The Design of Cryptosystems: The Interplay between Proofs and Attacks

French-German-Singaporean Workshop on Applied Cryptography

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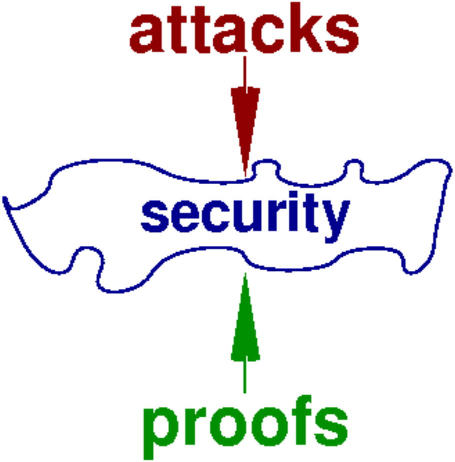
Roadmap


attacks
security
proofs

Example: Entity Recognition

The Problem with Proofs

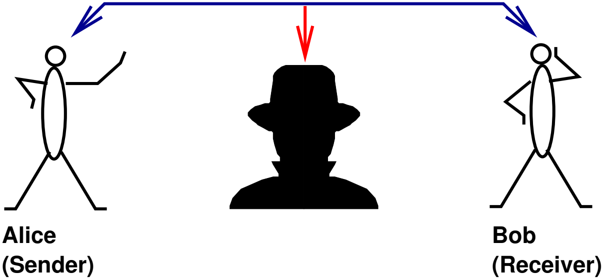
The Jane Doe Protocol

The Random Oracle Debate

The Jane Doe Protocol (revisited)

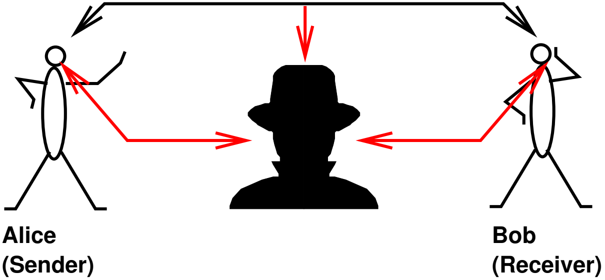
Summary

Example: Entity Recognition



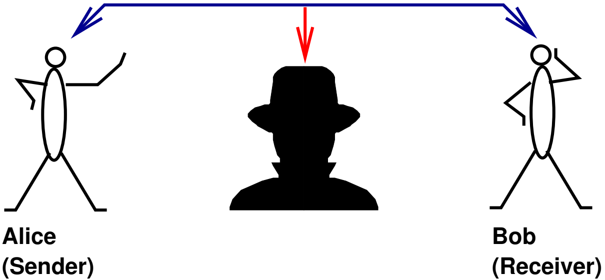
- Alice ("Jane Doe") and Bob meet at a party.
  They make a bet. Others listen.

Example: Entity Recognition



- Alice ("Jane Doe") and Bob meet at a party.
  They make a bet. Others listen.
- Much later, when it had turned out that Alice won, Bob receives a mail from "Jane Doe":
  "Bob, please transfer the money I have won to . . .
- How can Bob verify that this mail is from Alice?

Entity Recognition: More Formal



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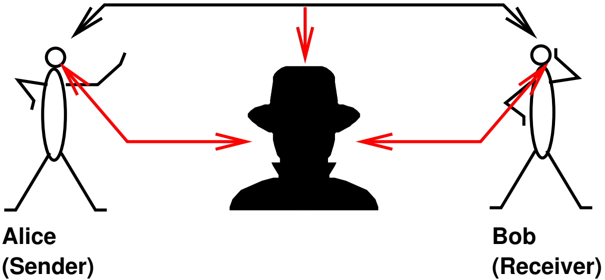
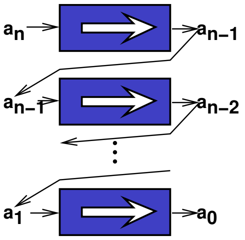


- **The initial communication** may be observed – but not tampered with
- **Later**, communication may be observed but also tampered with (read, modify, suppress, or re-send data).

