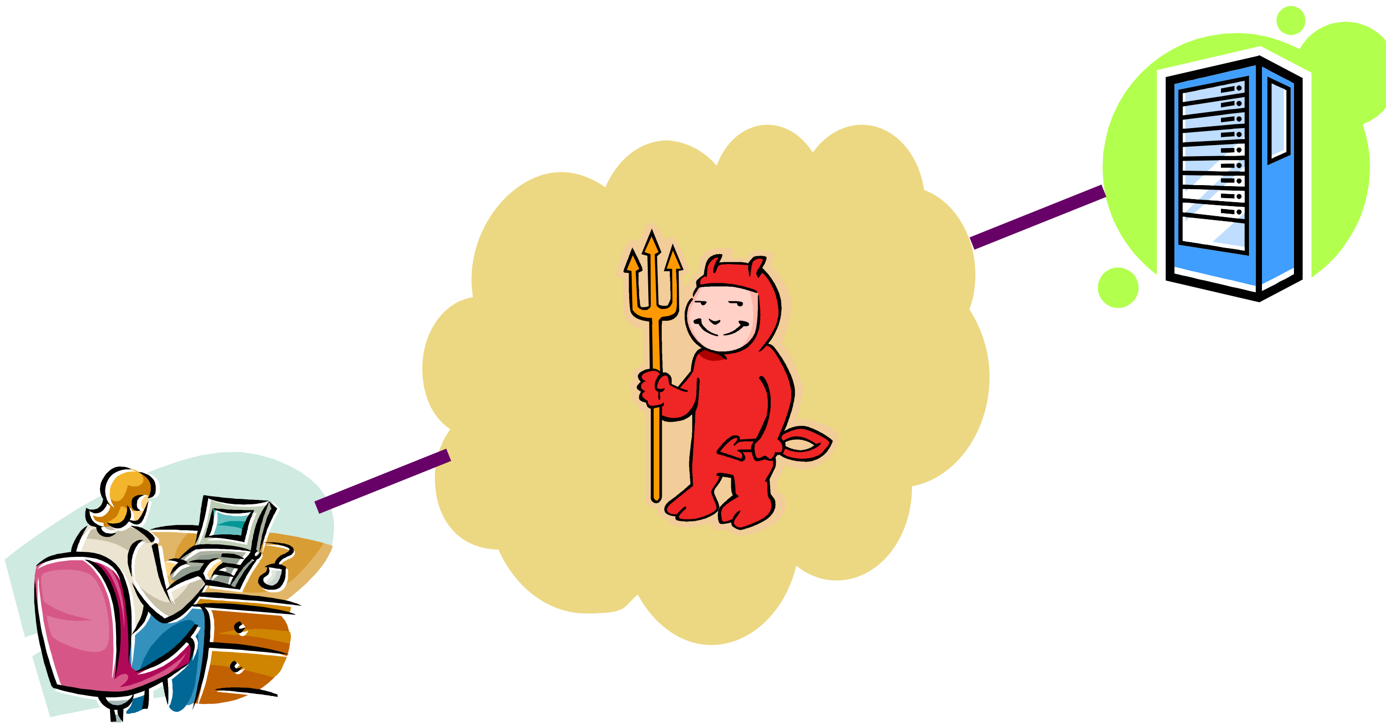
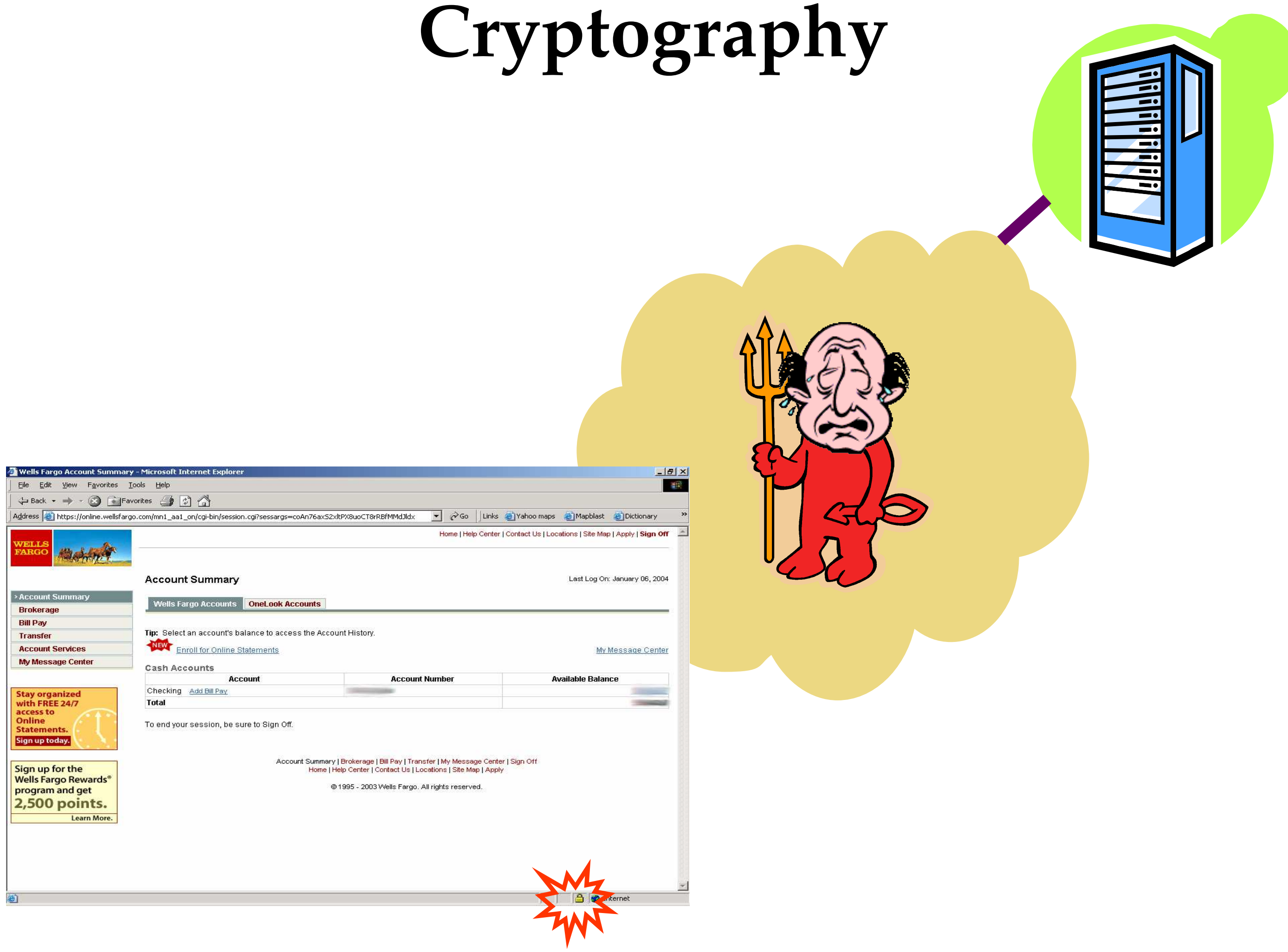
Recall from last lecture



