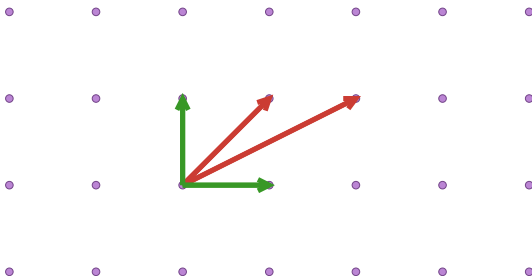


# ELI5: Lattice Reduction

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# Why should I care about lattices?

You may not need to care! Even so, hopefully you'll get a few ideas (and buzzwords!) that you can wield on your nerdy friends

- ▶ Cryptography will be a hot field for the next 100+ years
- ▶ One of the hottest areas is the use of lattice tools to build **post-quantum cryptography**, as well as fancy tools like **fully-homomorphic encryption**

This talk will give a brief introduction to lattices, specifically **lattice reduction**. A background in linear algebra will be helpful

# When could I use lattice reduction?

Lattice tools are often used in places where one would normally use linear algebra, but an integer-valued solution is desired

There are practical uses:

- ▶ Integer programming
- ▶ Post-quantum cryptography (LWE)
- ▶ Cryptanalysis (cracking SSH, HTTPS)
- ▶ Digital communication
- ▶ Encrypted ML (FHE in Julia)
- ▶ Coding theory
- ▶ Finding anagrams :-)

And there are theoretical uses

- ▶ Disproving Merten's Conjecture
- ▶ Sphere packing (with Julia!)
- ▶ Diophantine equations
  - ▶ Solving  $x^3 + y^3 + z^3 = d$
- ▶ Geometry of flat tori
- ▶ Finding Spigot formulas
- ▶ Factoring Polynomials
- ▶ Computing the Riemann theta function
- ▶ Physics (Feynman integrals)

# Outline

## Background

Basics, Definitions

Lattice Reduction

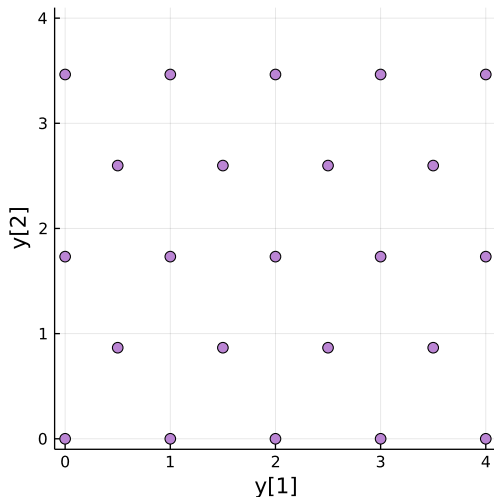
LLLplus.jl

What's in it?

## Demo

Cracking Merkle–Hellman knapsack cryptosystem

# What's a Lattice?



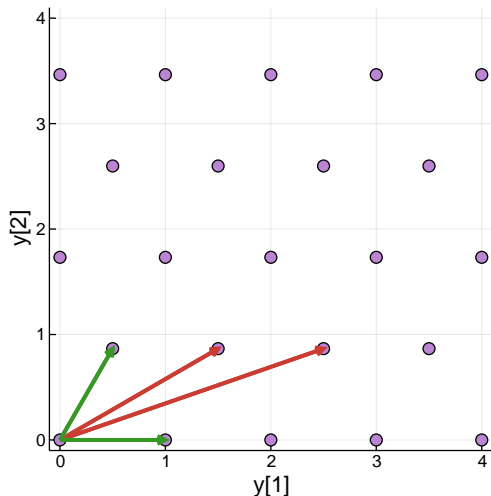
- ▶ A full-rank discrete additive subgroup of (say)  $\mathbb{R}^n$  or  $\mathbb{C}^n$
- ▶  $\mathbb{Z}^n$  is a lattice in  $\mathbb{R}^n$

## A practical definition

For a basis matrix  $B$ , and a vector of integers  $\mathbf{z}$ , the set of points  $\mathbf{y}$  reachable by  $\mathbf{y} = B\mathbf{z}$  is a lattice:

$$\mathcal{L}(B) = \{B\mathbf{z} : \mathbf{z} \in \mathbb{Z}^n\}$$

## For a lattice, how many bases are possible?



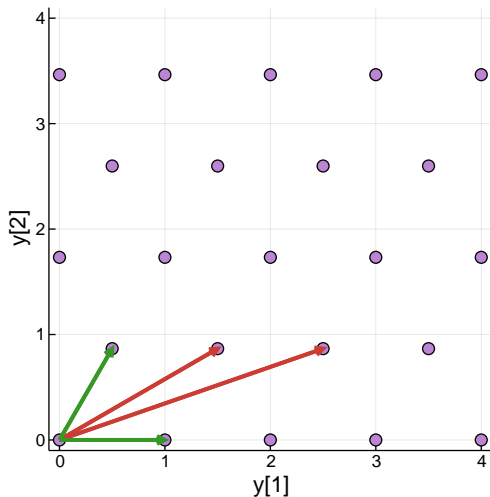
There are an infinite number of bases for a lattice; which one should we use?

