Symmetric Key Cryptography

PQCRYPTO Summer School on Post-Quantum Cryptography 2017

Stefan Kölbl

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DTU Compute, Technical University of Denmark

Introduction to Symmetric Key Cryptography

Symmetric Key Cryptography

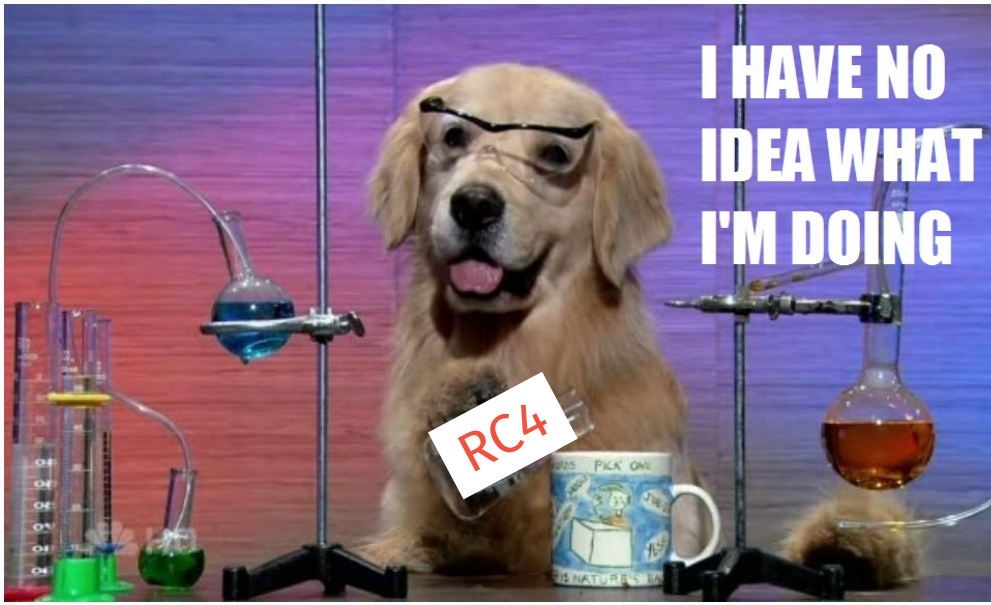
Where does security fail?

-
-
-
-

Symmetric Key Cryptography

Where does security fail?

- User
-
-
-



Don’t blame the user!

Symmetric Key Cryptography

Where does security fail?

- User
- Implementation
-
-

Heartbleed

Symmetric Key Cryptography

Where does security fail?

- User
- Implementation
- Protocols
-

Drown Attack

Symmetric Key Cryptography

Where does security fail?

- User
- Implementation
- Protocols
- Cryptographic Algorithms

Myth

”Cryptographic Algorithms are *never* the weakest link.”

Symmetric Key Cryptography

Hash Function MD5

- Not collision resistant [WY05]
- Constructing a rogue CA [Ste+09]

Hash Function SHA-1

- Not collision resistant [WYY05]
- First practical collisions this year

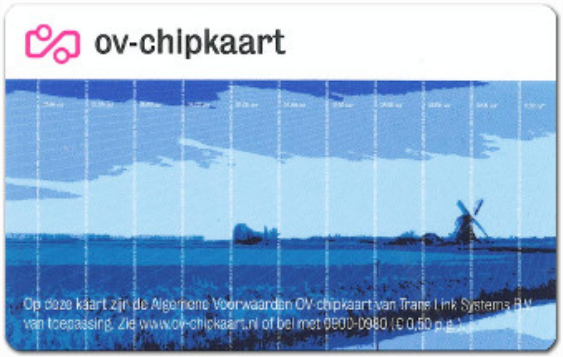
Stream Cipher RC4

- Plaintext Recovery in TLS [AlF+13]
- ...

Symmetric Key Cryptography

A long list...

- MIFARE Classic (Crypto 1)
- Keeloq
- A5/1, A5/2
- DECT
- Kindle Cipher
- ...



Symmetric Key Cryptography

What can we do?

- Encryption
- Authentication (MAC)
- Hashing
- Random Number Generation
- Digital Signature Schemes
- Key Exchange

Symmetric Key Cryptography

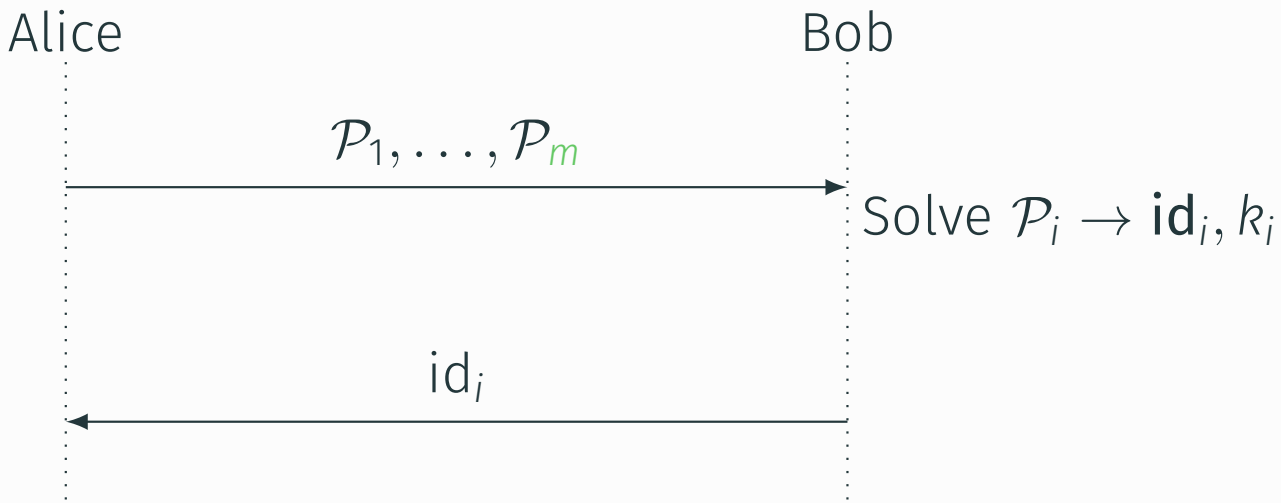
Digital Signatures

- Hash-based Signature Schemes (MSS, XMSS [BDH11], SPHINCS [Ber+15])
- Zero-Knowledge Proof Based (Fish [Cha+17], Picnic [Cha+17])

Symmetric Key Cryptography

Key Exchange with Merkle Puzzles (1978)

- Alice prepares m Puzzles: $\mathcal{P}_1, \ldots, \mathcal{P}_m$.
- Solving a puzzle requires n steps.
- Reveals an id and key k_{id}.

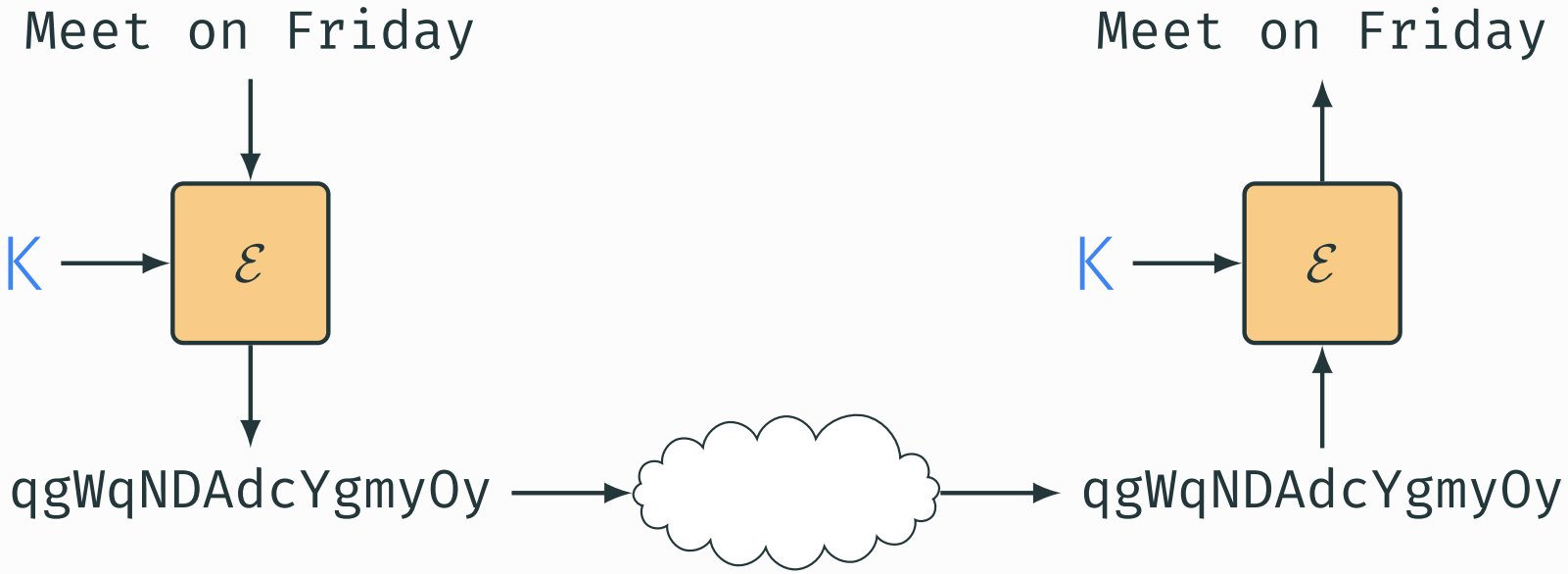


- Bob needs to compute n steps.
- Adversary needs to compute mn.

Symmetric Key Cryptography

Note

We need a shared secret between the parties.



Symmetric Key Cryptography

The adversary

- Eavesdrop on communication
- Modify transmission
- Delete/Insert messages
- ...

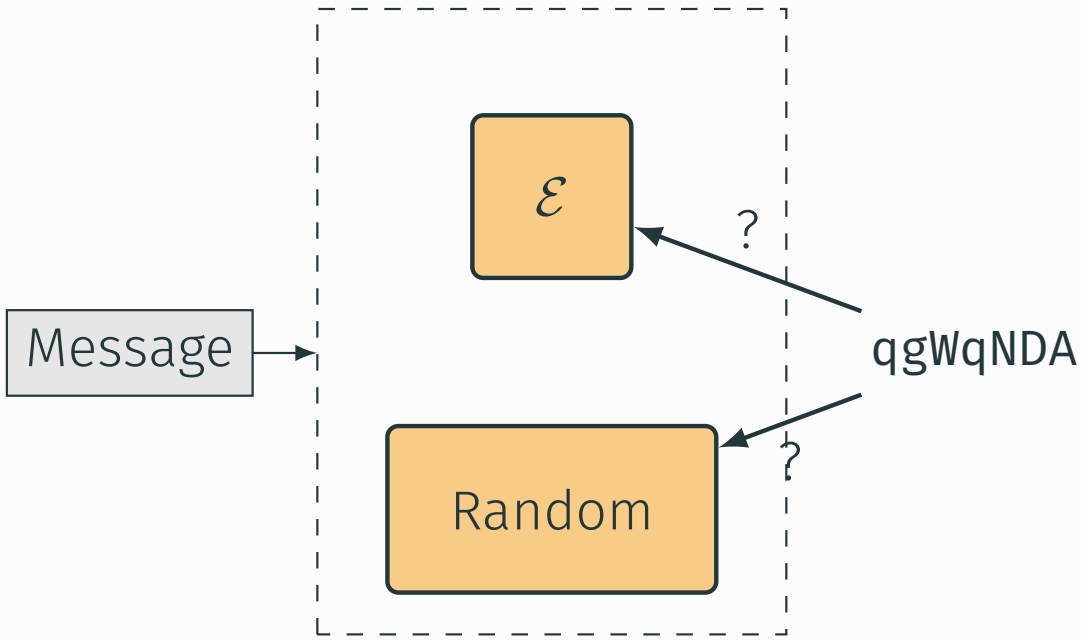
...but is bound in

- Computational power
- Available memory
- Time
- Data

Symmetric Key Cryptography

Goals of the attacker

- Decrypt a ciphertext
- Forge a signature
- Recover the secret key
- Distinguish output
- ...