- **To a first approximation, attackers control network**
- **Next two lectures: How to defend against this**
  1. Communicate securely despite insecure networks – *cryptography*
  2. Secure small parts of network despite wider Internet

Cryptography



- **Crypto important tool for securing communication**
  - But often misused
  - Have to understand what it guarantees and what it doesn't

How Cryptography Helps

- **Secrecy**
  - Encryption
- **Integrity**
  - Cryptographic hashes
  - Digital signatures
  - Message authentication codes (MACs)
- **Authentication**
  - Certificates, signatures, MACs
- **Availability**
  - Can't usually be guaranteed by cryptography alone

[Symmetric] Encryption

- **Both parties share a secret key K**
- **Given a message M, and a key K:**
  - M is known as the *plaintext*
  - $E(K, M) \rightarrow C$ (C known as the *ciphertext*)
  - $D(K, C) \rightarrow M$
  - Attacker cannot efficiently derive M from C without K
- **Note E and D take same argument K**
  - Thus, also sometimes called *symmetric* encryption
  - Raises issue of how to get K: more on that later
- **Example algorithms: AES, Blowfish, DES, RC4, . . .**

One-time pad

- **Share a completely random key K**
- **Encrypt M by XORing with K:**

$$E(K, M) = M \oplus K$$

- **Decrypt by XORing again:**

$$D(K, C) = C \oplus K$$

- **Advantage: Information-theoretically secure**
  - Given C but not K, any M of same length equally likely
  - Also: fast!
- **Disadvantage: K must be as long as M**
  - Makes distributing K for each message difficult

Idea: Computational security

- **Distribute small K securely (e.g., 128 bits)**
- **Use K to encrypt far larger M (e.g., 1 MByte file)**
- **Given $C = E(K, M)$, may be only one possible M**
  - If M has redundancy
- **But believed computationally intractable to find**
  - E.g., could try every possible K, but 2^{128} keys a lot of work!

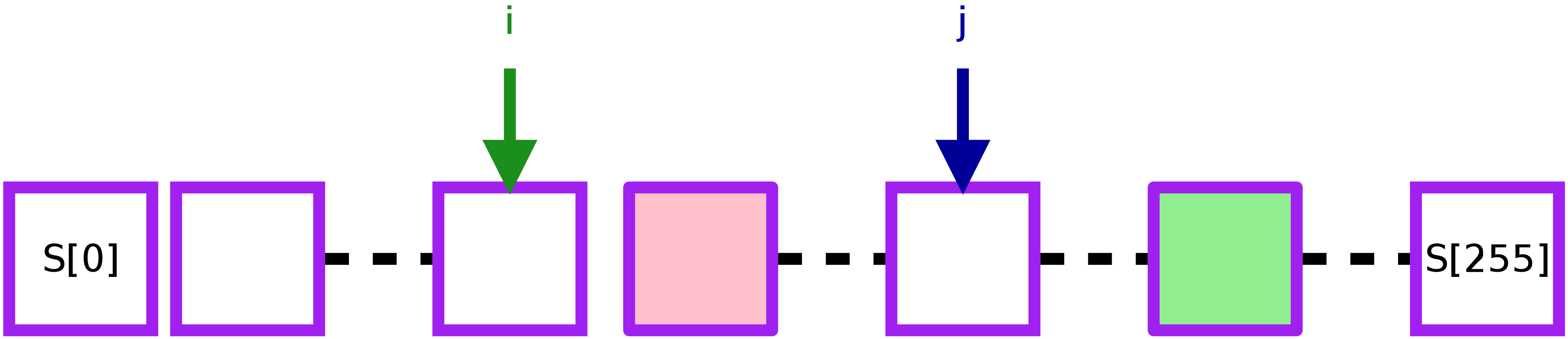
Types of encryption algorithms

- **Stream ciphers – pseudo-random pad**
  - Generate pseudo-random stream of bits from short key
  - Encrypt/decrypt by XORing with stream as if one-time pad
  - But **NOT** one-time PAD! (People who claim so are frauds!)
  - In practice, many stream ciphers uses have run into problems
- **More common algorithm type: Block cipher**
  - Operates on fixed-size blocks (e.g., 64 or 128 bits)
  - Maps plaintext blocks to same size ciphertext blocks
  - Today should use AES; other algorithms: DES, Blowfish, ...

Example stream cipher (RC4)

- **Initialization:**
  - $S[0 \ldots 255] \leftarrow$ permutation $\langle 0, \ldots 255 \rangle$ (based on key); $i \leftarrow 0$; $j \leftarrow 0$;
- **Generating pseudo-random bytes:**

$$i \leftarrow (i+1) \bmod 256;$$
$$j \leftarrow (j + S[i]) \bmod 256;$$
$$\textbf{swap } S[i] \leftrightarrow S[j];$$
$$\textbf{return } S\left[(S[i] + S[j]) \bmod 256\right];$$



