

## 1 The Subset-Sum Problem

We begin by recalling the definition of the *subset-sum* problem—sometimes also called the “knapsack” problem—in its search form.

**Definition 1.1 (Subset-Sum).** Given positive integer weights  $\mathbf{a} = (a_1, \dots, a_n)$  and  $s = \sum_{i=1}^n a_i x_i = \langle \mathbf{a}, \mathbf{x} \rangle \in \mathbb{Z}$  for some bits  $x_i \in \{0, 1\}$ , find  $\mathbf{x} = (x_1, \dots, x_n)$ .

The subset-sum problem (in its natural decision variant) is NP-complete. However, recall that NP-completeness is a *worst-case* notion, i.e., there does not appear to be an efficient algorithm that solves *every* instance of subset-sum. Whether or not “most instances” can be solved efficiently, and what “most instances” even means, is a separate question. As we will see below, certain “structured” instances of subset-sum are easily solved. Moreover, we will see that if the bit length of the  $a_i$  is large enough relative to  $n$ , then subset-sum is easy to solve for almost every choice of  $\mathbf{a}$ , using LLL.

## 2 Knapsack Cryptography

Motivated by the simplicity and NP-completeness of subset-sum, in the late 1970’s there were proposals to use it as the basis of public-key encryption schemes; see [Od90] for a survey. In these systems, the public key consists of weights  $\mathbf{a} = (a_1, \dots, a_n)$  chosen from some specified distribution, and to encrypt a message  $\mathbf{x} \in \{0, 1\}^n$  one computes the ciphertext

$$s = \text{Enc}_{\mathbf{a}}(\mathbf{x}) = \langle \mathbf{a}, \mathbf{x} \rangle.$$

A major advantage of this kind of encryption algorithm is its efficiency: encrypting involves just summing up  $n$  integers, which is much faster than operations like modular exponentiation, as used in other cryptosystems. As for security, recovering the message  $\mathbf{x}$  from the ciphertext is equivalent to solving the subset-sum instance  $(\mathbf{a}, s)$ , which we would like to be hard.<sup>1</sup> Of course, the receiver who generated the public key needs to have a way of recovering the message, i.e., decrypting the ciphertext. This is achieved by embedding a secret “trapdoor” into the weights, which allows the receiver to convert the ciphertext into a different, easily solvable subset-sum instance.

One class of easily solved subset-sum instances involves weights of the following type.

**Definition 2.1.** A *superincreasing sequence*  $\mathbf{a} = (a_1, \dots, a_n)$  is one where  $a_i > \sum_{j=1}^{i-1} a_j$  for all  $i$ .

Given any superincreasing sequence  $\mathbf{a}$  and  $s = \langle \mathbf{a}, \mathbf{x} \rangle$ , it is easy to find  $\mathbf{x}$ : observe that  $x_n = 1$  if and only if  $s > \sum_{i=1}^{n-1} a_i$ . Having found  $x_n$ , we can then recursively solve the instance  $(\mathbf{a}' = (a_1, \dots, a_{n-1}), s' = s - a_n x_n)$ , which still involves superincreasing weights.

Of course, we cannot use a superincreasing sequence as the public key, or it would be trivial for an eavesdropper to decrypt. The final idea is to embed a superincreasing sequence into a “random-looking” public key, along with a trapdoor that lets us convert the latter back to the former. The original method of doing so, proposed by Merkle and Hellman [MH78], permutes and multiplies the weights by a random secret (modulo another random modulus), as follows:

1. Start with some superincreasing sequence  $\mathbf{b} = (b_1, \dots, b_n)$ .

<sup>1</sup>For this lecture, we ignore the fact that accepted notions of security for encryption require much more than hardness of recovering the entire message. However, such hardness is clearly necessary: if the message is indeed easy to recover by an eavesdropper, then the scheme is insecure.

2. Choose some modulus  $m > \sum_{i=1}^n b_i$ , a uniformly random multiplier  $w \leftarrow \mathbb{Z}_m^*$ , and a uniformly random permutation  $\pi$  on  $\{1, \dots, n\}$ .
3. Let  $a_i = w \cdot b_{\pi(i)} \bmod m$ . The public key is  $\mathbf{a} = (a_1, \dots, a_n)$ , and the trapdoor is  $(m, w, \pi)$ .

The encryption of a message  $\mathbf{x} \in \{0, 1\}^n$  is then

$$s = \text{Enc}_{\mathbf{a}}(\mathbf{x}) = \langle \mathbf{a}, \mathbf{x} \rangle = w \cdot \sum_{i=1}^n b_{\pi(i)} x_i.$$

Given the trapdoor  $(m, w, \pi)$ , we can decrypt  $s$  as follows: simply compute

$$s' := w^{-1}s = \sum_{i=1}^n b_{\pi(i)} x_i \bmod m,$$

and then solve the subset-sum problem for the (permuted) superincreasing  $\mathbf{b}$  and  $s'$ , where we treat  $s'$  as its integer representative in  $\{0, \dots, m-1\}$ . This works because  $\sum_{i=1}^n b_{\pi(i)} x_i < m$ , so  $s'$  is the true subset-sum (not modulo anything).

