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Cryptographic Foundations of Network Security -- Contemporary Tales of Use & Misuse

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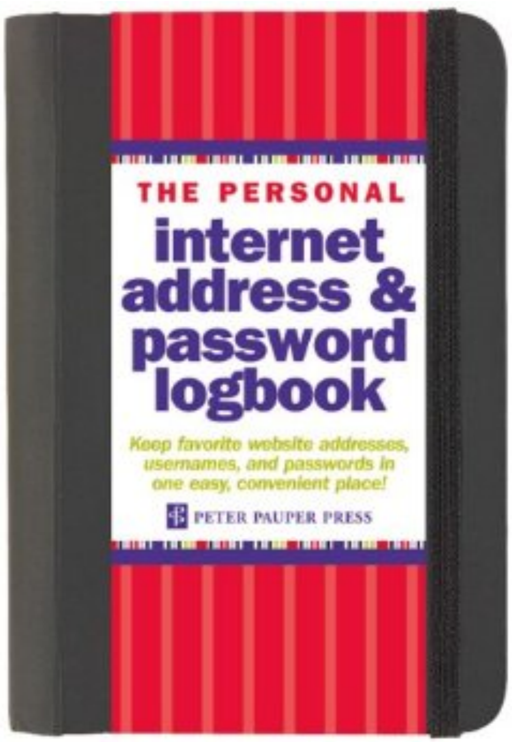
Network Security: the Evolution

- The early days
  - Internet security
    - Ad hoc mechanisms, obfuscation, little cryptography, address based authentication, firewalls, proprietary protocols
    - Applications: telnet, rlogin (.rhosts), smtp, dns, tcp, arp
  - Cryptography
    - Specialized and sensitive applications, proprietary
- Evolution: cryptography became pervasive
  - TLS/SSL (Web, VPN, WiFi), IPSec, DNSSEC, PGP, DKIM, Kerberos, Tor/Hidden Services, Bitcoin
  - Malicious: FLAME, Cryptolocker, Silk road

Cryptography is not a Panacea

- Secure building block are essential but not sufficient: integration, usability challenges



Outline

- Basics of cryptography: basics & best practices
  - Secret Key Cryptography (symmetric crypto)
  - Modes of Operation of Encryption Algorithms
  - Hashing and Message Authentication Codes
  - Public Key Algorithms (asymmetric crypto)
  - Cryptographic Pseudo Random Numbers Generation
- Overview of applications across the network stack
- Recent misuse of the basics
  - Android Apps, Adobe passwords leaks, Blizzard, PGP
- Systems, Standards
  - TLS/SSL overview, vulnerabilities, and misuse (e.g., WPA-Enterprise)
- Emerging trend of malicious use of cryptography
  - Worms, Ransomware
- Privacy

Cryptography & Network Security

- Cryptography provides the key building blocks for many network security services
- Network Security services
  - Authentication, Confidentiality, Integrity, Access control, Non-Repudiation, Availability, Key Management, Audit
- Cryptographic algorithms (building blocks)
  - Encryption:
    - Symmetric Encryption (e.g., AES), Asymmetric Encryption (e.g., RSA, El-Gamal)
  - Hashing functions
  - Message Authentication Code (e.g., HMAC + SHA1)
  - Digital Signature functions (e.g., RSA, El-Gamal)
  - Cryptographic Pseudo Random Numbers Generation

Terminology & Services

Terminology

- Network security services
  - Authentication, confidentiality, integrity, access control, non-repudiation, availability, key management, auditing
- Security attacks
  - Passive, active
- Cryptography models
  - Symmetric (secret key), asymmetric (public key)
- Cryptanalysis
  - Ciphertext only, known plaintext, chosen plaintext, chosen ciphertext, chosen text

Network Security Services X.800, RFC 2828

- Authentication:
  - assures the recipient of a message the authenticity of the claimed source
- Confidentiality:
  - protects against unauthorized release of message content
- Integrity:
  - guarantees that a message is received as sent (modifications are detected)
- Access control:
  - limits the access to authorized users
- Non-repudiation:
  - protects against sender/receiver denying sending/receiving a message
- Availability:
  - guarantees that the system services are always available when needed
- Security audit:
  - keeps track of transactions for later use (diagnostic, alarms…)
- Key management:
  - allows to negotiate, setup and maintain keys between communicating entities

Network Security Attacks

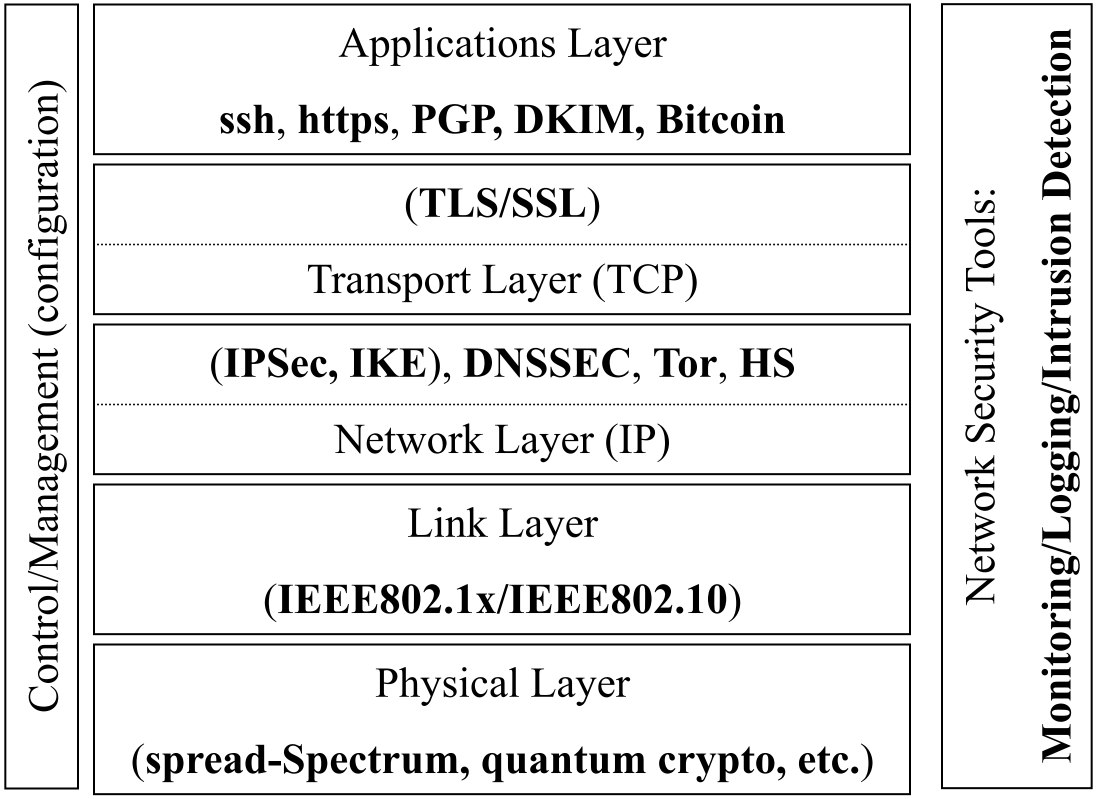
- Kent's classification
  - Passive attacks:
    - Release of message content
    - Traffic analysis
  - Active attacks:
    - Masquerade
    - Replay
    - Modification of message
    - Denial of service
- Security attacks
  - Interception (confidentiality)
  - Interruption (availability)
  - Modification (integrity)
  - Fabrication (authenticity)

Kerchoff's Principle

- The cipher should be secure even if the intruder knows all the details of the encryption process except for the secret key
- "No security by obscurity"
  - Examples of system that did not follow this rule and failed?

Securing Networks

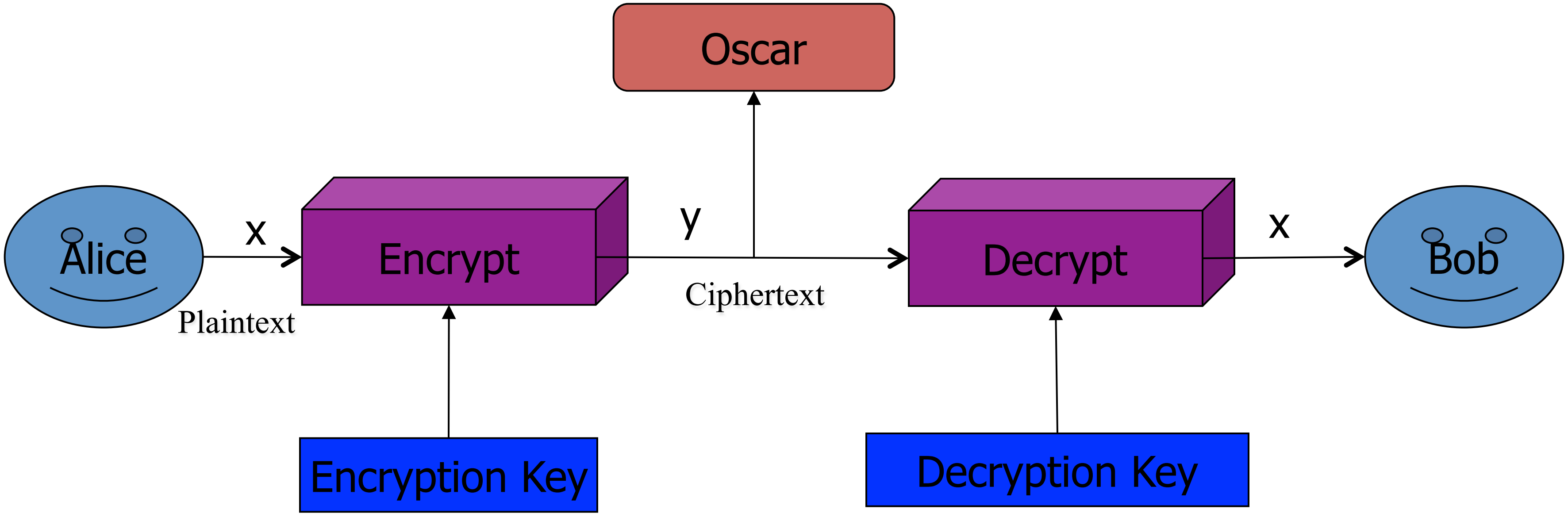
- Where to put the security in a protocol stack?
- Practical considerations:
  - End to end security
  - No modification to OS



Encryption

Encrypted Communication

- Basic Goal:
  - Allow two entities (e.g., Alice, and Bob) to communicate over an insecure channel, such that an opponent (e.g., Oscar) cannot understand what is being communicated

