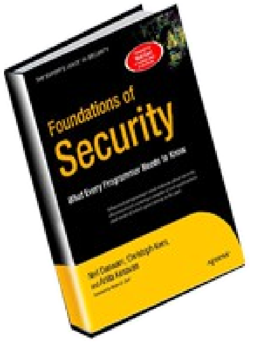
CHAPTER 12

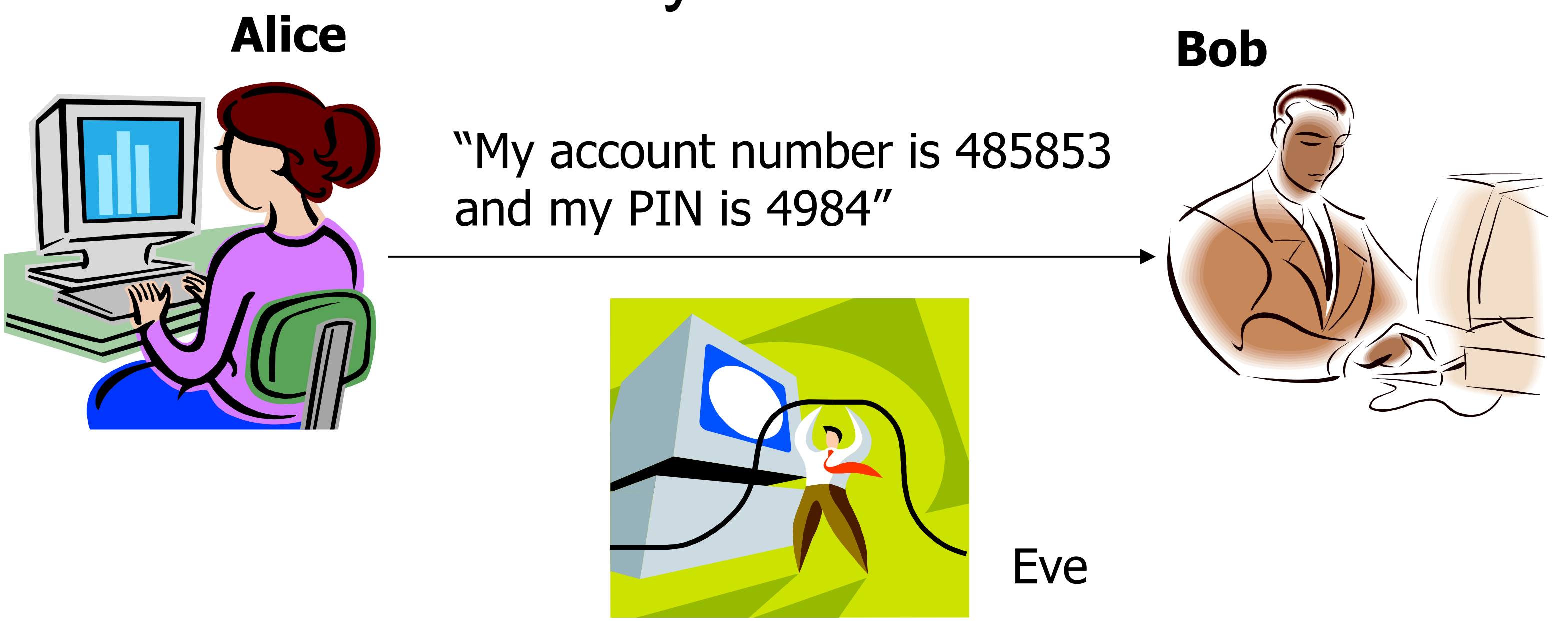
Symmetric Key Cryptography

Slides adapted from "Foundations of Security: What Every Programmer Needs To Know" by Neil Daswani, Christoph Kern, and Anita Kesavan (ISBN 1590597842; http://www.foundationsofsecurity.com). Except as otherwise noted, the content of this presentation is licensed under the Creative Commons 3.0 License.



12.1. Introduction to Cryptography

- Goal: Confidentiality



- Message “sent in clear”: Eve can overhear
- Encryption unintelligible to Eve; only Bob can decipher with his secret key (shared w/ Alice)

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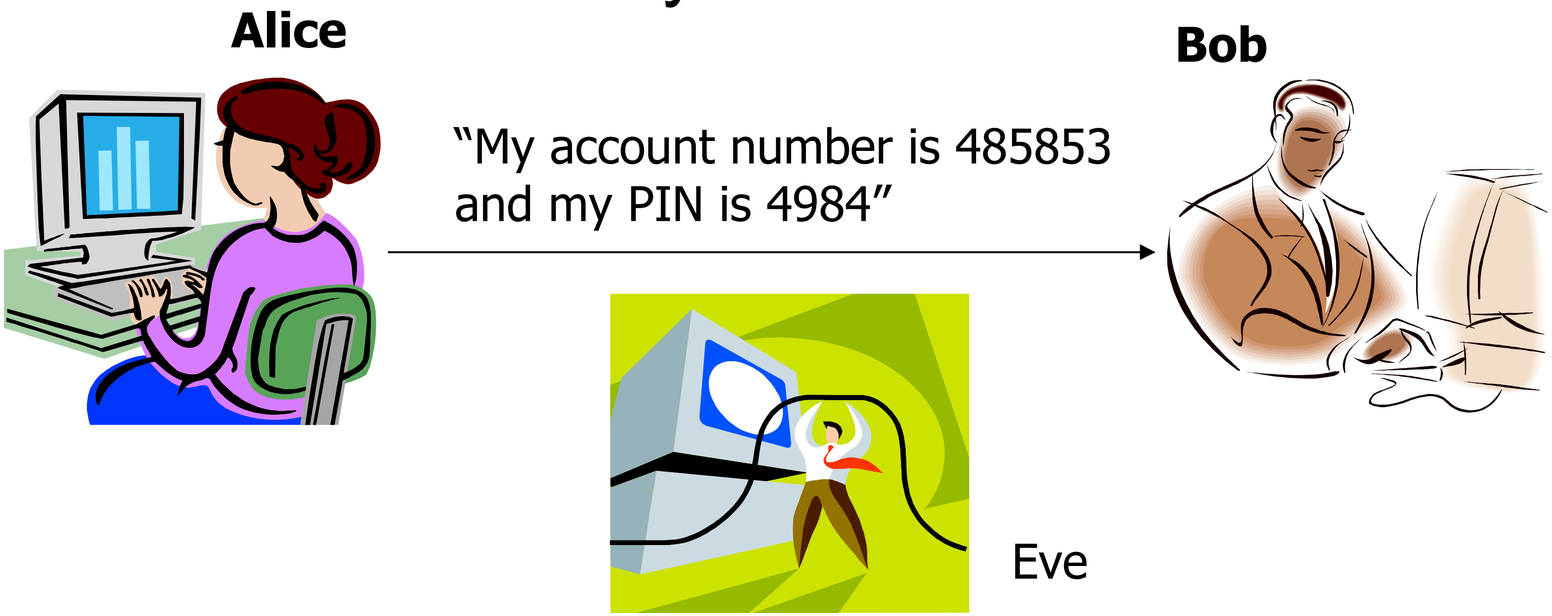


- Message “sent in clear”: Eve can overhear
- Encryption unintelligible to Eve; only Bob can decipher with his secret key (shared w/ Alice)

12.1.1. Substitution Ciphers

- Plaintext: **`meet me at central park`**
- Ciphertext: **`phhw ph dw fhqwudo sdun`**

- Plain: `abcdefghijklmnopqrstuvwxyz`
- Cipher: `defghijklmnopqrstuvwxyzabc`

- Key is 3, i.e. shift letter right by 3
- Easy to break due to frequency of letters
- Good encryption algorithm produces output that looks random: equal probability any bit is 0 or 1

12.1.2. Notation & Terminology

- m = message (plaintext), c = ciphertext
- F = encryption function
- F^{-1} = decryption function

Cipher

- k = key (secret number)

- $c = F(m,k) = F_k(m)$ = encrypted message
- $m = F^{-1}(c,k) = F^{-1}{}_k(c)$ = decrypted message
- Symmetric cipher: $F^{-1}(F(m,k), k) = m$, same key

Symmetric Encryption

- Alice encrypts a message with the ***same*** key that Bob uses to decrypt.

