Sigma Protocols

Distributed Lab

September 3, 2024

Plan

Introduction

Recap on Interactive Proofs

- **Interactive proofs** allows practically prover $\mathcal{P}$ to convince the verifier $\mathcal{V}$ that some statement is true.
- **Soundness** ensures that the prover cannot cheat the verifier, while **zero-knowledge** that the verifier learns nothing about the witness.
- **Argument of knowledge** ensures that the prover also "knows" the witness (that is, exists some extractor $\mathcal{E}$ that, acting as an admin, can extract the witness).
- If verifier's messages are random values, the protocol is **public-coin**.
- Any public-coin protocol can be transformed into a **non-interactive** proof using **Fiat-Shamir heuristic**.

Announcement

Today, we will build and code our first non-interactive proof system using the Fiat-Shamir heuristic based on **Sigma protocols**!

Motivation

In many cases, we need to prove relatively trivial statements without revealing the witness:

- "I know the discrete log of a point $P \in E(\mathbb{F}_p)$".
- "I know the representation of a point $P \in E(\mathbb{F}_p)$, that is $(\alpha, \beta) \in \mathbb{Z}_q^2$ such that $P = [\alpha]G + [\beta]H$".
- "I know the eth modular root w of $x \in \mathbb{Z}_N^{\times}$ (that is, $w^e = x$)". For $e = 2$, see previous lecture.
- "I know that $(P, Q, R) \in E(\mathbb{F}_p)^3$ is a Diffie-Hellman triplet".

Σ-protocols are also fundamentally similar to Bulletproofs!

Note

Everything that has a natural "homomorphic"/discrete-log-like structure can be proven using Sigma (Σ) protocols!

Schnorr Identification Protocol

Problem Statement

Suppose $\mathbb{G}$ is a cyclic group of order q with a generator g. Then, the relation and language being considered are:

$$\mathcal{R} = \{(u, \alpha) \in \mathbb{G} \times \mathbb{Z}_q : u = g^\alpha\}, \; \mathcal{L}_\mathcal{R} = \{u \in \mathbb{G} : \exists \alpha \in \mathbb{Z}_q : u = g^\alpha\}$$

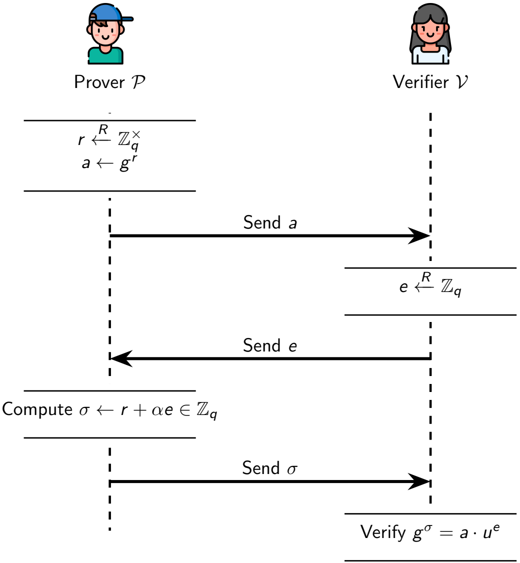
Problem #1

$\mathcal{P}$ wants to convince $\mathcal{V}$ that it knows the discrete log of $u \in \mathcal{L}_\mathcal{R}$. That is, he knows α such that $(u, \alpha) \in \mathcal{R}$.

Problem #2

Why cannot we simply send α? Because we do not want to reveal the witness! That is why we need a zero-knowledge non-interactive argument of knowledge (zk-NARK).

Protocol Flow



Protocol Flow

Definition

The Schnorr interactive identification protocol $\Pi_{\mathsf{Sch}} = (\mathsf{Gen}, \mathcal{P}, \mathcal{V})$ with a generation function Gen and prover $\mathcal{P}$ and verifier $\mathcal{V}$ is defined as:

- $\mathsf{Gen}(1^\lambda)$: Take $\alpha \xleftarrow{R} \mathbb{Z}_q$ and $u \leftarrow g^\alpha$. **Output:** *verification key* $\mathsf{vk} := u$, and *secret key* $\mathsf{sk} := \alpha$.
- The protocol between $(\mathcal{P}, \mathcal{V})$ is run as follows:
  - $\mathcal{P}$ computes $r \leftarrow \mathbb{Z}_q^\times, a \leftarrow g^r$ and sends a to $\mathcal{V}$.
  - $\mathcal{V}$ sends a random challenge $e \xleftarrow{R} \mathbb{Z}_q$ to $\mathcal{P}$.
  - $\mathcal{P}$ computes $\sigma \leftarrow r + \alpha e \in \mathbb{Z}_q$ and sends σ to $\mathcal{V}$.
  - $\mathcal{V}$ accepts if $g^\sigma = a \cdot u^e$, otherwise it rejects.

