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Figure 3. A new world with many gatekeepers



- Users hate passwords
- Security professionals hate passwords w
- Everybody hates passwords
- Criteria to do better than passwords
 - オ Security
 - Usability
 - Deployability

Security

- Physical observation
- Targeted impersonation
- Online or offline guessing
- Leaks
- Phishing
- **7** Theft
- Trusted third party
- Privacy

Usability

- Memoryless
- Nothing to carry
- Physically effortless

- Infrequent errors
- Easy recovery from loss

Deployability

- Accessible
- Low Cost
- Server compatible

Phew – long list!

- Browser (client) compatible
- Mature
- Non-proprietary

- Password managers
- Proxies
- Federated identity management
- Graphical
- Cognitive

- Paper tokens
- Visual cryptography
- Hardware tokens
- Phone-based
- **Biometric**

Figure 4. Risk-based user authentication





Risk score

Graphic: Deloitte University Press | DUPress.com



Tokens

Secure Software Systems

Authentication Tokens



Authenticate a human based on possession of a small machine

Enrollment

- At enrollment, human is issued a token
 - Ranges from dumb (a physical key, a piece of paper) to a smart machine (a cryptographic processor)
 - **7** Token becomes attribute of human's identity
- Easy to carry, maintenance-free, low cost
 - Only a subset of goals previously discussed!

- Activated by user (button press), provides entry past barrier (gate, door)
- One-pass protocol only one message sent
- Token stores serial number T
- Barrier stores all serial numbers for all authorized tokens
- ↗ To enter: Token->Barrier: T



- Attack 1 Replay attack
 - Thief waits nearby, captures serial number with antenna, programs new token with same number, gains entry
- Attack 2 Brute force
 - Thief programs device to try all serial numbers (e.g.
 16 bit numbers) and waits a little while to gain entry
- Countermeasure? Nonce

- Barrier has a (secret) master key mk
- **Token stores**
 - **7** Serial number *T*
 - Nonce N (sequence counter)
 - ➤ Shared key k which is H(mk, T)
- Barrier stores
 - Same values as token for all authorized tokens
 - Master key mk
- To enter: Token→Barrier: T, MAC(T, N; k)
 - **7** Token increments *N*
 - Barrier increments N if MAC tag verifies

- Problem: Desynchronization of nonce
- Partial Solution: "Rolling window" of nonces 7





Remote Authentication



Example: SecurID

Securl

- Token displays code that changes every 60 seconds
 - LCD display
 - Internal clock
 - No human input
 - Can compute hashes and MACs
 - Stores secret (factory encoded random key)
- "nonce" is now <u>current time</u> (still a number used once)
- ✓ Uses local device (L) to input PIN





Secured by RS

Example: SecurID

- 1. $Hu \rightarrow L$: I want to authenticate as *id_Hu* to *S*
- 2. L and S: Establish secure channel (against Eve)
- 3. L \rightarrow Hu: Enter pin and code on keyboard
- 4. $T \rightarrow Hu: code = MAC(time@T, id_T, kT)$
- 5. Hu \rightarrow L: pin, code
- 6. L: compute h=H(pin, code)
- 7. L \rightarrow S: *id_Hu*, h
- 8. S: lookup (pin, *id_T*, *kT*) for *id_Hu*;
 - id_Hu is authenticated if h=H(pin, MAC(time@S, id_T; ktT))

Assume

- Remote system S stores tuples (id_T, id_Hu, kT, pin)
- Local system L
- Human Hu stores PIN
- Token *T* stores *id_T, kT*

Example: SecurID

- Engineering challenge
 - Clock synchronization between T and S
 - **♂** S tracks clock skew on per-token basis
- Security challenge
 - Theft of kT from S for all tokens
 - ↗ 2011 data breach of RSA
 - Suspect that secure token seeds may have been stolen
 - RSA offered replacement tokens to 30,000 companies that used them

One-Time Password

VOTE MALE HIRE BEAU LAY <u>50</u>: MF:ND PUG LYRA CANT JUDY BOAR AVON <u>49</u>. LOAM OILY FISH CHAD BRIG NOV 48: 47: RUE CLOG LEAK FRAU CURD SAM 46: COY LUG DORA NECK OILY HEAL 45: SUN GENE LOU HARD ELY HOG 44: GET CANE SOY NOR MATE DUEL 43: LUST TOUT NOV HAN BACH FADE 42: HOLM GIN MOLL JAY EARN BUFF **41** · KEEN ABUT GALA ASIA DAM SINK . . .