Alice		Bob
1. Construct m		
2. Compute $c = F(m,\mathbf{k})$		
3. Send c to Bob	$\xrightarrow{c}$	4. Receive c from Alice
		5. Compute $d = F^{-1}(c,\mathbf{k})$
		6. $m = d$

- Eve can see c, but cannot compute m because k is only known to Alice and Bob

12.1.3. Block Ciphers

- Blocks of bits (e.g. 256) encrypted at a time

- Examples of several algorithms:
  - Data Encryption Standard (DES)
  - Triple DES
  - Advanced Encryption Standard (AES) or Rijndael

- Internal Data Encryption Algorithm (IDEA), Blowfish, Skipjack, many more… (c.f. Schneier)

12.1.3. DES

- Adopted in 1977 by NIST

- Input: 64-bit plaintext, 56-bit key (64 w/ parity)
- Parity Bits: redundancy to detect corrupted keys
- Output: 64-bit ciphertext
- Susceptible to Brute-Force (try all 2^{56} keys)
  - 1998: machine Deep Crack breaks it in 56 hours
  - Subsequently been able to break even faster
  - Key size should be at least 128 bits to be safe

12.1.3. Triple DES

- Do DES thrice w/ 3 different keys (slower)
- $c = F(F^{-1}(F(m\ ,k_1),k_2),k_3)$ where $F = DES$
  - Why decrypt with k_2?
  - Backwards compatible w/ DES, easy upgrade
- Keying Options: Key Size (w/ Parity)
  - $k_1 \neq k_2 \neq k_3$: 168-bit (192-bit)
  - $k_1 = k_3 \neq k_2$: 112-bit (128-bit)
  - $k_1 = k_2 = k_3$: 56-bit (64-bit) (DES)

12.1.3. AES (Rijndael)

- Invented by 2 Belgian cryptographers
- Selected by NIST from 15 competitors after three years of conferences vetting proposals
- Selection Criteria:
  - Security, Cost (Speed/Memory)
  - Implementation Considerations (Hardware/Software)
- Key size & Block size: 128, 192, or 256 bits (much larger than DES)
- Rely on algorithmic properties for security, not obscurity

12.1.4. Security by Obscurity: Recap

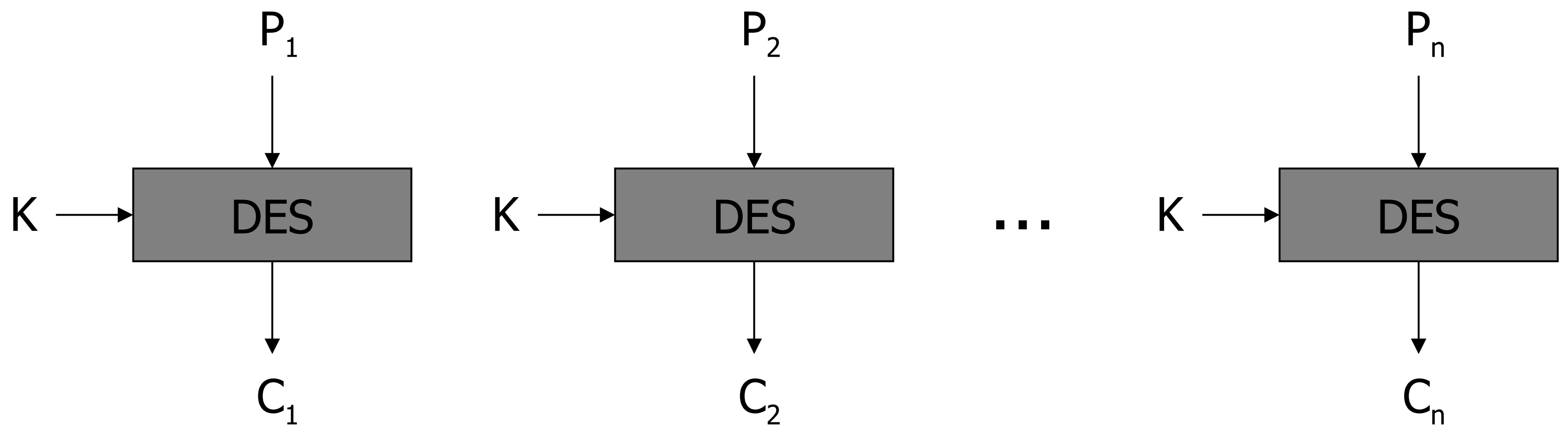
- Design of DES, Triple DES algorithms public
  - Security not dependent on secrecy of implementation
  - But rather on secrecy of key

- Benefits of Keys:
  - Easy to replace if compromised
  - Increasing size by one bit, doubles attacker's work

- If invent own algorithm, make it public! Rely on algorithmic properties (math), not obscurity.

12.1.5. Electronic Code Book

- Encrypting more data: ECB encrypt blocks of data in a large document



- Leaks info about structure of document (e.g. repeated plaintext blocks)

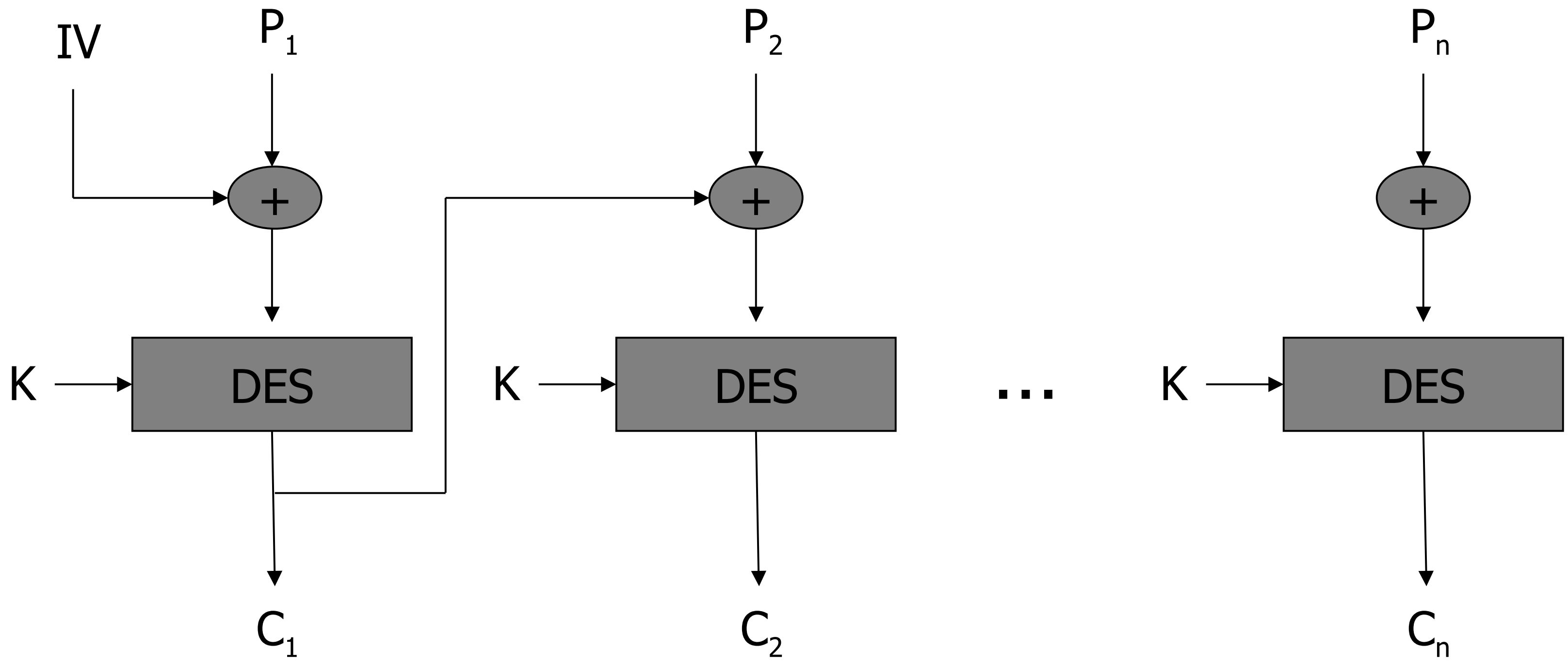
12.1.5. Review of XOR

- Exclusive OR (either x or y but not both)
- Special Properties:
  - x XOR y = z
  - z XOR y = x
  - x XOR z = y

