DI-FCT-UNL
Segurança de Redes e Sistemas de Computadores
Network and Computer Systems Security

Mestrado Integrado em Engenharia Informática
MSc Course: Informatics Engineering
1st Sem., 2019/2020

Secure Hashing and MACs Message Authentication Codes

Outline

- **Secure Hash Functions and Message Authentication**
  - Secure Hash Functions and Their Use
  - Security Properties of Secure Hash Functions
  - Secure Hash Algorithms
  - SHA-2-512 Case Study: Internal structure
  - Performance of Secure Hash Functions
  - Message authentication codes (MACs)
  - Confidentiality with Integrity using MACs
  - HMAC schemes
  - CMAC schemes

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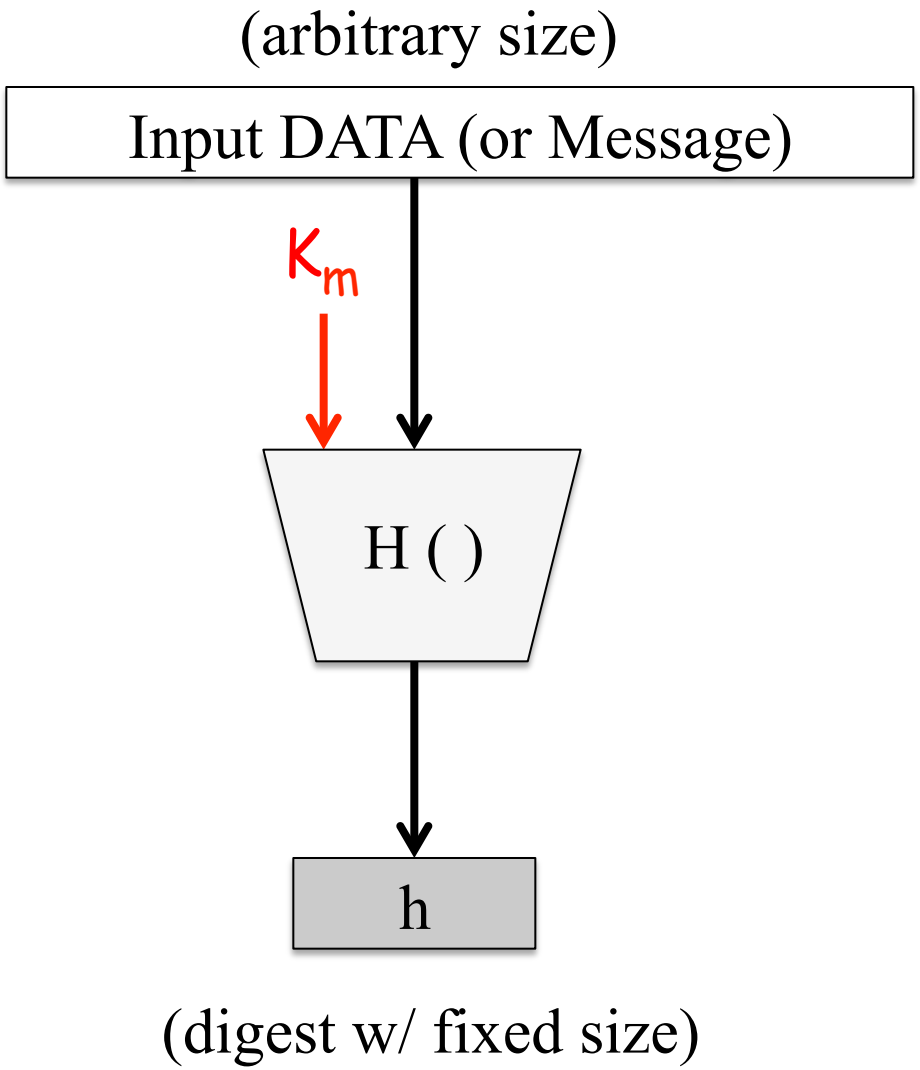
Secure Hash Functions



Secure Digesting
of arbitrary input data
to fixed size output

h = H(M)

Also known as:
Secure hash code
or Secure Message Digest

Can use as Not-Keyed Hash

Or Keyed-Hash =>MAC
$h = H_k(M)$

Use of Secure Hash Functions (not Keyed)

Used as integrity proofs of input data or messages

Detection of changes to validate the integrity in different situations, ex.;

- File Integrity Checks (or File Tampering Detection)
- Message Integrity Detection (or Message Tampering Detection
- DB Integrity Control (Tables, Attributes in Entity Sets, …)

Ex: Principle of File System Integrity Control in a HIDS:

- Files hashed and hash values stored a "secure place" (ex., read-only storage device)
  - If you compute the hash values of your supposed unchanged files, comparing with those hash values, you can detect anomalous changes (integrity breaks)

Use of Keyed Secure Hash Functions

Used as fast authentication and integrity proofs of input data or messages

- File Integrity with Authenticated Checks
- Message Authentication and Integrity
- DB Authenticated Integrity Controls

Ex: Principle of File System Integrity in a HIDS:

- Authenticated Hashing (HMACs) of files in a computer stored in a "secure place" (ex., read-only storage device)
  - Can use for am authenticated attestation of integrity

>> DEMO

Integrity Checks w/ Secure Hashing and MACs using openssl

Examples of Secure Hash Functions and MACs See for ex: openssl, Java/JCE-JCE Labs

Secure Hash Functions (Not Keyed Hash)

- MD2, MD4, MD5
- MDGOST-94

- SHA-1 (or SHA-160)
- RIPEMD-160

- Streebog256
- Streebog512
- SHA-2 (SHA-224, SHA-256, SHA-384, SHA-512)
- Whirlpool

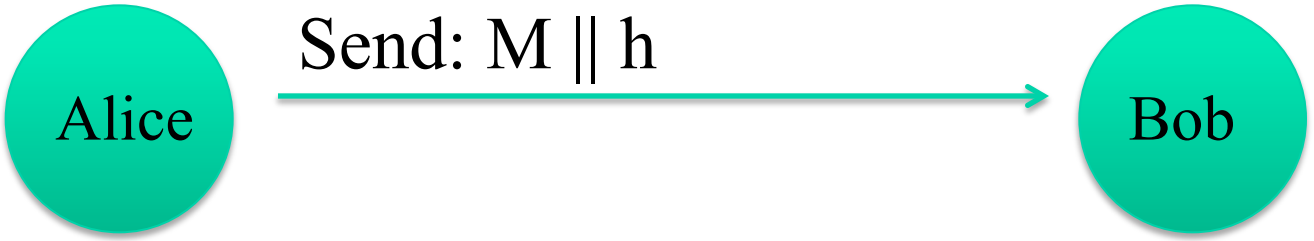
MAC Constructions (Keyed Hash)

- GOST-MAC
- HMAC variants …
- etc

See also Secure Hash Functions and MAC Functions on your Crypto Providers: (Lab 1 Materials)

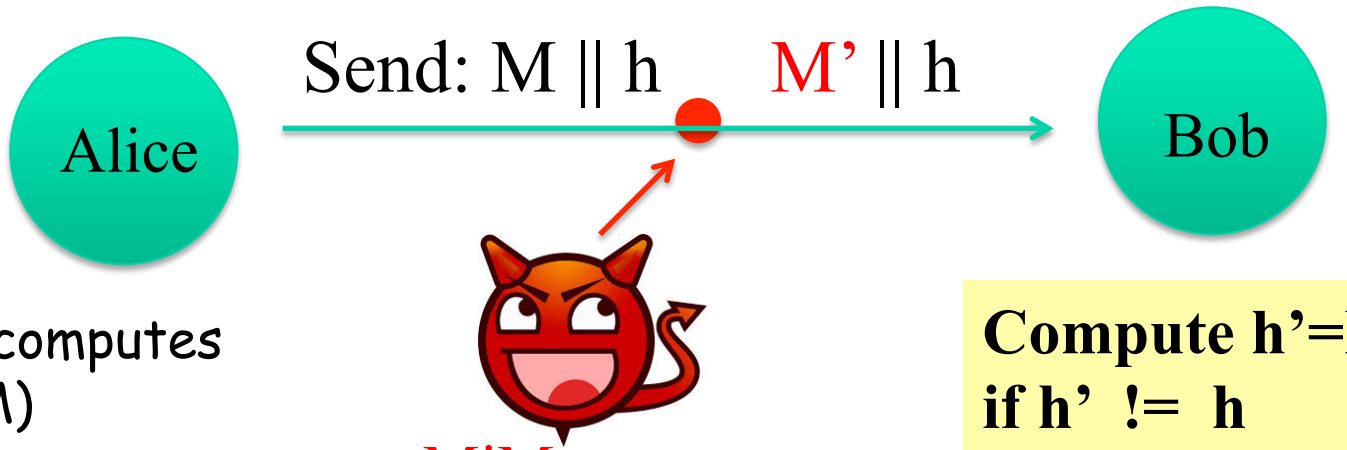
We will see also how to program with Secure Hash Functions and MACs (with detailed security observations) in Lab (Lab2 Materials)

Secure Hash Functions in Secure Communication



Alice computes
h=H(M)

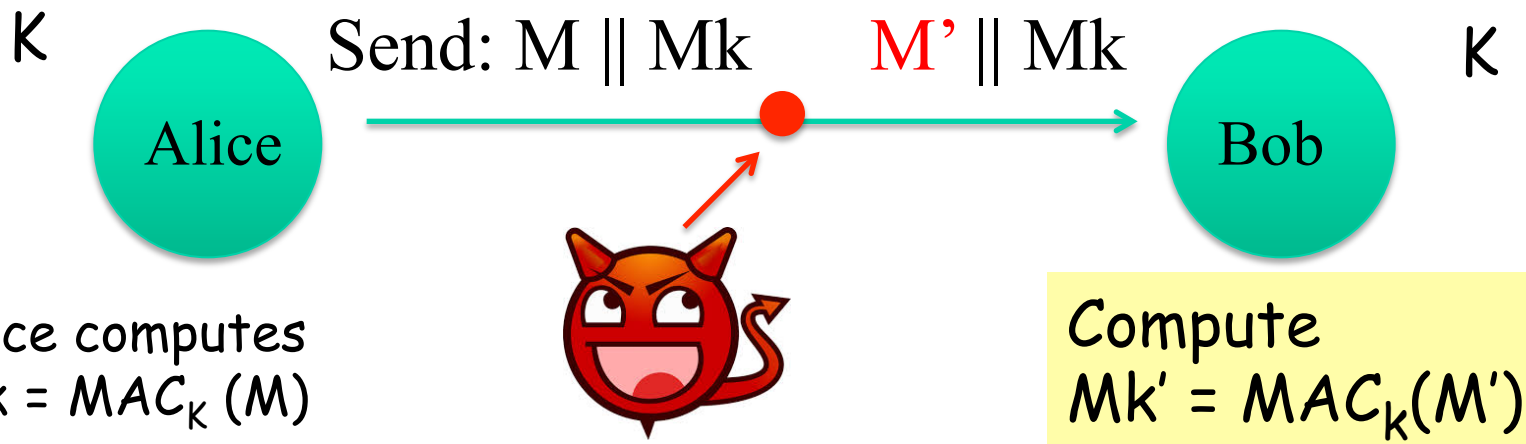
Compute h'=H(M)
if h' = h => M is OK !
(integrity)



