

**Network Security - ISA 656**  
**Cryptography II**  
**Block Ciphers (cont) - Public Key Encryption**

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# $n$ -bit Output Feedback

Block Ciphers  
(Cont)

**$n$ -bit Output Feedback**

Properties of Output Feedback Mode

Properties of Counter Mode

Which Mode for What Task?

Integrity Checks

Combined Modes of Operation

Stream Ciphers

Stream Ciphers (cont)

RC4

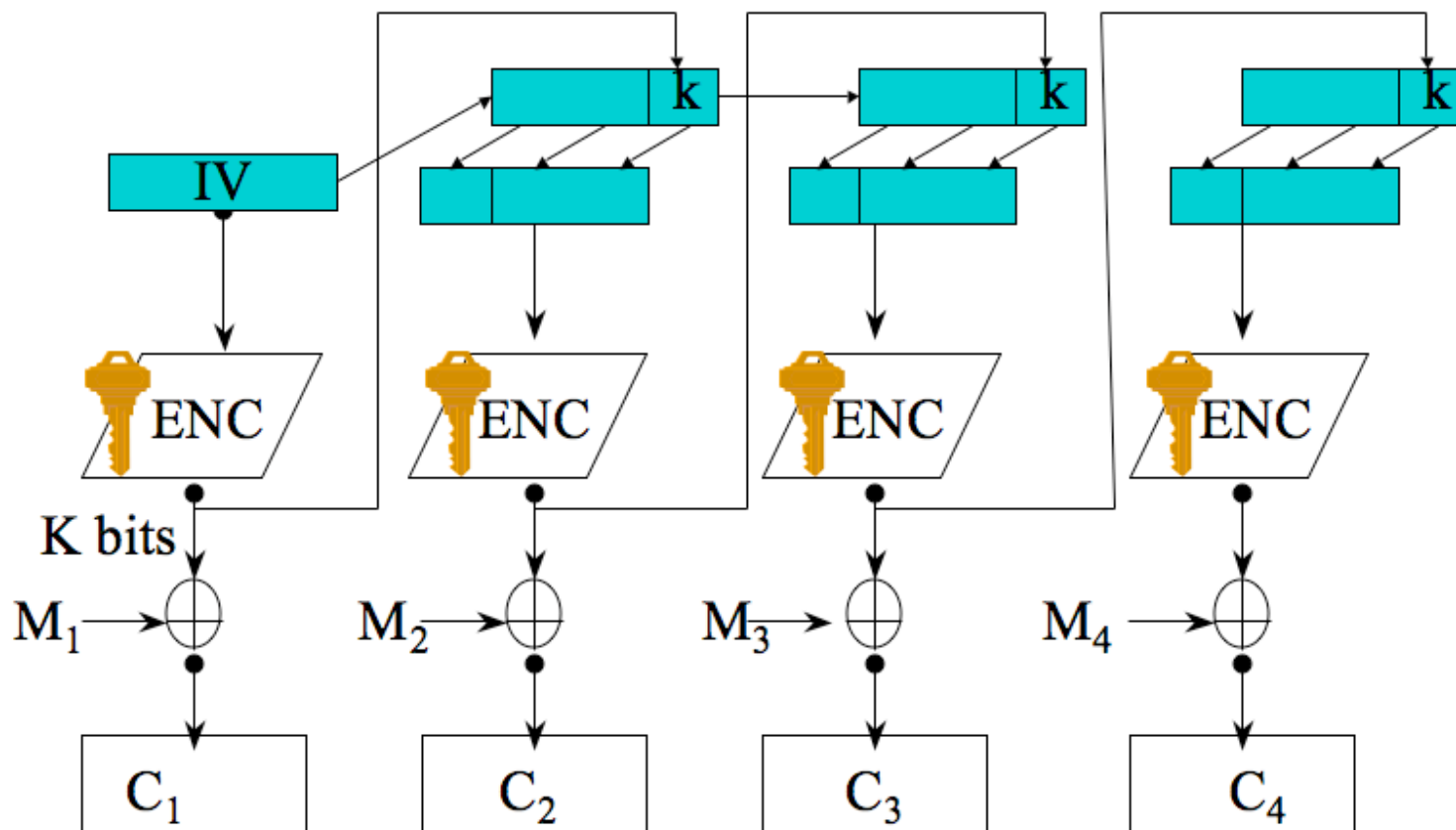
The Guts of RC4

Cipher Strengths

CPU Speed versus Key Size

Public Key Encryption

Cryptographic Hash Functions



# Properties of Output Feedback Mode

Block Ciphers  
(Cont)

