CSE 484 and CSE M 584 (Winter 2009)

Symmetric Encryption & Authentication

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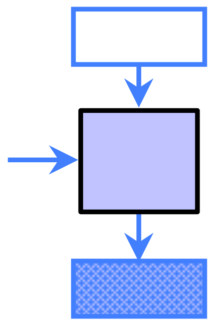
Thanks to Dan Boneh, Dieter Gollmann, John Manferdelli, John Mitchell, Vitaly Shmatikov, Bennet Yee, and many others for sample slides and materials ...

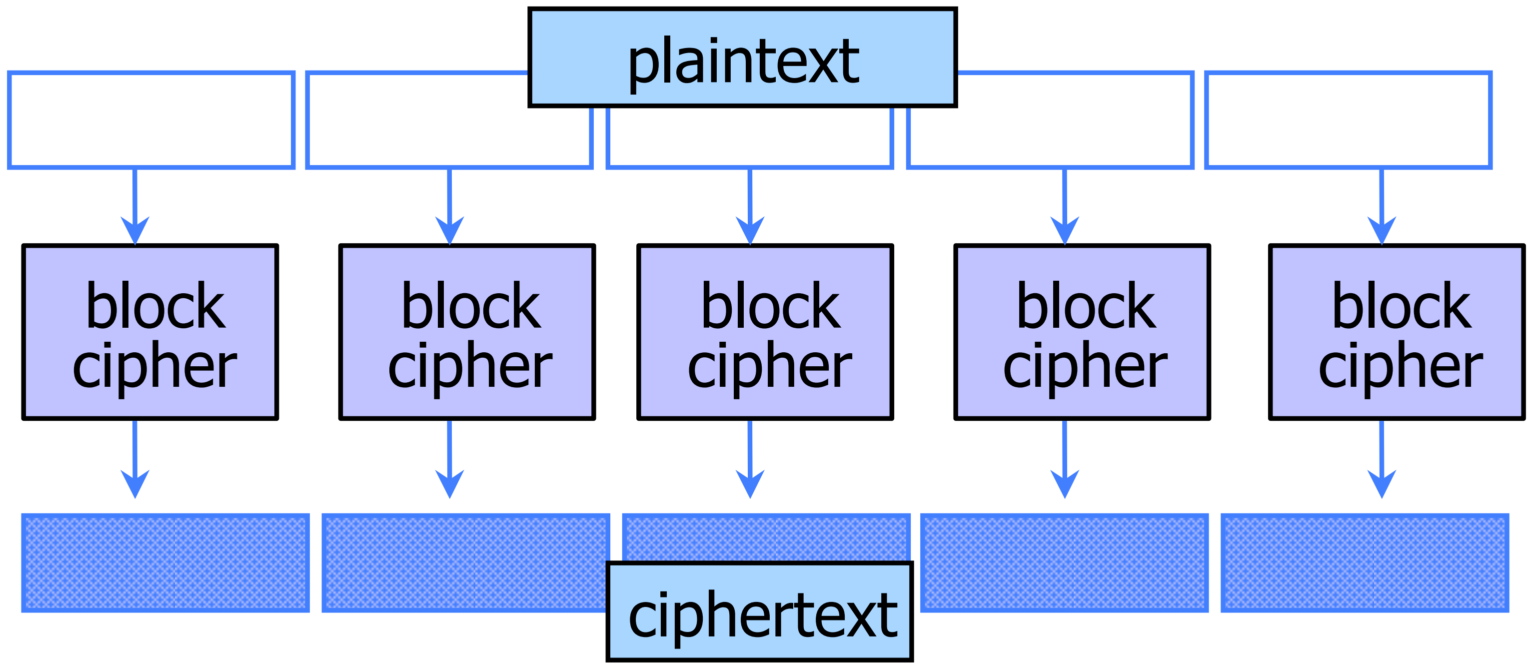
Encrypting a Large Message

- So, we've got a good block cipher, but our plaintext is larger than 128-bit block size
- Electronic Code Book (ECB) mode
  - Split plaintext into blocks, encrypt each one separately using the block cipher



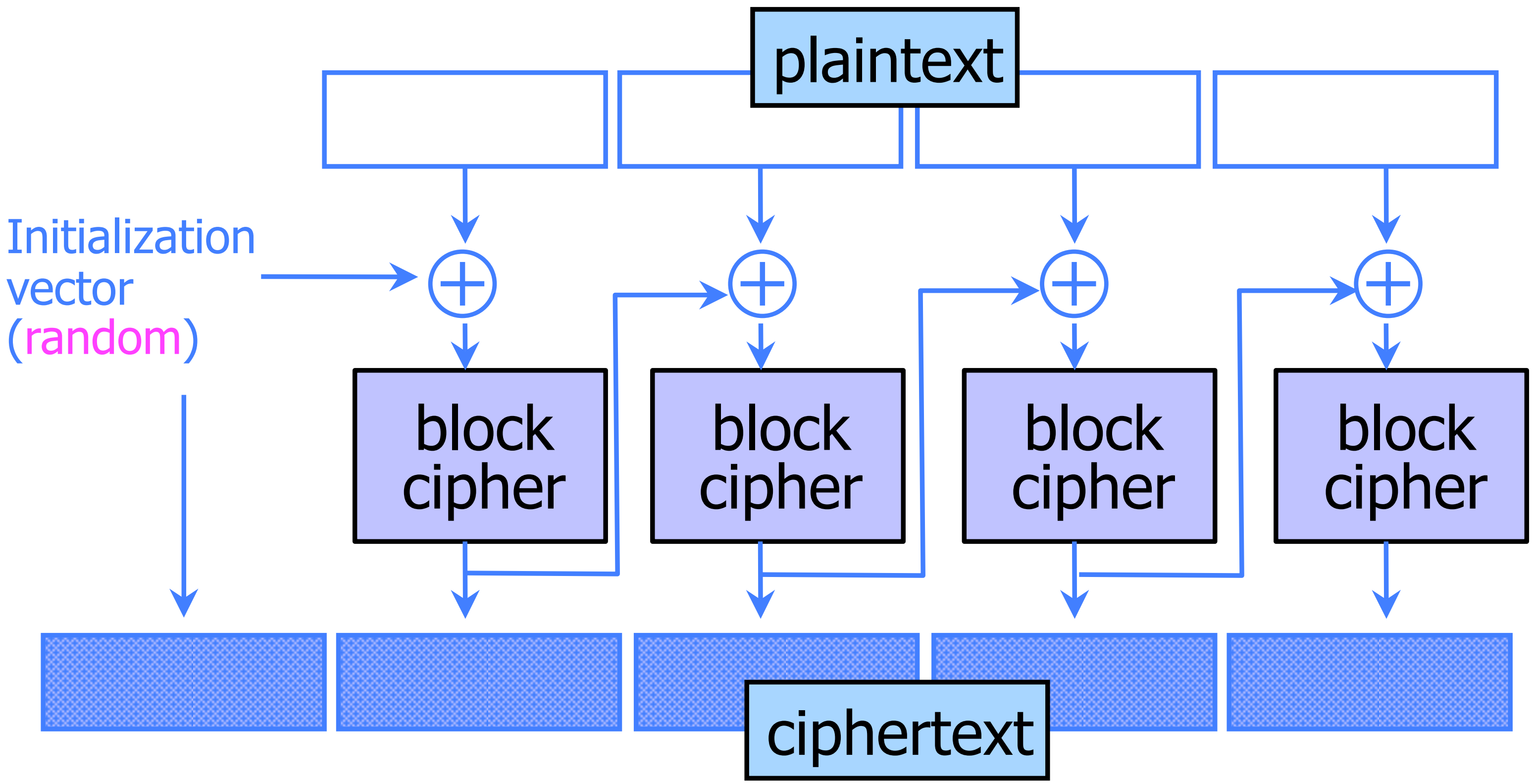
- Cipher Block Chaining (CBC) mode
  - Split plaintext into blocks, XOR each block with the result of encrypting previous blocks
- Counter (CTR) mode
  - Use block cipher to generate keystream, like a stream cipher
- …