x	y	x XOR y
0	0	0
0	1	1
1	0	1
1	1	0

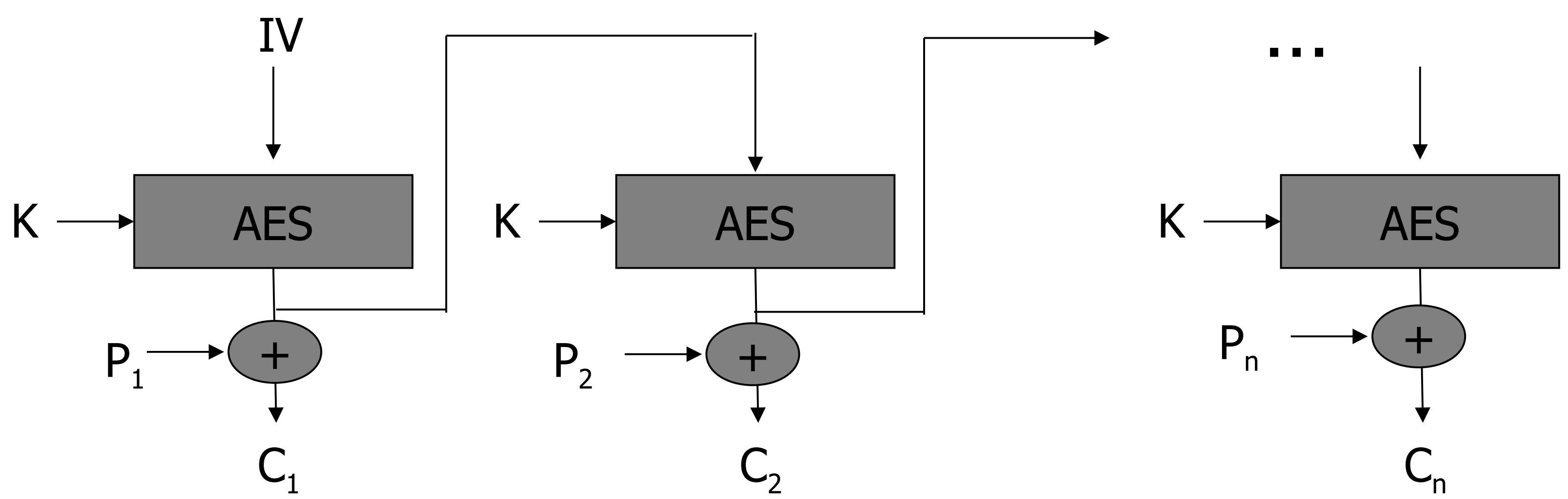
12.1.5. Cipher Block Chaining

- CBC: uses XOR, no patterns leaked!
- Each ciphertext block depends on prev block



12.1.5. Output Feedback (OFB)

- Makes block cipher into stream cipher
- Like CBC, but do XOR with plaintext after encryption



12.2. Stream Ciphers

- Much faster than block ciphers
- Encrypts one byte of plaintext at a time
- *Keystream*: infinite sequence (never reused) of random bits used as key
- Approximates theoretical scheme: one-time pad, trying to make it practical with finite keys

12.2.1 One-Time Pad

- Key as long as plaintext, random stream of bits
  - Ciphertext = Key XOR Plaintext
  - Only use key once!
- Impractical having key the same size as plaintext (too long, incurs too much overhead)
- Theoretical Significance: “perfect secrecy” (Shannon) if key is random.
  - Under brute-force, every decryption equally likely
  - Ciphertext yields no info about plaintext (attacker’s a priori belief state about plaintext is unchanged)

12.2.2. RC4

- Most popular stream cipher: 10x faster than DES
- Fixed-size key "seed" to generate infinite stream
- *State Table S* that changes to create stream
- 40/256-bit key used to seed table (fill it)

RC4 implementation

Table initialization

- for i = 0 to 255

  S[i] = i

  j = 0

  for i = 0 to 255

  j = (j + S[i] + key[i mod kl]) mod 256

  swap (S[i], S[j])
- kl=keylength

Encrypt/decrypt

- i = 0

  j = 0

  for l = 0 to len(input)

  i = (i + 1) mod 256

  j = (j + S[i]) mod 256

  swap (S[i], S[j])

  output[l] =

  S[(S[i] + S[j]) mod 256]

  XOR input[l]

12.2.2. RC4 Pitfalls

- Never use the same key more than once!

- Clients & servers should use different RC4 keys!
  - C $\rightarrow$ S: P XOR k [Eve captures P XOR k]
  - S $\rightarrow$ C: Q XOR k [Eve captures Q XOR k]
  - Eve: (P XOR k) XOR (Q XOR k) = P XOR Q!!!
  - If Eve knows either P or Q, can figure out the other

- Ex: Simple Mail Transfer Protocol (SMTP)
  - First string client sends server is `HELO`
  - Then Eve could decipher first few bytes of response

12.2.2. More RC4 Pitfalls

- Initial bytes of key stream are “weak”
  - Ex: WEP protocol in 802.11 wireless standard is broken because of this
  - Discard first 256-512 bytes of stream
- Active Eavesdropper
  - Could flip bit without detection
  - Can solve by including MAC to protect integrity of ciphertext

12.3. Steganography

- All ciphers transform plaintext to random bits
- Eve can tell Alice is sending sensitive info to Bob
- Conceal existence of secret message
- Use of a “covert channel” to send a message.

12.3.1. What is Steganography?

- Study of techniques to send sensitive info and hide the fact that sensitive info is being sent
- Ex: "All the tools are carefully kept" -> Attack
- Other Examples: Invisible ink, Hidden in Images
  - Least significant bit of image pixels
  - Modifications to image not noticeable by an observer
  - Recipient can check for modifications to get message

```
Red       Green     Blue
00000000  00000000  00000000

00000001  00000000  00000001        →  101
```

12.3.2. Steganography vs. Cryptography

- Key Advantage: when Alice & Bob don’t want Eve to know that they’re communicating secrets

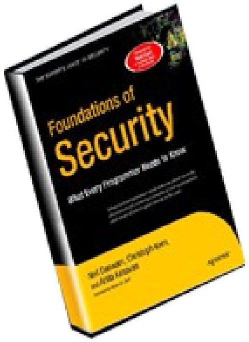
- Traffic Analysis can return useful information

- Disadvantages compared to encryption
  - Essentially relying on security by obscurity
  - Useless once covert channel is discovered
  - High overhead (ratio of plain bits/secret bits high)

- Can be used together with encryption, but even more overhead (additional computation for both)

Chapter 13

Asymmetric Key Cryptography

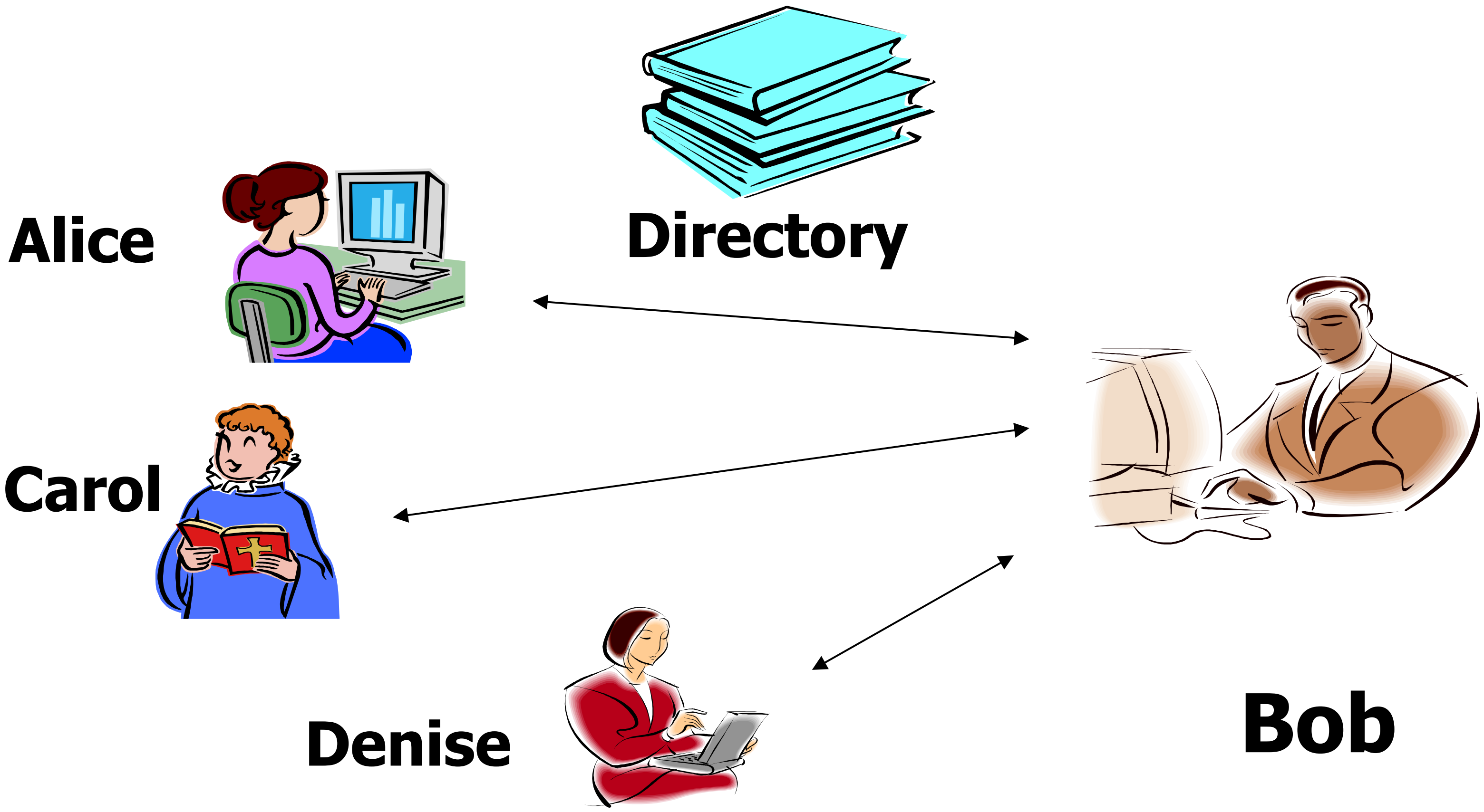


13.1. Why Asymmetric Key Cryptography?

- So two strangers can talk privately on Internet

- Ex: Bob wants to talk to Alice & Carol secretly
  - Instead of sharing different pairs of secret keys with each (as in symmetric key crypto)
  - Bob has 2 keys: *public* key and *private* (or secret) key
- Alice and Carol can send secrets to Bob encrypted with his public key
- Only Bob (with his secret key) can read them

