

On lattices generated by frames

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Tight frames

A spanning set $\{\mathbf{f}_1, \dots, \mathbf{f}_n\} \subset \mathbb{R}^k$, $n \geq k$, is called a **tight** (n, k) –**frame** if there exists a real constant γ such that for every $\mathbf{x} \in \mathbb{R}^k$,

$$\|\mathbf{x}\|^2 = \gamma \sum_{j=1}^n (\mathbf{x}, \mathbf{f}_j)^2,$$

where $(\ , \)$ stands for the usual dot-product.

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Tight frame $\mathcal{F}$ is **rational** if there exists a real number α so that

$$\alpha(\mathbf{f}_i, \mathbf{f}_j) \in \mathbb{Q} \ \forall \ 1 \leq i, j \leq n.$$

Group frames

Let G be a finite subgroup of $\mathcal{O}_k(\mathbb{R})$, the k -dimensional real orthogonal group, then G acts on $\mathbb{R}^k$ by left matrix multiplication. This action is **irreducible** if it has no invariant subspaces except for $\{\mathbf{0}\}$ and $\mathbb{R}^k$.

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Let $\mathbf{f} \in \mathbb{R}^k$ be a nonzero vector, then

$$G\mathbf{f} = \{U\mathbf{f} : U \in G\}$$

is called a **group frame** (or G -frame). If G acts irreducibly on $\mathbb{R}^k$, $G\mathbf{f}$ is called an **irreducible group frame**. Irreducible group frames are always tight.

Tight frames and lattices

Let $\mathcal{F} = \{\mathbf{f}_1, \dots, \mathbf{f}_n\}$ be a tight (n, k) -frame and define

$$L(\mathcal{F}) := \text{span}_{\mathbb{Z}} \mathcal{F} = \left\{ \sum_{i=1}^n a_i \mathbf{f}_i : a_1, \dots, a_n \in \mathbb{Z} \right\}.$$

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We are interested in studying the geometric properties of lattices generated by tight frames.

Some properties of lattices

Minimal norm of a lattice L is

$$|L| = \min \{ \|\mathbf{x}\| : \mathbf{x} \in L \setminus \{\mathbf{0}\} \},$$

where $\|\cdot\|$ is Euclidean norm. The set of **minimal vectors** of L is

$$S(L) = \{ \mathbf{x} \in L : \|\mathbf{x}\| = |L| \}.$$

From here on, let us write $S(L) = \{\mathbf{x}_1, \dots, \mathbf{x}_n\}$, where n , the cardinality of the set of minimal vectors of L must be even, and can be smaller or larger than (twice) the rank of the lattice. For example

$$S(\mathbb{Z}^k) = \{ \pm \mathbf{e}_1, \dots, \pm \mathbf{e}_k \},$$

so $n = 2k$.

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$$S(\mathbb{Z}^k) = \{ \pm \mathbf{e}_1, \dots, \pm \mathbf{e}_k \},$$

so $n = 2k$. A lattice L is **well-rounded** (WR) if

$$\text{span}_{\mathbb{R}} L = \text{span}_{\mathbb{R}} S(L).$$

Eutaxy and perfection

A lattice $L \subset \mathbb{R}^k$ is called **eutactic** if there exist positive real numbers $c_1, \dots, c_n$ such that

$$\|\mathbf{v}\|^2 = \sum_{i=1}^n c_i (\mathbf{v}, \mathbf{x}_i)^2$$

for every vector $\mathbf{v} \in \mathbb{R}^k$. If $c_1 = \dots = c_n$, we say that L is **strongly eutactic**.

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A lattice L is called **perfect** if the set of symmetric matrices

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Both, eutactic and perfect lattices are necessarily well-rounded. Up to similarity, there are only finitely many eutactic or perfect lattices in a given dimension.

Packing density

The **packing density** of a lattice L of rank k is defined as

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where ω_k is the volume of a unit ball in $\mathbb{R}^k$.

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Theorem 2 (G. Voronoi – 1908)

A lattice is extremal if and only if it is perfect and eutactic.

Strong eutaxy and group frames

Theorem 3 (A. Ash – 1977)

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Here is another way to think of strong eutaxy:

a lattice $L \subset \mathbb{R}^k$ is strongly eutactic if and only if its set of minimal vectors $S(L)$ forms a tight frame in $\mathbb{R}^k$.

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Theorem 4

Let G be a group of $k \times k$ real orthogonal matrices and $\mathbf{f} \in \mathbb{R}^k$ be a vector so that $\mathcal{F} = G\mathbf{f}$ is an irreducible rational group frame in $\mathbb{R}^k$. Then the lattice $L(\mathcal{F})$ is strongly eutactic.

