Lecture 09: 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 $s_1 = p(X=1)$, $s_2 = p(X=2)$, ..., $s_n = p(X=n)$
- Secret shares for party 1, party 2, ..., party n are s_1, s_2, ..., s_n, respectively

Shamir's Reconstruction Algorithm

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

- Use Lagrange Interpolation to construct a polynomial $p'(X)$ that passes through $(i_1, s^{(1)})$, …, $(i_t, ^{(t)})$ (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 $(3, 4)$

Lagrange Interpolation: Introduction II

- 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

Lagrange Interpolation: Introduction III

- 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), $\dots$, (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), $\dots$, (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 $X = x_1$, $X = x_2$, ..., $X = x_{d+1}$

Uniqueness of Polynomial IV

- 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 $p'(X)$

Summary

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})

Lagrange Interpolation II

- **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

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

- 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 $i \in \{1, \ldots, d+1\}$

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

$\square$

Summary of Interpolation

- Given points $(x_1, y_1), \ldots, (x_{d+1}, y_{d+1})$
- 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.