I – Zero-Knowledge Proofs and Applications

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ENS – Paris – 2018

Outline

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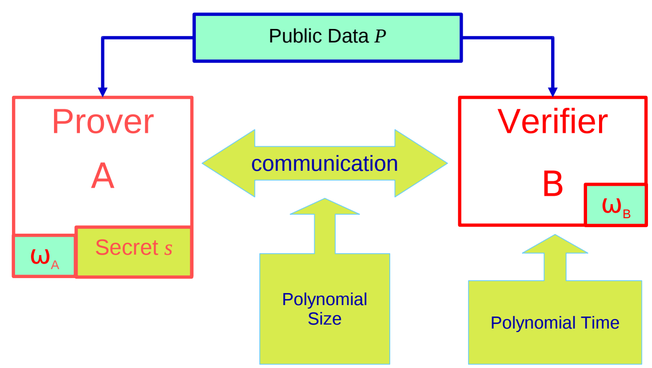
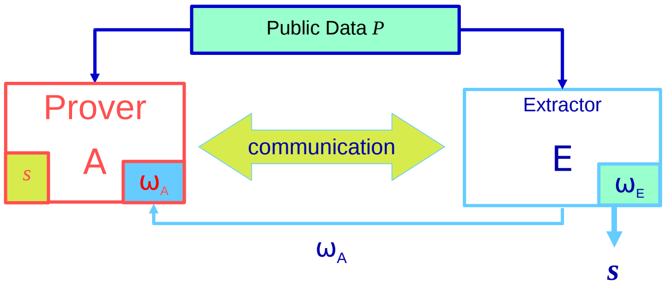
Proof of Knowledge

How do I prove that I know a solution s to a problem P?



Proof of Knowledge: Soundness

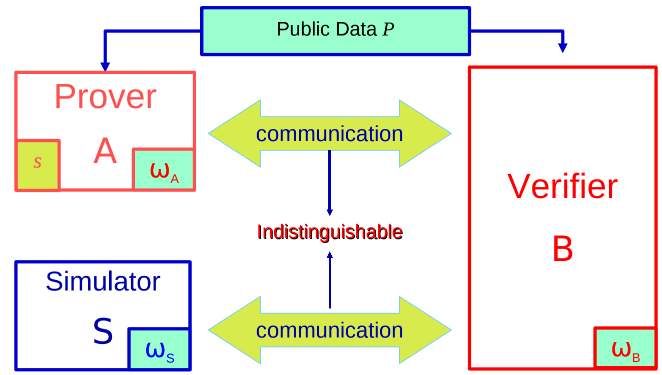
$\mathcal{A}$ knows something… What does it mean?
the information can be extracted: extractor



Proof of Knowledge: Zero-Knowledge

How do I prove that I know a solution s to a problem P?
I reveal the solution…

How can I do it without revealing any information?
Zero-knowledge: simulation and indistinguishability

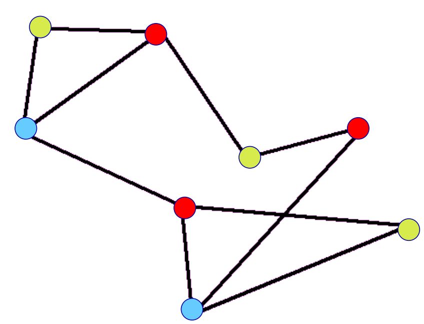


Outline

1. Zero-Knowledge Proofs of Knowledge
   - Introduction
   - 3-Coloring
   - Examples
2. Signatures
3. Zero-Knowledge Proofs of Membership

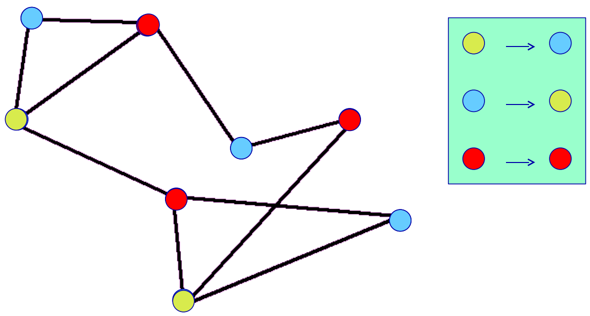
Proof of Knowledge

How do I prove that I know a 3-color covering,
without revealing any information?



Proof of Knowledge

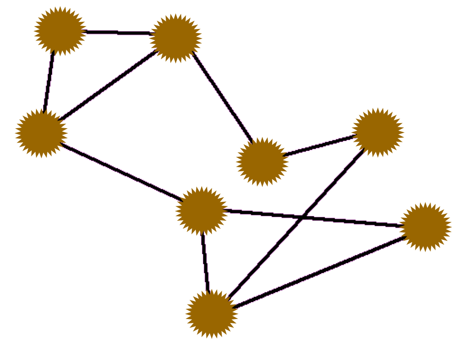
How do I prove that I know a 3-color covering,
without revealing any information?



