Lec 10: Cryptography (2)

CSED415: Computer Security

Spring 2026

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POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Cryptography roadmap

Goal \ Scheme	Symmetric Key	Asymmetric Key Today's topic
Confidentiality	✅ One Time Pad (OTP) ✅ Block ciphers (DES, AES) ✅ Stream ciphers	• DH secure key exchange • ElGamal encryption • RSA encryption
Integrity & Authentication	• Message Authentication Code (MAC)	• Digital signature + CA

Secure Key Exchange (Diffie-Hellman)

Key sharing problem

- Symmetric key cryptography assumes that Alice and Bob already share a secret key k
- Circular dependency:
  - To communicate securely, we can use symmetric encryption with shared key k
  - To share k securely, we need symmetric encryption
  - However, symmetric encryption does not work without a shared k

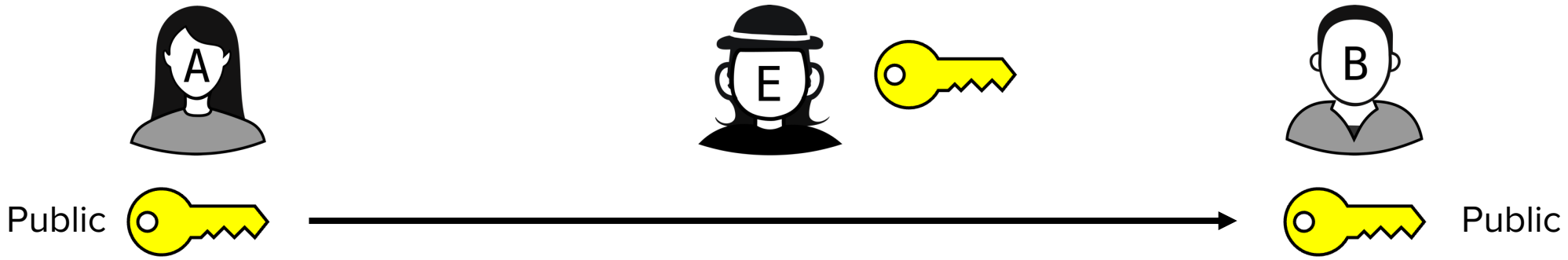
A secure key exchange algorithm is needed

Diffie-Hellman (DH) key exchange

- Named after Whitfield Diffie and Martin Hellman
- Key idea:
  - Both parties mathematically derive a shared secret key, rather than sending it directly

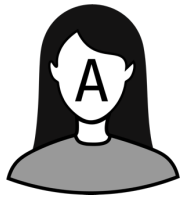
Intuitive example: Colored keys

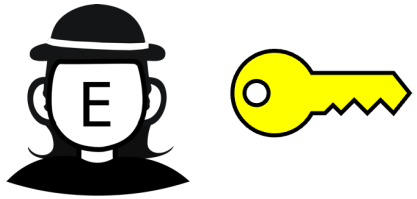
1. Alice shares a yellow key (public key) with Bob (and Eve)

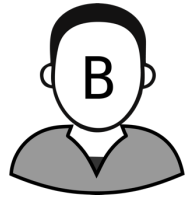


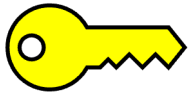
Intuitive example: Colored keys

2. Alice and Bob each select their own colored key (secret key) and keep it private

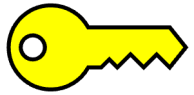


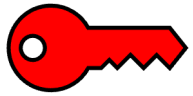




Public 

Alice's secret 

 Public

 Bob's secret

Intuitive example: Colored keys

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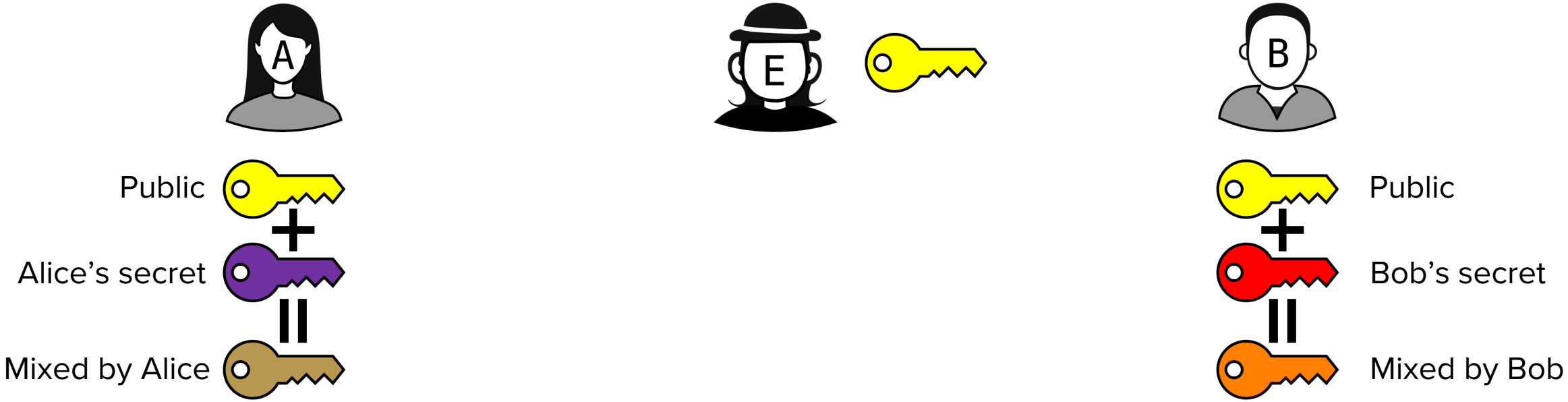
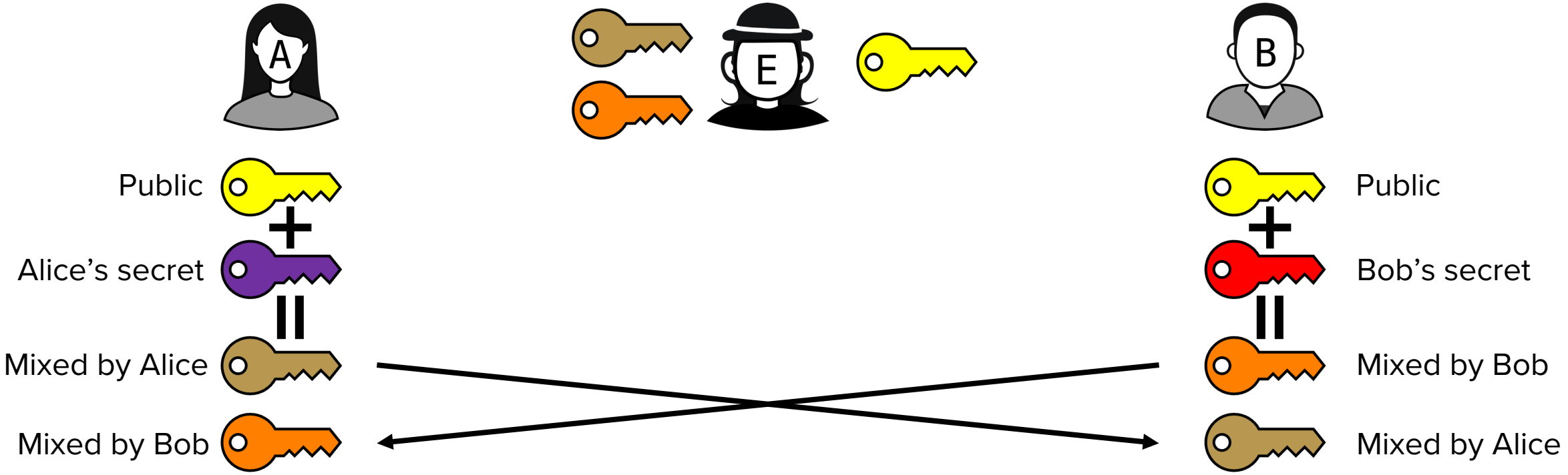
3. Alice and Bob each mix the colors of the public key with their own secret key to generate mixed keys



