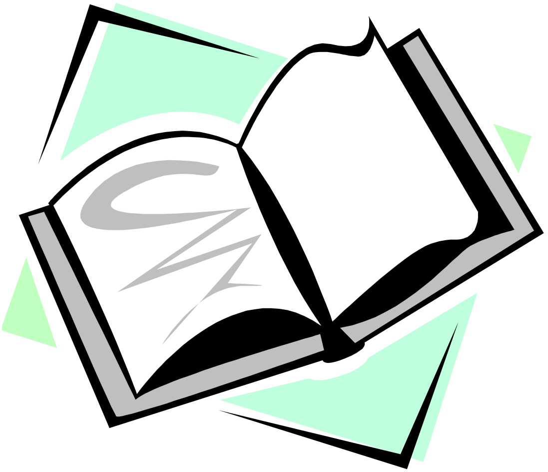
Computer Security
CS 526
Topic 4

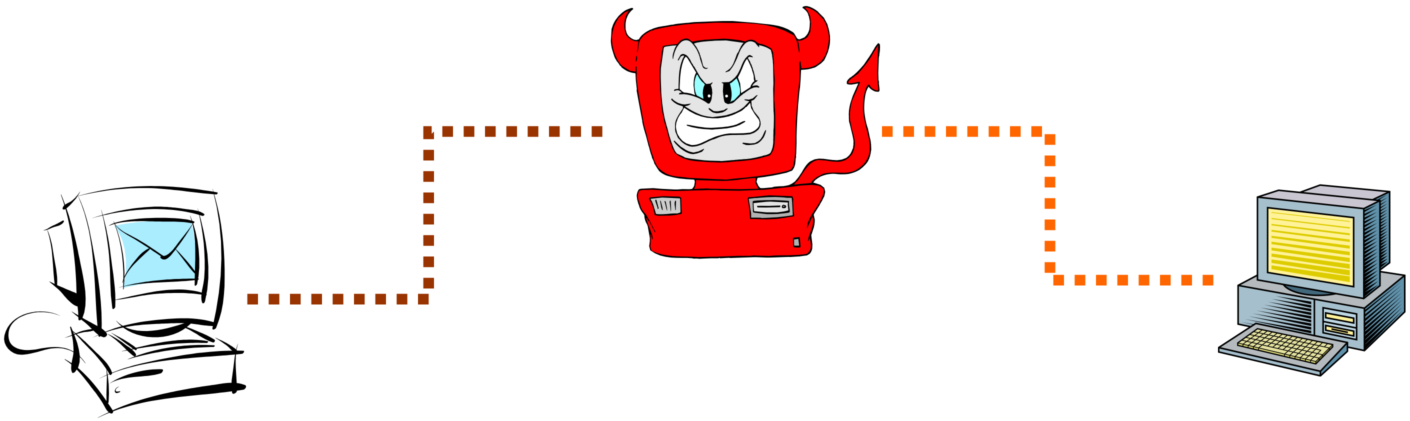
Cryptography: Cryptographic Hash Functions And Message Authentication Code

Readings for This Lecture

- Wikipedia
  - Cryptographic Hash Functions
  - Message Authentication Code



Data Integrity and Source Authentication



- Encryption does not protect data from modification by another party.
- Most encryption schemes are **malleable**:
  - Modifying ciphertext result in (somewhat) predictable change in plaintext
- Need a way to ensure that data arrives at destination in its original form as sent by the sender.

Hash Functions

- A hash function maps a message of an arbitrary length to a m-bit output
  - output known as the fingerprint or the message digest
- What is an example of hash functions?
  - Give a hash function that maps Strings to integers in $[0, 2^{32}-1]$
- Cryptographic hash functions are hash functions with additional security requirements

Using Hash Functions for Message Integrity

- Method 1: Uses a Hash Function h, assuming an authentic (adversary cannot modify) channel for short messages
  - Transmit a message M over the normal (insecure) channel
  - Transmit the message digest h(M) over the **authentic** channel
  - When receiver receives both M' and h, how does the receiver check to make sure the message has not been modified?

- This is insecure. How to attack it?
- A hash function is a many-to-one function, so collisions can happen.