Alice computes
h=H(M)

Compute h'=H(M')
if h' != h
=> M was tampered

MACs in Secure Communication

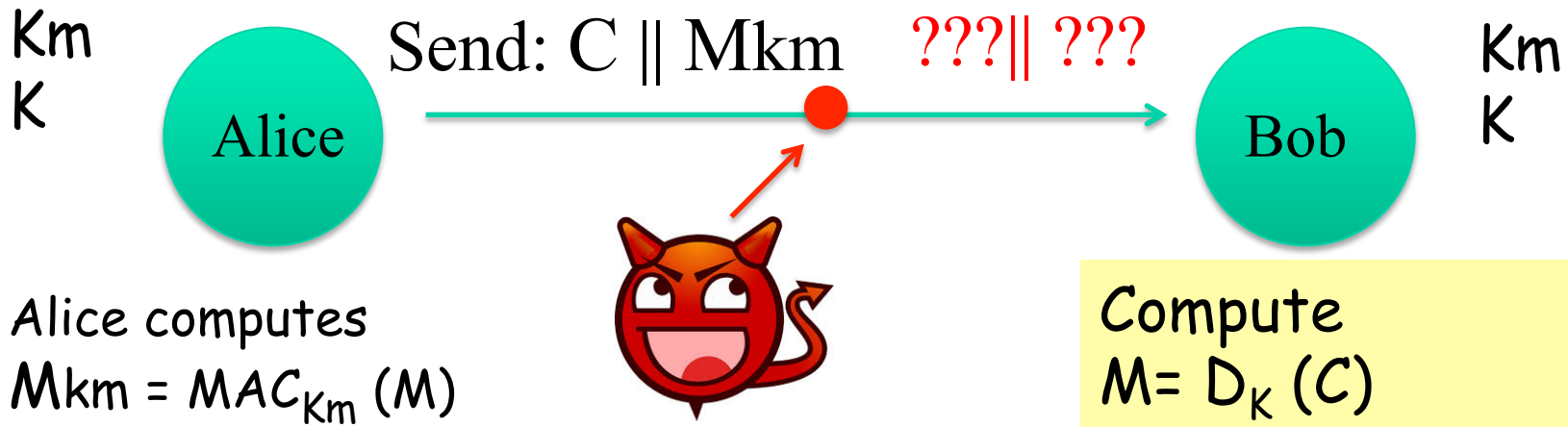


Alice computes
$Mk = MAC_K(M)$

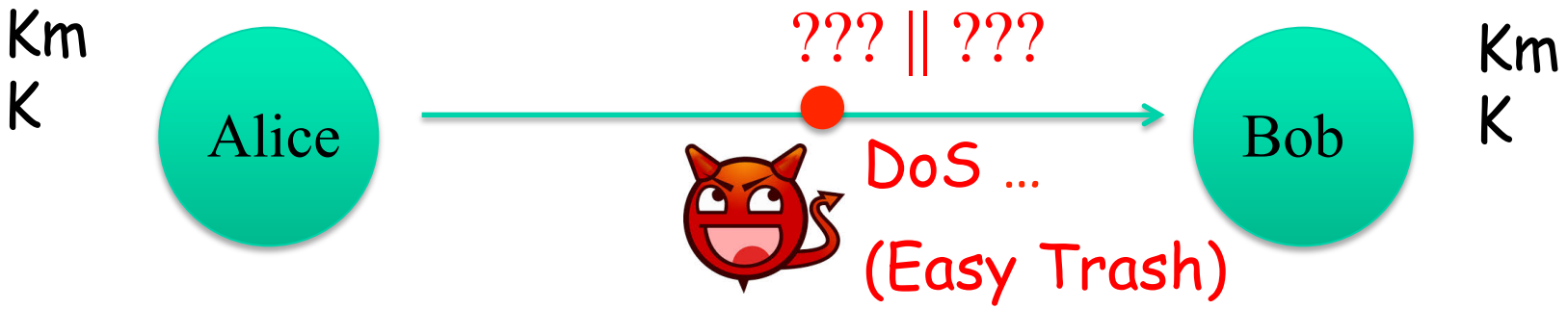
MiM
(Tampering Attack)

Compute
$Mk' = MAC_k(M')$
$Mk' \neq Mk$
$\Rightarrow$ **M was tampered**
$\Rightarrow$ **M not authentic**

Message
Confidentiality + Integrity + Authenticity



MSG Confidentiality + Integrity + Authenticity: What is better ? What is wrong ?



$C = E_K (M)$

Alice Could Send:

$C \,||\, H(C)$ — Insecure !

$C \,||\, H(M)$ — No Auth.

$C \,||\, MAC_K$ — Weak !

$C' = E_k (M \,||\, H(M))$ C'

$C' = E_k (M \,||\, MAC_k(M))$ C'

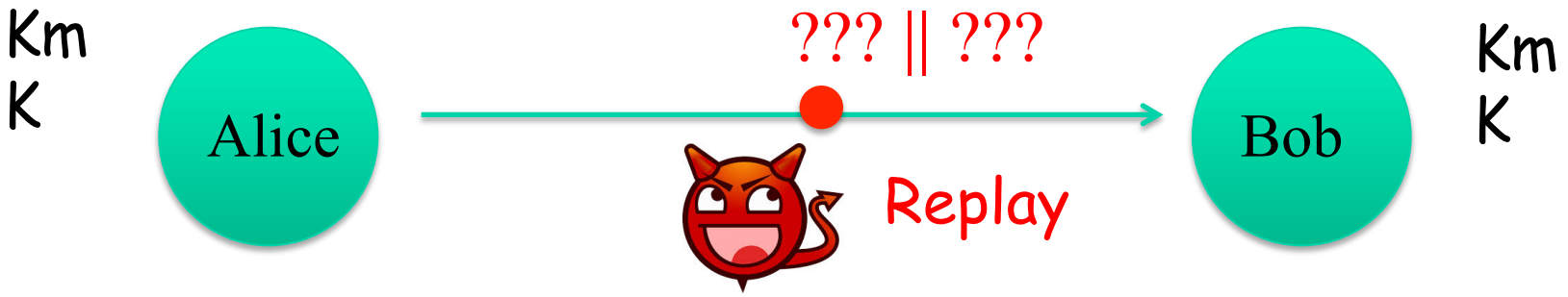
$C' = E_k (M \,||\, MAC_{kmac}(M))$ C'

Ok, Secure

But bad for

DoS

What in case of Message Replaying ?



$C = E_K(M)$

Alice Could Send:

$C \,||\, H(C)$

$C \,||\, H(M)$

$C \,||\, MAC_K$

$C' = E_k(M \,||\, H(M))$ C'

$C' = E_k(M \,||\, MAC_k(M))$ C'

$C' = E_k(M \,||\, MAC_{kmac}(M))$ C'

No Protection How to Protect ?

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Properties of Secure HASH Functions

1) **Arbitrary Input:** H( ) can be applied to **input blocks of data with any size**
2) **Fixed Output**: H( ) produces a **fixed length output (hash value with fixed size)**
3) **Performance:** H(x) is easy (**low computational work, fast) to compute H(x)** for any given x.

4) **Irreversibility (One-Way, Pre-Image Resistance)**: for any given block h, it is computationally infeasible to find x such that H(x)=h
5) **Weak collision resistance**: for any given block **x**, it is computationally infeasible to find **y**, with H(**y**) = H(**x**).

   Also known as **Second Pre-Image Resistance**
6) **Strong collision resistance**: it is computationally infeasible to find any pair (x, y), with H(x) = H(y)

7) **Uniform distribution of H(x) for any x**

Irreversibility and Collision Resistance

In "real practical secure hash algorithms" these are **probabilistic properties meaning: impossibility to break in useful computational time (or computational effort)**

Note: "strong" vs. "weak" collision resistance:

- For security protocols, in general, we are interested for maximum security in secure hash algorithms with Strong Collision Resistance
  - Subsumes Pre-Image and Second Pre-Image Resistance

… Think on it by the **Birthday Paradox**

- The chance that in a group of people two will share the same birthday: with 23 persons, $p > 0.5$
- Generalization: matching pair from any two sets: $2^{m/2}$ in each set to get a matching m-bit hash

A Simple and Naïve Hash Function (LRC MIC)

	bit 1	bit 2	• • •	bit *n*
Block 1	b_{11}	b_{21}		b_{n1}
Block 2	b_{12}	b_{22}		b_{n2}
	•	•	•	•
	•	•	•	•
	•	•	•	•
Block *m*	b_{1m}	b_{2m}		b_{nm}
Hash code	C_1	C_2		C_n

Simple: Bit by Bit Exclusive OR

MIC - Longitudinal Redundancy Check

(MIC means Message Integrity Check)

Is it Secure ?

Not secure ☹ … No Collision Resistance

- Suppose Ci = Bi1 xor Bi2 xor ….. xor Bim
  for 1 <= i <= n
- Good (acceptable) as a MIC ? probability of an error will result in an unchanged hash value is $1/2^n$
- Is it secure ? Ex., Predictable input as text with 128 bit hash, reduces P to 1/2^112
- Simple … don't means "Secure"
  - How to do it better ?

Need to provoke an effect of randomizing the input more completely and overcoming any regularities

MICs (No Secure Message Integrity Codes): used for FEC codes … very different from Secure MACs or Secure Hash Functions

An "improved" Hash Function. Is it Better ?

Use of RXOR (Rotated XOR)

- Ex., one-bit circular shift on the hash value after each block is processed would improve
- But is it secure ? Useful for integrity ?
- No ! See the demonstration (bibliography)

See also:
2^37 variations of a letter

[Dav 89], Stallings, Brown, Computer Security Principles and Practice

Collision-Attacks

- For a given "secure hash function" it takes a certain computational effort (or energy).

- Is it simple ?

