Provably Secure Cryptography: State of the Art and Industrial Applications

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Gemplus/R&D/ARSC/STD/Advanced Cryptographic Services

French-Japanese Joint Symposium on Computer Security

Outline

What is provable security?

Security Proofs for Signatures

Security Proofs for Encryption

Designing Cryptosystems

Proof Techniques

Present and Future Trends

Focus on Provable Security

Our ultimate goal:

- Providing evidence that a given cryptographic protocol is secure
- Find new ways of building secure protocols

Cryptographic protocols contain basic ingredients

- Asymmetric encryption schemes (and variations),
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So the first thing to do is trying to prove the security of these two primitives.

But what does it mean to be secure?

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- By trying to mount an attack
  - Attack found $\Rightarrow$ SYSTEM INSECURE!
  - Attack not found $\Rightarrow$ NOTHING CAN BE SAID
- By proving that no attack exists under some assumptions

When a security proof is provided, no one should be able to highlight a system defect. But the assumption has to be reasonnable... (e.g. the Ko-Lee assumption over Braid groups was recently proven wrong).

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Efficient proven secure schemes have been discovered

Sign. PSS(-R)-RSA, GHR, Cramer-Shoup, EDL...

Enc. RSA-OAEP, Cramer-Shoup, ...

There exist generic conversions to create more of them

Provably secure schemes are adopted in standards

Standard bodies ask for security proofs along with submissions

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This is no longer just theory. Product developers, security architects and users want to know

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To get a security proof, one needs to

1. Describe a cryptosystem and its operational modes,
2. Formally define a **security notion** to achieve,
3. Make precise computational assumptions,
4. Exhibit a **reduction** between an algorithm which breaks the security notion and an algorithm that breaks the assumptions.

Reduction

to prove

$$P_1 \Leftarrow P_2$$

i.e. that problem P_1 is reducible to problem P_2, one shows an algorithm with polynomial resources that solves P_1 with access to an oracle that solves P_2.

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Digital Signatures

- Signer Alice generates a public/private key pair (pk, sk) by running a probabilistic key generation algorithm $G(|pk|)$, $|pk|$ being the security parameter. Alice publishes pk.
- Whenever Alice wishes to sign a digital document $m \in \{0, 1\}^*$, she computes the signature $s = S(sk, m)$ where S is the (possibly probabilistic) signing algorithm. She outputs s and maybe also m.
- Knowing m and s (and Alice's public key pk), Bob can verify that s is a signature of m output by Alice by running the verification algorithm $V(pk, m, s)$ returning 1 if $s = S(sk, m)$ or 0 otherwise.

The cryptographic system given by the triple (G, S, V) and their domains is called a signature scheme.

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Security Notions

Depending on the context in which a given cryptosystem is used, one may formally define a security notion for this system,

- by telling what **goal** an adversary would attempt to reach,
- and what means or information are made available to her (the **attack model**).

A security notion (or level) is entirely defined by coupling an adversarial goal with an adversarial model.

Examples: UB-KMA, UUF-KOA, EUF-SOCMA, EUF-CMA.

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[Unbreakability] the attacker recovers the secret key sk from the public key pk (or an equivalent key if any). This goal is denoted **UB**. Implicitly appeared with public-key cryptography.

[Universal Unforgeability] the attacker, without necessarily having recovered sk, can produce a valid signature of any message in the message space. Noted **UUF**.

[Selective Unforgeability] the attacker can produce a valid signature of a message he committed to before knowing the public key. Noted **SUF**. Not often used in proofs (except in recent pairing-based signatures).

