Public-Algorithm Substitution Attacks: Subverting Hashing and Verification

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PKC 2025

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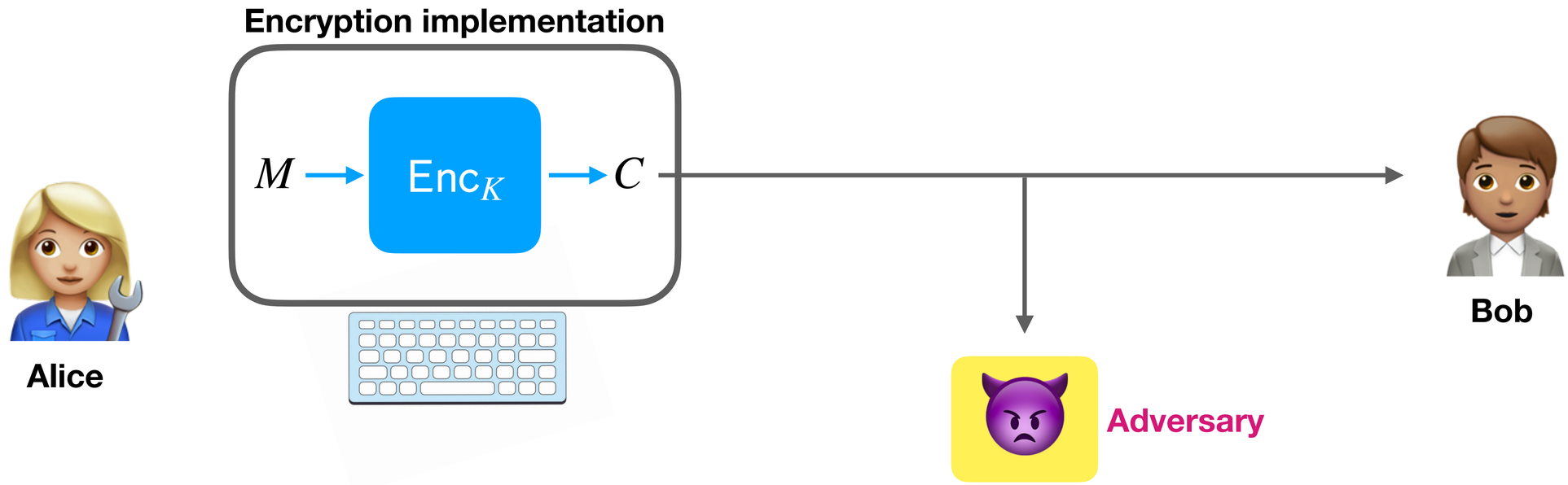
The textbook view of cryptography, illustrated for symmetric encryption:



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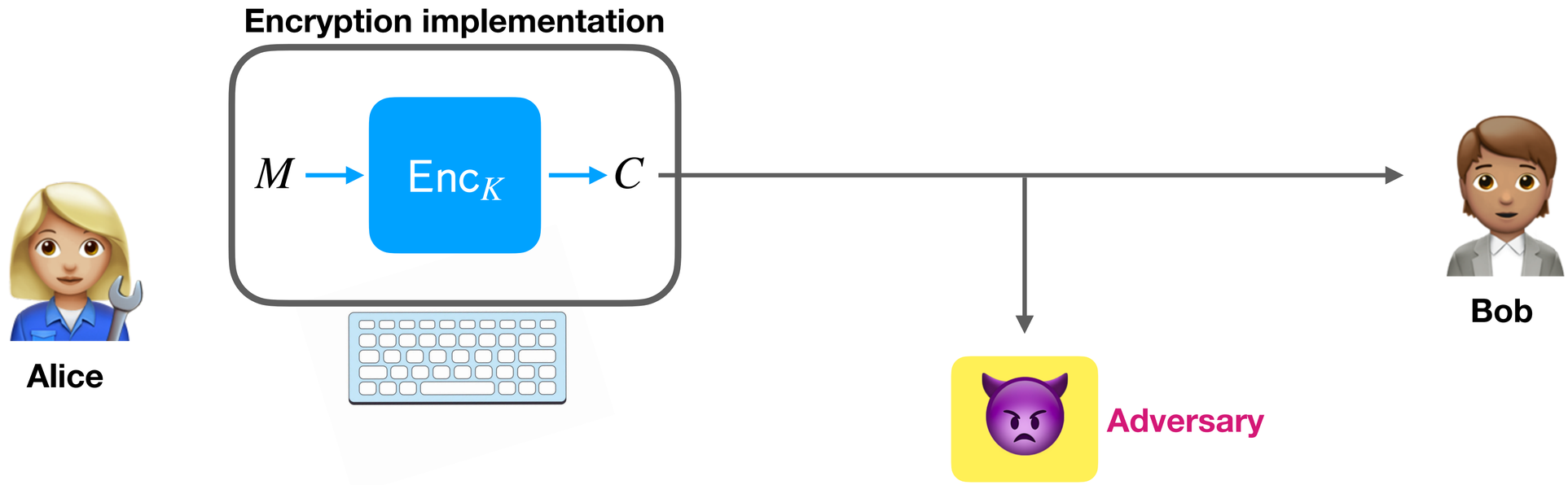
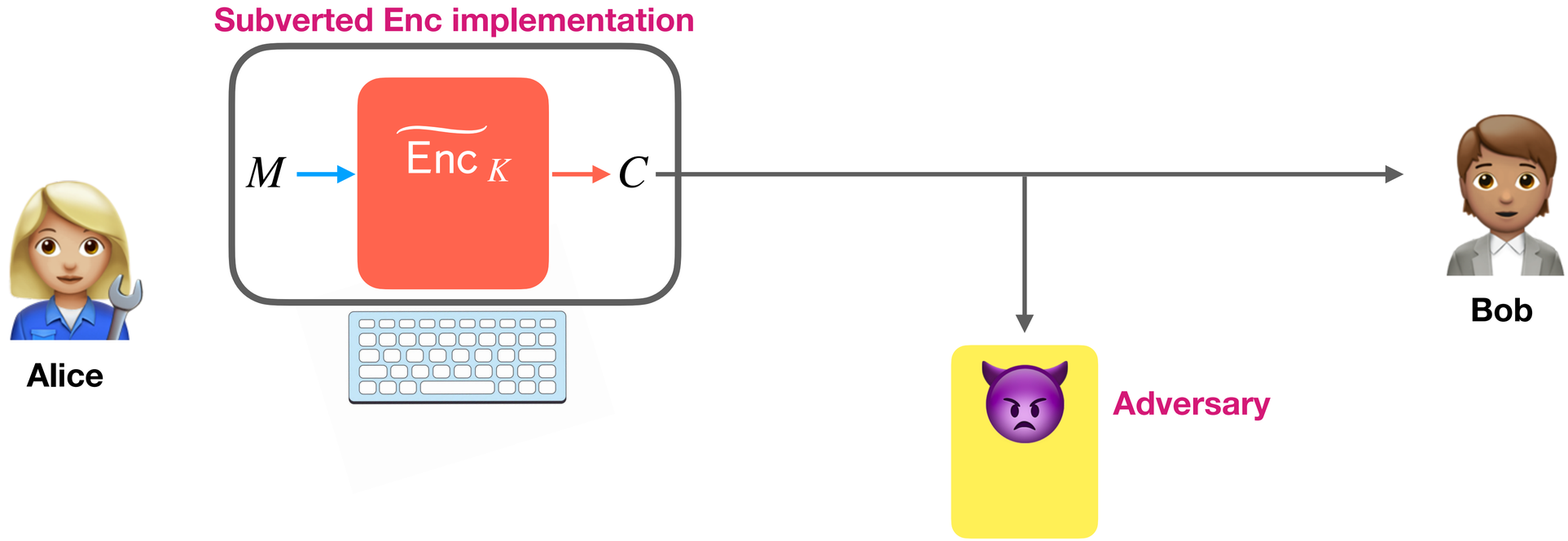


Here the encryption algorithm Enc_K is assumed to be CORRECTLY and HONESTLY implemented.

Our usual definitions, like IND-CPA, IND-CCA, AEAD, …
are all in this setting.

Cryptography, subverted !



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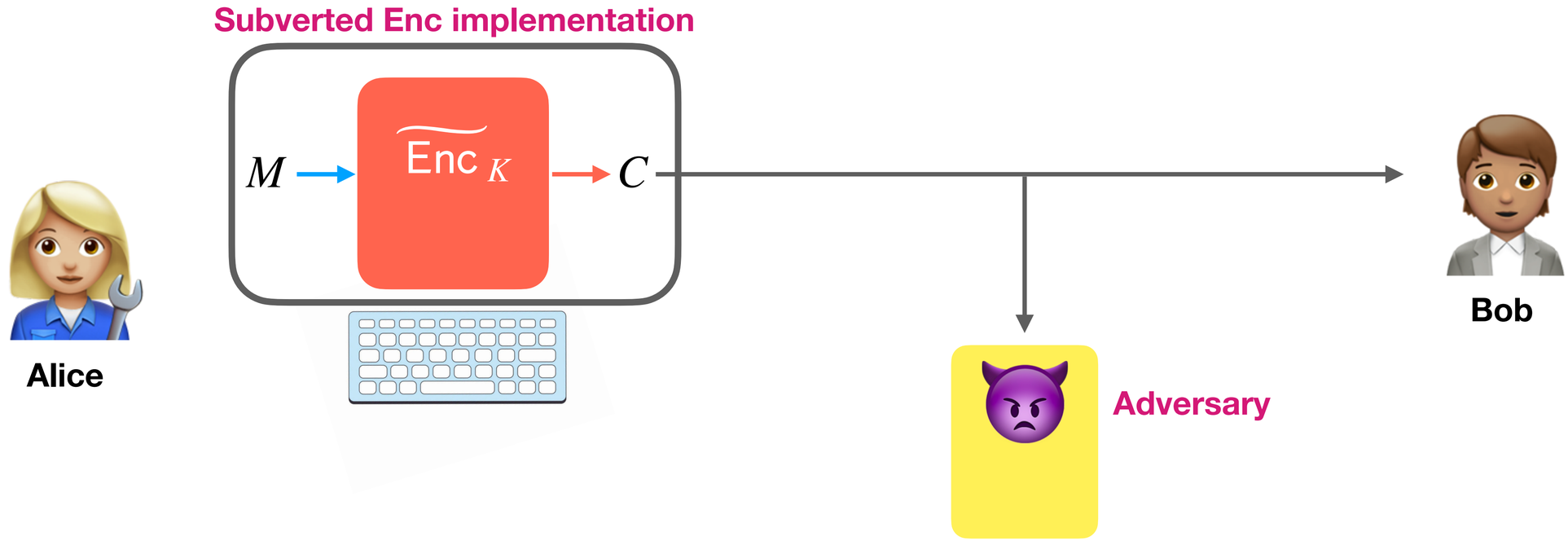

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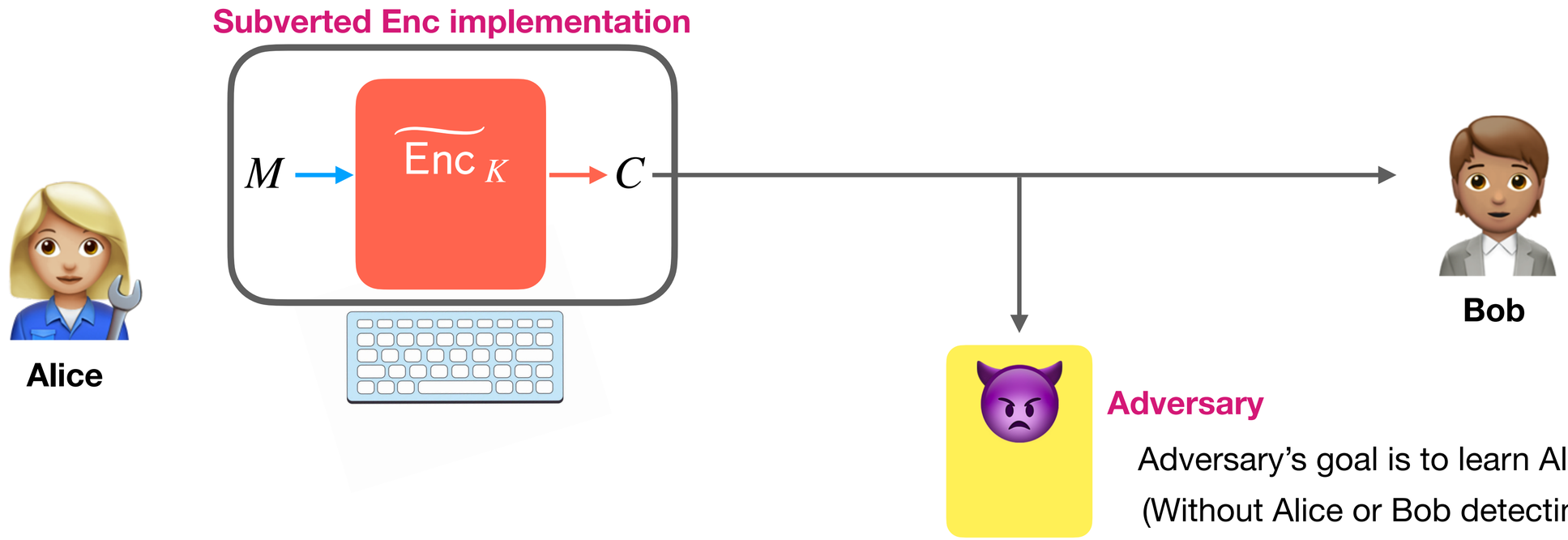

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(Without Alice or Bob detecting the subversion!)