I choose a random permutation on the colors
and I apply it to the vertices

Proof of Knowledge

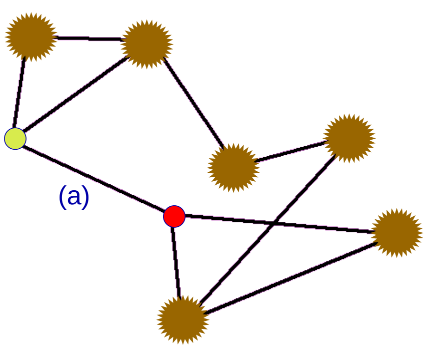
How do I prove that I know a 3-color covering,
without revealing any information?



I mask the vertices
and send it to the verifier

Proof of Knowledge

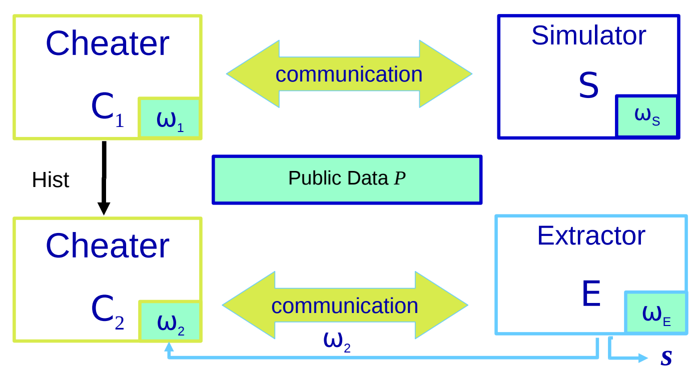
How do I prove that I know a 3-color covering,
without revealing any information?



The verifier chooses an edge
I open it
The verifier checks the validity: 2 different colors

Secure Multiple Proofs of Knowledge: Authentication

If there exists an efficient adversary,
then one can solve the underlying problem:



Outline

3-Pass Zero-Knowledge Proofs

Generic Proof

- Proof of knowledge of x, such that $\mathcal{R}(x, y)$
- $\mathcal{P}$ builds a commitment r and sends it to $\mathcal{V}$
- $\mathcal{V}$ chooses a challenge $h \stackrel{R}{\leftarrow} \{0,1\}^k$ for $\mathcal{P}$
- $\mathcal{P}$ computes and sends the answer s
- $\mathcal{V}$ checks (r, h, s)

Σ-Protocol

- Proof of knowledge of x
- $\mathcal{P}$ sends a commitment r
- $\mathcal{V}$ sends a challenge h
- $\mathcal{P}$ sends the answer s
- $\mathcal{V}$ checks (r, h, s)

Special soundness

If one can answer to two different challenges $h \neq h'$:
$\Longrightarrow$ s and s' for a unique r
$\Longrightarrow$ one can extract x

SQRT Fiat-Shamir Proof

[Fiat-Shamir – Crypto '86]

- Setting: $n = pq$
  $\mathcal{P}$ knows x, such that $X = x^2 \bmod n$ and wants to prove it to $\mathcal{V}$
- $\mathcal{P}$ chooses $r \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$, sets and sends $R = r^2 \bmod n$
- $\mathcal{V}$ chooses $b \stackrel{R}{\leftarrow} \{0,1\}$ and sends it to $\mathcal{P}$
- $\mathcal{P}$ computes and sends $s = x^b \times r \bmod n$
- $\mathcal{V}$ checks whether $s^2 \stackrel{?}{=} X^b R \bmod n$

One then reiterates t times

For a fixed R, two valid answers s and s' satisfy

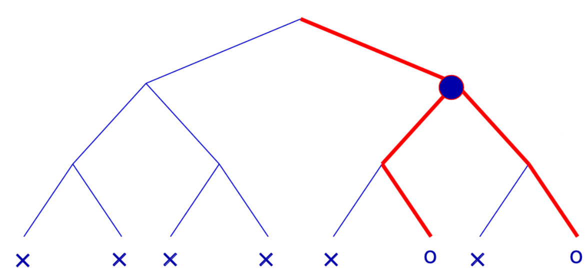
$$s^2/X = R = (s')^2 \bmod n \Longrightarrow X = (s/s')^2 \bmod n$$

And thus $x = s/s' \bmod n \Longrightarrow$ Special Soundness

Fiat-Shamir Proof: Extraction

More precisely: the execution of t repetitions depends on
- $(b_1, \ldots, b_t)$ from the verifier $\mathcal{V}$
- ω that (together with the previous b_i $(i < k)$) determines R_k from the prover $\mathcal{P}$

