Cryptography III

Crypto Security and Authentication

CS 1660: Introduction to Computer Systems Security

Formalizing Encryption Security

Crypto Adversary Models

- Alice and Bob are sending encrypted messages to each other
  - Adversary Eve can eavesdrop on those messages
  - …and maybe do other things as well
- Security goal: protect confidentiality w.r.t. Eve
  - Useful to formalize: What are Eve's capabilities as an adversary?

(Weaker) Adversary Models

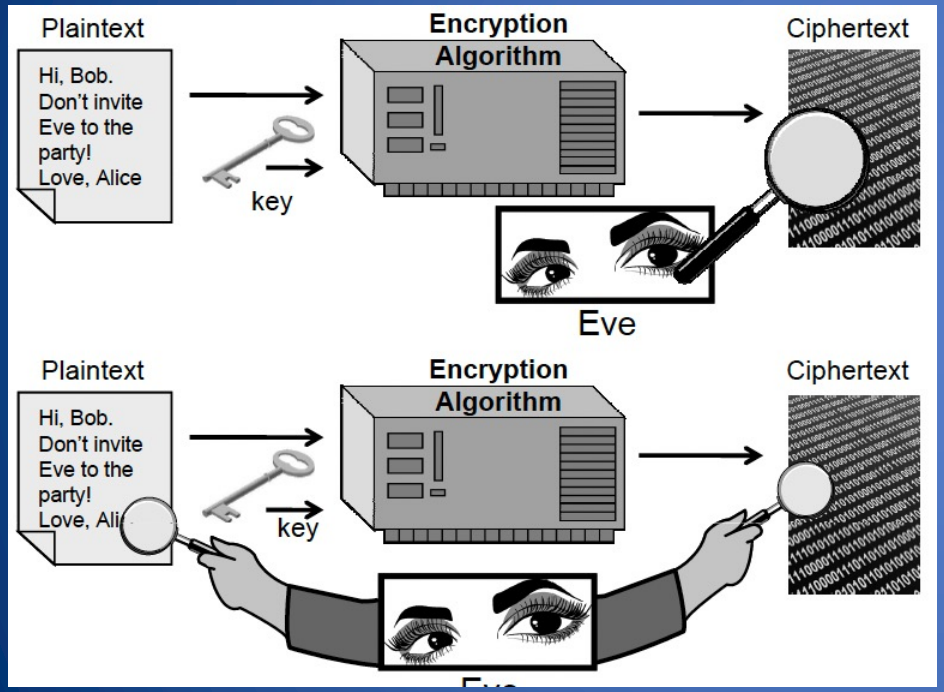
1. Ciphertext-only
   - Eve sees all ciphertexts, but has no / vague information about the underlying plaintext
2. Known plaintext
   - Eve also knows part of plaintext messages
   - How could this happen?
     - All of your internet requests start with the same header
     - Sending an order CSV in the same format every week
     - You text “hi” to people when you first start texting them

(Stronger) Adversary Models

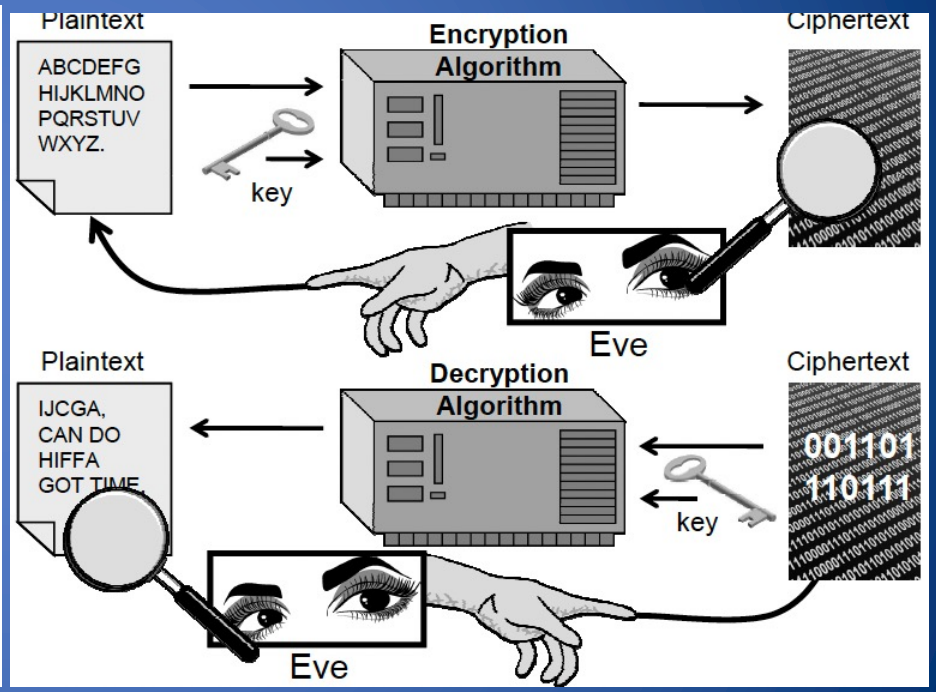
3. Chosen plaintext
   - Eve is able to encrypt plaintexts of Eve's choosing and see the resulting ciphertexts
   - How can this happen?
     - Eve sends Alice email spoofed from Alice's boss saying "Please securely forward this to Bob"
     - Public key cryptography
     - Your dorm room has a router that you can send plaintexts to…
4. Chosen ciphertext
   - Eve chooses ciphertexts and Alice reveals some info about the decryption
   - Mostly not covered too much in course…unless you're a CS1620/CS2660 student ☺

Threat modeling

Ciphertext-only



Chosen plaintext



Known plaintext

Chosen ciphertext

Formalization

- How do we show that our schemes are secure against these different kinds of attacker models?
- Intuitive definition: “No adversary can reconstruct plaintext M from ciphertext C”
  - This isn’t sufficient—what if adversary can tell first letter of M, but nothing else?
    - Satisfies the definition, but still a broken scheme
    - Adversary could still reconstruct other parts of M based on what they know about its format
  - Need something stronger than this

- *Goal*: Cryptosystem should not leak *any* information about M
  - Idea: No adversary should be able to distinguish between two messages based on their encryption
- We model ”security” of encryption schemes as a game
  - Played between a challenger (with access to the encryption algorithm and the secret key) and an adversary

IND-CPA

- ”Indistinguishability under Chosen Plaintext Attack”
- Adversary has polynomially-bounded access to an encryption oracle
  - If an adversary has access to this kind of oracle, we say they are an “IND-CPA adversary”

If adversary guessed correctly i, then adversary wins.

