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Non-Malleable Codes

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Non-Malleable Codes

a tool for securing
computer memory against
physical tampering
attacks

Introduced in **[D., Pietrzak, Wichs, ICS 2010]**.

Plan

1. Short introduction to physical attacks
2. Non-malleable codes – the definition
3. Non-malleable codes – constructions secure w.r.t different function families:
    1. bit-wise tampering
    2. tempering functions from sets of bounded size
    3. split-state model
4. Subsequent work

Cryptography: art vs science

In the past:

the **art** of encrypting messages (mostly for the military applications).

design method: “trial and error’

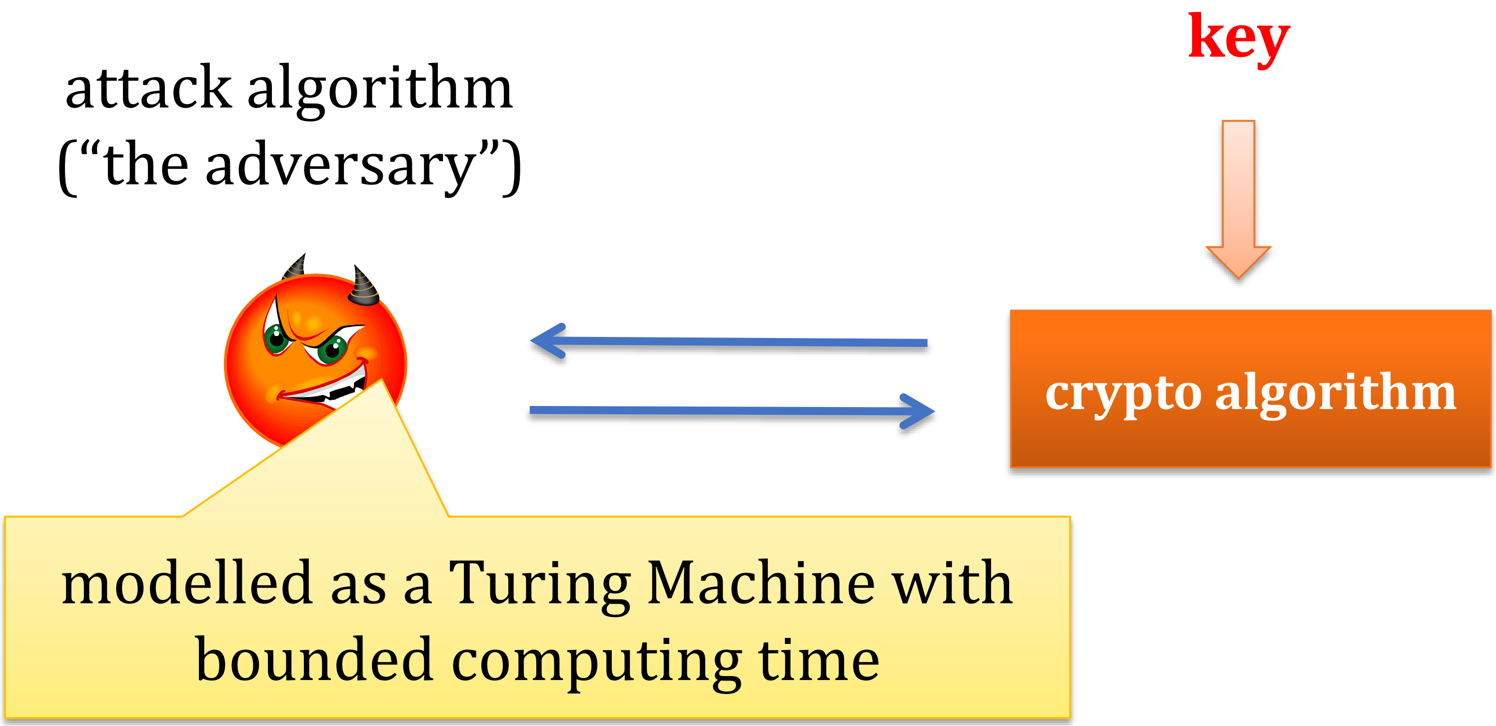
Nowadays:

the **science** of securing digital communication and transactions (encryption, authentication, digital signatures, e-cash, auctions, etc..)

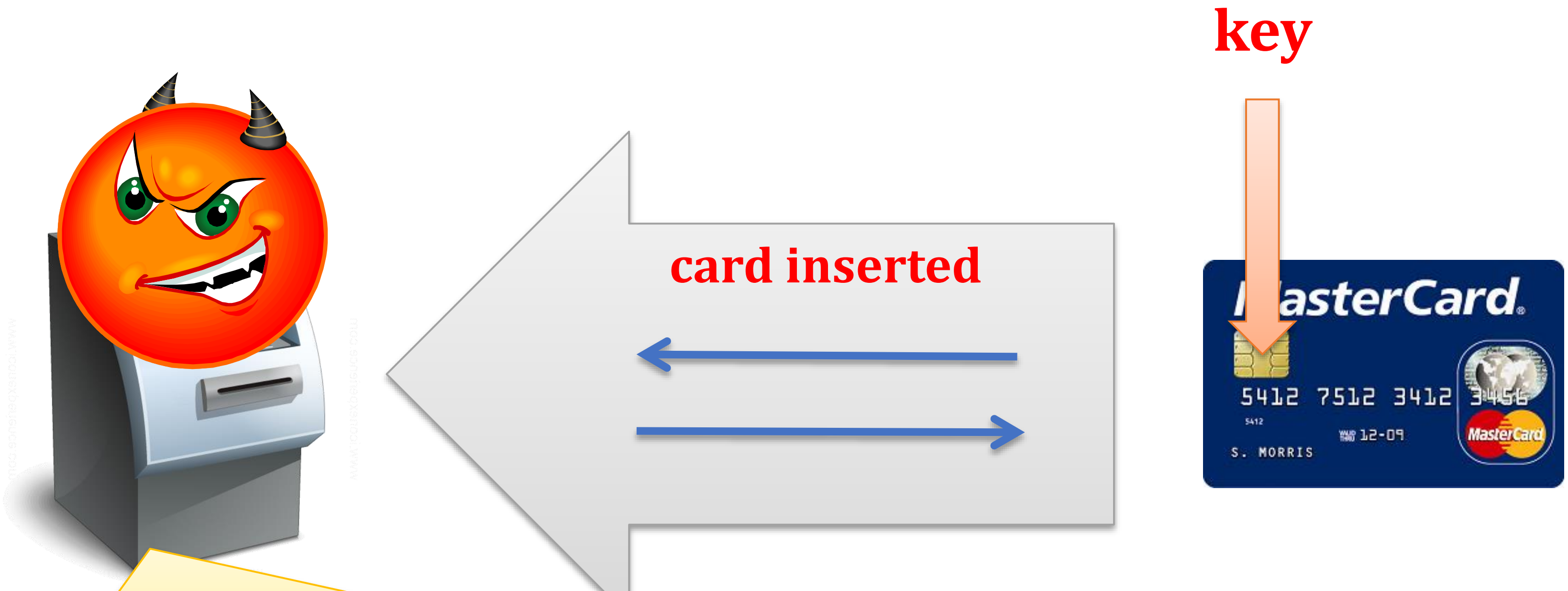
design method: “provable security”

proofs in a well-defined mathematical **model**

Standard model: black-box



Example: smart cards



even a **malicious** **ATM** should not be able to clone the card

Note: such cards are **much more secure** than cards with magnetic stripe.

“Black-Box Cryptography” – the situation

In general the problem of **constructing basic cryptographic protocols** secure in this model appears to be **solved**.

For example in symmetric encryption:

> even the “ancient” cipher **DES** (from 1970s) is broken only because its key is too short.
>
> (all other attacks are “theoretical”)

Can we relax?

Is the black-box model realistic?

No: Smart Cards can be broken by physical attacks.

The adversary obtains a temporary access to the device and can "play with it".
In particular: he can exploit its **physical properties**

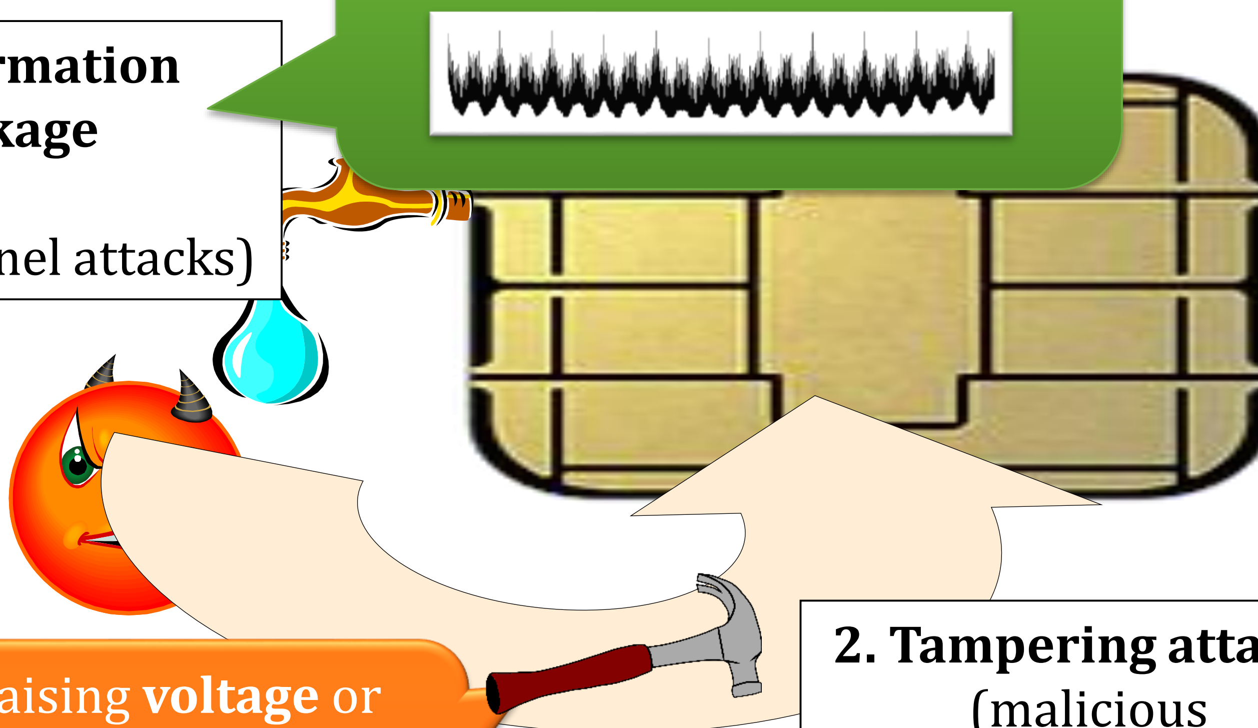
Much more powerful than the traditional "black-box" attacks!

