Operating Systems

21. Cryptographic Systems: An Introduction

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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

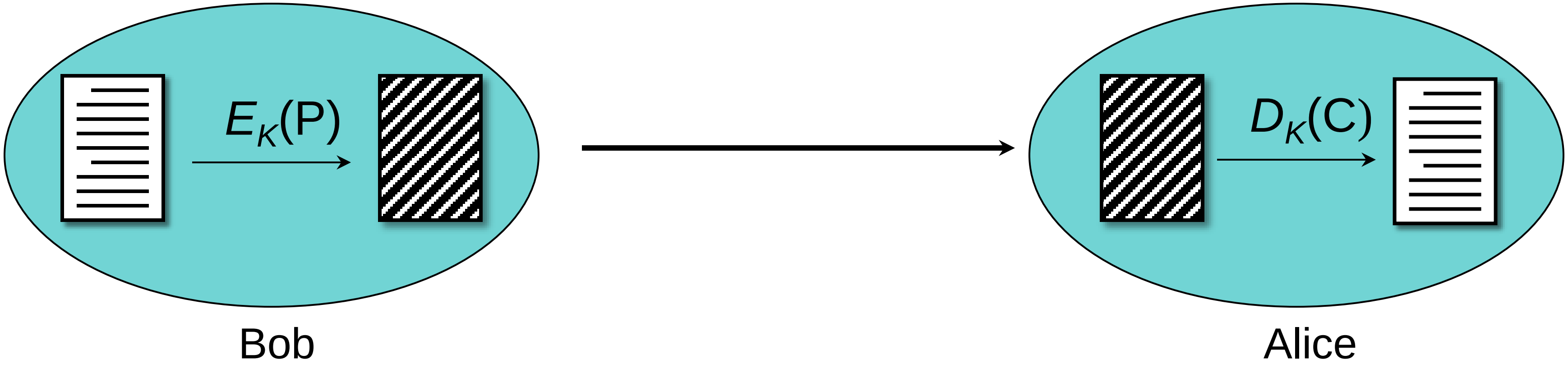
- Adding one extra bit to a key doubles the search space.
- Suppose it takes 1 second to search through all keys with a 20-bit key

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

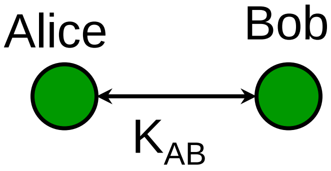
- Both parties must agree on a secret key, *K*
- Message is encrypted, sent, decrypted at other side



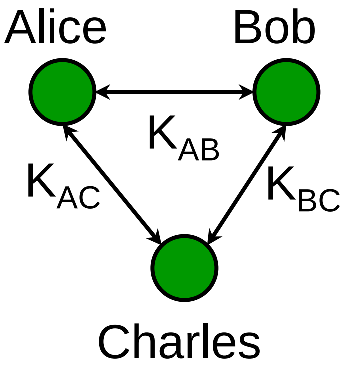
- Key distribution must be secret
  - – otherwise messages can be decrypted
  - – users can be impersonated

Key explosion

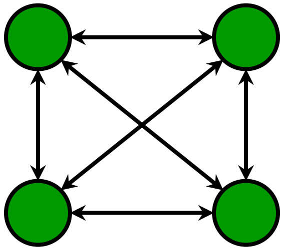
Each pair of users needs a separate key for secure communication



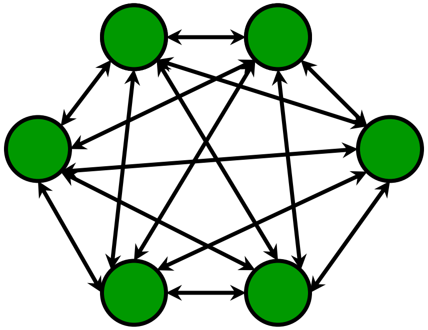
2 users: 1 key



3 users: 3 keys



4 users: 6 keys



6 users: 15 keys

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.

$$\left.\begin{array}{ll} C = E_{K1}(P) & P = D_{K2}(C) \\ C' = E_{K2}(P) & P = D_{K1}(C') \end{array}\right]$$

