EECS 388

Introduction to Computer Security

Lecture 2:

Message Integrity

August 31, 2023
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Cryptography

Cryptography

(From Greek: *kryptós+graphein*, "secret writing")

The study of techniques for communicating securely in the presence of an adversary

***Related*: Cryptanalysis**

the study of techniques for *breaking* cryptosystems

Goals for 388: Learn how to safely use **crypto primitives** as building blocks for security

Security properties we'll try to achieve:

Confidentiality
Message Integrity
Sender Authenticity

Cryptographic Theory

Beautiful, highly rigorous

Proofs based on computational complexity

An Unsettling Chasm

Cryptographic Practice

Delicate engineering

Assumptions based on empirical experience

This course gives only a brief (**and non-rigorous**) overview. Consider EECS 475 or 575 to dive deeper into cryptography!

Goal: Message Integrity

Message integrity ensures that attackers cannot modify messages *without being detected* (*they can still do plenty of other bad stuff!)

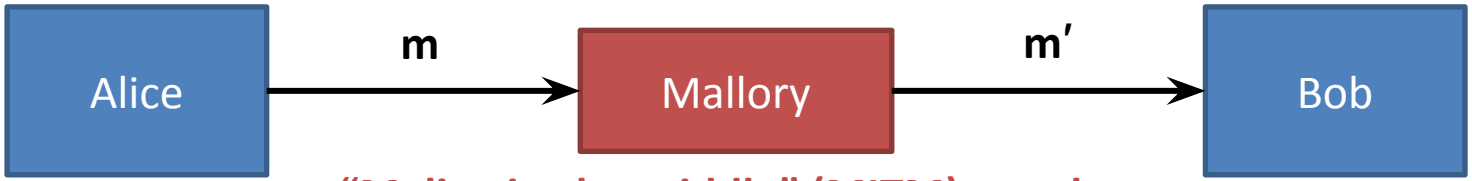
Message integrity is often *even more important* than confidentiality [Why?]

Alice wants to send message ***m*** to Bob

- They don't fully trust the messenger (or network) carrying the message
- They want to be sure what Bob receives is what Alice actually sent (**m′** = **m**)

Threat model:

- Mallory can see, modify, forge messages
- Mallory wants to trick Bob into accepting a message Alice didn't send



"Malice-in-the-middle" (MITM) attacker

a kind of **active attacker**

Approach: Message Verifier

1. Alice computes *verifier* **v** := ***f*(m)**

2. 

e.g. "Attack at dawn", 628369867…

3. Bob verifies that **v′** = ***f*(m′)**,
accepts message if and only if this is true

Properties we want for ***f*()** ?

Easily computable by Alice and Bob,
but ***not*** easily computable by Mallory

We lose the game if Mallory can deduce
***f*(x)** for any **x ≠ m**

Idea: Secret ***f*()** only Alice and Bob know

Candidate ***f*()**: **Random function (RF)**

Input: Fixed size (length of longest **m**)

Output: Fixed size (say, 256 bits)

Construct a giant lookup table by flipping coins for every possible input

0	→	0011111001010…
1	→	1110011010001…
2	→	0101010001010…
…		

Pro: ***Provably secure***

[Show Mallory can't do better than guessing]

Con: ***Completely impractical!***

[Estimate how much storage it would require]

Pseudorandom Functions

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

Pseudorandom function (PRF)

Let's build a PRF:

Start with a family of $2^{\mathbf{n}}$ functions

$f_0(), f_1(), f_2(), \ldots, f_{(2\text{\^{}}\mathbf{n})-1}()$

all ***known to Mallory***

Let our verification function $v() := f_k()$
where **k** is a secret **n**-bit index ("**key**")
known only to Alice and Bob.

What makes for a suitable function family $f()$?

Security definition: A game against Mallory—

1. Choose a secret **k** and a random function $g()$
2. We flip a coin secretly to get bit **b**
3. If **b**=0, let $h() := g()$
   If **b**=1, let $h() := f_k()$
4. Mallory chooses **x**; we announce $h(\mathbf{x})$.
   Repeat step 4 as often as Mallory likes
5. Mallory guesses **b** *in polynomial time**

We say $f()$ is a **secure PRF** if Mallory can't do meaningfully better than random guessing.

* **Note the reliance on computational complexity. Mallory can always win slowly!**
With RF, Mallory **can't possibly** learn unseen outputs
With PRF, M. can, but at *impractical* (exponential) cost by mounting a "**brute force attack**" on **k** [Explain?]

Using a PRF for Message Integrity

1. Let $f()$ by a secure PRF (known to everyone)
2. In advance, choose a random key **k** known to Alice and Bob but <u>not</u> Mallory
3. Alice computes $\mathbf{v} := f_k(\mathbf{m})$
4. 