$$B_{red} = \begin{bmatrix} 2.5 & 1.5 \\ .86602 & .86602 \end{bmatrix}$$

$$B_{green} = \begin{bmatrix} 1.0 & .5 \\ 0.0 & .86602 \end{bmatrix}$$

In many problems, we want a short, close-to-orthogonal basis, like the green basis

# How are different lattice bases related?



A **unimodular matrix** is square, integer-valued, and has determinant  $\pm 1$ . Its inverse is also unimodular

## Relation between Bases

Every pair of lattice bases  $B_1$  and  $B_2$  are related by a unimodular matrix  $T$ :

$$B_1 = B_2 T$$

For the bases in the figure,

$$B_{red} = B_{green} T, \text{ where}$$

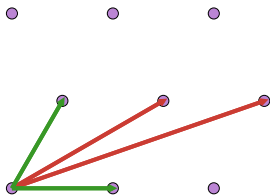
$$T = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$$

# How can we find a good basis?

## Use lattice reduction

Given lattice with basis  $B_1$ , the goal of lattice reduction is to find another basis  $B_2$  for the same lattice which has short, closer-to-orthogonal basis vectors

Often, “short” and “orthogonal” are defined according to the Euclidian norm. So  $B_2^T B_2$  is closer to diagonal than  $B_1^T B_1$ , and the diagonal elements of  $B_2^T B_2$  are smaller than those of  $B_1^T B_1$



‘Lattice reduction is like QR for integer problems.’

Jack Poulson

Instead of an orthonormal  $Q$ , we have a close-to-orthogonal reduced basis, and instead of a triangular  $R$  we have a unimodular matrix:

$$B_1 = B_2 T$$



# How does one do lattice reduction?

The most important lattice reduction technique is from Lenstra, Lenstra, and Lovász<sup>1</sup>, known as the LLL algorithm

## LLL in pseudocode

**Input:** a basis  $(\mathbf{b}_1, \dots, \mathbf{b}_d)$  of a lattice  $L$ .

**Output:** the basis  $(\mathbf{b}_1, \dots, \mathbf{b}_d)$  is LLL-reduced with factor  $\delta$ .

- 1: Size-reduce  $(\mathbf{b}_1, \dots, \mathbf{b}_d)$
- 2: **if** there exists an index  $j$  which does not satisfy Lovász' condition
- 3:     swap  $\mathbf{b}_j$  and  $\mathbf{b}_{j+1}$ , then return to Step 1.
- 4: **end if**

Lovász' condition is  $\|\mathbf{b}_{j+1}\|^2 \geq (\delta - \mu_{j+1,j}^2) \|\mathbf{b}_j\|^2$  where the coefficients  $\mu$  are Gram-Schmidt coefficients from size reduction

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<sup>1</sup>A. K. Lenstra; H. W. Lenstra Jr.; L. Lovász; "Factoring polynomials with rational coefficients". Mathematische Annalen 261, 1982.

# Size Reduction? Gram-Schmidt? Do I need to know this?

**No**, most LLL users can skip previous, current, next slides :-)

## Size Reduction pseudocode<sup>2</sup>

**Input:** A basis  $(\mathbf{b}_1, \dots, \mathbf{b}_d)$  of a lattice  $L$ .

**Output:** A size-reduced basis  $(\mathbf{b}_1, \dots, \mathbf{b}_d)$ .

```
1: Compute all the Gram-Schmidt coefficients  $\mu_{i,j}$ 
2: for  $i = 2$  to  $d$  do
3:   for  $j = i - 1$  downto  $1$  do
4:      $\mathbf{b}_i \leftarrow \mathbf{b}_i - \lceil \mu_{i,j} \rceil \mathbf{b}_j$ 
5:   for  $k = 1$  to  $j$  do
6:      $\mu_{i,k} \leftarrow \mu_{i,k} - \lceil \mu_{i,j} \rceil \mu_{j,k}$ 
7:   end for
8: end for
9: end for
```

There are LLL variants which use

- ▶ Gram-Schmidt (shown)
- ▶ Givens rotations
- ▶ Householder rotations
- ▶ A Cholesky decomposition (fastest)