K_1 is a public key

K_2 is a private key

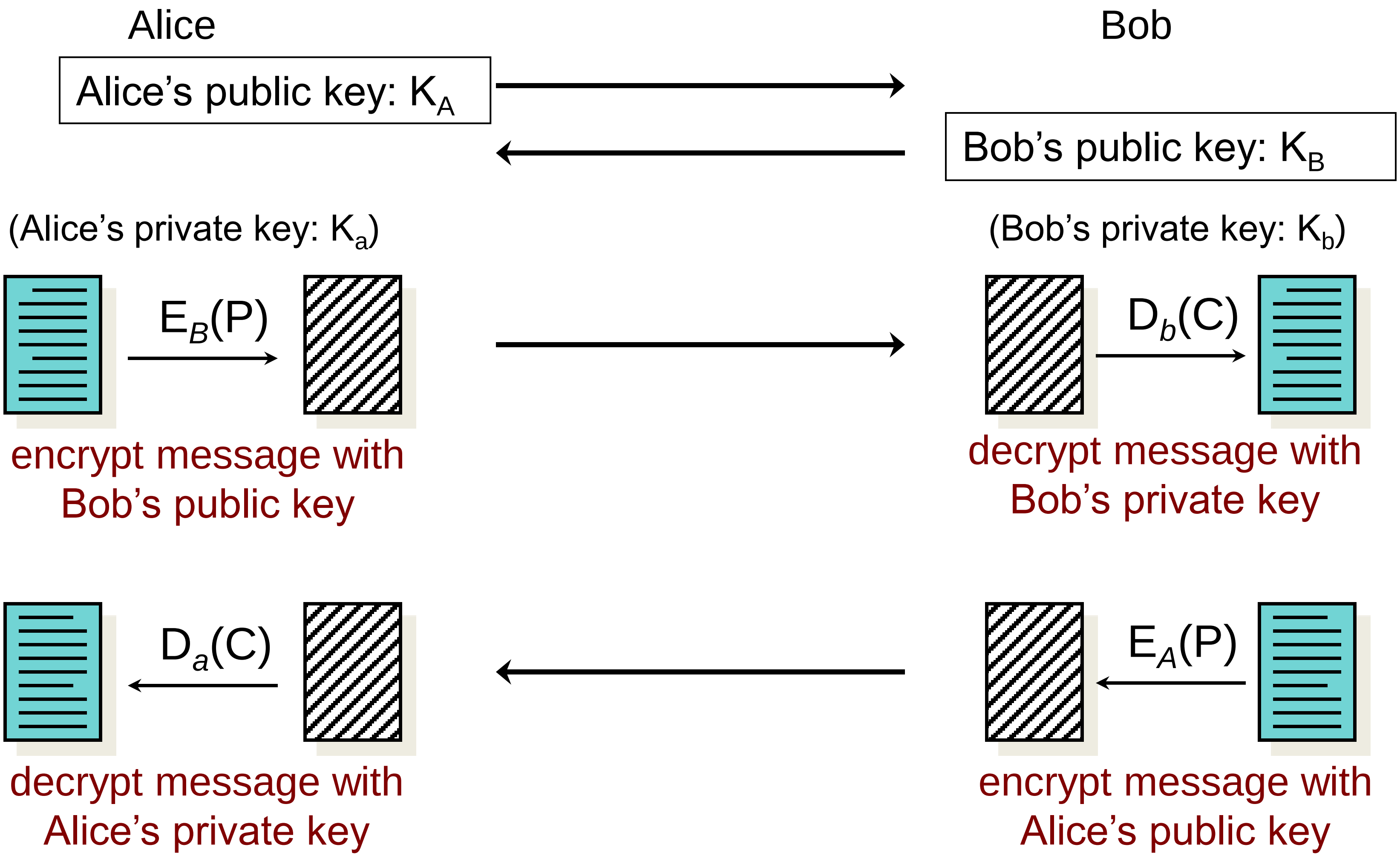
- Examples:
  - RSA, Elliptic curve algorithms
    DSS (digital signature standard),
    Diffie-Hellman (key exchange only!)
- Key length
  - Unlike symmetric cryptography, not every number is a valid key
  - 3072-bit RSA = 256-bit elliptic curve = 128-bit symmetric cipher
  - 15360-bit RSA = 521-bit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



Alice

Bob

Alice's public key: K_A

Bob's public key: K_B

(Alice's private key: K_a)

(Bob's private key: K_b)

