CSE 484 / CSE M 584: Computer Security and Privacy

Cryptography

[MACs and Hash Functions]

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Admin

- Homework 2
  - Out soon
- My office hours on Monday
  - 2-3pm (instead of right after class)
When is an Encryption Scheme “Secure”?

• Hard to recover the key? ✓
  – What if attacker can learn plaintext without learning the key?

• Hard to recover plaintext from ciphertext? ✓
  – What if attacker learns some bits or some function of bits?
How Can a Cipher Be Attacked?

• Attackers knows ciphertext and encryption algorithm
  – What else does the attacker know? Depends on the application in which the cipher is used!
Chosen Plaintext Attack

Crook #1 changes his PIN to a number of his choice

PIN is encrypted and transmitted to bank

cipher(key, PIN)

Crook #2 eavesdrops on the wire and learns ciphertext corresponding to chosen plaintext PIN

... repeat for any PIN value
How Can a Cipher Be Attacked?

• Attackers knows ciphertext and encryption algorithm
  – What else does the attacker know? Depends on the application in which the cipher is used!

• Ciphertext-only attack

• KPA: Known-plaintext attack (stronger)
  – Knows some plaintext-ciphertext pairs

• CPA: Chosen-plaintext attack (even stronger)
  – Can obtain ciphertext for any plaintext of his choice

• CCA: Chosen-ciphertext attack (very strong)
  – Can decrypt any ciphertext except the target
Very Informal Intuition

- Security against chosen-plaintext attack (CPA)
  - Ciphertext leaks no information about the plaintext
  - Even if the attacker correctly guesses the plaintext, he cannot verify his guess
  - Every ciphertext is unique, encrypting same message twice produces completely different ciphertexts
    - Implication: encryption must be randomized or stateful

- Security against chosen-ciphertext attack (CCA)
  - Integrity protection – it is not possible to change the plaintext by modifying the ciphertext

Minimum security requirement for a modern encryption scheme
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 (more in section!).
- NIST recommends a derivative called CMAC [FYI only]
Another Tool: Hash Functions
You Just Did This

```
franzi@codered:~/.sploits$ md5sum sploit0.c
3a2e6ce795bce4d06df1ff6835d25cea  sploit0.c
franzi@codered:~/.sploits$
```
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 $y$. 

$2^{160} = 2^{160}$
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 $\frac{1}{8}$ of this class 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 $\frac{365}{2} = 182.5$ 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 \( x \neq x' \) 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 not imply collision resistance.

Collision resistance does not imply one-wayness.

You can prove this by constructing a function that has one property but not the other. (Details on next slide, FYI only.)
One-Way vs. Collision Resistance
(Details here mainly FYI)

• One-wayness does **not** 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 **not** 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
• Cryptographic hashes are also known as “cryptographic checksums” or “message digests”
Application: Password Hashing

- Instead of user password, store $\text{hash(password)}$
- When user enters a password, compute its hash and compare with the entry in the password file
- Why is hashing better than encryption here?

- System does not store actual passwords!
- Don’t need to worry about where to store the key!
- Cannot go from hash to password!
Application: Password Hashing

• Which property do we need?
  – One-wayness?
  – (At least weak) Collision resistance?
  – Both?
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)
Application: Software Integrity

• Which property do we need?
  – One-wayness?
  – (At least weak) Collision resistance?
  – Both?
Which Property Do We Need?
One-wayness, Collision Resistance, Weak CR?

• 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
Which Property Do We Need?

• UNIX passwords stored as hash(password)
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• Private auction bidding
  – Alice wants to bid B, sends H(B), later reveals B
  – One-wayness: rival bidders should not recover B (this may mean that she needs to hash some randomness with B too)
  – Collision resistance: Alice should not be able to change her mind to bid B’ such that H(B)=H(B’)

Common Hash Functions

• MD5 – Don’t Use!
  – 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
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 | @russelbrandom | 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.

**MAC:** message authentication code (sometimes called a “tag”)

**Message authentication schemes:** A tool for protecting integrity.
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 $\rightarrow$ same MAC
Authenticated Encryption

• Instead: 
  Encrypt then MAC.

• (Not as good: MAC-then-Encrypt)

Encrypt-then-MAC