Cryptography basics – Integrity: Hashes and MACs

ECEN 4133
Jan 19, 2021

Alice and Bob

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

- Can't fully trust the messenger or network carrying the message
- Want to be sure what Bob receives is actually what Alice sent

Threat model:

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

Solution:
Message Authentication Code (MAC)

One approach:

- Alice computes **v** := ***f***(**m**)
- Bob verifies that **v'** = ***f***(**m'**)

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(**x**) for any **x** ≠ **m**!

Candidate *f*: Random Function

Input: Any size

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

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

in		out
0	→	0011111001010001…
1	→	1110011010010100…
2	→	0101010001010000…
⋮		⋮

Completely impractical [why?]

Provably secure [why?]

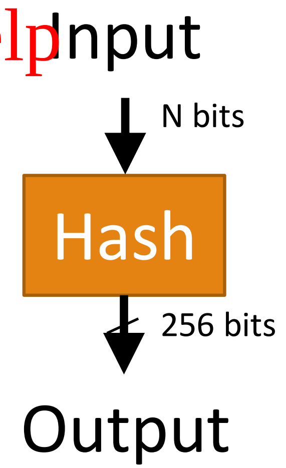
(Mallory can't do better than randomly guessing)

Hash Functions

Random Functions are impractical

Hash functions approximate a random function:

- Any size input
- Fixed size output (e.g. 256 bits)
- Hard (but not impossible!) to invert (given output, find input)



Properties of a secure cryptographic hash:

- First pre-image resistant – Given H(m), hard to find m
- Second pre-image resistant – Given m_1, hard to find m_2 s.t $H(m_1)==H(m_2)$
- Collision resistant – Hard to find m_1 != m_2 s.t $H(m_1)==H(m_2)$

Example Hash Function: SHA256

What is **SHA256**?

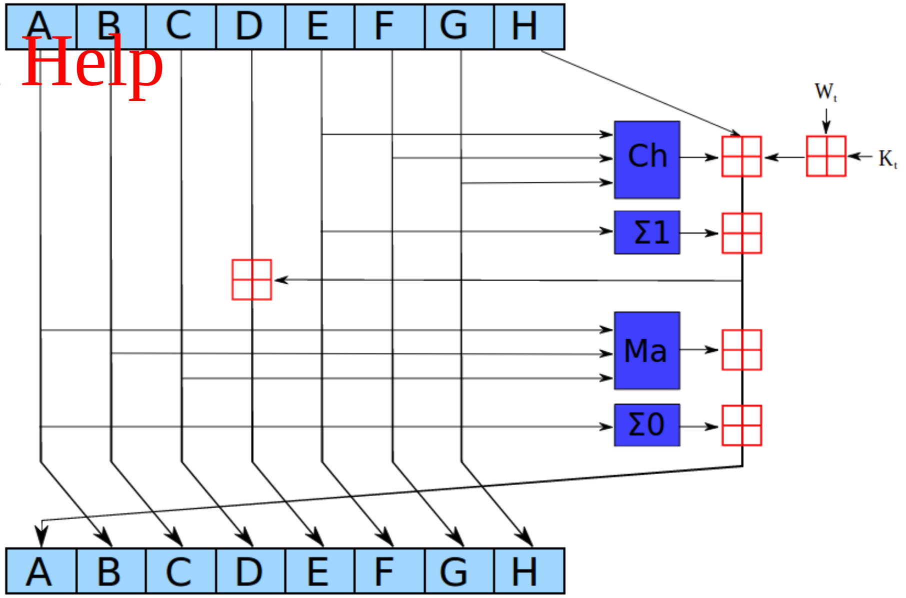
“Cryptographic hash function”