Physical attacks on the implementation

Example: power consumption measurements

1. Information leakage

(side-channel attacks)



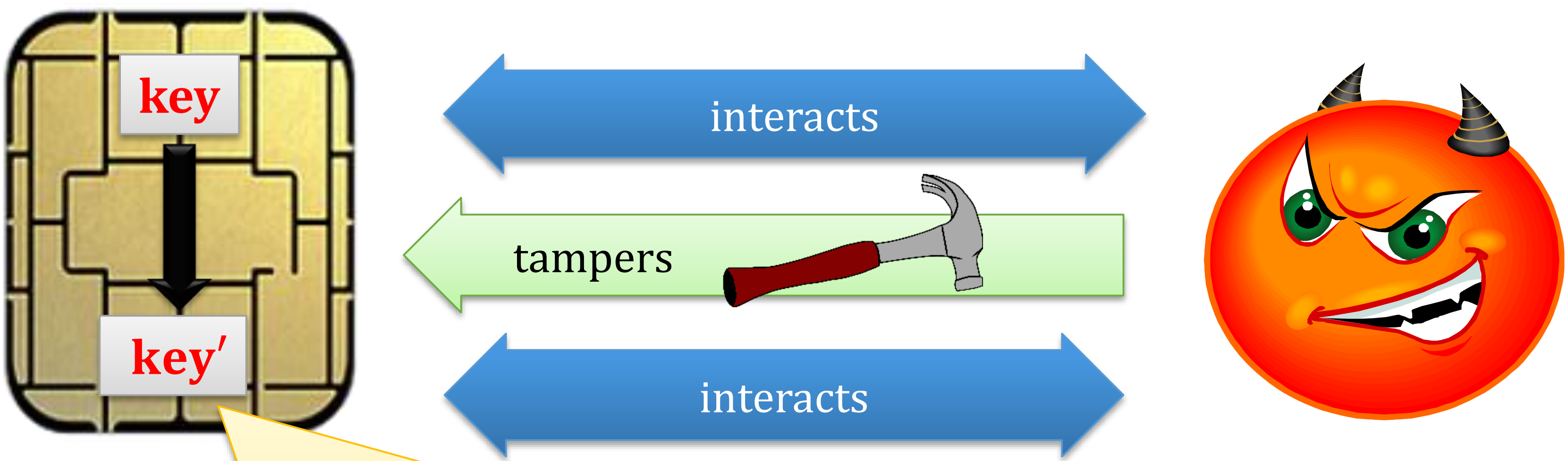
Example: raising **voltage** or **temperature**, tampering with **clock**, focusing **UV light** on the device…

2. Tampering attacks
(malicious modifications)

today we focus on this

How can the adversary exploit the tampering attacks?

Example: related key attacks

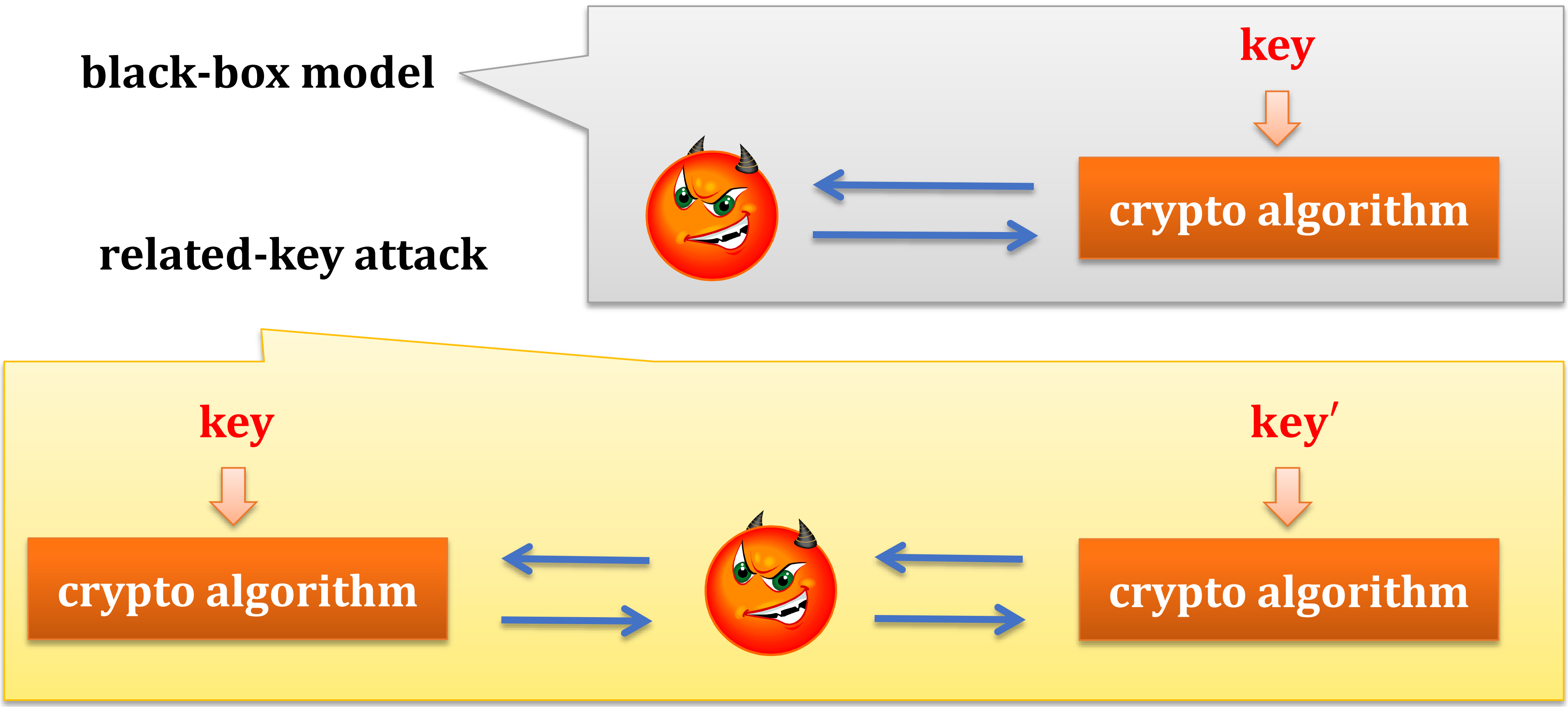


key′ is “related” to **key**

For example:

it’s equal to **key**, except that the first bit is negated.

This way the adversary obtains more power than in the black-box model!



Many successful attacks are based on this!

Countermeasures?

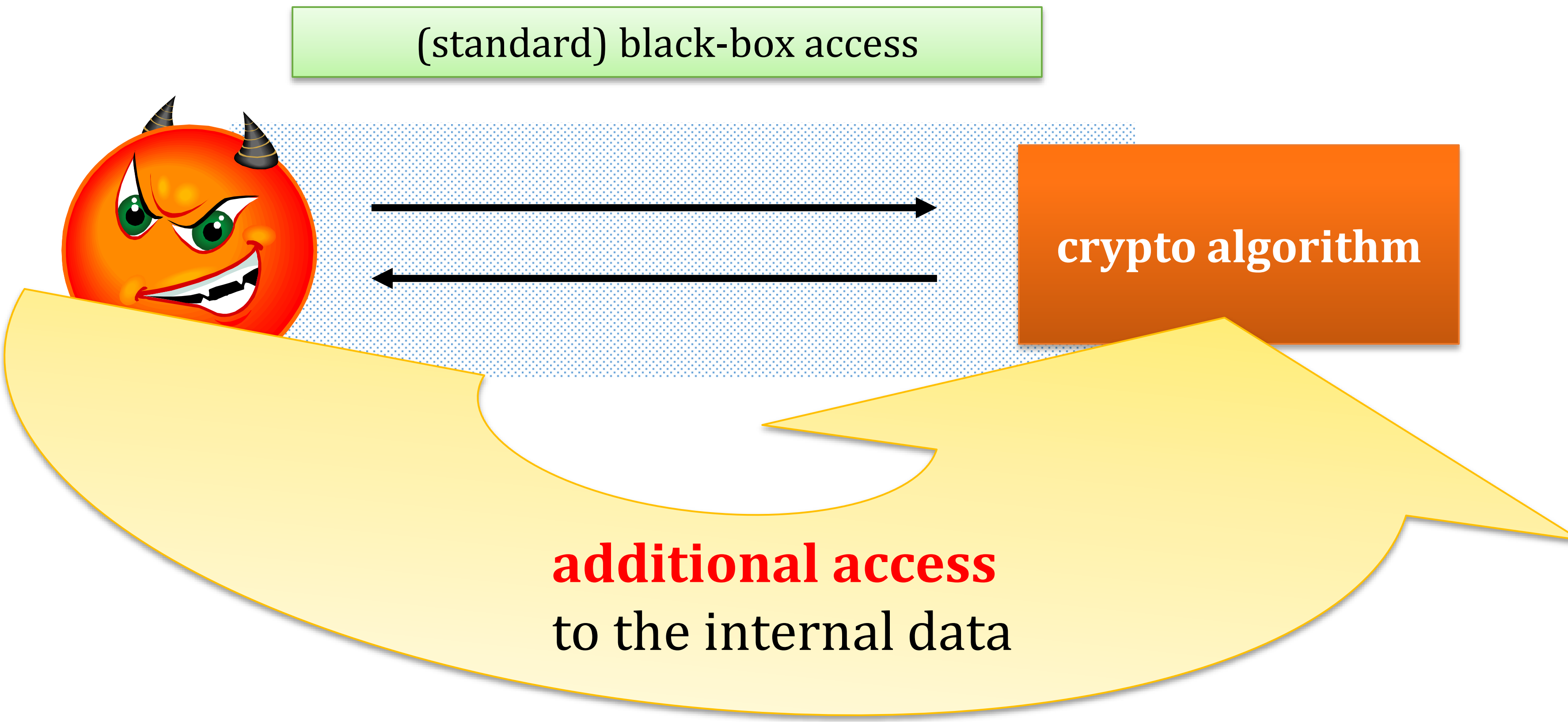
Lots of ad hoc practical solutions (a market worth billions of dollars)