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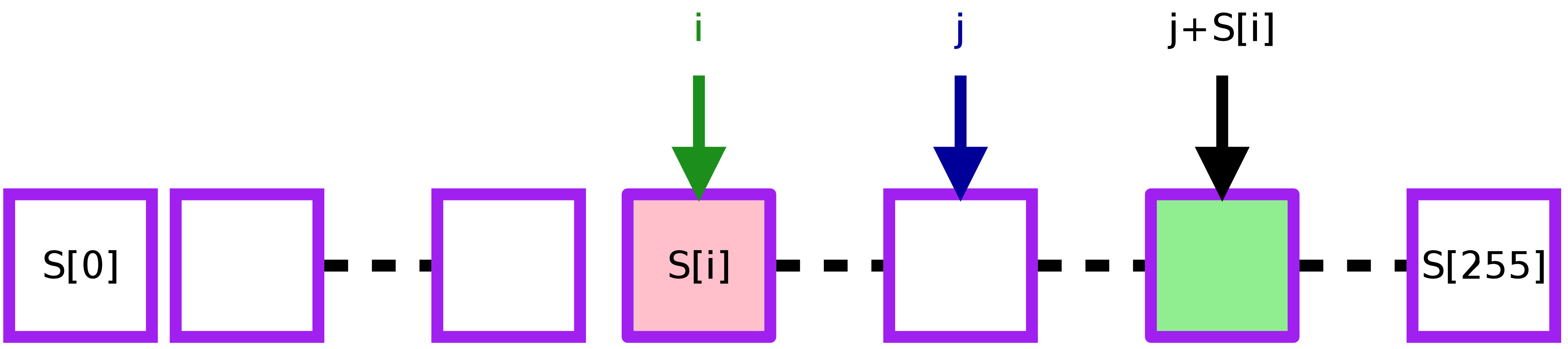

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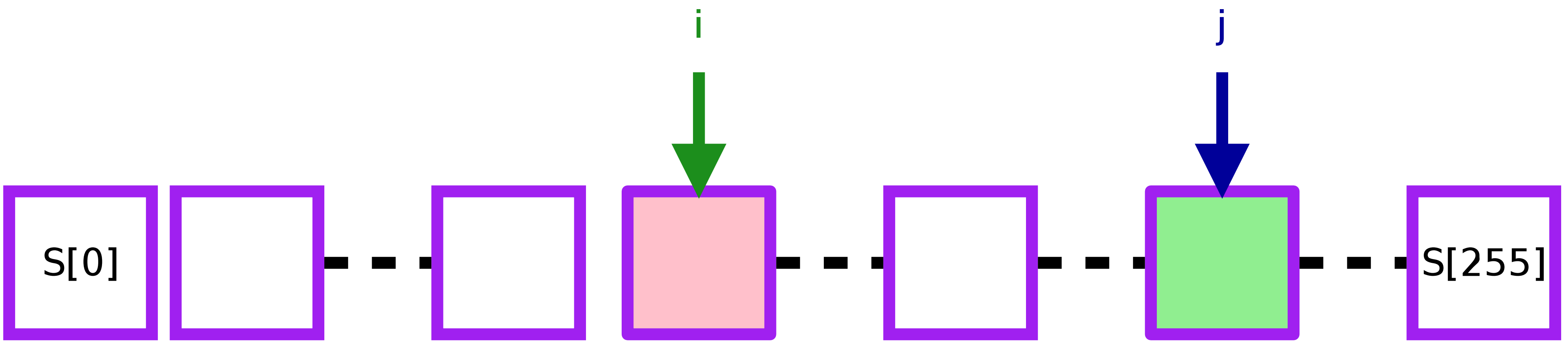

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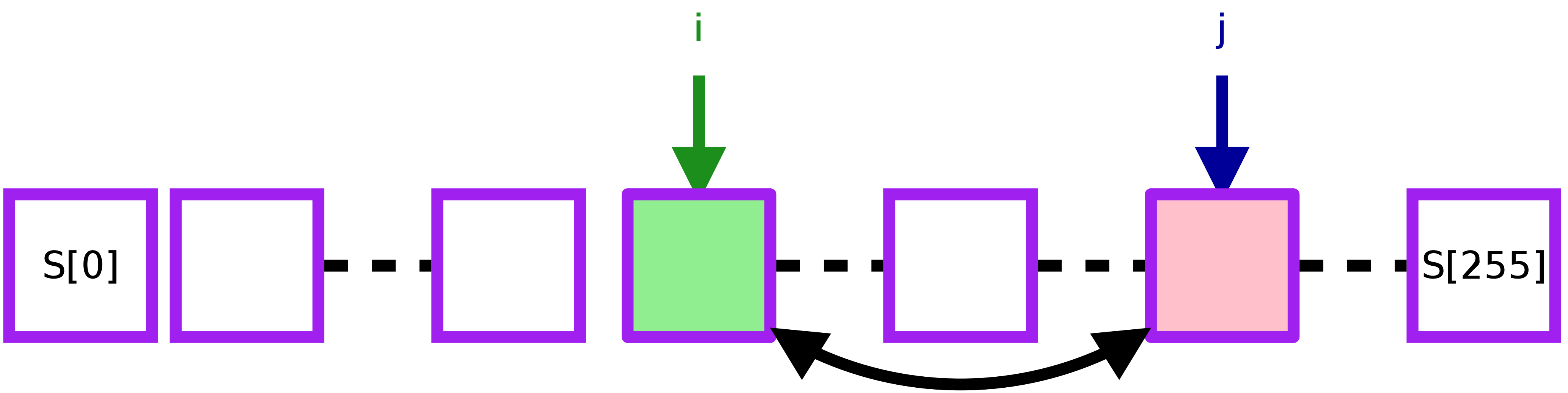

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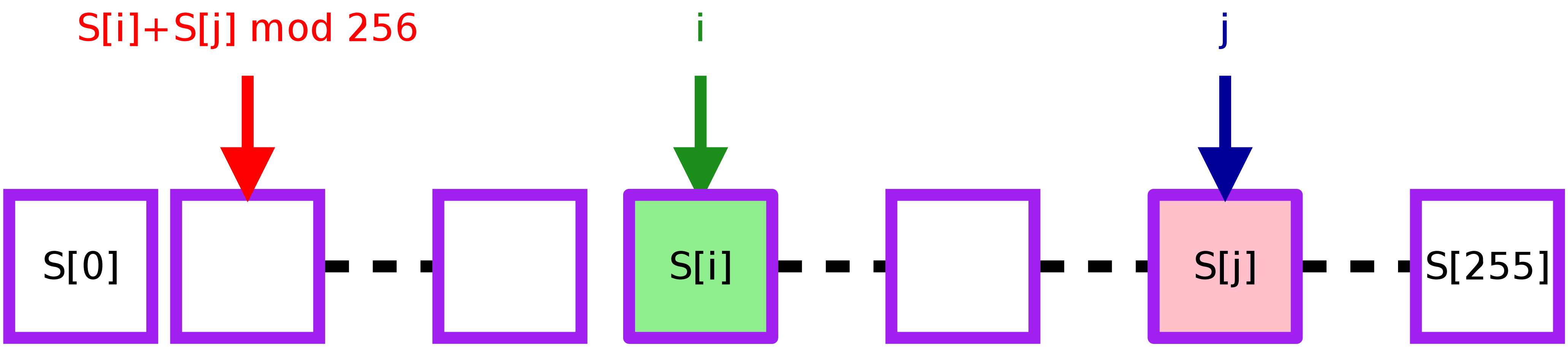