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Adversarial Models

Several types of computational resources an adversary has access to are considered:

- **Key-Only Attacks** (KOA), unavoidable scenario.
- **Known Message Attacks** (KMA) where an adversary has access to signatures for a set of known messages.
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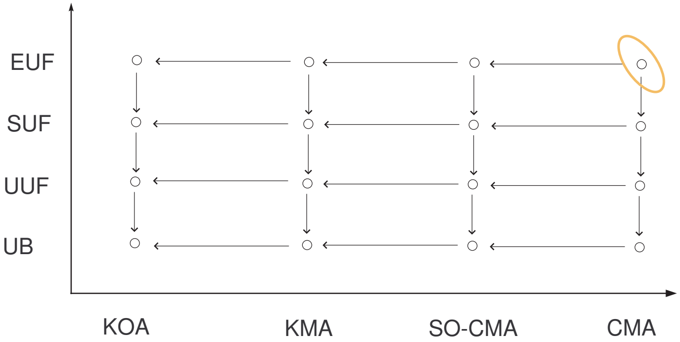

Chosen-Message Security

Because EUF-CMA is the upper security level (Goldwasser, Micali, Rivest, 1988), it is desirable to prove security with respect to this notion.

Formally, an signature scheme is said to be (q, τ, ε)-secure if for any adversary $\mathcal{A}$ with running time upper-bounded by τ,

$$\mathrm{Succ}^{\mathrm{EUF-CMA}}(\mathcal{A}) = \Pr\left[\begin{array}{l} (sk, pk) \leftarrow G(1^k), \\ (m^*, s^*) \leftarrow \mathcal{A}^{S(sk,\cdot)}(pk), \\ V(pk, m^*, s^*) = 1 \end{array} \right] < \varepsilon \ ,$$

where the probability is taken over all random choices.

The notation $\mathcal{A}^{S(sk,\cdot)}$ means that the adversary has access to a signing oracle throughout the game, but at most q times.

The message m^* output by $\mathcal{A}$ must not have been requested to the signing oracle.

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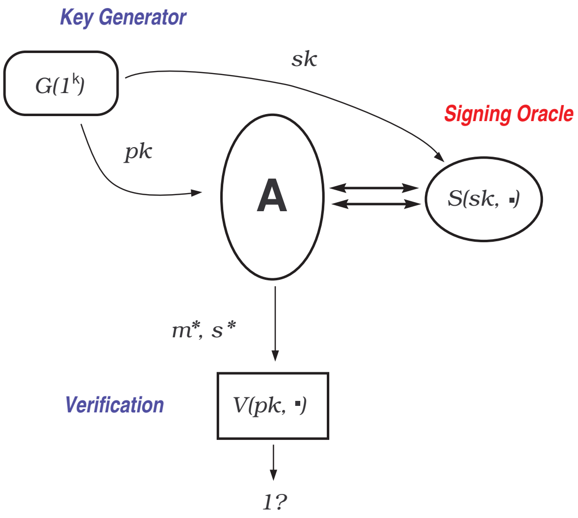
EUF-CMA: Playing the Game



Public-Key Encryption

An asymmetric encryption scheme is a triple of algorithms $(\mathcal{K}, \mathcal{E}, \mathcal{D})$ where

- $\mathcal{K}$ is a probabilistic key generation algorithm which returns random pairs of secret and public keys (sk, pk) depending on the security parameter κ,
- $\mathcal{E}$ is a probabilistic encryption algorithm which takes on input a public key pk and a plaintext $m \in \mathcal{M}$, runs on a random tape $u \in \mathcal{U}$ and returns a ciphertext c,
- $\mathcal{D}$ is a deterministic decryption algorithm which takes on input a secret key sk, a ciphertext c and returns the corresponding plaintext m or the symbol $\perp$. We require that if $(sk, pk) \leftarrow \mathcal{K}$, then $\mathcal{D}_{sk}(\mathcal{E}_{pk}(m, u)) = m$ for all $(m, u) \in \mathcal{M} \times \mathcal{U}$.

