Karlsruhe Institute of Technology

Resilient Networking

Disclaimer: Some parts have been inspired by Dan Boneh/Mark Manulis

Module 2b – Background on Crypto (Winter Term 2020)

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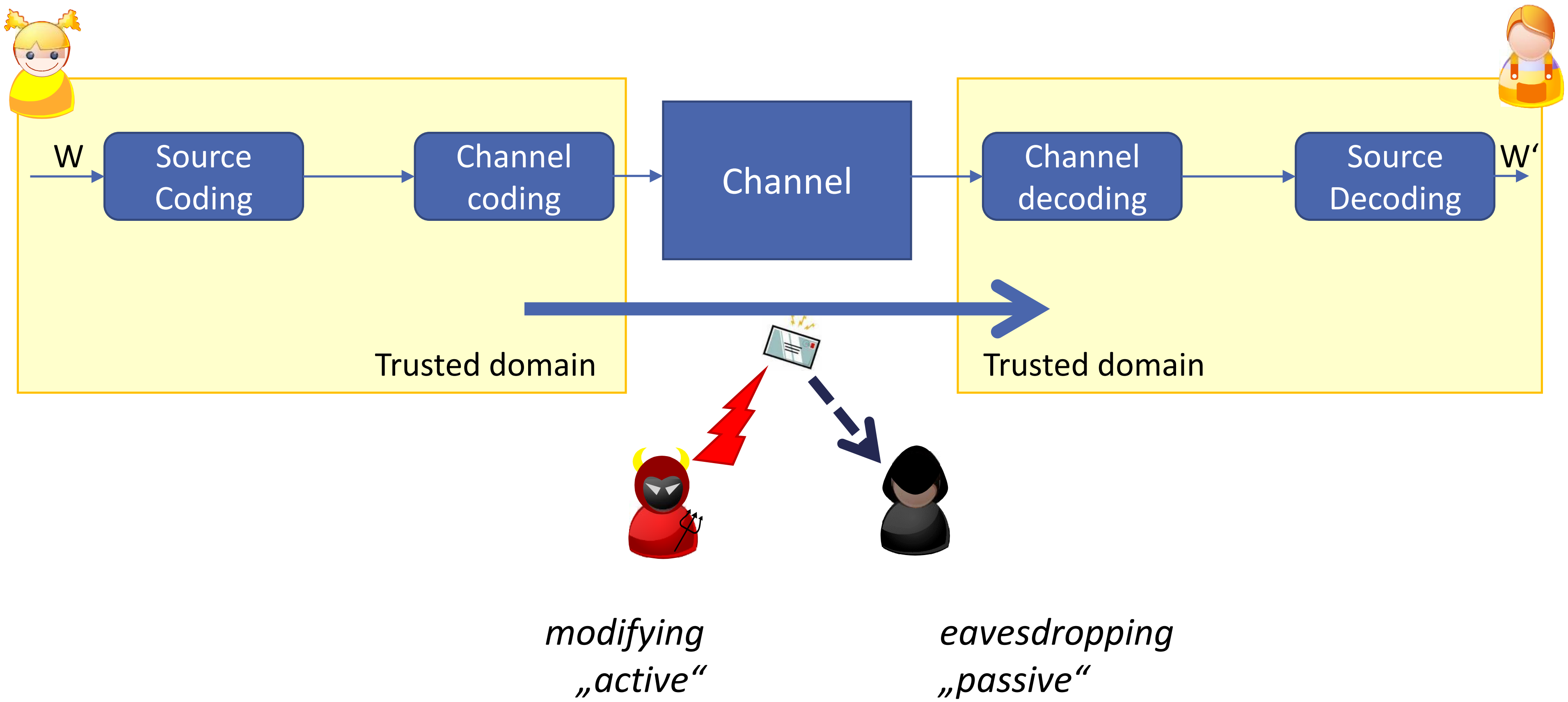
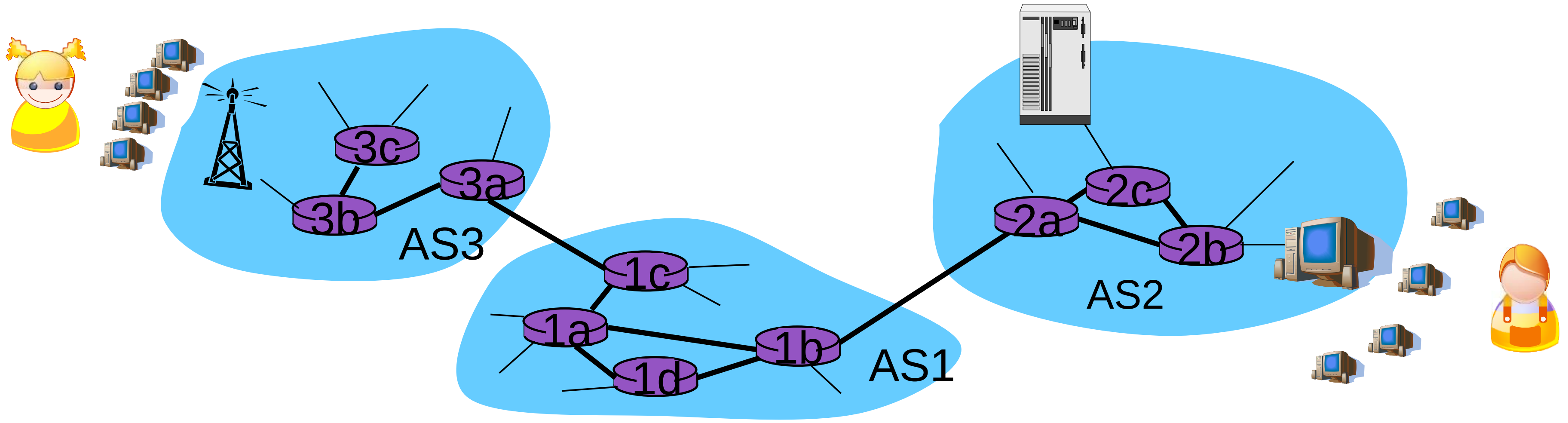
Security in Telecommunication



(Inter)networked Communication



More Specific: The Dolev - Yao Adversary

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- Mallory has full control over the communication channel
  - Intercept/eavesdrop on messages (passive)
  - Relay messages
  - Suppress message delivery
  - Replay messages
  - Manipulate messages
  - Exchange messages
  - Forge messages

- But:
  - Mallory ***can‘t*** break (secure) cryptographic primitives!

KASTEL

And what we (crypto) wants to achieve (CIA)

- ***Confidentiality:***
  - Data transmitted or stored should only be revealed to the intended audience
  - ***Confidentiality of entities*** is also referred to as ***anonymity***
- *(Data)* ***Integrity:***
  - It should be possible to detect any modification of data
  - This requires to be able to *identify* the creator of some data
- ***Availability:***
  - Services should be available and function correctly

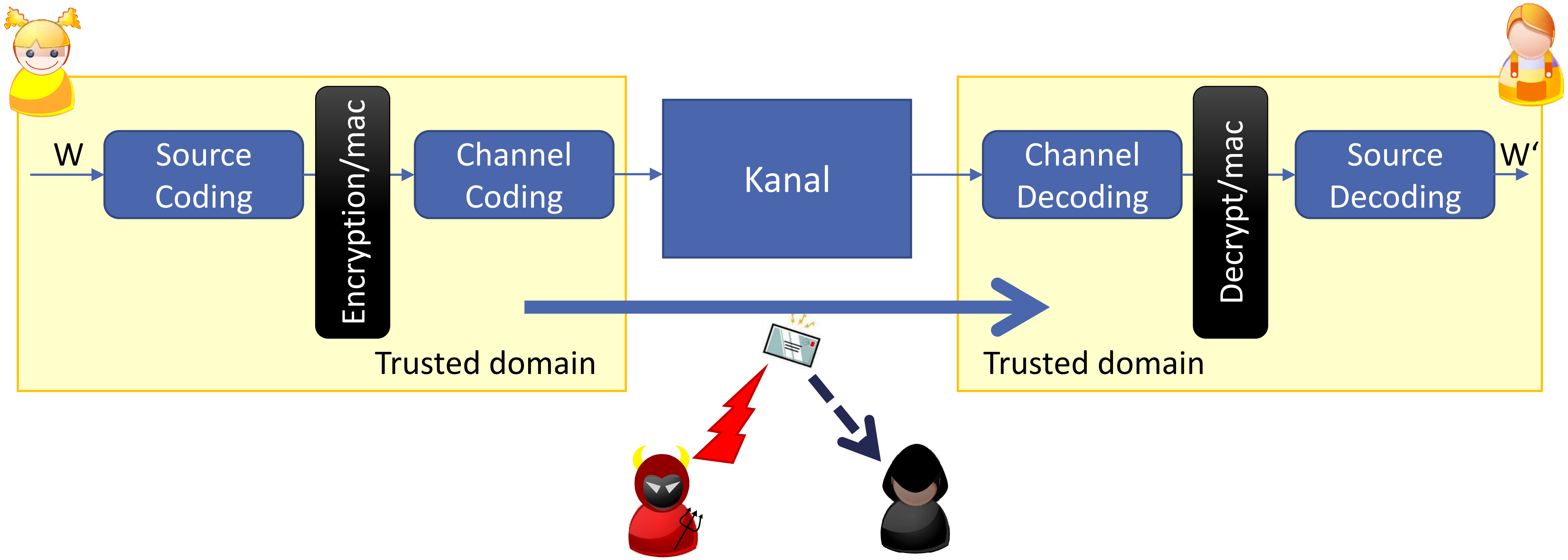
- *Accountability:*
  - *It should be possible to identify the entity responsible for any communication event*
- *Controlled Access:*
  - *Only authorized entities should be able to access certain services or information*

…By means of… *Security Services:*

- *Authentication*
  - Ensure that an entity has in fact the identity it claims to have
- *Integrity (authenticated modification detection)*
  - Ensure that data created by specific entity isn't modified ***without detection***
- *Confidentiality (content hiding)*
  - Ensure the secrecy of protected data
- *Access Control*
  - Ensure that each entity accesses only services and information it is entitled to
- *Non Repudiation*
  - Prevent entities participating in a communication exchange from later falsely denying that the exchange occurred

Extending the Channel Model:

- Crypto needs to transform payload, or add information, that cannot be interpreted nor predicted (iow: *“looks like random noise”*)



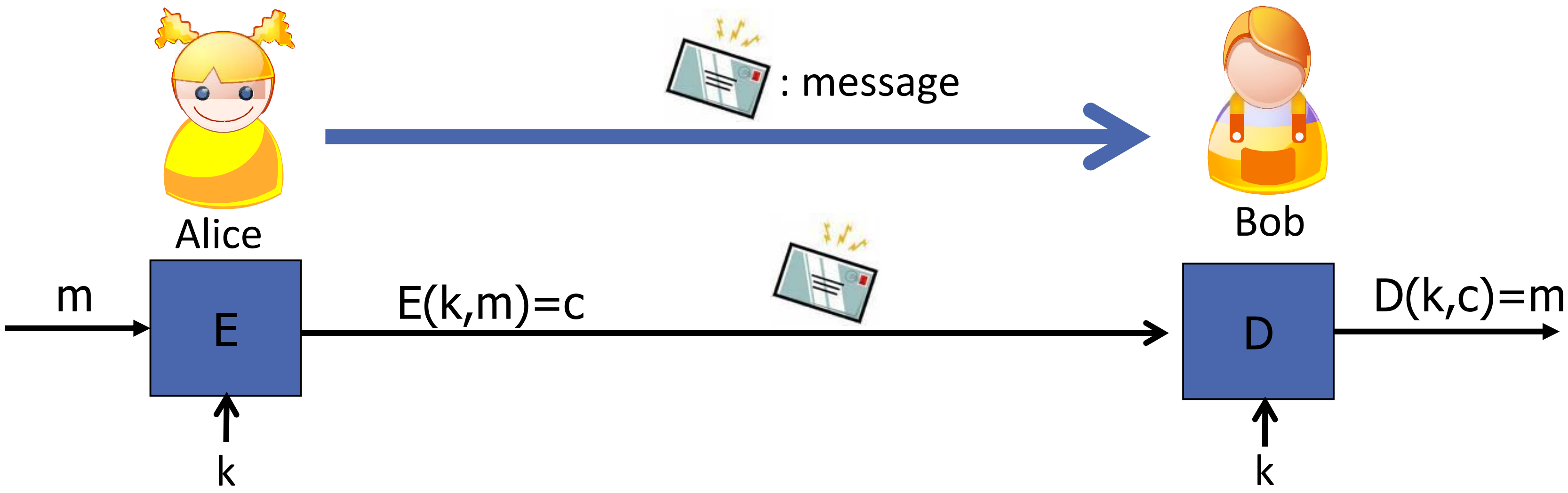
Confidential Communication with Integrity

Security Services for Confidentiality/Integrity

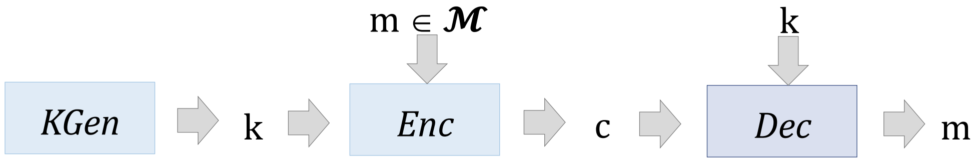
- We need algorithms (and protocols)
- To achieve confidentiality:
  - Conventional encryption
- To guarantee integrity:
  - Signing, „Message Authentication Codes“(MAC)
- Cryptographic algorithms for both…

Confidential Communication

- Alice sends Bob a private (any!) message…



- **m**: message (plaintext) $\in$ *M* (message space, sometimes *P*)
- **k**: key $\in$ *K* (key space)
- **c**: ciphertext $\in$ *C* (ciphertext space)



- A cipher is a triple of algorithms: **E, D**, *keygen* (random/deterministic?; sometimes: Enc, Dec)
- **Correctness:** for all $k \in \mathcal{K}, m \in \mathcal{M}$: $\mathrm{Dec}(k, \mathrm{Enc}(k, m)) = m$

