Certificates, Password Hashing, and Case Studies

Last Time: Public-Key Encryption and Digital Signatures

- Public-key cryptography: Two keys; one undoes the other
- Public-key encryption: One key encrypts, the other decrypts
  - Security properties similar to symmetric encryption
  - RSA: Produce a pair e and d such that $M^{ed} = M \bmod N$
    - Not IND-CPA secure on its own
- Hybrid encryption: Encrypt a symmetric key, and use the symmetric key to encrypt the message
- Digital signatures: Integrity and authenticity for asymmetric schemes
  - RSA: Same as RSA encryption, but encrypt the hash with the private key

Today

- Certificates: How do we distribute public keys securely?
- Password Hashing: How do we securely store passwords?
- Case studies
  - How can we discover bad cryptography?
  - How do we securely send messages in practice?
  - How can we report abusive behavior?

Certificates

Review: Public-Key Cryptography

- Public-key cryptography is great! We can communicate securely without a shared secret
  - Public-key encryption: Everybody encrypts with the public key, but only the owner of the private key can decrypt
  - Digital signatures: Only the owner of the private key can sign, but everybody can verify with the public key
- What's the catch?

Problem: Distributing Public Keys

- Public-key cryptography alone is not secure against man-in-the-middle attacks
- Scenario
  - Alice wants to send a message to Bob
  - Alice asks Bob for his public key
  - Bob sends his public key to Alice
  - Alice encrypts her message with Bob’s public key and sends it to Bob
- What can Mallory do?
  - Replace Bob's public key with Mallory’s public key
  - Now Alice has encrypted the message with Mallory’s public key, and Mallory can read it!

Problem: Distributing Public Keys

Alice

Mallory

Bob

Generate PK_B, SK_B

Send PK_B

Send PK_M

Receive PK_M

Send $\{M\}_{PK_M}$

Decrypt $\{M\}_{PK_M}$

Send $\{M\}_{PK_B}$

Decrypt $\{M\}_{PK_B}$

Problem: Distributing Public Keys

- Idea: Sign Bob's public key to prevent tampering
- Problem
  - If Bob signs his public key, we need his public key to verify the signature
  - But Bob's public key is what we were trying to verify in the first place!
  - Circular problem: Alice can never trust any public key she receives
- You cannot gain trust if you trust nothing. You need a root of trust!
  - **Trust anchor**: Someone that we implicitly trust
  - From our trust anchor, we can begin to trust others

Trust-on-First-Use

- **Trust-on-first-use**: The first time you communicate, trust the public key that is used and warn the user if it changes in the future
  - Used in SSH and a couple other protocols
  - Idea: Attacks aren't frequent, so assume that you aren't being attacked the first time communicate
  - Also known as "**Leap of Faith**"

Certificates

- **Certificate**: A signed endorsement of someone's public key
  - A certificate contains at least two things: The **identity** of the person, and the **key**
- Abbreviated notation
  - Encryption under a public key *PK*: {"Message"}$_{PK}$
  - Signing with a private key *SK*: {"Message"}$_{SK^{-1}}$
    - Recall: A signed message must contain the message along with the signature; you can't send the signature by itself!
- Scenario: Alice wants Bob's public key. Alice trusts Chao(PK_C, SK_C)
  - Chao is our trust anchor
  - If we trust PK_C, a certificate we would trust is {"Bob's public key is PK_B"}$_{SK_C^{-1}}$

Attempt #1: The Trusted Directory

- Idea: Make a central, trusted directory (TD) from where you can fetch anybody's public key
  - The TD has a public/private keypair PK_{TD}, SK_{TD}
  - The directory publishes PK_{TD} so that everyone knows it (baked into computers, phones, OS, etc.)
  - When you request Bob's public key, the directory sends a certificate for Bob's public key
    - {"Bob's public key is PK_B"}$_{SK_{TD}^{-1}}$
  - If you trust the directory, then now you trust every public key from the directory
- What do we have to trust?
  - We have received TD's key correctly
  - TD won't sign a key without verifying the identity of the owner

Attempt #1: The Trusted Directory

- Let’s say that Bojan Cukic (Dean of CCI) runs the TD
  - We want Jian’s public key: Ask BC
  - We want Chao’s public key: Ask BC
  - We want Min’s public key: Ask BC
  - BC has better things to do (like making sure his private key isn’t stolen)!
- Problems: Scalability
  - One directory won’t have enough compute power to serve the entire world
- Problem: Single point of failure
  - If the directory fails, *cryptography stops working*
  - If the directory is compromised, you can’t trust anyone
  - If the directory is compromised, it is difficult to recover