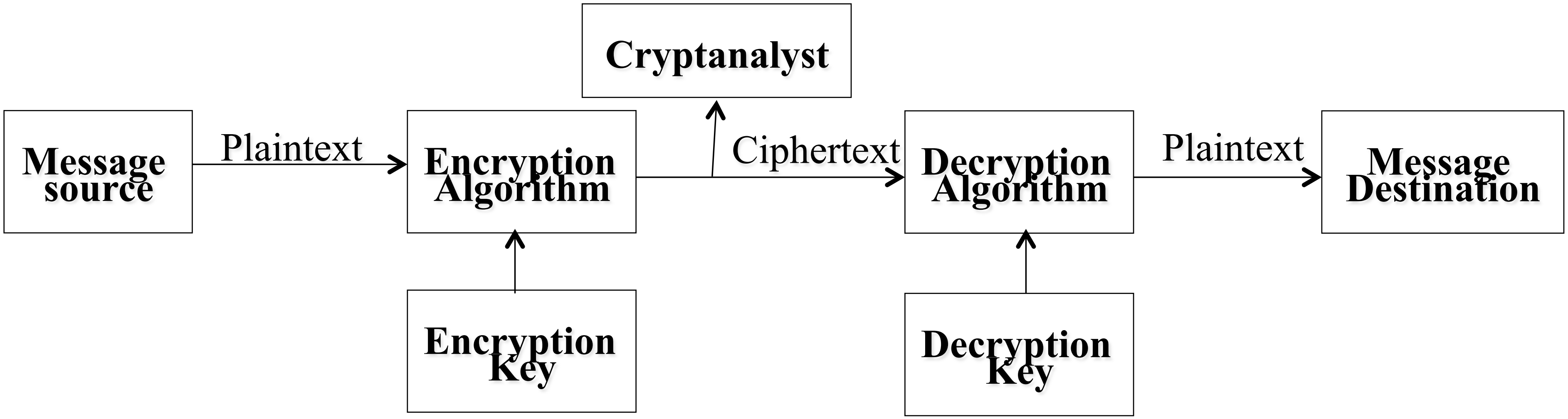


Encryption Algorithms Types

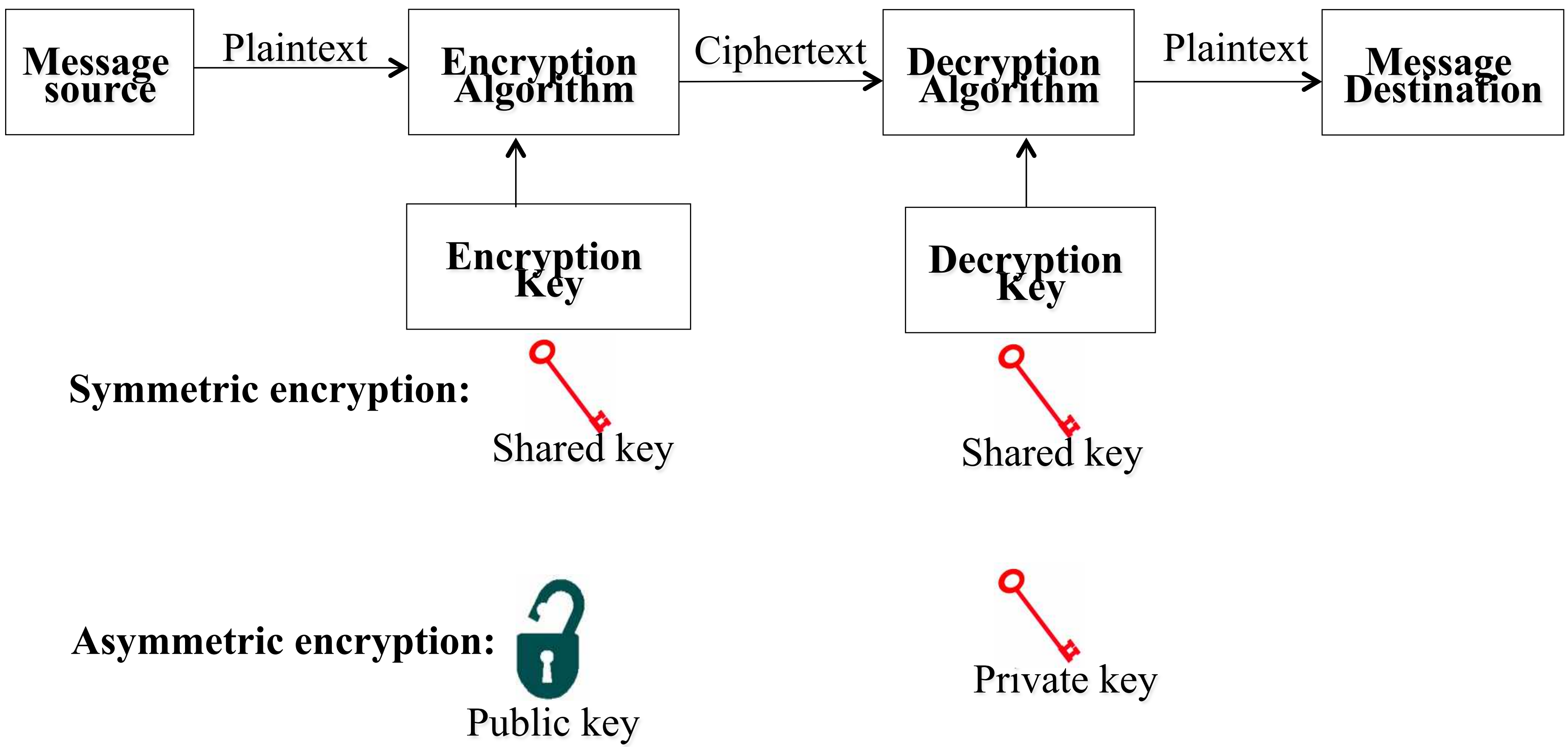
- Block vs. Stream ciphers
  - Block ciphers:
    - Input: block of *n* bits ; Output: block of *n* bits
    - Example: AES
  - Stream ciphers:
    - Input: stream of symbols ; Output: stream of symbols
    - Examples: RC4, GSM A5, SNOW 3G
  - Block ciphers can be used to build stream ciphers (under some assumptions)
    - Examples: AES-CBC

Encryption Models

- Symmetric encryption (conventional encryption)
  - Encryption Key = Decryption Key
  - i.e., Decryption key can be derived from encryption key
  - e.g., AES, ~~DES, FEAL, IDEA, BLOWFISH~~
- Asymmetric encryption
  - Encryption Key ≠ Decryption Key
  - i.e., Decryption key cannot be derived from encryption key
  - e.g., RSA, Diffie-Hellman, ElGamal



Encryption Models



Symmetric vs. Asymmetric Algorithms

- Symmetric algorithms are much faster
  - In the order of a 1000 times faster
- Symmetric algorithms require a shared secret
  - Impractical if the communicating entities don't have another secure channel
- Both algorithms are combined to provide practical and efficient secure communication
  - E.g., establish a secret session key using asymmetric crypto and use symmetric crypto for encrypting the traffic PGP, TLS/SSL, IKE
- Try it using `openssl`

Attacks on Encrypted Messages

- Ciphertext only:
  - encryption algorithm, ciphertext to be decoded
- Known plaintext:
  - encryption algorithm, ciphertext to be decoded, pairs of (plaintext, ciphertext)
- Chosen plaintext:
  - encryption algorithm, ciphertext to be decoded, plaintext (chosen by cryptanalyst) + corresponding ciphertext
- Chosen ciphertext:
  - encryption algorithm, ciphertext to be decoded, ciphertext (chosen by cryptanalyst) + corresponding plaintext
- Chosen text:
  - encryption algorithm, ciphertext to be decoded, plaintext + corresponding ciphertext (both can be chosen by attacker)

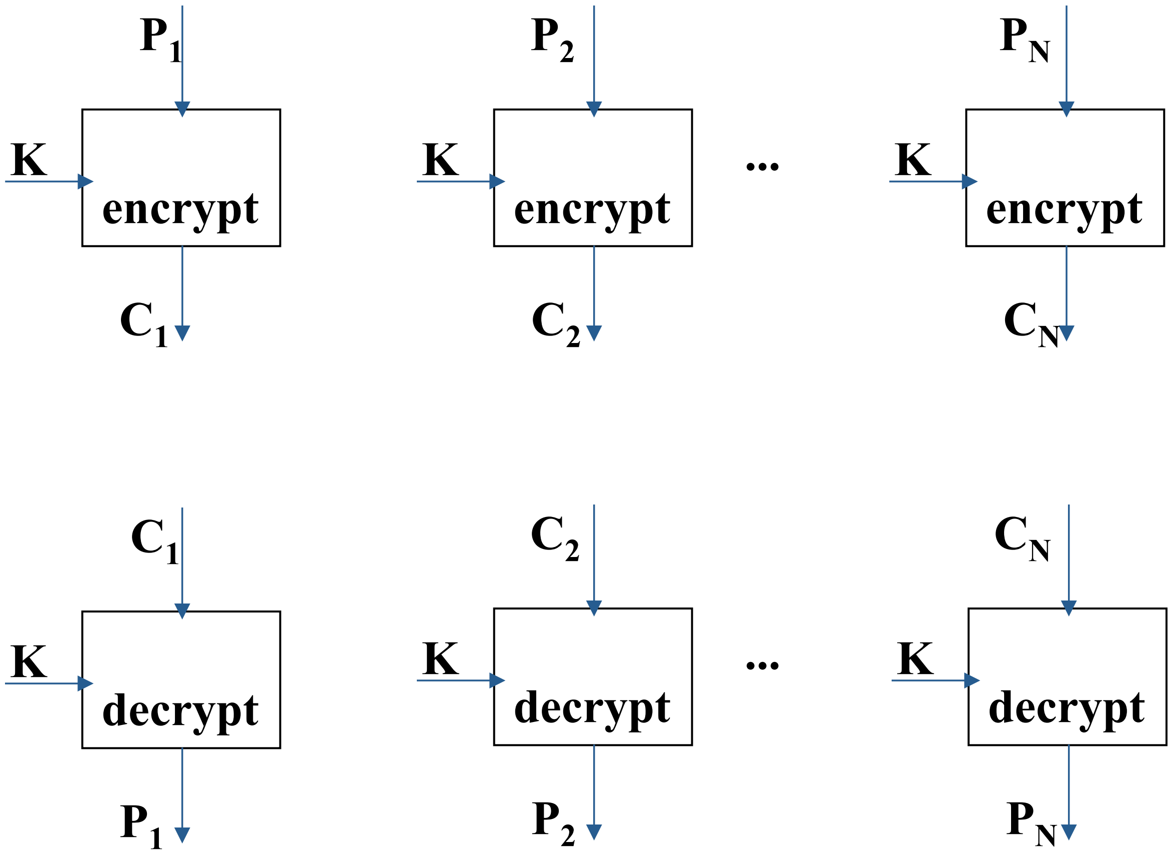
- Modern cryptography: better models (Game-based / indistinguishability proofs)
  - IND-CPA, etc.

Secret Key Cryptography

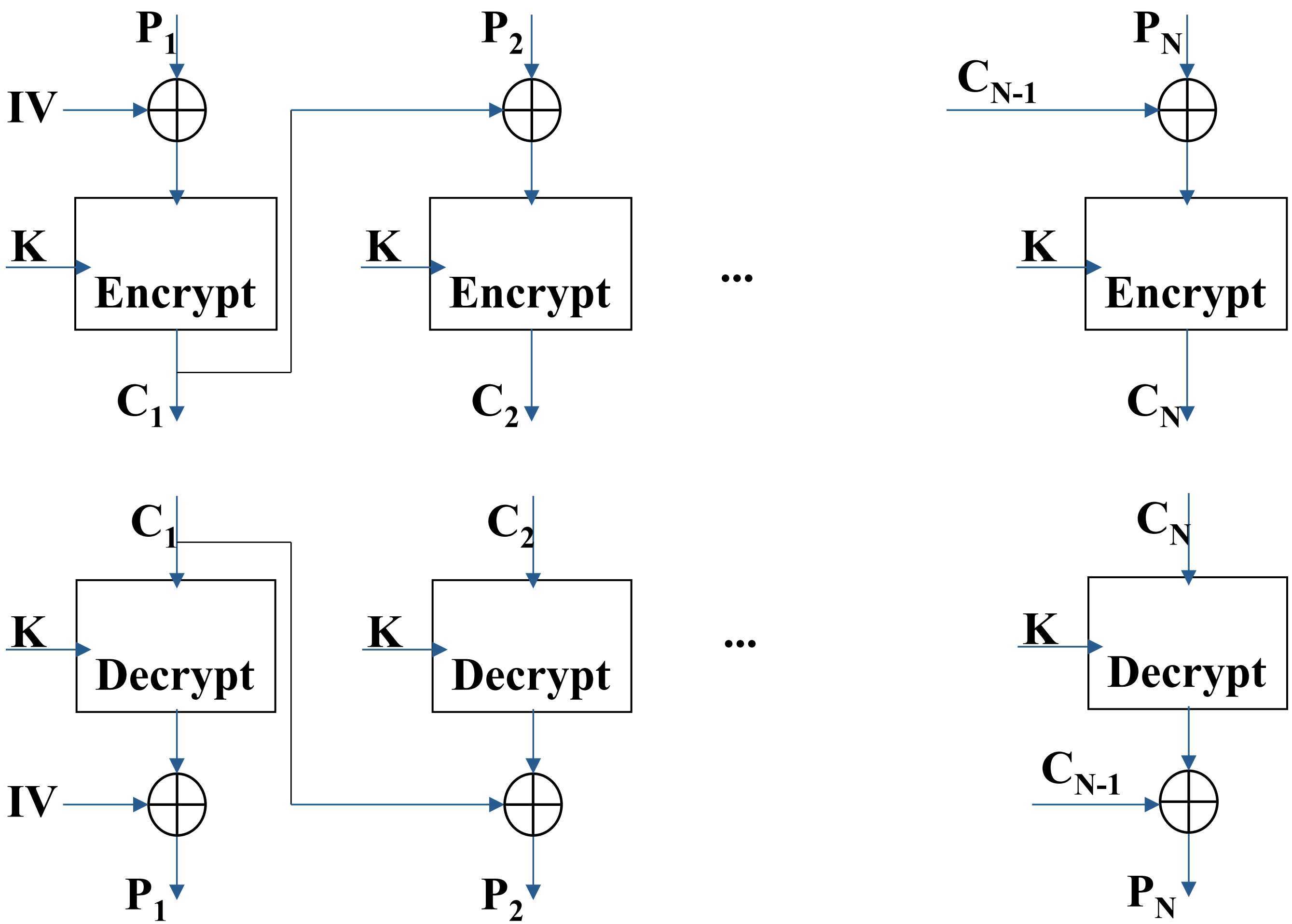
Examples of Symmetric Encryption Algorithms

- Advances Encryption Algorithm (AES)
  - Block size: 128 bits
  - Key size:128/192/256
- Data Encryption Standard (DES) – not secure
  - Block size: 64 bits
  - Key size: 56 bits
- DES is not recommended (broken)

Encryption Modes
I. Electronic Codebook (ECB)

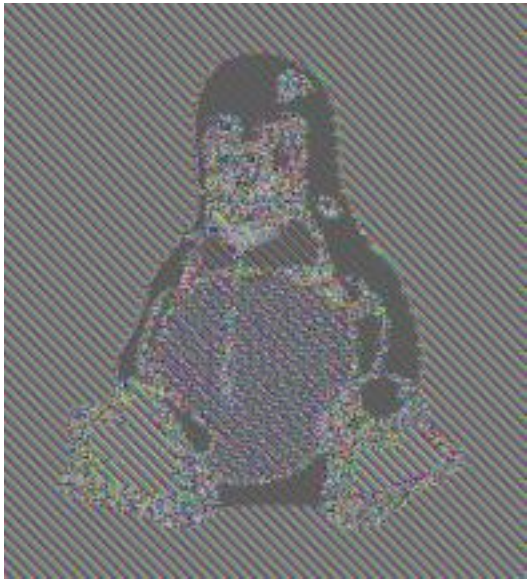


Encryption Modes: II. Cipher Block Chaining (CBC)