Intuitive example: Colored keys

4. Alice and Bob exchange the mixed keys
   - Eve can observe the mixed keys



Intuitive example: Colored keys

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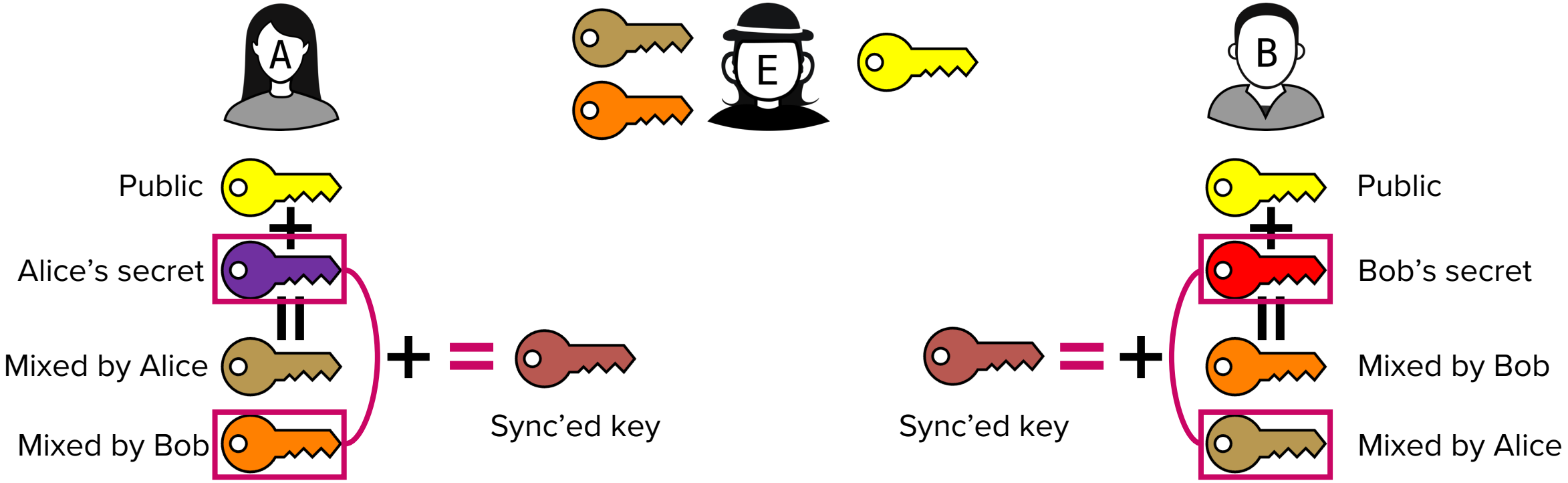
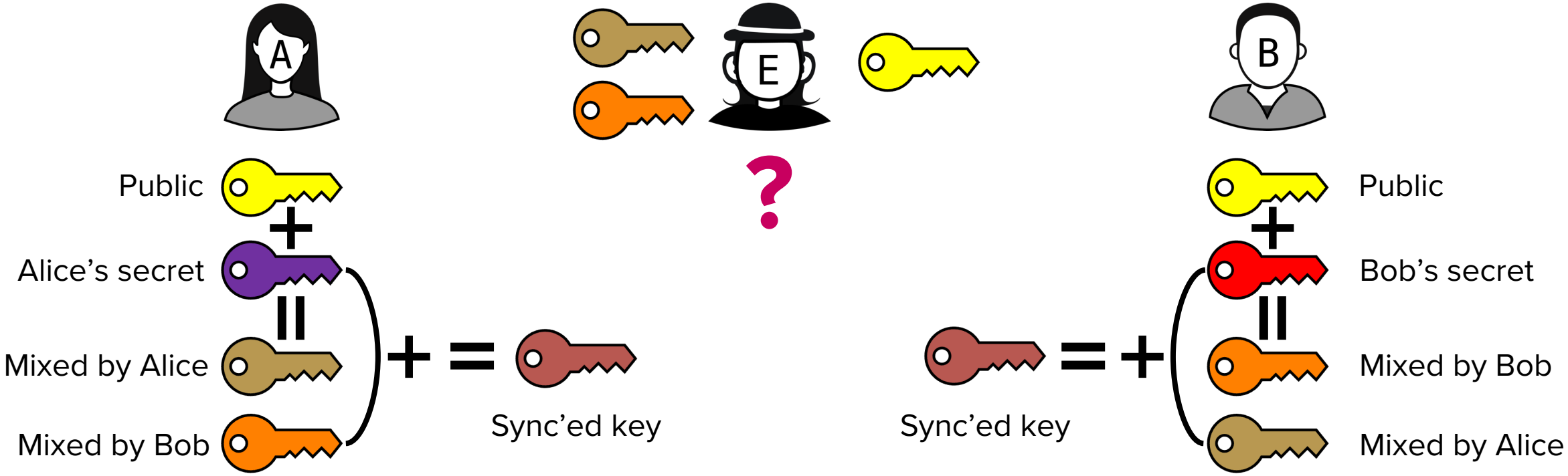
5. Finally, each party mixes the received mixed key with its own secret key, deriving an identical shared (synchronized) key



Intuitive example: Colored keys

6. However, Eve cannot derive the synchronized key without knowing Alice's or Bob's secret keys



Intuitive example: Colored keys

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6. However, Eve cannot derive the synchronized key without knowing Alice's or Bob's secret keys

Some operations are easy to perform in one direction but extremely hard to reverse

