The Atlas of Lie Groups and Representations

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For our purposes we may take a Lie group to be a group of (real or complex) matrices, such as the rotation group $O(3)$, the general linear group $GL(n, \mathbb{R})$ (consisting of all $n \times n$ invertible real matrices), an indefinite orthogonal group $SO(p, q)$ (preserving a symmetric form of signature p, q), or the symplectic group $Sp(2n, \mathbb{R})$ (preserving a symplectic form).

A *representation* of G is a (continuous) homomorphism $\pi : G \to Aut(V)$ of G to the (linear) automorphisms of a vector space. A representation π is *unitary* if V is a Hilbert space and the operators $\pi(g)$ preserve the Hilbert space structure, i.e.

$$(\pi(g)v, \pi(g)w) = (v, w) \quad \text{for all } v, w \in V, g \in G$$

Lie groups and their representations are basic objects in mathematics, physics, and other sciences.

We say two representations π_1, π_2 are *equivalent* if they are the same, up to a change of basis.

A unitary representation is *irreducible* if it cannot be written $V = V_1 \oplus V_2$ where V_1, V_2 are representations of G.

Basic Problem: Classify the set $\widehat{G}$ of (equivalence classes of) irreducible unitary representations of any Lie group G.

Note: In general V is infinite dimensional, and some more explanation is needed to make the concepts of representation, unitary and irreducible precise.

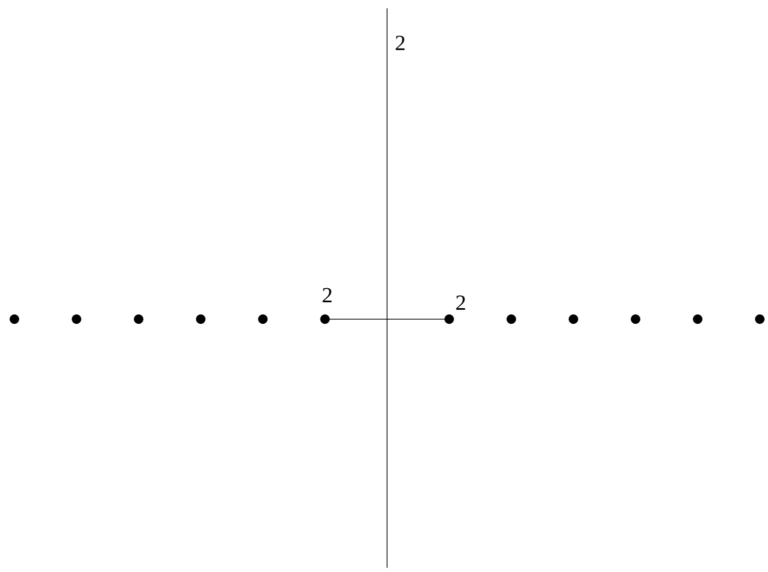
Example: If G is a finite group then $\widehat{G}$ is known by work of Frobenius and Schur. In particular $|\widehat{G}|$ is the number of conjugacy classes of G.

The **Atlas of Finite Groups** has a tremendous amount of information on finite groups and their representations.

Example: If $G = SO(3)$, the 3×3 matrices of determinant 1, satisfying $gg^t = I$, then there is one irreducible representation of G of dimension n for all $n > 0$ odd.

Example: If G is a compact group (like $SO(3)$) then every irreducible representation of G is unitary and finite dimensional, and they were classified by Cartan and Weyl in the 1920s. They are parametrized by a lattice intersected with a cone in $\mathbb{R}^n$.

Example: Take $G = SL(2, \mathbb{R})$, the 2×2 real matrices of determinant 1. Then $\widehat{G}$ was computed by Bargmann in the 1940s. Here is a picture: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The Problem of the Unitary Dual has been the object of intensive study for over 50 years. For non-compact groups it is only known in a few cases, such as $SL(2,\mathbb{R})$ and $GL(n,\mathbb{R})$.

Let G be any given Lie group.

Theorem 0.1 (Vogan) There is a finite algorithm to compute the unitary dual of G.

Note: This is much weaker than saying there is a finite algorithm for a single family of groups such as $GL(n,\mathbb{R})$.

Proposal A: Write a computer program to compute the unitary dual of a fixed real group.

Note: There is a big difference between a theorem asserting the existence of a finite algorithm, and a computer program.

Proposal B: Create a web site to make information about Lie groups and their representations available to the mathematical and scientific communities - much like the Atlas of Finite Groups.