$E_B(P)$

encrypt message with Bob's public key

$D_b(C)$

decrypt message with Bob's private key

$D_a(C)$

decrypt message with Alice's private key

$E_A(P)$

encrypt message with Alice's public key

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

Alice

Bob

Bob's public key: K_B

Pick a random session key, *K*

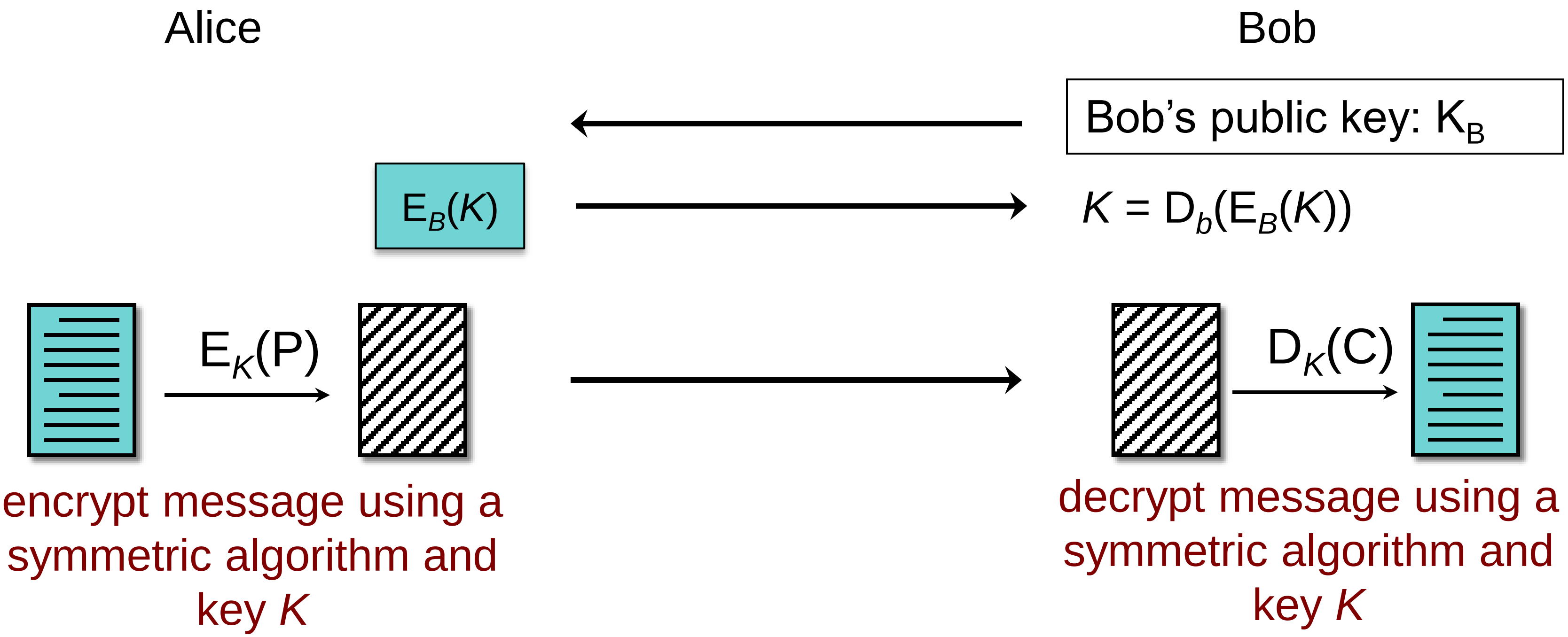
encrypt session key with Bob's public key