ECB Mode



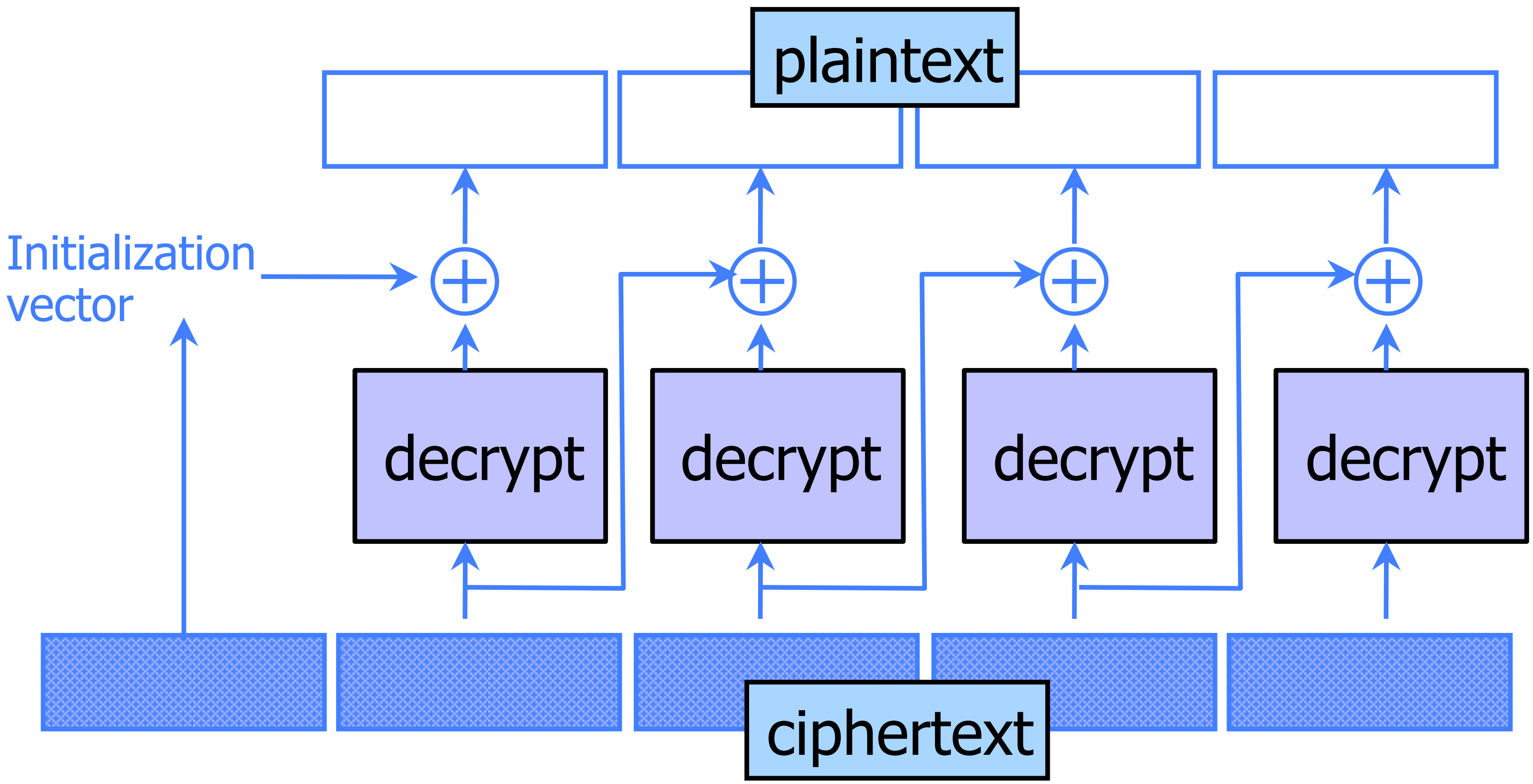
- Identical blocks of plaintext produce identical blocks of ciphertext
- No integrity checks: can mix and match blocks

