CSE 484 / CSE M 584: Computer Security and Privacy

Cryptography

[Message Authentication Codes and Hash Functions]

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Franziska (Franzi) Roesner
franzi@cs.washington.edu

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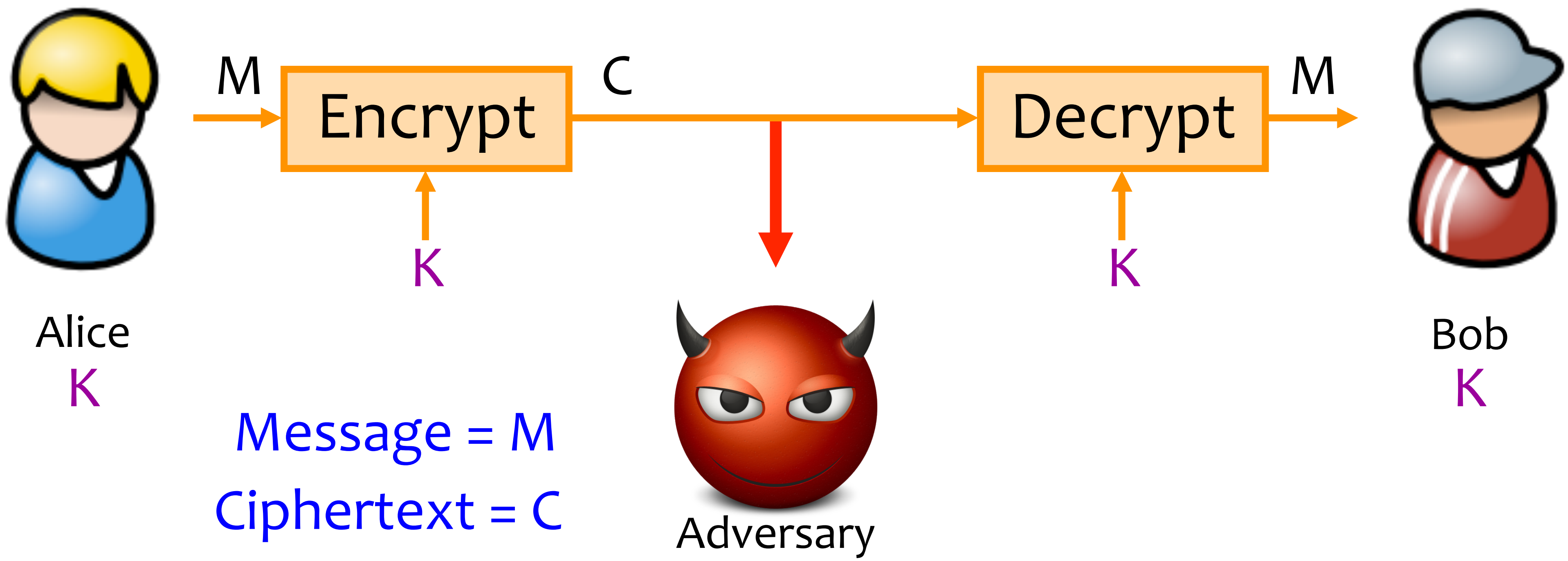
So Far: Achieving Privacy

Encryption schemes: A tool for protecting privacy.