Symmetric Key Cryptography

How do we achieve security for an algorithm?

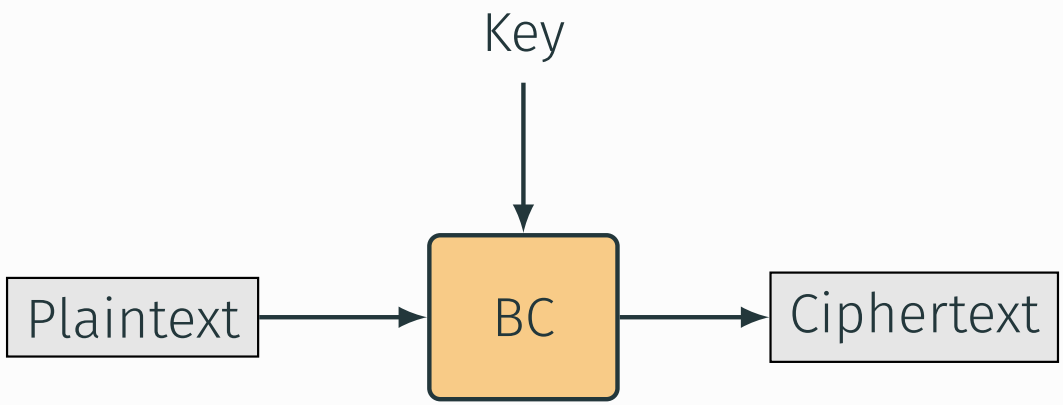
- Reduce security to a *hard* problem.
- Make it secure against all known attacks.

Note

We can **not** proof security for a primitive.

Encryption

Block Ciphers

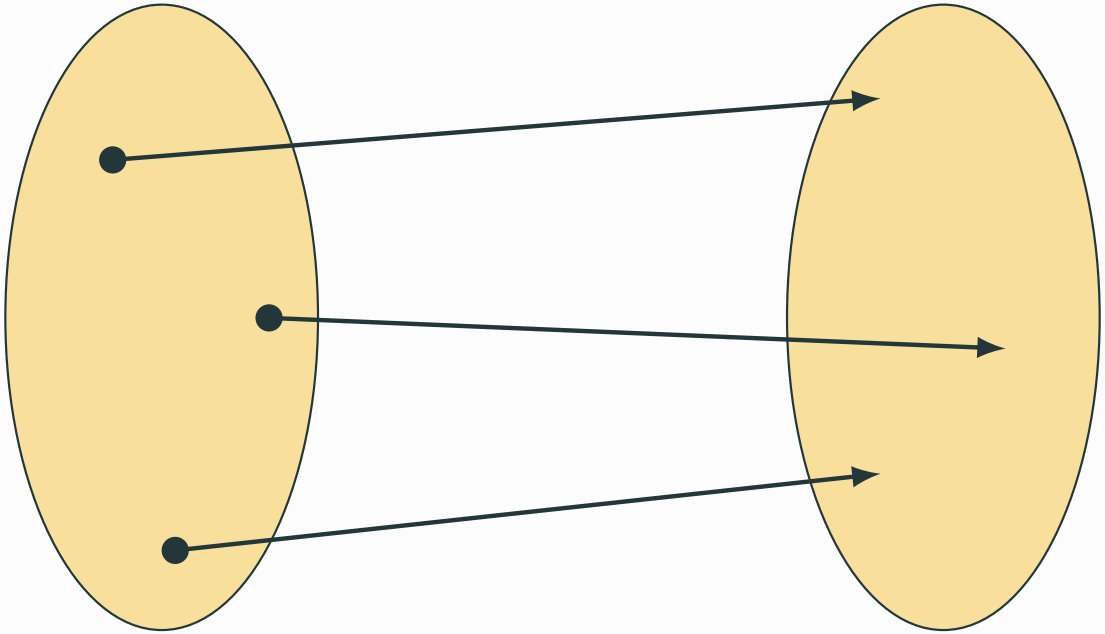


- Encrypts blocks of fixed size n with a key of size k.
- Requires a mode to encrypt arbitrary messages.

Block cipher is not an encryption scheme

Symmetric Key

Ideal Block Cipher



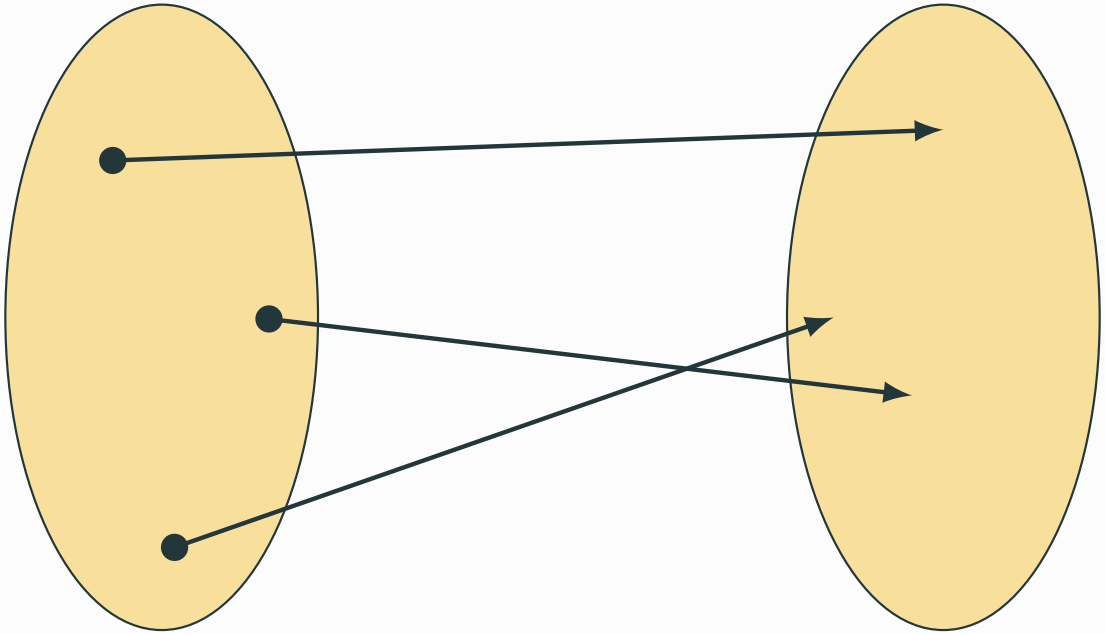
Plaintexts

Ciphertexts

$K = \texttt{101010111010...}$

Symmetric Key

Ideal Block Cipher



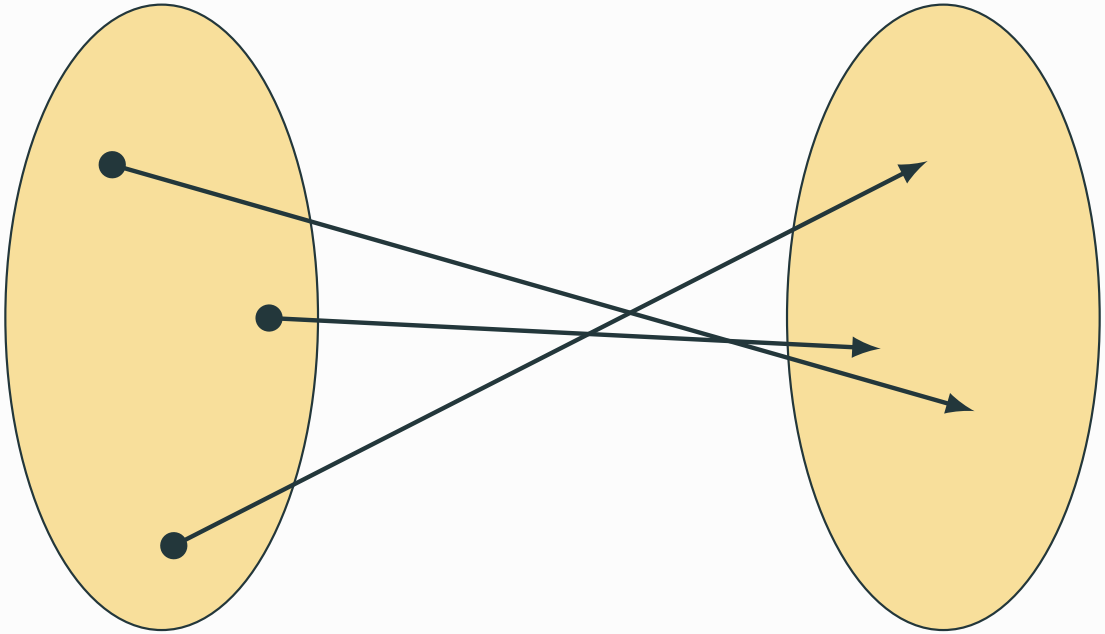
Plaintexts

Ciphertexts

$K = \texttt{001111110000...}$

Symmetric Key

Ideal Block Cipher



Plaintexts

Ciphertexts

$K = \texttt{111111001000...}$

Block Ciphers

A block cipher can be seen as a family of 2^k n-bit bijections.

