Lecture 10: Shamir Secret Sharing (Lagrange Interpolation)

Recall: Goal

We want to

- Share a secret $s \in \mathbb{Z}_p$ to n parties, such that $\{1, \ldots, n\} \subseteq \mathbb{Z}_p$,
- Any two parties can reconstruct the secret s, and
- No party alone can predict the secret s

Recall: Secret Sharing Algorithm

SecretShare(s, n)

- Pick a random line $\ell(X)$ that passes through the point $(0, s)$
  - This is done by picking a_1 uniformly at random from the set $\mathbb{Z}_p$
  - And defining the polynomial $\ell(X) = a_1 X + s$
- Evaluate $s_1 = \ell(X = 1)$, $s_2 = \ell(X = 2)$, $\dots$, $s_n = \ell(X = n)$
- Secret shares for party 1, party 2, $\dots$, party n are s_1, s_2, $\dots$, s_n, respectively

Recall: Reconstruction Algorithm

SecretReconstruct$(i_1, s^{(1)}, i_2, s^{(2)})$

Reconstruct the line $\ell'(X)$ that passes through the points $(i_1, s^{(1)})$ and $(i_2, s^{(2)})$

We will learn a new technique to perform this step, referred to as the Lagrange Interpolation

Define the reconstructed secret $s' = \ell'(0)$

General Goal

We want to

- Share a secret $s \in \mathbb{Z}_p$ to n parties, such that $\{1, \ldots, n\} \subseteq \mathbb{Z}_p$,
- Any t parties can reconstruct the secret s, and
- Less than t parties cannot predict the secret s

Shamir's Secret Sharing Algorithm

SecretShare(s, n)

Pick a polynomial $p(X)$ of degree $\leqslant (t-1)$ that passes through the point $(0, s)$

This is done by picking $a_1, \dots, a_{t-1}$ independently and uniformly at random from the set $\mathbb{Z}_p$

And defining the polynomial

$\ell(X) = a_{t-1}X^{t-1} + a_{t-2}X^{t-2} + \dots a_1 X + s$

Evaluate $s_1 = p(X=1)$, $s_2 = p(X=2)$, $\dots$, $s_n = p(X=n)$

Secret shares for party 1, party 2, $\dots$, party n are s_1, s_2, $\dots$, s_n, respectively

Shamir's Reconstruction Algorithm

SecretReconstruct$(i_1, s^{(1)}, i_2, s^{(2)}, \ldots, i_t, s^{(t)})$

Use Lagrange Interpolation to construct a polynomial $p'(X)$ that passes through $(i_1, s^{(1)})$, $\ldots$, $(i_t, {}^{(t)})$ (we describe this algorithm in the following slides)

Define the reconstructed secret $s' = p'(0)$

Lagrange Interpolation: Introduction I

Consider the example we were considering in the previous lecture

The secret was $s = 3$

Secret shares of party 1, 2, 3, and 4, were 0, 2, 4, and 1, respectively

Suppose party 2 and party 3 are trying to reconstruct the secret

- Party 2 has secret share 2, and
- Party 3 has secret share 4

We are interested in finding the line that passes through the points $(2, 2)$ and $(3, 4)$

Subproblem 1:

- Let us find the line that passes through $(2, 2)$ and $(3, 0)$
  - Note that at $X = 3$ this line evaluates to 0, so $X = 3$ is a root of the line
  - So, the line has the equation $\ell_1(X) = c \cdot (X - 3)$, where c is a suitable constant
  - Now, we find the value of c such that $\ell_1(X)$ passes through the point $(2, 2)$
  - So, we should have $c \cdot (2 - 3) = 2$, i.e., $c = 3$
- $\ell_1(X) = 3 \cdot (X - 3)$ is the equation of that line

Subproblem 2:

Let us find the line that passes through $(2, 0)$ and $(3, 4)$

Note that at $X = 2$ this line evaluates to 0, so $X = 2$ is a root of the line

So, the line has the equality $\ell_2(X) = c \cdot (X - 2)$, where c is a suitable constant

Now, we find the value of c such that $\ell_2(X)$ passes through the point $(3, 4)$

So, we should have $c \cdot (3 - 2) = 4$, i.e. $c = 4$

$\ell_2(X) = 4 \cdot (X - 2)$

Lagrange Interpolation: Introduction IV

Putting Things Together:

Define $\ell'(X) = \ell_1(X) + \ell_2(X)$

That is, we have

$$\ell'(X) = 3 \cdot (X - 3) + 4 \cdot (X - 2)$$

Evaluation of $\ell'(X)$ at $X = 0$ is

$$s' = \ell'(X = 0) = 3 \cdot (-3) + 4 \cdot (-2) = 3 \cdot 2 + 4 \cdot 3 = 1 + 2 = 3$$

Uniqueness of Polynomial I

We shall prove the following result

Theorem

There is a unique polynomial of degree at most d that passes through (x_1, y_1), (x_2, y_2), $\ldots$, (x_{d+1}, y_{d+1})

If possible, let there exist two distinct polynomials of degree $\leqslant d$ such that they pass through the points (x_1, y_1), (x_2, y_2), $\ldots$, (x_{d+1}, y_{d+1})

Let the first polynomial be:

$$p(X) = a_d X^d + a_{d-1} X^{d-1} + \cdots + a_1 X + a_0$$

Let the second polynomial be:

$$p'(X) = a'_d X^d + a'_{d-1} X^{d-1} + \cdots + a'_1 X + a'_0$$

Uniqueness of Polynomial II

Let $p^*(X)$ be the polynomial that is the difference of the polynomials $p(X)$ and $p'(X)$, i.e.,

$$p^*(X) = p(X) - p'(X) = (a_d - a'_d)X^d + \dots (a_1 - a'_1)X + (a_0 - a'_0)$$

Observation. The degree of $p^*(X)$ is $\leqslant d$

Uniqueness of Polynomial III

For $i \in \{1, \ldots, d+1\}$, note that at $X = x_i$ both $p(X)$ and $p'(X)$ evaluate to y_i