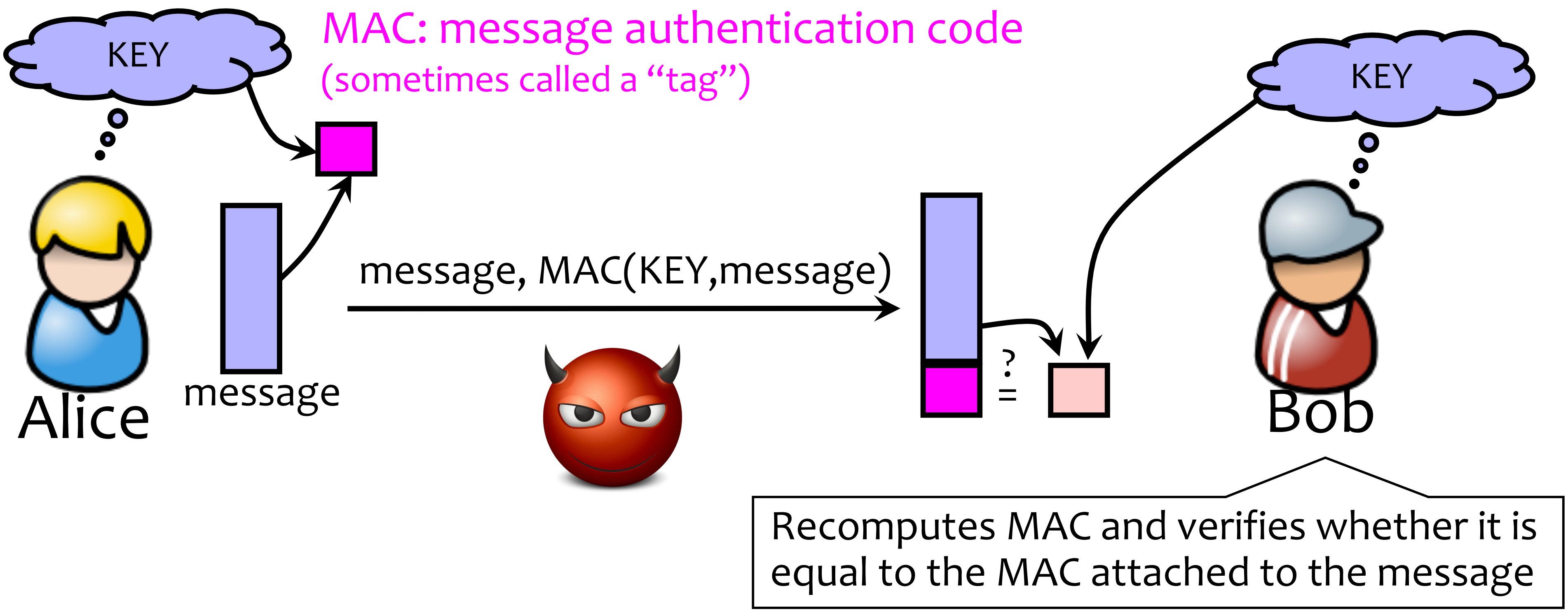


Message = M

Ciphertext = C

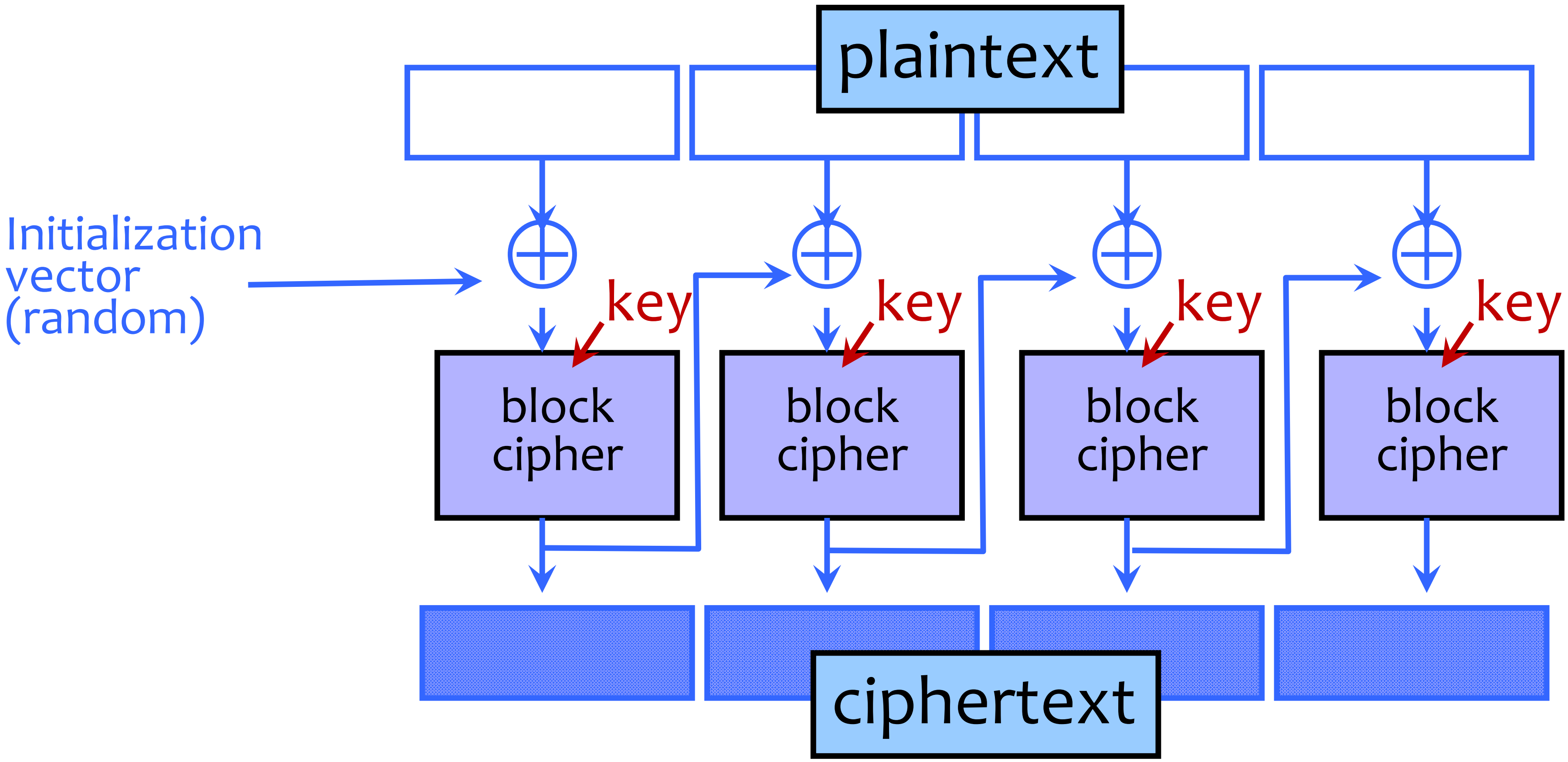
Now: Achieving Integrity

Message authentication schemes: A tool for protecting integrity.



