CSci 5271
Introduction to Computer Security
Day 17: Cryptographic protocols and failures

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Outline

Public key encryption and signatures

Announcements

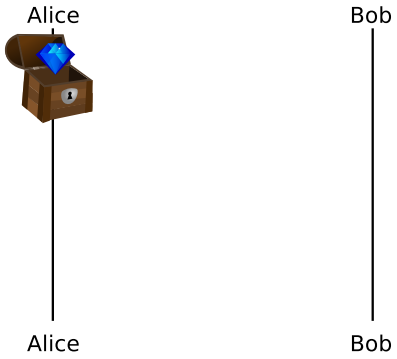
Cryptographic protocols

More causes of crypto failure

General description

- Public-key encryption (generalizes block cipher)
  - Separate encryption key EK (public) and decryption key DK (secret)
- Signature scheme (generalizes MAC)
  - Separate signing key SK (secret) and verification key VK (public)

Protocol with clip art



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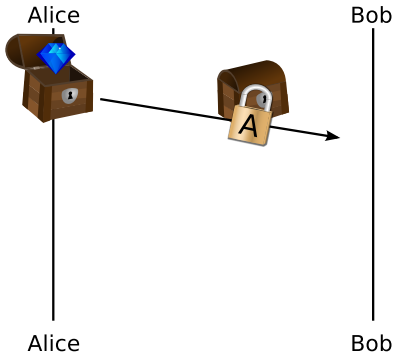

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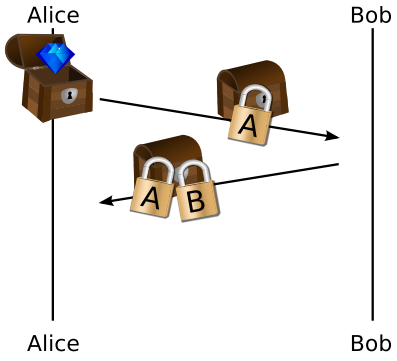

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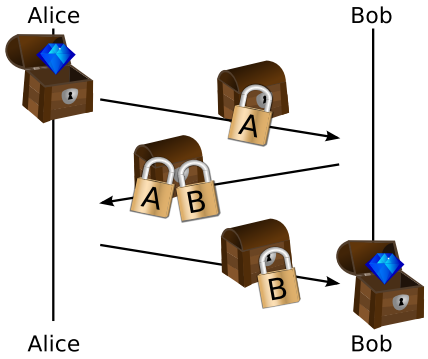

RSA setup

- Choose $n = pq$, product of two large primes, as modulus
- n is public, but p and q are secret
- Compute encryption and decryption exponents e and d such that

$$M^{ed} = M \pmod{n}$$

RSA encryption

- Public key is (n, e)
- Encryption of M is $C = M^e \pmod{n}$
- Secret key is (n, d)
- Decryption of C is $C^d = M^{ed} = M \pmod{n}$

RSA signature

- Signing key is (n, d)
- Signature of M is $S = M^d \pmod{n}$
- Verification key is (n, e)
- Check signature by $S^e = M^{de} = M \pmod{n}$
- Note: symmetry is a nice feature of RSA, not shared by other systems

RSA and factoring

- We're not sure factoring is hard (likely not even NP-complete), but it's been unsolved for a long time
- If factoring is easy (e.g., in P), RSA is insecure
- Converse might not be true: RSA might have other problems

Aside: stronger reduction

- Public-key algorithms actually equivalent to factoring and discrete log exist
  - But not widely used because of speed or other efficiency issues
- Even symmetric-key algorithms with such security
  - But they're *much* less efficient than AES et al.

Homomorphism

- Multiply RSA ciphertexts $\Rightarrow$ multiply plaintexts
- This *homomorphism* is useful for some interesting applications
- Even more powerful: fully homomorphic encryption (e.g., both $+$ and $\times$)
  - First demonstrated in 2009; still very inefficient

Problems with vanilla RSA

- Homomorphism leads to chosen-ciphertext attacks
- If message and e are both small compared to n, can compute $M^{1/e}$ over the integers
- Many more complex attacks too

Hybrid encryption

- Public-key operations are slow
- In practice, use them just to set up symmetric session keys

\+ Only pay RSA costs at setup time

– Breaks at either level are fatal

Padding, try #1

- Need to expand message (e.g., AES key) size to match modulus
- PKCS#1 v. 1.5 scheme: prepend 00 01 FF FF .. FF
- Surprising discovery (Bleichenbacher'98): allows adaptive chosen ciphertext attacks on SSL

