Lecture 18 – Message Integrity
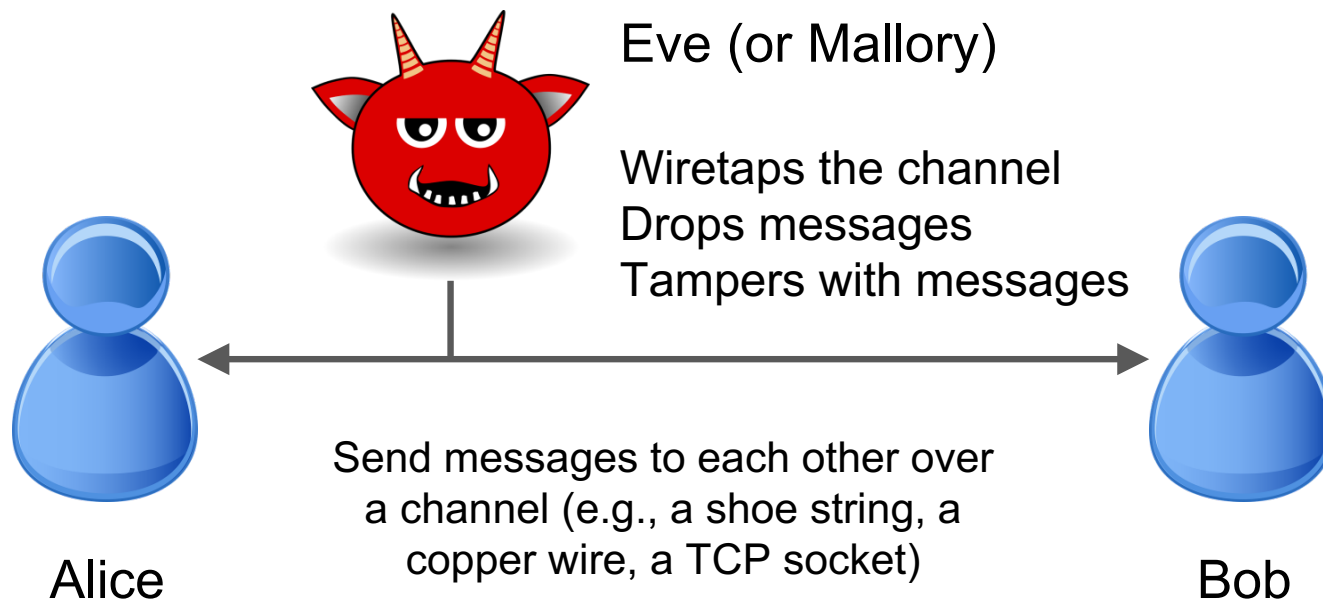
Stephen Checkoway
University of Illinois at Chicago
CS 487 – Fall 2017
Slides from Miller & Bailey's ECE 422

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

Eve (or Mallory)

Wiretaps the channel
Drops messages
Tampers with messages

Send messages to each other over a channel (e.g., a shoe string, a copper wire, a TCP socket)

Alice

Bob

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, or 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

m

m'