Certificate Authorities

- Addressing scalability: Hierarchical trust
  - The roots of trust may **delegate** trust and signing power to other authorities
    - {“Chao’s public key is PK_C, and I trust him to sign for SIS”}$_{SK_{BC}^{-1}}$
    - {“Jian’s public key is PK_J, and I trust him to sign for the junior faculties”}$_{SK_C^{-1}}$
    - {“Mallory’s public key is PK_M (but I don’t trust her to sign for anyone else)”}$_{SK_J^{-1}}$
  - BC is still the root of trust (**root certificate authority**, or **root CA**)
  - Chao and Jian receive delegated trust (**intermediate CAs**)
  - M’s identity can be trusted
- Addressing scalability: Multiple trust anchors
  - There are ~150 root CAs who are implicitly trusted by most devices
  - Public keys are hard-coded into operating systems and devices
  - Each delegation step can restrict the scope of a certificate’s validity
  - Creating the certificates is an *offline* task: The certificate is created once in advance, and then served to users when requested

Revocation

- What happens if a certificate authority messes up and issues a bad certificate?
  - Example: {“Bob’s public key is PK_M”}$_{SK_{CA}^{-1}}$
  - Example: Verisign (a certificate authority) accidentally issued a certificate saying that an average Internet user’s public key belonged to Microsoft

Revocation: Expiration Dates

- Approach #1: Each certificate has an expiration date
  - When the certificate expires, request a new certificate from the certificate authority
  - The bad certificate will eventually become invalid once it expires
- Benefits
  - Mitigates damage: Eventually, the bad certificate will become harmless
- Drawbacks
  - Adds management burden: Everybody has to renew their certificates frequently
  - If someone forgets to renew a certificate, their website might stop working
- Tradeoff: How often should certificates be renewed?
  - Frequent renewal: More secure, less usable
  - Infrequent renewal: Less secure, more usable
- LetsEncrypt (a certificate authority) chose very frequent renewal
  - It turns out frequent renewal is more usable:
    It forces automated renewal instead of a once-every 3 year task that gets forgotten!

Revocation: Announcing Revoked Certificates

- Approach #2: Periodically release a list of invalidated certificates
  - Users must periodically download a Certification Revocation List (CRL)
- How do we authenticate the list?
  - The certificate authority signs the list!
    - {“The certificate with serial number 0xdeadbeef is now revoked”}$_{SK_{CA}^{-1}}$
- Drawbacks
  - Lists can get large
    - Mitigated by shorter expiration dates (don’t have to list them once they expire)
  - Until a user downloads a list, they won’t know which certificates are revoked
- What happens if the certificate authority is unavailable?
  - Fail-safe default: Assume all certificates are invalid? Now we can’t trust anybody!
    - Possible attack: Attacker forces the CA to be unavailable (denial of service attack)
  - Use old list: Potentially dangerous if the old list is missing newly revoked certificates

Certificates: Complexity

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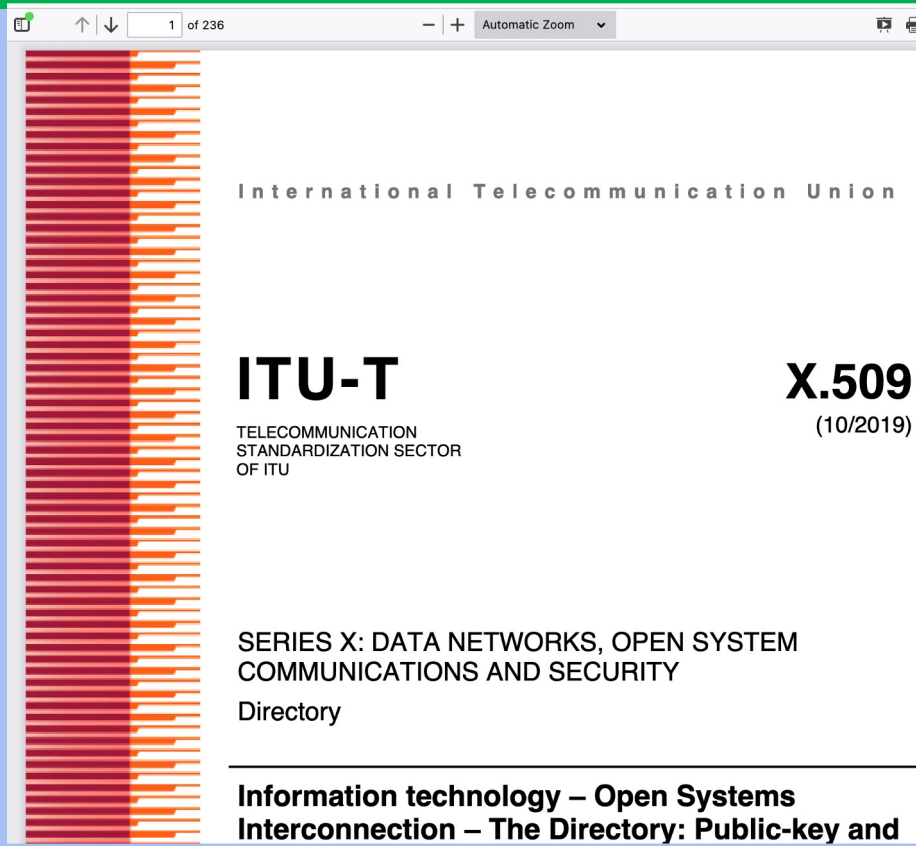
- Certificate protocols can get very complicated
  - Example: X.509 is incredibly complicated (a 236 page standard!) because it tried to do everything