RC4 security

- **Warning: Lecture goal just to give a feel**
  - May omit critical details necessary to use RC4 and other algorithms securely
- **RC4 Goal: Indistinguishable from random sequence**
  - Given part of the output stream, it should be intractable to distinguish it from a truly random string
- **Problems**
  - Second byte of RC4 is 0 with twice expected probability [MS01]
  - Bad to use many related keys (see WEP 802.11b) [FMS01]
  - Recommendation: Discard the first 256 bytes of RC4 output [RSA, MS]

Example use of stream cipher

- **Pre-arrange to share secret s with web vendor**
- **Exchange payment information as follows**
  - Send: $E(s,$ "Visa card #3273…")
  - Receive: $E(s,$ "Order confirmed, have a nice day")
- **Now an eavesdropper can't figure out your Visa #**

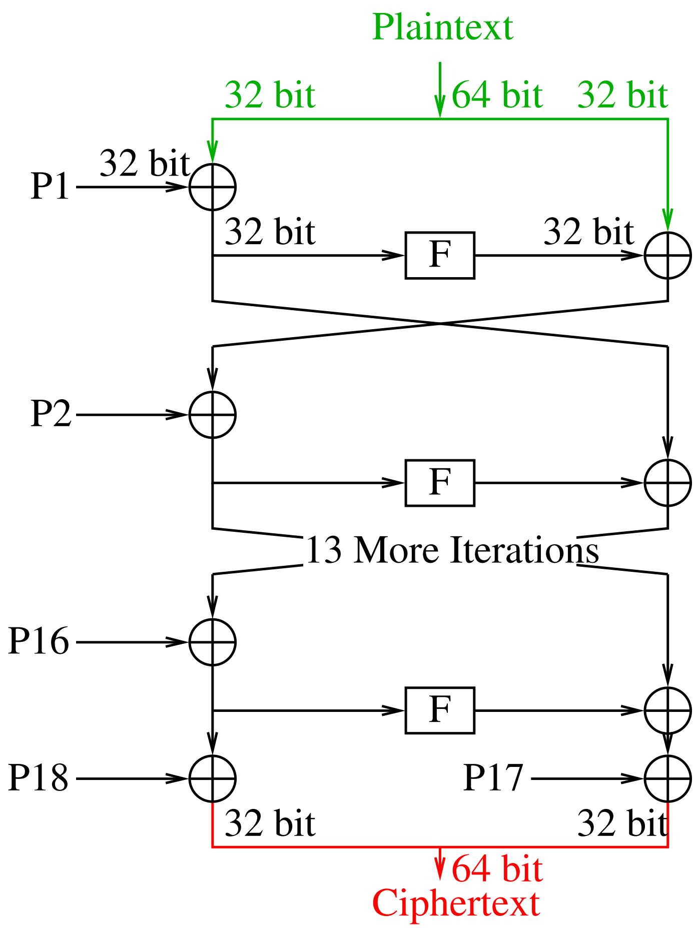
Wrong!

- **Let's say an attacker has the following:**
  - $c_1 = \text{Encrypt}(s, \text{“Visa card \#3273}\ldots\text{”})$
  - $c_2 = \text{Encrypt}(s, \text{“Order confirmed, have a nice day”})$
- **Now compute:**
  - $m \leftarrow c_1 \oplus c_2 \oplus$ “Order confirmed, have a nice day”
- **Lesson: Never re-use keys with a stream cipher**
  - Similar lesson applies to one-time pads
    (That's why they're called **one-time** pads.)

Wired Equivalent Privacy (WEP)

- **Initial security standard for 802.11**
  - Serious weaknesses discovered: able to crack a connection in minutes
  - Replaced by WPA in 2003
- **Stream cipher, basic mode uses 64-bit key: 40 bits are fixed and 24 bits are an initialization vector (IV), specified in the packet**
  - One basic flaw: if IV ever repeated (only 4 million packets), then key is reused
  - Many implementations would reset IV on reboot
- **Other flaws include IV collisions, altered packets, etc.**

Example block cipher (blowfish)



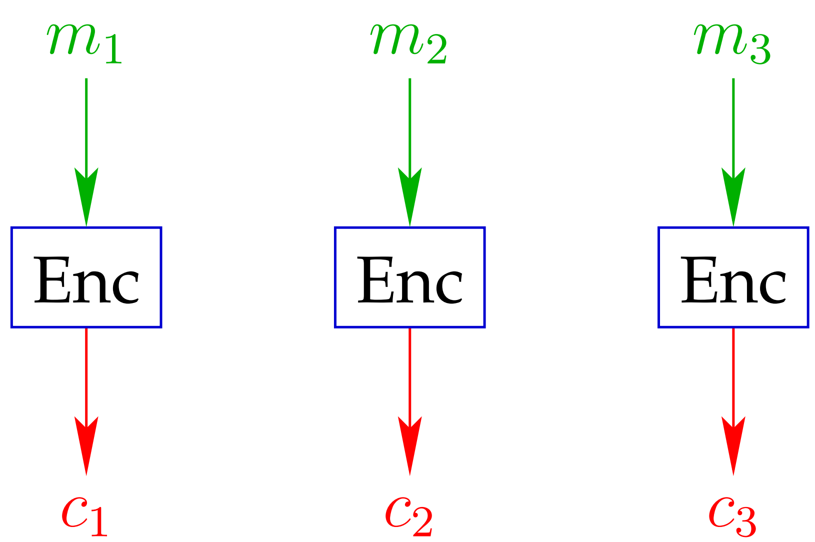
"Feistel network"