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- It is interesting and fun. A lot of people will be involved (I hope).
- The Atlas Web Site will be an invaluable tool to experts, non-experts, and students.

It is difficult to compute examples even for the most proficient expert, and for non-experts it is almost impossible.

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- Huge investment of time.
- Likelihood of failure: it is not clear this can be done.
- Can't trust computers. How do you know if the answer is correct?

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$$\frac{21}{512}\sin(x) - \frac{15}{512}\sin(3x) + \frac{15}{512}\sin(35x) - \frac{5}{1024}\sin(7x) + \frac{11}{11264}\sin(9x) + C$$

- Positive definiteness revisited:

  Let

$$X := \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 4 \\ 3 & 4 & 7 \end{pmatrix}$$

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  According to Mathematica the eigenvalues are:

$$\frac{11}{3} + \frac{23\,5^{\frac{2}{3}}}{3\left(241 + 9\,i\,\sqrt{34}\right)^{\frac{1}{3}}} + \frac{\left(5\,\left(241 + 9\,i\,\sqrt{34}\right)\right)^{\frac{1}{3}}}{3}$$

$$\frac{11}{3} - \frac{23\,5^{\frac{2}{3}}\,\left(1 + i\,\sqrt{3}\right)}{6\left(241 + 9\,i\,\sqrt{34}\right)^{\frac{1}{3}}} - \frac{\left(1 - i\,\sqrt{3}\right)\,\left(5\,\left(241 + 9\,i\,\sqrt{34}\right)\right)^{\frac{1}{3}}}{6}$$

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  Numerically:

$$\begin{array}{r} 10.79 + 0.i \\ -0.34 + 4.44 \times 10^{-16} i \\ 0.54 - 4.44 \times 10^{-16} i \end{array}$$

Some Computational Issues

1. Models of Representations of Weyl Groups

Suppose W is a Weyl group. This is a finite group, generated by reflections, associated to a root system R of type $A_n, B_n, C_n, D_n, E_6, E_7, E_8, F_4$ or G_2.

Type	$\|R\|$	Order(W)	realization
A_n	$\frac{n(n-1)}{2}$	n!	S^n
B_n/C_n	$2n^2$	$2^n n!$	$S^n \ltimes \mathbb{Z}_2^n$
D_n	$2n^2 - 2n$	$2^{n-1}n!$	$S^n \ltimes \mathbb{Z}_2^{n-1}$
E_6	72	51,840	$O(6, \mathbb{F}_2)$
E_7	126	2,903,040	$O(7, \mathbb{F}_2) \times \mathbb{Z}/2\mathbb{Z}$
E_8	240	696,729,600	$W \xrightarrow{2} O(8, \mathbb{F}_2)$
F_4	48	1152	
G_2	12	12	D_6

Representations of Weyl groups:

Type	Number	Maximum Dimension
A_n	$n!$	?
B_n/C_n	?	?
D_n	?	?
E_6	25	90
E_7	60	512
E_8	112	7,168
F_4	25	16
G_2	6	2

The irreducible representation of W are classified (the character table is known).

Problem: Write down explicit matrices realizing the irreducible representations of a Weyl group.

That is W is generated by elements $g_1, \ldots, g_n$, with relations (for example $g_i^2 = 1$). For a given representation π write down matrices $A_1, \ldots, A_n$ so that $\pi(g_i) = A_i$.

This is a hard problem, and there is no general solution for a general finite group.

We have done this over the rationals for all exceptional groups, and over the integers for all but E_8. One method is to use the "meataxe" algorithm from finite group theory.

An issue which arises is: suppose M is an $m \times n$ matrix with integral entries. View this as a homomorphism from $\mathbb{Z}^n$ to $\mathbb{Z}^m$. Find a basis of the kernel of M. Equivalently: find a basis of the row space of M (over $\mathbb{Z}$!).

The solution is given by Smith Normal Form. Implementing it runs into issues of "integer explosion".

We have many problems of this type involving **integral** or **rational** linear algebra.

