Operating Systems

21. Cryptographic Systems: An Introduction

Paul Krzyzanowski

Rutgers University

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Cryptography ≠ Security

Cryptography may be a component of a secure system

Adding cryptography may not make a system secure

Cryptography: what is it good for?

- Authentication
  - determine origin of message
- Integrity
  - verify that message has not been modified
- Nonrepudiation
  - sender should not be able to falsely deny that a message was sent
- Confidentiality
  - others cannot read contents of the message

Terms

Plaintext (cleartext) message P

Encryption *E(*P*)*

Produces Ciphertext, C = *E(*P*)*

Decryption, P = *D(*C*)*

Cipher = cryptographic algorithm

Terms: types of ciphers

- Types
  - restricted cipher
  - symmetric algorithm
  - public key algorithm
- Stream vs. Block
  - Stream cipher
    - Encrypt a message a character at a time
  - Block cipher
    - Encrypt a message a chunk at a time

Restricted cipher

Secret algorithm

- Vulnerable to:
  - Leaking
  - Reverse engineering
    - HD DVD (Dec 2006) and Blu-Ray (Jan 2007)
    - RC4
    - All digital cellular encryption algorithms
    - DVD and DIVX video compression
    - Firewire
    - Enigma cipher machine
    - Every NATO and Warsaw Pact algorithm during Cold War
- Hard to validate its effectiveness (who will test it?)
- Not a viable approach!

Symmetric-key algorithm

- Same secret key, K, for encryption & decryption

$$C = E_K(P) \quad P = D_K(C)$$

- Examples: AES, 3DES, IDEA, RC5
- Key length
  - Determines number of possible keys
    - DES: 56-bit key: $2^{56} = 7.2 \times 10^{16}$ keys
    - AES-256: 256-bit key: $2^{256} = 1.1 \times 10^{77}$ keys
  - *Brute force attack*: try all keys

The power of 2

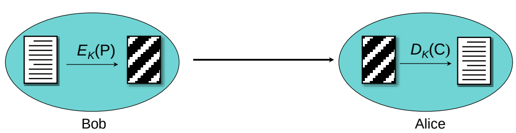
- Adding one extra bit to a key doubles the search space.
- Suppose it takes 1 second to search through all keys with a 20-bit key

key length	number of keys	search time
20 bits	1,048,576	1 second
21 bits	2,097,152	2 seconds
32 bits	4.3×10^9	~ 1 hour
56 bits	7.2×10^{16}	2,178 years
64 bits	1.8×10^{19}	> 557,000 years
256 bits	1.2×10^{77}	3.5×10^{63} years

Distributed & custom hardware efforts typically allow us to search between 1 and >100 billion 64-bit (e.g., RC5) keys per second

Communicating with symmetric cryptography

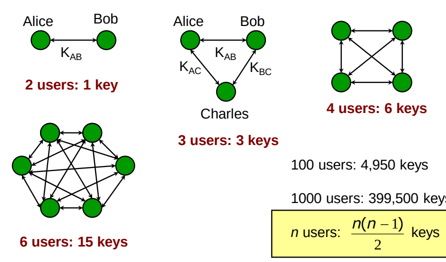
- Both parties must agree on a secret key, K
- Message is encrypted, sent, decrypted at other side



- Key distribution must be secret
  - otherwise messages can be decrypted
  - users can be impersonated

Key explosion

Each pair of users needs a separate key for secure communication



100 users: 4,950 keys

1000 users: 399,500 keys

n users: $\frac{n(n-1)}{2}$ keys

Key distribution

Secure key distribution is the biggest problem with symmetric cryptography

Public-key algorithm

- Two related keys.

$$C = E_{K1}(P) \quad P = D_{K2}(C)$$
$$C' = E_{K2}(P) \quad P = D_{K1}(C')$$

K_1 is a public key
K_2 is a private key

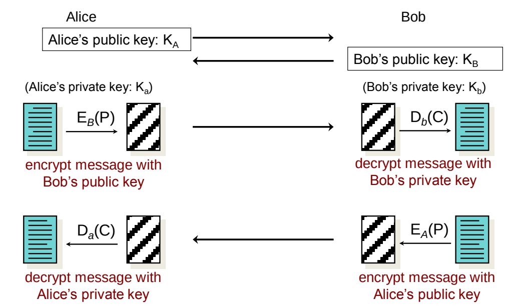
- Examples:
  - RSA, Elliptic curve algorithms
    DSS (digital signature standard),
    Diffie-Hellman (key exchange only!)
- Key length
  - Unlike symmetric cryptography, not every number is a valid key
  - 3072-bit RSA = 256-bit elliptic curve = 128-bit symmetric cipher
  - 15360-bit RSA = 521-bit elliptic curve = 256-bit symmetric cipher