Communication with Integrity

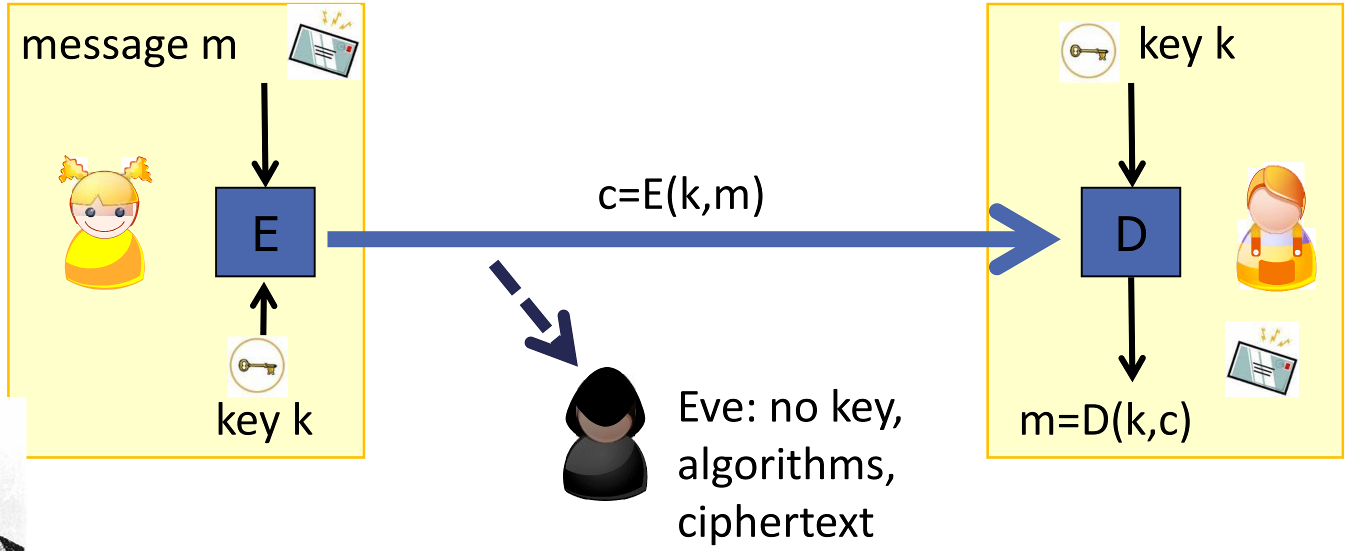
- Defining similar sets and spaces:

M:	Space of possible messages	$(\{0,1\}^*)$
T:	Space of possible „tags“	(e.g. $\{0,1\}^{160}$)
K:	Space of possible keys	(e.g. $\{0,1\}^{128}$)

- Algorithms
- KeyGen() -> k *randomized*
- S(k,m) -> t with $m \in \{0,1\}^n$, $t \in \{0,1\}^t$ (n>>t)
- V(k,m,t) -> {0,1} *both: deterministic*

Kerckhoffs' principle (*how to make this secure?*)

- KGen, Enc, und Dec will be lost to the adversary
  - → Publish all algorithms right away!
  - → Security must depend only on secrecy of the key (secret, unpredictable)



"The cipher method must not be required to be secret, and it must be able to fall into the hands of the enemy without inconvenience."

Kerckhoffs: La Cryptographie Militaire, 1883

So what does it mean „secure“?

- What can the adversary observe, what does she know?
- What is it she‘s not allowed to learn in addition, achieve?

- Confidentiality:
  - Cannot learn the plaintext of the message *(??)*
  - Cannot extract the key *(??)*
  - → *Shouldn‘t learn anything they don‘t already know!*

- Integrity:
  - Shouldn‘t be able to modify a message (flip „0“ to 1) *(??)*
  - → *Must not be able to generate a valid tuple of message and tag!*

Formalizing Security

Formalizing Security / Worst-Case

- Discussion/Analsysis requires to formalize „security“ (Conf./Int.)

- To be sure: Analyse Worst-Case!
  - Inputs for which the adversary would learn the most/could most easily tamper

  → If adversary doesn‘t achieve anything in this case, we‘re safe!

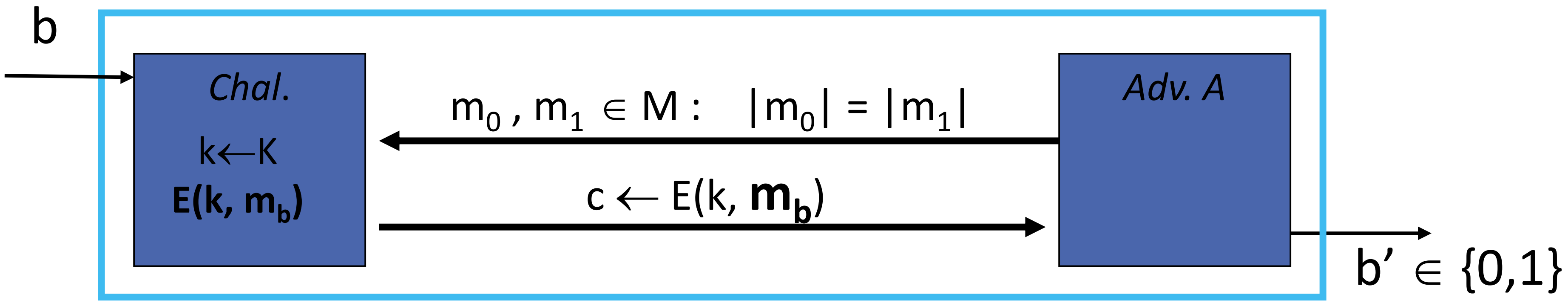
- Assuming, algorithms/protocols are weaker for some inputs
  - Adversary would choose these, if she was challenged to break the system!

- Rationale of our analysis
  - To model Worst-Case, we play a game and let the adversary choose their inputs arbitrarily
  - *OK, but what does she need to learn or to generate to win the game?*

Formalising Confidentiality as a Game

„Indistuingishability"
in variations IND-CPA/IND-CCA

- The confidentiality game with two parties:
  - Challenger (C) throws a coin (b={0,1})
  - Adversary (A) communicates with (C) and has to guess b:

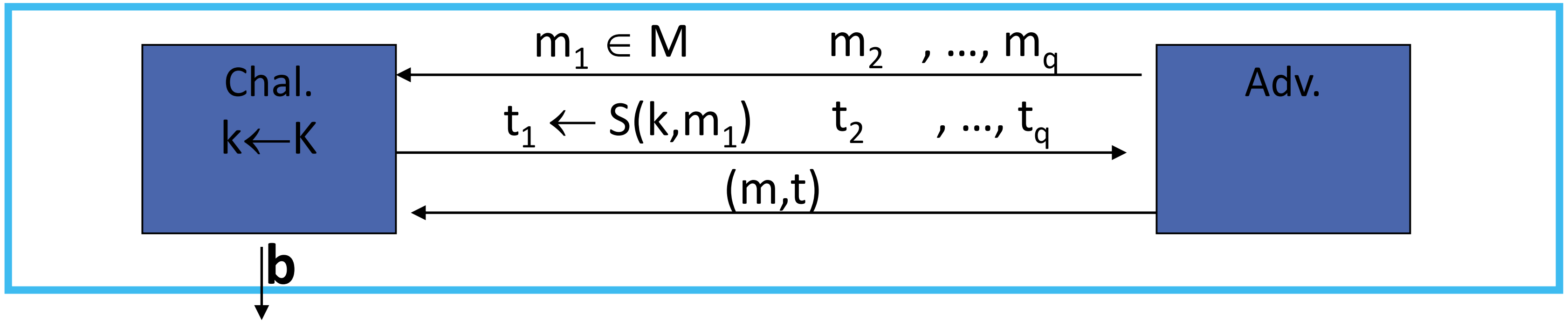


  - What is the frequency of the adversary to win the game beyond chance?

$$Adv_{Conf}[A, E] \coloneqq |\Pr[b' = b] - \Pr[b' \neq b]| \quad \in [0,1]$$ (*we demand this be: "≤* **ε**")

Formalising Integrity as a Game

- The integrity game with 2 parties, I = (S,V):
  - C produces valid tuple(s) (m,t) upon request
  - Adversary communicates with (C), has to generate **one** valid tuple:



$$\begin{cases} \mathbf{b}=1 & \text{if } V(k,m,t) = \text{`1'} \text{ and } (m,t) \notin \{(m_1,t_1), \dots, (m_q,t_q)\} \\ \mathbf{b}=0 & \text{otherwise} \end{cases}$$

- What is the frequency of the adversary to win the game?

$$\text{Adv}_{\text{MAC}}[A,I] = \Pr[\text{Chal. outputs } 1]$$ (*we demand this be: "$\leq \varepsilon$"*)

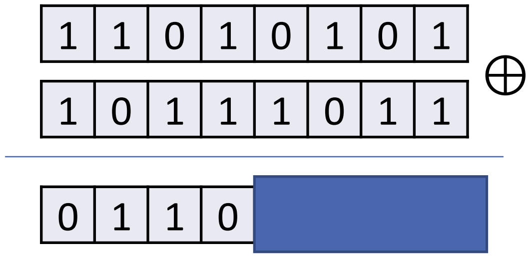
Concrete Examples

Let‘s try…

Intermezzo: XOR

- XOR of two strings in $\{0,1\}^n$ is their bitwise addition mod 2:

x	y	$x \oplus y$
0	0	0
0	1	1
1	0	1
1	1	0



- **<u>Theorem</u>**:
- Let Y be random variable over $\{0,1\}^n$
- Let X be an independent random variable with uniform distribution over $\{0,1\}^n$
- Then $Z := Y \oplus X$ has uniform distribution over $\{0,1\}^n$:
- (Proof on the blackboard)

Try more: let‘s define two ciphers

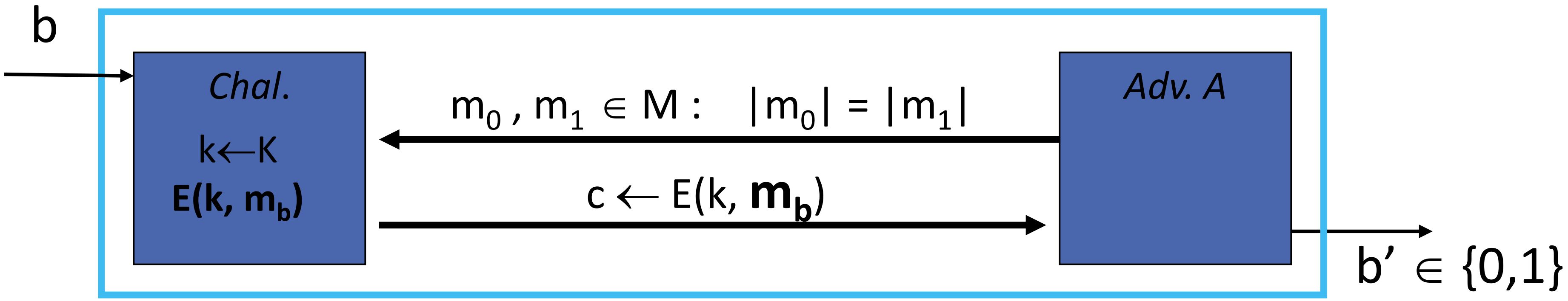
Let $m = m_0 \ldots m_{n-1}$ and

$k = k_0 \ldots k_{l-1}$ a string of uniform distributed random bits, with $l=n$

- $\mathrm{Enc}_1(k,m) := c_0 \,..\, c_{n-1}$ with $c_i = m_i \oplus m_{i+1}$ and $m_n = m_0$
- $\mathrm{Enc}_2(k,m) := c_0 \,..\, c_{n-1}$ with $c_i = m_i \oplus k_i$

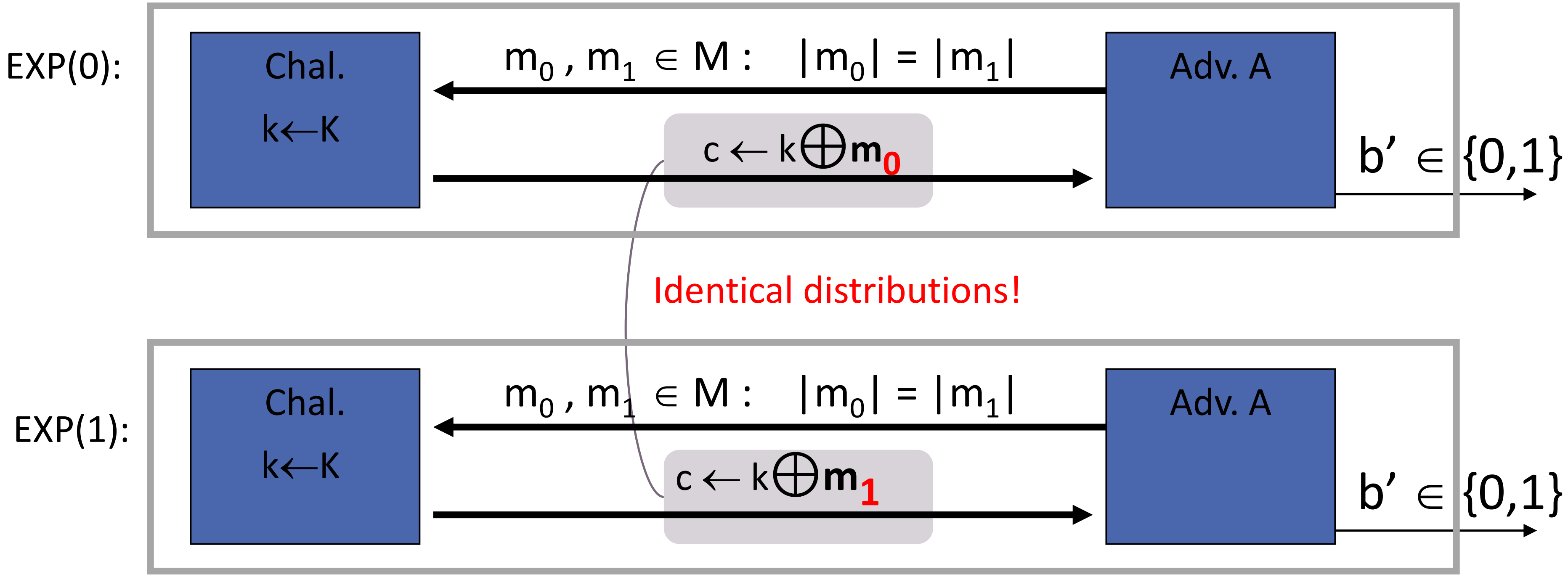
Analyis of Enc_1

- $\text{Enc}_1(k,m) := c_i = m_i \oplus m_{i+1}$
- which tuple of messages is the adversary going to choose?