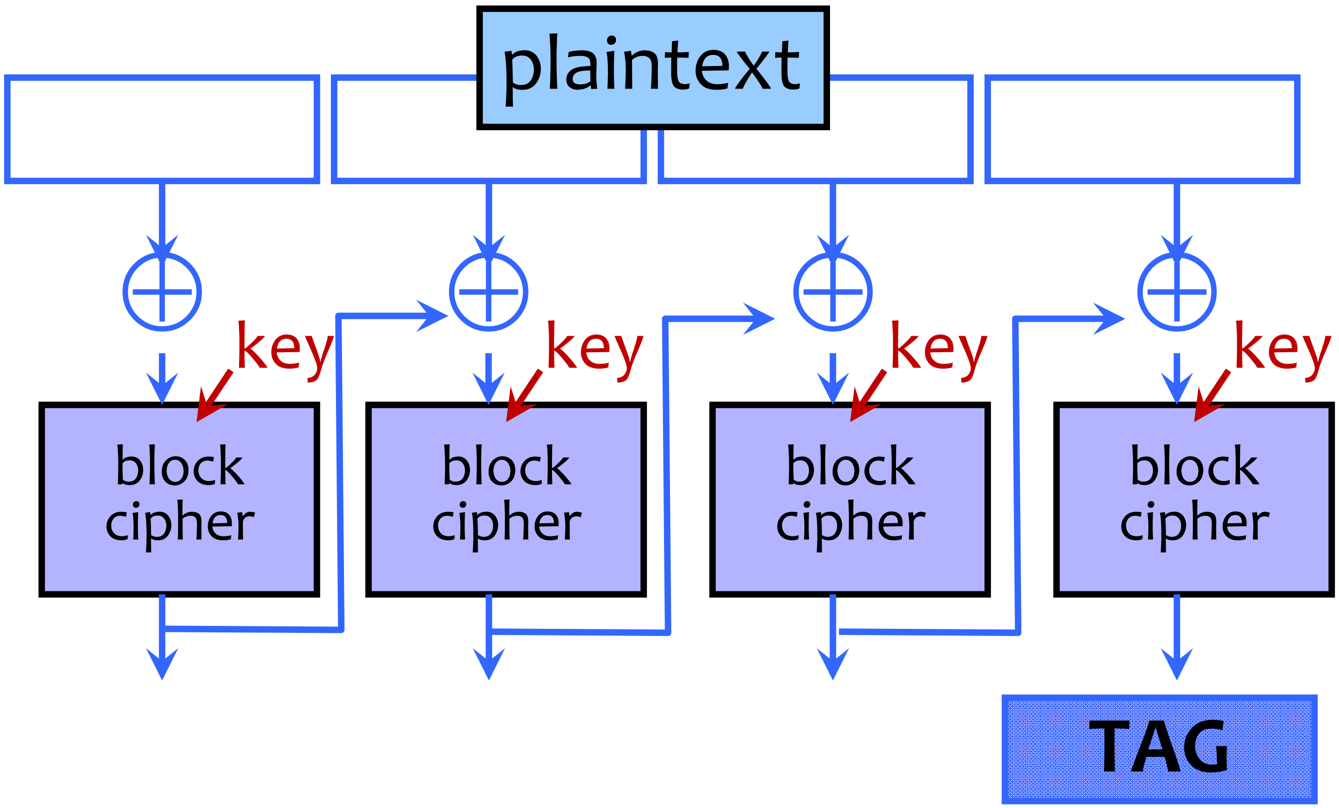
Integrity and authentication: only someone who knows KEY can compute correct MAC for a given message.

