McCarthy’s Spy Puzzle (1958)

The setting:
• Two countries are at war
• One country sends spies to the other country
• To return safely, spies must give the border guards a password

Conditions
• Spies can be trusted
• Guards chat – information given to them may leak

Solution to McCarthy’s puzzle

• Michael Rabin, 1958
• Use a one-way function, $B = f(A)$
  – Guards get $B$
  – Enemy cannot compute $A$ if they know $A$
  – Spies give $A$, guards compute $f(A)$
  – If the result is $B$, the password is correct.

Example function:
– Middle squares
  • Take a 100-digit number ($A$), and square it
  • Let $B$ = middle 100 digits of 200-digit result

One-way functions

• Easy to compute in one direction
• Difficult to compute in the other

Examples:
Factoring:
• $pq = N$  
  • find $p,q$ given $N$  
  • EASY  
  • DIFFICULT  

Discrete Log:
• $a^k \equiv c \pmod N$  
  • find $b$ given $a, c, N$  
  • EASY  
  • DIFFICULT

*Basis for RSA

*Basis for Diffie-Hellman & Elliptic Curve
Example of a one-way function

Example with an 18 digit number
A = 289407349786637777
A^2 = 837566141105250894845338203501729
Middle square, B = 1105250894845338

Given A, it is easy to compute B
Given B, it is difficult to compute A

“Difficult” = no known short-cuts; requires an exhaustive search

Cryptographic hash functions

Also known as a digests or fingerprints

Properties
- Arbitrary length input → fixed-length output
- Deterministic: you always get the same hash for the same message
- One-way function (pre-image resistance, or hiding)
  - Given H, it should be difficult to find M such that H=hash(M)
- Collision resistant
  - Infeasible to find any two different strings that hash to the same value: Find M, M' such that hash(M) = hash(M')
- Output should not give any information about any of the input
  - Like cryptographic algorithms, relies on diffusion
- Efficient
  - Computing a hash function should be computationally efficient

Hash functions are the basis of authentication

- Not encryption
- Can help us to detect:
  - Masquerading: Insertion of message from a fraudulent source
  - Content modification: Changing the content of a message
  - Sequence modification: Inserting, deleting, or rearranging parts of a message
  - Replay attacks: Replaying valid sessions

SHA-1 Overview

- Append the bit 1 to the message
- Pad message with 0 bits so its length = 448 mod 512
- Append length of message as a 64-bit big endian integer
- Initialize 5-word (160-bit) buffer to:
  a = 0x67452301  b = 0xefcdab89  c = 0x98badcfe  
  d = 0x10325476  e = 0xc3d2e1f0
- Process the message in 512-bit chunks
  - Expand the 16 32-bit words into 80 32-bit words via XORs & shifts
  - Iterate 80 times to create a hash for this chunk
  - Various sets of ANDs, ORs, shifts, and shifts
  - Add this hash chunk to the result so far

SHA-2 Overview

- 512-bits of message
- Next 512-bits of message
- Last 512-bits of message

256-bit Initialization Vector (IV)
Hash compression
Hash compression
Hash compression

Bits defined by the standard

Popular hash functions

- **MD5**  
  - R.I.P.  
  - 128 bits (rarely used now since weaknesses were found)
- **SHA-1**  
  - 160 bits – widely used: checksum in Git & torrents  
  - Google demonstrated a collision attack in Feb 2017  
  - Google had to run >9 quintillion SHA-1 computations to complete the attack  
  - but already being phased out since weaknesses were found earlier
  
  - Used for message integrity in GitHub
- **SHA-2** – believed to be secure  
  - Designed by the NSA; published by NIST  
  - SHA-224, SHA-256, SHA-384, SHA-512  
  - e.g., Linux passwords used MD5 and now SHA-512
  - SHA-256 used in bitcoin
- **SHA-3** – believed to be secure  
  - 256 & 512 bit

Linux commands

- **sha1sum**: create a SHA-1 hash  
  echo 'hello, world!' | sha1sum  
  e91ba0972b9055187fa2efa8b5c156f487a8293a
- **md5sum**: create an MD5 hash  
  echo 'hello, world!' | md5sum  
  910c8bc7311b0cd1bc5d2bcae782511

Collisions: The Birthday Paradox

How many people need to be in a room such that the probability that two people will have the same birthday is > 0.5?