$$Adv_{Conf}[A, \text{Enc}_1] := |\Pr[b' = b] - \Pr[b' \neq b]| \quad \in [0,1]$$

Analysis of Enc_2 (One Time Pad)



For all A: $Adv_{Conf}[A, Enc_2] = \left| \Pr[\, A(k \oplus m_0) = 1\,] - \Pr[\, A(k \oplus m_1) = 1\,] \right| =$

The One Time Pad (Vernam Cipher)

Gilbert Vernam
(1890-1960)

- Fundamental concept:
- Key: string, as long as the messge
- Choose key bits truly random (no discernable pattern)
- $\mathrm{Enc}(k, m) = c_0 \ldots c_{n-1}$ with $c_i = f(k_i, m_i)$ („+ mod |alphabet|“)

A	T	T	A	C	K	T	H	E	C	I	T	Y	A	T	T	W	E	L	V	E
P	S	P	I	U	H	G	D	S	P	H	G	D	S	P	I	W	E	E	W	O

(+ mod 26)

P	L	I	I	W	R	Z	K	W	R	P	Z	B	S	I	B	S	I	P	R	S

Y	H	P	R	S	R	G	F	F	D	D	X	N	S	Q	I	S	P	W	N	F
R	E	T	R	E	A	T	F	R	O	M	C	O	A	S	T	A	T	T	E	N

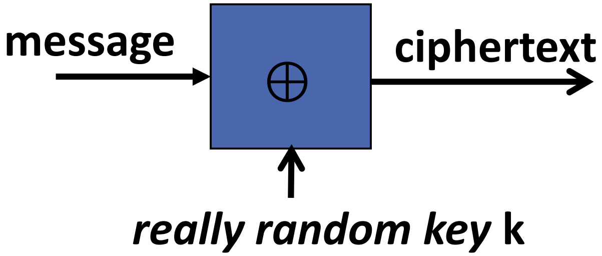
(+ mod 26)

- Adversary knows length, cipher text, no plain text – learns nothing!
- *What are the problems for application?*

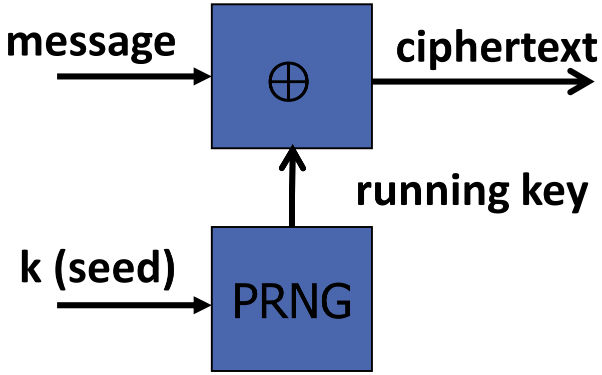
A useful approach

A practical cipher Enc_3

- OTP:



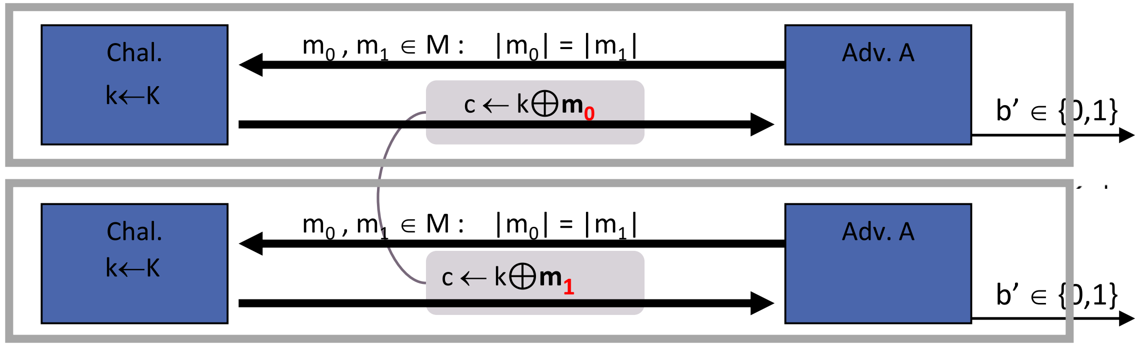
Enc_3:



- Idea: Use „pseudo random“ sequence as key bits
- PRNG is a function $G: \{0,1\}^s \rightarrow \{0,1\}^l \qquad l >> s$
- Det. algorithm from Seed- to key space (seemingly random)

- $k' = PRNG(k)$
- $Enc_3(k,m) := c_0 .. c_{n-1} \qquad \text{with } c_i = m_i \oplus k'_i$

Enc_2 vs Enc_3



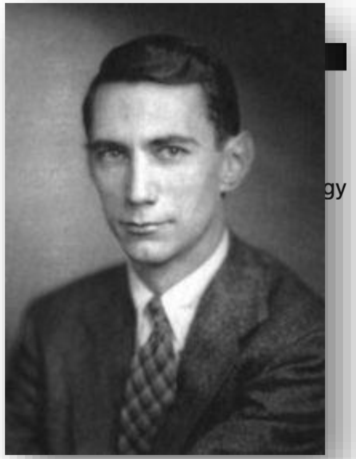
- Let PRNG be a „secure" (unpredictable) PRNG,
- → Distributions in EXP(0) and EXP(1) are (almost) identical

- Some assumptions regarding the adversary (Adv. model #3, ressources)
- Adv unlimited in time (theor.) vs. „efficient" (PPT) adversary

1. Tests Enc_3 with all 2^s possible keys and determins b'=b
2. Cannot test exponentially many keys (limited to poly. time)

- We call Enc_2 "***information theoretically secure***" (perfect secrecy)
- We call Enc_3 (best case) "***semantically secure***"

Information Theoretic Security



Shannon (1949):

- „CT should not reveal ***any*** information about PT"

Def: A cipher (E,D) over ($\mathcal{K}$, $\mathcal{M}$, $\mathcal{C}$) has ***perfect secrecy*** if

$\forall\ m_0, m_1 \in \mathcal{M}$ (with $len(m_0) = len(m_1)$)

$\forall\ c \in \mathcal{C}$ and $k \xleftarrow[R]{} \mathcal{K}$:

$$Pr[E(k,m_0) = c] = Pr[E(k,m_1) = c]$$

So being an attacker, what do I learn?

No CT attack can tell if msg is m_0, m_1 (or any other message)

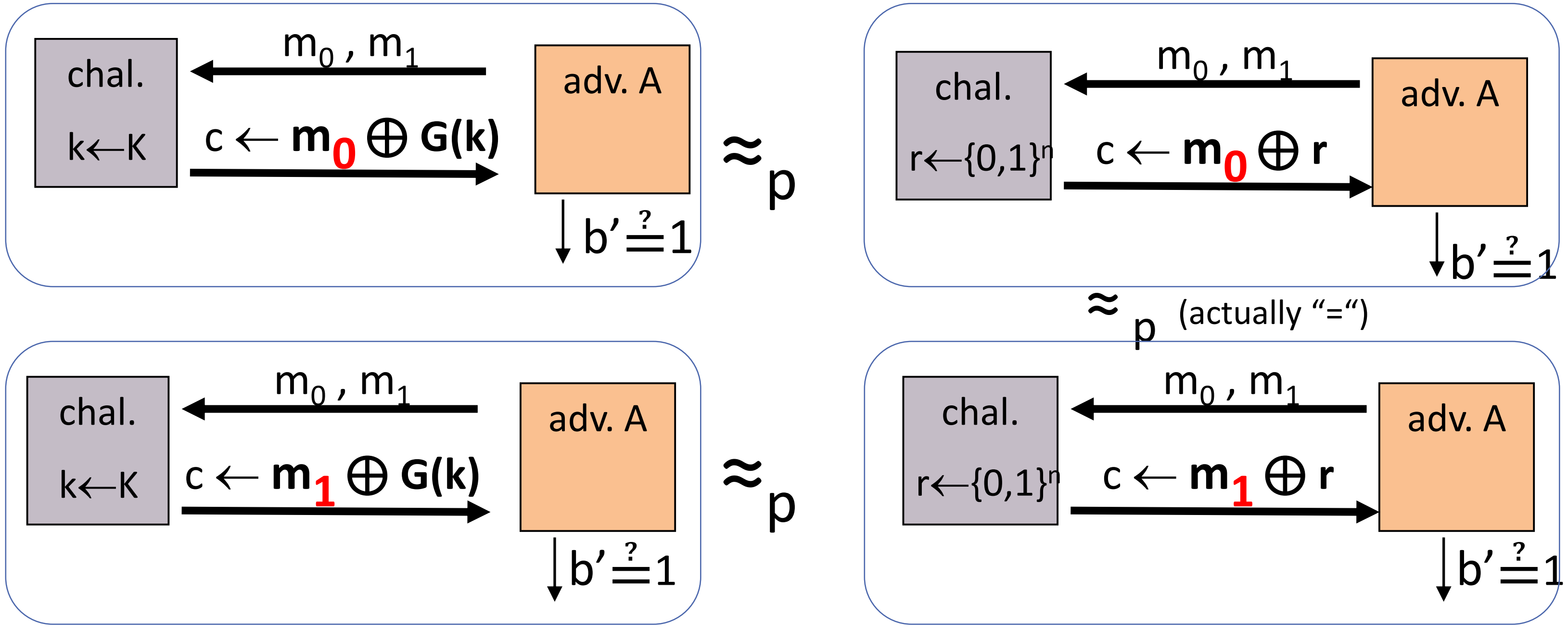
→ No CT only attacks

Does our stream cipher have semantic security?

- Assume our PRNG cannot be distinguished from „real randomness“ by an efficient adversary.
- We‘ve shown:

  OTP (XOR real random key) is secure

- Intuition for our new proof:

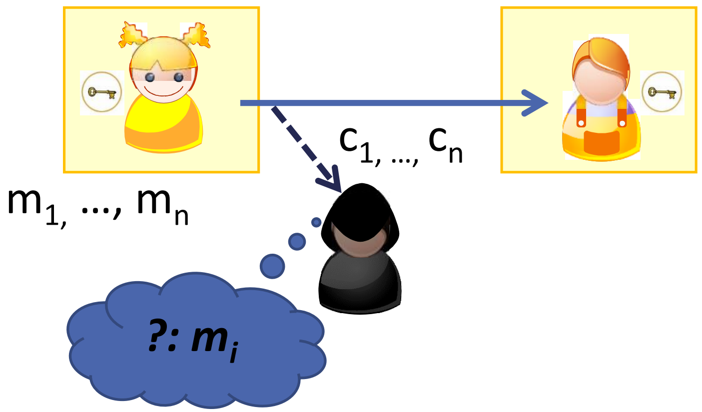


Variations of the Game…

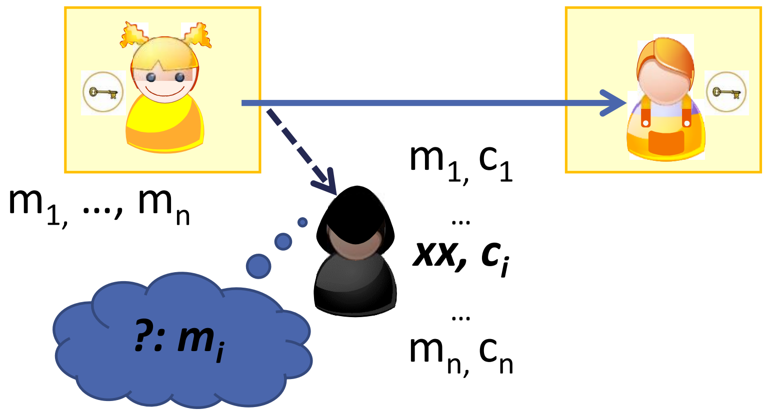
Defining different „security notions“

Security Notions, Variations of the Game

- **_Ciphertext-only attack:_**
  - despite concealed key
  - using ciphertext only
  - learn about plaintext (or key)



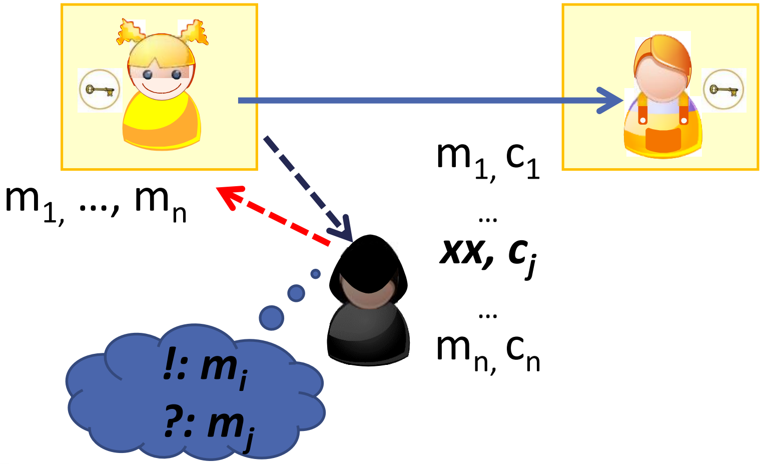
- **_Known-plaintext attack:_**
  - despite concealed key
  - Knowing some plaintexts
  - Learn about plaintext (or key)



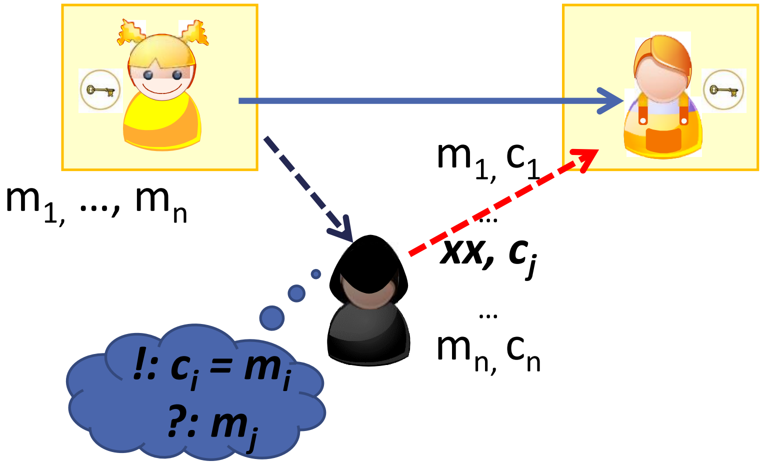
- *Weakest Adversary!*

Security Notions ctd.