cryptographic devices are everywhere: payment cards, tickets, SIM cards, pay TV cards, etc..

– usually based on a **trial-and-error methodology**…

A more formal approach?

An idea: incorporate physical attacks to the formal model

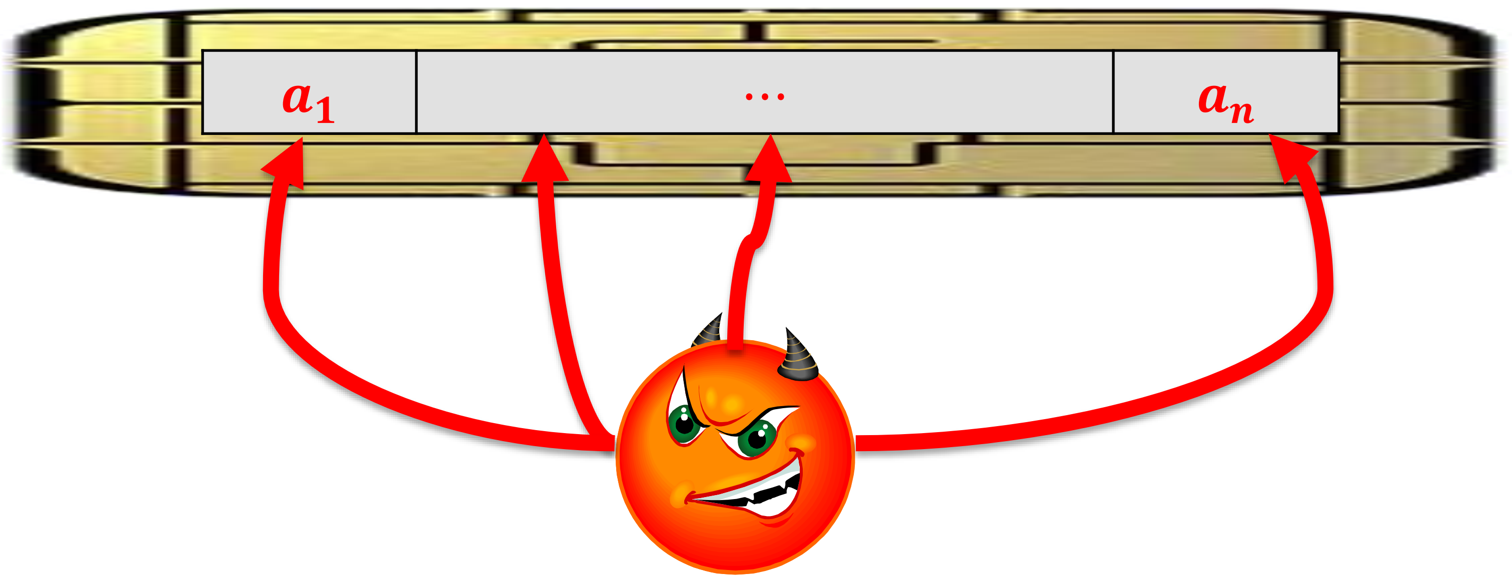


Hundreds of papers during the last decade!

Example: modelling leakage

"t-probing memory attacks"

The adversary can read-off up to t wires from the memory .



The fundamental building block

encoding schemes secure against the physical attacks.

Encoding scheme is a pair of algorithms

(Enc: $\mathcal{M} \rightarrow \mathcal{C}$, Dec : $\mathcal{C} \rightarrow \mathcal{M}$)

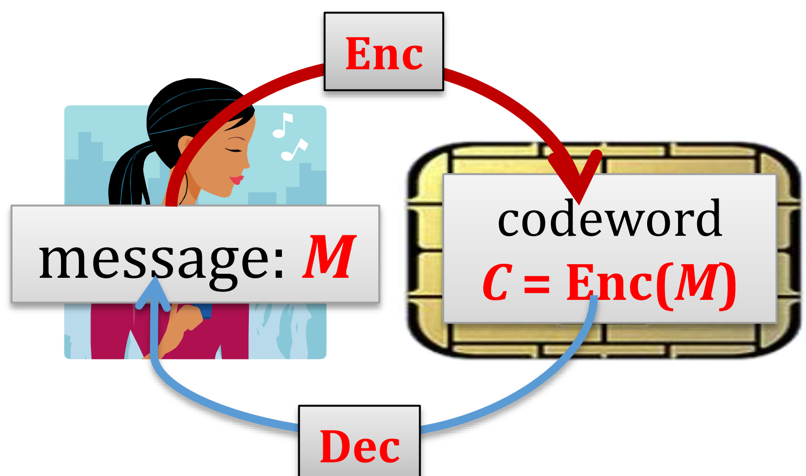
note: no secret key

$\mathcal{M}$ – set of **messages**

$\mathcal{C}$ – set of **codewords**

such that:

- **Enc** can be randomized,
- and $\forall_M$ **Dec(Enc(M)) = M**



Example

A bit encoding scheme $(\mathbf{Enc}: Z_2 \to Z_2^n, \mathbf{Dec}: Z_2^n \to Z_2)$ secure against $(n-1)$-**probing memory attacks**.

Let n be some natural parameter. To encode a bit $M \in Z_2$ take $a_1, \ldots, a_n \in Z_2$ uniformly at random such that

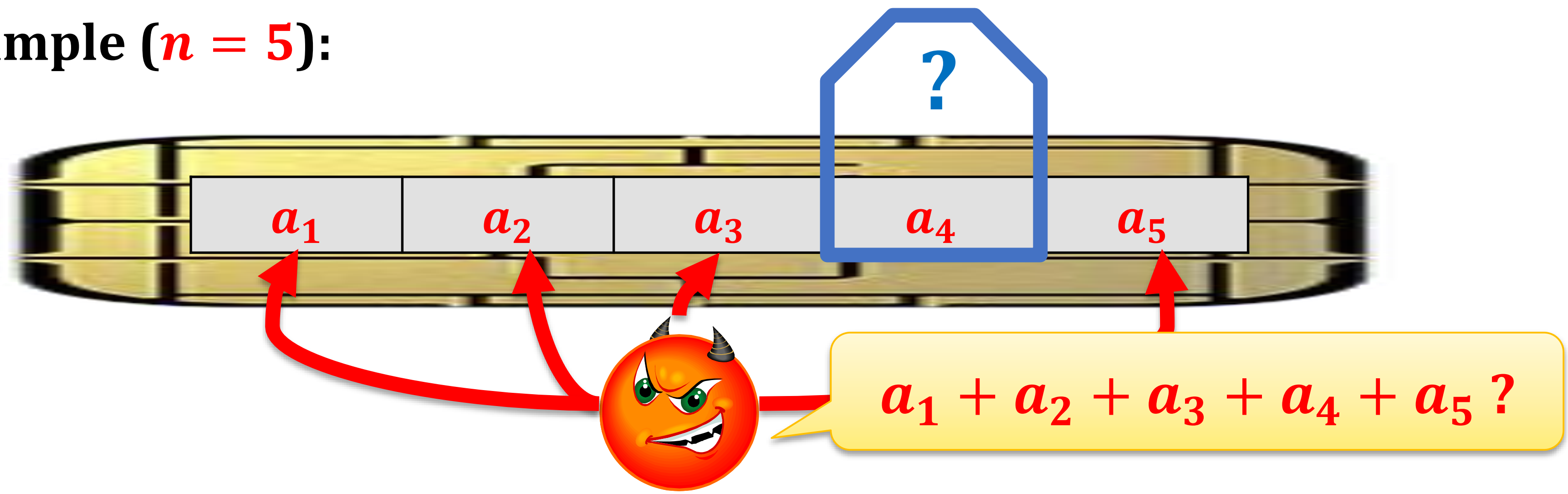
$$M = a_1 + \cdots + a_n \bmod 2$$

and let $\mathbf{Enc}(M) := (a_1, \ldots, a_n)$ and $\mathbf{Dec}(a_1, \ldots, a_n) = a_1 + \cdots + a_n$.

Now suppose that $C := \mathbf{Enc}(M)$ is stored on the device.

Then M remains secret even if the adversary learns up to $n-1$ bits of C.

Example ($n = 5$):



How to use such encoding schemes?

Note:

the encoding schemes are just a **building-block**, since they only provide security of "**memory**".

In practice we are usually interested in securing the **computation**.

This can be done by exploiting some **"homomorphic" properties of the encodings.**

For example: the encoding from the previous slide is linear.