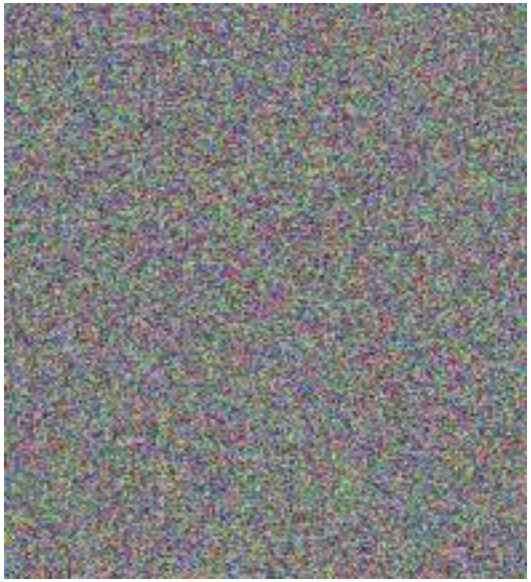


ECB vs. CBC

Plaintext



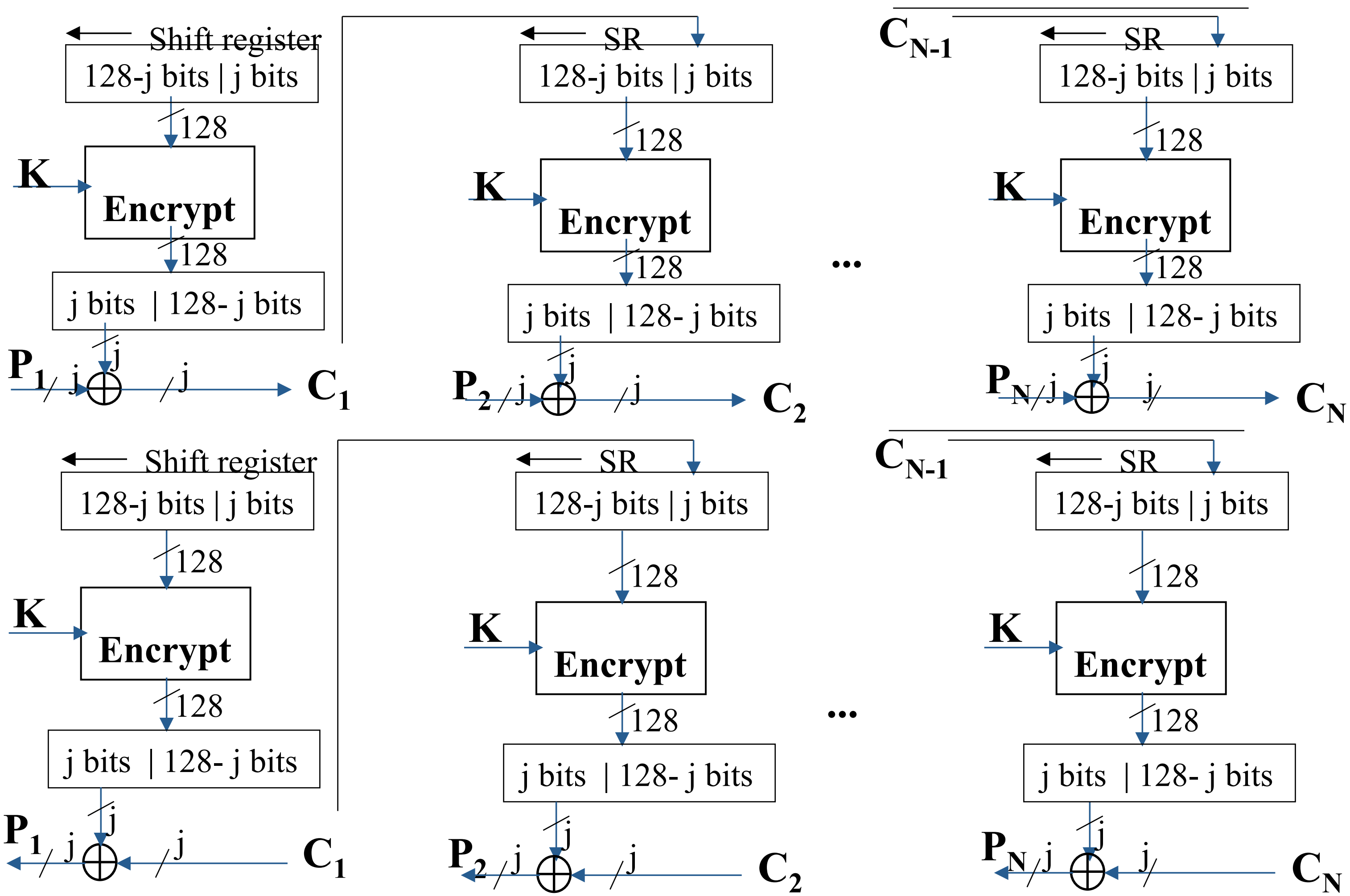
ECB Mode Encryption



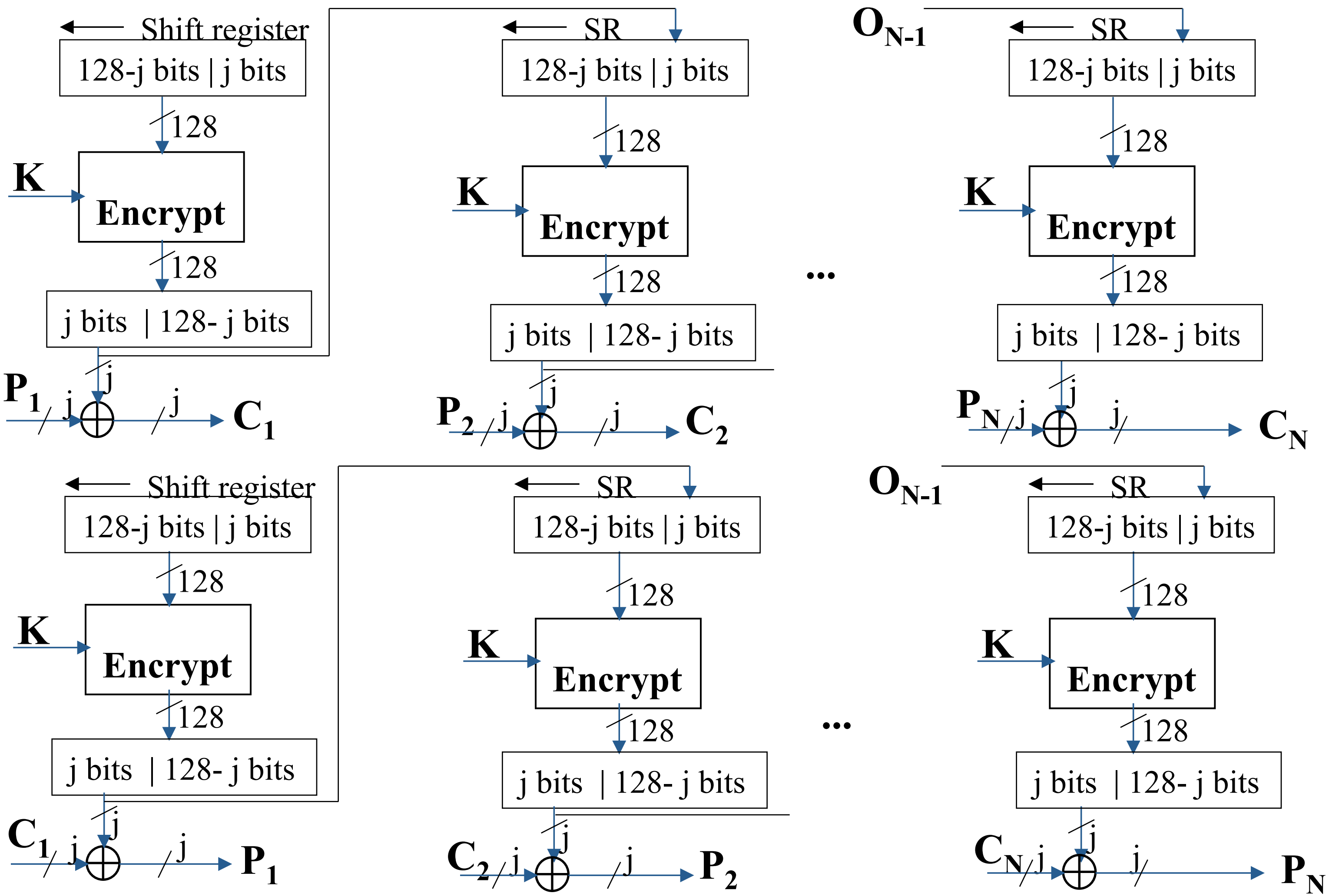
CBC Mode Encryption

Source: wikipedia

Encryption Modes: III. Cipher Feedback (CFB)



Encryption Modes:
IV. Output Feedback (OFB)



Encryption Modes: V. Counter (CTR)

- Similar to OFB but encrypts counter value rather than any feedback value
- Must have a different key & counter value for every plaintext block (never reused)

$$O_i = \mathrm{Encrypt}_{K1}(i)$$

$$C_i = P_i \text{ XOR } O_i$$

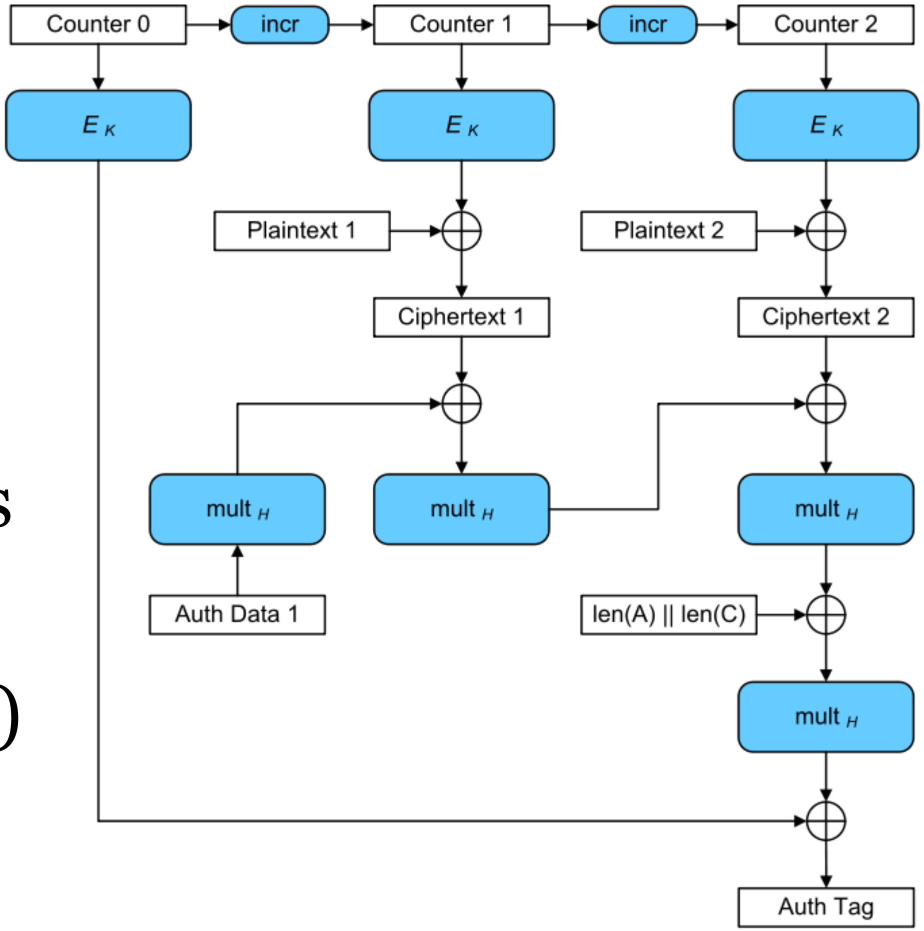
- Uses: high-speed network encryptions, random access to files

Galois Counter Mode

- Extension of Counter Mode to provide Integrity protection

Used in IEEE802.1ad, IPSec, TLS, SSH, etc.

Intel added instructions for GF multiplications in 2010 (PCLMULQDQ)



Hashing Functions

Hashing Functions and Message Digests

- Goal:
  - Input: long message
  - Output: short block (called *hash* or *message digest*)
  - Desired properties:
    - Pre-image: Given a hash *h* it is computationally infeasible to find a message that produces *h*
    - Second preimage
    - Collisions
- Examples: http://www.slavasoft.com/quickhash/links.htm
  - Recommended Hash Algorithm are SHA-2, SHA-3 by NIST
    - SHA-1 theoretical attacks but still OK for now
  - MD2, MD4, and MD5 by Ron Rivest [RFC1319, 1320, 1321]
  - SHA-1: output 160 bits being phased out
  - SHA-2: output 224-256-384-512 believed more secure than others
  - SHA-3: output 224-256-384-512 (+ variable length mode)
    http://csrc.nist.gov/groups/ST/hash/timeline.html

Birthday Attacks

- Is a 64-bit hash secure?
  - Brute force: 1ns per hash => 10^{13} seconds over 300 thousand years
- But by **Birthday Paradox** it is not
- Example: what is the probability that at least two people out of 23 have the same birthday? P > 0.5
- **Birthday attack technique**
  - opponent generates $2^{m/2}$ variations of a valid message all with essentially the same meaning
  - opponent also generates $2^{m/2}$ variations of a desired fraudulent message
  - two sets of messages are compared to find pair with same hash (probability > 0.5 by birthday paradox)
  - have user sign the valid message, then substitute the forgery which will have a valid signature
- Need to use larger MACs

Message Digest 5 (MD5) by R. Rivest [RFC1321]

- Input: message of arbitrary length
- Output: 128-bit hash
- Message is processed in blocks of 512 bits (padding if necessary)
- Security: not recommended
  - Designed to resist to the Birthday attack
  - Collisions where found in MD5, SHA-0, and almost found for SHA-1
  - Near-Collisions of SHA-0, Eli Biham, Rafi Chen, Proceedings of Crypto 2004, http://www.cs.technion.ac.il/~biham/publications.html
  - Collisions for Hash Functions MD4, MD5, HAVAL-128 and RIPEMD, Xiaoyun Wang and Dengguo Feng and Xuejia Lai and Hongbo Yu, http://eprint.iacr.org/2004/199.pdf
  - MD5 considered harmful today: creating a rogue CA certificate, Alexander Sotirov, Marc Stevens, Jacob Appelbaum, Arjen Lenstra, David Molnar, Dag Arne Osvik, Benne de Weger, December 30, 2008
  - Same attack as part of Flame malware 2012

Applications of Hashing Functions

- Authentication
- Encryption
- Message Authentication Codes

Message Authentication Code (MAC) Using an Encryption Algorithm

- Also called Message Integrity Code (MIC)
- Goal:
  - Detect any modification or forgery of the content by an attacker
- Some techniques:
  - Simple techniques have flaws
  - Use CBC mode, send only the last block (residue) along with the plaintext message
  - For confidentiality + integrity:
    - Use two keys (one for CBC encryption and one for CBC residue computation)
    - Append a cryptographic hash to the message before CBC encryption
  - Best practice technique:
    - Use a Nested MAC technique such as HMAC for integrity only
    - Use Galois Counter Mode (GCM) for confidentiality + MAC

HMAC

- $HMAC_K(x) = SHA\text{-}3((K \oplus \mathit{opad}) \mid SHA\text{-}3((K \oplus \mathit{ipad}) | x))$
  - *ipad* = 3636…36; *opad* = 5C5C…5C

- HMAC can be combined with any hashing function
- Proven to be secure under some assumptions…
  - HMAC is a pseudo random function family (PRF) if the compression function underlying the hashing function is PRF

Public Key Systems

Asymmetric cryptosystems

- Invented by Diffie and Hellman [DH76], and Merkle
  - When DES was proposed for standardization
- Asymmetric systems are much slower than the symmetric ones (~1000 times)
- Advantages:
  - does not require a shared key
  - simpler security architecture (no-need to a trusted third party)

Modular Arithmetic

- Modular addition:
  - E.g., $3 + 5 = 1 \bmod 7$
- Modular multiplication:
  - E.g., $3 * 4 = 5 \bmod 7$
- Modular exponentiation:
  - E.g., $3^3 = 6 \bmod 7$

- Group, Rings, Finite/Galois Fields …

Basic RSA Cryptosystem [RSA78]

- $E(M) = M^e \bmod n = C$ **(Encryption)**
- $D(C) = C^d \bmod n = M$ **(Decryption)**