Easy:  **Hard:** 

Background: Number theory

- Greatest common denominator $d = \gcd(a, b)$:
  - Largest integer d such that d divides a and d divides b
- Relatively prime (or, coprime)
  - If $\gcd(a, b) = 1$, then a and b are relatively prime
    - Is 15 relatively prime to 28? Yes. $\gcd(15,28) = 1$
    - Is 14 and 49 relatively prime? No. $\gcd(14,49) = 7$
    - Are 23 and 443 coprime? Yes. Two prime numbers are always coprime
      - Hint: 23 and 443 are prime numbers

Diffie-Hellman key exchange

1. Choose a prime num p and its generator g such that $g < p$
   - Both p and g are shared (public keys)
   - g is a generator of p if $g^k \ mod \ p$ can take any value in $[1, \dots, p-1]$
   - Example: $p = 11$

$g^k \ mod \ p$	$i=0$	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$	$i=7$	$i=8$	$i=9$	10	Generator?
$2^i \ mod \ 11$	1	2	4	8	5	10	9	7	3	6	1	Y
$3^i \ mod \ 11$	1	3	9	5	4	1	3	9	5	4	1	N
$4^i \ mod \ 11$	1	4	5	9	3	1	4	5	9	3	1	N
$5^i \ mod \ 11$	1	5	3	4	9	1	5	3	4	9	1	N
$6^i \ mod \ 11$	1	6	3	7	9	10	5	8	4	2	1	Y
…												

→ We can select $g = 6$

Diffie-Hellman key exchange

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2. Alice and Bob each choose a secret key
   - Assume Alice's secret key $a = 15$ and Bob's secret key $b = 8$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$

Diffie-Hellman key exchange

2. Alice and Bob each choose a secret key
   - Assume Alice's secret key $a = 15$ and Bob's secret key $b = 8$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$

3. Alice and Bob compute $g^x \ mod \ p$ where x is the secret key
   - Alice's mixed key $A = g^a \ mod \ p = 6^{15} \ mod \ 11$
   - Bob's mixed key $B = g^b \ mod \ p = 6^8 \ mod \ 11$

→ Too large to be calculated by hand?

Diffie-Hellman key exchange

- Note: Modular exponentiation
  - We can compute $x^y \ mod \ n$ by breaking y down into powers of 2
  - e.g., $6^{15} \ mod \ 11$ → 15 = 8 + 4 + 2 + 1
    - $6^{15} = 6^8 \times 6^4 \times 6^2 \times 6^1$
    - $6^1 \ mod \ 11 = 6$
    - $6^2 \ mod \ 11 = 36 \ mod \ 11 = 3$
    - $6^4 \ mod \ 11 = (6^2)^2 \ mod \ 11 = 3^2 \ mod \ 11 = 9$
    - $6^8 \ mod \ 11 = (6^4)^2 \ mod \ 11 = 9^2 \ mod \ 11 = 81 \ mod \ 11 = 4$
    - Thus, $6^{15} \ mod \ 11 = (4 \times 9 \times 3 \times 6) \ mod \ 11 = 648 \ mod \ 11 = 10$

Diffie-Hellman key exchange

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   - Assume Alice's secret key $a = 15$ and Bob's secret key $b = 8$

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3. Alice and Bob compute $g^x \ mod \ p$ where x is the secret key
   - Alice's mixed key $A = g^a \ mod \ p = 6^{15} \ mod \ 11 = 10$
   - Bob's mixed key $B = g^b \ mod \ p = 6^8 \ mod \ 11 = 4$

Modular exponentiation!

Diffie-Hellman key exchange

4. Alice and Bob exchange their mixed keys
   - $A = 6^{15} \ mod \ 11 = 10$
   - $B = 6^{8} \ mod \ 11 = 4$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	
$B = 4$	

Diffie-Hellman key exchange

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5. Alice and Bob then can generate a common shared key k by raising the exchanged mixed key to their respective secret keys
   - Alice: $k = B^a \ mod \ p = 4^{15} \ mod \ 11$
   - Bob: $k = A^b \ mod \ p = 10^8 \ mod \ 11$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	
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Diffie-Hellman key exchange

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Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	
$B = 4$	

$$4^{15} \ mod \ 11 = 4^8 \times 4^4 \times 4^2 \times 4 \ mod \ 11$$

$$4 \ mod \ 11 = 4$$
$$4^2 \ mod \ 11 = 16 \ mod \ 11 = 5$$
$$4^4 \ mod \ 11 = (4^2)^2 \ mod \ 11 = 5^2 \ mod \ 11 = 25 \ mod \ 11 = 3$$
$$4^8 \ mod \ 11 = (4^4)^2 \ mod \ 11 = 9 \ mod \ 11 = 9$$

Diffie-Hellman key exchange

5. Alice and Bob then can generate a common shared key k by raising the exchanged mixed key to their respective secret keys
   - Alice: $k = B^a \ mod \ p = 4^{15} \ mod \ 11 = 1$
   - Bob: $k = A^b \ mod \ p = 10^8 \ mod \ 11$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	
$B = 4$	

$$4^{15} \ mod \ 11 = 4^8 \times 4^4 \times 4^2 \times 4 \ mod \ 11 = 9 \times 3 \times 5 \times 4 \ mod \ 11 = 1$$

$$4 \ mod \ 11 = 4$$
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Diffie-Hellman key exchange

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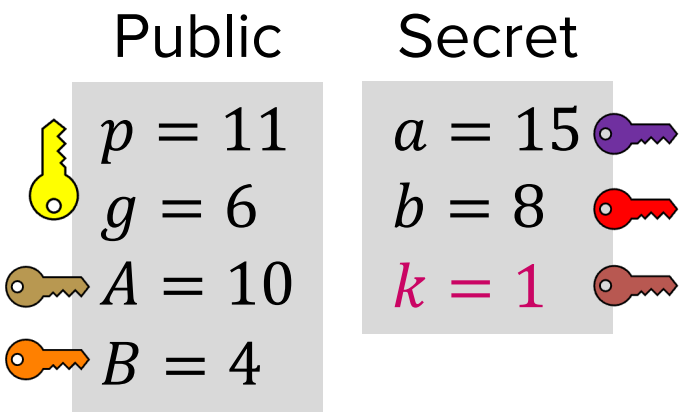
   - Alice: $k = B^a \ mod \ p = 4^{15} \ mod \ 11 = 1$
   - Bob: $k = A^b \ mod \ p = 10^8 \ mod \ 11 = 1$

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	
$B = 4$	

$$10 \ mod \ 11 \equiv -1 \ mod \ 11$$
$$10^8 \ mod \ 11 = (-1)^8 \ mod \ 11 = 1 \ mod \ 11 = 1$$

Diffie-Hellman key exchange

5. Alice and Bob then can generate a common shared key k by raising the exchanged mixed key to their respective secret keys
   - Alice: $k = B^a \ mod \ p = 4^{15} \ mod \ 11 = 1$
   - Bob: $k = A^b \ mod \ p = 10^8 \ mod \ 11 = 1$



Alice and Bob have successfully generated a shared secret key k

Diffie-Hellman key exchange

- Q) Can Eve derive the shared secret key?
  - Problem that Eve needs to solve:
    - Given p, g, A, and B, find a, b, and k such that $A^b \ mod \ p = B^a \ mod \ p = k$.
  - Discrete log problem (DLP):
    - Given p, g, and $B = g^a \ mod \ p$, it is computationally difficult to find a, especially for large prime number p
      - e.g., $g^a \ mod \ p = 6^a \ mod \ 11 = 4$ → Can you find a?
      - How about $43^a \ mod \ 17014118346046923173168730371588410572 7 = 107658615995071204650478536027214115641$?

