Practical Aspects of Modern Cryptography

Winter 2011

Josh Benaloh
Brian LaMacchia

Symmetric Cryptography

Agenda

- Symmetric key ciphers
  - Stream ciphers
  - Block ciphers
- Cryptographic hash functions

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  - They can be published in a directory, on a website, etc.

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- Common pattern we will come back to later:
  - Use a public key cryptosystem to send/negotiate a randomly-generated secret key with the party to whom you wish to communicate
  - Then use that secret key with a symmetric key cryptosystem

Symmetric Ciphers

Private-key (symmetric) ciphers are usually divided into two classes.

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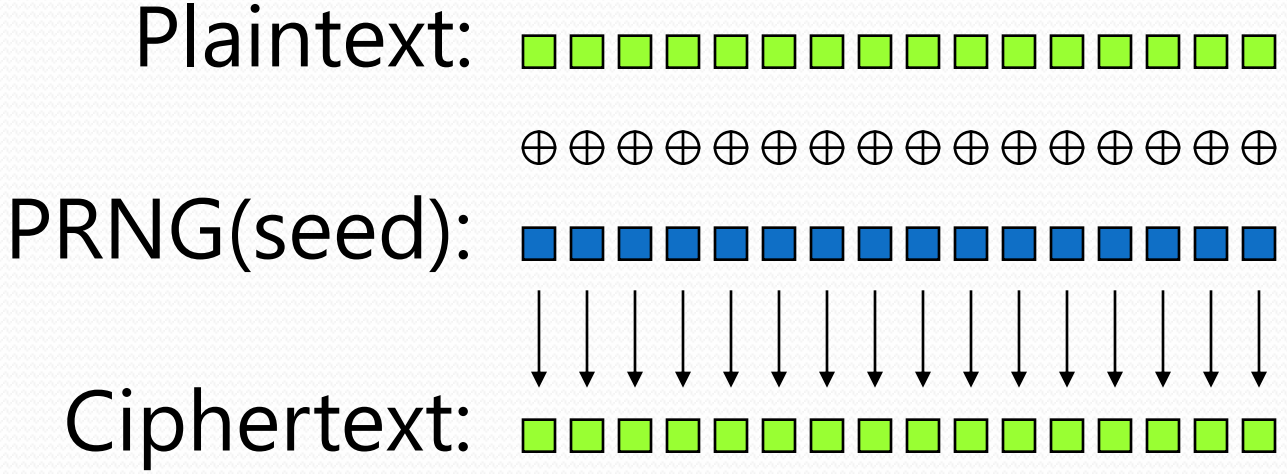
- Use the key as a seed to a pseudo-random number-generator.
- Take the stream of output bits from the PRNG and XOR it with the plaintext to form the ciphertext.

Stream Cipher Encryption



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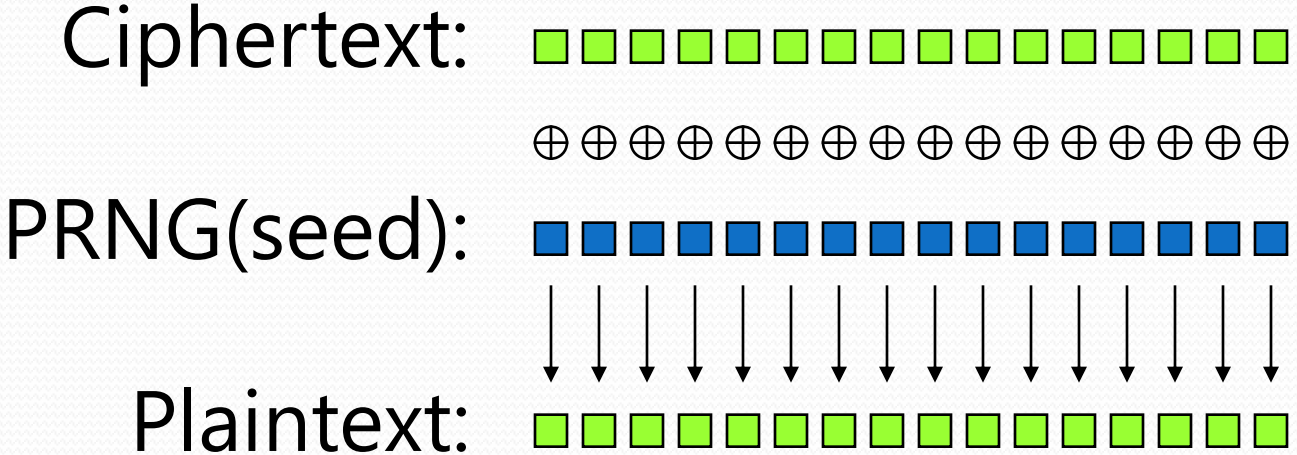

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- The same function is used for encryption and decryption.

A Sample PRNG: "Alleged RC4"

Initialization

S[0..255] = 0,1,…,255

K[0..255] = Key,Key,Key,…

for i = 0 to 255

    j = (j + S[i] + K[i]) mod 256

    swap S[i] and S[j]

A Sample PRNG: "Alleged RC4"

Iteration

i = (i + 1) mod 256

j = (j + S[i]) mod 256

swap S[i] and S[j]

t = (S[i] + S[j]) mod 256

Output S[t]

Stream Cipher Security

- If two plaintexts are *ever* encrypted with the same stream cipher and key

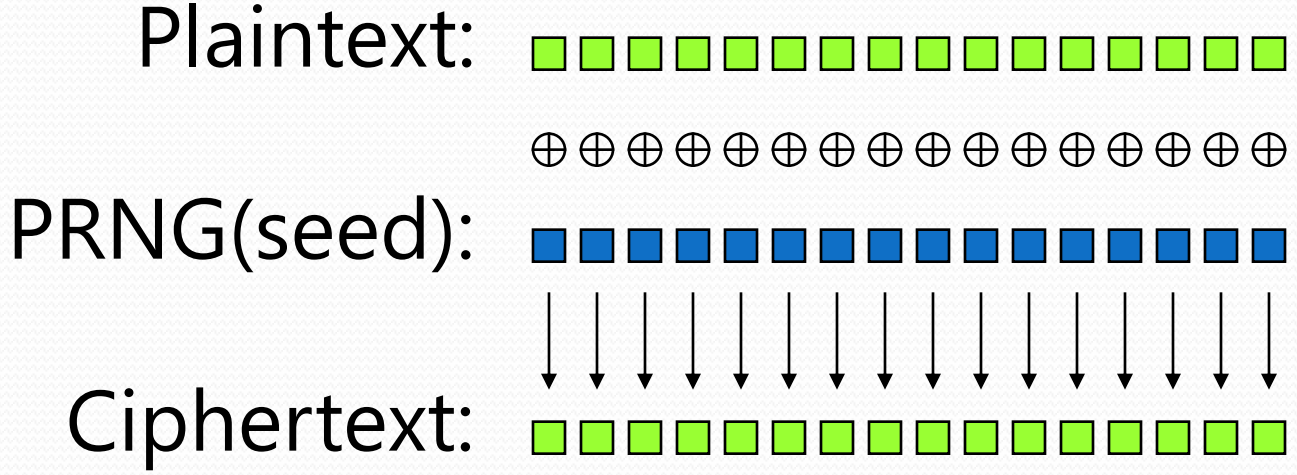
$$C_1 = K \oplus P_1$$
$$C_2 = K \oplus P_2$$

an attacker can easily compute

$$C_1 \oplus C_2 = P_1 \oplus P_2$$

from which P_1 and P_2 can usually be teased apart easily.

Stream Cipher Encryption



Stream Cipher Integrity

- It is easy for an adversary (even one who can't decrypt the ciphertext) to alter the plaintext in a known way.

Bob to Bob's Bank:

Please transfer $0,000,002.00 to the account of my good friend Alice.

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- This can be protected against by the careful addition of appropriate redundancy.

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- They are broken by key re-use.
- They require integrity checking.
- If you're going to use a stream cipher
  - Seriously consider other options. Make sure you understand the risks if you make a mistake in use

Symmetric Ciphers

Private-key (symmetric) ciphers are usually divided into two classes.

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- Block ciphers

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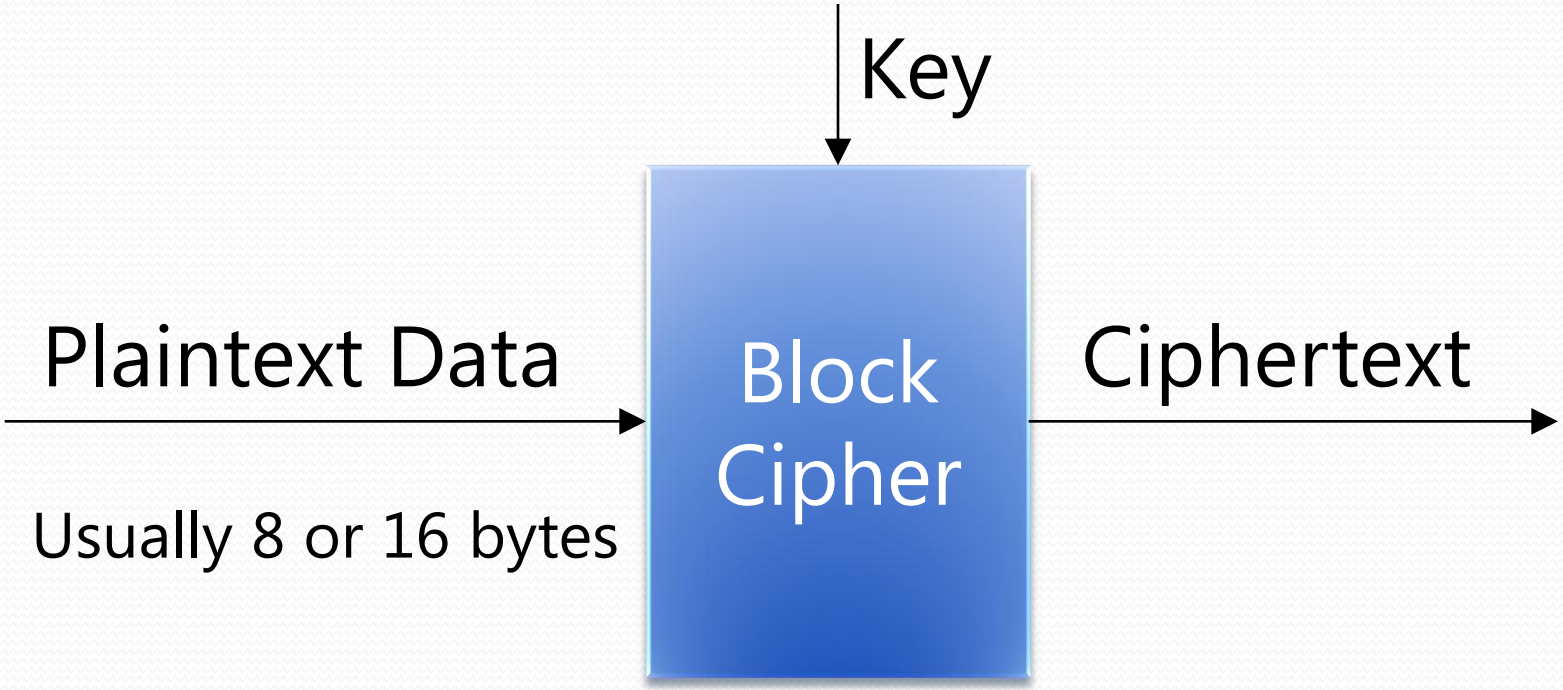
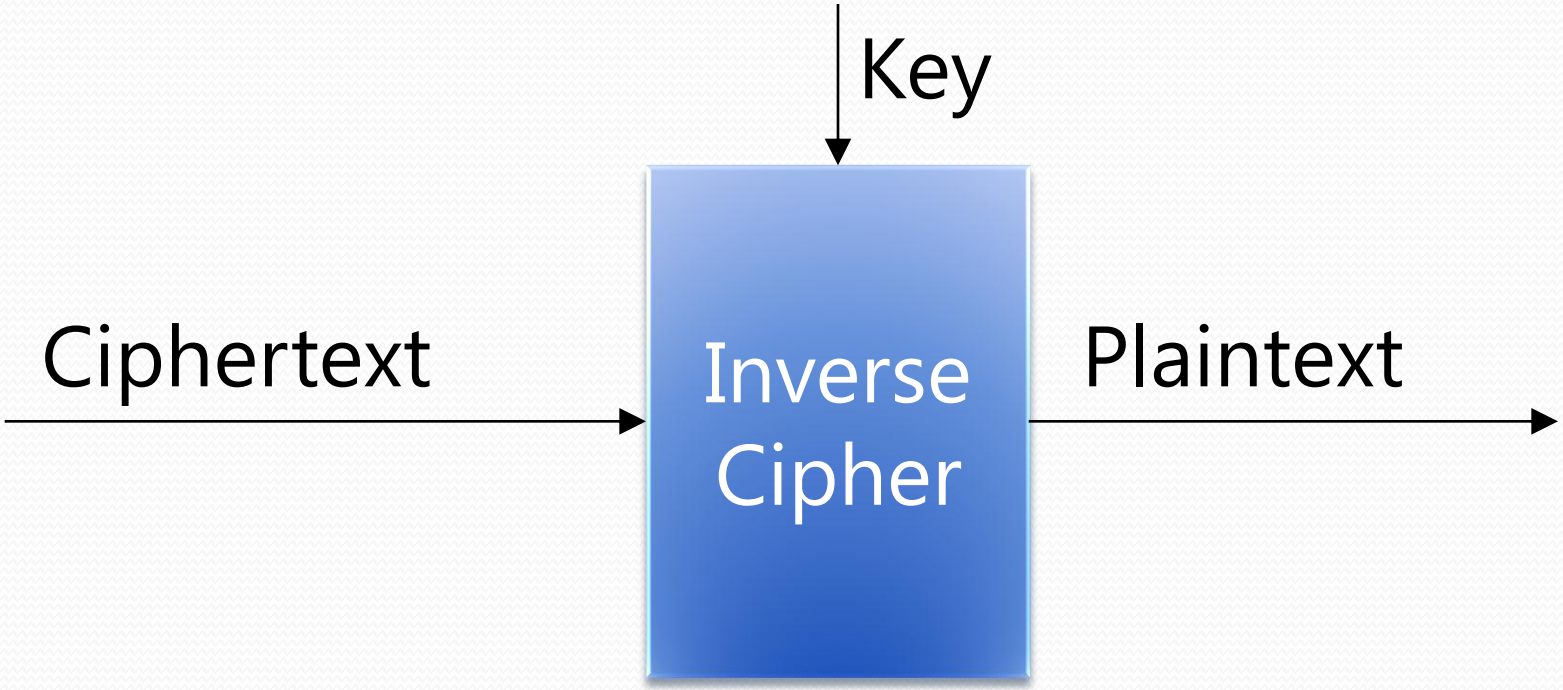
  - This is called the “block size” and is a fundamental parameter of the cipher.
  - Today 8- or 16-byte blocks are common, but other sizes are possible.
- Question: What’s the “block size” of a stream cipher?

Block Ciphers -- Encryption



Block Ciphers -- Decryption



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- Simple A: Divide the to-be-encrypted plaintext into block-size chunks, and then apply the cipher to each block.