- RSA parameters and basic (not secure) operations:
  - p, q, **two big prime numbers** **(private, chosen)**
  - $n = pq$, $\phi(n) = (p-1)(q-1)$ **(public, calculated)**
  - e, **with** $\gcd(\phi(n), e) = 1$, $1<e<\phi(n)$ **(public, chosen)**
  - $d = e^{-1} \bmod \phi(n)$ **(private, calculated)**

- $D(E(M)) = M^{ed} \bmod n = M^{k\phi(n)+1} = M$ **(Euler's theorem)**

Example of RSA

- Keys generation:
  - $p = 5$; $q = 11 \Rightarrow n =$
  - $e = 3 \Rightarrow d = 27$
    - Because $ed = 1 \bmod (p-1)(q-1)$
  - Public key: (e, n); Private Key: (d, n)
- Encryption
  - $M = 2$
  - $Encryption(M) = M^e \bmod n = 8$
  - $Decryption(8) = 8^d \bmod n = 2$
- Typical value $e = 2^{16}+1$, p & q 1000 bits

Prime Numbers Generation

- Density of primes (prime number theorem):
  - $\pi(x) \sim x/\ln(x)$
- Sieve of Erathostène
  - Try if any number less than SQRT(n) divides n
- Based on Fermat's Little Theorem but does not detect Carmichael numbers
  - $b^{n-1} = 1 \bmod n$ [if there exists b s.t. gcd(b, n) = 1 and $b^{n-1} \neq 1 \bmod n$ then n does not pass Fermat's test for half b's relatively prime with n]
- Solovay-Strassen primality test
  - If n is not prime at least 50% of b fail to satisfy the following:
    - $b^{(n-1)/2} = J(b, n) \bmod n$
- Rabin-Miller primality test
  - If n is not prime then it is not pseudoprime to at least 75% of $b<n$:
    - Pseudoprime: $n-1 = 2^s t$, $b^t = \pm 1 \bmod n$ **OR** $b^{t2^r} = -1 \bmod n$ for some r<s
  - Probabilistic test, deterministic if the Generalized Riemann Hypothesis is true
- Deterministic polynomial time primality test [Agrawal, Kayal, Saxena'2002]

Use of RSA

- Encryption (A wants to send a message to B):
  - A uses the public key of B and encrypts M (i.e., $E_B(M)$)
  - Since only B has the private key, only B can decrypt M (i.e., $M = D_B(M)$

- Digital signature (A want to send a signed message to B):
  - Based on the fact that $E_A(D_A(M)) = D_A(E_A(M))$
  - A encrypts M using its private key (i.e., $D_A(M)$) and sends it to B
  - B can check that $E_A(D_A(M)) = M$
  - Since only A has the decryption key, only can generate this message

Flaws in using Textbook RSA

- If message has low entropy
  - If $M \in \{0, 1\}$ $\Rightarrow$ easy to guess
  - If M is a random 64 bit *whp* $M = M_1 \times M_2$ *the* adversary can do a meet in the middle attack

Bit-length m	m_1	m_2	Probability
40	20	20	18%
	21	21	32%
	22	22	39%
	20	25	50%
64	32	32	18%
	33	33	29%
	34	34	35%
	30	36	40%

$\Rightarrow$ Importance of standards for best practices in using RSA and cryptography in general

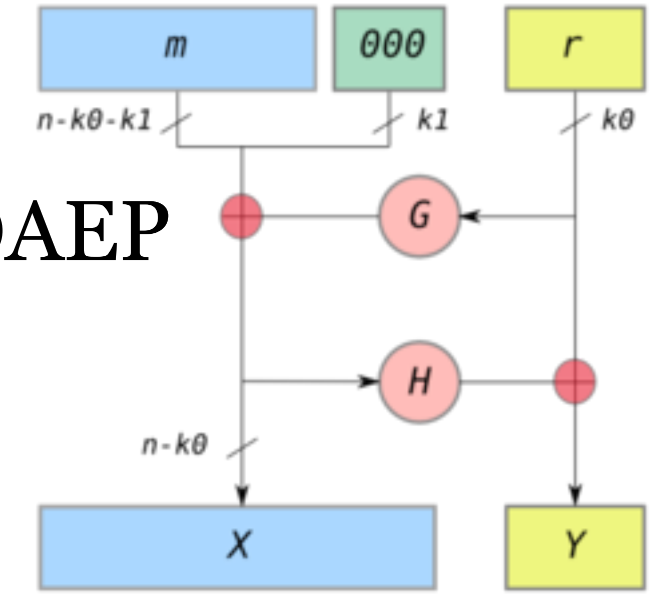
Ciphertext Indistinguishability

- Indistinguishable Chosen Plaintext Attack (IND-CPA)
  - Probabilistic asymmetric key encryption algorithm
  - Computational security
  - Adversary: probabilistic polynomial time Turing machine
- Game
  - Challenger generates a key pair *PK*, *SK* based on some security parameter k (e.g., a key size), publishes *PK*. The challenger retains *SK*.
  - Adversary performs a polynomially bounded number of encryptions/operations
  - Eventually, the adversary submits two chosen plaintexts M_0, M_1 to challenger
  - Challenger selects a bit b uniformly random, and sends $C = E(PK, M_b)$ to adversary
  - The adversary is free to perform additional computations or encryptions.
  - Finally, it outputs a guess for the value of b.
- Scheme is IND-CPA secure if $| \text{Prob}[\text{guessing } b] - ½| < \varepsilon(k)$ [negligible]

- Similar definition for symmetric key encryption algorithms using oracles

Optimal Asymmetric Encryption Padding (OAEP)

- Use of RSA is standardized by several PKCS public key crypto standards
- PKCS #1 v2 (RFC2437) uses OAEP



When combined with secure trapdoor one-way permutation is proven semantically secure under IND-CPA in Random Oracle model

Keys Establishment

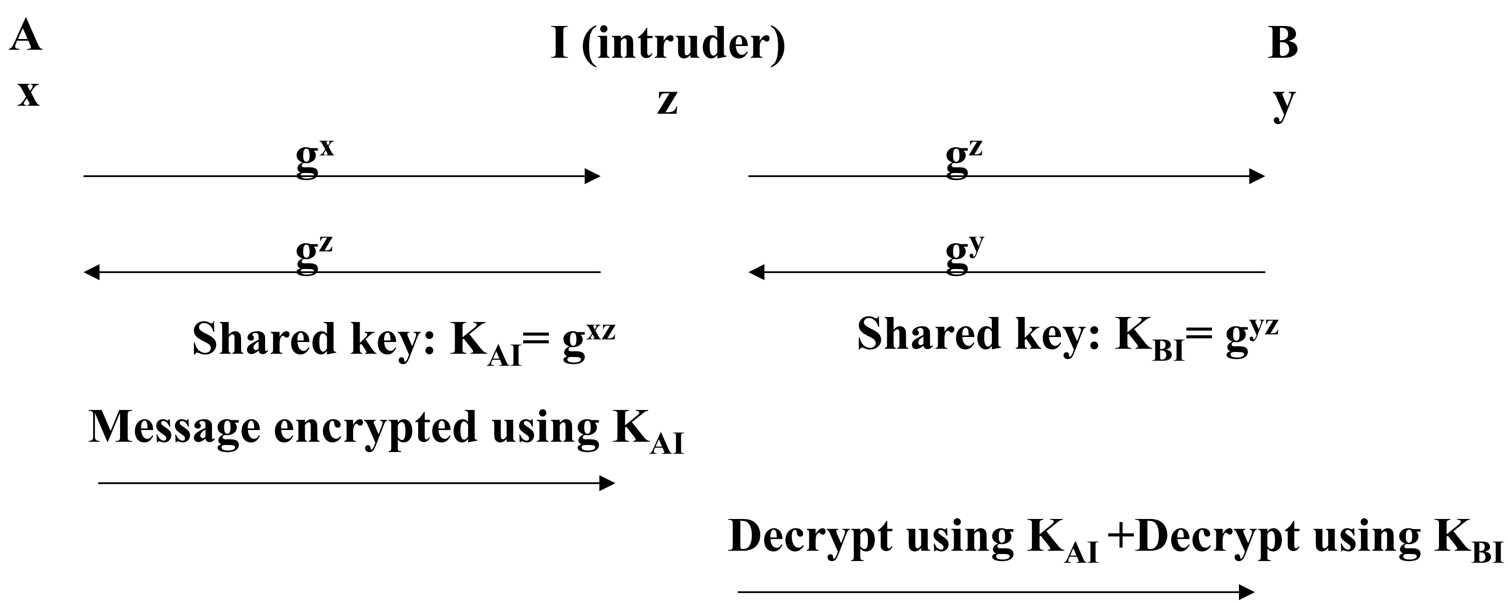
Diffie-Hellman Key Exchange

Private: A	**Public**	**Private: B**
x	**p: prime number,** **g: primitive element of GF(p)**	**y**
compute: $g^x \bmod p$		**compute:** $g^y \bmod p$
receive: $g^y \bmod p$		**receive:** $g^x \bmod p$
Compute shared key: $(g^y)^x \bmod p$	$K = g^{xy} \bmod p$	**Compute shared key:** $(g^x)^y \bmod p$

- Based on the difficulty of computing discrete logarithms
- Works also in extension Galois fields: $GF(p^q)$

Attack on Diffie-Hellman Scheme: Public Key Integrity

Man-in-the-Middle Attack



- Need for a mean to verify the public information: certification

Random Number Generation (RNG)

- RNG is a critical building block of security services
- Cryptographic RNG need to be computationally unguessable by an adversary and are quite different from RNG for simulations
- Blum Blum Shub 1986
  - $x_{n+1} = x_n^2 \bmod M$ where $M = pq$ the product of 2 large primes both congruent to 3 mod 4
  - x_0 co-prime with M
  - $r_i = \text{LSB}(x_i)$
  - Computationally reduces to the quadratic residue problem
  - Cons: too slow
- Rivest RNG
  - $r_i = \text{LSB}(\text{SHA-256}(\textit{secret-seed} \mid i))$

Building Network Security Services

- Confidentiality:
  - Use an encryption algorithm
  - Generally an symmetric algorithm for a stream of data
- Integrity:
  - MAC algorithm
- Access control:
  - Use access control tables
- Authentication
  - Use authentication protocols
- Non-repudiation
  - Digital signatures

Some Examples

- Email
  - PGP or S/MIME: basic use of crypto
    - Beware your mail client might be storing drafts on the server!
  - Anti-spam: Hashcash, DKIM
- DNSSEC, SSH
- Cryptocurrency: Bitcoin
- TLS/SSL
  - https, VPN, WPA-Enterprise, Tor, Hidden Services

Anti-Spam

- Current solutions:
  - Black/white listing IP addresses (e.g., zombie computers, addresses that sent spam to honeypots, ISP willingly hosting spammers)
  - Signatures/content matching rules
  - Distributed Checksum Clearinghouse: message fuzzy checksum is sent to DCC to check how many times it appeared
  - Sender Policy Framework: specify who can send email from a domain (relies on TXT/SPF DNS record)

    dig @8.8.8.8 neu.edu ANY

  - HashCash: add header

    Example: X-Hashcash: 1:20:101130:noubir@ccs.neu.edu::HdG5s/(oiuU7Ht7b:ePa+tr5

    The counter ePa+tr5 is found such that the hash of the X-Hashcash header has its first 20 bits = 0

    This information is found using brute force

    X-Hashcash constrains the destination email address and date => proof of work protects against spam replays

    `ver:bits:date:resource:[ext]:rand:counter`

    - `ver = 1`
    - `bits = how many bits of partial-preimage the stamp is claimed to have`
    - `date = YYMMDD[hhmm[ss]]`
    - `resource = resource string (eg IP address, email address)`
    - `ext = extension -- ignored in the current version`
  - Example of software combining these techniques: spamassassin

Sender MTA Authentication

- DomainKeys Identified Mail (DKIM RFC 4871, 2007 – RFC 6376, 2011)
  - DomainKeys initiated by Yahoo!, today a IETF standard DKIM
- The sending MTA adds a signature to the message
  - MIME header
  - Public key can be retrieved through DNS system
    dig @8.8.8.8 s1024._domainkey.yahoo.com any
    dig @8.8.8.8 gamma._domainkey.gmail.com any
- Example:

```
DKIM-Signature: v=1; a=rsa-sha256; c=relaxed/relaxed;
        d=gmail.com; s=gamma;
        h=domainkey-signature:mime-version:received:received:date:message-id
         :subject:from:to:content-type;
        bh=cvC34ODyPB/uEHubbDQQmwxZfqZboGjW5gpY4W6DuzE=;
        b=ASsElEtXCmM/x3aL38Efnvi9xDrBdleaaBqd24f7XS49pRzhXK/7Vak9+LyLLcN89e
         GZ7SZi7swY2xIlt3zJTiGrGif0bfQdf7LvlP12g53nczhBBRa8McBVtdK9+ImAZByg8o
         oEM4INNjMvdhXi9MVXtntkvmsTmWitAJxZgQQ=
DomainKey-Signature: a=rsa-sha1; c=nofws;
        d=gmail.com; s=gamma;
        h=mime-version:date:message-id:subject:from:to:content-type;
        b=JFWiE0YlmWxu+Sq4OJ9Ef5k3rjbZQ51dGEyaFyvKJYR8NkoGrNoPIUq5f29ld8P0AD
         Lg058evTVeuWxvfPQfa7K65J9AjEQt5U8d9zBKFfxRAz1h5nr7k2kCLRMnhbqVTkiOIS
         OUfxIQeMfgbYz0ydCgerEnfGreKMQIYax+dpo=
```

Misuse of the Basics

- Crypto libraries are widely available
- Developers still lack knowledge of crypto basics
- Default black-box use leads to vulnerabilities

Analysis of Android Apps

- Android SSL support can lead to the following
  - Trusting all certificates no matter who signed them
  - Accepting a certificate for an arbitrary different domain
  - 1,074 potentially vulnerable apps to MITM
  - 41 out 100 selected for manual verification are vulnerable: 39M – 185M users

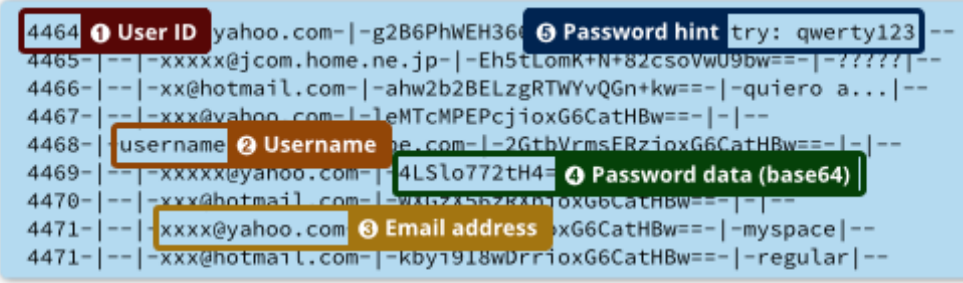
[FHMSBF'12] "Why Eve and Mallory Love Android: An Analysis of Android SSL (In)Security" CCS'2012.