Public	Secret
$p = 11$	$a = 15$
$g = 6$	$b = 8$
$A = 10$	$k = 1$
$B = 4$	

Generalization of Diffie-Hellman key exchange

- A large prime p and a generator g are shared

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- Mixing:
  - Alice chooses a secret integer a and computes $A = g^a \ mod \ p$
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- Deducing the shared secret:
  - Alice computes $k = B^a \ mod \ p = \left(g^b\right)^a \ mod \ p = g^{ab} \ mod \ p$
  - Bob computes $k = A^b \ mod \ p = (g^a)^b \ mod \ p = g^{ab} \ mod \ p$

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  - Bob computes $k = A^b \ mod \ p = (g^a)^b \ mod \ p = g^{ab} \ mod \ p$
- Eve knows p, g, A, and B
  - Eve cannot feasibly solve DLP to compute a nor b if p is large

Generalization of Diffie-Hellman key exchange

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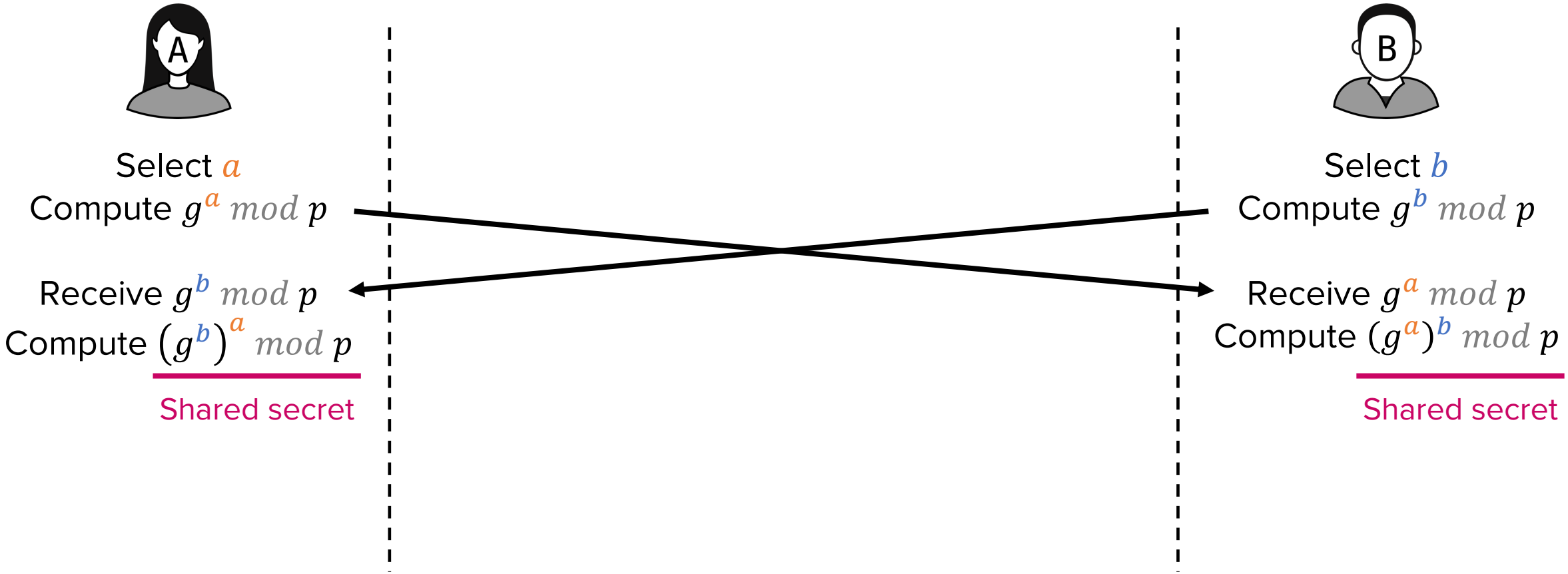
- A large prime p and a generator g are shared
- Mixing:

DH is secure against passive attacks

- Eve knows p, g, A, and B
  - Eve cannot feasibly solve DLP to compute a nor b if p is large

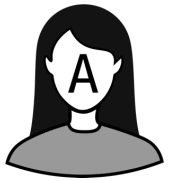
Diffie-Hellman key exchange

- Intended key exchange procedure



Diffie-Hellman – Man in the Middle (MitM) attack

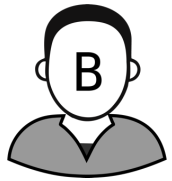
- What if Mallory actively alters key exchange messages?