- ***Chosen-plaintext attack:***
  - despite concealed key
  - asking Alice to encrypt m_a
  - learn about $\boldsymbol{m_j}$ (or key)

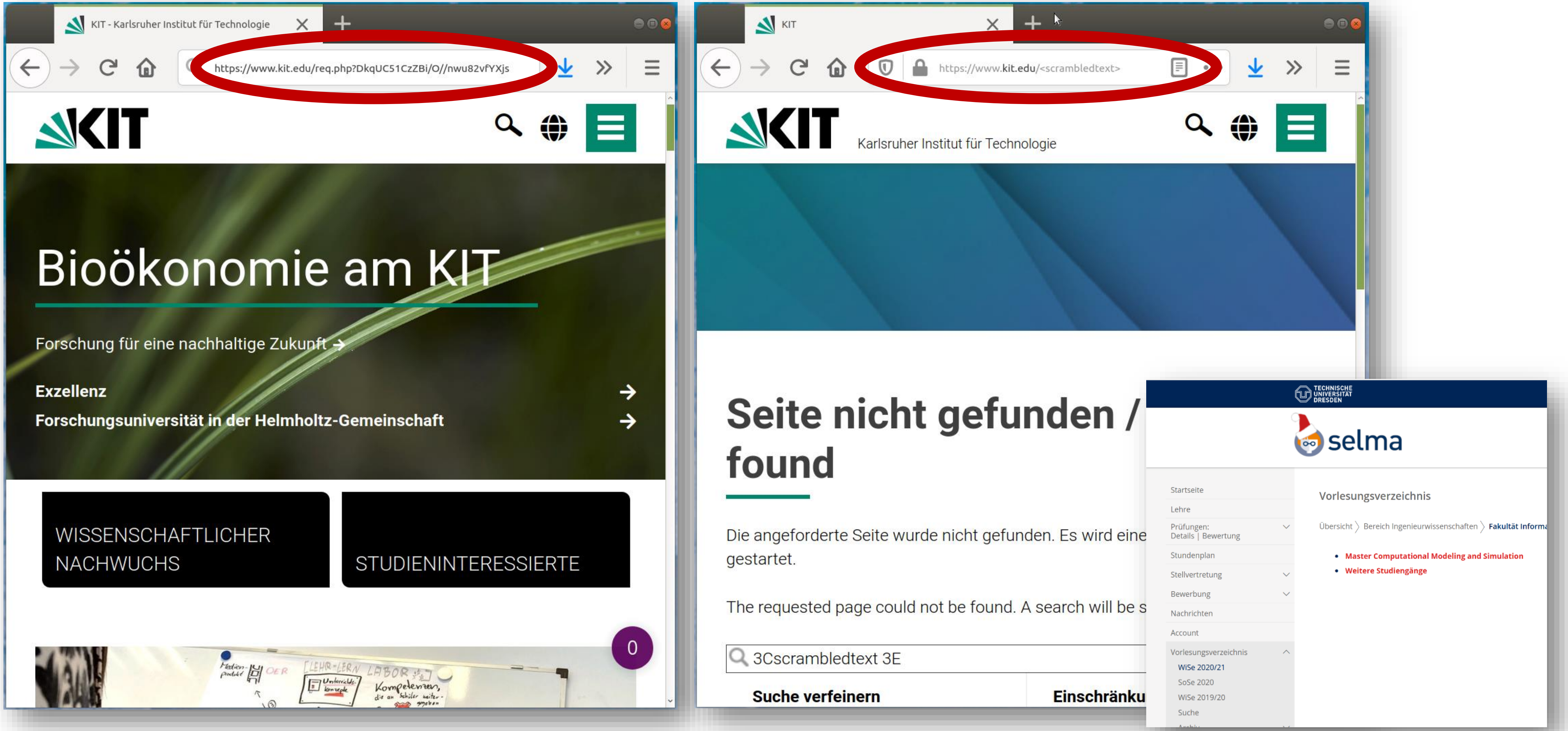


- ***Chosen-ciphertext attack:***
  - despite concealed key
  - asking Bob to decrypt c_a
  - learn about $\boldsymbol{m_j}$ (or key)



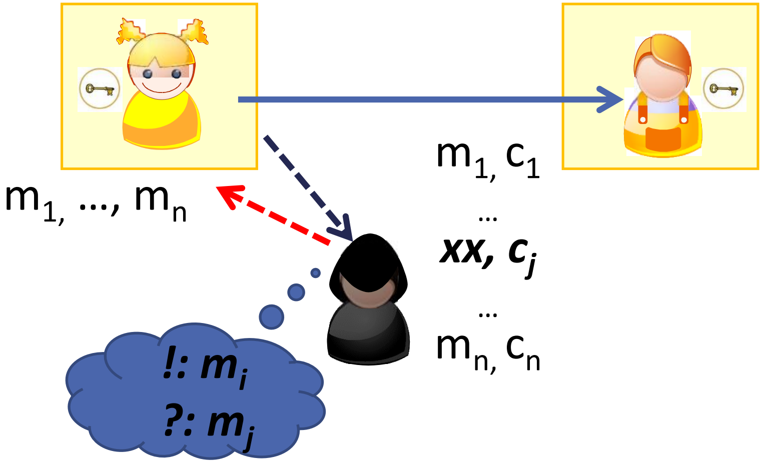
Asymmetric crypto: non-modifying („passive“) attack…

CCA Oracles in Reality…

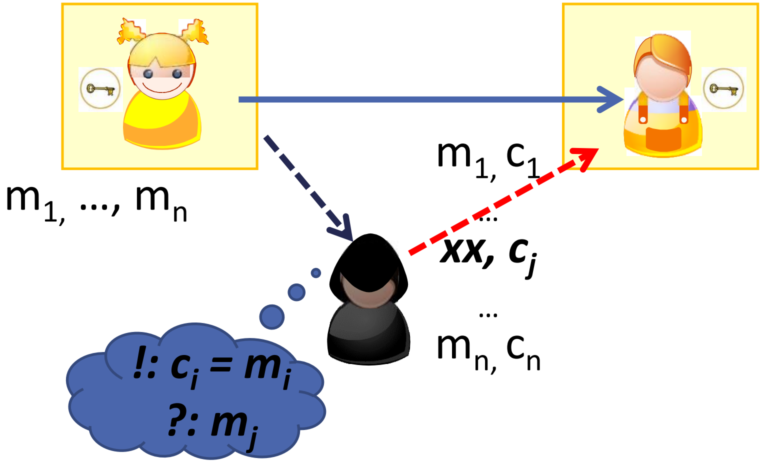


Security Notions ctd.

- ***Chosen-plaintext attack:***
  - despite concealed key
  - asking Alice to encrypt m_a
  - learn about $\boldsymbol{m_j}$ (or key)



- ***Chosen-ciphertext attack:***
  - despite concealed key
  - asking Bob to decrypt c_a
  - learn about $\boldsymbol{m_j}$ (or key)



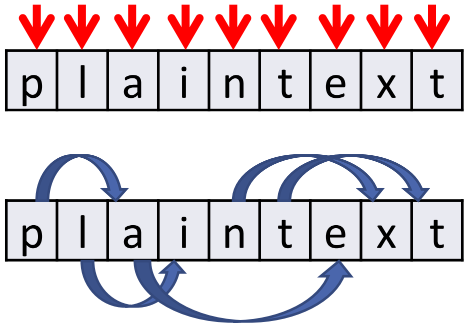
- *Strong adversary,* ***realistic****!*

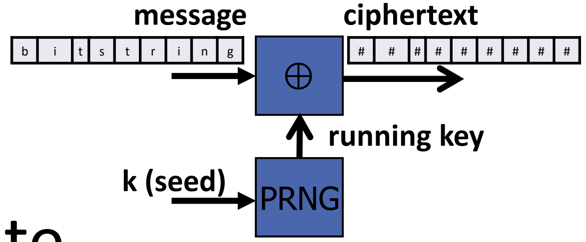
Asymmetric crypto: non-modifying („passive“) attack…

Constructing Ciphers

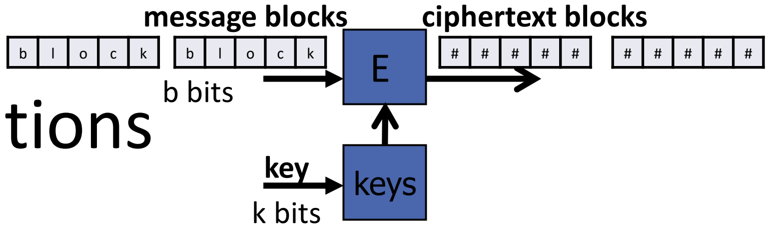
Constructing Ciphers

- Operations for Encryption
  - *Substitution* exchange symbols for others
  - *Transposition* permute symbols systematically





- Processing the plain text
  - *Stream ciphers* Generate key bits and substitute
  - *Block ciphers* Pseudo random permutations



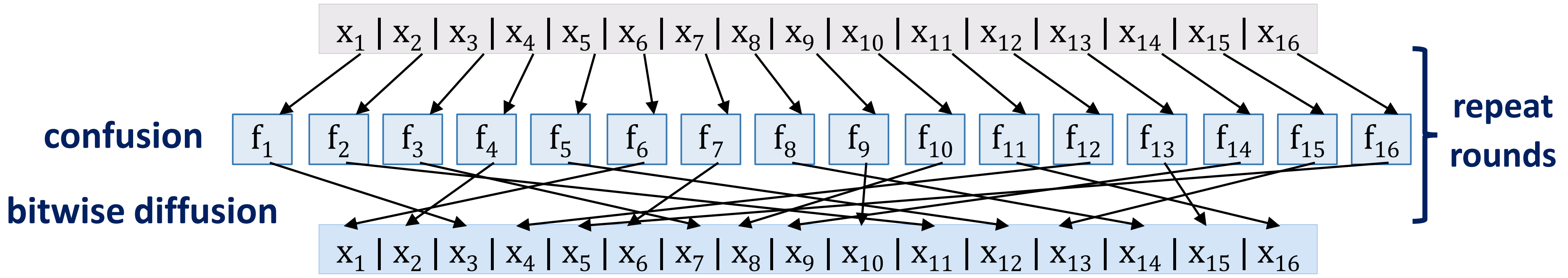
Constructing a Pseudo Random Permutation

Original idea of the confusion – diffusion paradigm (Shannon, 1949):

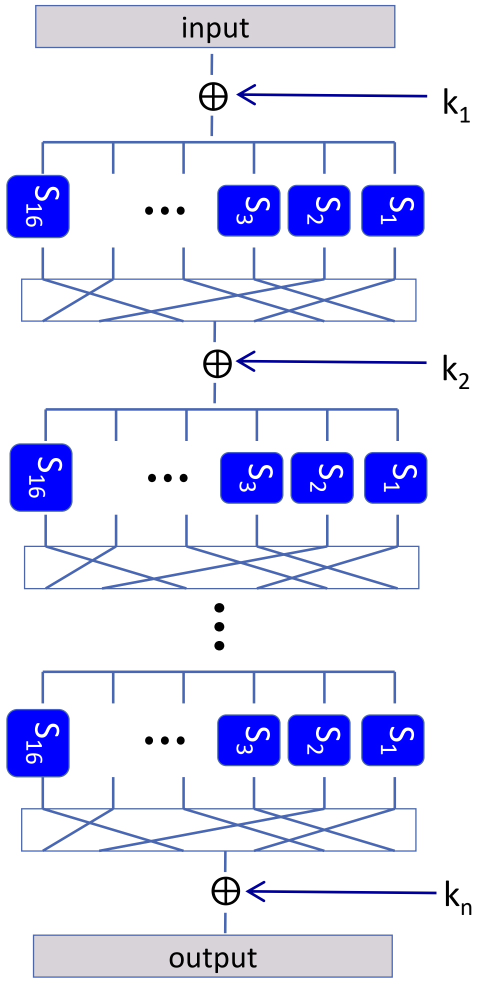
- Construct a random-looking permutation F with large block size using random-looking permutations $\{f_i\}$ with smaller block sizes.
- Create product cipher with confusion step (hide relation between CT and k) and diffusion step (distribute redundancy of PT)
- With ***avalanche effect***: Bit-flip in input should change half of the output bits, every output bit should depend on all input bits.