Problem

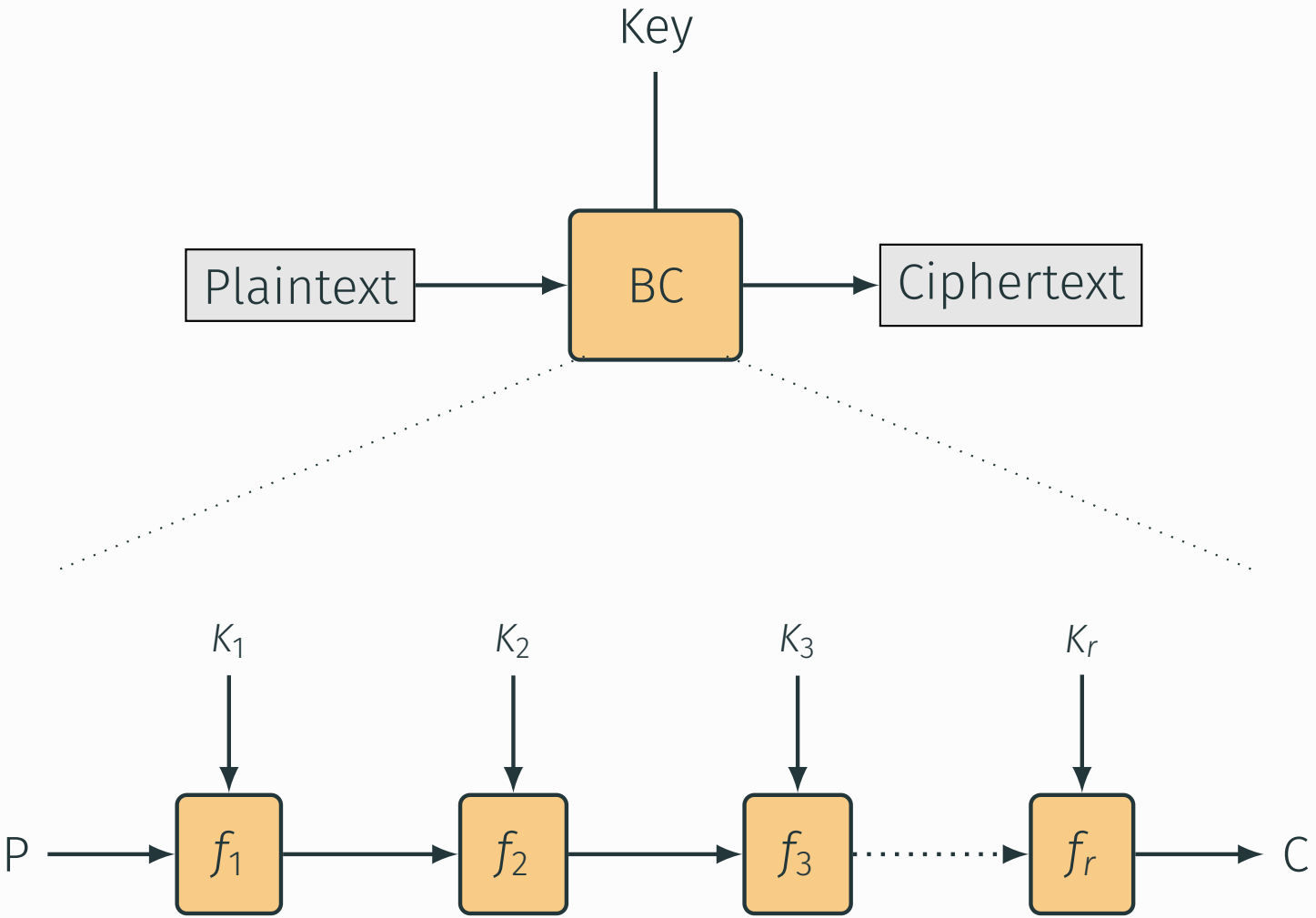
There are $2^n!$ bijections, we ideally want to choose 2^k uniformly at random.

Goal

We need something **efficient** to mimic this behaviour.

Block Ciphers

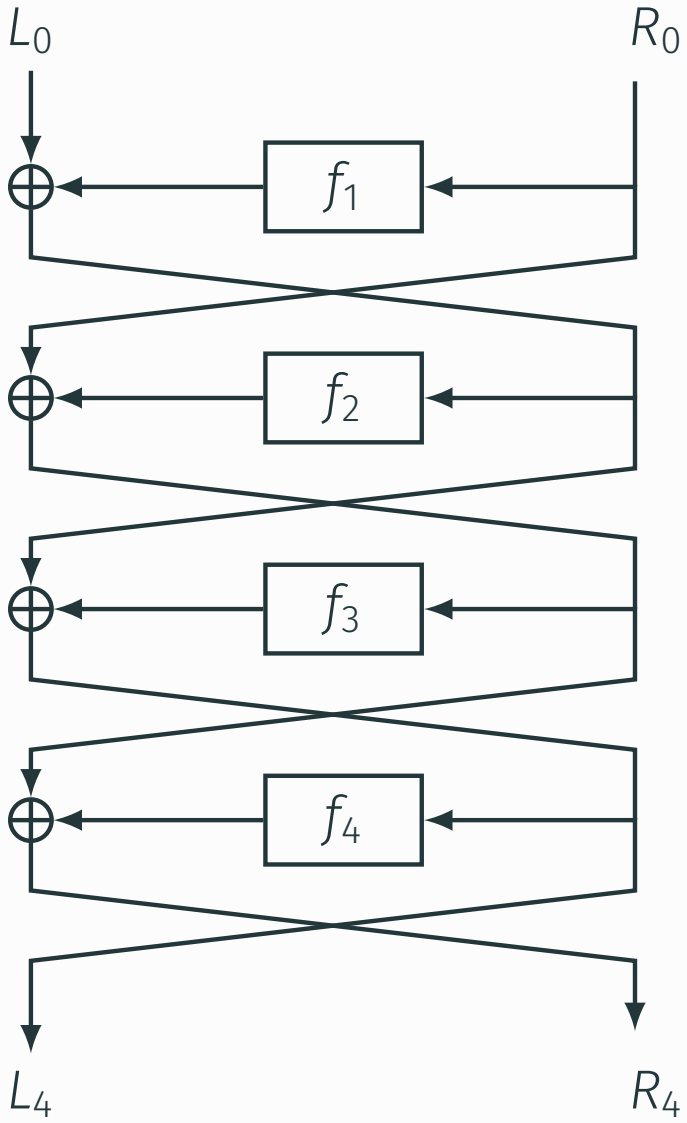
Iterated construction



Symmetric Key Cryptography

The Data Encryption Standard

- Developed in 1970s at IBM.
- Feistel Network with 16 rounds.
- Encrypts 64-bit blocks with 56-bit keys.
- Standardized in 1977.



Symmetric Key Cryptography

The Advanced Encryption Standard (AES)

- Public Competition hosted by NIST (1997-2001)
- Must support block size of 128 bits and key size of 128, 192 and 256 bits.

- CAST-256
- CRYPTON
- DEAL
- DFC
- E2
- FROG
- HPC
- LOKI97
- MAGENTA
- MARS
- RC6
- Rijndael
- SAFER+
- Serpent
- Twofish

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Block Ciphers

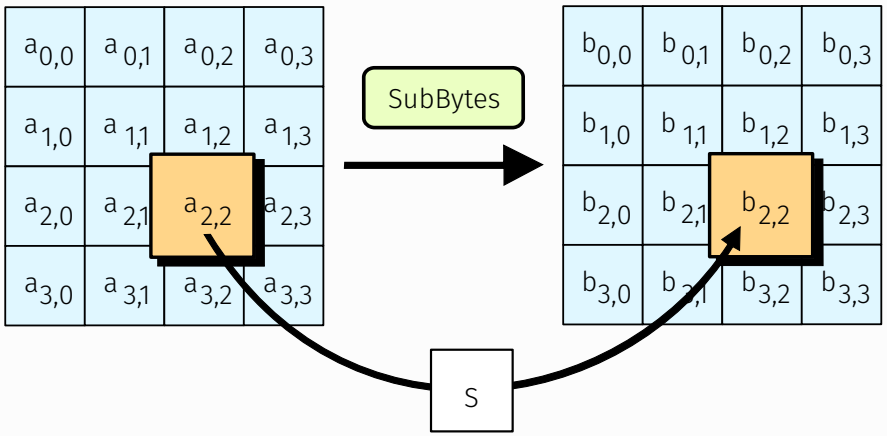
AES/Rijndael

- Blocksize: 128-bit
- Keysize: 128/192/256 bits
- Iterated block cipher with 10/12/14 rounds
- Is part of a wide-range of standards.
- Direct support by instructions in modern CPUs.

Block Ciphers

Update 4×4 state of bytes

- SubBytes
- ShiftRows
- MixColumns
- AddKey



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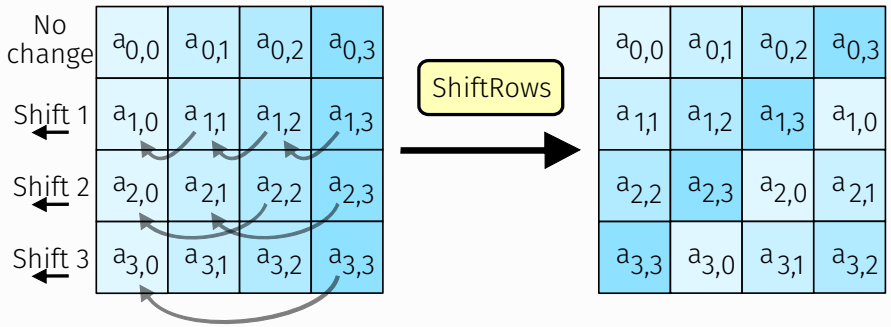

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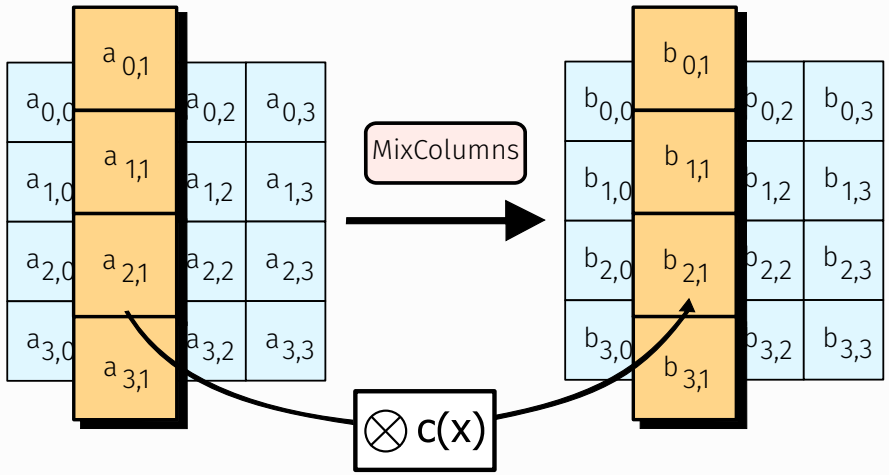

