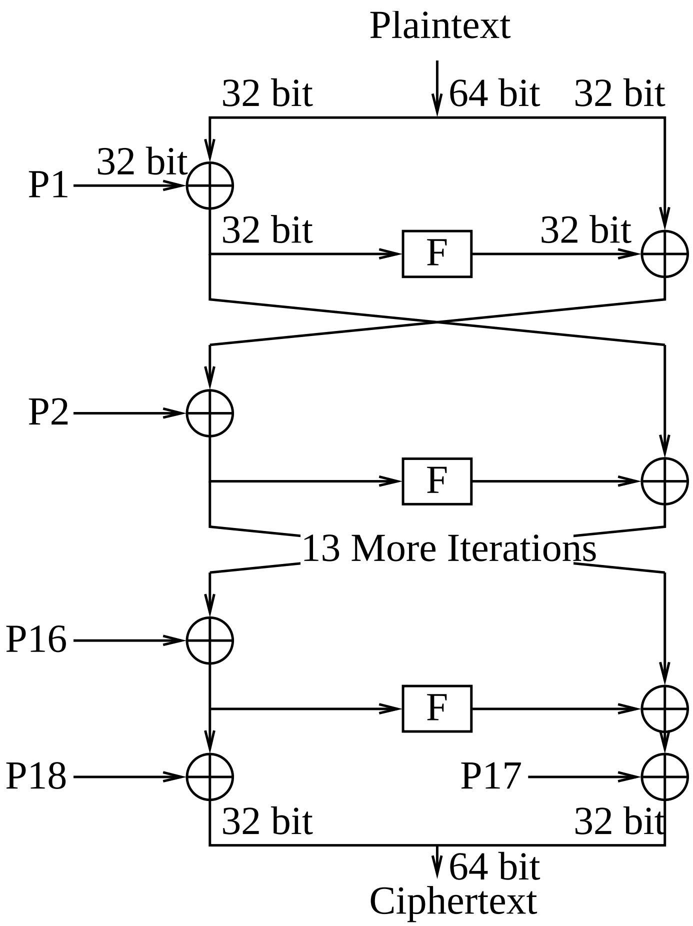
Keeping communications secret

- **Encryption guarantees secrecy**
- **Symmetric encryption**
  - Encryption algorithm comprises two functions E and D
  - To communicate secretly, parties share secret key K
  - Given message M, $E(K, M) \to C$, $D(K, C) \to M$
  - M is plaintext, C is ciphertext
  - Attacker cannot derive M from C without K
- **Most common algorithm type: Block cipher**
  - AES from Lab 4 is a block cipher
  - Operates on fixed-size blocks (e.g., 64 or 128 bits)
  - Maps plaintext blocks to same size ciphertext blocks

Example block cipher (blowfish)



- **Derive F and 18 subkeys from Key—$P_1 \ldots P_{18}$**
- **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)

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 like lab 4 (just protects against stolen or copied data)

Message authentication codes

- **Message authentication codes (MACs)**
  - Sender & receiver share secret key K
  - On message m, $\mathrm{MAC}(K, m) \rightarrow v$
  - Attacker cannot produce valid $\langle m, v\rangle$ without K
- **To send message securely, append MAC**
  - Send $\{m, \mathrm{MAC}(K, m)\}$, or encrypt $\{m, \mathrm{MAC}(K, m)\}_{K'}$
  - Receiver of $\{m, v\}$ checks $v \stackrel{?}{=} \mathrm{MAC}(K, m)\}$
- **Careful of Replay – don't believe previous** $\{m, v\}$

Cryptographic hashes

- **Hash arbitrary-length input to fixed-size output**
  - Typical output size 128 or 160 bits
  - Cheap to compute on large input (faster than network)
- **Collision-resistant: Computationally infeasible to find** $x \neq y,\ H(x) = H(y)$
  - Many such collisions exist
  - No one has been able to find one, even after analyzing the alrogithm
- **Several hashes in common use (SHA-1, MD5)**

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
- $\textbf{HMAC}(K, m) = H(K \oplus \mathsf{opad}, H(K \oplus \mathsf{ipad}, m))$
  - H is a cryptographic hash like SHA-1
  - ipad is 0x36 repeated 64 times, opad 0x5c repeated 64 times

Public key encryption

- **Three randomized algorithms:**
  - *Generate* – $G(1^k) \to K, K^{-1}$
  - *Encrypt* – $E(K, m) \to \{m\}_K$
  - *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 the same public key to encrypt messages for one recipient.