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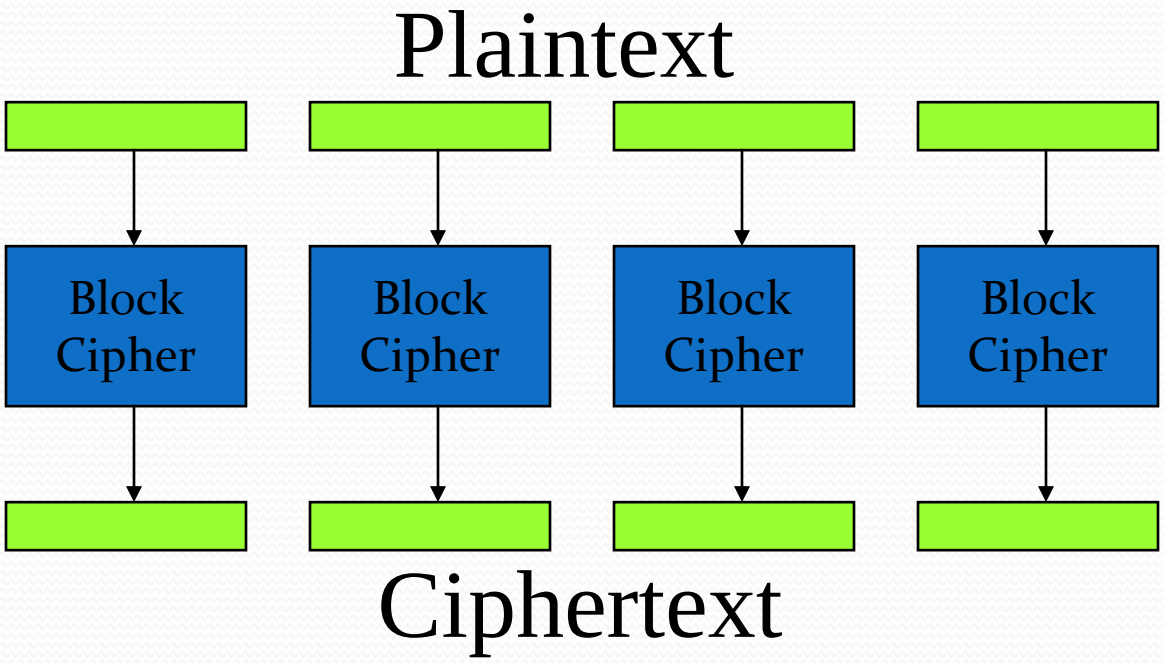
- Simple A: Divide the to-be-encrypted plaintext into block-size chunks, and then apply the cipher to each block.
- Real A: Divide the to-be-encrypted plaintext into block-size chunks, and then apply the cipher to the sequence of blocks using a *mode of operation*.

Block Cipher Modes

Electronic Code Book (ECB) Encryption:



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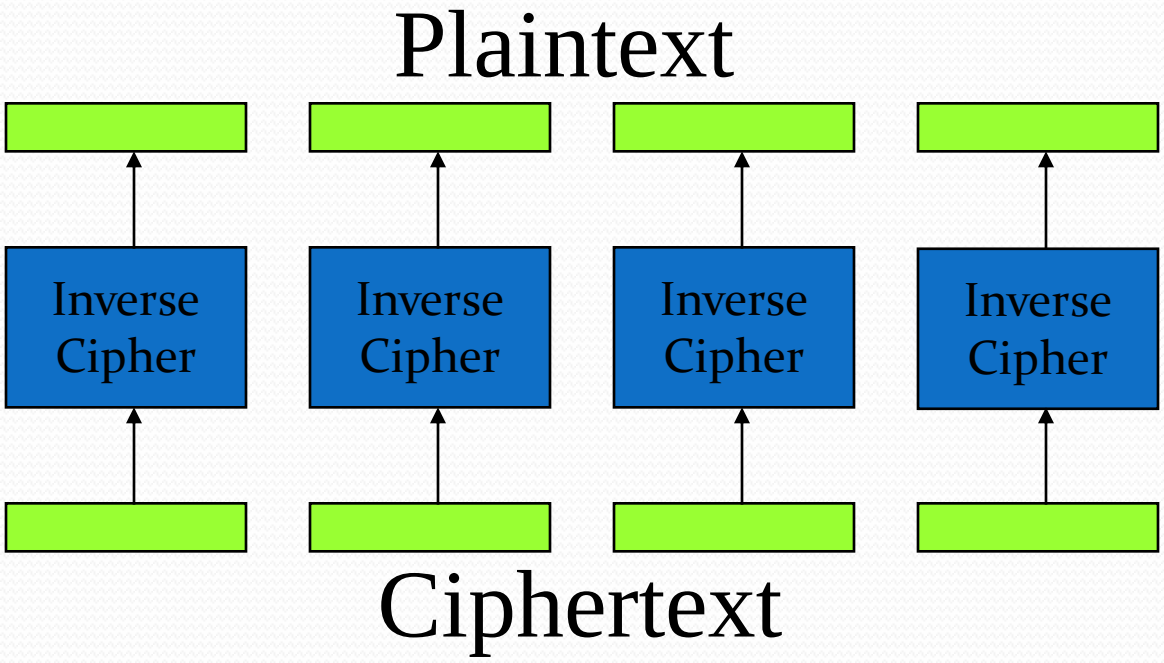
Electronic Code Book (ECB) Decryption:



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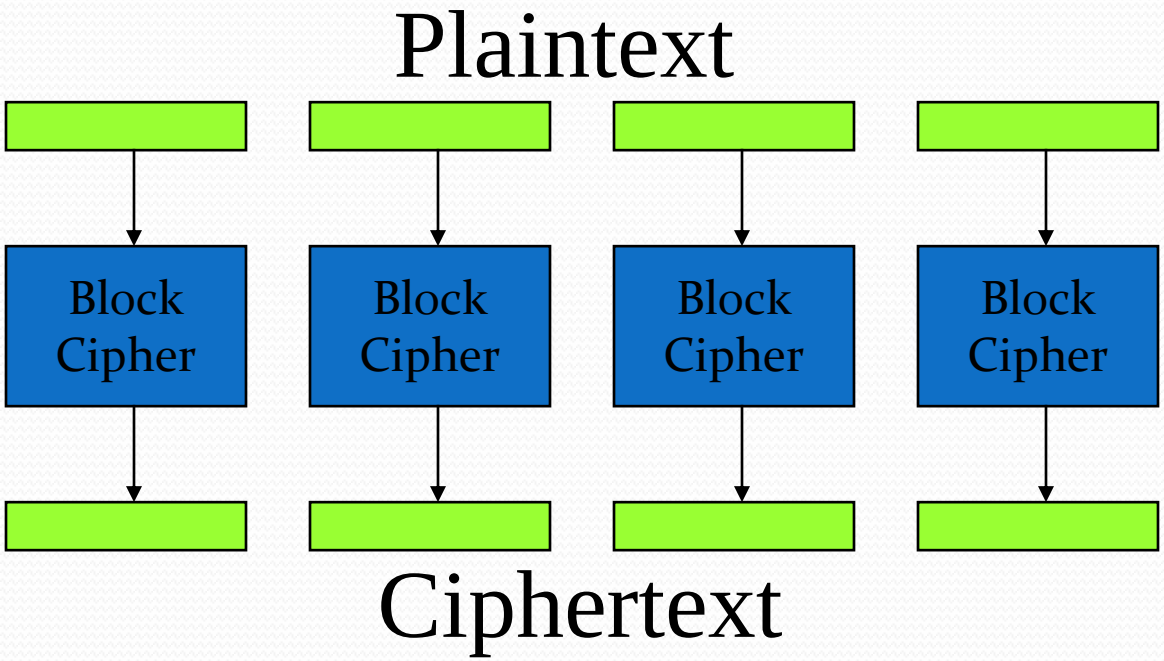

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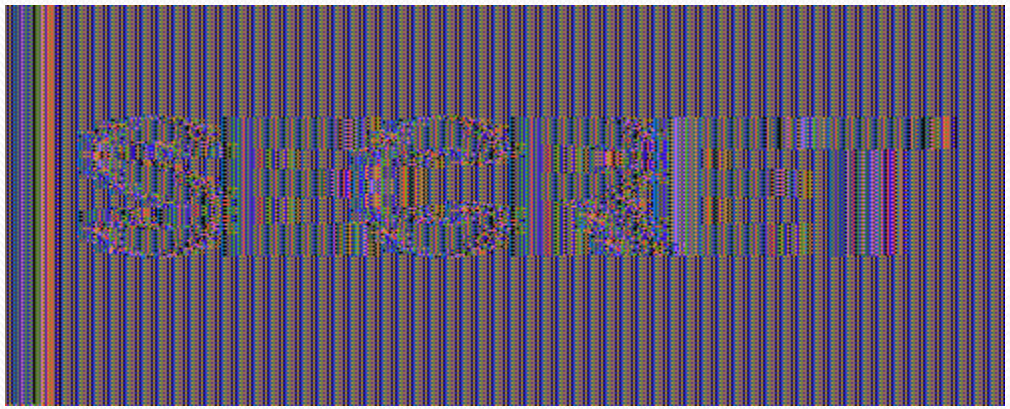
ECB



Block Cipher Modes

Cipher Block Chaining (CBC) Encryption:

Incorporate an *Initial Value (IV)* which changes with each encryption.

The IV can be

- A counter
- A random value
- Openly known

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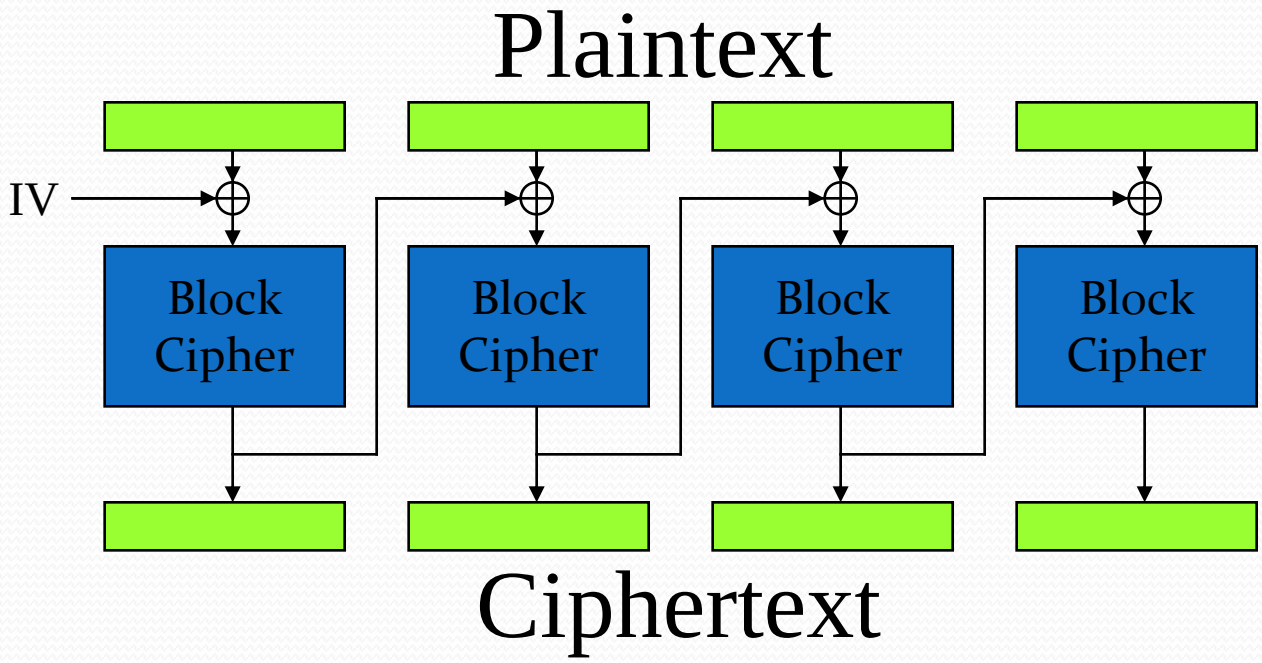

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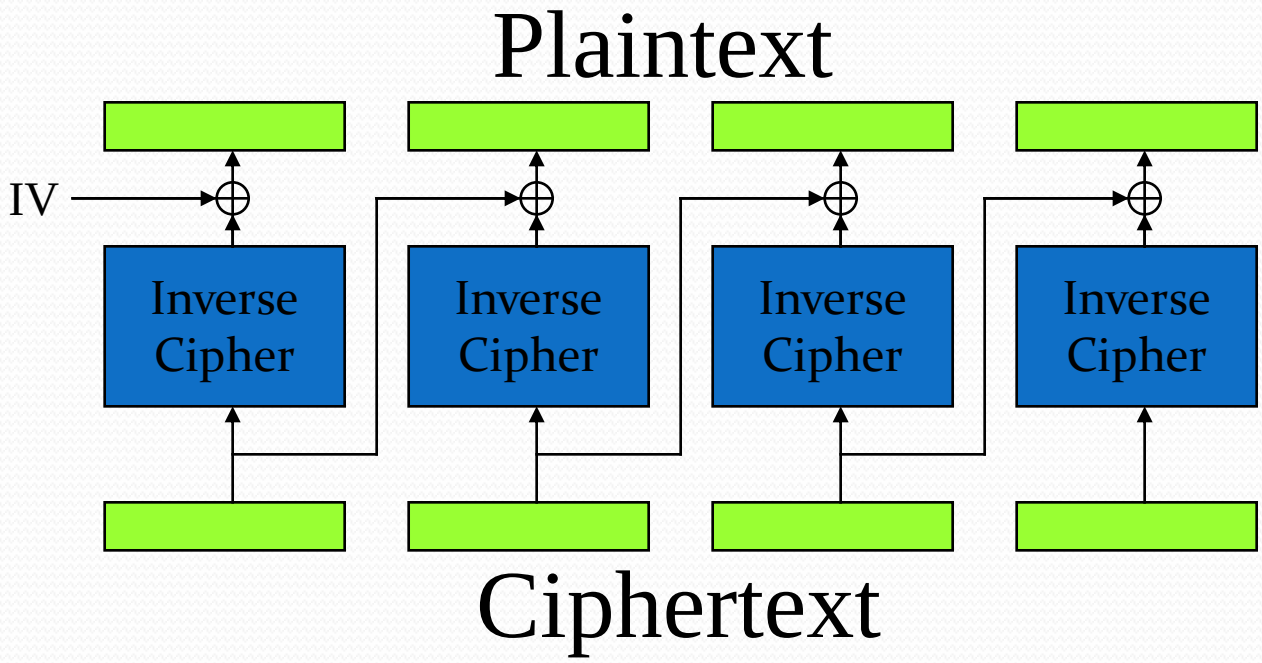

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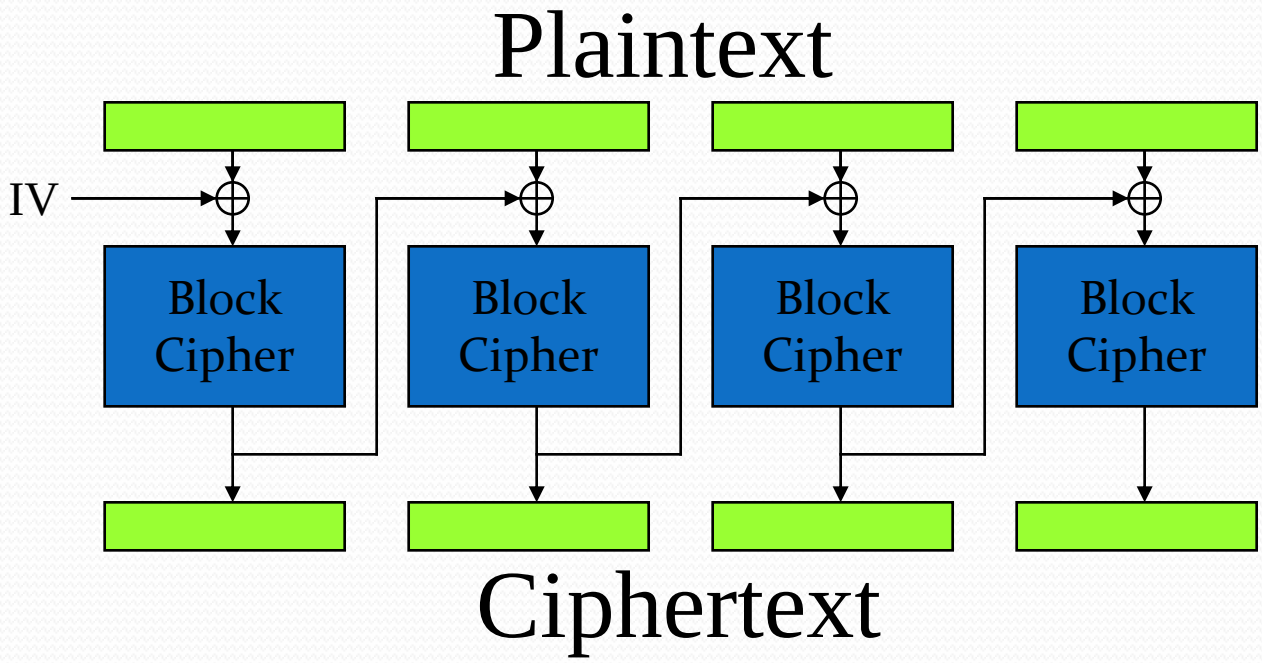

Example Block Ciphers

- DES
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- RC2, RC5, TwoFish, Serpent, etc.

