CIS 551 / TCOM 401

Computer and Network Security

Spring 2009

Lecture 15

Announcements

- Plan for Today:
  - Symmetric Key Cryptography
- Project 3 is due 6 April 2009 at 11:59 pm
  - Handout for SDES available in class today
  - Please read the project description *BEFORE* looking at the code
- Two talks of interest:
  - Andreas Haeberlen "Accountability for distributed systems"
    - 3:00pm TODAY in Wu & Chen Auditorium
  - Stefan Savage "Spamalytics: Exploring the Technical and Economic Underpinnings of Bulk E-mail Scams"
    - 3:00pm Thurs. in Wu & Chen Auditorium

Kinds of Industrial Strength Crypto

- Shared Key Cryptography
- Public Key Cryptography
- Cryptographic Hashes

- All of these aim for computational security
  - Not all methods have been proved to be intractable to crack.

Shared Key Cryptography

- Sender & receiver use the same key
- Key must remain private
- Also called *symmetric* or *secret key* cryptography
- Often are *block-ciphers*
  - Process plaintext data in blocks
- Examples: DES, Triple-DES, Blowfish, Twofish, AES, Rijndael, …

- For good detailed explanation of DES and AES see:
  - Cryptography and Network Security (4th Edition) William Stallings

Shared Key Notation

- Encryption algorithm

  E : key x plain → cipher

  Notation: K{msg} = E(K, msg)
- Decryption algorithm

  D : key x cipher → plain
- D inverts E

  D(K, E(K, msg)) = msg
- Use capital "K" for shared (secret) keys
- Sometimes E is the same algorithm as D

Secure Channel: Shared Keys

Alice

Bart

$K_{AB}\{Hello!\}$ →

← $K_{AB}\{Hi!\}$

K_{AB}

K_{AB}

Data Encryption Standard (DES)

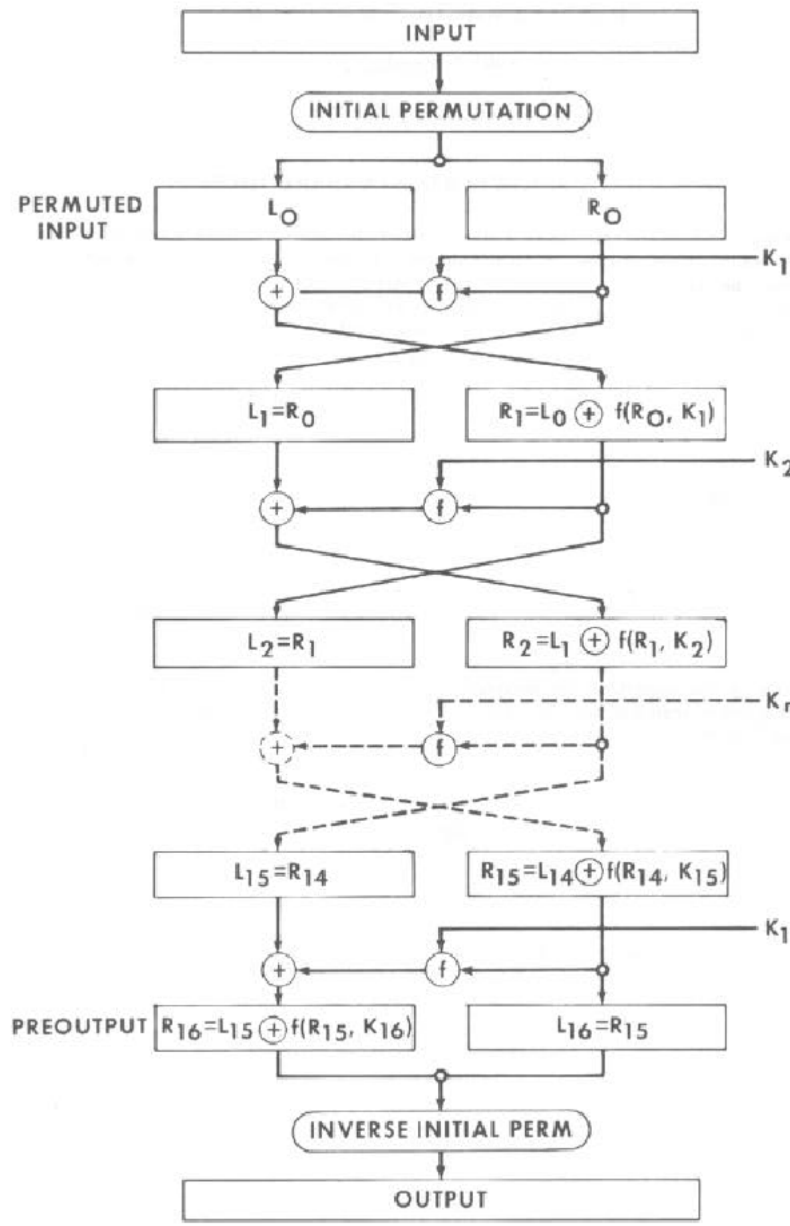
- Adopted as a standard in 1976
- Security analyzed by the National Security Agency (NSA)
  - http://csrc.nist.gov/publications/fips/fips46-3/fips46-3.pdf
- Key length is 56 bits
  - padded to 64 bits by using 8 parity bits
- Uses simple operators on (up to) 64 bit values
  - Simple to implement in software or hardware