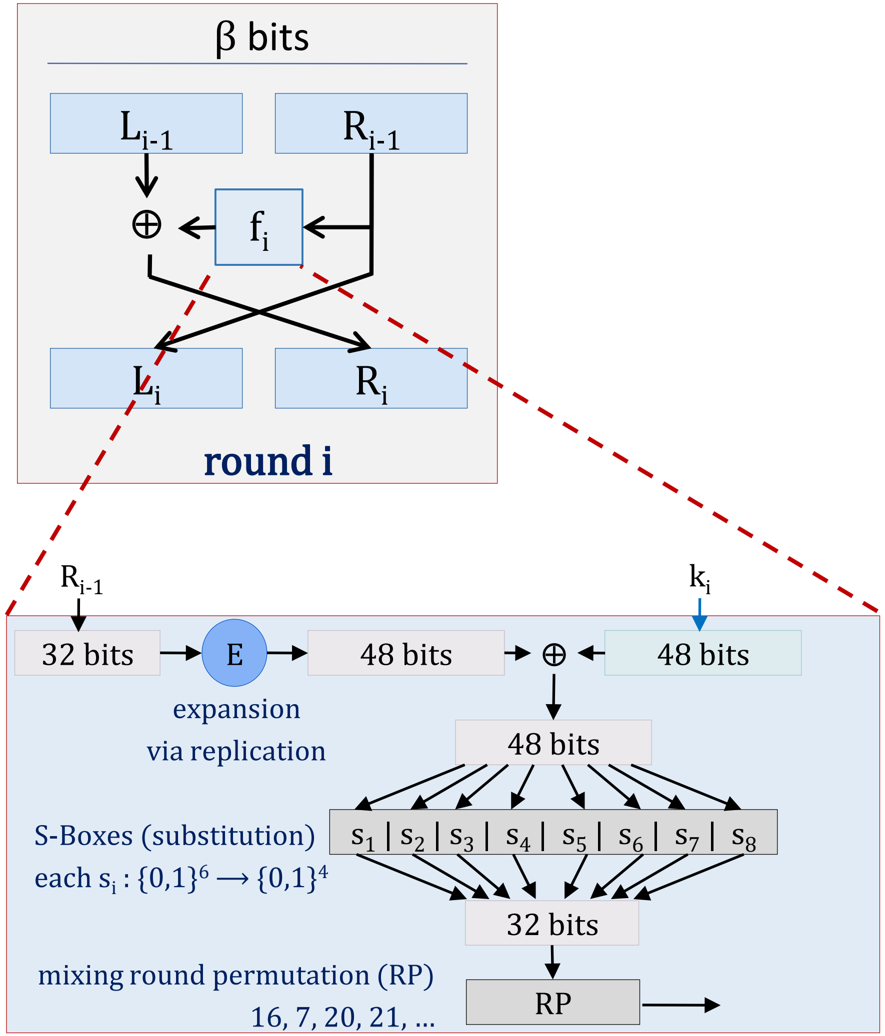
Construction:

- To construct $F_k : \{0,1\}^{128} \longrightarrow \{0,1\}^{128}$:
  - Combine $f_1,\ldots,f_{16}$ random-looking permutations $f_i : \{0,1\}^8 \longrightarrow \{0,1\}^8$ (s-boxes),
  - Perform subsequent bitwise transposition
  - Rinse and repeat (generate key per round, $\oplus$ vs round input)



Examples of PRPs: AES and Feistel Networks (DES)



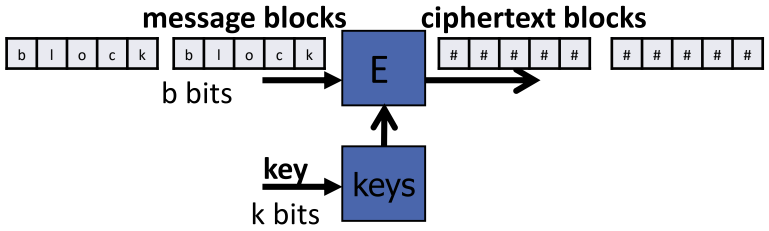


But PRPs aren‘t ciphers…

From PRPs to Block Ciphers (Mode of Operation)

- AES/DES are PRPs with fixed input length (64 or 128 bits)

- Messages in reality sometimes are slightly longer…

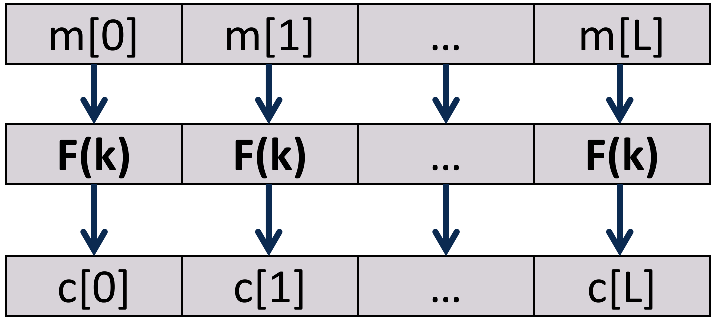


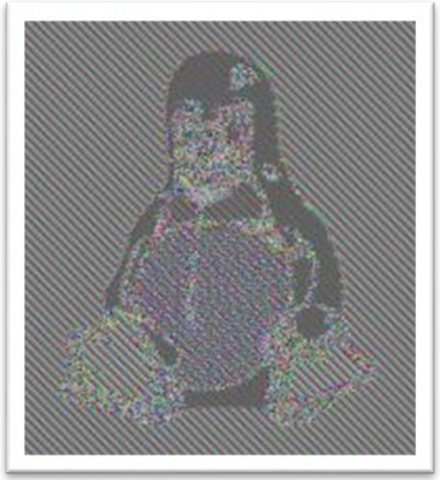
- ***How can we encrypt longer messages using PRPs?***

Electronic Code Book Mode

FAIL

- Independently encrypt every block with a PRP:



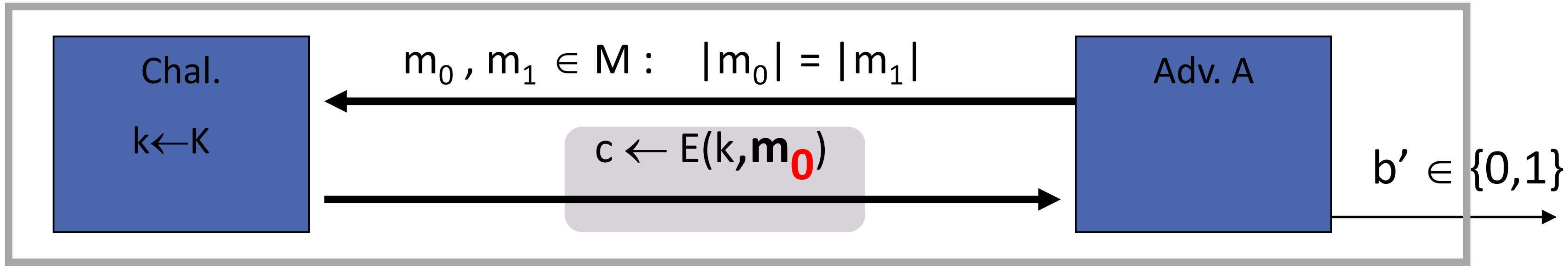


- ECB encryption is *deterministic*
- ⇒ identical PT blocks → same CT blocks

- *Is this "secure" (how)?*

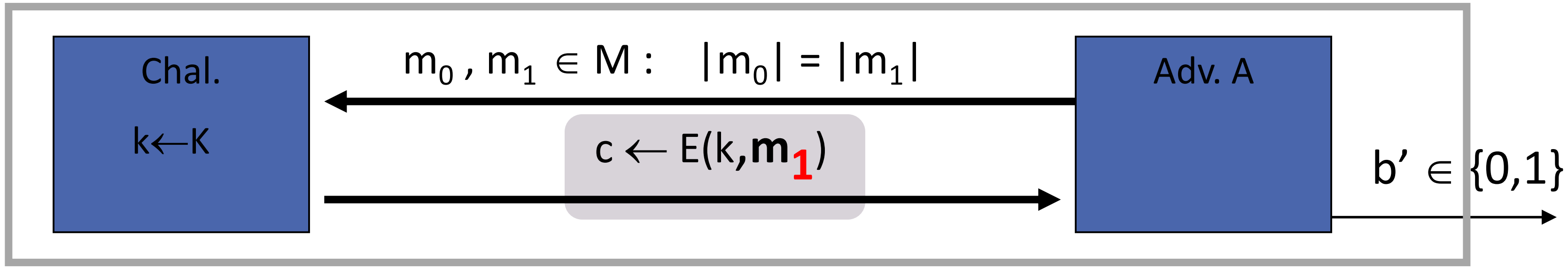
Semantic Security (One Time Key)

EXP(0):



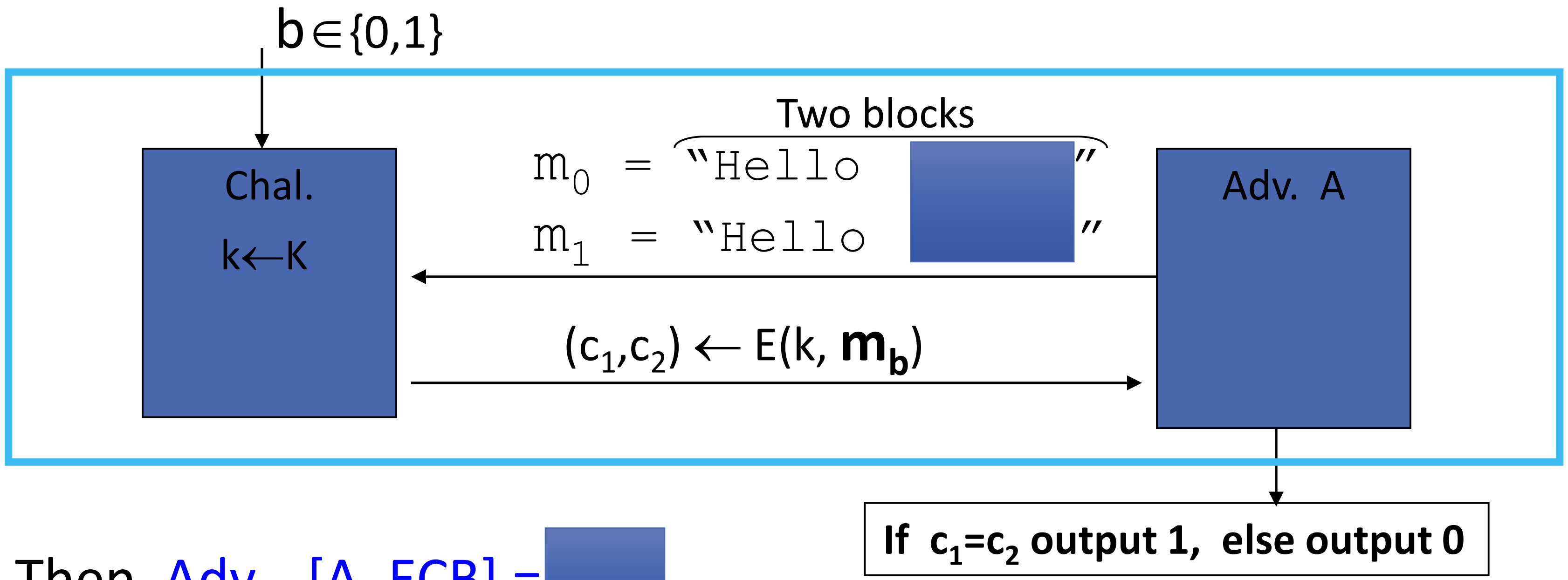
one time key ⇒ adversary sees only one ciphertext

EXP(1):



$Adv_{SS}[A,ECB] = \left| \Pr[\,\mathbf{EXP(0)}=1\,] - \Pr[\,\mathbf{EXP(1)}=1\,] \right|$ should be "neg."

ECB not semantically secure



Then Adv_{SS} [A, ECB] =

- ECB is not semantically secure for messages of more than one block.

Secure Modes of Operation

- ECB with deterministic PRP is insecure:
  - Two identical PT yield same CT if same key is used
  - Two identical PT blocks yield identical CT blocks

- So what can we do?
  - One-time key (internal):
    - Encrypt every block differentially
  - Many-time key (external):
    - Randomize, add random value to the input

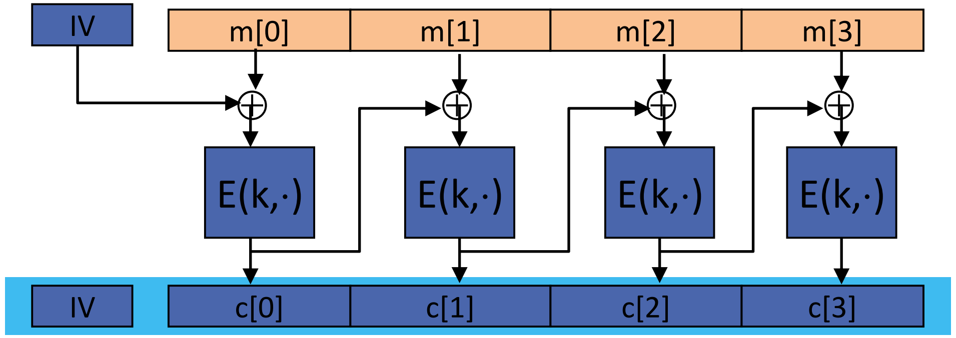
Counter Modes and Chaining

(1) Encrypt each block differently:

- integrate (changing) value in the encryption of each block
  - Nonces: $c_i = E(k,n_i,m_i) = E(k, (n_i,m_i))$ or $E((k,n_i),m_i)$?
  - …and transmit all n_i?
  - Counters to the rescue!

