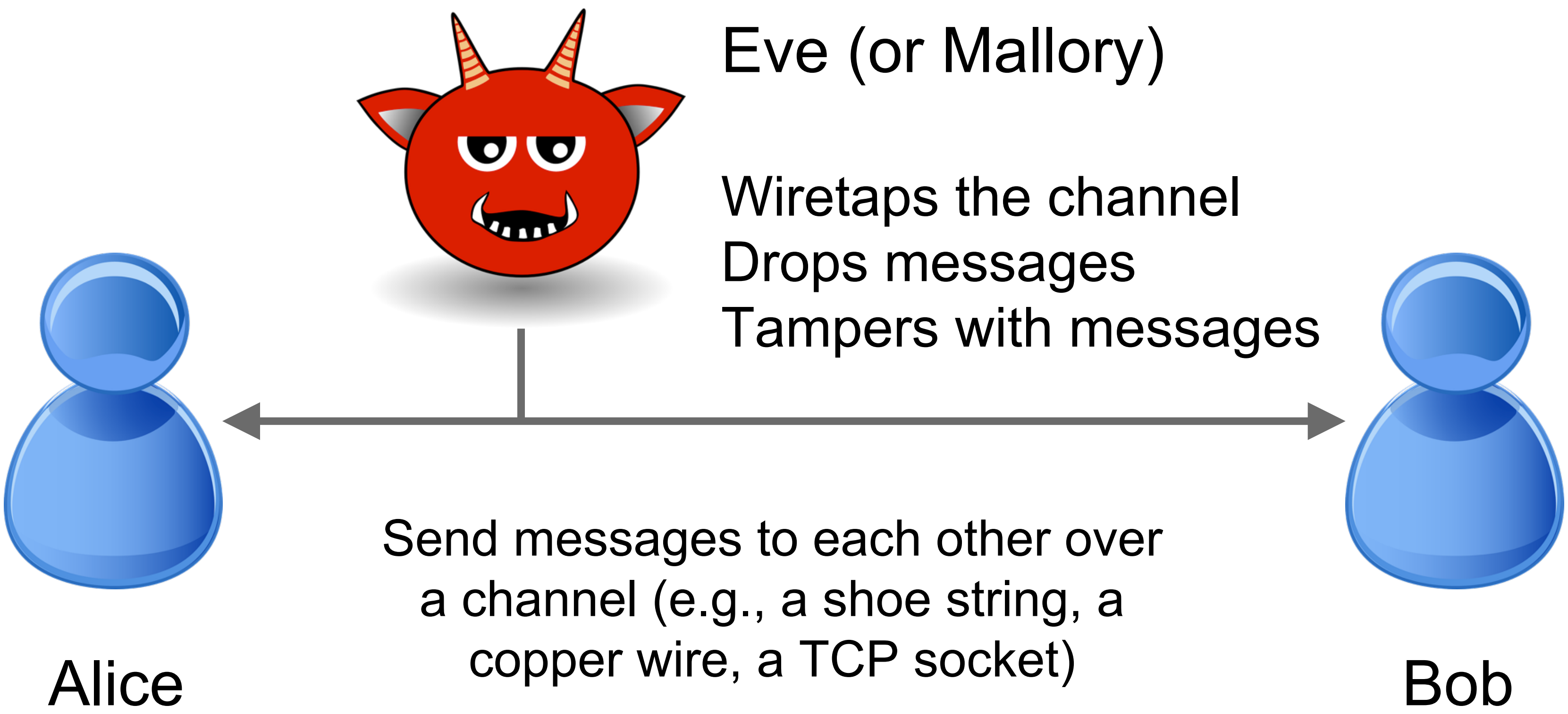
Cryptography 1 of 4
Message Integrity

ECE422 / CS461
Andrew Miller / Michael Bailey

Cryptography is the study/practice of techniques for secure **communication**, even in the presence of powerful **adversaries** who have **control** over the **underlying channel**



Learning goals of cryptography module

- Understand the interfaces of basic crypto primitives

Hashes, MACs, symmetric encryption, public key encryption, digital signatures, key exchange

- Apply the adversarial mindset to crypto protocols

- Appreciate the following warning:

"Don't roll your own Crypto!" …….

- Familiarity with concepts, vocabulary

Lectures are for breadth

Cryptography is not just encryption!

Cryptography can help ensure:

- Confidentiality: secrecy, privacy

- Integrity: tamper resilience

- Availability

- Non-repudiability: deniability

…. many more properties

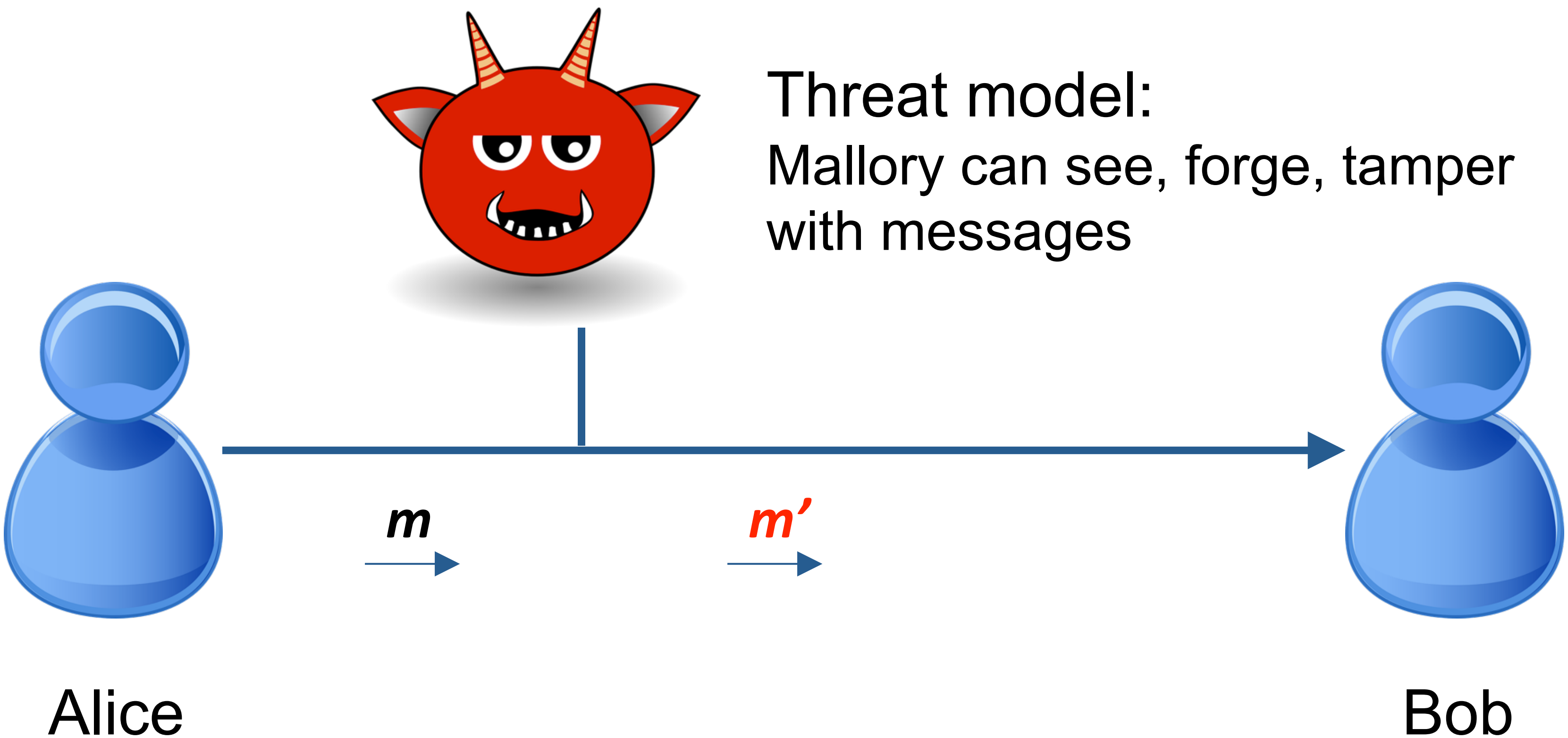
Message Integrity

Hashes, MACs

Goal: Secure File Transfer

Alice wants to send file ***m*** to Bob (let's say, a 4 Gigabyte movie)
Mallory wants to trick Bob into accepting a file Alice didn't send

Threat model:
Mallory can see, forge, tamper with messages



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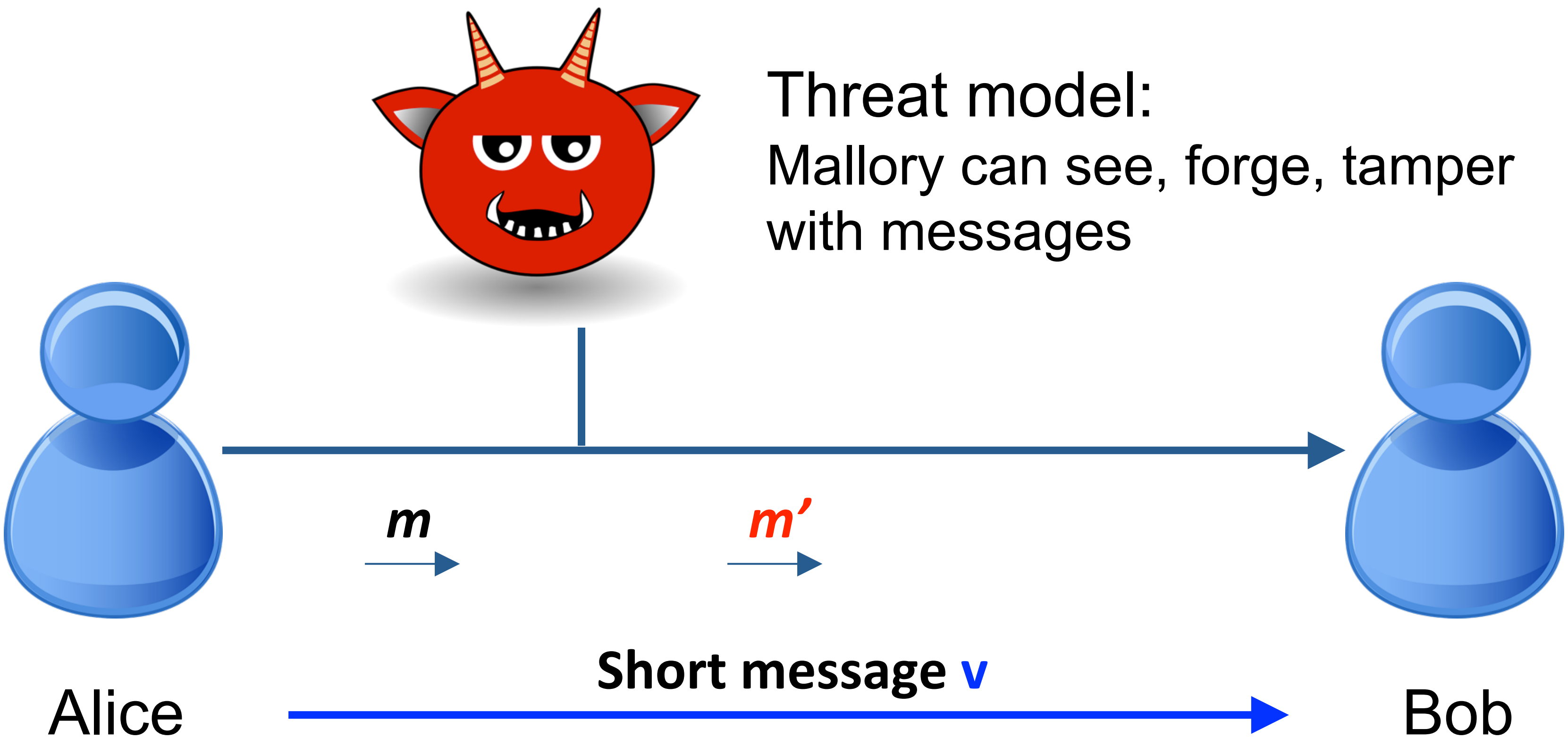
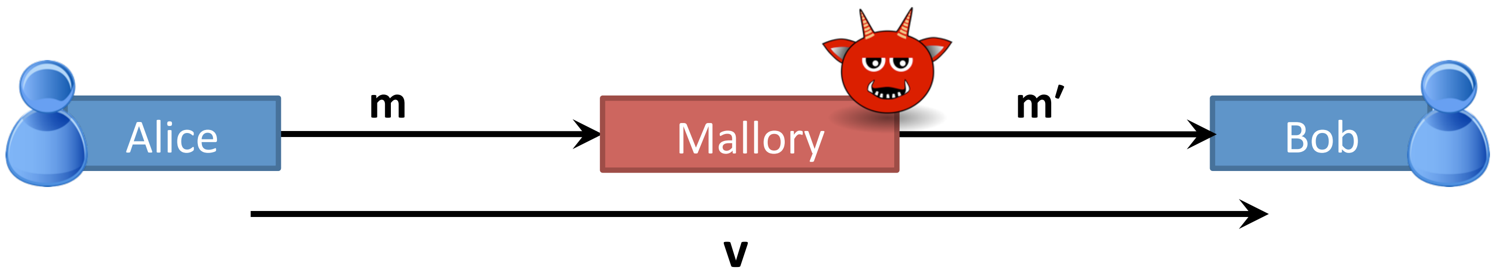