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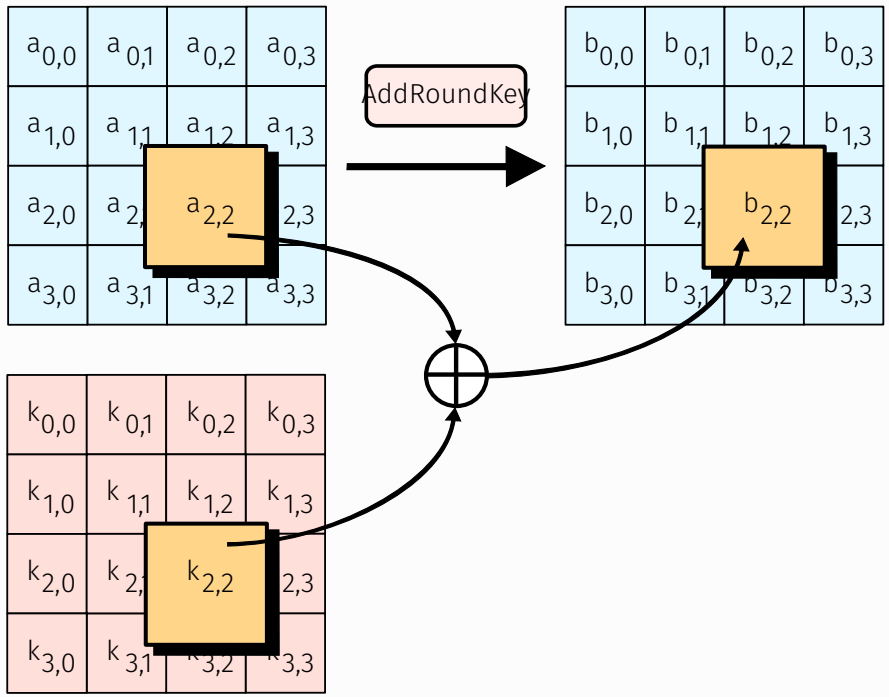
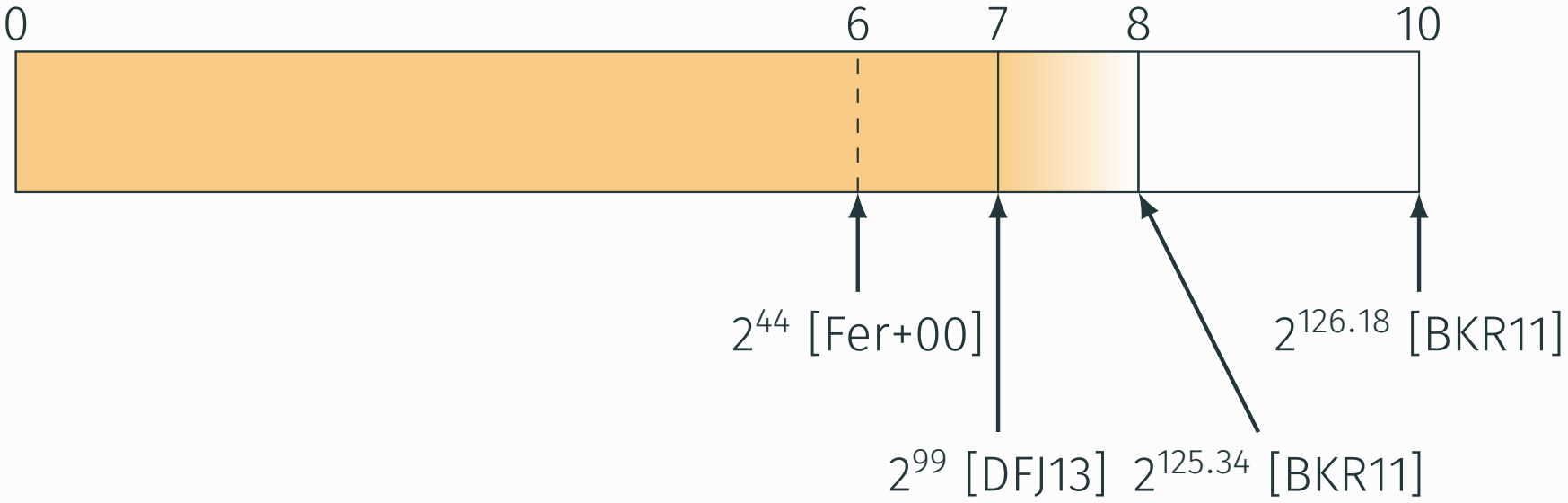


Block Ciphers

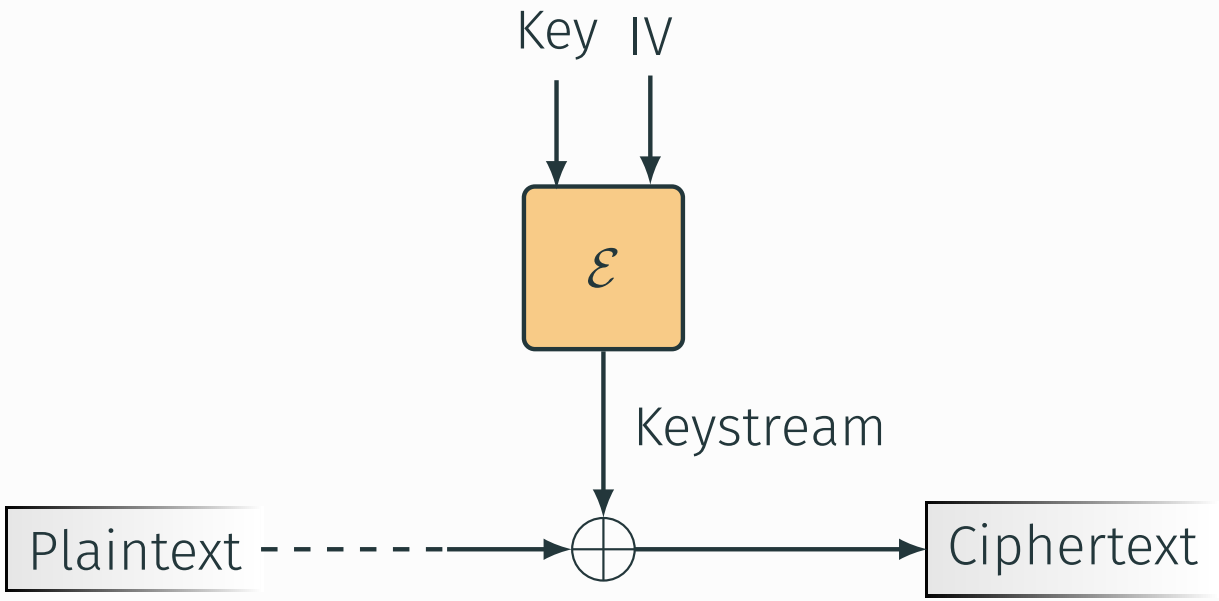
Current state of key recovery attacks for AES-128



There are many more attacks with different trade-offs of time/data/memory.

Stream Ciphers

Stream Ciphers



- Encrypts individual *digits*.
- IV to have multiple key stream for each K
- Requires no padding.
- Often used for low-bandwidth communication.

Stream Ciphers

Widely found in practice

- GSM standard (A5/1, A5/2)
- LTE (SNOW 3G, ZUC)
- Bluetooth (E0)
- TLS protocol (RC4, ChaCha20)

Stream Ciphers

eSTREAM Project (EU)

Goal

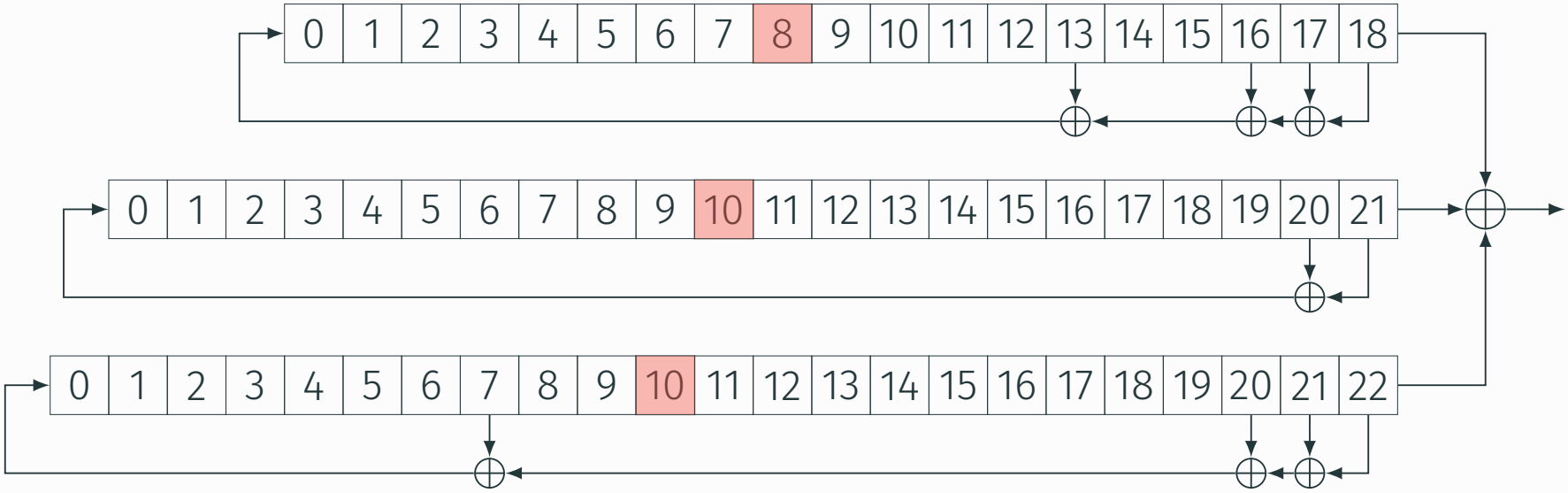
...promote the design of efficient and compact stream ciphers suitable for widespread adoption...

Software	Hardware
HC-128	Grain v1
Rabbit	MICKEY 2.0
Salsa20/12	Trivium
SOSEMANUK	

Stream Ciphers

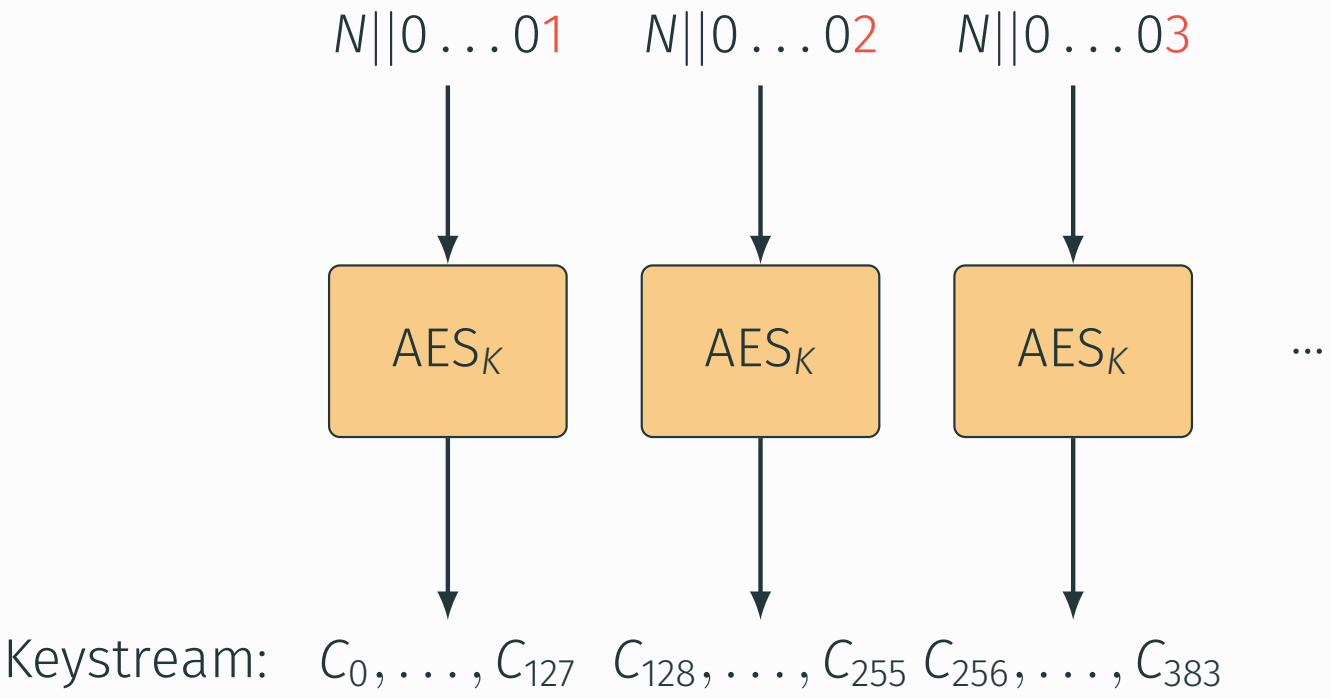
LFSR-based Constructions, e.g. A5/1

- Load IV and Key in registers.
- Shift registers depending on values in ■.
- Produces 1-bit output in each iteration.