- Input is processed in 64 bit blocks
- Based on a series of 16 *rounds*
  - Each cycle uses permutation & substitution to combine plaintext with the key

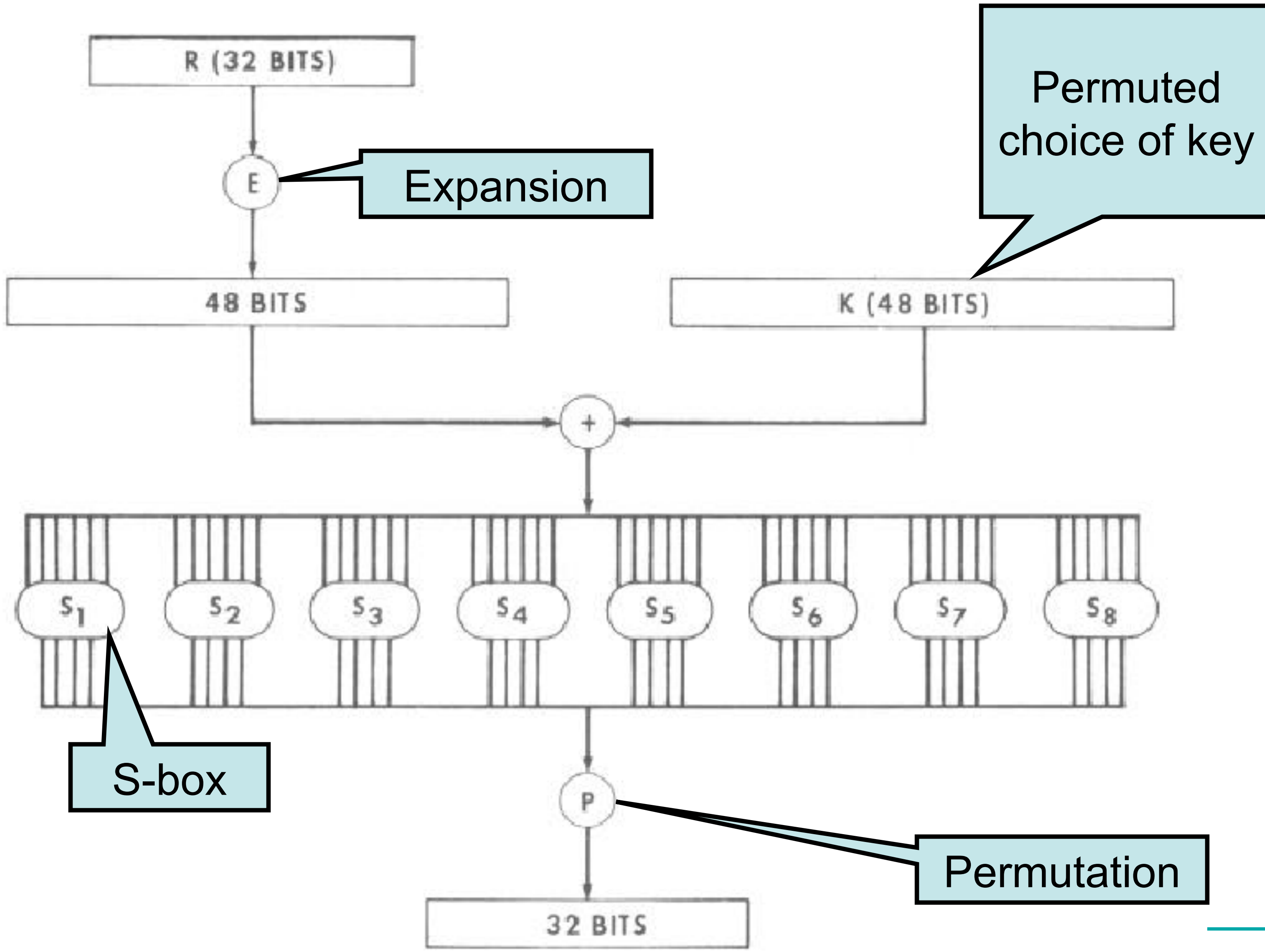
DES Encryption

DES follows the structure of a general class of encryption agorithms called *Feistel* ciphers:

- Rounds of encryption
- Each round merges one half of the input with the other using an “f” f

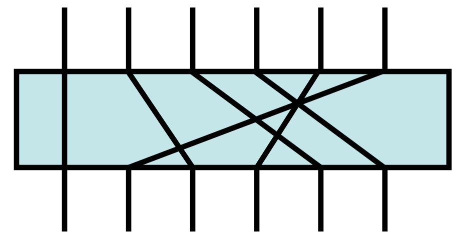


One Round of DES (f of previous slide)

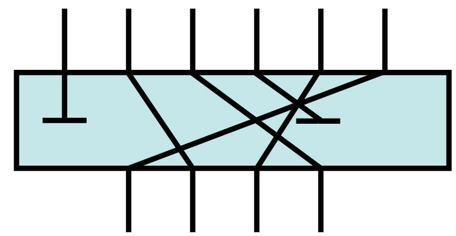


Types of Permutations in DES

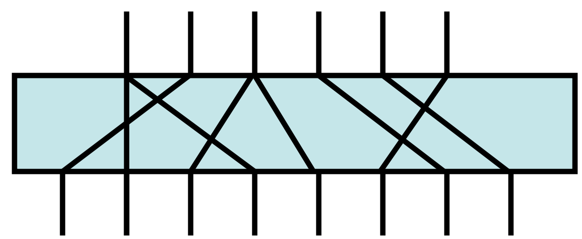
Permutation



Permuted Choice



Expansion Permutation



DES S-Boxes (Substitution tables)

- 6 bits of input replaced by 4 bits of output
- Implemented as a lookup table
  - 8 S-Boxes
  - Each S-Box has a table of 64 entries
  - Each entry specifies a 4-bit output
- S-Box design is complex: here is the “black art” of cryptography design.
- Example desiderata:
  - No output put of any S-Box should be close to a linear function of the inputs.
  - If two inputs to an S-Box differ by exactly one bit, the outputs must differ in at least two bits.
  - Each row of an S-Box should contain all 16 possible bit combinations
  - …

DES Decryption

- Use the same algorithm as encryption, but use $k_{16} \ldots k_1$ instead of $k_1 \ldots k_{16}$
- Proof that this works:
  - To obtain round j from j-1:

$$(1) \quad L_j = R_{j-1}$$
$$(2) \quad R_j = L_{j-1} \oplus f(R_{j-1}, k_j)$$

  - Rewrite in terms of round j-1:

$$(1) \quad R_{j-1} = L_j$$
$$(2) \quad L_{j-1} \oplus f(R_{j-1}, k_j) = R_j$$
$$L_{j-1} \oplus f(R_{j-1}, k_j) \oplus f(R_{j-1}, k_j) = R_j \oplus f(R_{j-1}, k_j)$$
$$L_{j-1} = R_j \oplus f(R_{j-1}, k_j)$$
$$L_{j-1} = R_j \oplus f(L_j, k_j)$$