Communication with public key algorithms

Different keys for encrypting and decrypting

- No need to worry about key distribution

Communication with public key algorithms



Hybrid Cryptosystems

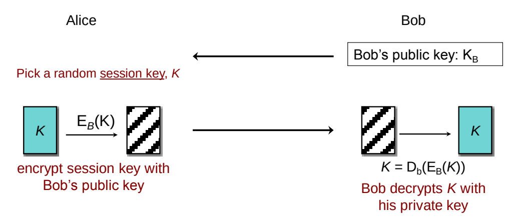
Session key: randomly-generated key for one communication session

- Use a public key algorithm to send the session key
- Use a symmetric algorithm to encrypt data with the session key

Public key algorithms are almost never used to encrypt messages

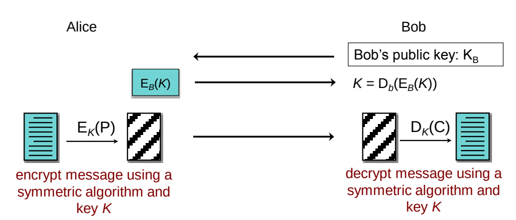
- MUCH slower; vulnerable to *chosen-plaintext attacks*
- RSA-2048 approximately 55x slower to encrypt and 2000x slower to decrypt than AES-256.

Communication with a hybrid cryptosystem

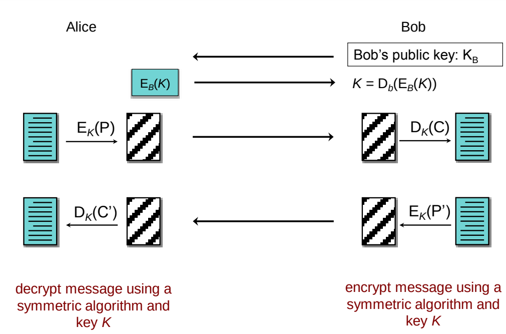


Now Bob knows the secret session key, K

Communication with a hybrid cryptosystem



Communication with a hybrid cryptosystem



Message Integrity & Authentication

One-way functions

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

Examples:

Factoring:

$pq = N$	EASY
find p,q given N	DIFFICULT

Discrete Log:

$a^b \bmod c = N$	EASY
find b given a, c, N	DIFFICULT

Example of a one-way function

Example with an 18 digit number

A = 289407349786637777

A^2 = 83756614110525308948445338203501729

Middle square, B = 110525308948445338

Given A, it is easy to compute B

Given B, it is difficult to compute A

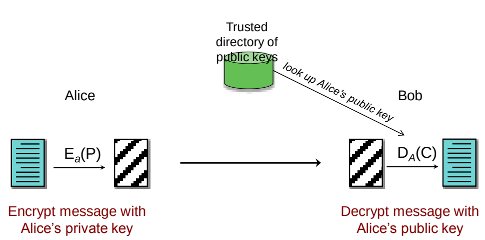
"Difficult" = no known short-cuts; requires an exhaustive search

Message Integrity: Digital Signatures

- Validate the creator (signer) of the content
- Validate the the content has not been modified since it was signed
- The content itself does not have to be encrypted

Digital Signatures: Public Key Cryptography

Encrypting a message with a private key is the same as signing it!



But…

- Not quite what we want
  - We don't want to permute or hide the content
  - We just want Bob to verify that the content came from Alice
- Moreover...
  - Public key cryptography is much slower than symmetric encryption
  - What if Alice sent Bob a multi-GB file – she didn't want to encrypt it but wants Bob to be able to validate that it hasn't been modified

Hashes to the rescue!

