Essential Cryptography II

EECS 588: Computer and Network Security
January 11, 2011

Today's Class

- Cipher Modes
- Building a Secure Channel
- Implementations

(BREAK)

- Diffie-Hellman Key Exchange
- RSA Encryption and Signing
- Establishing Trust

Cipher Modes

How do we encrypt more than one block?

Some definitions:

- P_i – i-th plaintext block
- C_i – i-th ciphertext block
- E() – encryption function
- D() – decryption function
- K – encryption key

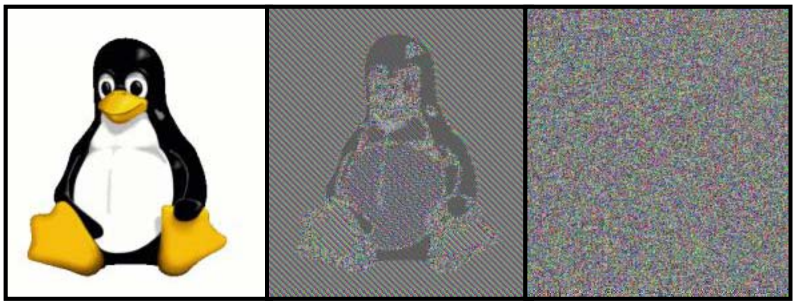
Cipher Modes: ECB

"Electronic codebook" (ECB) mode

C_i := E(K, P_i)   for i = 1, …, n

- Most "natural" construction
- Never use ECB

What's Wrong with ECB?



ECB Other Modes

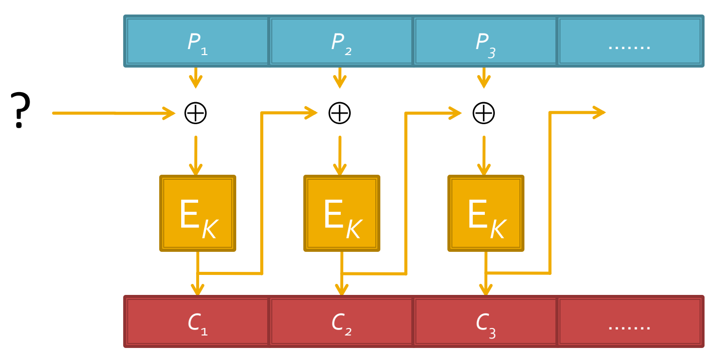
Same plaintext block always encrypts to same ciphertext block.

Don't use ECB mode.

Cipher Modes: CBC

"Cipher-Block Chaining" (CBC) mode

$C_i := E(K, P_i \oplus C_{i-1})$ for $i = 1, \ldots, n$



Cipher Modes: CBC

"Cipher-Block Chaining" (CBC) mode

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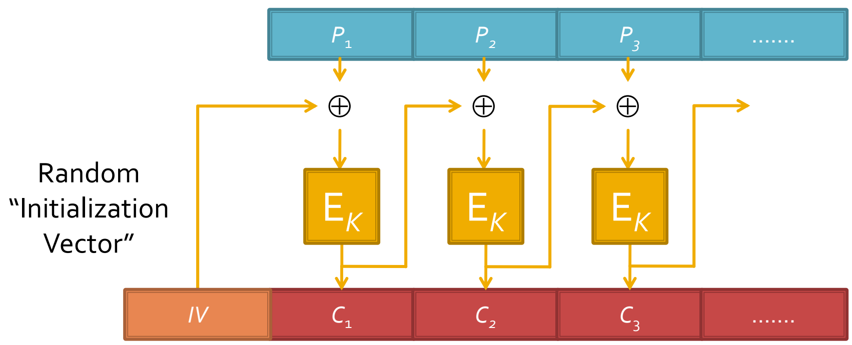


What if you reuse the IV? Bad.