CBC Mode: Encryption

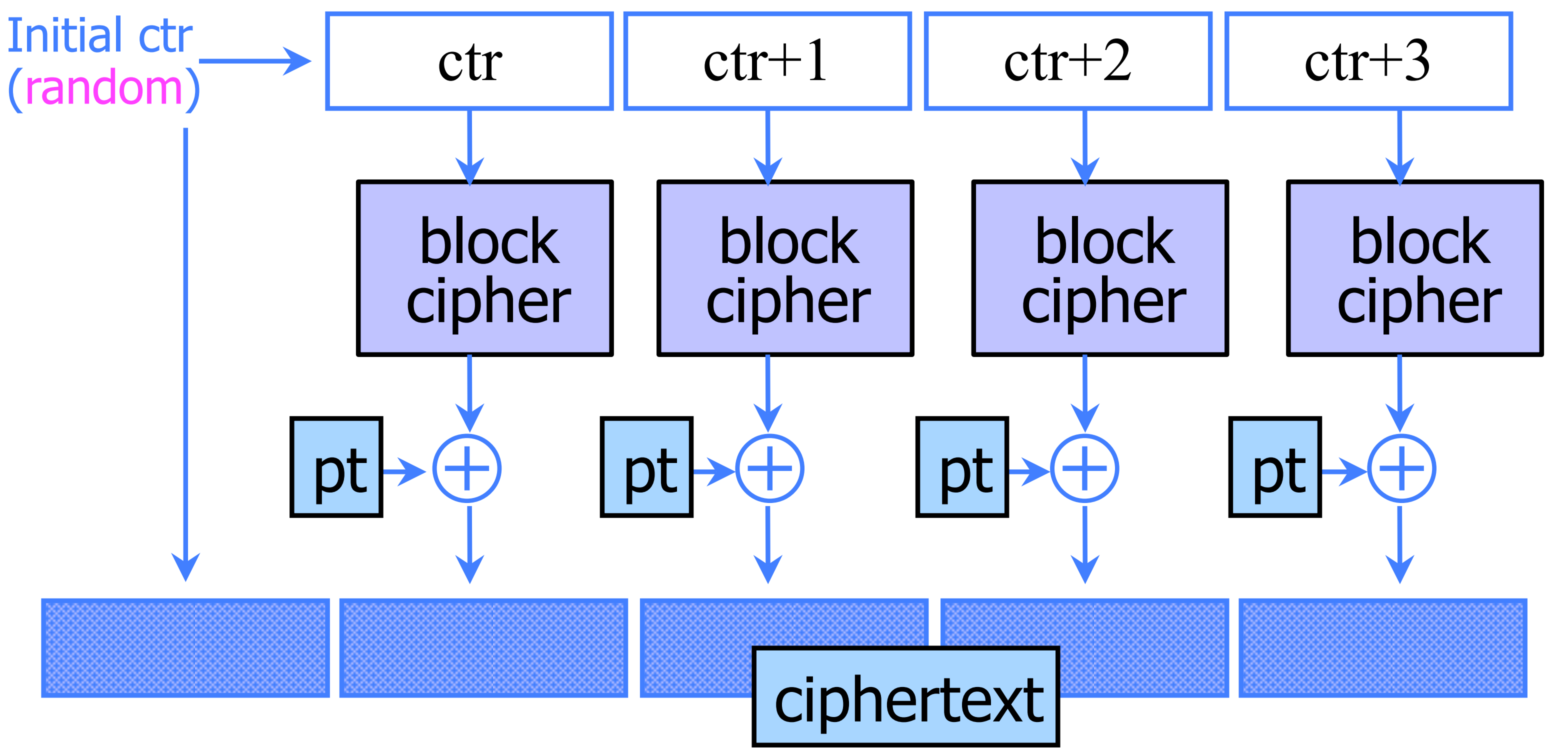


- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption

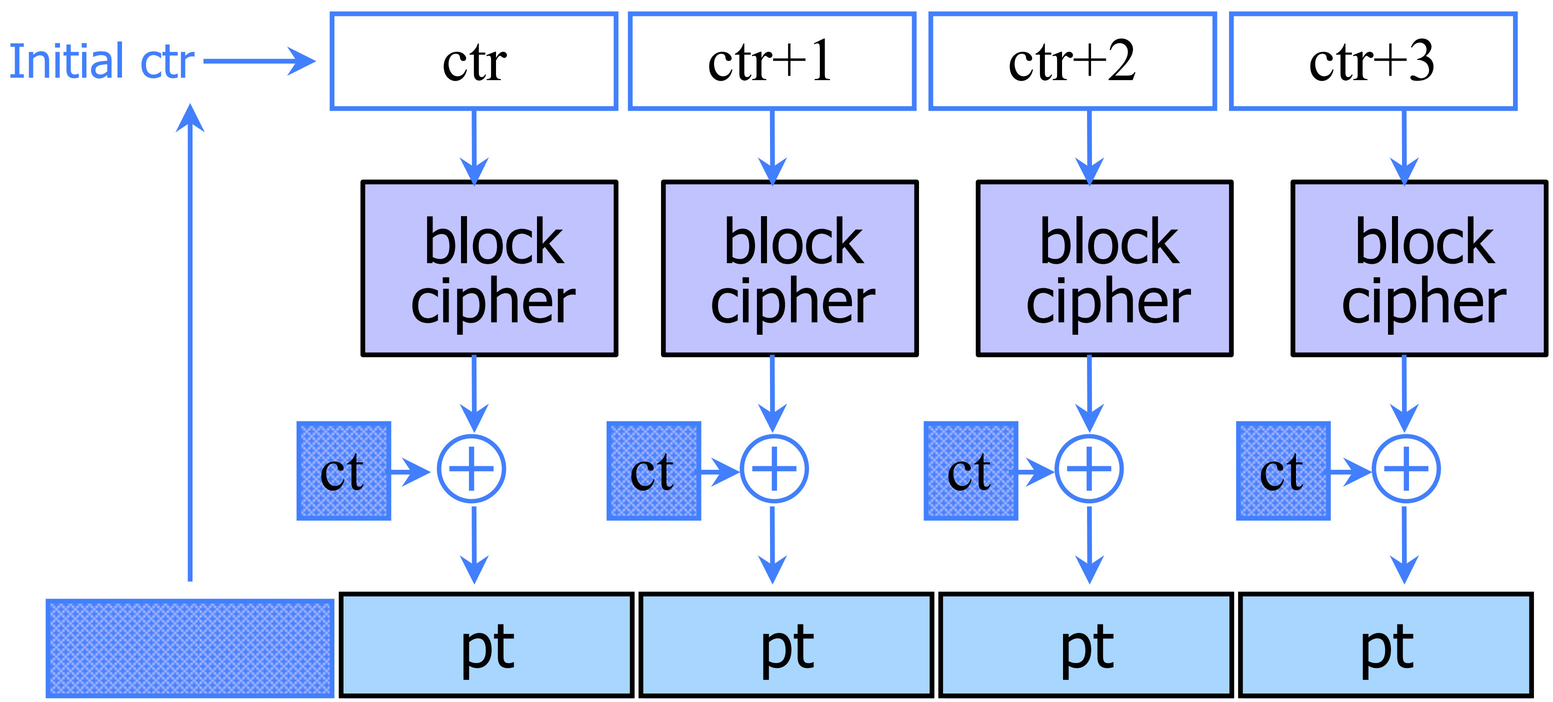


CTR Mode: Encryption



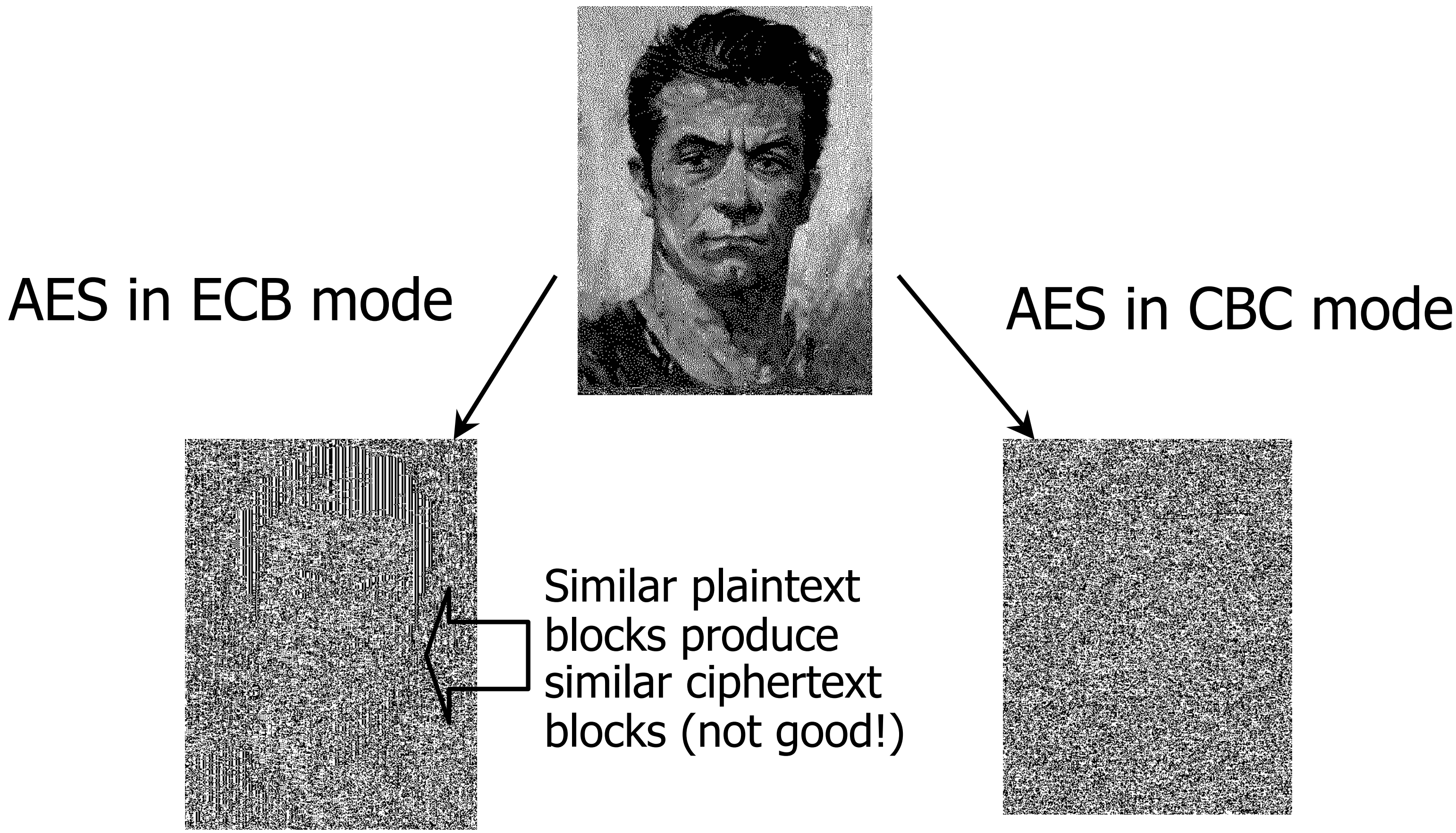
- Identical blocks of plaintext encrypted differently
- Still does not guarantee integrity

