CSE 484 / CSE M 584: Computer Security and Privacy

Cryptography
[Message Authentication Codes and Hash Functions]

Fall 2017

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Thanks to Dan Boneh, Dieter Gollmann, Dan Halperin, Yoshi Kohno, Ada Lerner, John Manferdelli, John Mitchell, Vitaly Shmatikov, Bennet Yee, and many others for sample slides and materials ...
Encryption schemes: A tool for protecting privacy.
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 \( x \neq x' \) such that \( h(x) = h(x') \)

• Birthday paradox (informal)
  – Let \( t \) be the number of values \( x, x', x'' \ldots \) 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? \( \text{Choose}(t, 2) = t(t-1)/2 \sim O(t^2) \)
  – 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 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 \rightarrow same hash value
  – Encrypt the same input twice \rightarrow different ciphertexts
• Cryptographic 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?
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 Brandon | @russellbrandon | 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 $\rightarrow$ same MAC
Authenticated Encryption

• Instead: Encrypt \textit{then} MAC.

• (Not as good: MAC-then-Encrypt)