Stream Ciphers

Counter Mode (CTR)



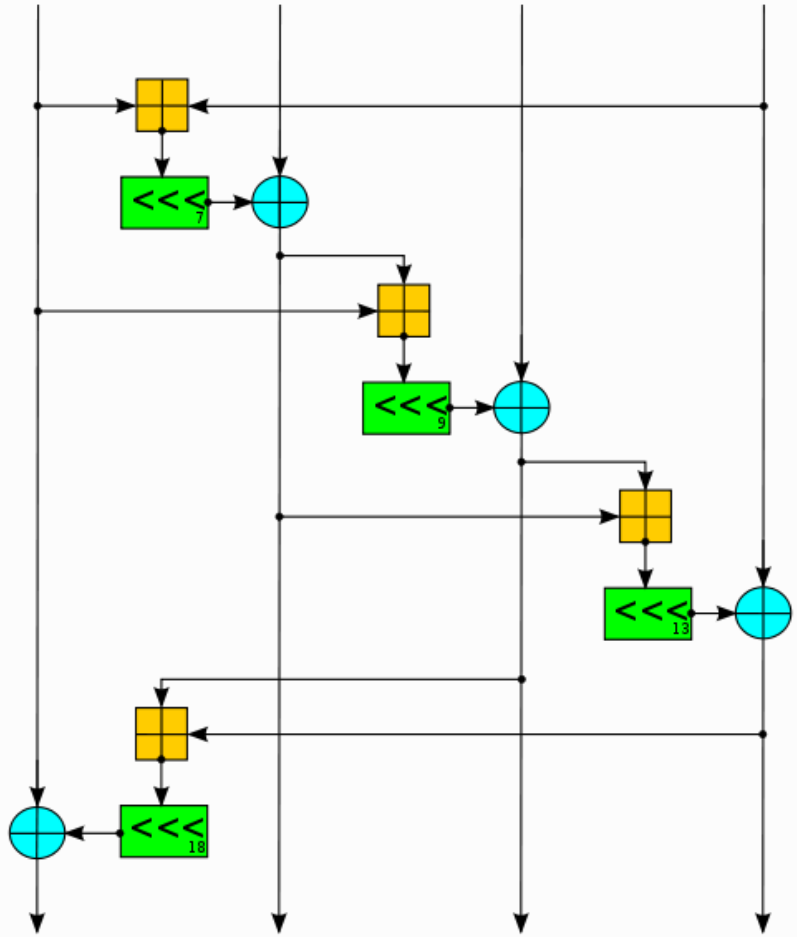
Note

Reusing nonce and counter gives same keystream.

Stream Ciphers

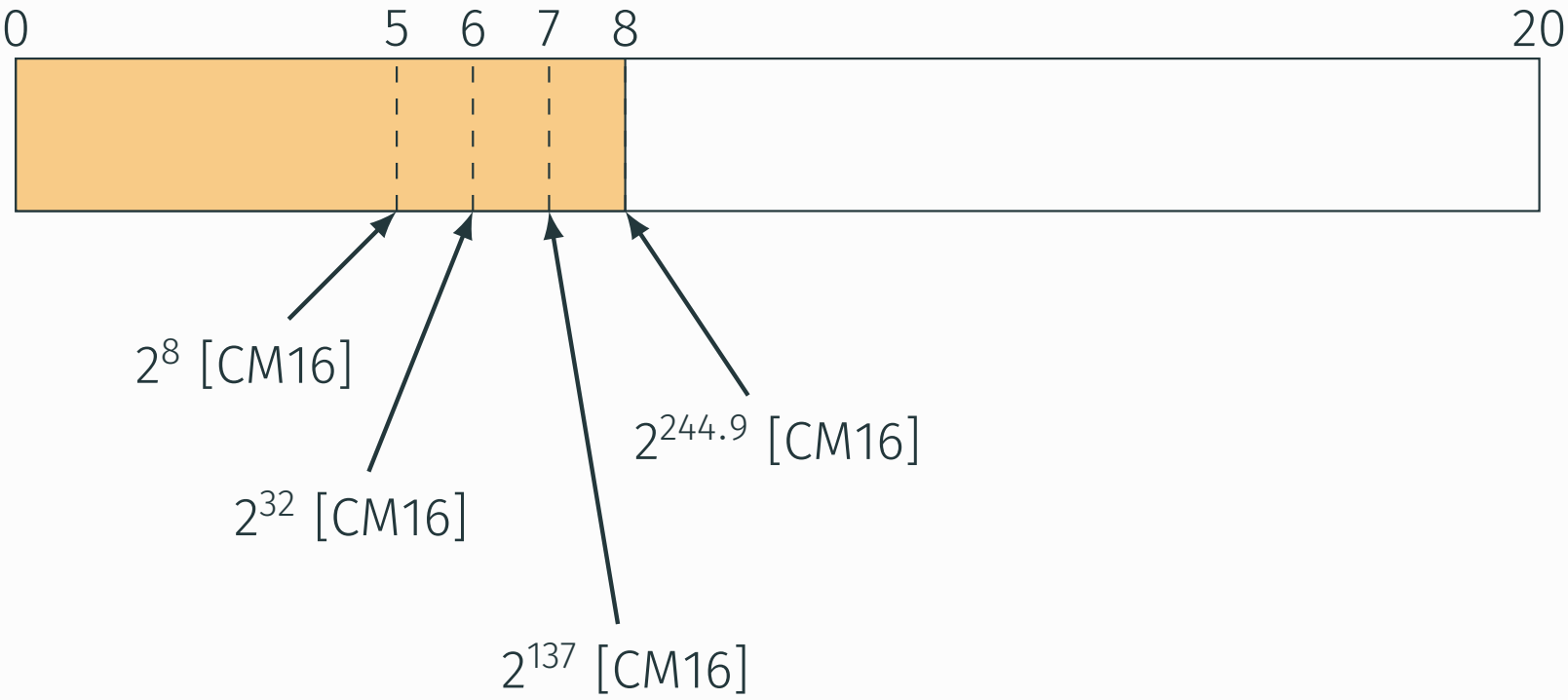
Salsa20 / ChaCha20

- ARX-based design
- 512-bit state
- Uses 256-bit key
- 20 rounds
- Fast in software
- ChaCha20-Poly1305 in TLS



Stream Ciphers

Current state of key recovery attacks for Salsa20

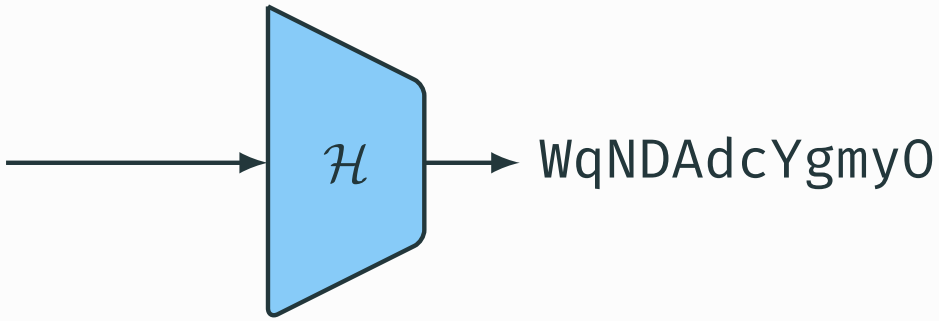


For ChaCha typically one round less.

Cryptographic Hash Functions

Hash Functions

”There was of course no way of knowing whether you were being watched at any given moment. How often, or on what system, the Thought Police plugged in on any individual wire was guesswork. It was even conceivable that they watched everybody all the time. But at any rate they could plug in your wire whenever they wanted to. You had to live – did live, from habit that became instinct – in the assumption that every sound you made was overheard, and, except in darkness, every movement scrutinized.”



Hash Functions

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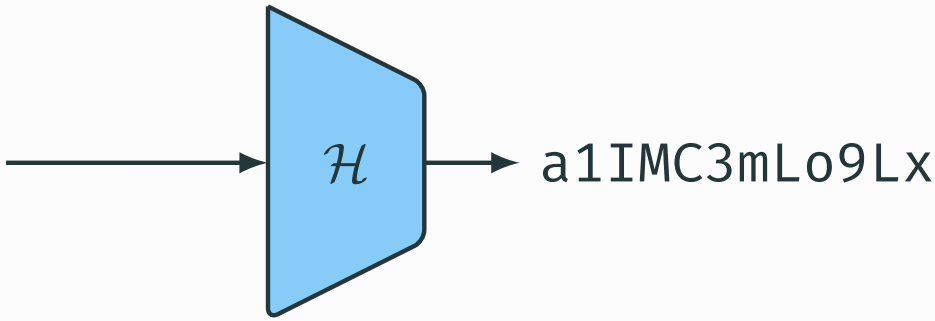


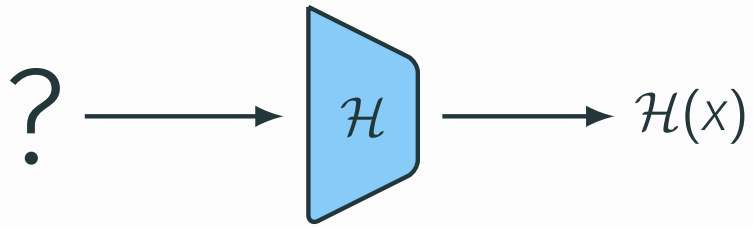
Hash Functions

Applications

- Integrity Check
- Digital Signature Schemes (this afternoon)
- Password Hashing (`https://password-hashing.net/`)
- Message Authentication
- Commitment Schemes
- ...