- **Derive F and 18 subkeys ($P_1 \ldots P_{18}$) from key**
- **Divide plaintext block into two halves, L_0 and R_0**
- $R_i = L_{i-1} \oplus P_i$
  $L_i = R_{i-1} \oplus F(R_i)$
- $R_{17} = L_{16} \oplus P_{17}$
  $L_{17} = R_{16} \oplus P_{18}$
- **Output $L_{17}R_{17}$.**

(Note: This is just to give an idea; it's not a complete description)

Using a block cipher

- **In practice, message may be more than one block**
- **Encrypt with ECB (electronic code book) mode:**
  - Split plaintext into blocks, and encrypt separately

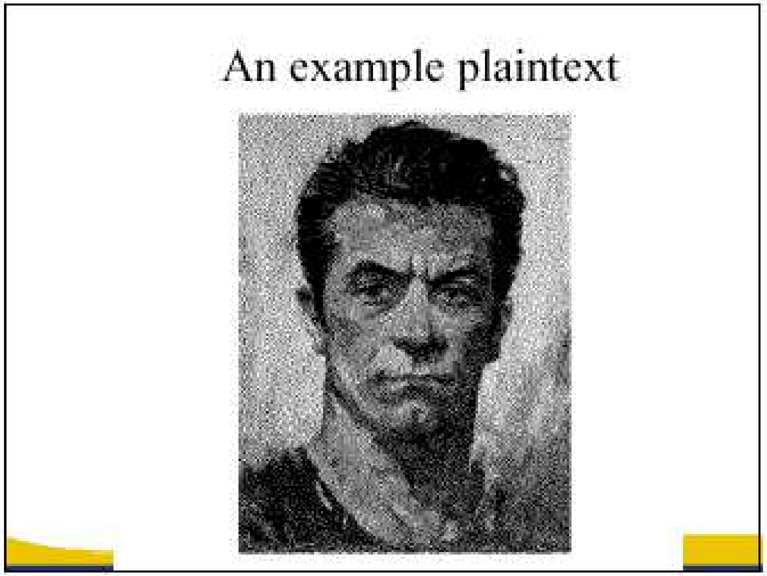


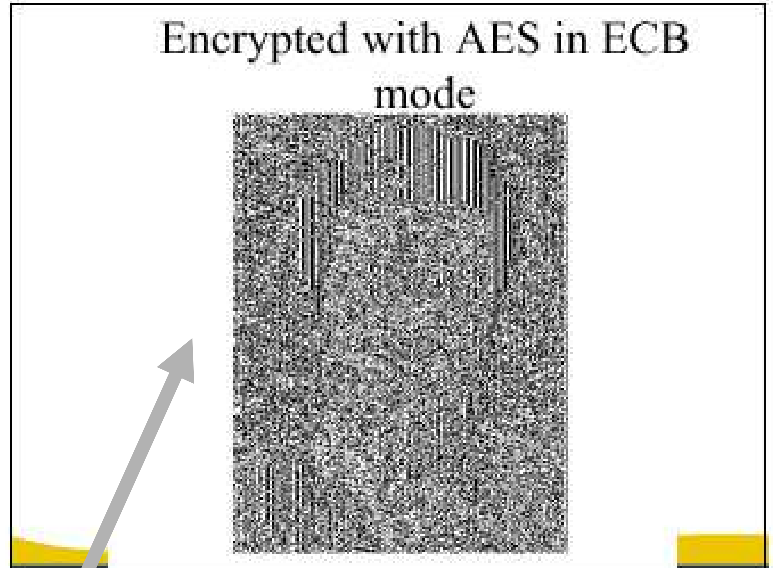
  - Attacker can't decrypt any of the blocks; message secure
- **Note: can re-use keys, unlike stream cipher**
  - Every block encrypted with cipher will be secure

Wrong!

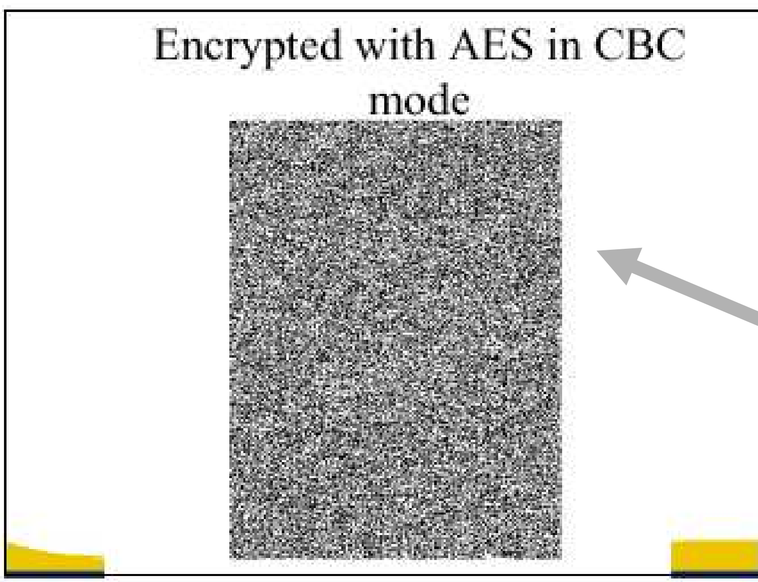
- **Attacker will learn of repeated plaintext blocks**
  - If transmitting sparse file, will know where non-zero regions lie
- **Example: Intercepting military instructions**
  - Most days, send encryption of “nothing to report.”
  - On eve of battle, send “attack at dawn.”
  - Attacker will know when battle plans are being made

Another example [Preneel]