**Your guess before you took a probability course**: 183

- This is true to the question of “how many people need to be in a room for the probability that someone else will have the same birthday as Alice?”

**Answer**: 23

\[
 p(n) = 1 - \frac{\binom{n}{1}}{365^n} 
\]

Approximate solution for # people required to have a 0.5 chance of a shared birthday, where \( m = n \) days in a year

\[
 n = \sqrt{2 \times 0.5 \times 365} 
\]

The Birthday Paradox: Implications

- Searching for a collision with a pre-image (known message) is A LOT harder than searching for two messages that have the same hash

  - Strength of a hash function is approximately \( \frac{1}{2} \) (\# bits)
  
  - 256-bit hash function has a strength of approximately 128 bits

Message Integrity

How do we detect that a message has been tampered?

- A cryptographic hash acts as a checksum  
  \[ H(M) \neq H(M') \]
- Associate a hash with a message  
  - we're not encrypting the message  
  - we're concerned with \textit{integrity}, not confidentiality

Hash Pointers

- We can use hash pointers instead of pointers in data structures
- Hash pointer = ( pointer, hash(data) )
- This allows us to verify that the information we're pointing to has not changed
Hash Pointers: Linked Lists

- Add new data blocks to the end of the list
- Tamper Evident Log = blockchain

Tamper detection

Suppose an adversary wants to data in this block

Then this hash pointer needs to be changed.

But that will change the hash of this data block

So this hash pointer needs to be changed too.

But now this data block hashes to a different value …

The adversary will have to change all hash pointers back to the root.

If we’re holding on to the head of the list so an adversary cannot modify it, then we will be able to detect tampering.

Merkle Trees: Binary trees with hash pointers

- Another tamper-resistant structure
- Only need to examine $O(\log n)$ hashes to validate data

$$\begin{align*}
H_0 &= \text{Hash}(D_0) \\
H_1 &= \text{Hash}(D_1) \\
H_{0,1} &= \text{Hash}(H_0 || H_1) \\
H_2 &= \text{Hash}(D_2) \\
H_3 &= \text{Hash}(D_3) \\
H_{2,3} &= \text{Hash}(H_2 || H_3) \\
H_{0,3} &= \text{Hash}(H_{0,1} || H_{2,3}) \\
\text{root hash pointer:} \\
\text{Merkle Tree Hash pointer} &= \{ \text{left_subtree}, \text{right_subtree}, \text{hash(left || right)} \}
\end{align*}$$
Tamperproof Integrity: Message Authentication Codes and Digital Signatures

April 10, 2019
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Message Integrity: MACs
- We rely on hashes to assert the integrity of messages
- An attacker can create a new message & a new hash and replace $H(M)$ with $H(M')$
- So let’s create a checksum that relies on a key for validation
  Message Authentication Code (MAC)

Hash-based MAC
We can create a MAC from a cryptographic hash function

\[
HMAC(m, k) = H((opad \oplus k) \parallel H(ipad \oplus k) \parallel m)
\]

Where
- $H$ = cryptographic hash function
- $opad$ = outer padding $0x5c5c5c5c \ldots (01011100 \ldots)$
- $ipad$ = inner padding $0x36363636 \ldots (00110110 \ldots)$
- $k$ = secret key
- $m$ = message
- $\oplus$ = XOR, $\parallel$ = concatenation

See RFC 2104

Block cipher based MAC: CBC-MAC
- Cipher block chaining assures that every encrypted block is a function of all previous blocks
- CBC MAC uses a zero initialization vector

MAC = final ciphertext block — others are discarded
Examples: AES-CBC-MAC, DES-MAC
Don’t use the same key for the MAC as for encrypting the message