Security Requirements for Cryptographic Hash Functions

Given a function $h: X \rightarrow Y$, then we say that h is:

- preimage resistant (one-way):

  if given $y \in Y$ it is computationally infeasible to find a value $x \in X$ s.t. $h(x) = y$

- 2-nd preimage resistant (weak collision resistant):

  if given $x \in X$ it is computationally infeasible to find a value $x' \in X$, s.t. $x' \neq x$ and $h(x') = h(x)$

- collision resistant (strong collision resistant):

  if it is computationally infeasible to find two distinct values $x', x \in X$, s.t. $h(x') = h(x)$

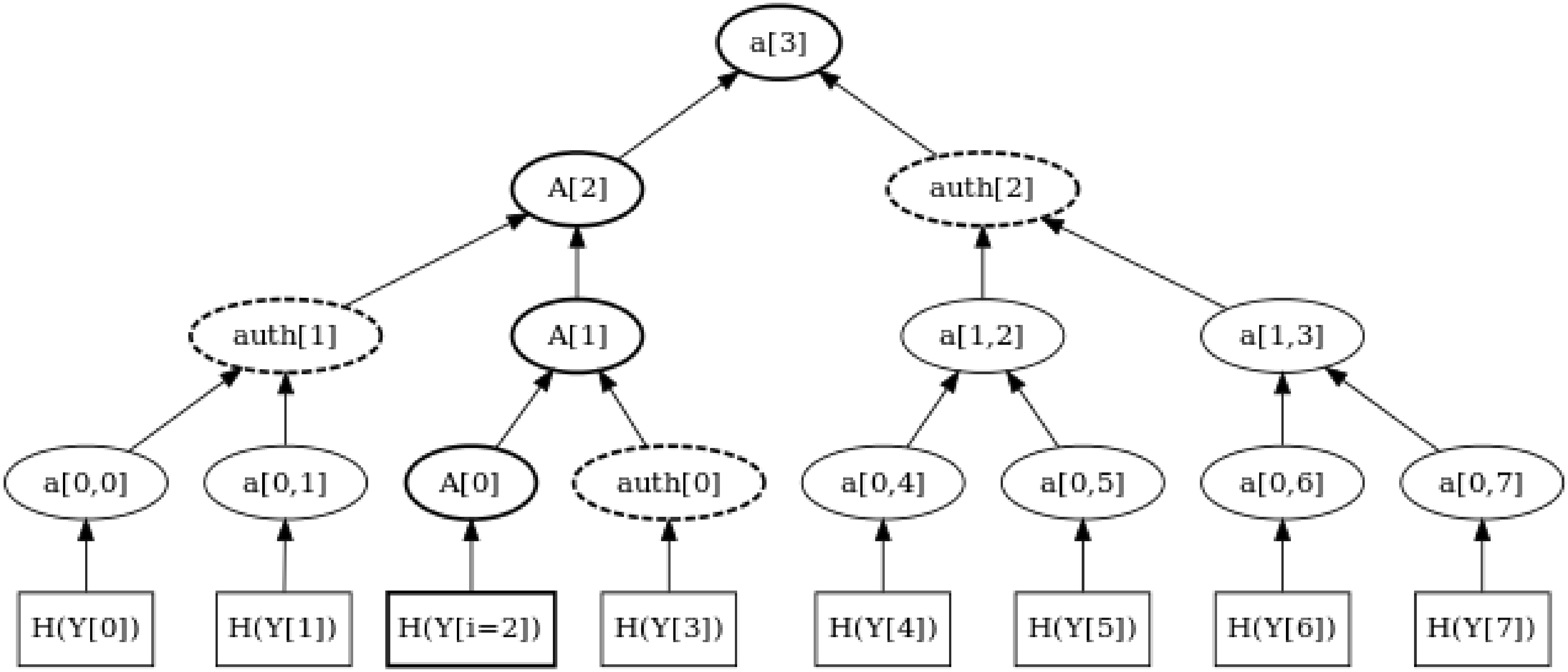
Usage of Hash Functions?

- Suppose that you have outsourced a database, and want to find a record; how to ensure that a result you get back is really in the database?

Merkle Hash Tree for Data Authentication

- Construct a binary tree where each leaf corresponds to a piece of data
- Each internal node is hash of two children
- Authentication the root using some method
- A leaf node along with the sibling node of each node to the path suffices to authenticate the node
  - Needs log(n) to authenticate any node

Merkle Hash Tree for Data Authentication



"MerkleTree2" by Tsuruya - Own work. Licensed under Public Domain via Commons - https://commons.wikimedia.org/wiki/File:MerkleTree2.svg#/media/File:MerkleTree2.svg

Usages of Cryptographic Hash Functions

- Software integrity
  – E.g., tripwire
- Timestamping (cryptographic commitment)
  – How to prove that you have discovered a secret on an earlier date without disclosing the context of a secret?
- Authenticating logs (a long history of events)
- Covered later
  – Message authentication
  – One-time passwords
  – Digital signature