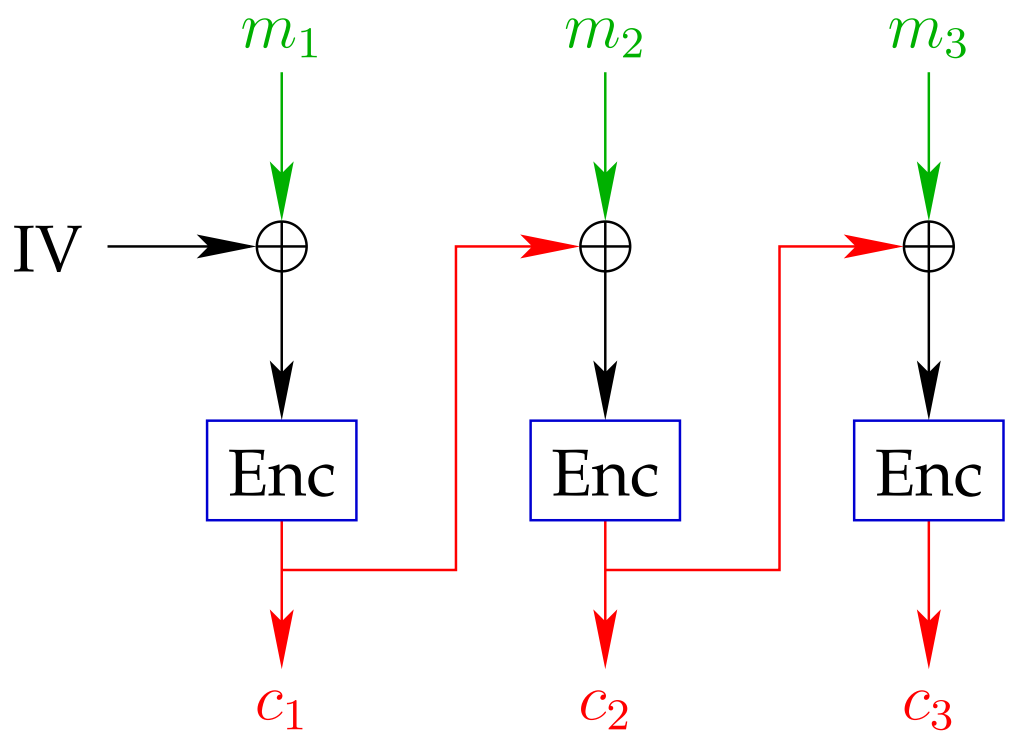


Similar plaintext blocks produce similar ciphertext (see outline of head)



What we want: No apparent pattern

Cipher-block chaining (CBC)



- **Choose initialization vector (IV) for each message**
  - Can be 0 if key only ever used to encrypt one message
  - Choose randomly for each message if key re-used
  - Can be publicly known (e.g., transmit openly with ciphertext)
- $c_1 = E(K, m_i \oplus IV)$**,** $\quad c_i = E(K, m_i \oplus c_{i-1})$
  - Ensures repeated blocks are not encrypted the same

Encryption modes

- **CBC, ECB are encryption modes, but there are others**
- **Cipher Feedback (CFB) mode:** $c_i = m_i \oplus E(K, c_{i-1})$
  - Useful for messages that are not multiple of block size
- **Output Feedback (OFB) mode:**
  - Repeatedly encrypt IV & use result like stream cipher
- **Counter (CTR) mode:** $c_i = m_i \oplus E(K, i)$
  - Useful if you want to encrypt in parallel
- **Q: Given a shared key, can you transmit files securely over net by just encrypting them in CBC mode?**

2-minute break

Problem: Integrity

- **Attacker can tamper with messages**
  - E.g., corrupt a block to flip a bit in next
- **What if you delete original file after transfer?**
  - Might have nothing but garbage at recipient
- **Encryption does not guarantee integrity**
  - A system that uses encryption alone (no integrity check) is often incorrectly designed.
  - Exception: Cryptographic storage (to protect disk if stolen)

Message authentication codes

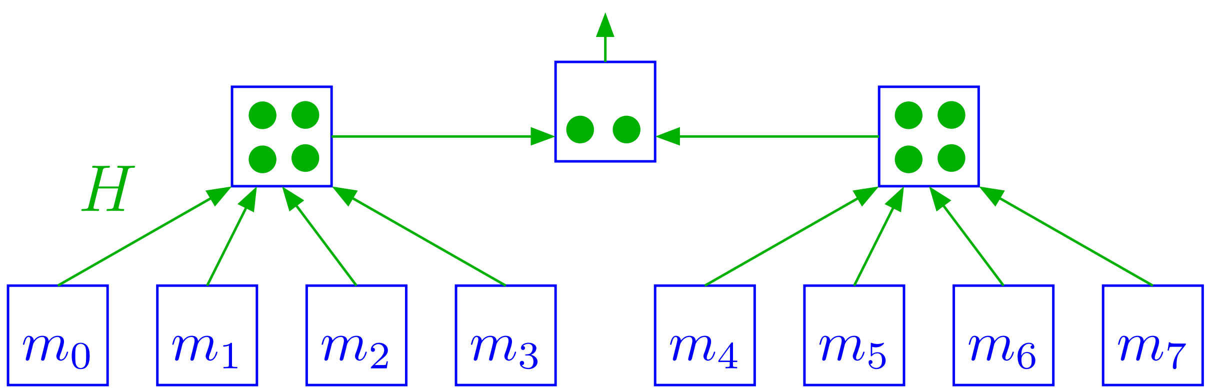
- **Message authentication codes (MACs)**
  - Sender & receiver share secret key K
  - For message m, compute $v \leftarrow \textsc{mac}(K, m)$
  - Recipient runs $\textsc{check}(K, v, m) \rightarrow \{\textbf{yes}, \textbf{no}\}$
  - Intractable to produce valid $\langle m, v \rangle$ without K
- **To send message securely, append MAC**
  - Send $\{m, \textsc{mac}(K, m)\}$ (m could be ciphertext, $E(K', M)$)
  - Receiver of $\{m, v\}$ discards unless $\textsc{check}(K, v, m) = \textbf{yes}$
- **Careful of Replay – don't believe previous $\{m, v\}$**

Cryptographic hashes

- **Hash arbitrary-length input to fixed-size output**
  - Typical output size 160–512 bits
  - Cheap to compute on large input (faster than network)
- **Collision-resistant: Intractable to find $x \neq y$ such that $H(x) = H(y)$**
  - Of course, many such collisions exist
  - But no one has been able to find one, even after analyzing the algorithm
- **Historically most popular hash SHA-1**
  - [Nearly] broken
  - Today should use SHA-256 or SHA-512
  - Competition underway for new hash standard