Using a MAC

Alice — Both have the shared key, $k$ — Bob

1. Bob receives the Message $m'$ and a MAC.
2. Knowing the key, $k$, he generates a MAC for the message:
   $MAC' = HMAC(m', k)$
3. If $MAC = MAC'$, he’s convinced that the message has not been modified

Digital Signatures
- MACs rely on a shared key
  - Anyone with the key can modify and re-sign a message
- Digital signature properties
  - Only you can sign a message but anyone can validate it
  - You cannot cut and paste the signature from one message to another
  - An adversary cannot forge a signature
    - Even after inspecting an arbitrary number of signed messages
Digital Signature Primitives

1. Key generation
   \( \{ \text{secret_key}, \text{verification_key} \} \leftarrow \text{gen_keys}(\text{key_size}) \)

2. Signing
   \( \text{signature} \leftarrow \text{sign}(\text{message}, \text{secret_key}) \)

3. Validation
   \( \text{isValid} \leftarrow \text{verify}(\text{verification_key}, \text{message}, \text{signature}) \)

We sign \( \text{hash(message)} \) instead of the \text{message}
- We’d like the signature to be a small, fixed size
- We trust hashes to be collision-free
- We can use a signature in a hash pointer
  - This will protect the integrity of the entire data structure

Popular Digital Signature Algorithms

- DSA: Digital Signature Algorithm
  - NIST standard
  - Uses SHA-1 or SHA-2 hash
  - Key pair based on difficulty of computing discrete logarithms

- ECDSA: Elliptic Curve Digital Signature Algorithm
  - Variant of DSA that uses elliptic curve cryptography
  - Used in bitcoin

- RSA cryptography
  - \( \text{E}_{\text{pri_key}}(\text{H(M)}) \cdot \text{D}_{\text{pub_key}}(\text{H(M)}) \)

Note: not Diffie-Hellman, which is only a key exchange algorithm

Digital signatures: public key cryptography

Alice

Bob

\( \text{H(P)} \)

Alice generates a hash of the message

Alice encrypts the hash with her private key

This is her signature.

Bob decrypts the hash using Alice’s public key

Bob computes the hash of the message sent by Alice

Alice sends Bob the message & the encrypted hash

Digital signatures: public key cryptography
If the hashes match, the signature is valid
- the encrypted hash must have been generated by Alice

Digital signatures: public key cryptography

Digital signatures & non-repudiation

- Digital signatures provide non-repudiation
  - Only Alice could have created the signature because only Alice has her private key
- Proof of integrity
  - The hash assures us that the original message has not been modified
  - The encryption of the hash assures us that an attacker could not have re-created the hash

Digital signatures: multiple signers

Covert AND authenticated messaging

If we want to keep the message secret
- combine encryption with a digital signature

Use a session key:
  - Pick a random key, K, to encrypt the message with a symmetric algorithm
  - encrypt K with the public key of each recipient
  - for signing, encrypt the hash of the message with sender’s private key

Covert and authenticated messaging

Covert and authenticated messaging

Alice generates a digital signature by encrypting the message with her private key

Alice picks a random key, K, and encrypts the message P with it using a symmetric cipher
Covert and authenticated messaging

Alice encrypts the session key for each recipient of this message using their public keys.

The aggregate message is sent to Bob & Charles.

Note: we do not have forward secrecy by doing this.

