CSE P 590 / CSE M 590 (Spring 2010)

Computer Security and Privacy

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

Goals for Today

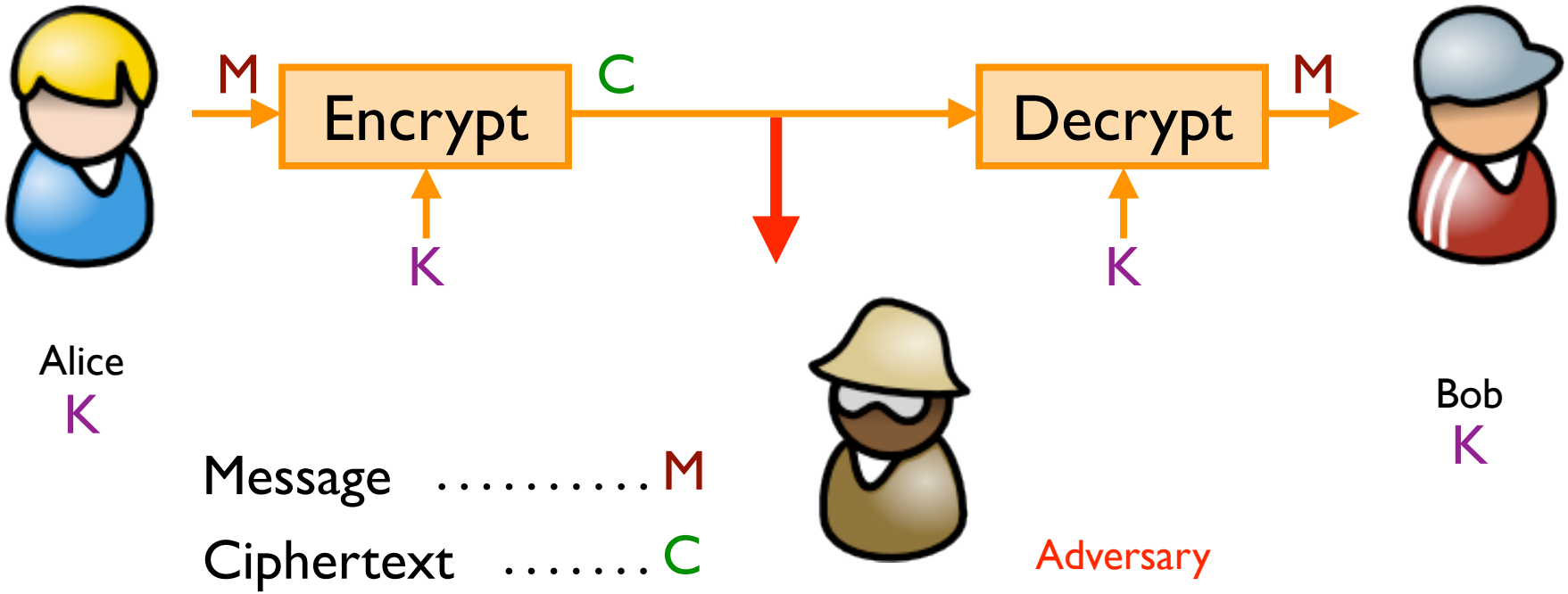
- Cryptography (Continued)
  - Symmetric cryptography
- Research:
  - Self-destructing data

First

- Under the hood: Symmetric encryption

Achieving Privacy (Symmetric)

Encryption schemes: A tool for protecting privacy.

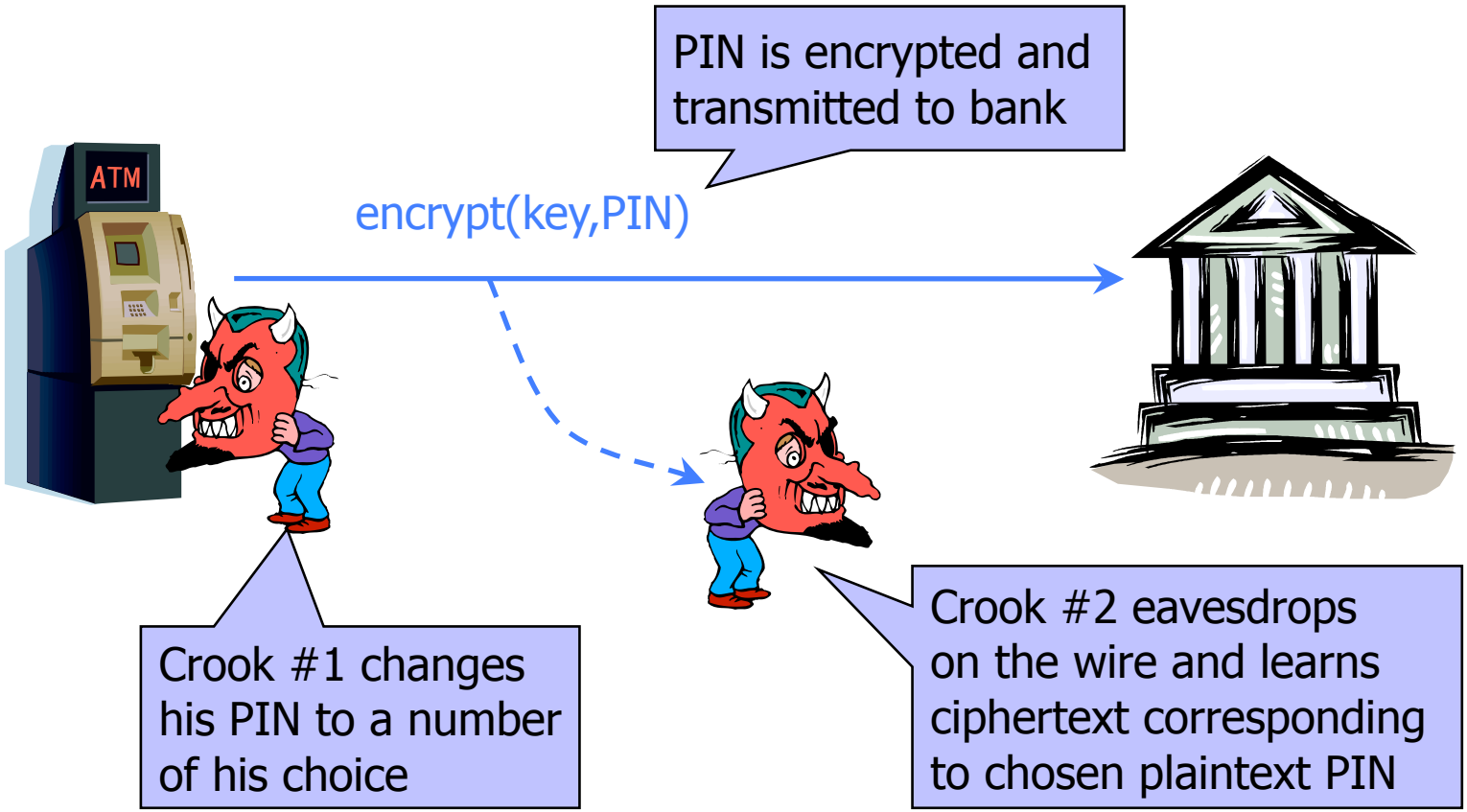


Attack Scenarios for Encryption

- Ciphertext-Only
- Known Plaintext
- Chosen Plaintext
- Chosen Ciphertext (and Chosen Plaintext)

- (General advice: Target strongest level of privacy possible -- even if not clear why -- for extra "safety")

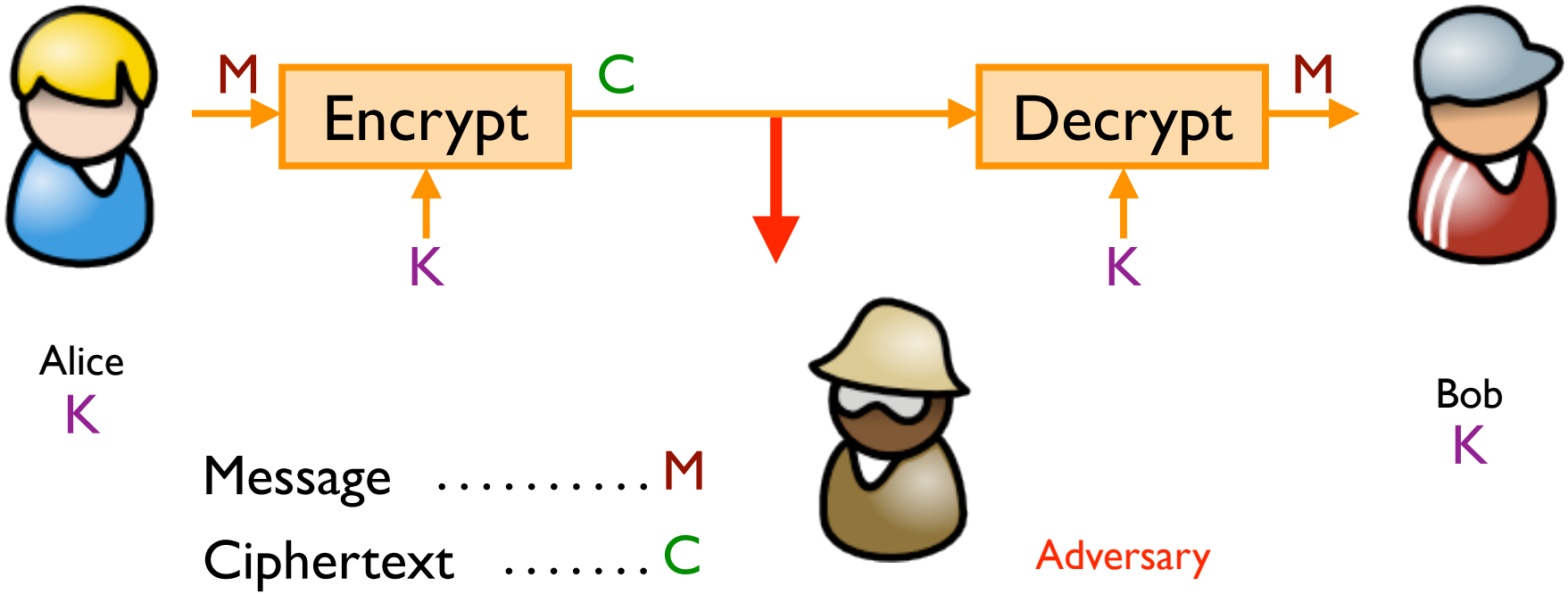
Chosen-Plaintext Attack



... repeat for any PIN value

Achieving Privacy (Symmetric)

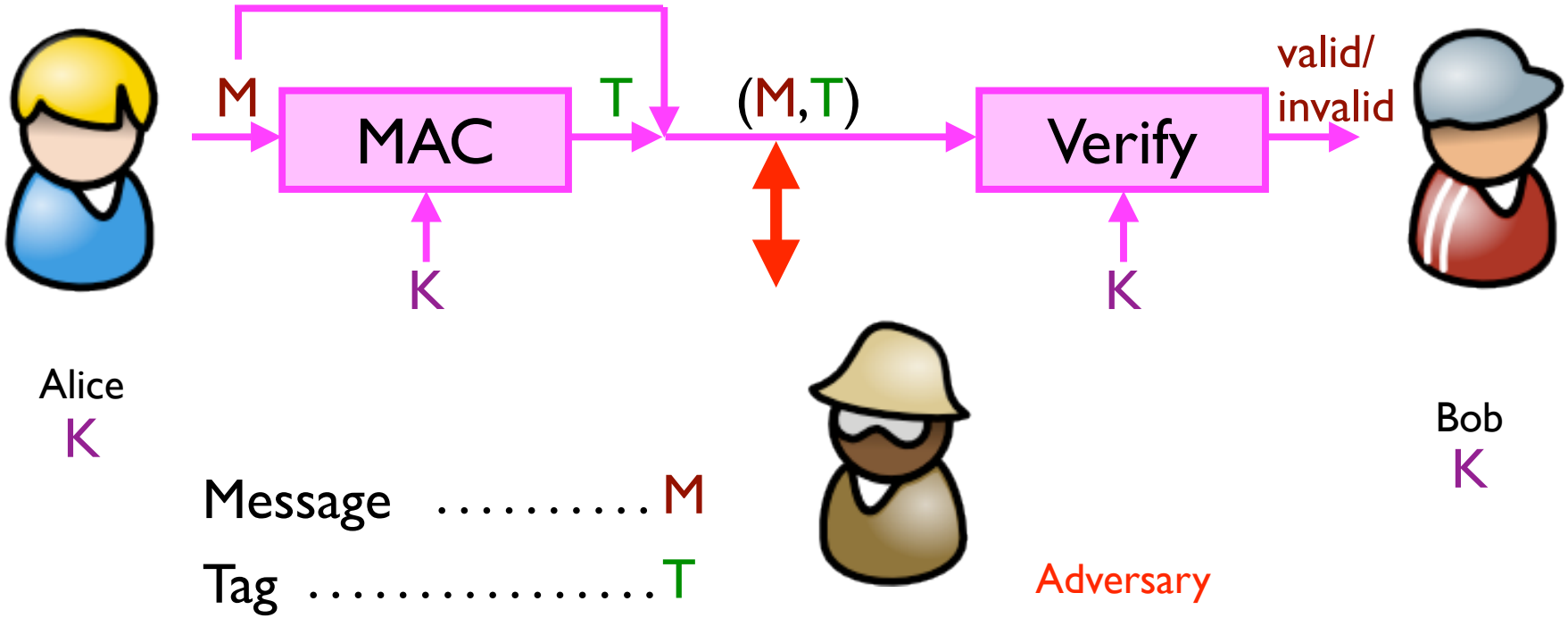
Encryption schemes: A tool for protecting privacy.