Digital signatures

- **Three (randomized) algorithms:**
  - *Generate* – $G(1^k) \to K, K^{-1}$
  - *Sign* – $S\left(K^{-1}, m\right) \to \{m\}_{K^{-1}}$
  - *Verify* – $V\left(K, \{m\}_{K^{-1}}, m\right) \to \{\mathbf{true}, \mathbf{false}\}$
- **Provides integrity, like a MAC**
  - Cannot produce valid $\langle m, \{m\}_{K^{-1}}\rangle$ pair without K^{-1}
- **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

Operation	msec
Encrypt	1.11
Decrypt	39.62
Sign	40.56
Verify	0.10

[1,280-bit Rabin-Williams keys on 550 MHz K6]

- **Cost of public key algorithms significant**
  - Encryption only on small messages (< size of key)
  - Signature cost relatively insensitive to message size
- **In contrast, symmetric algorithms much cheaper**
  - Symmetric can encrypt+MAC faster than 100Mbit/sec LAN

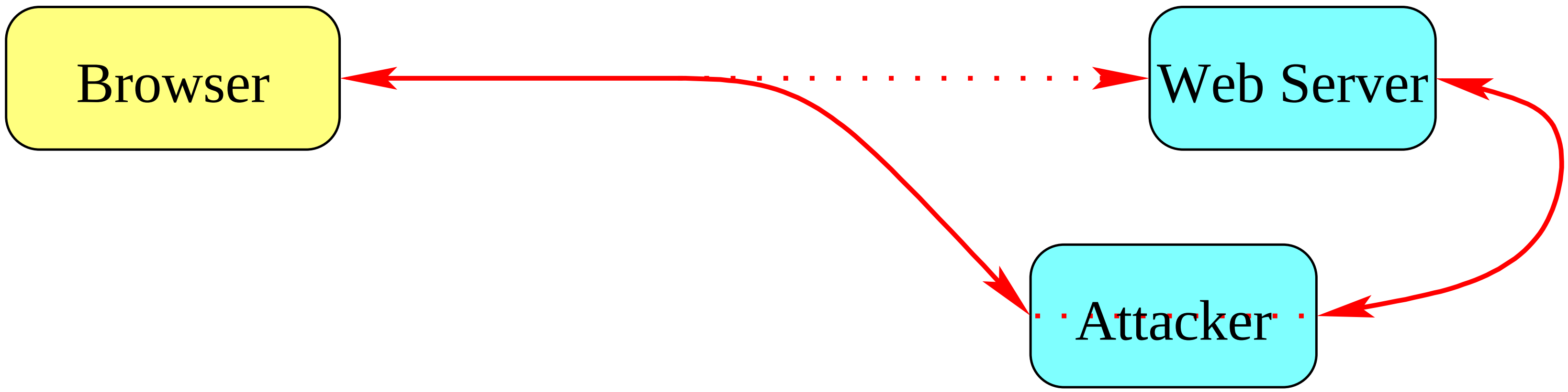
Hybrid schemes

- **Use public key to encrypt symmetric key**
  - Send message symmetrically encrypted:
    $K_S \leftarrow \{0,1\}^{128},\ \{\mathrm{msg}\}_{K_S}, \{K_S\}_{K_{\mathrm{Pub}}}$
- **Use PK to negotiate secret session key**
  - E.g., Client sends server $\{K_1, K_2, K_3, K_4\}_{K_P}$
  - Client sends server: $\{m_1\}_{K_1},\ \mathrm{MAC}\left(K_2, \{m_1\}_{K_1}\right)$
  - Server sends client: $\{m_2\}_{K_3},\ \mathrm{MAC}\left(K_4, \{m_2\}_{K_3}\right)$
  - Note: Better to MAC encryped data than vice versa
- **Often want mutual authentication (client & server)**
  - Or more complex, user(s), client, & server

Server authentication

- **An approach: Use public key cryptography**
  - Give client public key of server
  - Lets client authenticate secure channel to server
- **Problem: Key management problem**
  - How to get server′s public key?
  - How to know the key is really server′s?