Alice

Bob

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Short message v

Alice

Bob
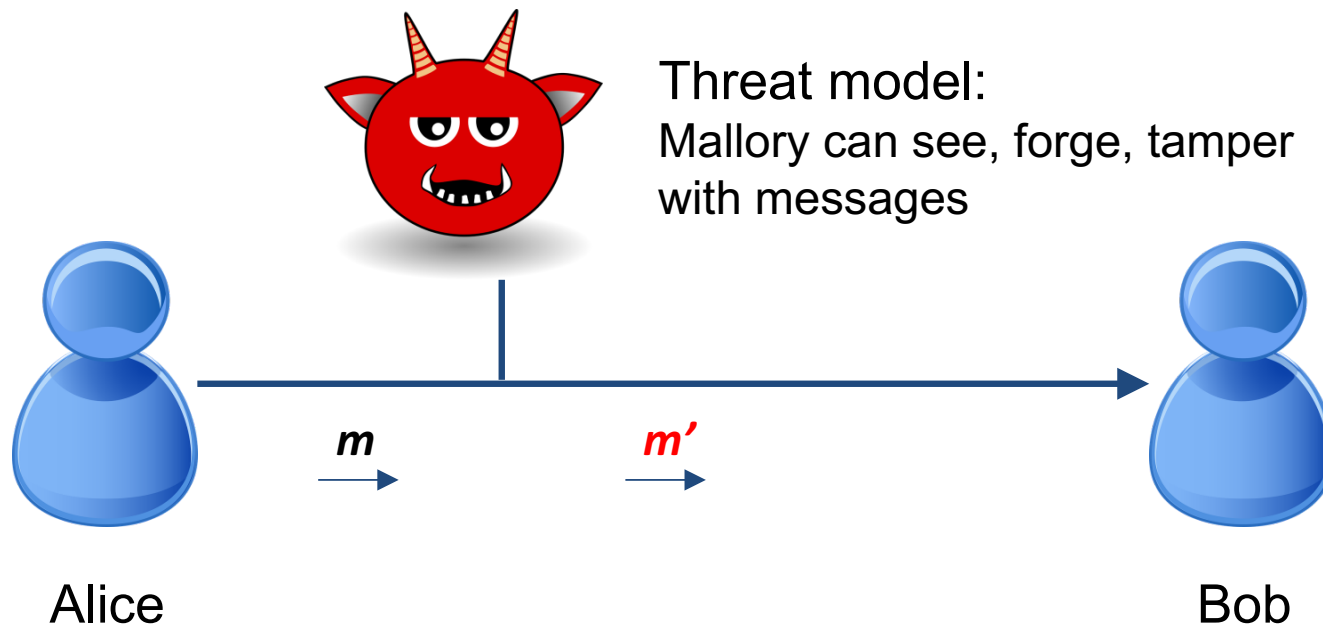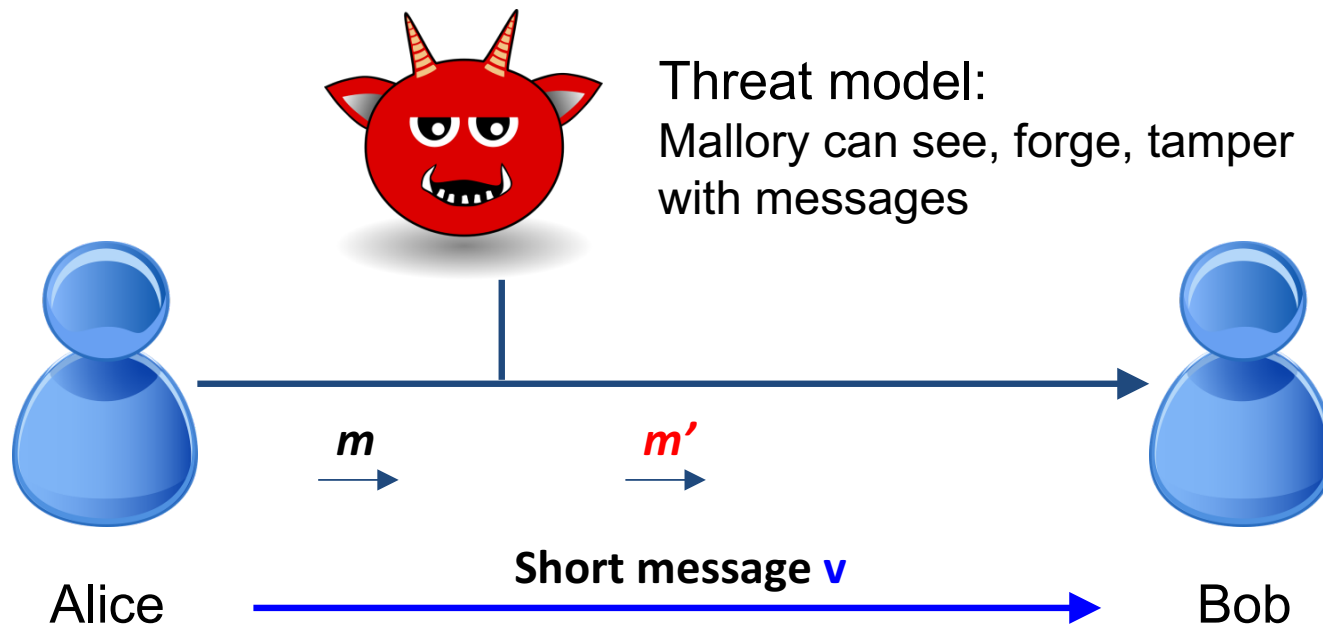
Setup assumption: *Securely transfer a short message!*