Public Keys as Identities

- A public signature verification key can be treated as an identity
  - Only the owner of the corresponding private key will be able to create the signature
- New identities can be created by generating new random (private, public) key pairs
- Anonymous – no identity management
  - A user is known by a random-looking public key
  - Anybody can create a new identity at any time
  - Anybody can create as many identities as they want
  - A user can throw away an identity when it is no longer needed
  - Example: Bitcoin identity = hash(public key)

Certificates: Identity Binding

Identity Binding

- How does Alice know Bob's public key is really his?
  - Get it from a trusted server?
    - What if the enemy tampers with the server?
    - Or intercepts Alice’s query to the server (or the reply)?
    - What set of public keys does the server manage?
    - How do you find it in a trustworthy manner?
- Another option
  - Have a trusted party sign Bob’s public key
  - Once signed, it is tamper-proof

X.509 Certificates

ISO introduced a set of authentication protocols

X.509: Structure for public key certificates:

Issuer = Certification Authority (CA)
X.509 certificates

To validate a certificate
1. Verify its signature:
   1. Hash contents of certificate data
   2. Decrypt CA's signature with CA's public key

If you trust the CA

Certification Authorities (CAs)

• How do you know the public key of the CA?
  – You can get it from another certificate!
  – This is called certificate chaining
  – But trust has to start somewhere: you need a public key you can trust
    (probably sitting inside a certificate) – this is the root CA
    • Apple's keychain is pre-loaded with hundreds of CA certificates
    • Windows stores them in the Certificate Store and makes them accessible
      via the Microsoft Management Console (mmc)
    • Android stores them in Credential Storage
• Can you trust a CA?
  – Maybe…
    check their reputation and read their Certification Practice Statement
    – Even trustworthy ones might get hacked (e.g., VeriSign in 2010)

Key revocation

• Used to invalidate certificates before expiration time
  – Usually because of a compromised key
  – Or policy changes (e.g., someone leaves a company)
• Certificate revocation list (CRL)
  – Lists certificates that are revoked
  – Only certificate issuer can revoke a certificate
• Problems
  – Need to make sure that the entity issuing the revocation is authorized to do this
  – Revocation information may not circulate quickly enough
    • Dependent on dissemination mechanisms, network delays & infrastructure
    • Some systems may not have been coded to process revocations

Code Integrity

We can sign code too

• Validate integrity of the code
  – If the signature matches, then the code has not been modified
• Enables
  – Distribution from untrusted sources
  – Distribution over untrusted channels
  – Detection of modifications by malware
• Signature = encrypted hash signed by trusted source
  – Does not validate the code is good … just where it comes from

Review: signed messages

Message M

Hash(M) → E_{private_key}(Hash(M))

Encrypt with Alice's private key = digital signature
Code Integrity: signed software

- Windows 7-10: Microsoft Authenticode
  - SignTool command
  - Hashes stored in system catalog or signed & embedded in the file
  - Microsoft-tested drivers are signed
- macOS
  - codesign command
  - Hashes & certificate chain stored in file
- Also Android & iOS

Code signing: Microsoft Authenticode

A format for signing executable code (dll, exe, cab, ocx, class files)

- Software publisher:
  - Generate a public/private key pair
  - Get a digital certificate: VeriSign class 3 Commercial Software Publisher's certificate
  - Generate a hash of the code to create a fixed-length digest
  - Encrypt the hash with your private key
  - Combine digest & certificate into a Signature Block
  - Embed Signature Block in executable
- Microsoft SmartScreen:
  - Manages reputation based on download history, popularity, anti-virus results
- Recipient:
  - Call WinVerifyTrust function to validate:
    - Validate certificate, decrypt digest, compare with hash of downloaded code

Per-page hashing

- Integrity check when program is first loaded
- Per-page signatures – improved performance
  - Check hashes for every page upon loading (demand paging)
- Per-page hashes can be disabled optionally on both Windows and macOS

Windows code integrity checks

- Implemented as a file system driver
  - Works with demand paging from executable
  - Check hashes for every page as the page is loaded
- Hashes stored in system catalog or embedded in file along with X.509 certificate.
  - Check integrity of boot process
    - Kernel code must be signed or it won't load
    - Drivers shipped with Windows must be certified or contain a certificate from Microsoft