So, the polynomial $p^*(X)$ at $X = x_i$ evaluates to $y_i - y_i = 0$, i.e. x_i is a root of the polynomial $p^*(X)$

Observation. The polynomial $p^*(X)$ has roots $X = x_1$, $X = x_2$, ..., $X = x_{d+1}$

We will use the following result

Theorem (Schwartz–Zippel, Intuitive)

A non-zero polynomial of degree d has at most d roots (over any field)

Conclusion.

Based on the two observations above, we have a $\leqslant d$ degree polynomial $p^*(X)$ that has at least $(d+1)$ distinct roots $x_1, \dots, x_{d+1}$
This implies, by Schwartz–Zippel Lemma, that the polynomial is the zero-polynomial.
That is, $p^*(X) = 0$.
This implies that $p(X)$ and $p'(X)$ are identical
This contradicts the initial assumption that there are two distinct polynomials $p(X)$ and $p'(X)$

The proof in the previous slides proves that

Given a set of points (x_1, y_1) , ..., (x_{d+1}, y_{d+1})

There is a unique polynomial of degree at most d that passes through all of them!

Lagrange Interpolation I

Suppose we are interested in constructing a polynomial of degree $\leqslant d$ that passes through the points (x_1, y_1), ..., (x_{d+1}, y_{d+1})

Subproblem i:

We want to construct a polynomial $p_i(X)$ of degree $\leqslant d$ that passes through (x_i, y_i) and $(x_j, 0)$, where $j \neq i$

So, $\{x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_{d+1}\}$ are roots of the polynomial $p_i(X)$

Therefore, the polynomial $p_i(X)$ looks as follows

$$p_i(X) = c \cdot (X - x_1) \cdots (X - x_{i-1})(X - x_{i+1}) \cdots (X - x_{d+1})$$

Tersely, we will write this as

$$p_i(X) = c \cdot \prod_{\substack{j \in \{1,\dots,d+1\} \\ \text{such that } j \neq i}} (X - x_j)$$

Lagrange Interpolation III

Now, to evaluate c we will use the property that
$p_i(x_i) = y_i$
Observe that the following value of c suffices

$$c = \frac{y_i}{\prod_{\substack{j \in \{1,\dots,d+1\} \\ \text{such that } j \neq i}} (x_i - x_j)}$$

So, the polynomial $p_i(X)$ that passes through (x_i, y_i) and $(x_j, 0)$, where $j \neq i$ is

$$p_i(X) = \frac{y_i}{\prod_{\substack{j \in \{1,\dots,d+1\} \\ \text{such that } j \neq i}} (x_i - x_j)} \cdot \prod_{\substack{j \in \{1,\dots,d+1\} \\ \text{such that } j \neq i}} (X - x_j)$$

Observe that $p_i(X)$ has degree d

Lagrange Interpolation IV

Putting Things Together:

Consider the polynomial

$$p(X) = p_1(X) + p_2(X) + \ldots + p_{d+1}(X)$$

This is the desired polynomial that passes through (x_i, y_i)

Claim

The polynomial $p(X)$ passes through (x_i, y_i), for $i \in \{1, \ldots, d+1\}$

Lagrange Interpolation V

Proof.

Note that, for $j \in \{1, \ldots, d+1\}$, we have

$$p_j(x_i) = \begin{cases} y_i, & \text{if } j = i \\ 0, & \text{otherwise} \end{cases}$$

Therefore, $p(x_i) = \sum_{j=1}^{d+1} p_j(x_i) = y_i$

□

Summary of Interpolation

Given points (x_1, y_1), ..., (x_{d+1}, y_{d+1})

Lagrange Interpolation provides <u>one</u> polynomial of degree $\leqslant d$ polynomial that passes through all of them

Theorem 1 states that this $\leqslant d$ degree polynomial is unique

Example for Lagrange Interpolation I

Let us find a degree $\leqslant 2$ polynomial that passes through the points (x_1, y_1), (x_2, y_2), and (x_3, y_3)

Subproblem 1:

We want to find a degree $\leqslant 2$ polynomial that passes through the points (x_1, y_1), $(x_2, 0)$, and $(x_3, 0)$
The polynomial is

$$p_1(X) = \frac{y_1}{(x_1 - x_2)(x_1 - x_3)}(X - x_2)(X - x_3)$$

Example for Lagrange Interpolation II

Subproblem 2:

We want to find a degree $\leqslant 2$ polynomial that passes through the points $(x_1, 0)$, (x_2, y_2), and $(x_3, 0)$.
The polynomial is

$$p_2(X) = \frac{y_2}{(x_2 - x_1)(x_2 - x_3)}(X - x_1)(X - x_3)$$

Subproblem 3:

We want to find a degree $\leqslant 2$ polynomial that passes through the points $(x_1, 0)$, $(x_2, 0)$, and (x_3, y_3).
The polynomial is

$$p_2(X) = \frac{y_3}{(x_3 - x_1)(x_3 - x_2)}(X - x_1)(X - x_2)$$

Example for Lagrange Interpolation III

Putting Things Together: The reconstructed polynomial is

$$p(X) = p_1(X) + p_2(X) + p_3(X)$$

Conclusion

This completes the description of Shamir's secret-sharing algorithm. In the following lectures, we will argue its security.