Setup assumption: *Securely transfer a short message!*

Solution: Collision Resistant Hash Function (CRHF)

Hash Function h: $\{0,1\}^* \rightarrow \{0,1\}^{256}$ (or other fixed number)

1. Alice computes **v** := h(**m**)
2. Alice transfers **v** over secure channel, **m** over insecure channel



3. Bob verifies that **v** = h(**m'**), accepts file iff this is true

Function h ? We're sunk if Mallory can compute **m'** ≠ **m** where h(**m**) = h(**m'**)! A *collision*!

Contrast with: "checksums" e.g. CRC32.... defend against random errors, not a deliberate attacker!

Hash function properties

Good hash functions should make it difficult to find …

First pre-image:

given $h(m)$, find m

Second pre-image:

given m_1, find m_2 s.t. $h(m_1) = h(m_2)$

Collision:

find *any* $m_1 \neq m_2$ s.t. $h(m_1) = h(m_2)$

Which of these properties implies which others?

What is SHA256?

`$ sha256sum file.dat`

Cryptographic hash

Input: arbitrary length data
(<u>No key</u>)
Output: 256 bits

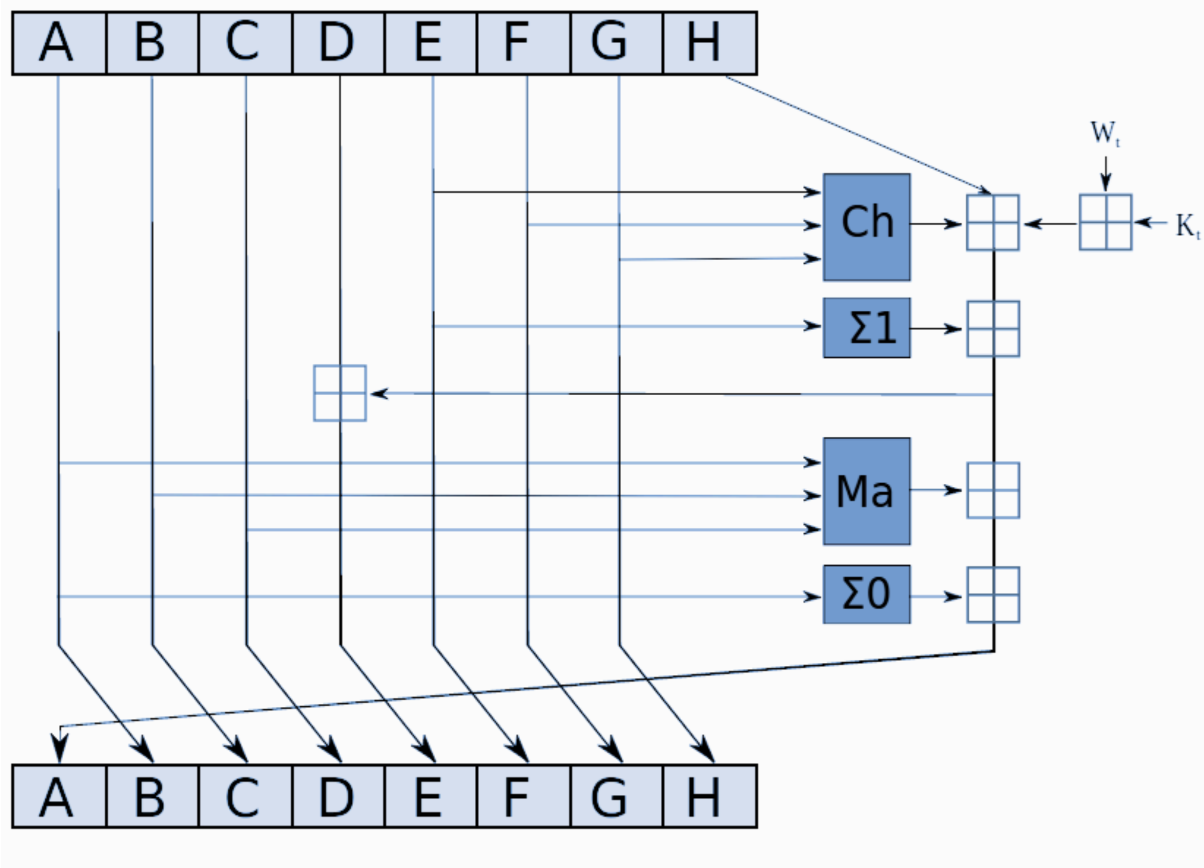
Built with compression function, ***h***

(256 bits, 512 bits) in → 256 bits out

Designed to be really hairy (64 rounds of this)!