Achieving Integrity (Symmetric)

Message authentication schemes: A tool for protecting integrity.

(Also called message authentication codes or MACs.)



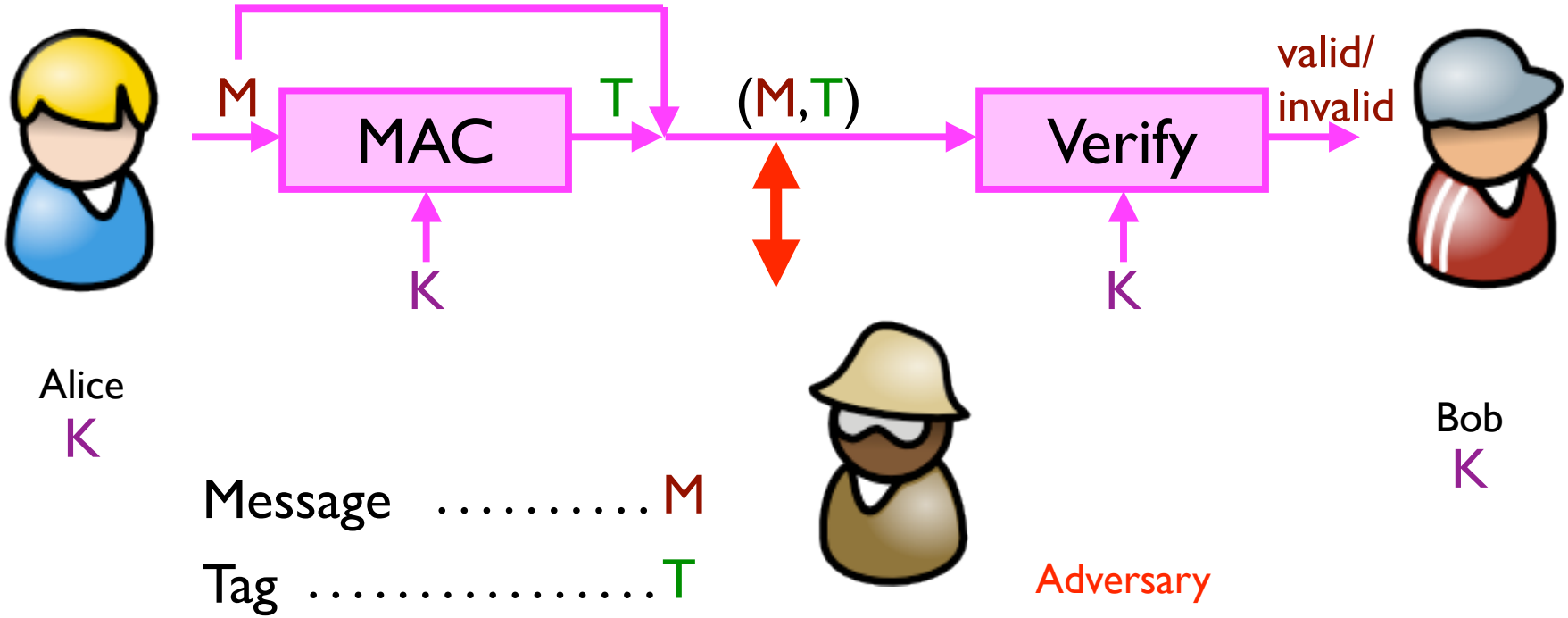
Attack Scenarios for Integrity

- What do you think these scenarios should be?

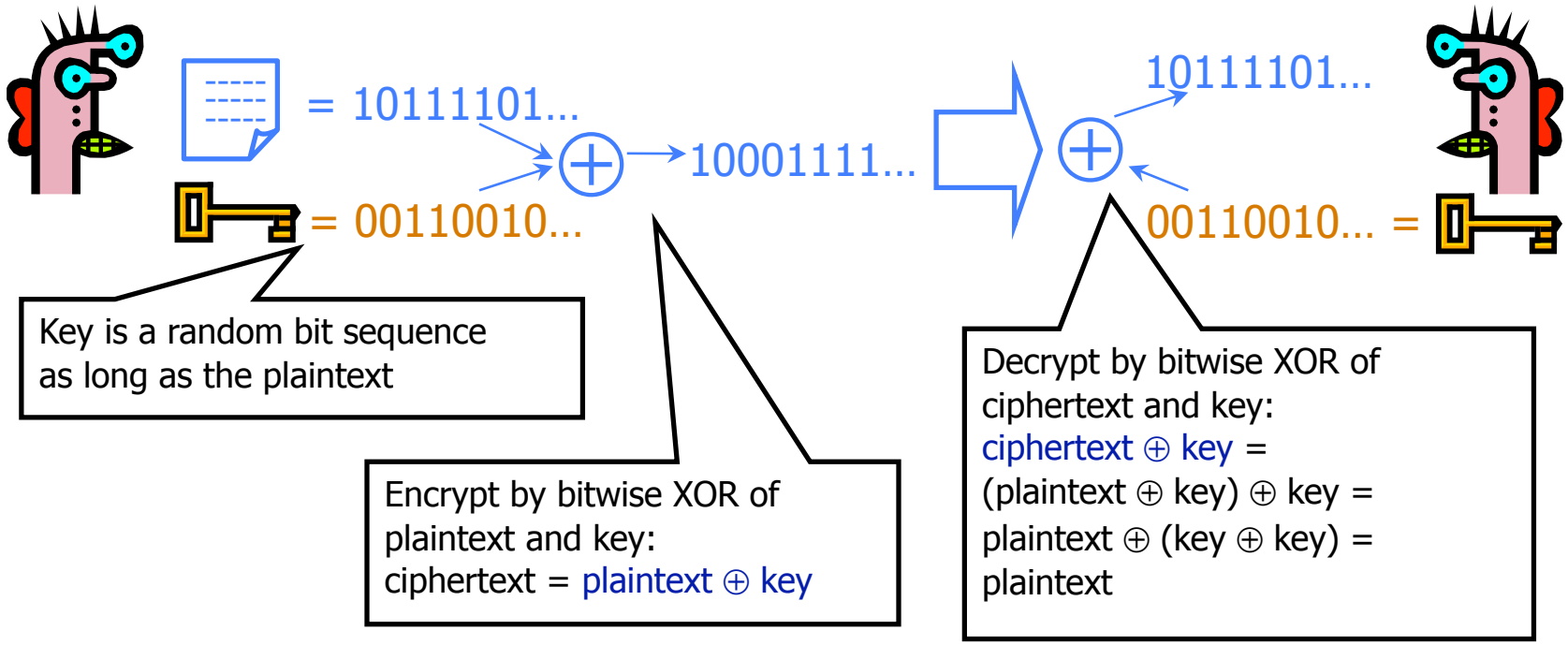
Achieving Integrity (Symmetric)

Message authentication schemes: A tool for protecting integrity.

(Also called message authentication codes or MACs.)



One-Time Pad

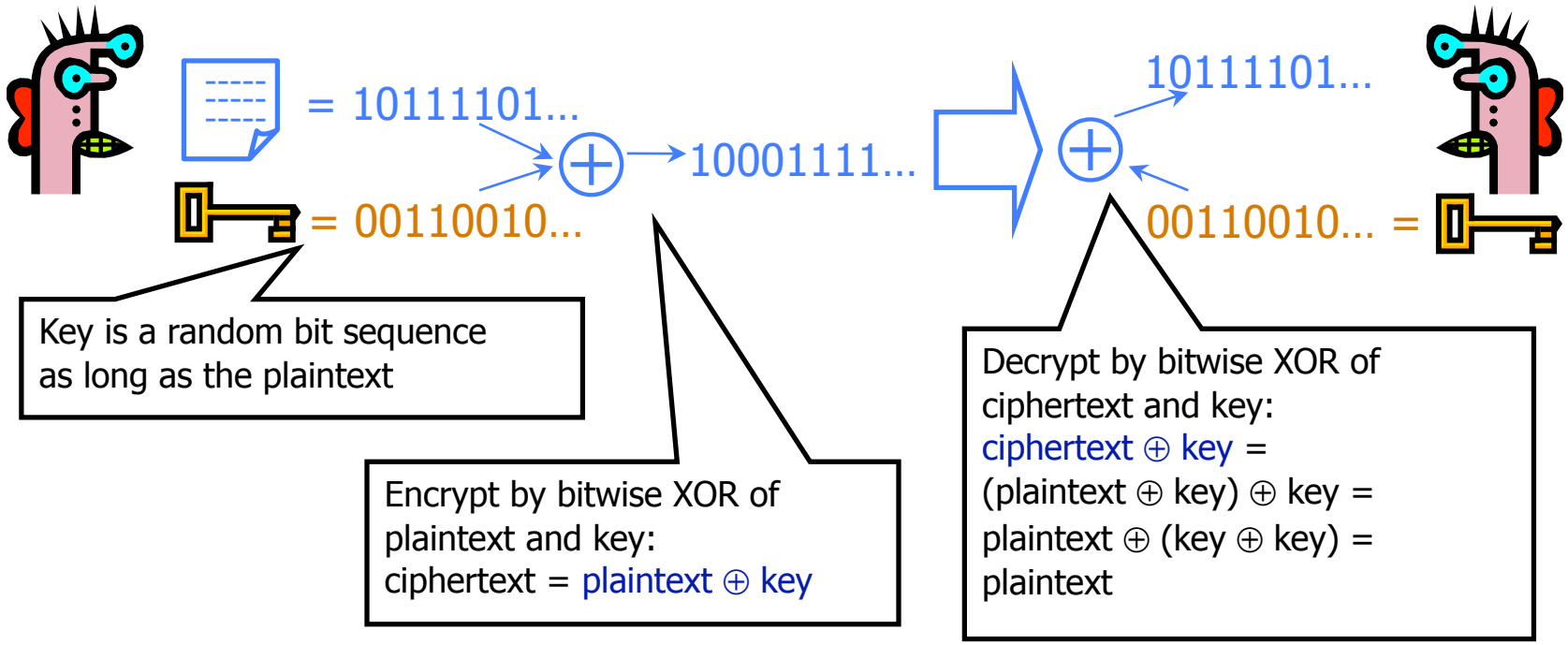


Cipher achieves perfect secrecy if and only if there are as many possible keys as possible plaintexts, and every key is equally likely (Claude Shannon)

Advantages of One-Time Pad

- Easy to compute
  - Encryption and decryption are the same operation
  - Bitwise XOR is very cheap to compute
- As secure as theoretically possible
  - Given a ciphertext, all plaintexts are equally likely, regardless of attacker's computational resources
  - …as long as the key sequence is truly random
    - True randomness is expensive to obtain in large quantities
  - …as long as each key is same length as plaintext
    - But how does the sender communicate the key to receiver?

Disadvantages

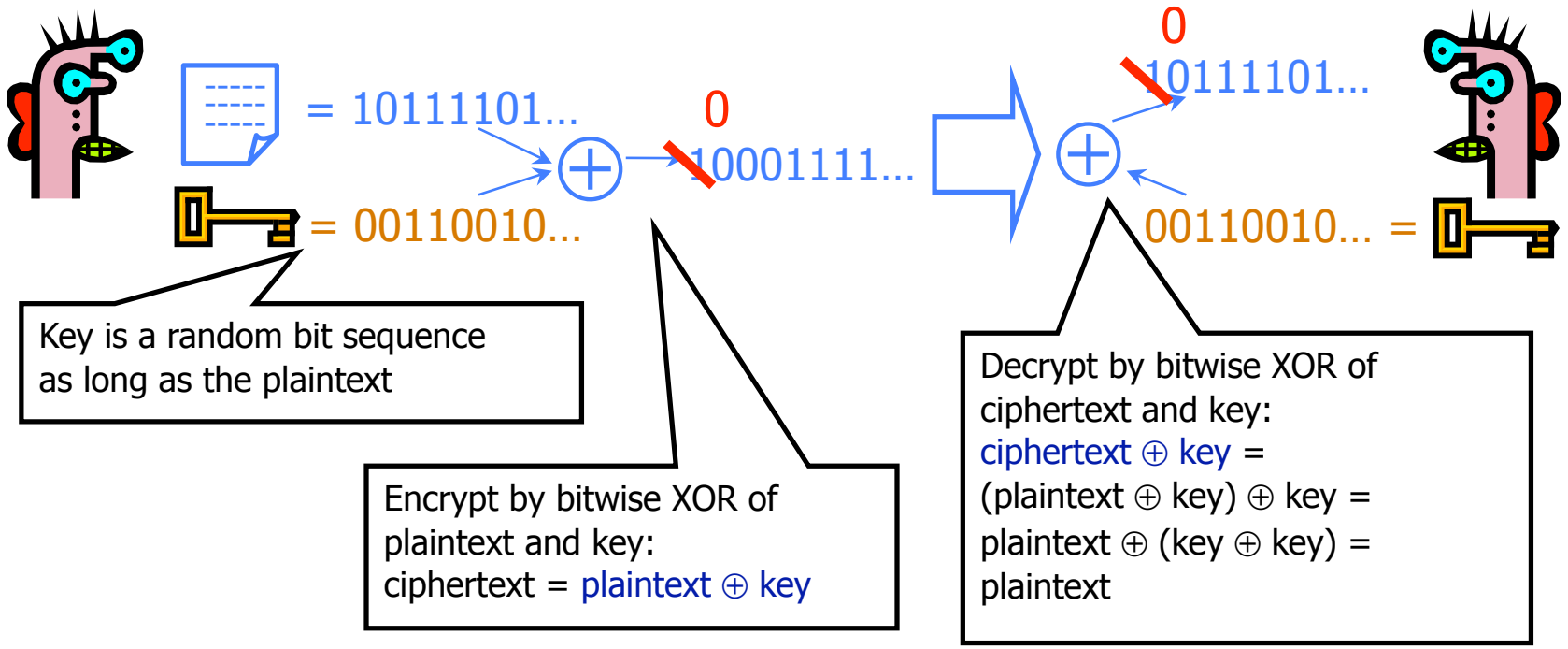


Disadvantage #1: Keys as long as messages.