If $\Pr_{\omega,(b_i)}[\mathcal{V} \text{ accepts } \mathcal{P}] > 1/2^t + \varepsilon$,
there is a good fraction of ω (more than $\varepsilon/2$)
such that $\Pr_{(b_i)}[\mathcal{V} \text{ accepts } \mathcal{S}] \geq 1/2^t + \varepsilon/2$.
For such a good ω: a good node along the successful path



Fiat-Shamir Proof: Simulation

Honest Verifier

Simulation of a triplet: $(R = r^2 \bmod n, b, s = x^b \times r \bmod n)$
for $r \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$ and $b \stackrel{R}{\leftarrow} \{0,1\}$
Similar to: $(R = s^2/X^b \bmod n, b, s)$
for $s \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$ and $b \stackrel{R}{\leftarrow} \{0,1\}$
Simulation: random s and b, and set $(R = s^2/X^b \bmod n, b, s)$

Any Verifier

Simulation of a triplet: $(R = r^2 \bmod n, b = \mathcal{V}(\text{view}), s = x^b \times r \bmod n)$
for $r \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$ only!
Similar to: $(R = s^2/X^b \bmod n, b = \mathcal{V}(\text{view}), s)$ for $s \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$
Simulation: random s and β, and set $R = s^2/X^\beta \bmod n$
upon reception of b: if $b = \beta$, output s, else rewind
b and β independent: rewind once over 2 $\Longrightarrow$ linear time

RSA GQ Proof

[Guillou-Quisquater – Crypto '87 – Eurocrypt '88]

- Setting: $n = pq$ and an exponent e
  $\mathcal{P}$ knows x, such that $X = x^e \bmod n$ and wants to prove it to $\mathcal{V}$
- $\mathcal{P}$ chooses $r \stackrel{R}{\leftarrow} \mathbb{Z}_n^\star$, sets and sends $R = r^e \bmod n$
- $\mathcal{V}$ chooses $b \stackrel{R}{\leftarrow} \{0,1\}^t$ and sends it to $\mathcal{P}$
- $\mathcal{P}$ computes and sends $s = x^e \times r \bmod n$
- $\mathcal{V}$ checks whether $s^e \stackrel{?}{=} X^b R \bmod n$

For a fixed R, two valid answers s and s' satisfy

$$s^e/X^b = R = (s')^e/X^{b'} \bmod n \Longrightarrow X^{b'-b} = (s'/s)^e \bmod n$$

If e prime and bigger than 2^t, then e and $b' - b$ are relatively prime:
Bezout: $ue + v(b' - b) = 1 \Longrightarrow X^{v(b'-b)} = (s'/s)^{ve} = X^{1-ue} \bmod n$
As a consequence: $X = ((s'/s)^v X^u)^e \Longrightarrow$ Special Soundness

DL Schnorr Proof

[Schnorr – Eurocrypt '89 - Crypto '89]

- Setting: $\mathbb{G} = \langle g \rangle$ of order q
  $\mathcal{P}$ knows x, such that $y = g^{-x}$ and wants to prove it to $\mathcal{V}$
- $\mathcal{P}$ chooses $k \stackrel{R}{\leftarrow} \mathbb{Z}_q^\star$, sets and sends $r = g^k$
- $\mathcal{V}$ chooses $h \stackrel{R}{\leftarrow} \{0,1\}^t$ and sends it to $\mathcal{P}$
- $\mathcal{P}$ computes and sends $s = k + xh \bmod q$
- $\mathcal{V}$ checks whether $r \stackrel{?}{=} g^s y^h$

For a fixed r, two valid answers s and s' satisfy

$$g^s y^h = r = g^{s'} y^{h'} \Longrightarrow y^{h'-h} = g^{s-s'}$$

And thus $x = (s - s')(h' - h)^{-1} \bmod q \Longrightarrow$ Special Soundness

Outline

Generic Zero-Knowledge Proofs

Zero-Knowledge Proof

- Proof of knowledge of x, such that $\mathcal{R}(x, y)$
- $\mathcal{P}$ builds a commitment r and sends it to $\mathcal{V}$
- $\mathcal{V}$ chooses a challenge $h \stackrel{R}{\leftarrow} \{0,1\}^k$ for $\mathcal{P}$
- $\mathcal{P}$ computes and sends the answer s
- $\mathcal{V}$ checks (r, h, s)

Signature

$\mathcal{H}$ viewed as a random oracle

- Key Generation $\rightarrow (y, x)$
  private: x public: y
- Signature of $m \rightarrow (r, h, s)$
  Commitment r
  Challenge $h = \mathcal{H}(m, r)$
  Answer s
- Verification of (m, r, s)
  compute $h = \mathcal{H}(m, r)$
  and check (r, h, s)