- Cryptographic hash function (also known as a digest)
  - Input: arbitrary data
  - Output: fixed-length bit string
- Properties
  - **One-way function**
    - Given *H=hash(M)*, it should be difficult to compute *M*, given *H*
  - **Collision resistant**
    - Given *H=hash(M)*, it should be difficult to find *M'*, such that *H=hash(M')*
    - For a hash of length L, a perfect hash would take $2^{(L/2)}$ attempts
  - **Efficient**
    - Computing a hash function should be computationally efficient

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Popular hash functions

- SHA-2
  - 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-3
  - NIST standardization still in progress
- MD5
  - 128 bits (not often used now since weaknesses were found)
- Derivations from ciphers:
  - Blowfish (used for password hashing in OpenBSD)
  - 3DES – used for old Linux password hashes

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Digital signatures using hash functions

- You do this to create a signature:
  - Create a hash of the message
  - Encrypt the hash with <u>your private key</u> & send it with the message
- Recipient does this to validate the message:
  - Decrypts the encrypted hash using your public key
  - Computes the hash of the received message
  - Compares the decrypted hash with the message hash
  - If they're the same then the message has not been modified

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Digital signatures: public key cryptography

Alice generates a hash of the message

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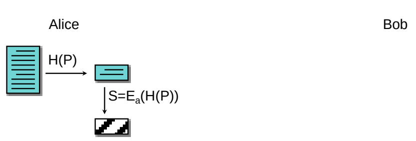
Digital signatures: public key cryptography



Alice encrypts the hash with her private key
This is her **<u>signature</u>**.

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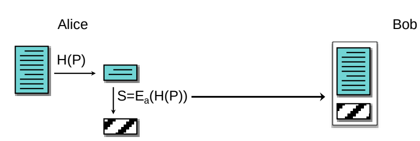
Digital signatures: public key cryptography



Alice sends Bob the message & the encrypted hash

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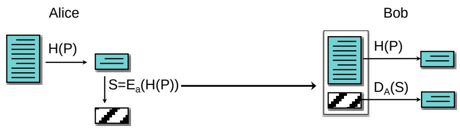
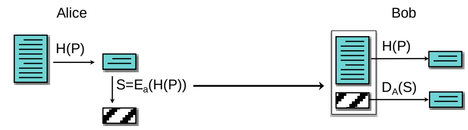
Digital signatures: public key cryptography



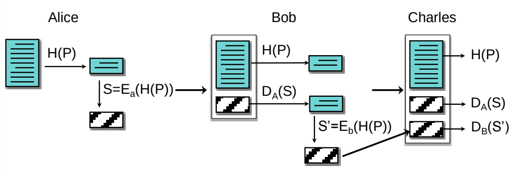
1. Bob decrypts the hash using Alice's public key
2. Bob computes the hash of the message sent by Alice

Digital signatures: public key cryptography



If the hashes match, the signature is valid
– the encrypted hash *must* have been generated by Alice

Digital signatures: multiple signers



Charles:
- Generates a hash of the message, H(P)
- Decrypts Alice's signature with Alice's public key
  - Validates the signature: $D_A(S) \stackrel{?}{=} H(P)$
- Decrypts Bob's signature with Bob's public key
  - Validates the signature: $D_B(S) \stackrel{?}{=} H(P)$

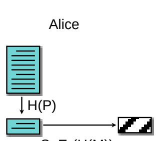
Covert AND authenticated messaging

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

Use a session key:

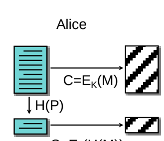
- Pick a random key, *K*, to encrypt the message with a symmetric algorithm
- encrypt *K* with the public key of each recipient
- for signing, encrypt the hash of the message with sender's private key

Covert and authenticated messaging



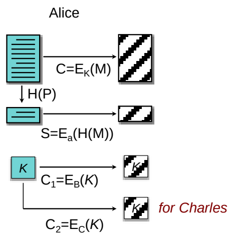
Alice generates a digital signature by encrypting the message with her private key

Covert and authenticated messaging



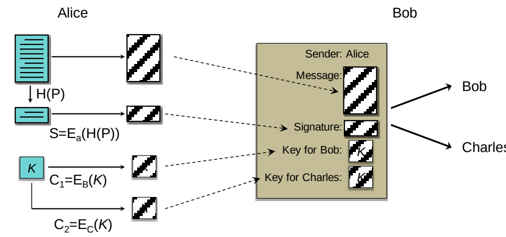
Alice picks a random key, *K*, and encrypts the message *P* with it using a symmetric cipher

Covert and authenticated messaging



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

Covert and authenticated messaging



The aggregate message is sent to Bob & Charles

Cryptographic toolbox

- Symmetric encryption
- Public key encryption
- One-way hash functions
- Random number generators

The End