Reminder: CBC Mode Encryption



- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

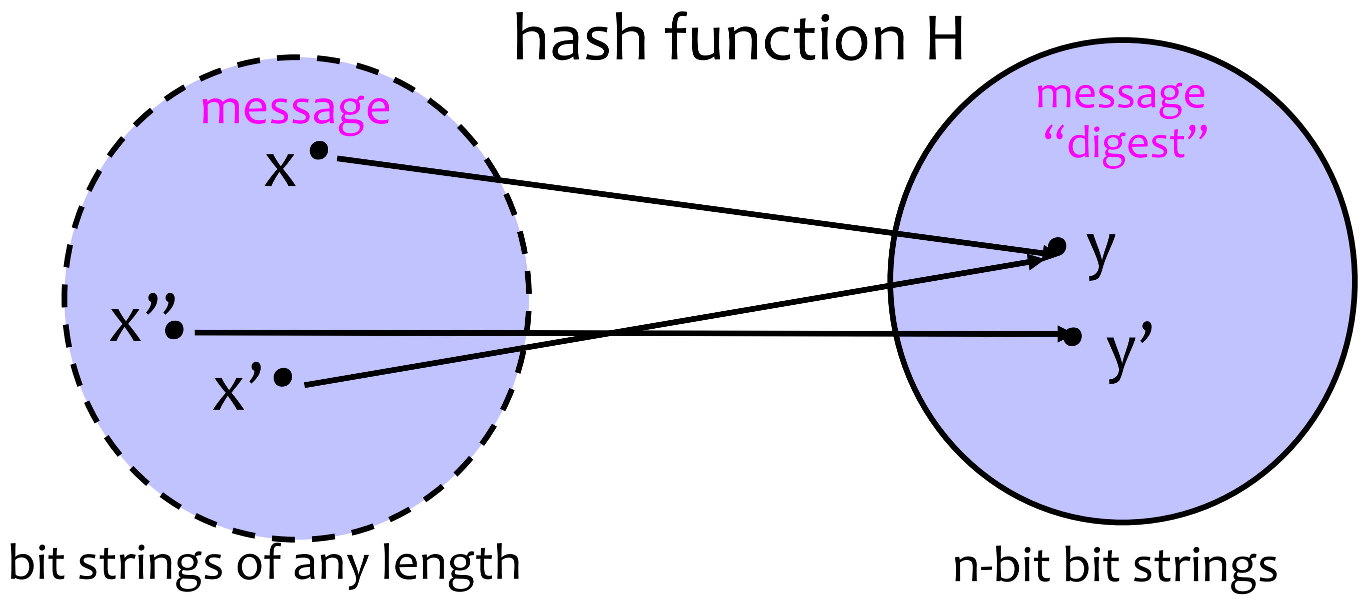
CBC-MAC



- Not secure when system may MAC messages of different lengths.
- NIST recommends a derivative called CMAC [FYI only]

Another Tool: Hash Functions

Hash Functions: Main Idea



- Hash function H is a lossy compression function
  - Collision: h(x)=h(x') for distinct inputs x, x'
- H(x) should look "random"
  - Every bit (almost) equally likely to be 0 or 1
- Cryptographic hash function needs a few properties…

Property 1: One-Way

- Intuition: hash should be hard to invert
  - "Preimage resistance"
  - Let h(x') = y $\in \{0,1\}^n$ for a random x'
  - Given y, it should be hard to find any x such that h(x)=y
- How hard?
  - Brute-force: try every possible x, see if h(x)=y
  - SHA-1 (common hash function) has 160-bit output
    - Expect to try 2^{159} inputs before finding one that hashes to y.

Property 2: Collision Resistance

- Should be hard to find $x \neq x'$ such that $h(x)=h(x')$

Birthday Paradox

- Are there two people in the first 1/3 of this classroom that have the same birthday?
  - 365 days in a year (366 some years)
    - Pick one person. To find another person with same birthday would take on the order of 365/2 = 182.5 people
    - Expect birthday "collision" with a room of only 23 people.
    - For simplicity, approximate when we expect a collision as sqrt(365).
- Why is this important for cryptography?
  - 2^{128} different 128-bit values
    - Pick one value at random. To exhaustively search for this value requires trying on average 2^{127} values.
    - Expect "collision" after selecting approximately 2^{64} random values.
    - 64 bits of security against collision attacks, not 128 bits.

Property 2: Collision Resistance

- Should be hard to find x≠x' such that h(x)=h(x')
- Birthday paradox (informal)
  - Let t be the **number** of values x,x',x''… we need to look at before finding the first pair x,x' s.t. h(x)=h(x')
  - What is probability of collision for each **pair** x,x'? $1/2^n$
  - How many **pairs** would we need to look at before finding the first collision? $O(2^n)$
  - How many **pairs** x,x' total? Choose(t,2)=t(t-1)/2 ~ $O(t^2)$
  - What is t, the **number** of values we need to look at? $2^{n/2}$
- Brute-force collision search is only $O(2^{n/2})$, *not* $O(2^n)$
  - For SHA-1, this means $O(2^{80})$ vs. $O(2^{160})$

Property 2: Collision Resistance

- Should be hard to find $x \neq x'$ such that $h(x)=h(x')$
- Birthday paradox means that brute-force collision search is only $O(2^{n/2})$, *not* $O(2^n)$
  - For SHA-1, this means $O(2^{80})$ vs. $O(2^{160})$

One-Way vs. Collision Resistance

- One-wayness does <u>not</u> imply collision resistance
  - Suppose g is one-way
  - Define h(x) as g(x') where x' is x except the last bit
    - h is one-way (to invert h, must invert g)
    - Collisions for h are easy to find: for any x, h(x0)=h(x1)
- Collision resistance does <u>not</u> imply one-wayness
  - Suppose g is collision-resistant
  - Define y=h(x) to be 0x if x is n-bit long, 1g(x) otherwise
    - Collisions for h are hard to find: if y starts with 0, then there are no collisions, if y starts with 1, then must find collisions in g
    - h is not one way: half of all y's (those whose first bit is 0) are easy to invert (how?); random y is invertible with probab. ½

Property 3: Weak Collision Resistance

- Given randomly chosen x, hard to find x' such that h(x)=h(x')
  - Attacker must find collision for a specific x. By contrast, to break collision resistance it is enough to find any collision.
  - Brute-force attack requires $O(2^n)$ time
- Weak collision resistance does not imply collision resistance.