Notation

\[ Z \| W \]
- Z concatenated with W

\[ X \rightarrow Y: \{ Z \| W \} k_{A,B} \]
- X sends a message to Y
  - The message is the concatenation of Z & W and is encrypted by key \( k_{A,B} \), which is shared by users A & B

\[ X \rightarrow Y: \{ Z \} k_{A} \| \{ W \} k_{A,Y} \]
- X sends a message to Y
  - The message is a concatenation of Z encrypted using A's key and W encrypted by a key shared by A and Y

\( r_1, r_2 \)
- nonces – strings of random bits
Bootstrap problem

- How to Alice & Bob communicate securely?
- Alice cannot send a key to Bob in the clear
  - We assume an unsecure network
- We looked at two mechanisms:
  - Diffie-Hellman key exchange
  - Public key cryptography
- Let’s examine the problem some more

Simple Protocol

Use a trusted third party — Trent — who has all the keys
Trent transmits a session key to Alice and Bob

```
Trent
```

Alice

```
( Request session key to Bob ) ks
```

Trent

Alice

```
( ks ) ks || ( ks ) ks
```

Trent

Alice

```
( ks ) ks
```

Bob

Alice

```
( m ) ks
```

Bob

```
Let's examine the problem some more

Problems

- How does Bob know he is talking to Alice?
  - Trusted third party, Trent, has all the keys
  - Trent knows the request came from Alice since only he and Alice can have the key
  - Trent can authorize Alice’s request
  - Bob gets a message (session key) encrypted with his key, which only Trent could have created
- Vulnerable to replay attacks
  - Eve records the message from Alice to Bob and later replays it
  - Bob might think he’s talking to Alice, reusing the same session key
- Protocols should provide authentication & defend against replay

Needham-Schroeder

Add nonces – random strings – avoid replay attacks

```
Trent
```

Alice

```
( Alice || Bob || r )
```

Trent

Alice

```
( Alice || Bob || r || ks || ( Alice || ks ) ) ks
```

Trent

Alice

```
( Alice || ks ) ks
```

Bob

Alice

```
( r ) ks
```

Bob

```
( r - 1 ) ks
```

Bob

```
Message must have been created by Trent & is in a response to the first message (contains r). Use of r ensures it’s not a replay attack.
```

This is an authentication step: Bob asks Alice to prove she has ks.

Denning-Sacco Modification

- We assume all keys are secret
- But suppose Eve can obtain the session key from an old message (she worked hard, got lucky, and cracked an earlier message)

```
Eve
```

```
( Alice || ks ) ks
```

Bob

```
( r ) ks
```

Bob

```
( r - 1 ) ks
```

Bob

```
Eve the eavesdropper: She decrypted an old session key and is trying to get Bob to use it to think he’s talking to Alice.
```