Cipher Modes: CTR

"Counter" (CTR) mode

$K_i := E(K, Nonce \,||\, i\,)$ for $i = 1, \ldots, n$

$C_i := P_i \oplus K_i$

- Stream cipher construction – like OTP
- Plaintext never passes through *E*
- Don't need to pad the message
- Allows parallelization and seeking
- Never reuse same *K*+*Nonce* (like OTP)

Building a Secure Channel

Session Key *K*
Never reuse

Session Key *K*
Never reuse

// Initialization (Both Parties)

Separate keys for each function:

KeySendEnc := HMAC-SHA256(*K*, "Enc A-to-B")
KeyRecvEnc := HMAC-SHA256(*K*, "Enc B-to-A")
KeySendAuth := HMAC-SHA256(*K*, "Auth A-to-B")
KeyRecvAuth := HMAC-SHA256(*K*, "Auth B-to-A")

if Bob then
    swap(*KeySendEnc*, *KeyRecvEnc*)
    swap(*KeySendAuth*, *KeyRecvAuth*)

MsgCntSend := 0
MsgCntRecv := 0

Building a Secure Channel

// Sender

MsgCntSend := *MsgCntSend* + 1
i := *MsgCntSend*
a := HMAC-SHA256(*KeySendAuth*,
    i || len(*m*) || *m*)
t := *a* || *m*
K := *KeySendEnc*
// to length of *t* :
MsgKey := E(*K*, *i* || 0) || E(*K*, *i* || 1) || …
Transmit(*i* || (*t* ⊕ *MsgKey*))

// Receiver

i || t := Receive()
K := *KeyRecvEnc*
// to length of *t* :
MsgKey := E(*K*, *i* || 0) || E(*K*, *i* || 1) || …
a || *m* := *t* ⊕ *MsgKey*
a' := HMAC-SHA256(*KeyRecvAuth*,
    i || len(*m*) || *m*)
Check(*a'* == *a*)
Check(*i* > *MsgCntRecv*)
MsgCntRecv := *i*

Implementations: OpenSSL

- Try not to implement crypto functions.
  Use OpenSSL libraries if possible.
  - Open source implementation
  - SSL protocol plus general crypto functions
  - Very fast hand-tuned assembly language

OpenSSL on the Command Line

- Hashing (a.k.a. "message digest")
```
$ openssl dgst -sha256 myfile
```
- Encryption and decryption
```
$ openssl enc -aes-256-cbc \
              -in myfile -out myfile.enc
$ openssl enc -d -aes-256-cbc \
              -in myfile.enc -out myfile
```
- Performance tests
```
$ openssl speed sha
$ openssl speed aes
```

See man page

OpenSSL in C – Authentication

```
#include <openssl/hmac.h>
#include <openssl/sha.h>
#include <openssl/evp.h>

  unsigned char *mac;
  mac = HMAC(
     EVP_sha256(), // use SHA-256 hash function
     (unsigned char*) key,
     (unsigned long ) keyNumBytes,
     (unsigned char*) data,
     (unsigned long ) dataNumBytes,
     NULL, NULL
  );
```

OpenSSL in C – Encryption

```
#include <openssl/evp.h>

// 256-bit AES in CBC mode with padding
void AesEncrypt(unsigned char key[32], unsigned char iv[16])
{
   unsigned char inData[16], outData[16];
   Int inLen, outLen;
   EVP_CIPHER_CTX ctx;

   EVP_CIPHER_CTX_init(&ctx);
   EVP_EncryptInit_ex(&ctx, EVP_aes_256_cbc(), NULL,
       (unsigned char *)key, (unsigned char *)iv);

   while ((inLen = fread(inData, 1, 16, stdin)) > 0) {
       EVP_EncryptUpdate(&ctx, outData, &outLen, inData, inLen);
       fwrite(outData, 1, outLen, stdout);
   }

   EVP_EncryptFinal_ex(&ctx, outData, &outLen);
   fwrite(outData, 1, outLen, stdout);
   EVP_CIPHER_CTX_cleanup(&ctx);  // zeroize the key
}
```