Select a
Compute $g^a \ mod \ p$

MitM

Select m
Compute $g^m \ mod \ p$



Select b
Compute $g^b \ mod \ p$

Diffie-Hellman – Man in the Middle (MitM) attack

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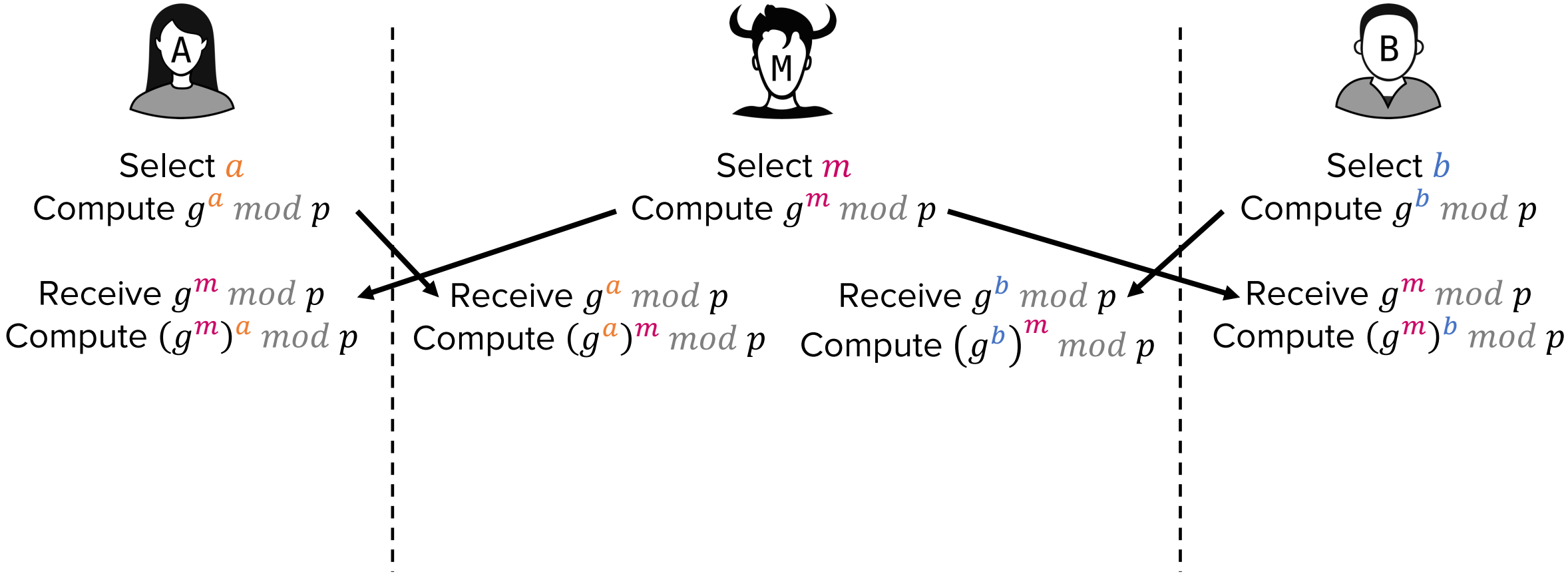

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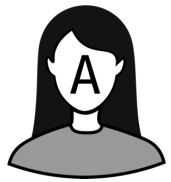
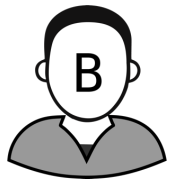




Select a
Compute $g^a \bmod p$

Receive $g^m \bmod p$
Compute $(g^m)^a \bmod p$

$k = g^{ma} \bmod p$

Select m
Compute $g^m \bmod p$

Receive $g^a \bmod p$
Compute $(g^a)^m \bmod p$

$k = g^{ma} \bmod p$

Receive $g^b \bmod p$
Compute $(g^b)^m \bmod p$

$k' = g^{mb} \bmod p$

Select b
Compute $g^b \bmod p$

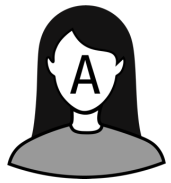
Receive $g^m \bmod p$
Compute $(g^m)^b \bmod p$

