Semi-stable lattices in higher rank

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April 26, 2025

Outline

1. Introduction
2. In 2 dimensional
3. In dimension at least 3

Historical motivation - [4]

Serre and Quillen used the notion of semistable vector bundle on an algebraic curve to study $\mathrm{SL}_n(\mathcal{O})$ when $\mathcal{O}$ is a Dedekind domain finitely generated over a finite field. Stuhler then realized he can used the same method to adapt some work of Harder and Narasimhan on stable vector bundles to yields new facts about lattices in a Euclidean space.

Due to [1] , it is heuristic that the semi-stable lattices are the lattices in which the successive minima are closed.

Definition of two-dimensional lattices

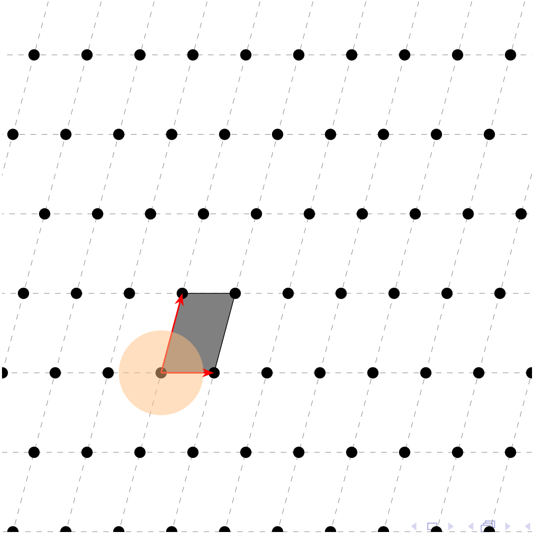
Lattice

A lattice $L \subset \mathbb{R}^2$ is a set of the form

$$L = \mathbb{Z}e_1 \oplus \mathbb{Z}e_2$$

where e_1, e_2 are linearly independent over $\mathbb{R}$.

Example of a 2-dim lattice



Classification of lattices

Do we know all the possible 2 dimensional "lattice shapes"?

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Answer: Up to maginifcation, rotation and change of basis, the answer is yes.

Fundamental domain

Up to rorations and magnifications, we can reduce a lattice

$$L = \mathbb{Z}\omega_1 \oplus \mathbb{Z}\omega_2$$

to a lattice of the form

$$L_z = \mathbb{Z}z \oplus \mathbb{Z}, \quad \Im(z) > 0$$

So the upper half-plane parametrizes the 2 dimensional lattices.

Classification of unit lattices

The map $z \mapsto \mathbb{Z}z \oplus \mathbb{Z}$ induces a bijection

$$\mathrm{SL}_2(\mathbb{Z})\backslash\mathbb{H} \cong \{\text{ lattices}\} / \mathbb{C}^\times$$

Fundamental domain

So we reduce to study the space of lattices by looking the action of $\mathrm{SL}_2(\mathbb{Z})$ on the upper half plane. Geometrically, the domain is given by

$$\mathfrak{D} = \{z = x + iy \in \mathbb{H} : |z| \geq 1, -1/2 \leq x \leq 1/2\}$$

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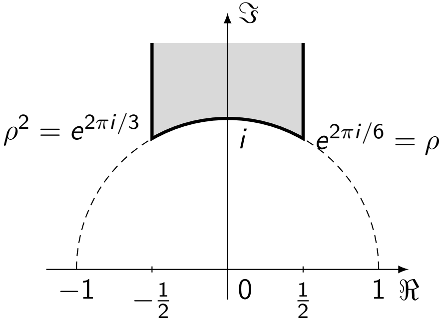

Canonical plot

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1. Put $(0,0)$ to the plot.
2. For each primitive vector $v \in L$, he assigns the point $(1, \log(||v||))$ to the plot.
3. Put the point $(2, \log(vol(L)))$ to the plot.

Canonical plot

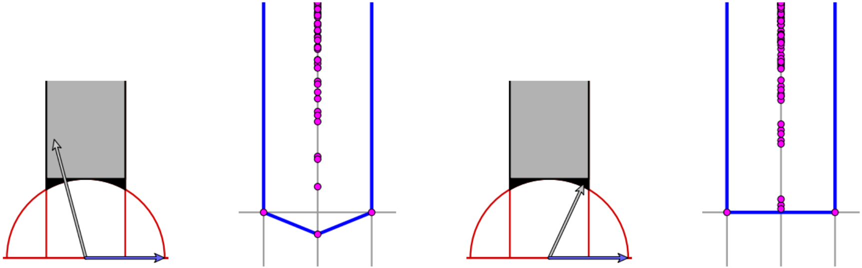

Figure: [2] - The figure on the left corresponds to $z = -2/5 + 3i/2$ and on the right corresponds to $z = 7/16 + 15i/16$

Canonical plot

Since the lattice is discrete, there is a shortest primitive vector - on the plot we have the lowest point on the vertical line $x = 1$.