Size reduction is GS with rounding

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<sup>2</sup>The LLL and size reduction pseudocode are from P. Q. Nguyen "Hermite's constant and lattice algorithms," a chapter of [The LLL Algorithm](#), Springer, Berlin, Heidelberg, 2009, pp 19-69

# Givens-based LLL in Julia

```
function lll(H::Matrix{Td},δ::Float64=3/4) where {Td<:Number}
    B = copy(H);    N,L = size(B);    _,R = qr(B)
    lx = 2
    while lx <= L
        for k=lx-1:-1:1
            rk = R[k,lx]/R[k,k]
            mu = round(rk)
            if abs(mu)>0
                B[:,lx] -= mu * B[:,k]
                R[1:k,lx] -= mu * R[1:k,k]
            end
        end
        nrm = norm(R[lx-1:lx,lx])
        if δ*abs(R[lx-1,lx-1])^2 > nrm^2
            B[:, [lx-1,lx]] = B[:, [lx,lx-1]]
            R[1:lx, [lx-1,lx]] = R[1:lx, [lx,lx-1]]
            cc = R[lx-1,lx-1] / nrm
            ss = R[lx,lx-1] / nrm
            Θ = [cc' ss; -ss cc] # Givens rotation
            R[lx-1:lx,lx-1:end] .= Θ * R[lx-1:lx,lx-1:end]
            lx = max(lx-1,2)
        else; lx = lx+1; end
    end
    return B
end
```

# What should I remember about the LLL?

Remember two things:

- ▶ LLL runs fast;  $O(d^5)$  for bases of size  $d$
- ▶ LLL reduces the basis:  $\|\mathbf{b}_1\| \leq (\frac{2}{\sqrt{4\delta-1}})^{d-1} \lambda_1(\mathcal{L})$

The LLL is a baseline lattice tool. Its polynomial speed and acceptable reduction quality is what brought interest to lattice tools

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- Lattice Reduction

## LLLplus.jl

- What's in it?

## Demo

- Cracking Merkle–Hellman knapsack cryptosystem

# Lattice Tools in LLLplus.jl

Lattice Tool	Function	Use case
LLL lattice reduction	lll	most lattice problems
Seysen lattice reduction	seysen	math, WiFi
Brun lattice reduction	brun	math, WiFi
CVP solver	cvp	WiFi, GGH
SVP solver	svp	NTRU, RLWE

Demo function	Application
subsetsum	cryptanalysis, integer relations
integerfeasibility	integer programming feasibility
rationalapprox	find rational approx for vector
spigotBBP	spigot formulas for irrationals

## How about an LLL demo?

```
julia> Br=[2.5      1.5; 0.866025 0.866025];  
julia> Pkg.add("LLLplus"); using LLLplus
```

```
julia> B,T,_ = lll(Br); B  
2×2 Array{Float64,2}:  
-1.0  -0.5  
 0.0   0.866025
```

```
julia> T  
2×2 Array{Int64,2}:  
-1  -2  
 1   3
```

```
julia> [det(T) det(inv(T))]  
1×2 Array{Float64,2}:  
-1.0  -1.0
```

```
julia> islllreduced(B)  
true
```

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# Subset-Sum and Integer Relations

## Subset-Sum

Given a vector  $\mathbf{a}$  of integers, and a sum  $s$ , if there is a binary vector  $\mathbf{x}$  such that  $\mathbf{x}^T \mathbf{a} = s$ , find it.

The LLL-based technique from [Lagarias and Oldyzko](#) was designed to solve low-density subset-sum problems. It breaks the Merkle–Hellman knapsack cryptosystem and is widely useful, for example to solve related problems like:

## Integer Relations

Given a vector  $\mathbf{a}$  of real numbers, if there is an integer vector  $\mathbf{x}$  such that  $\mathbf{x}^T \mathbf{a} = 0$ , find it.

Integer relations solvers can be used to make spigot algorithms, say giving the  $n$ th digit of  $\pi$  without computing any of the other digits

## Demo: A subset-sum problem

```
julia> setprecision(BigFloat,300); N=50; Bitdepth=190;
julia> # Bitdepth can be 256+, just doesn't fit on screen
      a=rand(0:2^BigInt(Bitdepth)-1,N);
julia> a[1:3]
3-element Array{BigInt,1}:
 911200129391658686469201173324473216271570073348033300075
 666563007748951582781404496296235427608875017772431026416
 832622399672004543019820919656212490862510181960061392073
julia> xtrue=rand(Bool,N); s=a'*xtrue;
julia> @elapsed x,_=LLLplus.subsetsum(a,s)
2.535546165
julia> s-x'*a
0.0
```

Are there any...

Questions?