It turns out that some care is needed in choosing the superincreasing sequence  $b_1, \dots, b_n$ . For example, the natural choice of  $b_i = 2^{i-1}$  ends up admitting some simple attacks. We won't discuss this issue in any detail, because it turns out that the Merkle-Hellman scheme (and almost all of its subsequent variants) can be broken using tools like LLL, regardless of what superincreasing sequence is used.

### 3 Lattice Attacks on Knapsack Cryptography

In 1982, Shamir [Sha82] showed how to break the basic Merkle-Hellman class of schemes in polynomial time. His attack uses Lenstra's polynomial-time algorithm for fixed-dimension integer programming, which uses LLL as a subroutine. (Shamir's attack has been extended to break many subsequent versions of the Merkle-Hellman system.) Shortly thereafter, Lagarias and Odlyzko [LO83] gave an incomparable attack, later simplified by Frieze [Fri86], that solves almost all instances of "low-density" subset-sum problems.

**Definition 3.1.** The *density* of a subset-sum instance is  $n / \max_i \log a_i$ .

**Theorem 3.2 (Lagarias-Odlyzko, Frieze).** *There is an efficient algorithm that, given uniformly random and independent weights  $a_1, \dots, a_n \in \{1, \dots, X\}$ , where  $X \geq 2^{n^{2(1/2+\epsilon)}}$  for some arbitrary constant  $\epsilon > 0$ , and  $s = \langle \mathbf{a}, \mathbf{x} \rangle$  for some arbitrary  $\mathbf{x} \in \{0, 1\}^n$ , outputs  $\mathbf{x}$  with probability  $1 - 2^{-n^{2(\epsilon-o(1))}}$  over the choice of the  $a_i$ .*

Notice that the density of the above subset-sum instances is roughly  $2/n$ .

*Proof.* We are given a subset-sum instance  $(\mathbf{a} = (a_1, \dots, a_n), s = \langle \mathbf{a}, \mathbf{x} \rangle)$  for some  $\mathbf{x} \in \{0, 1\}^n$ . Without loss of generality, we may assume that  $s \geq (\sum_i a_i)/2$ : if not, we replace  $s$  by  $(\sum_{i=1}^n a_i) - s$ , which corresponds to flipping all the bits of  $\mathbf{x}$ . Note that this assumption implies that  $\mathbf{x} \neq \mathbf{0}$ .

The main idea is to define a lattice where not only is  $\mathbf{x}$  a shortest nonzero lattice vector, but all lattice vectors not parallel to  $\mathbf{x}$  are much longer, by a factor of  $2^{n/2}$  or more. Then because LLL gives a  $2^{n/2}$ -factor approximation to the shortest lattice vector, it must yield  $\mathbf{x}$ .

Let  $B = \lceil \sqrt{n \cdot 2^n} \rceil$ , and define the lattice  $\mathcal{L} = \mathcal{L}(\mathbf{B})$  using the basis

$$\mathbf{B} = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & \ddots & & \\ & & & 1 & \\ Ba_1 & Ba_2 & \dots & Ba_n & -Bs \end{pmatrix} \in \mathbb{Z}^{(n+1) \times (n+1)}.$$

Clearly,  $\begin{pmatrix} \mathbf{x} \\ 0 \end{pmatrix} \in \mathcal{L}$ . As we will see in a moment, the  $B$  factor in the last row serves to amplify the norms of lattice vectors that do not correspond to *exact* equalities  $\langle \mathbf{a}, \mathbf{z} \rangle = z_{n+1}s$  for integral  $\mathbf{z}, z_{n+1}$ .

The algorithm simply runs LLL on the above basis  $\mathbf{B}$  to obtain a nonzero lattice vector whose length is within a  $2^{n/2}$  factor of  $\lambda_1(\mathcal{L})$ . The following analysis shows that with high probability, the obtained vector is of the form  $k \begin{pmatrix} \mathbf{x} \\ 0 \end{pmatrix}$  for some nonzero integer  $k$ , which reveals the solution  $\mathbf{x} \in \{0, 1\}^n$ .

Notice that  $\mathbf{B} \begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix} = \begin{pmatrix} \mathbf{x} \\ 0 \end{pmatrix} \in \mathcal{L}$  is a nonzero lattice vector, and has norm at most  $\sqrt{n}$ . Also, any lattice vector has a final coordinate divisible by  $B$ , and if this coordinate is nonzero, then the vector has length at least  $B > 2^{n/2} \cdot \|\mathbf{x}\| \geq 2^{n/2} \cdot \lambda_1(\mathcal{L})$ . Therefore, LLL always yields some nonzero lattice vector whose final coordinate is zero, and whose norm is at most  $2^{n/2} \sqrt{n}$ . We next show that with high probability, nonzero integer multiples of  $\begin{pmatrix} \mathbf{x} \\ 0 \end{pmatrix}$  are the *only* such lattice vectors; therefore, LLL must return one of these.