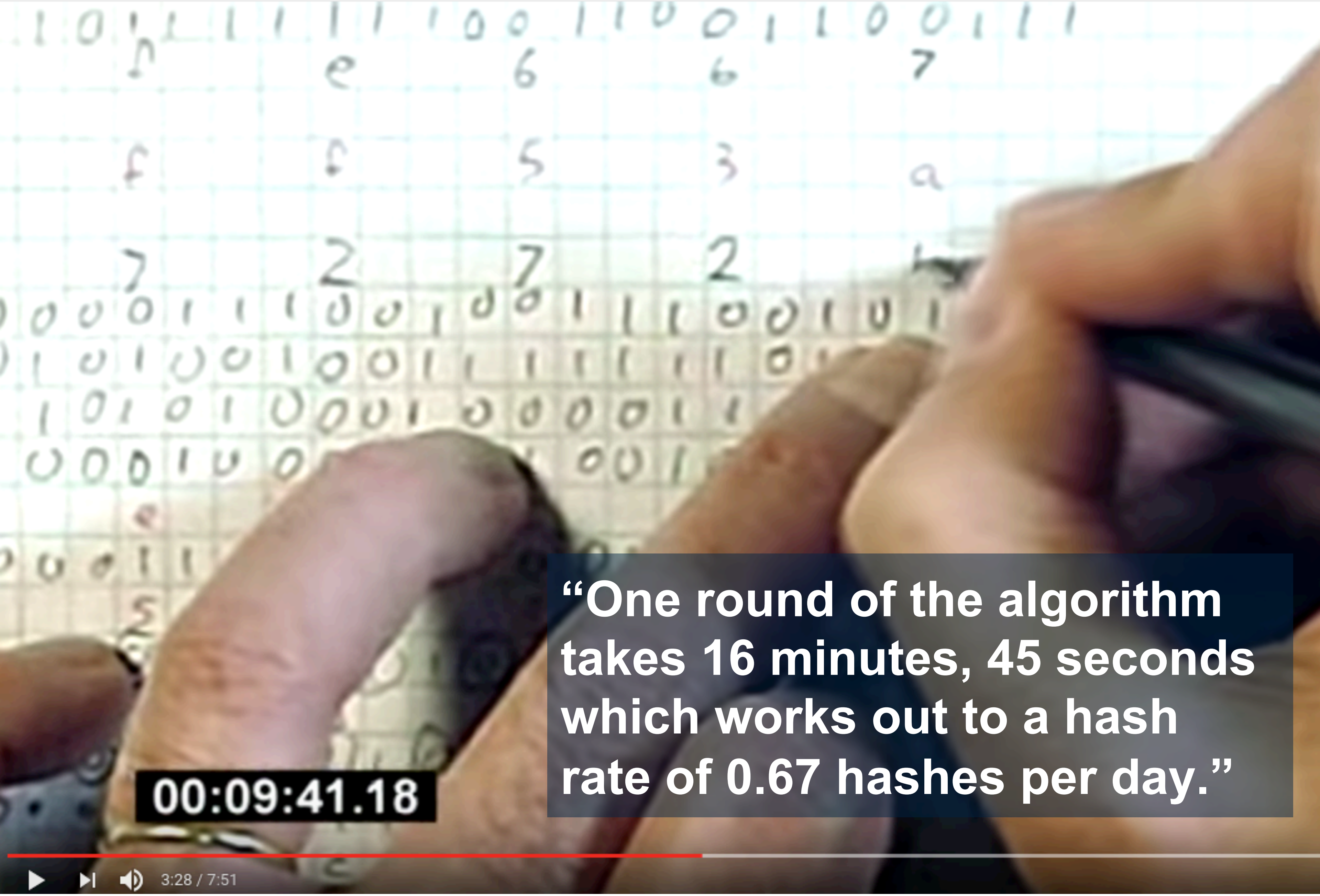
Confusion and Diffusion

The **SHA256** compression function, **h**



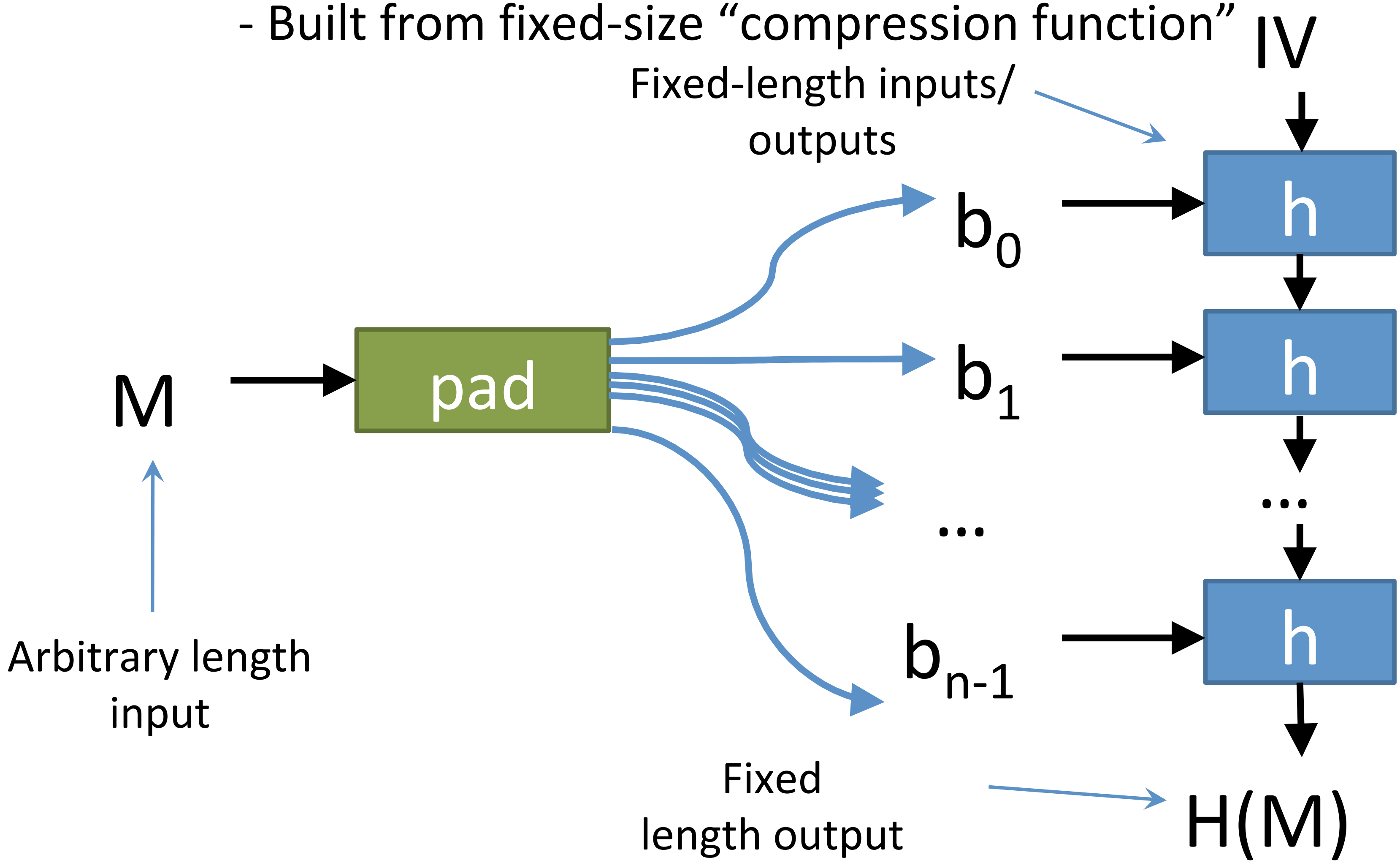
$$\mathrm{Ch}(E,F,G) = (E \wedge F) \oplus (\neg E \wedge G)$$
$$\mathrm{Ma}(A,B,C) = (A \wedge B) \oplus (A \wedge C) \oplus (B \wedge C)$$
$$\Sigma_0(A) = (A \ggg 2) \oplus (A \ggg 13) \oplus (A \ggg 22)$$
$$\Sigma_1(E) = (E \ggg 6) \oplus (E \ggg 11) \oplus (E \ggg 25)$$