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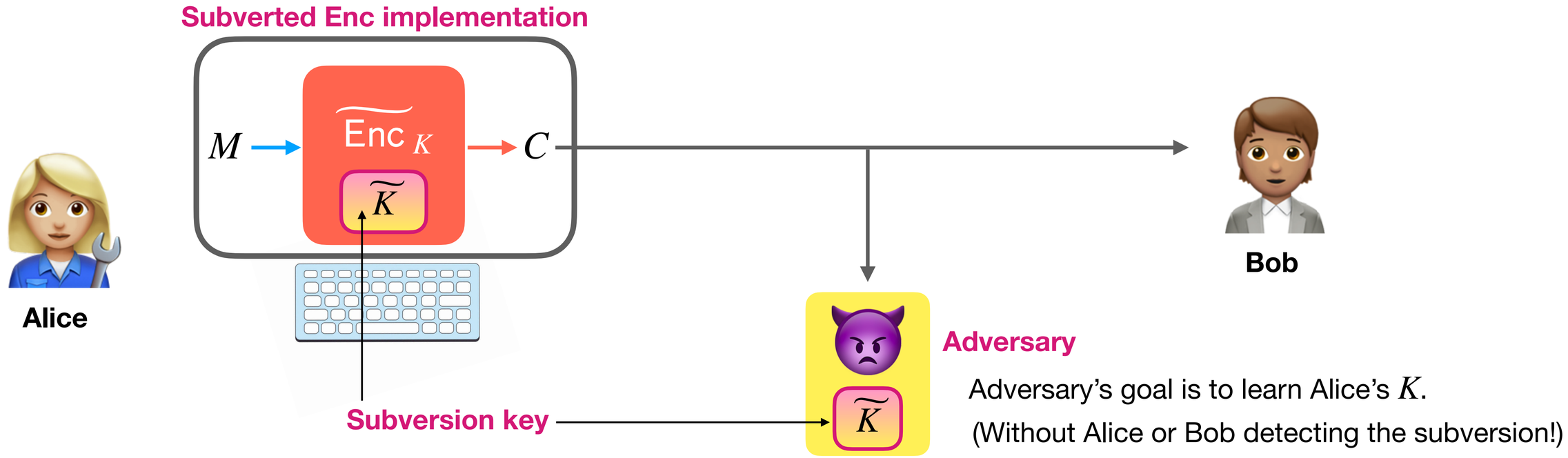

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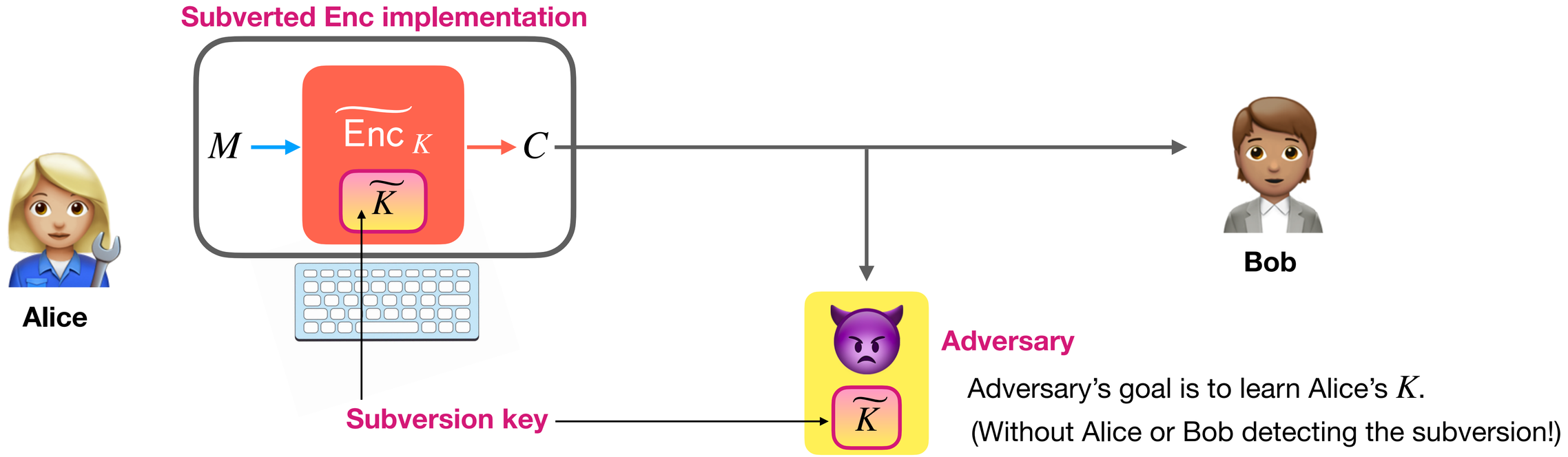

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Kleptography [YY96]

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or: Should We Trust Capstone?

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First (academic) suggestion of this category of attack.

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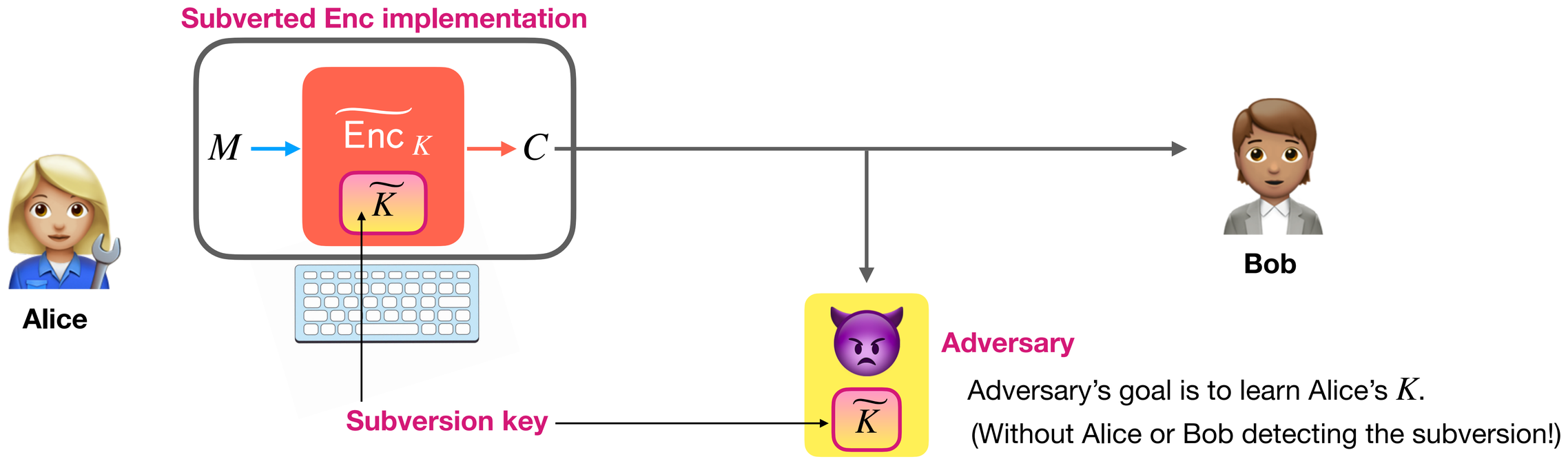

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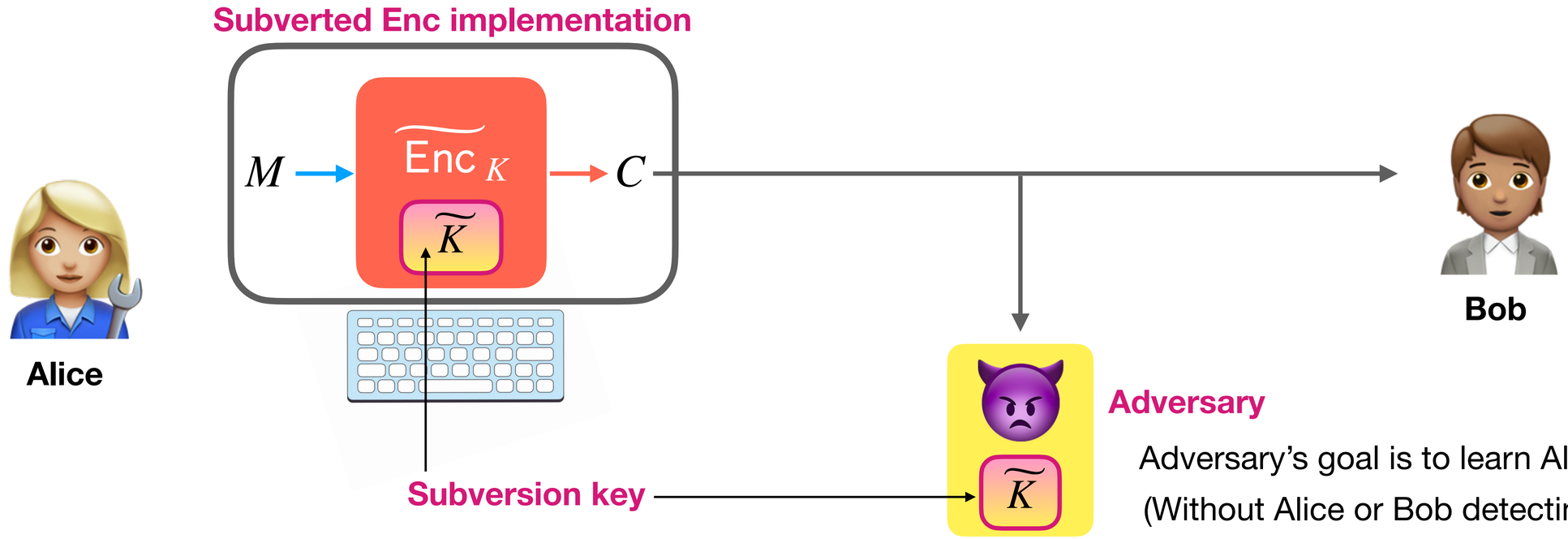

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Algorithm Substitution Attack **[BPR14]**

Security of Symmetric Encryption against Mass Surveillance

Mihir Bellare[1], Kenneth G. Paterson[2], and Phillip Rogaway[3]

A new formalism in response, with many extensions to follow…

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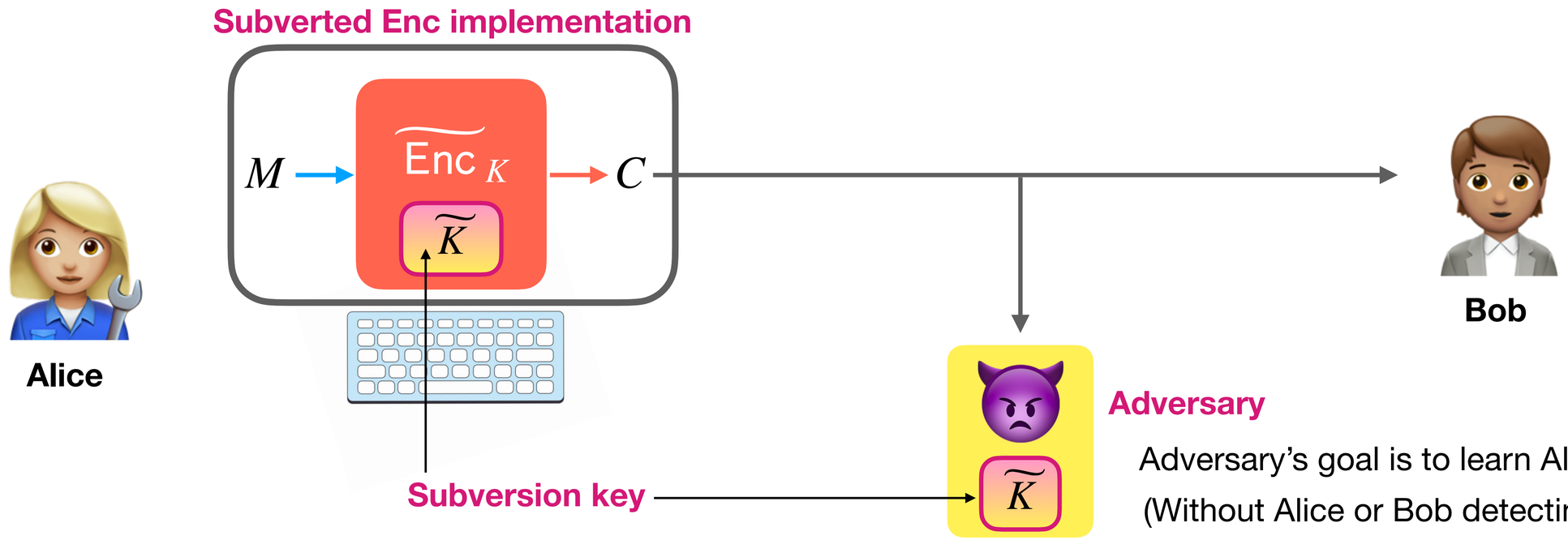

BPR14 Defined two critical properties:

Algorithm Substitution Attack **[BPR14]**

(1) Exfiltration

The adversary successfully learns Alice's secret K.

(2) Undetectability

Alice and Bob cannot tell that the subversion occurred.

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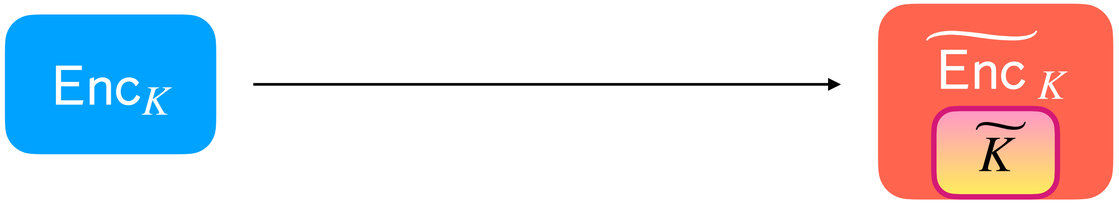
Algorithm Substitution Attack (ASA)



Symmetric encryption [BPR14, BJK15, DFP15, …]

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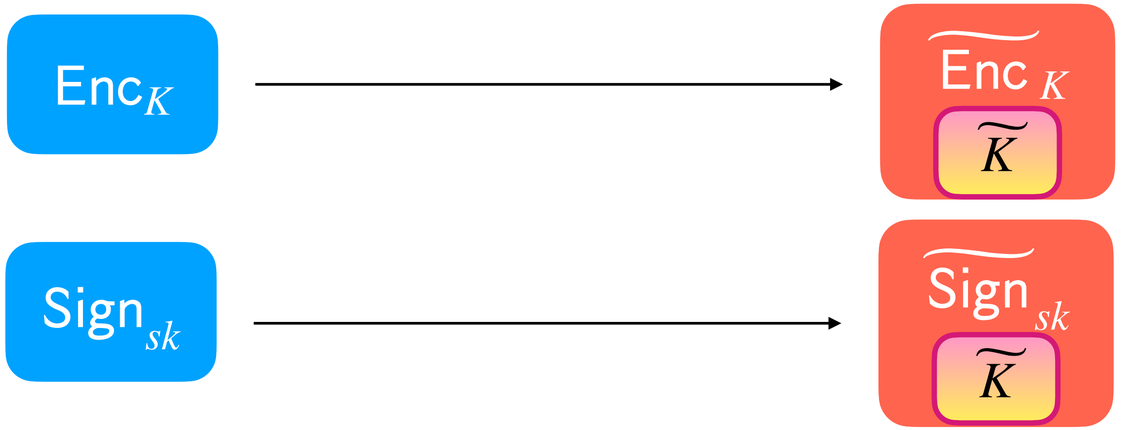

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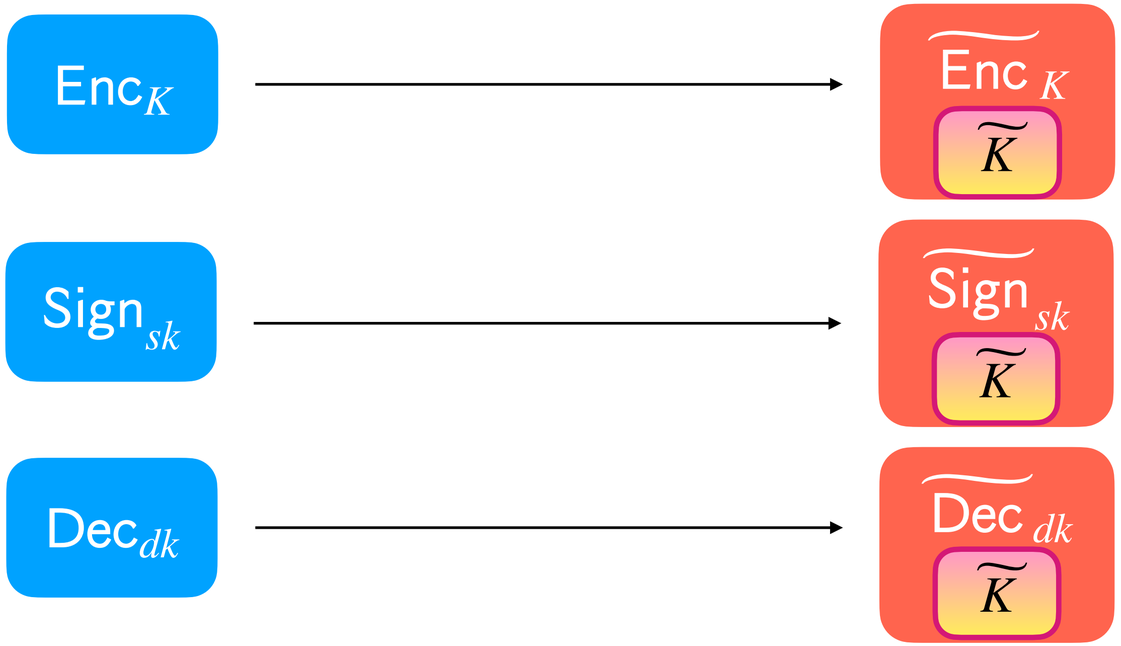