Try OpenSSL at Home

- Install OpenSSL or use try it on a cluster
  - Sign and encrypt a message
  - Compare the speed of various functions
  - Think… How does the AES implementation compare to the speed of your Internet connection? Your hard disk? Your RAM?
- Use C, Python, or Perl and the OpenSSL library to implement our secure message passing protocol

Summary of Practical Advice

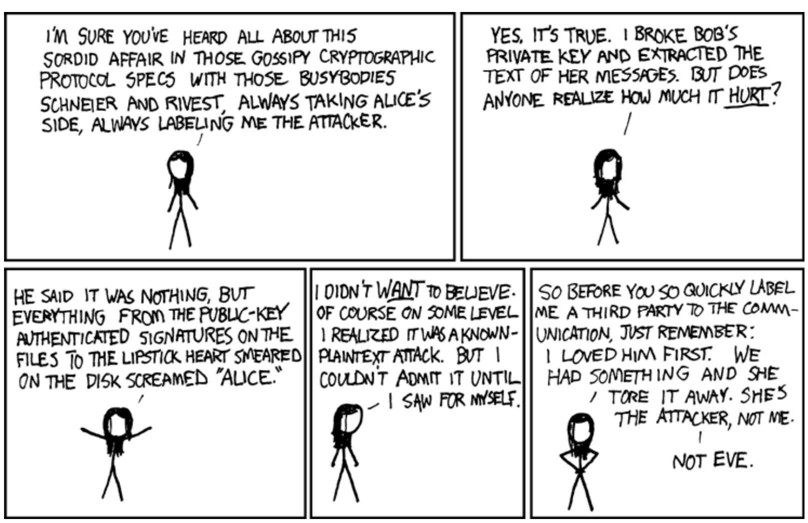
- Don't use MD5; avoid hash function pitfalls
- Don't use DES; avoid ECB mode
- Don't use `rand()` and its ilk

- For a hash/MAC, use **HMAC-SHA256**
- For a block cipher, use **AES-256**
- For randomness, use the **OS's CPRNG**
- For implementations, use **OpenSSL**

Related Research Problems

- *Cryptanalysis:* Ongoing work to break crypto functions… rapid progress on hash collisions
- *Cryptographic function design:* We badly need better hash functions… NIST competition now to replace SHA
- *Attacks:* Only beginning to understand implications of MD5 breaks – likely enables many major attacks

5 Minute Break



Public-Key Cryptography

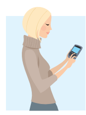
- **Problem:** With symmetric ciphers, every sender-receiver pair must share a secret key
- **Question:** What if we could use *different keys* for encryption and decryption?

Diffie-Hellman Key Exchange

- Whitfield Diffie and Martin Hellman, 1976

- Lets Alice and Bob establish a shared secret even if Eve is listening in

Diffie-Hellman Key Exchange



Alice

Agree on a large prime p
and primitive element g
that generates the group Z_p^*
(p, g can be public)

Bob

Alice: Chooses random $x < p$ (secret)

$a := g^x \bmod p$ →

Bob: Chooses random $y < p$ (secret)