$K = D_b(E_B(K))$

Bob decrypts *K* with his private key

Now Bob knows the secret session key, K

Communication with a hybrid cryptosystem



Alice

Bob

Bob's public key: K_B

$E_B(K)$

$K = D_b(E_B(K))$

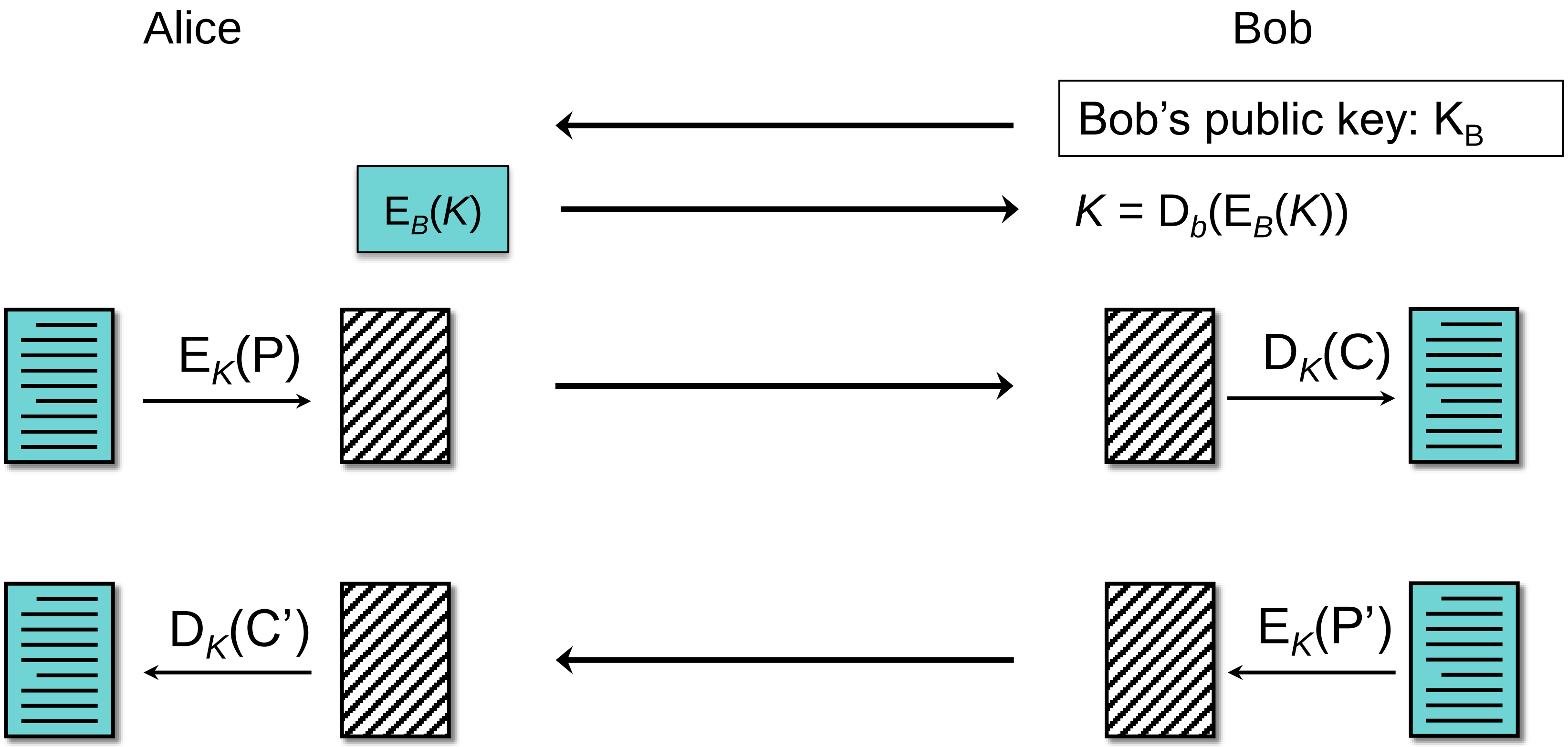
$E_K(P)$

$D_K(C)$

encrypt message using a symmetric algorithm and key *K*

decrypt message using a symmetric algorithm and key *K*

Communication with a hybrid cryptosystem



Alice

Bob

Bob’s public key: K_B

$E_B(K)$

$K = D_b(E_B(K))$

$E_K(P)$

$D_K(C)$

$D_K(C')$

$E_K(P')$

decrypt message using a symmetric algorithm and key *K*

encrypt message using a symmetric algorithm and key *K*

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

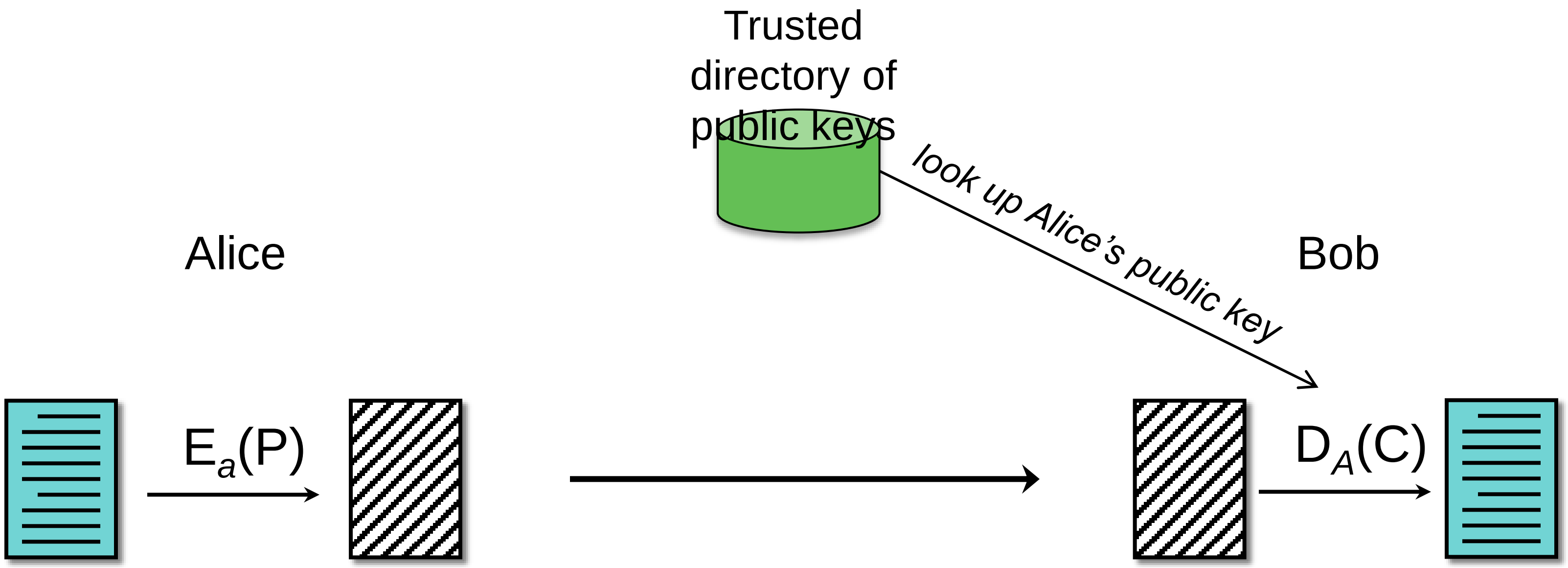
"Difficult" = no known short-cuts; requires an exhaustive search

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!



