Confidentiality

Review

Problem:

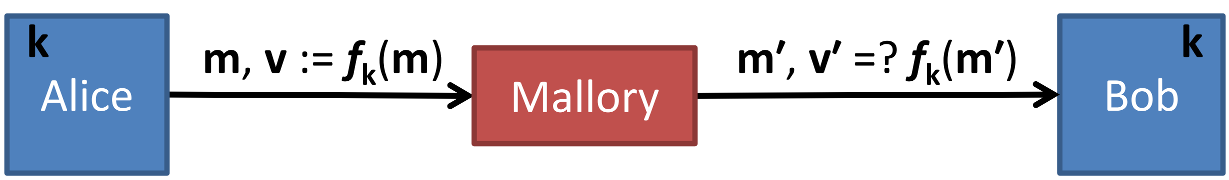
Integrity of message from Alice to Bob over an untrusted channel

Alice must append bits to message that only Alice (or Bob) can make

Solution:

Random function

Practical solution:



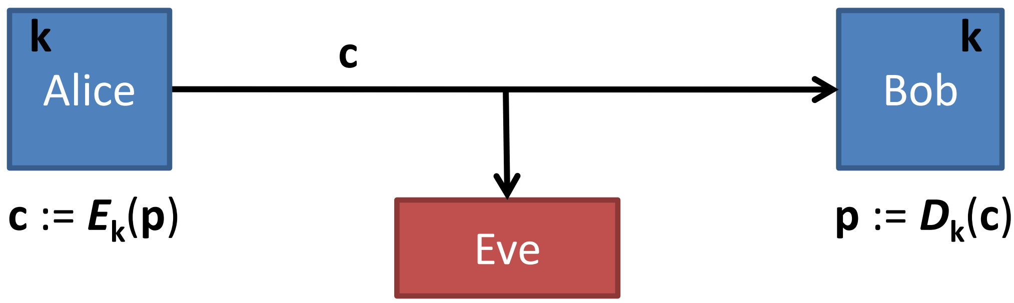
e.g. "Attack at dawn", 628369867…

(Hash-based) MAC

f_k is (we hope!) indistinguishable in practice from a random function, unless you know **k**

Review: Confidentiality

Goal: Keep contents of message **p** secret from an *eavesdropper*



Terminology

p	plaintext
c	ciphertext
k	secret key
E	encryption function
D	decryption function

Review: One-time Pad (OTP)

Alice and Bob jointly generate a secret, very long, string of <u>random</u> bits (the *one-time pad*, **k**)

To encrypt: $\mathbf{c_i} = \mathbf{p_i}$ xor $\mathbf{k_i}$

To decrypt: $\mathbf{p_i} = \mathbf{c_i}$ xor $\mathbf{k_i}$

a	**b**	**a** xor **b**
0	0	0
0	1	1
1	0	1
1	1	0

a xor **b** xor **b** = **a**

a xor **b** xor **a** = **b**

"one-time" means you should <u>never</u> reuse any part of the pad.
If you do:

- Let $\mathbf{k_i}$ be pad bit
- Adversary learns (**a** xor $\mathbf{k_i}$) and (**b** xor $\mathbf{k_i}$)
- Adversary xors those to get (**a** xor **b**), which is useful to him [How?]

Provably secure [Why?]

Usually impractical [Why? Exceptions?]

Obvious idea: Use a **pseudorandom generator** instead of a truly random pad

(Recall: Secure **PRG** inputs a seed **k**, outputs a stream that is practically indistinguishable from true randomness unless you know **k**)

Called a **stream cipher**:

1. Start with shared secret key **k**
2. Alice & Bob each use **k** to seed the PRG
3. To encrypt, Alice XORs next bit of her generator's output with next bit of plaintext
4. To decrypt, Bob XORs next bit of his generator's output with next bit of ciphertext

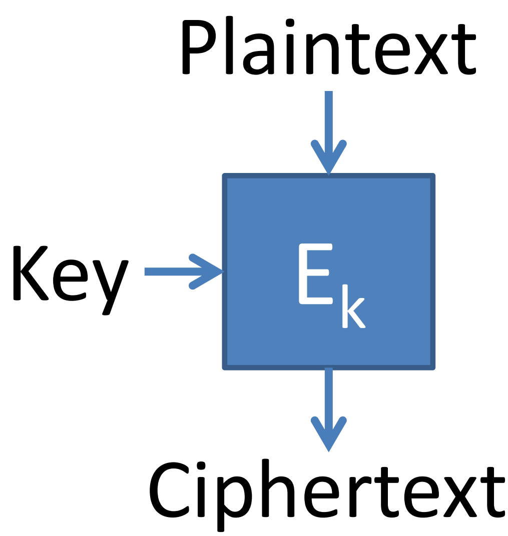
Works nicely, but: don't <u>ever</u> re-use the key, or the generator output bits!