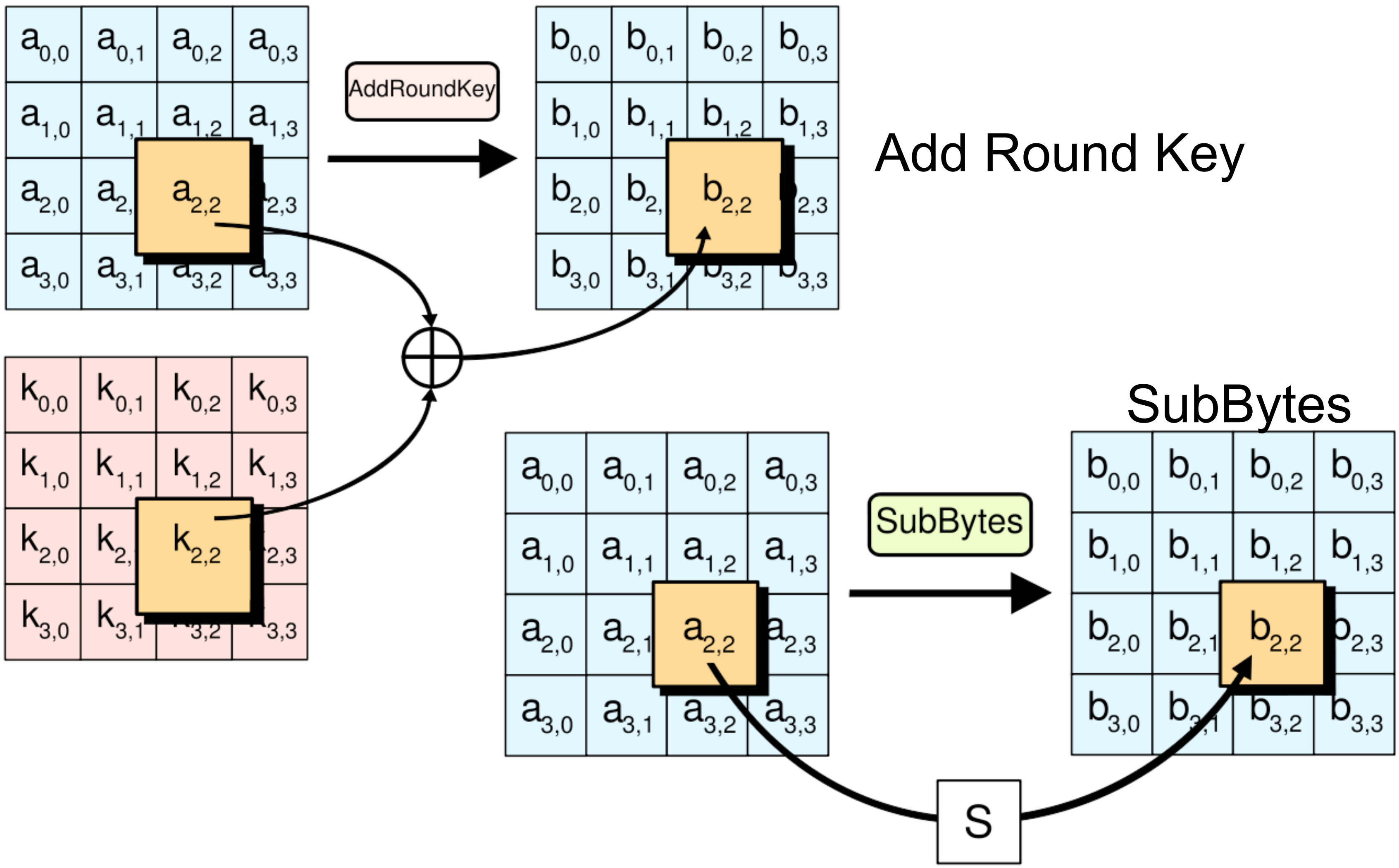
Problems with DES

- Key length too short: 56 bits
  - www.distributed.net broke a DES challenge in 1999 in under 24 hours (parallel attack)
- Other problems
  - Bit-wise complementation of key produces bit-wise complemented ciphertext
  - Not all keys are good (half 0's half 1's)
  - Differential cryptanalysis (1990): Carefully choose pairs of plaintext that differ in particular known ways (e.g. they are complements)
    - But particular choice of S boxes is secure against this (!) (developers of DES knew about differential cryptanalysis before it was "publically" known in the research community)

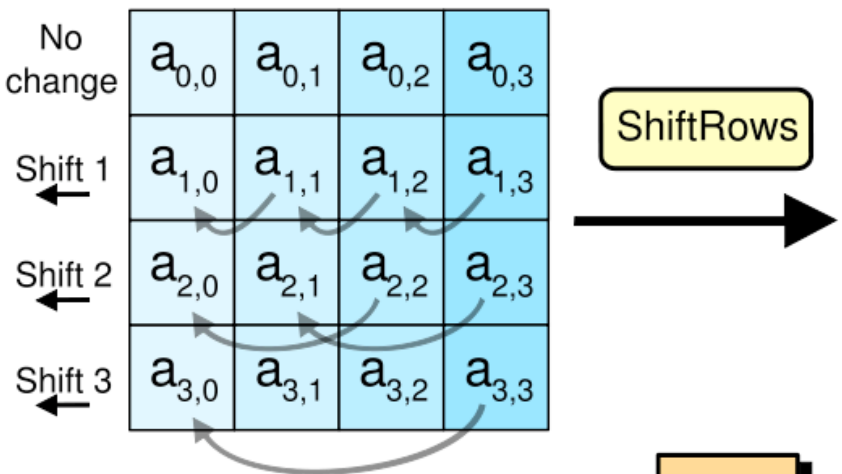
Advanced Encryption Standard (AES)

- National Institute of Standards & Technology NIST
  - Computer Security Research Center (CSRC)
  - http://csrc.nist.gov/
- Uses the Rijndael algorithm
  - Invented by Belgium researchers
    Dr. Joan Daemen & Dr. Vincent Rijmen
  - Adopted May 26, 2002
  - Key length: 128, 192, or 256 bits
  - Block size: 128, 192, or 256 bits
- Not a Feistel cipher
  - 10 rounds, each consisting of: SubBytes / Shift Rows / Mix Columns / Add Round Key