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It shouldn't be feasible to:

- Compute the secret key *sk* from the public key *pk* (unbreakability or UBK). Implicitly appeared with public-key crypto.
- Invert the encryption function over any ciphertext under any given key *pk* (one-wayness or OW). Diffie and Hellman, late 70's.
- Recover even a *single bit of information* about a plaintext given its encryption under any given key *pk* (indistinguishability of encryptions or IND). Goldwasser and Micali, 1984.
- *Transform* some ciphertext into another ciphertext such that plaintext are meaningfully related (non-malleability or NM). Dolev, Dwork and Naor, 1991.

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Several types of computational resources an adversary has access to have been considered:

- **chosen-plaintext attacks** (CPA), unavoidable scenario.
- **non-adaptive chosen-ciphertext attacks** (CCA1) (also known as lunchtime or midnight attacks), wherein the adversary gets, in addition, access to a decryption oracle before being given the challenge ciphertext. Naor and Yung, 1990.
- **adaptive chosen-ciphertext attacks** (CCA2) as a scenario in which the adversary queries the decryption oracle before and *after* being challenged; her only restriction here is that she may not feed the oracle with the challenge ciphertext itself. This is the strongest known attack scenario. Rackoff and Simon, 1991.

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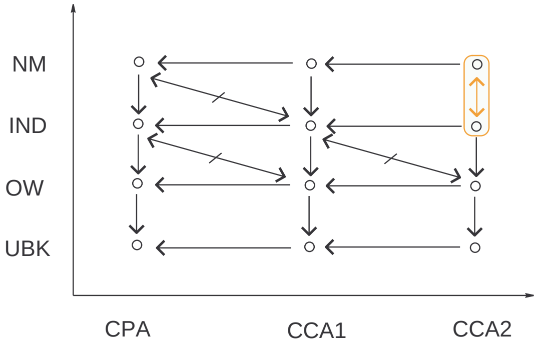

$\leftarrow$ indicates an implication: a scheme secure in notion A is also secure in notion B.

$\not\leftarrow$ indicates a separation: there exists a scheme secure in notion A but not in B.

Chosen-Ciphertext Security

Because IND-CCA2 $\equiv$ NM-CCA2 is the upper security level, it is desirable to prove security with respect to this notion. It is also denoted by IND-CCA and called chosen ciphertext security.

Formally, an asymmetric encryption scheme is said to be (τ, ε)-IND-CCA if for any adversary $\mathcal{A} = (\mathcal{A}_1, \mathcal{A}_2)$ with running time upper-bounded by τ,

$$\mathsf{Adv}^{\mathsf{ind}}(\mathcal{A}) = 2 \times \Pr_{\substack{b \xleftarrow{R} \{0,1\} \\ u \xleftarrow{R} \mathcal{U}}} \left[\begin{array}{l} (sk, pk) \leftarrow \mathcal{K}(1^\kappa), (m_0, m_1, \sigma) \leftarrow \mathcal{A}_1(pk) \\ c \leftarrow \mathcal{E}_{pk}(m_b, u) : \mathcal{A}_2(c, \sigma) = b \end{array} \right] - 1 < \varepsilon \,,$$

where the probability is taken over the random choices of $\mathcal{A}$. The two plaintexts m_0 and m_1 chosen by the adversary have to be of identical length. Access to a decryption oracle is allowed throughout the game. We also have

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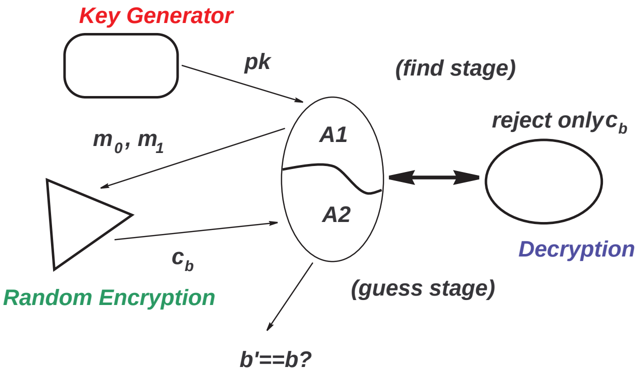