Another approach: **Block Ciphers**

Functions that encrypts fixed-size blocks with a reusable key.

Inverse function decrypts when used with same key.

The most commonly used approach to encrypting for confidentiality.



A block cipher is <u>not</u> a pseudorandom function [Why?]

What we want instead:
pseudorandom permutation (PRP)

function from **n**-bit input to **n**-bit output

distinct inputs yield distinct outputs

Defined similarly to **PRF**:

practically indistinguishable from a *random permutation* without secret **k**

Basic challenge: Design a hairy function that is invertible, but only if you have the key

Minimal properties of a good block cipher:

Highly nonlinear ("confusion")

Mixes input bits together ("diffusion")

Depends on the key

Today's most common block cipher:

AES (**Advanced Encryption Standard**)

- Designed by NIST competition, long public comment/discussion period
- Widely believed to be secure, but we don't know how to prove it

- Variable **key size** and **block size**
- We'll use 128-bit key, 128-bit block (are also 192-bit and 256-bit versions)
- Ten **rounds**: Split **k** into ten **subkeys**, performs set of operations ten times, each with diff. subkey

Each AES round

128-bits in, 128-bit sub-key,
128-bits out

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

Four steps:
picture as operations on a
4x4 grid of 8-bit values

1. Non-linear step

   Run each byte thru a non-linear function (lookup table)

2. Shift step

   Circular-shift each row: **i**th row shifted by **i** (0-3)

3. Linear-mix step

   Treat each column as a 4-vector; multiply by a constant invertible matrix

4. Key-addition step

   XOR each byte with corresponding byte of round subkey

To decrypt, just undo the steps,
in reverse order

Remaining problem:
How to encrypt longer messages?

Padding

Can only encrypt in units of cipher blocksize, but message might not be multiples of blocksize

Solution: Add padding to end of message

Must be able to recognize and remove padding afterward

Common approach:
Add **n** bytes that have value **n**

[Caution: What if message ends at a block boundary?]

Cipher modes

We know how to encrypt one block,
but what about multiblock messages?

Different methods, called “cipher modes”

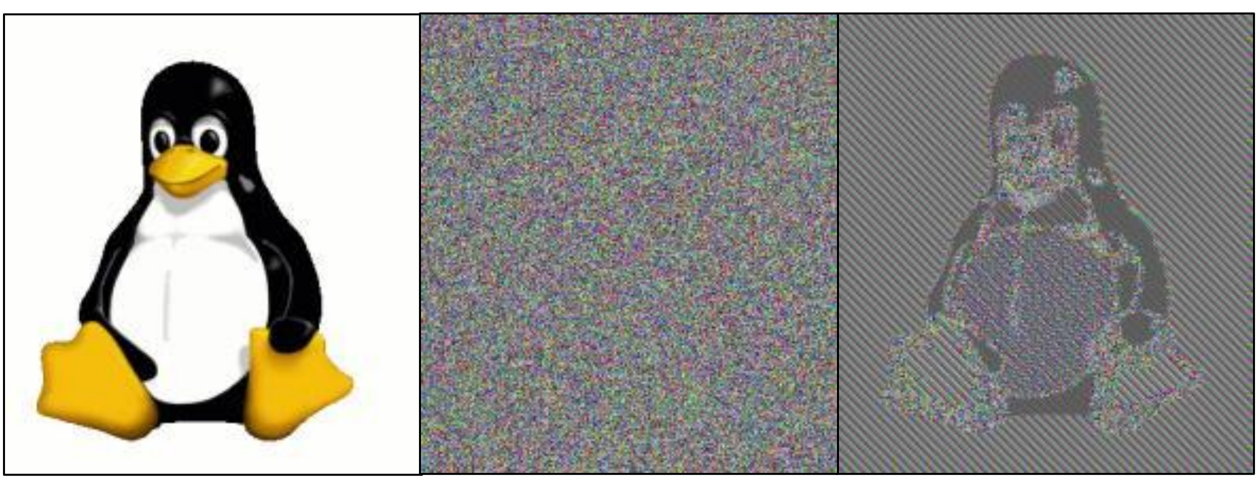
Straightforward (but bad) approach:

ECB mode (encrypted codebook)

Just encrypt each block independently

$\mathbf{C}_i := \boldsymbol{E}_k(\mathbf{P}_i)$

[Disadvantages?]