- Misuse of Android Crypto Service Providers (15K Apps)
  - 5,656: ECB (BouncyCastle default)
  - 3,644: Constant symmetric key
  - 2,000: ECB (Explicit use)
  - 1,932: Uses constant IV
  - 1,636: Used iteration count < 1,000 for PBE
  - 1,629: Seeds SecureRandom with static data
  - 1,574: Uses static salt for PBE

[EBFK CCS'13] "An Empirical Study of Cryptographic Misuse in Android Applications" CCS'2013.

Adobe Breach (October 2013)


```
4464-|--|-xxx@yahoo.com-|-g2B6PhWEH366cdBSCql/UQ==-|-try: qwerty123|--
4465-|--|-xxxxx@jcom.home.ne.jp-|-Eh5tLomK+N+82csoVwU9bw==-|-?????|--
4466-|--|-xx@hotmail.com-|-ahw2b2BELzgRTWYvQGn+kw==-|-quiero a...|--
4467-|--|-xxx@yahoo.com-|-leMTcMPEPcjioxG6CatHBw==-|-|--
4468-|-username-|-xxxxx@adobe.com-|-2GtbVrmsERzioxG6CatHBw==-|-|--
4469-|--|-xxxxx@yahoo.com-|-4LSlo772tH4=-|-rugby|--
4470-|--|-xxx@hotmail.com-|-WXGzX56zRXnioxG6CatHBw==-|-|--
4471-|--|-xxxx@yahoo.com-|-x3eI/bgfUNrioxG6CatHBw==-|-myspace|--
4471-|--|-xxx@hotmail.com-|-kbyi9I8wDrrioxG6CatHBw==-|-regular|--
```

– Passwords encrypted with 64 bits 3DES in ECB
  - Not hashed, not salted, not in CBC, not AES

Password data (hex)	Password hint
0b4c27d8f75cc41a	-> Same old, same old
e826ef87cc7a3029 e2a311ba09ab4707	-> You'll never guess
0842ccb7edf3e343 e2a311ba09ab4707	->
92663700893c3f27 a667d747891a8255	-> Dog + digit
88fc540356d561ec	-> Dog
fb0a9047a5dd5ef8 f3c512b0e38a5392 a3f492fbd917f632	-> Virtuously long
92bb535704f0ae7f	-> Geburtestag

Pwd data length	Count (logarithmic scale)
8	461016
16	538396
24	526
32	53
40	6
48	3

Source: Naked Security

Adobe Breach (October 2013)

- ECB, no salting

⇒ same password results in the same hash

⇒ combining the hints makes he guesses easy

Adobe password data		Password hint	
110edf2294fb8bf4	->	numbers 123456	① 123456
110edf2294fb8bf4	->	==123456	
110edf2294fb8bf4	->	c'est "123456"	
8fda7e1f0b56593f e2a311ba09ab4707	->	numbers	② 12345678
8fda7e1f0b56593f e2a311ba09ab4707	->	1-8	
8fda7e1f0b56593f e2a311ba09ab4707	->	8digit	
2fca9b003de39778 e2a311ba09ab4707	->	the password is password	③ password
2fca9b003de39778 e2a311ba09ab4707	->	password	
2fca9b003de39778 e2a311ba09ab4707	->	rhymes with assword	
e5d8efed9088db0b	->	q w e r t y	④ qwerty
e5d8efed9088db0b	->	ytrewq tagurpidi	
e5d8efed9088db0b	->	6 long qwert	
ecba98cca55eabc2	->	sixxone	⑤ 111111
ecba98cca55eabc2	->	1*6	
ecba98cca55eabc2	->	sixones	

Weak Pseudo-Random Number Generators

- Out or 4.7 million distinct 1024-bit RSA 12,720 have a shared prime

- Many embedded devices

[LHABK] "Ron was wrong, Whit is right", IACR, 2012.

TLS/SSL

- A closer look at the popular TLS/SSL
- Overview
- Vulnerabilities
  - Design, integration, implementation

General Description of SSL/TLS

- Terminology:
  - SSL: Secure Socket Layer
  - TLS: Transport Layer Security
- Concept: secure connections on top of TCP
  - OS independent
  - TCP instead of UDP
    - Cons: Rogue packet problem
    - Pro: SSL/TLS doesn't have to deal with packet retransmission
- History:
  - SSLv2 proposed and deployed in Netscape 1.1 (1995)
  - PCT (Private Communications Technology) by Microsoft
  - SSLv3: (1995)
  - TLS proposed by the IETF based on SSLv3 but not compatible (1996)
    - Uses patent free DH and DSS instead of RSA which patent didn't expire yet
  - TLS 1.2 (2008)
    - Updated in 2011 does not allow SSLv2

SSL Architecture

- There is a **Client** and a **Server**
- **SSL session**
  - An association between client & server
  - Created by the Handshake Protocol
  - Defines a set of cryptographic parameters
  - May be shared by multiple SSL connections
- **SSL connection**
  - A transient, peer-to-peer, communications link
  - Associated with 1 SSL session

SSL/TLS Basic Protocol

- Basic Protocol:
  - A -> B: I want to talk, ciphers I support, R_A
  - B -> A: certificates, cipher I choose, R_B
  - A -> B: $\{S\}_B$, {keyed hash of handshake msgs}
  - B -> A: {keyed hash of handshake msgs}
  - A <-> B: data encrypted and integrity checked with keys derived from K
  - Keyed hashes use $K = f(S, R_A, R_B)$

- SSL/TLS partitions TCP byte stream into records:
  - A record has: header, cryptographic protection => provides a reliable encrypted, and integrity protected stream of octet
  - Record types:
    - Handshake messages
    - Change cipher spec
    - Application data
    - Alerts: error messages or notification of connection closure

SSL/TLS Basic Protocol (Cont'd)

- How do you make sure that keyed hash in message 3 is different from *B*'s response?
  - Include a constant *CLNT/client finished* (in SSL/TLS) for *A* and *SRVR/server finished* for *B*
- Keyed hash is sent encrypted and integrity protected
  - Not necessary
- Keys: derived by hashing *K* and R_A and R_B
  - 3 keys in each direction: encryption, integrity and IV
  - Write keys (to send: encrypt, integrity protect)
  - Read keys (to receive: decrypt, integrity check)

What's still missing?

- SSL/TLS allowed to authenticate the server
- How would the server authenticate the user?
  - SSL/TLS allows clients to authenticate using certificates:
    - *B* requests a certificate in message 2
    - *A* sends: certificate, signature of hash of the handshake messages

Session Resumption

- Many secure connections can be derived from the session
  - Cheap: how?
- Session initiation: modify message 2
  - *B* -> *A*: session_id, certificate, cipher, R_B
- *A* and *B* remember: (session_id, master key)
- To resume a session: *A* presents the session_id in message 1
  - *A* -> *B*: session_id, ciphers I support, R_A
  - *B* -> *A*: session_id, cipher I choose, R_B, {keyed hash of handshake msgs}
  - *A* -> *B*: {keyed hash of handshake msgs}
  - *A* <-> *B*: data encrypted and integrity checked with keys derived from *K*

Computing the Keys

- S: pre-master secret (forget it after establishing K)
- $K = f(S, R_A, R_B)$
- 6 keys = $g_i(K, R_A, R_B)$
- Rs: 32 bytes (usually the first 4 bytes are Unix time)

PKI in SSL

- Client comes configured with a list of "trusted organizations": CA
- What happens when the server sends its certificate?
- When the server whishes to authenticate the client
  - Server sends a list of CA it trusts and types of keys it can handle
- In SSLv3 and TLS a chain of certificates can be sent

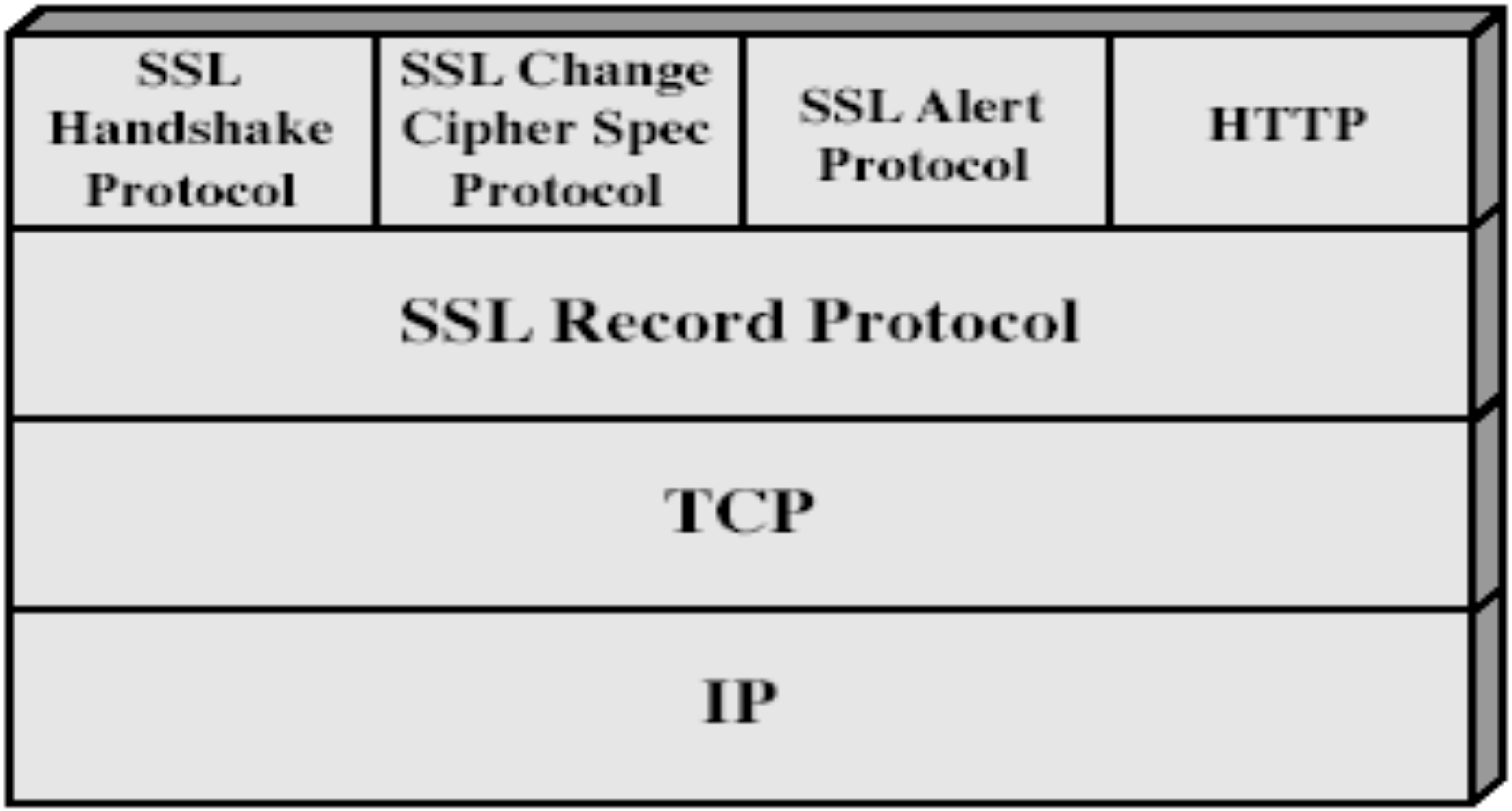
Negotiating Cipher Suites

- A cipher suite is a complete package:
  - (encryption algorithm, key length, integrity checksum algorithm, etc.)
- Cipher suites are predefined:
  - Each assigned a unique value (contrast with IKE)
  - SSLv2: 3 bytes, SSLv3: 2 bytes => upto 65000 combinations
    - 30 defined,
    - 256 reserved for private use: FFxx (risk of non-interoperability)
- Selection decision:
  - In v3 A proposes, B chooses
  - In v2 A proposes, B returns acceptable choices, and A chooses
- Suite names examples:
  - SSL_RSA_EXPORT_WITH_DES40_CBC_SHA
  - SSL2_RC4_128_WITH_MD5

Attacks fixed in v3

- Downgrade attack:
  - In SSLv2 there is no integrity protection for the initial handshake
  - Active attacker can remove strong crypto algorithm from proposed cipher suite by *A* => forcing *A* and *B* to agree on a weak cipher
  - Fixed by adding a *finished* message containing a hash of previous messages
- Truncation attack:
  - Without the *finished* message an attacker can send a TCP FIN message and close the connection without communicating nodes detecting it
- Attacks not fixed: session renegotiation, BEAST, CRIME/ BREACH…

SSL/TLS Detailed Protocol SSL Stack



SSL Record Protocol

- SSL Record Protocol defines these two services for SSL connections:
  - **Confidentiality**
    - Using symmetric encryption with a shared secret key defined by Handshake Protocol
    - AES, IDEA, RC2-40, DES-40, DES, 3DES, Fortezza, RC4-40, RC4-128
    - CBC mode (except for RC4)
    - Message is compressed before encryption
  - **Message integrity**
    - Using a MAC with shared secret key
    - Based on HMAC and MD5 or SHA (with a padding difference due to a typo in an early draft of HMAC RFC2104)
- Records sent after *ChangeCipherSpec* record are cryptographically protected
- Record header:
  - [record type, version number, length]
    - ChangeCipherSpec = 20, Alert = 21, Handshake = 22, Application_data = 23

SSL Change Cipher Spec Protocol

- One of 3 SSL-specific protocols which use the SSL Record Protocol
- Single message
  - – Causes pending state to become current
  - ⇒ all records following this will be protected with the ciphers agreed upon

SSL Alert Protocol

- Conveys SSL-related alerts to peer entity
- Severity
  - warning or fatal
- Specific alerts
  - Unexpected message, bad record mac, decompression failure, handshake failure, illegal parameter
  - Close notify, no certificate, bad certificate, unsupported certificate, certificate revoked, certificate expired, certificate unknown
- Compressed & encrypted