Question

$\mathcal{V}$ only sends a random scalar to $\mathcal{P}$. How to turn this into a non-interactive proof?

Applying Fiat-Shamir Transformation

Reminder

Suppose prover had messages $(m_1, m_2, \dots, m_n)$ before verifier sends a challenge c. If x is a public statement, it suffices to choose $c \leftarrow H(x, m_1, \dots, m_n)$ without any interaction.

Definition (The Schnorr non-interactive identification protocol)

Define $\Gamma_{\text{Sch}} := (\text{Gen}, \text{Prove}, \text{Verify})$:

- $\text{Gen}(1^\lambda)$: **Output** $\alpha \xleftarrow{R} \mathbb{Z}_q$ and $u \leftarrow g^\alpha$.
- Prove: on input (u, α) do:
  - Compute $r \leftarrow \mathbb{Z}_q^\times, a \leftarrow g^r$.
  - Compute challenge $e \leftarrow H(u, a)$.
  - Computes $\sigma \leftarrow r + \alpha e$. Output (a, σ).
- Verify: accept iff $g^\sigma = a \cdot u^e$.

Schnorr's Signature Scheme

It easy to turn the non-interactive identification protocol into a signature scheme! Simply regard (u, m) as a public statement with a message m!

Definition

The Schnorr Signature Scheme is $\Sigma_{\mathsf{Sch}} = (\mathsf{Gen}, \mathsf{Sign}, \mathsf{Verify})$, where:

- $\mathsf{Gen}(1^\lambda)$: **Output** $\alpha \xleftarrow{R} \mathbb{Z}_q$ and $u \leftarrow g^\alpha$.
- $\mathsf{Sign}(m, \mathsf{sk})$: The signer computes $r \leftarrow \mathbb{Z}_q^\times, a \leftarrow g^r, e \leftarrow H(u, m, a), \sigma \leftarrow r + \alpha e$ and outputs (a, σ).
- $\mathsf{Verify}((a, \sigma), m, \mathsf{pk})$: The verifier checks if $g^\sigma = a \cdot u^e$ for $e \leftarrow H(u, m, a)$.

Note: In **green** we marked the only difference between the identification and signature protocols.

Sigma Protocols

Generalization

Now, can we generalize the Schnorr protocol to any relation $\mathcal{R}$?
Well, not for any, but for a large class of relations called **Sigma protocols**!

Definition

Let $\mathcal{R} \subset \mathcal{X} \times \mathcal{W}$ be an effective relation. A **Sigma protocol** for $\mathcal{R}$ is an interactive protocol $(\mathcal{P}, \mathcal{V})$ that satisfies the following properties:

- In the beginning, $\mathcal{P}$ computes a **commitment** a and sends it to $\mathcal{V}$.
- $\mathcal{V}$ chooses a random **challenge** $c \in \mathcal{C}$ from the challenge space $\mathcal{C}$ and sends it to $\mathcal{P}$.
- Upon receiving c, $\mathcal{P}$ computes the response z and sends it to $\mathcal{V}$.
- $\mathcal{V}$ outputs either accept or reject based on the **conversation** (a, c, z).

Definition

(a, c, z) is an **accepting conversation** if $\mathcal{V}$ outputs accept on this tuple.

Why Σ?

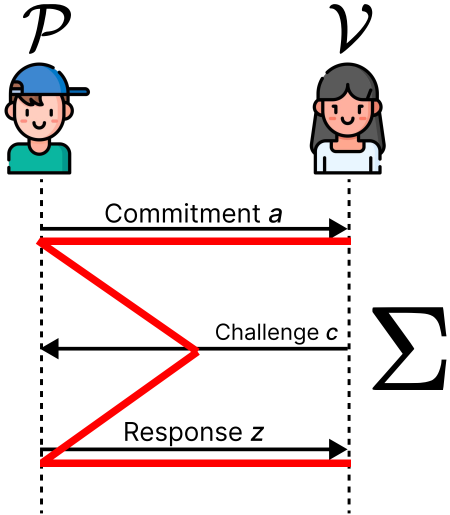


Figure: Why Σ-protocols are called so.