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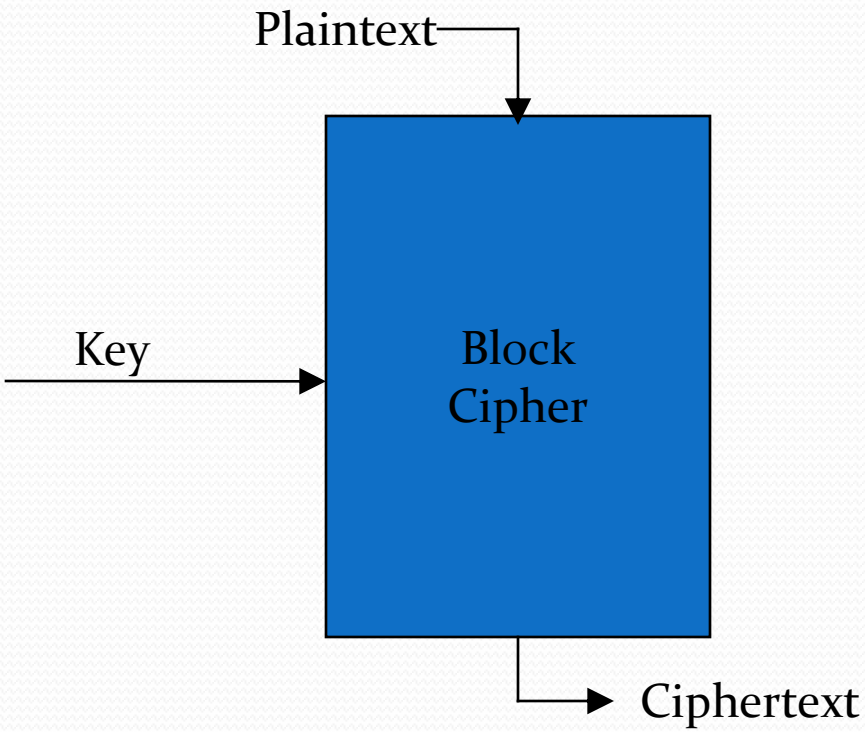
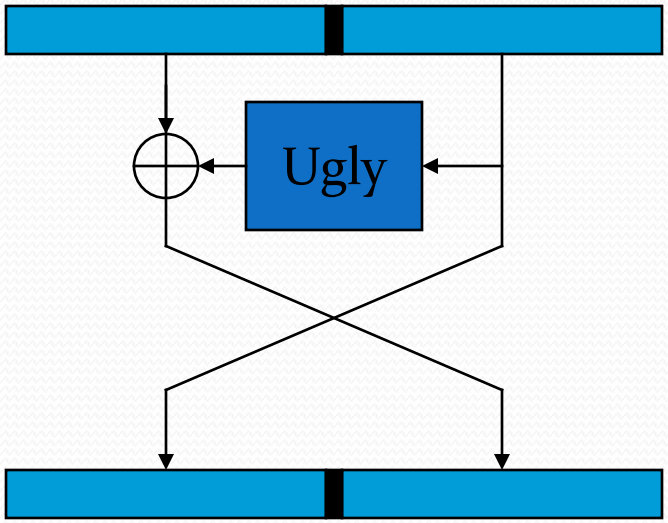
How to Build a Block Cipher



Feistel Ciphers



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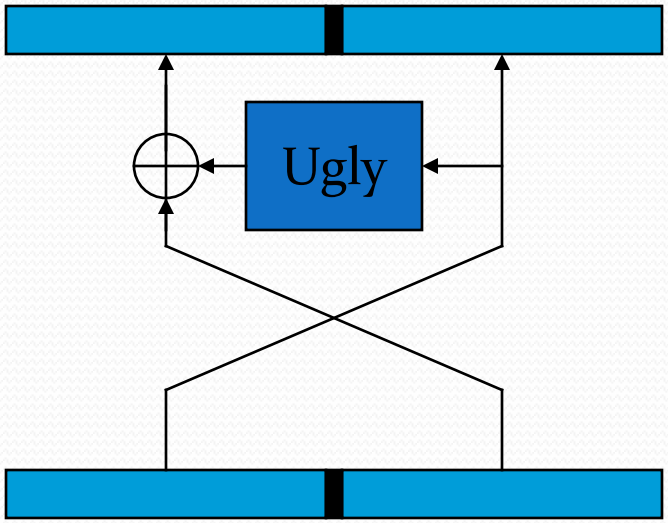

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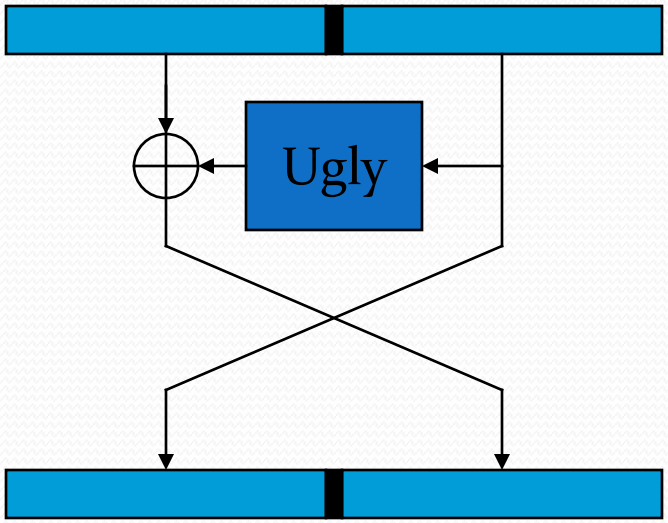

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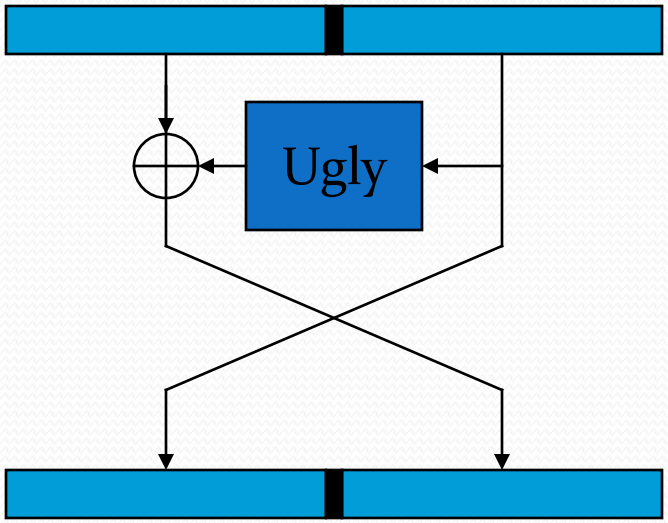

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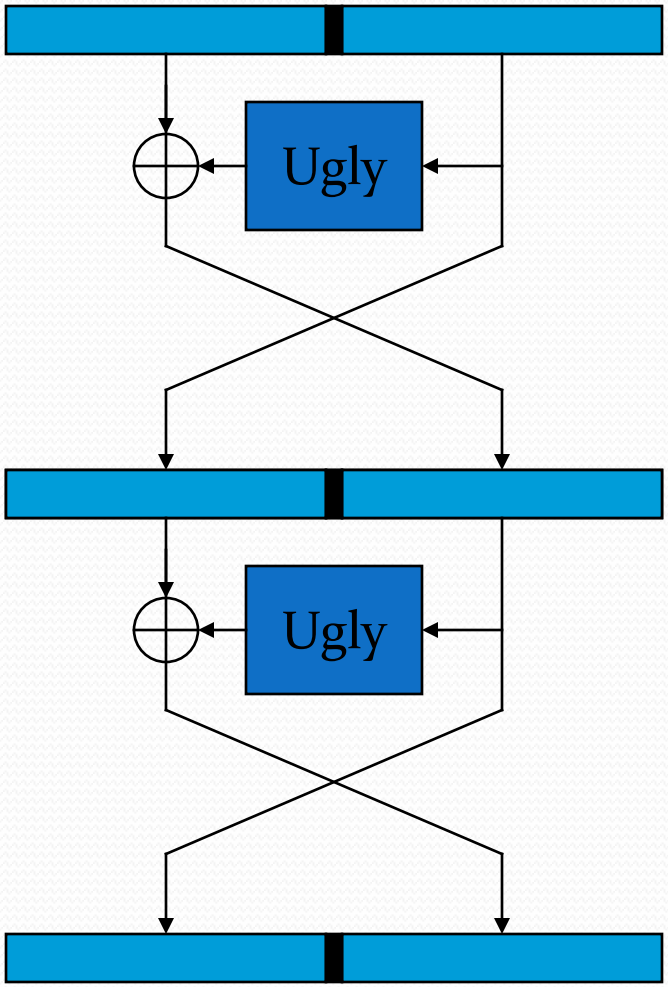
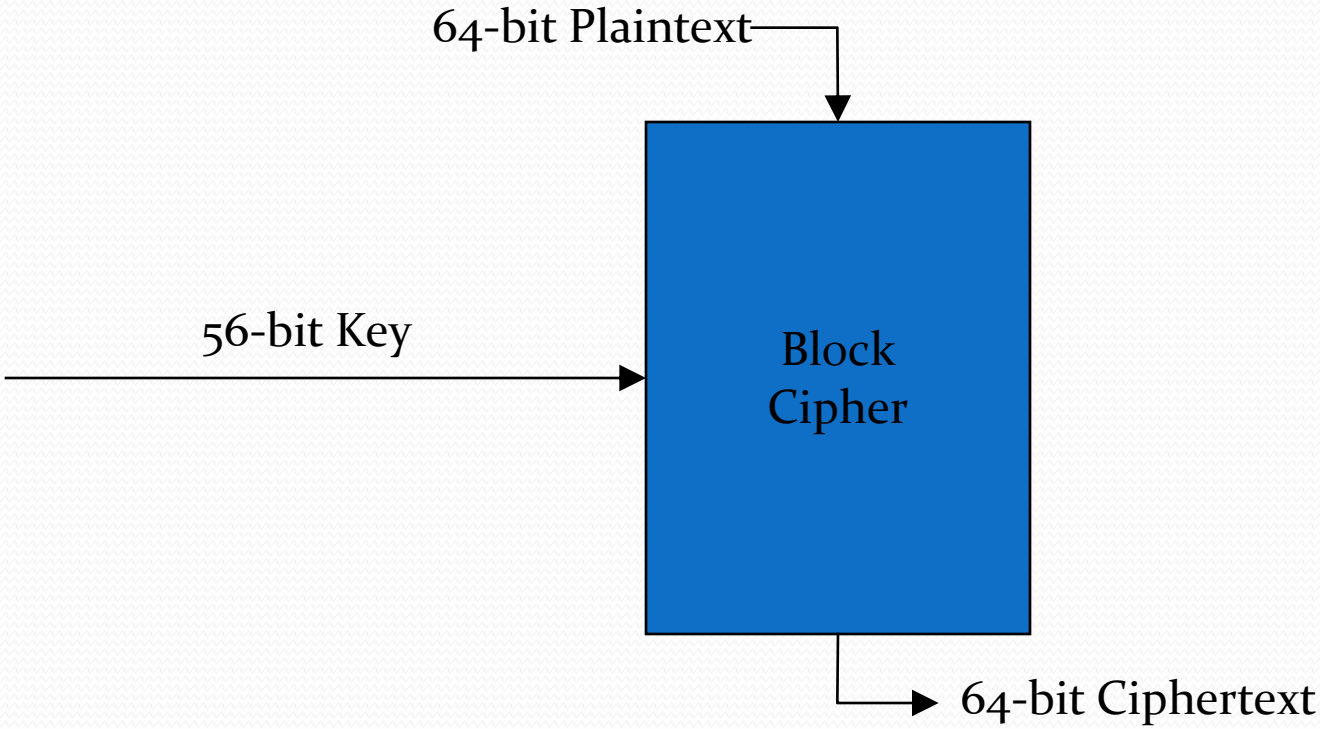


Feistel Ciphers

- Typically, most Feistel ciphers are iterated for about 16 rounds.
- Different “sub-keys” are used for each round.

- Even a weak round function can yield a strong Feistel cipher if iterated sufficiently.