Trusted directory of public keys

look up Alice's public key

Alice

Bob

$E_a(P)$

$D_A(C)$

Encrypt message with Alice's private key

Decrypt message with Alice's public key

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

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

Digital signatures using hash functions

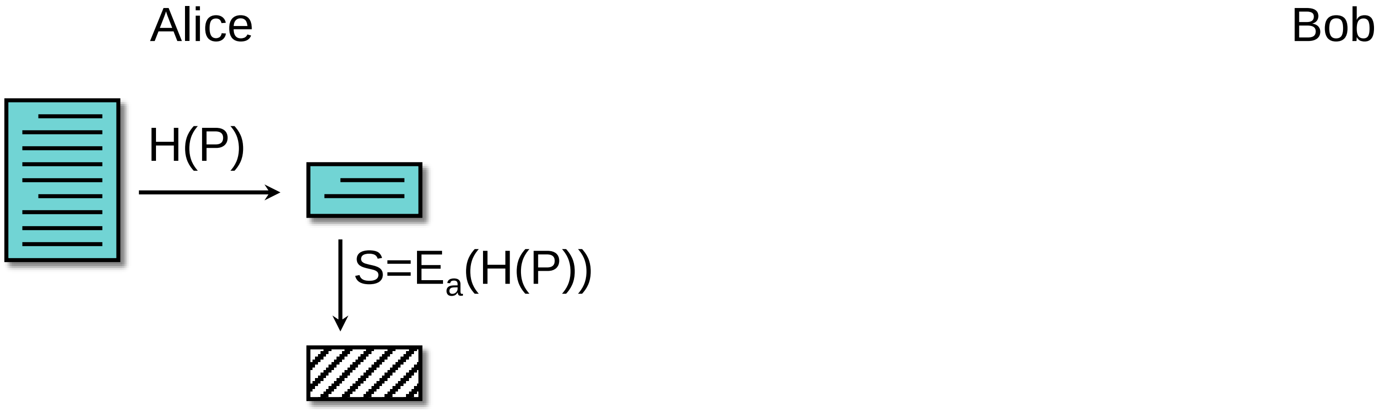
- You do this to create a signature:
  - Create a hash of the message
  - Encrypt the hash with your private key & send it with the message

- 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

Digital signatures: public key cryptography

Alice generates a hash of the message

Digital signatures: public key cryptography



Alice

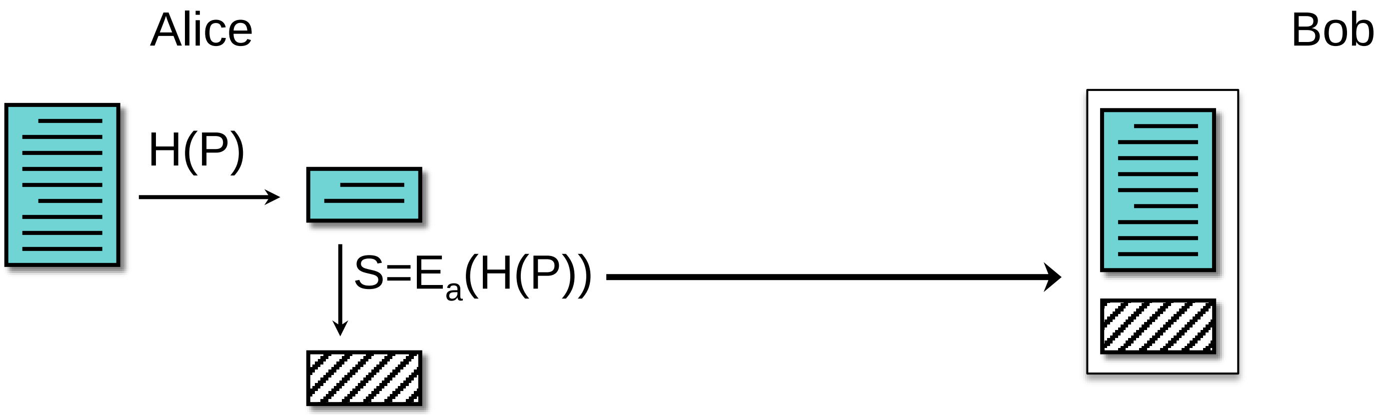
Bob

H(P)