```
Bob sees this as a legitimate request approved by Trent. It was (but earlier)...
```

April 10, 2019

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Solution

- Problem: replay in the third step of the protocol
  - Eve replays the message: \( \text{Alice} \| k_S \| k_B \)
- Solution: use a time stamp \( T \) to detect replay attacks

Problem with timestamps

- Use of timestamps relies on synchronized clocks
  - Messages may be falsely accepted or falsely rejected because of bad time
- Time synchronization becomes an attack vector
  - Create fake NTP responses
  - Generate fake GPS signals

Otway-Rees Protocol: Session IDs

- Another way to correct the third message replay problem
- Instead of using timestamps
  - Use a random integer, \( n \), that is associated with all messages in the key exchange

Otway-Rees Protocol

Use nonces \( (r_1, r_2) \) & session IDs \( n \)

Kerberos

Needham-Shroeder w/Denning-Sacco mods

Add nonces — random strings — AND a timestamp

April 10, 2019

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Kerberos

- Authentication service developed by MIT
  - project Athena 1983-1988
- Uses a trusted third party & symmetric cryptography
- Based on Needham Schroeder with the Denning Sacco modification
- Passwords not sent in clear text
  - assumes only the network can be compromised

Kerberos

Users and services authenticate themselves to each other

To access a service:
- user presents a ticket issued by the Kerberos authentication server
- service examines the ticket to verify the identity of the user

Kerberos is a trusted third party
- Knows all (users and services) passwords
- Responsible for
  - Authentication: validating an identity
  - Authorization: deciding whether someone can access a service
  - Key exchange: giving both parties an encryption key (securely)

Authenticate, get permission

Alice

"I'm Alice and want to talk to Bob"

Authentication Server (AS)

"Alice" [ Bob ]

If Alice is allowed to talk to Bob, generate session key, S

Alice decrypts this:
- Gets ID of "Bob's server"
- Gets session key & timestamp
- Knows message came from AS

{ "Alice", T, kS } kA

Alice & Bob communicate by encrypting data with S

Authenticate recipient of message

Alice

Encrypt Alice's timestamp in return message

Bob

{ T+T } kS

Alice validates timestamp

[Tickets]

(Alice & Bob communicate by encrypting data with S)
Kerberos key usage

• Every time a user wants to access a service
  – User’s password (key) must be used to decode the message from Kerberos

• We can avoid this by caching the password in a file
  – Not a good idea

• Another way: create a temporary password
  – We can cache this temporary password
  – Similar to a session key for Kerberos – to get access to other services
  – Split Kerberos server into Authentication Server + Ticket Granting Server

Ticket Granting Server (TGS)

• TGS works like a temporary ID
• User first requests access to the TGS
  – Contact Kerberos Authentication Server
  – Knows all users & their secret keys
  – User enters a password to do this
  – Gets back a ticket & session key to the TGS – these can be cached

• To access any service
  – Send a request to the TGS – encrypted with the TGS session key along with the ticket for the TGS
  – The ticket tells the TGS what your session key is
  – It responds with a session key & ticket for that service

Using Kerberos

$ kinit
Password: enter password
ask AS for permission (session key) to access TGS
Alice gets:

\[
\begin{align*}
\{ & "TGS", S \} \cdot k_A \\
\{ & "Alice", S \} \cdot k_{TGS} \\
\{ T \} \cdot k_S
\end{align*}
\]

Session key
TGS Ticket
Encrypted timestamp

Compute key (A) from password to decrypt session key S and get TGS ID.

You now have a ticket to access the Ticket Granting Service

Using Kerberos

$ rlogin somehost
rlogin uses the TGS Ticket to request a ticket for the rlogin service on somehost
Alice sends session key, S, to TGS

\[
\begin{align*}
\{ & "rlogin@somehost", S \} \cdot k_{TGS} \\
\{ & "Alice", S \} \cdot k_A
\end{align*}
\]

Alice receives session key for rlogin service & ticket to pass to rlogin service

\[
\begin{align*}
(\{ & "rlogin@somehost", S \} \cdot k_{TGS}) \cdot k_S \\
(\{ & "Alice", k_S \} \cdot k_{TGS}) \cdot k_A
\end{align*}
\]

S’ = session key for rlogin
Ticket for rlogin server on somehost

Public Key Exchange

We did this
• Alice’s & Bob’s public keys known to all: e_A, e_B
• Alice & Bob’s private keys are known only to the owner: d_A, d_B
• Simple protocol to send symmetric session key: k_S

\[
(\{ & k_S \} \cdot d_A) \cdot e_B
\]

Alice \hspace{2cm} Bob

Problem

• Vulnerable to forgery or replay
• Public keys are known to anyone
  – Bob has no assurance that Alice sent the message
• Fix: have Alice sign the session key

\[
(\{ & k_S \} \cdot d_A) \cdot e_B \rightarrow Bob
\]

Key k_S encrypted with Alice’s private key
Entire message encrypted with Alice’s public key
**Problem #2**

- How do we know we have the right public keys?
- Send a certificate so Bob can verify it

\[
\{ \{ \{ } d_{A} \} \} m_{A}, X \rightarrow Bob
\]

Add Alice’s certificate, which contains Alice’s verifiable public key

---

**Cryptographic toolbox**

- Symmetric encryption
- Public key encryption
- Hash functions
- Random number generators

---

**The End**