Input: arbitrary length data (No key)
Output: 256 bits

Built with “compression function” ***h***

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

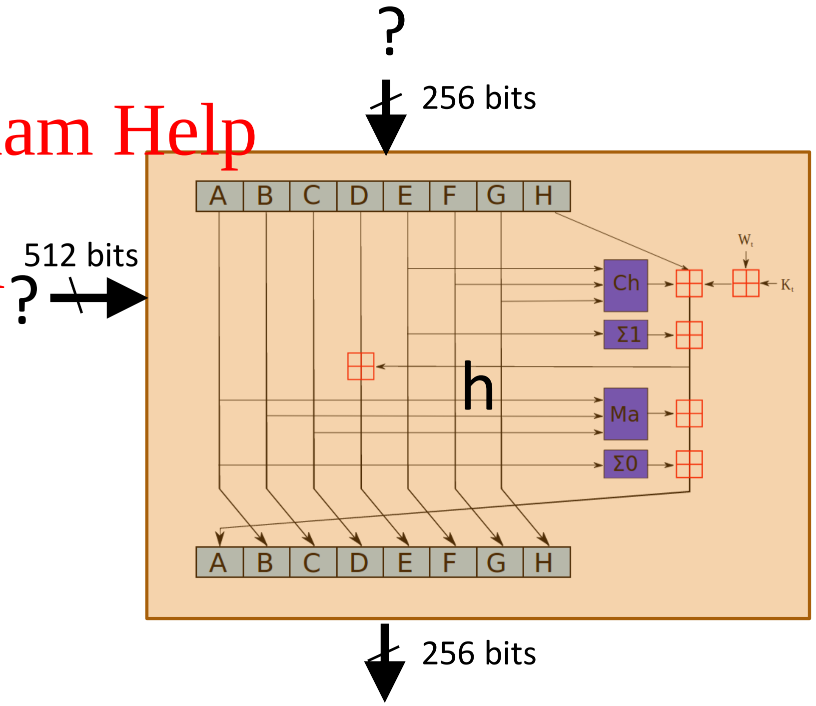
Designed to be really hairy (64 rounds of this:)

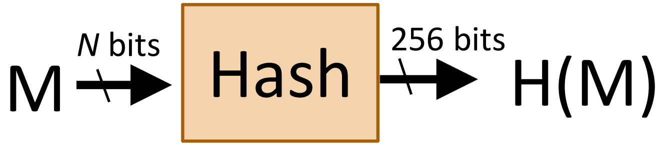


Compression functions

Compression function **h** take (two) fixed-length inputs, produce fixed-length output

How do we build a hash function from **h** that takes an arbitrary length input?