$S=E_a(H(P))$

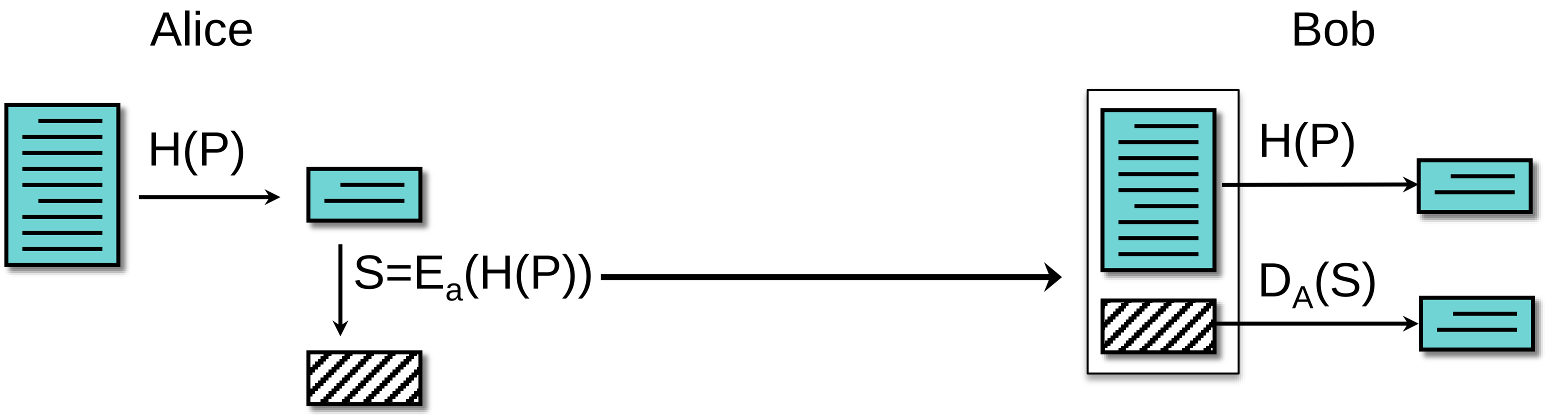
Alice encrypts the hash with her private key
This is her **signature.**

Digital signatures: public key cryptography



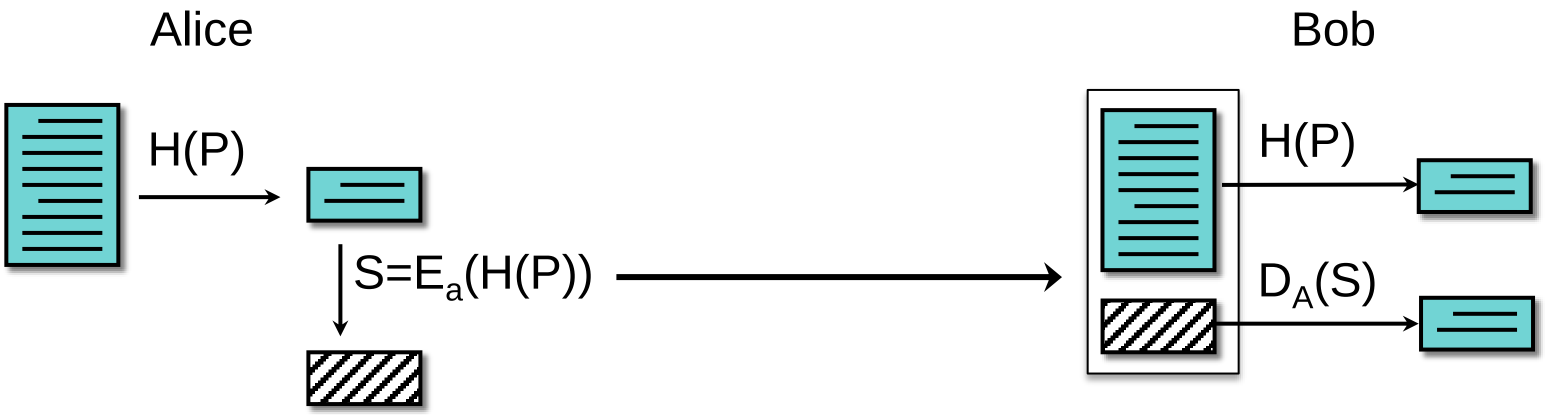
Alice sends Bob the message & the encrypted hash