"Cheap" Symmetric Operations

Hash Chain

$a_0 := \mathbf{H}(\mathbf{H}(\ldots(\mathbf{H}(\mathbf{a_n})))):$



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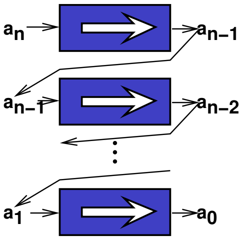

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given $\mathbf{a_{i-1}}$:

infeasible to find any $\mathbf{a'}$ with

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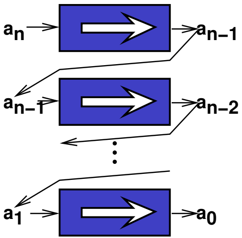

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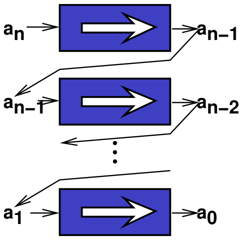

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Message Authentication Code (MAC)

Assumption (secure against existential forgery):
given many (tag,message) pairs:
infeasible to forge tag for another message

Protocols for Entity Recognition

- "Zero Common-Knowledge": Weimerskirch, Westhoff, 2003.
- "Jane Doe": (not yet using that name):
  Lucks, Zenner, Weimerskirch, Westhoff, 2005.
- "Jane Doe": Lucks, Zenner, Weimerskirch, Westhoff, 2008.

The Zero Common Knowledge Protocol

- one hash chain $(a_0, a_1, \ldots)$ for Alice, another one $(b_0, b_1, \ldots)$ for Bob.
- Bob knows $\mathbf{a_{i-1}}$, Alice knows $\mathbf{b_{j-1}}$.
- Alice authenticates m by tag := $\mathrm{MAC}_{\mathbf{a_{j+1}}}(m)$, and $\mathbf{a_j}$.
- Bob verifies $\mathbf{H}(\mathbf{a_i}) = \mathbf{a_{i-1}}$ and responds $\mathbf{b_i}$.
  Alice verifies $\mathbf{H}(\mathbf{b_i}) = \mathbf{b_{i-1}}$.
- Alice sends $\mathbf{a_{j+1}}$.
  Bob verifies $\mathbf{H}(\mathbf{a_{j+1}}) = \mathbf{a_j}$ and $\mathrm{MAC}_{\mathbf{a_{j+1}}}(m) = \text{tag}$.

The Attack

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- Alice authenticates m by tag $:= \mathrm{MAC}_{\mathbf{a_{j+1}}}(m)$, and $\mathbf{a_j}$.
- Bob verifies $\mathbf{H}(\mathbf{a_i}) = \mathbf{a_{i-1}}$ and responds $\mathbf{b_i}$.
  Alice verifies $\mathbf{H}(\mathbf{b_i}) = \mathbf{b_{i-1}}$.
- Alice sends $\mathbf{a_{j+1}}$. **Eve does not deliver this to Bob.**
- Next time, Alice will send tag $:= \mathrm{MAC}(\ldots)$, and $\mathbf{a_{j+2}}$.
- Eve then knows $\mathbf{a_{j+1}}$ and $\mathbf{a_{j+2}}$ from Alice's hash chain, which are unknown to Bob.
- This allows her to forge a message for Bob.

Comments

- The *Zero Common Knowledge Protocol* has been published at SAC 2003 and *proven secure!*
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- The proof makes the (implicit) assumption that messages are always delivered.
- We could "repair" this by *making the assumption explicit*.
- The proof would be theoretically sound, but (most probably) practically useless!

The Problem with Proofs

- Lars Knudsen: *"If it is provably secure, it is probably not"*
- Birgit Pfitzmann, Michael Waidner: *"How To Break and Repair A 'Provably Secure' Untraceable Payment System"*, CRYPTO 1991
- Birgit Pfitzmann, Matthias Schunter, Michael Waidner: *"How to Break Another Provably Secure Payment System"*, EUROCRYPT 1995:

  > *"Short statements of cryptographic properties (formal or informal) should always come with an explicit trust model, i.e., for whom a property is guaranteed, and which other participants have to be trusted to guarantee this."*

The Trinity of Cryptographic Security Proofs

A cryptographic “Security Proof” is actually a trinity of

1. some definitions (trust model, cryptographic assumptions, . . .),
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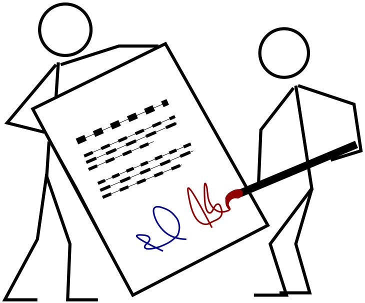
2. a theorem, and
3. the proof itself.