Transitive graphs

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We define the **distance** between two vertices in a graph to be the number of edges in a shortest path connecting them. A connected graph Γ is called **distance transitive** if for any two pairs of vertices i, j and k, l at the same distance from each other there exists an automorphism $\tau \in G$ such that $\tau(i) = k$ and $\tau(j) = l$.

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Since $G \leq S_n$, we can identify it with its representation in the orthogonal group $\mathcal{O}_n(\mathbb{R})$ and its action extends to $\mathbb{R}^n$: $\forall \tau \in G$,

$$\tau \mathbf{e}_i = \mathbf{e}_{\tau(i)},$$

where $\mathbf{e}_1, \dots, \mathbf{e}_n$ are standard basis vectors.

Graphs to frames

Γ = distance transitive graph on n vertices

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A = adjacency matrix of Γ

λ = eigenvalue of A

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Hence, if $\mathbf{f} \in V_\lambda$, $\mathbf{f} \neq \mathbf{0}$, then $G\mathbf{f}$ is an irreducible group frame. Since there are many distance transitive graphs with rational eigenvalues, this becomes a valuable source for our lattice construction, leading to the following result.

Lattices from graphs

Theorem 5

Let Γ be a *vertex transitive* graph on n vertices and G its automorphism group. Let A be the adjacency matrix of Γ , λ a rational eigenvalue of multiplicity m and V_λ the corresponding m -dimensional eigenspace. Let P_λ be a rational orthogonal projection matrix of $\mathbb{R}^n$ onto V_λ . Then

$$L_{\Gamma,\lambda} := P_\lambda \mathbb{Z}^n$$

is a lattice of full rank in V_λ , and its automorphism group contains a subgroup isomorphic to a factor group of G . If Γ is *distance transitive*, $L_{\Gamma,\lambda}$ is strongly eutactic.

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We will refer to lattices obtained in this way as **lattices generated by graphs**. All vertex transitive examples known to us also generate strongly eutactic lattices, but we do not have a proof that this is true in general.

Hadwiger's Theorem

We compare our result to a classical theorem of H. Hadwiger.

Theorem 6 (H. Hadwiger – 1940)

A set $S = \{\mathbf{x}_1, \dots, \mathbf{x}_n\}$ of cardinality n in k -dimensional space V , $n > k$, is eutactic, i.e. there exist positive real numbers $c_1, \dots, c_n$ such that

$$\|\mathbf{v}\|^2 = \sum_{i=1}^n c_i (\mathbf{v}, \mathbf{x}_i)^2$$

for every vector $\mathbf{v} \in \mathbb{R}^k$ if and only if it is an orthogonal projection onto V of an orthonormal basis in an n -dimensional space containing V .

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Our graph construction considers precisely such a projection, namely the set of vectors $\{P_\lambda \mathbf{e}_i\}_{i=1}^n$ where $\mathbf{e}_1, \dots, \mathbf{e}_n$ is the standard basis in $\mathbb{R}^n$. This set is therefore eutactic by Hadwiger.

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Basic properties of this construction

Theorem 7

- *The completely disconnected graph 0_n on n vertices generates the integer lattice $\mathbb{Z}^n$.*
- *The complete graph K_n generates (a lattice similar to) the root lattice*

$$A_{n-1} := \left\{ \mathbf{x} \in \mathbb{Z}^n : \sum_{i=1}^n x_i = 0 \right\}.$$

- *If Γ is a disjoint union of k copies of a vertex transitive graph Δ with a rational eigenvalue λ , then λ is also an eigenvalue of Γ and*

$$L_{\Gamma, \lambda} = L_{\Delta, \lambda} \perp \cdots \perp L_{\Delta, \lambda}.$$

More properties

If Γ is a vertex transitive graph on n vertices, then its **complement** is the vertex transitive graph Γ' on the same vertices that has no common edges with Γ and their union is the complete graph K_n .

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Theorem 8

Let Γ be a vertex transitive graph on n vertices of degree k and Γ' its complement. Then for each rational eigenvalue $\lambda \neq k$ of Γ there is a rational eigenvalue $\lambda' = -\lambda - 1$ of Γ' of the same multiplicity and the lattices

$$L_{\Gamma, \lambda} = L_{\Gamma', \lambda'}.$$

Product graphs

There are three standard commutative product operations on graphs:

- **Cartesian product:** $\Delta_1 \square \Delta_2$ is the graph whose vertices are pairs (u, v) , where u is a vertex of Δ_1 and v is a vertex of Δ_2 , and (u_1, v_1) and (u_2, v_2) are connected by an edge if and only if either $u_1 = u_2$ and v_1, v_2 are connected by an edge in Δ_2 , or $v_1 = v_2$ and u_1, u_2 are connected by an edge in Δ_1 .