Impractical in most scenarios

(Supposedly still used by intelligence communities)

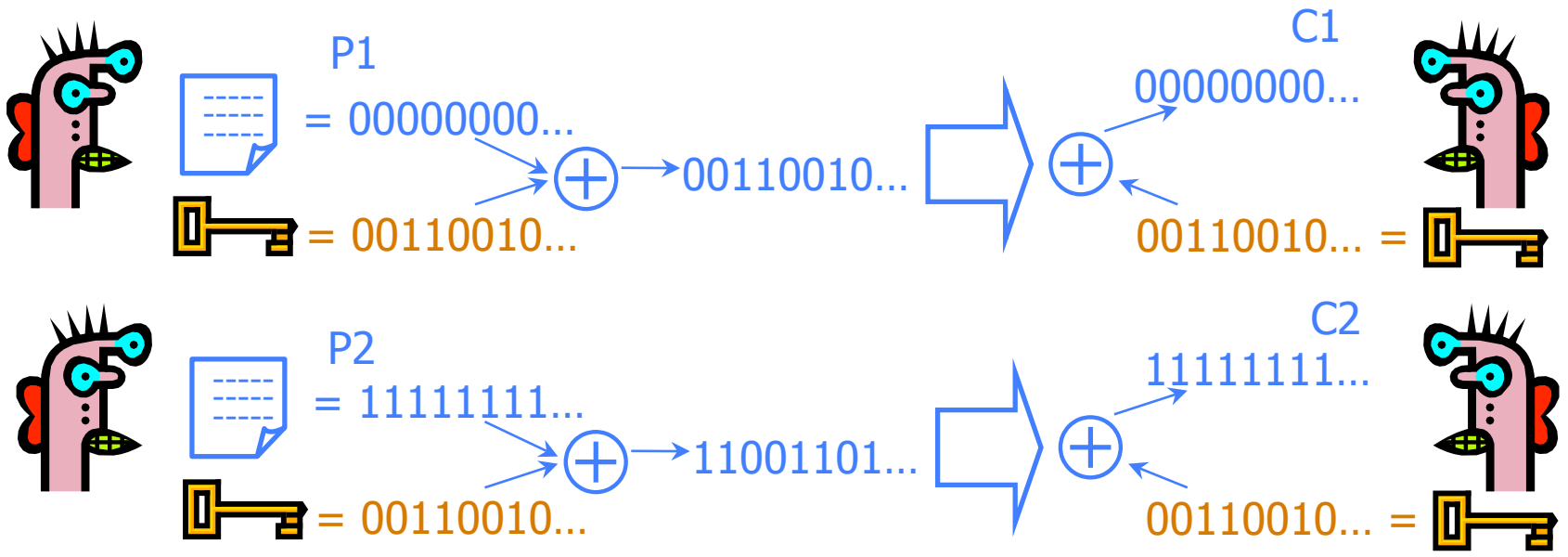
Disadvantages



Disadvantage #2: No integrity protection

Disadvantages

Disadvantage #3: Keys cannot be reused



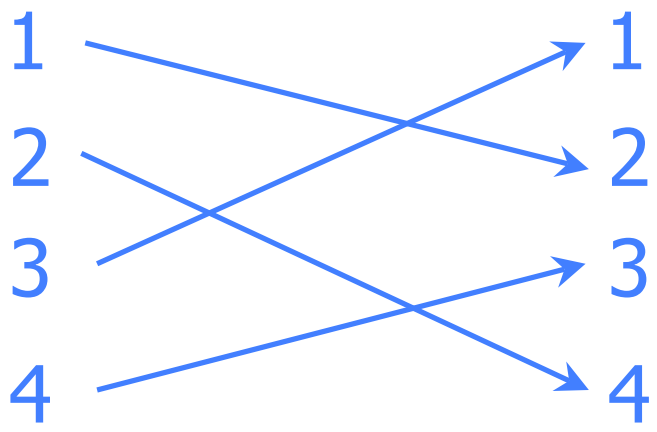
Learn relationship between plaintexts:

$C1 \oplus C2 = (P1 \oplus K) \oplus (P2 \oplus K) = (P1 \oplus P2) \oplus (K \oplus K) = P1 \oplus P2$

Reducing Keysize

- What do we do when we can't pre-share huge keys?
  - When OTP is unrealistic
- We use special cryptographic primitives
  - Single key can be reused (with some restrictions)
  - But no longer provable secure (in the sense of the OTP)
- Examples: Block ciphers, stream ciphers

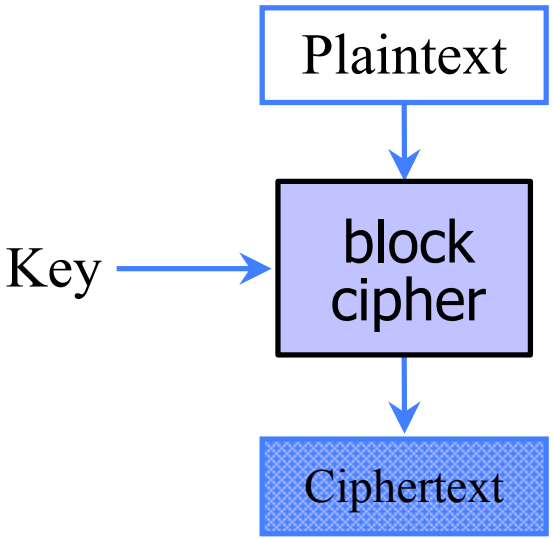
Background: Permutation



- For N values, N! possible permutations
- For N-bit inputs, 2^N! possible permutations!
- Idea for how to use: split plaintext into blocks; for each block use secret key to pick a permutation
  - Without the key, permutation should "look random"

Block Ciphers

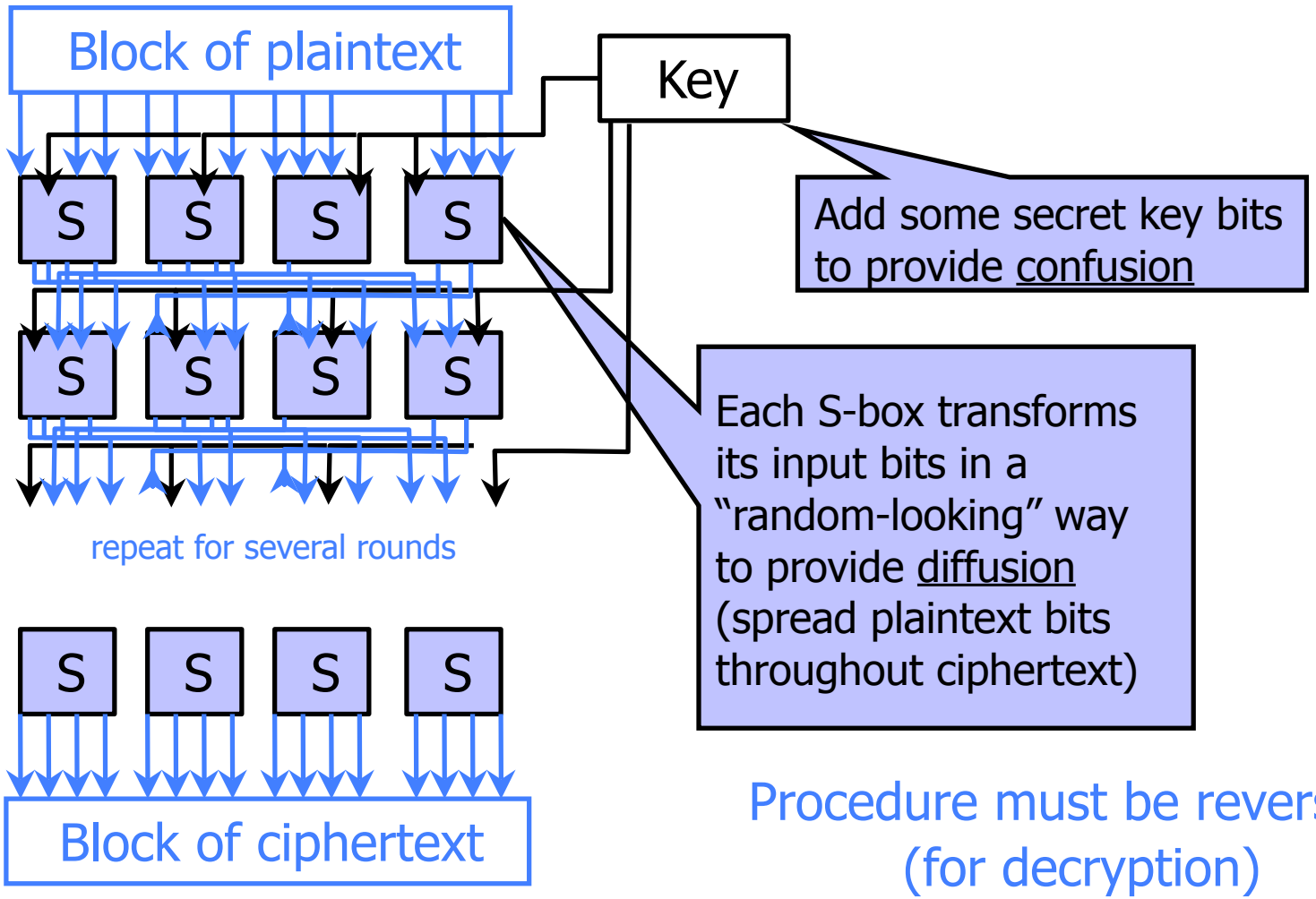
- Operates on a single chunk ("block") of plaintext
  - For example, 64 bits for DES, 128 bits for AES
  - Same key is reused for each block (can use short keys)



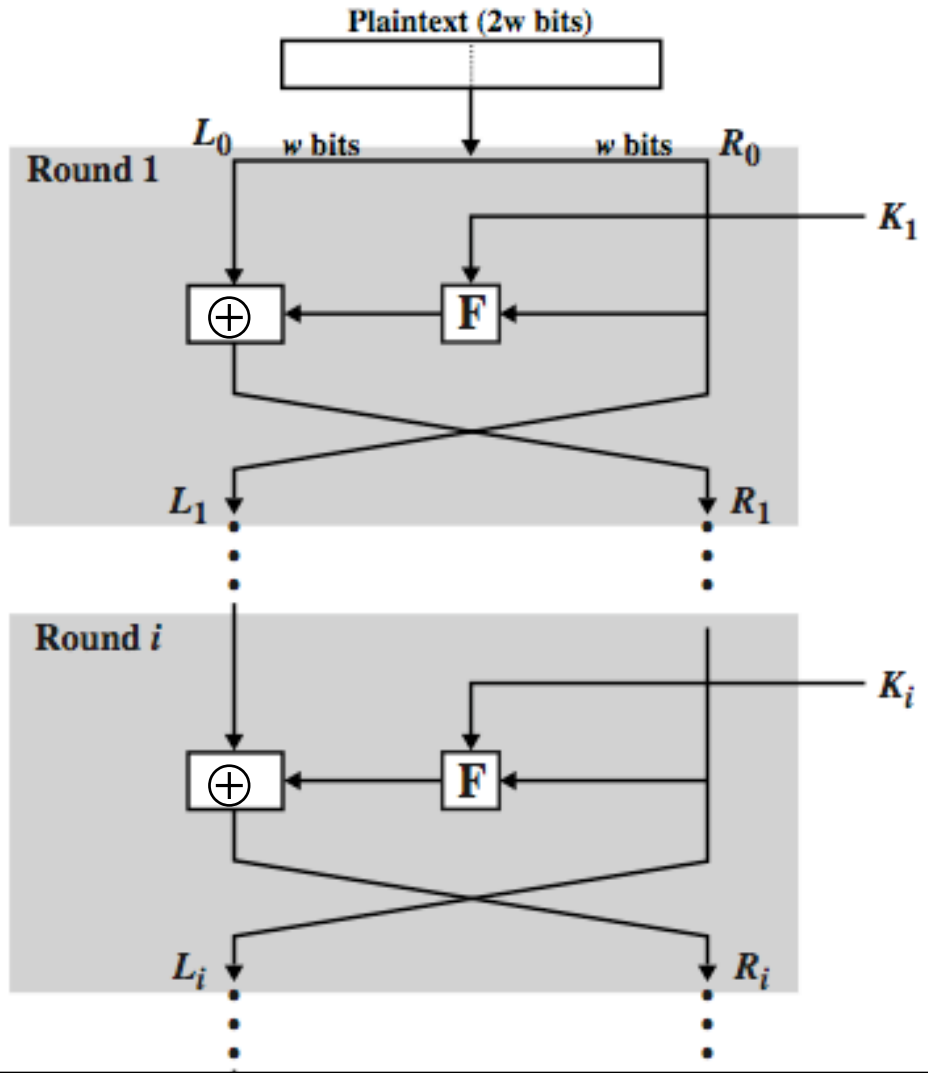
Block Cipher Security

- Result should look like a random permutation
  - "As if" plaintext bits were randomly shuffled
- Only computational guarantee of secrecy
  - Not impossible to break, just very expensive
    - If there is no efficient algorithm (unproven assumption!), then can only break by brute-force, try-every-possible-key search
  - Time and cost of breaking the cipher exceed the value and/or useful lifetime of protected information

