9123
```

Now let us maximize this cost function over the given knapsack polytope. Note that by default, the digging algorithm as described in [5] is used.

```
./latte-maximize EXAMPLES/cuww1
```

The last couple of lines that Latte prints to the screen look as follows:

```
Finished computing a rational function.  
Time: 0.158203 sec.
```

```
There is one optimal solution.
```

```
No digging.  
An optimal solution for [213 -1928 -11111 -2345 9123] is: [7334 0 0 0 0].  
The projected down opt value is: 191928257104  
The optimal value is: 1562142.  
The gap is: 7995261.806  
Computation done.  
Time: 0.203124 sec.
```

The solution (7334, 0, 0, 0, 0) is quickly found. Now let us try to find the optimal value again by a different algorithm, the binary search algorithm.

```
./latte-maximize bbs EXAMPLES/cuww1
```

The last couple of lines that Latte prints to the screen look as follows:

```
Total of Iterations: 26  
The total number of unimodular cones: 125562  
The optimal value: 1562142
```

```
The number of optimal solutions: 1  
Time: 0.042968
```

Note that we get the same optimal value, but no optimal solution is provided.

6 Release Information

6.1 System Requirements

Latte runs on Unix-like systems, including Mac OS X and GNU/Linux.

6.2 Additional Maple Connection

The call

```
count --simplified-ehrhart-series fileName
```

requires **Maple** for simplifications of expressions. It should be sufficient to have a copy of **Maple** installed on your machine, without any additional special configuration required. **LattE** will still run even if **Maple** is not installed, but this simplification feature to “count” will not be available.

We have tested this connection with **Maple** 5.1, 8.0, and 14.0 and experienced no problem. Please let us know about any problem you experience with our connection to **Maple**.

6.3 License Agreement

This program is free software; you can redistribute it and/or modify it under the terms of the version 2 of GNU General Public License as published by the Free Software Foundation.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details. (The careful user can find an install script for the source code in the directory “code/”.)

You should have received a copy of the GNU General Public License along with this program; see the file COPYING. If not, write to the Free Software Foundation, Inc., 59 Temple Place - Suite 330, Boston, MA 02111-1307, USA.

We have included a copy of the GNU General Public License also at the end of this document.

6.4 How to Cite LattE

Although **LattE** is free software, your acknowledgment is requested. If **LattE** is useful in your research or applications please acknowledge it by referencing this manual as

V. Baldoni, N. Berline, J.A. De Loera, B. Dutra, M. Köppe, S. Mor-
einis, G. Pinto, M. Vergne, J. Wu,
A User's Guide for LattE integrale v1.7.1, 2013, software package
LattE is available at <http://www.math.ucdavis.edu/~latte/>

6.5 The LattE Team

Project directors

- Prof. Jesús A. De Loera (**LattE** v1.2, **LattE integrale** v1.5–)
- Prof. Matthias Köppe (**LattE macchiato**, **LattE integrale** v1.5–)

Students currently working on the project

- Brandon Dutra (`LattE integrale v1.5-`)

Distinguished LattE scientists, collaborators and advisors

- Prof. Raymond Hemmecke (`LattE v1.2`)
- Prof. Ruriko Yoshida (`LattE v1.2`)
- Dr. David Haws (`LattE v1.2`)
- Dr. Peter Huggins (`LattE v1.2`)
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- Prof. Nicole Berline (`LattE integrale v1.6`)
- Prof. Michele Vergne (`LattE integrale v1.6`)
- Prof. Alexander Barvinok
- Prof. Bernd Sturmfels

Alumni of the project

- Gregory Pinto (`LattE integrale v1.5`)
- Stanislav Moreinis (`LattE integrale v1.5`)
- Jianqiu Wu (`LattE integrale v1.5`)
- Jeremy Tauzer (`LattE v1.2`)
- Jonathan Brooks (`LattE v1.2`)
- Carol Shih (`LattE v1.2`)
- Esteban Pauli (`LattE v1.2`)
- Mike Zhang (`LattE v1.2`)

6.6 Acknowledgments

`LattE` currently uses many wonderful pieces of software. First is `cddlib` [6], developed by Komei Fukuda, whose webpage can be found at:

<http://www.cs.mcgill.ca/~fukuda/>

Next, `LattE` uses `4ti2` [1] whose webpage can be found at:

<http://www.4ti2.de>

`cddlib` and `4ti2` is used for finding vertices of polytopes and the triangulation of cones.

In addition, `LattE` currently uses NTL, a Library for doing Number Theory, written by Victor Shoup [10], for LLL algorithm, matrix manipulations, storing variable length integers, and floating point numbers. NTL can be found at:

<http://shoup.net/ntl/>

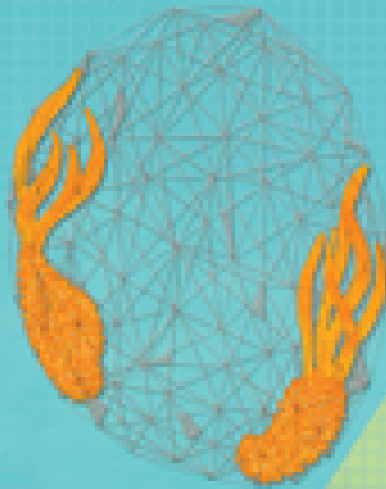
In addition, **LattE** optionally uses the LiDIA library, developed at TU Darmstadt.

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ALGEBRAIC AND GEOMETRIC IDEAS IN THE THEORY OF DISCRETE OPTIMIZATION



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