CTR Mode: Decryption



ECB vs. CBC

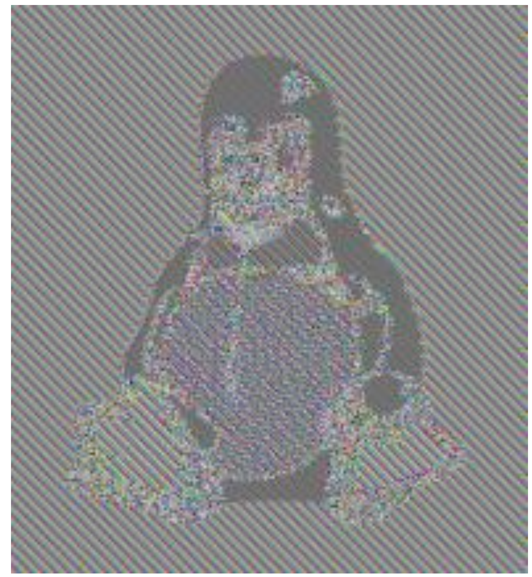
[Picture due to Bart Preneel]



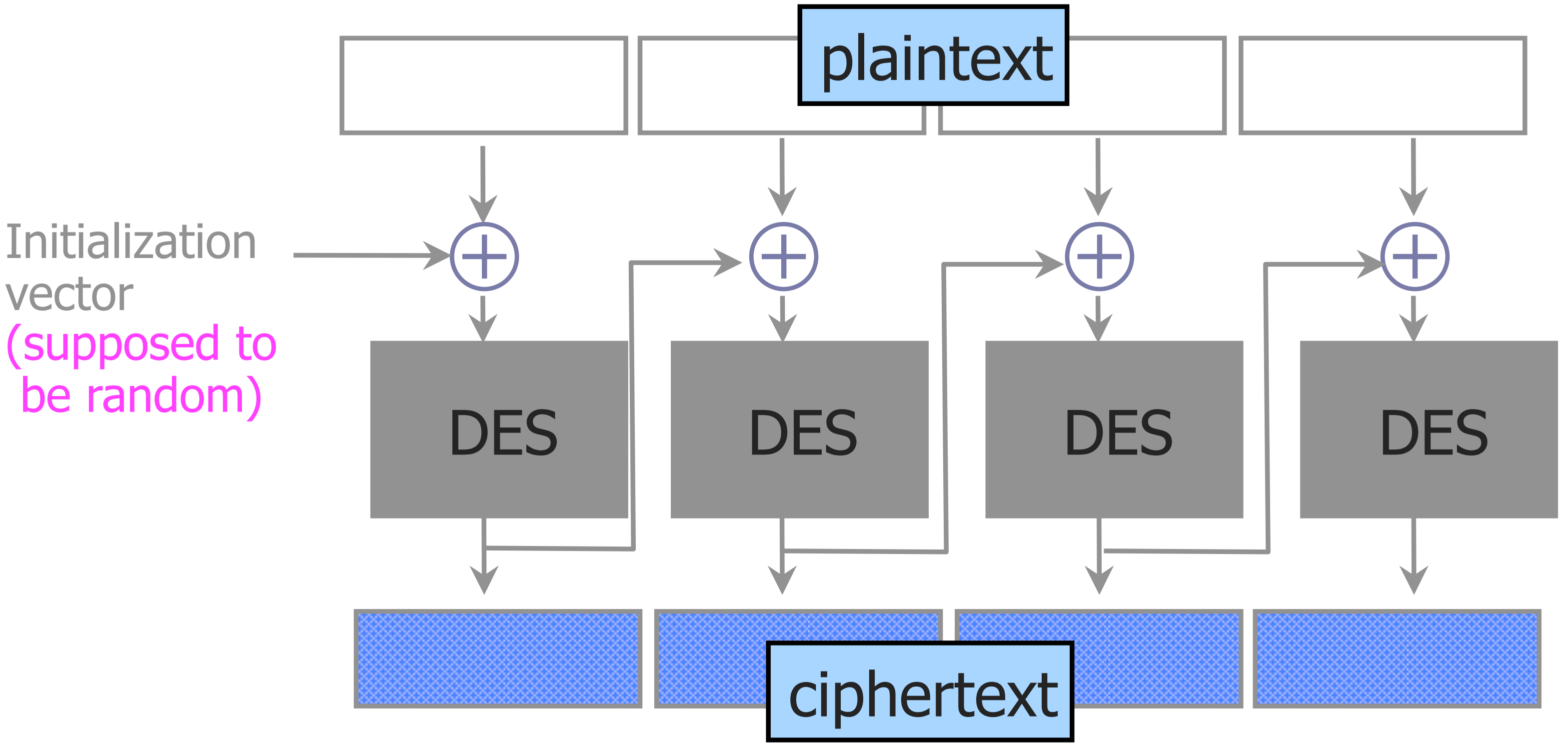
Information Leakage in ECB Mode

[Wikipedia]

Encrypt in ECB mode



CBC and Electronic Voting



Found in the source code for Diebold voting machines:

```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
        totalSize, DESKEY, NULL, DES_ENCRYPT)
```

When Is a Cipher "Secure"?

- Hard to recover the key?
  - What if attacker can learn plaintext without learning the key?
- Hard to recover plaintext from ciphertext?
  - What if attacker learns some bits or some function of bits?
- Fixed mapping from plaintexts to ciphertexts?
  - What if attacker sees two identical ciphertexts and infers that the corresponding plaintexts are identical?
  - Implication: encryption must be randomized or stateful

How Can a Cipher Be Attacked?

- Assume that the attacker knows the encryption algorithm and wants to decrypt some ciphertext
- Main question: what else does attacker know?
  - Depends on the application in which cipher is used!
- Ciphertext-only attack
- Known-plaintext attack (stronger)
  - Knows some plaintext-ciphertext pairs
- Chosen-plaintext attack (even stronger)
  - Can obtain ciphertext for any plaintext of his choice
- Chosen-ciphertext attack (very strong)
  - Can decrypt any ciphertext <u>except</u> the target
  - Sometimes very realistic model

The Chosen-Plaintext Game

- Attacker does not know the key
- He chooses as many plaintexts as he wants, and learns the corresponding ciphertexts
- When ready, he picks two plaintexts M_0 and M_1
  - He is even allowed to pick plaintexts for which he previously learned ciphertexts!
- He receives either a ciphertext of M_0, or a ciphertext of M_1
- He wins if he guesses correctly which one it is

Why Hide Everything?