Block Cipher Operation (Simplified)



Feistel Structure (Stallings Fig 2.2)



DES

- Feistel structure
  - "Ladder" structure: split input in half, put one half through the round and XOR with the other half
  - After 3 random rounds, ciphertext indistinguishable from a random permutation **if** internal F function is a pseudorandom function (Luby & Rackoff)
    - Theoretical results: Evidence that the "ladder" structure is a solid design
    - In practice: Use more than 3 rounds
- DES: Data Encryption Standard
  - Feistel structure
  - Invented by IBM, issued as federal standard in 1977
  - 64-bit blocks, 56-bit key + 8 bits for parity

DES and 56 bit keys (Stallings Tab 2.2)

- 56 bit keys are quite short

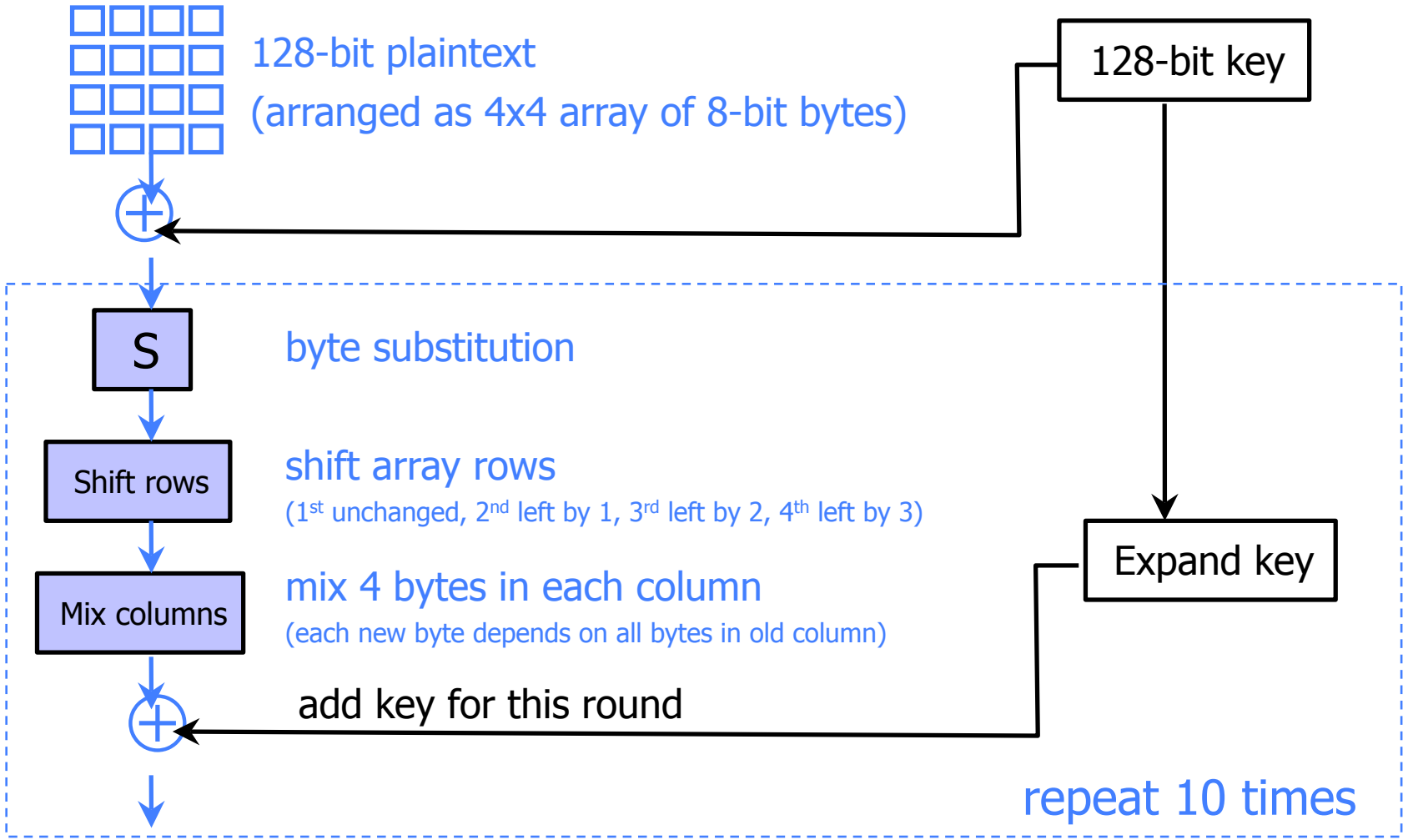
Key Size (bits)	Number of Alternative Keys	Time required at 1 encryption/μs	Time required at 10^6 encryptions/μs
32	$2^{32} = 4.3 \times 10^9$	$2^{31}\ \mu s = 35.8$ minutes	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	$2^{55}\ \mu s = 1142$ years	10.01 hours
128	$2^{128} = 3.4 \times 10^{38}$	$2^{127}\ \mu s = 5.4 \times 10^{24}$ years	5.4×10^{18} years
168	$2^{168} = 3.7 \times 10^{50}$	$2^{167}\ \mu s = 5.9 \times 10^{36}$ years	5.9×10^{30} years
26 characters (permutation)	$26! = 4 \times 10^{26}$	$2 \times 10^{26}\ \mu s = 6.4 \times 10^{12}$ years	6.4×10^{6} years

- 1999: EFF DES Crack + distibuted machines
  - < 24 hours to find DES key
- DES ---> 3DES
  - 3DES: DES + inverse DES + DES (with 2 or 3 diff keys)

Advanced Encryption Standard (AES)

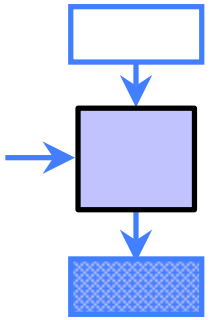
- New federal standard as of 2001
- Based on the Rijndael algorithm
- 128-bit blocks, keys can be 128, 192 or 256 bits
- Unlike DES, does not use Feistel structure
  - The entire block is processed during each round
- Design uses some very nice mathematics

Basic Structure of Rijndael



Encrypting a Large Message

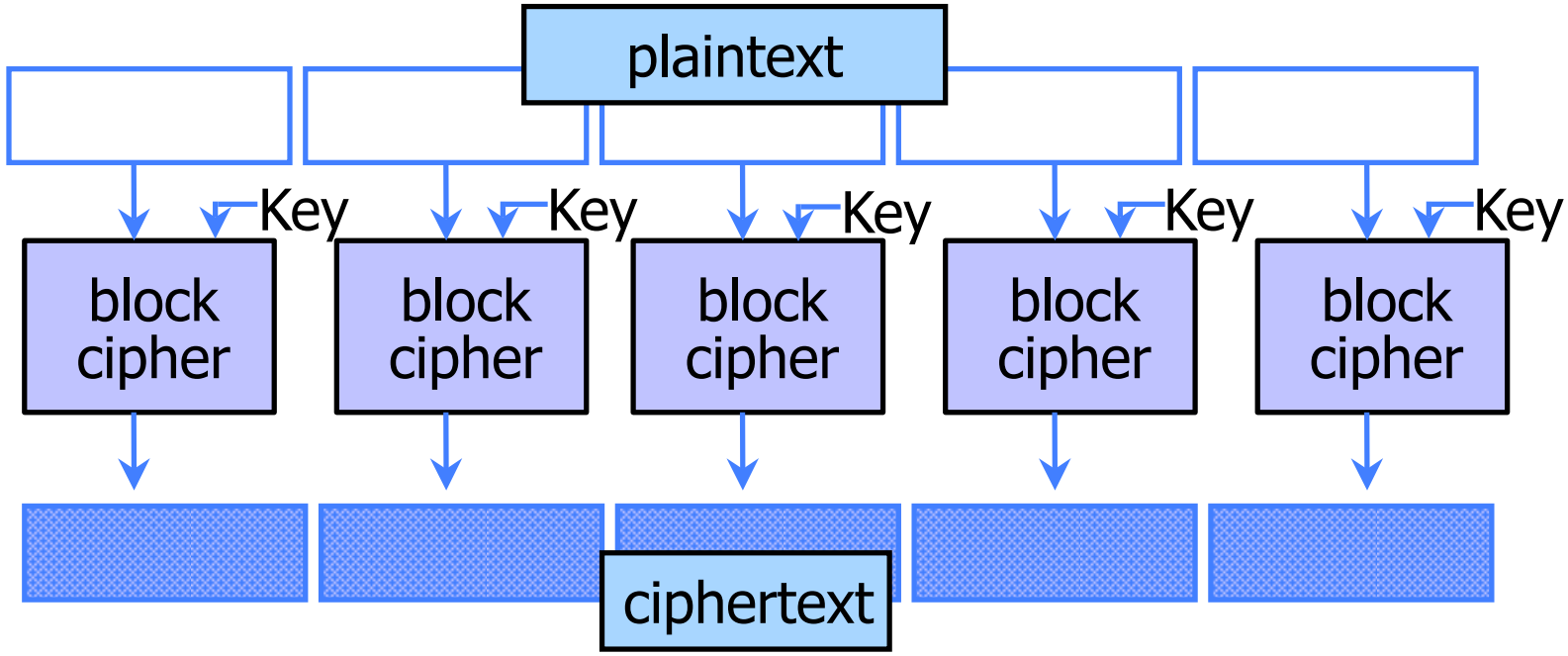
- So, we've got a good block cipher, but our plaintext is larger than 128-bit block size
- Electronic Code Book (ECB) mode
  - Split plaintext into blocks, encrypt each separately using the block cipher



one

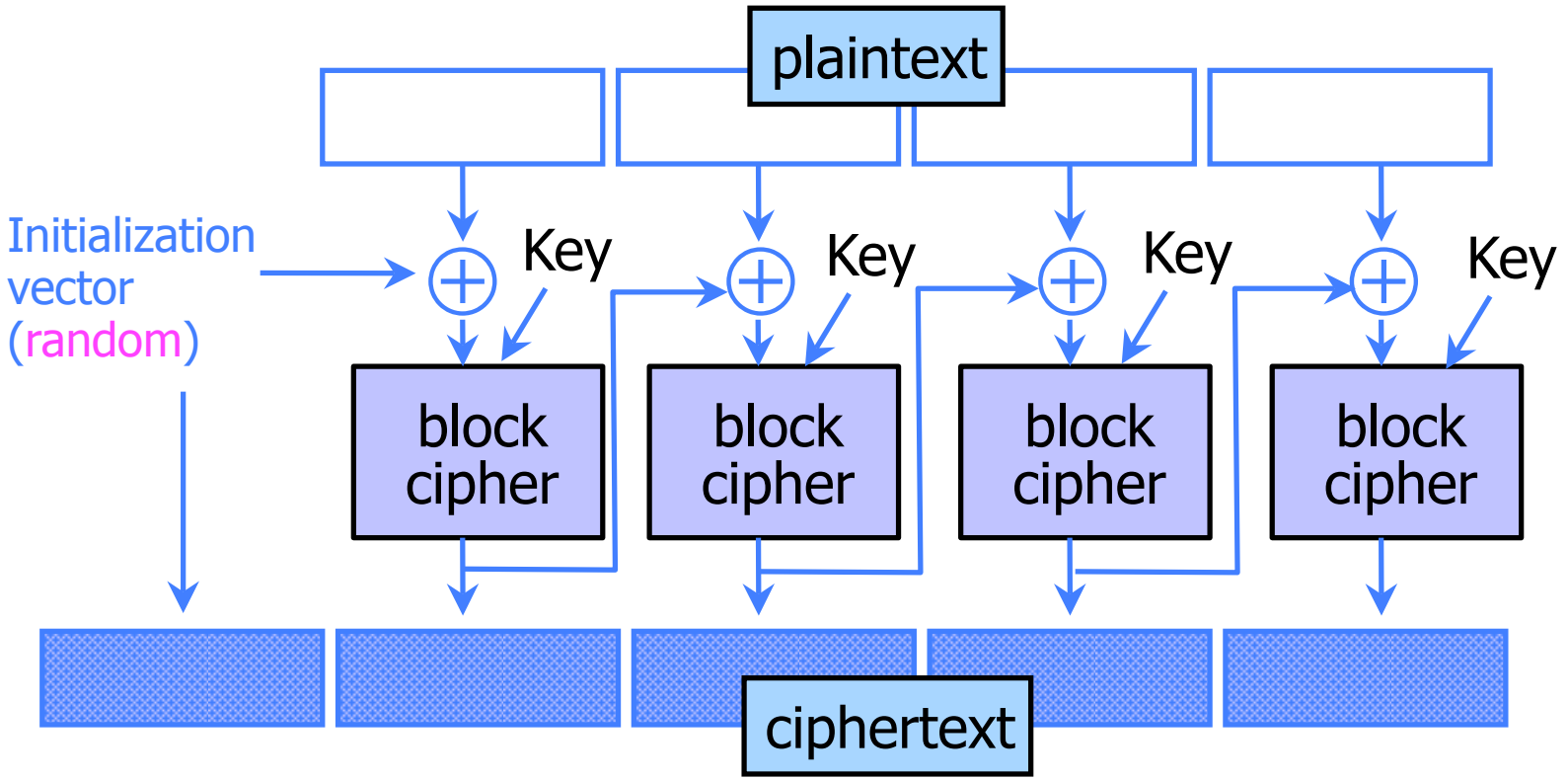
- Cipher Block Chaining (CBC) mode
  - Split plaintext into blocks, XOR each block with the result of encrypting previous blocks
- Counter (CTR) mode
  - Use block cipher to generate keystream, like a stream cipher
- ...