---

*n*-bit Output  
Feedback

Properties of Output  
Feedback Mode

Properties of  
Counter Mode  
Which Mode for  
What Task?

Integrity Checks  
Combined Modes of  
Operation

Stream Ciphers  
Stream Ciphers  
(cont)

RC4

The Guts of RC4

Cipher Strengths  
CPU Speed versus  
Key Size

Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

- No error propagation
- Active attacker can make controlled changes to plaintext
- OFB is a form of *stream cipher*

# Properties of Counter Mode

Block Ciphers  
(Cont)

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*n*-bit Output

Feedback

Properties of Output

Feedback Mode

Properties of  
Counter Mode

Which Mode for  
What Task?

Integrity Checks

Combined Modes of  
Operation

Stream Ciphers

Stream Ciphers  
(cont)

RC4

The Guts of RC4

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Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

- Another form of stream cipher
- Frequently split the counter into two sections: message number and block number within the message
- Active attacker can make controlled changes to plaintext
- Highly parallelizable; no linkage between stages
- Vital that counter never repeat for any given key

# Which Mode for What Task?

Block Ciphers  
(Cont)

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*n*-bit Output  
Feedback  
Properties of Output  
Feedback Mode  
Properties of  
Counter Mode

Which Mode for  
What Task?

Integrity Checks  
Combined Modes of  
Operation  
Stream Ciphers  
Stream Ciphers  
(cont)  
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Cryptographic Hash  
Functions

---

- General file or packet encryption: CBC.  
⇒ Input must be padded to multiple of cipher block size
- Risk of byte or bit deletion:  $CFB_8$  or  $CFB_1$
- Bit stream; noisy line and error propagation is undesirable: OFB
- Very high-speed data: CTR
- In most situations, an integrity check is needed

# Integrity Checks

Block Ciphers  
(Cont)

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*n*-bit Output  
Feedback  
Properties of Output  
Feedback Mode  
Properties of  
Counter Mode  
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**Integrity Checks**

Combined Modes of  
Operation

Stream Ciphers

Stream Ciphers  
(cont)

RC4

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Key Size

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Encryption

---

Cryptographic Hash  
Functions

---

- Actually, integrity checks are almost always needed
- Frequently, attacks on integrity can be used to attack confidentiality
- Usual solution: use separate integrity check along with encryption

# Combined Modes of Operation

Block Ciphers  
(Cont)

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*n*-bit Output  
Feedback  
Properties of Output  
Feedback Mode  
Properties of  
Counter Mode  
Which Mode for  
What Task?

Integrity Checks

Combined Modes of  
Operation

Stream Ciphers  
Stream Ciphers  
(cont)

RC4

The Guts of RC4

Cipher Strengths

CPU Speed versus  
Key Size

Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

- Integrity checks require a separate pass over the data
- Such checks generally cannot be parallelized
- For high-speed implementations, this is a considerable burden
- Solution: *combined modes* such as Galois Counter Mode (GCM) or Counter with CBC-MAC (CCM), which provide confidentiality and integrity protection in one pass

# Stream Ciphers

Block Ciphers  
(Cont)

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*n*-bit Output

Feedback

Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of

Operation

**Stream Ciphers**

Stream Ciphers

(cont)

RC4

The Guts of RC4

Cipher Strengths

CPU Speed versus

Key Size

Public Key

Encryption

---

Cryptographic Hash

Functions

---

- Key stream generator produces a sequence  $S$  of pseudo-random bytes; key stream bytes are combined (generally via XOR) with plaintext bytes
- $P_i \oplus S_i \rightarrow C_i$
- Stream ciphers are very good for asynchronous traffic
- Best-known stream cipher is RC4; commonly used with SSL