Hash Functions

Preimage Resistance

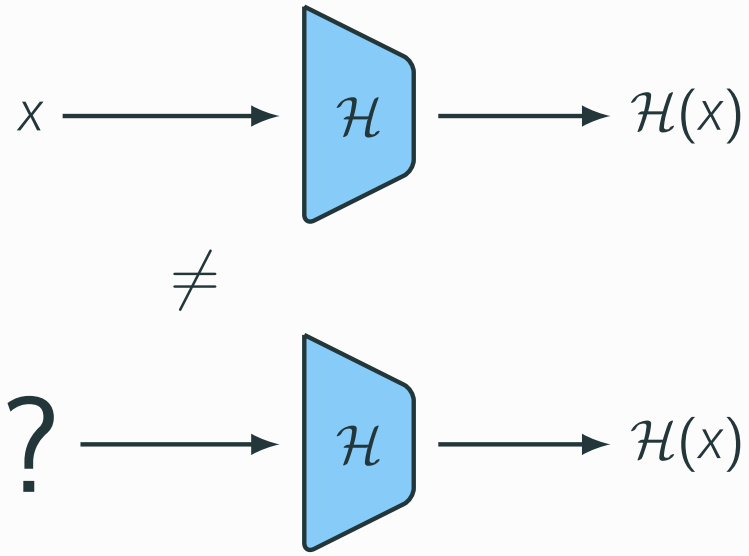


For n-bit output size

- Best attack: 2^n

Hash Functions

Second-Preimage Resistance

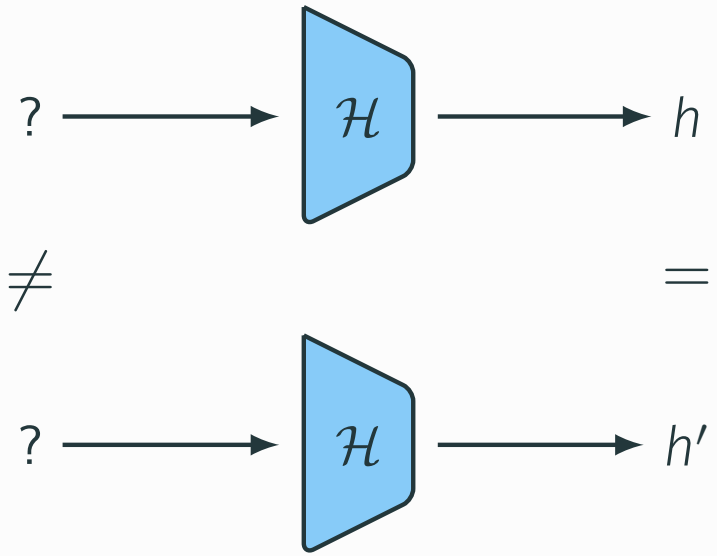


For n-bit output size

- Best attack: 2^n

Hash Functions

Collision Resistance



For n-bit output size

- Best attack: $2^{n/2}$

Hash Functions

Hardness of finding collision vs. preimages in practice

Algorithm	Year	n	Collision	Preimage
MD4	1990	128	< 1 sec	
MD5	1992	128	< 1 sec	
SHA-1	1995	160	2^{63}	
SHA-256	2001	256	$2^{65.5}$ 31/64 rounds	

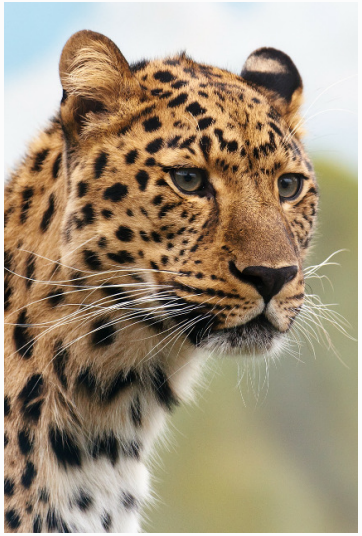
Hash Functions

Hardness of finding collision vs. preimages in practice

Algorithm	Year	n	Collision	Preimage
MD4	1990	128	< 1 sec	$2^{78.4}$ [Guo+10]
MD5	1992	128	< 1 sec	$2^{123.4}$ [SA09]
SHA-1	1995	160	2^{63}	$2^{151.1}$ [KK12] 57/80 rounds
SHA-256	2001	256	$2^{65.5}$ 31/64 rounds	$2^{255.5}$ [KRS12] 45/64 rounds

Hash Functions

Requirements for security and performance can vary on application.



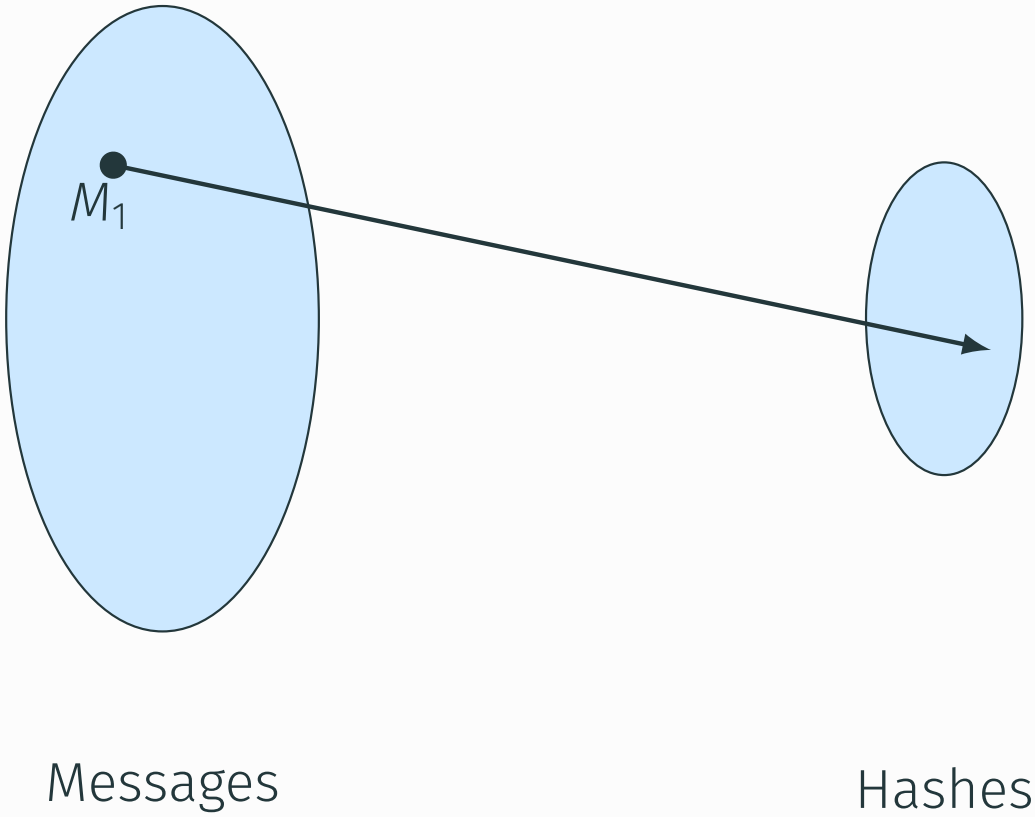
Performance on long/short messages.

Password Hashing should be slow!

Collision resistance not required!

Hash Functions

Ideal Hash Function



Hash Functions

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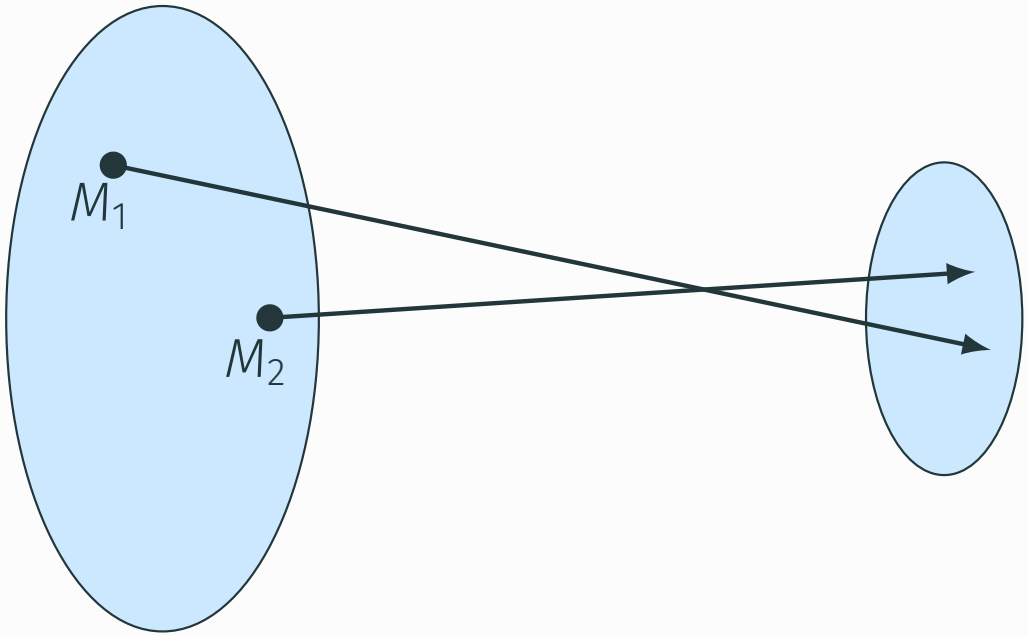

Hash Functions

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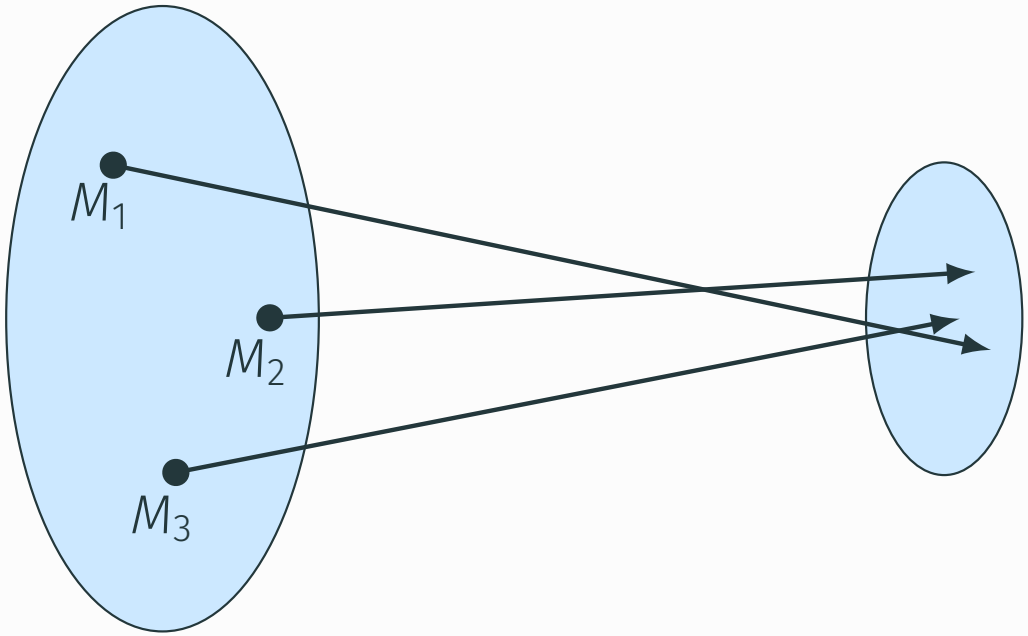


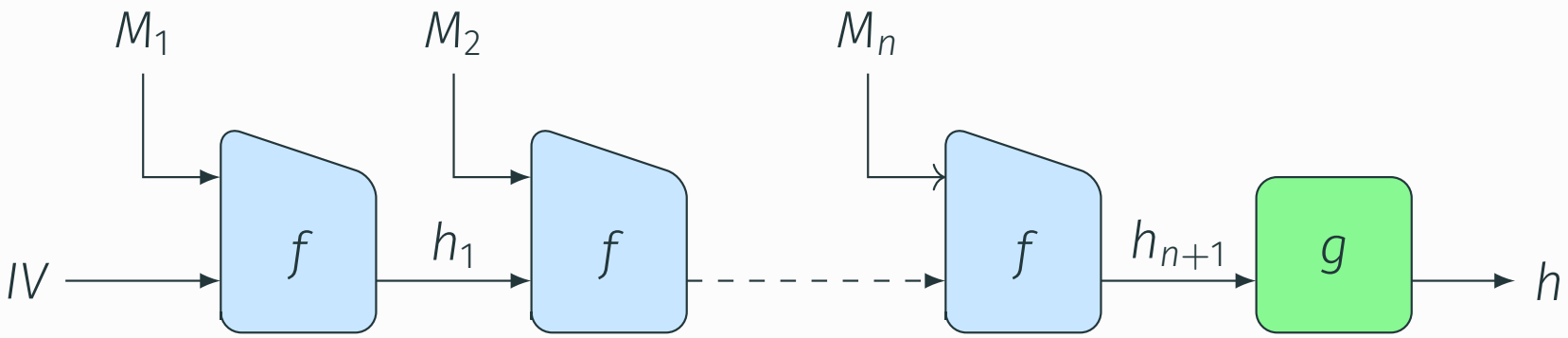
Messages

Hashes

Hash Functions

How to construct a hash function?