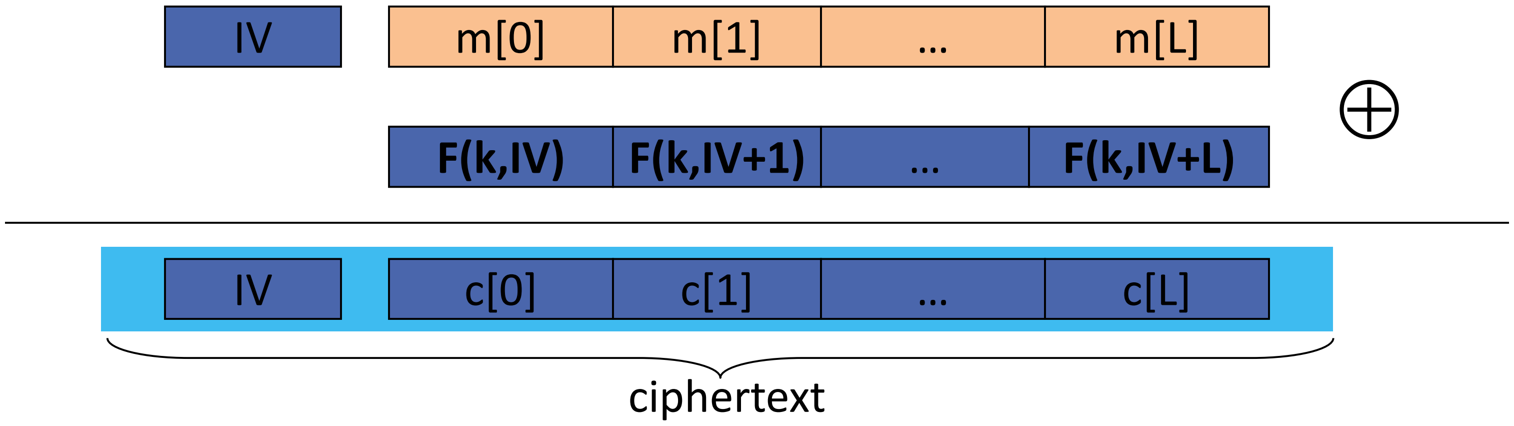
(2) Many-time key (random initialization vector):

- integrate (changing) value in the encryption of each message!
  - May we don‘t need indepent randomness *for each block*?
  - Choose random IV
  - Chain the encryption of the blocks



Randomized Counter Mode R-CTR

- Let $F: K \times \{0,1\}^n \longrightarrow \{0,1\}^n$ be a secure PRF.
- E(k,m): choose a random $IV \in \{0,1\}^n$ and do:

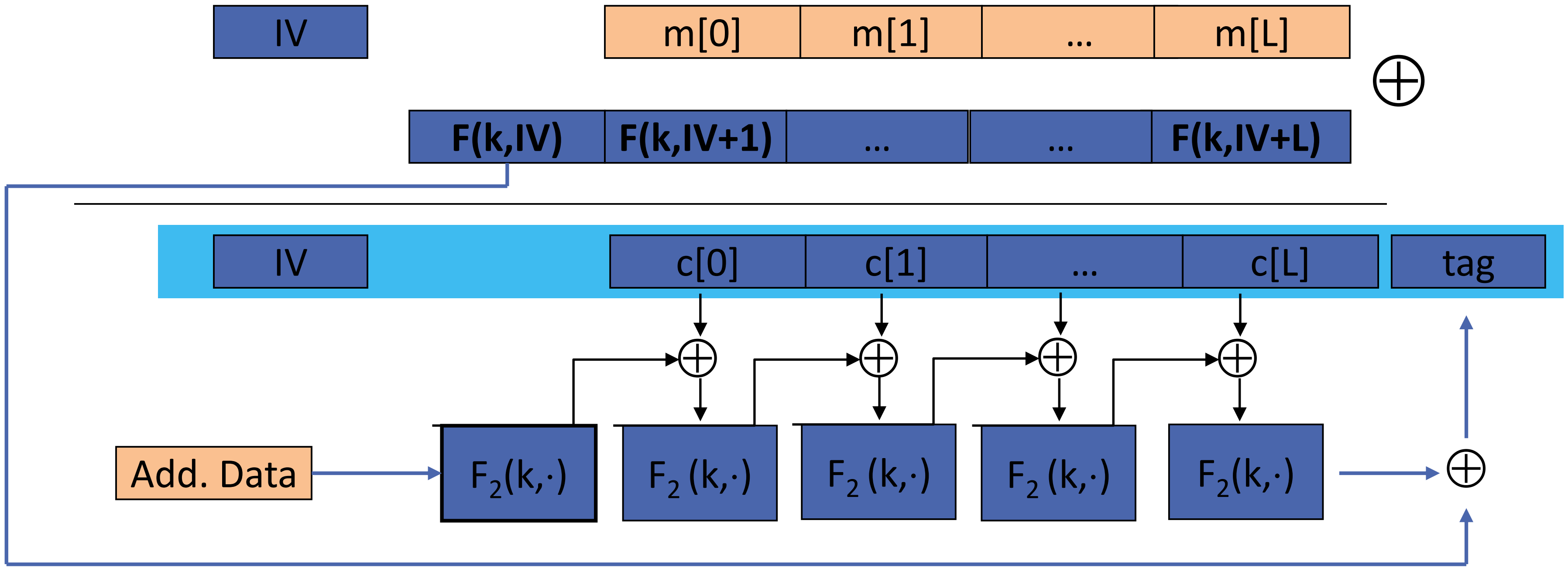


- Variation: Choose 128 bit IV as: nonce || counter

- *Remarks:*
- E, D can be parallelized and F(k,IV+i) can be precomputed
- R-CTR allows random access, any block can be decrypted on its own
- Again: F can be any PRF, no need to invert

Galois Counter-Mode

- Anticipating future module, we may want „authenticated encryption“
- May be also unencrypted (header) data shouldn‘t be manipulated („AEAD“)
- Idea: extend process by parallel authentication function



Intermediate Summary

Karlsruhe Institute of Technology

- Attackers and adversary model
- Threats
- Security Objectives (CIA)
- Security services
- Definitions and Foramlizing Security as a game
- Perfect security/ semantic security
- One-Time-Pad, Stream cipher
- Block-Cipher and modes of operation

Next stop: Integrity

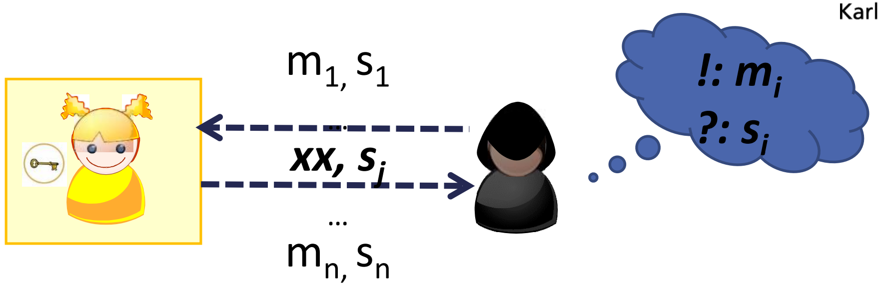
Constructing an integrity service

- Aim: Detect unauthorized manipulation (*recall: we‘ve got nothing to hide!*)
- Map message of arbitrary length to a tag of (short) fixed length
- Tag authenticates sender and proves absence of modification
- → „Message Authentication Code“ (MAC)

- Algorithms
- $KeyGen() \rightarrow k \in K$
- $S(k,m) \rightarrow t$ with $m \in \{0,1\}^n, t \in \{0,1\}^t$ $(n >> t)$
- $V(k,m,t) \rightarrow \{0,1\}$

Security Notions: Existential Forgery

- ***Chosen Message Attack:***
  - given s_1, s_2, … s_n for chosen m_i



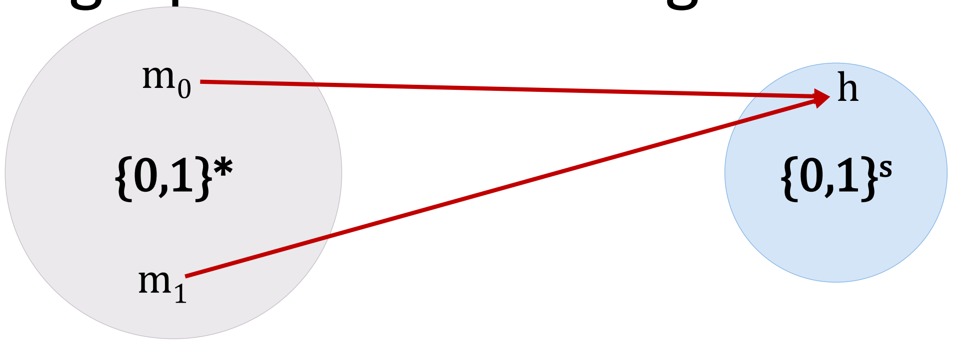
- (Variations: known verification key / known signature attacks)

- ***Existential Forgery:***
- Produce arbitrary, valid tuple (m,t) (arbitrary message even gibberish)
- ⇒ adversary cannot produce valid tag for new message
- ⇒ can't even produce (m,t'), (m',t) for (m,t) and t' ≠ t or m ≠ m'

- *General notions:*
- *Exist. forgery < selective forgery < universal forgery < total break*

Constructing MACs

- Ideas:
  - Authenticating the sender → secret
  - Map message to fingerprint of fixed length → Hash functions

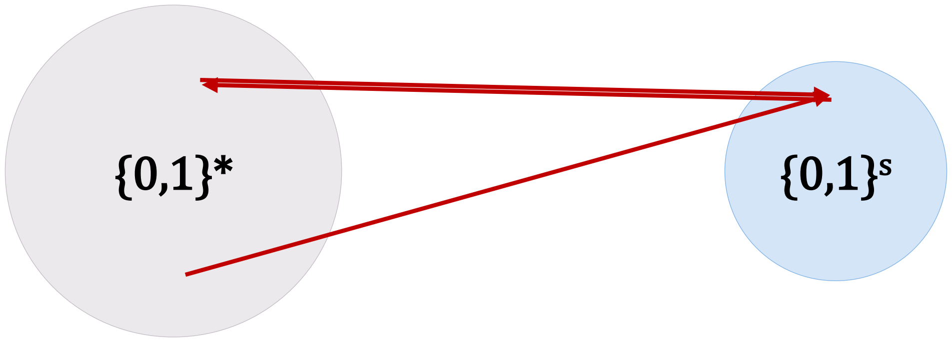


- Secret remains secret (no encryption involved) → one-way functions
- Smallest modification of m unpredictable in t → „Chaos“

What were those fingerprints?

Requirements for *secure* Hash/MACs

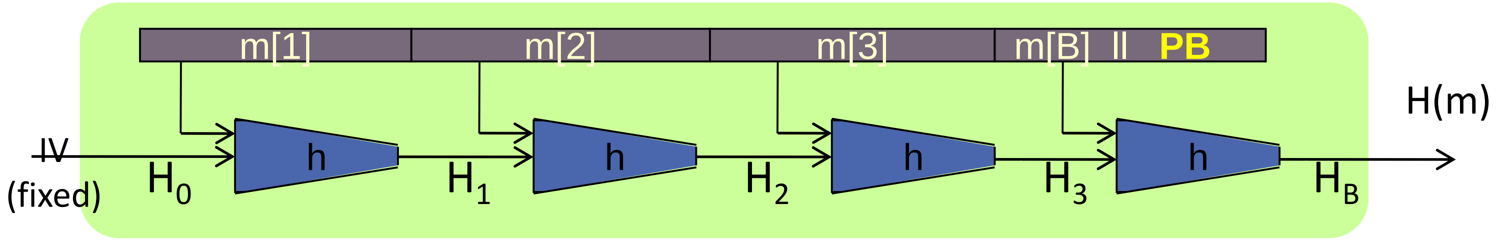
1. One-way property (preimage resistance)
2. Strong collision resistence (collision resistance)
3. Weak collision resistence (2nd preimage resistance)



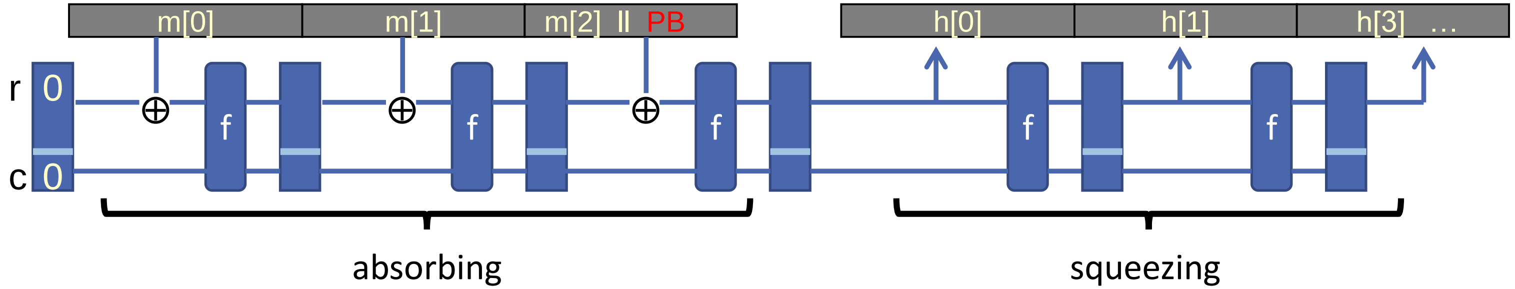
- *Why don‘t we design* ***collision free*** *hash functions?*

Two examples for secure Hash functions

- Merkle-Damgård: Cascade of PRP without encryption (MD5/SHA1..)



- SHA-3: Ingesting the entire message into pseudorandom state

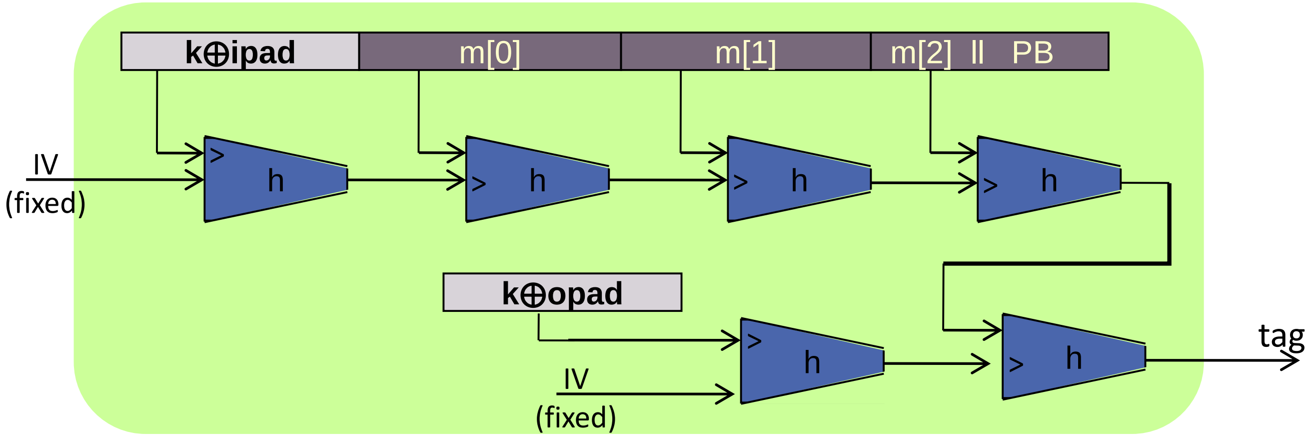


Finally: Ensuring Integrity!