Summary: Certificates

- Certificates: A signed attestation of identity
- Trusted directory: One server holds all the keys, and everyone has the TD's public key
  - Not scalable: Doesn't work for billions of keys
  - Single point of failure: If the TD is hacked or is down, cryptography is broken
- Certificate authorities: Delegated trust from a pool of multiple root CAs
  - Root CAs can sign certificates for intermediate CAs
  - Revocation: Certificates contain an expiration date
  - Revocation: CAs sign a list of revoked certificates

Password Hashing

Review: Cryptographic Hashes

- Hashes accept arbitrarily large inputs
- Hashes “look” random
  - Change a single bit on the input and each output bit has a 50% chance of flipping
  - And until you change the input, you can't predict which output bits are going to change
- The ones we talked about are *fast*
  - Can operate at many many MB/s: Faster at processing data than block ciphers
- Recall: Security properties
  - One way: Given an output y, it is infeasible to find any input x such that $H(x) = y$.
  - Collision resistant: It is infeasible to find another any pair of inputs $x' \neq x$ such that $H(x) = H(x')$.

Storing Passwords

- Password: A secret string a user types in to prove their identity
  - When you create an account with a service: Create a password
  - When you later want to log in to the service: Type in the same password again
- How does the service check that your password is correct?
- Bad idea #1: Store a file listing every user's password
  - Problem: What if an attacker hacks into the service? Now the attacker knows everyone's passwords!
- Bad idea #2: Encrypt every user's password before storing it
  - Problem: The attacker could steal the passwords file *and* the key and decrypt everyone's passwords!
- We need a way to verify passwords *without* storing any information that would allow someone to recover the original password

Password Hashing

- For each user, store a *hash* of their password
- Verification process
  - Hash the password submitted by the user
  - Check if it matches the password hash in the file
- What properties do we need in the hash?
  - Deterministic: To verify a password, it has to hash to the same value every time
  - One-way: We don’t want the attacker to reverse hashes into original passwords

Password Hashing: Attacks

- What if two different users decide to use **`password123`** as their password?
  - Hashes are deterministic: They'll have the same password hash
  - An attacker can see which users are using the same password
- Brute-force attacks
  - Most people use insecure, common passwords
  - An attacker can pre-compute hashes for common passwords: *H*(**`"password123"`**), *H*(**`"password1234"`**), *H*(**`"1234567890"`**), etc.
  - **Dictionary attack**: Hash an entire dictionary of common passwords
- **Rainbow tables**: An algorithm for computing hashes that makes brute-force attacks easier

Salted Hashes

- Solution #1: Add a unique, random salt for each user
- **Salt**: A random, public value designed to make brute-force attacks harder
  - For each user, store: username, salt, *H*(password || salt)
  - To verify a user: look up their salt in the passwords file, compute *H*(password || salt), and check it matches the hash in the file
  - Salts should be long and random
  - Salts are not secret (think of them like nonces or IVs)
- Brute-force attacks are now harder
  - Assume there are *M* possible passwords and *N* users in the database
  - Unsalted database: Hash all possible passwords, then lookup all users' hashes ⇒ $O(M + N)$
  - Salted database: Hash all passwords for each user's salt ⇒ $O(MN)$

Slow Hashes

- Solution #2: Use slower hashes
- Cryptographic hashes are usually designed to be fast
  - SHA is designed to produce a checksum of your 1 GB document as fast as possible
- Password hashes are usually designed to be slow
  - Legitimate users only need to submit a few password tries. Users won't notice if it takes 0.0001 seconds or 0.1 seconds for the server to check a password.
  - Attackers need to compute millions of hashes. Using a slow hash can slow the attacker by a factor of 1,000 or more!
  - Note: We are not changing the asymptotic difficulty of attacks. We're adding a large constant factor, which can have a huge practical impact for the attacker