https://www.youtube.com/watch?v=y3dqhixzGVo

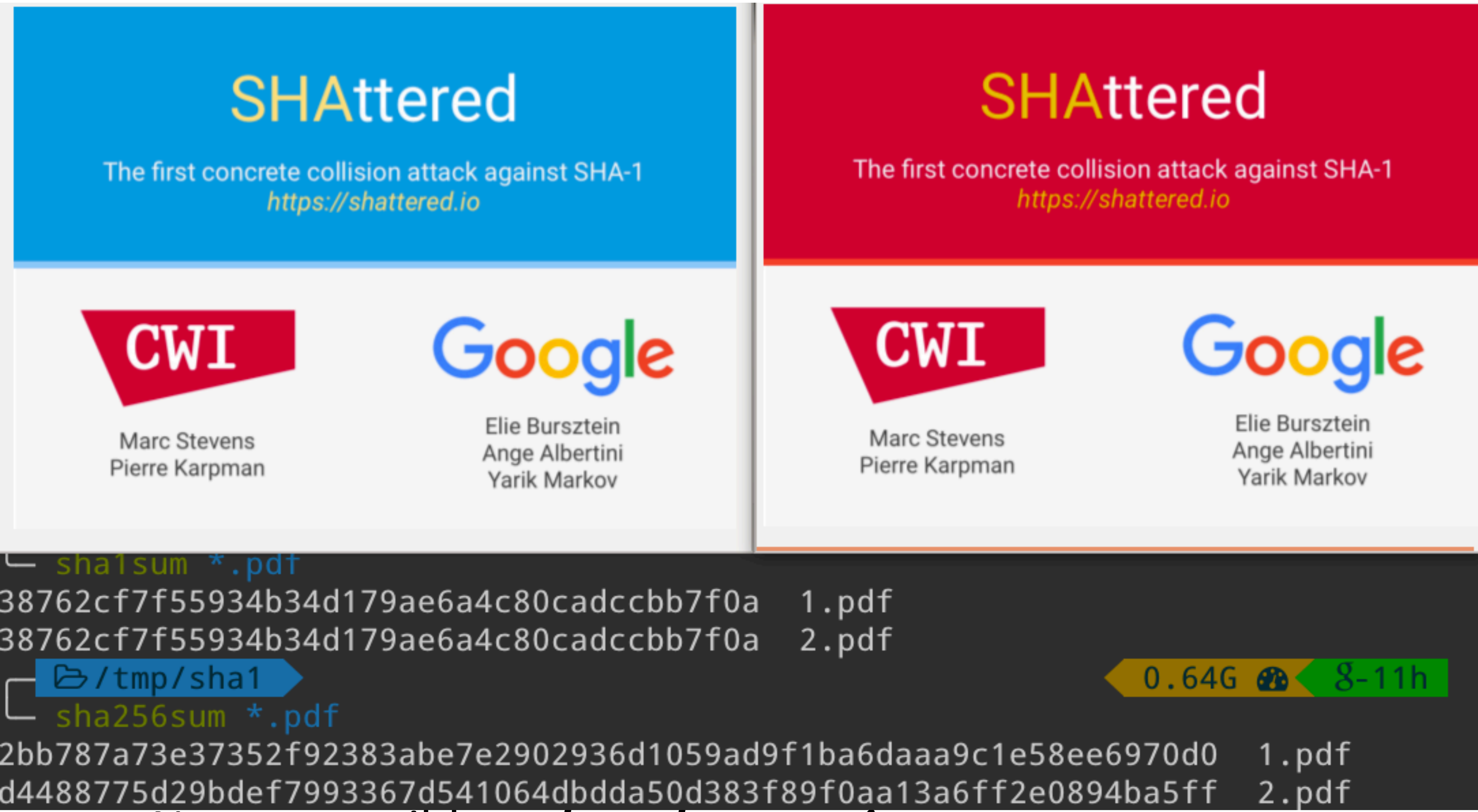


Merkle–Damgård Construction

- Arbitrary-length input
- Fixed-length output
- Built from fixed-size “compression function”



Other hash functions:



Not susceptible to ***length-extension*** http://valerieaurora.org/hash.html

Lifetimes of popular cryptographic hashes (the rainbow chart)

Function	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Snefru																												
MD2 (128-bit)[1]																												
MD4																												
MD5															[2]													
RIPEMD															[2]													
HAVAL-128[1]															[2]													
SHA-0																												
SHA-1																												[3]
RIPEMD-160																												
SHA-2 family																		[4]										
SHA-3 (Keccak)																												

Key	Didn't exist/not public	Under peer review	Considered strong	Minor weakness	Weakened	Broken	Collision found

How do you find a collision?

- **Pigeonhole principle:** collisions must exist