13.1. Public Key System



13.1. The Public Key Treasure Chest

- Public key = Chest with open lock
- Private key = Key to chest
- Treasure = Message
- Encrypting with public key
  - Find chest with open lock
  - Put a message in it
  - Lock the chest
- Decrypting with private key
  - Unlock lock with key
  - Take contents out of the chest

13.1. Asymmetric Encryption

- Alice encrypts a message with ***different*** key than Bob uses to decrypt
- Bob has a public key, k_p, and a secret key, k_s. Bob's public key is known to Alice.
- Asymmetric Cipher: $F^{-1}(F(m,k_p),k_s) = m$

Alice		**Bob**
1. Construct m		
2. Compute $c= F(m,k_p)$		
3. Send c to Bob	$\xrightarrow{c}$	4. Receive c from Alice
		5. Compute $d=F^{-1}(c,k_s)$
		6. $m = d$

13.2. RSA (1)

- Invented by Rivest/Shamir/Adelman (1978)
  - First asymmetric encryption algorithm
  - Most widely known public key cryptosystem
- Used in many protocols (e.g., SSL, PGP, …)

- Number theoretic algorithm: security based on difficulty of factoring ***large*** prime numbers
- 1024, 2048, 4096-bit keys common

13.2. RSA (2)

- Public Key Parameters:
  - Large composite number n with two prime factors
  - Encryption exponent e coprime (no common factor) to $\phi(n) = (p-1)(q-1)$
- Private Key:
  - Factors of n: p, q ($n = pq$)
  - Decryption exponent d such that ed *1 $(mod\ \phi(n))$

- Encryption: Alice sends $c = m^e \ mod\ n$
- Decryption: Bob computes $m = c^d \ mod\ n$

Key generation and proof :-)

- Choose two distinct prime p and q and compute n = pq.
- n is used as the modulus for both the public and private keys
- Compute φ(n) = (p – 1)(q – 1), where φ is Euler's totient function.
- Choose an integer e where 1 < e < φ(n) and gcd of (e, φ(n)) = 1
- e is released as the public key exponent.
- Determine d = e–1 mod φ(n); i.e., d is the multiplicative inverse of e mod φ(n) = solve for d given (de) mod φ(n) = 1.
- d is kept as the private key exponent.

$$m^{ed} = m^{(ed-1)}m = m^{h(p-1)(q-1)}m = \left(m^{p-1}\right)^{h(q-1)}m \equiv 1^{h(q-1)}m \equiv m \bmod p,$$

$$a^{(p-1)} \equiv 1 \pmod{p}.$$

Fermat little theorem

13.3. Elliptic CurveCryptography

- Invented by N. Koblitz & V. Miller (1985)

- Based on hardness of elliptic curve discrete log problem
- Standardized by NIST, ANSI, IEEE for government, financial use
- Certicom, Inc. currently holds patent

- Small keys: 163 bits (<< 1024-bit RSA keys)

13.3: RSA vs. ECC

- RSA Advantages:
  - Has been around longer; math well-understood
  - Patent expired; royalty free
  - Faster encryption
- ECC Advantages:
  - Shorter key size
  - Fast key generation (no primality testing)
  - Faster decryption

13.4. Symmetric vs. Asymmetric Key Cryptography

- Symmetric-Crypto (DES, 3DES, AES)
  - Efficient (smaller keys / faster encryption) because of simpler operations (e.g. discrete log)
  - Key agreement problem
  - Online

- Asymmetric-Crypto (RSA, ECC)
  - RSA 1000x slower than DES, more complicated operations (e.g. modular exponentiation)
  - How to publish public keys? Requires PKI / CAs
  - Offline or Online

13.5. Certificate Authorities

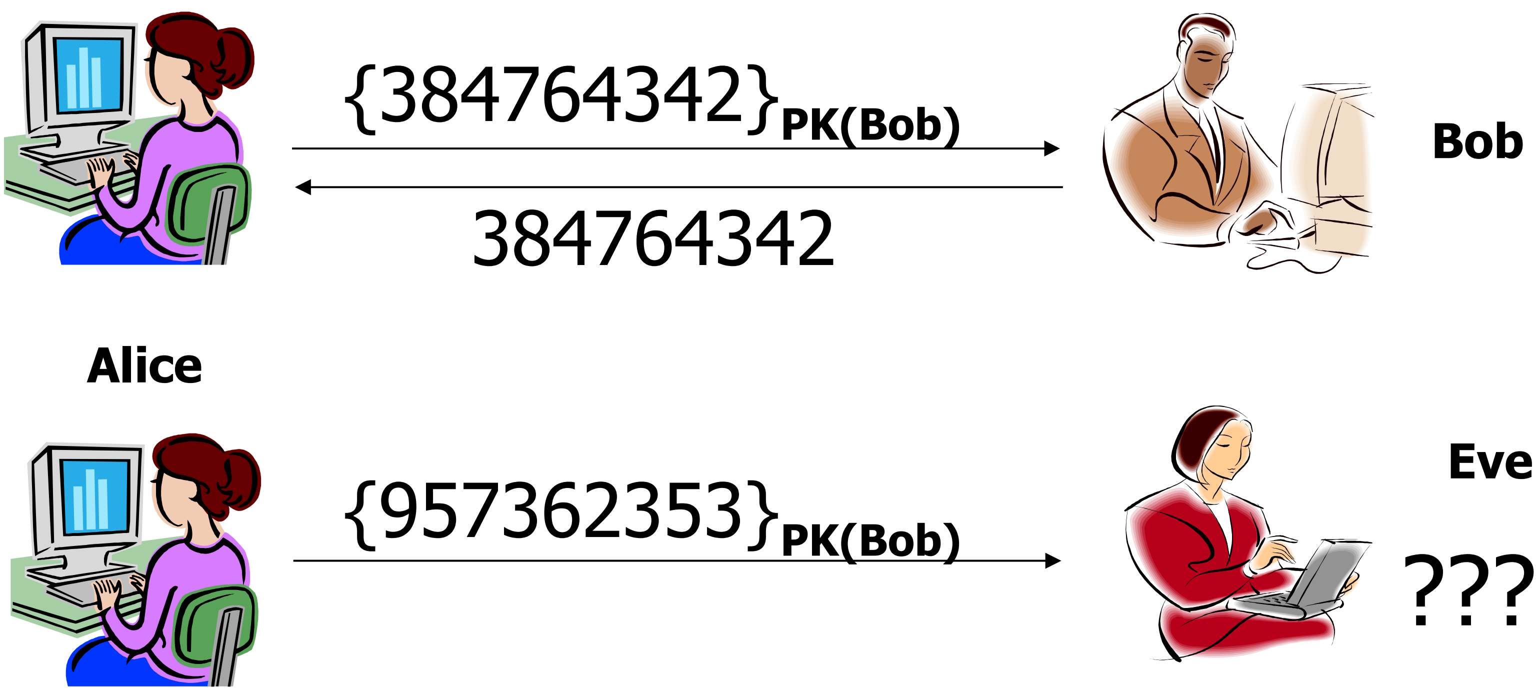
- Trusted third party: CA verifies people's identities
- Authenticates Bob & creates *public key certificate* (binds Bob's identity to his public key)

- CA also revokes keys and certificates
- Certificate Revocation List: compromised keys

- Public Key Infrastructure (PKI): CA + everything required for public key encryption

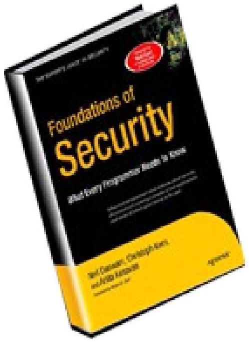
13.7. Challenge – Response with Encryption

- Alice issues "challenge" message to person
  - Random # (nonce) encrypted with Bob's public key
  - If person is actually Bob, he will be able to decrypt it



CHAPTER 14

Key Management & Exchange



14.1. Types of Keys

- *Encryption* keys can be used to accomplish different security goals
- Identity Keys
- Conversation or Session Keys
- Integrity Keys
- One Key, One Purpose: Don’t reuse keys!