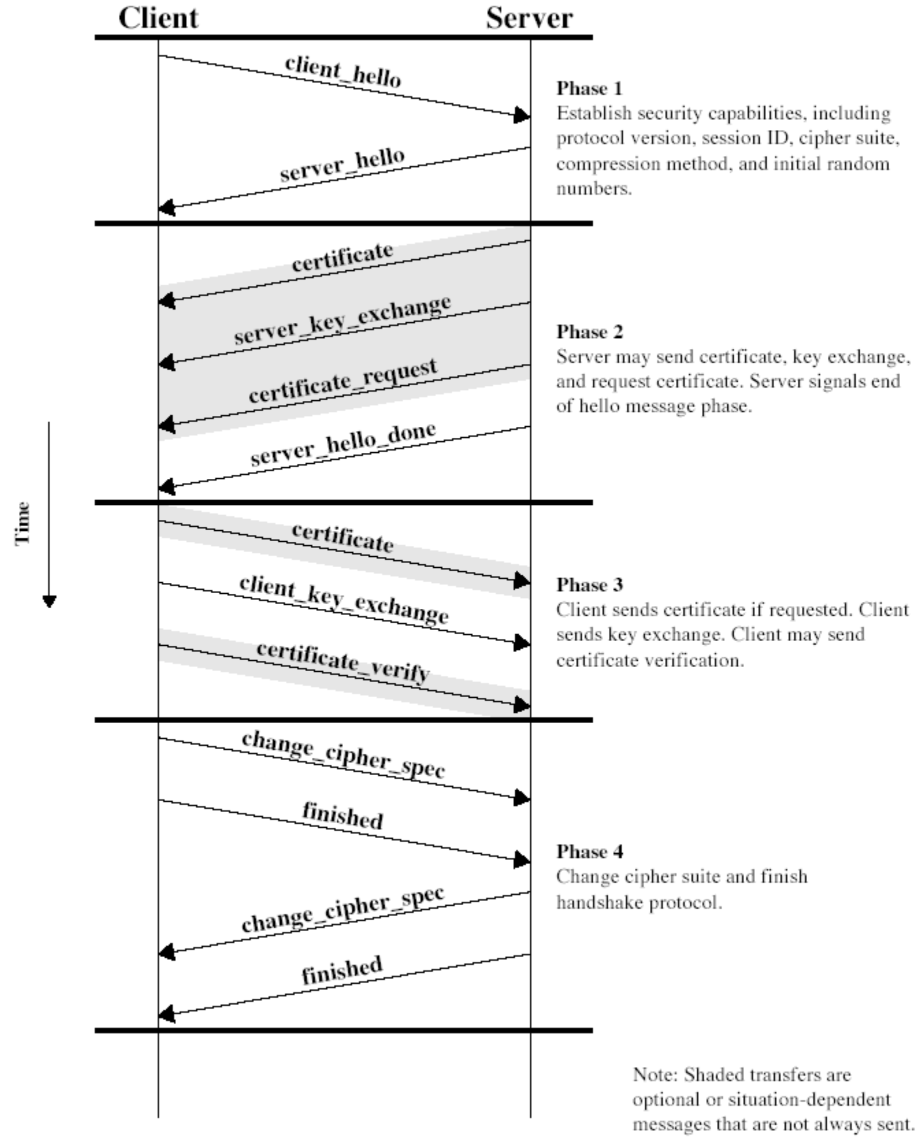
SSL Handshake Protocol

- Allows server & client to:
  - Authenticate each other
  - Negotiate encryption & MAC algorithms
  - Negotiate cryptographic keys to be used
- Comprises a series of messages in phases
  - Establish Security Capabilities
  - Server Authentication and Key Exchange
  - Client Authentication and Key Exchange
  - Finish

Handshake Messages

- ***ClientHello* message:**
  - [type=1, length, version number, R_A, length of session_id, session_id, length of cipher suite list, sequence of cipher suites, list of compression methods]
- ***ServerHello*:** [type=2, length, version number, R_B, length of session_id, session_id, chosen cipher, chosen compression method]
- ***Certificate*:** [type=11, length, length of first certificate, first certificate, ...]
- ***ServerKeyExchange*:** (for export: ephemeral public key)
  - [type=12, length, length of modulus, modulus, length of exponent, exponent]
- ***CertificateRequest*:** [type=13, length, length of key type list, list of types of keys, length of CA name list, length of first CA name, 1stCA name, ...]
- ***ServerHelloDone*:** [type=14, length=0]
- ***ClientKeyExchange*:** [type=16, length, encrypted pre-master secret]
- ***CertificateVerify***:[type=15, length, length of signature, signature]
- ***HandshakeFinished***:[type=20, length=36 (SSL) or 12 (TLS), digest]

SSL Handshake Protocol



Exportability Issues

- Exportable suites in SSLv2:
  - 40 secret bits out of 128 in symmetric keys
  - 512-bits RSA keys
- Exportability in SSLv3:
  - Integrity keys computed the same way
  - Encryption keys: 40 bits secret
  - IV non-secret
  - When a domestic server (e.g., 1024-bit RSA key) communicates with an external client the server creates an ephemeral key of 512-bits and signs it with it's 1024-bit key

TLS (Transport Layer Security)

- TLS is and IETF standard similar to SSLv3
  - RFC 2246, RFC 4346, and RFC 5246
- Minor differences
  - Record format version number
  - HMAC for MAC
  - Pseudo-random function to expand the secrets
  - Additional alert codes
  - Changes in supported ciphers
  - Changes in certificate negotiations
  - Changes in use of padding

Session Renegotiation Flaw/Attack (2009)

- The adversary carries a MITM

```
Client                      Attacker                          Server
------                      -------                           ------
                                <----------- Handshake ------------>
                                <======= Initial Traffic ==========>
<-------------------------- Handshake ============================>
<======================== Client Traffic ==========================>
```

- Initial traffic:

```
GET /pizza?toppings=pepperoni;address=attackersaddress HTTP/1.1
X-Ignore-This:
```

  Note no: CR LF

- Client traffic

```
GET /pizza?toppings=sausage;address=victimssaddress HTTP/1.1
Cookie: victimscookie
```

- Server sees:

```
GET /pizza?toppings=pepperoni;address=attackersaddress HTTP/1.1
X-Ignore-This: GET /pizza?toppings=sausage;address=victimssaddress HTTP/1.1
Cookie: victimscookie
```

OS X (2014)

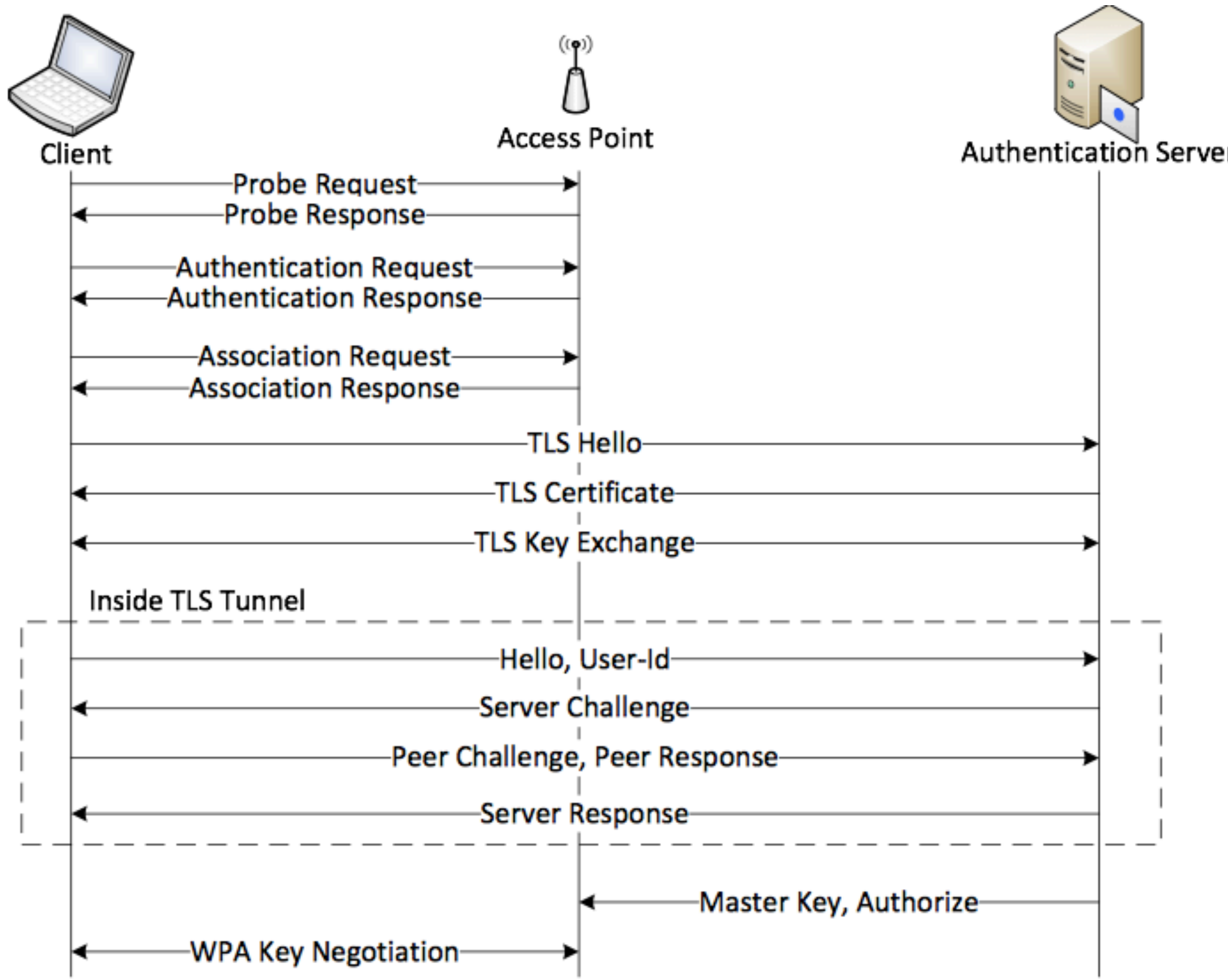
```
static OSStatus
SSLVerifySignedServerKeyExchange(SSLContext *ctx, bool isRsa, SSLBuffer signedParams,
                                 uint8_t *signature, UInt16 signatureLen)
{
    OSStatus        err;
(…)
    if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
        goto fail;
        goto fail;
    if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
        goto fail;

  err = sslRawVerify(ctx,
                     ctx->peerPubKey,
                     dataToSign,        /* plaintext */
                     dataToSignLen,     /* plaintext length */
                     signature,
                     signatureLen);
  if(err) {
    sslErrorLog("SSLDecodeSignedServerKeyExchange: sslRawVerify "
                "returned %d\n", (int)err);
    goto fail;
  }

fail:
    SSLFreeBuffer(&signedHashes);
    SSLFreeBuffer(&hashCtx);
    return err;
}
```

Other Attacks

- BEAST (2011)
  - Attack on CBC mode by re-injecting IVs…
- CRIME/BREACH
  - Attack on compression when combined with
- Require attacker to be on the routing path
  - e.g., controls Access Point
- Heartbleed (2014)
  - Implementation

- Check: https://www.trustworthyinternet.org/ssl-pulse/

WPA-Enterprise Attacks [CKRN'12]

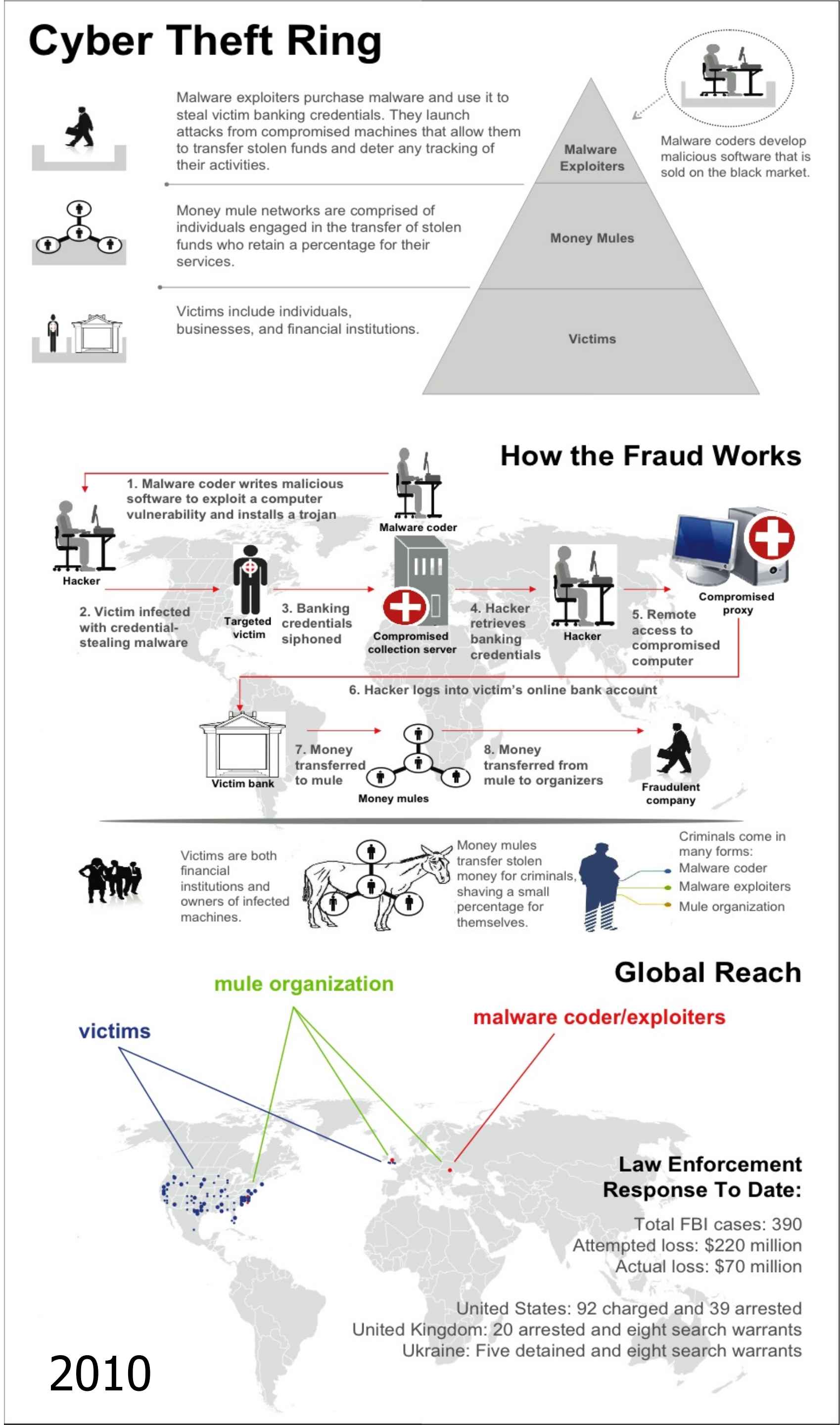


Worms: Buffer Overflow to Crypto-Based

- Popularized by R. Morris 1988, re-emerged in late 90s - ~2003 mostly DoS
  - Code Red CRv1 (7/13/2001), Code Red CRv2 (7/19/2001), Code Red II (8/4/2001), Nimbda (9/18/2001), …
- MS SQL Slammer
  - Date January 25, 2003
  - Buffer overflow in MS SQL Server
  - Doubled every 8.5 seconds until network collapse
  - 90% of vulnerable hosts infected in 10 minutes (75,000)
- Helpful worms: Welchia/Nachia worm (installs patches)
- Check: http://en.wikipedia.org/wiki/Timeline_of_notable_computer_viruses_and_worms
- Where did all the worms go?
  - Stealthy, instrumented for financial benefits, cyber-crime, cyber-warfare targeted attacks
  - Conficker A, B, C, D, E: since November 2008 infected 9-15 million hosts
  - In 2009, PandaLabs analyzed 2M machines and found 6% infected
  - Stuxnet, FLAME (2009 – 2012 see next slides)
  - In 2013: Cryptolocker encrypts the files on a user's hard drive, and asks for a ransom