Example: a 64-dimensional representation of $W(E_6)$

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pi(g_1):
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```

```
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1/2 1/3 1/6 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 20/9 -1/18 0 0 -35/54 -1/18 0 0 5/6 -2/27 0 0 0 0 0 0 0 0 0
[0 0 0 -35/72 35/72 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 29/108 25/108 0 0 -17/36 5/36 0 0 11/36 1/36 0
[0 0 0 7/24 -7/24 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 5/36 13/36 0 0 1/12 -5/12 0 0 1/60 19/60 0 0 -1/5
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8/9 -7/18 0 0 7/54 5/18 0 0 -1/6 4/27 0 0 0 0 0 0 0 0 0 -2/9
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -35/18 -1/18 0 0 25/54 11/72 0 0 5/24 -5/27 0 0 0 0 0 0 0 0
[0 0 0 -5/12 5/12 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -17/36 5/36 0 0 1/2 0 0 0 0 0 0 0 0 0 0 0 0 0 -11
[0 0 0 1/4 -1/4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/12 -5/12 0 0 0 1/2 0 0 0 0 0 0 0 0 0 0 0 0 1/24 -
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -5/18 5/18 0 0 -5/54 5/72 0 0 11/24 1/27 0 0 0 0 0 0 0 0 0 -
[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 50/9 -5/9 0 0 50/27 -25/18 0 0 5/6 -13/54 0 0 0 0 0 0 0 0 0
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[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 5/6 -1/3 0 0 0 0 0 0 0 0 0 0 0 -1/2
[0 0 0 1/4 -1/4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/12 -1/12 0 0 0 0 0 0 0 0 0 0 1/2 0 0 0 0 0 1/24 -
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[0 0 0 1/2 -1/2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/6 -1/6 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 1/12 -1/1
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[0 0 0 11/48 -11/48 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 179/144 121/144 0 0 7/3 11/6 0 0 7/15 11/30 0 0
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pi(g_5)
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[0 3/2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1/2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -29/100 -13/
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[0 9/4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3/4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -3/40 0 9/5
[0 -9/2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -3/2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3/20 0 0 0
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pi(g_6)
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2. Testing for Positive Semidefiniteness

Suppose A is an $n \times n$ symmetric matrix with rational entries. How do you tell if A is positive semi–definite? That is we can find B so that BAB^t is a diagonal matrix, with real entries. Are all of the entries non–negative? Eqivalently are all eigenvalues of A (which are necessarily real) non–negative?

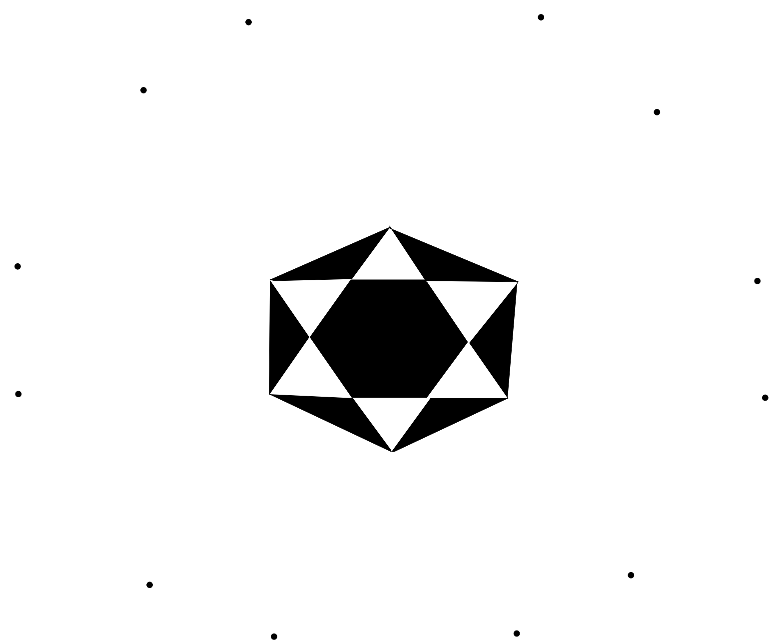
The standard test is: if and only if every minor has non–negative determinant. There are 2^n such minors. If $n = 7,168$ this won't do; there are better methods, but we are not sure if they will suffice.

Note that we need to do rational, and not real, arithmetic. An eigenvalue may be a very small real number; to tell whether it is positive or negative it is not sufficient to work with any fixed precision. (The sgn function is very difficult to compute).

How to present the answer?

The unitary dual of G is a countable union of sets, each of which is the quotient of a subset of a vector space by a finite group (something like the Weyl group).

The spherical unitary dual of G_2 (this is a subset of one of the vector spaces V):



The subset of each vector space is a finite union of facets. We can give a representative point on facet. This gives a list, which may or may not be useful. We need to make the answer comprehensible (by first comprehending it!).