If adversary’s probability of winning the game is equal to ½, then our scheme is “IND-CPA secure” (why ½?)

Challenger **Adversary**

Setup Phase

Generate a key $k = \text{KeyGen}()$

Query Phase

m ←

$c = Enc_k(m)$

c →

Repeat as many times as desired polynomially

Challenge Phase

m_1, m_2 (of equal length) with $m_1 \neq m_2$ ←

Randomly pick $m_i \in \{m_1, m_2\}$

$c' = Enc_k(m_i)$

c' →

Output guess if $i = 1$ or $i = 2$ ←

Is the Caesar cipher cryptosystem IND-CPA secure?

What's the adversary's strategy in the IND-CPA game against Caesar?

- Setup phase: Not necessary
- Challenge phase: Send plaintexts "AB" and "AA"
  - If output is in the form "XY" (where X != Y), then output "AB"
  - Otherwise, output must be in form "XX"; then output "AA"

Is the one-time-pad cryptosystem IND-CPA secure?

What's the adversary's strategy in the IND-CPA game against OTP?

- Setup phase: Send messages m_1, m_2 to get c_1, c_2
- Challenge phase: Send plaintexts m_1, m_2; challenger returns c_i
  - If $c_i \oplus c_1 = 0$, then output c_1
  - Otherwise, it must be that $c_i \oplus c_2 = 0$, so output c_2
  - Why does this work?

Is the encryption function $Enc_k(m) = 1$ IND-CPA secure?

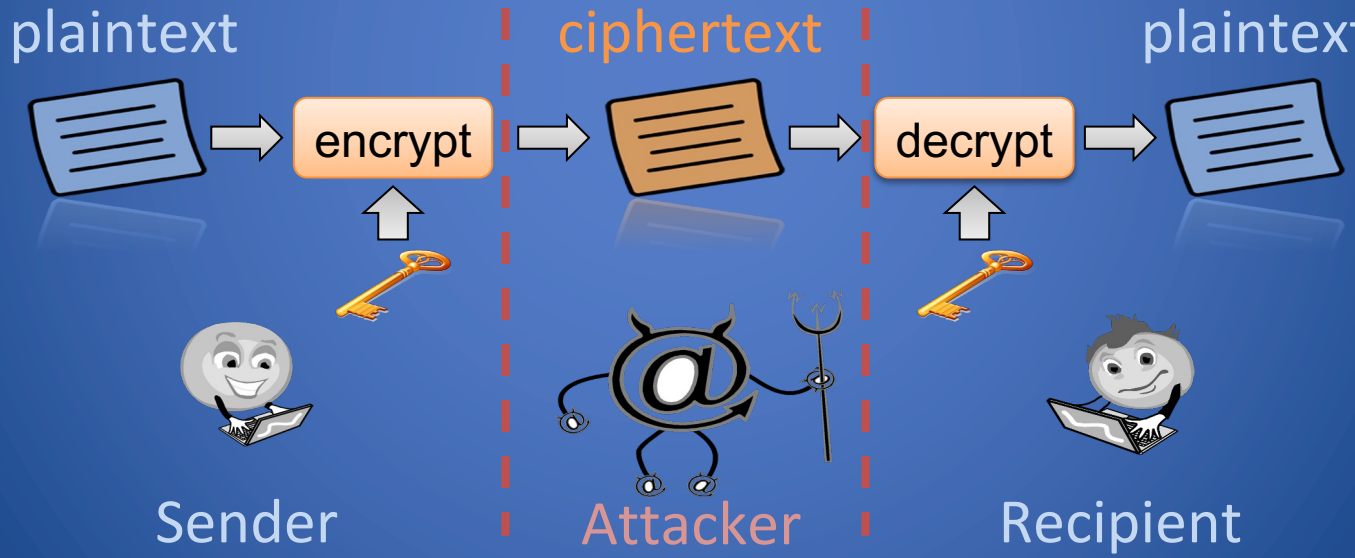
Yes, but it's not "correct"…

We also care about *correctness*—i.e. , that we can actually decrypt a given encryption.

AUTHENTICATION IN CRYPTO

Symmetric Encryption (recap)

- Same key is used for encryption and decryption
- Encryption and decryption algorithms are one the reverse of the other
- We need a secure channel to set up key



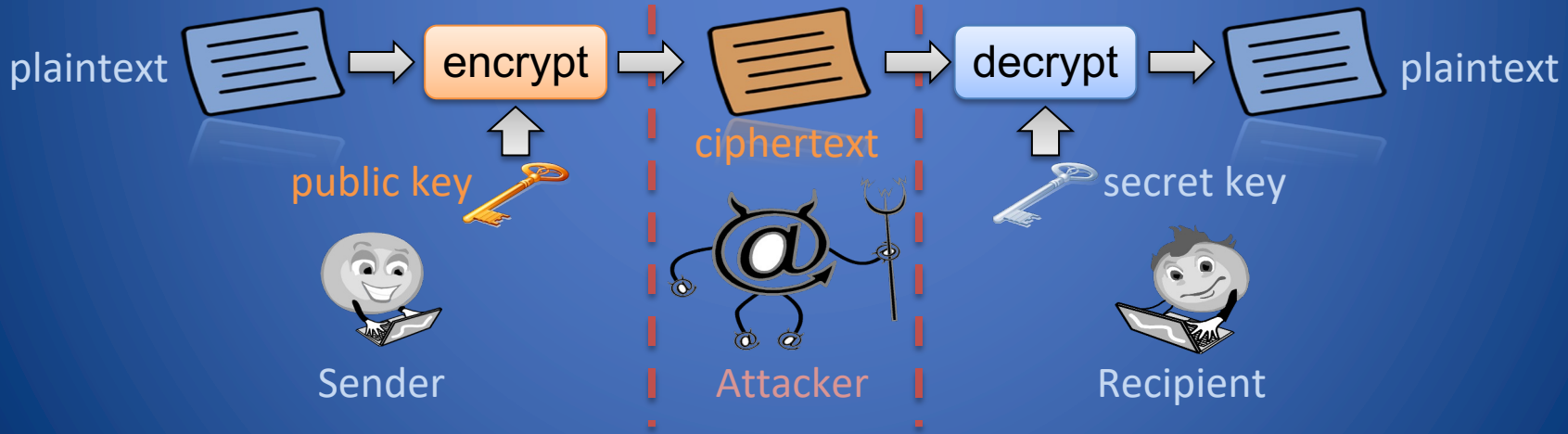
Public Key Cryptography (recap)

Key pair

- Public key: shared with everyone
- Secret key: kept secret, hard to derive from the public key