Bruteforce Attacks on Hash Functions

- Attacking one-wayness
  - Goal: given $h: X \rightarrow Y$, $y \in Y$, find x such that $h(x)=y$
  - Algorithm:
    - pick a random value x in X, check if $h(x)=y$, if $h(x)=y$, returns x; otherwise iterate
    - after failing q iterations, return fail
  - The average-case success probability is

$$\varepsilon = 1 - \left(1 - \frac{1}{|Y|}\right)^q \approx 1 - e^{-\frac{q}{|Y|}} \approx \frac{q}{|Y|}$$

    - The first approximation holds when |Y| is large,
    - The second roughly holds when q/|Y| is small (e.g., < 0.5)
  - Let $|Y|=2^m$, to get ε to be close to 0.5, $q \approx 2^{m-1}$

Bruteforce Attacks on Hash Functions

- Attacking collision resistance
  - Goal: given h, find x, x' such that h(x)=h(x')
  - Algorithm: pick a random set X_0 of q values in X
    for each $x \in X_0$, computes $y_x = h(x)$
    if $y_x = y_{x'}$ for some $x' \neq x$ then return (x,x') else fail
  - The average success probability is

$$1-\left(1-\frac{1}{|Y|}\right)^{\frac{q(q-1)}{2}} \approx 1-e^{-\frac{q(q-1)}{2|Y|}}$$

  - Let $|Y|=2^m$, to get ε to be close to 0.5, $q \approx 2^{m/2}$
  - This is known as the birthday attack.

Choosing Parameters

- The level of security (for collision resistance) of a hash function that outputs n bits, is about n/2 bits
  – i.e., it takes $2^{n/2}$ time to bruteforce it
  – Assuming that no better way of attacking the hash function is known
- Longer outputs often means more computation time and more communication overhead
- The level of security for encryption function using k-bit key is about k bits

Choosing the length of Hash outputs

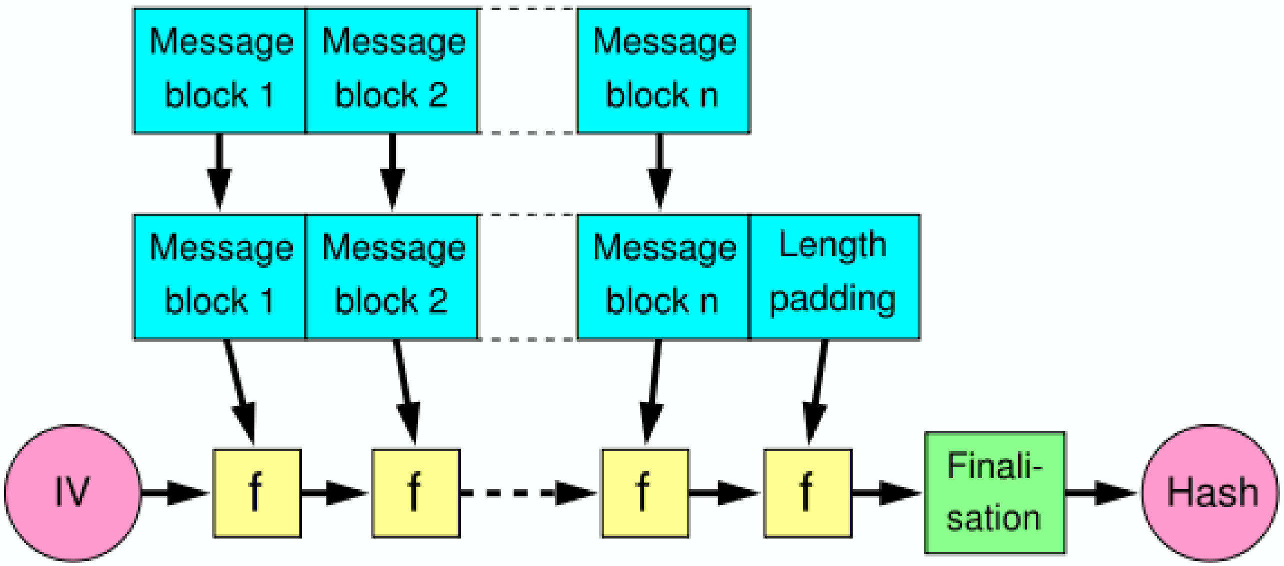
- The Weakest Link Principle:
  - A system is only as secure as its weakest link.
  - Hence all links in a system should have similar levels of security.
- Because of the birthday attack, the length of hash outputs in general should double the key length of block ciphers
  - SHA-224 matches the 112-bit strength of triple-DES (encryption 3 times using DES)
  - SHA-256, SHA-384, SHA-512 match the new key lengths (128,192,256) in AES
  - If small output size is highly important, and one is sure that collision-resistance is not needed (only one-wayness is needed), then same size should be okay.