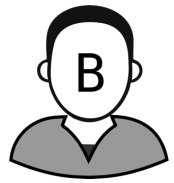
$k' = g^{mb} \bmod p$

Mallory keeps two shared keys: k for Alice, and k' for Bob, respectively

Diffie-Hellman – Man in the Middle (MitM) attack

- Then, Mallory can tamper with messages





Select a
Compute $g^a \bmod p$

Select m
Compute $g^m \bmod p$

Select b
Compute $g^b \bmod p$

Receive $g^m \bmod p$
Compute $(g^m)^a \bmod p$

Receive $g^a \bmod p$
Compute $(g^a)^m \bmod p$

Receive $g^b \bmod p$
Compute $(g^b)^m \bmod p$

Receive $g^m \bmod p$
Compute $(g^m)^b \bmod p$

$k = g^{ma} \bmod p$

$k = g^{ma} \bmod p$

$k' = g^{mb} \bmod p$

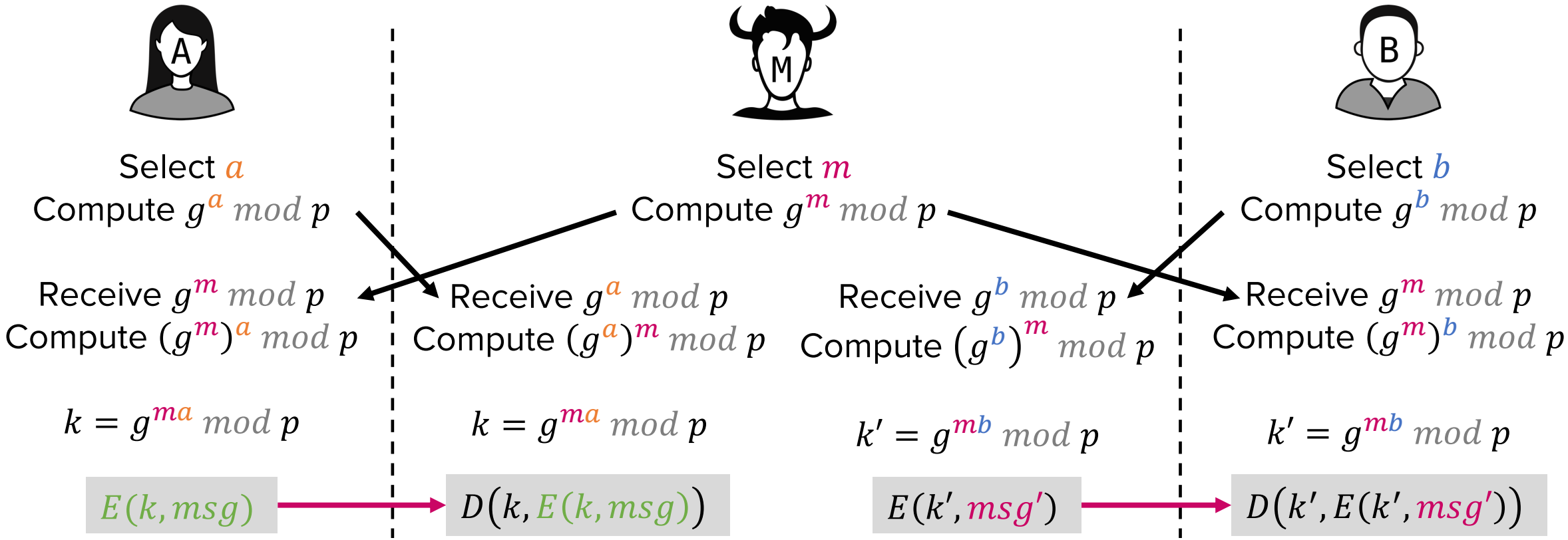
$k' = g^{mb} \bmod p$

$E(k, msg)$ → $D(k, E(k, msg))$

Mallory can decrypt Alice's msg using k

Diffie-Hellman – Man in the Middle (MitM) attack

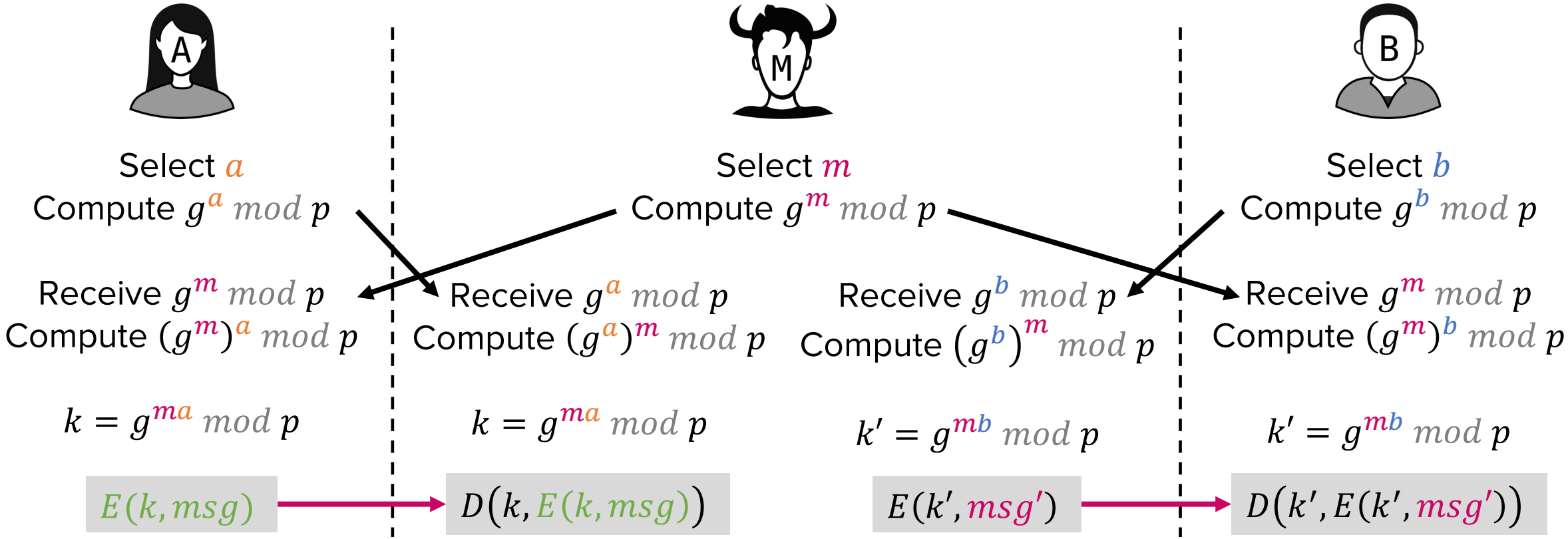
- Then, Mallory can tamper with messages



Mallory can modify the msg to msg' and re-encrypt it using k' for Bob

Diffie-Hellman – Man in the Middle (MitM) attack

- Then, Mallory can tamper with messages



Alice and Bob are tricked into believing that they are securely communicating

Diffie-Hellman – Man in the Middle (MitM) attack

- What if Mallory actively changes key exchange messages?

DH key exchange is insecure against active attacks

$k = g^{ma} \bmod p$ | $k = g^{ma} \bmod p$ | $k' = g^{mb} \bmod p$ | $k' = g^{mb} \bmod p$

$E(k, msg)$ → $D(k, E(k, msg))$ | $E(k', msg')$ → $D(k', E(k', msg'))$

Alice and Bob are tricked into believing that they are securely communicating

Key exchange in the presence of active attacker

- When Mallory (an active attacker) exists, it is impossible for Alice and Bob to start from scratch and exchange messages to derive a shared key unknown to the adversary
- Why?
  - Bob cannot distinguish Alice from Mallory because DH does not provide authentication
- Solution:
  - Alice and Bob needs an “information advantage” over the adversary
    - Typically, in the form of long-lived keys (e.g., previously shared keys)
    - More on this next week!

Cryptography roadmap

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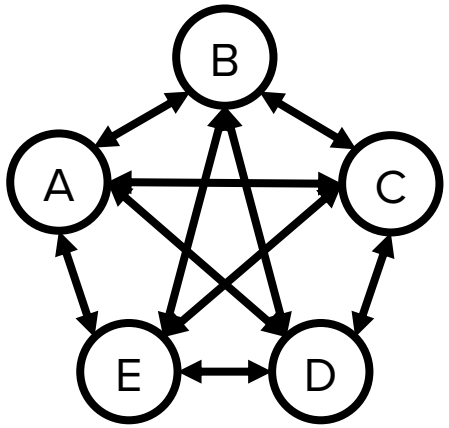
Goal \ Scheme	Symmetric Key	Asymmetric Key
Confidentiality	✅ One Time Pad (OTP) ✅ Block ciphers (DES, AES) ✅ Stream ciphers	✅ DH secure key exchange • ElGamal encryption • RSA encryption
Integrity & Authentication	• Message Authentication Code (MAC)	• Digital signature + CA

Asymmetric Cryptography (Public key Scheme)

Motivation

- Another limitation of symmetric key schemes
  - The number of symmetric keys needed grows exponentially



→ $\binom{n}{2} = \frac{n(n-1)}{2}$ keys are needed for n people to securely communicate using symmetric key schemes

Solution: Public-key cryptography

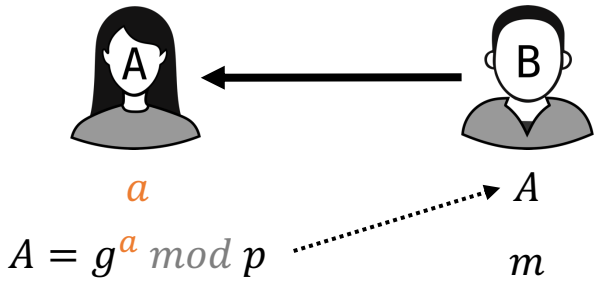
- Idea:
  - Utilize an asymmetric key pair $< k_p, k_s >$, where
    - k_p: Public key that is publicly released
    - k_s: Secret key (a.k.a. private key), which is confidential
  - Any sender can encrypt a message using the receiver's public key
    - $c = E(k_p, m)$
  - Only the receiver can decrypt the ciphertext using the receiver's own secret key
    - $m = D(k_s, c)$

ElGamal encryption

- An extension of Diffie-Hellman key exchange
  - DH only provides only a shared secret derivation
    - Alice and Bob needs to do enc/decryption separately using the shared secret
  - ElGamal supports direct encryption and decryption of messages on top of DH key exchange