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These security notions are **targets** *for* **scheme designers**. *But how does one design (secure) cryptosystems?*

Public-key design allows to construct systems by assembling and connecting smaller structures together. These may be *smaller* cryptosystems or atomic primitives:

- one-way functions, one-way trapdoor functions, one-way trapdoor permutations,
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Computational Assumptions

Cryptographic primitives are connected to plenty of (supposedly) intractable problems:

- RSA is one-way, Strong RSA is hard,
- discrete log is hard,
- computational/decisional Diffie-Hellman is hard,
- factoring is hard,
- shortest lattice vector is hard,
- computing residuosity classes is hard,
- deciding residuosity is hard, . . .

Hard = Intractable = no PPT algorithm can solve the problem with non-negligible probability.

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Schemes/Problems Reductions

Suppose we want to build some cryptosystem $\mathcal{S}$ and want a proof that (for instance)

$$\begin{aligned} RSA &\Leftarrow \text{EUF-CMA}(\mathcal{S}) && (1) \\ RSA &\Leftarrow \text{OW-CCA2}(\mathcal{E}) && (2) \end{aligned}$$

We have to show that breaking EUF-CMA($\mathcal{S}$) or OW-CCA2($\mathcal{E}$) allows to solve RSA, *i.e.* that an adversary breaking $\mathcal{S}$ can be used as a black box tool to answer RSA requests with non-negligible probability.

There is no such thing as a proof of security. There are only reductions

Probability Spaces: the reduction has to simulate the attacker's environment in a way that preserves (or does not alter too much) the distribution of all random variables which interact with it.

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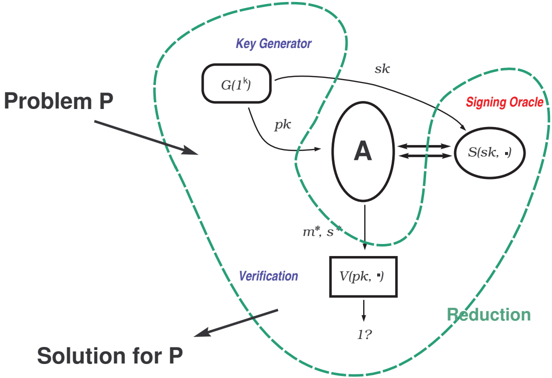
Simulating the Attacker's Environment



Concrete Security

Provable security guarantees us that a scheme is asymptotically secure *i.e.* that all attacks asymptotically vanish thanks to polynomial reductions.

But what we need in real life is to provide explicit reductions.

Exhibiting a reduction helps to decide how to tune the security parameter so that the scheme has a given concrete security.

For a practical impact, we need tight reductions to strong computational problems.

Some cryptosystems may feature asymptotic security but with an inefficient reduction ⇒ forces to use large keys ⇒ heavier implementations: schemes may reveal useless. We need **tight** reductions so that we can guarantee security for **efficient** schemes.

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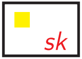
Security Products with Top-Level Security

Security notions (goal + attack model) capture real-life attack scenarios. They really describe what we want.



Smart Card

Decryption request

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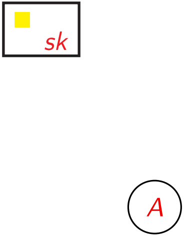

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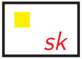

$E_{pk}(m)$

Smart Card

Decryption request

Signature request

A

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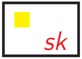

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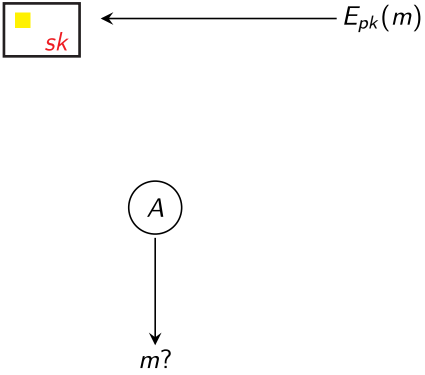