>> DEMO

Breaking MD5 Collision Resistance

Security of Secure Hash Functions

- Resistance against attacks to break the security properties

- Attacks (and studies) conducted (as in the case of symmetric encryption algorithms) by:

  BRUTE FORCE

  CRYPTANALYSIS

Brute Force on Hash Functions

Strong collision resistance:

Hash cost with complexity $O(2^{m/2})$

- Proposal for HW MD5 cracker (see the book)
- 128-bit hash looks vulnerable, 160-bits better
- More bits => Even better

MACs (pre-keyed Hashes) with known message-MAC pairs

- Can either attack keyspace (key search) or MAC
- Cost im this cas: O (min 2^k, 2^n) which is similar to symmetric encryption algorithms
- At least 128-bit MAC is needed for security today
  - Similar discussion on Symmetric Encryption Algorithms

Collision Resistance on Secure Hash Functions

- **Cryptanalytic attacks** exploit the internal structure
  - Like block ciphers want brute-force attacks to be the best alternative

- Have a number of analytic attacks on iterated hash functions
  - $CV_i = f[CV_{i-1}, M_i]$; $H(M)=CV_N$
  - Typically focus on collisions in function f
  - Like block ciphers is often composed of rounds
    - Many rounds are ok (to improve the randomization: confusion and diffusion effect)
  - Attacks exploit properties of core-round functions

Collision Resistance Metrics for Secure Hash Functions with Hash Size N

Security Property	Metrics	Probability of Attack	Example (SHA 256)
Pre-image Resistance	2^N	$1/2^N$	$1/2^{256}$
Second Preimage Resistance	2^N	$1/2^N$	$1/2^{256}$
(Strong) Collison Resistance	$2^{N/2}$	$1/2^{N/2}$	$1/2^{128}$

Collision Resistance Metrics for Secure Hash Functions with Hash Size N

Security Property	Example (SHA 256)		My Computer (openssl lib.)	Time to Attack
Pre-image Resistance	2^{256}	~1.2×10^{77}	22×10^6 *h/s*	~54×10^{68} *s*
Second Preimage Resistance	2^{256}	~1.2×10^{77}	22×10^6 *h/s*	~54×10^{68} *s*
(Strong) Collison Resistance	2^{128}	~3.4×10^{38}	22×10^6 *h/s*	154×10^{29} *s*

Collision Resistance Metrics for Secure Hash Functions with Hash Size N

Security Property	Time to Attack	My Computer (openssl lib.)	ASIC Dragomint 16T ~10^{12} h/s
Pre-image Resistance	~54×10^{68} s	~1.7×10^{62} years	~10^{50} years
Second Preimage Resistance	~54×10^{68} s	~1.7×10^{62} years	~10^{50} years
(Strong) Collison Resistance	154×10^{29} s	~$4{,}9 \times 10^{23}$ years	~10^{11} years

https://www.buybitcoinworldwide.com/mining/hardware/dragonmint-16t/

Birthday Attacks … and Proofs of Work (PoW)

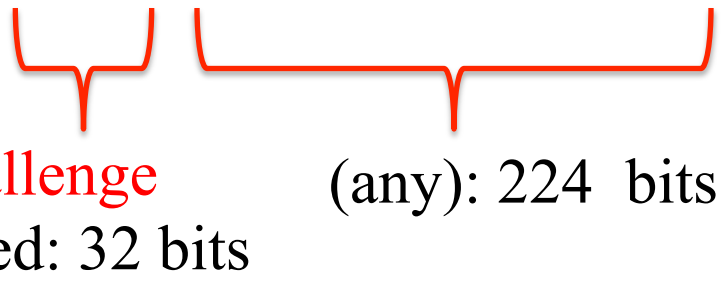
Might think a 64-bit hash is secure ? 128 is better ?
what about … 224, 256, 384, 512 … Etc ?

The Security vs. Performance Tradeoff

PoW - Proof of Work (using Secure Hash-Functions)

- The required computational work or energy ;-(to find a collision, given a cerrtain challenge

- Ex: Find a collision in such a way that
  SHA-2-256(X || NONCE) = 0000 .....
  => H(X) < 2^224



Some examples of Proof of Work uses

Countermeasures for DoS or DDoS Attacks

Ex:

Henrique Domingos, J. Martins, Ricardo Martins, EIP – Preventing DDoS with Ephemeral IP Identifiers Cryptographically Generated, Proc. of SecNets / Cornell University arXiv 1612.07065, Dec 2016

A "competitive" form of Probabilistic Consensus in Bitcoin Mineration (ex. Bitcoin/Blockchain PoW strategy)

- Challenge regulated for required computation and energy to close a block of transactions each ~10 minutes (or ~2016 blocks each 2 weeks)
- What does it means ?

See more, ex: https://en.bitcoin.it/wiki/Bitcoin

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Well known (classic) Secure HASH algorithms: So far … so weak ? … !

	MD5	RIPEMD-160	SHA-1
Output Digest length	128 bits	160 bits	160 bits
Basic unit of processing	512 bits	512 bits	512 bits
Number of steps	64 (4 rounds of 16)	60 (5 paired rounds of 16)	80 (4 rounds of 20)
Maximum input message size	2^{64}-1 bits	2^{64}-1 bits	2^{64}-1 bits
Cryptanalysis (metrics) published Collision Resistance	$1/2^{24}$ to $1/2^{39}$ PIR: $1/2^{123}$	$1/2^{70}$ to $1/2^{75}$ PIR: $1/2^{148}$ to $1/2^{158}$	$1/2^{52}$ to $1/2^{63}$ PRI: $1/2^{150}$ to $1/2^{159}$

Considered Weak Today → Possible Weakenesses → Possible Weakenesses

SHA-2

NIST rev FIPS PUB 180-2 (2002), FIPS PUB 180-3 (2008)
SHA-2 (Families) now also in IETF RFC 6234
SHA-1 Phaseout (NIST): 2005 to 2010
SHA-1 Attacks (Collision Resistance w/ $1/2^{63}$)

	SHA-1	SHA-224	SHA-256	SHA-384	SHA-512
Message Digest Size	160	224	256	384	512
Message Size	$< 2^{64}$	$< 2^{64}$	$< 2^{64}$	$< 2^{128}$	$< 2^{128}$
Block Size	512	512	512	1024	1024
Word Size	32	32	32	64	64
Number of Steps	80	64	64	80	80
Security	80	112	128	192	256

Notes: 1. All sizes are measured in bits.

2. Security refers to the fact that a birthday attack on a message digest of size n produces a collision with a workfactor of approximately $2^{n/2}$.

SHA-2 Family and Revisions

NIST issued revisions FIPS 180-2 (2002) and 180-3 (2008)

- Designed for compatibility with increased security as also provided by the AES cipher
- However, structure & detail is similar to SHA-1
- Hence analysis should be similar
- But security levels are rather higher (esp. SHA-256, SHA-384, SHA-512)

NIST announced in 2007 a competition for the SHA-3 next gen NIST hash function

Goal to have in place by 2012 but not fixed

Only initially standardized in Oct/2015 after a big debate

Standardized (SHA-3)

Also known as "Keccak" family of secure hash functions

- The new kids in town !

- Hash outputs with variable size:
  - 128, 224, 256, 384, 512

- New structure (Sponge constructions)
- SHA-3 family (and variants) are evolving, and some IETF RFC Drafts on going very recently (Feb, Mar 2019): you can expect very dynamic work in the short-medium term …

For on-going SHA-3: see (if you want the details):

https://en.wikipedia.org/wiki/SHA-3

NIST Standardization:

https://www.nist.gov/news-events/news/2015/08/nist-releases-sha-3-cryptographic-hash-standard

See also … About SPONGE Constructions (in the SHA-3 Core)

http://keccak.noekeon.org

SHA-3 Variants

Instance	Definition
SHA3-224(*M*)	Keccak[448](*M* ll 01, 224)
SHA3-256(*M*)	Keccak[512](*M* ll 01, 256)
SHA3-384(*M*)	Keccak[768](*M* ll 01, 384)
SHA3-512(*M*)	Keccak[1024](*M* ll 01, 512)
SHAKE128(*M*, *d*)	Keccak[256](*M* ll 1111, *d*)
SHAKE256(*M*, *d*)	Keccak[512](*M* ll 1111, *d*)

We can use these implementations in crypto-providers available for JAVA JCE

SHA-3 Requirements and On-Going Research

- It must replace SHA-2 with SHA-3 in any use
  - So use same hash sizes
- Preserve the online nature of SHA-2
  - So must process small blocks (512 / 1024 bits)

- Evaluation criteria (over the table)
  - Security close to theoretical max for hash sizes
  - Cost in time & memory (efficiency)
  - Tradeoff Characteristics: security, performance, flexibility & simplicity

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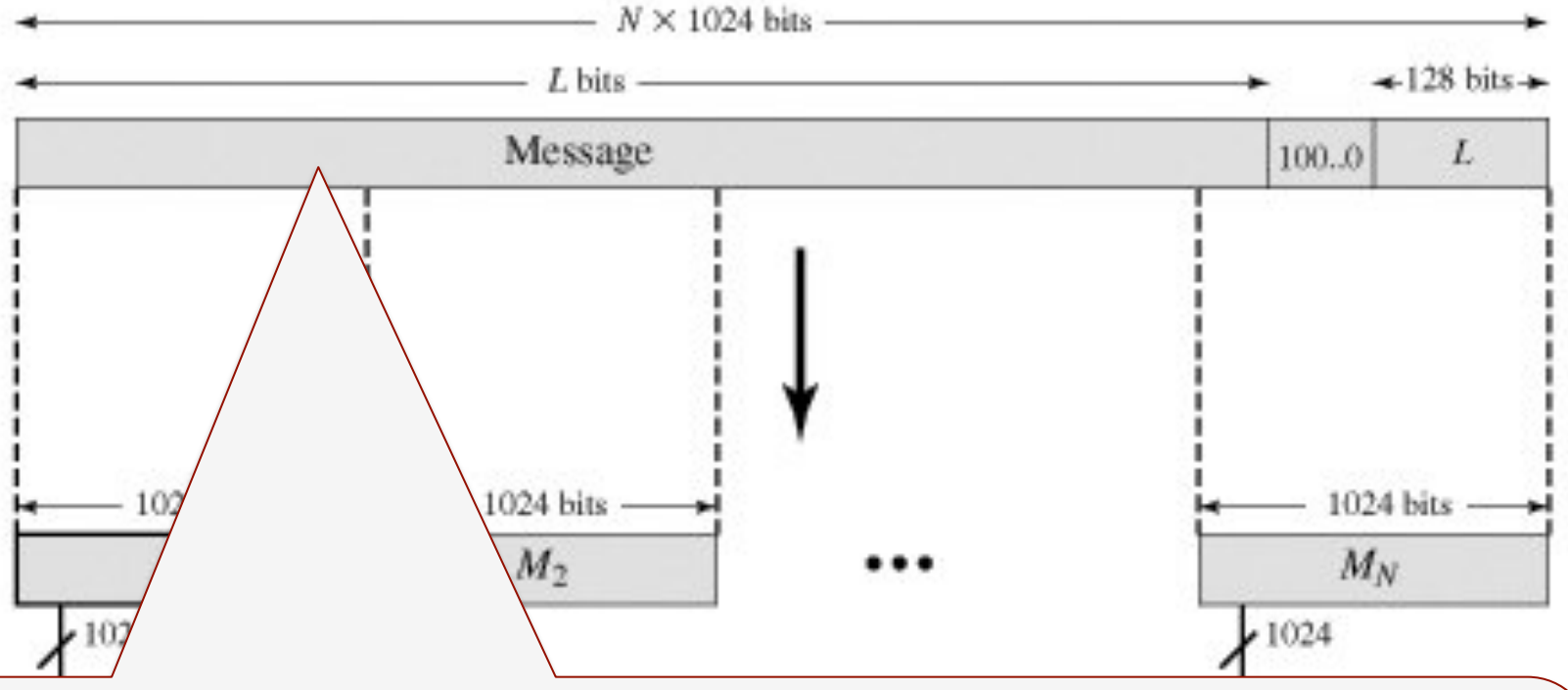
Internal Structure for SHA-2 512 (1)
How SHA-2 (SHA-512) Works …