Data Encryption Standard (DES)



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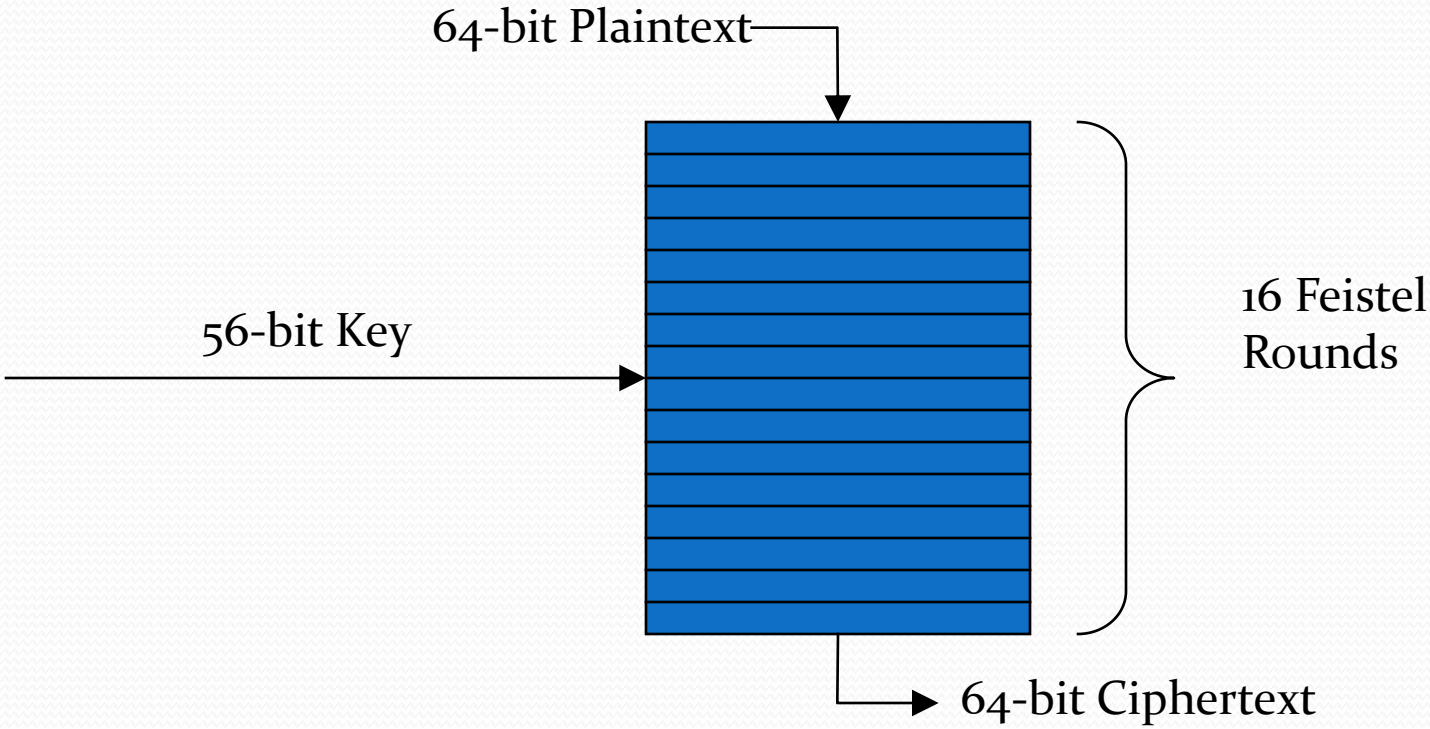

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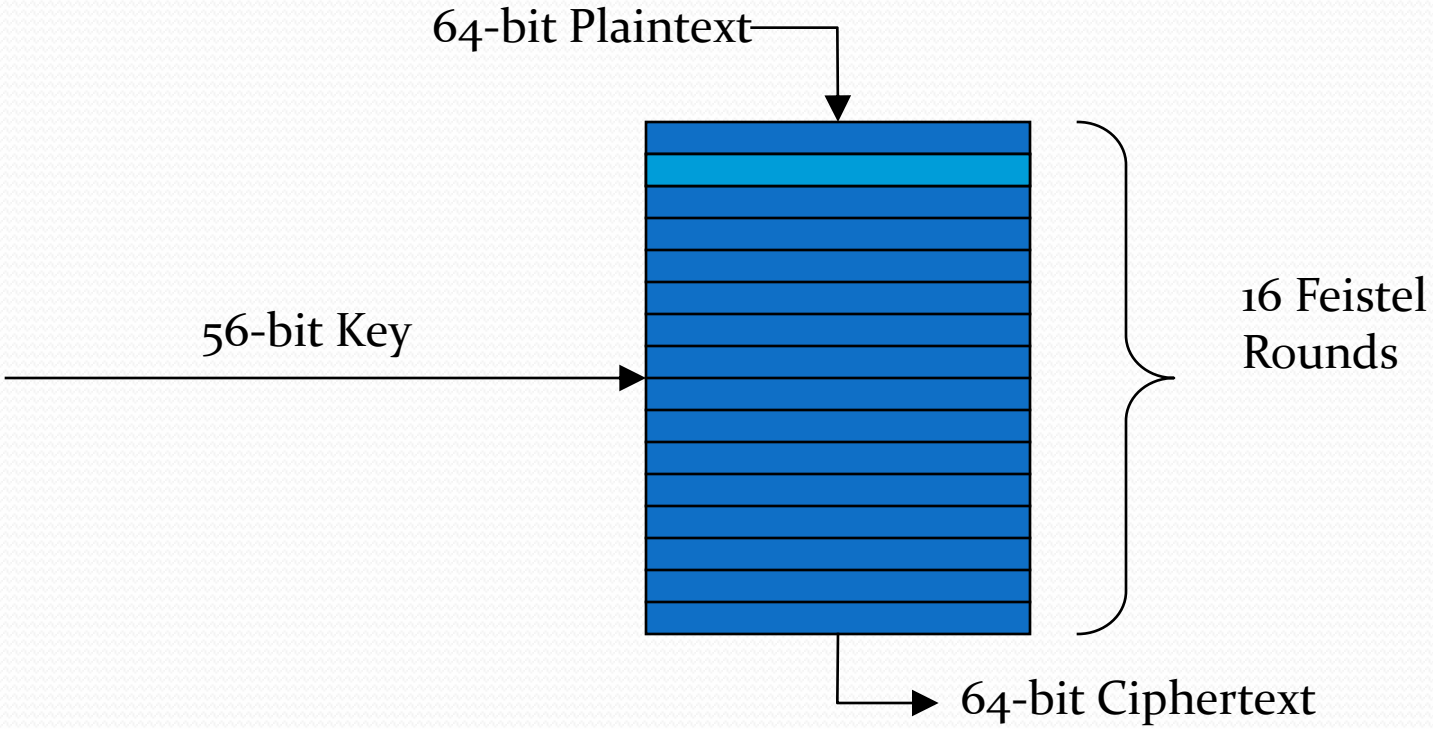
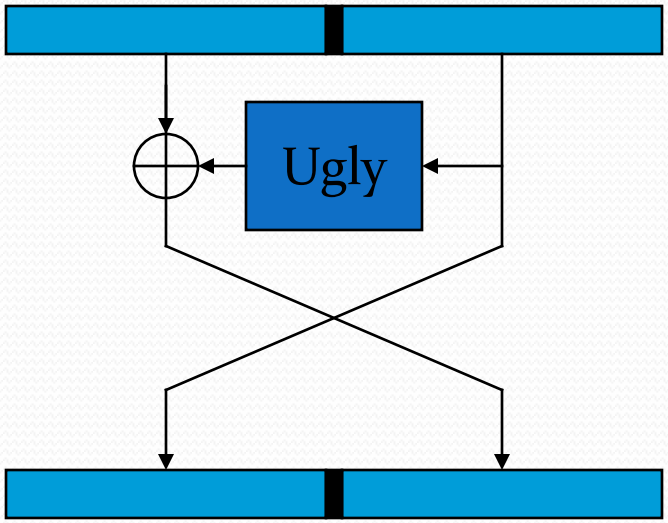
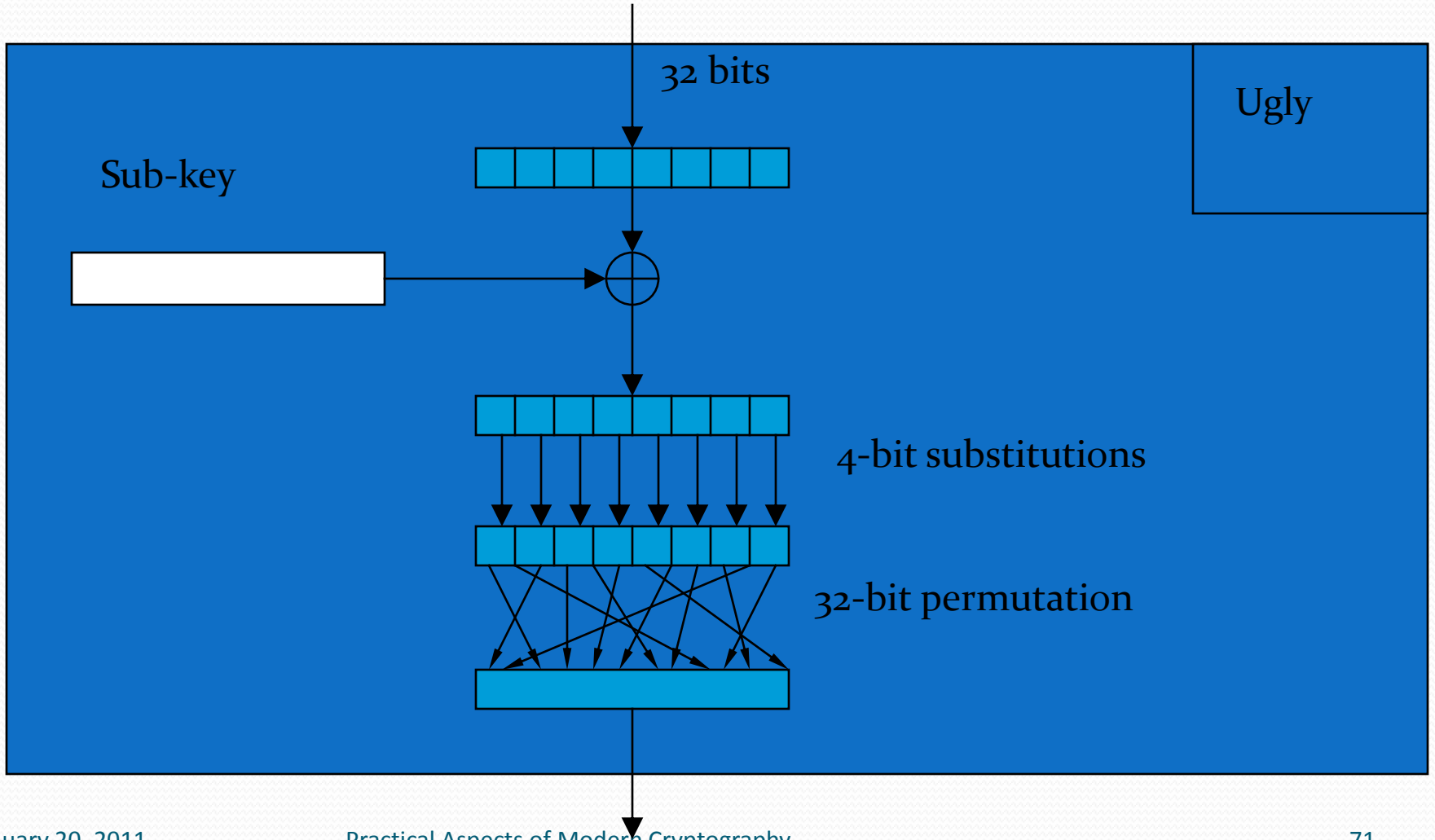


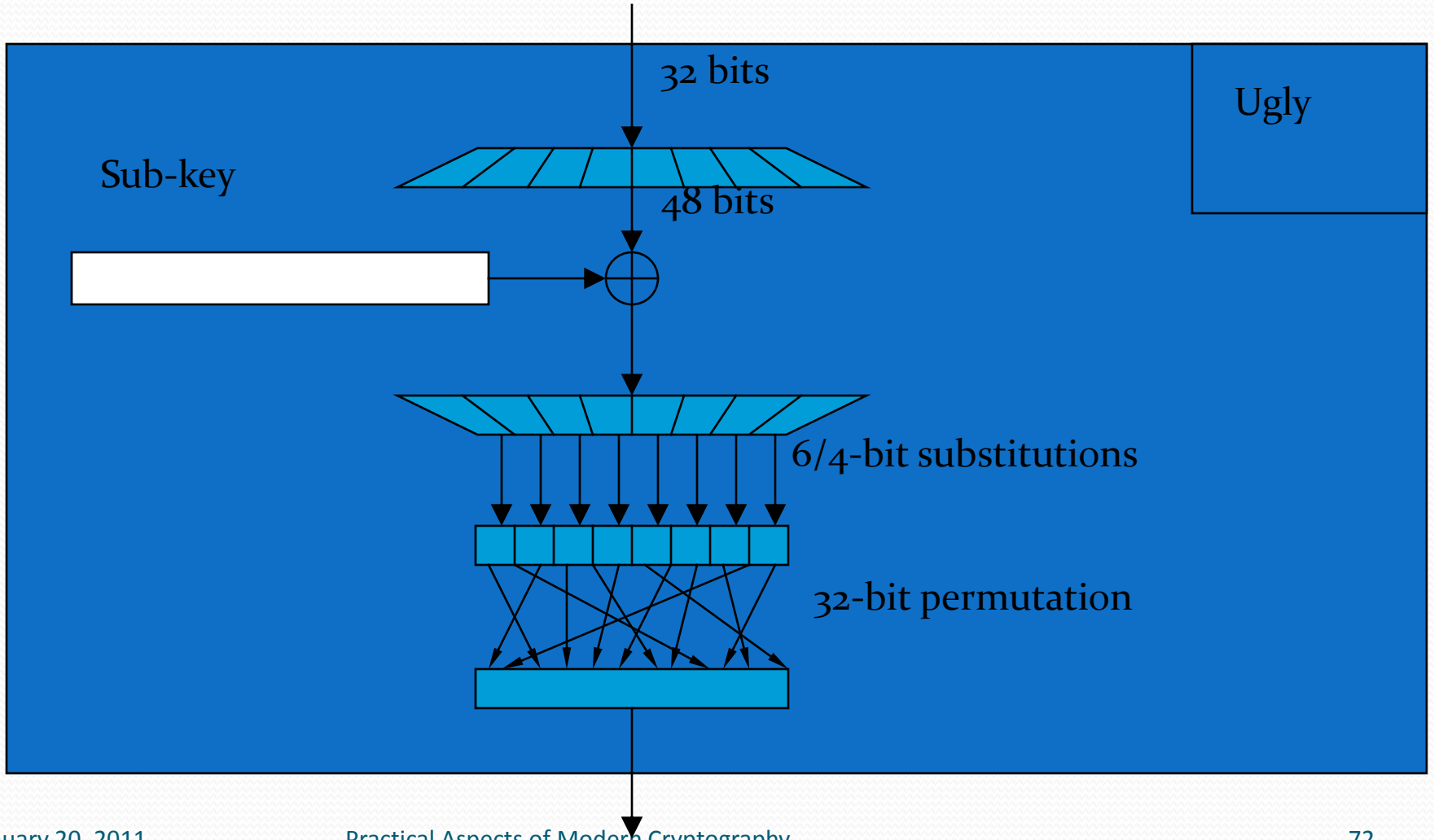
DES Round



Simplified DES Round Function



Actual DES Round Function



Advanced Encryption Standard

- Open competition run by NIST to replace DES
- 128-bit block size
- Key sizes of 128, 192, and 256 bits

- 15 ciphers were submitted
- 5 finalists were chosen

AES Finalists

- MARS (IBM submission)
- RC6 (RSA Labs submission)
- Rijndael (Joan Daemen and Vincent Rijmen)
- Serpent (Anderson, Biham, and Knudsen)
- Twofish (Schneier, et. al.)

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Rijndael

$k_{0,0}$	$k_{0,1}$	$k_{0,2}$	$k_{0,3}$	$k_{0,4}$	$k_{0,5}$	$k_{0,6}$	$k_{0,7}$
$k_{1,0}$	$k_{1,1}$	$k_{1,2}$	$k_{1,3}$	$k_{1,4}$	$k_{1,5}$	$k_{1,6}$	$k_{1,7}$
$k_{2,0}$	$k_{2,1}$	$k_{2,2}$	$k_{2,3}$	$k_{2,4}$	$k_{2,5}$	$k_{2,6}$	$k_{2,7}$
$k_{3,0}$	$k_{3,1}$	$k_{3,2}$	$k_{3,3}$	$k_{3,4}$	$k_{3,5}$	$k_{3,6}$	$k_{3,7}$

16, 24, or 32 bytes of key

16, 24, or 32 bytes of data

$a_{0,0}$	$a_{0,1}$	$a_{0,2}$	$a_{0,3}$	$a_{0,4}$	$a_{0,5}$	$a_{0,6}$	$a_{0,7}$
$a_{1,0}$	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{1,4}$	$a_{1,5}$	$a_{1,6}$	$a_{1,7}$
$a_{2,0}$	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$	$a_{2,4}$	$a_{2,5}$	$a_{2,6}$	$a_{2,7}$
$a_{3,0}$	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$	$a_{3,4}$	$a_{3,5}$	$a_{3,6}$	$a_{3,7}$

Rijndael

4 transformations per round

- ByteSub: nonlinearity
- ShiftRow: inter-column diffusion
- MixColumn: inter-byte diffusion
- Round key addition

Rijndael ByteSub

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

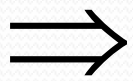
$\Rightarrow$

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

A single 8-bit to 8-bit (invertible) S-box is applied to each byte.