Special Soundness

Definition (Special Soundness)

Let $(\mathcal{P}, \mathcal{V})$ be a Σ-protocol for $\mathcal{R} \subseteq \mathcal{X} \times \mathcal{Y}$. We that that $(\mathcal{P}, \mathcal{V})$ is **special sound** if there exists a witness extractor $\mathcal{E}$ such that, given statement $x \in \mathcal{X}$ and two accepting conversations (a, c, z) and (a, c', z') (where $c \neq c'$)[a], the extractor can always efficiently compute the witness w such that $(x, w) \in \mathcal{R}$.

[a] Notice that initial commitments in both conversations are the same!

Example

The Schnorr protocol is special sound because, given two accepting conversations (a, e, σ) and (a, e', σ'), we can compute the witness α. You can verify that $\alpha = \Delta\sigma/\Delta e$ for $\Delta\sigma = \sigma' - \sigma$ and $\Delta e = e' - e$ suffices.

Sigma Protocols Examples

Okamoto's Protocol

Again, let $\mathbb{G}$ be a cyclic group of prime order q with a generator $g \in \mathbb{G}$ and let $h \in \mathbb{G}$ an arbitrary group element.

Definition

For $u \in \mathbb{G}$, a **representation** relative to g and h is a pair $(\alpha, \beta) \in \mathbb{Z}_q \times \mathbb{Z}_q$ such that $u = g^\alpha h^\beta$.

Remark

Notice that for the given u there are exactly q representations relative to g and h. Indeed, $\forall \beta \in \mathbb{Z}_q \, \exists! \alpha \in \mathbb{Z}_q : g^\alpha = uh^{-\beta}$.

Question

How do we actually prove that $\mathcal{P}$ knows the representation of u?

$$\mathcal{R} = \left\{(u, (\alpha, \beta)) \in \mathbb{G} \times \mathbb{Z}_q^2 : u = g^\alpha h^\beta\right\}$$

Okamoto's Protocol Flow

Definition (Okamoto's Identification Protocol)

Okamoto's Protocol consists of two algorithms: $(\mathcal{P}, \mathcal{V})$, where the prover is assumed to know $(u, (\alpha, \beta)) \in \mathcal{R}$ defined above. The protocol is defined as follows:

1. $\mathcal{P}$ computes $\alpha_r \xleftarrow{R} \mathbb{Z}_q,\ \beta_r \xleftarrow{R} \mathbb{Z}_q,\ u_r \leftarrow g^{\alpha_r} h^{\beta_r}$ and sends commitment u_r to $\mathcal{V}$.
2. $\mathcal{V}$ samples the challenge $c \xleftarrow{R} \mathbb{Z}_q$ and sends c to $\mathcal{P}$.
3. $\mathcal{P}$ computes $\alpha_z \leftarrow \alpha_r + \alpha c, \beta_z \leftarrow \beta_r + \beta c$ and sends $\mathbf{z} = (\alpha_z, \beta_z)$.
4. $\mathcal{V}$ checks whether $g^{\alpha_z} h^{\beta_z} = u_r u^c$ and accepts or rejects the proof.

Announcement

We will code the non-interactive Okamoto's protocol in the next section! Stay tuned!

Okamoto's Protocol Correctness

Theorem

Okamoto's Protocol is a Σ-protocol for the relation $\mathcal{R}$ which is Honest-Verifier Zero-Knowledge (HVZK).

Part of the proof. Again, let us show *correctness* and *special soundness* without honest-verifier zero-knowledge properties.

Completeness. Suppose indeed that $(u, (\alpha, \beta)) \in \mathcal{R}$. Then, the verification condition can be written as follows:

$$g^{\alpha_z} h^{\beta_z} = g^{\alpha_r + \alpha c} h^{\beta_r + \beta c} = g^{\alpha_r} g^{\alpha c} h^{\beta_r} h^{\beta c} = \underbrace{(g^{\alpha_r} h^{\beta_r})}_{=u_r} \cdot (\underbrace{g^{\alpha} h^{\beta}}_{=u})^c = u_r u^c$$

Okamoto's Protocol Special Soundness

Special Soundness. Suppose we are given two accepting conversations: $(u_r, c, (\alpha_z, \beta_z))$ and $(u_r, c', (\alpha'_z, \beta'_z))$ and we want to construct an extractor $\mathcal{E}$ which would give us a witness (α, β). In this case, we have the following holding:

$$g^{\alpha_z} h^{\beta_z} = u_r u^c, \; g^{\alpha'_z} h^{\beta'_z} = u_r u^{c'}$$

We can divide the former by the latter to obtain:

$$g^{\alpha_z - \alpha'_z} h^{\beta_z - \beta'_z} = u^{c-c'} = g^{\alpha(c-c')} h^{\beta(c-c')},$$

from which the extractor $\mathcal{E}$ can efficiently compute witness as follows: $\alpha \leftarrow (\alpha_z - \alpha'_z)/(c - c')$ and $\beta \leftarrow (\beta_z - \beta'_z)/(c - c')$.