- Leave it to the theoreticians to verify the proof.
- But understand that the theorem, with the associated definitions, is like a contract between
  - a **service provider** (the crypto-designer) and
  - a **client** (the application designer).

The Proof as a Contract

- obligations for the **client**, such as choosing primitives (MAC, Hash, ...), secure against well-defined classes of attack
- responsibility of the **service provider** (security against the specified class of attacks in the specified trust model)
- if the **client** follows her obligations, **mathematical laws** guarantee the promised security



This is an extremely useful concept for Applied Cryptography!
But **the client must understand the contract!**

The Jane Doe Protocol

- Two hash chains $(a_0, a_1, \ldots)$ for Alice, and $(b_0, b_1, \ldots)$ for Bob. Initially, Alice knows $\mathbf{b_{i-1}}$ and Bob knows $\mathbf{a_{i-1}}$.
- Later, Alice will reveal $\mathbf{a_i}$, and Bob will reveal $\mathbf{b_i}$.

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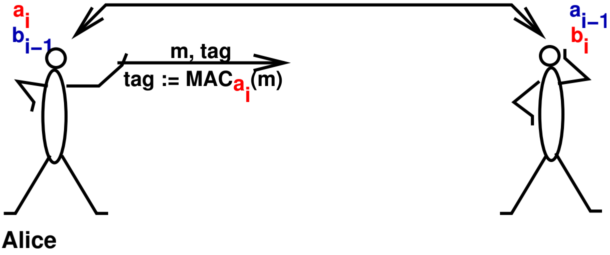

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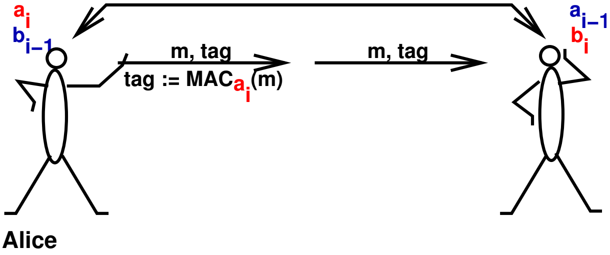

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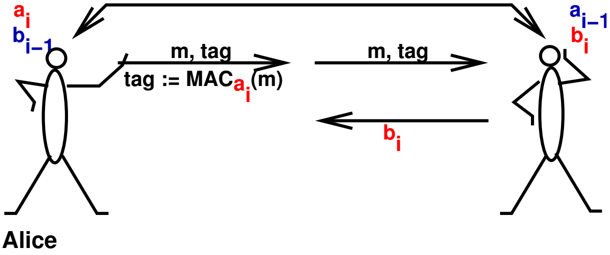

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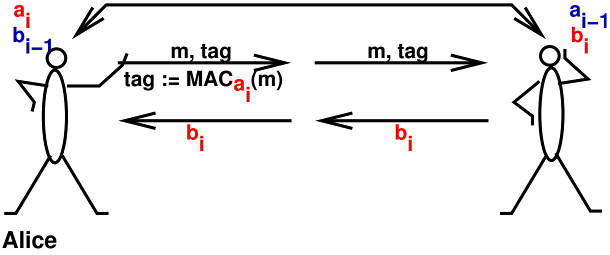

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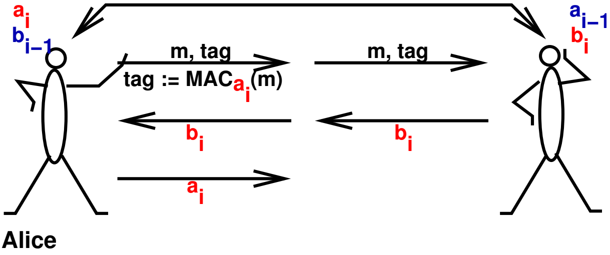