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Protocols and more! [BWP+22, GBPG03, …]

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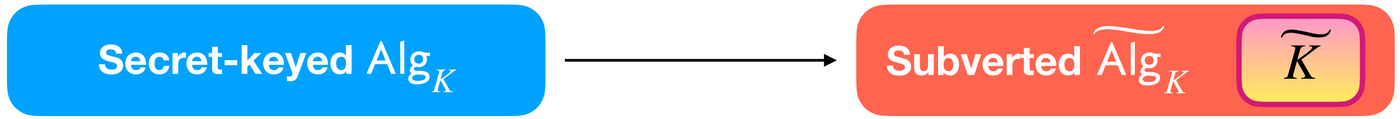

Alice's *secret-keyed* algorithm subverted…

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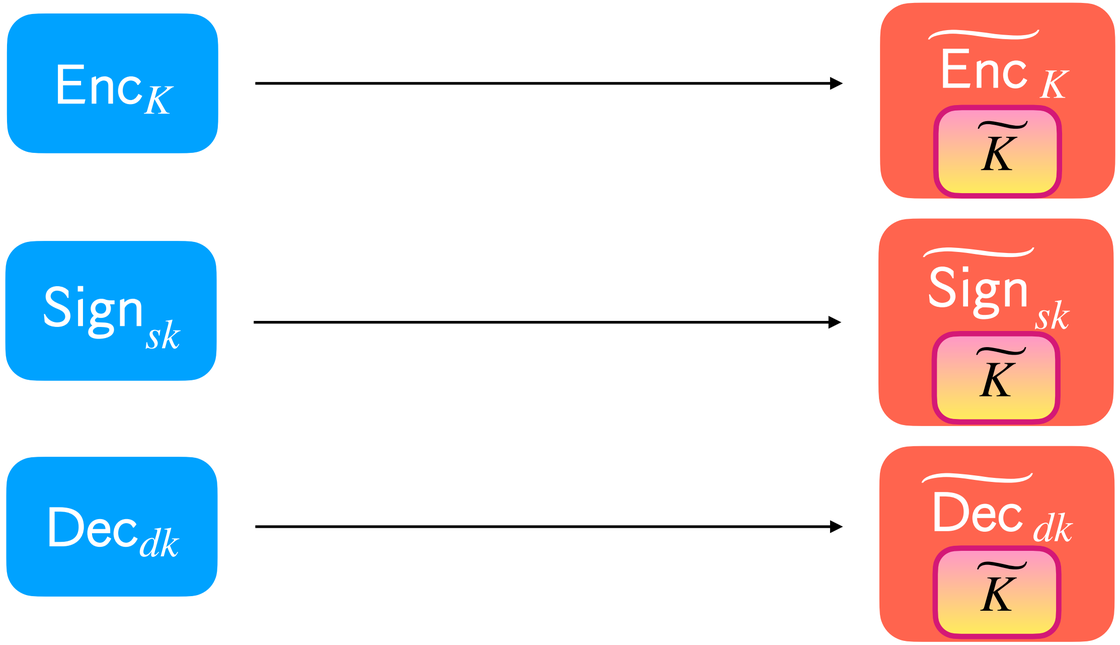

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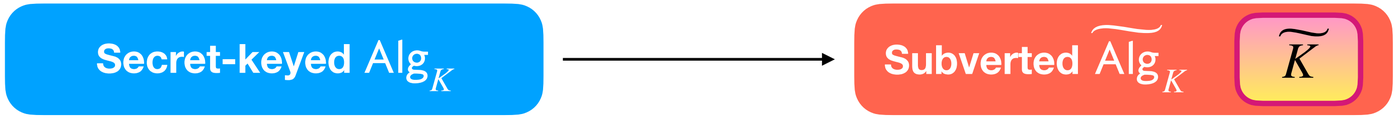
Secret-Algorithm Substitution Attack (*S*-ASA)

We call these **Secret-ASAs**.



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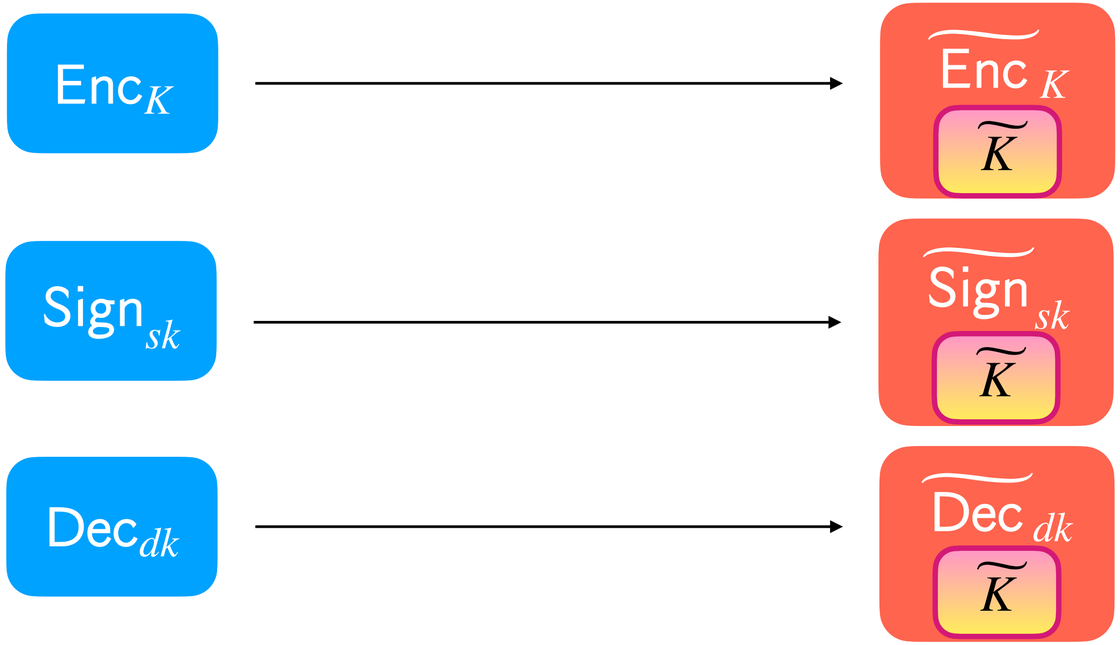

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Topic of this talk:

Public-Algorithm Substitution Attack (*P*-ASA)

Summary of contributions:

1. Give a definition for an ASA on a *public* algorithm.
2. Design a construction satisfying the definition.

} **For an *arbitrary* public algorithm**

3. Look in more detail at important applications:

   Hash functions, as used in certificates or password-based authentication.

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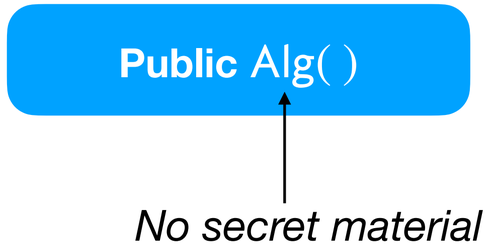

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Public $\mathrm{Alg}(\,)$

No secret material

The two components of a **P-ASA** on $\mathrm{Alg}(\,)$:

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Exploit Expl( )

AND, the attacker retains some kind of **Exploit** algorithm.

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It is a subversion generator:

$$(\widetilde{\text{Alg}}, \text{Expl}) \xleftarrow{\$} \text{SubGen}(\text{Alg})$$

which takes the target algorithm, and produces the two attack components.

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"Utility is *exclusive* to the holder of Expl."

For anyone else, it's hard to find an input x on which $\widetilde{\text{Alg}}$ and Alg differ.

+ With oracle access to Expl( )
+ And with white-box descriptions of $\widetilde{\text{Alg}}$ and Alg.

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We construct a P-ASA using an SUF signature scheme, and an “embedding function.”

Generalizing GKVZ22 (“ML backdoors”)

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These are all specific cases of our general construction

☑ Introductory picture & overview of results

Public-Algorithm Substitution Attacks on Hash functions

- ☐ **Definitions: Undetectability, Exclusivity, Utility**
- ☐ Construction of a Public-ASA
- ☐ One application

☐ Concluding remarks on the general case

The honest picture for a Hash function H

$H \xleftarrow{\$} \text{HGen}$

H is selected honestly by generator HGen,
and may include a hardcoded key.

Desired security property: CR

H is collision-resistant to any (efficient) adversary,
when the adversary is given H.

The subverted picture for a Hash function H

A P-ASA is a “subversion generator”
which generates $\widetilde{H}$ and Expl given H.

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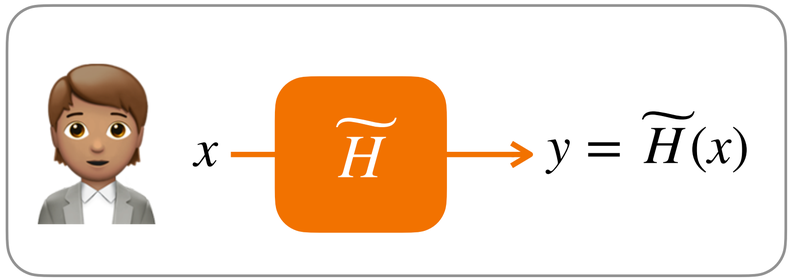

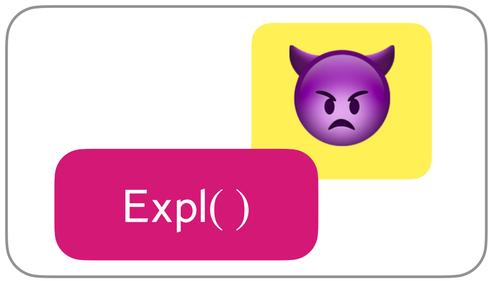

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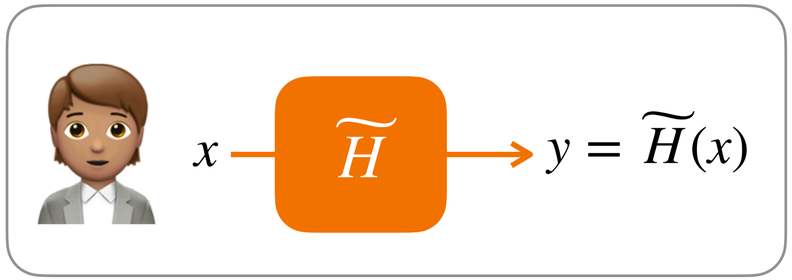

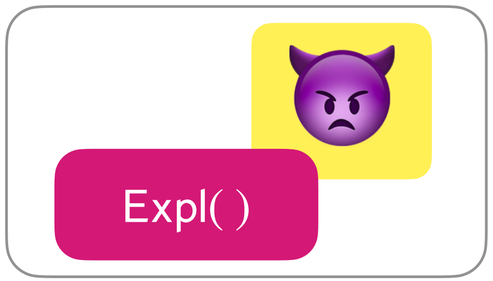

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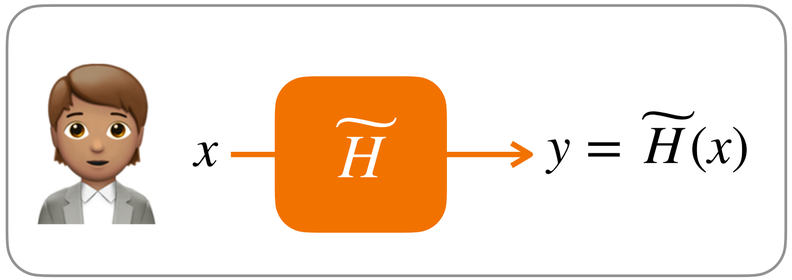

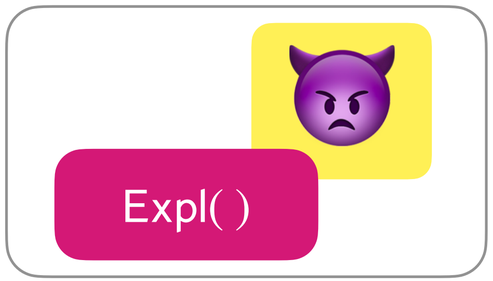

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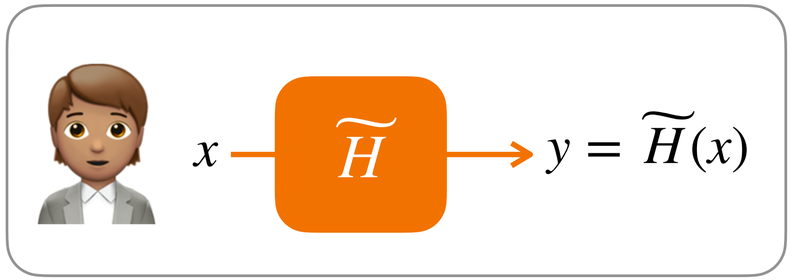

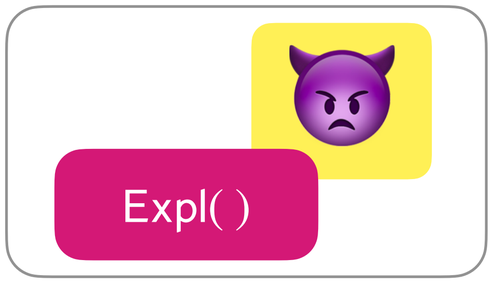

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What "structure" is this possible for?

- Requiring a specific prefix or suffix
- Requiring that x be an X.509 cert with certain data
- …more! The paper gives constraints.