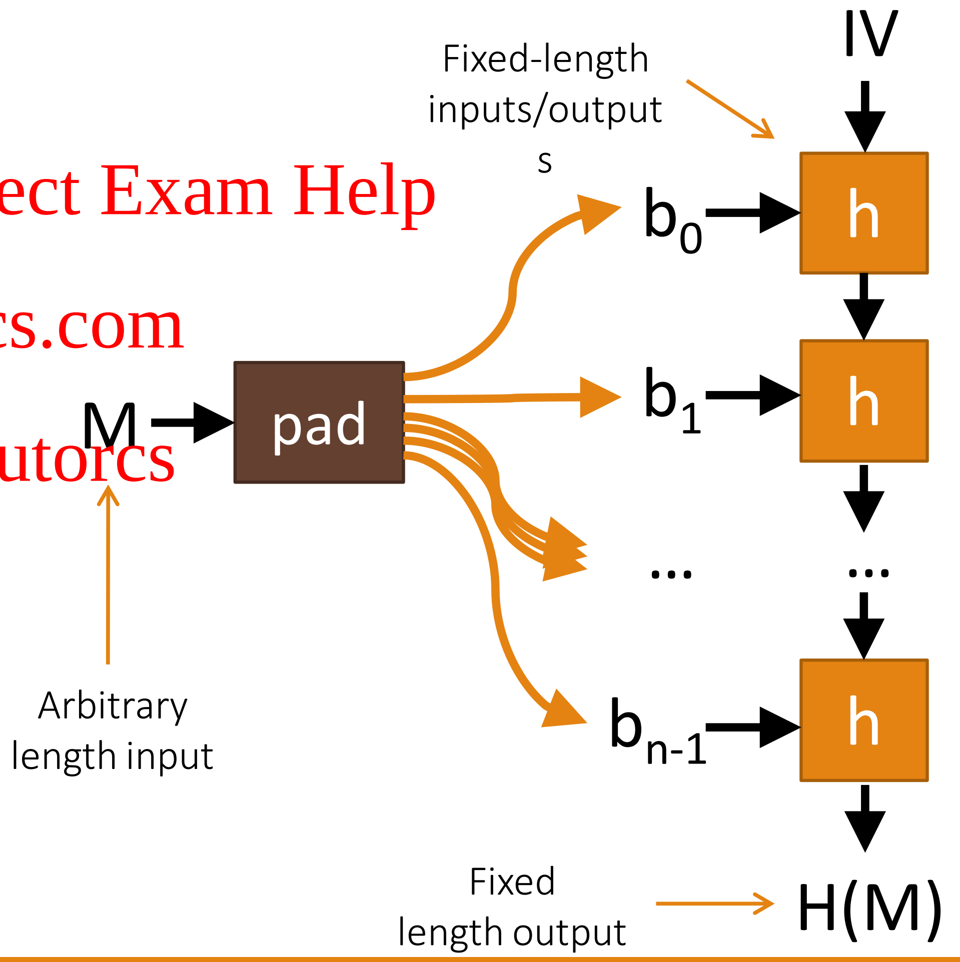




Solution: Merkle–Damgård Construction

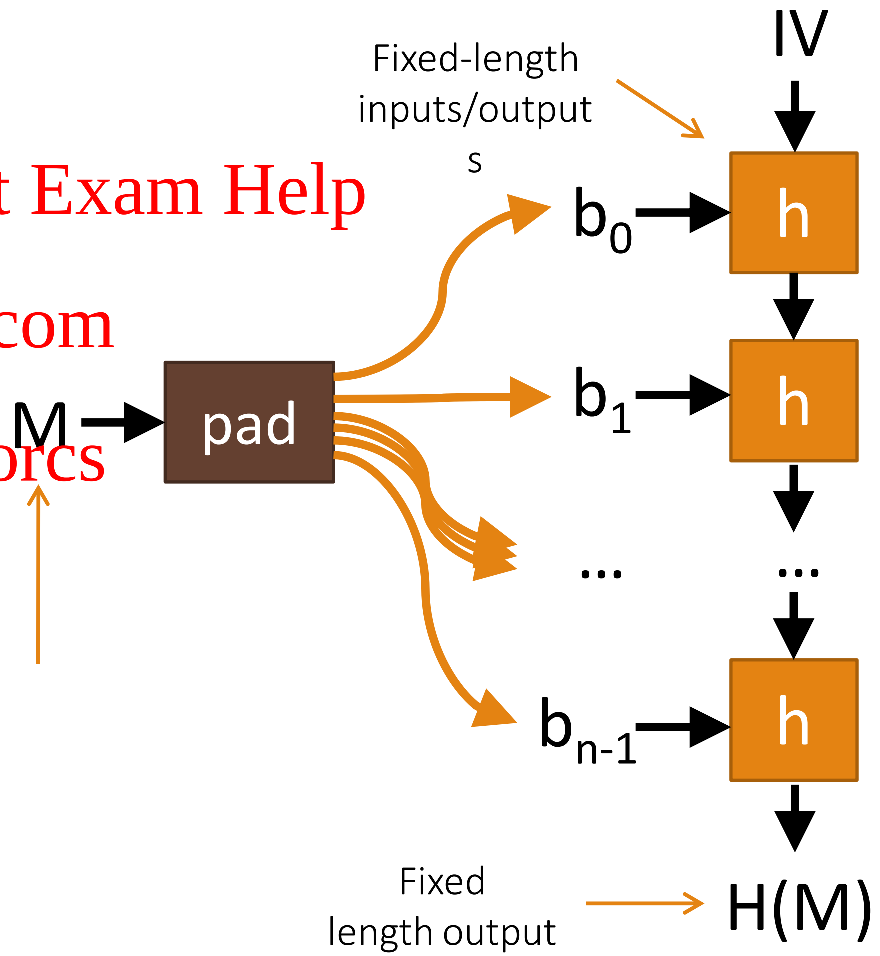
Entire algorithm:

1. Pad input M to a multiple of 512 bits
2. Break into 512-bit blocks $\mathbf{b}_0$, $\mathbf{b}_1$, … $\mathbf{b}_{n-1}$
3. $\mathbf{y}_0$ = const (IV),
   $\mathbf{y}_1 = \boldsymbol{h}(\mathbf{y}_0,\mathbf{b}_0)$,
   …,
   $\mathbf{y}_i = \boldsymbol{h}(\mathbf{y}_{i-1},\mathbf{b}_{i-1})$
4. Return $\mathbf{y}_n$



Merkle–Damgård Problem:
Length Extension Attacks

Given H(m), attacker can compute H(m || x)
for arbitrary x, ***without knowing m!*** [How?]

