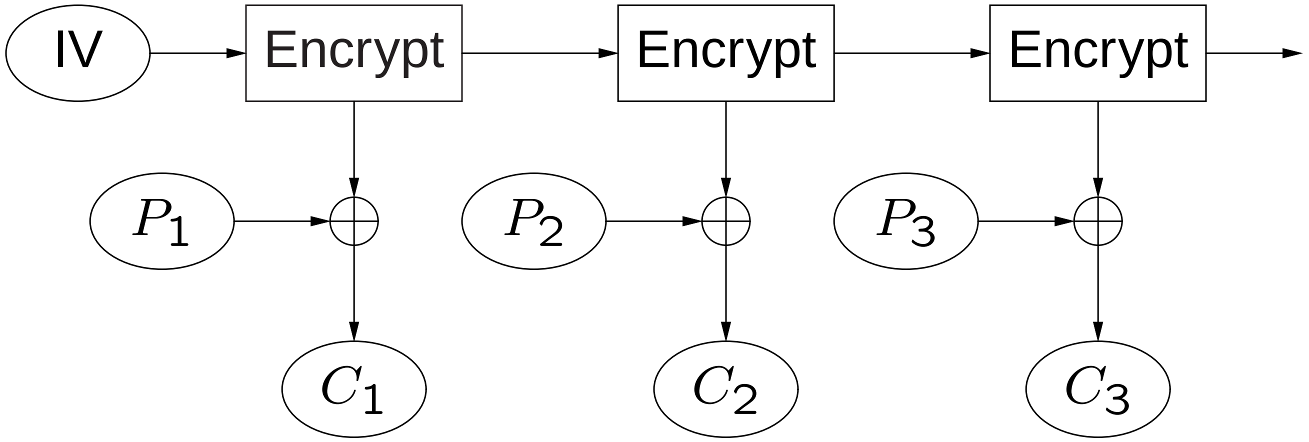
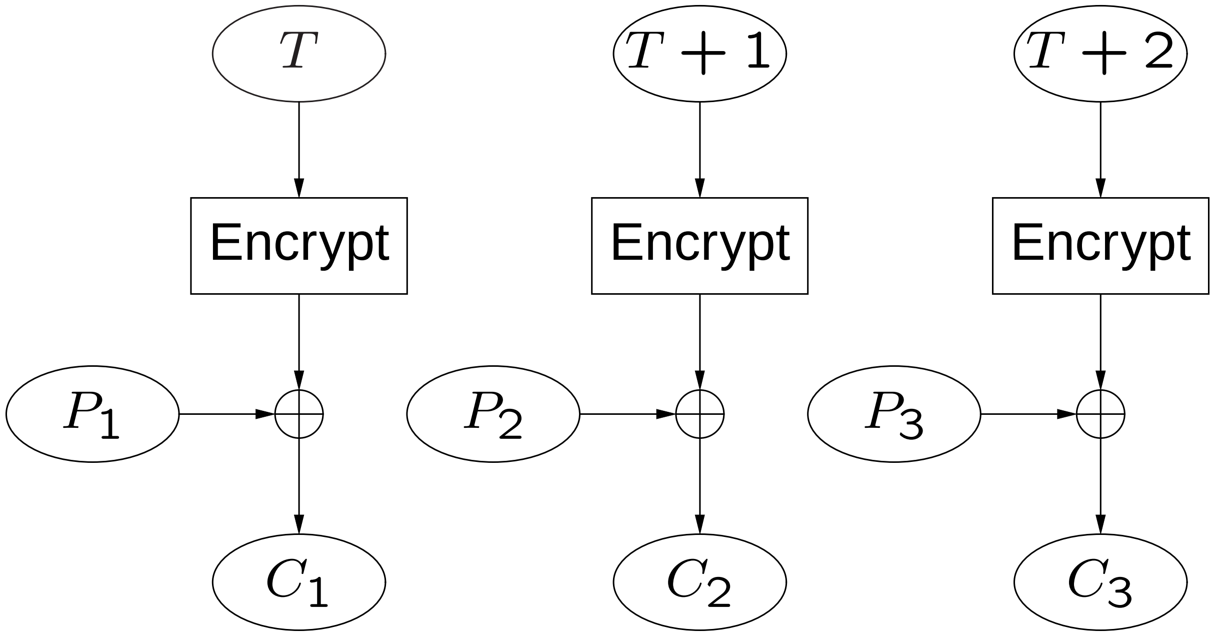
n-bit Output Feedback



Properties of Output Feedback Mode

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

Counter Mode



Properties of Counter Mode

- 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?

- 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

- 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

- 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

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

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

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

RC4

- 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

```
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] ˆ= state[xorIndex];
 }
```

Cipher Strengths

- 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

- 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

- 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?

- 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

- 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

- 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 $ed \equiv 1 \bmod (p-1)(q-1)$. 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 $c = m^e \bmod n$; to decrypt c, calculate $m = c^d \bmod n$.
- 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

- 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

- 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”^{3} 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

- 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

- 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

- 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

- 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 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?

- 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

- 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

- 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

- 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

- 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 eg 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

- 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

- 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

- 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

- 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 Collisons

- 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