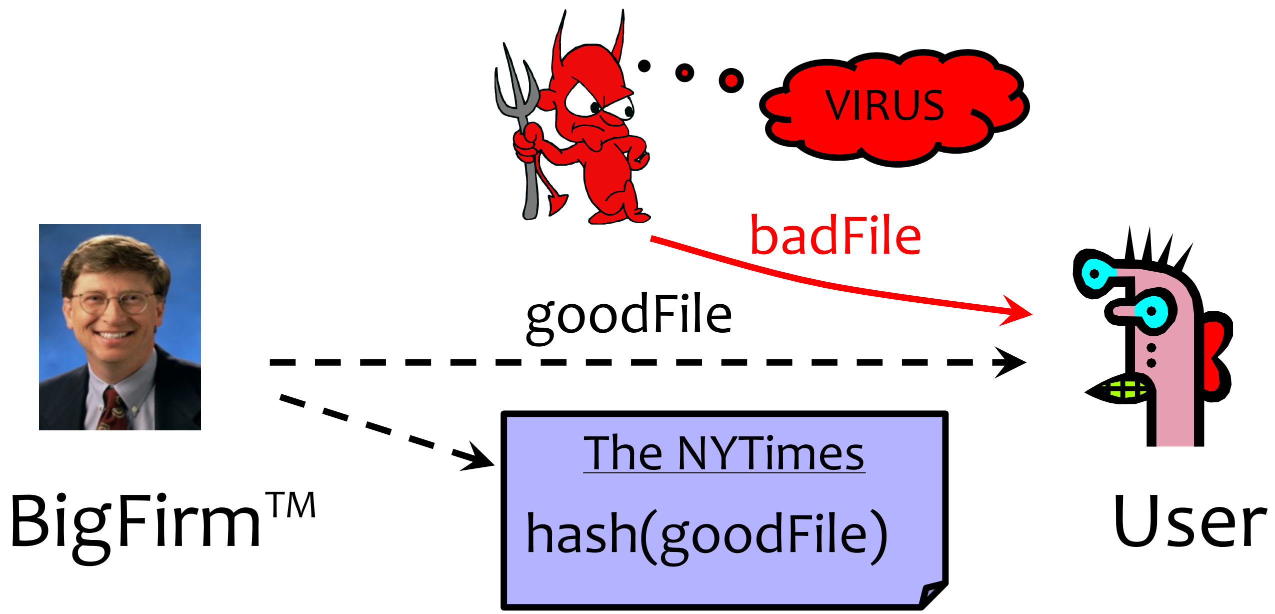
Hashing vs. Encryption

- Hashing is one-way. There is no "un-hashing"
  - A ciphertext can be decrypted with a decryption key… hashes have no equivalent of "decryption"
- Hash(x) looks "random" but can be compared for equality with Hash(x')
  - Hash the same input twice → same hash value
  - Encrypt the same input twice → different ciphertexts
- Crytographic hashes are also known as "cryptographic checksums" or "message digests"

Application: Password Hashing

- Instead of user password, store hash(password)
- When user enters a password, compute its hash and compare with the entry in the password file
  - System does not store actual passwords!
  - Cannot go from hash to password!
- Why is hashing better than encryption here?

Application: Software Integrity



Goal: Software manufacturer wants to ensure file is received by users without modification.

Idea: given goodFile and hash(goodFile), very hard to find badFile such that hash(goodFile)=hash(badFile)

Which Property Do We Need?