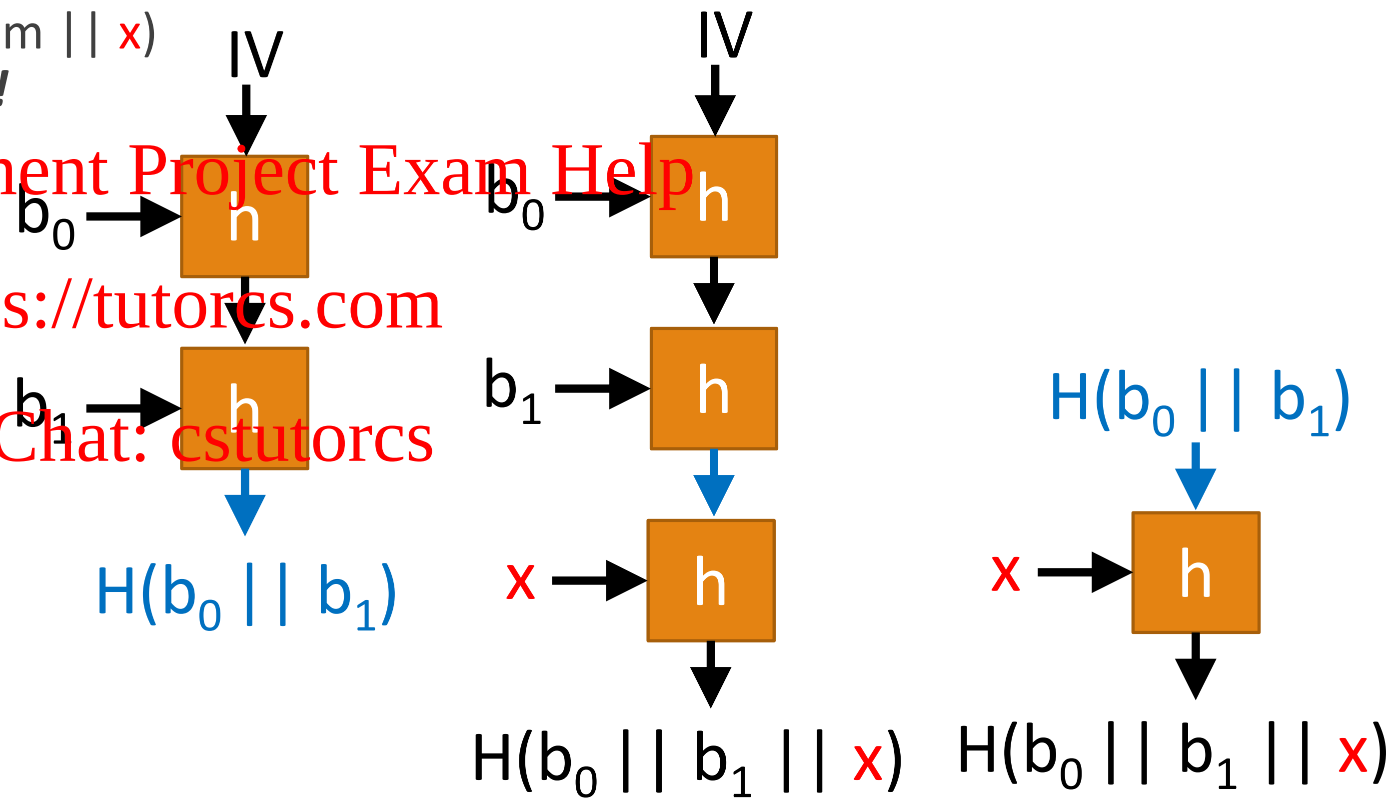


Length Extension Attack

Given H(m), attacker can compute H(m || x) for arbitrary x, ***without knowing m!***

H(m) is essentially the *internal state* of the hash function after hashing m.

Can just feed H(m) as IV to compute hash of H(m || x)



Other hash functions

MD5

- Once ubiquitous, *broken in 2004*
- Turns out to be easy to find ***collisions*** (pairs of messages with same MD5 hash)
- You'll investigate this in Project 1

SHA1

- Deprecated in 2011, but still widely used
- Collisions found in 2017:
  - Took 9,223,372,036,854,775,808 SHA1 computations to find (6,500+ CPU-years)
- Don't use!