14.1.1. Identity Keys

- Used to help carry out authentication
- Authentication once per connection between two parties
- Generated by principal, long-lifetime (more bits)
- Bound to identity with certificate (e.g. public keys in asymmetric system)

14.1.2. Conversation or Session Keys

- Helps achieve confidentiality

- Used after 2 parties have authenticated themselves to each other

- Generated by key exchange protocol (e.g. Diffie-Hellman algorithm)

- Short-lifetime (fewer bits)

14.1.3. Integrity Keys

- Key used to compute Message Authentication Codes (MACs)
- Alice and Bob share integrity key
  - Can use to compute MACs on message
  - Detect if Eve tampered with message
- Integrity keys used in digital signatures

14.2. Key Generation

- Key generated through algorithms (e.g. RSA)
  - Usually involves random # generation as a step
  - But for Identity Based Encryption, master key
- Avoid weak keys (e.g. in DES keys of all 1s or 0s, encrypting twice decrypts)
- Don’t want keys stolen: After generation
  - Don’t store on disk connected to network
  - Also eliminate from memory (avoid *core dump* attack)
- Generating keys from passwords: Use password-based encryption systems to guard against dictionary attacks

14.2.1. Random Number Generation

- Ex: Alice & Bob use RSA to exchange a secret key for symmetric crypto (faster)
  - Alice generates random # *k*
  - Sends to Bob, encrypted with his public key
  - Then use *k* as key for symmetric cipher

- But if attacker can guess *k*, no secrecy
- Active eavesdropper can even modify/inject data into their conversation
- Problem: Generating hard to guess random #s

14.2.2. The rand() function

- How about using `rand()` function in C?
  - Uses linear congruential generator
  - After some time, output repeats predictably
- Can infer seed based on few outputs of `rand()`
  - Allows attacker to figure out all past & future output values
  - No longer unpredictable
- Don't use for security applications

14.2.3. Random Device Files

- Virtual devices that look like files: (e.g. on Linux)
  - Reading from file provides unpredictable random bits generated based on events from booting
  - `/dev/random` – blocks until random bits available
  - `/dev/urandom` – doesn't block, returns what's there

```
$ head -c 20 /dev/random > /tmp/bits # read 20 chars
$ uuencode --base64 /tmp/bits printbits # encode,
print
begin-base64 644 printbits
bj4Ig9V6AAaqH7jzvt9T60aogEo===== # random output
```

14.2.4. Random APIs

- Windows OS: `CryptGenKey()` – to securely generate keys

- Java: `SecureRandom` class in `java.security` package (c.f. `AESEncrypter` example, Ch. 12)
    - Underlying calls to OS (e.g. `CryptGenKey()` for Windows or reads from `/dev/random` for Linux)
    - No guarantees b/c cross-platform
    - But better than `java.util.Random`

14.3. Key (Secret) Storage

- Secret to store for later use
  - Cryptographic key (private)
  - Password or any info system's security depends on
- Recall Kerchoff's principle: security should depend not on secrecy of algorithm, but on secrecy of cryptographic keys
- Options for storing secrets?

The general principle

- Cryptography does not solve a problem but simplifies it
- We have encrypted a huge file with a small key
- How we protect the key?
- The file is protected provided that we can protect the key

14.3.1. Keys in Source Code

- Ex: Program storing a file on disk such that no other program can touch it Might use key to encrypt file: Where to store it?
- Maybe just embed in source code? Easy since you can use at runtime to decrypt.

- Can reverse-engineer binary to obtain the key (even if obfuscated) e.g. `strings` utility outputs sequence of printable chars in object code

14.3.1. Reverse-Engineering

```
/* vault program (from 6.1.2) */
int checkPassword() {
    char pass[16];
    bzero(pass, 16); // Initialize
    printf ("Enter password: ");
    gets(pass);
    if (strcmp(pass, "opensesame") == 0)
      return 1;
    else
      return 0;
}

void openVault() {
      // Opens the vault
}

main() {
    if (checkPassword()) {
          openVault();
          printf ("Vault opened!");
    }
}
```

Key Leaked!

```
# partial output of printable
# characters in object code
$ strings vault
C@@0@
$ @
Enter password:
opensesame
__main
_impure_ptr
calloc
cygwin_internal
dll_crt0__FP11per_process
free
gets
malloc
printf
realloc
strcmp
GetModuleHandleA
cygwin1.dll
KERNEL32.dll
```

14.3.2. Storing the Key in a File on Disk

- Alternative to storing in source code, could store in file on disk

- Attacker with read access could
  - Find files with high entropy (randomness)
  - These would be candidate files to contain keys

- C.f. “Playing Hide and Seek with Stored Keys” (Shamir and van Someren)

14.3.3. “Hard to Reach” Places

- Store in Windows Registry instead of file?
  - Part of OS that maintains config info
  - Not as easy for average user to open
- But `regedit` can allow attacker (or slightly above-average user) to read the registry
  - Also registry entries stored on disk
  - Attacker with full read access can read them
- Registry not the best place to store secrets

14.3.4. Storing Secrets in External Devices (1)

- Store secrets in device external to computer!
  - Key won’t be compromised even if computer is
  - Few options: smart card, HSMs, PDAs, key disks

- Smart Card (contains tamper-resistant chip)
  - Limited CPU power, vulnerable to power attacks
  - Must rely on using untrusted PIN readers
  - Attacker observes power of circuits, computation times to extract bits of the key

14.3.4. Storing Secrets in External Devices (2)

- Hardware Security Module (HSM)
  - Device dedicated to storing crypto secrets
  - External device, add-on card, or separate machine
  - Higher CPU power, key never leaves HSM (generated and used there)

- PDA or Cell phone
  - No intermediate devices like PIN readers
  - More memory, faster computations
  - Can have security bugs of their own

14.3.4. Storing Secrets in External Devices (3)

- Key Disk
  - USB, non-volatile memory, 2nd authentication factor
  - No CPU, not tamper-resistant
  - No support for authentication
  - Ex: IronKey, secure encrypted flash drive

- External Devices & Keys
  - Allows key to be removed from host system
  - Problem: connected to compromised host
  - Advantage: if crypto operation done on device & key never leaves it, damage limited
  - Can attack only while connected, can't steal key

14.4. Key Agreement and Exchange

- Keys have been generated and safely stored, now what?
  - If Alice & Bob both have it, can do symmetric crypto
  - Otherwise, have to agree on key

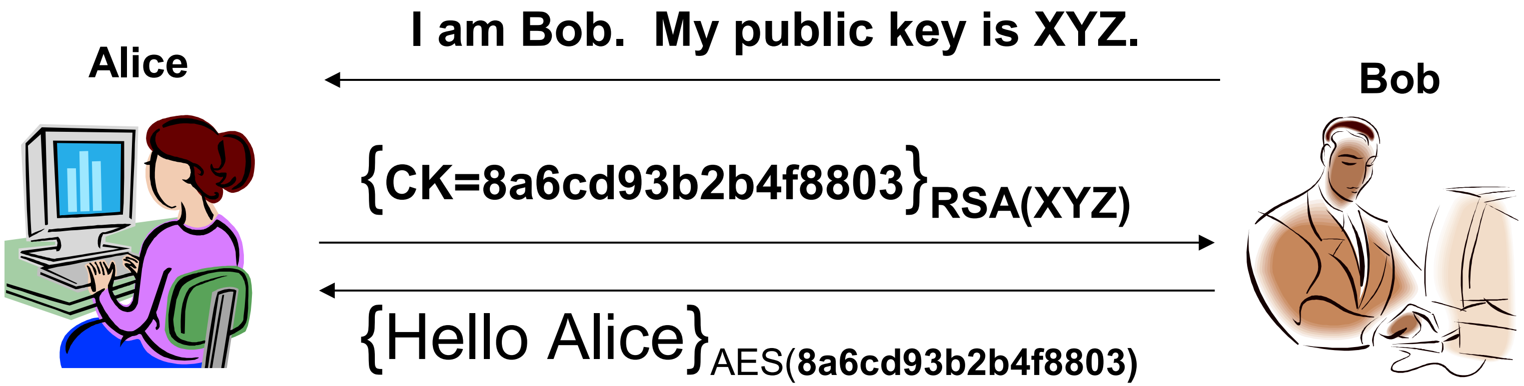
- How to create secure communication channel for exchange?