- UNIX passwords stored as hash(password)
  - **One-wayness:** hard to recover the/a valid password
- Integrity of software distribution
  - **Weak collision resistance**
  - But software images are not really random… may need **full collision resistance** if considering malicious developers

Common Hash Functions

- MD5
  - 128-bit output
  - Designed by Ron Rivest, used very widely
  - Collision-resistance broken (summer of 2004)
- RIPEMD-160
  - 160-bit variant of MD5
- SHA-1 (Secure Hash Algorithm)
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Theoretically broken 2005; practical attack 2017!
- SHA-256, SHA-512, SHA-224, SHA-384
- SHA-3: standard released by NIST in August 2015

SHA-1 Broken in Practice (2017)

Google just cracked one of the building blocks of web encryption (but don't worry)

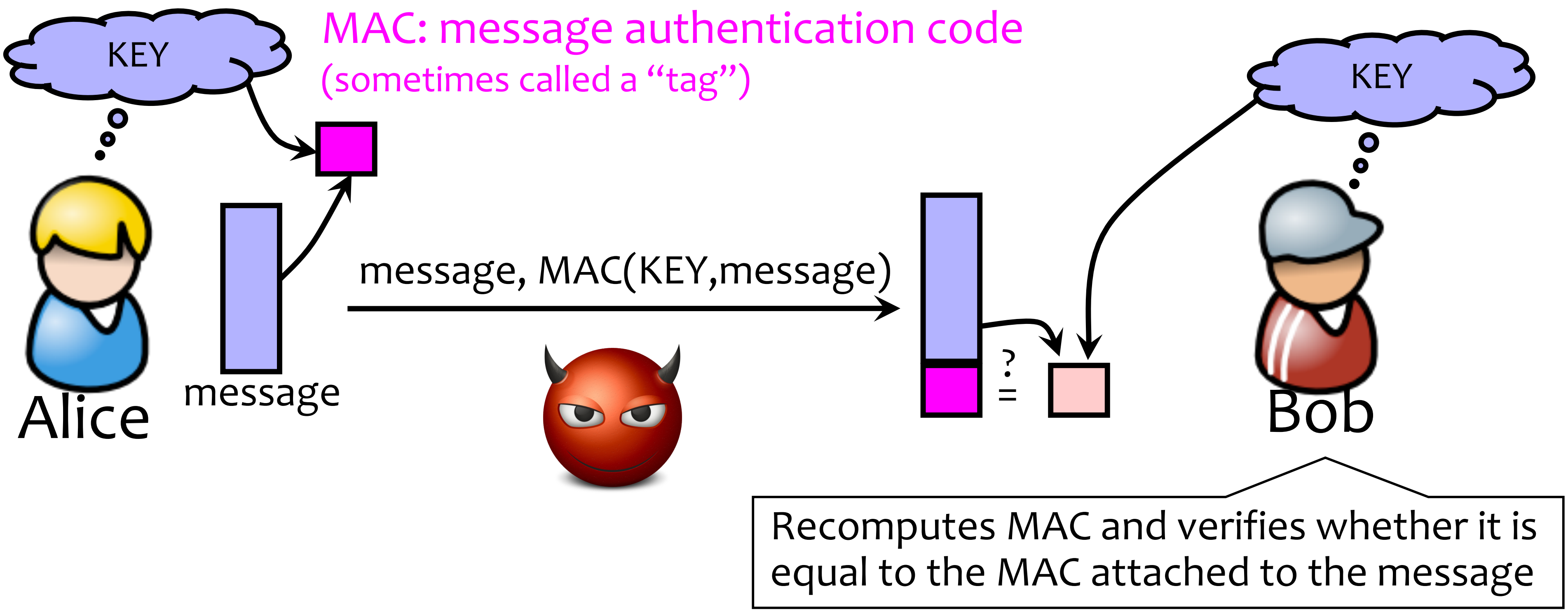
It's all over for SHA-1

by Russell Brandom | @russellbrandom | Feb 23, 2017, 11:49am EST

https://shattered.io

Recall: Achieving Integrity

Message authentication schemes: A tool for protecting integrity.