SHA3

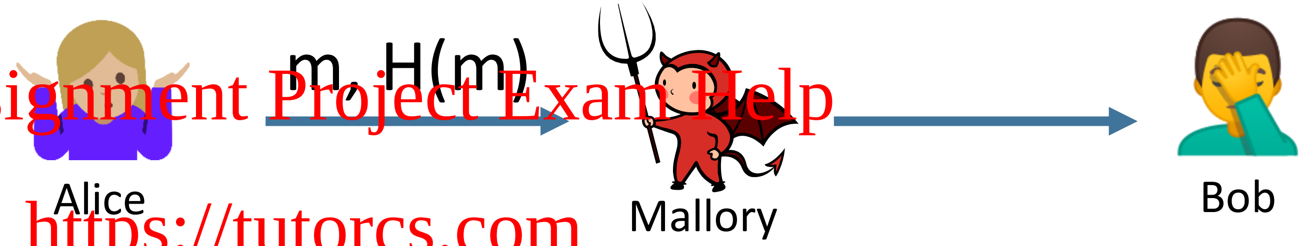
- Different "sponge" construction
- Not susceptible to length-extension

Try hash functions yourself!

```
$ echo -n "Hello, World" | sha256sum
03675ac53ff9cd1535ccc7dfcdfa2c458c5218371f418dc136f2d19ac1fbe8a5  -
$ echo -n "Hello, World" | openssl dgst -sha3-256
(stdin)= 844af7bf6a5d414359dcd8845c652d915397410e1668e00c8469ea8728c4ffe8
$ echo -n "Hello, Worle" | openssl dgst -sha3-256
(stdin)= 7cccfd7c35d3b321c85bce74564b8da936bcd9eed4877ad775f262f106b71f3d
```

Hash functions -> Integrity?

Can we use hash functions to provide integrity?



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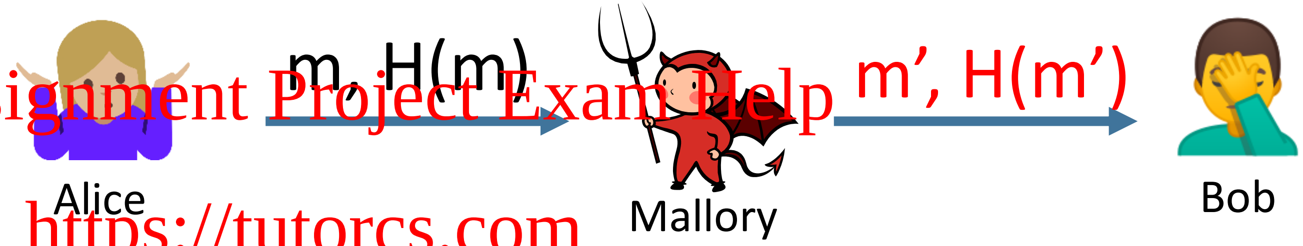
Can we use hash functions to provide integrity?



Not directly: Mallory could still change m to m’, and compute H(m’)

[Alternative?]

Keyed hash function: Message Authentication Code (MAC)

Assume Alice and Bob have a
shared secret k

Alice computes MAC over the message **m** with her key **k:**

$\mathbf{v = MAC_k(m)}$

Mallory doesn't know **k**, so cannot produce $\mathbf{v' = MAC_k(m')}$

Building a MAC from a hash function: HMAC

HMAC-SHA256(k, m) = $\text{SHA256}\left(k \oplus c_1 \parallel \text{SHA256}\left(k \oplus c_2 \parallel m\right)\right)$

XOR

0x3636
…

Concatenation

0x5c5c
…

SHA256 function
takes arbitrary length input,
returns 256-bit output

Not vulnerable to length extension!

Using HMAC

```
$ echo "Hello, World" | openssl dgst -sha256 -hmac "NotVerySecret"

(stdin)= a502137ae2ad88313fcb267747a0474f0286ae671a1e639d5448a82bc5efb44a
```

Tricky question: are hashes secure?

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Answer: **we don't know!**

Hashes have been broken in the past:

- MD5 introduced in 1992, first collision in 2004
- SHA1 introduced in 1995, first collision in 2017
- SHA2 introduced in 2001, no known collision *…yet!*
- SHA3 introduced in 2015, no known collision *…yet!*

We know collisions exist, but hope they are difficult to find [Why?]

MAC crypto game

Game against Mallory

1. Give Mallory MAC(K, m_i) $\forall\, mi \in M$ and M (but not K!)
2. Mallory tries to discover MAC(K, m') for a new $\mathrm{m}' \notin M$
3. If Mallory succeeds, MAC is **insecure**

Other uses for hashes/HMACs?