5. Bob verifies that $\mathbf{v'} = f_k(\mathbf{m'})$, accepts message if and only if this is true

If Bob accepts **m'** then, with very high confidence, **m'** is identical to **m**. (How high? $1-1/2^n$) [Important assumptions?]

What if Alice and Bob want to send more than one message? [Attacks?] [Solutions?]

This approach follows **Kerckhoffs's Principle**:
"A cryptosystem should remain secure even if attackers know ***everything but the key.***" [Why?]

Annoying question:
Do PRFs *actually exist*?

Annoying answer:
We don't know. (Would imply P≠NP!)

Best we can do:
Use well studied functions where we haven't spotted a problem yet

Cryptographic Hashes

Cryptographic Hash Function

Fixed function ***H***(). ***No key*!**

Input: arbitrary length data

Output: fixed size *digest* (**n** bits)

Properties of strong hash functions:

Preimage resistance

Given output **h**, hard to find input **m** s.t. **h** = ***H***(**m**)

Second-preimage resistance

Given input $\mathbf{m}_1$, hard to different $\mathbf{m}_2$ s.t. ***H***($\mathbf{m}_1$) = **H**($\mathbf{m}_2$)

Collision resistance

Hard to find any pair of inputs $\mathbf{m}_1$,$\mathbf{m}_2$ s.t. ***H***($\mathbf{m}_1$)=**H**($\mathbf{m}_2$)

Note: Collisions exist [why?], but should be hard to find

Computing hashes with **OpenSSL:**

```
$ echo "hello world 1" | openssl dgst -sha256
07bafbe63a0e7c57c572aedf1c228022
b537e28785013d7be017fc78731a8cc5
$ echo "hello world 0" | openssl dgst -sha256
8bfa9a398e97152beaaf385847808ad2
d828c1c7251f1a45bc7697723827e7e7
```

Observe how changing even a single bit of the input produces output that appears completely unrelated.

Annoying question:

Are existing hashes *actually strong*?

Annoying answer:

We don't know.

Candidates: ~~MD5~~, ~~SHA-1~~, **SHA-256**, SHA-512, SHA-3

Hash Function Failures

MD5

Once ubiquitous … broken in 2004

Now it's easy to find collisions
(pairs of messages with the same MD5 hash)

Exploited to attack real systems

You'll do this in Project 1!

```
$ echo d131dd02c5e6eec4693d9a0698aff95c2fcab58712467eab4004583eb8fb7f89
       55ad340609f4b30283e488832571415a085125e8f7cdc99fd91dbdf280373c5b
       d8823e3156348f5bae6dacd436c919c6dd53e2b487da03fd02396306d248cda0
       e99f33420f577ee8ce54b67080a80d1ec69821bcb6a8839396f9652b6ff72a70
    | xxd -r -p  | openssl dgst -md5
79054025255fb1a26e4bc422aef54eb4

$ echo d131dd02c5e6eec4693d9a0698aff95c2fcab50712467eab4004583eb8fb7f89
       55ad340609f4b30283e4888325f1415a085125e8f7cdc99fd91dbd7280373c5b
       d8823e3156348f5bae6dacd436c919c6dd53e23487da03fd02396306d248cda0
       e99f33420f577ee8ce54b67080280d1ec69821bcb6a8839396f965ab6ff72a70
    | xxd -r -p  | openssl dgst -md5
79054025255fb1a26e4bc422aef54eb4
```

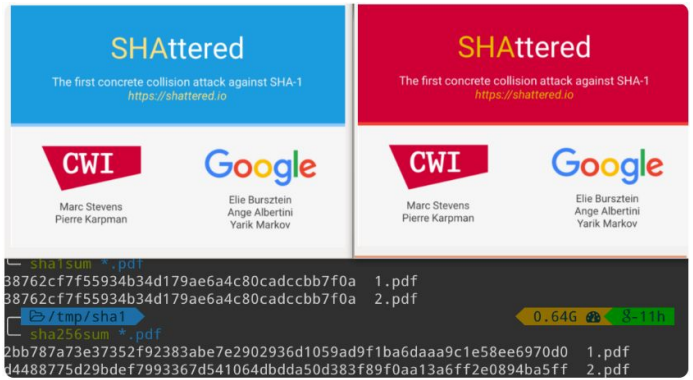
SHA-1

Once ubiquitous … broken in 2017

Rapidly being phased out

Computing first collision cost >$100,000
Today, with improvements <$10,000

Expect attacks will keep getting better!