# Stream Ciphers (cont)

Block Ciphers  
(Cont)

*n*-bit Output

Feedback

Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of

Operation

Stream Ciphers

Stream Ciphers  
(cont)

RC4

The Guts of RC4

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CPU Speed versus

Key Size

Public Key

Encryption

Cryptographic Hash

Functions

- Key stream  $S$  must *never* be reused for different plaintexts:

$$C = A \oplus K$$

$$C' = B \oplus K$$

$$\begin{aligned} C \oplus C' &= A \oplus K \oplus B \oplus K \\ &= A \oplus B \end{aligned}$$

- Guess at  $A$  and see if  $B$  makes sense; repeat for subsequent bytes

# RC4

Block Ciphers  
(Cont)

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*n*-bit Output

Feedback

Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of

Operation

Stream Ciphers

Stream Ciphers

(cont)

**RC4**

The Guts of RC4

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Public Key

Encryption

---

Cryptographic Hash

Functions

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- Extremely efficient
- After key setup, it just produces a key stream
- No way to resynchronize except by rekeying and starting over
- Internal state is a 256-byte array plus two integers
- Note: weaknesses if used in ways other than as a stream cipher.

# The Guts of RC4

Block Ciphers

(Cont)

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*n*-bit Output

Feedback

Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of

Operation

Stream Ciphers

Stream Ciphers

(cont)

RC4

**The Guts of RC4**

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Cryptographic Hash

Functions

---

```
for(counter = 0; counter < buffer_len; counter ++)  
    {  
        x = (x + 1) % 256;  
        y = (state[x] + y) % 256;  
        swap_byte(&state[x], &state[y]);  
        xorIndex = (state[x] + state[y]) % 256;  
        buffer_ptr[counter] ^= state[xorIndex];  
    }
```

# Cipher Strengths

Block Ciphers  
(Cont)

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*n*-bit Output  
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Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of  
Operation

Stream Ciphers

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(cont)

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The Guts of RC4

Cipher Strengths

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Encryption

---

Cryptographic Hash  
Functions

---

- A cipher is no stronger than its key length: if there are too few keys, an attacker can enumerate all possible keys
- DES has 56 bits — arguably too few in 1976; far too few today.
- Strength of cipher depends on how long it needs to resist attack.
- No good reason to use less than 128 bits
- NSA rates 128-bit AES as good enough for SECRET traffic; 256-bit AES is good enough for TOP-SECRET traffic.
- But a cipher can be considerably weaker! (A monoalphabetic cipher over all bytes has a 1684-bit key, but is trivially solvable.)

# CPU Speed versus Key Size

Block Ciphers  
(Cont)

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Properties of Output

Feedback Mode

Properties of

Counter Mode

Which Mode for

What Task?

Integrity Checks

Combined Modes of

Operation

Stream Ciphers

Stream Ciphers

(cont)

RC4

The Guts of RC4

Cipher Strengths

CPU Speed versus  
Key Size

Public Key

Encryption

Cryptographic Hash

Functions

- Adding one bit to the key doubles the work factor for brute force attacks
- The effect on encryption time is often negligible or even free
- It costs *nothing* to use a longer RC4 key
- Going from 128-bit AES to 256-bit AES takes (at most) 40% longer, but increases the attacker's effort by a factor of  $2^{128}$
- Using triple DES costs  $3\times$  more to encrypt, but increases the attacker's effort by a factor of  $2^{112}$
- Moore's Law favors the defender

# Alice and Bob

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

Alice and Bob

Pre-Arranged Key  
Lists?

The Solution: Public  
Key Cryptography

RSA

Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- Alice wants to communicate security with Bob
- (Cryptographers frequently speak of Alice and Bob instead of  $A$  and  $B$ ...
- What key should she use?

# Pre-Arranged Key Lists?

Block Ciphers  
(Cont)

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Encryption

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Alice and Bob

Pre-Arranged Key  
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Complexities

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Scenario

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■ What if you run out of keys?

■ What if a key is stolen?

“Why is it necessary to destroy yesterday’s [key] . . . list if it’s never going to be used again?”