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- **Direct product:** $\Delta_1 \times \Delta_2$ is the graph whose vertices are pairs (u, v) , where u is a vertex of Δ_1 and v is a vertex of Δ_2 , and two vertices (u_1, v_1) and (u_2, v_2) are connected by an edge if and only if both pairs u_1, u_2 and v_1, v_2 are connected by an edge in Δ_1, Δ_2 , respectively.

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- **Strong product:** $\Delta_1 \boxtimes \Delta_2$, is the graph whose vertices are pairs (u, v) , where u is a vertex of Δ_1 and v is a vertex of Δ_2 , and two vertices (u_1, v_1) and (u_2, v_2) are connected by an edge if and only if u_1, u_2 and v_1, v_2 are either equal or connected by an edge in Δ_1, Δ_2 , respectively.

Eigenvalues of product graphs

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- **Direct product:**

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is an eigenvalue of $\Delta_1 \times \Delta_2$.

- **Strong product:**

$$f(\lambda, \mu) = (\lambda + 1)(\mu + 1) - 1$$

is an eigenvalue of $\Delta_1 \boxtimes \Delta_2$.

Lattices from product graphs

Theorem 9

Let Δ_1, Δ_2 be vertex transitive graphs on m_1, m_2 vertices, respectively, and let Γ be a product graph $\Gamma = \Delta_1 * \Delta_2$ on $m_1 m_2$ vertices, where $*$ stands for $\square, \times$, or $\boxtimes$. Let ν be an eigenvalue of Γ and (λ_i, μ_i) for $1 \leq i \leq k$ pairs of eigenvalues of Δ_1, Δ_2 respectively so that $\nu = f(\lambda_i, \mu_i)$ for all $1 \leq i \leq k$ for the appropriate f . Let L_{Δ_1, λ_i} and L_{Δ_2, μ_i} for each $1 \leq i \leq k$ be the corresponding lattices. Then $L_{\Gamma, \nu}$ is the orthogonal projection of $\mathbb{Z}^{m_1 m_2}$ onto the space spanned by

$$(L_{\Delta_1, \lambda_1} \otimes_{\mathbb{Z}} L_{\Delta_2, \mu_1}) \perp \cdots \perp (L_{\Delta_1, \lambda_k} \otimes_{\mathbb{Z}} L_{\Delta_2, \mu_k}),$$

where $\perp$ is the orthogonal direct sum. In particular, if $k = 1$ then

$$L_{\Gamma, \nu} = L_{\Delta_1, \lambda_1} \otimes_{\mathbb{Z}} L_{\Delta_2, \mu_1},$$

up to similarity.

And now examples!

Graph Γ	# of vertices	Eig. λ	Mult. of λ	Lattice $L_{\Gamma, \lambda}$
Cube Q_3	(8)	1	(3)	A_3^* , dual of A_3
Hamming $H(2, 3)$	(9)	1	(4)	$A_2 \otimes_{\mathbb{Z}} A_2$
Petersen graph	(10)	-2	(4)	A_4^* , dual of A_4
Petersen graph	(10)	1	(5)	Coxeter lattice A_5^2
Petersen line graph	(15)	-1	(5)	A_4^* , dual of A_4
Petersen line graph	(15)	-2	(5)	Coxeter lattice A_5^3
Clebsch graph	(16)	-3	(5)	D_5^* , dual of D_5
Shrikhande graph	(16)	2	(6)	D_6^+
Schläfli graph	(27)	4	(6)	E_6^* , dual of E_6
Gosset graph	(56)	9	(7)	E_7^* , dual of E_7

Examples of strongly eutactic lattices from vertex transitive graphs

(Dual: $L^* := \{\mathbf{x} \in \mathbb{R}^n : (\mathbf{x}, \mathbf{y}) \in \mathbb{Z} \text{ for all } \mathbf{y} \in L\}$)

Lattices E_8 , E_7 , E_6

For each $n \geq 2$,

$$D_n := \left\{ \mathbf{x} \in \mathbb{Z}^n : \sum_{i=1}^n x_i \equiv 0 \pmod{2} \right\}.$$

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$$D_n^+ := D_n \cup \left(\frac{1}{2} \sum_{i=1}^n \mathbf{e}_i + D_n \right).$$

Then $E_8 := D_8^+$, and

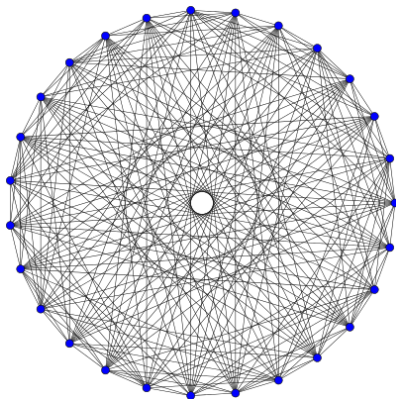
$$E_7 := \{ \mathbf{x} \in E_8 : x_7 = x_8 \}, \quad E_6 := \{ \mathbf{x} \in E_8 : x_6 = x_7 = x_8 \}.$$