Plaintext Pseudorandom ECB mode

Better (and common):

CBC mode (cipher-block chaining)

Lame-CBC (for illustration only)

For each block $\mathbf{P_i}$:

1. Generate random block $\mathbf{R_i}$
2. $\mathbf{C_i} := (\mathbf{R_i} \mid\mid E_k(\mathbf{P_i} \text{ xor } \mathbf{R_i}))$

[Pros and cons?]

Real CBC

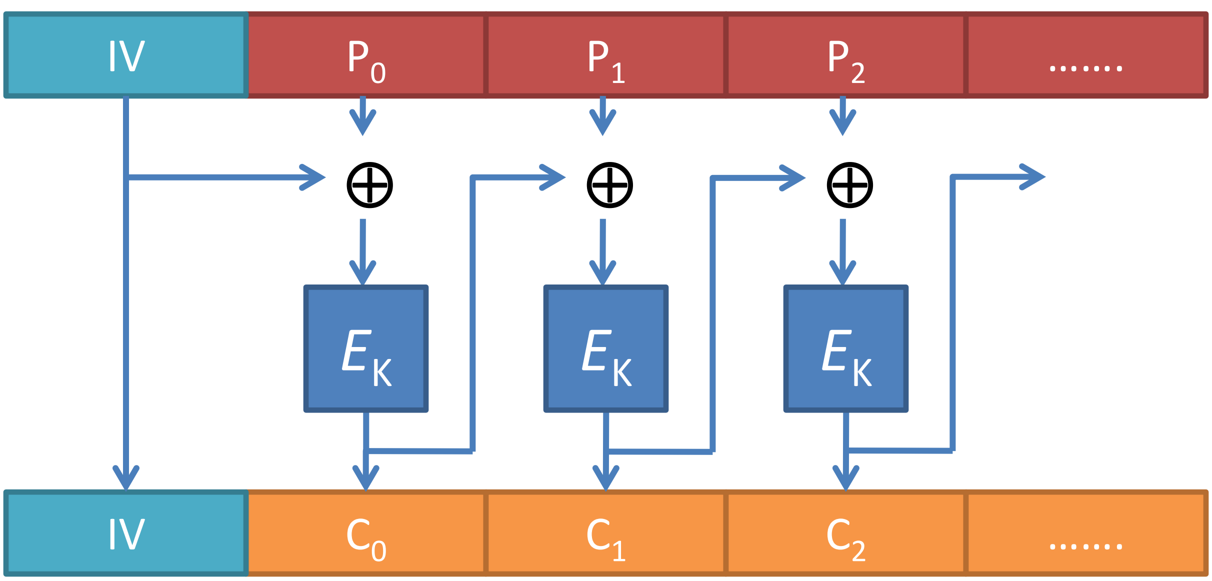
Replace $\mathbf{R_i}$ with $\mathbf{C_{i\text{-}1}}$

No need to send separately

Must still add one random $\mathbf{R_{\text{-}1}}$ to start, called "**initialization vector**" ("**IV**")

[Is CBC space-efficient?]

Illustration: CBC Encryption



[Decryption?]

Other modes

OFB, CFB, etc. – used less often

Counter mode

Essentially uses block cipher as a pseudorandom generator

XOR **i**th block of message with $\boldsymbol{E}_{\mathbf{k}}$(message_id || **i**)

[Why do we need message_id?]

Building a secure channel

What if you want confidentiality and integrity at the same time?

- *Encrypt, then add integrity*, not the other way around (reasons are subtle)
- Use separate keys for confidentiality and integrity
- Need two shared keys, but only have one? That's what PRGs are for!
- If there's a reverse (Bob to Alice) channel, use separate keys for that

Assumption we've been making so far:
Alice and Bob shared a secret key in advance

Amazing fact:
Alice and Bob can have a <u>public</u> conversation to derive a shared key!

So Far

The Security Mindset

Randomness and Pseudorandomness

Message Integrity

Confidentiality

Next week…

The single greatest advance
in the history of cryptography:
Public-key crypto