“A used key, Your Honor, is the most critical key there is. If anyone can gain access to that, they can read your communications.”

(trial of Jerry Whitworth, a convicted spy.)

■ What if Alice doesn’t know in advance that she’ll want to talk to Bob?

# The Solution: Public Key Cryptography

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

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Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario  
Perfect Forward  
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Who Sent a  
Message?

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They're Not Like  
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Cryptographic Hash  
Functions

---

- Allows parties to communicate without prearrangement
- Separate keys for encryption and decryption
- Not possible to derive decryption key from encryption key
- Permissible to publish encryption key, so that anyone can send you secret messages
- All known public key systems are very expensive to use, in CPU time and bandwidth.
- Most public systems are based on mathematical problems.

# RSA

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?  
The Solution: Public  
Key Cryptography

**RSA**

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Usage

Complexities

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Scenario

Perfect Forward  
Secrecy

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Exchange

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Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- The best-known public key system is RSA.
- Generate two large (at least 512 bit) primes  $p$  and  $q$ ; let  $n = pq$
- Pick two integers  $e$  and  $d$  such that  $ed \equiv 1 \pmod{(p-1)(q-1)}$ . Often,  $e = 65537$ , since that simplifies encryption calculations.
- The public key is  $\langle e, n \rangle$ ; the private key is  $\langle d, n \rangle$ .
- To encrypt  $m$ , calculate  $c = m^e \pmod n$ ; to decrypt  $c$ , calculate  $m = c^d \pmod n$ .
- The security of the system relies on the difficulty of factoring  $n$ .
- Finding such primes is relatively easy; factoring  $n$  is believed to be extremely hard.

# Classical Public Key Usage

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

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Pre-Arranged Key  
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Key Cryptography

RSA

Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- Alice publishes her public key in the phone book.
- Bob prepares a message and encrypts it with that key by doing a large exponentiation.
- Alice uses her private key to do a different large exponentiation.
- It's not that simple...

# Complexities

Block Ciphers  
(Cont)

---

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Encryption

---

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Pre-Arranged Key  
Lists?

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Key Cryptography

RSA  
Classical Public Key  
Usage

**Complexities**

A More Realistic  
Scenario

Perfect Forward  
Secrecy

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Exchange

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Who Sent a  
Message?

Digital Signatures  
They're Not Like  
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Cryptographic Hash  
Functions

---

- RSA calculations are *very* expensive; neither Bob nor Alice can afford to do many.
- RSA is too amenable to mathematical attacks; encrypting the wrong numbers is a bad idea.
- Example: “yes”<sup>3</sup> is only 69 bits, and won’t be reduced by the modulus operation; finding  $\sqrt[3]{503565527901556194283}$  is easy.
- We need a better solution

# A More Realistic Scenario

Block Ciphers  
(Cont)

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---

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Key Cryptography

RSA  
Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- Bob generates a random key  $k$  for a conventional cipher.
- Bob encrypts the message:  $c = \{m\}_k$ .
- Bob pads  $k$  with a known amount of padding, to make it at least 512 bits long; call this  $k'$ .
- $k'$  is encrypted with Alice's public key  $\langle e, n \rangle$ .
- Bob transmits  $\{c, (k')^e \bmod n\}$  to Alice.
- Alice uses  $\langle d, n \rangle$  to recover  $k'$ , removes the padding, and uses  $k$  to decrypt ciphertext  $c$ .
- In reality, it's even more complex than that...

# Perfect Forward Secrecy

Block Ciphers  
(Cont)

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Public Key  
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---

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Key Cryptography

RSA  
Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures  
They're Not Like  
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Cryptographic Hash  
Functions

---

- If an endpoint is compromised (i.e., captured or hacked), can an enemy read old conversations?
- Example: if an attacker has recorded  $\{c, (k')^e \bmod n\}$  and then recovers Alice's private key, he can read  $c$ .
- Solution: use schemes that provide *perfect forward secrecy*, such as Diffie-Hellman key exchange.

# Diffie-Hellman Key Exchange

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?