  Input space {0,1}* larger than output {0,1}

256

- **Birthday attack:** build a table with 2^{128} entries

  With ~50% probability, have a collision

- **Cycle finding:** “Tortoise and hare” algorithm

  h(x), h(h(x)), h(h(h(x), .., $h^i(x)$

- These are **generic** - actual attacks rely on **structure** of the particular function

Most cryptographic primitives come with a **security parameter**

Usually k, or λ

- Often Corresponds to a key size
- Cryptography protocols run in **polynomial** time

  i.e., as a function of λ, $O(poly(\lambda))$
- Ideally, we can show that the chance of failure is **negligible**, or **vanishingly** small as a function of λ

$O(negl(\lambda))$

Concrete Parameterization

How large of a digest size should we choose?

1. Estimate an attacker's budget

E.g., the entire NSA

2. Consider the best known attacks

Reduction from protocol to well-studied problem

3. Add a safety margin

If all goes well, adding 1 bit increases search space by 2x

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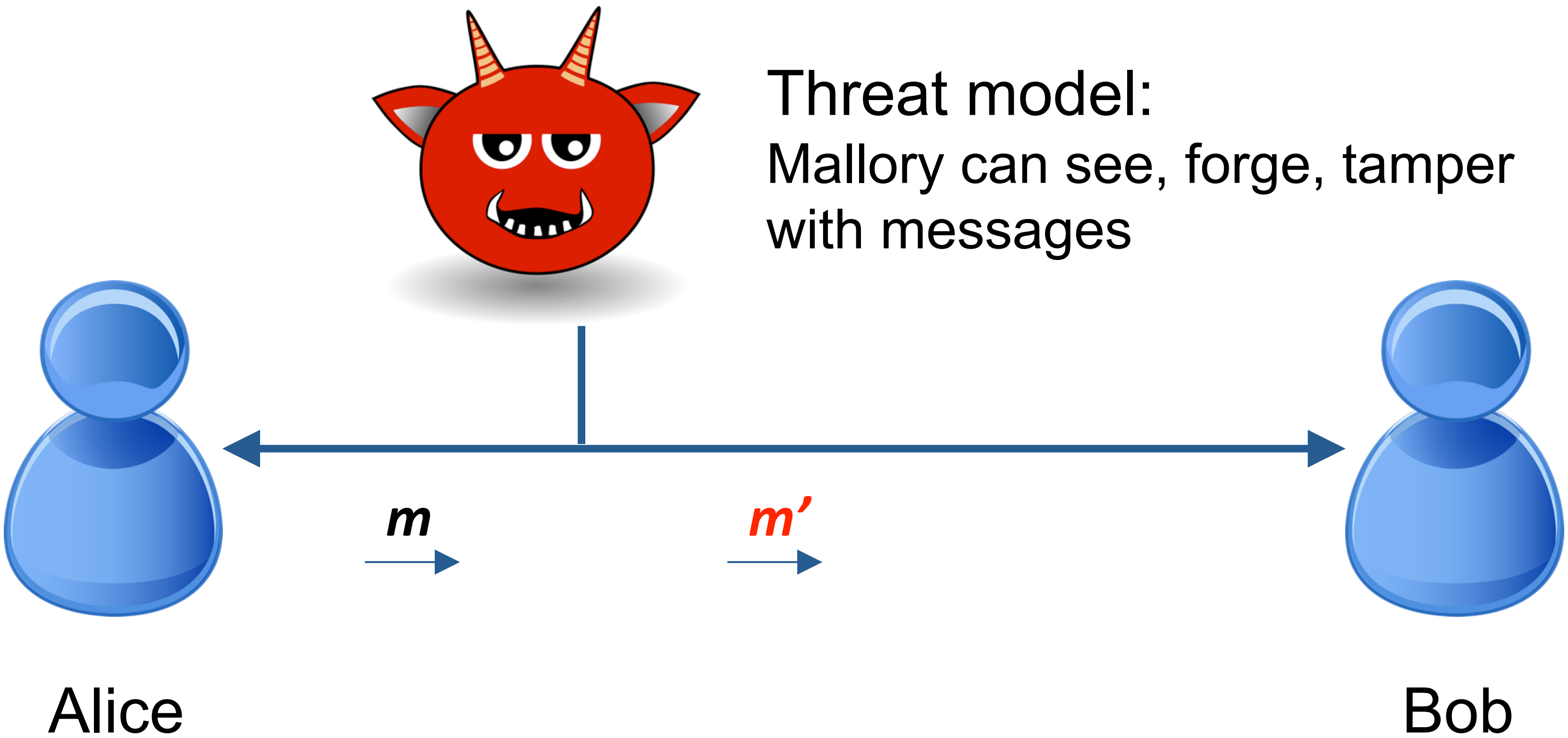