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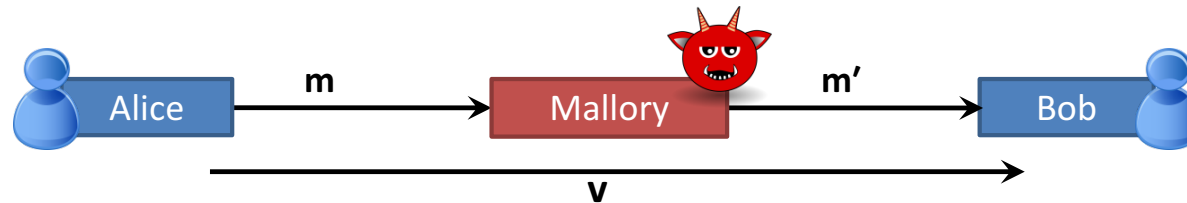
3. Bob verifies that $v = h(m')$, accepts file iff this is true

Function h ?   We're sunk if Mallory can compute $m' \neq m$

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 have the following properties

First pre-image resistance:

Which of these properties implies which others?

Given $h(m)$, it is computationally infeasible to find m' s.t. $h(m') = h(m)$

Second pre-image resistance:

Given m_1, it is computationally infeasible to find $m_2 \neq m_1$ s.t. $h(m_1) = h(m_2)$

Collision resistance:

It is computationally infeasible to find *any* $m_1 \neq m_2$ s.t. $h(m_1) = h(m_2)$

Hash function construction

- Merkle–Damgård construction
  - Pad message to a multiple of block size
  - Run a compression function over each block and the output of the previous compressed block (see next slide)
  - Used for MD5, SHA-1, SHA-2
- Sponge construction
  - Pad message to a multiple of a fixed size (the bitrate r)
  - "Absorb" the message r bits at a time by XORing with part of the internal state, and permuting the whole state by permutation f
  - "Squeeze" out the output r bits at a time, applying f in between
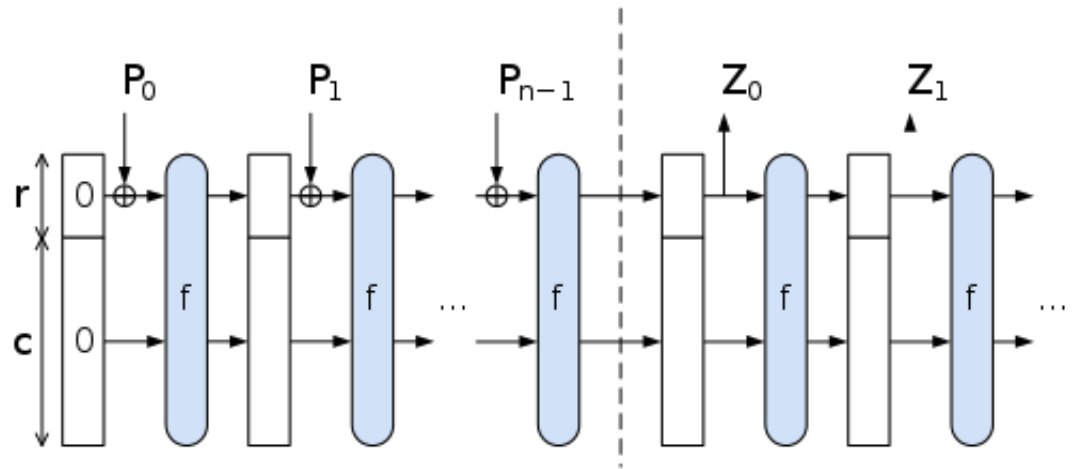 - SHA-3

Merkle–Damgård Construction

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

IV

Fixed-length inputs/outputs

M

pad

b_0

b_1

...

b_{n-1}

h

h

...

h

H(M)