Their duals are

$$E_7^* = \{ \mathbf{x} \in \text{span}_{\mathbb{R}} E_7 : (\mathbf{x}, \mathbf{y}) \in \mathbb{Z} \ \forall \ \mathbf{y} \in E_7 \},$$

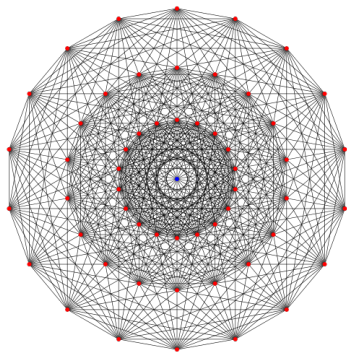
$$E_6^* = \{ \mathbf{x} \in \text{span}_{\mathbb{R}} E_6 : (\mathbf{x}, \mathbf{y}) \in \mathbb{Z} \ \forall \ \mathbf{y} \in E_6 \}.$$

Schläfli graph



Γ is the complement of the intersection graph of the 27 lines on a cubic surface. It is a strongly regular graph on 27 vertices with parameters $k = 16$, $\ell = 10$, $m = 8$ and has eigenvalue 4 of multiplicity 6: $L_{\Gamma,4} = E_6^*$.

Gosset graph



Γ has 56 vertices corresponding to the set of edges of two copies of the complete graph K_8 . Two vertices from the same copy of K_8 are connected by an edge if they correspond to disjoint edges of K_8 ; two vertices from different copies of K_8 are connected by an edge if they correspond to edges that meet in a vertex. Γ has eigenvalue 9 of multiplicity 7: $L_{\Gamma,9} = E_7^*$.

Contact polytope

Contact polytope of a lattice L is

$$C(L) = \text{Conv}\{S(L)\}.$$

Its vertices are points on the sphere centered at the origin in the sphere packing associated to L at which neighboring spheres touch it. Hence the number of vertices of $C(L)$ is the kissing number of L .

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Sometimes $C(L)$ is represented as a **diplo-polytope**. The prefix “diplo” means double: for a polytope Π a diplo- Π polytope is a polytope whose vertices are vertices of Π and its opposite $-\Pi$.

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The **skeleton graph** of the polytope $C(L)$, $\text{skel}(C(L))$ is the graph consisting of vertices and edges of $C(L)$.

A curious duality

Let $L = E_6^*$. The contact polytope of E_6^* has 54 vertices, split into $27 \pm$ pairs: it is a diplo-Schläfli polytope. The Schläfli polytope, has 27 vertices corresponding to the 27 lines on a cubic surface. Its skeleton is the Schläfli graph Γ , which has an eigenvalue 4 of multiplicity 6, and $L_{\Gamma,4} = E_6^*$.

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Let $L = E_7^*$, its contact polytope is the Gosset polytope (also called Hess polytope), which has 56 vertices. Its skeleton is the Gosset graph Γ , which has an eigenvalue 9 of multiplicity 7, and $L_{\Gamma,9} = E_7^*$.

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Let $L = A_3^*$. Its contact polytope is a cube (which is a diplo-simplex), whose skeleton graph Q_3 has eigenvalue 1 (and -1) of multiplicity 3, and $L_{Q_3,1} = A_3^*$.

Lattices generated by ETF's

Table: There exists an (n, k) real unit ETF $\mathcal{F}$ with:

(n, k)	$c(\mathcal{F})$	Eutactic?	Perfect?	$\delta(\Lambda(\mathcal{F}))$	$\delta_{\max}$
$(k+1, k)$	$1/k$	strongly	only $(3, 2)$	—	—
(6, 3)	$1/\sqrt{5}$	n/a	n/a	n/a	n/a
(10, 5)	$1/3$	strongly	no	0.3701...	0.4652...
(16, 6)	$1/3$	strongly	no	0.2725...	0.3729...
(14, 7)	$1/\sqrt{13}$	n/a	n/a	n/a	n/a
(28, 7)	$1/3$	strongly	yes	0.2157...	0.2953...
(18, 9)	$1/\sqrt{17}$	n/a	n/a	n/a	n/a
(26, 13)	$1/5$	strongly	no	0.0024...	0.0320...
(276, 23)	$1/5$	yes	yes	?	0.0019...
(50, 25)	$1/7$	?	no	—	—

$\delta_{\max} = \max$ packing density known in $\mathbb{R}^k$.

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