Rijndael MixColumn

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



$b_{0,0}$	$b_{0,1}$	$b_{0,2}$	$b_{0,3}$
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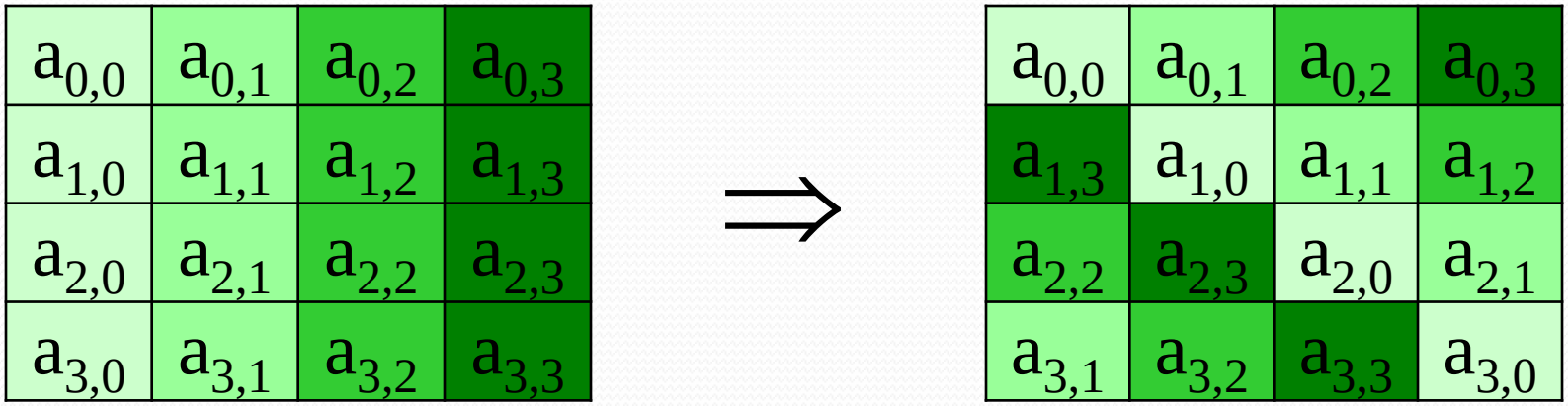
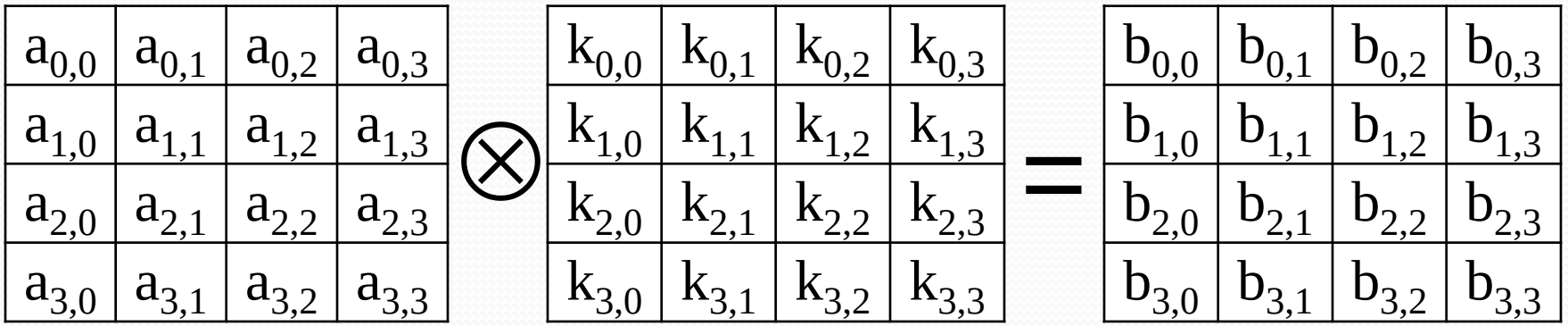
An (invertible) linear transform is applied to each column.

Rijndael ShiftRow



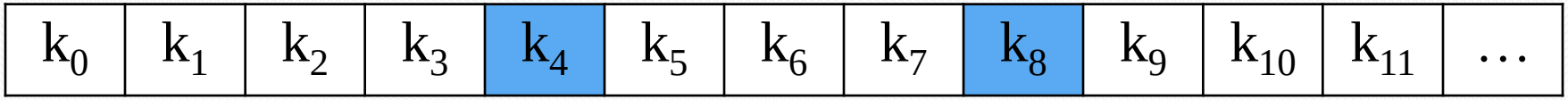
A different cyclic shift is applied to each row.

Rijndael Round key addition



The round key is XORed to complete the round.

Rijndael Key Schedule



The key schedule is defined on 4-byte words by

- $k_i = k_{i-4} \otimes k_{i-1}$ when i is not a multiple of 4
- $k_i = k_{i-4} \otimes f(k_{i-1})$ when i is a multiple of 4

Agenda

- Symmetric key ciphers
  - Stream ciphers
  - Block ciphers
- Cryptographic hash functions

One-Way Hash Functions

Generally, a *one-way hash function* is a function $H : \{0,1\}^* \rightarrow \{0,1\}^k$ such that given an input value x, one cannot find a value $x' \neq x$ such $H(x) = H(x')$.

One-Way Hash Functions

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- Typically k is 128, 160, 256, 384, or 512

One-Way Hash Functions

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- When forming a digital signature, the signature need only be applied to a hash of the message. [Message Digest]

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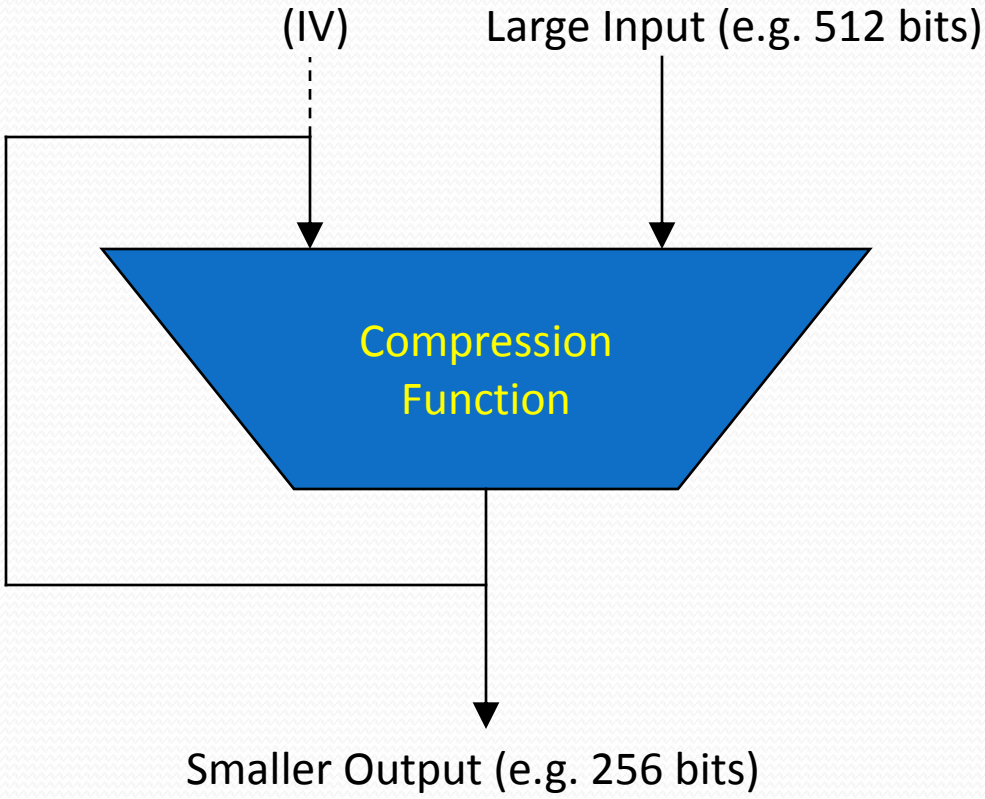
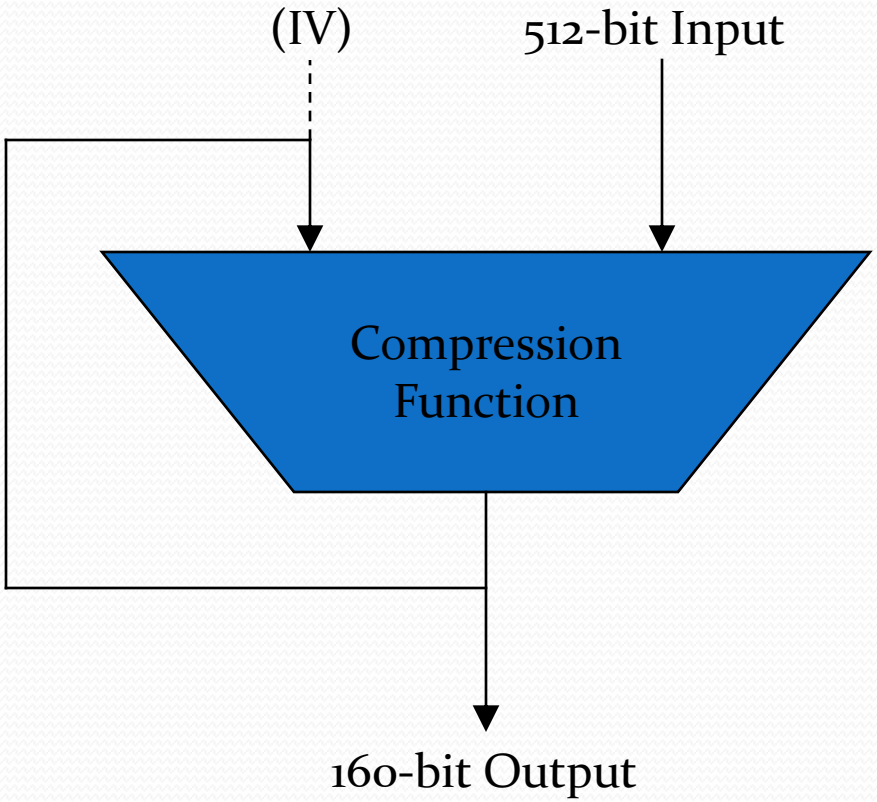
Merkle-Damgård Construction



A Cryptographic Hash: SHA-1



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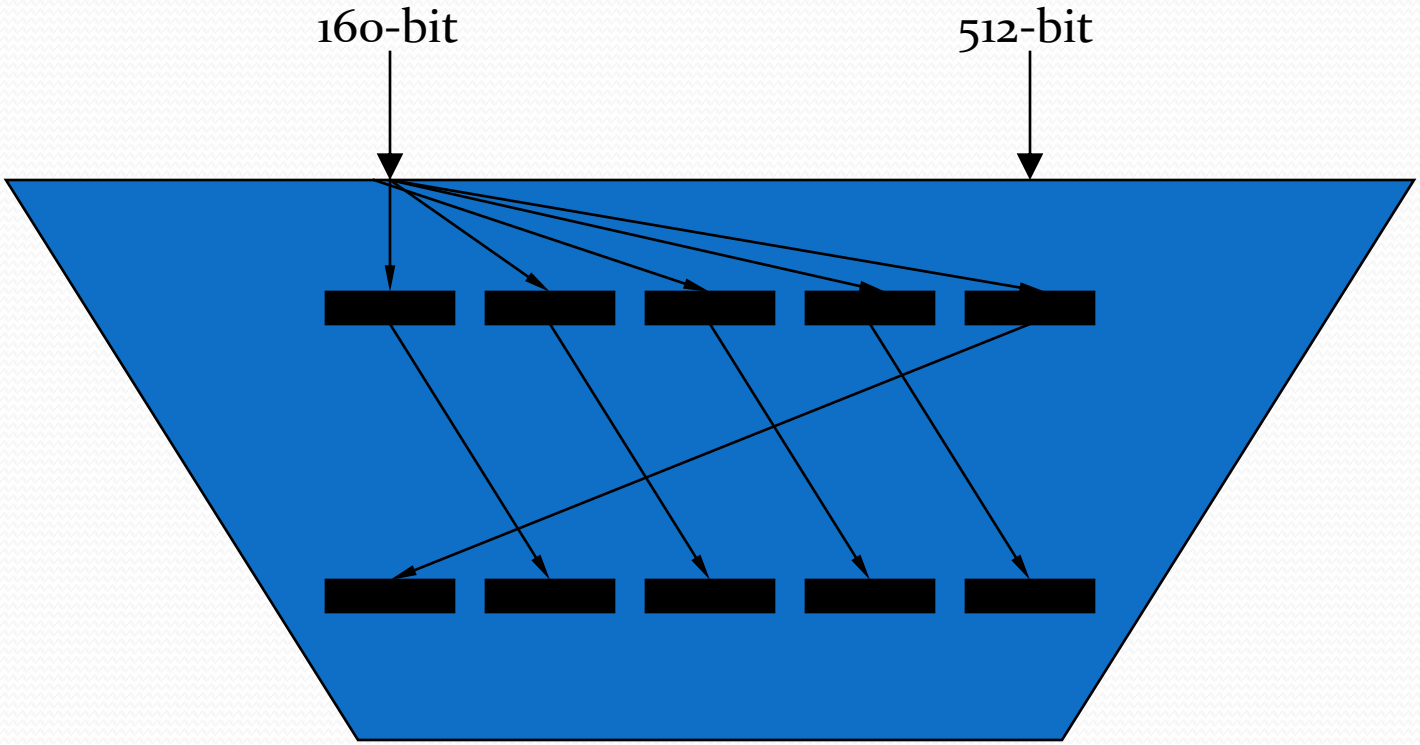