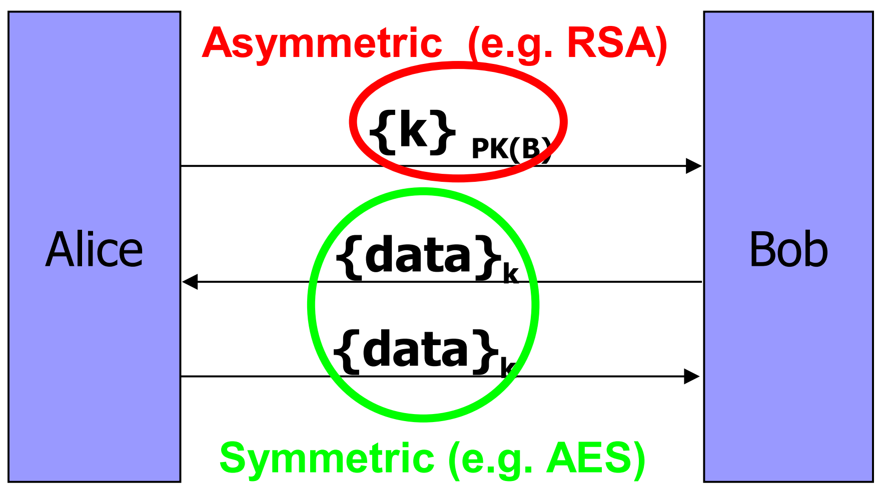
- Few Options
  - Use Asymmetric Keys
  - Diffie-Hellman (DH) Key Exchange

14.4.1. Using Asymmetric Keys

- Public-key crypto much more computationally expensive than symmetric key crypto
- Use RSA to send cryptographically random conversation key *k*
- Use *k* as key for faster symmetric ciphers (e.g. AES) for rest of conversation

14.4.1. Key Exchange Example





14.4.2. Diffie-Hellman (DH) (1)

- Key exchange (over insecure channel) without public-key certificates?
- DH: use public parameters *g*, *p*
  - Large prime number *p*
  - Generator *g* (of $Z_p = \{1, \ldots, p\text{-}1\}$), i.e. powers g, g^2, …, g^{p-1} produce all these elements
- Alice & Bob generate rand #s *a*, *b* respectively
- Using *g*, *p*, *a*, *b*, they can create a secret known only to them (relies on hardness of solving the discrete log problem)

14.4.2. Diffie-Hellman (DH) (2)

Alice		**Bob**
Choose a	$g^a \bmod p$ →	**Choose b**
	← $g^b \bmod p$	
Compute $(g^b)^a$ mod p		**Compute $(g^a)^b$ mod p**
	Secret Key = g^{ab} mod p	

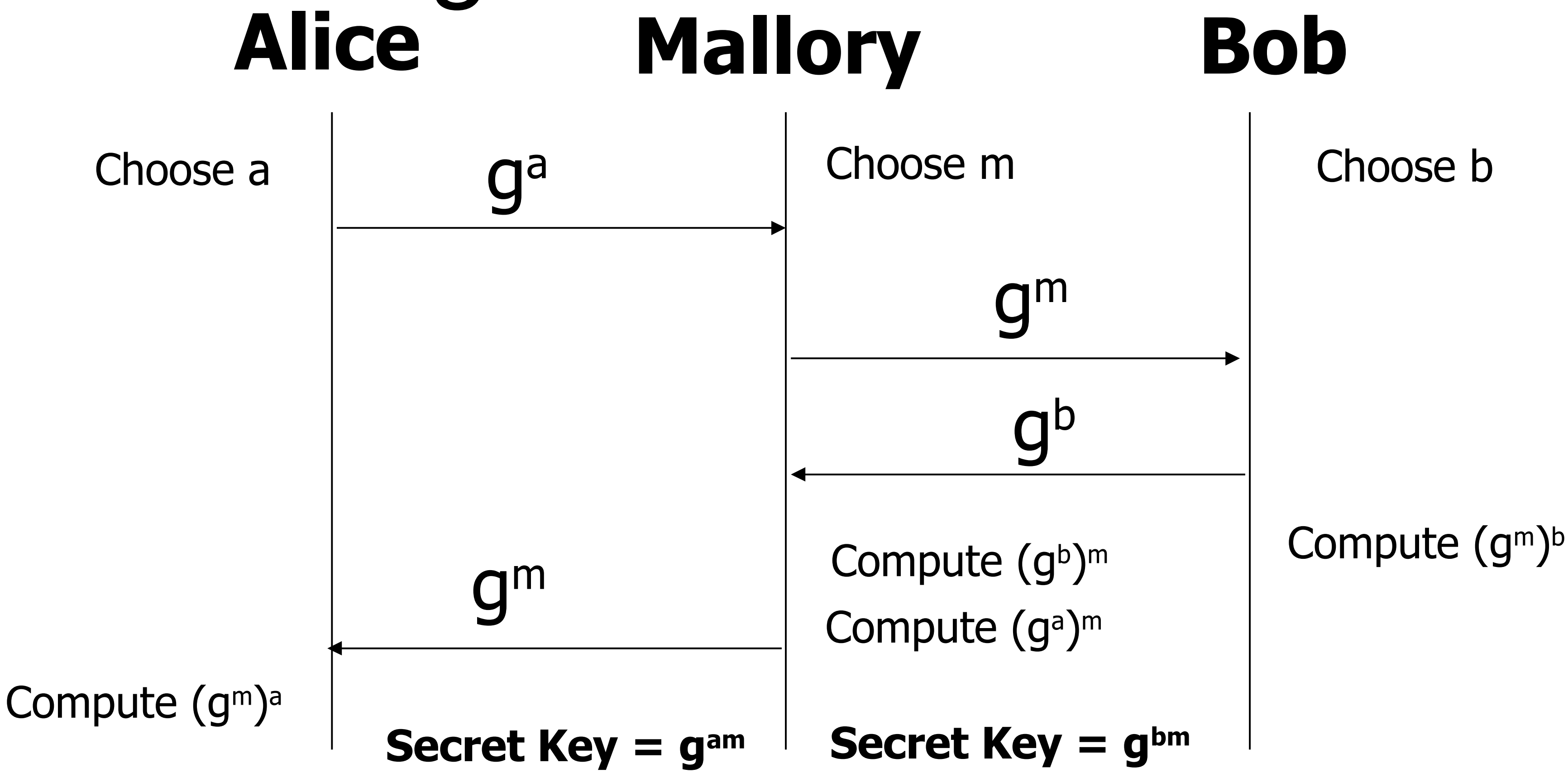
Eve can compute $(g^a)(g^b) = g^{a+b}$ mod p but that's not the secret key!

14.4.2. Diffie-Hellman (DH) (2)

Alice		**Bob**
Choose a	$g^a \bmod p$ $\longrightarrow$	**Choose b**
	$\longleftarrow$ $g^b \bmod p$	
Compute $(g^b)^a$ mod p		**Compute $(g^a)^b$ mod p**
	Secret Key = g^{ab} mod p	

Eve can compute $(g^a)(g^b)= g^{a+b}$ mod p but that's not the secret key!

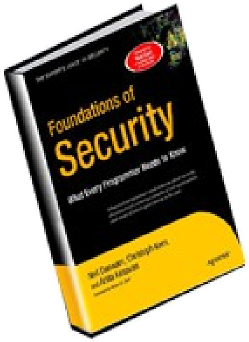
14.4.2. Man-in-the-Middle Attack against DH



Mallory can see all communication between Alice & Bob!

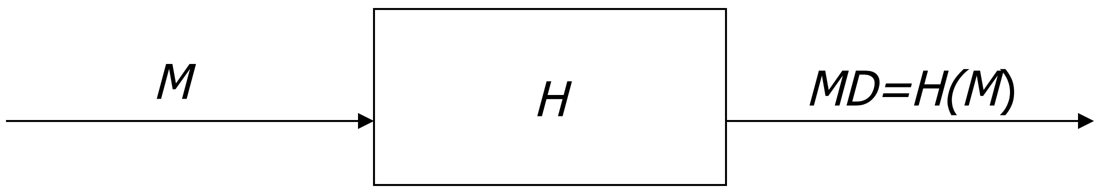
CHAPTER 15

MACs and Signatures



15.1. Secure Hash Functions

- Given arbitrary-length input, *M*, produce fixed-length output (message digest), *H(M)*, such that:



- *Efficiency*: Easy to compute *H*
- *One-Way/Pre-Image resistance*: Given *H(M)*, hard to compute *M* (*pre-image*)
- *Collision resistance*: Hard to find $M_1 \neq M_2$ such that $H(M_1) = H(M_2)$

15.1. Secure Hash Functions Examples

- Non-Examples:
  - Add ASCII values (collisions): *H('AB') = H('BA')*
  - Checksums CRC32 not one-way or collision-resistant