- Leaking even a little bit of information about the plaintext can be disastrous
- Electronic voting
  - 2 candidates on the ballot (1 bit to encode the vote)
  - If ciphertext leaks the parity bit of the encrypted plaintext, eavesdropper learns the entire vote
- D-Day: Pas-de-Calais or Normandy?
  - Allies convinced Germans that invasion will take place at Pas-de-Calais
    - Dummy landing craft, feed information to double spies
  - Goal: hide a 1-bit secret
- Also, want a strong definition, that implies others

Defining Security

- Idea: attacker should not be able to learn even a single bit of the encrypted plaintext
- Define Enc(M_0,M_1,b) to be a function that returns encrypted M_b

  0 or 1

  - Given two plaintexts, Enc returns a ciphertext of one or the other depending on the value of bit b
  - Think of Enc as a magic box that computes ciphertexts on attacker's demand. He can obtain a ciphertext of any plaintext M by submitting $M_0=M_1=M$, or he can try to learn even more by submitting $M_0 \neq M_1$.
- Attacker's goal is to learn just one bit b

Chosen-Plaintext Security

- Consider two experiments (A is the attacker)

Experiment 0

A interacts with Enc(-,-,0)
and outputs bit d

Experiment 1

A interacts with Enc(-,-,1)
and outputs bit d

  - Identical except for the value of the secret bit
  - d is attacker's guess of the secret bit

If A "knows" secret bit, he should be able to make his output depend on it

- Attacker's advantage is defined as

| Prob(A outputs 1 in Exp0) - Prob(A outputs 1 in Exp1)) |

- Encryption scheme is chosen-plaintext secure if this advantage is negligible for any efficient A

Simple Example

- Any deterministic, stateless symmetric encryption scheme is insecure
  - Attacker can easily distinguish encryptions of different plaintexts from encryptions of identical plaintexts
  - This includes ECB mode of common block ciphers!

Attacker A interacts with Enc(-,-,b)

Let X,Y be any two different plaintexts

$C_1 \leftarrow$ Enc(X,Y,b); $C_2 \leftarrow$ Enc(Y,Y,b);

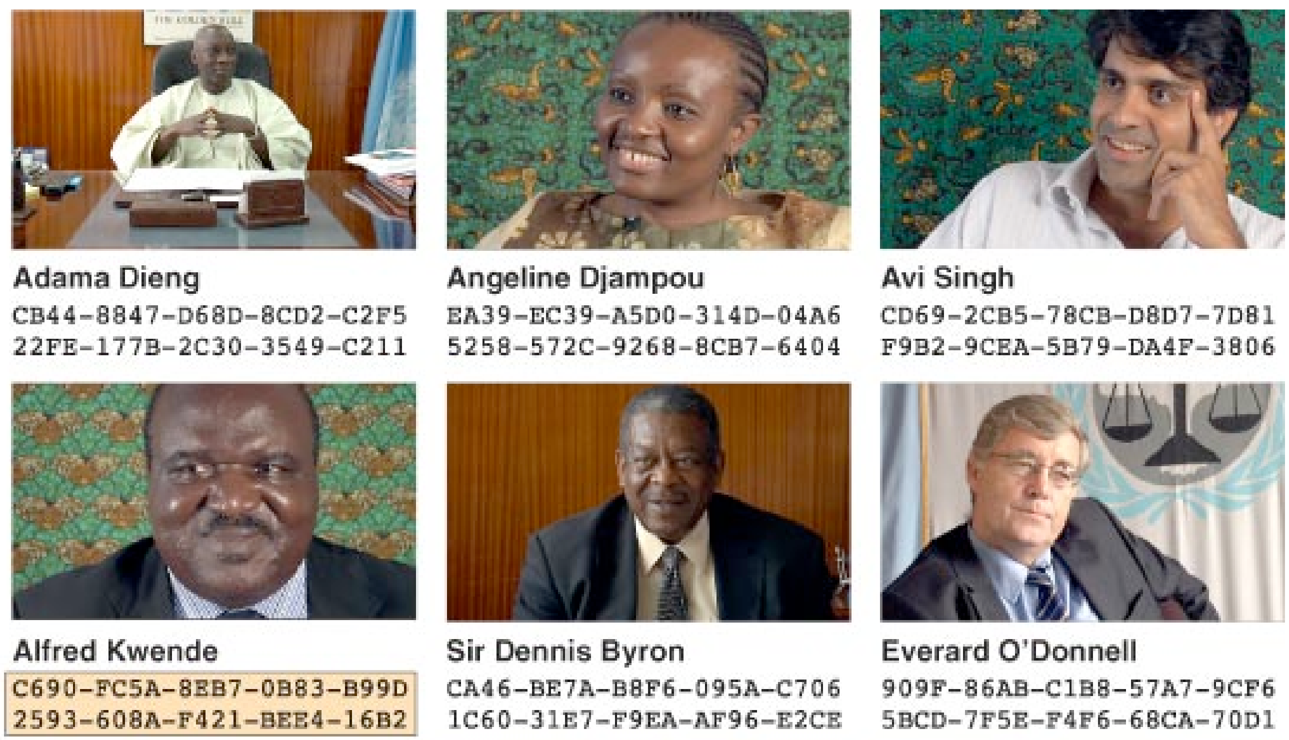
If $C_1=C_2$ then b=1 else say b=0

- The advantage of this attacker A is 1

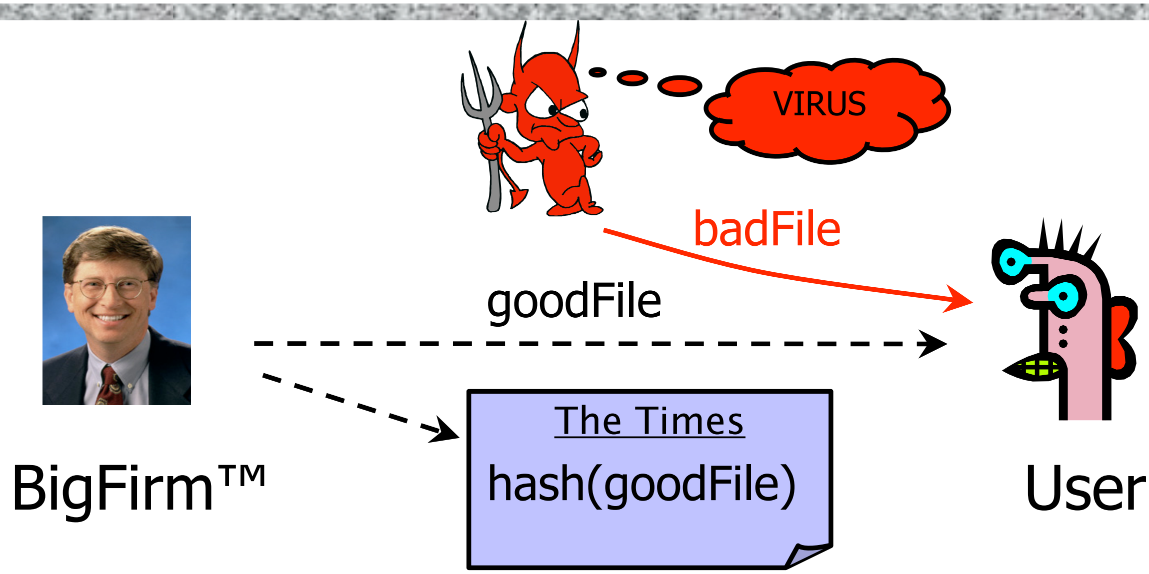
Prob(A outputs 1 if b=0)=0 Prob(A outputs 1 if b=1)=1

International Criminal Tribunal for Rwanda

- http://www.nytimes.com/2009/01/27/science/27arch.html?_r=1&ref=science
- Credits: Alexei Czeskis, Karl Koscher, Batya Friedman



Integrity



Software manufacturer wants to ensure that the executable file is received by users without modification.