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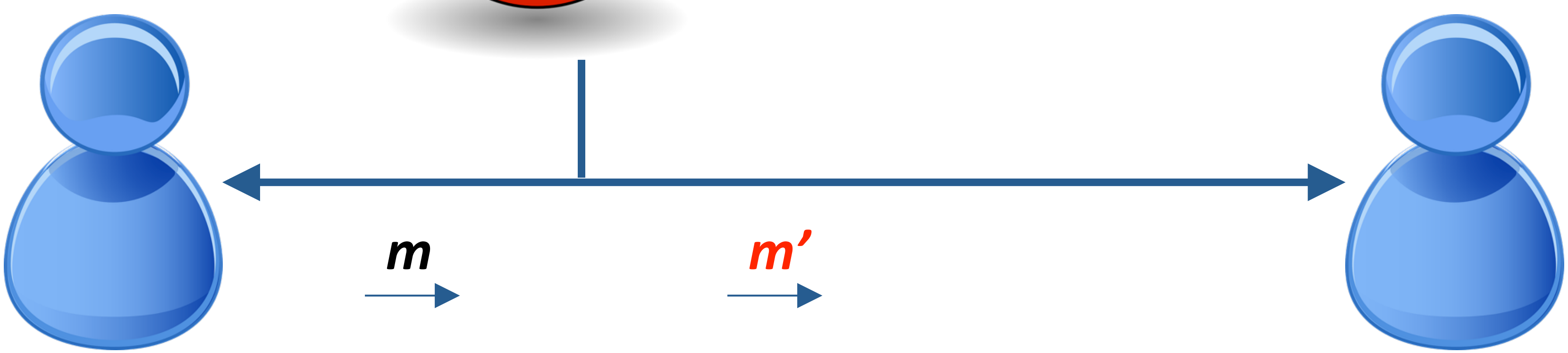

Alice, ***x***

Bob, ***x***

Setup assumption: ***shared secret***

Solution: Message Authentication Code (MAC)

1. Alice computes $\mathbf{v} := \boldsymbol{f}(\mathbf{m})$

2.

e.g. “Attack at dawn”, 628369867…

3. Bob verifies that $\mathbf{v'} = \boldsymbol{f}(\mathbf{m'})$,
   accepts message iff this is true

Function $\boldsymbol{f}$?

Easily computable by Alice and Bob;
not computable by Mallory

(Idea: Secret only Alice & Bob know)

We’re sunk if Mallory can learn
$\boldsymbol{f}(\mathbf{m'})$ for any $\mathbf{x} \neq \mathbf{m'}$!

Candidate ***f***:

Random function

Input: Any size up to huge maximum

Output: Fixed size (e.g. 256 bits)

Defined by a giant lookup table that's filled in by flipping coins

0	→	0011111001010001...
1	→	1110011010010100...
2	→	0101010001010000...
⋮		⋮

Completely <u>impractical</u> [Why?]

Provably <u>secure</u> [Why?]

Want a function that's practical but "looks random"…

Pseudorandom function (PRF)

Let's build one:

Start with a big *family of functions*

$\boldsymbol{f}_0, \boldsymbol{f}_1, \boldsymbol{f}_2, \ldots$ all known to Mallory

Use $\boldsymbol{f}_{\mathbf{k}}$, where **k** is a secret value (or "key") known only to Alice/Bob

k is (say) 256 bits, chosen randomly

Kerckhoffs's Principle [Why?]

Don't rely on secret functions

Use a secret key, to choose from a function family

More formal definition of a secure **PRF**:

Game against Mallory

1. We flip a coin secretly to get bit **b**
2. If **b**=0, let ***g*** be a random function
   If **b**=1, let ***g*** = $\boldsymbol{f}_{\mathbf{k}}$, where **k** is a randomly chosen secret
3. Repeat until Mallory says "stop":
   Mallory chooses **x**; we announce ***g***(**x**)
4. Mallory guesses **b**

We say ***f*** is a *secure PRF* if Mallory can't do better than random guessing*

i.e., $\boldsymbol{f}_{\mathrm{k}}$ is indistinguishable in practice from a random function, unless you know k

Important fact: There's an algorithm that always wins for Mallory

[What is it?] [How to fix it?]

A solution for Alice and Bob:

1. Let f by a secure PRF
2. In advance, choose a random **k** known only to Alice and Bob
3. Alice computes **v** := f_k(**m**)
4. 

5. Bob verifies that **v'** = f_k(**m'**),
   accepts message iff this is true

[Important assumptions?]

What if Alice and Bob want to send more than one message?

[Attacks?] [Solutions?]