Arbitrary length input

Fixed length output
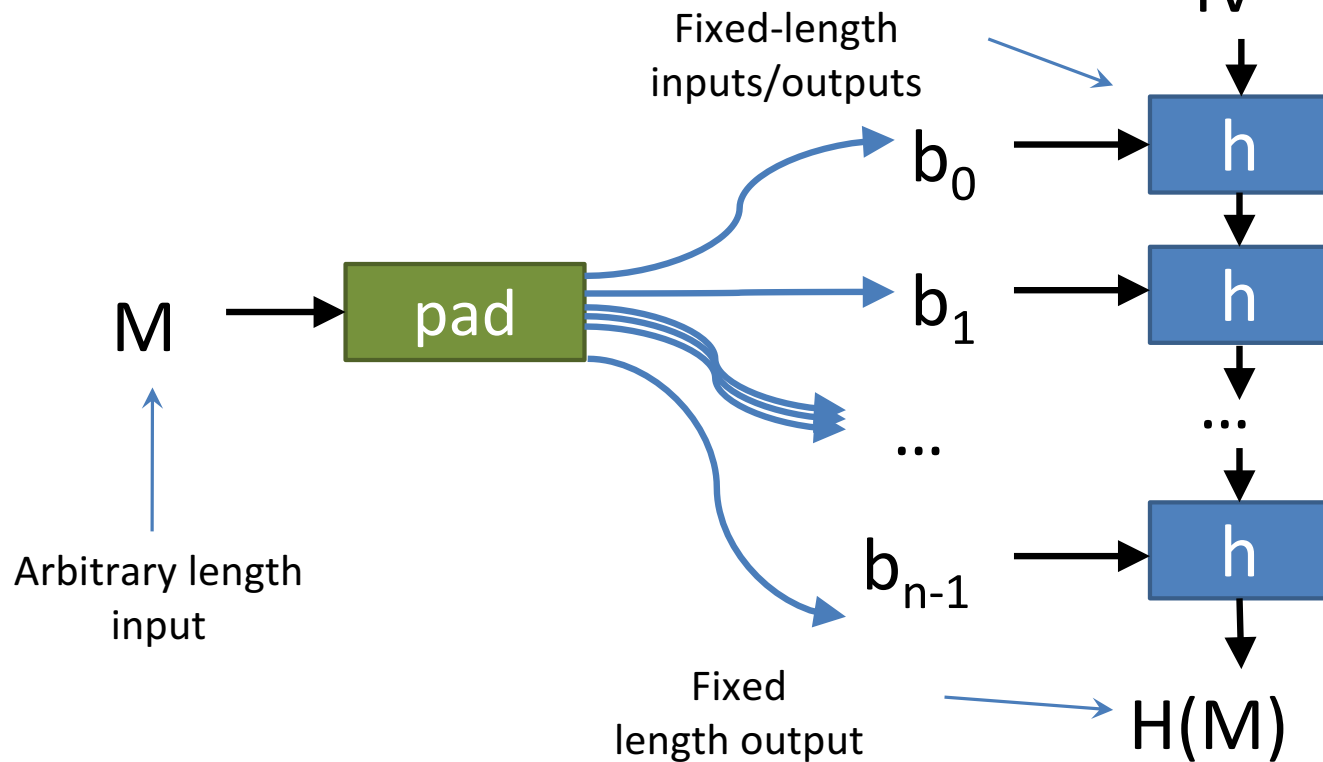
Sponge construction

- Internal state initially 0
  r+c total bits
- P_i are message blocks
- Z_i are the output blocks

What is SHA256?