One of 80 rounds

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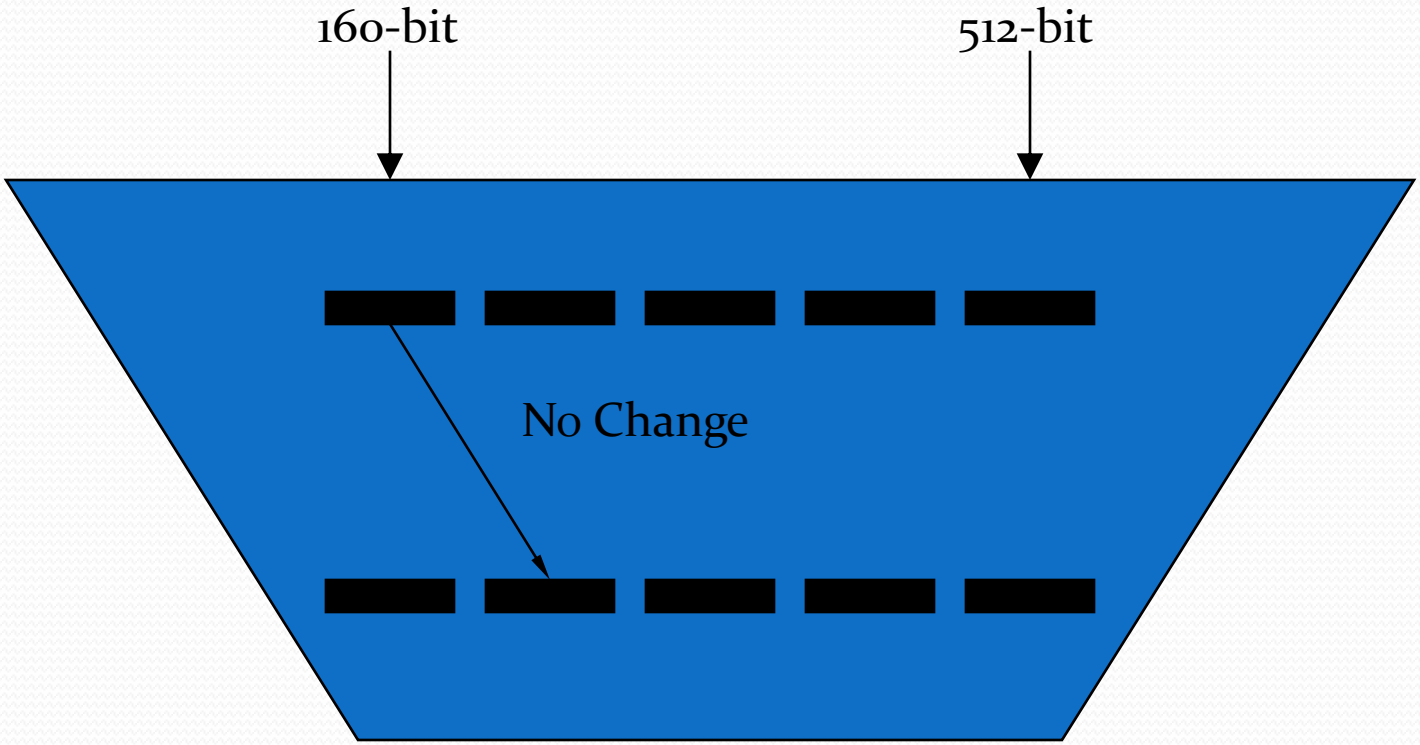

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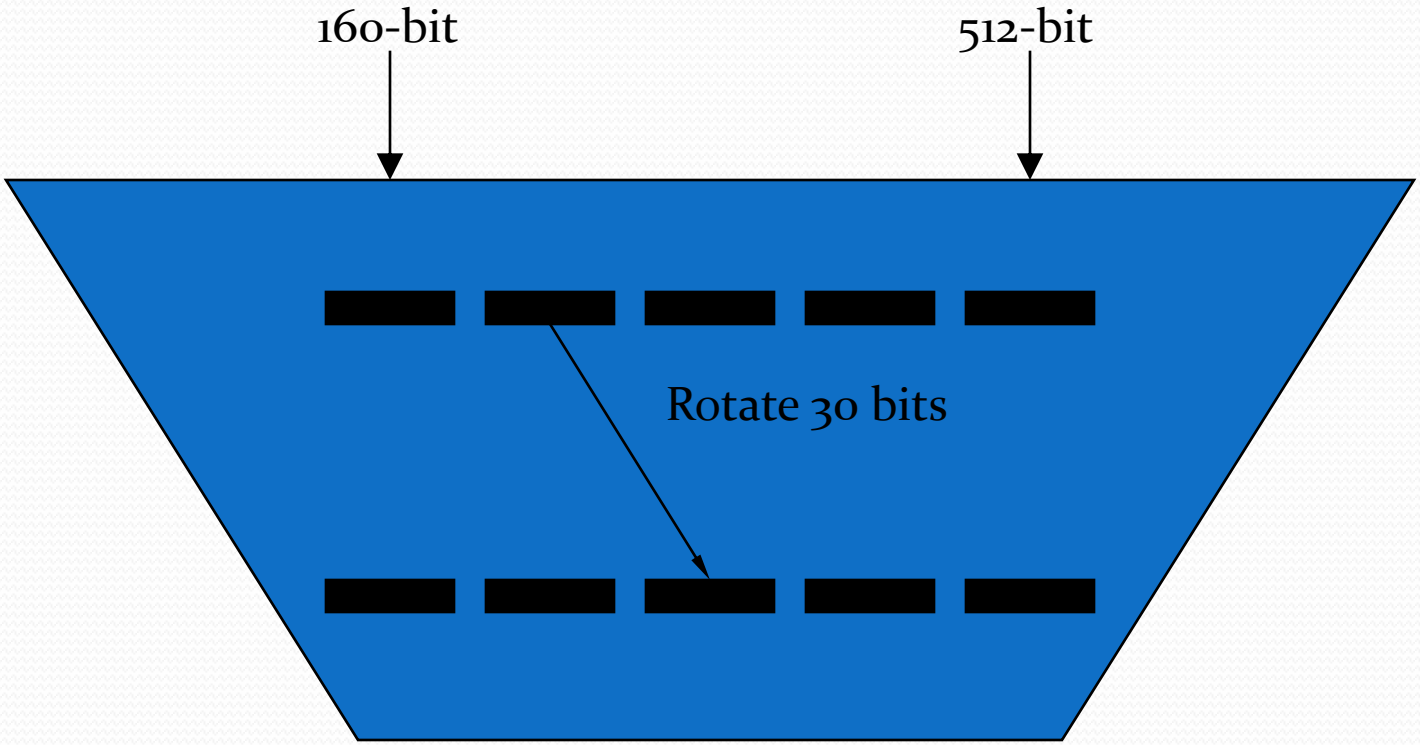

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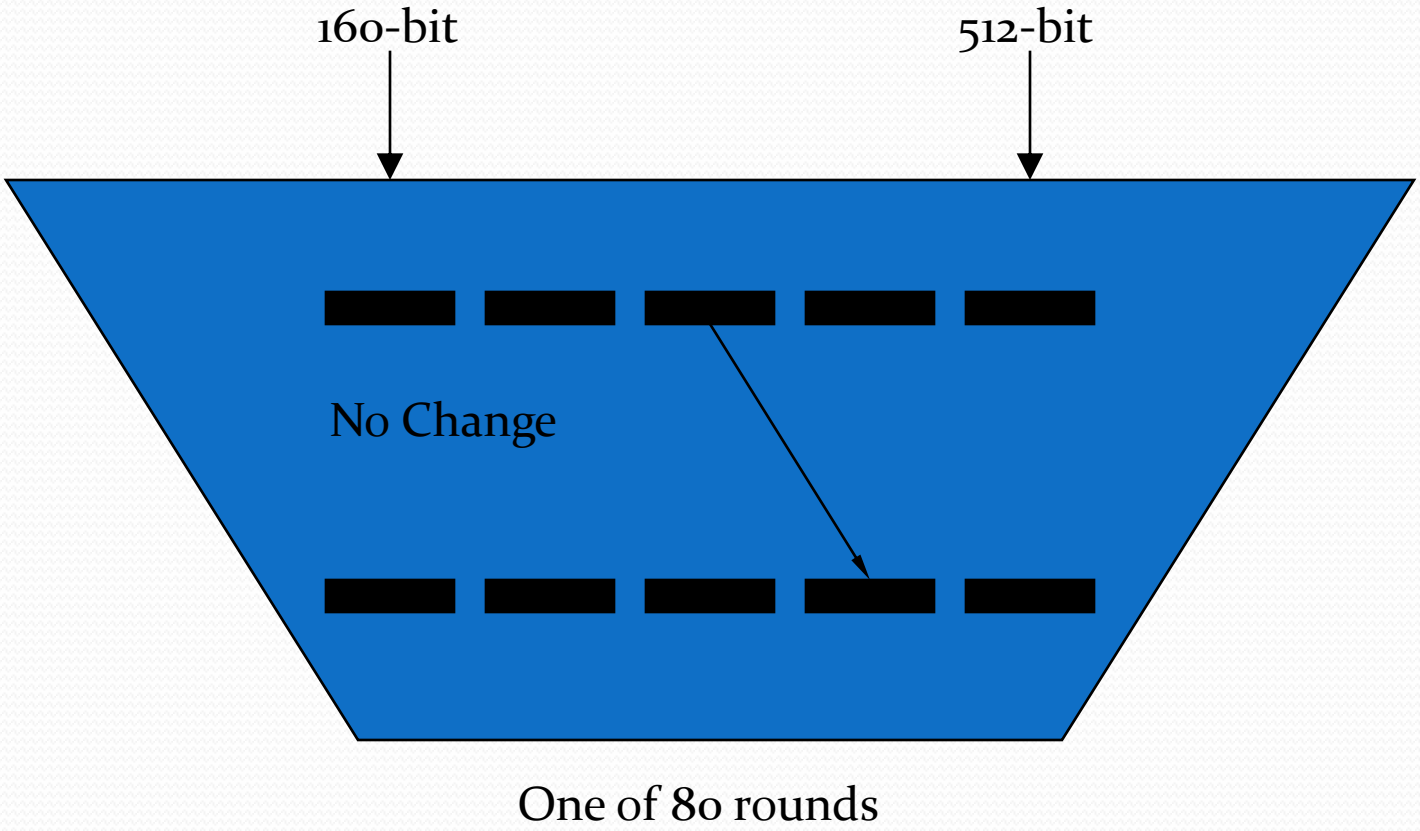

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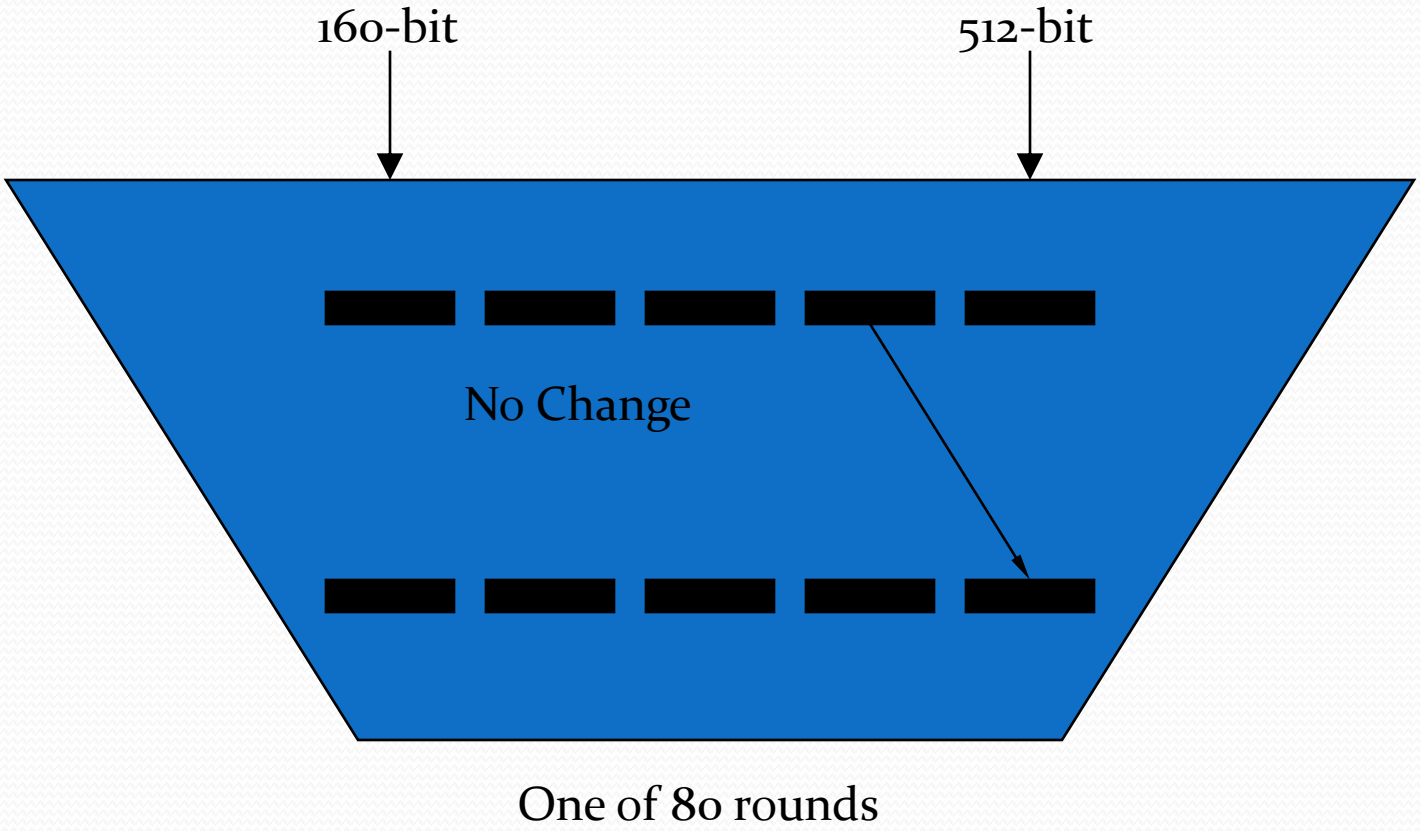

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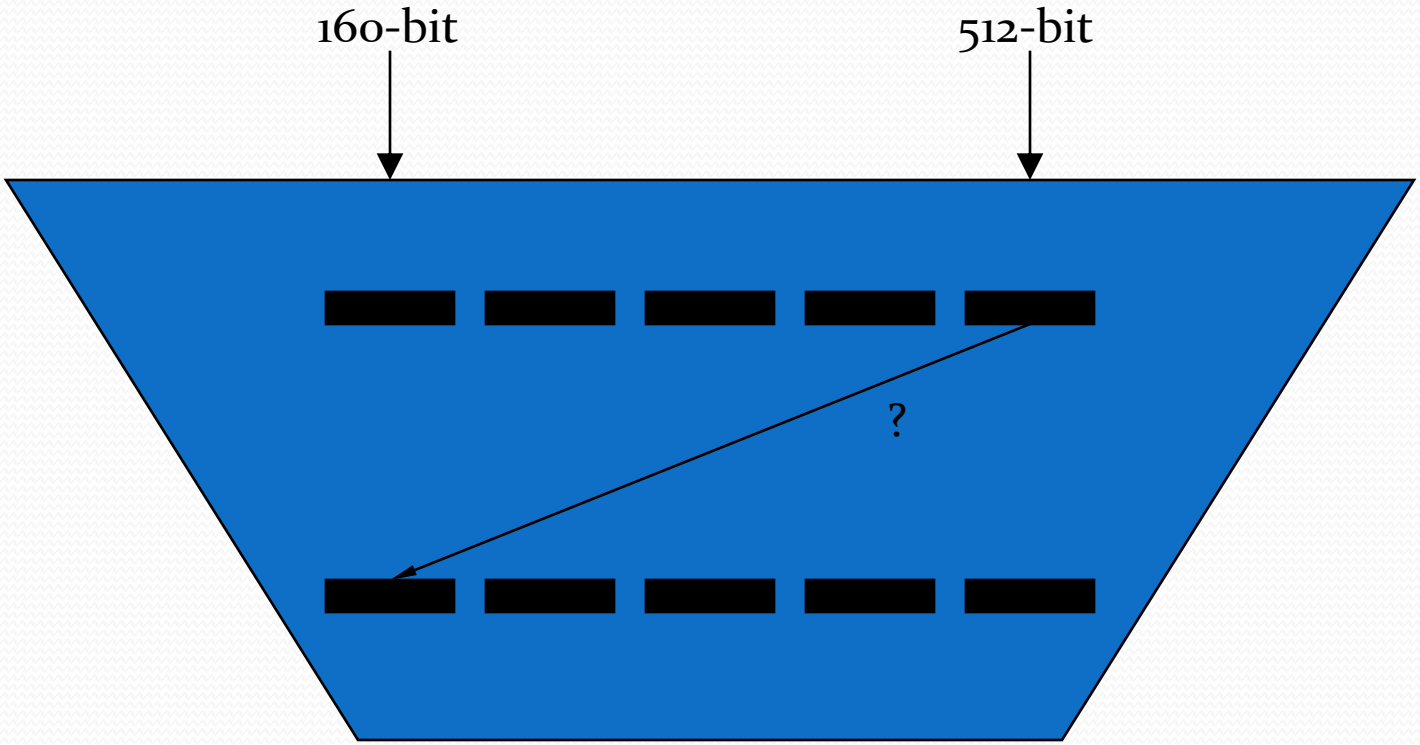

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- Take the rightmost word.