Modern "padding"

- Much more complicated encoding schemes using hashing, random salts, Feistel-like structures, etc.
- Common examples: OAEP for encryption, PSS for signing
- Progress driven largely by improvement in random oracle proofs

Simpler padding alternative

- "Key encapsulation mechanism" (KEM)
- For common case of public-key crypto used for symmetric-key setup
  - Also applies to DH
- Choose RSA message r at random mod n, symmetric key is $H(r)$

– Hard to retrofit, RSA-KEM insecure if e and r reused with different n

Box and locks revisited

- Alice and Bob's box scheme fails if an intermediary can set up two sets of boxes
- Real world analogue: challenges of protocol design and public key distribution

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Upcoming assignments

- HA2: can start registering groups
  - Send email to TA
  - Tell us even if same group as HA1
- Project progress report: due Wednesday 11/5
- Exercise set 3: due Thursday 11/6

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A couple more security goals

- Non-repudiation: principal cannot later deny having made a commitment
  - I.e., consider proving fact to a third party
- Forward secrecy: recovering later information does not reveal past information
  - Motivates using Diffie-Hellman to generate fresh keys for each session

Abstract protocols

- Outline of what information is communicated in messages
  - Omit most details of encoding, naming, sizes, choice of ciphers, etc.
- Describes honest operation
  - But must be secure against adversarial participants
- Seemingly simple, but many subtle problems

Protocol notation

$A \rightarrow B : N_B, \{T_0, B, N_B\}_{K_B}$

- $A \rightarrow B$: message sent from Alice intended for Bob
- B (after :): Bob's name
- $\{\cdots\}_K$: encryption with key K

Example: simple authentication

$A \rightarrow B : A, \{A, N\}_{K_A}$

- E.g., Alice is key fob, Bob is garage door
- Alice proves she possesses the pre-shared key K_A
  - Without revealing it directly
- Using encryption for authenticity and binding, not secrecy

Nonce

$A \rightarrow B : A, \{A, N\}_{K_A}$

- N is a *nonce*: a value chosen to make a message unique
- Best practice: pseudorandom
- In constrained systems, might be a counter or device-unique serial number

Replay attacks

- A nonce is needed to prevent a verbatim replay of a previous message
- Garage door difficulty: remembering previous nonces
  - Particularly: lunchtime/roommate/valet scenario
- Or, door chooses the nonce: *challenge-response* authentication

Man-in-the-middle attacks

- Gender neutral: middleperson attack
- Adversary impersonates Alice to Bob and vice-versa, relays messages
- Powerful position for both eavesdropping and modification
- No easy fix if Alice and Bob aren't already related

Chess grandmaster problem

- Variant or dual of MITM
- Adversary forwards messages to simulate capabilities with his own identity
- How to win at correspondence chess
- Anderson's MiG-in-the-middle

Needham-Schroeder

Authenticated key exchange assuming public keys (core):

$A \rightarrow B: \{N_A, A\}_{K_B}$
$B \rightarrow A: \{N_A, N_B\}_{K_A}$
$A \rightarrow B: \{N_B\}_{K_B}$

Needham-Schroeder MITM

$A \rightarrow C: \{N_A, A\}_{K_C}$
$C \rightarrow B: \{N_A, A\}_{K_B}$
$B \rightarrow C: \{N_A, N_B\}_{K_A}$
$C \rightarrow A: \{N_A, N_B\}_{K_A}$
$A \rightarrow C: \{N_B\}_{K_C}$
$C \rightarrow B: \{N_B\}_{K_B}$

Certificates, Denning-Sacco

- A certificate signed by a trusted third-party S binds an identity to a public key
  - $C_A = \mathsf{Sign}_S(A, K_A)$
- Suppose we want to use S in establishing a session key K_{AB}:

$A \rightarrow S: A, B$
$S \rightarrow A: C_A, C_B$
$A \rightarrow B: C_A, C_B, \{\mathsf{Sign}_A(K_{AB})\}_{K_B}$

Attack against Denning-Sacco

$A \rightarrow S: A, B$
$S \rightarrow A: C_A, C_B$
$A \rightarrow B: C_A, C_B, \{\mathsf{Sign}_A(K_{AB})\}_{K_B}$

$B \rightarrow S: B, C$
$S \rightarrow B: C_B, C_C$
$B \rightarrow C: C_A, C_C, \{\mathsf{Sign}_A(K_{AB})\}_{K_C}$