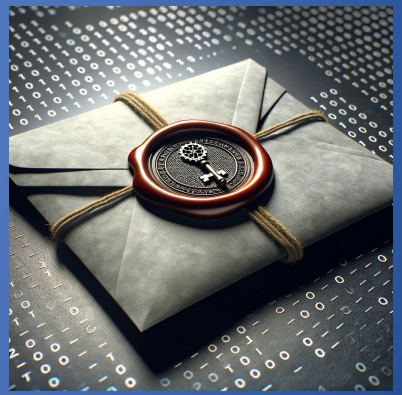
Protocol

- Sender encrypts using recipient's public key
- Recipient decrypts using its secret key



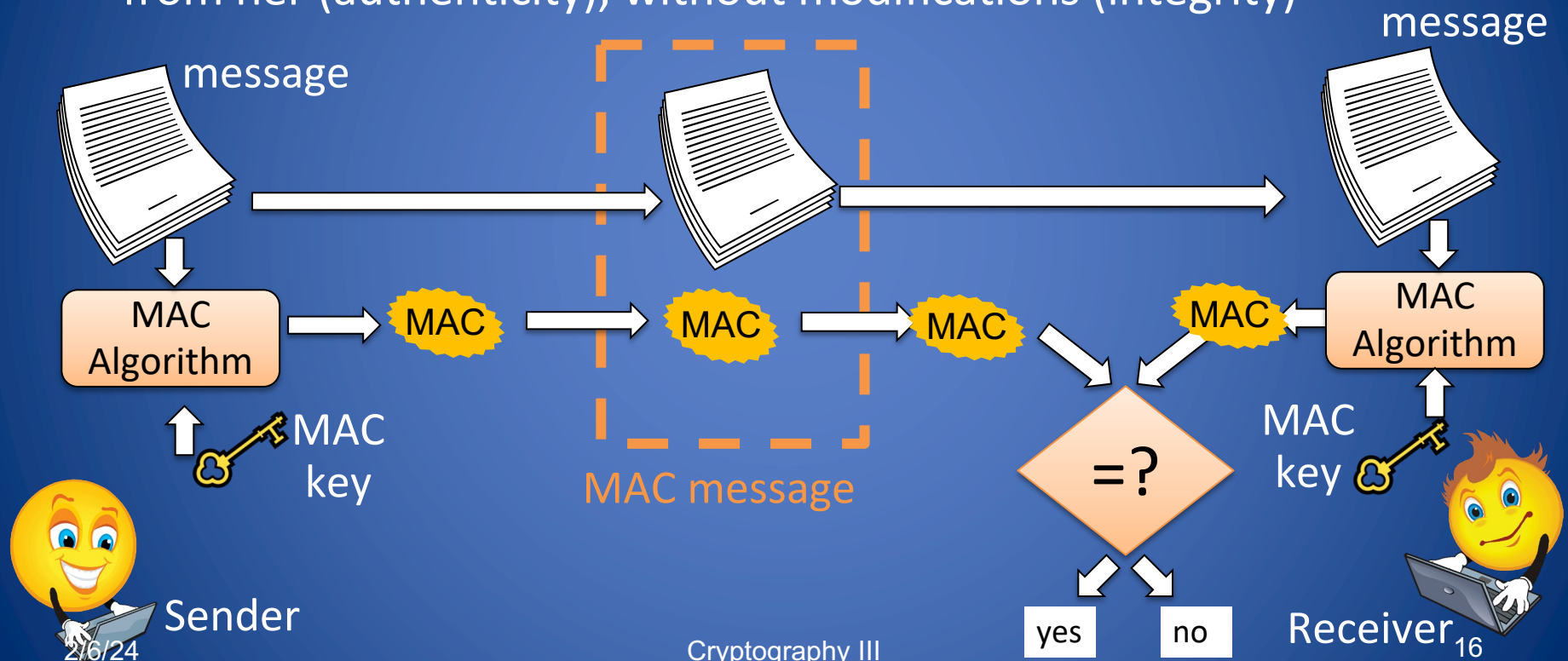
Authentication

- The goal is to confirm that the message came from the original sender (authenticity) instead of a fake source (spoofing)
  - Like a seal on a letter
- Multiple ways to achieve this:
  - MACs (Symmetric Crypto)
  - Digital signatures (Asymmetric Crypto)



Message Authentication Codes (MACs)

- The sender wants to send a message and prove that it comes from her (authenticity), without modifications (integrity)



MAC Security Properties

- Unforgeability
  - Even after seeing many MAC-message pairs, an attacker cannot produce a valid MAC for a new message
- Integrity
  - If the MAC or the message is altered, the recipient can detect it

Issues in Implementing MACs

Block Ciphers

- CBC-MAC
  - Using a block cipher in CBC mode, encrypt a message and use the last cipher block as a MAC
  - *Requires some tweaks!* You must fix the IV, and you must prepend each message with its length

Cryptographic Hash Functions

- HMAC
  - Use hash function and a shared secret
  - Theoretical construction:
    - $H(M||K)$
  - In practice:
    - There are length extension attacks require padding schemes
    - RFC 2104

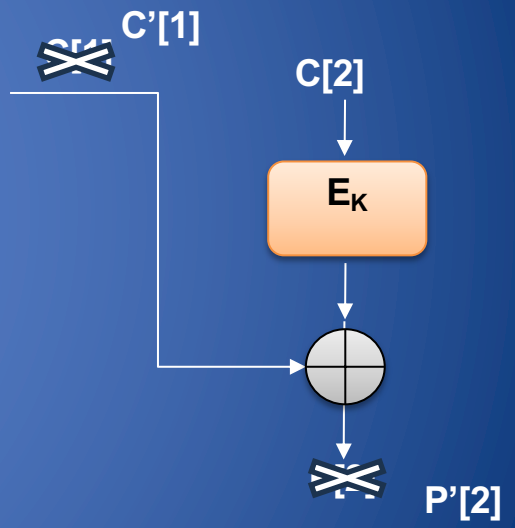
Padding Oracle

Padding Oracle – an external device that tells you whether a given block has valid padding or not (e.g. a server):

- Suppose I have a block of ciphertext that I want to send to a server.
- Server decrypts it using its crypto key, and obtains a plaintext
- Server checks, “Is this padding valid?”
  - If yes, returns you “padding valid”
  - If no “padding not valid”

Padding Oracle Attack

- Attacker has two ciphertext blocks C[1], C[2] and wants to decrypt the second block to get plaintext P[2]
- Attacker changes the last byte of C[1] creating C'[1]
- Attacker sends C'[1], C[2] to server
- Server returns if P'[2] has a valid padding
  - If the server says padding no valid, the attacker changes the last byte of C'[1]
  - How many possibilities?
    - 256
- When the server says padding valid, the attacker knows that the last byte of
  E_K (C[2]) $\oplus$ C'[1] = 01 (because of the padding)
- You can iterate the same approach to obtain the previous bytes