Fix an arbitrary nonzero vector  $\begin{pmatrix} \mathbf{z} \\ 0 \end{pmatrix} \in \mathbb{Z}^{n+1}$ , where  $\|\mathbf{z}\| \leq 2^{n/2} \sqrt{n}$  and  $\mathbf{z}$  is not an integer multiple of  $\mathbf{x}$ . We want to bound the probability that this vector is in  $\mathcal{L}$ , i.e., that  $\begin{pmatrix} \mathbf{z} \\ 0 \end{pmatrix} = \mathbf{B} \begin{pmatrix} \mathbf{z} \\ z_{n+1} \end{pmatrix}$  for some  $z_{n+1} \in \mathbb{Z}$ . In such an event, we have

$$s \cdot |z_{n+1}| = |s \cdot z_{n+1}| = |\langle \mathbf{a}, \mathbf{z} \rangle| \leq \|\mathbf{z}\| \sum_{i=1}^n a_i \leq 2\|\mathbf{z}\|s,$$

so  $|z_{n+1}| \leq 2\|\mathbf{z}\|$ . Fix any such  $z_{n+1}$ . In order for  $\begin{pmatrix} \mathbf{z} \\ 0 \end{pmatrix}$  to be in  $\mathcal{L}$ , it must be the case that

$$\langle \mathbf{a}, \mathbf{z} \rangle = z_{n+1} \cdot s = z_{n+1} \langle \mathbf{a}, \mathbf{x} \rangle,$$

which implies that  $\langle \mathbf{a}, \mathbf{y} \rangle = 0$  where  $\mathbf{y} = \mathbf{z} - z_{n+1}\mathbf{x}$ . Since  $\mathbf{z}$  is not an integer multiple of  $\mathbf{x}$ , some  $y_i \neq 0$ , and we can assume that without loss of generality that  $i = 1$ . Therefore, we must have  $a_1 = -(\sum_{i=2}^n a_i y_i) / y_1$ .

With these observations, for any fixed  $\mathbf{z}, z_{n+1}$  satisfying the above constraints, the probability that  $\begin{pmatrix} \mathbf{z} \\ 0 \end{pmatrix} \in \mathcal{L}$  is bounded by

$$\Pr_{\mathbf{a}}[\langle \mathbf{a}, \mathbf{y} \rangle = 0] = \Pr_{a_1} \left[ a_1 = - \left( \sum_{i=2}^n a_i y_i \right) / y_1 \right] \leq 1/X,$$

because the  $a_i$  are chosen uniformly from  $\{1, \dots, X\}$ .

Finally, we apply the union bound over all relevant choices of  $\mathbf{z}, z_{n+1}$ . Because  $\|\mathbf{z}\| \leq 2^{n/2} \sqrt{n} \leq B$ , each coordinate of  $\mathbf{z}$  has magnitude at most  $B$ , and similarly,  $|z_{n+1}| \leq 2\|\mathbf{z}\| \leq 2B$ . Therefore, the number of choices for  $\mathbf{z}, z_{n+1}$  is (crudely) upper bounded by

$$(2B + 1)^n \cdot (4B + 1) \leq (5B)^{n+1} \leq 2^{n^2(1/2+o(1))}.$$

Because  $X = 2^{n^2(1/2+\epsilon)}$  for some constant  $\epsilon > 0$ , the probability that there exists any  $\begin{pmatrix} \mathbf{z} \\ 0 \end{pmatrix} \in \mathcal{L}$  satisfying the above constraints is at most  $2^{-n^2(\epsilon-o(1))}$ , as claimed.  $\square$

**Variants.** We have shown that, except for integer multiples of  $\begin{pmatrix} x \\ 0 \end{pmatrix}$ , no lattice vector has length less than  $2^{n/2}\sqrt{n}$  (with high probability). So, LLL’s approximation factor of  $2^{n/2}$  guarantees that it returns  $k\begin{pmatrix} x \\ 0 \end{pmatrix}$  for some nonzero integer  $k$ . Inspecting the analysis, the  $2^{n/2}$  approximation factor corresponds to the density bound of  $2/n$ . More generally, for an approximation factor  $\gamma$ , to dispense with lattice vectors having a nonzero final coordinate we set  $B \approx \gamma$ , so the union bound is taken over  $\approx B^n$  vectors, so we set  $X \approx B^n$ , giving a density of  $n/\log X \approx 1/\log B \approx 1/\log \gamma$ .

What if we had an algorithm that achieves a better approximation factor, e.g., one that solves SVP *exactly*, or to within a  $\text{poly}(n)$  factor? For a density of about  $1/1.6$ , following the same kind of argument, but with tighter bounds on the number of allowed  $\mathbf{z}$ , one can show that  $\pm\begin{pmatrix} x \\ 0 \end{pmatrix}$  are the *only* shortest vectors in the lattice (with high probability). Similarly, for density  $1/\Theta(\log n)$ , one can show that all lattice vectors not parallel to  $\begin{pmatrix} x \\ 0 \end{pmatrix}$  are some  $\text{poly}(n)$  factor longer than it. However, at densities above  $2/3$  or so,  $\begin{pmatrix} x \\ 0 \end{pmatrix}$  may no longer be a shortest nonzero vector in the lattice, so even an exact-SVP oracle might not reveal a subset-sum solution.

## References

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