$ sha256sum file.dat

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

Cryptographic hash

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

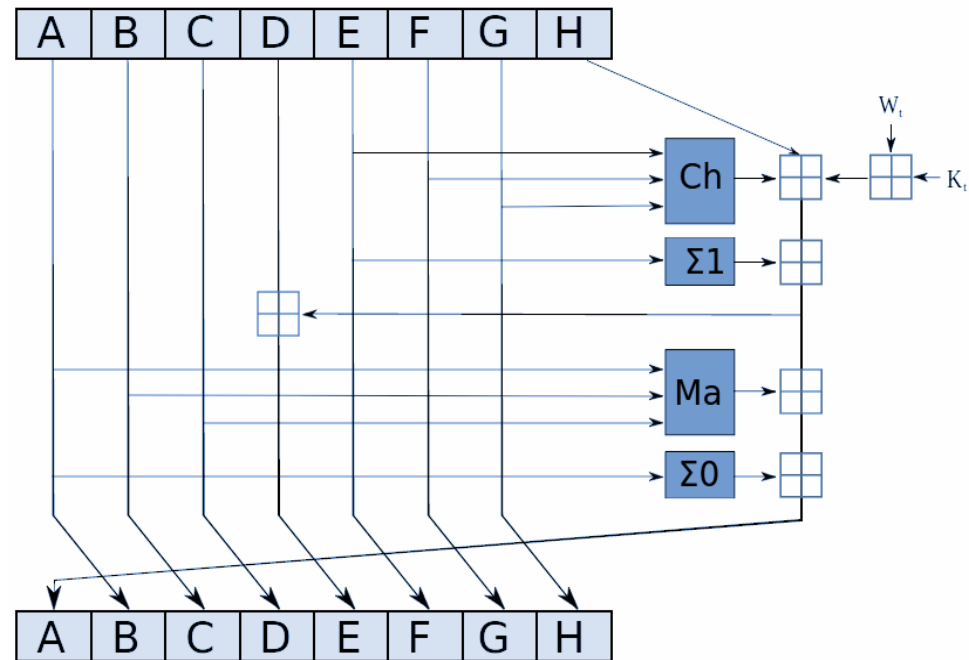Built with compression function, **h**

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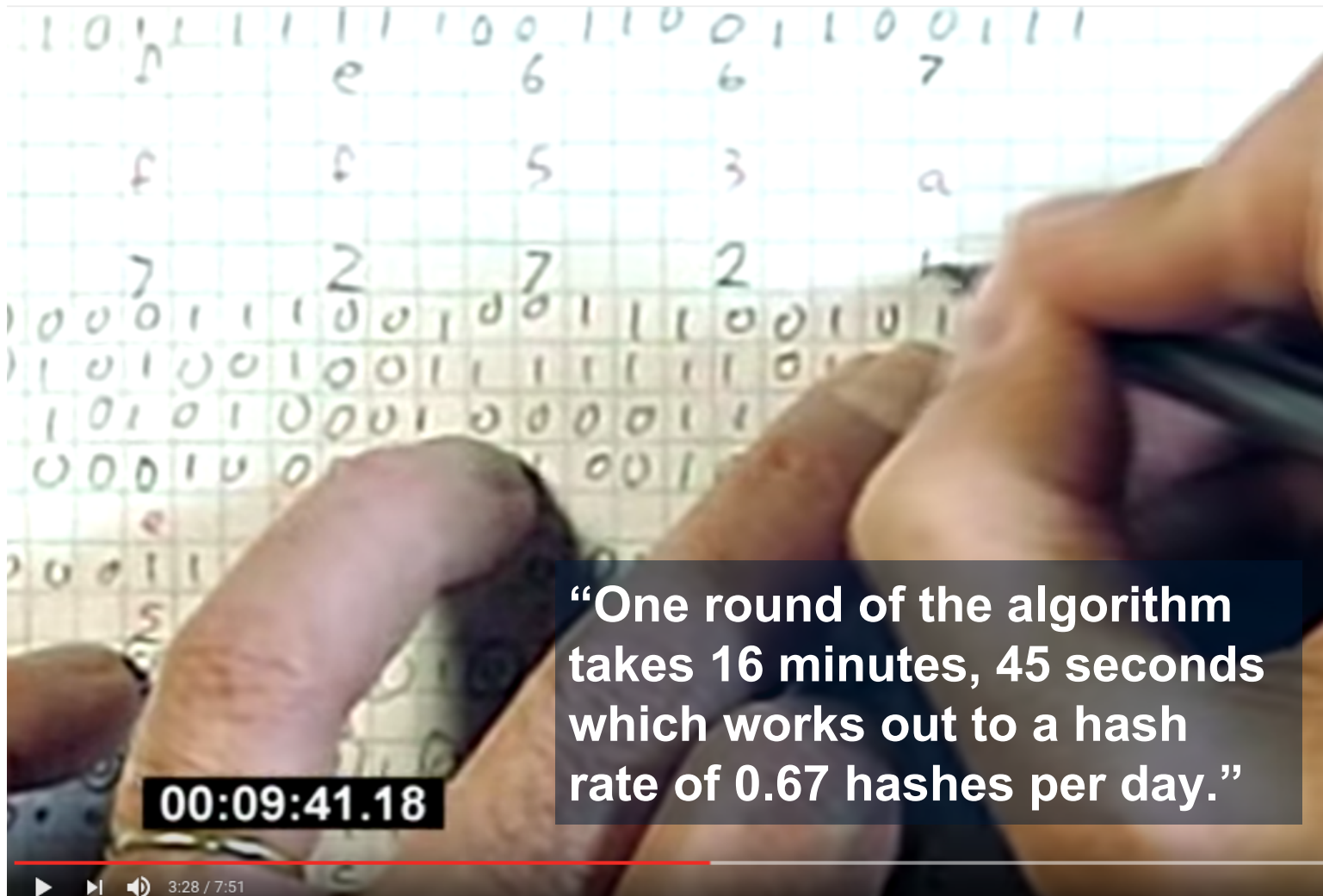256 bits out

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

Confusion and Diffusion

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

"One round of the algorithm takes 16 minutes, 45 seconds which works out to a hash rate of 0.67 hashes per day."

