CSE 484 / CSE M 584:
Finish Symmetric Encryption +
Start MACs

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Announcements

• Homework 2 (crypto) to be released today
  – Due Friday, Nov 4
  – Gradescope submission
  – You can get started now, but some problems will require content we will cover next week
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!

• 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
Chosen Plaintext Attack

Attacker #1 changes their PIN to a number of their choice

PIN is encrypted and transmitted to bank

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

... repeat for any PIN value
Very Informal Intuition

• Security against chosen-plaintext attack (CPA)
  – Ciphertext leaks no information about the plaintext
  – Even if the attacker correctly guesses the plaintext, they cannot verify their 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
So Far: Achieving Privacy

Encryption schemes: A tool for protecting privacy.

Message = M
Ciphertext = C

Alice
K

Encrypt

Decrypt

Bob
K

Adversary
K
K

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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!*).
- Use a different key – not encryption key
- NIST recommends a derivative called CMAC [FYI only]
Another Tool: Hash Functions
You Just Did This

```
[franzi@cse484:~/sploits$ md5sum sploit0.c
567878670559400a4d24f434142d589d  sploit0.c
franzi@cse484:~/sploits$
```
• 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 1/8 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. (Next slide has details, FYI.)
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 probability $\frac{1}{2}$
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?

• This is not the whole story on password storage; we’ll return to this later in the course.
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
Common Hash Functions

- **SHA-2**: SHA-256, SHA-512, SHA-224, SHA-384
- **SHA-3**: standard released by NIST in August 2015
- **MD5** – Don’t use for security!
  - 128-bit output
  - Designed by Ron Rivest, used very widely
  - Collision-resistance broken (summer of 2004)
- **SHA-1** (Secure Hash Algorithm) – Don’t use for security!
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Theoretically broken 2005; practical attack 2017!
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

https://shattered.io