Input MSG: must be smaller than 2^{128} bits representation

Step 1: Append of Padding bits: 100000...0000, for congruency w/ 896 mod 1024

Step 2: Append 128 bits (Total Length, Multiple of 1024 bits)

Internal Structure for SHA-2 512 (1)
How SHA-2 (SHA-512) Works …

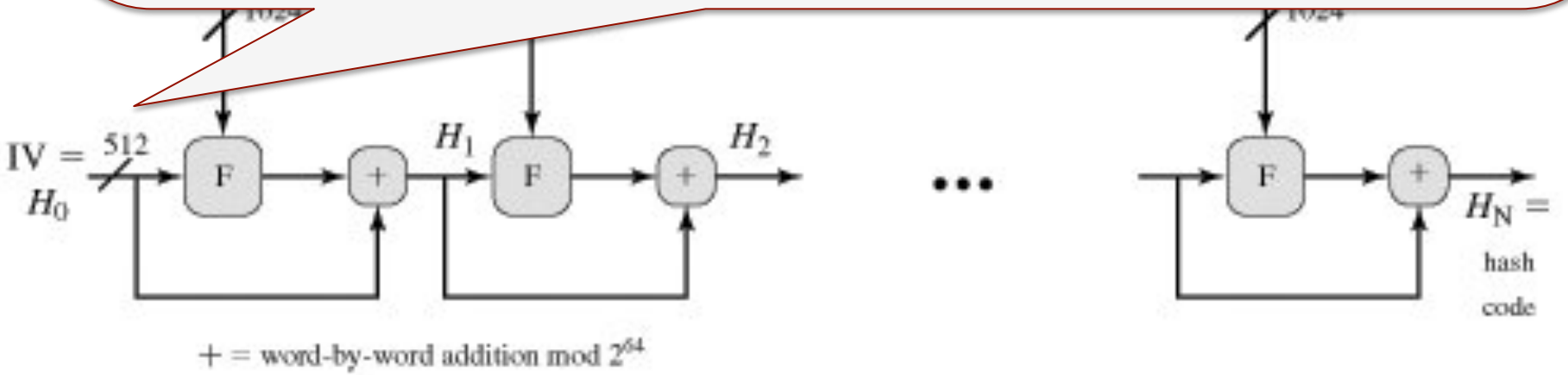
Now we have N words of 2014 bits

Step 3: Initialization of Hash Buffers w/ Pre-Defined Constants:

512 bits = 32 bit x 8 value-letters

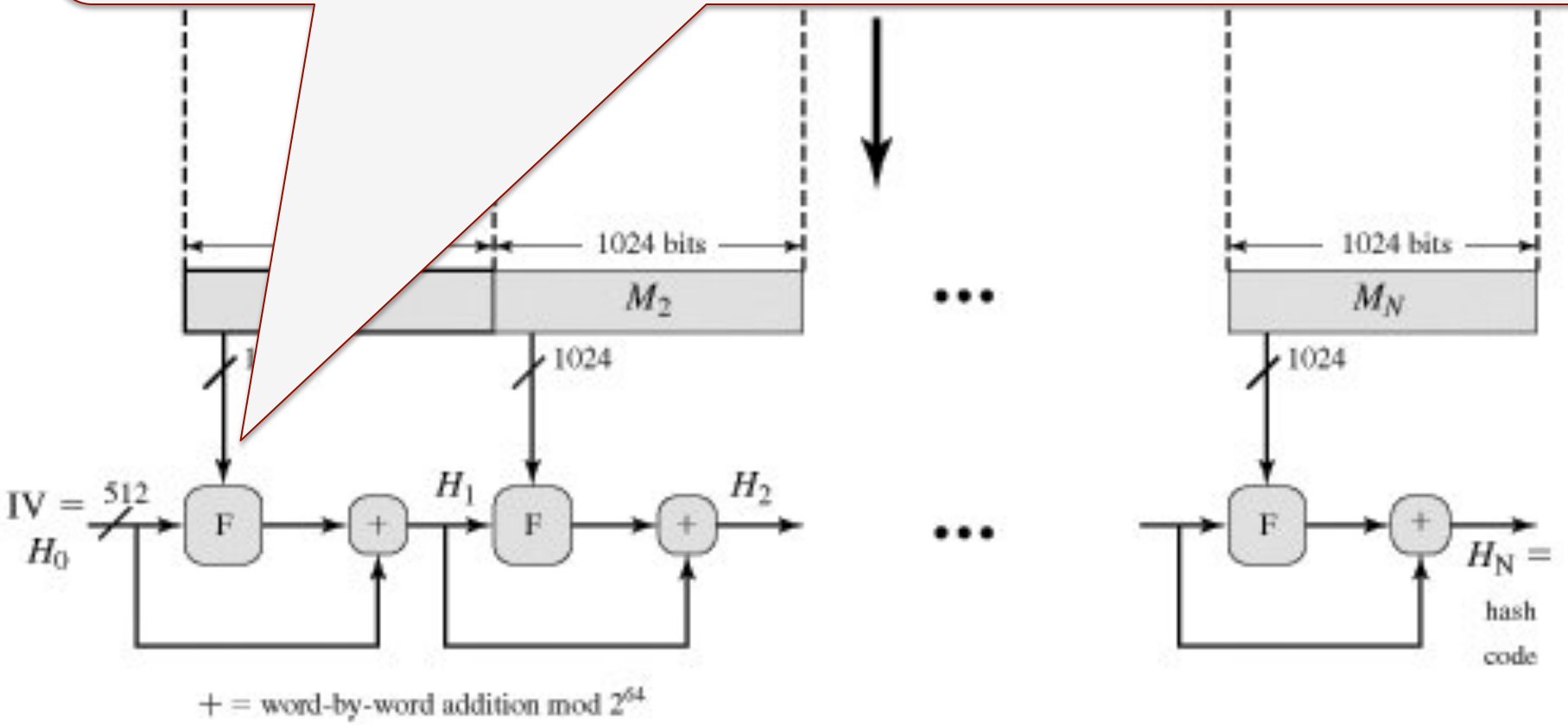
The 64 MSBs of fractional part of Root Squares of the first 8 Prime Numbers

```
a = 6A09 E667 F3BC C908;   b = BB67 AE85 84CA A73B
c = 3C6E F372 FE94 F82B;   d = A54F F53A 5F1D 36F1
e = 510E 527F ADE6 82D1;   f = 9B05 688C 2B3E 6C1F
g = 1F83 D9AB FB41 BD6B;   h = 5BE0 CD19 137E 2179
```



Internal Structure for SHA-2 512 (1)
How SHA-2 (SHA-512) Works …

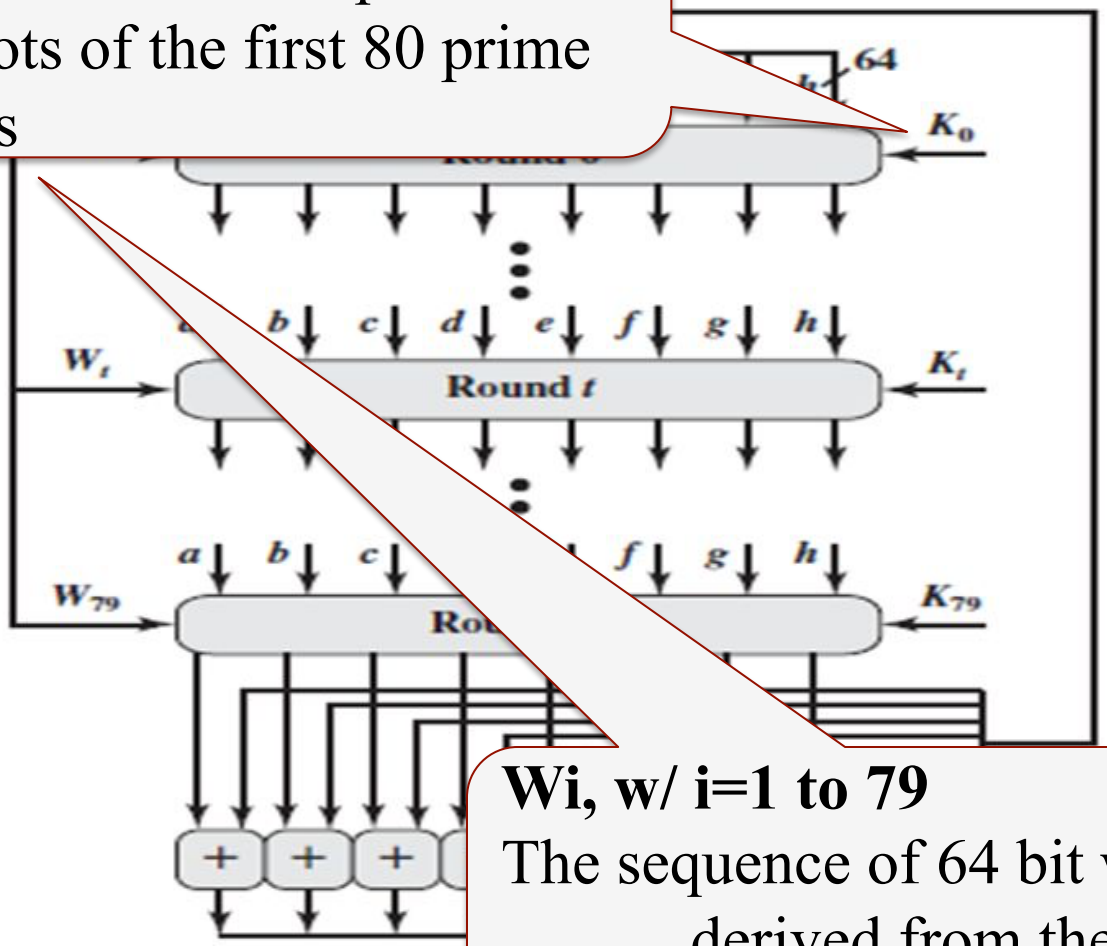
Step 4: Message is processed in 1024 bit (64 bits per round) blocks with the SHA-512 Core Function, executed in 80 Steps:



Internal Structure for SHA-2 512 (2)
How SHA-2 (SHA-512) Works …

Ki, w/ i=1 to 79

First 64 bits of the fractional part of the cube roots of the first 80 prime numbers