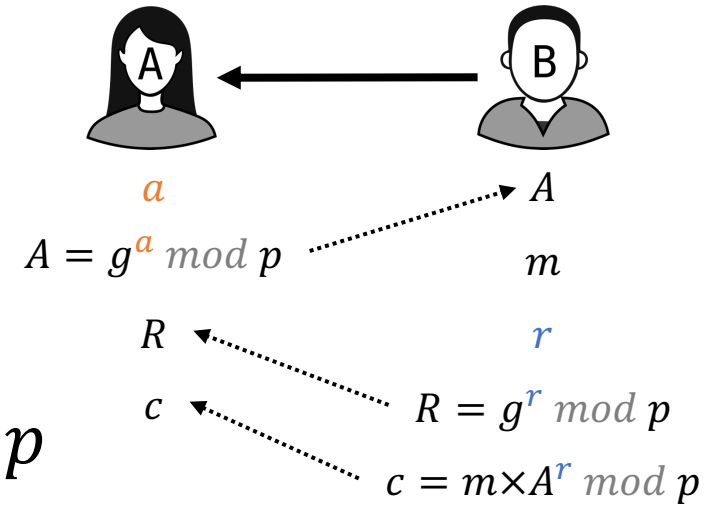
ElGamal encryption

- Alice chooses a secret key a
- Alice generates a public key $A = g^a \ mod \ p$
  - p (prime number) and g (generator) are public
- Bob wants to encrypt m for Alice



ElGamal encryption

- Alice chooses a secret key a
- Alice generates a public key $A = g^a \ mod \ p$
- Bob wants to encrypt m for Alice
  - Bob picks a random r and computes $R = g^r \ mod \ p$
  - Bob sends $c = m \times A^r \ mod \ p$ and R to Alice



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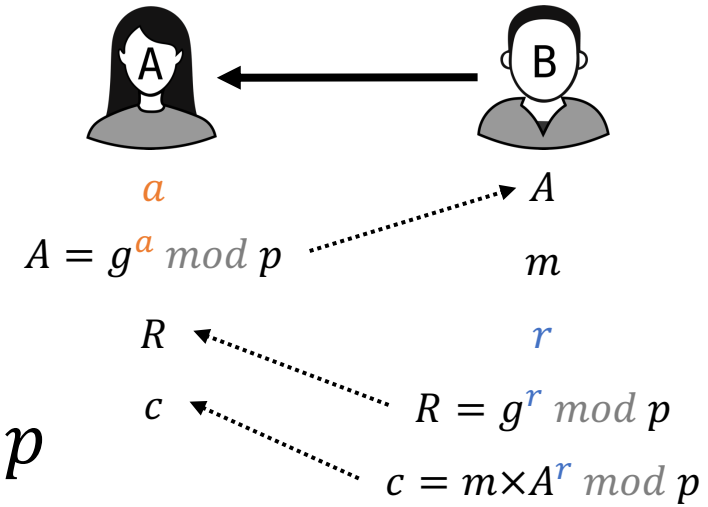

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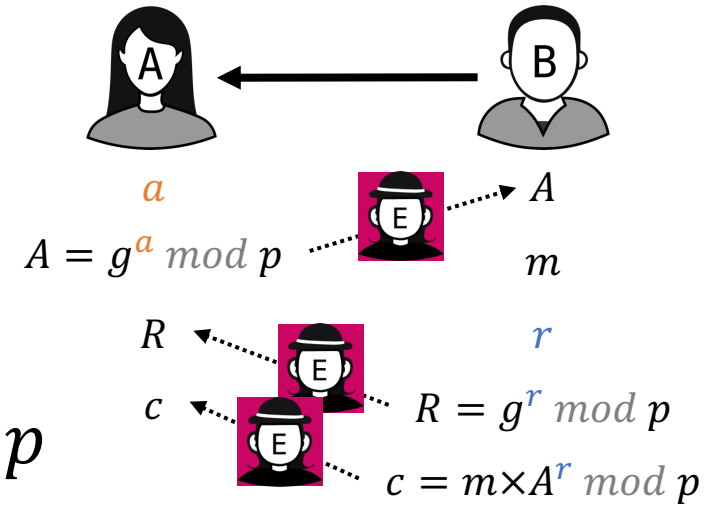
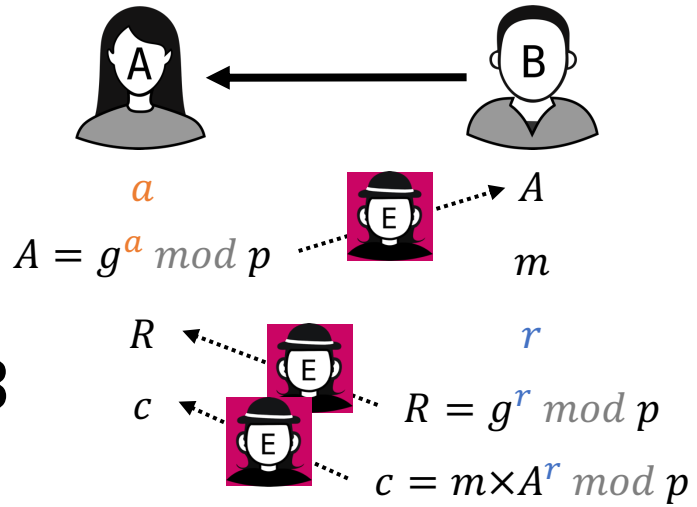


Security: Given A, R, and c, Eve cannot recover m (DLP!)

ElGamal encryption

- Example
  - Public parameters: $p = 13, g = 2$
  - Alice's secret key $a = 3$ // randomly chosen
  - Alices' public key $A = g^a \ mod \ p = \ 2^3 \ mod \ 13 = 8$
  - Bob's message $m = 11$
  - Bob's random $r = 5$
  - Bob computes $R = g^r \ mod \ p = 2^5 \ mod \ 13 = 6$
  - Bob encrypts m: $c = m \times A^r \ mod \ p = 11 \times 8^5 \ mod \ 13 = 10$
  - Alice receives R and c from Bob and decrypts c to obtain m
    - $m = c \times (R^a)^{-1} \ mod \ p = 10 \times 6^{-3} \ mod \ 13 = 11$ Correctly decrypted!



Using Python: `10 * pow(6, -3, 13) % 13`

Summary of ElGamal encryption

- ElGamal encryption provides confidentiality
  - Discrete logarithm problem
- ElGamal encryption still does not provide integrity
  - Mallory can tamper with the ciphertext without decrypting it
  - e.g.,
    - Mallory (MitM) receives R and c from Bob
    - Mallory sends R and $\mathbf{c}' = c \times 2$ to Alice
    - Alice decrypts $\mathbf{c}'$ and retrieves $m \times 2 \; mod \; 13$

Cryptography roadmap

POSTECH

Goal \ Scheme	Symmetric Key	Asymmetric Key
Confidentiality	✅ One Time Pad (OTP) ✅ Block ciphers (DES, AES) ✅ Stream ciphers	✅ DH secure key exchange ✅ ElGamal encryption • RSA encryption
Integrity & Authentication	• Message Authentication Code (MAC)	• Digital signature

RSA Encryption

- Idea: Prime factorization of large numbers is hard
  - Q) What are the prime factors of 10403?