Diffie-Hellman Triplets

Suppose we are given the cyclic group $\mathbb{G}$ or prime order q and generator $g \in \mathbb{G}$.

Definition

A triplet $(u, v, w) \in \mathbb{G}^3$ is a **Diffie-Hellman triplet** if $\exists \alpha, \beta \in \mathbb{Z}_q : u = g^\alpha, v = g^\beta, w = g^{\alpha\beta}$.

Alternative DH-triple Definition

(u, v, w) is a DH-triplet iff $\exists \beta \in \mathbb{Z}_q : v = g^\beta, w = u^\beta$.

Now, this makes it easier to define the relation $\mathcal{R}$ for the Chaum-Pedersen protocol:

$$\mathcal{R} = \left\{((u, v, w), \beta) \in \mathbb{G}^3 \times \mathbb{Z}_q : v = g^\beta \wedge w = u^\beta\right\}$$

Chaum-Pedersen Protocol

Definition (Chaum-Pedersen Protocol)

Chaum-Pedersen Protocol consists of two algorithms: $(\mathcal{P}, \mathcal{V})$, where the prover is assumed to know $(\beta, (u, v, w)) \in \mathcal{R}$ defined above. The protocol is defined as follows:

1. $\mathcal{P}$ computes $\beta_r \xleftarrow{R} \mathbb{Z}_q,\ v_r \xleftarrow{R} g^{\beta_r},\ w_r \leftarrow u^{\beta_r}$ and sends (u_r, w_r) to $\mathcal{V}$.
2. $\mathcal{V}$ samples the challenge $c \xleftarrow{R} \mathbb{Z}_q$ and sends c to $\mathcal{P}$.
3. $\mathcal{P}$ computes $\beta_z \leftarrow \beta_r + \beta c$ and sends β_z to $\mathcal{V}$.
4. $\mathcal{V}$ checks whether two conditions hold: $g^{\beta_z} = v_r v^c$ and $u^{\beta_z} = w_r w^c$, and accepts or rejects the proof accordingly.

Theorem

Chaum-Pedersen Protocol is a Σ-protocol for the relation $\mathcal{R}$ which is Honest-Verifier Zero-Knowledge (HVZK).

Homomorphism

Let us formulate the core objects that we will use in this section:

- $(\mathbb{H}, +)$ is a finite abelian input group.
- $(\mathbb{T}, \times)$ is a finite abelian output group.
- $\psi : \mathbb{H} \to \mathbb{T}$ is a hard-to-invert homomorphism.
- $\mathcal{F} = \mathrm{Hom}(\mathbb{H}, \mathbb{T})$ is a set of all homomorphisms from $\mathbb{H}$ to $\mathbb{T}$.

Reminder

Homomorphism $\psi : \mathbb{H} \to \mathbb{T}$ is a function, satisfying the following property:

$$\forall h_1, h_2 \in \mathbb{H} : \psi(h_1 + h_2) = \psi(h_1)\psi(h_2)$$

Note

If between input and output we have an easy-to-compute and hard-to-invert homomorphism, we can use Sigma protocols to prove pre-images of this homomorphism!

Problem Statement

Define the following relation:

$$\mathcal{R} = \{((t, \psi), h) \in (\mathbb{T} \times \mathcal{F}) \times \mathbb{H} : \psi(h) = t\}$$

$\mathcal{P}$ wants to convince $\mathcal{V}$ that he knows witness h to the statement (t, ψ).

Example

Now, why does this generalize the previous protocols? Well, let us consider all previous examples:

- **Schnorr Protocol:** Here we have $\mathbb{H} = \mathbb{Z}_q$, $\mathbb{T} = \mathbb{G}$, and $\psi : \mathbb{Z}_q \to \mathbb{G}$ is defined as $\psi(\alpha) = g^\alpha$. Moreover, here ψ is an isomorphism!
- **Okamoto Protocol:** Here we have $\mathbb{H} = \mathbb{Z}_q^2$, $\mathbb{T} = \mathbb{G}$, and $\psi : \mathbb{Z}_q^2 \to \mathbb{G}$ is defined as $\psi(\alpha, \beta) = g^\alpha h^\beta$.
- **Chaum-Pedersen Protocol:** Here we have $\mathbb{H} = \mathbb{Z}_q$, $\mathbb{T} = \mathbb{G}^2$, and $\psi : \mathbb{Z}_q \to \mathbb{G}^2$ is defined as $\psi(\beta) = (g^\beta, u^\beta)$.