Applications of cryptographic hashes

- **Small hash uniquely specifies large data**
  - Hash a file, remember the hash value
  - Recompute hash later, if same value no tampering
  - Hashes often published for software distribution
- **Hash tree [Merkle] lets you check small piece of large file or database with log number of nodes**



HMAC

- **Use cryptographic hash to produce MAC**
- $\textbf{HMAC}(K, m) = H(K \oplus \mathsf{opad}, H(K \oplus \mathsf{ipad}, m))$
  - H is a cryptographic hash such as SHA-1
  - ipad is 0x36 repeated 64 times, opad 0x5c repeated 64 times
- **To verify, just recompute HMAC**
  - $\text{CHECK}(K, v, m) = \left(v \stackrel{?}{=} \text{HMAC}(K, m)\right)$
  - Many MACs are deterministic and work like this ("PRFs"), but fastest MACs randomized so CHECK can't just recompute
- **Note: Don't just use H(K,M) as a MAC**
  - Say you have $\{M, \text{SHA-1}(K, M)\}$, but not K
  - Can produce $\{M', \text{SHA-1}(K, M')\}$ where $M' \neq M$
  - Hashes provide collision resistance, but do not prevent spoofing new messages

Order of Encryption and MACs

- **Should you Encrypt then MAC, or vice versa?**
- **MACing encrypted data is always secure**
- **Encrypting $\{$Data+MAC$\}$ may not be secure!**
  - Consider the following secure, but stupid encryption alg
  - Transform $m \to m'$ by mapping each bit to two bits:
    Map $0 \to 00$ (always), $1 \to \{10, 01\}$ (randomly pick one)
  - Now encrypt m' with a stream cipher to produce c
  - Attacker flips two bits of c—if msg rejected, was 0 bit in m

Public key encryption

- **Three randomized algorithms:**
  - *Generate* – $G(1^k) \to K, K^{-1}$ (randomized)
  - *Encrypt* – $E(K, m) \to \{m\}_K$ (randomized)
  - *Decrypt* – $D(K^{-1}, \{m\}_K) \to m$
- **Provides secrecy, like conventional encryption**
  - Can't derive m from $\{m\}_K$ without knowing K^{-1}
- **Encryption key K can be made public**
  - Can't derive K^{-1} from K
  - Everyone can use same pub. key to encrypt for one recipient
- **Note: Encrypt *must* be randomized**
  - Same message must encrypt to different ciphertext each time
  - Otherwise, can easily guess plaintext from small message space (E.g., encrypt "yes", encrypt "no", see which matches message)

Digital signatures

- **Three (randomized) algorithms:**
  - *Generate* – $G(1^k) \to K, K^{-1}$ (randomized)
  - *Sign* – $S\left(K^{-1}, m\right) \to \{m\}_{K^{-1}}$ (can be randomized)
  - *Verify* – $V\left(K, \{m\}_{K^{-1}}, m\right) \to \{\mathbf{yes}, \mathbf{no}\}$
- **Provides integrity, like a MAC**
  - Cannot produce valid $\langle m, \{m\}_{K^{-1}}\rangle$ pair without K^{-1}
  - But only need K to verify; cannot derive K^{-1} from K
  - So K can be publicly known

Popular public key algorithms

- **Encryption: RSA, Rabin, ElGamal**
- **Signature: RSA, Rabin, ElGamal, Schnorr, DSA, …**
- **Warning: Message padding critically important**
  - E.g., basic idea behind RSA encryption simple
  - Just modular exponentiation of large integers
  - But simple transformations of messages to numbers not secure
- **Many keys support both signing & encryption**
  - But Encrypt/Decrypt and Sign/Verify different algorithms!
  - Common error: Sign by "encrypting" with private key

Cost of cryptographic operations

- **Cost of public key algorithms significant**
  - E.g., encrypt or sign only ~ 100 msgs/sec
  - Can only encrypt small messages ($<$ size of key)
  - Signature cost relatively insensitive to message size
  - Some algorithm variants provide faster encrypt/verify (e.g., Rabin, RSA-3 can encrypt $\sim 10,000$ msgs/sec)
- **In contrast, symmetric algorithms much cheaper**
  - Symmetric can encrypt+MAC faster than 1Gbps/sec LAN

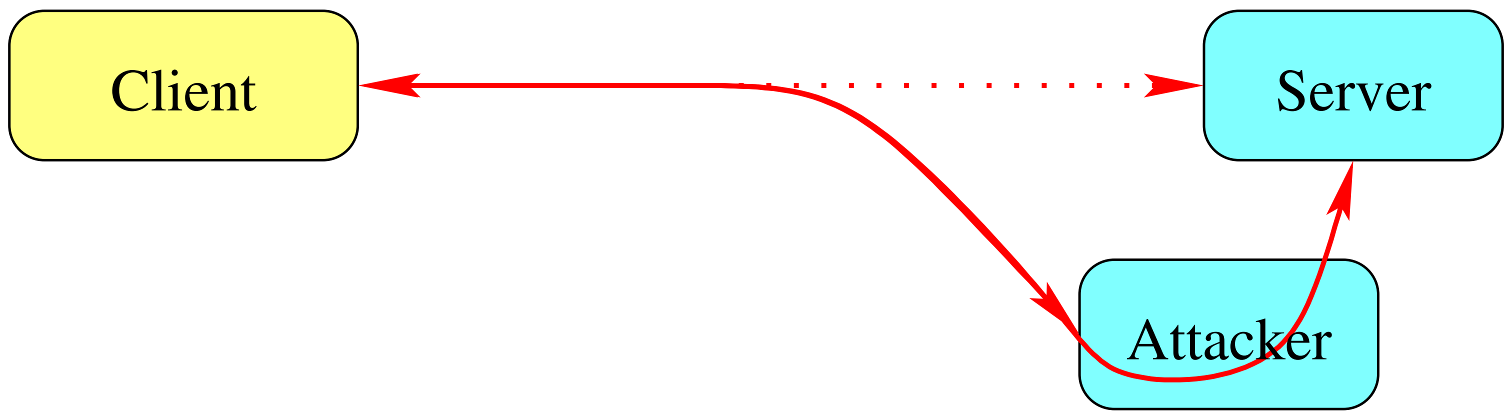
Hybrid schemes

- **Use public key to encrypt symmetric key**
  - Send message symmetrically encrypted: $\{\text{msg}\}_{K_S}, \{K_S\}_{K_P}$
- **Use PK to negotiate secret session key**
  - Use Public Key crypto to establish 4 keys symmetric keys
  - Client sends server: $\{\{m_1\}_{K_1}, \text{MAC}(K_2, \{m_1\}_{K_1})\}$
  - Server sends client: $\{\{m_2\}_{K_3}, \text{MAC}(K_4, \{m_2\}_{K_3})\}$
- **Often want mutual authentication (client & server)**
  - Or more complex, user(s), client, & server
- **Common pitfall: signing underspecified messages**
  - E.g., Always specify intended recipient in signed messages
  - Should also specify expiration, or better yet fresh data
  - Otherwise like signing a blank check…