- Merkle-Damgård with compression function (SHA-1, SHA-2)



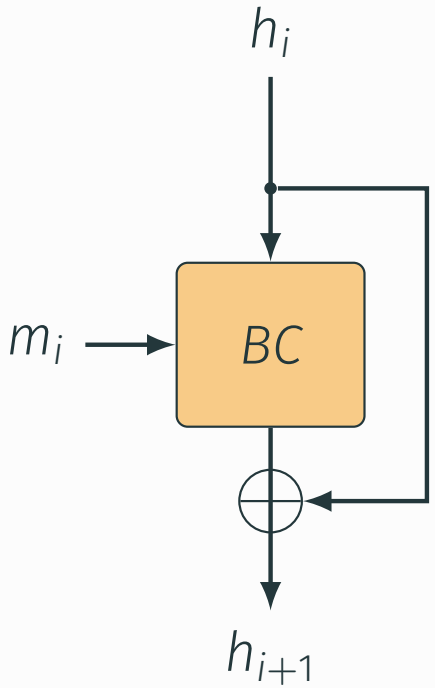
Problem

How do we construct the compression function?

Hash Functions

How to construct a hash function?

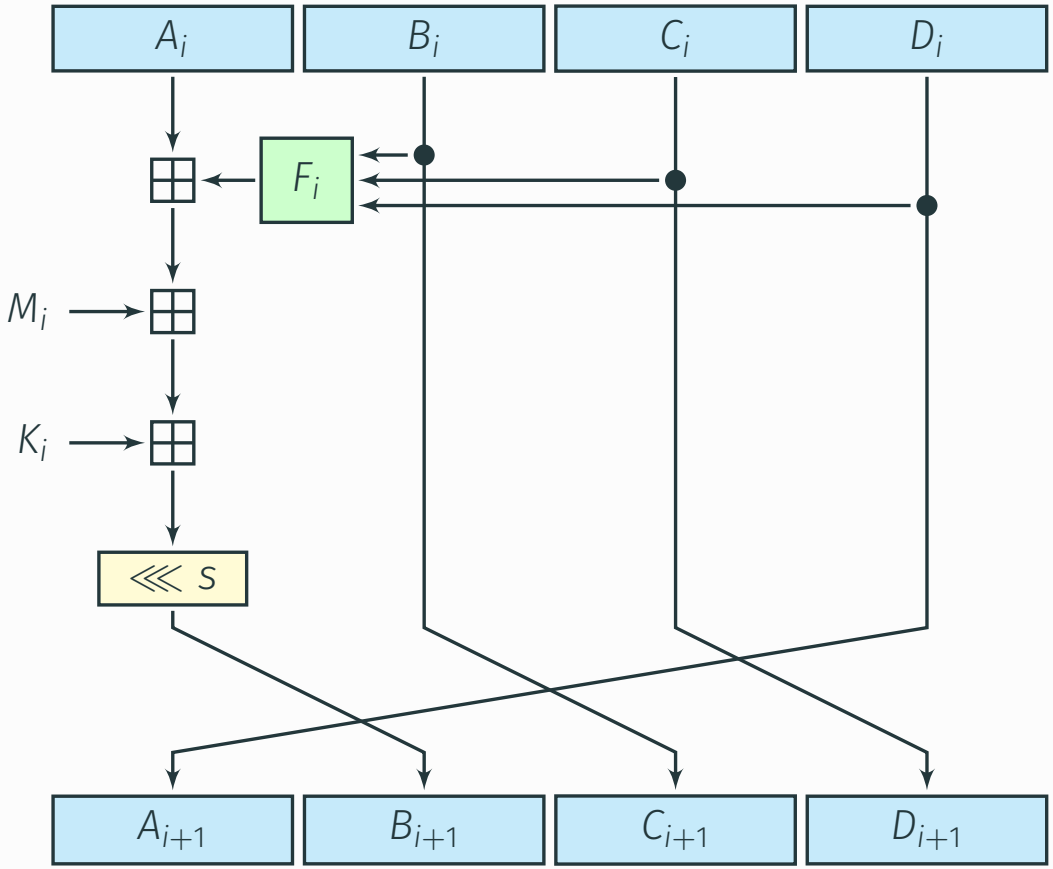
- Merkle-Damgård with compression function (SHA-1, SHA-2)



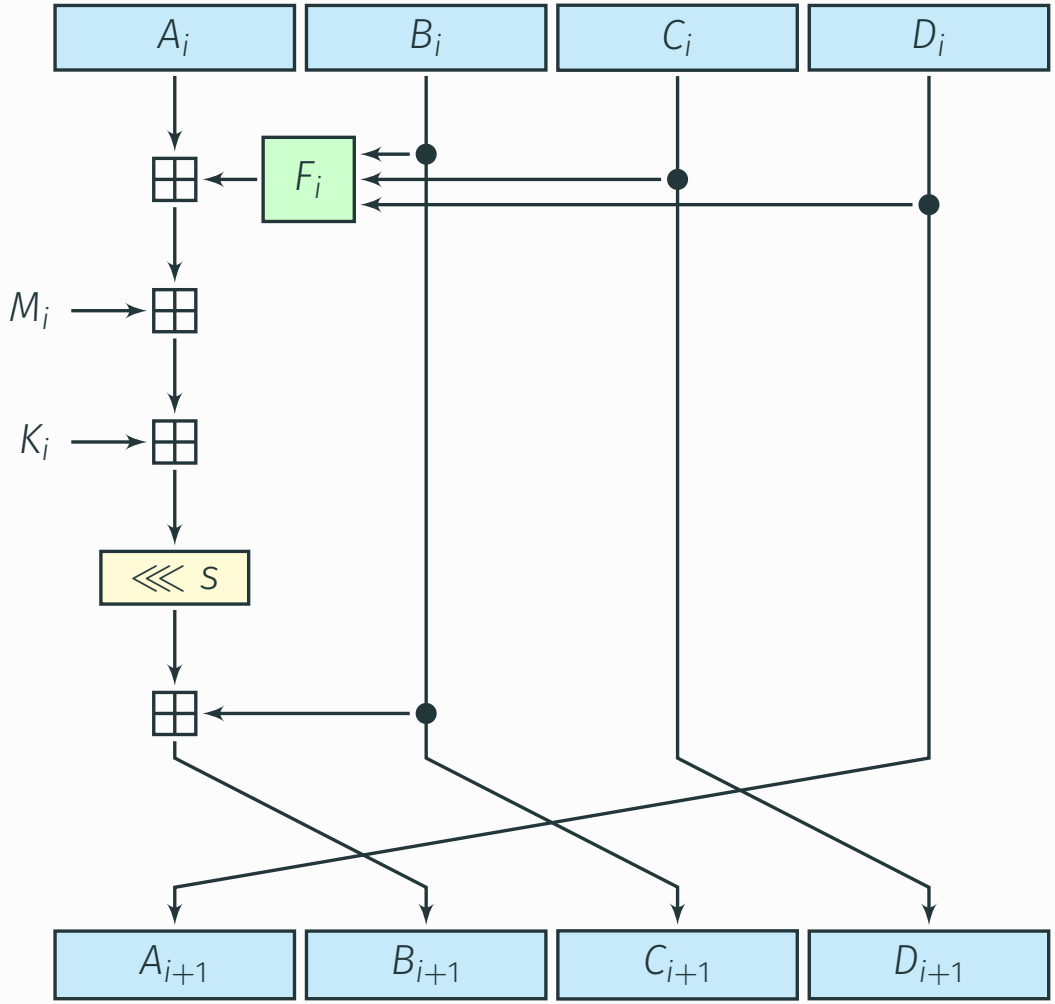
Solution

Use a block cipher! … but often state is too small.

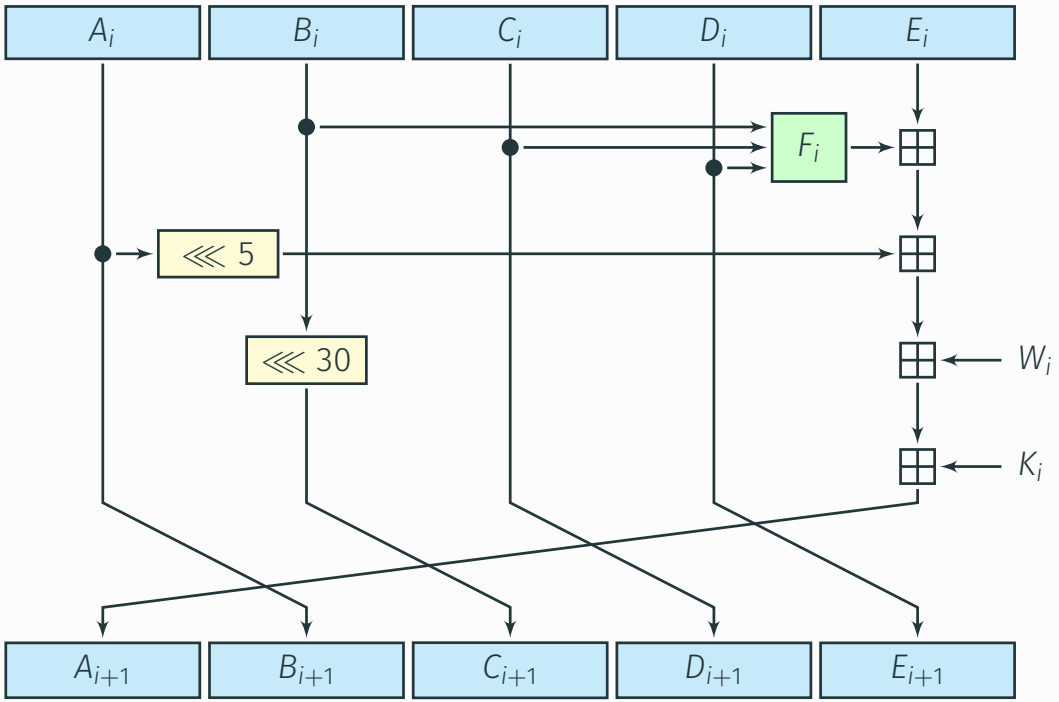
Compression Function Design (MD4)