Constructing MACs from Hash functions

- Security requirements of hash functions (one-way/collision resistance)
- Security requirements of MACs (no Existential Forgery)

- MAC:= Enc(k,h(m))?
- HMAC:



Intermediate Summary

- Threats for communication and networks

- Security objectives
  - **C**onfidentiality
  - **I**ntegrity
  - **A**vailability

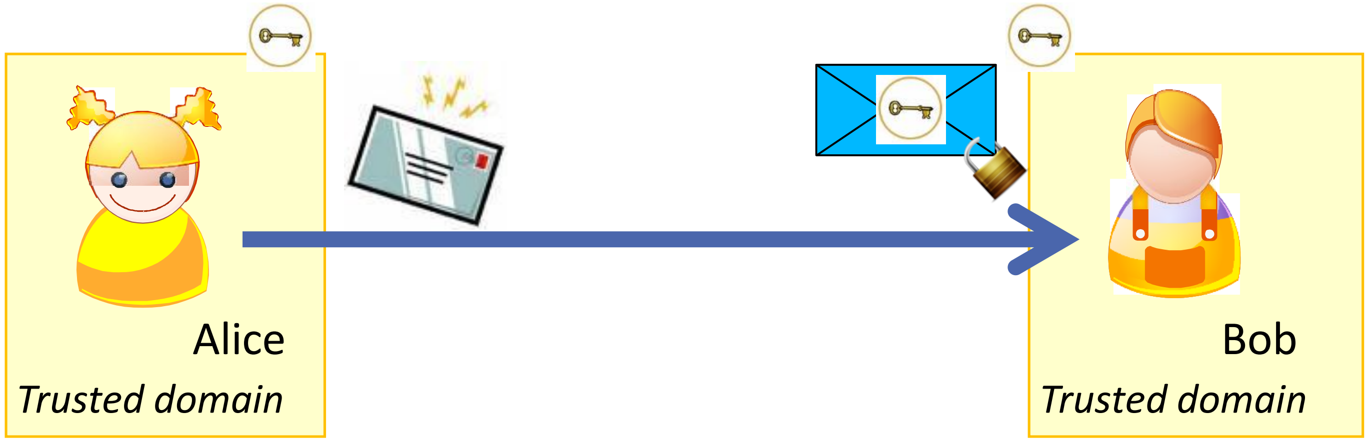
- Definition and Design of Security Services

- Game-based analysis of encryption and signing
- Perfect secrecy and semantic security

- Design of stream ciphers (OTP) and block ciphers/modes of operation
- Design of hash functions and Message Authentication Codes (MACs)

Now where do we get those keys?

Key Distribution/Agreement



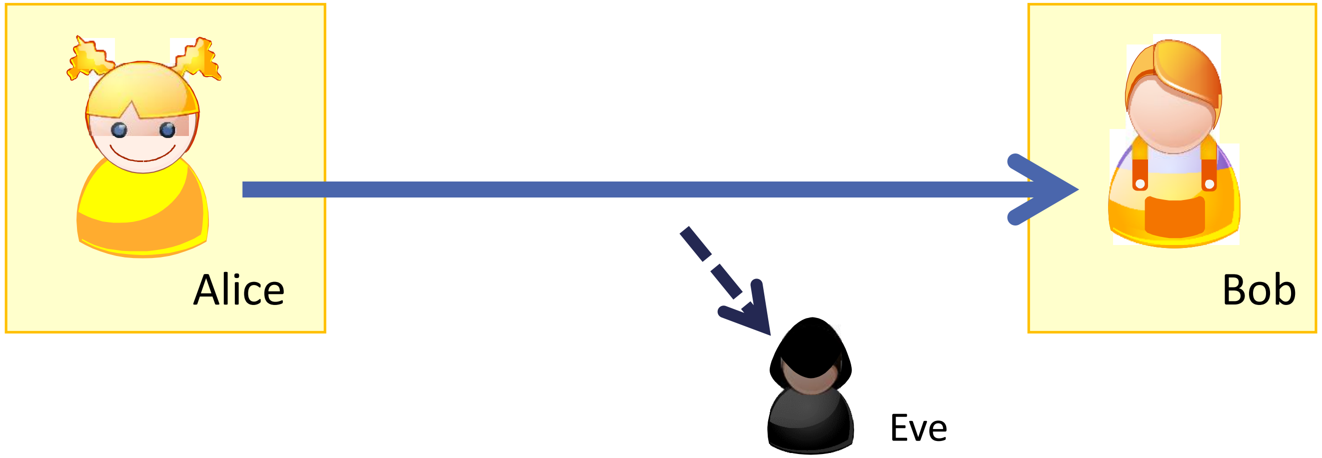
Alternatives:

- Alice/Bob agree mutually
  - In advance
  - When establishing their connection
- Alice and Bob delegate trust into a third entity („*TTP*“, „*KDC*“)

First Attempt: A Passive Adversary

Eve can:

- Eavesdrop on the channel



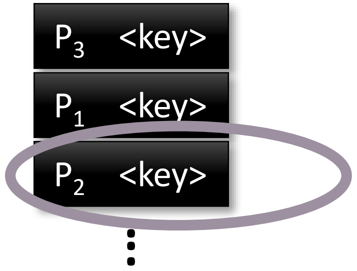
- Can Alice and Bob securely exchange a key?

Key Agreement

Aim:

- Given open and public communication
- Output: A key secret to Alice and Bob

Ralph Merkle, Martin Hellman, Whitfield Diffie



Initial Idea (Merkle, ’74):

- Alice creates 2^{32} Puzzles (with an Index P_i and key)
- Alice shuffles the puzzles and sends them to Bob
- Bob chooses one at random and solves it
- Bob informs Alice of the index P_j, both know the respective key.

How much effort does Eve have to invest?

Polynomial Advantage: Diffie-Hellman(-Merkle)

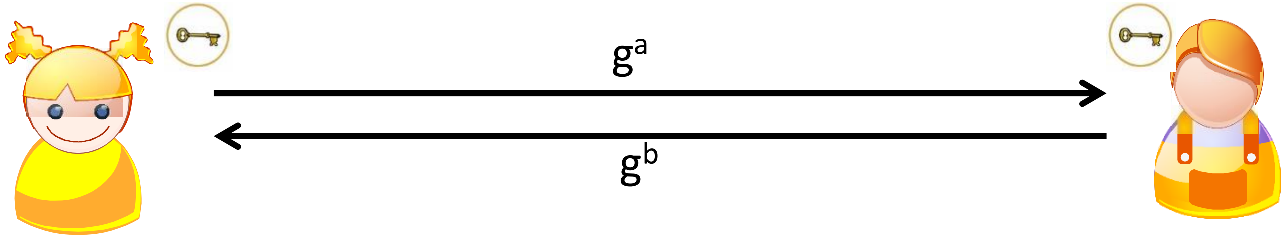
Can we make Eve‘s life more difficult?

Observations:

1. Discrete Logarithm (some inversions) hard to solve
2. Power Law: $(g^x)^y = g^{xy} = g^{yx} = (g^y)^x$

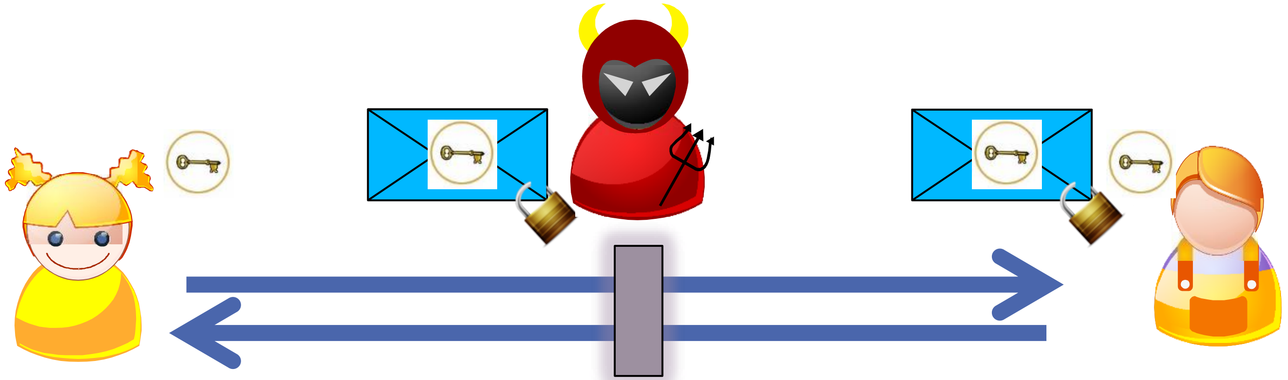
Idea:

- Choose cyclic group $\mathbb{Z}_p^*$, generated over g, and $\varphi(p) = p-1$
- Alice chooses $a \overset{R}{\longleftarrow} \{1,\dots,(p-1)\}$, Bob chooses $b \overset{R}{\longleftarrow} \{1,\dots,(p-1)\}$



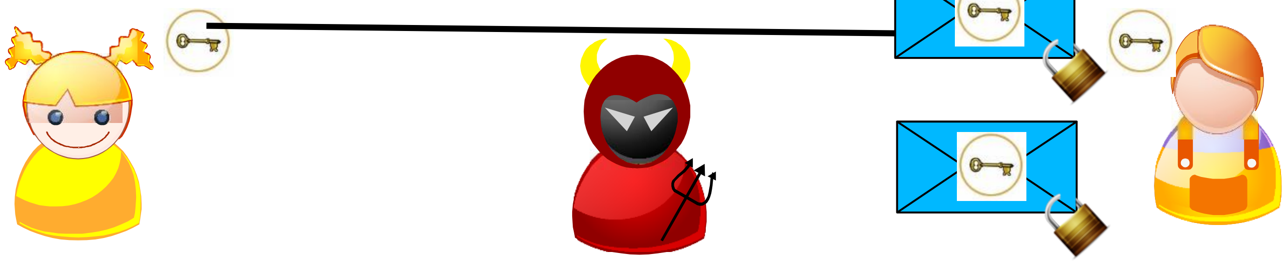
- Alice calculates: $(g^b)^a \bmod p = g^{ab} \bmod p =$ Bob calculates:

Two Specific Attacks



- Man-in-the-middle

Identify/ authenticate parties pro-actively or with external help

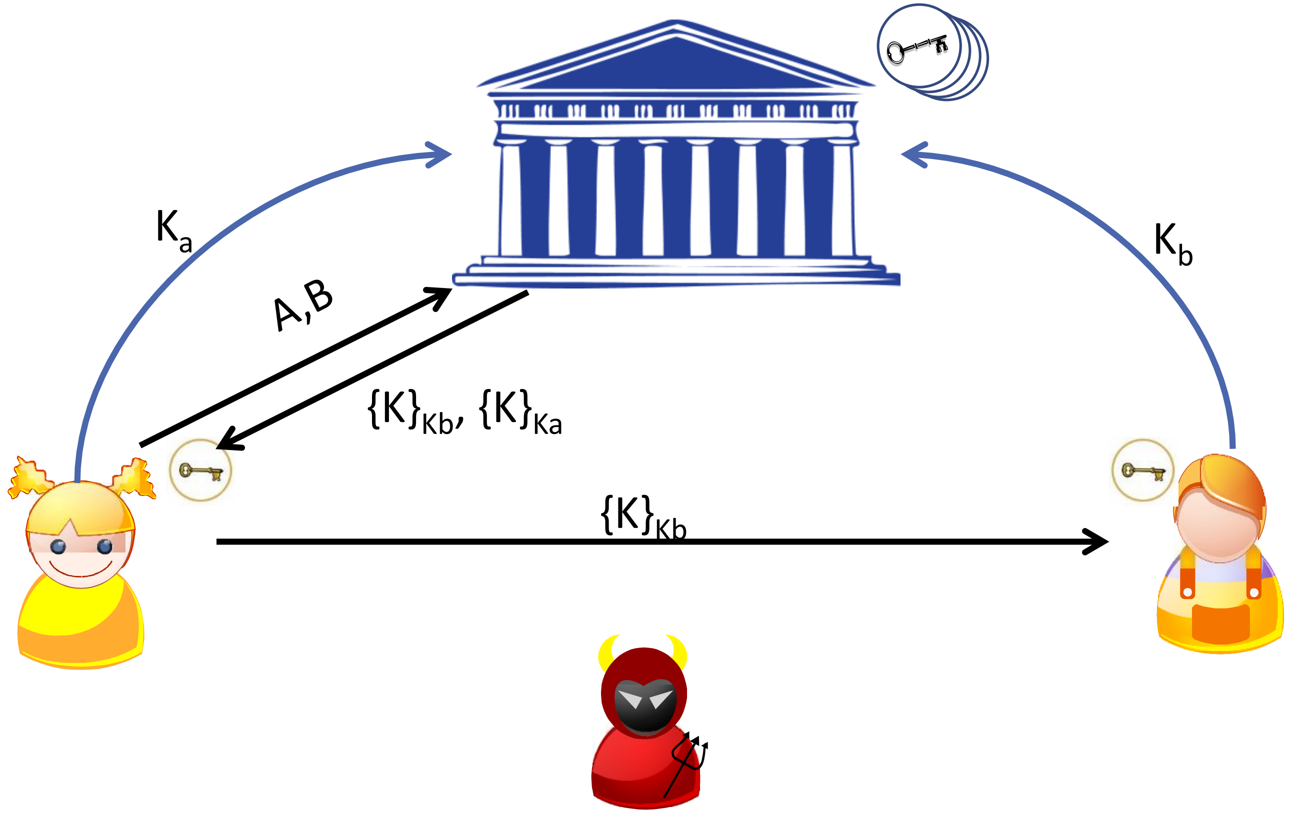


- Replay

Ensure freshness!