← $b := g^y \bmod p$

Alice: Calculates $k := b^x \bmod p$

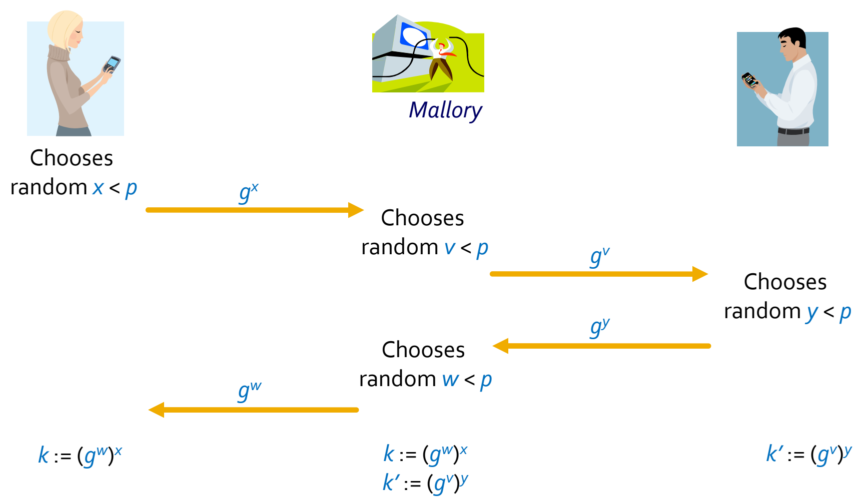
Bob: Calculates $k := a^y \bmod p$

Why this works:
$b^x = (g^y)^x = (g^x)^y = a^y \pmod p$

Difficulty?

- Diffie-Hellman (DH) problem:
  Compute g^{xy} given g^x and g^y (mod p)
- Best *known* approach: Compute x from g^x
  - Called the discrete logarithm (DL) problem
  - No *known* efficient algorithm
- Modular exponentiation believed to be a one-way function
  - Easy to compute
  - Hard to invert

Attacking Diffie-Hellman



RSA

- Ron Rivest, Adi Shamir, Len Adleman (1977)
- Used for encryption and signatures
- Based on a trapdoor function
  - Easy to compute
  - Hard to invert without special information
- Based on apparent difficulty of factoring large numbers

RSA in One Slide

p, q	large random primes
$n := pq$	modulus
$t := (p\text{-}1)(q\text{-}1)$	ensures $x^t = 1 \pmod{n}$
$e :=$ [small odd value]	public exponent
$d := 1/e \bmod t$	private exponent

Public key: (n, e)
Private key: any of p, q, t, d

Encryption: $c := m^e \bmod n$
Decryption: $m := c^d \bmod n$

Why? $(m^e)^d = m^{ed} = m^{kt+1} = (m^t)^k m = 1^k m = m \pmod{n}$

RSA for Encryption

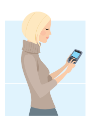
- Publish: (n, e)
  Store secretly: d
- Encryption of m
  Choose random k same size as n
  $c := k^e \bmod n$
  Send c, encrypt m with AES using k
- Decryption
  $k := c^d \bmod n$; decrypt m with AES using k

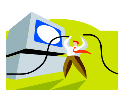
Why don't we use RSA to directly encrypt the message?

RSA for Signatures

- Publish: (n, e)
  Store secretly: d
- Signing m
  - Seed a CPRNG with m and calculate pseudorandom string s same size as n
  - $\sigma := s^d \bmod n$
- Verifying a signature on m
  - Recalculate s from m
  - Check $s = \sigma^e \bmod n$

D-H with Authentication





Mallory

Alice: Chooses random $x < p$ (secret)

$a := g^x \bmod p$ $\quad \text{Sign}_{Alice}(a)$ →

Bob: Chooses random $y < p$ (secret)

← $b := g^y \bmod p$ $\quad \text{Sign}_{Bob}(a,b)$

Alice: Verifies signature

Calculates $k := b^x \bmod p$

Bob: Verifies signature

Calculates $k := a^y \bmod p$

Establishing Trust

How do Alice and Bob learn each others' signature verification keys?

- Web of Trust
  - Transitive trust among associates (e.g. PGP)
- Public Key Infrastructure (PKI)
  - Trusted third-party Certificate Authority (CA) binds keys-identities (e.g. SSL)

Security Reading Group

- Thursdays 12-1:30pm
- Read 1 paper, get free lunch
- Get on the mailing list, http://wiki.eecs.umich.edu/secrit/

Thursday's Class: Alex's Intro