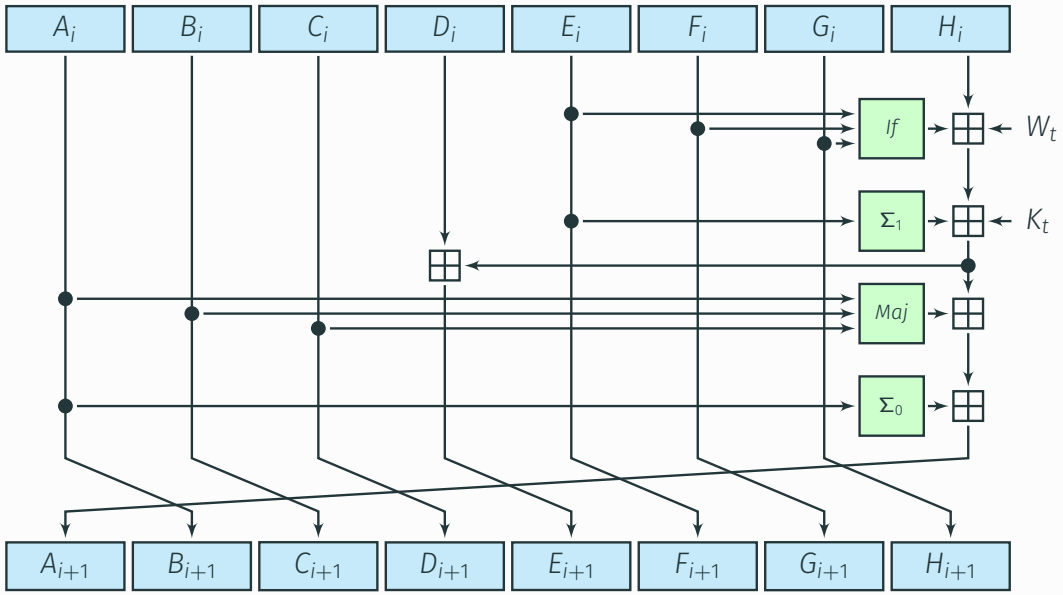
Compression Function Design (MD5)



Compression Function Design (SHA-1)



Compression Function Design (SHA-2)



Hash Functions

The 2005 Hash Crisis

- Wang and Yu show that MD5 is not collision resistant [WY05]...
- ... and SHA-1 isn't either [WYY05].
- Concerns that SHA-2 will also fail.

Hash Functions

The SHA-3 Competition

- Public Competition to find a new standard SHA-3.
- From 2007 to 2012

- Abacus
- ARIRANG
- AURORA
- Blake
- Blender
- Blue Midnight Wish
- Boole
- Cheetah
- CHI
- CRUNCH
- CubeHash
- DCH
- Dynamic SHA
- Dynamic SHA2
- ECHO
- ECOH
- Edon-R
- EnRUPT
- ESSENCE
- FSB
- Fugue
- Grøstl
- Hamsi
- HASH 2X
- JH
- Keccak
- Khichidi-1
- LANE
- Lesamnta
- Luffa
- LUX
- Maraca
- MCSSHA-3
- MD6
- MeshHash
- NaSHA
- NKS2D
- Ponic
- SANDstorm
- Sarmal
- Sgàil
- Shabal
- SHAMATA
- SHAvite-3
- SIMD
- Skein
- Spectral Hash
- StreamHash
- SWIFFTX
- Tangle
- TIB3
- Twister
- Vortex
- WaMM
- Waterfall
- ZK-Crypt

Hash Functions

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- CHI
- CRUNCH
- CubeHash
- DCH
- Dynamic SHA
- Dynamic SHA2
- ECHO
- ECOH
- Edon-R
- EnRUPT
- ESSENCE
- FSB
- Fugue
- **Grøstl**
- Hamsi
- HASH 2X
- **JH**
- **Keccak**
- Khichidi-1
- LANE
- Lesamnta
- Luffa
- LUX
- Maraca
- MCSSHA-3
- MD6
- MeshHash
- NaSHA
- NKS2D
- Ponic
- SANDstorm
- Sarmal
- Sgàil
- Shabal
- SHAMATA
- SHAvite-3
- SIMD
- **Skein**
- Spectral Hash
- StreamHash
- SWIFFTX
- Tangle
- TIB3
- Twister
- Vortex
- WaMM
- Waterfall
- ZK-Crypt

Hash Functions

The SHA-3 Competition

- Public Competition to find a new standard SHA-3.
- From 2007 to 2012

- Abacus
- ARIRANG
- AURORA
- Blake
- Blender
- Blue Midnight Wish
- Boole
- Cheetah
- CHI
- CRUNCH
- CubeHash
- DCH
- Dynamic SHA
- Dynamic SHA2
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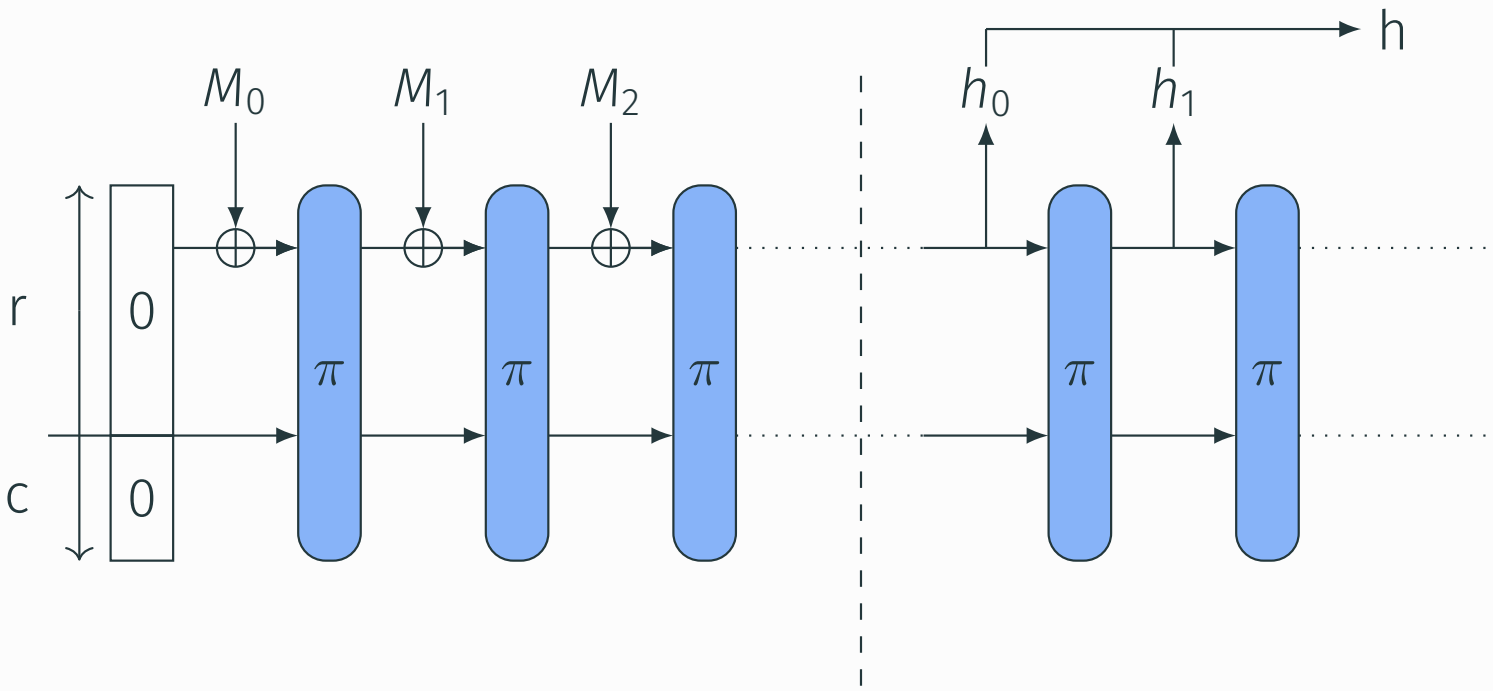
Hash Functions

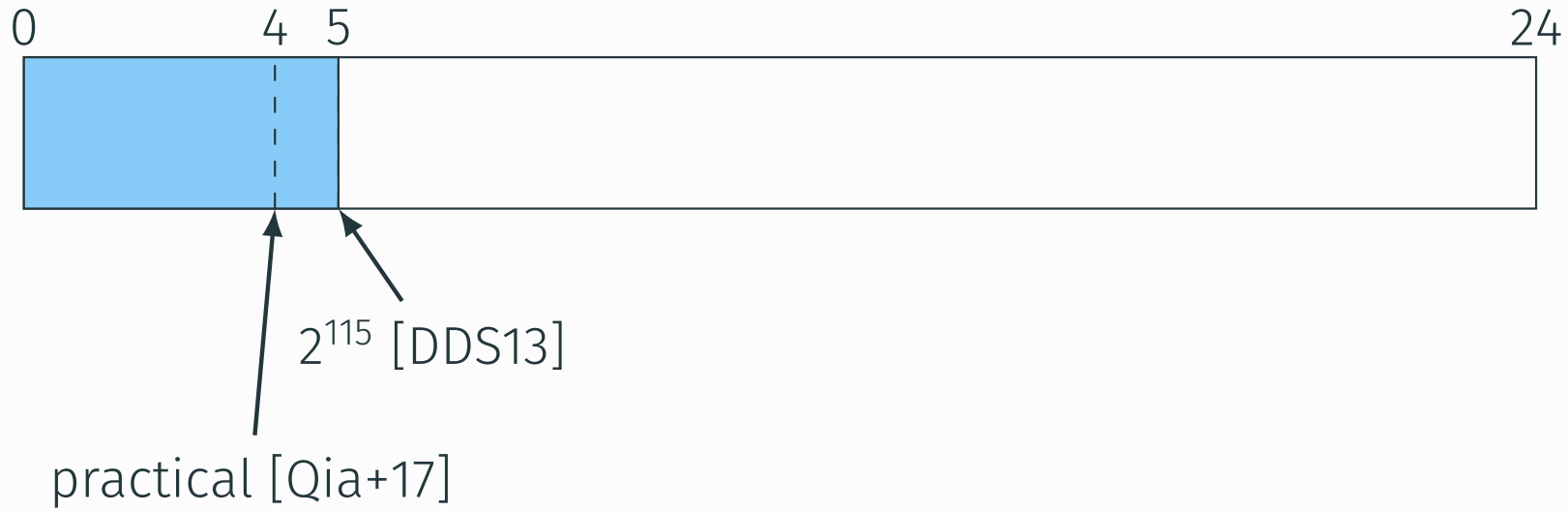
SHA-3 Winner Keccak



- Based on the sponge construction.
- Uses 1600-bit permutation π.
- Parameters: rate r and capacity c.
- Security claim of $2^{c/2}$.

Hash Functions

SHA3-256 ($c = 512$) collision resistance



Practical Attacks for $c = 160$[1]:

- Collisions for 6 rounds
- Preimages for 4 rounds

[1] http://keccak.noekeon.org/crunchy_contest.html

Hash Functions

What should you use now?

> *"We don't need another slow, secure hash function—we've already got SHA-2."*
> —Adam Langley, Mar. 2017[2]

SHA-3 standard too conservative?[3]

- Use different parameters.
- Tree hashing mode for better performance.
- RFC for Kangaroo12[4]

[2] https://www.imperialviolet.org/2017/05/31/skipsha3.html
[3] http://keccak.noekeon.org/is_sha3_slow.html
[4] https://tools.ietf.org/html/draft-viguier-kangarootwelve-00

Symmetric Key Cryptography

What can we do?

- Encryption
- Authentication (MAC)
- Hashing
- Random Number Generation
- Digital Signature Schemes
- Key Exchange

Questions?

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