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Grayson called the set of points plotted above as **canonical plot**. The convex hull of the collection of the plot points is called **profile**.

For any $z \in \mathbb{H} = \{\mathrm{Im}(z) > 0\}$, we can assign to it a unit lattices

$$z \mapsto L_z = \mathbb{Z}\frac{e_1}{\sqrt{y}} + \mathbb{Z}\left(\frac{x}{\sqrt{y}}e_1 + \sqrt{y}e_2\right)$$

The shortest vector is then $e_1/\sqrt{y}$, with length $\dfrac{1}{\sqrt{y}}$. So for $y < 1$, the lowest point is below the horizontal axis.

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The element z corresponds to the lattice L_z such that its lowest point on the vertical line $x = 1$ lies below the x-axis is called **semi-stable**, otherwise it is called **unstable**.

Semi-stable locus in fundamental domain

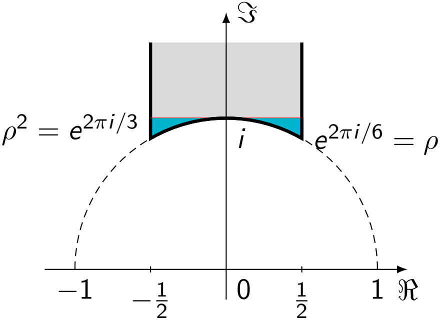

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Figure: The blue part is the semistable locus in the fundamental domain

Since the semi-stability is preserved under the action of $\mathrm{SL}_2(\mathbb{Z})$, the semi-stable locus in the upper half plane $\mathbb{H}$ is as follows

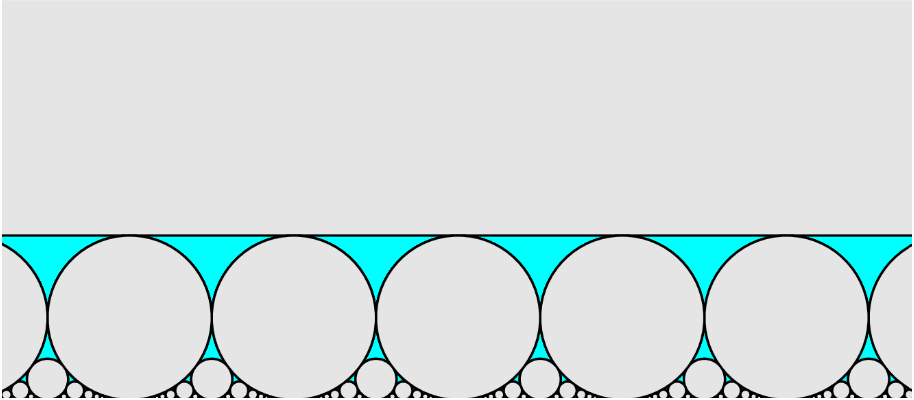

Figure: [2] - Semi-stable locus over $\mathbb{H}$ - it is the complement of the union of the gray area

In higher dimensional

We work with the lattices of the form $g\mathbb{Z}^n$ for $g \in \mathrm{GL}_n(\mathbb{R})$ or $g \in \mathrm{SL}_n(\mathbb{R})$. The latter is just the lattice with unit volume. Even if we want to work with unit lattices, we still need to consider the sublattices of arbitrary volumes.

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Sublattice

A discrete subgroup M of the lattice L is called **sublatice** if it satisfies one of the the following equivalent conditions:

1. L/M is torsion-free.
2. M is a direct summand in L.
3. Every basis of M can be extended to a basis in L.
4. The quotient L/M is a free $\mathbb{Z}-$module.

Volume of lattice

The volume of $L = g\mathbb{Z}^n$ is just $\det(g)$. Assume that M is a sublattice of L of rank $k \leq n$ with a basis

$$\{v_1, v_2, \ldots, v_k\}$$

Let $e_1, e_2, \ldots, e_n$ be the standard basis in $L \otimes \mathbb{R} \cong \mathbb{R}^n$. We can form a matrix of size $k \times n$

$$A = \left[\langle v_i, e_j \rangle\right]$$

The volume of M is defined to be the sum of the squares of the determinants of the $k \times k$ minor matrices in the matrix A.

Canonical plot in higher dimension

Grayson assigns the lattice L to a canonical plot as follows:

1. Assign the point $(0, 0)$ to the plot.
2. For each sublattice $M \subset L$, assign a point with coordinates $l(M) = (\text{rank}(M), \log(\text{vol}(M)))$ to the plot.
3. Assign the point $(n, \log(\text{vol}(L)))$ to the lattice.

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As before, we call the convex hull of this plot its **profile**.

We have the following proposition:

Lemma 1.15 [4]

Fix a lattice L of rank n and a positive number c. For each $k \leq n$, there are only finitely many sublattices $M \subset L$ such that $\mathrm{vol}(M) < c$.

