CSE 484: Computer Security and Privacy

Cryptography
[MACs and Hash Functions]

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Admin

• Homework 2
  • Out soon™
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 algthm
  - 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

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
The shape of the formal approach

- **INDistinguishability under Chosen Plaintext Attack**
  - IND-CPA

- Formalized *cryptographic game*

  - Adversary submits pairs of *plaintexts* \((M_a, M_b)\)
    - Gets back ONE of the *ciphertexts* \((C_x)\)

  - Adversary must guess which ciphertext this is \((C_a \text{ or } C_b)\)
    - If they can do better than 50/50, they win
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 (*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$
```

md5
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 $y$. 

\[ H(x) \text{ no key} \]
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 1/8 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 \textbf{not} imply collision resistance. \times

Collision resistance does \textbf{not} imply one-wayness. \times

You can prove this by constructing a function that has one property but not the other.
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?
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?

\[ h(x) \quad h(x') \]
Application: Password Hashing + Salting

• Salting
  • We ‘salt’ hashes for password by adding a randomized suffix to the password
    • E.g. Hash("coolpassword"+"35B67C2A")
    • We then store the salt with the hashed password!

• The goal is to prevent precomputation attacks
  • If the adversary doesn’t know the salt, they can’t precompute common passwords
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)
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)
  • 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

• Commitments (e.g. auctions)
  • 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’)

1/27/2021
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-bit version is OK
  - 128-bit version is not good

- **SHA-1** (Secure Hash Algorithm) – Don’t Use!
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Theoretically broken 2005; practical attack 2017!

- **SHA-2**: 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 Branden | @russelbranden | Feb 23, 2017, 11:49am EST

https://shattered.io

100,000×

110 years CPU
Aside: How we evaluate hash functions

• Speed
  • Is it amenable to hardware implementations?

• Diffusion
  • Does changing 1 bit in the input affect all output bits?

• Resistance to attack approaches
  • Collisions?
  • Length extensions?
  • etc
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 $\rightarrow$ same MAC

\[\begin{align*}
C_1 & \xrightarrow{\text{Encrypt}_{K_e}} T_1 & \xrightarrow{\text{MAC}_{K_m}} \text{FIRE} \\
C_2 & \xrightarrow{\text{Encrypt}_{K_e}} T_2 & \xrightarrow{\text{MAC}_{K_m}} \text{DON'T FIRE} \\
C_3 & \xrightarrow{\text{Encrypt}_{K_e}} T_3 & \xrightarrow{\text{MAC}_{K_m}} \text{FIRE}
\end{align*}\]
Authenticated Encryption

• Instead:
  \[
  \text{Encrypt then MAC.}
  \]

• (Not as good: MAC-then-Encrypt)