By re-encrypting the signed key, Bob can pretend to be Alice to Charlie

Envelopes analogy

- Encrypt then sign, or vice-versa?
- On paper, we usually sign inside an envelope, not outside. Two reasons:
  - Attacker gets letter, puts in his own envelope (c.f. attack against X.509)
  - Signer claims "didn't know what was in the envelope" (failure of non-repudiation)

Design robustness principles

- Use timestamps or nonces for freshness
- Be explicit about the context
- Don't trust the secrecy of others' secrets
- Whenever you sign or decrypt, beware of being an oracle
- Distinguish runs of a protocol

Implementation principles

- Ensure unique message types and parsing
- Design for ciphers and key sizes to change
- Limit information in outbound error messages
- Be careful with out-of-order messages

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Random numbers and entropy

- Cryptographic RNGs use cipher-like techniques to provide indistinguishability
- But rely on truly random seeding to stop brute force
  - Extreme case: no entropy $\rightarrow$ always same "randomness"
- Modern best practice: seed pool with 256 bits of entropy
  - Suitable for security levels up to 2^{256}

Netscape RNG failure

- Early versions of Netscape SSL (1994-1995) seeded with:
  - Time of day
  - Process ID
  - Parent process ID
- Best case entropy only 64 bits
  - (Not out of step with using 40-bit encryption)
- But worse because many bits guessable

Debian/OpenSSL RNG failure (1)

- OpenSSL has pretty good scheme using `/dev/urandom`
- Also mixed in some uninitialized variable values
  - "Extra variation can't hurt"
- From modern perspective, this was the original sin
  - Remember undefined behavior discussion?
- But had no immediate ill effects

Debian/OpenSSL RNG failure (2)

- Debian maintainer commented out some lines to fix a Valgrind warning
  - "Potential use of uninitialized value"
- Accidentally disabled most entropy (all but 16 bits)
- Brief mailing list discussion didn't lead to understanding
- Broken library used for ~2 years before discovery

Detected RSA/DSA collisions

- Up to about 1% of the SSL and SSH keys on the public net are breakable
  - Some sites share complete keypairs
  - RSA keys with one prime in common (detected by large-scale GCD)
- One likely culprit: insufficient entropy in key generation
  - Embedded devices, Linux `/dev/urandom` vs. `/dev/random`
- DSA signature algorithm also very vulnerable

Side-channel attacks

- Timing analysis:
  - Number of 1 bits in modular exponentiation
  - Unpadding, MAC checking, error handling
  - Probe cache state of AES table entries
- Power analysis
  - Especially useful against smartcards
- Fault injection
- Data non-erasure
  - Hard disks, "cold boot" on RAM

WEP "privacy"

- First WiFi encryption standard: Wired Equivalent Privacy (WEP)
- F&S: designed by a committee that contained no cryptographers
- Problem 1: note "privacy": what about integrity?
  - Nope: stream cipher + CRC = easy bit flipping

WEP shared key

- Single key known by all parties on network
- Easy to compromise
- Hard to change
- Also often disabled by default
- Example: a previous employer

WEP key size and IV size

- Original sizes: 40-bit shared key (export restrictions) plus 24-bit IV = 64-bit RC4 key
  - Both too small
- 128-bit upgrade kept 24-bit IV
  - Vague about how to choose IVs
  - Least bad: sequential, collision takes hours
  - Worse: random or everyone starts at zero

WEP RC4 related key attacks

- Only true crypto weakness
- RC4 "key schedule" vulnerable when:
  - RC4 keys very similar (e.g., same key, similar IV)
  - First stream bytes used
- Not a practical problem for other RC4 users like SSL
  - Key from a hash, skip first output bytes

Trustworthiness of primitives

- Classic worry: DES S-boxes
- Obviously in trouble if cipher chosen by your adversary
- In a public spec, most worrying are unexplained elements
- Best practice: choose constants from well-known math, like digits of π

Dual_EC_DRBG (1)

- Pseudorandom generator in NIST standard, based on elliptic curve
- Looks like provable (slow enough!) but strangely no proof
- Specification includes long unexplained constants
- Academic researchers find:
  - Some EC parts look good
  - But outputs are statistically distinguishable

Dual_EC_DRBG (2)

- Found 2007: special choice of constants allows prediction attacks
  - Big red flag for paranoid academics
- Significant adoption in products sold to US govt. FIPS-140 standards
  - Semi-plausible rationale from RSA (EMC)
- NSA scenario basically confirmed recently by Snowden leaks
  - NIST and RSA immediately recommend withdrawal

Next time

- Crypto in SSH, TLS, DNSSEC
- Public-key infrastructure