RSA Encryption

- Idea: Prime factorization of large numbers is hard
  - Q) What are the prime factors of 10403?
    - Naïve algorithm:

```
# N = pq where p and q are primes
def factorize(N):
    for i in range(2, sqrt(N)):
        if N mod i == 0:
            p = i
            q = N / i
            return (p, q)
```

This algorithm works, but takes time $O(\sqrt{N})$

e.g., using a 2048-bit N, naïve factorization takes $O(\sqrt{2^{2048}})$

RSA Encryption

- Choose two large primes p and q
- Compute public $N = pq$
- Compute the totient, $T = (p-1)(q-1)$
- Select public key e, such that e is relatively prime to T
- Compute private key $d = e^{-1} \; mod \; T$ // modular inverse of e
  - $ed = 1 \; mod \; T$

RSA Encryption

- Encryption function:
  - $E(e, m) = m^e \ mod \ N = c$ // Anyone can encrypt using the public key e
- Decryption function:
  - $D(d, c) = c^d \ mod \ N$ // Only the receiver can decrypt using the private key d
  - Magically, $m = c^d \ mod \ N$ holds:
    - $c^d \ mod \ N = (m^e)^d \ mod \ N$
      $= m^{ed} \ mod \ N$ ⋯ $ed = kT + 1$ because $ed = 1 \ mod \ T$
      $= m^{kT} m^1 \ mod \ N$
      $= m \ mod \ N$ ⋯ $m^T = 1 \ mod \ N$ by Euler's theorem*

* If m and $N = pq$ are relatively prime, then $m^T = 1 \ mod \ N$ where $T = (p-1)(q-1)$

RSA example

- $p = 7, q = 11$
- $N = 77$
- $T = (p-1)(q-1) = 6 \times 10 = 60$
- Select public key e that is coprime to 60 → $e = 7$
- Private key $d = e^{-1} \; mod \; T = 7^{-1} \; mod \; 60 = 43$
  - Problem: Find e such that $7 \times e \; mod \; 60 = 1$
    - Can be obtained by the Extended Euclid's algorithm
  - In Python: `pow(7, -1, 60)`

RSA example

- Given
  - Secret: $p = 7, q = 11, d = 43$
  - Public: $N = 77, e = 7$
- Plaintext $m = 8$
- Encryption
  - $c = m^e \ mod \ N = 8^7 \ mod \ 77 = 57$
- Decryption
  - $m = c^d \ mod \ N = 57^{43} \ mod \ 77 = 8$

RSA example

- Given
  - Secret: $p = 7, q = 11, d = 43$
  - Public: $N = 77, e = 7$
- Plaintext $m = 8$
- Encryption
  - $c = m^e \ mod \ N = 8^7 \ mod \ 77 = 57$
- Decryption
  - $m = c^d \ mod \ N = 57^{43} \ mod \ 77 = 8$ ← Correctly decrypted!

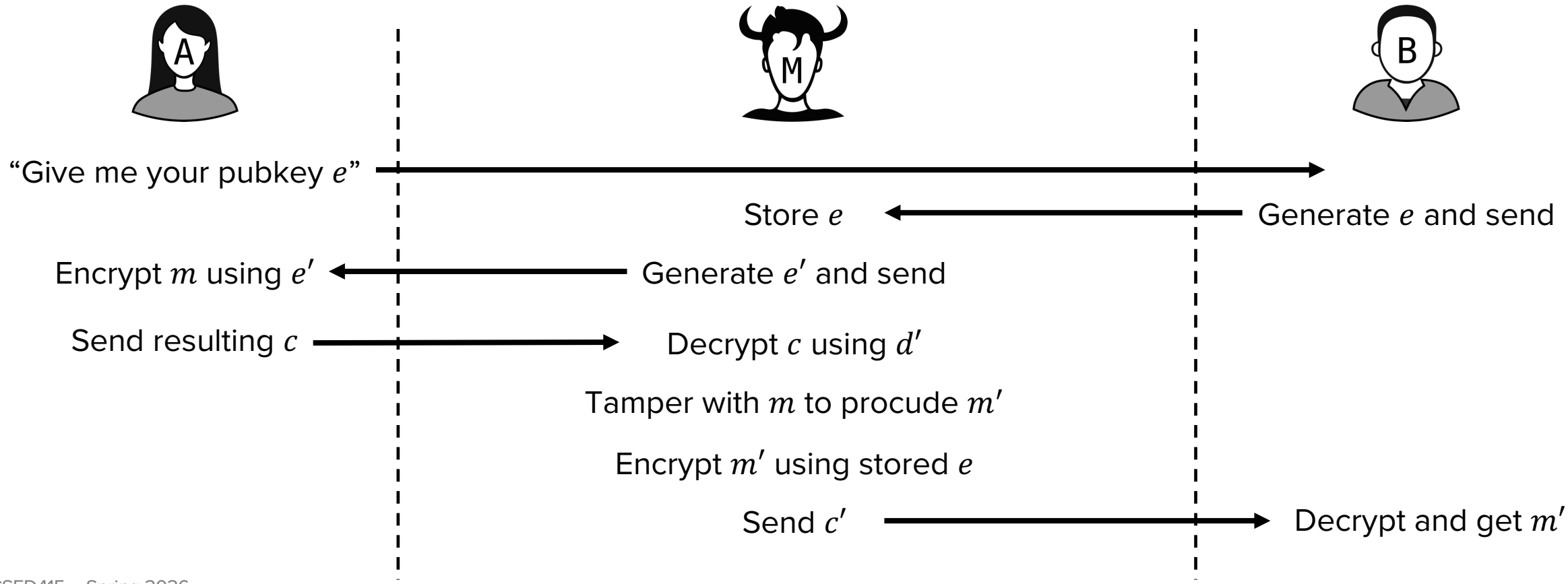
(Use modular exponentiation for computation)

RSA security – Confidentiality

- RSA provides confidentiality based on the hardness of integer factorization problem
  - Steps for Eve to decipher c given public N and public key e,
    - To compute $m = c^d \ mod \ N$, Eve needs to find the secret key d
    - To derive $d = e^{-1} \ mod \ T$, Eve needs to find T
    - To find $T = (p-1)(q-1)$, Eve needs to find p and q
    - To find p and q such that $N = pq$, Eve needs to prime factorize N
    - However, there is no polynomial time algorithm that can factor a large integer N to find its prime factors p and q

RSA security – Integrity

- RSA does not guarantee integrity
  - Still susceptible to MitM attacks



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Questions?