One-Time Password

- One-Time Password is only valid once (first use)
 - Similar to changing your password each time
 - Prevents replay attacks
 - Man-in-the-middle attacks still possible
- Use case: Login at untrusted public machine where keylogging is possible
- Use case: Account recovery if main password or two-factor device (e.g. phone) is lost
 - Google backup codes

One-Time Password

- Naïve-implementation
 - Pre-registered one-time passwords distributed on paper (hassle to obtain, risk of running out of passwords)
- Real implementation
 - Algorithmic generation of one-time passwords
 - SecurID is an example each code is a password valid for only 60 seconds
 - **7** Generation method: *Iterated hashing*





Secure Software Systems

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Digital Certificate

- **Digital certificate** binds together
 - Identity of principal
 - Public key of principal (encryption or verification key)
- Cert(S; I): Certificate issued by principal I for principal S
 - **↗** Issuer I certifies that K_S belongs to Subject id_S
 - b = id_S, K_S (id of subject, key of subject)
 - Cert(S; I) = b, Sign(b; k_I)
- → Fingerprint: H(Cert(S; I))

Digital Certificate Authentication



Digital Certificate Authentication

- S: Let msg = "I'm id_S". Compute s = Sign(msg; k_S)
- 2. S \rightarrow A: msg, s
- 3. A: Find Cert(S; I)
 - 1. Verify I's signature on cert
 - 2. Verify id_S
 - 3. Retrieve K_S
 - 4. Accept if Ver(msg; s; K_S).

- Notes
 - I must be trusted to issue certificate
 - A must verify id_S don't omit!

X.509 Certificates

Overview

- Standard format for certificates
 - **7** RFC 5280
- Used for
 - オ SSL/TLS

Contents

- → Serial number
- Issuer distinguished name
- Validity period (start and end time)
- Subject distinguished name
- Subject public key (and name of algorithm)
- Issuer's signature for all above data (and name of algorithm)

X.500 Distinguished Names

- General purpose directory
- Common options for X.509 certificates
 - Common Name (CN): Human full name, server name, or domain name
 - **7** Organization unit (OU): Finance, HR, ...
 - Organization (O): Pacific, Google, ...

Certificate Chain

- Problem
 - Receive a message signed by A, but don't know A's public verification key
 - Find a certificate Cert(A; B)
 - ↗ Certificate for A signed by B
 - But don't know B's public key either!

Certificate Chain

オ Solution: <u>Recursion</u> ☺

- Set of certificates
- Cert(A; B), then Cert(B; C); then Cert(C; D), and hopefully you know D's public key
- Certificate chain sequence of certificates that certify each other
 - One end: Certificate for principal you want to authenticate
 - **7** Other end: Certificate for principal you already know
 - Root or anchor of trust
 - Must trust every issuer in the chain to issue certificates

Public-Key Infrastructure

- System for managing distribution of certificates
- Two models
 - Decentralized peer to peer, no leader
 - **P**GP
 - Centralized oligarchy, leadership by elite
 - 7 CA

PKI Decentralized: PGP



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- "Pretty Good Privacy"
 - Encryption tool for emails and files
 - Dates back to early days of crypto (1991)
 - Developed by Phil Zimmermann
 - Investigated by US Government for "Munitions export without a license"

- **Each user manages a** *keyring*
- Alice has her key in her keyring
- Alice meets Bob at key-signing party
 - **Ϡ** She copies his key into her keyring
 - She marks Bob as *fully* or *marginally trusted* as an *introducer*
 - ➔ She copies other keys he might have collected, too
- Other option: Downloading keys from a key server (but you have little proof of who they actually belong to)



Never bring tequila to a key-signing party....

https://xkcd.com/364/

- Entries on the keyring are certificates
- Alice's own key on her keyring
 - Cert(A; A) <- Self-signed certificate!</p>
- When Alice imports a key signed by Bob, she gets Cert(C; B)
 - ↗ She can import as-is and put Cert(C; B) into keyring
 - ➔ She can vouch for it and put Cert(C; A) into keyring
- Can phone Bob and manually verify a certificate taken from a key server

- Keys on keyring are *fully valid* only if
 - Signed by 1 fully trusted introducer or 3 marginally trusted introducers
 - The certificate chain leading from key to user's own key has length of 5 or less
- Valid keys can be used for encryption and signing

"As time goes on, you will accumulate keys from other people that you may want to designate as trusted introducers. Everyone else will each choose their own trusted introducers. And everyone will gradually accumulate and distribute with their key a collection of certifying signatures from other people, with the expectation that anyone receiving it will trust at least one or two of the signatures. This will cause the emergence of a **decentralized fault-tolerant web of confidence** for all public keys."

Phil Zimmermann, 1992

PKI Centralized: CAs

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PKI Example: CAs

- Certificate Authority (CA)
 - Principal whose purpose is to issue certificates
- Centralized PKI philosophy

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PKI Example: CAs

- Everyone enrolls with CA to get certificate
 - Example: Alice enrolls and get Cert(Alice; CA)
- Bob's system comes pre-installed with CA's selfsigned certificate Cert(CA; CA)
- When Bob receives message signed by Alice
 - Bob contacts CA to get Cert(Alice; CA)
 - Or Alice includes that certificate with her message

PKI Example: CAs

- ✓ Web server has Cert(server; CA) installed
 - Server identity is hostname
 - CA is a root for which Cert(CA; CA) is installed in browser
- Browser authenticates web server using hostname and public key from certificate