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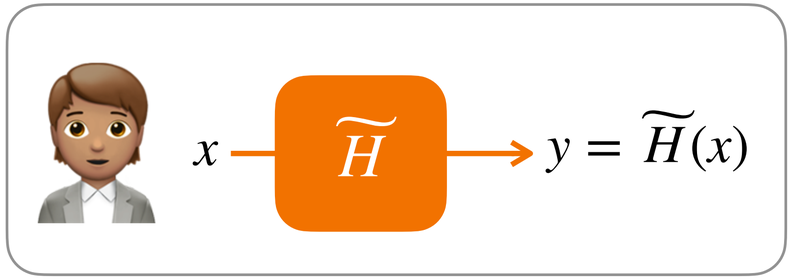

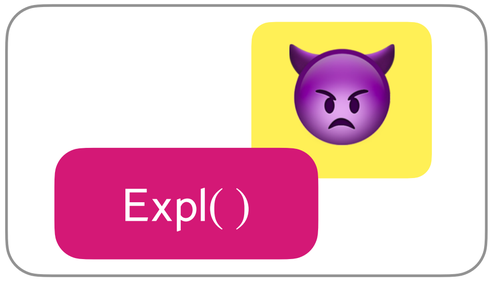

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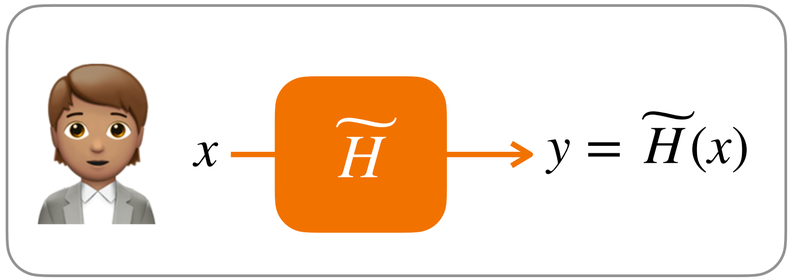
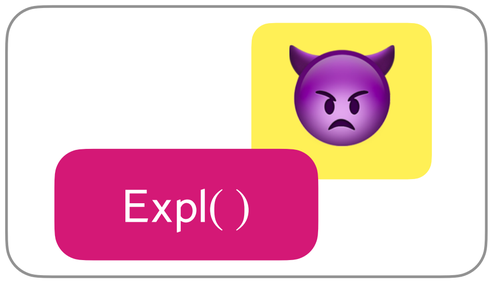
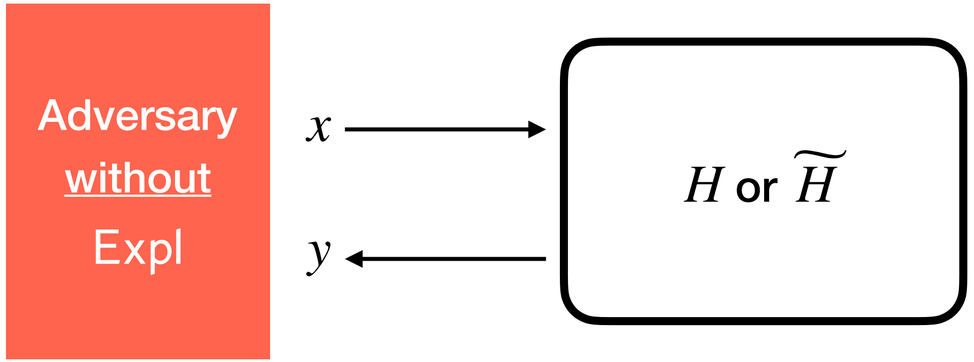




Undetectability



The subverted picture for a Hash function H

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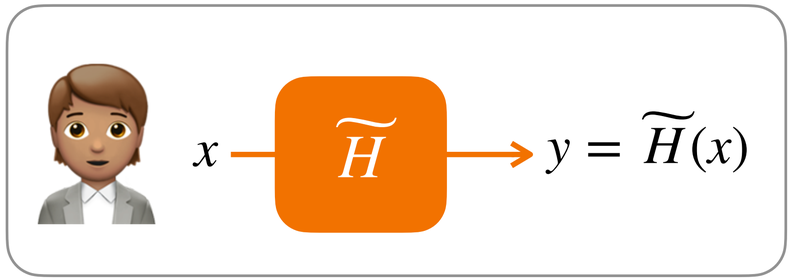

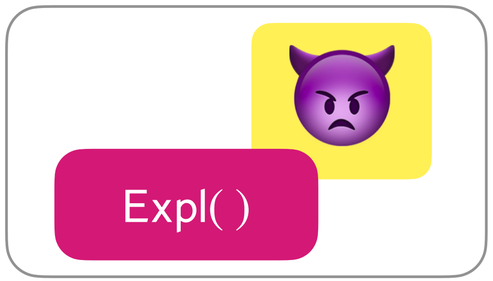

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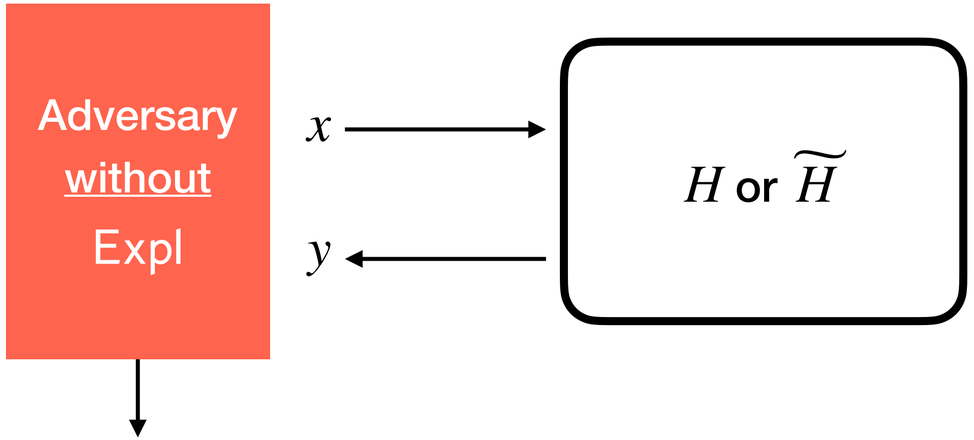

Decide which is in the box

Undetectability says:

It’s hard to correctly decide which of H or $\widetilde{H}$ is in the box, for all (efficient) adversaries without Expl.

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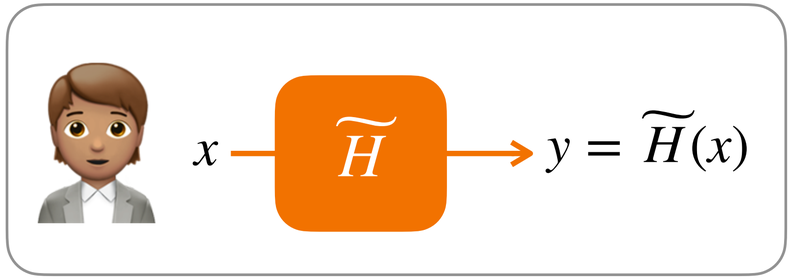

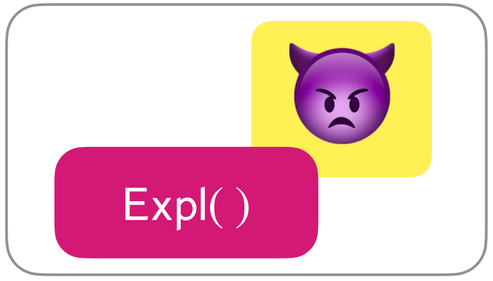

Exclusivity

Adversary
<u>without</u>
Expl

The subverted picture for a Hash function H

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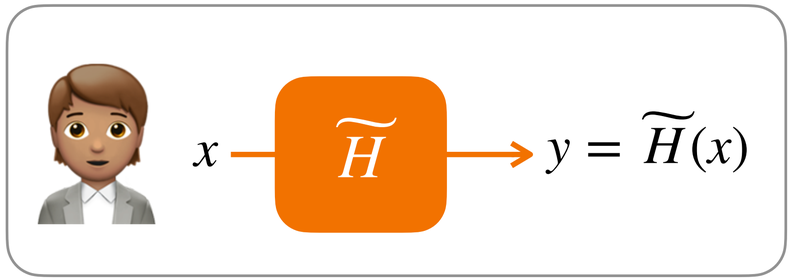

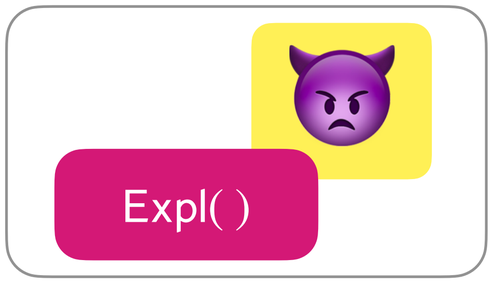

Exclusivity

Descriptions of H and $\widetilde{H}$

↓

Adversary **without** Expl

↓

An x such that $H(x) \neq \widetilde{H}(x)$

Exclusivity says:

Any differences between H and $\widetilde{H}$ are only findable by the adversary with the exploit, not by anyone else.

The subverted picture for a Hash function H

A P-ASA is a "subversion generator" which generates $\widetilde{H}$ and Expl given H.

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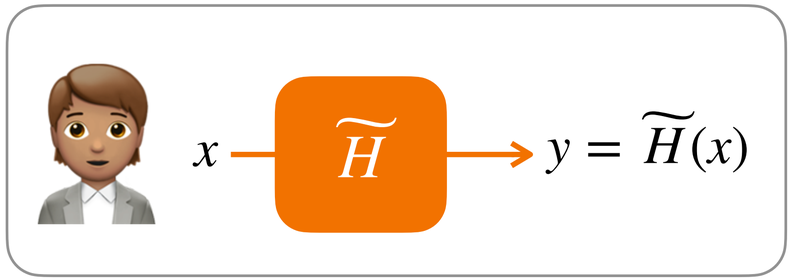

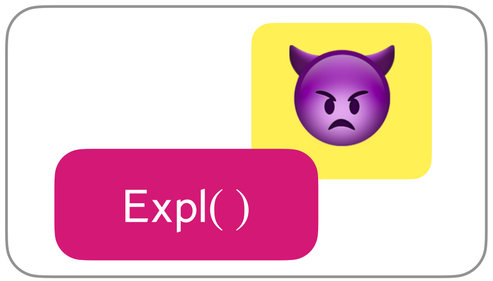

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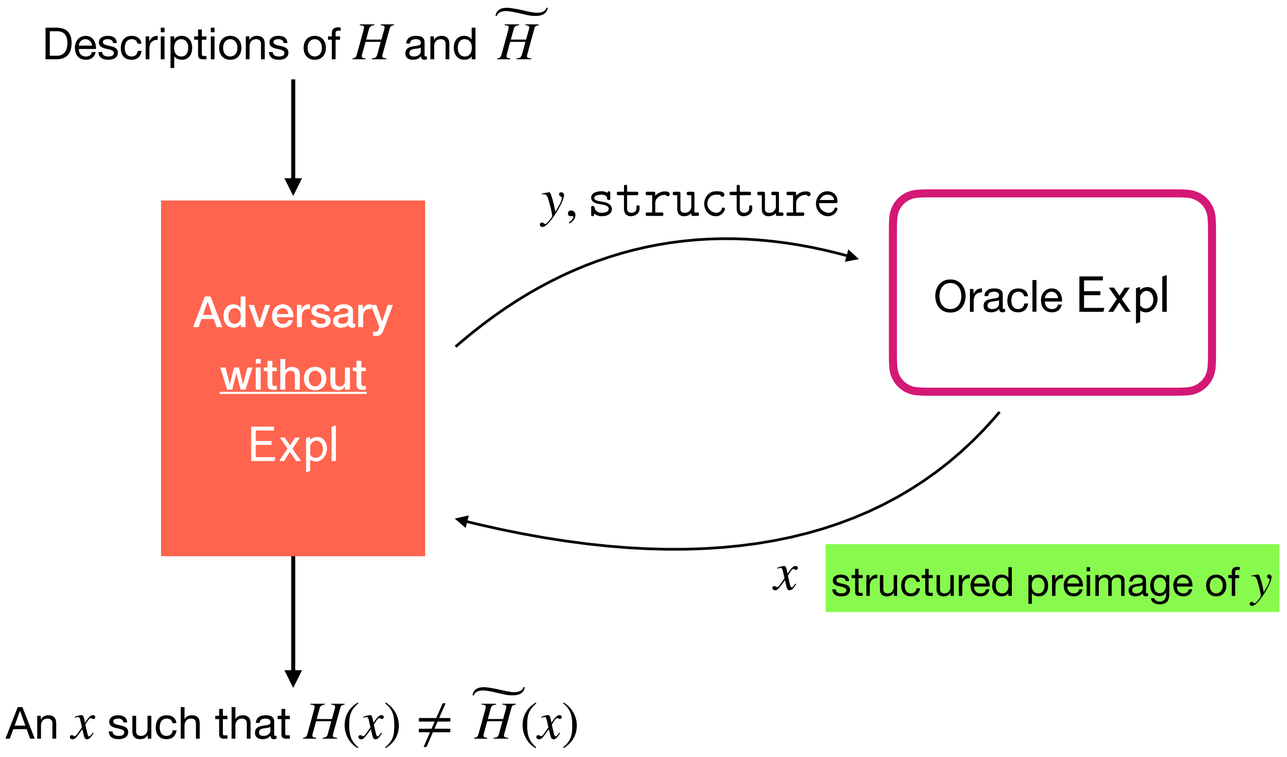

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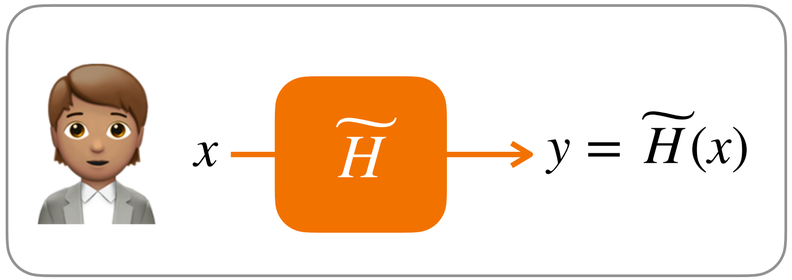

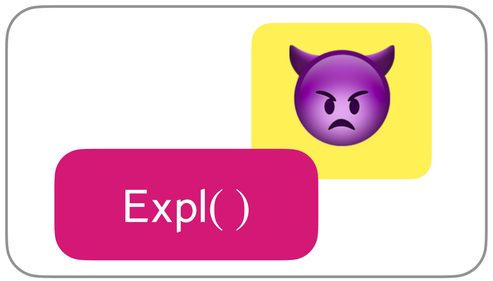

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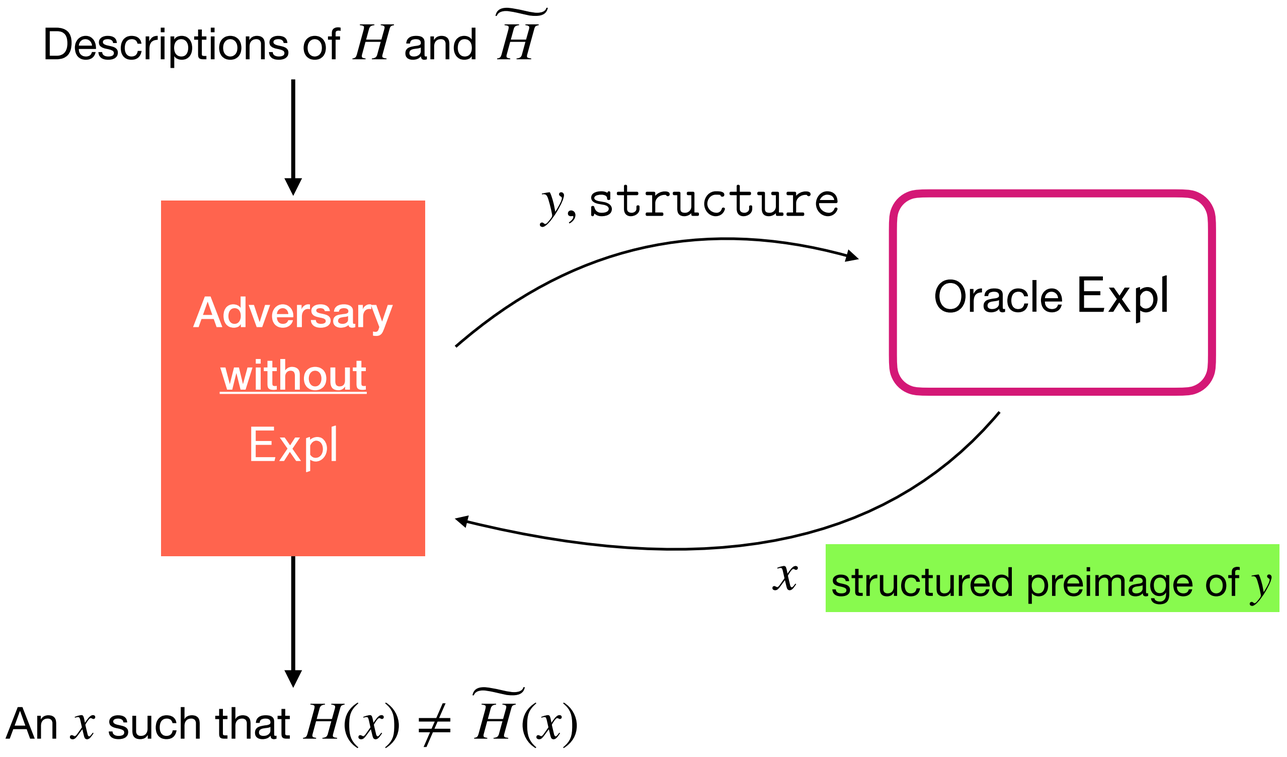

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Remark: This implies undetectability!