Leakage-resilient encodings

The "leakage model" on the previous slide is **very simple** (the adversary learns "up to $\boldsymbol{n-1}$ bits").

This is not always realistic. In practice we need something stronger.

Tons of different models and constructions.

What about encoding secure against tampering?

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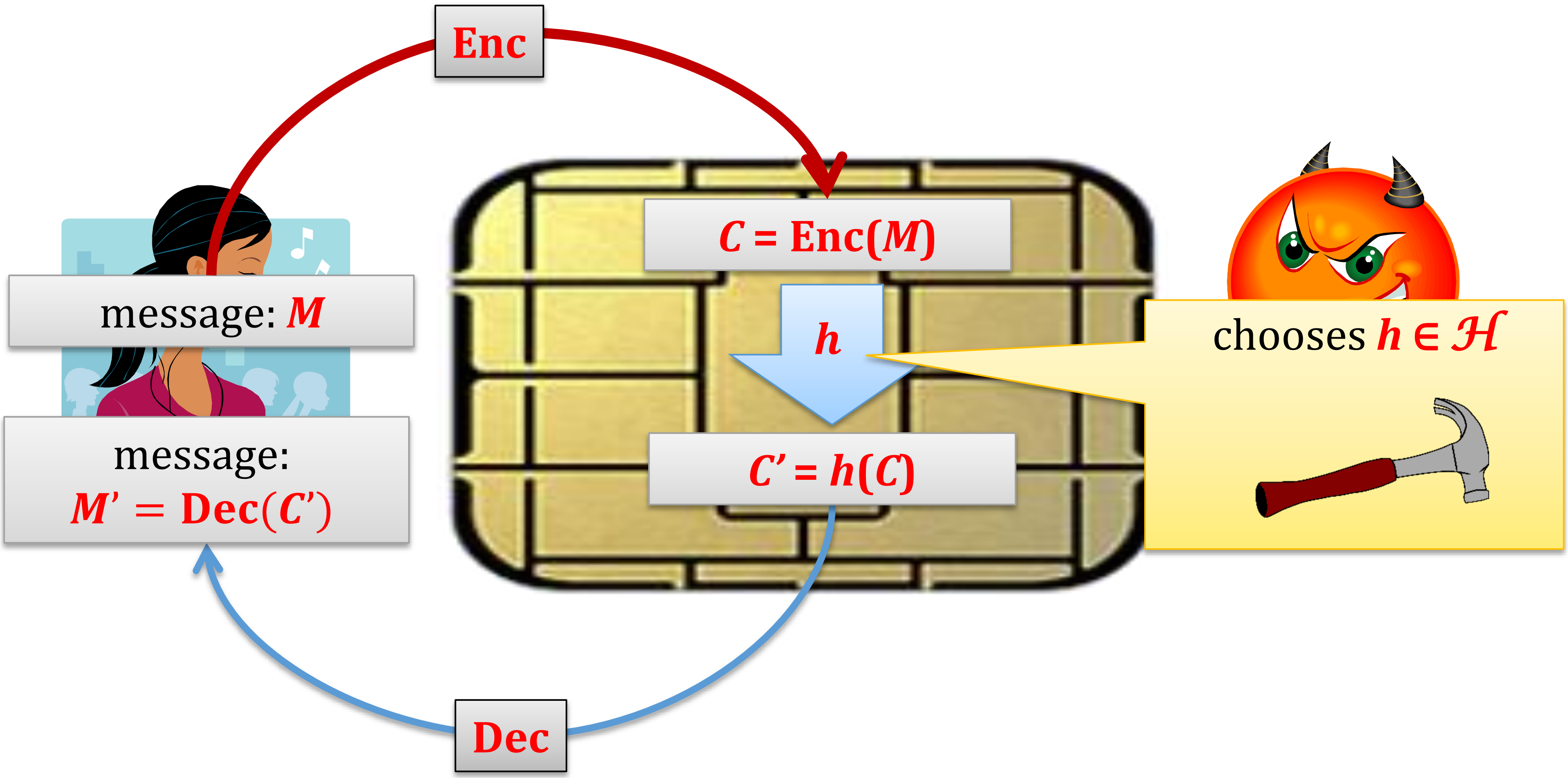
Tampering attacks



"Induced functions"

fix some $h \in \mathcal{H}$

Consider the tampering experiment (for some fixed M):

$$M \xrightarrow{\mathbf{Enc}} C = \mathbf{Enc}(M) \xrightarrow{h} C' = h(C) \xrightarrow{\mathbf{Dec}} M' = \mathbf{Dec}(C')$$

We say that $h: C \to C$ **induces** $h': \mathcal{M} \to \mathcal{M}$ defined for every M as:

$$h'(M) = \mathbf{Dec}\big(h\big(\mathbf{Enc}(M)\big)\big)$$

$$M \xrightarrow{\qquad h' \qquad} M' = \mathbf{Dec}(C')$$

What functions can the adversary induce?

Even for very restricted families $\mathcal{H}$ he can

- make $h'(M) = M$

by choosing $h(C) := C$

or

- make $h'(M)$ = constant X "independent from M"

by choosing $h(C) := \mathbf{Enc}(X)$

Non-Malleable Codes (NMC)

Main idea

The "identity" and the "constant" attacks should be the only thing that the adversary can do.

In other words: $\boldsymbol{M}$ should be either

- **equal** to $\boldsymbol{M}$
- or **unrelated** to it.

Informally

(Enc, Dec) is **non-malleable with respect to family** $\mathcal{H}$ if $\boldsymbol{h'}$ can be represented as a **probabilistic combination** of:

- the **identity** function
- and **constant** functions

(we formalize it a bit later)

Non-malleability in cryptography

Introduced in **[Dolev, Dwork, and Naor, STOC'91]**

Informally:

a cryptographic primitive $\boldsymbol{X}$ (with a secret key $\boldsymbol{S}$) is **malleable** if there exists an adversary who is able to produce output "related to" $\boldsymbol{X}(\boldsymbol{S})$, but not equal to it (even if he does not know $\boldsymbol{S}$).

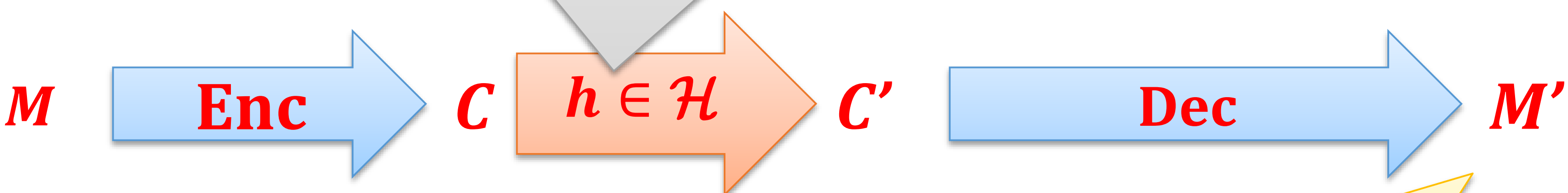
(it is **non-malleable** otherwise)

Can we have an NMC secure against the family of all functions?

no!

Attack example:

1. Decodes $\boldsymbol{M} = \mathbf{Dec}(\boldsymbol{C})$
2. Let $\boldsymbol{M}' := \boldsymbol{M}$ with all bits negated
3. Let $\boldsymbol{C}' := \mathbf{Enc}(\boldsymbol{M}')$



Clearly: $\boldsymbol{M}'$ is related to $\boldsymbol{M}$ (but $\boldsymbol{M}' \neq \boldsymbol{M}$)

Moral

$\mathcal{H}$ **has to be restricted in some way.**

Popular variants:

- **independent bit tampering** – C is a bit-string and h tampers with each bit independently,
- **split state model** – C is divided into **2** (or more) independent parts, and the adversary can tamper with each part **independently**,
- **low complexity tampering** – h has to be represented by a small circuit

How to formalize that *h'* is a probabilistic combination of **constant** functions?

$(\mathbf{Enc}\colon \mathcal{M} \to \mathcal{C}, \mathbf{Dec}\colon \mathcal{C} \to \mathcal{M})$ is **non-malleable w.r.t.** $\mathcal{H}$ if

$\forall$ $h \in \mathcal{H}$ $\exists$ D – random variable taking values from $\mathcal{M}$

such that $\forall$ $M \in \mathcal{M}$ $h'(M) \equiv D$

equality of distributions

Question: what with the "**identity**" function?