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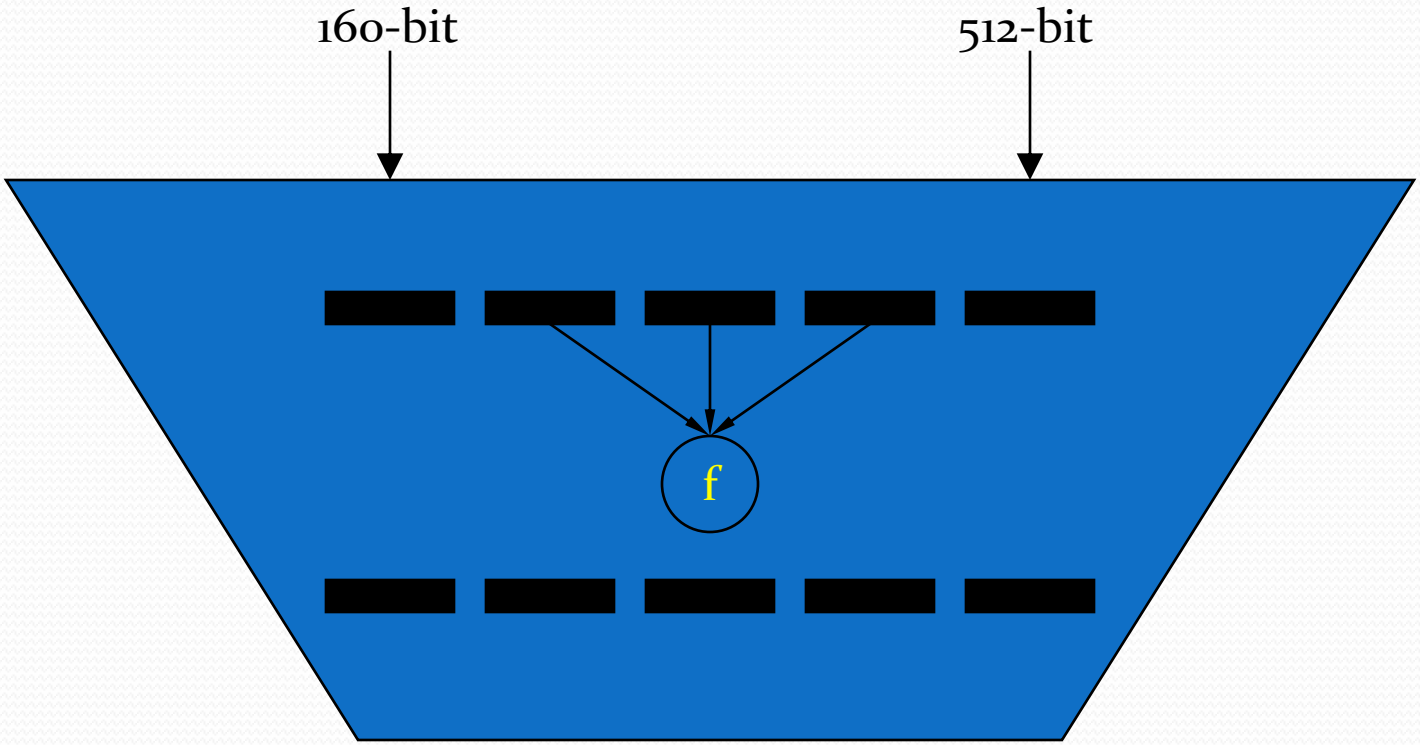

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A Cryptographic Hash: SHA-1

Depending on the round, the "non-linear" function f is one of the following.

$$f(X,Y,Z) = (X \wedge Y) \vee ((\neg X) \wedge Z)$$

$$f(X,Y,Z) = (X \wedge Y) \vee (X \wedge Z) \vee (Y \wedge Z)$$

$$f(X,Y,Z) = X \oplus Y \oplus Z$$

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- Add in a portion of the 512-bit message.

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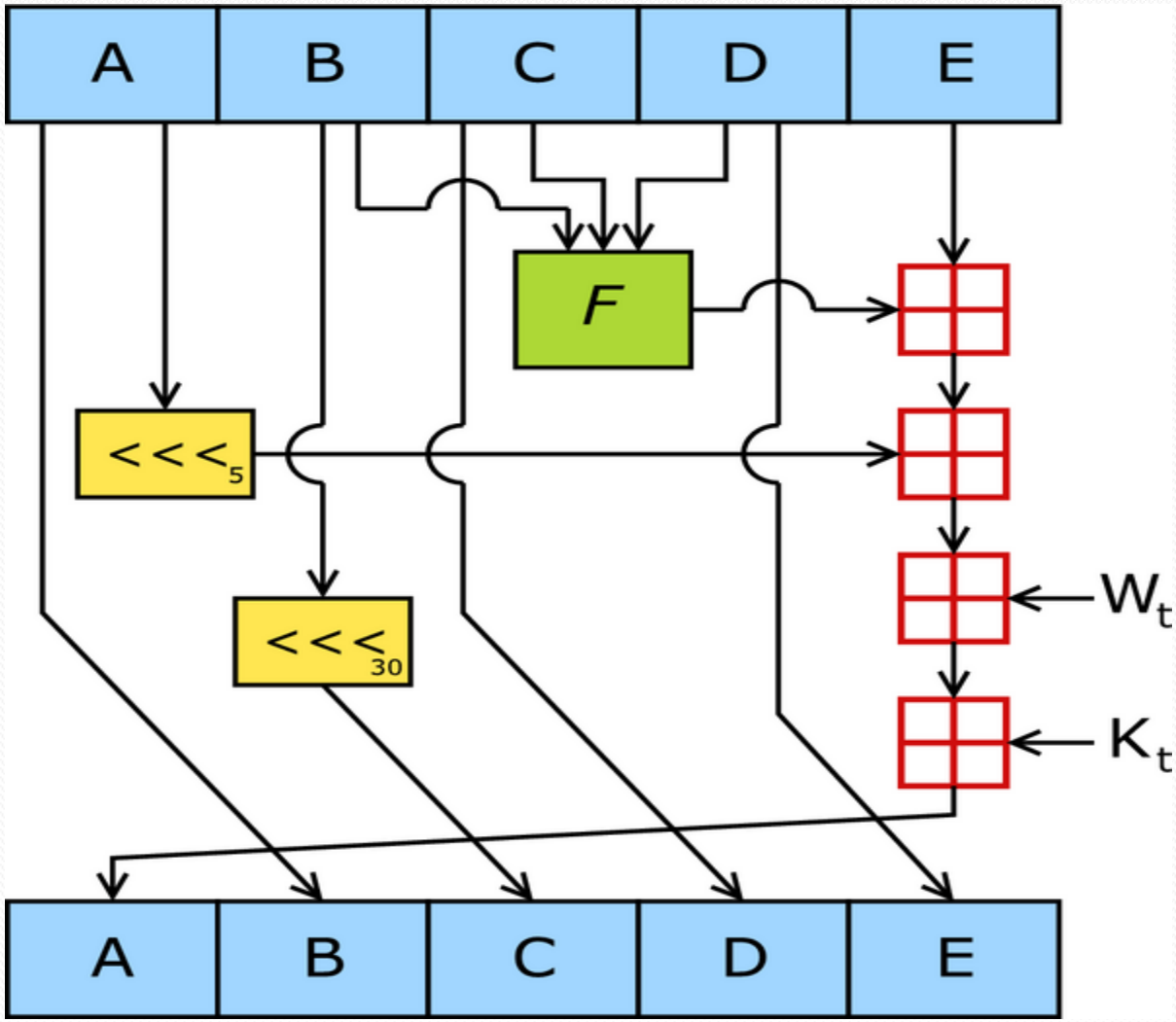

Picture from Wikipedia

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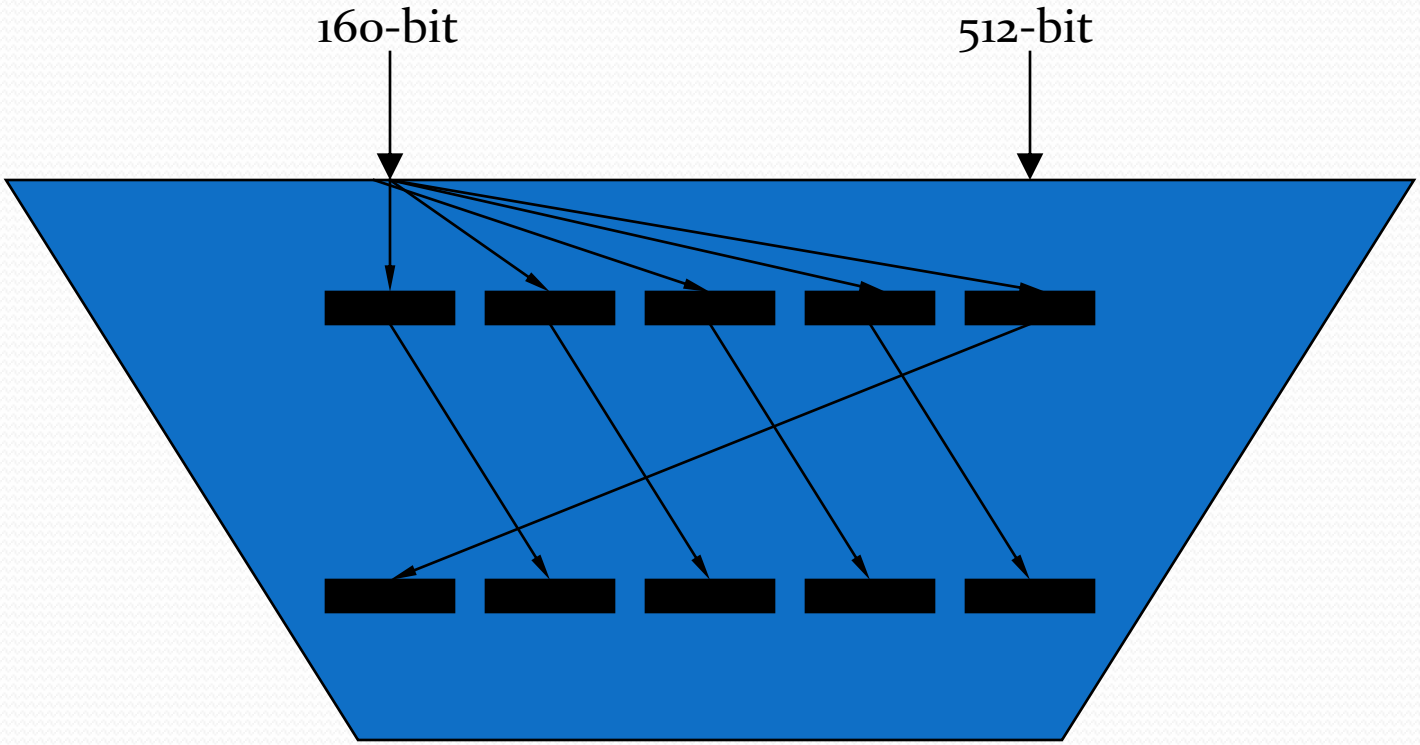

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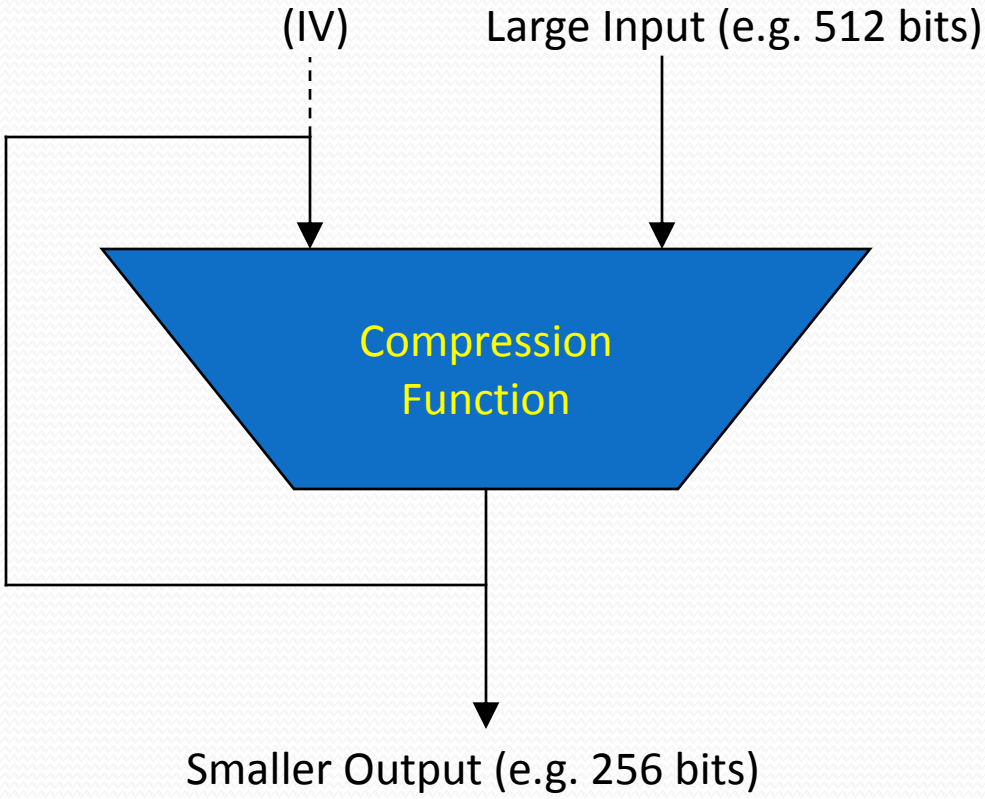