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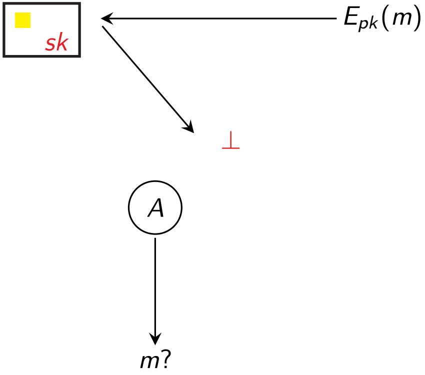

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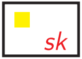

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Smart Card

Decryption request

Signature request

$E_{pk}(m_1)$

A

$\downarrow$

$m?$

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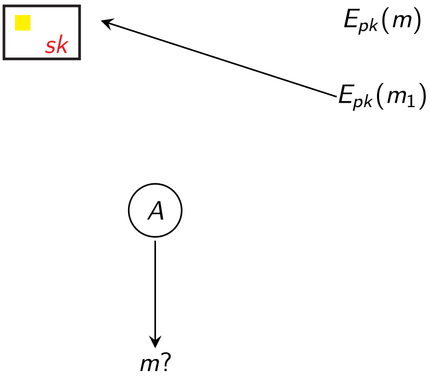
Smart Card
Decryption request
Signature request



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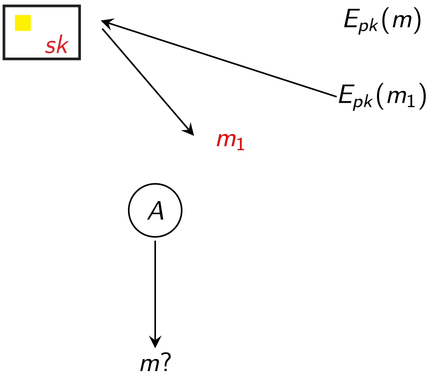

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sk

$E_{pk}(m)$

Smart Card

Decryption request

Signature request

$E_{pk}(m_1)$

$E_{pk}(m_2)$

A

$\downarrow$

$m?$

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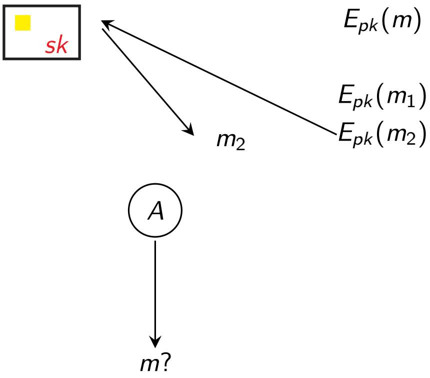

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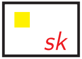

$E_{pk}(m)$

Smart Card

Decryption request

Signature request

$E_{pk}(m_1)$

$E_{pk}(m_2)$

$\vdots$

$E_{pk}(m_n)$

A

$\downarrow$

$m?$

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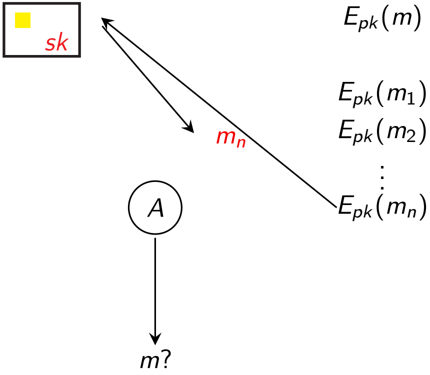

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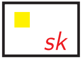

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Decryption request

Signature request

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$\downarrow$

$m?$ not a clue!

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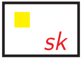

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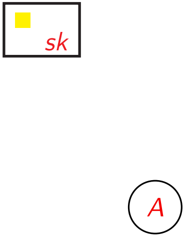

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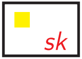

$m =$ "You owe me \$1M"

Smart Card

Decryption request

Signature request

A

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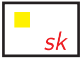

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A

$\downarrow$

$\sigma(m)$?