Solution

$\boldsymbol{D}$ – random variable taking values from $\mathcal{M} \cup \{\underline{\textbf{same}}\}$

For $\boldsymbol{M} \in \mathcal{M}$ and $\boldsymbol{d} \in \mathcal{M} \cup \{\underline{\textbf{same}}\}$ define:

$$\mathbf{Tamper}_{\boldsymbol{M}}(\boldsymbol{d}) := \begin{cases} \text{if } \boldsymbol{d} = \underline{\textbf{same}} \text{ then } \textbf{output } \boldsymbol{M} \\ \text{otherwise } \textbf{output } \boldsymbol{d} \end{cases}$$

$(\mathbf{Enc}, \mathbf{Dec})$ is **non-malleable w.r.t.** $\mathcal{H}$ if

$$\underset{\boldsymbol{h} \in \mathcal{H}}{\forall} \quad \underset{\boldsymbol{D}}{\exists} \quad \textbf{such that} \quad \underset{\boldsymbol{M} \in \mathcal{M}}{\forall} \quad \boldsymbol{h}'(\boldsymbol{M}) \equiv \mathbf{Tamper}_{\boldsymbol{M}}(\boldsymbol{D})$$

In practice it's useful to relax this definition a bit

$(\mathbf{Enc}, \mathbf{Dec})$ is ϵ-**non-malleable w.r.t.** $\mathcal{H}$ if

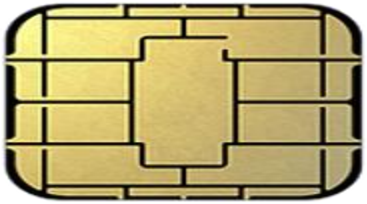
$$\underset{h \in \mathcal{H}}{\forall} \quad \underset{D}{\exists} \text{ such that } \underset{M \in \mathcal{M}}{\forall} \quad h'(M) \approx^{\epsilon} \mathbf{Tamper}_M(D)$$

ϵ-closeness of distributions
(we skip the formal definition)

One way to look at it

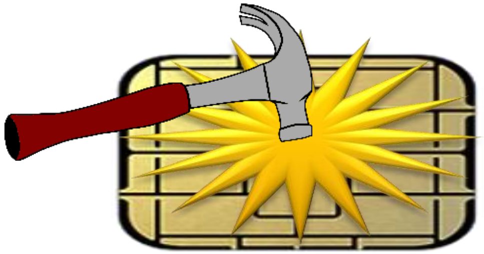
The adversary can either

- leave the device **unchanged**,

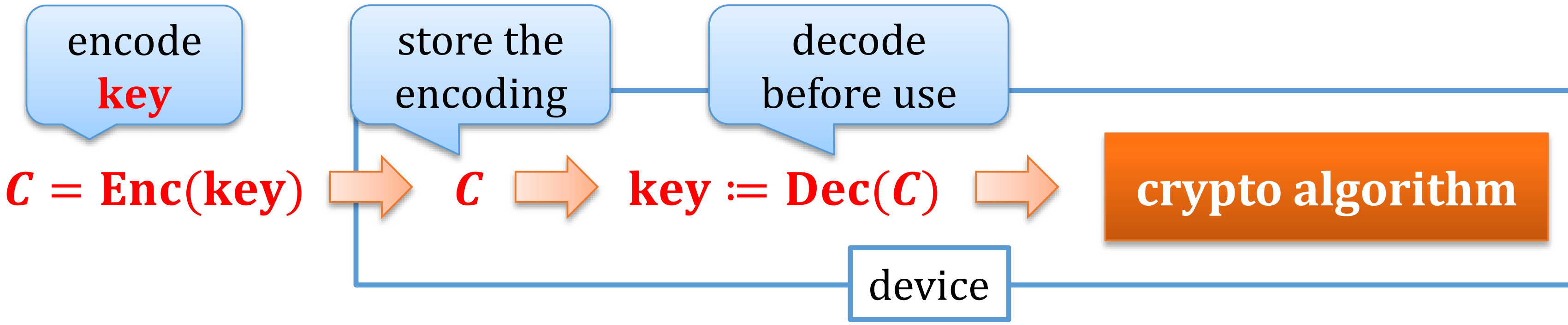


or

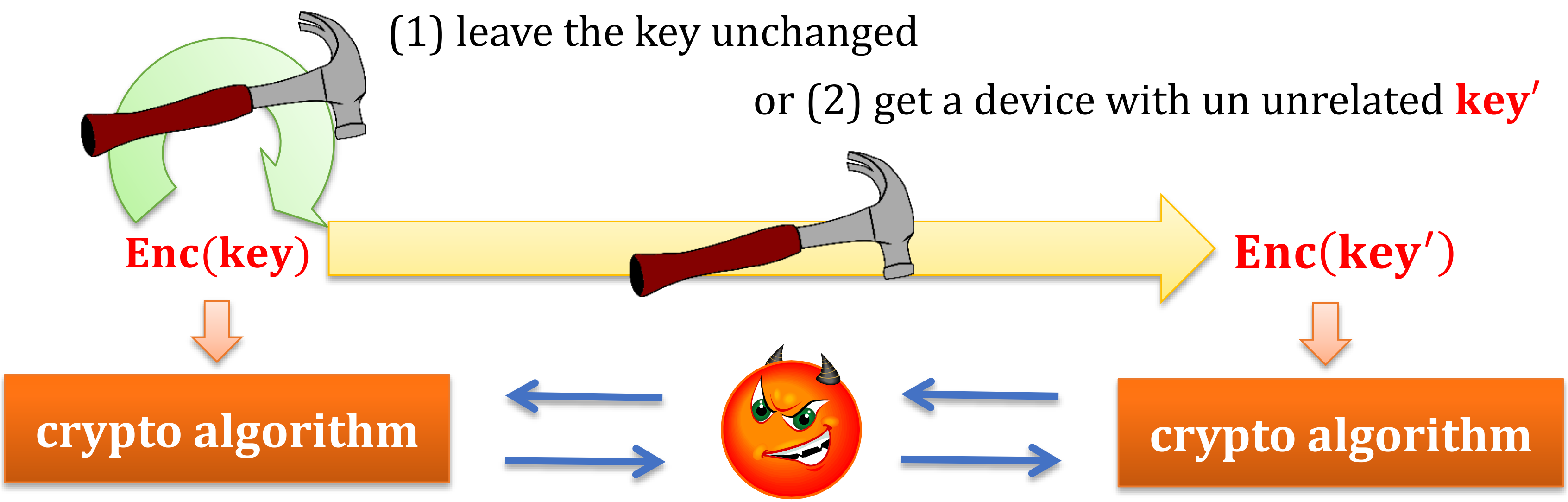
- **destroy it completely**



How to use NMCs to protect against the related key attacks?



What can the adversary do?



This gives him no more power than in the black-box model!

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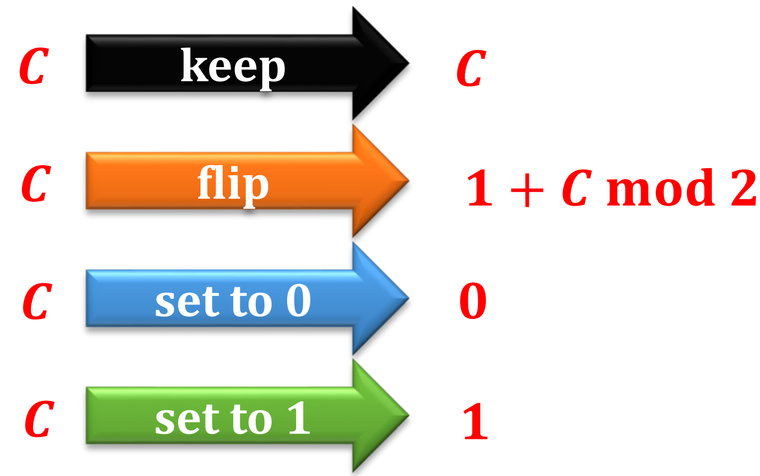
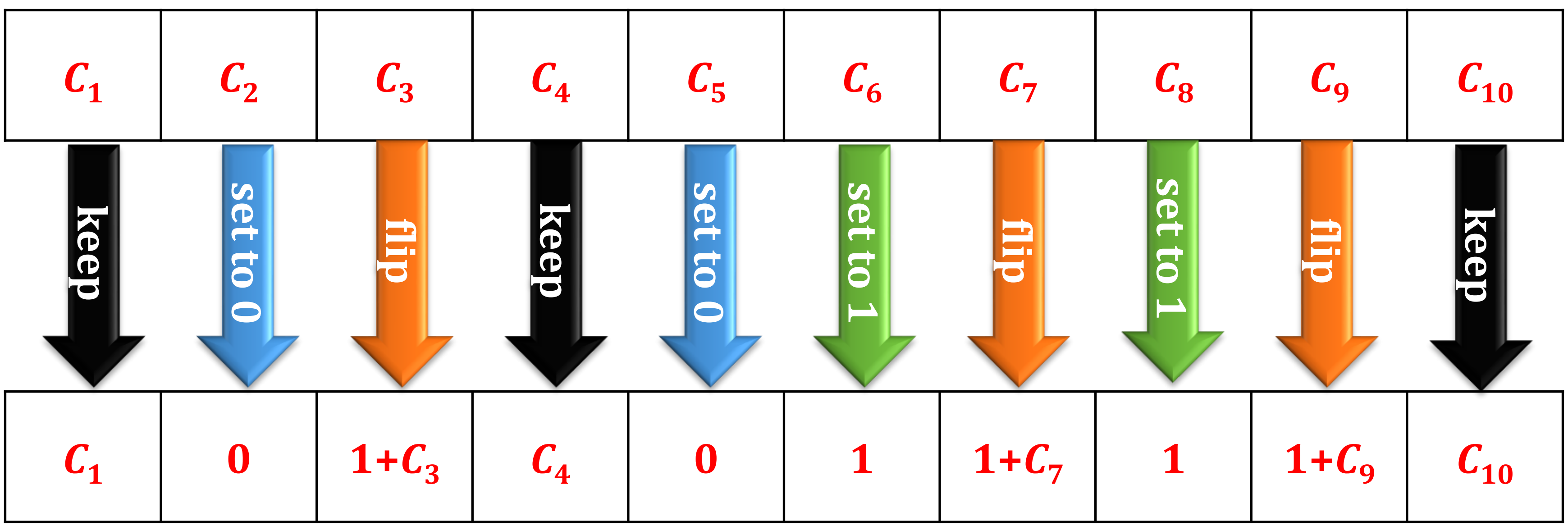
Independent Bit Tampering

set of codewords: Z_2^n
(where n is some parameter)

4 types of functions acting on bits:





How to design an NMC secure w.r.t. such tampering?

Simple ideas don't work.