ECB Mode



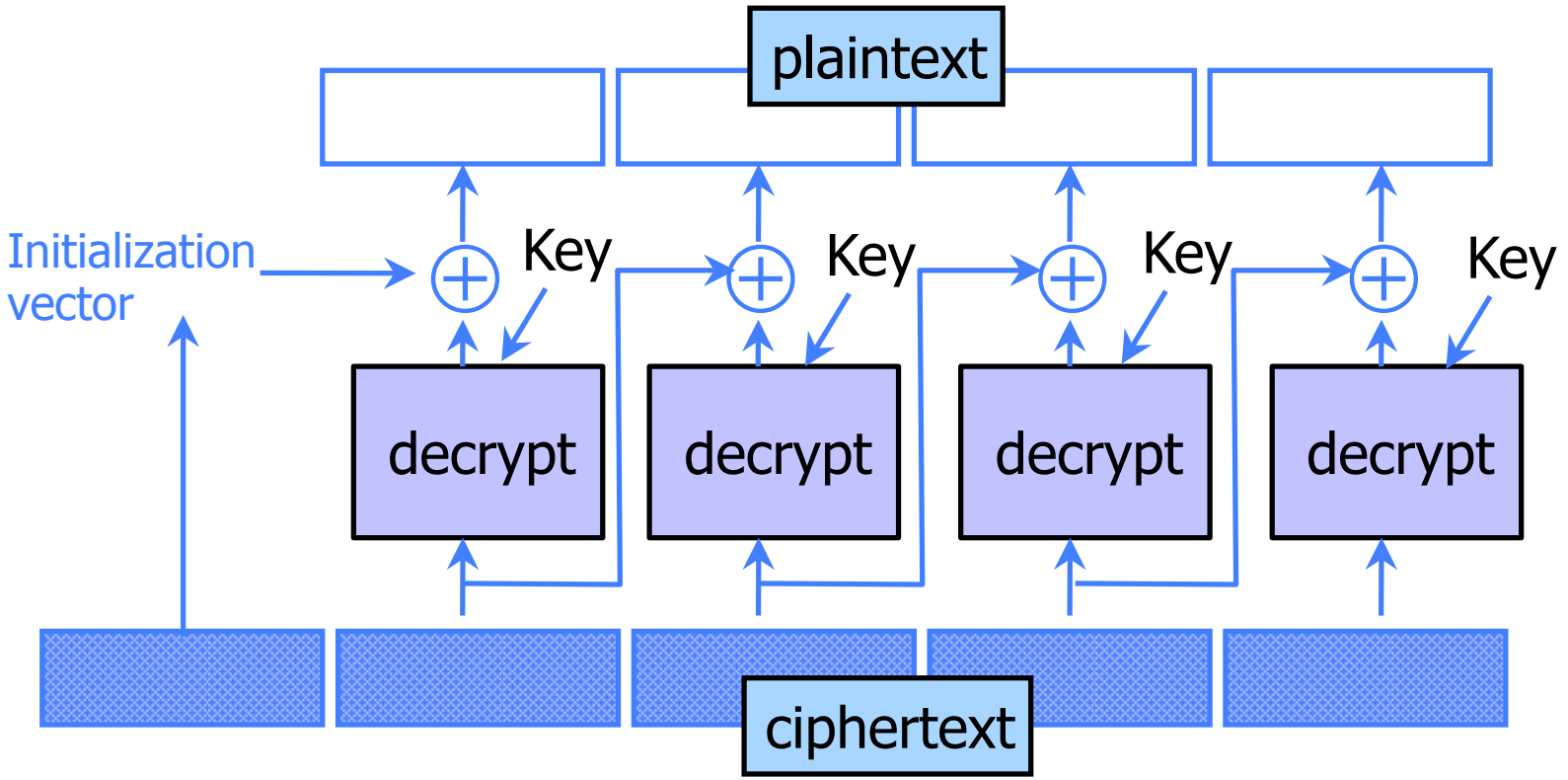
- Identical blocks of plaintext produce identical blocks of ciphertext
- No integrity checks: can mix and match blocks

CBC Mode: Encryption



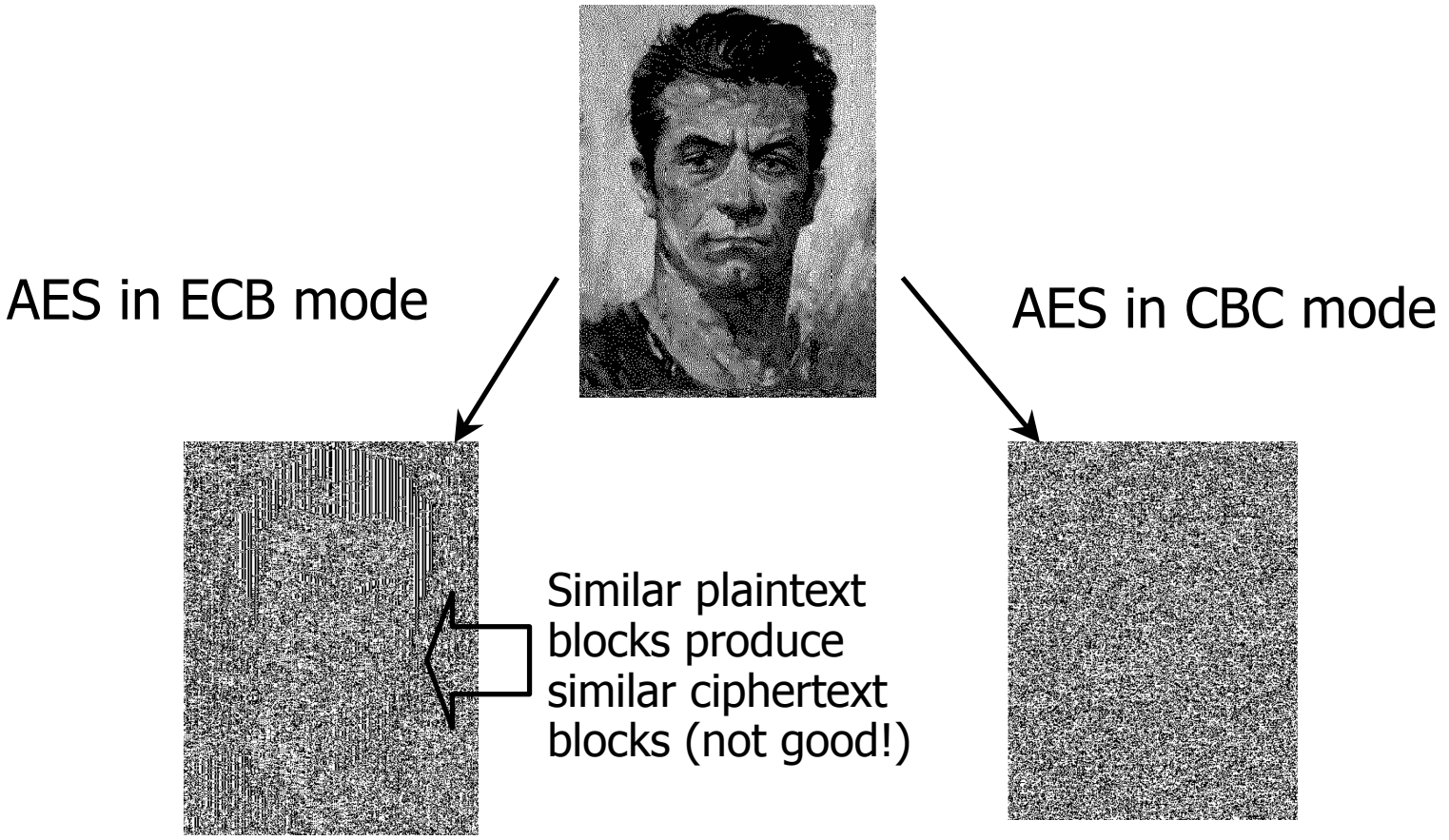
- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption



ECB vs. CBC

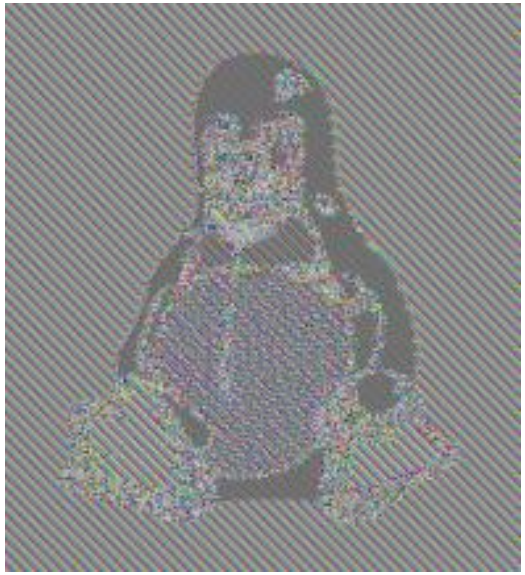
[Picture due to Bart Preneel]



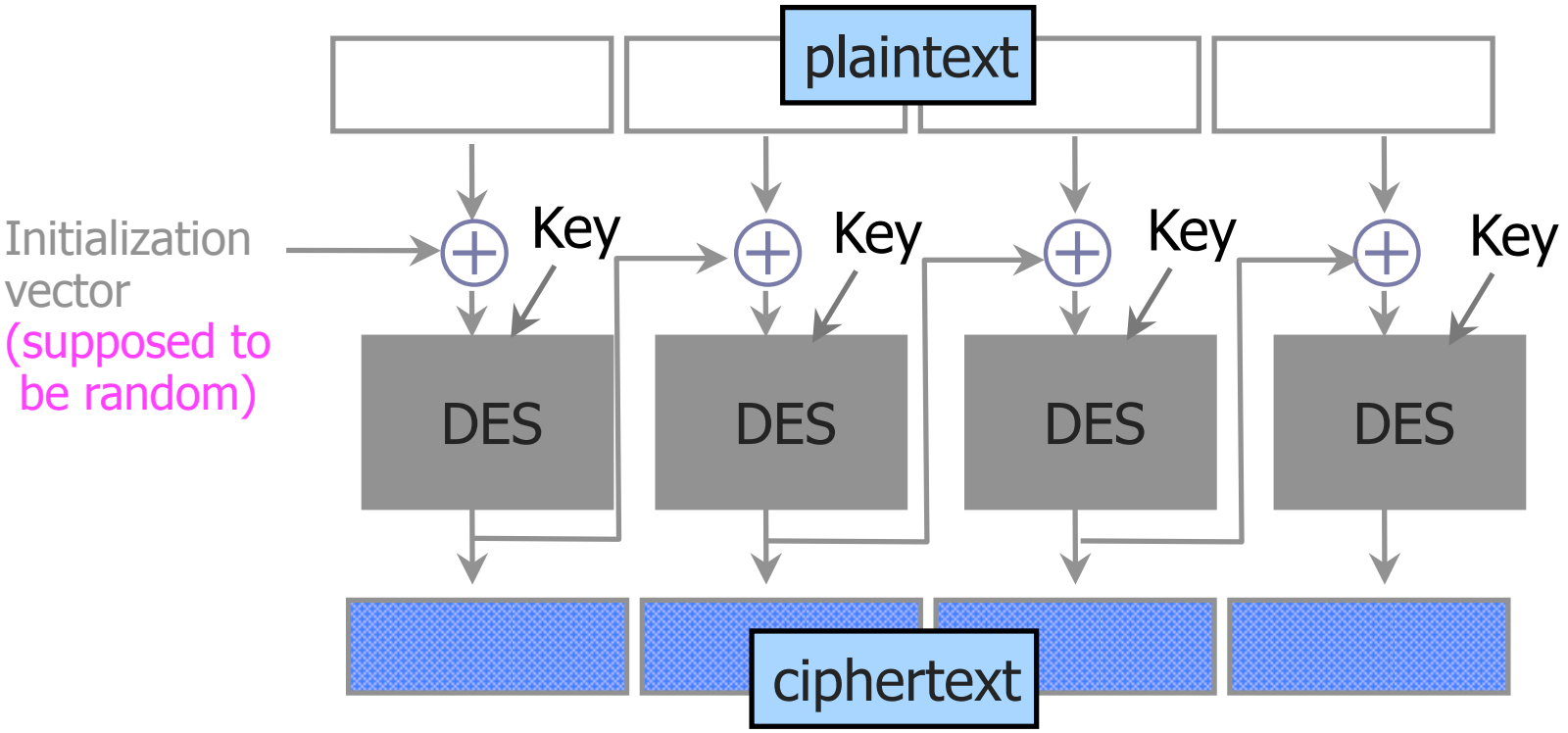
Information Leakage in ECB Mode

[Wikipedia]