It sends out the file to users and publishes its hash in NY Times.

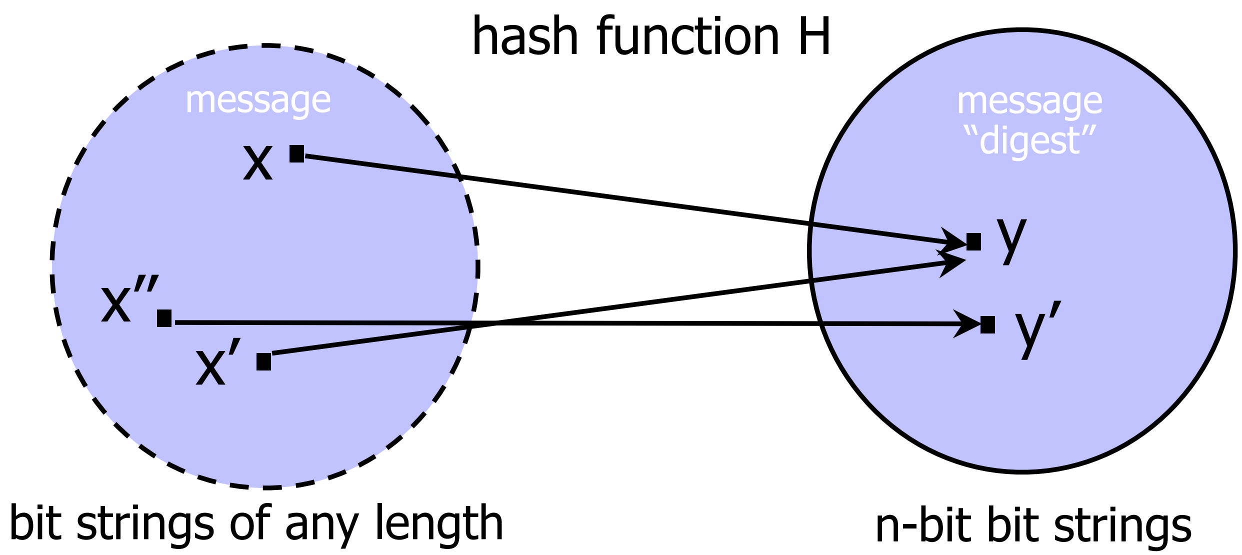
The goal is <u>integrity</u>, not secrecy

Idea: given goodFile and hash(goodFile), very hard to find badFile such that hash(goodFile)=hash(badFile)

Integrity vs. Secrecy

- Integrity: attacker cannot tamper with message
- Encryption does not always guarantee integrity
  - Intuition: attacker may able to modify message under encryption without learning what it is
    - One-time pad: given key K, encrypt M as $M \oplus K$
    - This guarantees perfect secrecy, but attacker can easily change unknown M under encryption to $M \oplus M'$ for any M'
    - Online auction: halve competitor's bid without learning its value
  - This is recognized by industry standards (e.g., PKCS)
    - "RSA encryption is intended primarily to provide confidentiality… It is not intended to provide integrity" (from RSA Labs Bulletin)

Hash Functions: Main Idea



- H is a lossy compression function
  - Collisions: h(x)=h(x') for distinct inputs x, x'
  - Result of hashing should "look random" (make this precise later)
    - Intuition: half of digest bits are "1"; any bit in digest is "1" half the time
- Cryptographic hash function needs a few properties…

One-Way

- Intuition: hash should be hard to invert
  - "Preimage resistance"
  - Let $h(x')=y\in\{0,1\}^n$ for a random x'
  - Given y, it should be hard to find any x such that h(x) =y
- How hard?
  - Brute-force: try every possible x, see if h(x)=y
  - SHA-1 (common hash function) has 160-bit output
    - Suppose have hardware that'll do 2^{30} trials a pop
    - Assuming 2^{34} trials per second, can do 2^{89} trials per year
    - Will take around 2^{70} years to invert SHA-1 on a random image

Collision Resistance

- Should be hard to find distinct x, x′ such that h(x)=h(x′)
  - Brute-force collision search is only $O(2^{n/2})$, not $O(2^n)$
  - For SHA-1, this means $O(2^{80})$ vs. $O(2^{160})$
- Birthday paradox (informal)
  - Let t be the number of values x,x′,x″… we need to look at before finding the first pair x,x′ s.t. h(x)=h(x′)
  - What is probability of collision for each pair x,x′? $1/2^n$
  - How many pairs would we need to look at before finding the first collision? $O(2^n)$
  - How many pairs x,x′ total? $\text{Choose}(2,t)=t(t-1)/2 \sim O(t^2)$
  - What is t? $2^{n/2}$

One-Way vs. Collision Resistance

- One-wayness does <u>not</u> imply collision resistance
  - Suppose g is one-way
  - Define h(x) as g(x’) where x’ is x except the last bit
    - h is one-way (to invert h, must invert g)
    - Collisions for h are easy to find: for any x, h(x0)=h(x1)
- Collision resistance does <u>not</u> imply one-wayness
  - Suppose g is collision-resistant
  - Define h(x) to be 0x if x is n-bit long, 1g(x) otherwise
    - Collisions for h are hard to find: if y starts with 0, then there are no collisions, if y starts with 1, then must find collisions in g
    - h is not one way: half of all y’s (those whose first bit is 0) are easy to invert (how?); random y is invertible with probab. 1/2

Weak Collision Resistance

- Given randomly chosen x, hard to find x′ such that h(x)=h(x′)
  - Attacker must find collision for a specific x. By contrast, to break collision resistance, enough to find any collision.
  - Brute-force attack requires $O(2^n)$ time
  - AKA **second-preimage collision resistance**
- Weak collision resistance does not imply collision resistance