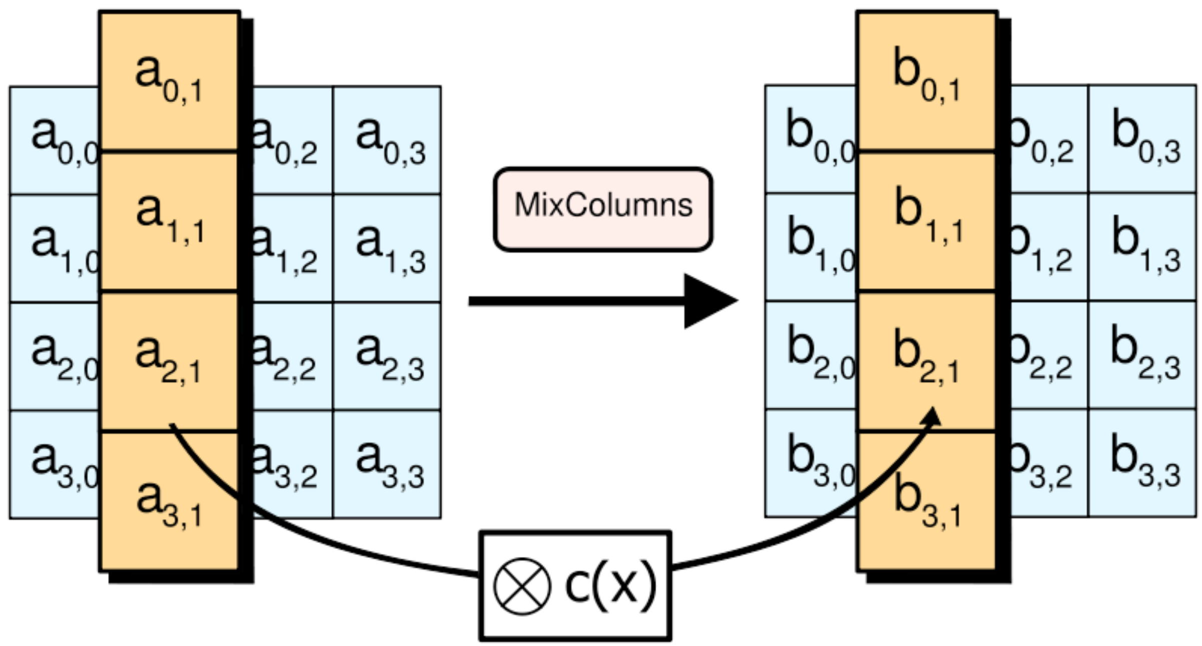
AES Operations



AES Operations



ShiftRows



MixColumns

$c(x) = 3x^3 + x^2 + x + 2$

Block Cipher Modes of Operation

- Often want to encrypt large pieces of data, but block ciphers only work on fixed, small chunks.
- Various Options:
  - *Electronic Code Book* – each block of plaintext bits is encoded independently using the same key:

    $C_j = K\{P_j\}$

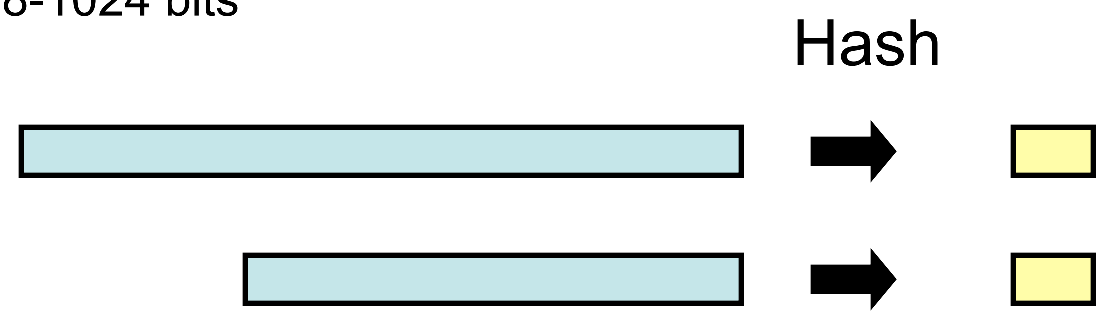
  - *Cipher Block Chaining* – each block of plaintext is XORed with the preceding block of ciphertext, starting with initialization vector C_0:

    $C_j = K\{P_j \oplus C_{j-1}\}$ and C_0 is an initialization vector

  - Other options: Cipher Feedback (to convert a block cipher to a streaming cipher), Counter mode (XOR an encryption counter with each block)