Analysis

- Let's suppose a block is 128 bits =16 bytes
- Attacker gets plaintext P[x] in at most $256 \cdot 16 = 4096 = 2^{12}$ attempts
- Much faster than 2^{128} attempts to brute force 128-bit key
- **How do we get server to act like an oracle?**
- **Timing difference:**
  - If padding is invalid then server does not compute MAC
  - If padding is valid then server computes MAC $\Longrightarrow$ it takes more time!
- **Real attacks at TLS based on Padding Oracle, e.g. Poodle, Lucky13**

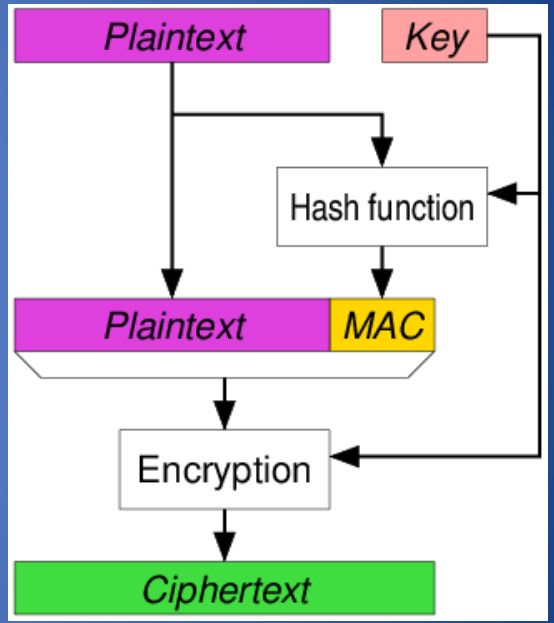
Authenticated Encryption with Associated Data (AEAD)

Often, we need both Confidentiality and Integrity in addition to Authentication

- How to do both?
- We add Associated Data to achieve this, but there are some subtle challenges…

MAC then Encrypt (MtE)

- E(*Message* || MAC(*Message*))
- Was used for secure web connection - TLS (although with special padding schemes)
- Does not provide integrity of ciphertext, only plaintext
- **Not** proven to be secure in general case (some exceptions like TLS)



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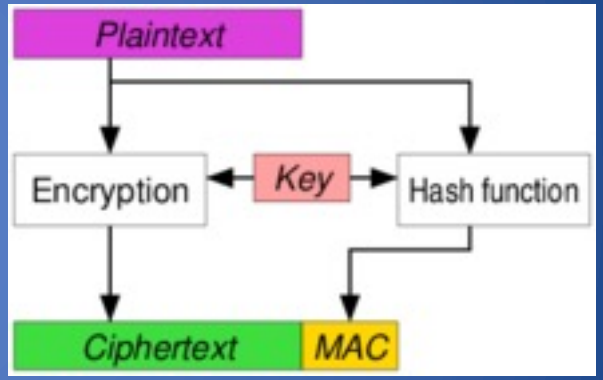
MAC and Encrypt (M&E)

- (E(*Message*), MAC(*Message*))
- Can leak message equality even if E() does not
  - Unless you use the Key in counter mode
- Does not provide integrity of ciphertext, only plaintext
- Not proven to be secure (but again, some variants are in SSH)



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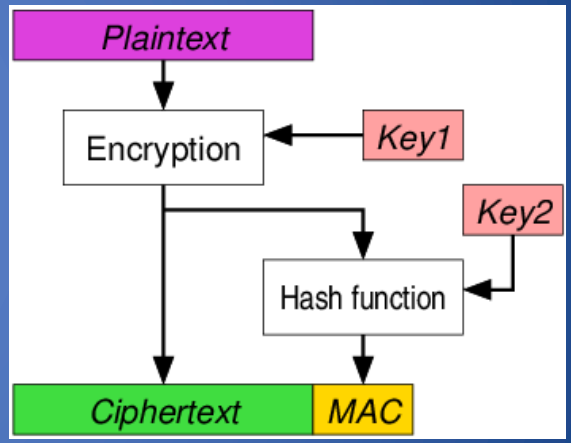
Encrypt then MAC (EtM)

- (E(*Message*), MAC(E(*Message*)))
- Integrity guarantee on ***both*** ciphertext and plaintext
- Generally recommended order of operations
- Proposed to replace MtE in TLS (RFC 7366) and used in IPSEC
- You should use EtM! (We will see more in last project…)



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More methods…

- Counter Mode uses an arbitrary number (the counter) that changes with each block of text encrypted.
  - Together with a unique IV (nonce) It allows parallelism in the encryption.
- Galois/Counter Mode (GCM) is a block cipher mode that uses hashing over a Galois field to provide authenticated encryption and integrity verification.
- Why? Abstracts away details from programmer!
- Out of scope for this class, but now very common.

BREAK!