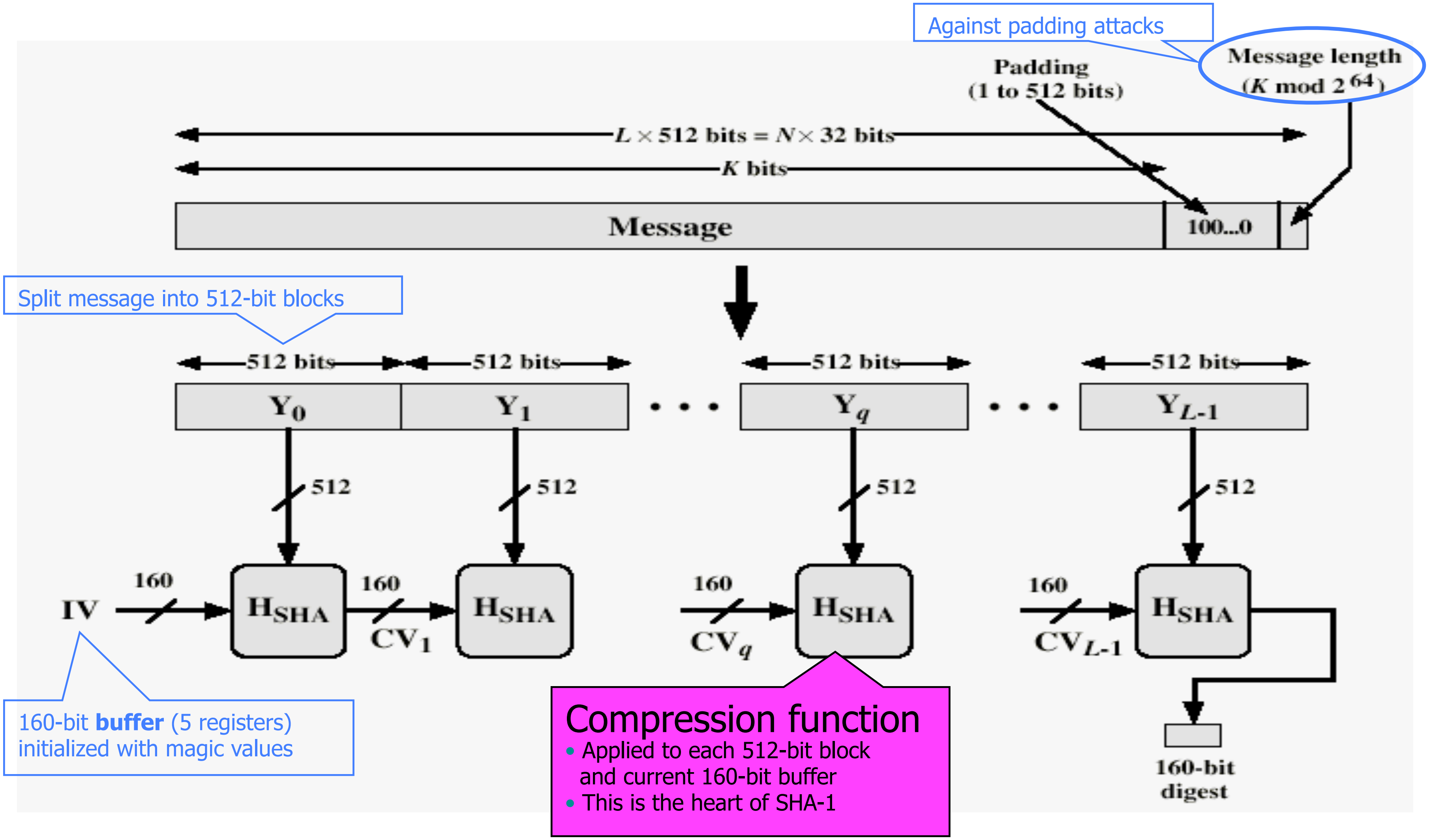
Which Property Do We Need?

- UNIX passwords stored as hash(password)
  - One-wayness: hard to recover password
- Integrity of software distribution
  - Weak collision resistance
  - But software images are not really random… maybe need full collision resistance
- Auction bidding
  - Alice wants to bid B, sends H(B), later reveals B
  - One-wayness: rival bidders should not recover B
  - Collision resistance: Alice should not be able to change her mind to bid B′ such that H(B)=H(B′)

Common Hash Functions

- MD5
  - 128-bit output
  - Designed by Ron Rivest, used very widely
  - Collision-resistance broken (summer of 2004)
- RIPEMD-160
  - 160-bit variant of MD5
- SHA-1 (Secure Hash Algorithm)
  - 160-bit output
  - US government (NIST) standard as of 1993-95
    - Also the hash algorithm for Digital Signature Standard (DSS)
- SHA-256, SHA-512 (today)
- AHS (NIST competition, future)

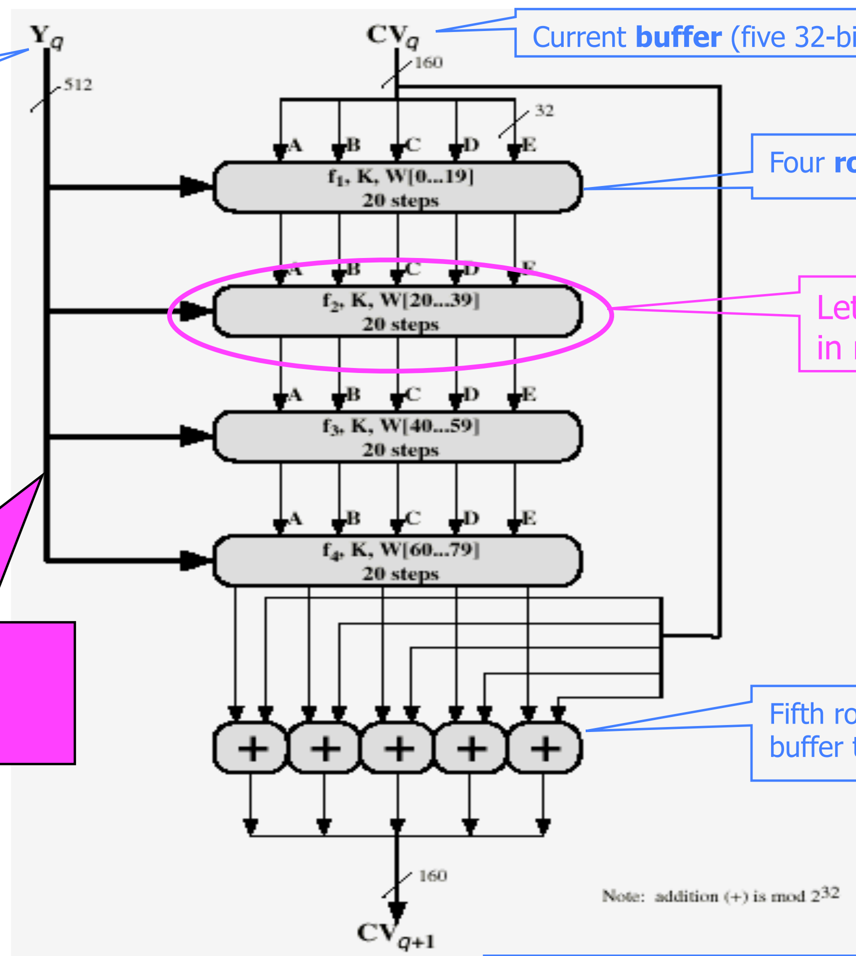
Basic Structure of SHA-1 (Skip)



SHA-1 Compression Function (Skip)

Current **message block**

Current **buffer** (five 32-bit registers A,B,C,D,E)