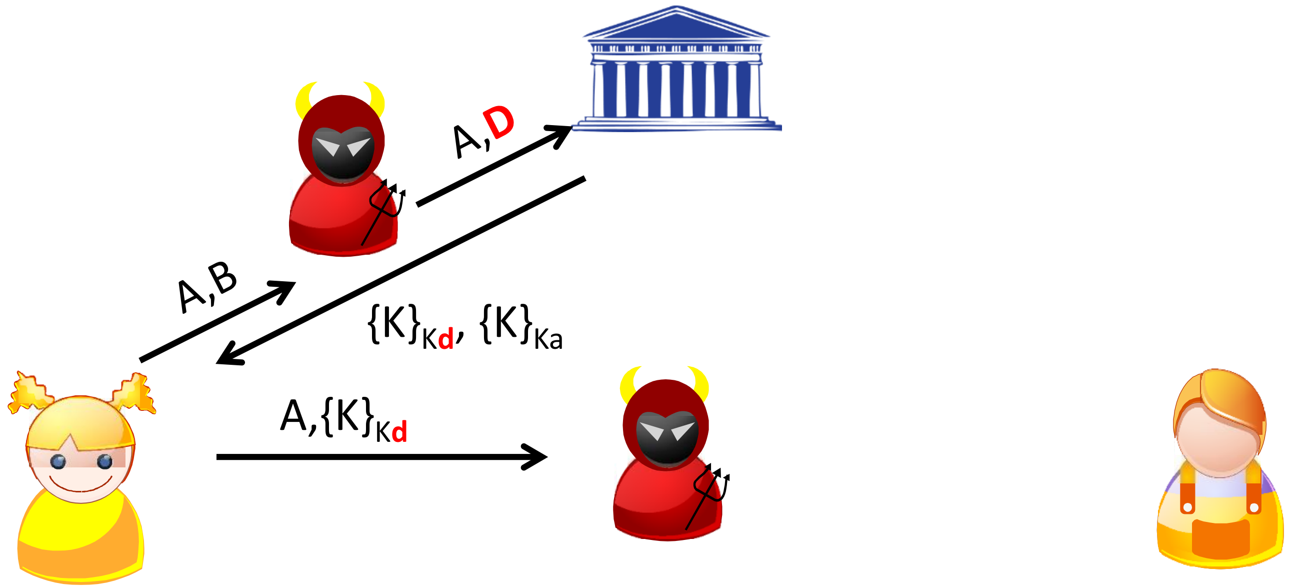
Key distribution with an arbiter

A simple (insecure) Protocol

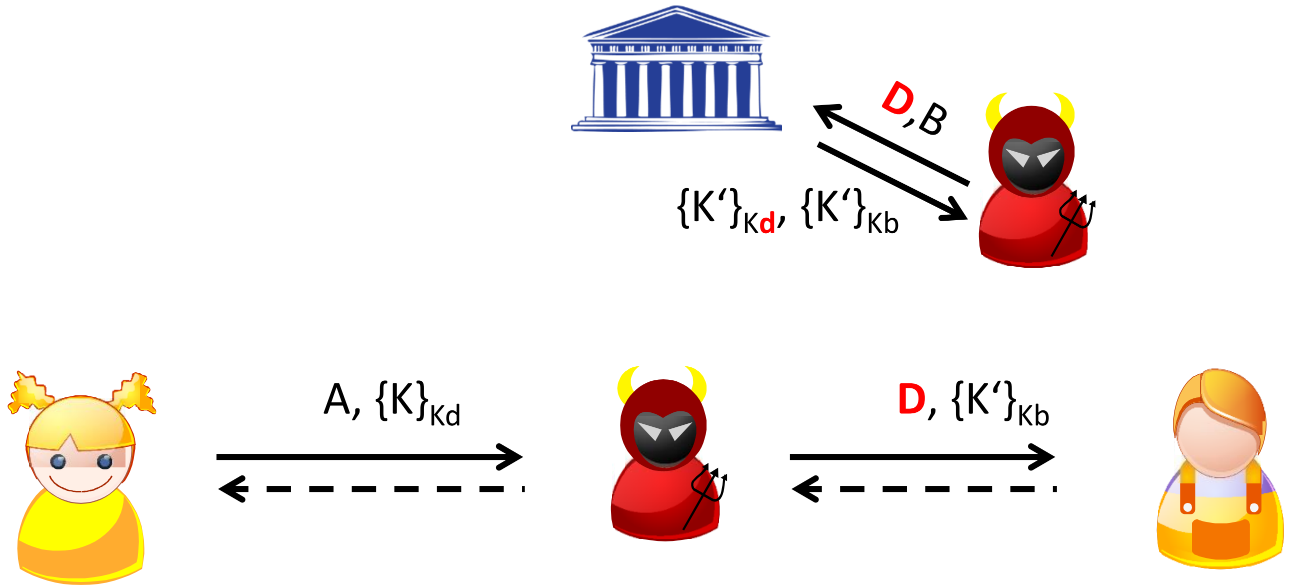


Man in the Middle - 1

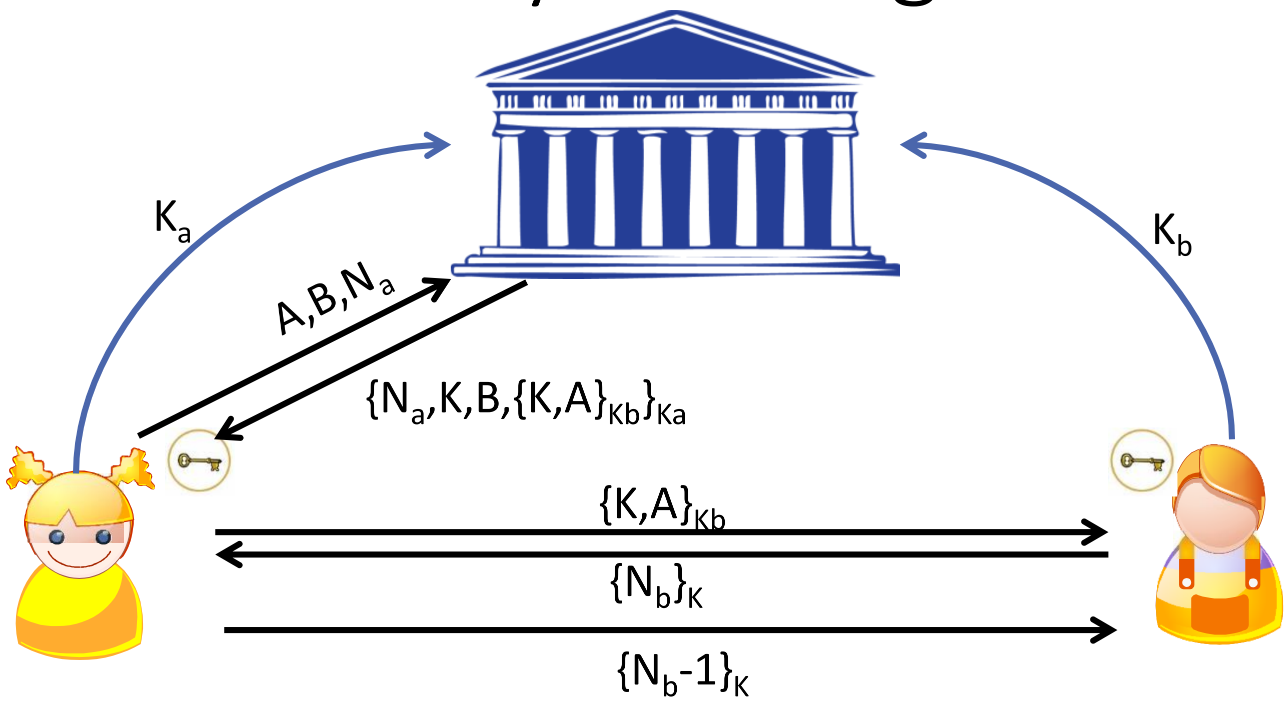
Karlsruhe Institute of Technology



Man in the Middle - 2



Schroeder-Needham Key Exchange



Observation:

- Prevent *MitM* through *Identification*
  - Alice and Bob are authenticated through knowledege of key K (need K_a or K_b)
- Prevent *Replay* by „*Nonces*"
- *Extension: Timestamps for Freshness, in case that Mallory guesses an old key*

Applying this to encryption...

Asymmetry (RSA) – Math Background

- Given randomly chosen, large primes *p* and *q:*
  - Multiplying $n = p \cdot q$ is simple
  - Factoring *n* to prime factors *p* and *q* is hard

- Given cyclic multiplicative groups: Multiplication is trivial, Division hard…

- Knowing prime factors using ext. Eucl. algorithm, simply calculate the mult. inverse:

- For cyclic mult. group Z_n^* and ***e*** (coprime to *n*):

$\boldsymbol{e^{-1}}$: $gcd(e,n) = 1: d \cdot e + k \cdot n$

$$k \cdot n \equiv 0 \bmod n$$

$$e \cdot e^{-1} \equiv 1 \bmod n$$

=> $e^{-1} = d$

RSA – Key Generation

- Each participant
  - Chooses two independent, large random primes p, q
  - Calculates $N = p \cdot q$ and $\varphi(N) = N-p-q+1 = (p-1)(q-1)$
  - Chooses random ***e***, with $2 < e < \varphi(N)$, $gcd(e, \varphi(N)) = 1$
  - And calculates ***d*** such that $e \cdot d = 1 \mod (\varphi(N))$

- Subsequently:
  - Store (p,q,d) (as secret key sk)
  - Publish (N,e) (as public key pk)

RSA – Encryption and Decryption

- ***Permute („Encryption“)***
- Given *pk = (N,e):*
- RSA (pk, m): $\mathbb{Z}_N^* \longrightarrow \mathbb{Z}_N^*$; c = RSA(e,m) = m^e mod N (in $\mathbb{Z}_N$)

- ***Invert ("Decryption")***
- Given sk (p,q,d):
- m = RSA^{-1} (pk, c) = $c^{1/e}$ = c^d = RSA(d,c) mod N (in $\mathbb{Z}_N$)

- $c^d = \mathbf{RSA(m)^d} = m^{ed} = m^{k\varphi(N)+1} = (m^{\varphi(N)})^k \cdot \mathbf{m} = m$ (c in $\mathbb{Z}^*_N$)

- ***Bonus: „Signing“ a message***
- Given sk (p,q,d):
- tag = RSA^{-1} (pk, h(m)) = RSA(d,h(m))

Factoring (prime decomposition)

- <u>Theorem</u>: all integers > 1 are either prime or a product of primes.

- ***<u>Factoring</u>***:
- Consider set of integers $\mathbb{Z}_{(2)}(n) = \{ N=pq$, where p,q are n-bit primes$\}$

- Task: Find the prime factors (*p and q*) of a random *N* in $\mathbb{Z}_{(2)}(n)$

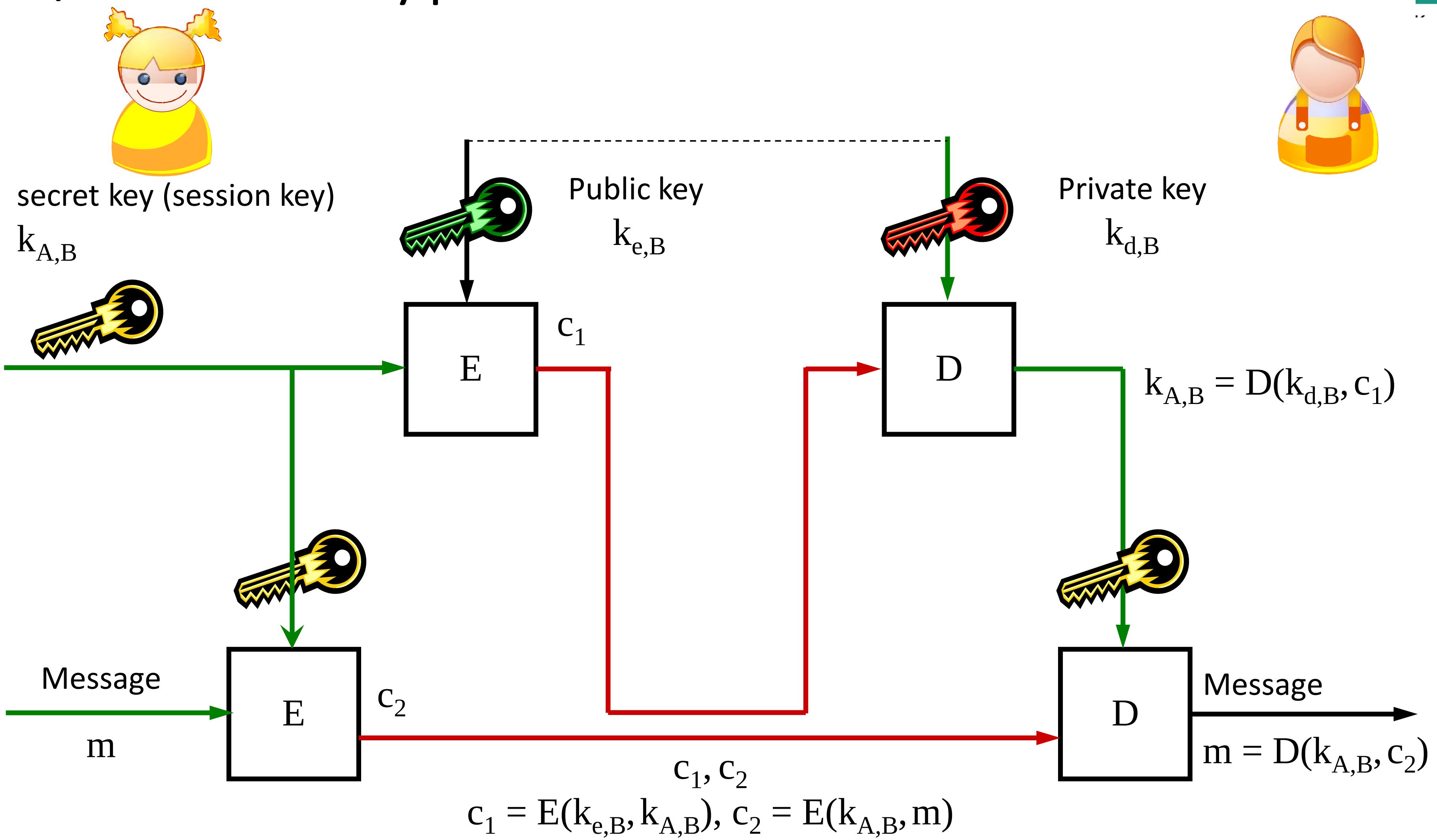
- Best known algorithm (NFS): $\exp(\tilde{O}(\sqrt[3]{n}))$ for n-bit integers

- ***Current world record***: RSA-768 (232 digits) (200 machine years)

- *Consumed enough energy to heat to boiling point 2 olympic pools…*
- *(Breaking RSA-2380 equivalent to evaporating all water on earth)*

Lenstra, Kleinjung, Thomé

Hybrid / ISO Encryption



Summary

- Adversaries, Attacker Models, and Threats
- Security Objectives (CIA) and Security Services
- Defining and formalizing security as a game
- Perfect secrecy / semantic security
- One-Time-Pad, Stream-Cipher
- Block-Cipher and modes of operation
- Hash functions and MACs
- Key Agreement direct and with arbiter
- Asymmetric encryption and signatures