Is this a PRF?

$$\boldsymbol{f}_{\mathbf{k}}(\mathbf{m}) = \mathrm{SHA256}(\ \mathbf{k}\ ||\ \mathbf{m}\ )$$

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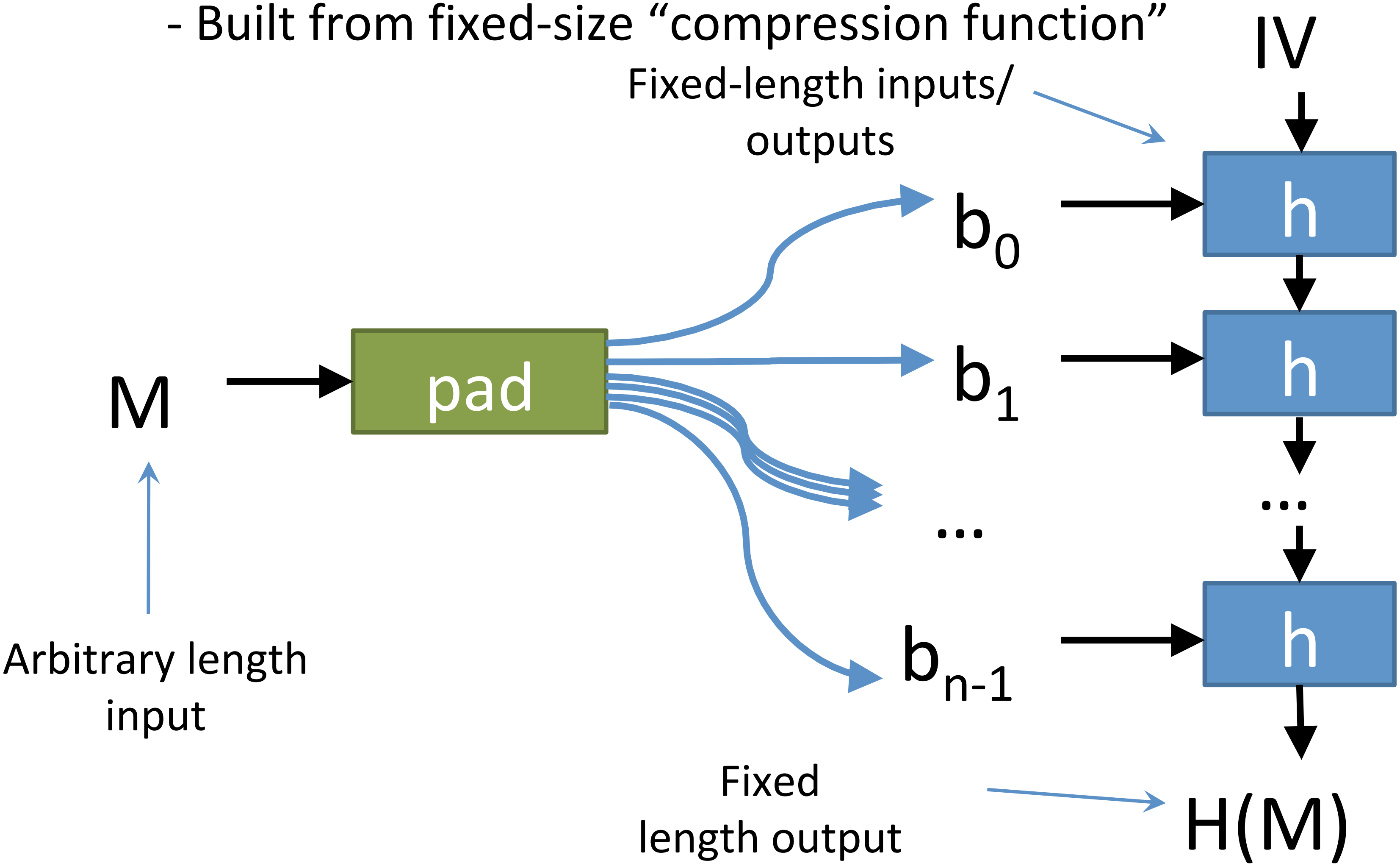

Recommended Approach: Hash-based MAC (HMAC)

HMAC-SHA256

see RFC 2104

$\text{HMAC}_{\mathbf{k}}(\mathbf{m})$ =

$$\text{SHA256}\left(k \oplus c_1 \;\|\; \text{SHA256}\left(k \oplus c_2 \;\|\; m\right)\right)$$

XOR

`0x3636…`

Concatenation

`0x5c5c…`

SHA256 function

takes arbitrary length input,

returns 256-bit output

Message Authentication Code (MAC)

e.g. HMAC-SHA256

vs.

Cryptographic hash function

e.g. SHA256

<u>not</u> a strong PRF

Used to think the distinction didn't matter, now we think it does

e.g., ***length extension attacks***

Better to use a MAC/PRF (not a hash)

```
$ openssl dgst -sha256 -hmac <key>
```

MAC Crypto Game

Game against Mallory

1. Give Mallory MAC(k, m_i) for all m_i in M
In other words, Mallory has an ***oracle***
Mallory can choose next m_i after seeing answer

2. Mallory tries to discover MAC(k, m') for a new m' not in M

We can show the **MAC game** ***reduces*** to the **PRF game**. Mallory wins MAC game → she wins PRF game.

This is a **Security Proof**

What is a **Security Proof**?

- A ***reduction*** from an ***attack on your protocol*** to an attack on a ***widely studied, hard problem***
- Excludes large classes of attacks, guides **composition**
  - Proofs are in **models**. So, attack outside the model!
- It does **NOT** ***prove*** that your protocol is ***secure***
- We don't know if there are any hard problems!
- The field of **Modern Cryptography** is based on proofs
- Most widely used primitives (SHA-256, AES, DSA) have no security proof. We rely on them because they're widely studied

So Far

Message Integrity

Next time …

The classic problem in crypto:

How can Alice send Bob a message, with **confidentiality**?