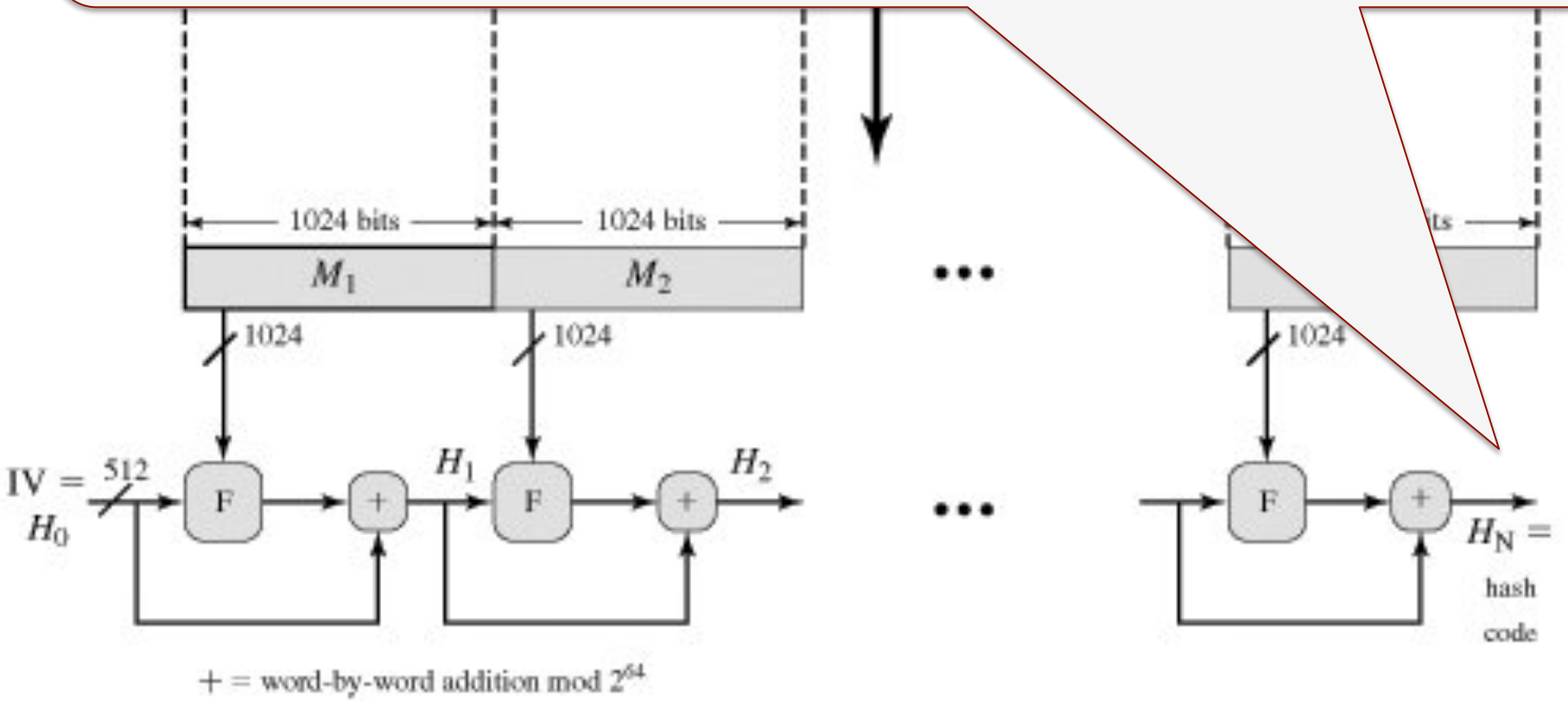
Wi, w/ i=1 to 79

The sequence of 64 bit words, derived from the current 1024 bit block

Internal Structure for SHA-2 512 (1)
How SHA-2 (SHA-512) Works …

Step 5: Output

After all N 1024 bit blocks have been processed, he output from the Nth stage will be the 512 bit output hash value



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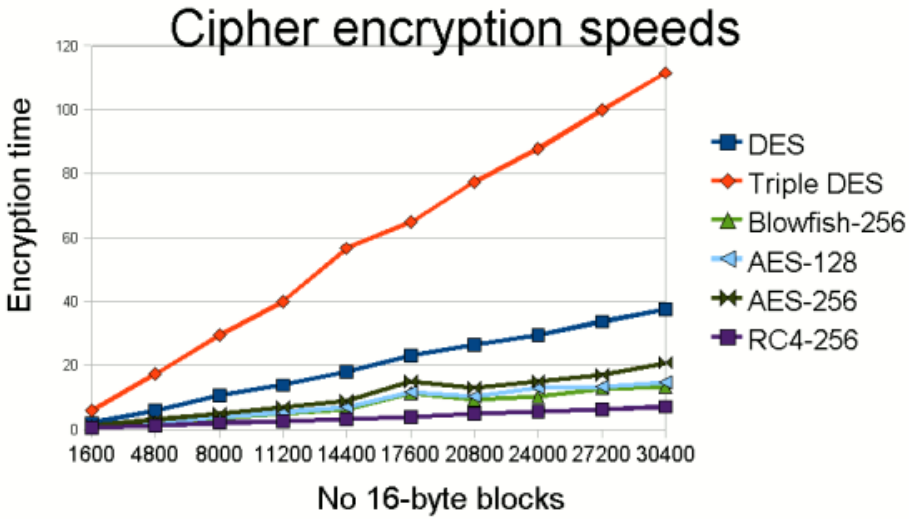
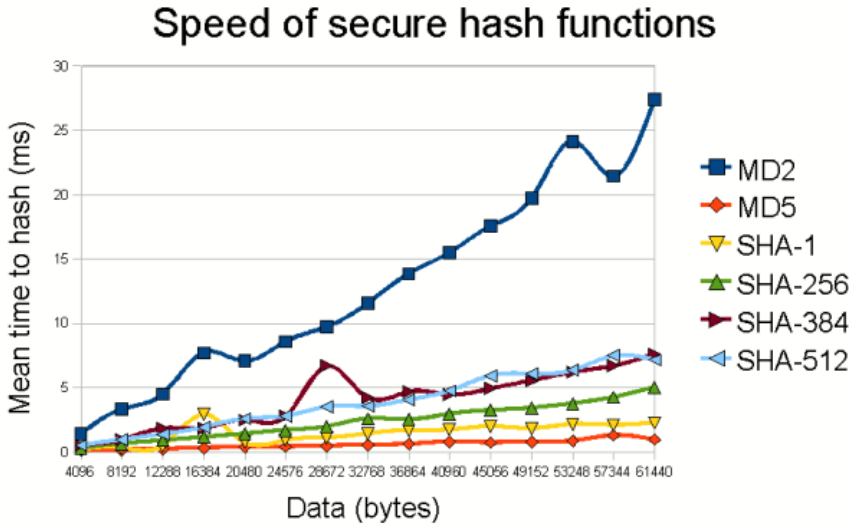
Performance of Secure Hash Algorithms

Comparisons in Java (standard JDK and Sun Crypto-Provider)
http://www.javamex.com/tutorials/cryptography/ciphers.shtml
http://www.javamex.com/tutorials/cryptography/hash_functions_algorithms.shtml





as ref: hash (ex., SHA-512) ~100 x faster than symmetric encryption (ex., 3DES)
hash (ex., SHA-512) ~ 4x faster than symmetric encryption (ex., AES-256)
hash (ex., SHA-1) ~ 18x faster than symmetric encryption (ex., AES-128)

See also:
Openssl speed benchmark (speed test library performance)
http://wikis.sun.com/display/CryptoPerf/UltraSPARC+cryptographic+performance

Performance analysis: Secure Hashing vs. Symmetric Encryption

Try to make these performance evaluations in your computer using JAVA JCE (cryptography) and the materials we provide for LABs !

Or use openssl (linux. mac, windows) to see the performance in processing input blocks of different sizes with different algorithms … Examples:

openssl speed sha512

…

Bytes/Second:

```
type             16 bytes     64 bytes    256 bytes   1024 bytes   8192 bytes
sha512           23798.27k    93818.06k   169995.47k   261958.66k   301029.51k
```

openssl speed aes-256-cbc

…

Bytes/Second:

```
type             16 bytes     64 bytes    256 bytes   1024 bytes   8192 bytes
des cbc          72212.05k    74651.61k    74132.22k    74070.99k    73933.64k
```

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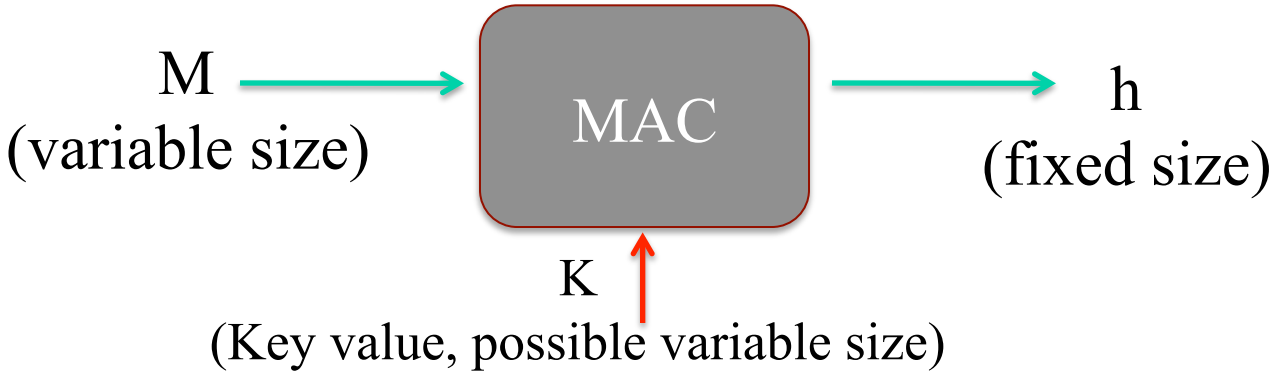
MACs as Keyed Secure Hash Functions