Digital signatures: public key cryptography



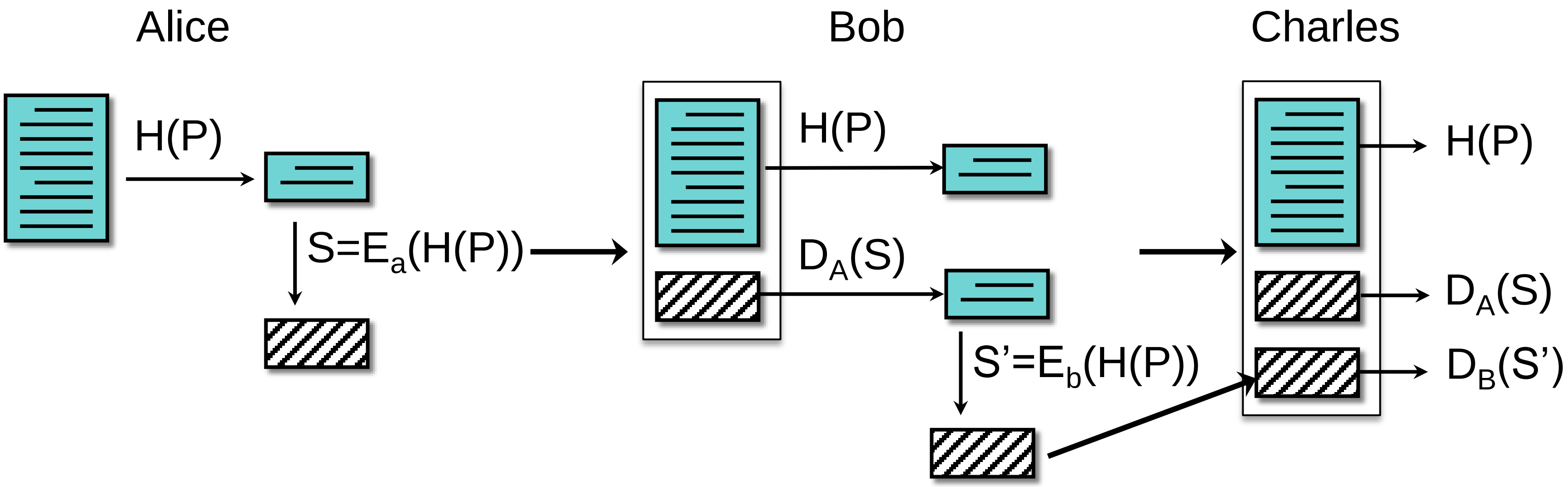
1. Bob decrypts the hash using Alice's public key
2. Bob computes the hash of the message sent by Alice

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: $D_A(S) \overset{?}{=} H(P)$
- Decrypts Bob's signature with Bob's public key
  - Validates the signature: $D_B(S) \overset{?}{=} H(P)$

Covert AND authenticated messaging

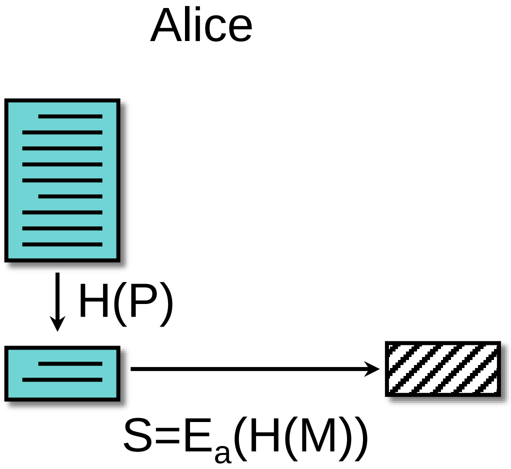
If we want to keep the message secret

- combine encryption with a digital signature

Use a session key:

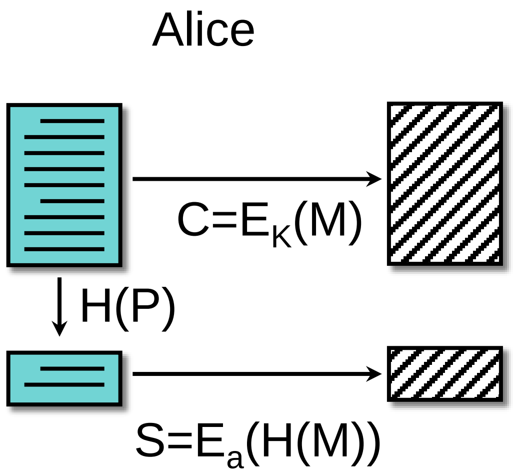
- Pick a random key, *K*, to encrypt the message with a symmetric algorithm
- encrypt *K* with the public key of each recipient
- for signing, encrypt the hash of the message with sender's private key

Covert and authenticated messaging



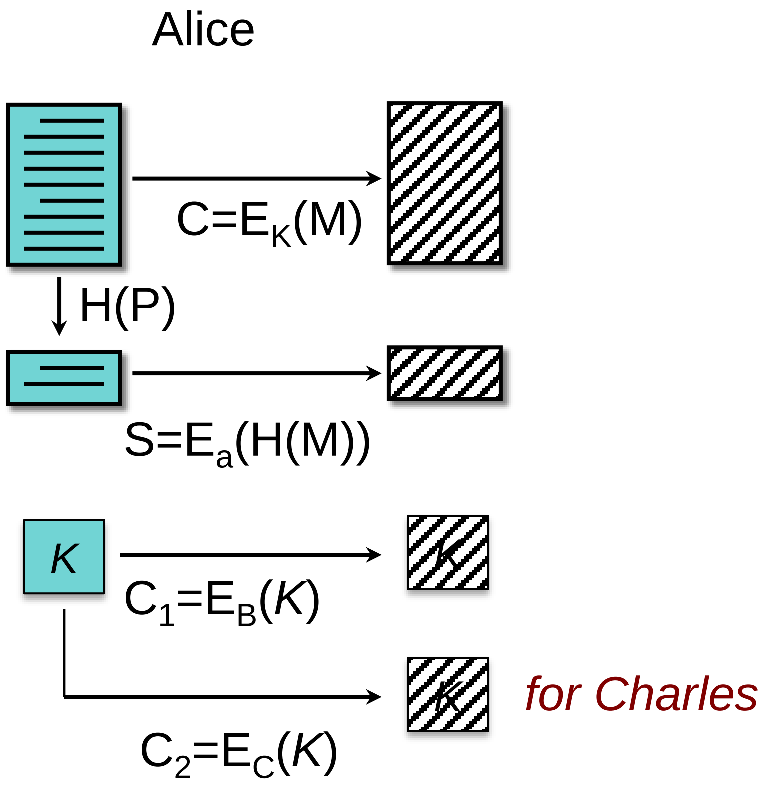
Alice generates a digital signature by
encrypting the message with her private key