Well Known Hash Functions

- MD5
  - output 128 bits
  - collision resistance completely broken by researchers in China in 2004
- SHA1
  - output 160 bits
  - no collision found yet, but method exist to find collisions in less than 2^80
  - considered insecure for collision resistance
  - one-wayness still holds
- SHA2 (SHA-224, SHA-256, SHA-384, SHA-512)
  - outputs 224, 256, 384, and 512 bits, respectively
  - No real security concerns yet
- SHA3 (224, 256, 384, 512)

Merkle-Damgard Construction for Hash Functions

- Message is divided into fixed-size blocks and padded
- Uses a compression function f, which takes a chaining variable (of size of hash output) and a message block, and outputs the next chaining variable
- Final chaining variable is the hash value



$$M=m_1m_2\ldots m_n;\ C_0=IV,\ C_{i+1}=f(C_i,m_i);\ H(M)=C_n$$

NIST SHA-3 Competition

- NIST completed a competition for SHA-3, the next generation of standard hash algorithms
- 2007: Request for submissions of new hash functions
- 2008: Submissions deadline. Received 64 entries. Announced first-round selections of 51 candidates.
- 2009: After First SHA-3 candidate conference in Feb, announced 14 Second Round Candidates in July.
- 2010: After one year public review of the algorithms, hold second SHA-3 candidate conference in Aug. Announced 5 Third-round candidates in Dec.
- 2011: Public comment for final round
- 2012: October 2, NIST selected SHA3
  - Keccak (pronounced "catch-ack") created by Guido Bertoni, Joan Daemen and Gilles Van Assche, Michaël Peeters

Limitation of Using Hash Functions for Authentication

- Require an authentic channel to transmit the hash of a message
  - Without such a channel, it is insecure, because anyone can compute the hash value of any message, as the hash function is public
  - Such a channel may not always exist

- How to address this?
  - use more than one hash functions
  - use a key to select which one to use

Hash Family

- A hash family is a four-tuple (X, Y, K, H), where
  - X is a set of possible messages
  - Y is a finite set of possible message digests
  - K is the keyspace
  - For each $K \in K$, there is a hash function $h_K \in H$. Each $h_K: X \to Y$
- Alternatively, one can think of H as a function $K \times X \to Y$

Message Authentication Code (MAC)

- A MAC scheme is a hash family, used for message authentication
- $MAC(K,M) = H_K(M)$
- The sender and the receiver share secret K
- The sender sends $(M, H_k(M))$
- The receiver receives (X,Y) and verifies that $H_K(X)=Y$, if so, then accepts the message as from the sender
- To be secure, an adversary shouldn't be able to come up with (X',Y') such that $H_K(X')=Y'$.

MAC: Using a shared secret (or a limit-bandwidth confidential channel) to achieve authenticity/integrity.

Security Requirements for MAC

- Secure against the "Existential Forgery under Chosen Plaintext Attack"
  - Challenger chooses a random key K
  - Adversary chooses a number of messages M_1, M_2, .., M_n, and obtains $t_j = MAC(K, M_j)$ for $1 \leq j \leq n$
  - Adversary outputs M' and t'
  - Adversary wins if $\forall j$ $M' \neq M_j$, and $t' = MAC(K, M')$

- Basically, adversary cannot create the MAC value for a message for which it hasn't seen an MAC

Constructing MAC from Hash Functions

- Let h be a one-way hash function
- MAC(K,M) = h(K || M), where || denote concatenation
  - Insecure as MAC with a hash function that uses the Merkle-Damgard construction:
  - given M and t=h(K || M), adversary can compute M'=M||Pad(M)||X and t', such that h(K||M') = t'

HMAC: Constructing MAC from Cryptographic Hash Functions

$$HMAC_K[M] = Hash[(K^+ \oplus opad) \,||\, Hash[(K^+ \oplus ipad)||M)]]$$

- K^+ is the key padded (with 0) to B bytes, the input block size of the hash function
- ipad = the byte 0x36 repeated B times
- opad = the byte 0x5C repeated B times.

At high level, $HMAC_K[M] = H(K \,||\, H(K \,||\, M))$

Hash function is used twice, in nested fashion.

HMAC Security

- If used with a secure hash functions (e.g., SHA-256) and according to the specification (key size, and use correct output), no known practical attacks against HMAC

MAC Can also be Constructed using Block Cipher

- The CBC mode can be used to define CBC-MAC
- GCM (Galois/Counter Mode) is currently widely used
  - Provide message authentication and encryption at the same time

Coming Attractions …

- Cryptography: Public Key Cryptography