Other hash functions:

MD5

Once ubiquitous

Broken in 2004

Turns out to be easy to find **collisions**

(pairs of messages with same MD5 hash)

SHA-1

Currently widely used, but going away

Broken in 2017

Don't use in new applications

SHA-3

Different construction: "Sponge"

Not susceptible to **length-extension**

http://valerieaurora.org/hash.html

Function	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Snefru																		
MD2 (128-bit)[1]																		
MD4																		
MD5															[2]			
RIPEMD															[2]			
HAVAL-128[1]															[2]			
SHA-0																		
SHA-1																		
RIPEMD-160																		
SHA-2 family																		[3]
SHA-3 (Keccak)																		

Lifetimes of popular cryptographic hashes (the rainbow chart)

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

[1] Note that 128-bit hashes are at best 2^64 complexity to break; using a 128-bit hash is irresponsible based on sheer digest length.

[2] What happened in 2004? Xiaoyun Wang and Dengguo Feng and Xuejia Lai and Hongbo Yu happened.

[3] In 2007, the NIST launched the SHA-3 competition because "Although there is no specific reason to believe that a practical attack on any of the SHA-2 family of hash functions is imminent, a successful collision attack on an algorithm in the SHA-2 family could have catastrophic effects for digital signatures." One year later the first strength reduction was published.

The Hash Function Lounge has an excellent list of references for most of the dates. Wikipedia now has references to the rest.

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, $O(\text{poly}(\lambda))$

- Ideally, we can show that the chance of failure is **negligible**, or **vanishingly** small as a function of λ

      $O(\text{negl}(\lambda))$

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

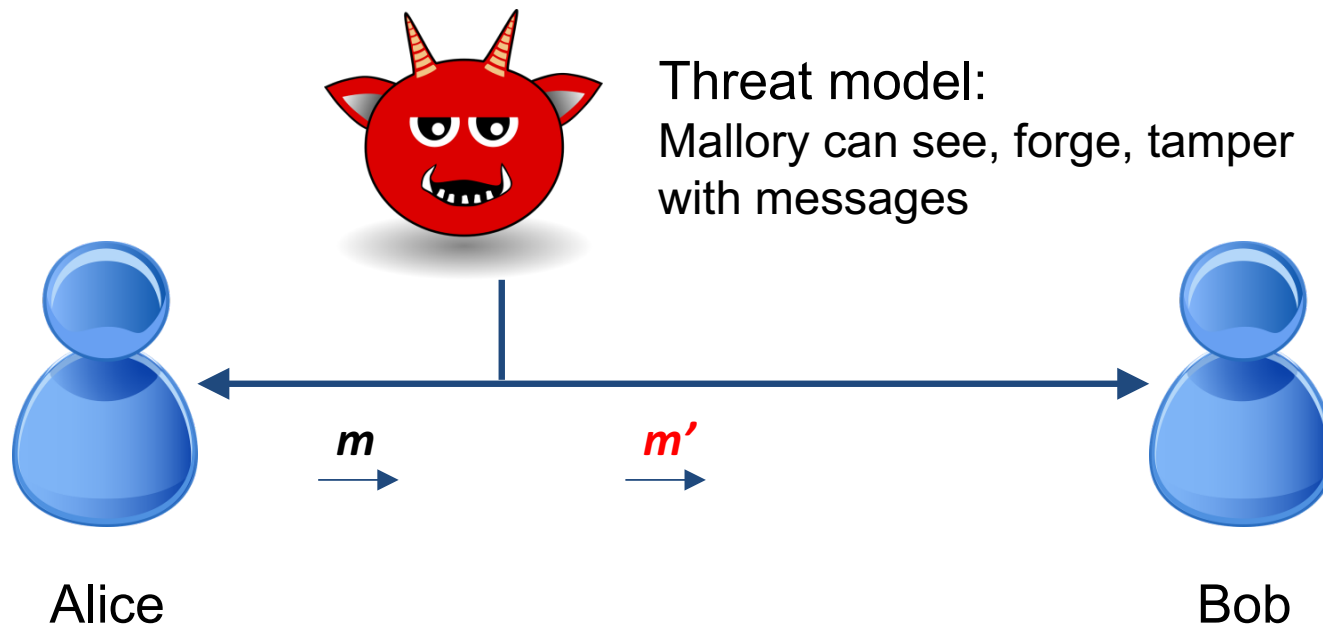Reduction from protocol to well-studied problem