Covert and authenticated messaging



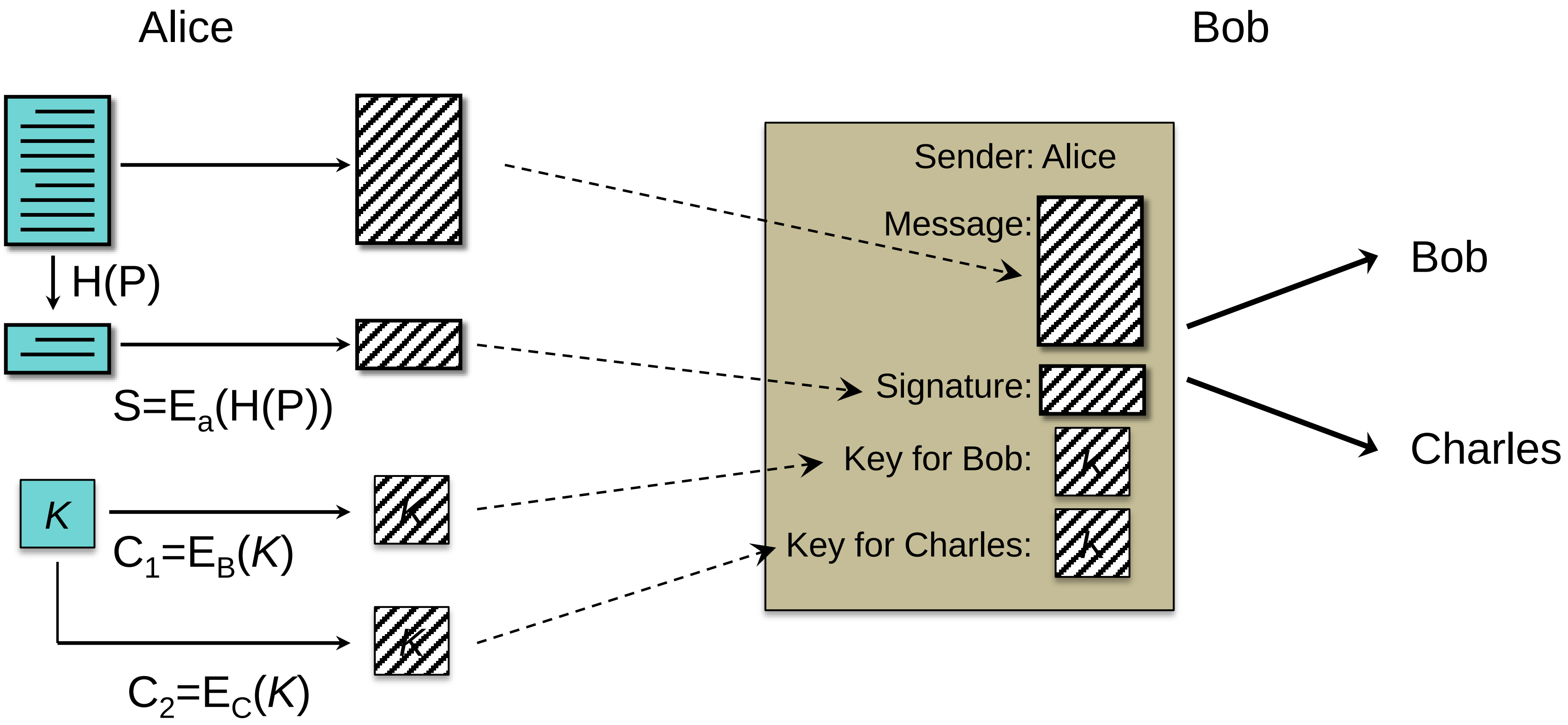
Alice picks a random key, *K*, and encrypts the message *P* with it using a symmetric cipher

Covert and authenticated messaging



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

Covert and authenticated messaging



Alice

Bob

H(P)

$S=E_a(H(P))$

K

$C_1=E_B(K)$

$C_2=E_C(K)$

Sender: Alice

Message:

Signature:

Key for Bob:

Key for Charles:

Bob

Charles

The aggregate message is sent to Bob & Charles

Cryptographic toolbox

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

The End