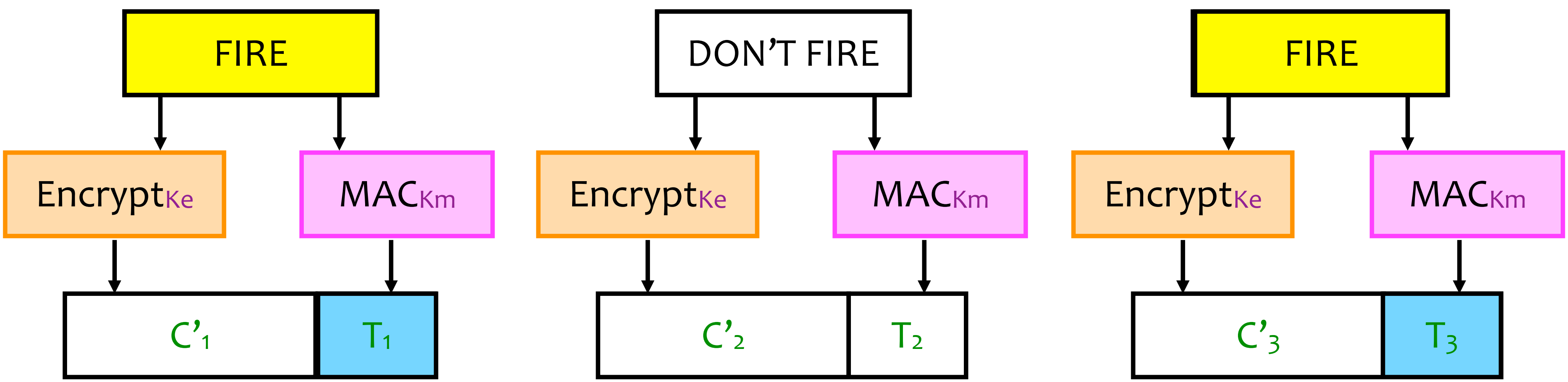
Integrity and authentication: only someone who knows KEY can compute correct MAC for a given message.

HMAC

- Construct MAC from a cryptographic hash function
  - Invented by Bellare, Canetti, and Krawczyk (1996)
  - Used in SSL/TLS, mandatory for IPsec
- Why not encryption?
  - Hashing is faster than block ciphers in software
  - Can easily replace one hash function with another
  - There used to be US export restrictions on encryption

Authenticated Encryption

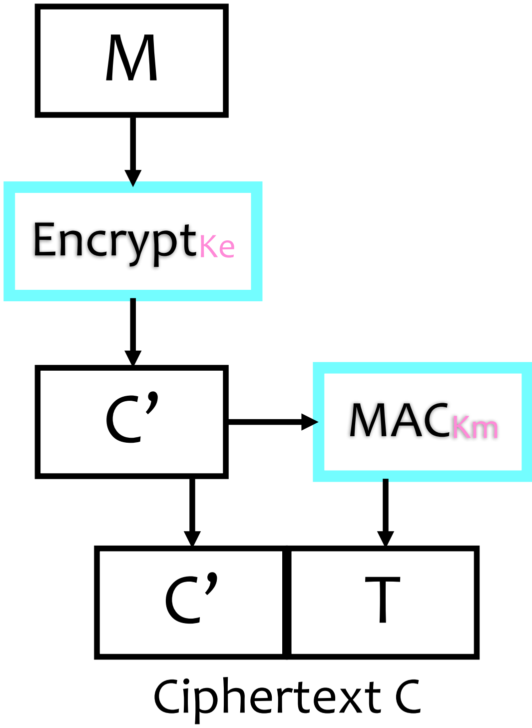
- What if we want both privacy and integrity?
- Natural approach: combine encryption scheme and a MAC.
- But be careful!
  - Obvious approach: Encrypt-and-MAC
  - Problem: MAC is deterministic! same plaintext → same MAC



Authenticated Encryption

- Instead:
  Encrypt *then* MAC.

- (Not as good:
  MAC-then-Encrypt)



Encrypt-then-MAC