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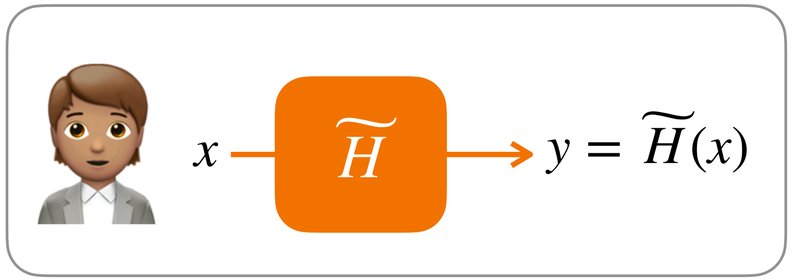

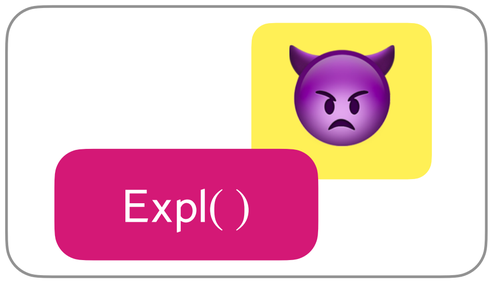

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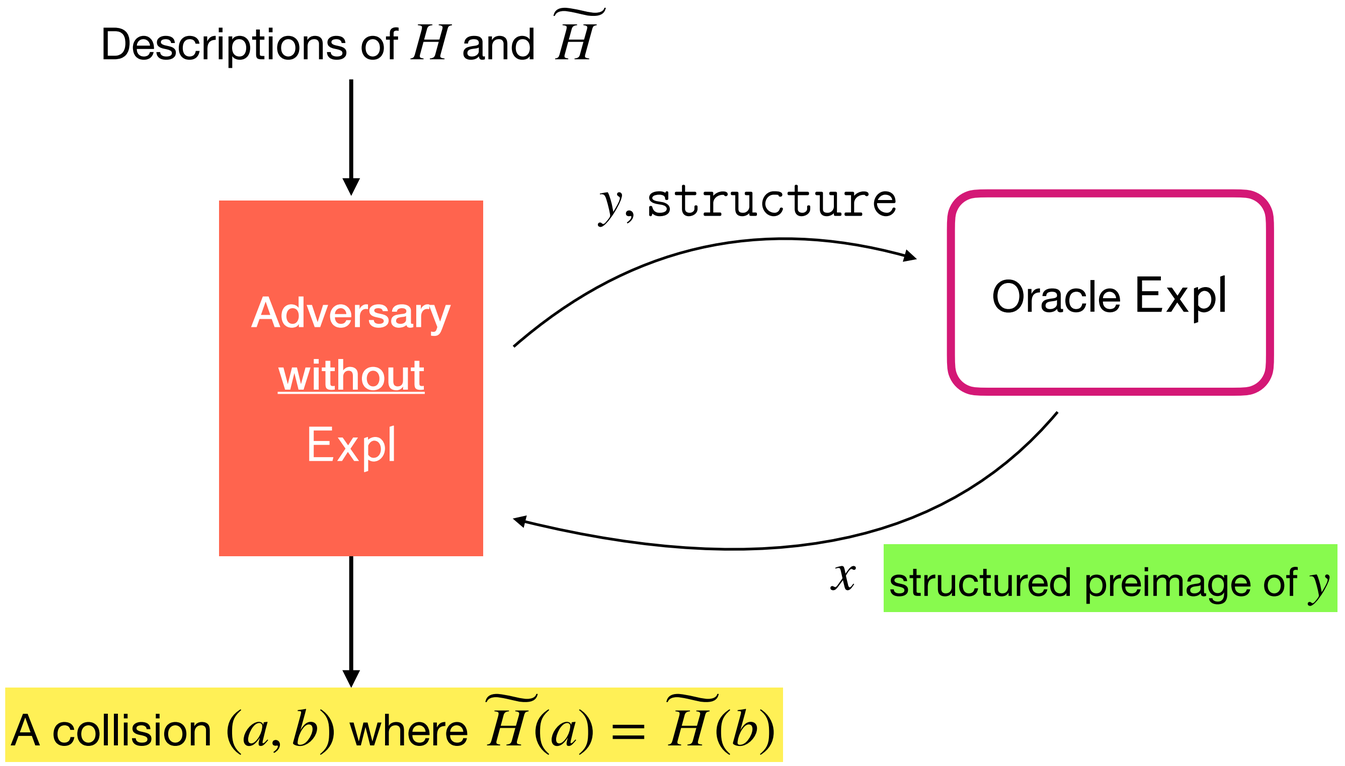

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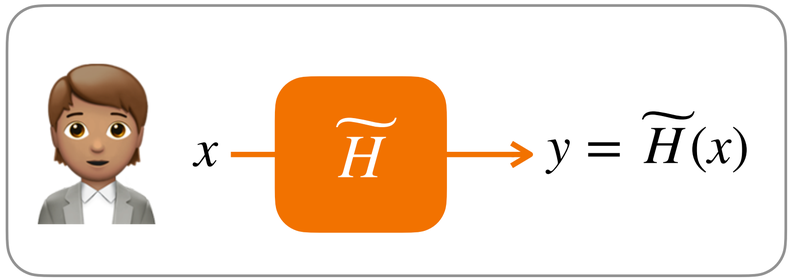
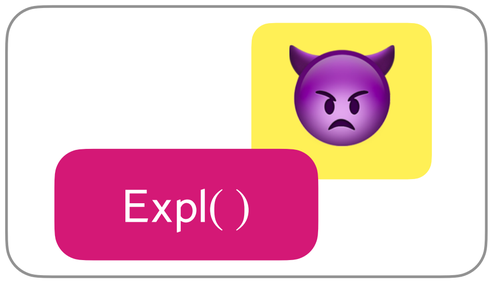
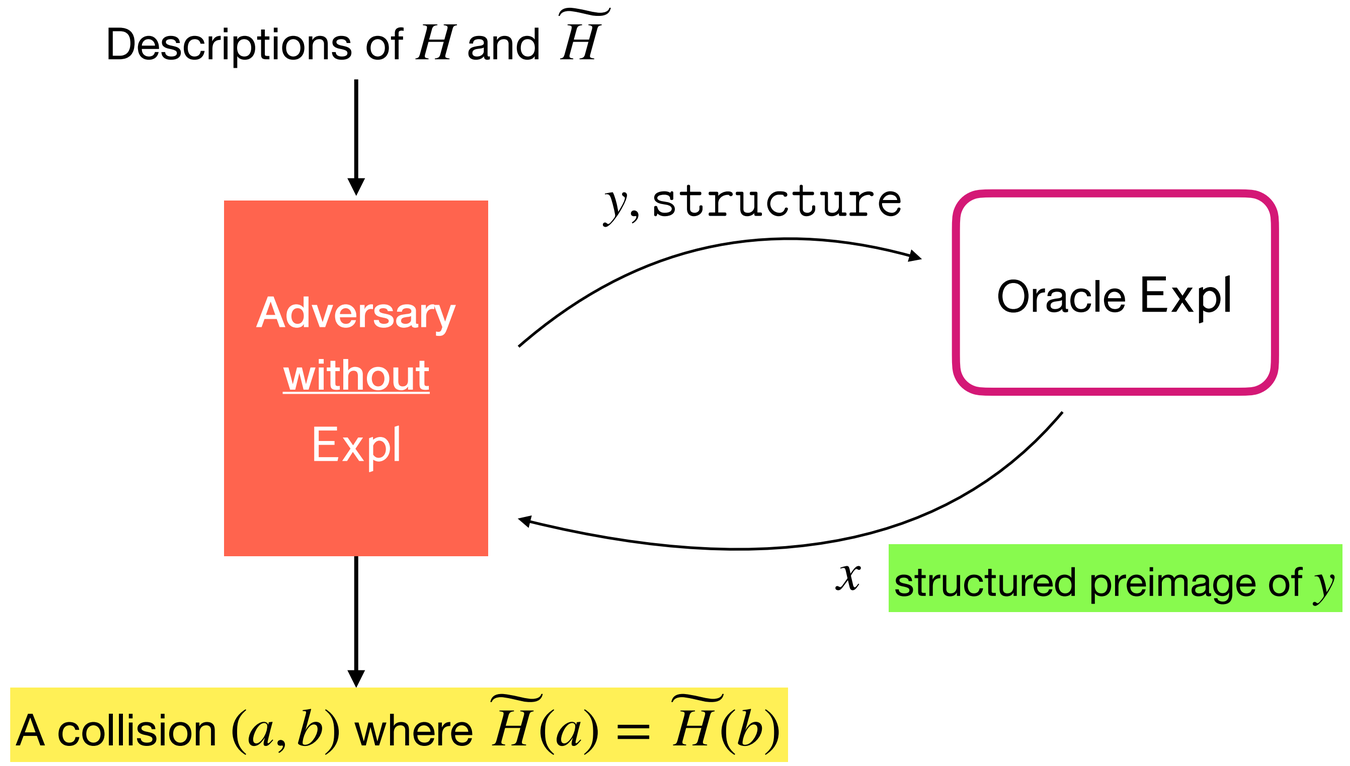




"CR Exclusivity" for a Hash function



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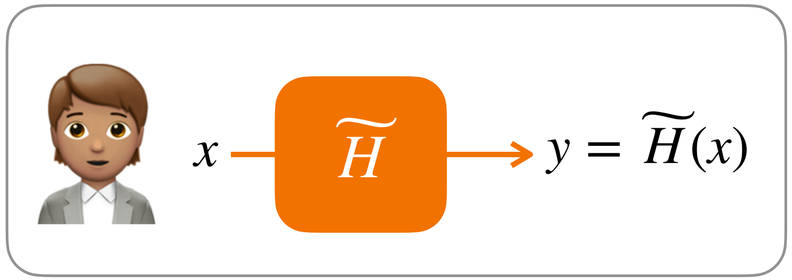

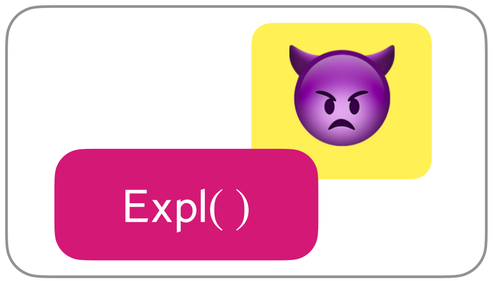

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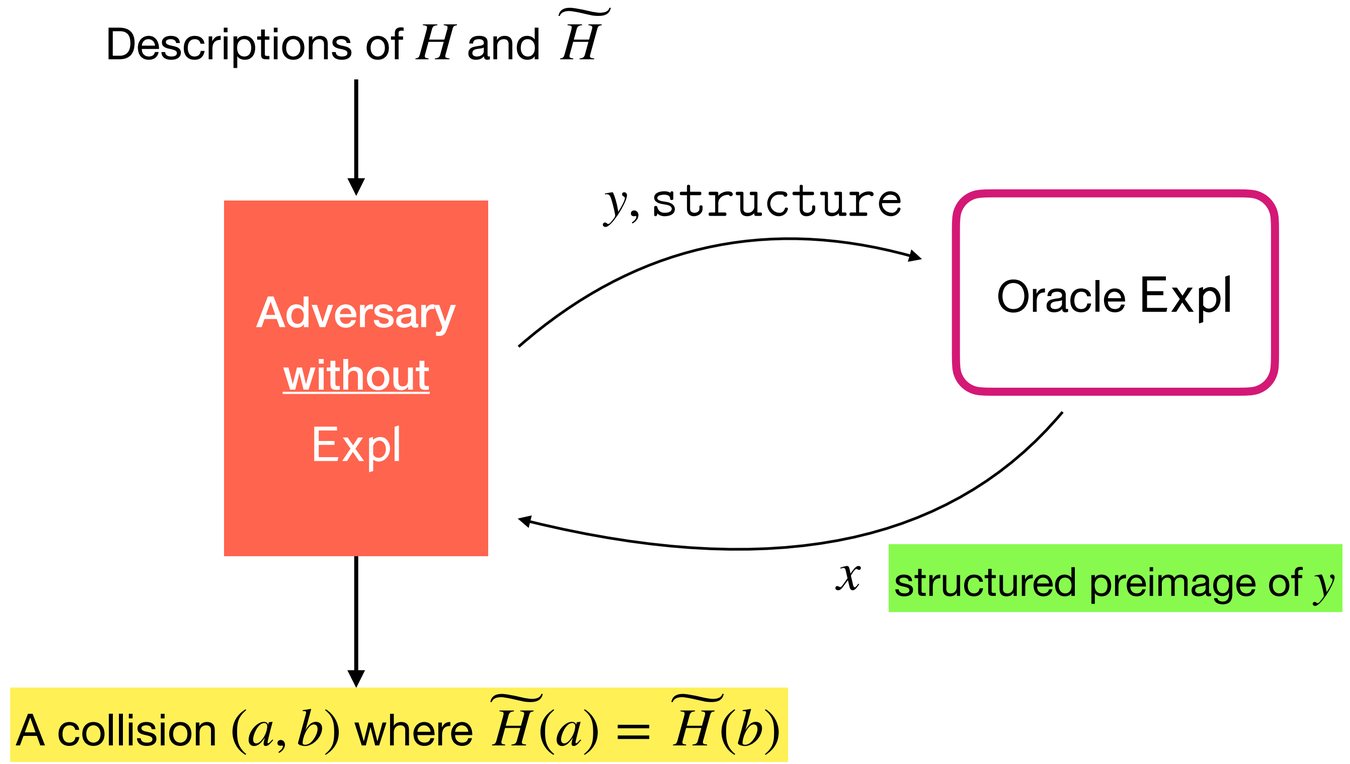


We can ask for "CR Exclusivity" as well.

It turns out to be implied by **Exclusivity** on the prior slides, and **CR** of the original H.

Other styles of subversion CR were considered by [FJM18, AAEMS14], specifically for Hash functions.