Four **rounds**, 20 steps in each

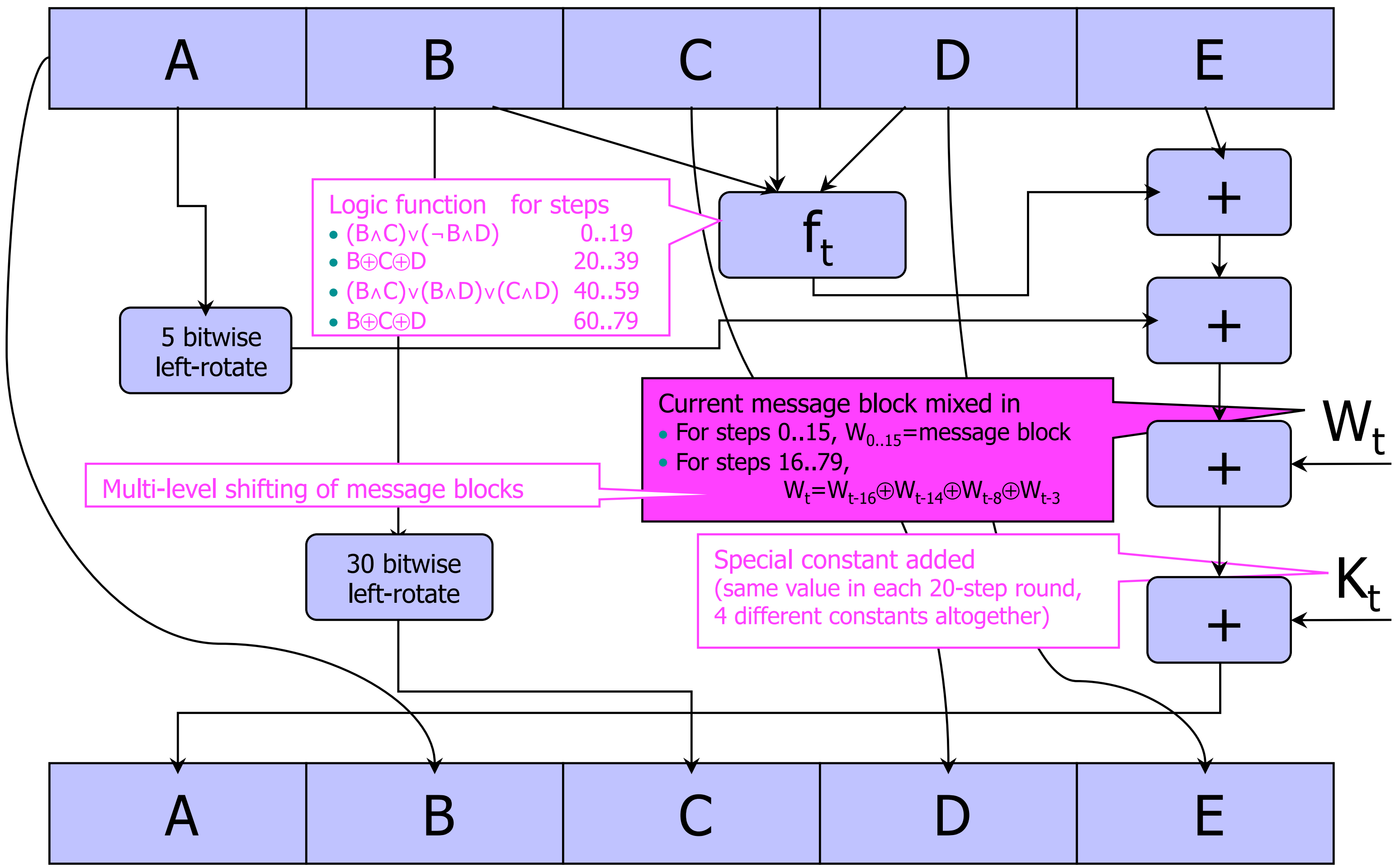
Let's look at each step in more detail…

Very similar to a block cipher, with message itself used as the key for each round

Fifth round adds the original buffer to the result of 4 rounds

Buffer contains final hash value

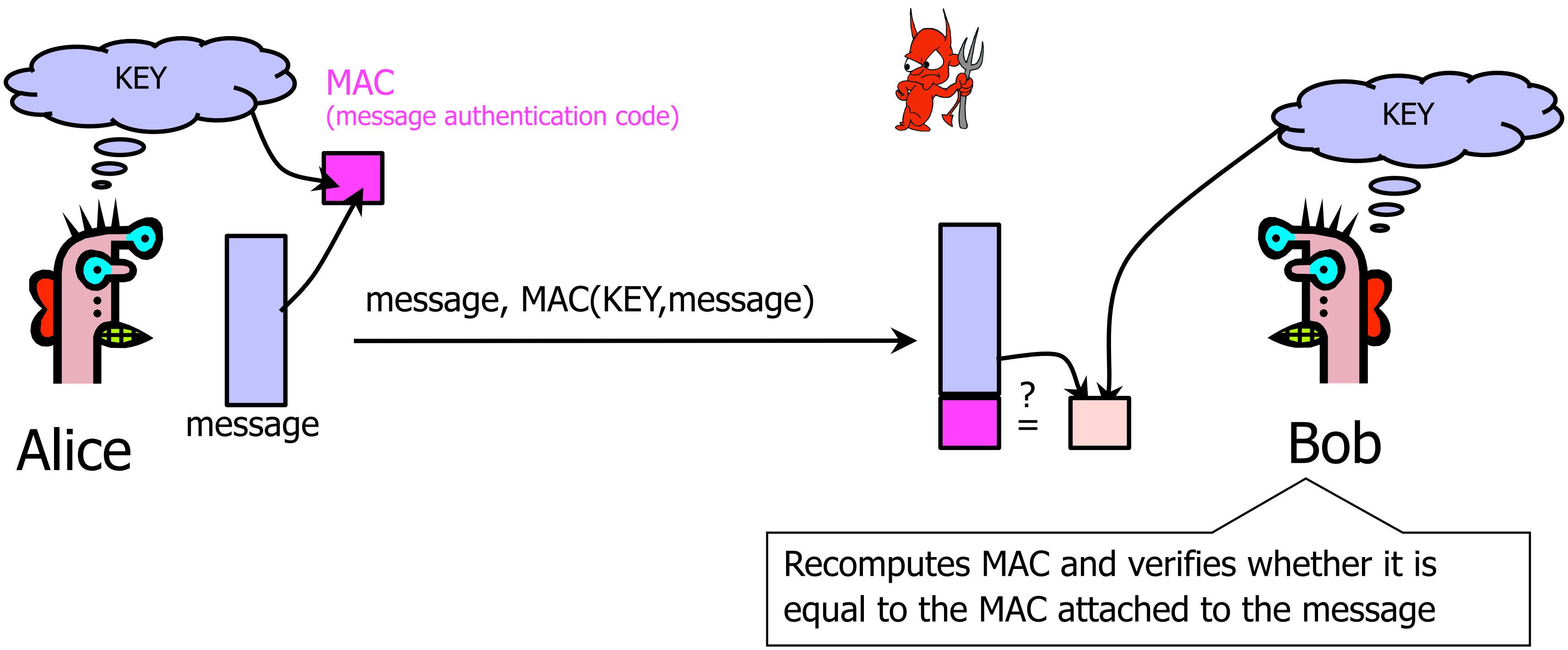
One Step of SHA-1 (80 steps total) (Skip)



How Strong Is SHA-1?

- Every bit of output depends on every bit of input
  - Very important property for collision-resistance
- Brute-force inversion requires 2^{160} ops, birthday attack on collision resistance requires 2^{80} ops
- Some recent weaknesses
  - Collisions can be found in 2^{63} ops (2005)

Authentication Without Encryption



Integrity and authentication: only someone who knows KEY can compute MAC for a given message

HMAC

- Construct MAC by applying a cryptographic hash function to message and key
  - Could also use encryption instead of hashing, but…
  - Hashing is faster than encryption in software
  - Library code for hash functions widely available
  - Can easily replace one hash function with another
  - There used to be US export restrictions on encryption
- Invented by Bellare, Canetti, and Krawczyk (1996)
  - HMAC strength established by cryptographic analysis
- Mandatory for IP security, also used in SSL/TLS

Structure of HMAC