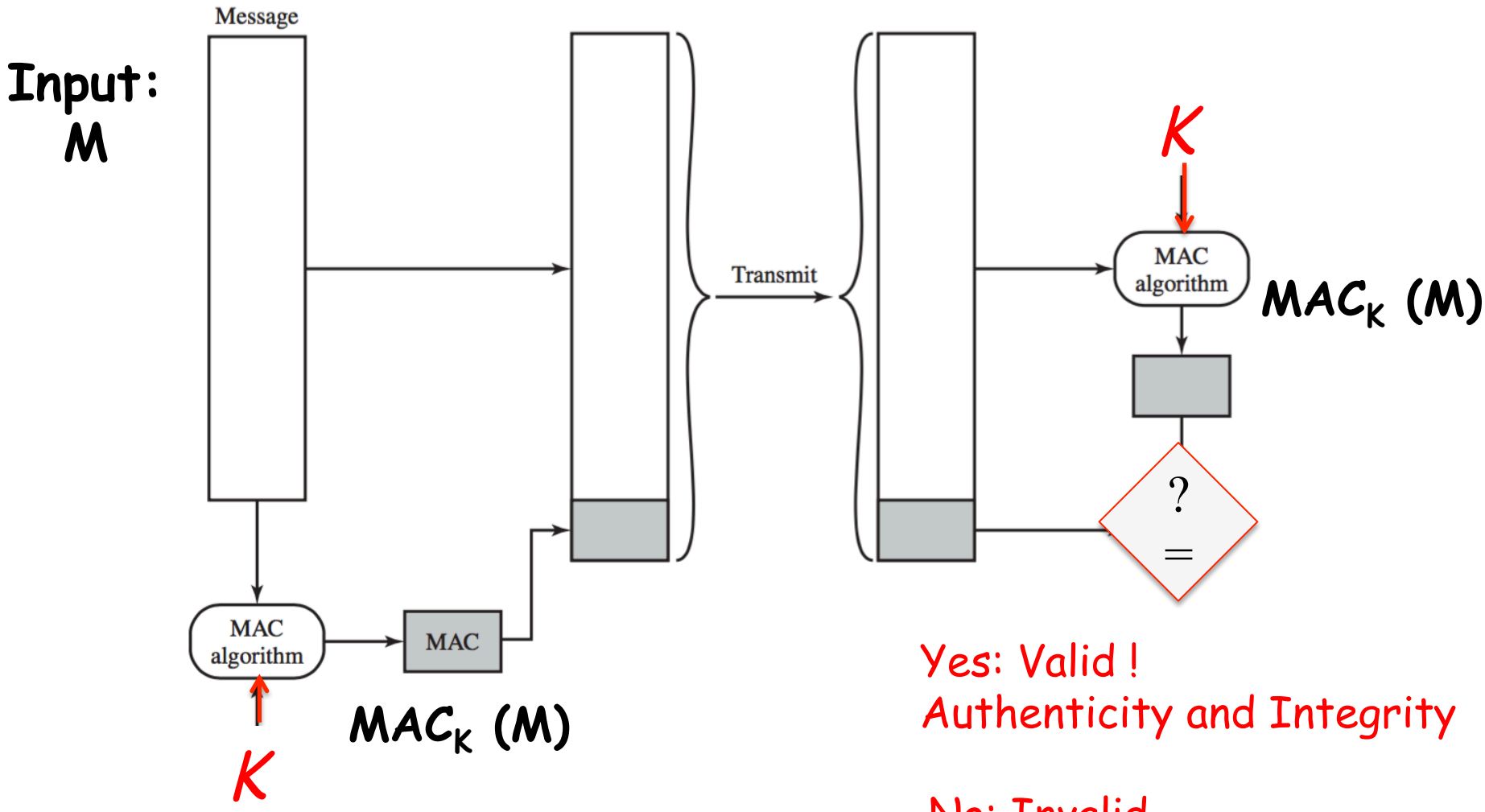
- Used as a **Message Authentication Code**

  $MAC_{M,k}$ = H(f(M,K)) : hash code or message digest



- Can use in various ways with message
  - Examples :
    - $MAC_{M,K}$ = H (M || K) // Append M with K
    - $MAC_{M,K}$ = H (M xor K) // M and K "xored"
    - $MAC_{M,K}$ = H (F(M,K)) // with a known F( )
- Most often to create a "*fast or light-weight message signature*", for a previously shared K

Use of MACs (MAC Algorithm Constructions)



Message Authentication

- Message authentication: proof of origin, confirming the sender (identity of originator)
  - Protecting (implicitly) the message integrity
    - Contents have not been altered (tampering detection)
    - Proof that, it was sent at a certain time or sequence (message replay detection or non-sequence detection)
  - Validating message authenticity as coming from the expected originator
    - Message came from an origin sharing the MAC key
- In some cases… message authentication is arguably more important than secrecy (ex., E-Commerce)

Message Authentication Codes

- As shown, **MAC provides authentication and implicit integrity (but no confidentiality)**
- **Why use a MAC with no confidentiality warranties?**
  - Sometimes only authentication is needed
  - Sometimes need authentication and integrity to persist longer than the encryption (eg. archival use)

    (Integrity checking may be supported with other schemes (MICs, other checksum functions but these are weak solutions !)
- **But can be combined with encryption for secrecy (combining authentication + integrity + confidentiality)**
  - Generally use separate keys for each
  - Can compute MAC either before or after encryption
  - Is generally regarded as better done before
  - … But must consider also balance requirements for authentication, confidentiality, integrity vs. DoS

MAC Properties (is not a Digital Signature)

- **A MAC works as a cryptographic secure checksum**

  $MAC = C_K(M)$ or $MAC_K(M)$ or $MAC(K, M)$

- Note that a MAC is not a digital signature (authentication of principals) in the sense of digital signatures for principals
  - A MAC requires shared keys
  - Used like "fast or light-weight message signature scheme" based on a NDA of the KEY. Why ?

- Is it a "many-to-one" function ?
  - potentially many messages have same MAC. Why ?
    - Not warranted collision free
  - but finding these needs to be very difficult
    - With appropriate security properties of MAC cryptographic functions. **Which properties ?**

Birthday Attacks on MACs

Birthday attack works thus:

- opponent generates $2^{m/2}$ variations of a valid message all with essentially the same meaning
- opponent also generates $2^{m/2}$ variations of a desired fraudulent message (to get a matching m-bit hash)
- two sets of messages are compared to find pair with same hash (probability > 0.5 by birthday paradox)
- have user sign the valid message, then substitute the forgery which will have a valid signatures

- Conclusion: need to use larger MAC/hash values

Outline

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  - Secure Hash Functions and Their Use
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  - HMAC schemes
  - CMAC schemes

Security properties of MACs

Same as Keyed Hash Functions:

- **Irreversibility (one way, pre-image resistance)**

  If Y = MAC (X1)

  it is not possible to find X1 knowing Y

- **Collision resistance**: knowing a message and MAC, is infeasible to find another message with same MAC
  - **Weak collision resistance**

    Given Y=MAC (X1) and X1 : no other X2 with Y=MAC(X2)
  - **Strong collision resistance**

    Given a value y, it is not possible to find any Z1 and Z2, in a way that MAC (Z1) = MAC (Z2) = Y

- **Uniform distribution**
  - MACs should be uniformly distributed, independently of the message input
  - MAC should depend equally on all bits of the message

Examples (typical uses): hands-on discussion on LABs

- Ex. 1:

Header | {M, TS, NS, … }$_{k1}$ | MAC$_{K2}$ (M, TS, NS, …)

- Ex. 2:

Header | {M, TS, SN, … , MAC$_{KS}$ (M, TS, SN, …) }$_{ks}$

- Ex. 3:

Content-Type | M version | m version | Compressed length |
{ compress [M, TS, SN,… MAC$_{Km}$ (M, TS, N,…)] }$_{KS}$

- Ex. 4: (DoS minimization tradeoff)

Content-Type | M version | m version | Compressed length |
{ compress [M,TS,SN, …] }$_{KS}$ | MAC$_{Km}$ (M,TS,NS, …)

› Note: you must take in account other issues for security assumptions: Block modes of operation, key-distribution, attacks to weaknesses of MAC properties

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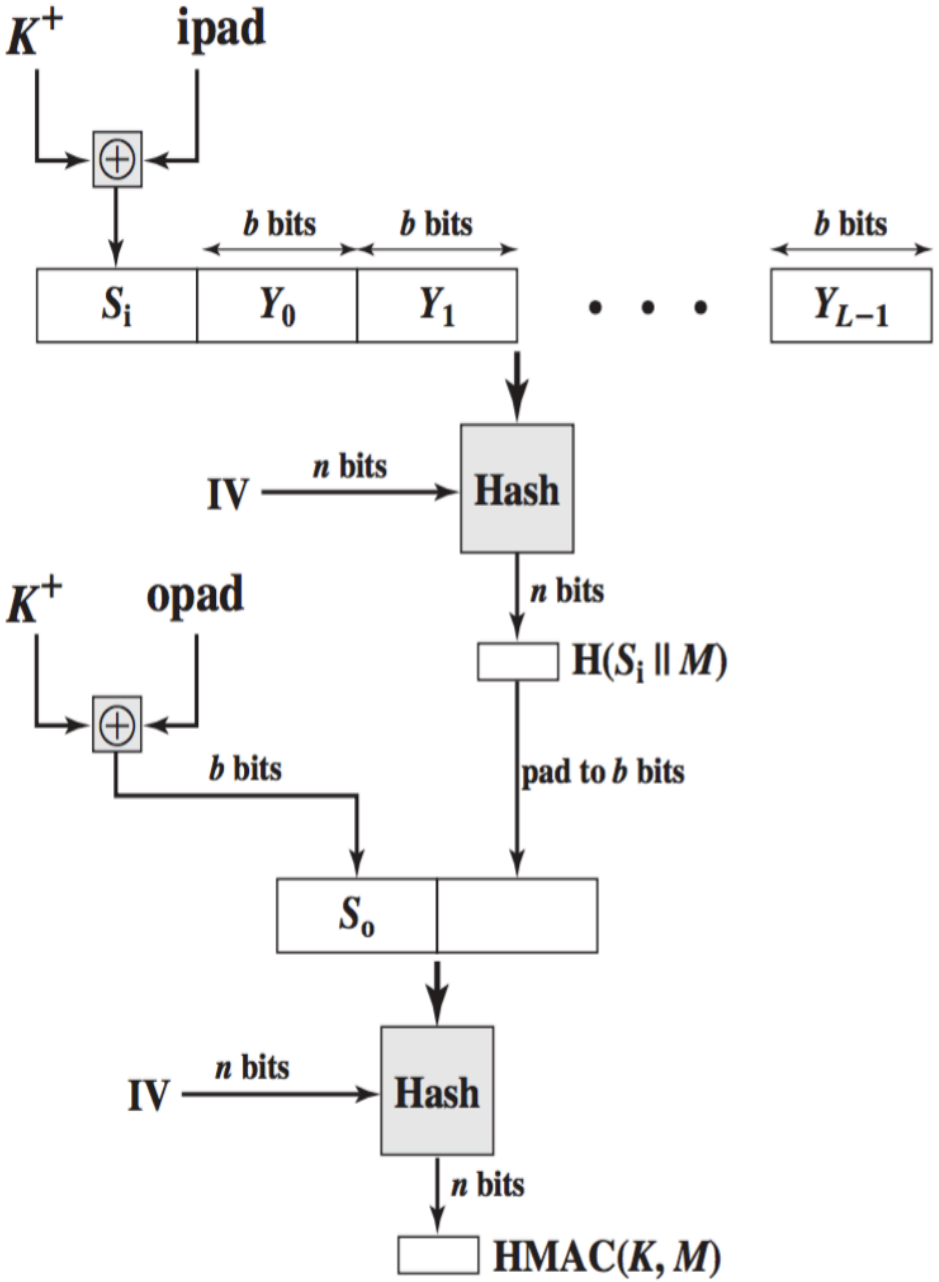
HMAC (RFC 2104)