Slow Hashes: PBKDF2

- **Password-based key derivation function 2 (PBKDF2)**: A slow hash function
  - Setting: An underlying function that outputs random-looking bits (e.g. HMAC-SHA256)
  - Setting: The desired length of the output (*n*)
  - Setting: Iteration count (higher = hash is slower, lower = hash is faster)
  - Input: A password
  - Input: A salt
  - Output: A long, random-looking *n*-bit string derived from the password and salt
  - Implementation: Basically computing HMAC 10,000 times
- Benefits (assuming the user password is strong)
  - Derives an arbitrarily long string from the user's password
  - Output can be directly used as a symmetric key
  - Output can also be used to seed a PRNG or generate a public/private key pair
  - Algorithm is slow, but doesn't use a lot of memory (alternatives like Scrypt and Argon2 use more memory)

Offline and Online Attacks

- **Offline attack**: The attacker performs all the computation themselves
  - Example: Mallory steals the password file, and then computes hashes herself to check for matches.
  - The attacker can try a huge number of passwords (e.g. use many GPUs in parallel)
  - Defenses: Salt passwords, use slow hashes
  - If an attacker can do an offline attack, you need a really strong password (e.g. 7 or more random words)
- **Online attack**: The attacker interacts with the service
  - Example: Mallory tries to log in to a website by trying every different password. Mallory is forcing the server to compute the hashes.
  - The attacker can usually only try a few times per second, with no parallelism
  - Defenses: Add a timeout or rate limit the number of tries to prevent the attacker from trying too many times

Summary: Password Hashing

- Store hashes of passwords so that you can verify a user's identity without storing their password
- Attackers can use brute-force attacks to learn passwords (especially when users use weak passwords)
  - Defense: Add a different **salt** for each user: A random, public value designed to make brute-force attacks harder
- **Offline attack**: The attacker performs all the computation themselves
  - Defense: Use salted, slow hashes instead of unsalted, fast hashes
- **Online attack**: The attacker interacts with the service
  - Defense: Use timeouts

Case Study: iPhone Security

iPhone Security

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- Apple's security philosophy:
  - In your hands, you can access everything on your phone
  - In anybody else's hands, the phone is an inert "brick" (nothing can be accessed)
- Apple uses a small co-processor in the phone to handle all cryptography
  - The "Secure Enclave" (recall: small TCB)
- The rest of the phone is untrusted
  - Memory is untrusted, so all data must be encrypted
  - The CPU must ask the Secure Enclave to decrypt data
  - Some data (e.g. credit card information for Apple Pay) is only readable by the Secure Enclave
- Effaceable Storage
  - Data is often stored in multiple places for redundancy, or not entirely wiped on deletion (for speed)
  - Effaceable storage: A section of memory where if memory is wiped, it is guaranteed to be gone
  - Requires some electrical engineering trickery to implement

iPhone Security

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- A lot of keys encrypted by keys
  - There is a random master key, K_{phone}, that can be used to decrypt all the other keys
- K_{phone} is encrypted by the user's password and stored in flash memory
  - Run PBKDF on the password to get K_{user}, and use K_{user} to encrypt K_{phone}
- How do we prevent an offline brute-force attack?
  - Include a random 256-bit secret hardcoded into the Secure Enclave for encryption
  - The only way to get this secret is to take apart the chip!
  - The Secure Enclave can’t read the secret, but can only use it as an input for hardware cryptography
  - The user key K_{user} is actually function of the password and Enc(secret, password)
  - Offline attacks are not possible without the secret
- **Takeaway**: Mixing in on-chip secret requires online attacks!
  - If the attacker doesn't know the on-chip secret, they can’t perform an offline attack

iPhone Security

- How do we prevent online brute-force attacks?
  - Online attacks must go through the secure enclave
  - Timeouts: After 5 tries, add a delay to slow down each try
  - After 10 tries, optionally wipe K_{phone} forever
  - Remember: K_{phone} is the root key for decrypting everything else. Erasing K_{phone} effectively erases everything on the phone!
  - Even if an attacker compromises the secure enclave, guessing is still limited to 10 tries per second
- **Takeaway**: Timeouts and slow algorithms prevent online attacks. If possible, limit attackers to online attacks

iPhone Security: Backups

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- A necessary weakness: Backups
  - Backup: Copying all data from the phone somewhere else
  - The data is copied unencrypted (decrypted with the secret on the chip)
  - Backups are necessary so you can recover your data on another phone
- Attack: Use backups to steal your data
  - The attacker finds a way to unlock your phone without your password (e.g. hold it to your face or use your fingerprint)
  - Remember: consider human factors!
  - The attacker syncs your phone with a new computer
- Change of policy as of iOS 11
  - To create a backup on a new computer, you need to enter your password to trust the computer
  - Previous attack is no longer possible: can't create a backup without knowing the password