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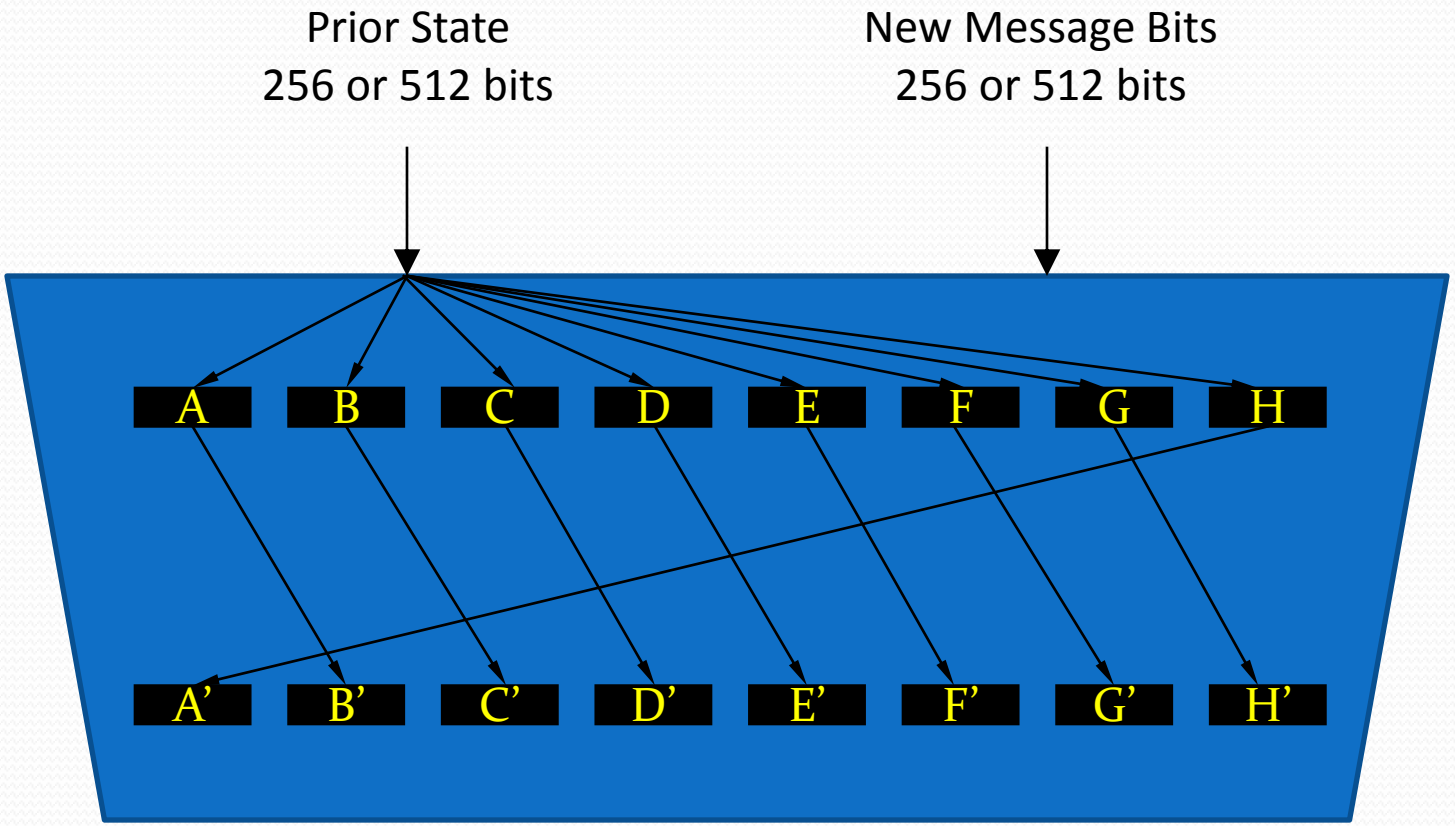

One of 64 rounds

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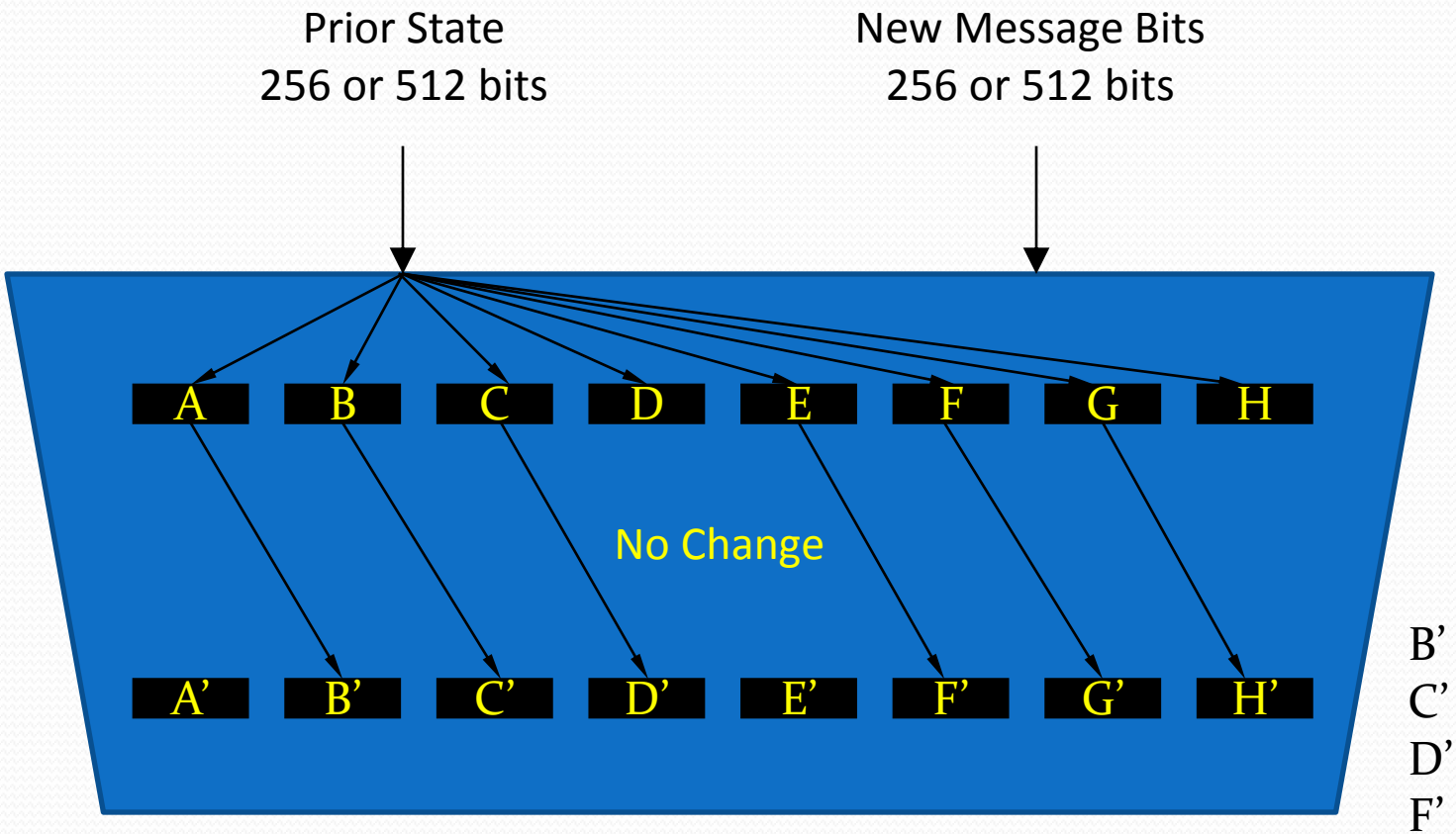

One of 64 rounds

B' = A
C' = B
D' = C
F' = E
G' = F
H' = G

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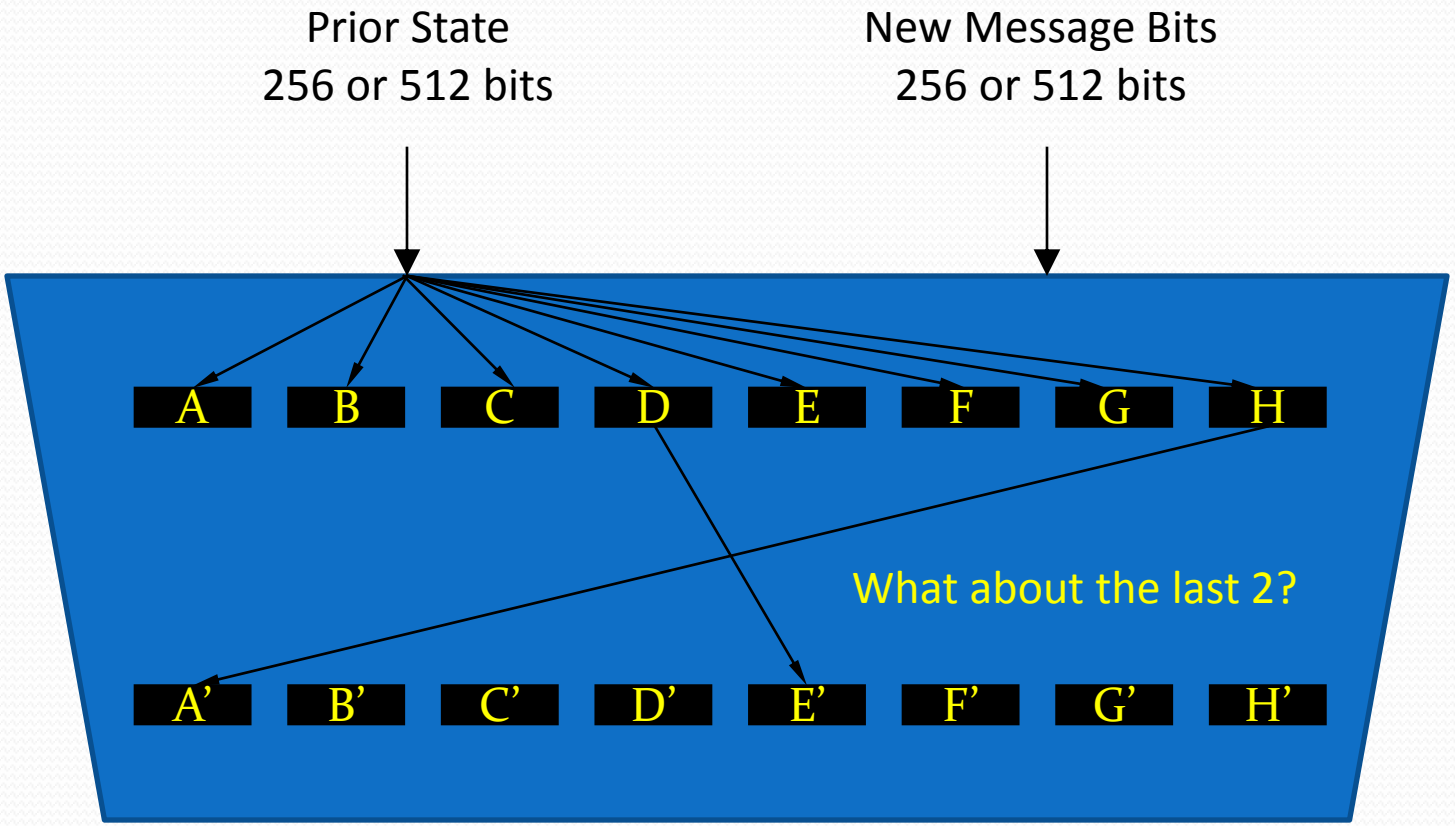

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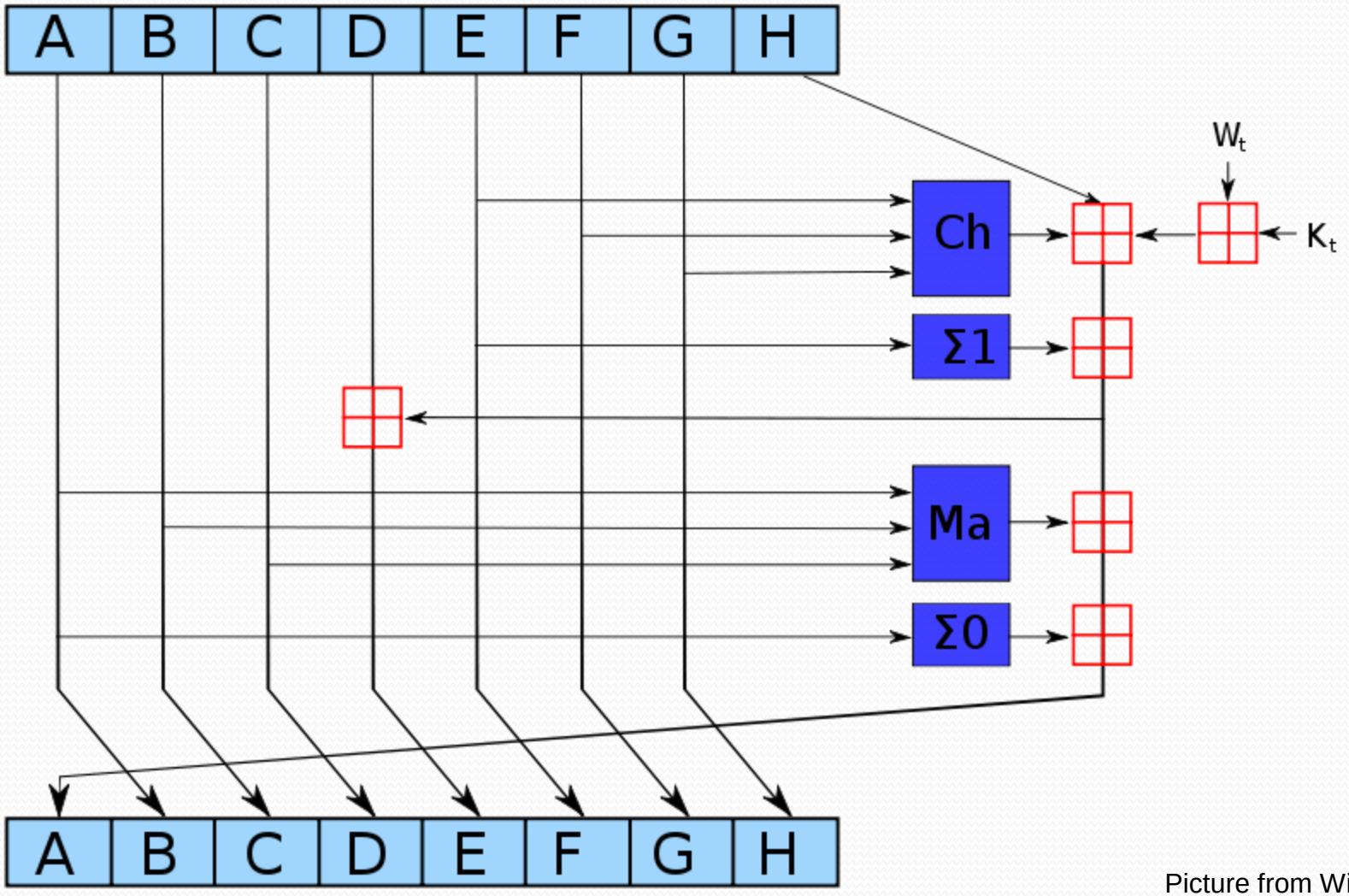

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- SHA-3 expected to be formally selected in 2012

The SHA-3 Finalists

- BLAKE
- Grøstl (Knudsen et al.)
- JH
- Keccak (Keccak team, Daemen et al.)
- Skein (Schneier et al.)

State of the Art for Hashes

- Collisions have been demonstrated for MD4 and MD5 !
- The first SHA-1 collisions are likely to be found soon.

Integrity Checking

- Desirable for block ciphers
- Essential for stream ciphers

One-Way Hash Functions

- The idea of a checksum is great, but it is designed to prevent accidental changes in a message.
- For cryptographic integrity, we need an integrity check that is resilient against a smart and determined adversary.

Message Authentication Codes

A *Message Authentication Code* (MAC) is often constructed with a *keyed hash*.

If one hashes a secret key together with the correct message, an attacker who doesn't know the key will be unable to change the message without detection.

But how?

Cipher Integrity

- Original plaintext P.
- Encryption key K_1.
- MAC key K_2.
- Ciphertext $C=E_{K_1}(P)$.
- MAC $M=H_{K_2}(P)$ or $M=H_{K_2}(C)$.
- Transmit (C,M).

Message Authentication Codes

MAC key K, plaintext P, ciphertext $C=E(P)$.

$MAC=H(K,P)$? $MAC=H(P,K)$?
$MAC=H(K,C)$? $MAC=H(C,K)$?

There are weaknesses with *all* of the above.

$HMAC = H(K,H(K,P))$

Crypto Hygiene

Do I really need to use different keys for encryption and integrity?

It's always a good idea to use separate keys for separate functions, **but the keys can be derived from the same master**.

K_1=H("Key1",K) K_2=H("Key2",K)

Message Digests

A *message digest* is a short "unforgeable" fingerprint of a long message.

A simple hash can serve as a message digest.