3. Add a safety margin

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

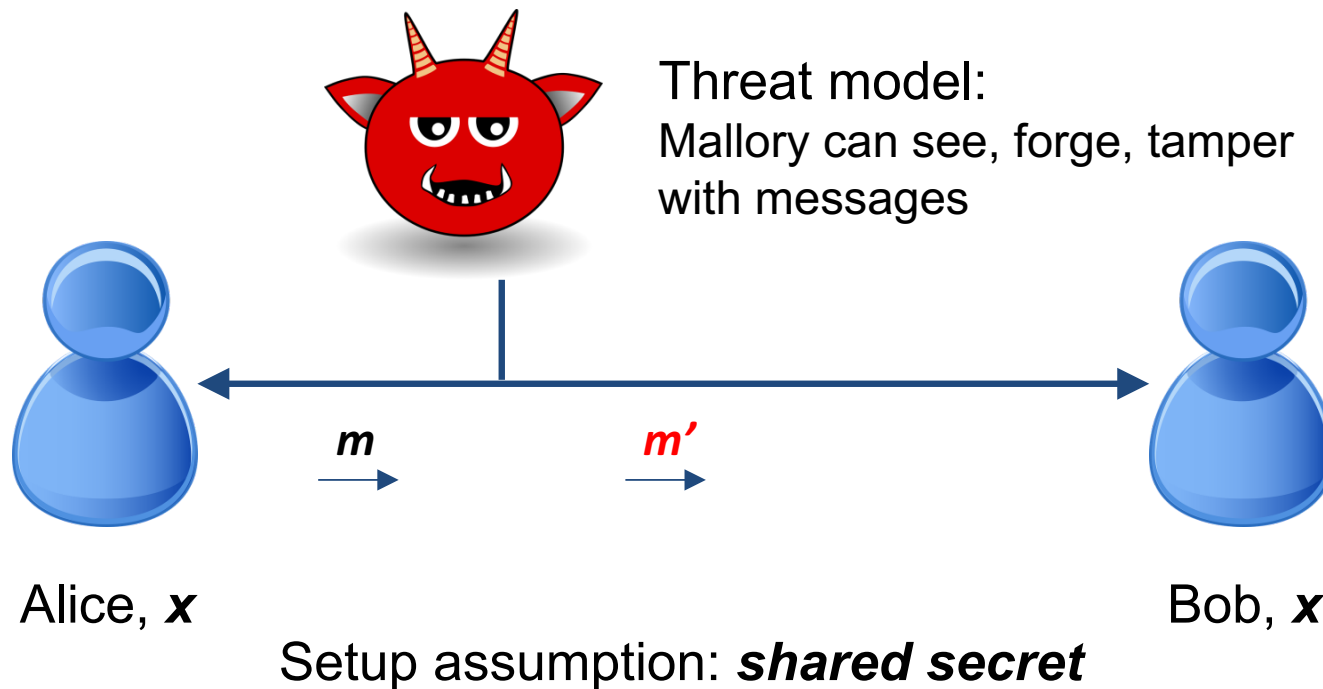# Goal: Message Integrity

Alice wants to send message *m* to Bob
Mallory wants to trick Bob into accepting a message Alice didn't send

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

m

m'

Alice

Bob

Goal: Message Integrity

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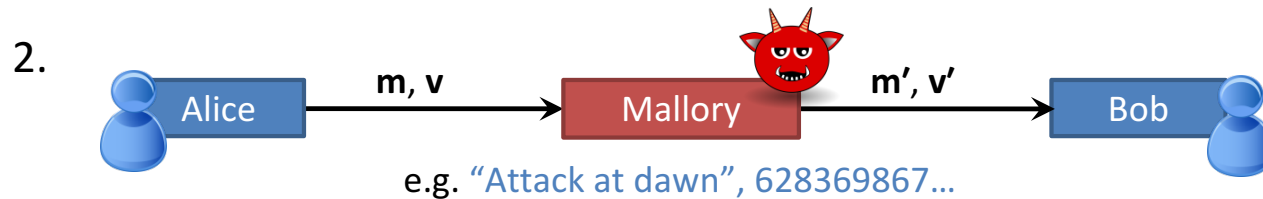Mallory wants to trick Bob into accepting a message Alice didn't send

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

m

m'

Alice, *x*

Bob, *x*

Setup assumption: *shared secret*

Solution: Message Authentication Code (MAC)

1. Alice computes $v := f(m)$

2.

e.g. "Attack at dawn", 628369867…

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

Function f ?

Easily computable by Alice and Bob;
   <u>not</u> computable by Mallory

(Idea: Secret only Alice & Bob know)

We're sunk if Mallory can learn
   $f(m')$ for any $m \neq m'$!

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>

Provably <u>secure</u>

[Why?]

[Why?]