- It was born from the idea of a "keyed hash"
- Uses hash function on the message:
  $HMAC_K$ =
  Hash[(K^+ XOR opad) || Hash[(K^+ XOR ipad)||M)]]
- Where K^+ is the key padded out to size; opad and ipad are specified padding constants
- Overhead is just 3 more hash calculations than the message needs alone
- Flexibility and Security: Any hash function can be composed

HMAC Structure (RFC 2018)

Initial Motivations:

- Cryptographic hash functions executes faster in software than encryption algorithms such as DES
- Library code for cryptographic hash functions is widely available
- No export restrictions from the US



HMAC Security vs. Speed

- Proved security of HMAC relates to that of the underlying hash algorithm
- Attacking HMAC requires either:
  - Brute force attack on key used
  - Birthday attack (but since keyed would need to observe a very large number of messages)
- Choose hash function used based on speed verses security constraints (Parameterized Constructions)

- HMAC very used for "fast (or light-weight) signatures" (comparing with CMACs or PubKey Signatures)

- But…
  - CMAC with AES 256 can run faster than HMAC with SHA-3
  - AES implementations also provided in Hardware (cryptographic modules)
  - And in some processors (ex., INTEL, **Advanced Encryption Standard New Instructions**; **AES-NI**)
  - https://en.wikipedia.org/wiki/AES_instruction_set

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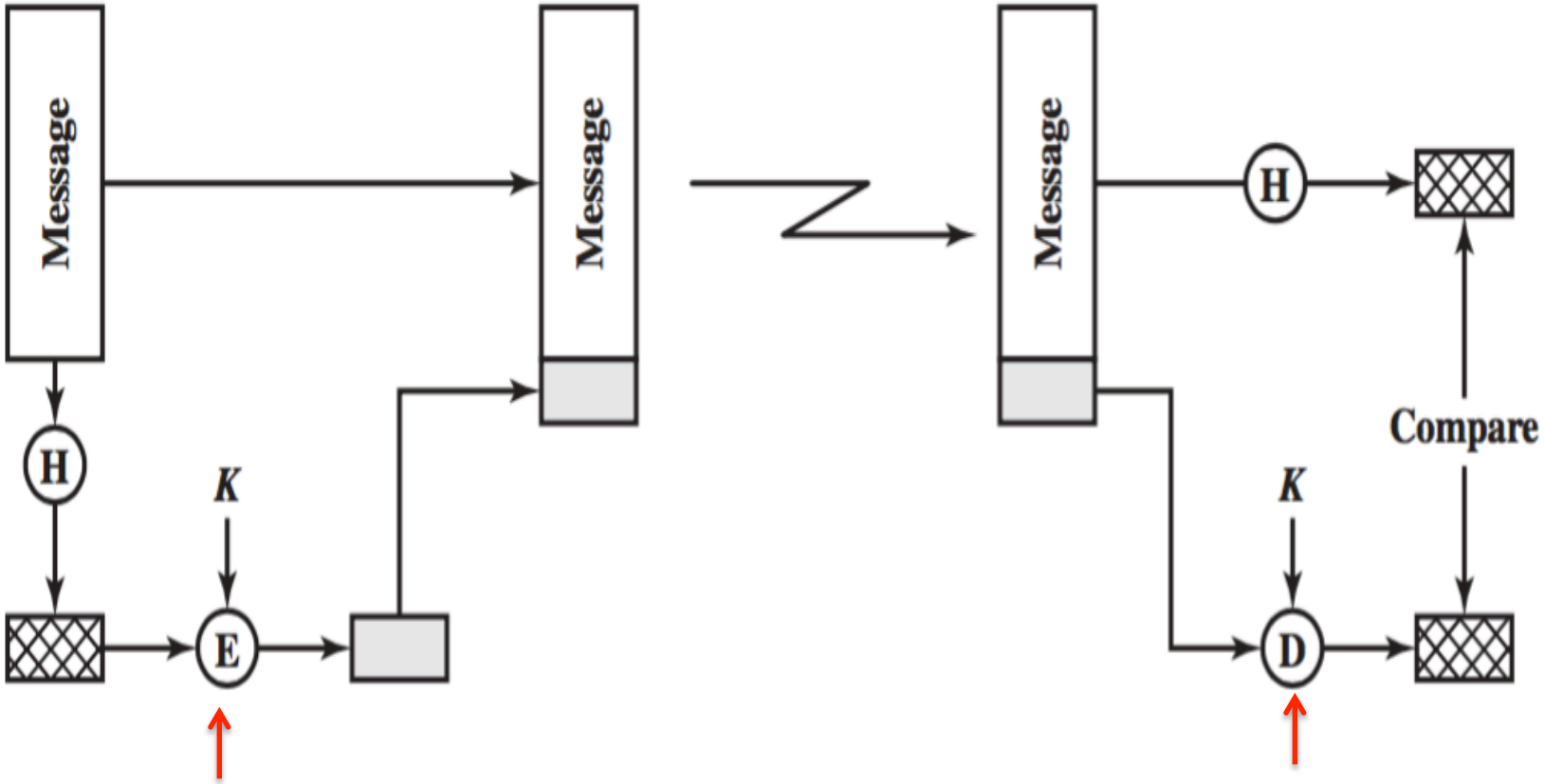
CMAC: MACs w/ Symmetric Encryption Alg.



Block Ciphers used as Hash Functions

- Without secret keys: instead using the message blocks as "keys"
- can use block ciphers as hash functions
  - using H_0=0 and zero-pad of final block
  - compute: $H_i = E_{M_i} [H_{i-1}]$
  - and use final block as the hash value
  - similar to CBC but "without" a key
- Problems ?
- resulting hash too small depending on the crypto algorithm used (ex., 64-bit using DES)
  - both due to direct birthday attack
  - and to "meet-in-the-middle" attack
- Other variants … also susceptible to attack

We must be careful [Jueneman, Matyas and Meyer] Message Authentication, IEEE Communications, Sep 1988]

Ex., Operation with CBC mode

- M = set of words of (ex., 64 bits): X1, X2, ... Xn with some standard (known) padding
- H(M) = Xn+1 = X1 xor X2 xor X3, ... Xn-1 xor Xn
- C = E (k, (M || H(M)) , using CBC
- C = Y1, Y2, Y3, ... Yn

So we need SECURE HASH FUNCTIONS

From the CBC mode we know that:

X1 = IV xor D (k, Y1), Xi = Yi-1 xor D (k, Yi)

H(M) = Xn+1 = Yn xor D (k, Yn+1)

= X1 xor X2 xor .... xor Xn

= [IV xor D(k, Y1)] xor [Y1 xor D(k, H2)] xor ....

xor [Yn-1 xor D(k, Yn)]

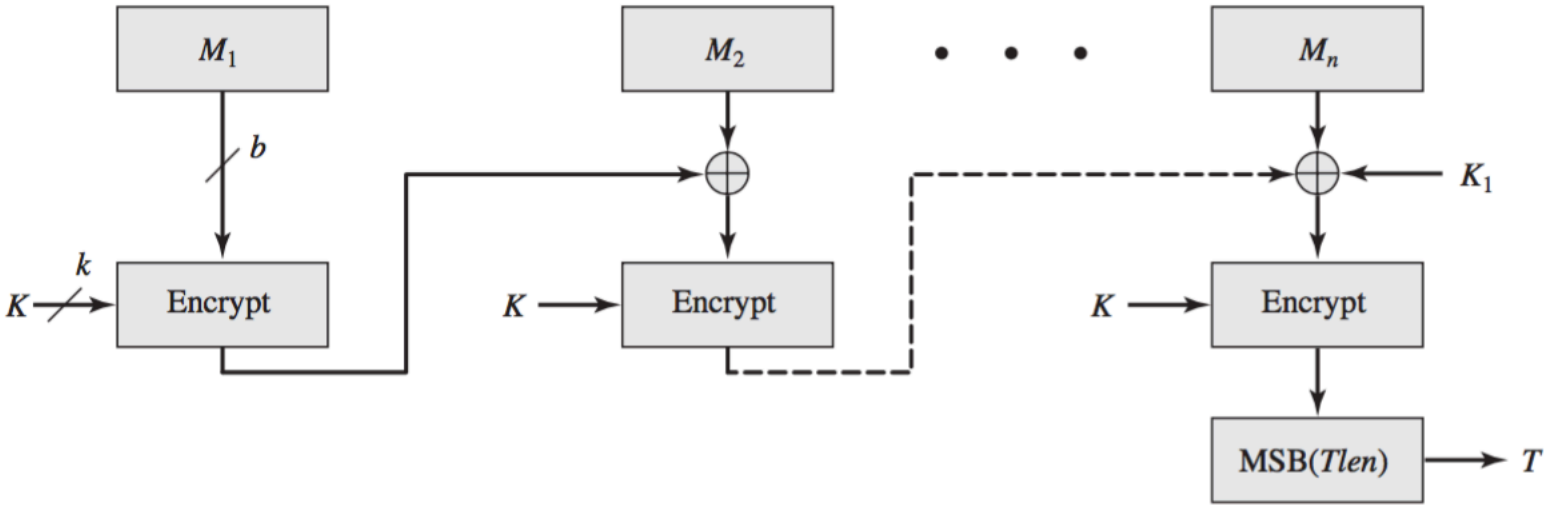
Problem ? The hash is the same if you permute the cipher text blocks (non collision resistance) !!!

CMAC based schemes

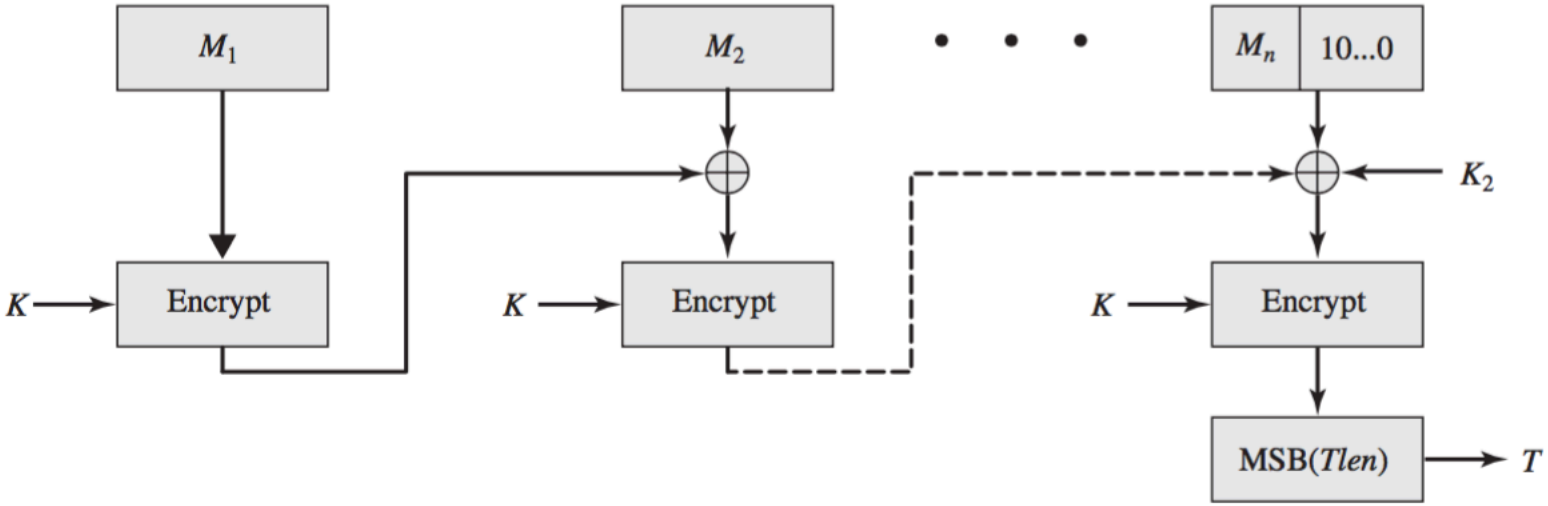
- Can use any block cipher chaining mode and use final block as a MAC
- **Data Authentication Algorithm (DAA)** was a widely used MAC based on DES-CBC (scheme known as CMAC with DES)
  - Using IV=0 and zero-pad of final block
  - Encrypt message using DES in CBC mode