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Key Cryptography

RSA

Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures

They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

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- Agree on a large (at least 1024-bit) prime  $p$ , usually of the form  $2q + 1$  where  $q$  is also prime.
- Find a generator  $g$  of the group “integers modulo  $p$ ”. (This is easy to do if  $p$  is prime.)
- Alice picks a large random number  $x$  and sends Bob  $g^x \bmod p$ . Bob picks a large random number  $y$  and sends Alice  $g^y \bmod p$ .
- Alice calculates  $k = (g^y)^x \equiv g^{xy} \bmod p$ ; Bob does a similar calculation.
- If  $x$  and  $y$  are really random, they can't be recovered if Alice or Bob's machine is hacked.
- Eavesdroppers can't calculate  $x$  from  $g^x \bmod p$ , and hence can't get the shared key. This is called the *discrete logarithm* problem.

# Random Numbers

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?  
The Solution: Public  
Key Cryptography

RSA  
Classical Public Key  
Usage

Complexities  
A More Realistic  
Scenario  
Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers

Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- Random numbers are very important in cryptography.
- They need to be as random as possible — an attacker who can guess these numbers can break the cryptosystem. (This is a common attack!) To the extent possible, use true-random numbers, not pseudo-random numbers.
- Where do true-random numbers come from?
- Physical processes are best — radioactive decay, thermal noise in amplifiers, oscillator jitter, etc.
- Often, a true-random number is used to seed a cipher — modern cryptographic functions are very good pseudo-random numbers.

# Who Sent a Message?

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?  
The Solution: Public  
Key Cryptography  
RSA  
Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers

Who Sent a  
Message?

Digital Signatures  
They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

---

- When Bob receives a message from Alice, how does he know who sent it?
- With traditional, symmetric ciphers, he may know that Alice has the only other copy of the key; with public key, he doesn't even know that
- Even if he knows, can he prove to a third party — say, a judge — that Alice sent a particular message?

# Digital Signatures

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?  
The Solution: Public  
Key Cryptography

RSA  
Classical Public Key  
Usage

Complexities  
A More Realistic  
Scenario  
Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures

They're Not Like  
Real Signatures

Cryptographic Hash  
Functions

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- RSA can be used backwards: you can encrypt with the private key, and decrypt with the public key.
- This is a *digital signature*: only Alice can sign her messages, but anyone can verify that the message came from Alice, by using her public key
- Again, it's too expensive to sign the whole message. Instead, Alice calculates a *cryptographic hash* of the message and signs the hash value.
- If you sign the plaintext and encrypt the signature, the signer's identity is concealed; if you sign the ciphertext, a gateway can verify the signature without having to decrypt the message.

# They're Not Like Real Signatures

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

Alice and Bob  
Pre-Arranged Key  
Lists?  
The Solution: Public  
Key Cryptography  
RSA  
Classical Public Key  
Usage

Complexities

A More Realistic  
Scenario

Perfect Forward  
Secrecy

Diffie-Hellman Key  
Exchange

Random Numbers  
Who Sent a  
Message?

Digital Signatures

They're Not Like  
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Cryptographic Hash  
Functions

---

- Real signatures are strongly bound to the person, and weakly bound to the data
- Digital signatures are strongly bound to the data, and weakly bound to the person — what if the key is stolen (or deliberately leaked)?
- A better term: digital signature algorithms provide *non-repudiation*

# Cryptographic Hash Functions

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Cryptographic Hash  
Functions

Cryptographic Hash  
Functions

Recent

Developments

Abusing a Weak  
Hash Function

The Birthday  
Paradox

The Birthday Attack

Birthday Attacks  
and Block Ciphers

Practical Stunts  
from MD5 Collisions

- Produce relatively-short, fixed-length output string from arbitrarily long input.
- Computationally infeasible to find two different input strings that hash to the same value
- Computationally infeasible to find any input string that hashes to a given value
- Strength roughly equal to half the output length
- Best-known cryptographic hash functions: MD5 (128 bits), SHA-1 (160 bits), SHA-256/384/512 (256/384/512 bits)
- 128 bits and shorter are not very secure for general usage

# Recent Developments

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

Cryptographic Hash  
Functions

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Developments

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Practical Stunts  
from MD5 Collisions

- At CRYPTO '04, several hash functions were cracked by Wang et al.
  - More precisely, collisions were found:  
$$H(M) = H(M'), M \neq M'$$
  - Cracked functions include MD4, MD5, HAVAL-128, RIPEMD, and SHA-0.
  - But SHA-0 was known to be flawed; NSA replaced it with SHA-1 in 1994
  - In 2005, Wang et al. showed that SHA-1 was considerably weaker than its design strength
  - Are SHA-256/384/512 still secure?
- ⇒ MD5 is still commonly used, though weaknesses have long been suspected.