Digital Signatures

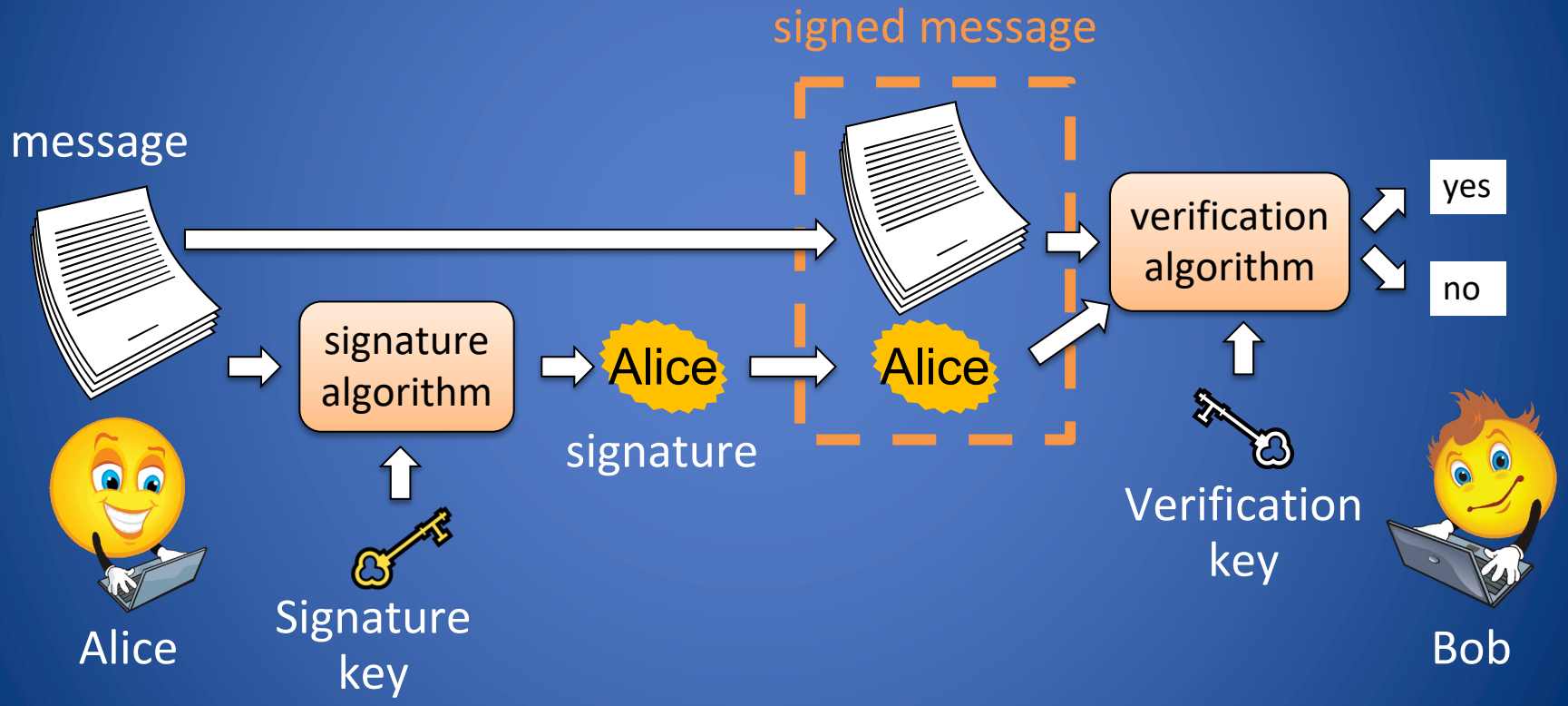
Signatures: from Ink to Digital

- Signature in the real world
  - Contracts
  - Checks
  - Job offers
  - Affidavits

- Digital signatures are a matter of both computer security and law
- ESIGN Act (2000 US)
- eIDAS Regulation (2014 EU)
- Technological failures can have legal consequences

What is a Digital Signature?

- Alice wants to send a message and prove that it comes from her



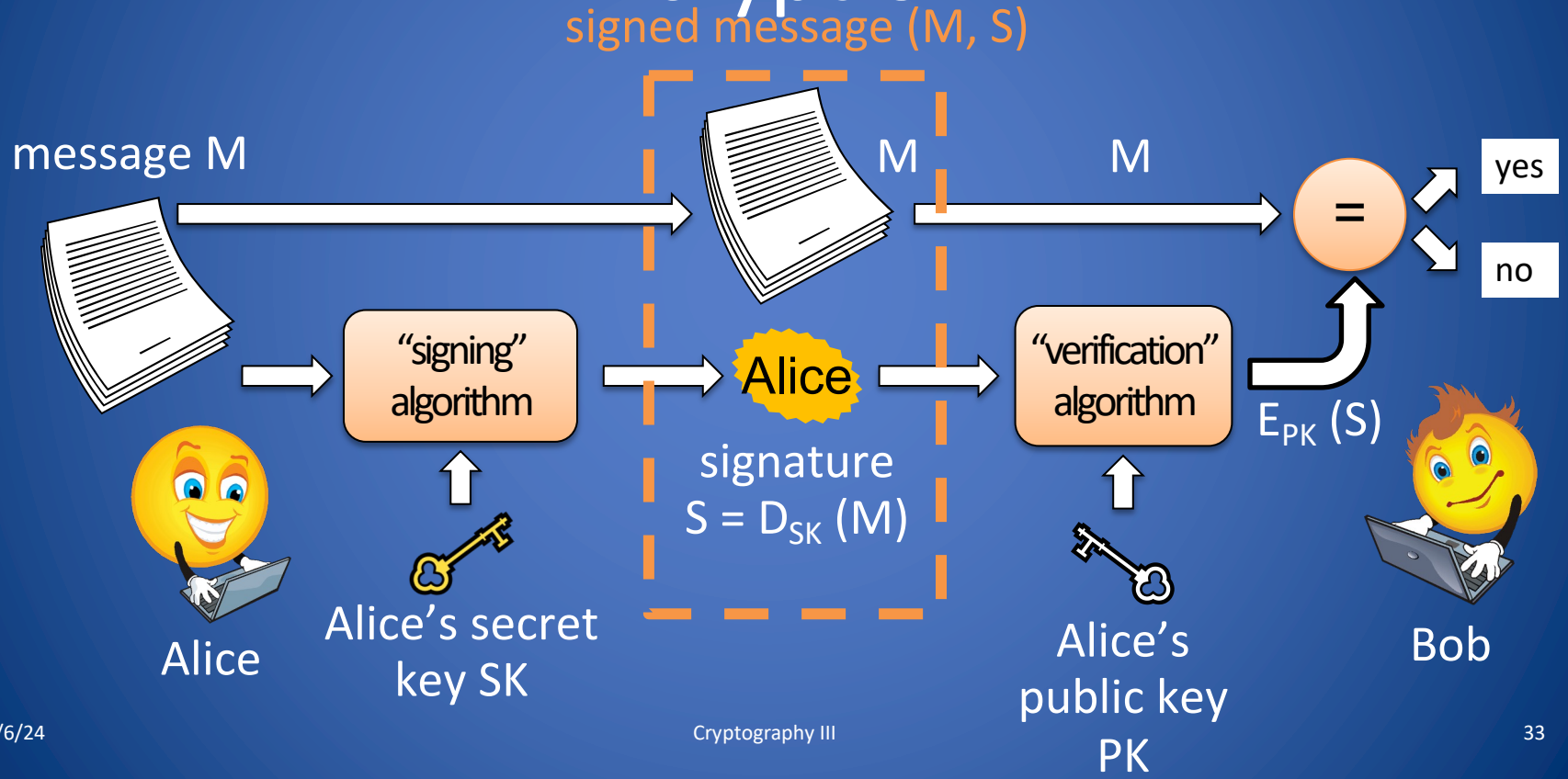
Goals for a Digital Signature

- Authenticity
  - Binds an identity (signer) to a message
  - Provides assurance of the signer
- Unforgeability
  - An attacker cannot forge a signature for a different identity
- Nonrepudiation
  - Signer cannot deny having signed the message
- Integrity
  - An attacker cannot take a signature by Alice for a message and create a signature by Alice for a different message

Digital Signatures in practice

- Use symmetric key encryption…
  - Requires previous secure communication
  - Only works with single recipient
- Can we use public key encryption?