Many Certificate Authorities

Many many Certificate Authorities

- No single CA will be trusted by all world governments, militaries, businesses, ...
- OS and web browsers come with some CAs preinstalled
- Organizations act as their own CAs
 - Company issues certificates to employees for VPN
 - Central bank issues certificates to other banks
 - Manufacturer issues certificates to sensing devices

Enrollment with CA

- You create a key pair the CA never knows your private key
- You generate a certificate signing request (CSR) containing the identity you are claiming
- → You send the CSR to a CA (w/payment?)
- CA verifies your identity (how well?)
- CA signs your public key, creating a certificate, and sends certificate to you

Identity Verification

- Extended Validation (EV) certificate
 - **7** CA does extra checking of your identity
 - Certificate marked as having received EV
 - Web browser displays EV mark in GUI
- Extra checking (in exchange for more \$\$\$)
 - Verify legal existence of organization
 - Verify physical presence of organization
 - Verify ownership/control over domain
- CA records that data in certificate as part of subject identity

Extended Validation Certificate



Transfer Funds Now

Log into Your Account

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Domain Validated Certificate



Issuing Certificates

- Conflicting goals
- CA private signing key must be kept secret
 - Public verification key is pre-installed on user systems and hard to update
 - A leaked private signing key could forge certificates
 - Solution: Keep private key offline in "cold storage"
- CA private signing key must be *available* for use
 - Needed to sign new certificates for customers
 - Solution: Keep it in computer memory

Issuing Certificates

- Solution? Use root and intermediate CAs
- Root CA
 - Certificate at root of trust in chain
 - Public key pre-installed at client PCs
 - Private key kept offline / highly secure
- Intermediate CAs
 - Certified by root CA
 - Used to certify user keys
 - Might by run by different organization than root CA



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- Key gets compromised (subject or issuer)
 - Your website gets hacked and private key stolen
- Subject leaves an organization (and certificates need to be revoked)
- Several (mediocre) options
 - **オ** Fast expiration
 - Certificate revocation list (CRL)
 - Online certificate validation

Fast expiration

- Idea
 - Validity interval is short (10 mins to 24 hours)
 - Any compromise is for a bounded time period
- Problems
 - CAs have to issue new certificates frequently (do they need to re-check identity?)
 - Machines have to update certificates frequently
 - ➤ Would need to automate

Certificate Revocation List (CRL)

- 7 Idea
 - CA posts lists of revoked certificates
 - Clients download and check list every time they need to validate certificate
- Problems
 - Clients don't bother checking (usability problems)
 - ↗ Large list, download time
 - Or clients cache (TOCTOU attack)
 - CRL must always be available (DDOS attack?)
- Chromium example limit of 250kB
 - https://dev.chromium.org/Home/chromium-security/crlsets

- Online Certificate Validation
- Idea
 - CA runs validation server
 - Client contacts server each time to validate certificate
- Problems
 - Clients don't bother
 - Checking adds latency to each new session
 - Server must always be available (DDOS?)
 - Clients "soft fail" to mitigate risk and users don't notice
 - **Reveals to CA which websites you want to access privacy**

- Online Certificate Status Protocol (OCSP)
 - Support: IE, Firefox, Safari, but not Chrome



Note: Alice and Bob both trust Carole as CA. (Have Carole's root cert preinstalled)

OCSP Stapling (aka TLS Certificate Status Request)

- オ Idea
 - Certificate must be accompanied by "fresh" attestation from CA that certificate is valid (window of a few days)
 - Whoever presents certificate to client is *also* responsible for acquiring the fresh assertation and *stapling* it to the certificate
- Bypasses most problems with online validation
 - No privacy concern the CA only knows their customer (website), not the client (visitor)
 - Performance better Certificate holder requests verification once (per time interval) no need for each client to verify!
 - Clients don't incur latency of verification request
- Support: Firefox, IE, Chrome

- https://blog.hboeck.de/archives/886-The-Problemwith-OCSP-Stapling-and-Must-Staple-and-why-Certificate-Revocation-is-still-broken.html
 - Still not perfect! (as of early 2017)
 - Implementation issues with Apache and Nginx make it risky to enable OCSP Stapling without risking your clients receiving errors in the case of temporary failure of OCSP verification server
- Doesn't work with intermediate CA certs (can only staple one OCSP response at a time)

Problem 2: Authority

- CA goes rogue or gets hacked
 - Already discussed in cryptography discussion
- Mediocre solutions

HTTP Public Key Pinning (HPKP)

- Upon first connection to server, client leans of public keys. In future connections, certificate must contain one of those keys
- Deprecated by Chrome too risky to deploy!
- Certificate transparency
 - Maintain public log of issued certificates and monitor log to detect malicious activity

DNS Certificate Authority Authorization (CAA)

- DNS record for entity specifies list of allowed CAs
- For the CA, not for the client! Legitimate CA won't issue cert unless in DNS list
- DNS-based Authentication of Named Entities (DANE)
 - Bypasses CAs entirely and relies on DNS to bind certificates to host names