For example take the encoding that we constructed before:

To encode a bit $\boldsymbol{M} \in \boldsymbol{Z_2}$ take $\boldsymbol{a_1, \dots, a_n} \in \boldsymbol{Z_2}$ uniformly at random such that $\boldsymbol{M = a_1 + \cdots + a_n \bmod 2}$ and let

$$\mathbf{Enc}(\boldsymbol{M}) \coloneqq (\boldsymbol{a_1, \dots, a_n}) \text{ and } \mathbf{Dec}(\boldsymbol{a_1, \dots, a_n}) = \boldsymbol{a_1 + \cdots + a_n}.$$

This is clearly **malleable** w.r.t. independent bit tampering because negating one bit negates the message:

$$\mathbf{Dec}(\mathbf{1} + \boldsymbol{a_1, \dots, a_n}) = \mathbf{1} + \boldsymbol{a_1 + \cdots + a_n} = \mathbf{1} + \boldsymbol{M}.$$

Non-malleable code secure against independent bit tampering

[DPW10]:
A construction of an efficient non-malleable code secure against independent bit tampering.

It achieves the rate of **≈ 0.1887**.

(later improved in some subsequent work)

Uses the **algebraic manipulation detection** codes **[CDFPW08]**.

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The existential result

Consider codes with the set of codewords $\boldsymbol{Z_2^n}$ (for some parameter $\boldsymbol{n}$).

Theorem [DPW10]

Suppose $\mathcal{H}$ is a subset of tampering functions $\boldsymbol{Z_2^n} \rightarrow \boldsymbol{Z_2^n}$ such that

$$\mathbf{log_2(log_2(|\mathcal{H}|)) < \boldsymbol{n}.}$$

Then there exists a code that is non-malleable with respect to $\mathcal{H}$.

In particular: a random code is non-malleable with a very high probability.

Note:

The set of ALL functions $\boldsymbol{h}\colon \boldsymbol{Z_2^n} \rightarrow \boldsymbol{Z_2^n}$ is such that

$$\mathbf{log_2(log_2(|ALL|)) = \boldsymbol{n} + log_2 \boldsymbol{n}}$$

Because: $\mathbf{2}^{\boldsymbol{n}\cdot \mathbf{2}^{\boldsymbol{n}}} \xrightarrow{\mathbf{log_2}} \xrightarrow{\mathbf{log_2}} \mathbf{log_2}\boldsymbol{n} + \boldsymbol{n}$

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The “split-state model”

Suppose that

$$\mathbf{Enc}\colon \mathcal{M} \to \mathcal{L} \times \mathcal{R}$$
$$\mathbf{Dec}\colon \mathcal{L} \times \mathcal{R} \to \mathcal{M}$$

and $\mathbf{Enc}(M) = (L, R)$

(f, g) – arbitrary tampering functions.

f and g are applied separately to L and R:

Formally: $\mathcal{H} = \{(f, g)\colon f\colon \mathcal{L} \to \mathcal{L},\, g\colon \mathcal{R} \to \mathcal{R}\}$.

Split-state model – motivation

- easily **implementable** in practice

- well-studied model in the **leakage**-resilient crypto
- **generalizes** some other models (e.g. the independent bit tampering)

Consequence of the existential result

Observation

If $\mathcal{L} = \mathcal{R} = Z_2^{n/2}$ then a random code is secure against the split-state encoding.

Proof.

The set of codewords is: $\mathcal{L} \times \mathcal{R} = Z_2^{n}$ and hence the number of tampering functions is:

$$\left(2^{\frac{n}{2}\cdot 2^{n/2}}\right)^2 = 2^{n\cdot 2^{n/2}} \xrightarrow{\log_2} \xrightarrow{\log_2} \log_2 n + \frac{n}{2} < n$$

Therefore a random code is non-malleable w.r.t. such functions.

An open problem from [DPW10]

Construct an explicit and efficient non-malleable code secure in **the split-state model**.

Closed in the recent **(2012-2015)** line of work.

We will now talk more about it.

In particular, we will describe NMCs in this model that works for **one-bit messages**.

Progress towards solving this problem

1. **[DPW10]**: existential result
2. **[Liu and Lysyanskaya, Crypto 2012]**: **computational**-security, assuming **common reference string**

we will show this now

3. **[D., Kazana, Obremski, Crypto 2013]**: secure encoding for **1-bit messages**
4. **[Aggarwal, Dodis, and Lovett, STOC 2014]:** first result for messages of arbitrary length.
5. **[Chattopadhyay and Zuckerman, FOCS’14]**:**[Aggarval, Dodis, Kazana, Obremski, STOC 2015]**: improving capacity..

NMCs for **1**-bit messages?

Not directly useful.

But interesting as a building block.

Easier to analyze since in this case NMCs have a simpler (but equivalent) definition.

Fact

For any $\mathcal{H}$ any scheme $(\mathbf{Enc}: \boldsymbol{Z_2} \rightarrow \mathcal{C}, \mathbf{Dec}: \mathcal{C} \rightarrow \boldsymbol{Z_2})$ is **non-malleable w.r.t. a family** $\mathcal{H}$ if:

Recall:
$\boldsymbol{h'(M) = \mathbf{Dec}(h(\mathbf{Enc}(M)))}$

$$\forall_{h \in \mathcal{H}} \quad \boldsymbol{P(M \neq h'(M)) \leq \frac{1}{2}}$$

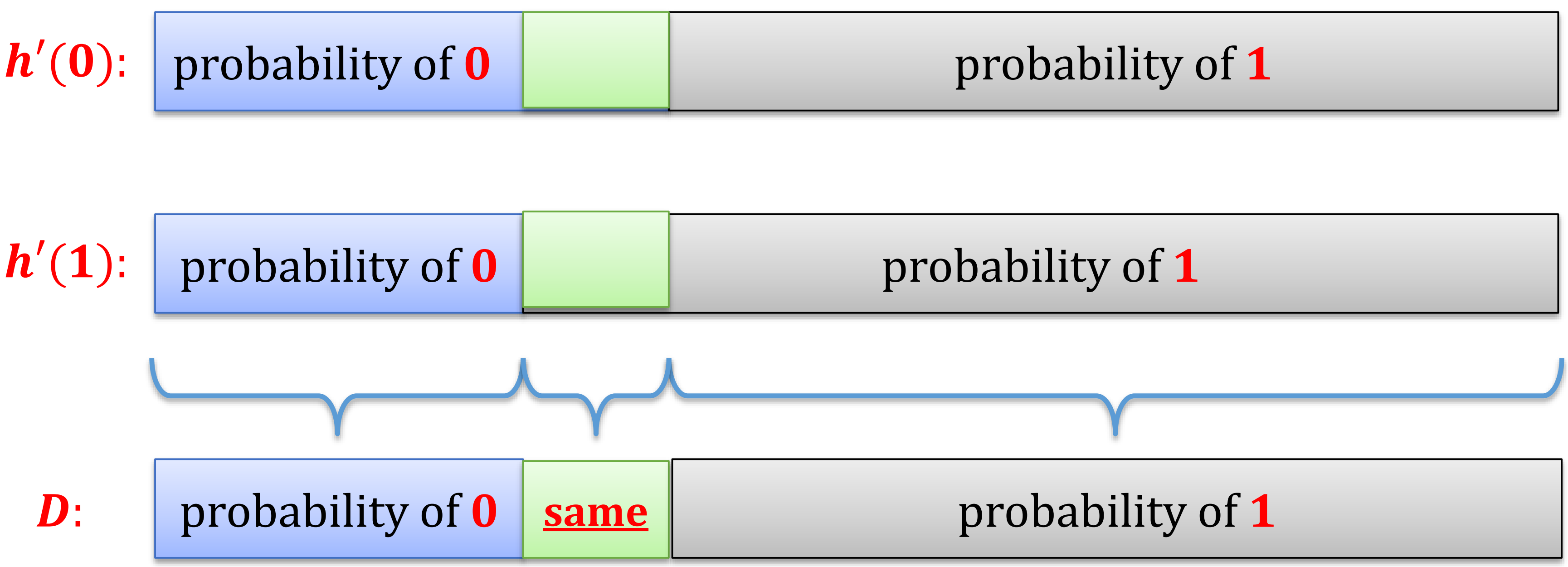
where $\boldsymbol{M}$ is uniformly distributed over $\boldsymbol{\{0, 1\}}$.