Zeus

- Trojan horse (2007 -)
  - Steals banking information
  - Man-in-the-browser keystroke logging and Form Grabbing
  - Spreads through drive-by downloads, phishing
  - 3.6M infected in the US
- Used sophisticated scheme to funnel stolen money to exploiters through mules
  - More recently: Bitcoin, MoneyPak
- New versions using Tor HS



Stuxnet

- Stuxnet is a computer worm with unique characteristics
  - Time frame 2009-2010?
- Targets specific SCADA systems
  - Supervisory Control and Data Acquisition systems
  - Control industrial systems such as power plants
- Stuxnets spreads slowly searching for specific SCADA systems and reprograms their PLC

How does it operate?

- Stuxnet uses 4 zero-day attacks as infection vectors + other bugs
  - USB drive, print spooler, two elevation of privilege bugs
- Spreads slowly (to max three nodes)
- When spreading over the network remains local to the company
- Looks for a MS Windows machine with
  - WinCC/PCS 7 Siemens Software that controls PLC
  - Checks for Variable Frequency Drives (AC rotational speed controllers)
  - Focuses on two vendors (Vacon & Fararo Paya)
  - Attacks systems that run between 807-1210Hz
  - Modifies the output frequency for a short interval of time to 1410Hz and then to 2Hz and then to 1064Hz
- Tries default/hardcoded passwords
- Hides existence by installing malicious drivers signed using two stolen keys (Realtek, JMicron)
- 60% damage believed to be in Iran
- Variants: Duqu similar to Stuxnet but with different purpose
- Seems there was another variant that started in 2007 (stealthier, replays recorded physical process, propagates through contractors)

FLAME

- Perceived goal: cyber-espionage in middle east
  - Time frame 2010 – 2012?
  - Targets MS Windows: screenshots, network traffic, records audio/keyboard, skype calls, bluetooth beaconing
  - http://www.crysys.hu/skywiper/skywiper.pdf
- Similar to stuxnet but more sophisticated
  - Size: 20MB
  - Propagates through LAN or USB stick
  - Stealthy: identifies which anti-virus is used and avoids it e.g., changing files extensions
  - 5 encryption algorithms
  - Used a fraudulent MD5-based certificate similar to rogue CA technique

Remarks

- Security is about the whole system
- Software vulnerabilities are still a major issue
- Crypto-based solutions are replacing ad hoc solutions
- Public Key Infrastructure and deployment is weak
- Network architecture not designed with sufficient security
- Human factor, users, passwords, policies
- SCADA system are vulnerable and critical
- Attacks are becoming more sophisticated and targeted

Conclusions

- Cryptographic provides powerful mechanisms and is becoming ubiquitous in systems and Apps
- Misuse Challenges
  - Lack of basic understanding of building blocks
  - Unsafe defaults
  - Security libraries should be better scrutinized
- Crypto an enabled of future cybercrime
  - Tor/HS + Bitcoin: Cryptolocker, silk road
  - How to prevent criminal misuse?
- Privacy in the Era of Big Data
  - Cryptography can play a key role: privacy-preserving services

Basics Reading

- **Introduction to Modern Cryptography: Principles and Protocols**
  Jonathan Katz, Yehuda Lindell, Chapman & Hall/CRC

- **Network Security: Private Communication in a Public World [Chap. 2-8]**
  Charles Kaufman, Mike Speciner, Radia Perlman, Prentice-Hall

- **Cryptography and Network Security**
  William Stallings, Prentice Hall

Internals of Symmetric Encryption Algorithms (auxiliary material)

- Unconditional security: One-Time Pad
- Historical ciphers
- DES, AES

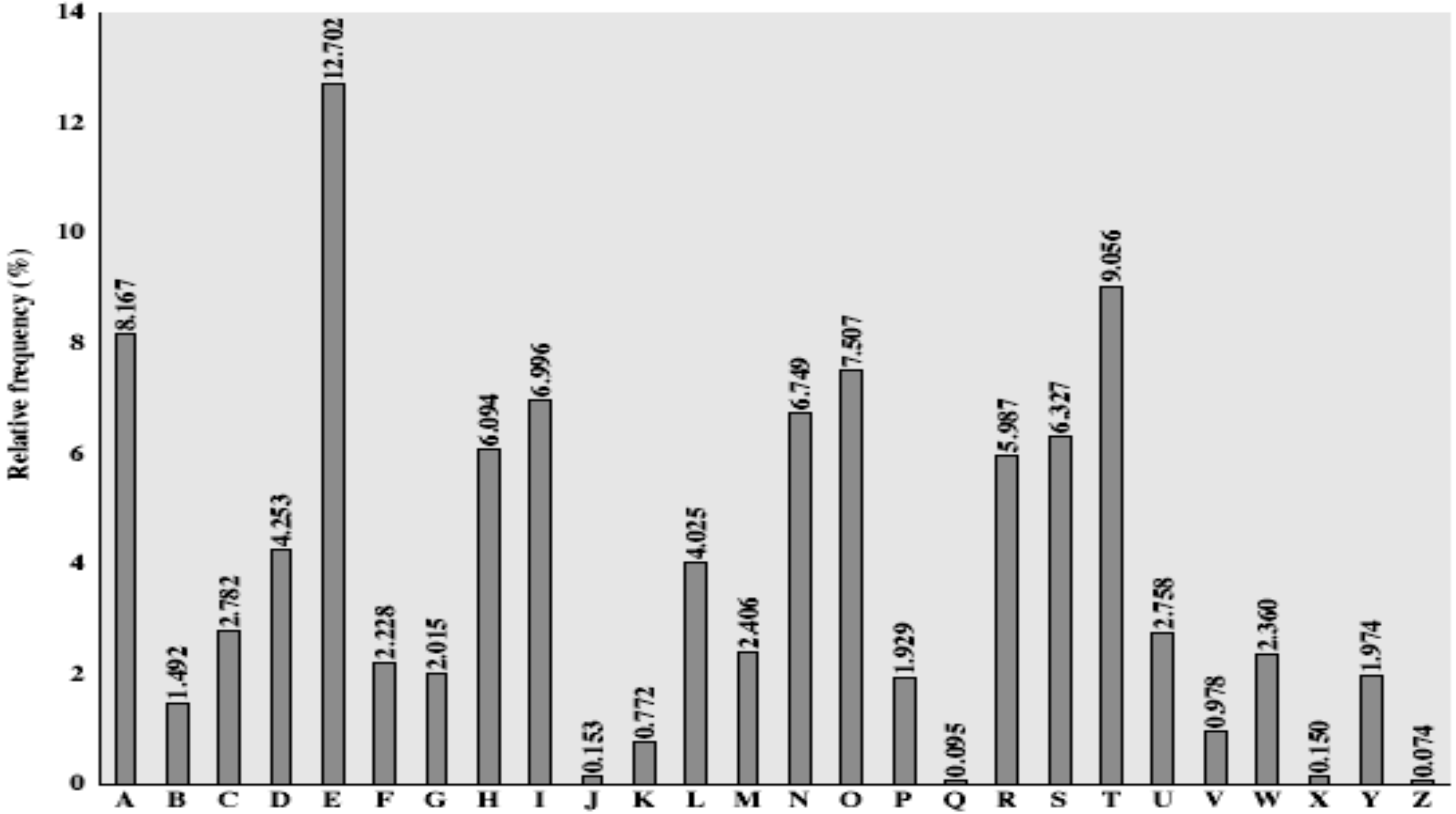
One-Time Pad

- Introduced by G. Vernam (AT&T, 1918), improved by J. Mauborgne
- Scheme:
  - Encryption: $c_i = p_i \oplus k_i$
  - c_i : i^{th} binary digit of plaintext, p_i: plaintext, k_i: key
  - Decryption: $p_i = c_i \oplus k_i$
  - Key is a random sequence of bits as long as the plaintext
- One-Time Pad is unbreakable
  - No statistical relationship between ciphertext and plaintext
  - Example (Vigenère One-Time Pad):
    - Cipher: **ANKYODKYUREPFJBYOJDSPLREYIUN**
    - Plain-1 (with k1): **MR MUSTARD WITH THE CANDLE**
    - Plain-2 (with k2) : **MISS SCARLET WITH THE KNIFE**
- Share the same long key between the sender & receiver

Symmetric cryptosystems (conventional cryptosystems)

- Substitution techniques:
  - Caesar cipher
    - Replace each letter with the letter standing x places further
    - Example: (x = 3)
      - plain: **`meet me after the toga party`**
      - cipher: **`phhw ph diwhu wkh wrjd sduwb`**
    - Key space: 25
    - Brut force attack: try 25 possibilities
  - Monoalphabetic ciphers
    - Arbitrary substitution of alphabet letters
    - Key space: $26! > 4 \times 10^{26} >$ key-space(DES)
    - Attack if the nature of the plaintext is known (e.g., English text):
      - compute the relative frequency of letters and compare it to standard distribution for English (e.g., E:12.7, T:9, etc.)
      - compute the relative frequency of 2-letter combinations (e.g., TH)

English Letters Frequencies



Symmetric cryptosystems (Continued)

- Multiple-Letter Encryption (Playfair cipher)
  - Plaintext is encrypted two-letters at a time
  - Based on a 5x5 matrix
  - Identification of individual diagraphs is more difficult (26x26 possibilities)
  - A few hundred letters of ciphertext allow to recover the structure of plaintext (and break the system)
  - Used during World War I & II
- Polyalphabetic Ciphers (Vigenère cipher)
  - 26 Caesar ciphers, each one denoted by a key letter
    - key: **deceptivedeceptivedeceptive**
    - plain: **wearediscoveredsaveyourself**
    - cipher: **ZICVTWQNGRZGVTWAVZHCQYGLMGJ**
  - Enhancement: auto-key (key = initial||plaintext)
- Rotor machines: multi-round monoalphabetic substitution
  - Used during WWII by Germany (ENIGMA) and Japan (Purple)

Transposition/Permutation Techniques

- Based on permuting the plaintext letters
- Example: rail fence technique

  memattrhtgpry

  etefeteoaat
- A more complex transposition scheme
  - Key: **4312567**
  - Plain: **attackp**

    ostpone

    duntilt

    woamxyz
  - Cipher: **TTNAAPTMTSUOAODWCOIXKNLYPETZ**
- Attack: letter/diagraph frequency
- Improvement: multiple-stage transposition

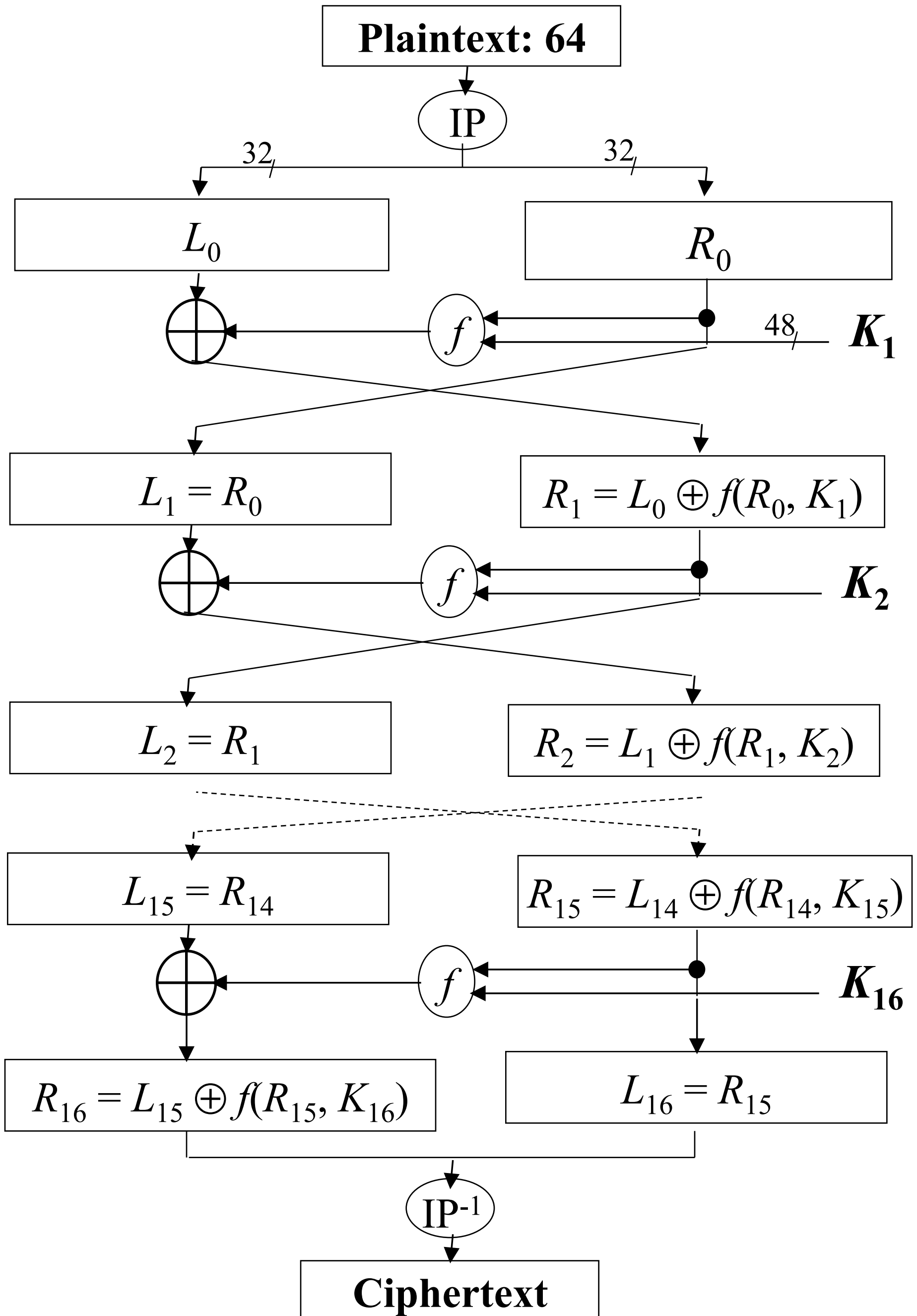
Today's Block Encryption Algorithms

- Key size:
  - Too short => easy to guess
- Block size:
  - Too short easy to build a table by the attacker: (plaintext, ciphertext)
  - Minimal size: 64 bits
- Properties:
  - One-to-one mapping
  - Mapping should look random to someone who doesn't have the key
  - Efficient to compute/reverse
- How:
  - Substitution (small chunks) & permutation (long chunks)
  - Multiple rounds