☑ Introductory picture & overview of results

Public-Algorithm Substitution Attacks on Hash functions

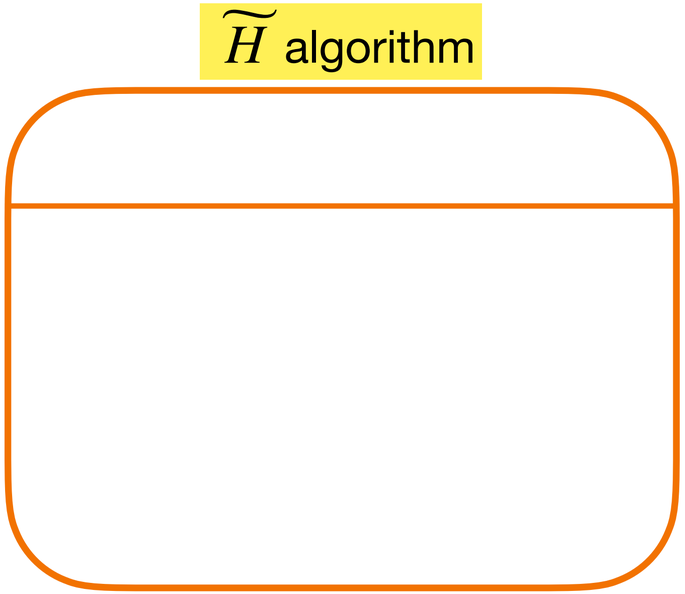
- ☑ Definitions: Undetectability, Exclusivity, Utility
- ☐ **Construction of a Public-ASA**
- ☐ One application

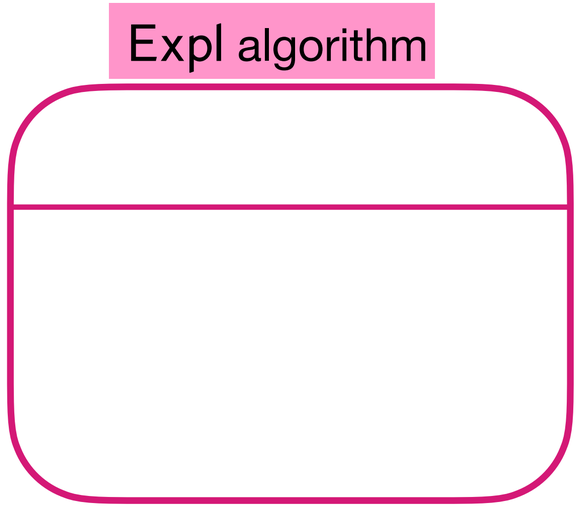
☐ Concluding remarks on the general case

Can you build such a Public-ASA?

One idea:
FJM18

$(\widetilde{H}, \mathsf{Expl}) \xleftarrow{\$} \mathsf{FJMSubGen}(H)$





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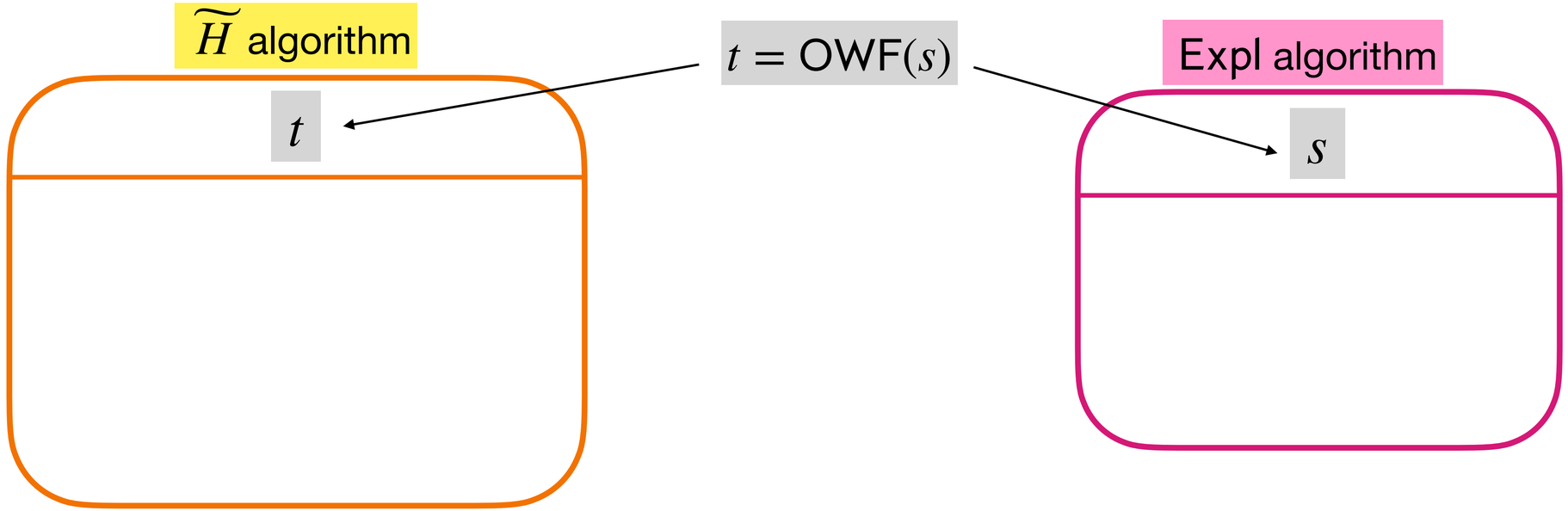

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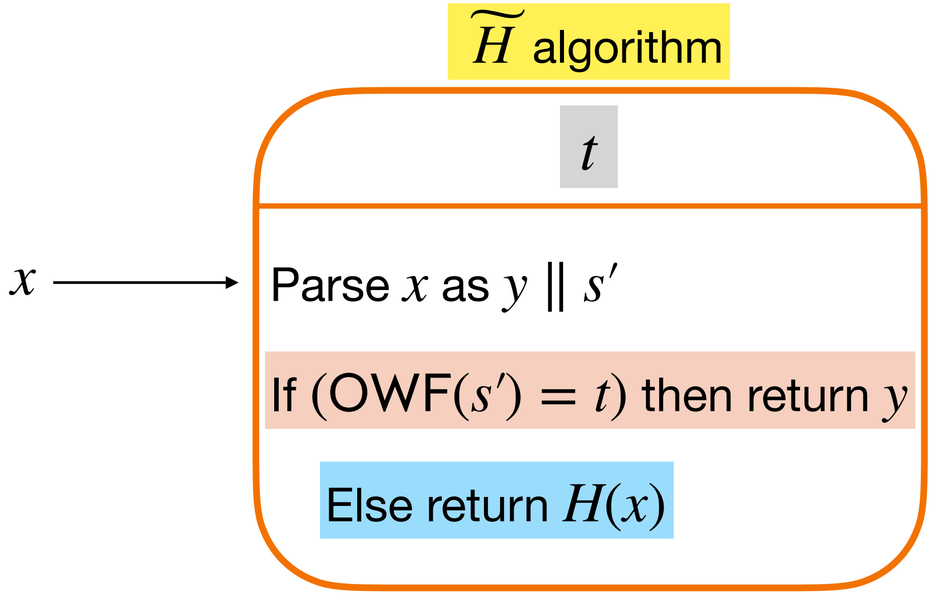
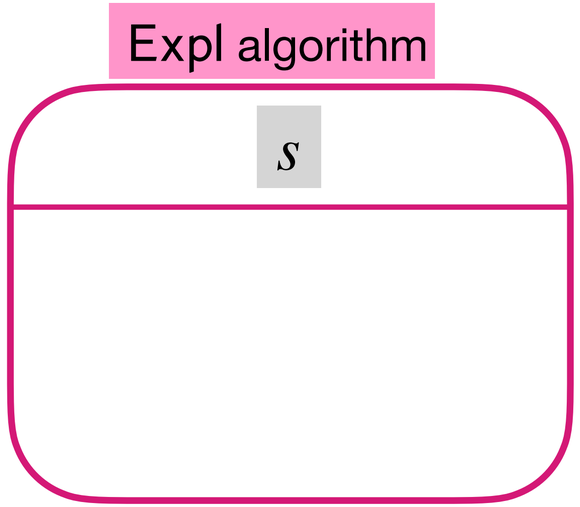


$t = \text{OWF}(s)$



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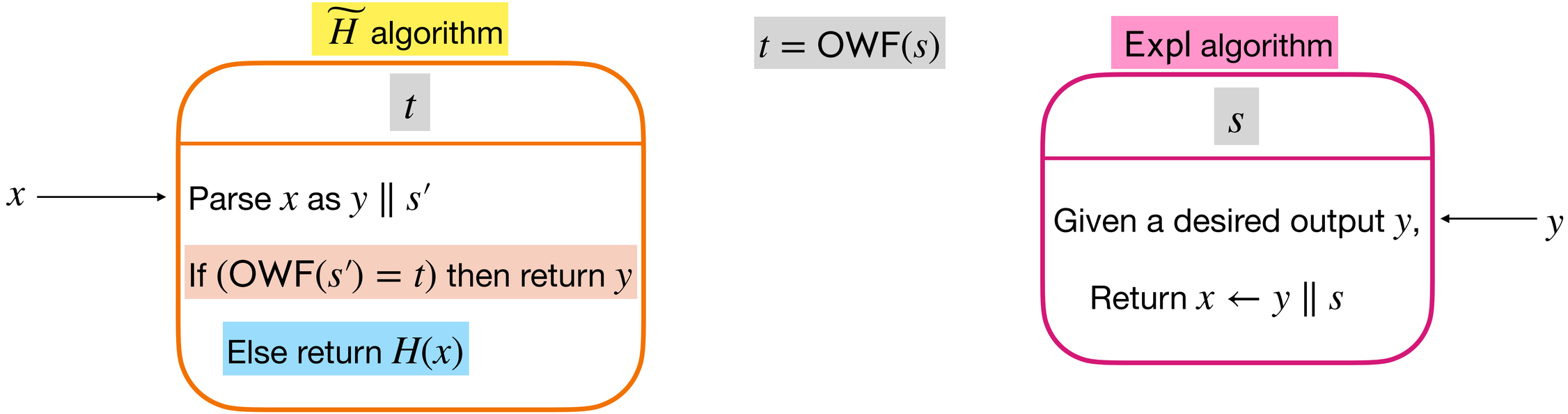

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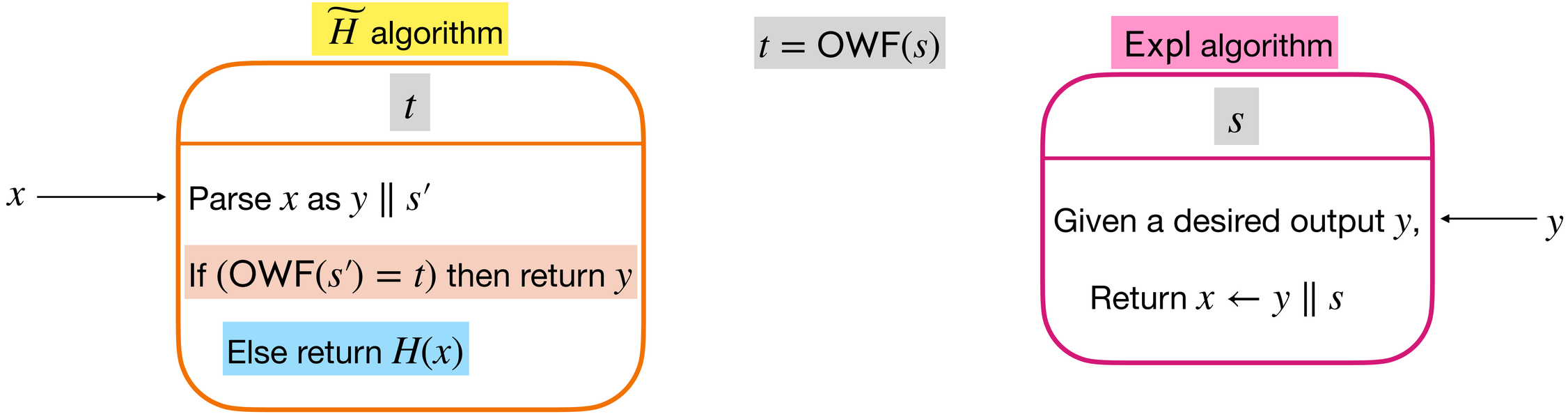

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The attacker, with Expl, can find preimages, but they *can only* be structured as $y \| s$.

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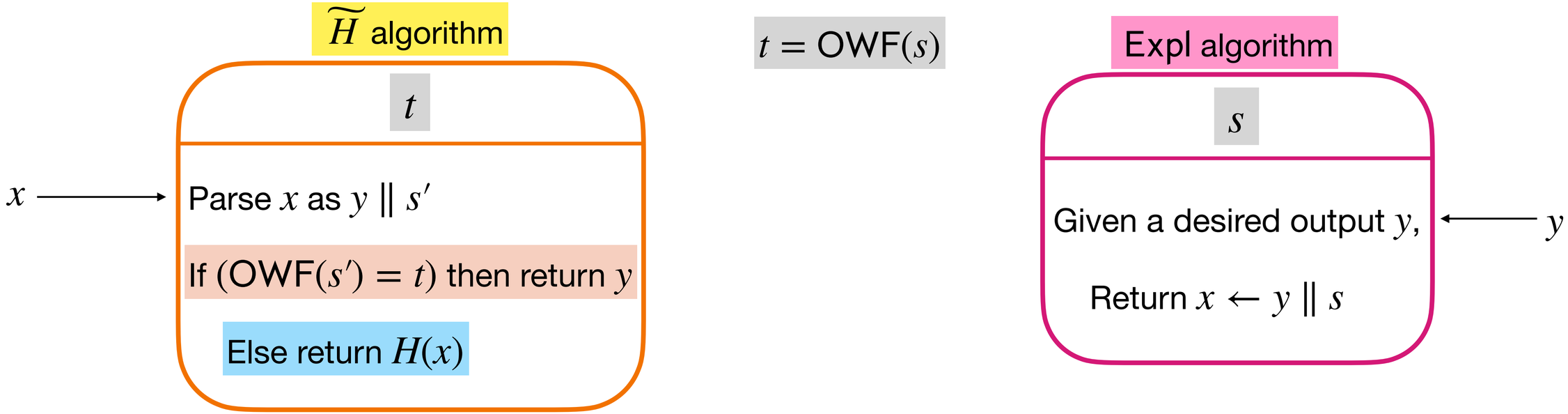

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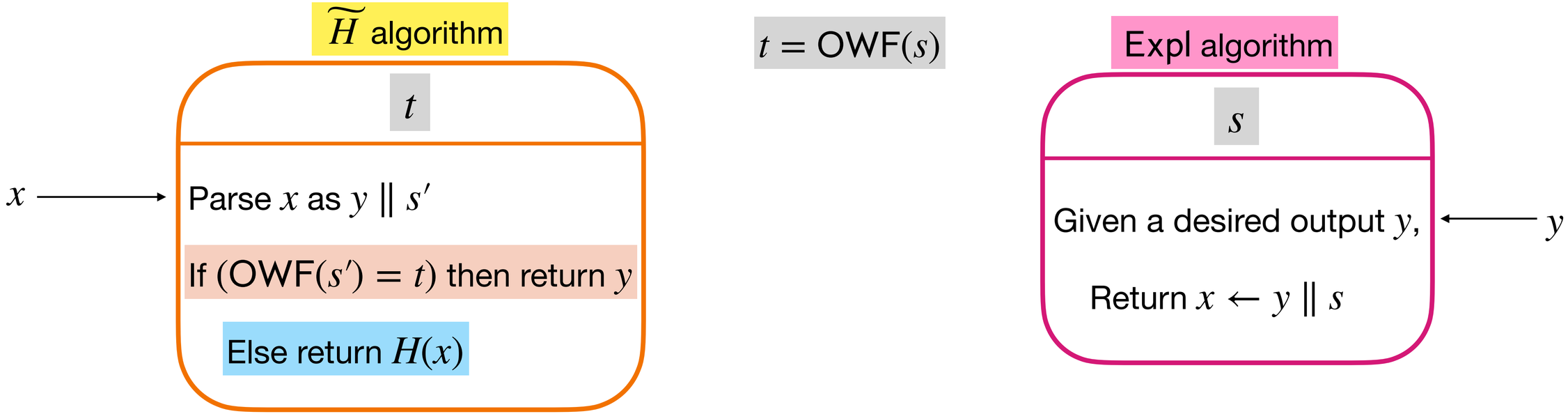

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Exclusive? NO.