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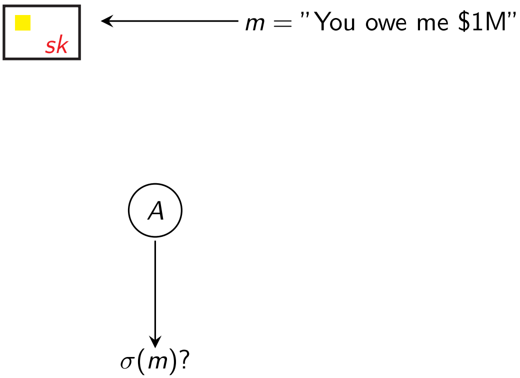

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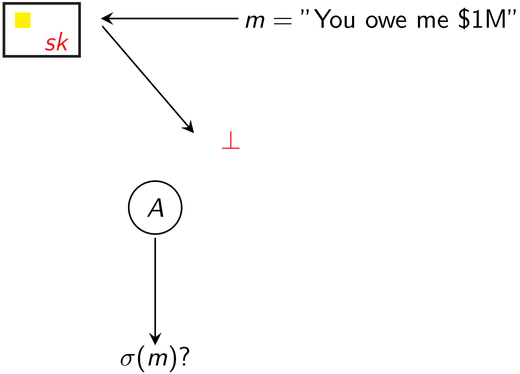

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Decryption request

Signature request

m_1

A

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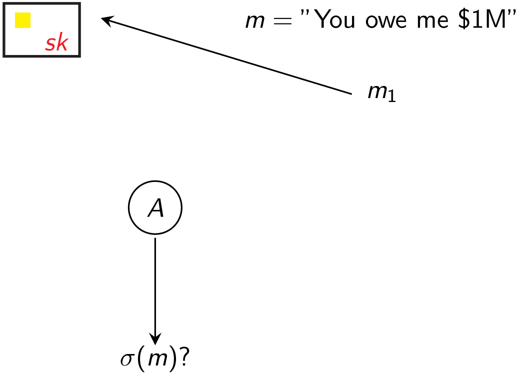
Smart Card
Decryption request
Signature request



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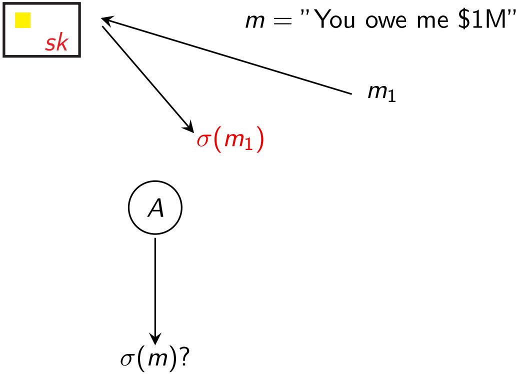

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m_2

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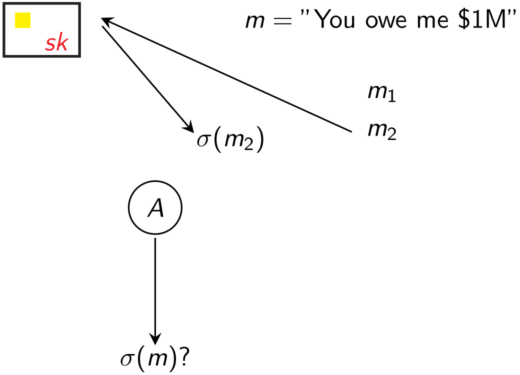

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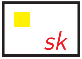

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$\vdots$

m_n

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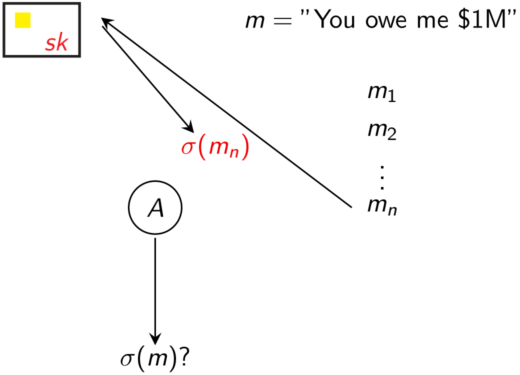

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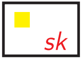

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But we need security proofs for that!