Hash Algorithms

- Take a variable length string
- Produce a fixed length digest
  - Typically 128-1024 bits



- (Noncryptographic) Examples:
  - Parity (or byte-wise XOR)
  - CRC (cyclic redundancy check) used in communications
  - Ad hoc hashes used for hash tables
- Realistic Example
  - The NIST Secure Hash Algorithm (SHA) takes a message of less than 2^{64} bits and produces a digest of 160 bits

Cryptographic Hashes

- Create a hard-to-invert summary of input data
- Useful for integrity properties
  - Sender computes the hash of the data, transmits data and hash
  - Receiver uses the same hash algorithm, checks the result
- Like a check-sum or error detection code
  - Uses a cryptographic algorithm internally
  - More expensive to compute
- Sometimes called a Message Digest
- History:
  - Message Digest (MD4 -- invented by Rivest, MD5)
  - Secure Hash Algorithm - 1993 - (SHA-0)
  - Secure Hash Algorithm (SHA-1)
  - SHA-2 (actually a family of hash algorithms with varying output sizes)
  - SHA-3 currently being developed via a competition

- Attacks have been found against both SHA-0 and SHA-1

Uses of Hash Algorithms

- Hashes are used to protect *integrity* of data
  - Virus Scanners
  - Program fingerprinting in general
  - Modification Detection Codes (MDC)
- Message Authenticity Code (MAC)
  - Includes a cryptographic component
  - Send (msg, hash(msg, key))
  - Attacker who doesn’t know the key can’t modify msg (or the hash)
  - Receiver who knows key can verify origin of message
- Make digital signatures more efficient (we'll see this later)

Desirable Properties

- The probability that a randomly chosen message maps to an n-bit hash should ideally be $(\frac{1}{2})^n$.
  – Attacker must spend a lot of effort to be able to modify the source message without altering the hash value

- Hash functions *h* for cryptographic use as MDC's fall in one or both of the following classes.
  – *Collision Resistant Hash Function:* It should be computationally infeasible to find two distinct inputs that hash to a common value (ie. $h(x) = h(y)$).
  – *One Way Hash Function:* Given a specific hash value y, it should be computationally infeasible to find an input x such that $h(x)=y$.

Secure Hash Algorithm (SHA)

- Pad message so it can be divided into 512-bit blocks, including a 64 bit value giving the length of the original message.
- Process each block as 16 32-bit words called *W(t)* for *t* from 0 to 15.
- Expand from these 16 words to 80 words by defining as follows for each t from 16 to 79:
  - $W(t) := W(t-3) \oplus W(t-8) \oplus W(t-14) \oplus W(t-16)$
- Constants H0, …, H5 are initialized to special constants
- Result is final contents of H0, … , H5

```
for each 16-word block begin
    A := H0; B := H1; C := H2; D := H3; E := H4
    for I := 0 to 19 begin
        TEMP := S(5,A) + ((B ∧ C) ∨ (¬ B ∧ D)) + E + W(I) + 5A827999;
        E := D; D := C; C := S(30,B); B := A; A := TEMP
    end
    for I := 20 to 39 begin
        TEMP := S(5,A) + (B ⊕ C ⊕ D) + E + W(I) + 6ED9EBA1;
        E := D; D := C; C := S(30,B); B := A; A := TEMP
    end
    for I := 40 to 59 begin
        TEMP := S(5,A) + ((B ∧ C) ∨ (B ∧ D) ∨ (C ∧ D)) + E + W(I) + 8F1BBCDC;
        E := D; D := C; C := S(30,B); B := A; A := TEMP
    end
    for I := 60 to 79 begin
        TEMP := S(5,A) + (B ⊕ C ⊕ D) + E + W(I) + CA62C1D6;
        E := D; D := C; C := S(30,B); B := A; A := TEMP
    end
    H0 := H0+A; H1 := H1+B; H2 := H2+C; H3 := H3+D; H4 := H4+E
end
```

Chaining Variables

Shift A left 5 bits

Attacks against SHA-1

- In early 2005, Rijmen and Oswald published an attack on a reduced version of SHA-1 (53 out of 80 rounds) which finds collisions with a complexity of fewer than 2^{80} operations.
- In February 2005, an attack by Xiaoyun Wang, Yiqun Lisa Yin, and Hongbo Yu was announced. The attacks can find collisions in the full version of SHA-1, requiring fewer than 2^{69} operations (brute force would require 2^{80}.)
- In August 2005, same group lowered the threshold to 2^{63}.