Encrypt in ECB mode



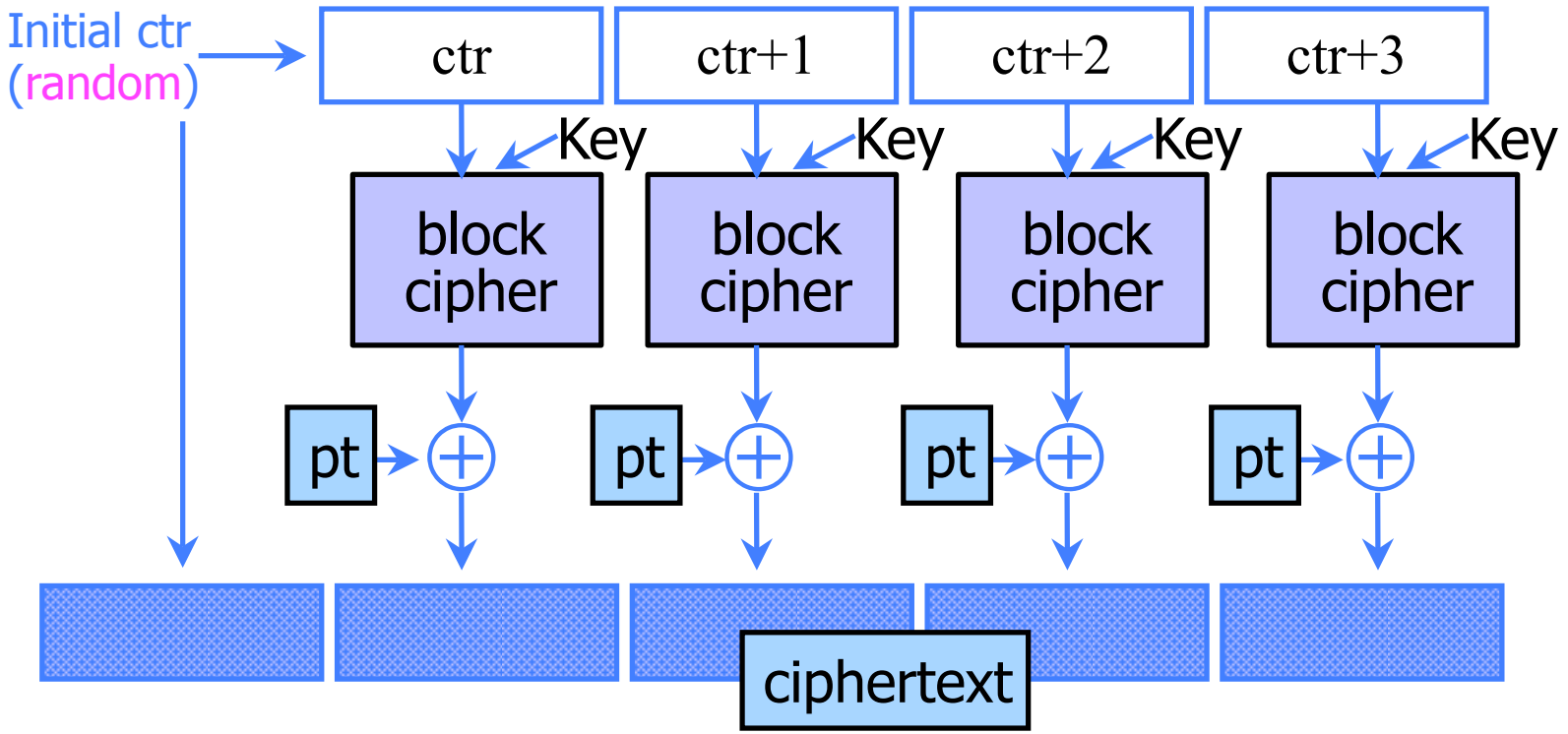
CBC and Electronic Voting



Found in the source code for Diebold voting machines:

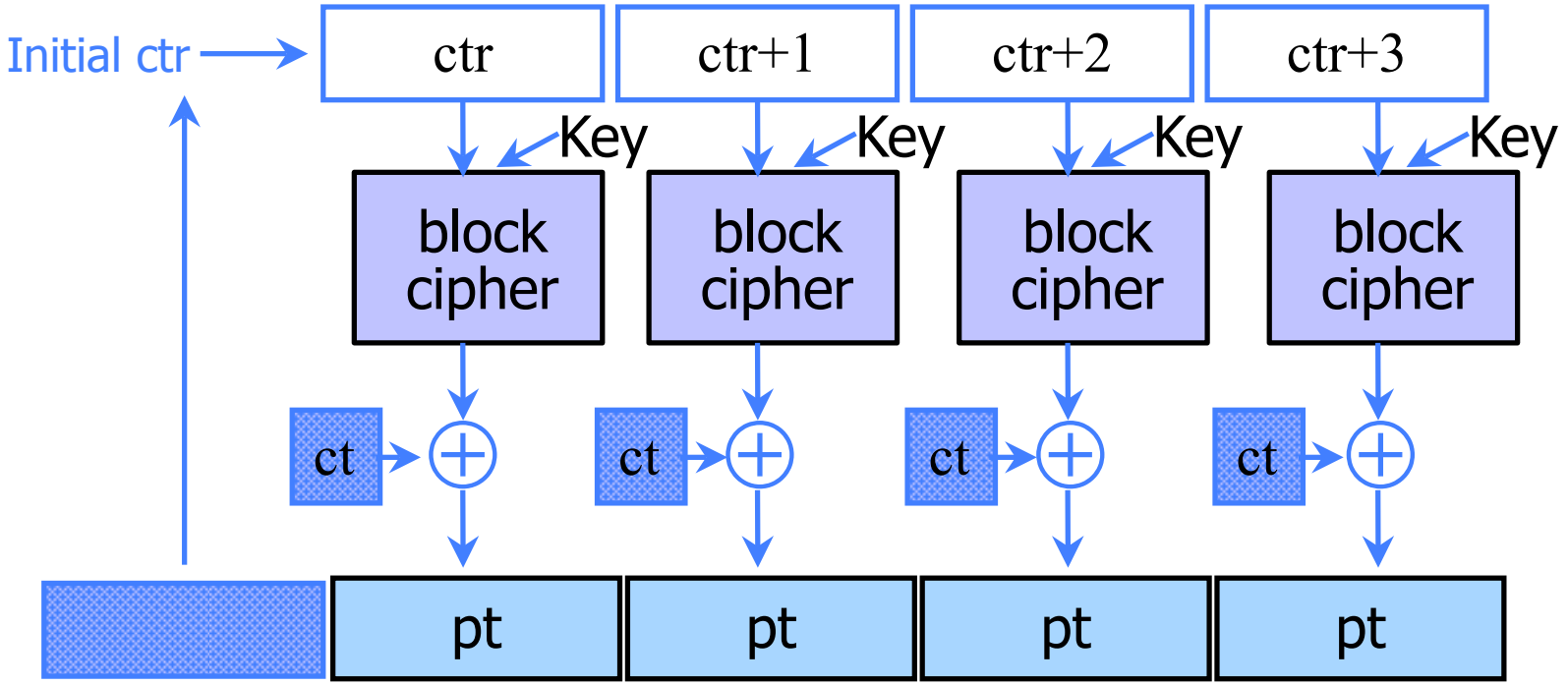
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
              totalSize, DESKEY, NULL, DES_ENCRYPT)
```

CTR Mode: Encryption



- Identical blocks of plaintext encrypted differently
- Still does not guarantee integrity
- Fragile if ctr repeats

CTR Mode: Decryption



Next

- Defining security for symmetric encryption

When Is a Cipher "Secure"?

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

How Can a Cipher Be Attacked?

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

Defining Security (Not Required)

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

Defining Security (Not Required)

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

  0 or 1

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

Chosen-Plaintext Security (Not Required)

- Consider two experiments (A is the attacker)

  Experiment 0

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

  Experiment 1

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

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

- Attacker's advantage is defined as

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

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

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

"Simple" Example (Not Required)

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

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

Let X,Y be any two different plaintexts

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

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

- The advantage of this attacker A is 1

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

Why Hide Everything?

- Leaking even a little bit of information about the plaintext can be disastrous
- Electronic voting
  - 2 candidates on the ballot (1 bit to encode the vote)
  - If ciphertext leaks the parity bit of the encrypted plaintext, eavesdropper learns the entire vote
- Also, want a strong definition that implies others

Birthday attacks

- Are there two people in this classroom that have the same birthday?
  - Yes?
  - No?

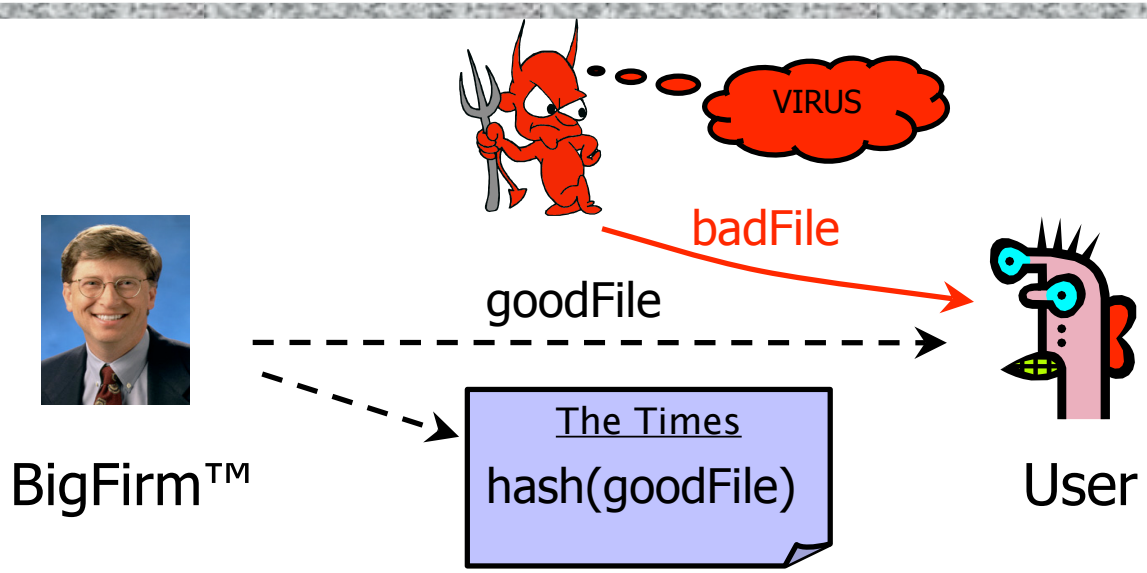
Birthday attacks

- Why is this important for cryptography?
  - 365 days in a year (366 some years)
    - Pick one person. To find another person with same birthday would take on the order of 365/2 = 182.5 people
    - Expect "collision" -- two people with same birthday -- with a room of only 23 people
    - For simplicity, approximate when we expect a collision as the square root of 365.
  - 2^{128} different 128-bit keys
    - Pick one key at random. To exhaustively search for this key requires trying on average 2^{127} keys.
    - Expect a "collision" after selecting approximately 2^{64} random keys.
    - 64 bits of security against collision attacks, not 128 bits.

Next

- Under the hood: Hash functions and MACs

Integrity



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

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

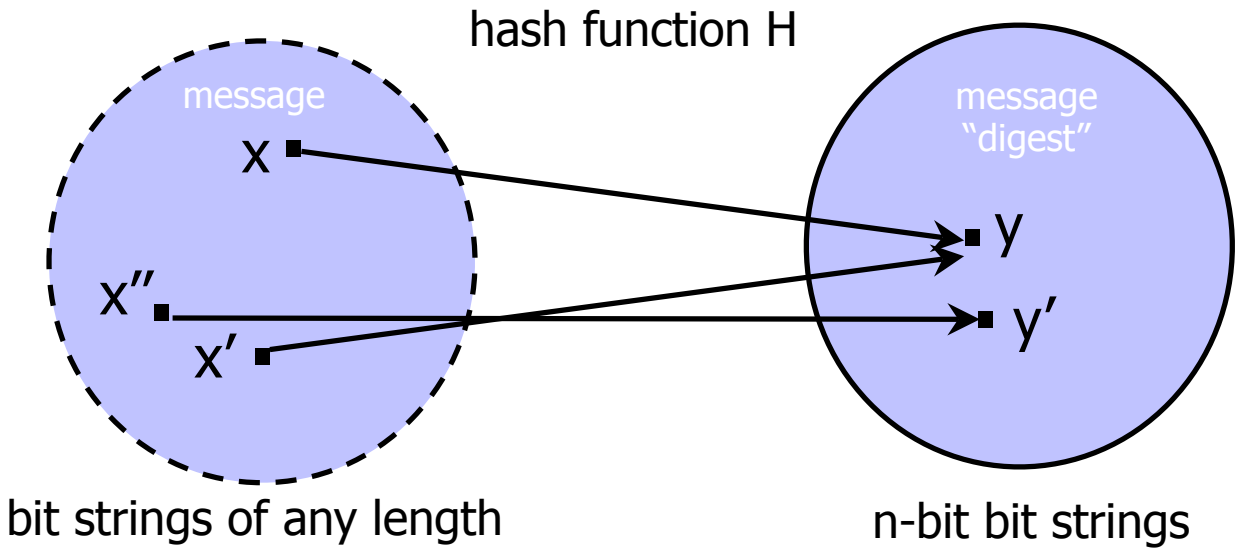
The goal is integrity, not secrecy

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

Integrity vs. Secrecy

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