hard to negate ⇒non-malleable

$$\frac{1}{2}\cdot P(h'(1)=0)+\frac{1}{2}\cdot P(h'(0)=1)\leq\frac{1}{2}$$

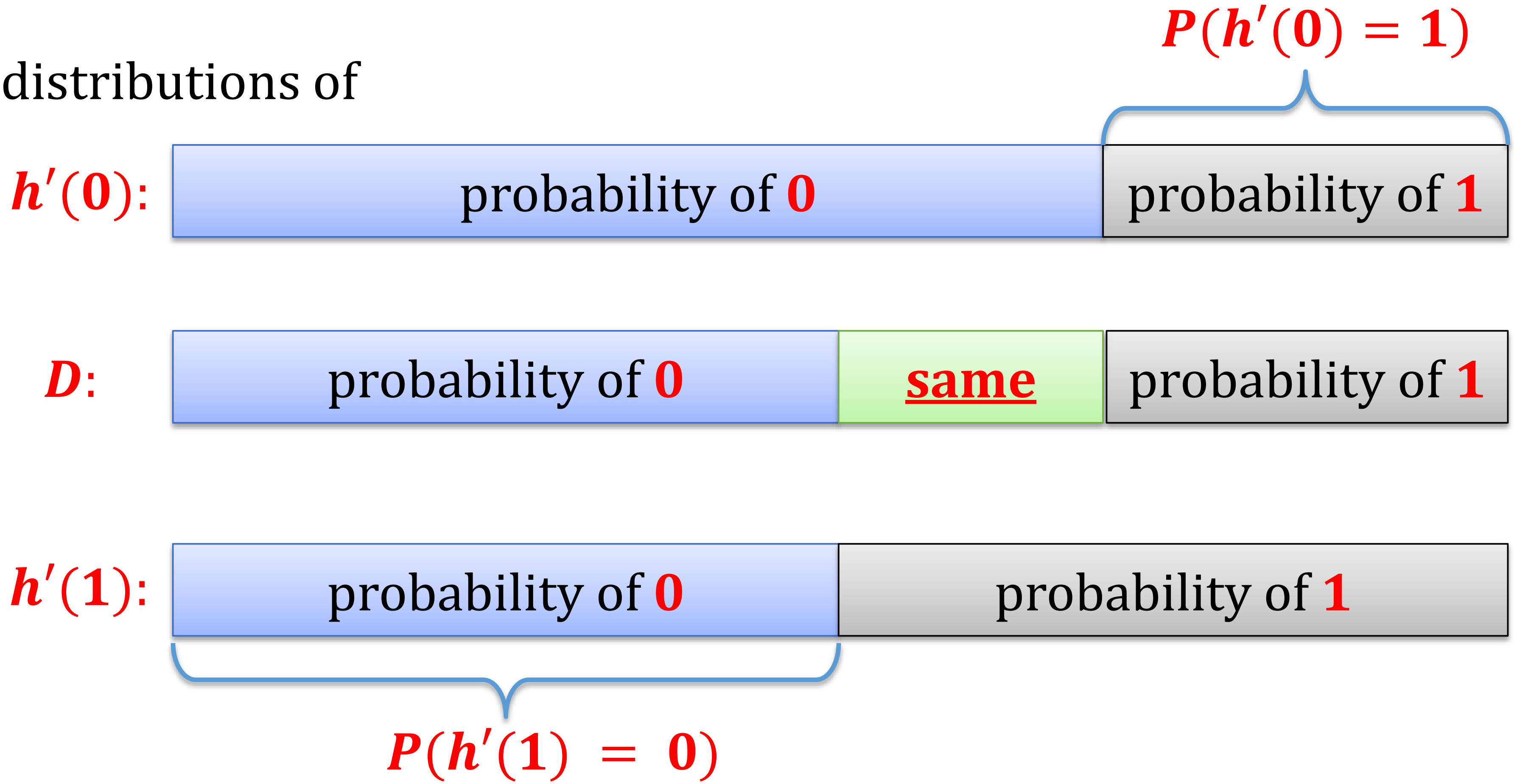
$$P(h'(1)=0)+P(h'(0)=1)\leq 1$$

look at the distributions of:



non-malleable ⇒ hard to negate

distributions of



Hence: $P(h'(1) = 0) + P(h'(0) = 1) \leq 1$

Look again at our problem:

M – uniformly random over Z_2

$\mathrm{Enc}(M)$

$L' = f(L)$

$M' := \mathrm{Dec}(L', R')$

$R' = g(R)$

Goal:

construct encoding such that for every f, g we have:

$$P(M' \neq M) \leq \frac{1}{2}$$

Our construction

Based on the “inner product function”:

F – finite field

$$\langle \underbrace{(L_1, \ldots, L_k)}_{L \in \mathbf{F}^k}, \underbrace{(R_1, \ldots, R_k)}_{R \in \mathbf{F}^k} \rangle = \sum_{i=1}^{k} L_i \times R_i$$

where $\forall_i \; L_i, R_i \in \mathbf{F}$

How to base encoding on this?

Define the following encoding for messages $\boldsymbol{M} \in \mathbf{F}$:

- $\mathbf{Enc}(\boldsymbol{M}) = (\boldsymbol{L}, \boldsymbol{R})$

- where $\boldsymbol{L}, \boldsymbol{R}$ are random vectors from $\mathbf{F}^m$ such that $\langle \boldsymbol{L}, \boldsymbol{R} \rangle = \boldsymbol{M}$

and

- $\mathbf{Dec}(\boldsymbol{L}, \boldsymbol{R}) = \langle \boldsymbol{L}, \boldsymbol{R} \rangle$

This encoding is very useful for protecting against physical attacks

Why?

Informally:

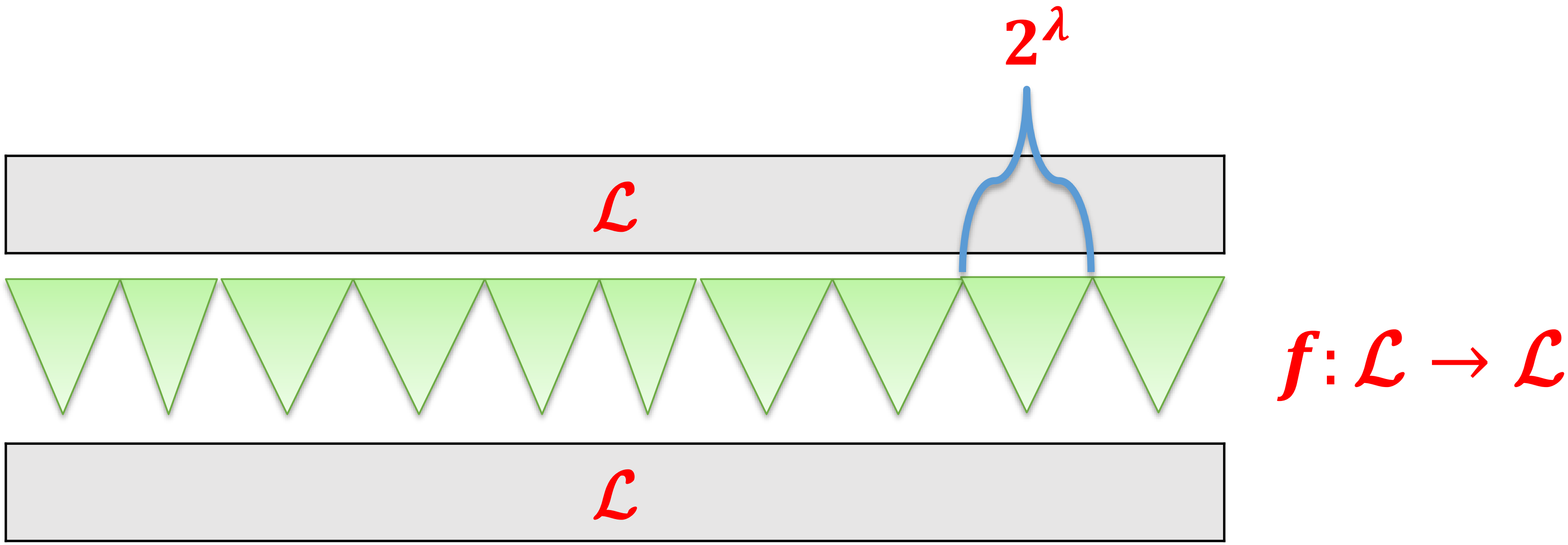
"incomplete information" about $\boldsymbol{L}$ (and complete information about $\boldsymbol{R}$) gives (almost) no information about $\langle \boldsymbol{L}, \boldsymbol{R} \rangle$.

For example: for every $\boldsymbol{L} \in \mathbf{F}^m$
$|\{L' : f(L') = f(L)\}| \geq 2^{\lambda}$ for some large λ.

In particular if one applies a function $\boldsymbol{f}$ to $\boldsymbol{L}$ that "glues" many elements together then $(\boldsymbol{f}(\boldsymbol{L}), \boldsymbol{R})$ gives almost no information about $\langle \boldsymbol{L}, \boldsymbol{R} \rangle$.

Of course: it's symmetric for $\boldsymbol{R}$.

"Gluing 2^λ elements together"



Example: a function that "forgets" first λ bits of input

$$f(a_1, \dots, a_n) = (0, \dots, 0, a_{\lambda+1}, \dots, a_n)$$

“incomplete information” about $\boldsymbol{L}$ (and complete information about $\boldsymbol{R}$) gives (almost) no information about $\langle \boldsymbol{L}, \boldsymbol{R} \rangle$.

Some intuition why this is true

Suppose $\mathbf{F} = \boldsymbol{Z_2}$. Then

$$\boldsymbol{M} = \langle (\boldsymbol{L_1}, \dots, \boldsymbol{L_k}), (\boldsymbol{R_1}, \dots, \boldsymbol{R_k}) \rangle =$$

parity of the set $\{\boldsymbol{i}: \boldsymbol{L_i} = \boldsymbol{R_i} = \mathbf{1}\}$

Intuitively:

If one learns only partial information about $(\boldsymbol{L_1}, \dots, \boldsymbol{L_k})$ then $\boldsymbol{M}$ is hidden (the same for $(\boldsymbol{R_1}, \dots, \boldsymbol{R_k})$).

Why it looks useful?

If the adversary uses a function $\boldsymbol{f}$ or $\boldsymbol{g}$ that is "gluing" many inputs then for sure $\mathbf{Dec}\big(\boldsymbol{f}(\boldsymbol{L}),\boldsymbol{g}(\boldsymbol{R})\big)$ is independent from $\mathbf{Dec}(\boldsymbol{L},\boldsymbol{R})$.

Moral: the adversary has to choose functions that do not glue too many inputs.

In other words: they have to be **close to being bijections**.

Hope: maybe this is easier to analyze?

Is this encoding non-malleable?