Constructing SHA-256

SHA-256 is a widely used hash function that is currently thought to be strong

Input: arbitrary length data
Output: 256-bit digest

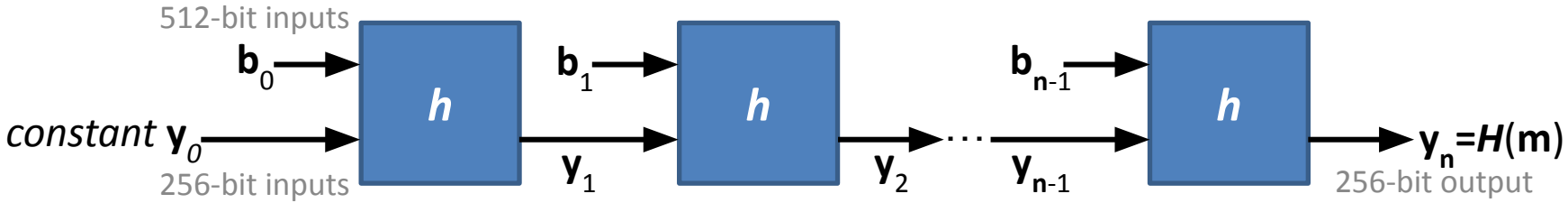
Built from a **compression function *h***:

Inputs: (256 bits, 512 bits), **Output:** 256 bits

"compresses" 768 bits to 256 bits using "really hairy and scary" function (details out of scope for 388)

Uses the **Merkle–Damgård (MD) construction** (illustrated below) to accept arbitrary-length input by repeatedly applying ***h***():

1. Pad input **m** to the next multiple of 512 bits (adds at least 1 bit, uses fixed algorithm [why?]) and split into 512-bit blocks: $\mathbf{b}_0, \mathbf{b}_1, \ldots \mathbf{b}_{n-1}$
2. $\mathbf{y}_0$:= *<256-bit constant>*
   $\mathbf{y}_1 := \boldsymbol{h}(\mathbf{y}_0,\mathbf{b}_0) \ldots \mathbf{y}_i := \boldsymbol{h}(\mathbf{y}_{i-1},\mathbf{b}_{i-1})$
3. Return $\mathbf{y}_n$ which is defined to be **SHA-256(m)**



MD Hash Pitfall: Length Extension Attacks

Merkle–Damgård hash functions are susceptible to **length extension attacks**:

Given **y** = ***H***(**x**) for some unknown **x**, attackers can calculate

z = ***H***(**x** // *padding* // **s**)

for arbitrary **s**.

concatenation

That is, given:

y = **SHA-256**(???)

An attacker can produce:

z = **SHA-256**(??? | *original pad* | suffix)

Note that this doesn't violate preimage, second-preimage, or collision resistance.

[But why is it a problem?]

Suppose Alice and Bob use this as a verifier:

v := **SHA-256**(**k** // **m**)

1. Alice sends **m** = "Please go to the bank."
2. Mallory doesn't know **k**, but *can* apply length extension to (**m**, **v**) to calculate **v′** for:
   m′ = "Please go to the bank.[*original_pad*] Then transfer $10,000 to Mallory."
   (*original_pad* is some bytes beyond Mallory's control, but which the recipient might ignore)
3. Since **v′** is the correct verifier for **m′**, Bob will accept the modified message as valid

You'll explore how this is done in Project 1!

Practical Solution: HMAC

Message Authentication Code (MAC)

Designed to be used as a secure verifier:

Inputs: key, arbitrary length data
Output: fixed size digest (**n** bits)

HMAC construction turns any secure hash function ***H***() into a MAC:

$$\mathrm{HMAC}_k(m) = H(k \oplus c_1 \parallel H(k \oplus c_2 \parallel m))$$

XOR — constant 363636… — constant 5c5c5c… — concatenation

Design protects against length extension!

Example: HMAC-SHA-256 is an HMAC constructed using **SHA-256** for ***H***()

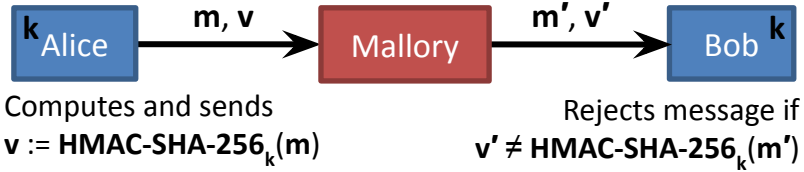
For practical purposes, we (think/hope) we can treat **HMAC-SHA-256** as a PRF

Can *reduce* PRF security of HMAC-SHA-256 to a (weaker) security property of SHA-256's compression function

```
$ echo "hi" | openssl dgst -sha256 -hmac Secr3t
8074cdfd007e5cfdc71c2c1cd393a5fe
fa890d7702956a1366a155d79d1cbe77
```

At last, this gives Alice and Bob a suitable approach for protecting message integrity:

v := HMAC-SHA-256$_k$(m)



Coming Up

Reminders:

Selfies were due today
Quiz on Canvas after every lecture
Lab Assignment 1 available today, due next Thursday at 6pm
Project 1 available today; Part 1 due Sept. 14 at 6pm

Tuesday

Randomness and Pseudorandomness

Generating randomness,
PRGs, one-time pads

Thursday

Confidentiality

Simple ciphers,
AES,
block cipher modes