# Abusing a Weak Hash Function

Block Ciphers  
(Cont)

Public Key  
Encryption

Cryptographic Hash  
Functions

Cryptographic Hash  
Functions

Recent  
Developments

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Practical Stunts  
from MD5 Collisions

- Alice prepares two contracts,  $m$  and  $m'$ , such that
$$H(m) = H(m')$$
  - Contract  $m$  is favorable to Bob; contract  $m'$  is favorable to Alice
- ⇒ The exact terms aren't important; Alice can prepare many different contracts while searching for two suitable ones.
- Alice sends  $m$  to Bob; he signs it, producing
$$\{H(m)\}_{K_B^{-1}}.$$
  - Alice shows  $m'$  and  $\{H(m)\}_{K_B^{-1}}$  to the judge and asks that  $m'$  be enforced
  - Note that the signature matches. . .

# The Birthday Paradox

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

Cryptographic Hash  
Functions

Recent

Developments

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The Birthday Attack

Birthday Attacks  
and Block Ciphers

Practical Stunts  
from MD5 Collisions

- How many people need to be in a room for the probability that two will have the same birthday to be  $> .5$ ?
- Naive answer: 183
- Correct answer: 23
- The question is not “who has the same birthday as Alice?”; it’s “who has the same birthday as Alice or Bob or Carol or ...” assuming that none of them have the same birthday as any of the others

# The Birthday Attack

Block Ciphers  
(Cont)

---

Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

Cryptographic Hash  
Functions

Recent

Developments

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Hash Function

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Paradox

**The Birthday Attack**

Birthday Attacks  
and Block Ciphers

Practical Stunts  
from MD5 Collisions

- Alice can prepare lots of variant contracts, looking for any two that have the same hash
- More precisely, she generates many trivial variants on  $m$  and  $m'$ , looking for a match between the two sets
- This is much easier than finding a contract that has the same hash as a given other contract
- As a consequence, the strength of a hash function against brute force attacks is approximately half the output block size: 64 bits for MD5, 80 bits for SHA-1, etc.

# Birthday Attacks and Block Ciphers

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

Cryptographic Hash  
Functions

---

Cryptographic Hash  
Functions

Recent

Developments

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Hash Function

The Birthday

Paradox

The Birthday Attack

**Birthday Attacks  
and Block Ciphers**

Practical Stunts

from MD5 Collisions

- How many blocks can you encrypt with one key before you start getting collisions?
- The same rule applies:  $2^{B/2}$  blocks, where  $B$  is the cipher's block size
- Thus:  $2^{32}$  blocks for DES or 3DES;  $2^{64}$  blocks for AES
- $2^{32}$  64-bit blocks is  $2^{35}$  bytes. That's 34GB — smaller than most modern drives
- It's also 275Gb; on a 1Gb/sec network, it's less than 5 minutes
- Conclusion: the block size of DES and 3DES is too small for high-speed networks or large disks

# Practical Stunts from MD5 Collisions

Block Ciphers  
(Cont)

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Public Key  
Encryption

---

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Functions

---

Cryptographic Hash  
Functions

Recent

Developments

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Hash Function

The Birthday

Paradox

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and Block Ciphers

Practical Stunts  
from MD5 Collisions

- A general style of attack for exploiting hash function collisions has been devised
- Create two prologues to a message file, using a collision assigned to some variable in each version
- In the body of the message, conditionally display one version or the other, depending on that variable
- Get the harmless version signed
- Transmit the harmful one
- If no conditionals in your page description language, put the collision in a font definition file or the like