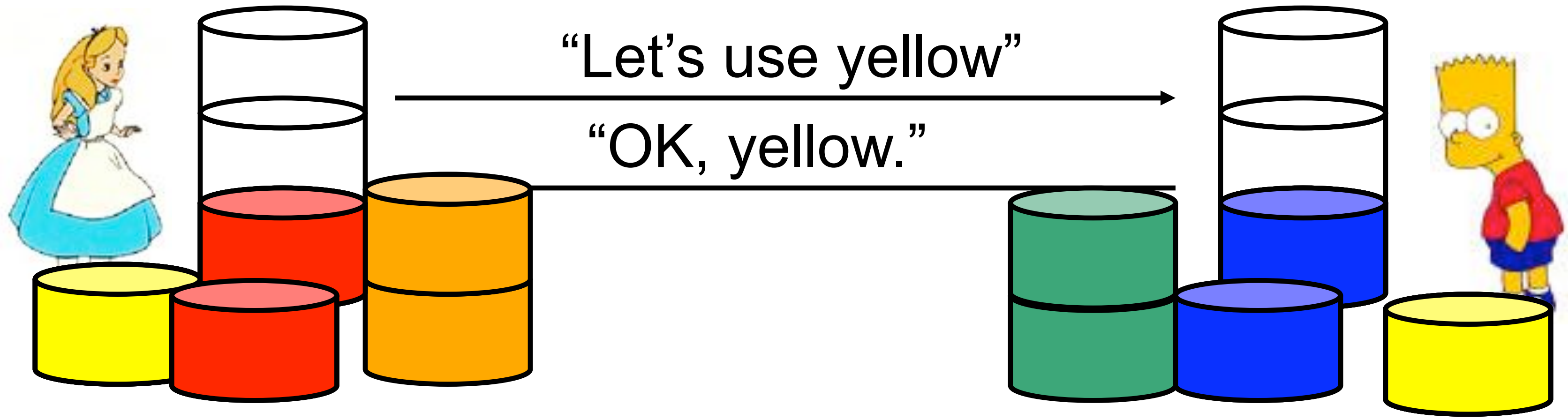
- May lead to more attacks…

Diffie-Hellman Key Exchange

- Problem with shared-key systems:
  Distributing the shared key
- Suppose that Alice and Bart want to agree on a secret (i.e. a key)
  - Communication link is public
  - They don't already share any secrets

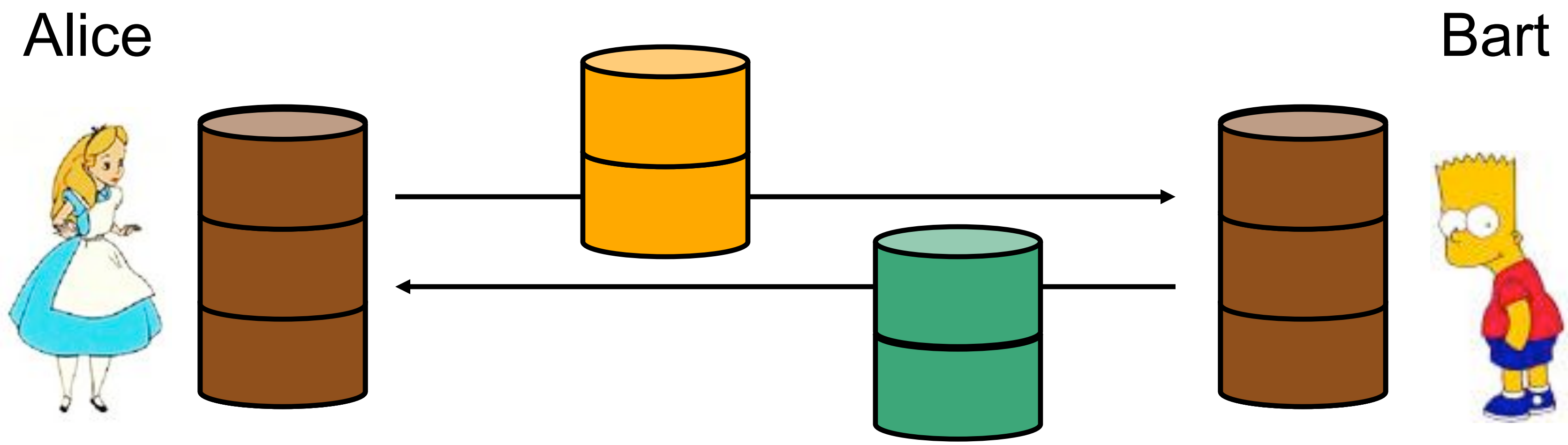
Diffie-Hellman by Analogy: Paint

Alice Bart



1. Alice & Bart decide on a public color, and mix one liter of that color.
2. They each choose a random secret color, and mix two liters of their secret color.
3. They keep one liter of their secret color, and mix the other with the public color.