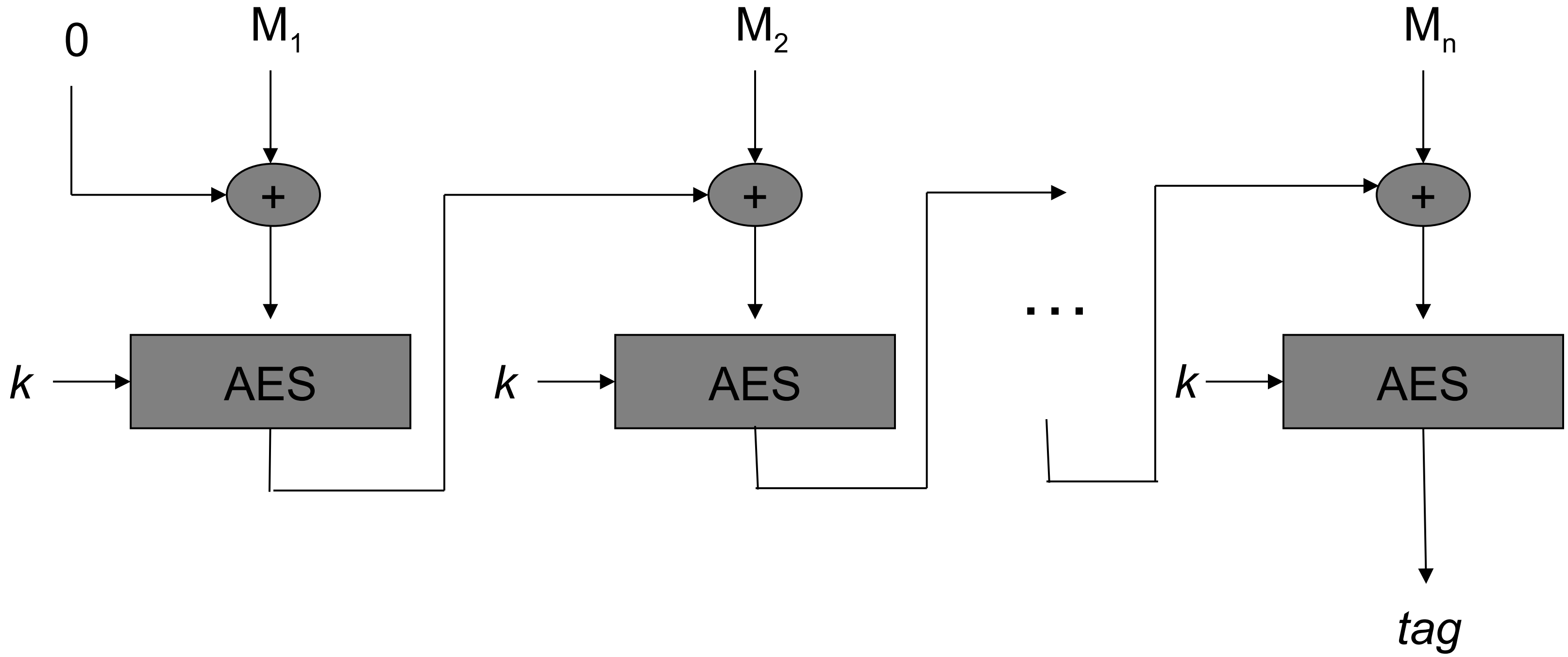
- MD5: “Message Digest 5” invented by Rivest
  - Input: multiple of 512-bits (padded)
  - Output: 128-bits
- SHA1: developed by NIST & NSA
  - Input: same as MD5, 512 bits
  - Output: 160-bits

15.2. MACs

- Used to determine sender of message
- If Alice and Bob share key *k*, then Alice sends message *M* with MAC *tag t* = *MAC(M,k)*
- Then Bob receives *M'* and *t'* and can check if the message or signature has been tampered by verifying *t'* = *MAC(M', k)*

15.2.1. CBC MACs

- Encrypt message with block cipher in CBC mode
- IV = 0, last encrypted block can serve as tag
- Insecure for variable-length messages



15.2.2. HMAC

- Secure hash function to compute MAC
- Hash function takes message as input while MAC takes message and key
- Simply prepending key onto message is not secure enough (e.g. given MAC of *M*, attacker can compute MAC of *M*||*N* for desired *N*)

- Def: $HMAC(M,k) = H((K \oplus \text{opad}) \| H((K \oplus \text{ipad}) \| M))$
  - Where *K* is key *k* padded with zeros
  - opad, ipad are hexadecimal constants

15.3. Signatures (1)

- Two major operations: *P*, principal
  - *Sign(M, k)* – *M* is message
  - *Verify(M, sig, P)* – *sig* is signature to be verified
- *Signature*: sequence of bits produced by *Sign()* such that *Verify(M, sig, P)* , *(sig == Sign(M, k))*
  - Non-repudiable evidence that *P* signed *M*
  - Many applications: SSL, to sign binary code, authenticate source of e-mail
- Use asymmetric encryption ops *F* & F^{-1}

15.3. Signatures (2)

- $S()$ & $V()$: implement sign & verify functions

- Signature is $s = S(M, k_s) = F^{-1}(h(M), k_s)$
  - Decrypt hash with secret key
  - Only signer (principal with secret key) can sign

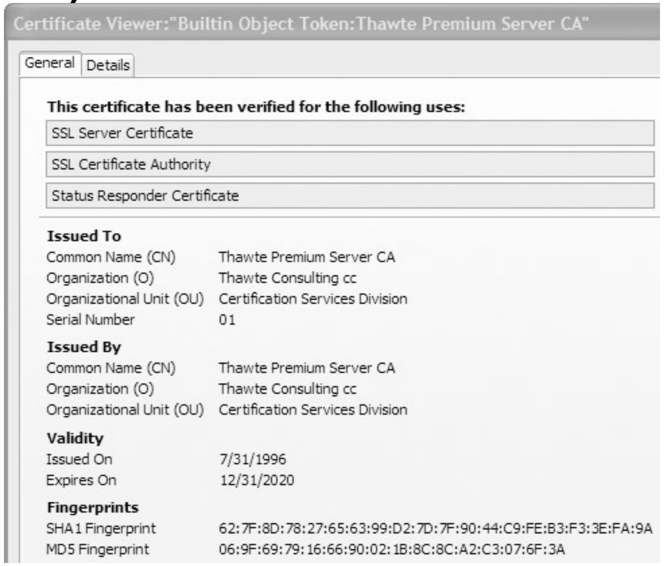
- Verify s: $V(M, s, k_p) = (F(s,k_p) == h(M))$
  - Encrypting with public key
  - Allows anyone to verify a signature
  - Need to bind principal's identity to their public key

15.3.1. Certificates & CAs (1)

- Principal needs certificate from CA (i.e. its digital signature) to bind his identity to his public key
- CA must first sign own certificate attesting to own identity (“root”)
- Certificate, *C(P)*, stored as text: name of principal *P*, public key ($k_{p(P)}$), expiration date
- $C(P) = (C_{text}(P), C_{sig}(P))$
- Root Certificate, *C(CA)*, looks like
  - $C_{text}(CA)$ = ("CA", $\mathrm{k}_{\mathrm{p(CA)}}$, exp)
  - $C_{sig}(CA) = S(\mathrm{C}_{\mathrm{text}}(\mathrm{CA}), \mathrm{k}_{\mathrm{s(CA)}})$

15.3.1. Certificates & CAs (2)

- Alice constructs certificate text:
  - $C_{text}(Alice)=(\text{"Alice"}, k_{p(Alice)}, exp)$
  - Authenticates herself to CA (through “out-of-band” mechanism such as driver’s license)



- CA signs Alice’s certificate: $C_{sig}(Alice)=S(C_{text}(Alice),k_{s(CA)})$

- Alice has *public key* certificate
  - $C(Alice)=(C_{text}(Alice),C_{sig}(Alice))$
  - Can use to prove that $k_{p(Alice)}$ is her public key

15.3.2. Signing and Verifying

- Signing: $sig = Sign(M, k_{s(P)}) = (S(M, k_{s(P)}), C(P))$
  - Compute $S()$ with secret key: $sig.S$
  - Append certificate: $sig.C$

- Verifying: $Verify(M, sig, P) =$
  - $V(M, sig.S, k_{p(P)})$ & **signature verifies message?**
  - $V(sig.C_{text}(P), sig.C_{sig}(P), k_{p(CA)})$ & **signed by CA?**
  - $(C_{text}(P).name == P)$ & **name matches on cert?**
  - $(today < sig.C_{text}(P).date)$ **certificate not expired?**

15.3.3. Registration Authorities

- Authenticating every principal can burden CA
- Can authorize RA to authenticate on CA's behalf
  - CA signs certificate binding RA's identity to public key
  - Signature now includes RA's certificate too
  - Possibly many intermediaries in the verification process starting from "root" CA certificate
  - More links in chain, more weak points: careful when verifying signatures
- Ex: IE would not verify intermediate certificates and trust arbitrary domains (anyone could sign)

15.3.4. Web of Trust

- Pretty Good Privacy (PGP): digital signatures can be used to sign e-mail
- “Web of trust” model: users sign own certificates and other’s certificates to establish trust
- Two unknown people can find a certificate chain to a common person trusted by both

Source:
http://xkcd.com/364/

15.4. Attacks Against Hash Functions

- Researchers have been able to obtain collisions for some hash functions
  - Collision against SHA-1: 2^{63} computations (NIST recommends phase out by 2010 to e.g. SHA-256)
  - MD5 seriously compromised: phase out now!