Case Study: Samsung

- Samsung has a similar concept
  - But their implementation has, umm, issues…
- Guess with, GCM with IV reuse!
  - And although “fixed”, you could do a downgrade attack to cause the fixed version to still reuse IVs
- **Takeaway**: CTR mode is dangerous when used improperly…and even experts misuse it!

Cryptology ePrint Archive: Report 2022/208 Link

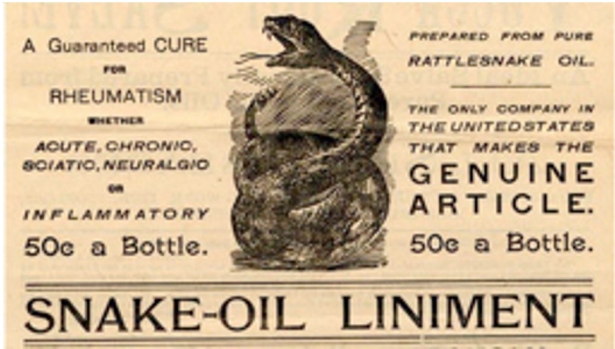
Alon Shakevsky and Eyal Ronen and Avishai Wool *February 20, 2022*

In this work, we expose the cryptographic design and implementation of Android's Hardware-Backed Keystore in Samsung's Galaxy S8, S9, S10, S20, and S21 flagship devices. We reversed-engineered and provide a detailed description of the cryptographic design and code structure, and we unveil severe design flaws. We present an IV reuse attack on AES-GCM that allows an attacker to extract hardware-protected key material, and a downgrade attack that makes even the latest Samsung devices vulnerable to the IV reuse attack. We demonstrate working key extraction attacks on the latest devices. We also show the implications of our attacks on two higher-level cryptographic protocols between the TrustZone and a remote server: we demonstrate a working FIDO2 WebAuthn login bypass and a compromise of Google’s Secure Key Import.

Case Study: Snake Oil Cryptography

Snake Oil

- Original meaning: Fraudulent “cure-all” medicines sold in the 1700s and 1800s
  - Sellers promised buyers that snake oil cures all diseases (even though it doesn’t)
  - Took advantage of uninformed buyers and lack of regulations
- Modern meaning: Scams
  - Using deceptive advertising to trick uninformed buyers into buying useless products
- **Snake oil security** (**snake oil cryptography**): Useless security products advertised to uninformed buyers



Signs of Snake Oil Cryptography

- Amazingly long key lengths
  - Once brute-forcing a key becomes astronomically hard, making it longer probably doesn't provide extra security
  - The NSA is super paranoid, and even they don’t use >256-bit symmetric keys or >4,096-bit public keys
- New algorithms and wild protocols
  - There is no reason to use a brand-new block cipher, hash algorithm, public-key algorithm, etc.
  - Existing protocols have been vetted by security experts for years: They’re widespread for a good reason!
  - New protocols probably means someone is trying to write their own crypto (and asking for trouble!)
- Fancy-sounding technical buzzwords
  - Claims of inventing “new math”

Signs of Snake Oil Cryptography

- “One time pads”
  - Recall: One-time pads are secure if you never reuse the key
  - Recall: Secure one-time pads are highly impractical
  - Almost all schemes advertised as “one-time pads” probably aren't true one-time pads
  - Wacky stream ciphers (often self-designed) are often advertised as “one-time pads”
- Rigged “cracking contests”
  - Advertising a secure scheme by challenging the public to break the scheme
  - The challenge is often “decrypt this message” with no context or structure
  - Example: Telegram offered a $300,000 prize in a contest to break their encryption

Example: Cryptocurrency Snake Oil

- IOTA: A cryptocurrency designed for the Internet of Things (IoT)
  - Uses a hash-based scheme instead of standard public key signatures, meaning you can never reuse a key
  - 10,000-bit signatures (compare with 450-bit RSA signatures, which are considered big)
  - Created their own hash function… that was quickly broken
  - Claims to be a distributed system, but relies entirely on a central authority (not distributed)
  - Uses trinary math? (Requiring entirely new processors?)
- **Takeaway**: Be able to recognize snake oil cryptography