Diffie-Hellman by Analogy: Paint

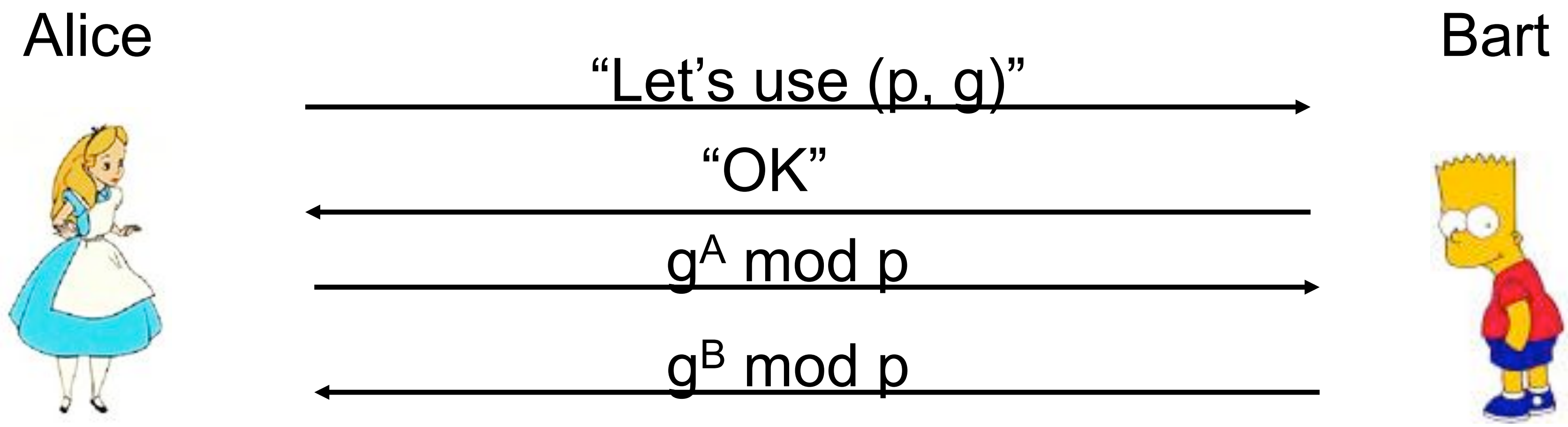


4. They exchange the mixtures over the public channel.
5. When they get the other person’s mixture, they combine it with their retained secret color.
6. The secret is the resulting color: Public + Alice’s + Bart’s

Diffie-Hellman Key Exchange

- Choose a prime p (publicly known)
  - Should be about 512 bits or more
- Pick g < p (also public)
  - g must be a *primitive root* of p.
  - A primitive root *generates* the finite field p.
  - Every n in {1, 2, …, p-1} can be written as g^k mod p
  - Example: 2 is a primitive root of 5
  - $2^0 = 1$ $2^1 = 2$ $2^2 = 4$ $2^3 = 3$ (mod 5)
  - Intuitively means that it's hard to take logarithms base g because there are many candidates.

Diffie-Hellman



1. Alice & Bart decide on a public prime p and primitive root g.
2. Alice chooses secret number A. Bart chooses secret number B
3. Alice sends Bart $g^A \bmod p$.
4. The shared secret is $g^{AB} \bmod p$.

Details of Diffie-Hellman

- Alice computes g^{AB} mod p because she knows A:
  - g^{AB} mod p = $(g^{B}$ mod p$)^{A}$ mod p

- An eavesdropper gets g^{A} mod p and g^{B} mod p
  - They can easily calculate g^{A+B} mod p but that doesn't help.
  - The problem of computing discrete logarithms (to recover A from g^{A} mod p is hard.

Example

- Alice and Bart agree that $q=71$ and $g=7$.
- Alice selects a private key $A=5$ and calculates a public key $g^A \equiv 7^5 \equiv 51 \pmod{71}$. She sends this to Bart.
- Bart selects a private key $B=12$ and calculates a public key $g^B \equiv 7^{12} \equiv 4 \pmod{71}$. He sends this to Alice.
- Alice calculates the shared secret:
  $S \equiv (g^B)^A \equiv 4^5 \equiv 30 \pmod{71}$
- Bart calculates the shared secret
  $S \equiv (g^A)^B \equiv 51^{12} \equiv 30 \pmod{71}$

Why Does it Work?

- Security is provided by the difficulty of calculating discrete logarithms.
- Feasibility is provided by
  - The ability to find large primes.
  - The ability to find primitive roots for large primes.
  - The ability to do efficient modular arithmetic.
- Correctness is an immediate consequence of basic facts about modular arithmetic.