Digital Signature with Public-Key Encryption



Digital Signature with Public-Key Encryption

- In a public-key cryptosystem (e.g., RSA), we can often reverse the order of encryption and decryption

$$E_{PK}(D_{SK}(M)) = M$$

- Alice "decrypts" plaintext message M with the secret key and obtains a digital signature on M

```
sign(M, SK) {
  return S = D_SK (M) }
```

- Knowing Alice's public key, PK, can verify the validity of signature S on M
- Bob "encrypts" signature S with PK, and
- Checks if it the result is message M

```
verify(M, S, PK) {
    return (M == E_PK (S) ) }
```

Signing Hashes

- Basic method for public-key digital signatures
  - Signature as long as the message
  - Slow public-key encryption/decryption
- Preferred method
  - Sign a cryptographic hash of the message
  - Hash is short and fast to compute

- Sign

$$S = D_{SK}(h(M))$$

- Verify

$$h(M) == E_{PK}(S)$$

- Security of signing hash
  - Security of digital signature
  - Collision resistance of hash function

Clicker Question (1)

Alice wants to increase the efficiency of her public-key digital signature system by signing a cryptographic hash of each message instead of the message itself. Given the decryption function D, secret key SK, and message M, how can we represent Alice's digital signature S on the hash of the message?

A. $S = D_{SK}(M)$

B. $S = D_{SK}(h(M))$

C. $S = (h(M), D_{SK}(M))$

D. $S = h(D_{SK}(M))$

Clicker Question (1) - Answer

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A. $S = D_{SK}(M)$

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D. $S = h(D_{SK}(M))$

Clicker Question (2)

Bob wants to send Alice an encrypted message. He found Alice's profile online, and it lists her public key, PK. How can Bob verify that this is really Alice's public key?

A. Check whether E_{PK} (D_{PK} (M)) = M
B. Use PK to encrypt message *M* = "If you can decrypt this message, reply with password **MySecretPassword**" and send it to the profile. Check whether you get the correct password back.
C. Send a request to the profile asking for a message digitally signed with the secret key corresponding to PK. Check whether the signature is valid.
D. None of the above

Clicker Question (2) - Answer

Bob wants to send Alice an encrypted message. He found Alice's profile online, and it lists her public key. How can Bob verify that this is really Alice's public key?

ANSWER: D. None of the above.

Bob cannot use method A since he does not have the private key. Also, it's unclear what message M would be in this method.

Methods B and C assure Bob that he is interacting with a party who has possession of the private key corresponding to the posted public key. However, they do not prove this party is Alice.

Send a message securely

- Alice wants to send a message that only Bob can read and that only she can have sent.
- Requirements
  - Confidentiality of all communication
  - Bob understands he is communicating with Alice
- Message M needs to be encrypted and digitally signed

- Active adversary, Eve
  - Can eavesdrop and modify messages
- Eve knows:
  - PK_{Alice}
  - PK_{Bob}

Encrypt then Sign

- Encrypt then sign
  - Alice encrypts $C = E((M, PK_{Bob}))$
  - Alice signs $C_S=(C, SK_{Alice})$
  - Alice sends C_S to Bob
  - Bob verifies $C=(C_s, PK_{Alice})$ and decrypts C to (C_s, SK_{Bob})

- Attack
  - Eve replace S with her signature S' on $C_{S'}$ and forwards (C, S') to Bob
  - Bob now thinks he is communicating with Eve
  - Eve can then forward Bob's response (intended for Eve) to Alice

This is a subtle risk but it could be dangerous

- during a transaction
- Authentication protocol
- ...

Sign then Encryp

- Sign then encrypt
  - Alice signs M_S=(M, SK_{Alice})
  - Alice encrypts C = E((M_S, PK_{Bob}))
  - Alice sends C to Bob
  - Bob decrypts C to (M_s, SK_{Bob}) and verifies M=(M_s, PK_{Alice})

- Attack
  - Eve does not know SK_{Bob}
    - She can not read M
  - Eve does not know SK_{Alice}
    - She can not tamper M

This is the correct order

Relying on Public Keys

- The verifier of a signature must be assured that the public key corresponds to the correct party
- The signer should not be able to deny the association with the public key
- Public keys usually are stored in browsers or in OS
- A trusted party could keep and publish pairs (identity, public key)
  - Government?
  - Private organizations?
- What if the private key is compromised?
  - Need for key revocation mechanism

Practical Examples

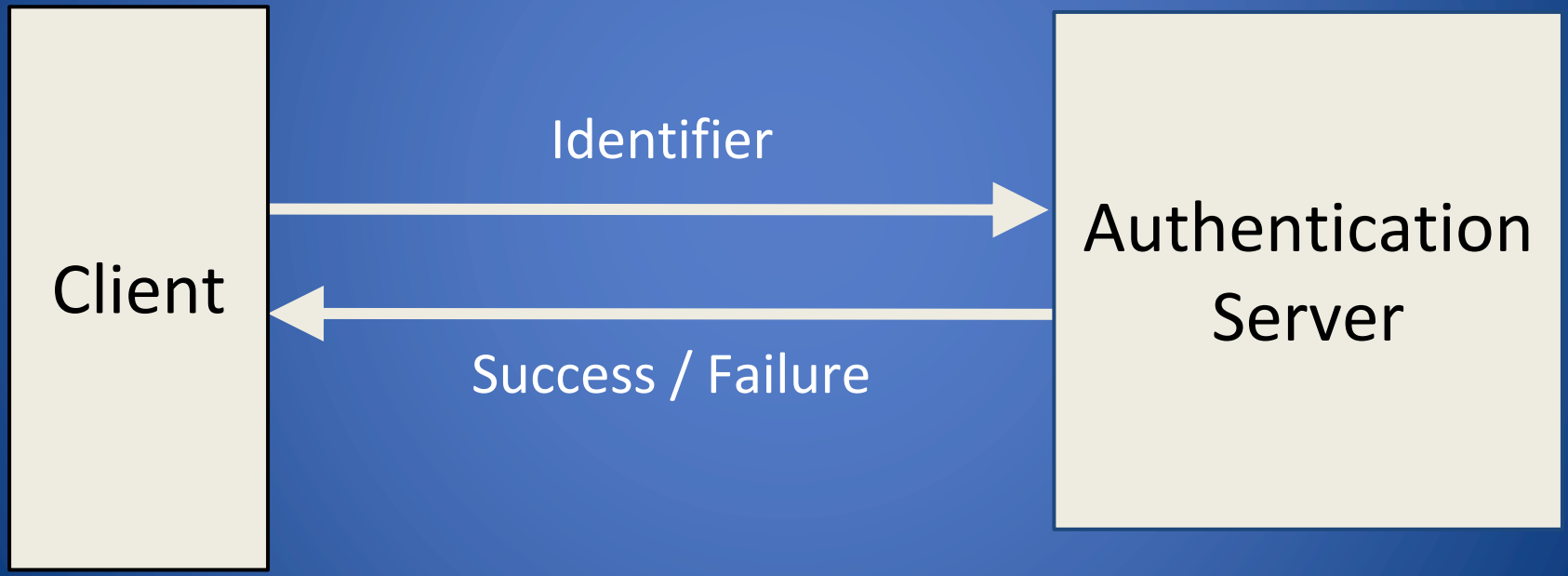
SSH “Do you want to accept fingerprint (HASH) public key”

```
bernardo@Bibi-MacBook-Pro-4394 ~ % ssh  bpalazzi@ssh.cs.brown.edu
The authenticity of host 'ssh.cs.brown.edu (128.148.33.12)' can't be established
.
RSA key fingerprint is SHA256:P4ZsteVHDJ1nFV6UfH1VTK0RgRjXvBMti6IhLS+EeoI.
This key is not known by any other names.
Are you sure you want to continue connecting (yes/no/[fingerprint])?
```