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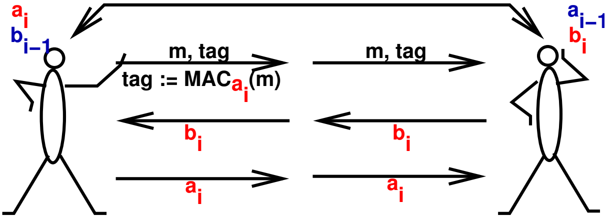

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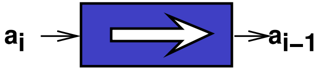
Assumptions

We need both a one-way (hash) function and secure MAC.



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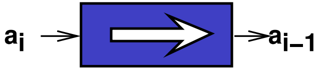

Problem: For the same Key, the protocol uses both Hash(Key) and MAC(Key,$*$). Thus, MAC(Key,$*$) must provide security, even if Hash(Key) is known.

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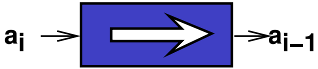

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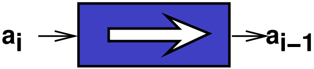

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- One can (maliciously) define a secure Hash and a secure MAC
- such that the Jane Doe protocol is actually *insecure* when using both of them together.

Two Alternative Solutions

1. introduce a complex nonstandard security definition for the *combined security* of MAC and Hash
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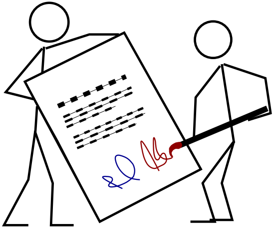
If the security definitions are complex and nonstandard, the **client** will find it hard to understand the contract. That is bad!



Definitions in the random oracle model are quite easy to understand.
So why not just assume the Hash is a random oracle?

The Random Oracle Debate

Two reasons to criticize the usage of random oracles:

1. "Separation Results":
   Some (maliciously designed) cryptosystems are provable secure in the ROM, but insecure under any real-world instantiation.
   So far, this is a theoretical issue, only.
2. "Spoiling the Contract":
   Even if "good" primitives exist, the definition and the theorem don't tell the **client** how to choose "good" primitives.

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- no “real world object”
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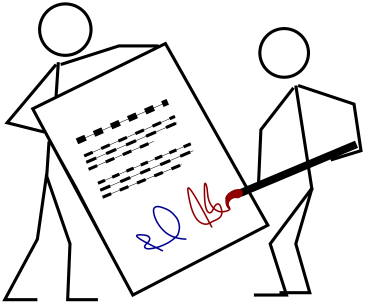
- no "real world object"
- **client** must choose a real-world object, and thus (formally) violate her obligations
- **no guarantee by mathematical laws** for **client**
  "Trust me! If the primitive is good, you are secure."
  "Sorry, the primitive you used is not good! That is not my fault!"



The Jane Doe Protocol (revisited)

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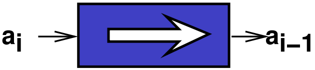

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Same Protocol – but Slightly Different Requirements

Start with a single primitive m^* (a MAC):

- assume m^* to be one-way, <u>and</u>
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Derive a one-way function h and a new MAC m from M^*:

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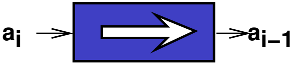
One-way function: $h(\text{Key}) := m^*(\text{Key}, 0)$



New MAC: $m(\text{Key}, \text{Message}) := m^*(\text{Key}, 1||\text{Message})$

Summary

- Security proofs are an important tool for Applied Cryptography.

- If you want to benefit from security proofs, you must understand what the proof is about (the definitions and the theorem, not necessarily the proof itself).
- If you want people benefit from your proofs, try to make reading and understanding your definitions and your theorem as simple as possible.

- Theoretical abstractions (random oracle model, ideal cipher model, . . .) help to avoid complex definitions, but hinder the selection of real primitives (famous example: TDES-RMAC).