Want a function that's practical but "looks random"…
Pseudorandom function (PRF)

Let's build one:

Start with a big *family of functions*
$f_0, f_1, f_2, …$ all known to Mallory

Use f_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** = f_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., f_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 $\mathbf{v} := f_k(\mathbf{m})$

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

[Important assumptions?]

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

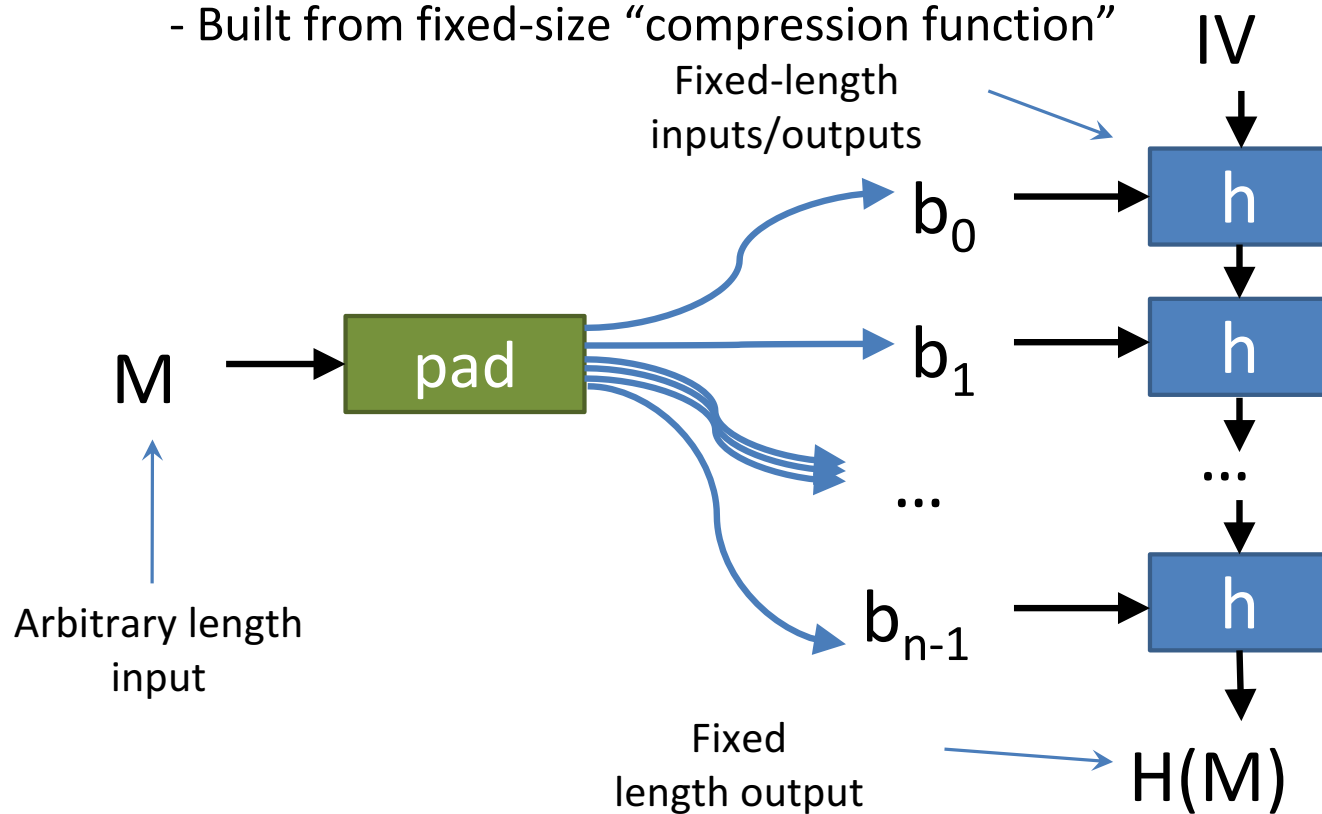[Attacks?]   [Solutions?]

Is this a secure PRF?

$$f_k(\mathbf{m}) = \text{SHA256}(\ \mathbf{k}\ ||\ \mathbf{m}\ )$$

Merkle–Damgård Construction

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

Recommended Approach:
Hash-based MAC (HMAC)
HMAC-SHA256   see RFC 2104

$\text{HMAC}_k(\mathbf{m}) =$

$$\text{SHA256}\Big(k \oplus c_1 \parallel \text{SHA256}(k \oplus c_2 \parallel m)\Big)$$

XOR   0x3636…   0x5c5c…

Concatenation

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 $\rightarrow$ 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**?