Seeing one Expl-produced $x = y \| s$ reveals s, which allows finding preimages (breaking CR).

Our construction

$(\widetilde{H}, \mathsf{Expl}) \xleftarrow{\$} \mathsf{SubGen}(H)$

Invertible embedding function:
$\mathsf{Embed}, \mathsf{Embed}^{-1}$

Signature scheme S

$\widetilde{H}$ algorithm

Expl algorithm

Our construction

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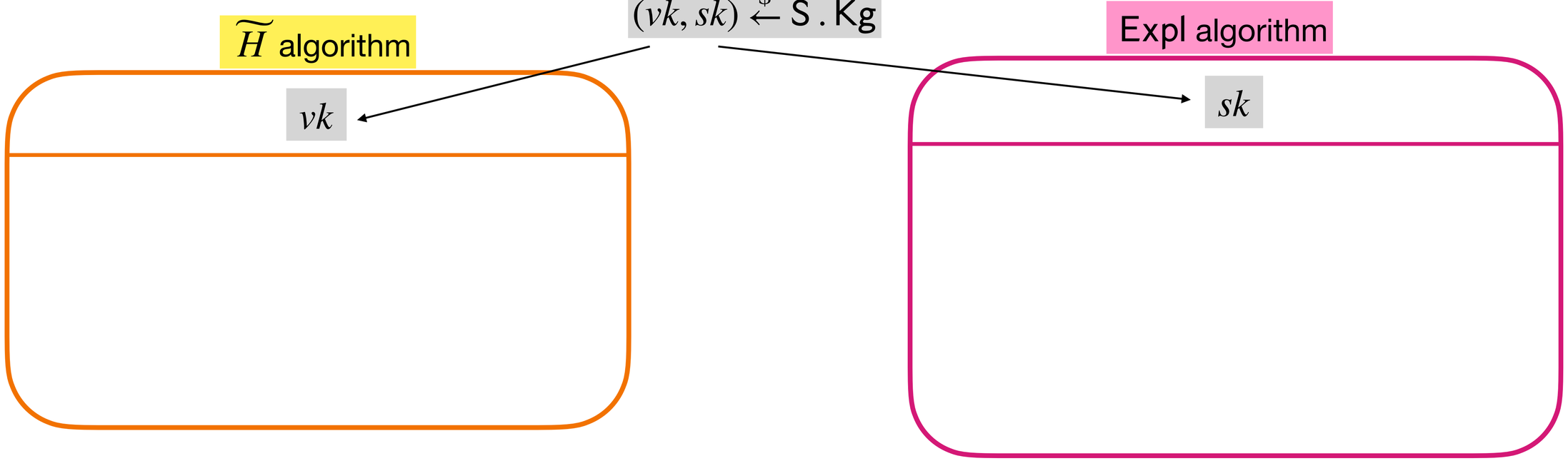

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$\widetilde{H}$ algorithm

vk

x →

Run $(y, struc, \sigma) \leftarrow \text{Embed}^{-1}(x)$

If $\text{S . Vfy}(vk, (y, struc), \sigma)$ then return y

Else return $H(x)$

Expl algorithm

sk

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$y, struc$

Given a **desired output** y
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Utility? YES, for structures that can be embedded this way.

The attacker can find *structured preimages*, assuming S is correct and the embedding "works."

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Running "$x \leftarrow \mathsf{Embed}(y, struc, \sigma)$" means x has this desired $struc$.

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Black-box undetectable? YES, assuming UF-CMA of signature scheme S.

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Return $x \leftarrow \text{Embed}(y, struc, \sigma)$

Exclusive? YES.

Assuming SUF-CMA of the signature scheme S, and that the embedding "works."

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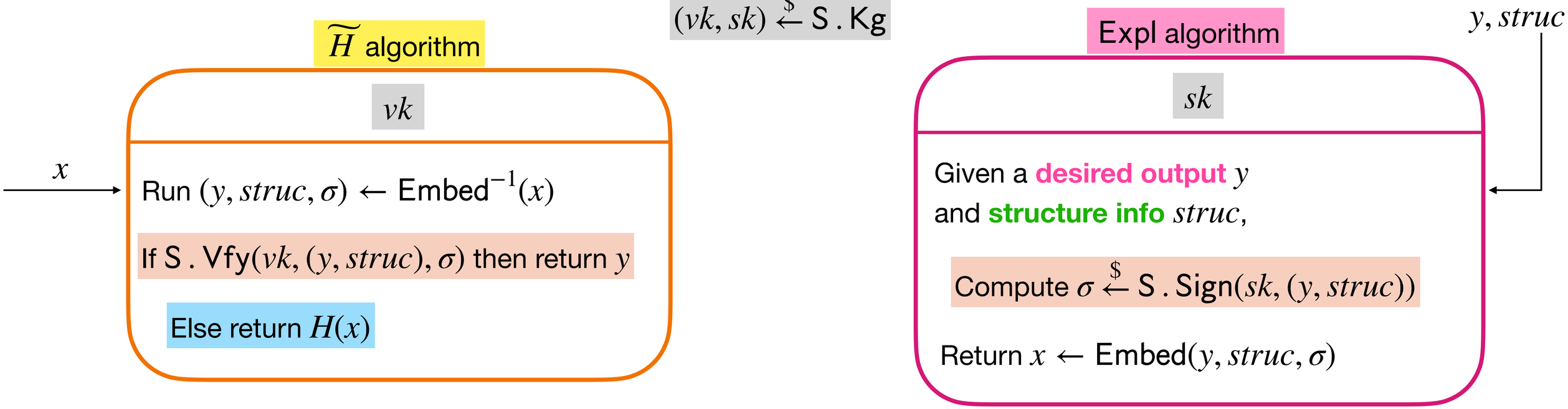
Signature scheme S

$(vk, sk) \xleftarrow{\$} \mathsf{S}.\mathsf{Kg}$



Exclusive? YES.
Assuming SUF-CMA of the signature scheme S, and that the embedding "works."

CR Exclusive? YES.
Additionally assuming that the original H is CR.

☑ Introductory picture & overview of results

Public-Algorithm Substitution Attacks on Hash functions

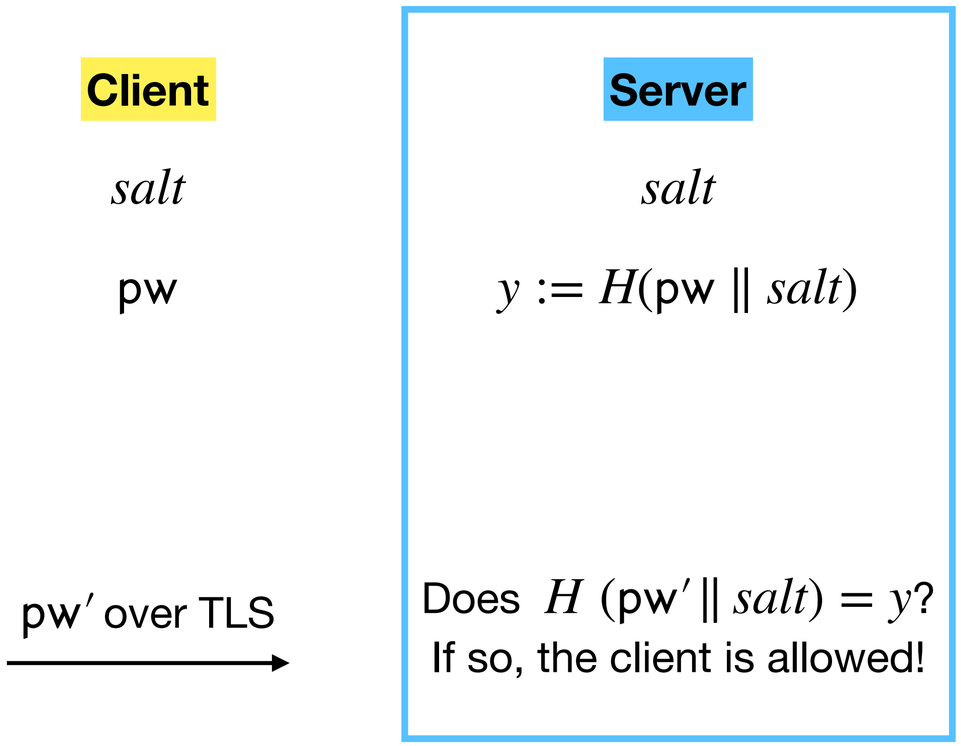
- ☑ Definitions: Undetectability, Exclusivity, Utility
- ☑ Construction of a Public-ASA
- ☐ **One application**

☐ Concluding remarks on the general case

Application: Password-based authentication

Client	Server
$salt$	$salt$
pw	$y := H(\text{pw} \,\|\|\, salt)$

Application: Password-based authentication



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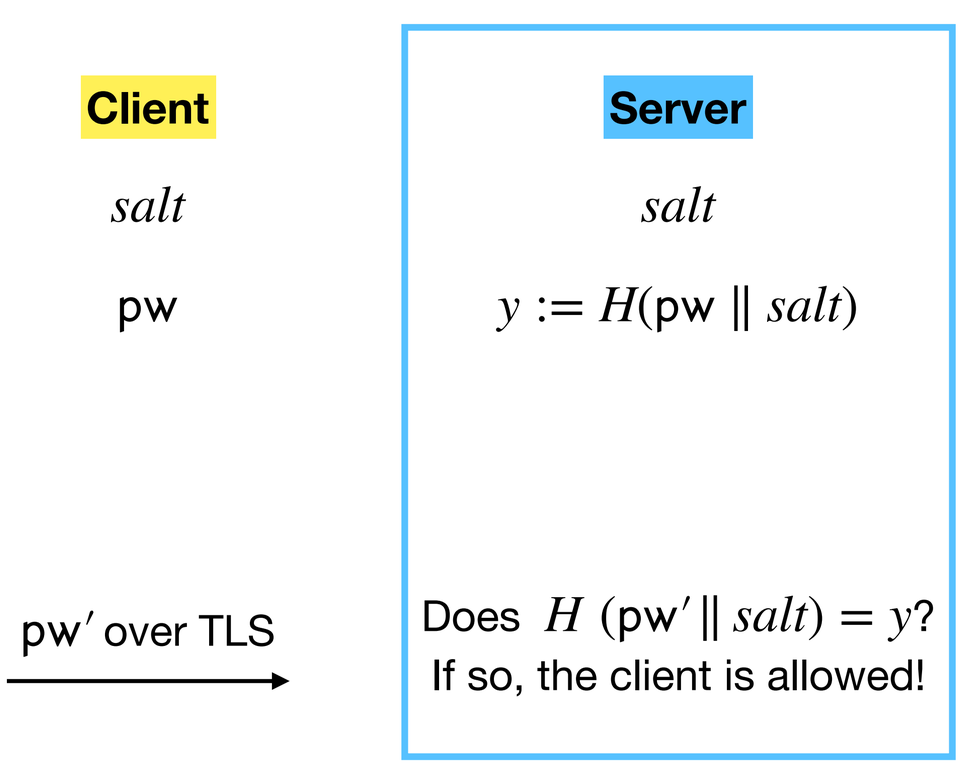

The Public-ASA attack

0. The attacker learns the Server's $(salt, y)$

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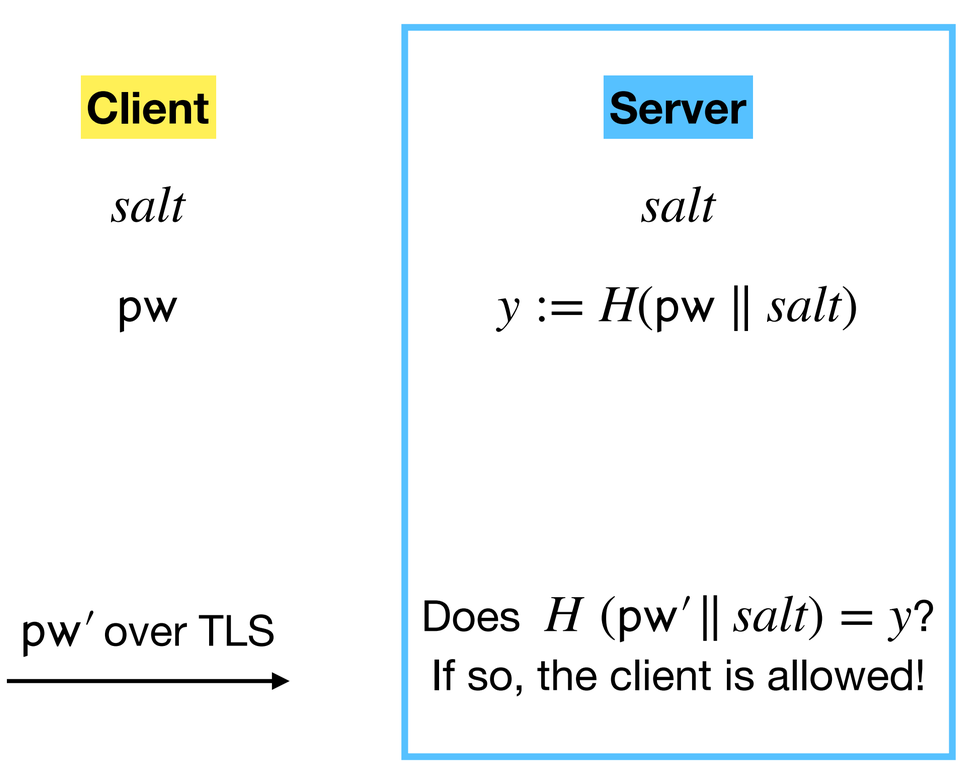

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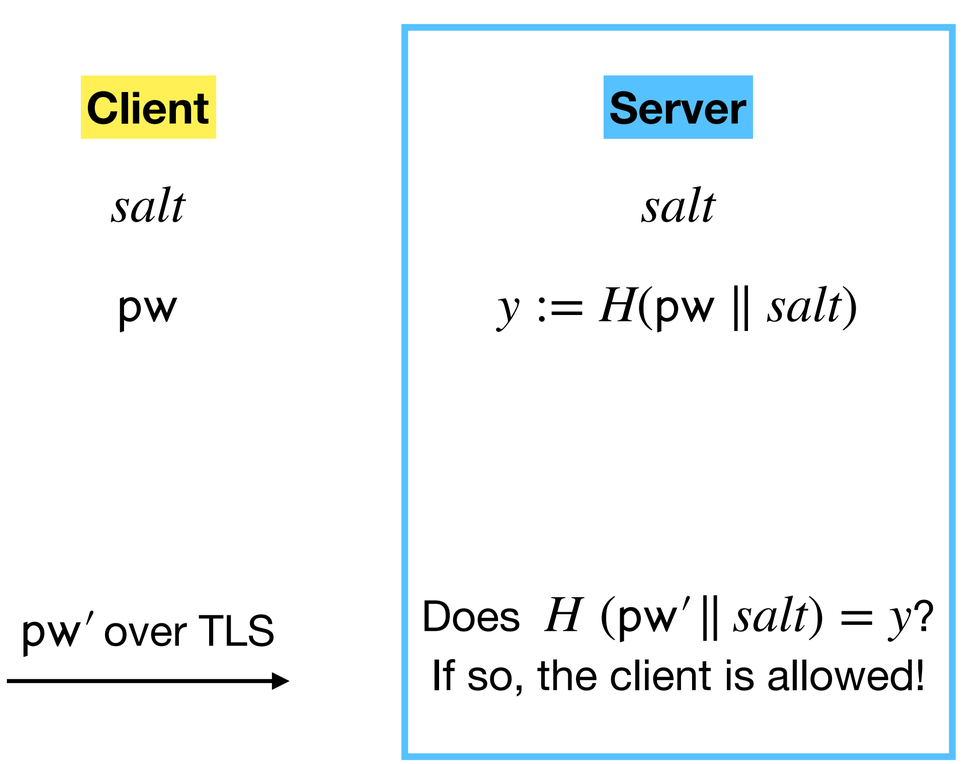