- Collision attacks can’t fake arbitrary digital signatures (requires finding pre-images)

- However could get 2 documents with same hash and sign one and claim other was signed

15.5. SSL

- *Handshake*: steps client & server perform before exchanging sensitive app-level data

- Goal of handshake: client & server agree on master secret used for symmetric crypto

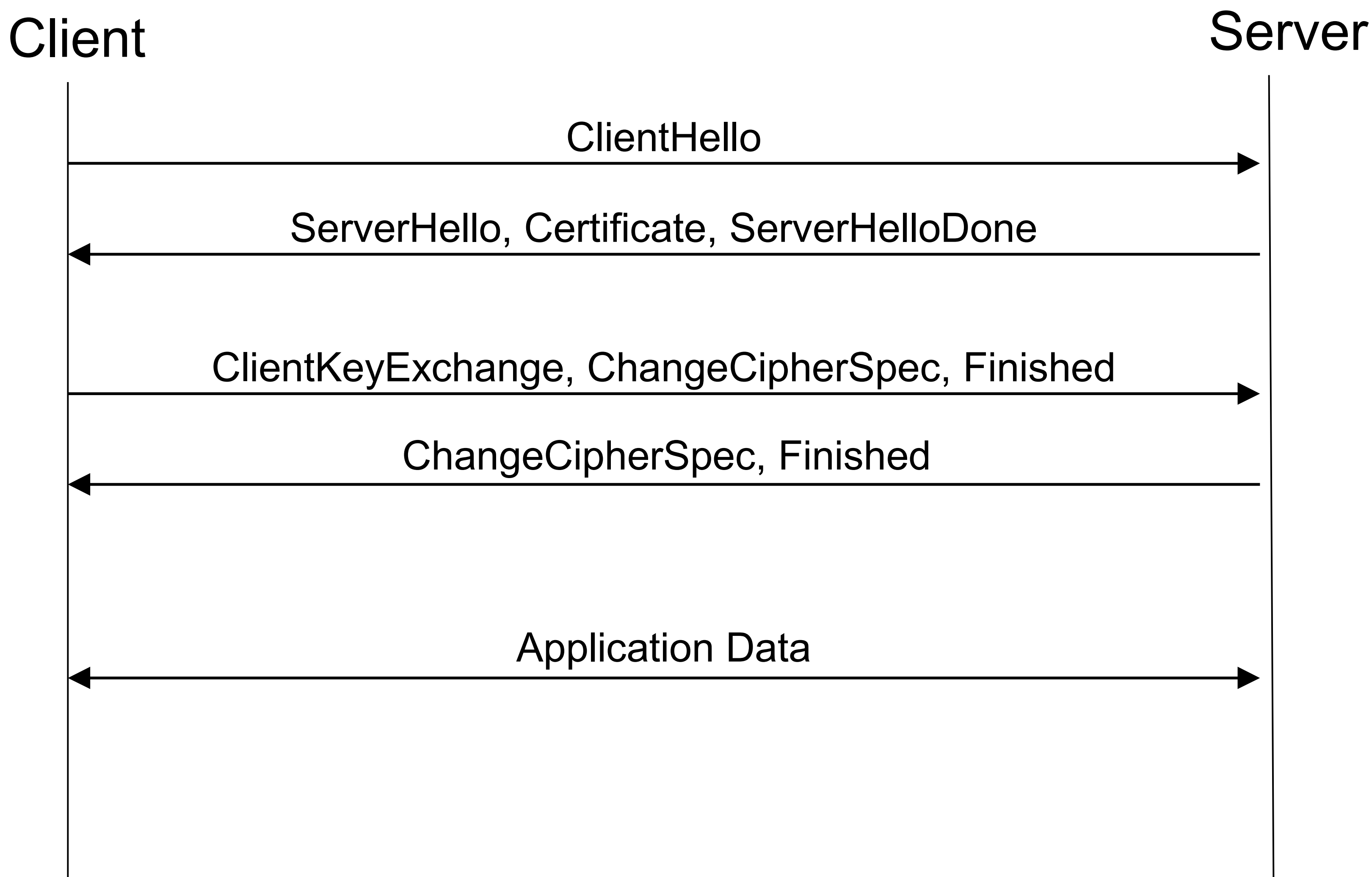
- Two round trips:
  - 1st trip is “hello” messages: what versions of SSL and which cryptographic algorithms supported
  - 2nd varies based on client or mutual authentication

15.5.1. Server-Authenticated Only (1)

- Client creates random pre-master secret, encrypts with server's public key
- Server decrypts with own private key
- Both compute hashes including random bytes exchanged in "hello" to create master secret

- With master secret, symmetric session key and integrity key derived (as specified by SSL)
- App Data encrypted with symmetric key

15.5.1. Server-Authenticated Only (2)

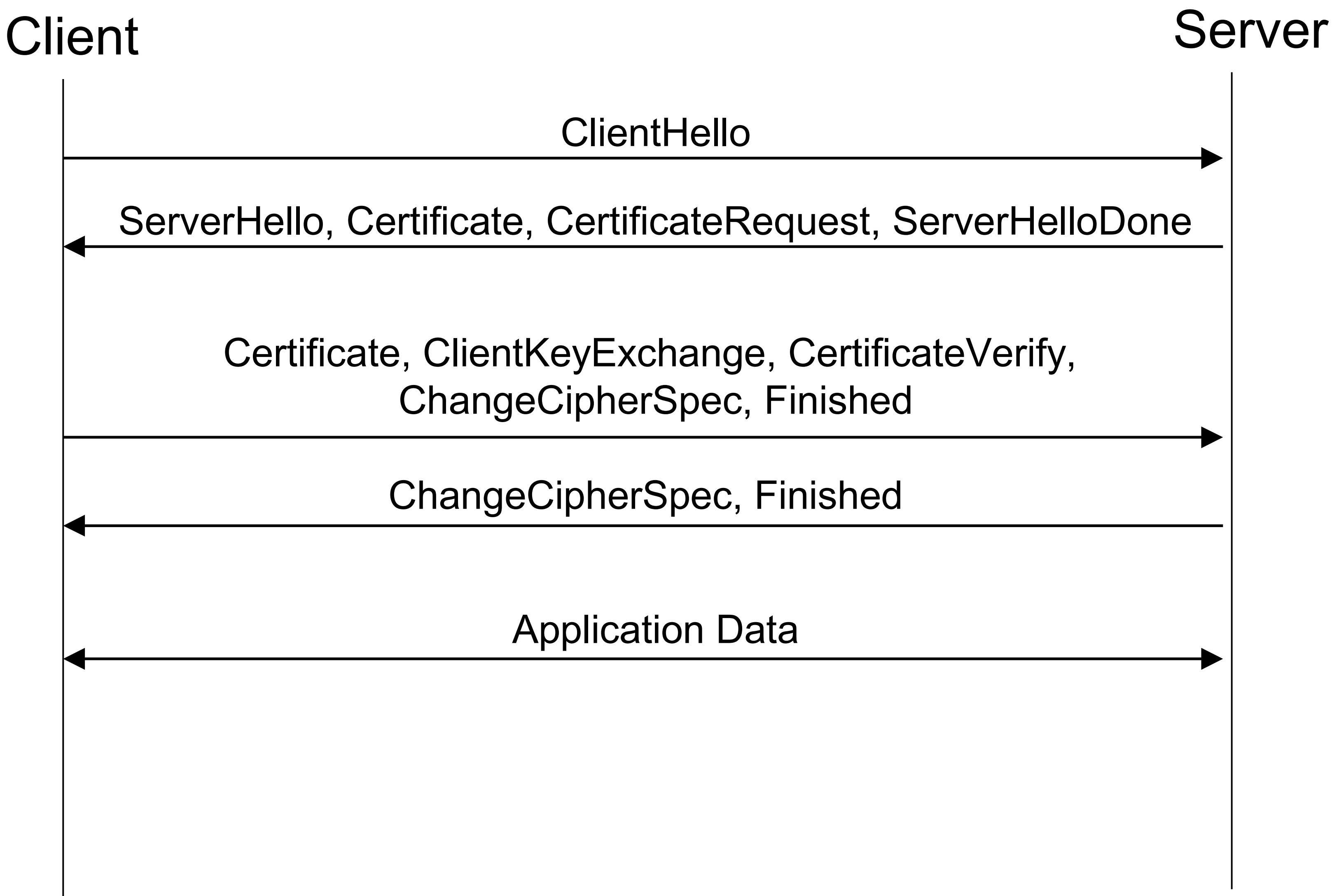


15.5.2. Mutual Authentication (1)

- Client also sends own certificate to server
- Sends CertificateVerify message to allow server to authenticate client's public key
- Pre-master secret set, compute master secret
- Derive symmetric key & exchange data

- SSL mechanisms prevent many attacks (e.g. man-in-the-middle) and has performance optimizations (e.g. caching security params)

15.5.2. Mutual Authentication (2)



Summary

- MACs - protect integrity of messages
  - Compute *tag* to detect tampering
  - Ex: CBC-MAC, HMAC (relies on secure hashes)
- Signatures – binds messages to senders
  - Allows anyone to verify sender
  - Prevents forged signatures
  - Use CAs to bind identities to public keys
  - Or use Web of Trust model
- Application: SSL (“Putting it all together”)
  - Relies on Cryptography: symmetric & public-key
  - And MACs & signatures

Some final words

- Using cryptography in a system full of vulnerabilities = fortness built on sand because the keys can be stolen
- Cryptography does not solve the problems, it just simplifies them

  You cannot hide a 1 Terabyte file

  You can encrypt the file with a 512 bits key and hide the key =

  The same problem but much more simpler