$\sigma(m)$?

What Are Ideal Assumptions?

Providing reductions is rarely as easy as just seen. We often need to idealize our view of primitive objects in order to simplify the proof.

- ideal random hash functions $\rightrightarrows$ random oracle model,
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A reduction is easier between a given problem and a generic adversary!

Do people buy these proofs?

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Shoup introduced a proof design which facilitates public scrutiny.

The proof is given as a series of **rounds** or **games**.

The Difference (aka Shoup's) Lemma: Assume A, B, E are events and $\Pr[A \wedge \neg E] = \Pr[B \wedge \neg E]$. Then

$$|\Pr[A] - \Pr[B]| \leq \Pr[E] \ .$$

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The Difference (aka Shoup's) Lemma: Assume A, B, E are events and $\Pr[A \wedge \neg E] = \Pr[B \wedge \neg E]$. Then

$$|\Pr[A] - \Pr[B]| \leq \Pr[E] \ .$$

Shoup's Modular Proofs

- the first game Game_0 is the one defined by the security model. **No reduction or simulations whatsoever**. The success probability $\Pr[S_0]$ of the adversary $\mathcal{A}$ is $\Pr[S_0] = \varepsilon_{\mathcal{A}}$.
- Game_{i+1} is described as being an **incrementally** modified version of Game_i. Then $\Pr[S_{i+1}]$ is expressed as a function of $\Pr[S_i]$ and scheme parameters.
- the last game Game_ℓ describes the complete reduction algorithm.

The last game provides $\varepsilon_{\mathcal{R}} = \Pr[S_\ell]$ as a function of $\Pr[S_0] = \varepsilon_{\mathcal{A}}$ and parameters. Execution time τ_ℓ is also expressed as a function of $\tau_0 = \tau_{\mathcal{A}}$.

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Adopting Shoup's methodology allows to

- check proofs more easily (longer proofs are possible),
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The Ideal Cipher Model

Similar to the random oracle model, except that a **blockcipher** is replaced by a random permutation.

The random permutation E takes a pair (k, x) and returns $y = E(k; x)$. Of course $E^{-1}(k; y) = x$. Both E or E^{-1} may be queried.

A random permutation is easy to simulate: for any fresh pair (k, x), pick y at random such that $(k, x \leftrightarrow y) \notin \mathrm{Hist}[E]$ for any x, set $E(k; x) = y$ and return y. The history $\mathrm{Hist}[E]$ must be updated with the correspondence $(k, x \leftrightarrow y)$.

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The Generic Model

The generic model assumes that a given group G is ideal *i.e.* has no hidden structure behind the group structure.

No one can perform operations on group elements a, b other than group operations $c \leftarrow a \star b$, $c \leftarrow a^{-1}$ and test if $a \in G$.

All parties are provided with subroutines $\{\star, \cdot^{-1}, \text{test}\}$ that use their own representation of group elements as strings.

A proof standing in the generic model means that a successful adversary must exploit the structure of the group in a non classical fashion.

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Convergence of Techniques. Proving equivalence of weakened proof models. Is it true that ROM $\equiv$ ICM?

Alleviate Proofs Models. Programmable vs. Non-programmable ROM/ICM/GGM. n-programmable oracles.

Getting Rid of These. ROM/ICM/GGM will become essentially pedagogical. Only the Standard Model will remain.

New Complexity Assumptions. New computational assumptions appear every year. Hope for a convergence towards simplified assumptions.

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