Otherwise: Attacker impersonates server

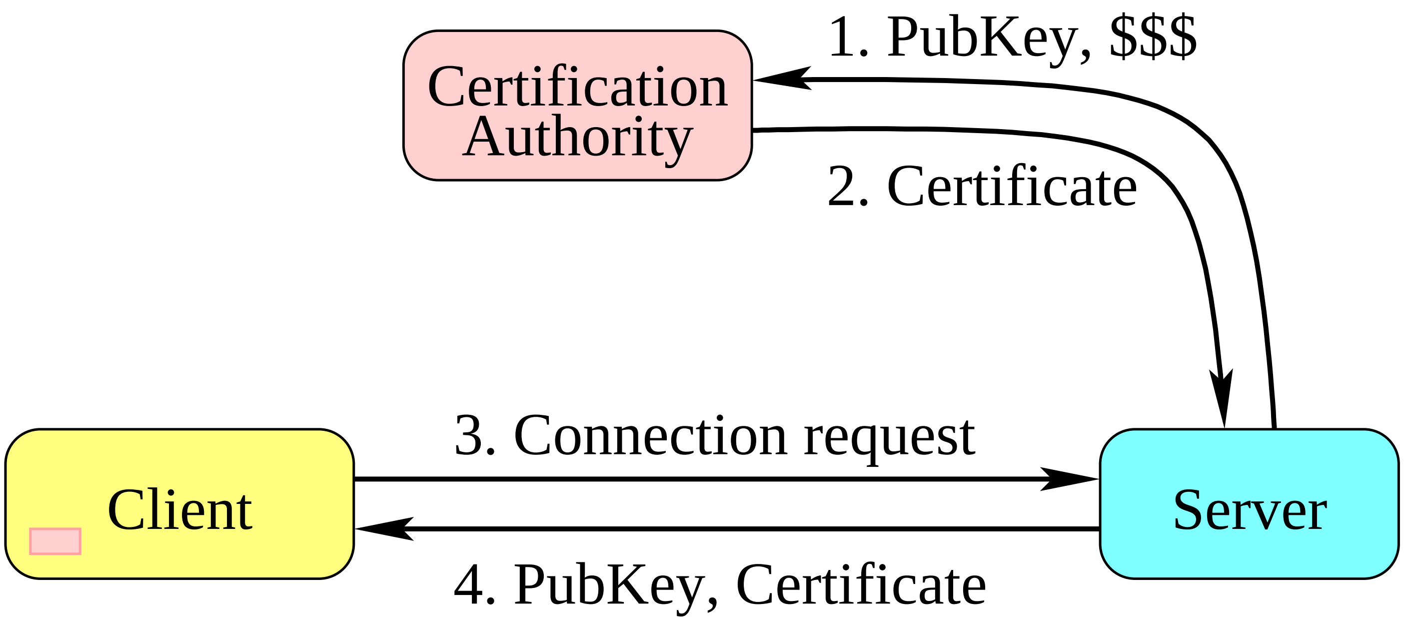


- **Man-in-the-middle attack:**
  - Attacker emulates server when talking to client
  - Attacker emulates client when talking to server
  - Attacker passes most messages through unmodified
  - Attacker substitutes own public key for client's & server's
  - Attacker records secret data, or tampers to cause damage

Key management

- **Put public keys in the phone book**
  - How do you know you have the real phone book?
  - How is a program supposed to use phone book www.phonebook.com? (are you talking to real web server)
- **Exchange keys with people in person**
- **"Web of trust" – get keys from friends you trust**

Certification authorities



- **Everybody trusts some certification authority**
- **Everybody knows authority's public key**
  - E.g., built into web browser