Server authentication

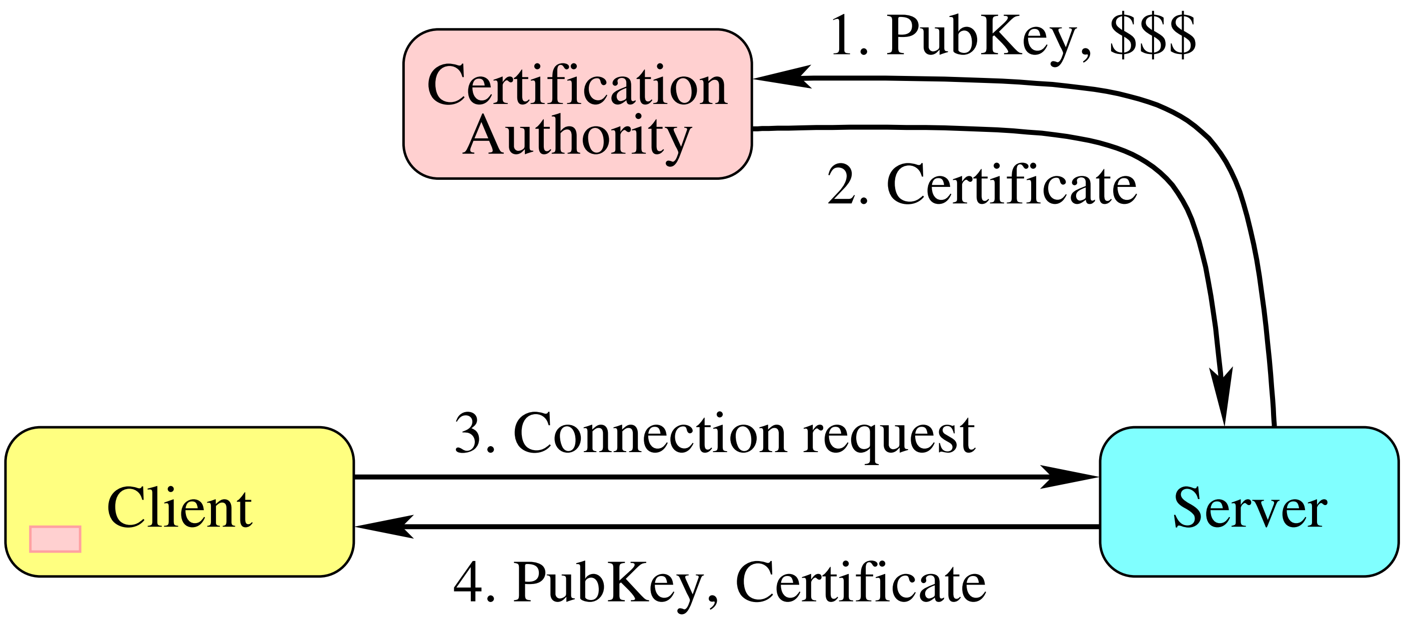
- **Often want to communicate securely with a server**
- **Easy once you have server's public key**
  - Use public key to bootstrap symmetric keys
- **Problem: Key management**
  - How to get server's public key?
  - How to know the key is really server's?

Danger: impersonating servers



- **Attacker pretends to be server, gives its own pub key**
- **Attacker mounts man-in-the-middle attack**
  - Looks just like server to client (except for different public key)
  - Attacker sees, then re-encrypts sensitive communications
  - Attacker can also send bad data back to client

One solution: Certificate authorities (CAs)



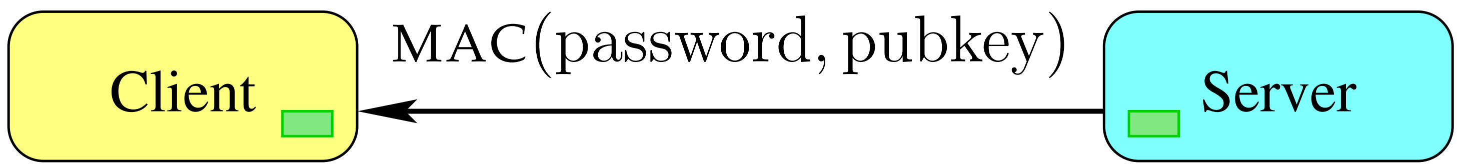
- **Everybody trusts some certificate authority**
- **Everybody knows CA's public key**
  - E.g., built into web browser
- **This is how HTTPS (over SSL/TLS) works**
  - Active when you see padlock in your web browser

Digital certificates

- **A digital certificate binds a public key to name**
  - E.g., "`www.ebay.com`'s public key is 0x39f32641..."
  - Digitally signed with a CA's private key
- **Certificates can be *chained***
  - E.g., start with root CAs like Verisign
  - Verisign can sign Stanford's public key
  - Stanford can sign keys for `cs.stanford.edu`, etc.
  - Not as widely supported as it should be
    (Maybe because CAs want $300 for every Stanford server)
- **Assuming you trust the CA, solves the key management problem**

Another solution: Use passwords

- **User remembers a password to authenticate himself**
  - Server stores password or secret derived from password
  - Can then use password to authenticate server to client, as well
- **Simplest example:**



- **Big limitations of above (simple) protocol:**
  - Users choose weak passwords
  - Since pubkey known, attacker gets one message from server, then guess all common passwords offline
  - Also, users employ same passwords at multiple sites
- **Limitations addressed by fancier crypto protocols**
  - E.g., SRP, PAKE$_2^+$ protocols developed here at Stanford