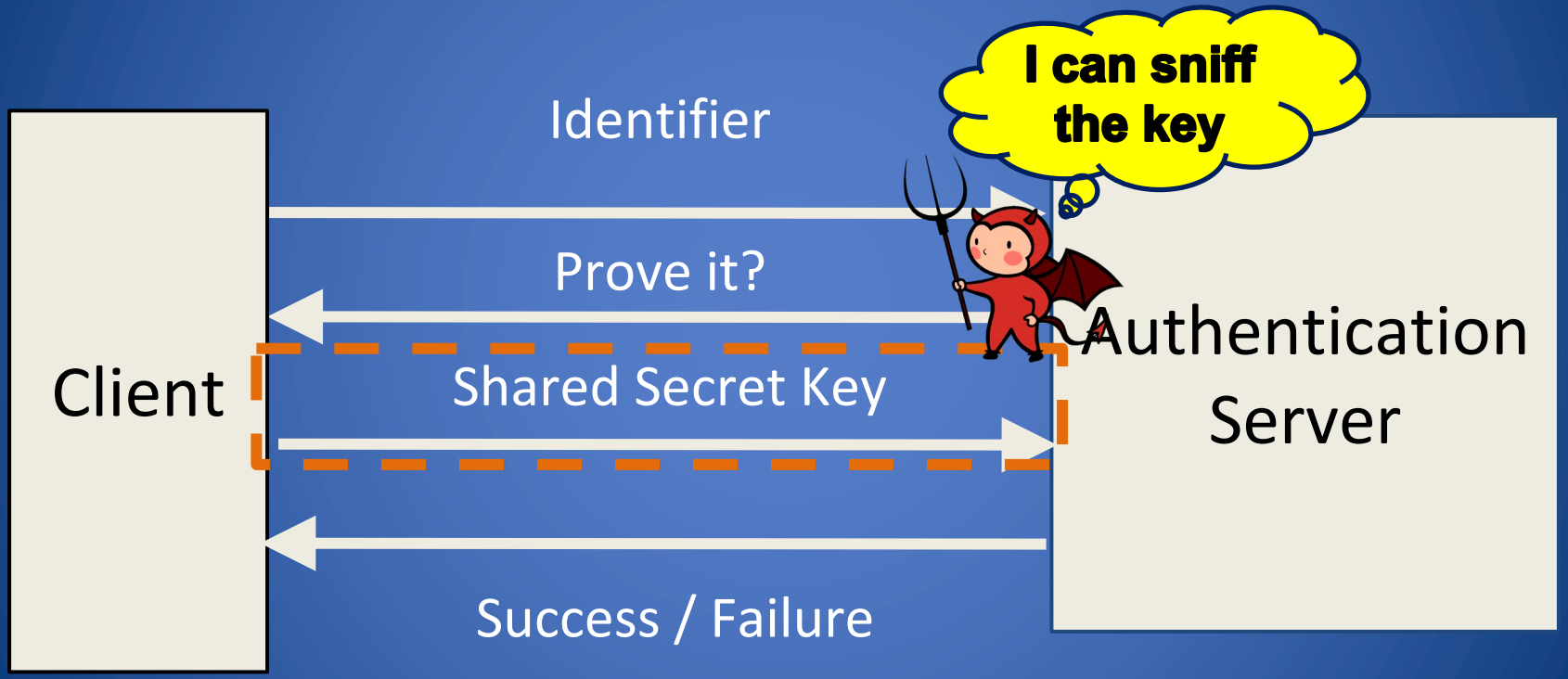
- TLS certificates (details much later in the course)