Sigma Protocol

Definition (Sigma Protocol for the pre-image of a homomorphism)

The protocol consists of two algorithms: $(\mathcal{P}, \mathcal{V})$, where the prover is assumed to know the witness $h \in \mathbb{H}$ defined above. The protocol is defined as follows:

1. $\mathcal{P}$ computes $h_r \xleftarrow{R} \mathbb{H}$, $t_r \leftarrow \psi(h_r) \in \mathbb{T}$ and sends t_r to the verifier $\mathcal{V}$.
2. $\mathcal{V}$ samples the challenge $c \xleftarrow{R} \mathcal{C} \subset \mathbb{Z}$ from the challenge space and sends c to $\mathcal{P}$.
3. $\mathcal{P}$ computes $h_z \leftarrow h_r + h \cdot c$ and sends h_z to $\mathcal{V}$.
4. $\mathcal{V}$ checks whether $\psi(h_z) = t_r t^c$, and accepts or rejects the proof.

Theorem

Such protocol is a Σ-protocol for the relation $\mathcal{R}$ which is Honest-Verifier Zero-Knowledge (HVZK).

Combining Σ-Protocols

One of the features (which we are not going to delve into) is the ability to combine Σ-protocols to prove more complex statements. Namely,

- Given two relations $\mathcal{R}_0$ and $\mathcal{R}_1$, we can prove that the prover knows witnesses for both relations.
- Given two relations $\mathcal{R}_0$ and $\mathcal{R}_1$, we can prove that the prover knows a witness for at least one of the relations.

Example

$\mathcal{P}$ can prove that he either knows the discrete log of u or the representation of u relative to g and h. Moreover, $\mathcal{V}$ does not know which of the two statements $\mathcal{P}$ is proving.

Coding Time!

Methodology

Reminder

Suppose prover had messages $(m_1, m_2, \ldots, m_n)$ before verifier sends a challenge c. If x is a public statement, it suffices to choose $c \leftarrow H(x, m_1, \ldots, m_n)$ without any interaction.

Let us turn **Okamoto's Protocol** into a non-interactive proof using the Fiat-Shamir heuristic!

Reminder: Okamoto's Identification Protocol

1. $\mathcal{P}$ computes $\alpha_r \xleftarrow{R} \mathbb{Z}_q$, $\beta_r \xleftarrow{R} \mathbb{Z}_q$, $u_r \leftarrow g^{\alpha_r} h^{\beta_r}$ and sends commitment u_r to $\mathcal{V}$.
2. $\mathcal{V}$ samples the challenge $c \xleftarrow{R} \mathbb{Z}_q$ and sends c to $\mathcal{P}$.
3. $\mathcal{P}$ computes $\alpha_z \leftarrow \alpha_r + \alpha c, \beta_z \leftarrow \beta_r + \beta c$ and sends $\mathbf{z} = (\alpha_z, \beta_z)$.
4. $\mathcal{V}$ checks whether $g^{\alpha_z} h^{\beta_z} = u_r u^c$ and accepts or rejects the proof.

Non-Interactive Okamoto Protocol

Okamoto's Non-Interactive Identification Protocol

Now, we apply the *Fiat-Shamir Transformation*.

- $\text{Gen}(1^\lambda)$: On input $(u, (\alpha, \beta)) \in \mathbb{G} \times \mathbb{Z}_q^2$,
  1. Sample $\alpha_r, \beta_r \xleftarrow{R} \mathbb{Z}_q$ and compute $u_r \leftarrow g^{\alpha_r} h^{\beta_r}$.
  2. Using the hash function $H : \mathbb{G} \times \mathbb{G} \to \mathcal{C}$, compute $c \leftarrow H(u, u_r)$.
  3. Compute $\alpha_z \leftarrow \alpha_r + \alpha c, \beta_z \leftarrow \beta_r + \beta c$ and publish (u_r, α_z, β_z) as a proof π.
- Verify: Upon receiving statement u and a proof $\pi = (u_r, \alpha_z, \beta_z)$, the verifier:
  1. Recomputes the challenge c using the hash function.
  2. Accepts if and only if $g^{\alpha_z} h^{\beta_z} = u_r u^c$.

https://github.com/ZKDL-Camp/lecture-7-sigma

Thank you for your attention!