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Semi-stable lattice

Construct the profile of a lattice L as above. If the bottom of the profile is just a line, then we call the lattice L **semi-stable**.

Example of a higher rank profile

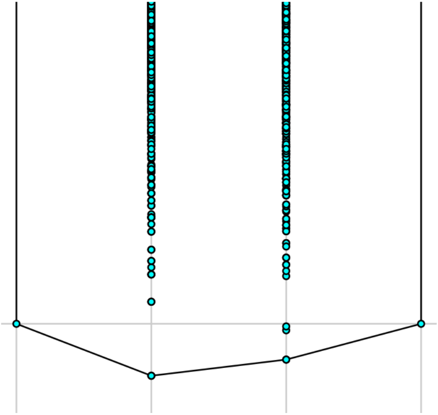

Figure: An unstable lattice

Iwasawa decomposition

We recall the Iwasawa decomposition for $G = \mathrm{GL}_n$:

$$G = K \times A \times N$$

where:

1. K is the orthogonal subgroup.
2. A is the group of diagonal matrices with positive entries along the diagonal.
3. N is the unipotent subgroup.

Parabolic subgroups

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Standard Parabolic subgroups of GL_n

For each partition

$$n = n_1 + n_2 + \ldots + n_k$$

We denote $P_{n_1, n_2, \ldots, n_k}$ the standard parabolic subgroup of type $(n_1, \ldots, n_k)$ to be the subgroup of matrices of the form

$$P_{n_1, \ldots, n_k} = \left\{ \begin{bmatrix} \mathfrak{m}_1 & * & \ldots & * \\ 0 & \mathfrak{m}_2 & \ldots & * \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & \mathfrak{m}_k \end{bmatrix} \right\}$$

where $\mathfrak{m}_\mathfrak{i}$ is invertible of size $n_i \times n_i$.

Degree of instability

Now we are ready to define the degree of instability

Degree of instability, [3]

For each $x \in G$, we define its degree of instability to be

$$\deg_{\text{inst}}(x) := \min_{P \in \text{ParSt}, \gamma \in G/P} \langle \rho_P, H_P(x\gamma) \rangle$$

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We define the notion of ρ-semistable as follows

ρ-semistable

A point $x \in G$ is called **semi-stable** iff $\deg_{\text{inst}}(x) \geq 0$.

Equivalent between two notions of semi-stable lattices

We have the following Lemma

Lemma 2.2.1, [3]

The following are equivalent:

1. $\deg_{\text{inst}}^{Q}(x) \geq 0$;
2. For every parabolic subgroup $P \subset Q$, every $\delta \in Q(F)/P(F)$, and every $\varpi \in \hat{\Delta}_P^Q$, we have:
$$\langle \varpi, H_P(x\delta) \rangle \geq 0;$$
3. For every maximal parabolic subgroup $P \subset Q$, every $\delta \in Q(F)/P(F)$, and every $\varpi \in \hat{\Delta}_P^Q$, we have:
$$\langle \varpi, H_P(x\delta) \rangle \geq 0.$$

Equivalent between two notions of semi-stable

Use the previous lemma, we can reduce to consider only maximal parabolic subgroups. We can further replace H_P with H_B, where B is the minimal parabolic subgroup in the formula of degree of instability.
This means we have

$$\langle \rho_{Q_i}, H_B(x\gamma) \rangle = a_1 a_2 \dots a_i$$

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This means we have

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where

$$x = k_x a_x n_x \in K \times A \times N,$$

in which

$$a_x = \begin{bmatrix} a_1 & 0 & \dots & 0 \\ 0 & a_1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & a_n \end{bmatrix}$$

This suggests that there should be a connection between the maximal parabolic subgroups of G and sublattices of L. Indeed we have

$$\mathrm{GL}_n(\mathbb{Z})/(Q_i(\mathbb{Q}) \cap \mathrm{GL}_n(\mathbb{Z})) \longleftrightarrow \{ \text{ sublattices of rank } i \text{ of } \mathbb{Z}^n\}$$

So we have the main theorem

Main theorem

Let $x \in X_n = K\backslash \mathrm{GL}_n(\mathbb{R})$ - the space of unit lattice. Then x is semi-stable if one of the following equivalent conditions holds

1. The bottom of the profile of x is a line connect solely two points: the origin and $(n, 0)$.
2. The degree of instability of x is nonnegative, namely, $\deg_{\text{inst}}(x) \geq 0$.

Thomas Borek.
Successive minima and slopes of hermitian vector bundles over number fields.
Journal of Number Theory, 113(2):380–388, 2005.

Bill Casselman.
Stability of lattices and the partition of arithmetic quotients.
2004.

Pierre-Henri Chaudouard.
Sur une variante des troncatures d'arthur.
In *Simons Symposium on the Trace Formula*, pages 85–120. Springer, 2016.

Daniel R Grayson.
Reduction theory using semistability.
Commentarii Mathematici Helvetici, 59(1):600–634, 1984.

THANK YOU FOR YOUR ATTENTION.