Authentication protocols

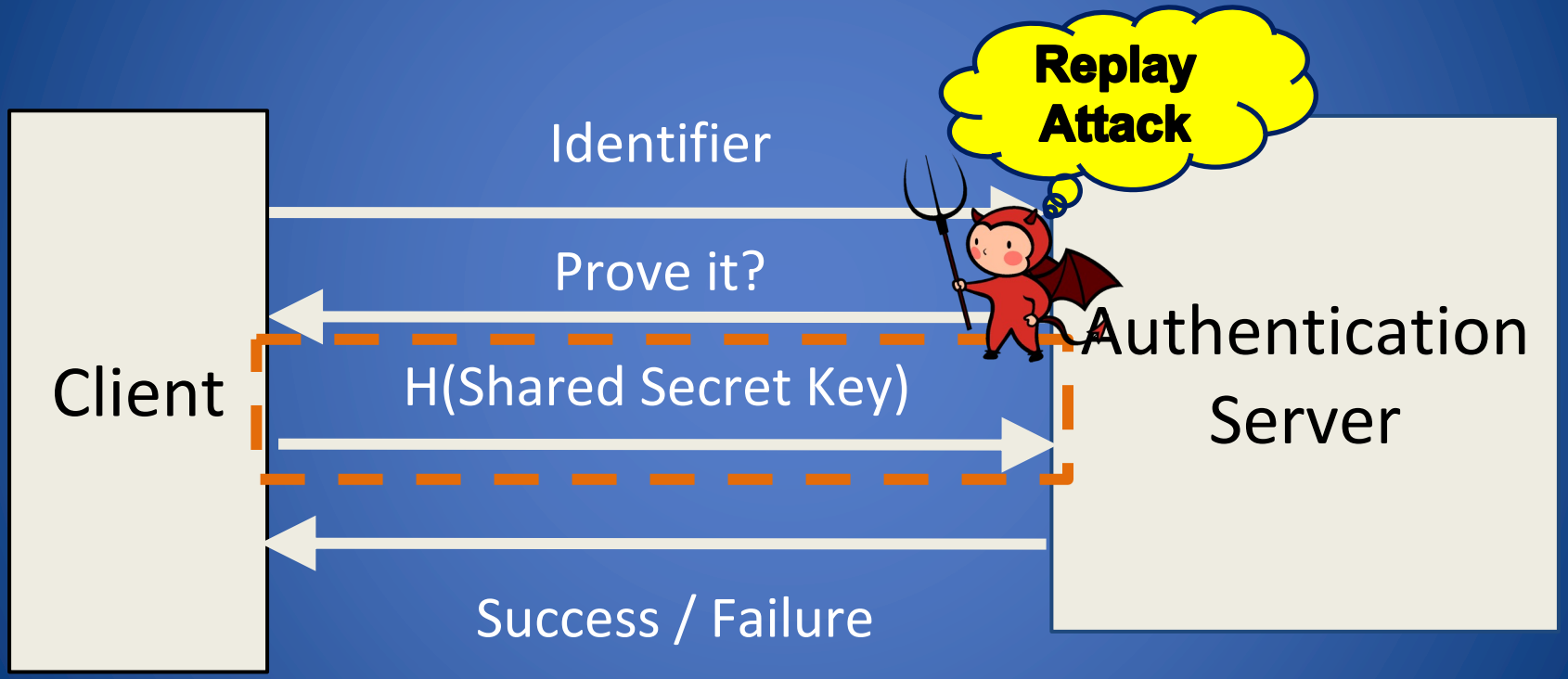
How to authenticate two *systems*?



Better Authentication



Even Better Authentication



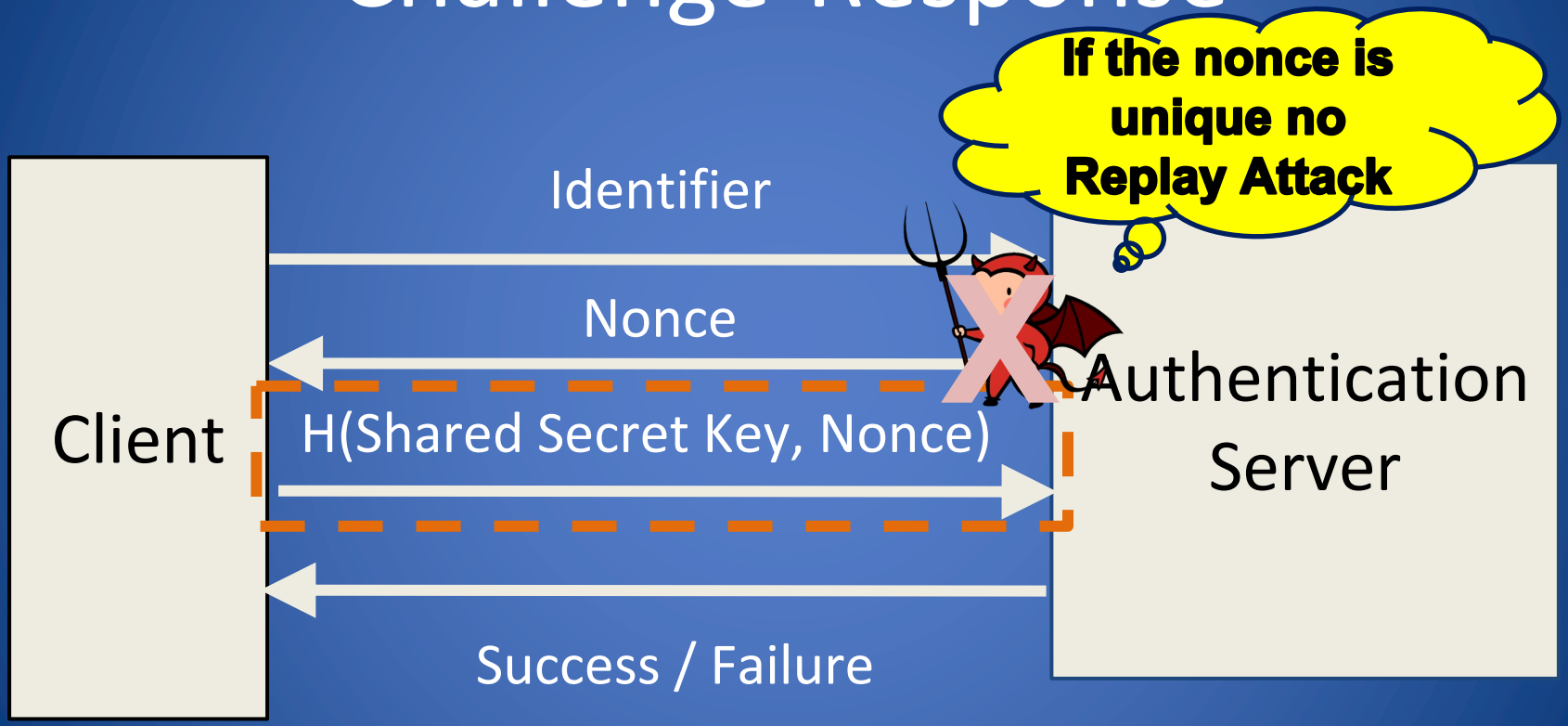
Challenge-Response

- Use ***challenge-response***, to prevent replay attack
  - Goal is to avoid the reuse of the same credential
- Suppose Client wants to authenticate Server
  - ***Challenge*** sent from Server to Client
- Challenge is chosen so that…
  - Replay is not possible
  - Only Client can provide the correct ***response***
  - Server can verify the response

Nonce

- To ensure “freshness”, can employ a **nonce**
  - Nonce == **n**umber used **once**
- What to use for nonces?
  - A unique random string
- What should the Client do with the nonce?
  - Transform the nonce using the shared secret
- How can the Server verify the response?
  - Server knows the shared secret and the nonce, so can check if the response is correct

Challenge-Response



Authentication protocols

- Challenge response mainly relies on nonce
- What if nonce wasn’t random?
- Harder to authenticate humans, more on that later…

Summary

- Formalizing Encryption Security
  - IND-CPA model
- Authentication in Crypot
  - Message Authentication Codes
  - CBC-MAC and HMAC
  - Padding Oracle
  - Authenticated Encryption with Associated Data (AEAD)
- Digital signature
  - Authenticity, Unforgeability, Nonrepudiation, Integrity
- Challenge Response authentication