$\mathbf{F}$ – finite field

- $\mathbf{Enc}(M) :=$ **random** (L, R) **such that** $\langle L, R \rangle = M$
- $\mathbf{Dec}(L, R) = \langle L, R \rangle$

Problem: linearity of the inner product (let $c \in \mathbf{F}$)

$$\langle c \cdot L, R \rangle = c \cdot \langle L, R \rangle$$

So: if we choose

$$f(L) = c \cdot L \text{ and } g(R) = R$$

then $M' = c \cdot M$

Observation

If $\mathbf{F} = \boldsymbol{Z_2}$ then then $\boldsymbol{c}$ can only be $\mathbf{0}$ or $\mathbf{1}$

- if $\boldsymbol{c} = \mathbf{0}$ then it is a "**constant attack**":

$$\boldsymbol{M'} = \mathbf{0} \text{ for every } \boldsymbol{M}$$

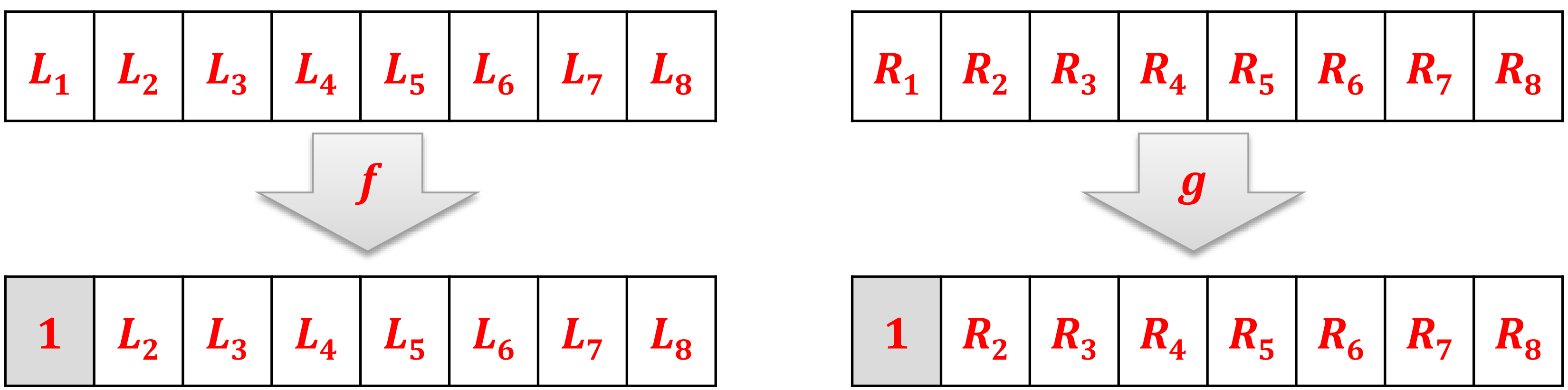
- if $\boldsymbol{c} = \mathbf{1}$ then it is an "**identity attack**"

$$\boldsymbol{M'} = \boldsymbol{M} \text{ for every } \boldsymbol{M}$$

Hope: maybe it works over $\mathbf{Z}_2$?

Unfortunately in this case another attack is possible:

"the tampering functions set $L_1 := 1$ and $R_1 := 1$"



Note: the inner product changes iff $L_1 R_1 = 0$.
This happens with probability $3/4$.

Observation

The attack from the previous slide does not work if **$|\mathbf{F}|$** is exponential.

This is because

$$\boldsymbol{P(L_1 \cdot R_1 = 0) \approx \frac{2}{|F|}}$$

So, this is the situation:

	large **F**	$\mathbf{F} = \boldsymbol{Z_2}$
the "linear attack"	**works**	**doesn't work**
the "$\boldsymbol{L_1 := 1}$ and $\boldsymbol{R_1 = 1}$" attack	**doesn't work**	**works**

Question: is it possible to combine these two solutions so that none of these attacks works?

Answer: **yes**! (for messages of length **1**)

Let $\mathbf{F}$ be a field of exponential size.

Define

$$(\mathbf{Enc}\colon \boldsymbol{Z}_2 \to \mathbf{F}^n \times \mathbf{F}^n,\ \mathbf{Dec}\colon \mathbf{F}^n \times \mathbf{F}^n \to \boldsymbol{Z}_2)$$

as

$$\mathbf{Enc}(\boldsymbol{M}) := \begin{cases} \text{random } (\boldsymbol{L}, \boldsymbol{R}) \text{ such that } \langle \boldsymbol{L}, \boldsymbol{R} \rangle = \mathbf{0} \text{ if } \boldsymbol{M} = \mathbf{0} \\ \text{random } (\boldsymbol{L}, \boldsymbol{R}) \text{ such that } \langle \boldsymbol{L}, \boldsymbol{R} \rangle \neq \mathbf{0} \text{ if } \boldsymbol{M} = \mathbf{1} \end{cases}$$

$\mathbf{Dec}(\boldsymbol{L}, \boldsymbol{R})$ just computes $\langle \boldsymbol{L}, \boldsymbol{R} \rangle$ and checks if it is $\mathbf{0}$.

For security proof – see the paper.

Encoding for messages of arbitrary length [Aggarwal, Dodis, and Lovett, STOC 2014]

General outline of their method:

1. show that mauling the inner product encoding can induce only **affine functions** $\boldsymbol{h'}$ (or their random combinations)
2. on top of it use encoding that is **resilient to affine mauling**.

A drawback of their construction:

$$|\boldsymbol{C}| = \boldsymbol{O}(|\boldsymbol{M}|^7)$$

Why affine? Look at this:

Let $\boldsymbol{M} = \langle \boldsymbol{L}, \boldsymbol{R} \rangle, \boldsymbol{M}' = \langle \boldsymbol{f}(\boldsymbol{L}), \boldsymbol{g}(\boldsymbol{R}) \rangle$

How can $\boldsymbol{M}'$ depend on $\boldsymbol{M}$?

- if $\boldsymbol{f}(\boldsymbol{L}) = \boldsymbol{a} \cdot \boldsymbol{L}$ (for $\boldsymbol{b} \in \mathbf{F}$) then
$$\boldsymbol{M}' = \boldsymbol{a} \cdot \boldsymbol{M}$$
- the adversary can also make $\boldsymbol{M}$ equal to any constant $\boldsymbol{b}$ chosen by him.

these are affine functions
$$\boldsymbol{f}(\boldsymbol{M}) = \boldsymbol{a} \cdot \boldsymbol{M} + \boldsymbol{b}$$

Main observation of **[ADL14]**

The affine functions are **the only ones** that the adversary can induce!

> They show it using the techniques from additive combinatorics (***Quasi-polynomial Freiman-Ruzsa Theorem***)

Plan

1. Short introduction to physical attacks
2. Non-malleable codes – the definition
3. Non-malleable codes – constructions secure w.r.t different function families:
    1. bit-wise tampering
    2. tempering functions from sets of bounded size
    3. split-state model
4. Subsequent work

Non-Malleable Codes – subsequent work

A very active area of research!

- constructions secure w.r.t. different function families,
- efficiency improvements
- extensions (continual tampering, updatable codes, local decodability…)
- new applications.

Conference papers from 2014–2016 with "non-malleable codes" in the title

- A. Kiayias, F. L., Y. Tselekounis: **Practical Non-Malleable Codes from l-more Extractable Hash Functions**. **ACM CCS 2016**
- M. Ball, D. Dachman-Soled, M. Kulkarni, T. Malkin: **Non-malleable Codes for Bounded Depth, Bounded Fan-In Circuits**. **EUROCRYPT 2016**
- N. Chandran, V. Goyal, P. Mukherjee, O. Pandey, J. Upadhyay: **Block-Wise Non-Malleable Codes**. **ICALP 2016**
- D. Aggarwal, J. Briët: **Revisiting the Sanders-Bogolyubov-Ruzsa theorem in Fpn and its application to non-malleable codes**. **ISIT 2016**
- E. Chattopadhyay, V. Goyal, X. Li: **Non-malleable extractors and codes, with their many tampered extensions**. **STOC 2016**
- N. Chandran, B. Kanukurthi, S. Raghuraman: **Information-Theoretic Local Non-malleable Codes and Their Applications**. **TCC 2016**
- D. Aggarwal, S. Agrawal, D. Gupta, H. K. Maji, O. Pandey, M. Prabhakaran: **Optimal Computational Split-state Non-malleable Codes**. **TCC 2016**
- E. Chattopadhyay, V. Goyal, X. Li: **Non-malleable extractors and codes, with their many tampered extensions**. **STOC 2016**
- S. Agrawal, D. Gupta, H. K. Maji, O. Pandey, M. Prabhakaran: **Explicit Non-malleable Codes Against Bit-Wise Tampering and Permutations**. **CRYPTO 2015**
- S. Agrawal, D. Gupta, H. K. Maji, O. Pandey, M. Prabhakaran: **A Rate-Optimizing Compiler for Non-malleable Codes Against Bit-Wise Tampering and Permutations.** **TCC 2015**
- D. Aggarwal, S. Dziembowski, T. Kazana, M. Obremski: **Leakage-Resilient Non-malleable Codes**. **TCC 2015**
- D. Dachman-Soled, F. L., E. Shi, H.-S. Zhou: **Locally Decodable and Updatable Non-malleable Codes and Their Applications**. **TCC 2015**
- Z. Jafargholi, D. Wichs: **Tamper Detection and Continuous Non-malleable Codes**. **TCC 2015**
- S. Coretti, U. Maurer, B. Tackmann, D. Venturi: **From Single-Bit to Multi-bit Public-Key Encryption via Non-malleable Codes**. **TCC 2015**
- S. Faust, P. Mukherjee, D. Venturi, D. Wichs: **Efficient Non-malleable Codes and Key-Derivation for Poly-size Tampering Circuits**. **EUROCRYPT 2014**
- E. Chattopadhyay, D. Zuckerman: **Non-malleable Codes against Constant Split-State Tampering.** **FOCS 2014**
- M. Cheraghchi, V. Guruswami: **Non-malleable Coding against Bit-Wise and Split-State Tampering**. **TCC 2014**
- M. Cheraghchi, V. Guruswami: **Capacity of non-malleable codes**. **ITCS 2014**
- D. Aggarwal, Y. Dodis, S. Lovett: **Non-malleable codes from additive combinatorics**. **STOC 2014**
- S. Faust, P. Mukherjee, J. Buus Nielsen, D. Venturi: **Continuous Non-malleable Codes**. **TCC 2014**

Thank you!

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