    … and send just the final block as the MAC
    - or the leftmost M bits (16≤M≤64) of final block

CMAC computations



(a) Message length is integer multiple of block size



(b) Message length is not integer multiple of block size

DAA - Data Authentication Algorithm

FIPS PUB 113 / ANSI X.917 MAC (with DES-CBC)

… final MAC with DEC CBC is today considered too small for security

In general, is possible to use CMACs with other symmetric algorithms to have more strong CMACs

CMAC (NIST improvement 800-38B)

- Previously saw the DAA (CBC-MAC), widely used in govt & industry
  - But has message size limitation (DES and DES blocks)
  - **AdHoc practices** with other algorithms

- NIST standardization
- Can overcome using 2 keys & padding (use of Triple DES with two keys), thus forming a more secure Cipher-based Message Authentication Code (CMAC)
  - adopted by NIST SP800-38B for use with AES and Triple DES

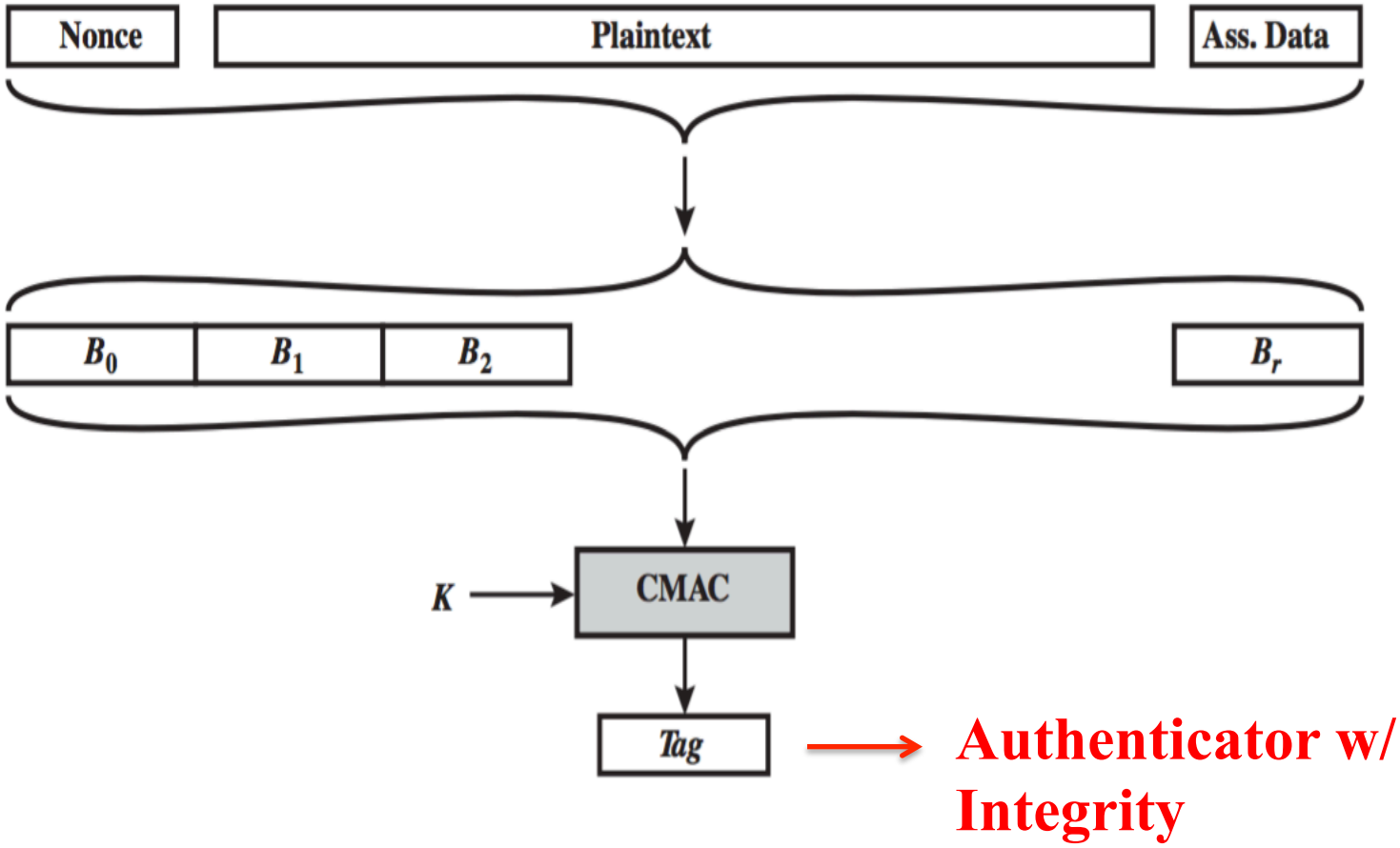
Counter with CBC MAC (NIST SP 800-38C)

- It is known as: CCM Mode

- A more recent scheme used for the combination of encryption (confidentiality) and message authentication (authentication + integrity)

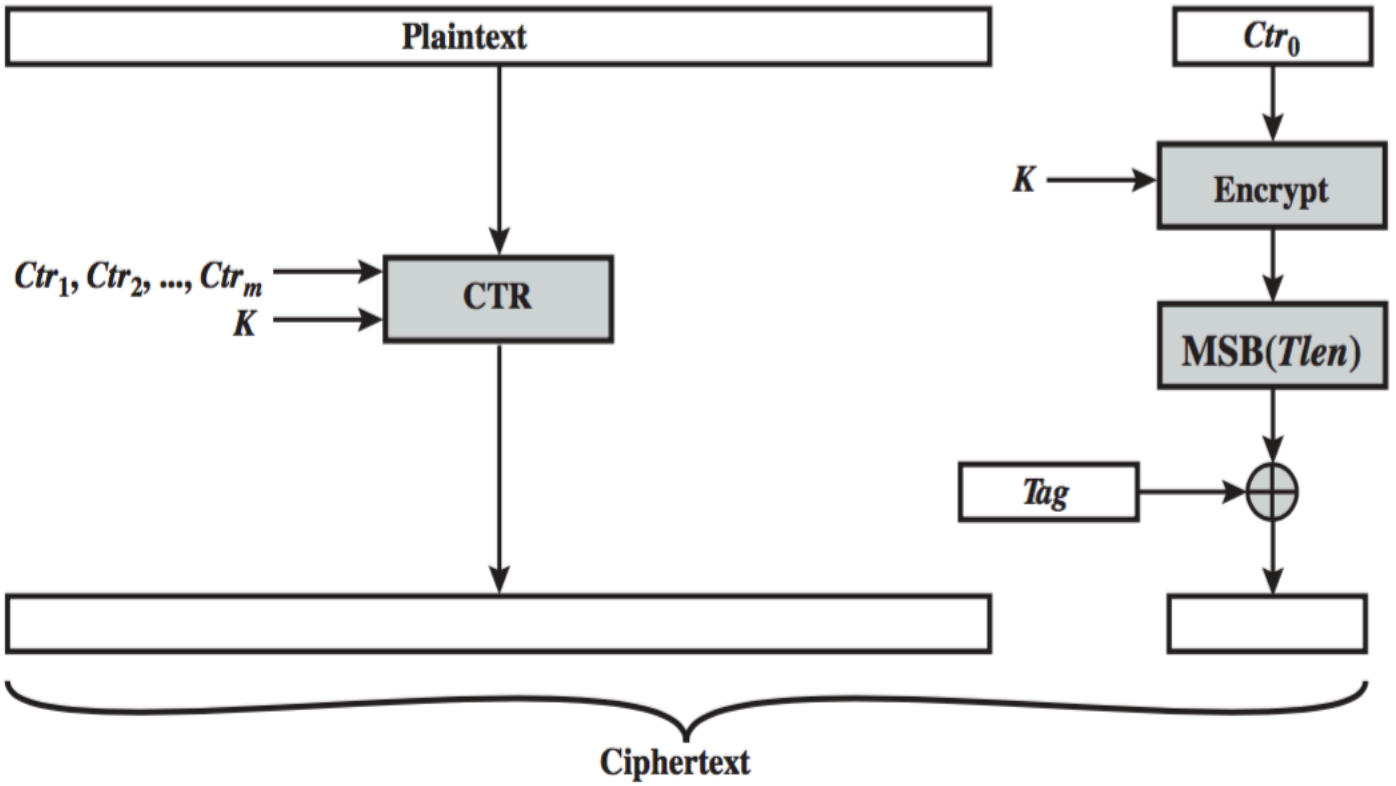
Counter with CBC MAC (NIST SP 800-38C)

- For Authentication + Integrity



Counter with CBC MAC (NIST SP 800-38C)

- Encryption with CCM



Confidentiality (with internal CMAC proof)

GCM

- Galois Mode is also a CMAC Construction combined together with encryption
- Remember the class of Symmetric Encryption
  - See Cipher Modes of Operation

So … In summary !

- We need secure hash-functions, cryptographically SAFE !
- Secure Hash Functions: Specific Family of Cryptographic Algorithms, for this specific purpose : secure hashing ! (not-keyed)
- Implementing the security properties as initially stated !

- Keyed-Hash functions, equivalent to Message Authenticatipn Codes (MACs), can use both:
  - Secure Hash Functions: HMACs
  - Symmetric Encryption Algorithms: CMACs

We discussed all this outline …

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Revision: Suggested Readings

Suggested Readings:

W. Stallings, Network Security Essentials – Applications and Standards, Chap 3., sections 3.1, 3.2

Optional Complementary Readings

Optional / Complementary Readings:

(Internals of Secure Hash Algorithms), more detail for those who are interested :

W. Stallings, Cryptography and Network Security – Principles and Practices, Pearson – Prentice Hall, Chap. 11 and 12