  ⇒ SPN (Substitution and Permutation Networks) and variants

Data Encryption Standard (DES)

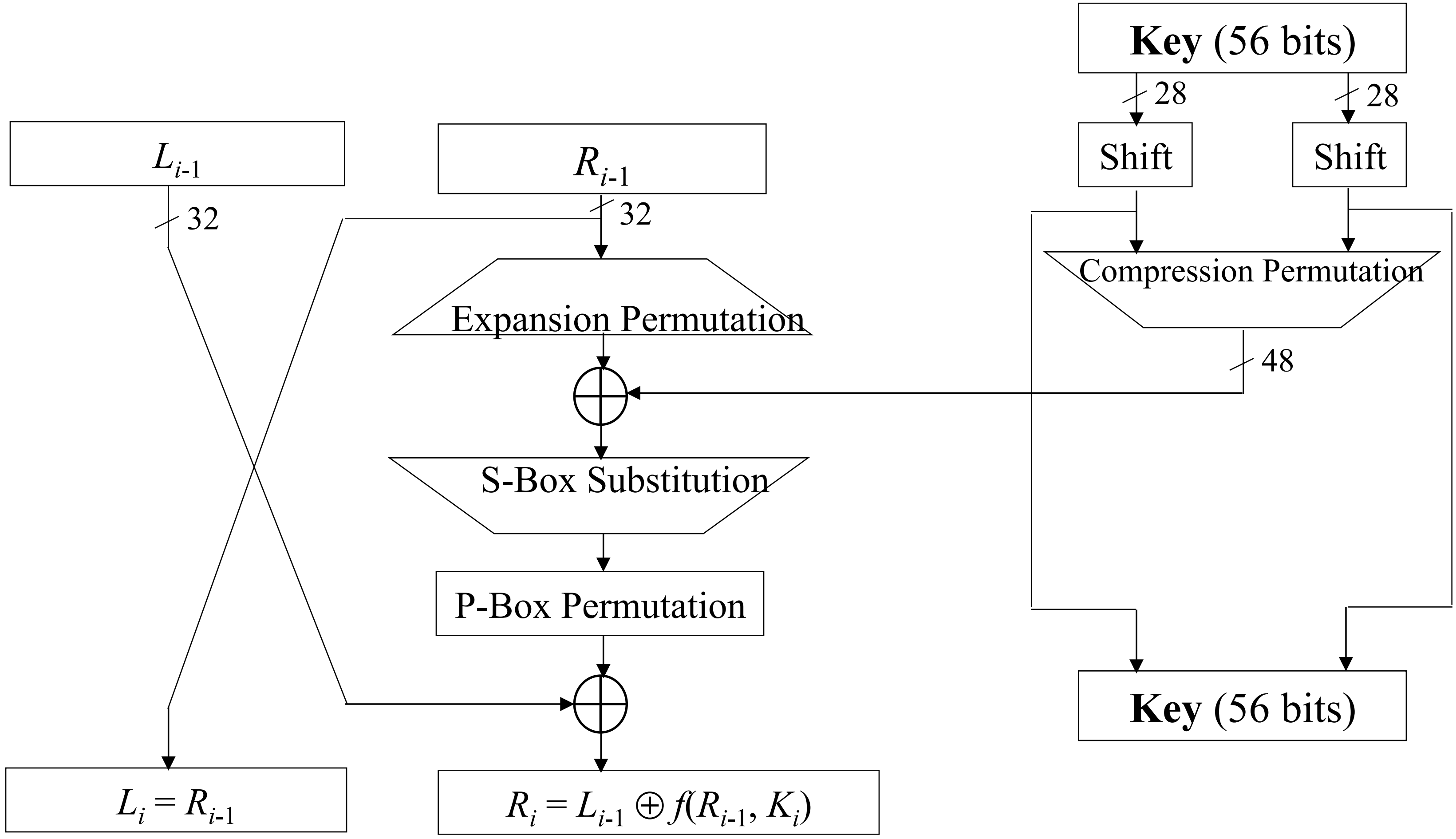
- Developed by IBM for the US government
- Based on Lucifer (64-bits, 128-bits key in 1971)
- To respond to the National Bureau of Standards CFP
  - Modified characteristics (with help of the NSA):
    - 64-bits block size, 56 bits key length
  - Concerns about trapdoors, key size, sbox structure
- Adopted in 1977 as the DES (FIPS PUB 46, ANSI X3.92) and reaffirmed in 1994 for 5 more years
- Replaced by AES (DES not secure today)



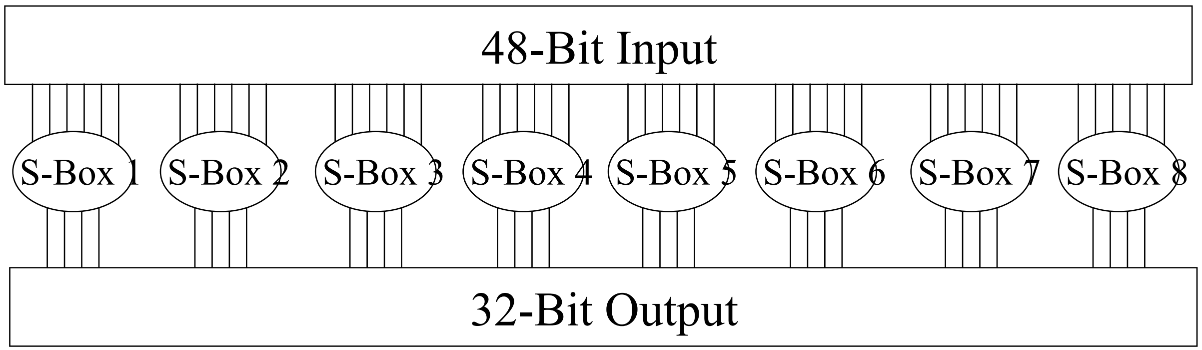
DES is based on Feistel Structure

$$L_i = R_{i-1}$$
$$R_i = L_{i-1} \oplus f(R_{i-1}, K_i)$$

One DES Round



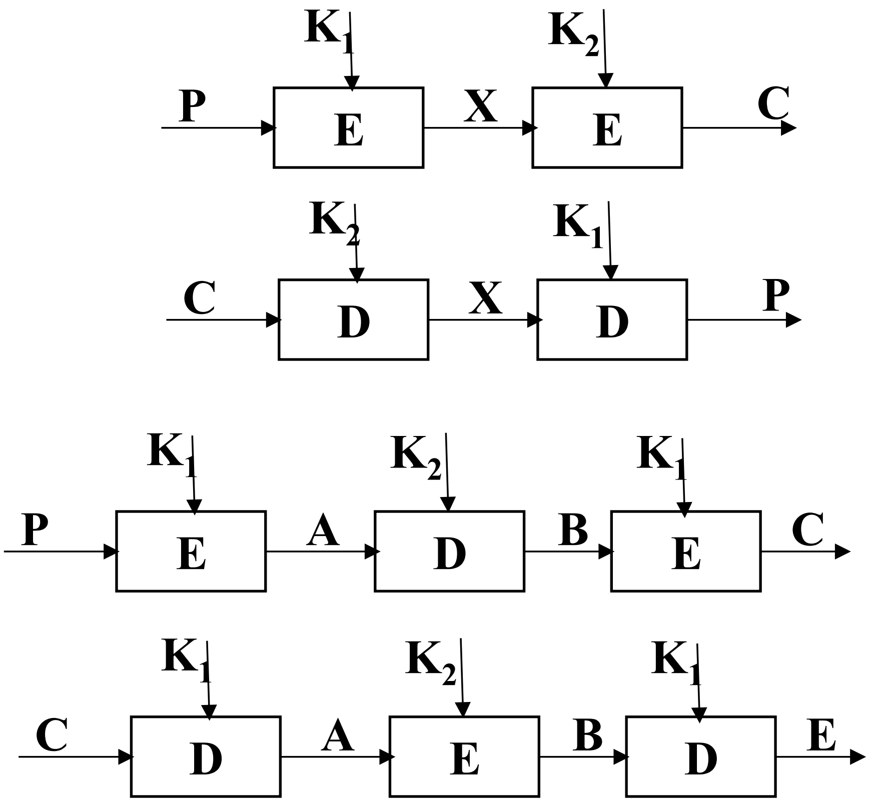
S-Box Substitution



- S-Box heart of DES security
- S-Box: 4x16 entry table
  - Input 6 bits:
    - 2 bits: determine the table (1/4)
    - 4 bits: determine the table entry
  - Output: 4 bits
- S-Boxes are optimized against Differential cryptanalysis

Double/Triple DES

- Double DES
  - Vulnerable to Meet-in-the-Middle Attack [DH77]
- Triple DES
  - Used two keys K_1 and K_2
  - Compatible with simple DES (K1=K2)
  - Used in ISO 8732, PEM, ANS X9.17



Linear/Differential Cryptanalysis

- Differential cryptanalysis
  - "Rediscovered" by E. Biham & A. Shamir in 1990
  - Based on a chosen-plaintext attack:
    - Analyze the difference between the ciphertexts of two plaintexts which have a known fixed difference
    - The analysis provides information on the key
  - 8-round DES broken with 2^{14} chosen plaintext
  - 16-round DES requires 2^{47} chosen plaintext
- DES design took into account this kind of attacks
- Linear cryptanalysis
  - Uses linear approximations of the DES cipher (M. Matsui 1993)
- IDEA first proposal (PES) was modified to resist to this kind of attacks
- GSM A3 algorithm is sensitive to this kind of attacks
  - SIM card secret key can be recoverd => GSM cloning

Breaking DES

- Electronic Frontier Foundation built a "DES Cracking Machine" [1998]
  - Attack: brute force
  - Inputs: two ciphertext
  - Architecture:
    - PC
    - array of custom chips that can compute DES

      24 search units/chip x 64chips/board x 27 boards
  - Power:
    - searches 92 billion keys per second
    - takes 4.5 days for half the key space
  - Cost:
    - $130'000 (all the material: chips, boards, cooling, PC etc.)
    - $80'000 (development from scratch)

- COPACOBANA (Cost-Optimized Parallel Code Breaker) [2006]
  - FPGA based, takes less than week, for a cost of $10K

The Advanced Encryption Standard (AES) Cipher - Rijndael

- Designed by Rijmen-Daemen (Belgium)
- Key size: 128/192/256 bit
- Block size: 128 bit data
- Properties: **iterative** rather than **Feistel** cipher
  - Treats data in 4 groups of 4 bytes
  - Operates on an entire block in every round
- Designed to be:
  - Resistant against known attacks
  - Speed and code compactness on many CPUs
  - Design simplicity

AES

- State: 16 bytes structured in a array

$S_{0,0}$	$S_{0,1}$	$S_{0,2}$	$S_{0,3}$
$S_{1,0}$	$S_{1,1}$	$S_{1,2}$	$S_{1,3}$
$S_{2,0}$	$S_{2,1}$	$S_{2,2}$	$S_{2,3}$
$S_{3,0}$	$S_{3,1}$	$S_{3,2}$	$S_{3,3}$

- Each byte is seen as an element of $\mathbf{F}_{2^8}$=GF(2^8)
  - $\mathbf{F}_{2^8}$ finite field of 256 elements
    - Operations
      - Elements of $\mathbf{F}_{2^8}$ are viewed as polynomials of degree 7 with coefficients {0, 1}
      - Addition: polynomials addition $\Rightarrow$ XOR
      - Multiplication: polynomials multiplication modulo $x^8+ x^4+ x^3+x+1$

AES Outline

1. Initialize State $\leftarrow x \oplus$ RoundKey;

2. For each of the Nr-1 rounds:
   1. SubBytes(State);
   2. ShiftRows(State);
   3. MixColumns(State);
   4. AddRoundKey(State);

3. Last round:
   1. SubBytes(State);
   2. ShiftRows(State);
   3. AddRoundKey(State);

4. Output $y \leftarrow$ State

Implementation Aspects

- Can be efficiently implemented on 8-bit CPU
  - byte substitution works on bytes using a table of 256 entries
  - shift rows is a simple byte shifting
  - add round key works on byte XORs
  - mix columns requires matrix multiply in $GF(2^8)$ which works on byte values, can be simplified to use a table lookup

Implementation Aspects

- Can be efficiently implemented on 32-bit CPU
  - redefine steps to use 32-bit words
  - can pre-compute 4 tables of 256-words
  - then each column in each round can be computed using 4 table lookups + 4 XORs
  - at a cost of 16Kb to store tables
- Designers believe this very efficient implementation was a key factor in its selection as the AES cipher