Σ-Protocols

Zero-Knowledge Proof

- Proof of knowledge of x
- $\mathcal{P}$ sends a commitment r
- $\mathcal{V}$ sends a challenge h
- $\mathcal{P}$ sends the answer s
- $\mathcal{V}$ checks (r, h, s)

Signature

- Key Generation $\rightarrow (y, x)$
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  Commitment r
  Challenge $h = \mathcal{H}(m, r)$
  Answer s
- Verification of (m, r, s)
  compute $h = \mathcal{H}(m, r)$
  and check (r, h, s)

Special soundness

If one can answer to two different challenges $h \neq h'$: s and s' for a unique commitment r, one can extract x

Outline

Forking Lemma

[Pointcheval-Stern – Eurocrypt '96]

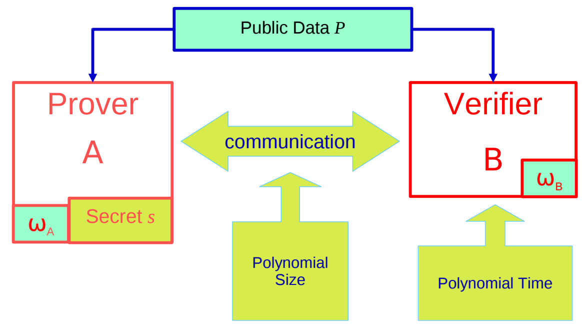
The Forking Lemma shows an efficient reduction between the signature scheme and the identification scheme, but basically, if an adversary $\mathcal{A}$ produces, with probability $\varepsilon \geq 2/2^k$, a valid signature (m, r, h, s), then within $T' = 2T$, one gets two valid signatures (m, r, h, s) and (m, r, h', s'), with $h \neq h'$ with probability $\varepsilon' \geq \varepsilon^2/32q_H^3$.

The special soundness provides the secret key.

Outline

Proof of Membership

How do I prove that a word w lies in a language $\mathcal{L}$: $P = (w, \mathcal{L})$?
- if $\mathcal{L} \in \mathcal{BPP}$: anybody can publicly check it
- if $\mathcal{L} \in \mathcal{NP} \backslash \mathcal{BPP}$: a witness s can help prove that $w \in \mathcal{L}$



If $w \notin \mathcal{L}$:
- Proof (perfect soundess): a powerful $\mathcal{A}$ cannot cheat
- Argument (computational soundness): a limited $\mathcal{A}$ cannot cheat

Proof of Membership

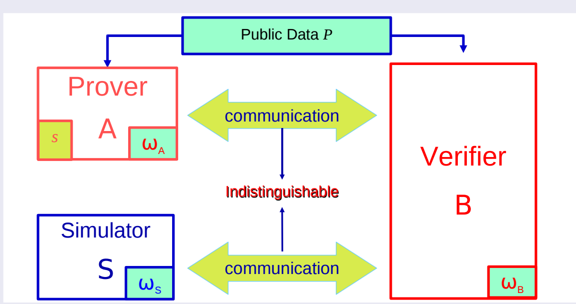
Soundness

$w \in \mathcal{L} \ldots$ what does it mean?
a witness exists, different from knowing it: no need of extractor

Zero-Knowledge

How do I prove there exists a witness s? I reveal it...
How can I do it without revealing any information?

Zero-knowledge:
simulation
and indistinguishability



Outline

Diffie-Hellman Language

In a group $\mathbb{G} = \langle g \rangle$ of prime order q,
the **DDH**(g, h) assumption states it is hard to distinguish
$\mathcal{L} = (u = g^x, v = h^x)$ from $\mathbb{G}^2 = (u = g^x, v = h^y)$

- $\mathcal{P}$ knows x, such that $(u = g^x, v = h^x)$ and wants to prove it to $\mathcal{V}$
- $\mathcal{P}$ chooses $k \stackrel{R}{\leftarrow} \mathbb{Z}_q^\star$, sets and sends $U = g^k$ and $V = h^k$
- $\mathcal{V}$ chooses $h \stackrel{R}{\leftarrow} \{0, 1\}^t$ and sends it to $\mathcal{P}$
- $\mathcal{P}$ computes and sends $s = k + xh \bmod q$
- $\mathcal{V}$ checks whether $U \stackrel{?}{=} g^s u^h$ and $V \stackrel{?}{=} h^s v^h$

For a fixed (U, V), two valid answers s and s' satisfy

$$g^s u^h = U = g^{s'} u^{h'} \quad h^s v^h = V = h^{s'} v^{h'}$$

- if one sets $y = (s - s')(h' - h)^{-1} \bmod q \Longrightarrow u = g^y$ and $v = h^y$
- there exists a witness: Perfect Soundness