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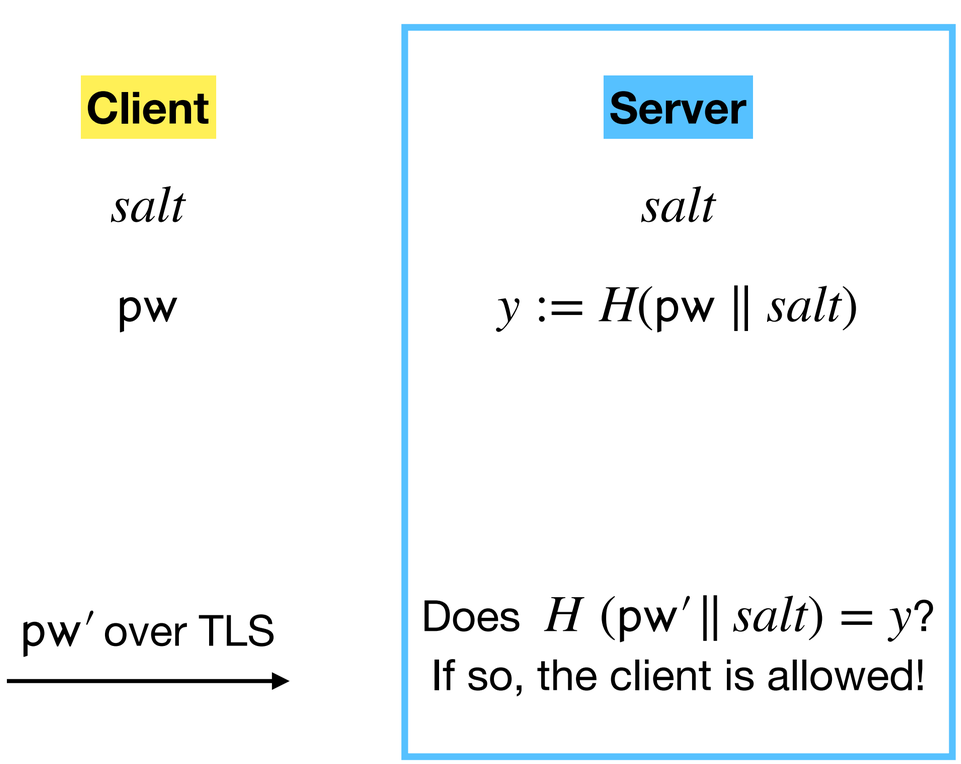

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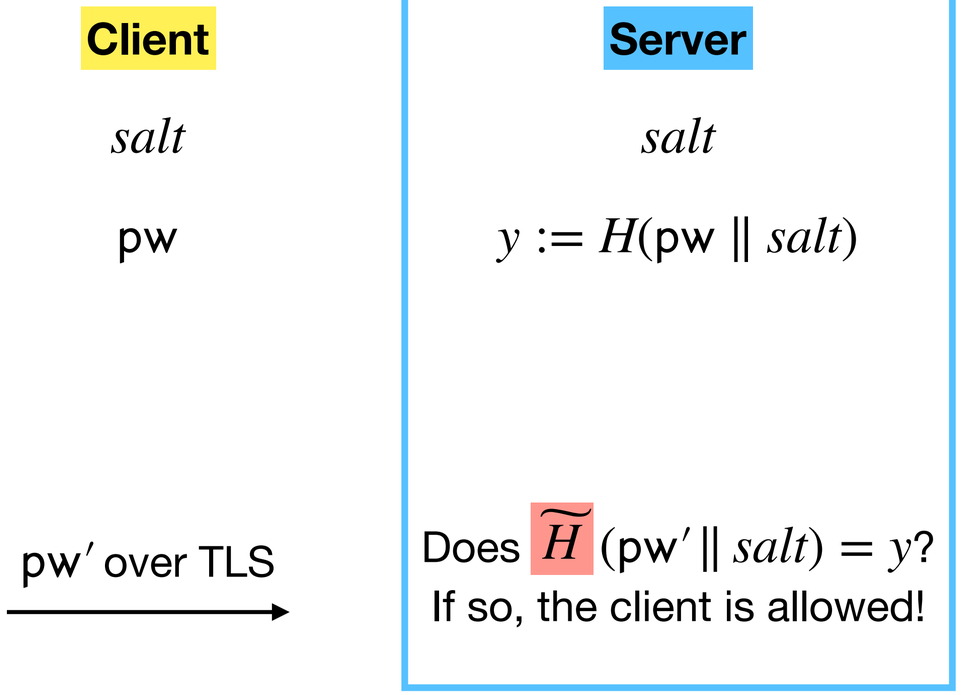

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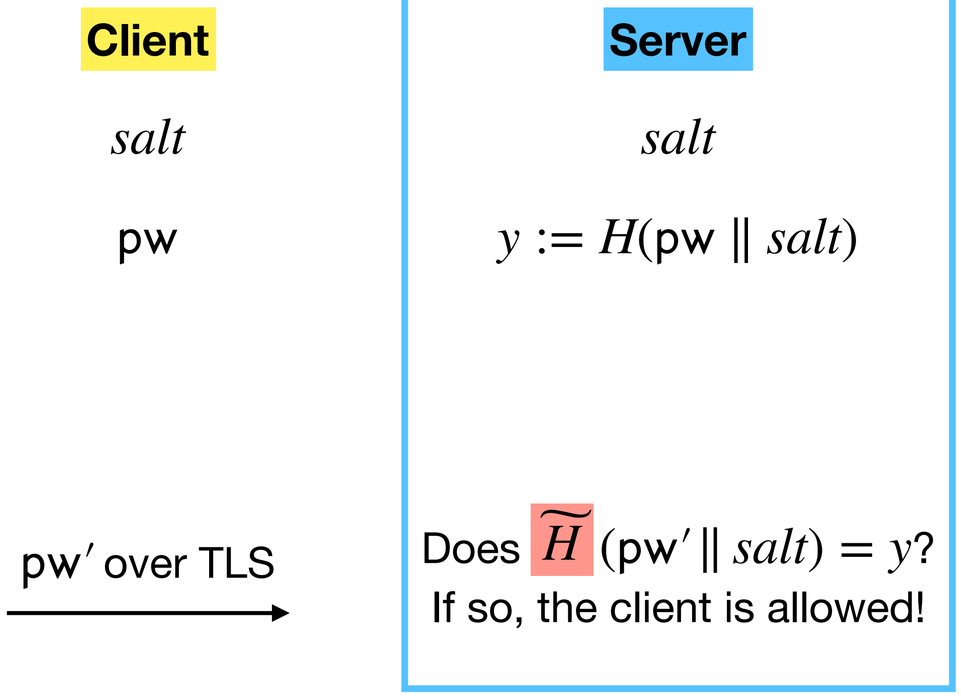

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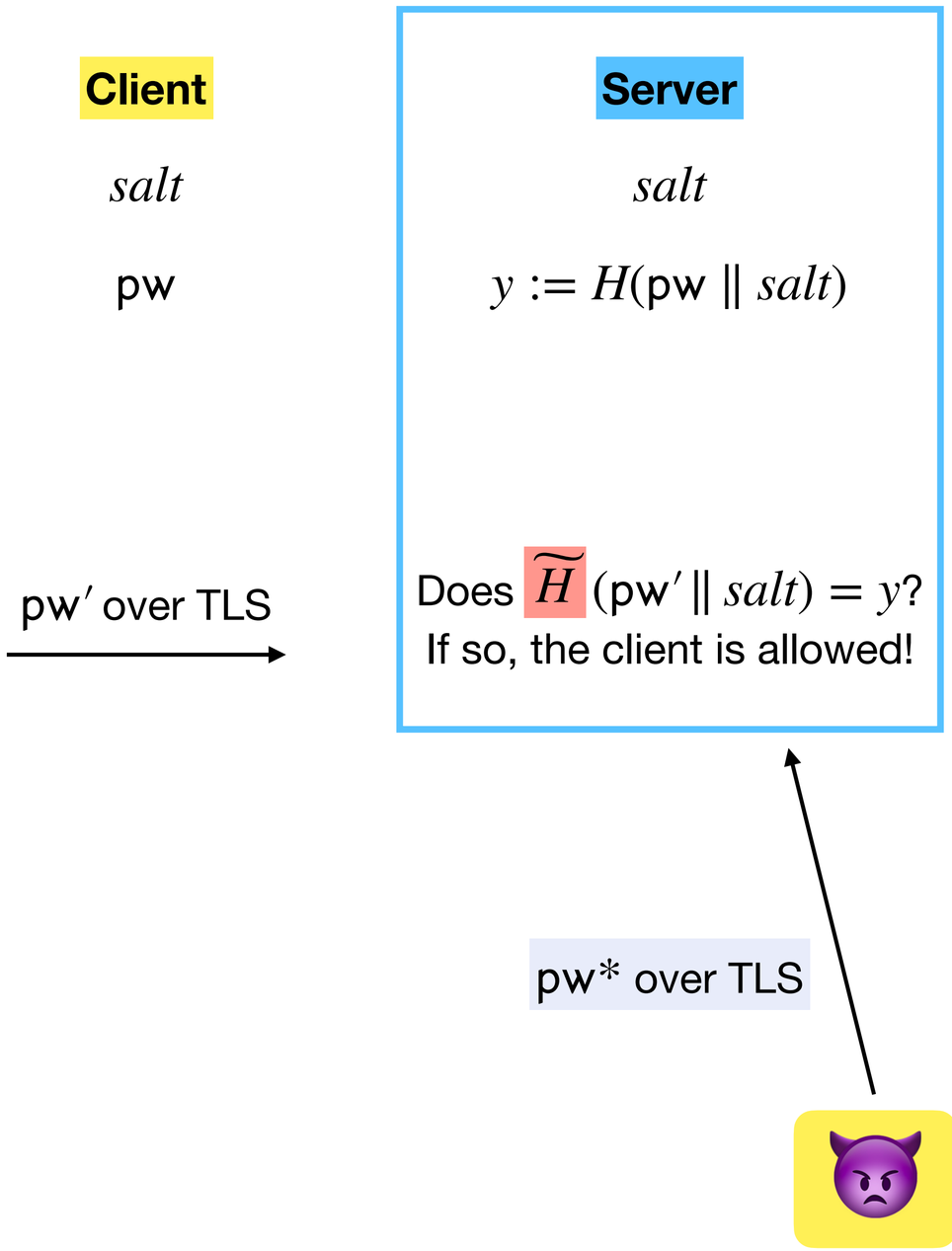

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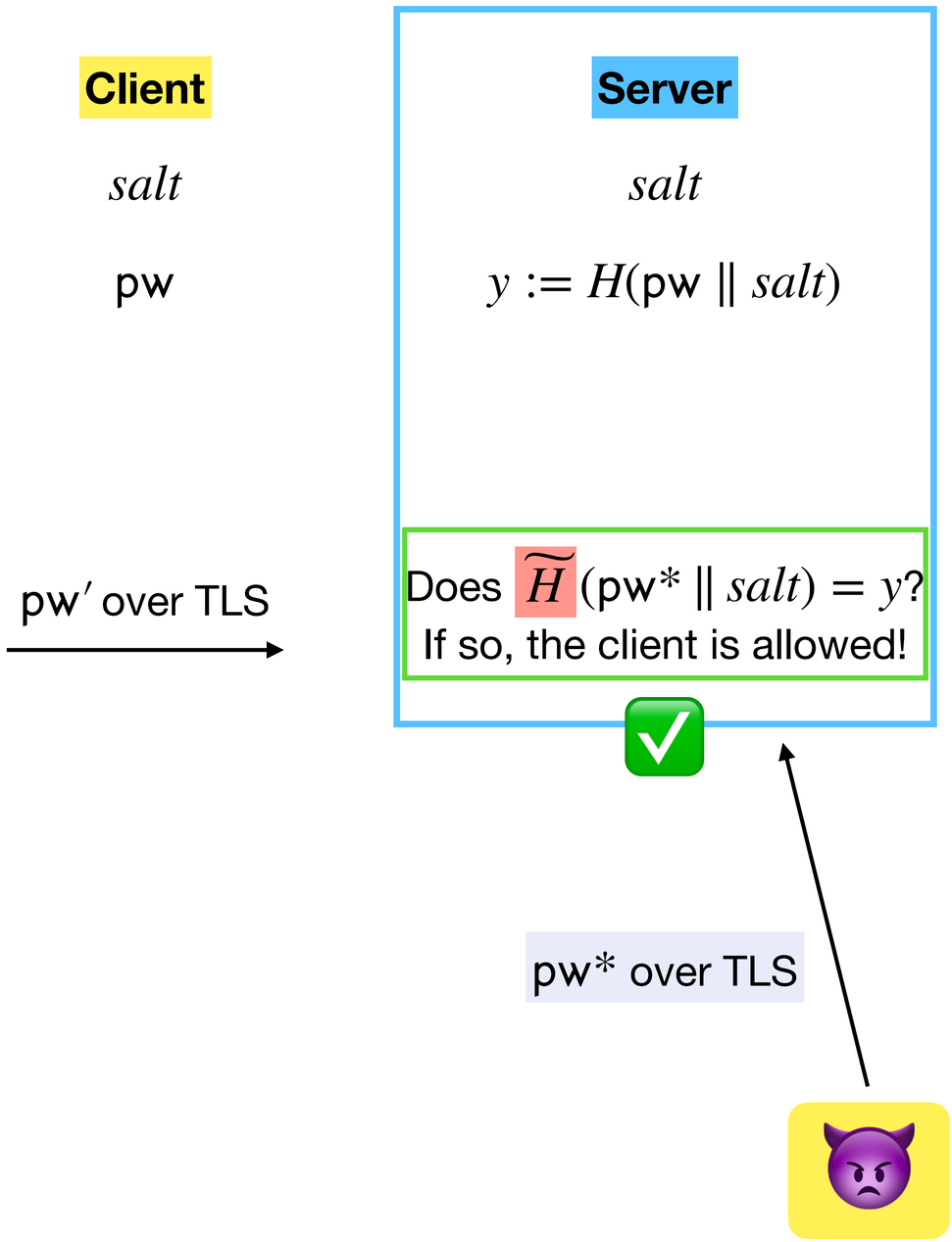

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pw

Server

$salt$

$y :=$

Does $\widetilde{H}$

If so, th

pw′ over TLS

pw* over TLS

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- Realistically, **Utility** *should* care about structure, and how information is embedded. (See paper for actual definitions.)
- A second example in the paper is about forging X.509 certificates, where it is again easy to imagine the attacker wants a particular structure.
- There, the Expl( ) oracle in **Exclusivity** is also motivated.

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Subversion of other public algorithms?

For example, GKVZ22 considered a Machine Learning classifier.

Target public algorithm: Classify : $x \mapsto -1 \text{ or } +1$

Target output: +1 or -1

Structure: The preimage x is “close to” a desired x'.

Topic of this talk:

Public-Algorithm Substitution Attack (*P*-ASA)

Summary of contributions:

1. Give a definition for an ASA on a *public* algorithm.
2. Design a construction satisfying the definition.

3. Look in more detail at important applications:

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Thank you for listening! Any questions?

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