Hash Functions: Main Idea



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

One-Way

- Intuition: hash should be hard to invert
  - "Preimage resistance"
  - Let $h(x')=y \in \{0,1\}^n$ for a random x'
  - Given y, it should be hard to find any x such that $h(x)=y$
- How hard?
  - Brute-force: try every possible x, see if $h(x)=y$
  - SHA-1 (common hash function) has 160-bit output
    - Expect to try 2^{159} inputs before finding one that hashes to y.

Collision Resistance

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

One-Way vs. Collision Resistance

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

Weak Collision Resistance

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

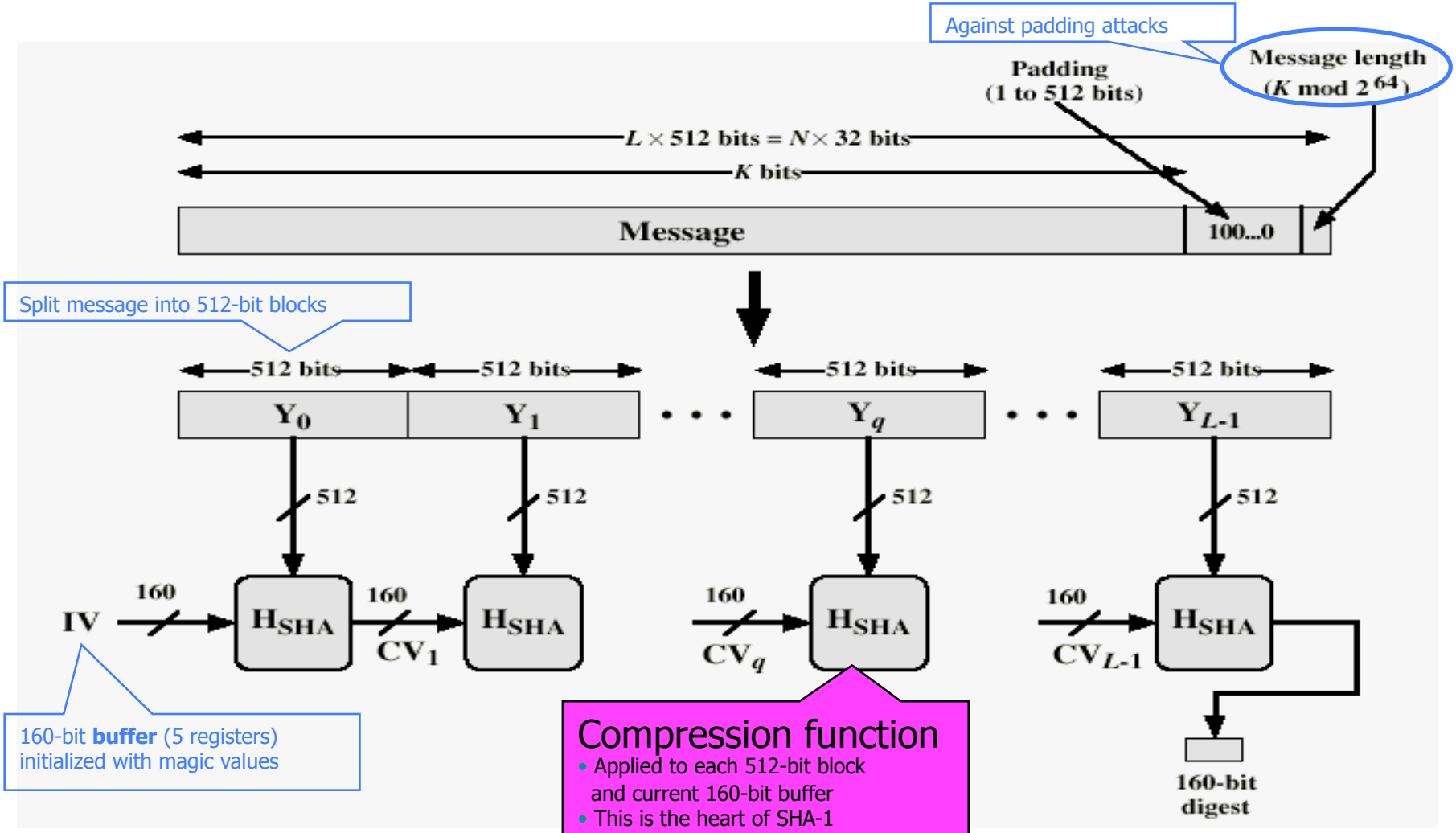
Which Property Do We Need?

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

Common Hash Functions

- MD5
  - 128-bit output
  - Designed by Ron Rivest, used very widely
  - Collision-resistance broken (summer of 2004)
- RIPEMD-160
  - 160-bit variant of MD5
- SHA-1 (Secure Hash Algorithm)
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Also recently broken! (Theoretically -- not practical.)
- SHA-256, SHA-512, SHA-224, SHA-384
- SHA-3: Forthcoming.

Basic Structure of SHA-1 (Not Required)



How Strong Is SHA-1?

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

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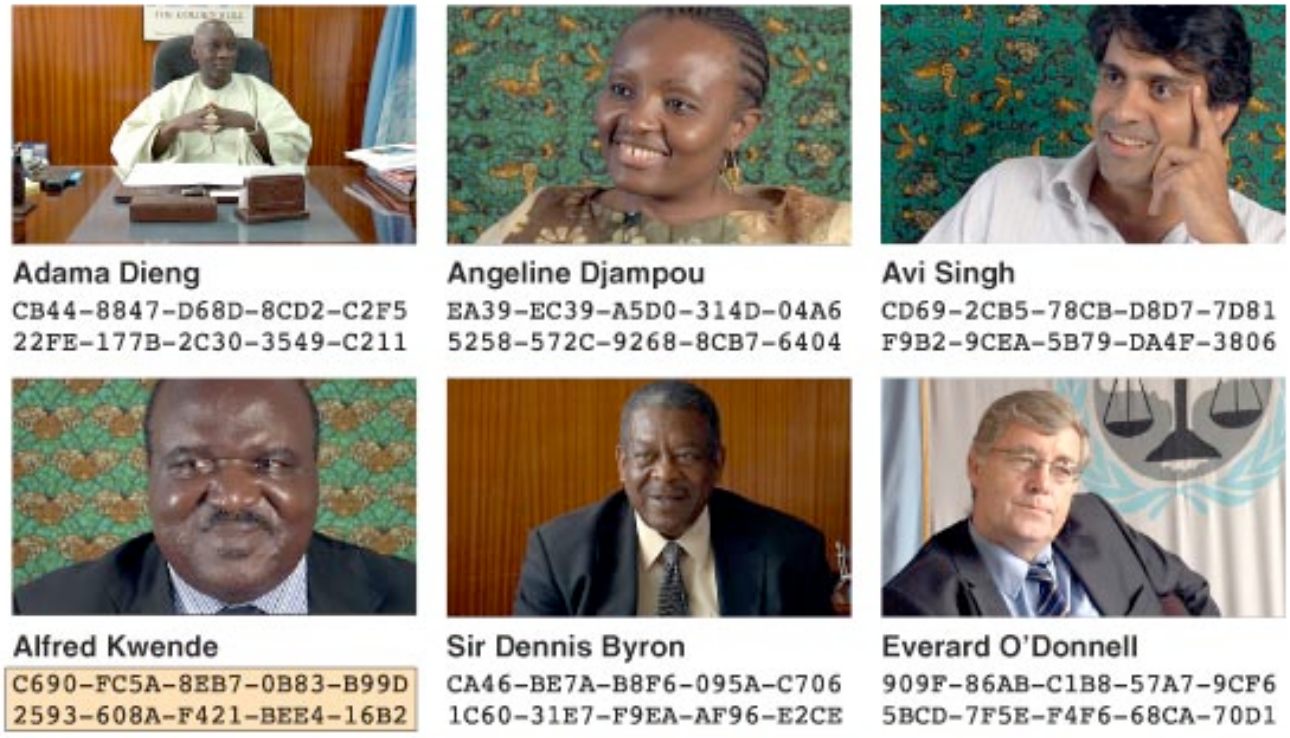
- SHA-256, SHA-512, SHA-224, SHA-384
- SHA-3: Forthcoming.

International Criminal Tribunal for Rwanda (Which Properties of Hash Functions?)

- http://www.nytimes.com/2009/01/27/science/27arch.html?_r=1&ref=science



Adama Dieng
CB44-8847-D68D-8CD2-C2F5
22FE-177B-2C30-3549-C211

Angeline Djampou
EA39-EC39-A5D0-314D-04A6
5258-572C-9268-8CB7-6404

Avi Singh
CD69-2CB5-78CB-D8D7-7D81
F9B2-9CEA-5B79-DA4F-3806

Alfred Kwende
C690-FC5A-8EB7-0B83-B99D
2593-608A-F421-BEE4-16B2

Sir Dennis Byron
CA46-BE7A-B8F6-095A-C706
1C60-31E7-F9EA-AF96-E2CE

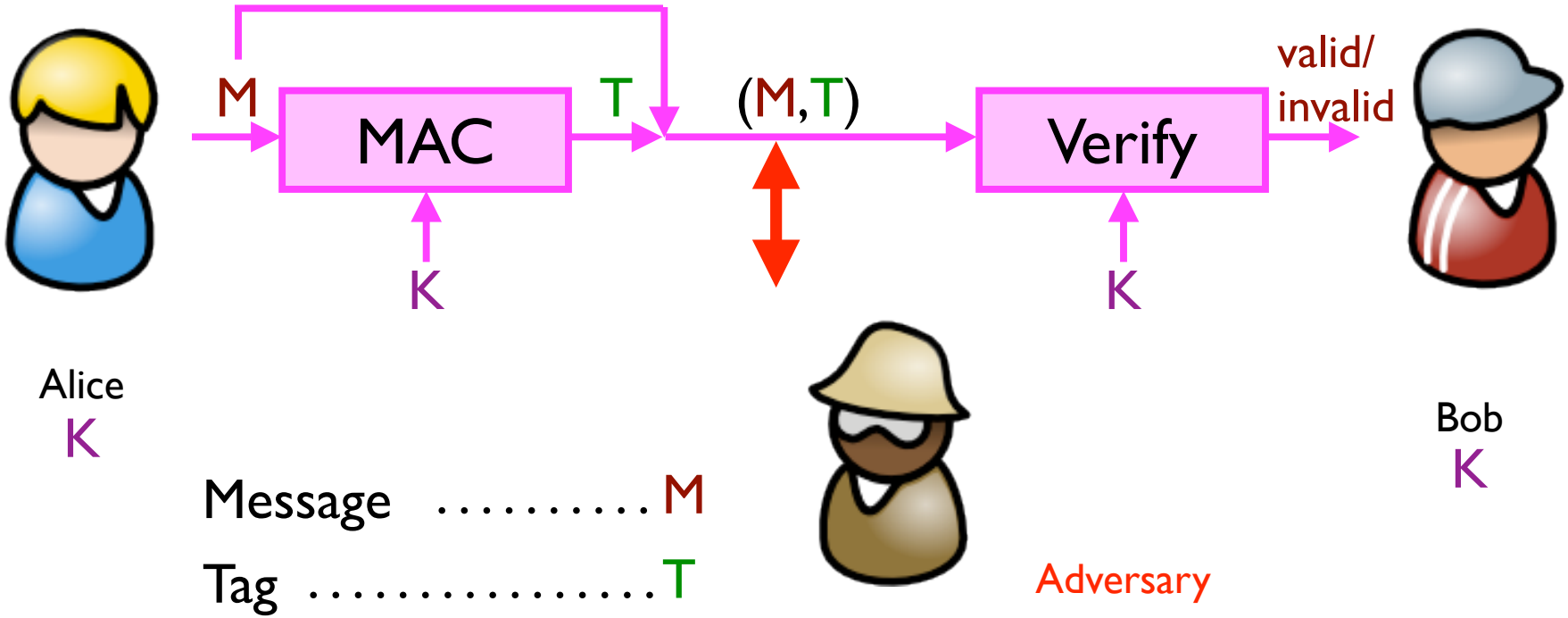
Everard O'Donnell
909F-86AB-C1B8-57A7-9CF6
5BCD-7F5E-F4F6-68CA-70D1

- Credits: Alexei Czeskis, Karl Koscher, Batya Friedman

Achieving Integrity (Symmetric)

Message authentication schemes: A tool for protecting integrity.

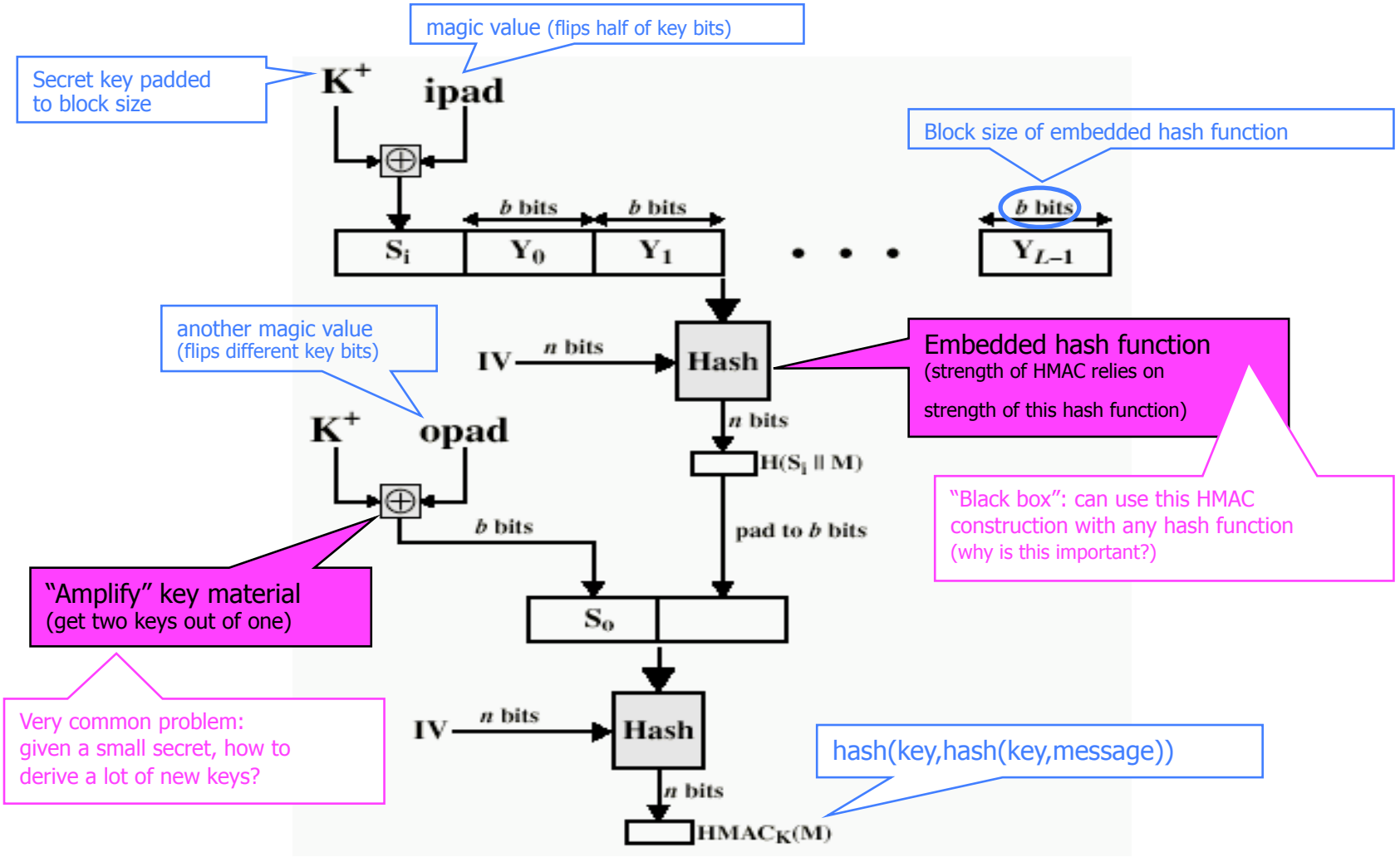
(Also called message authentication codes or MACs.)



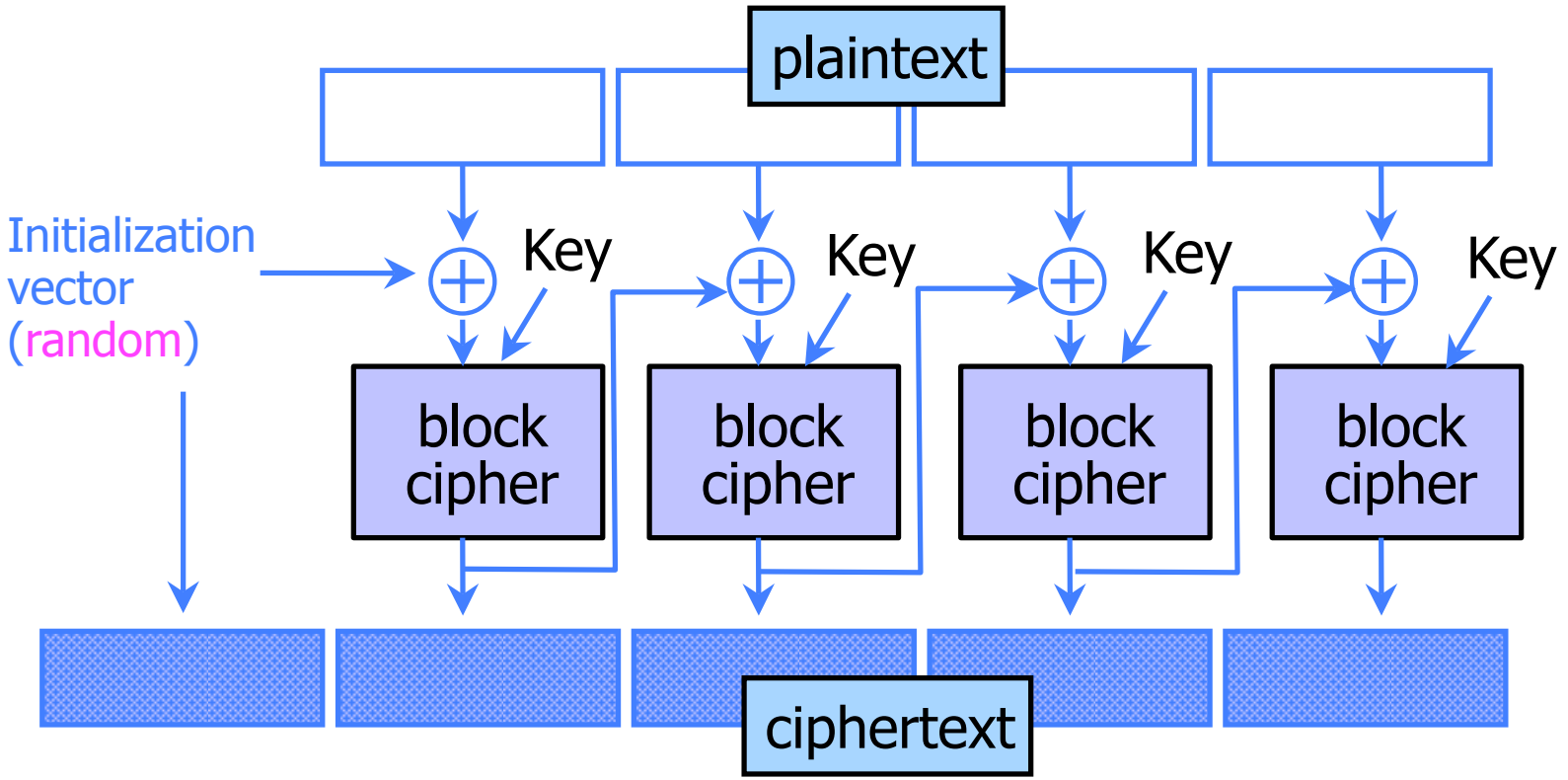
HMAC

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

Structure of HMAC

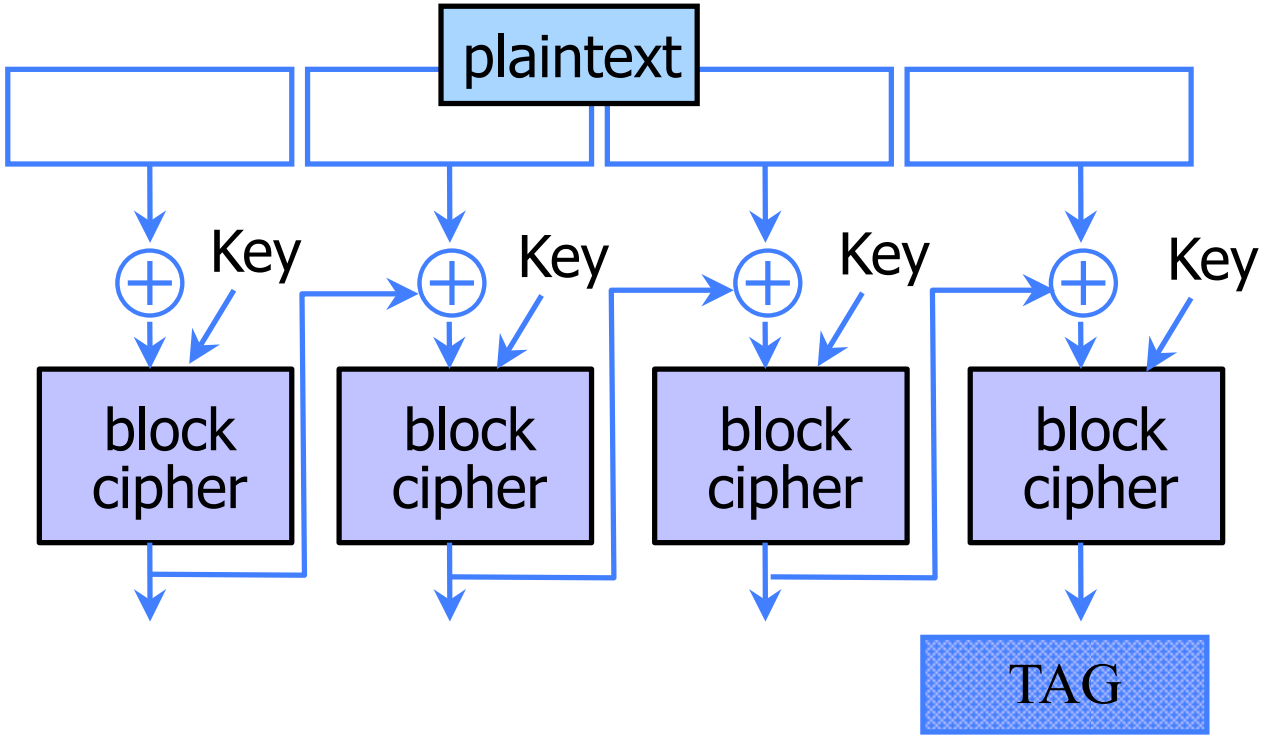


CBC Mode: Encryption



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

CBC-MAC



- Not secure when system may MAC messages of different lengths.
  - Encode length at beginning
  - Use a derivative called CMAC
- Internal collisions and birthday attacks

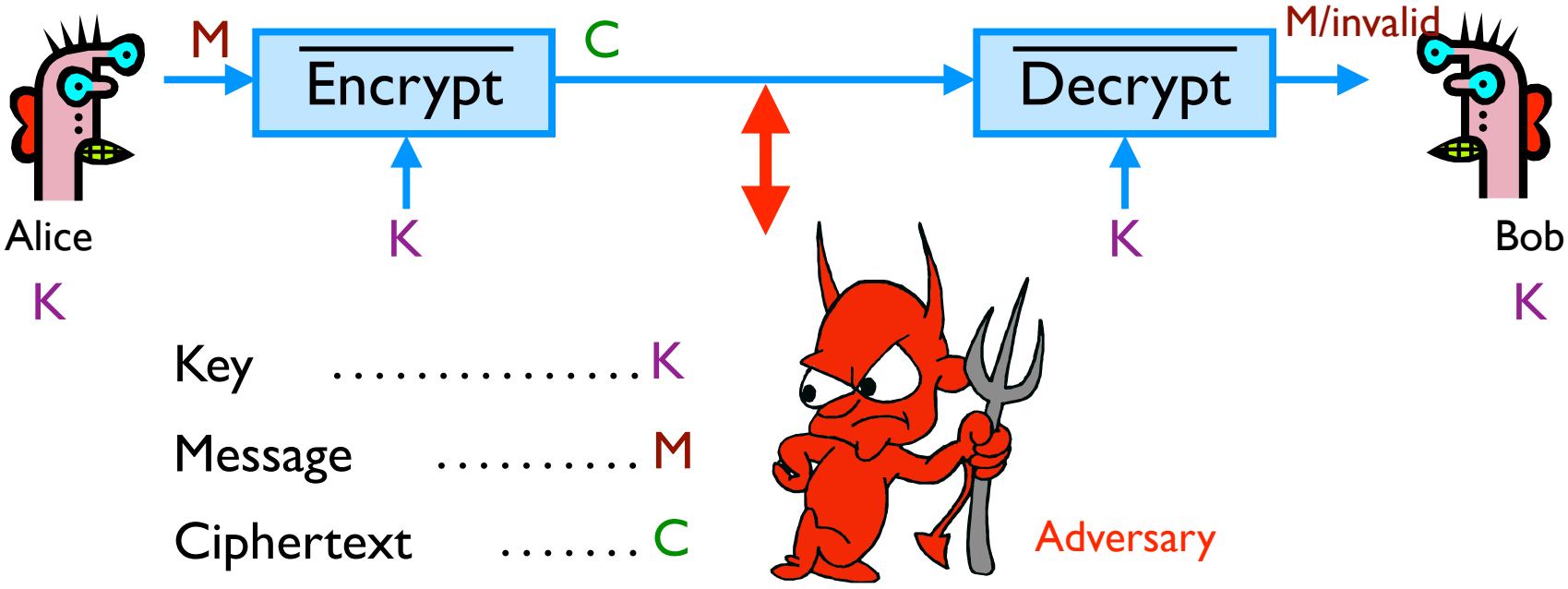
Example attacks to CBC-MAC

- Example problems (for whiteboard):
  - When process messages of different length
  - When process messages of different length and encode length at end of message
  - When a collision occurs
- Recommendations
  - Include length at beginning of message before CBC-MAC
  - Use CMAC (which is like CBC-MAC but handles last block differently)

Achieving Both Privacy and Integrity

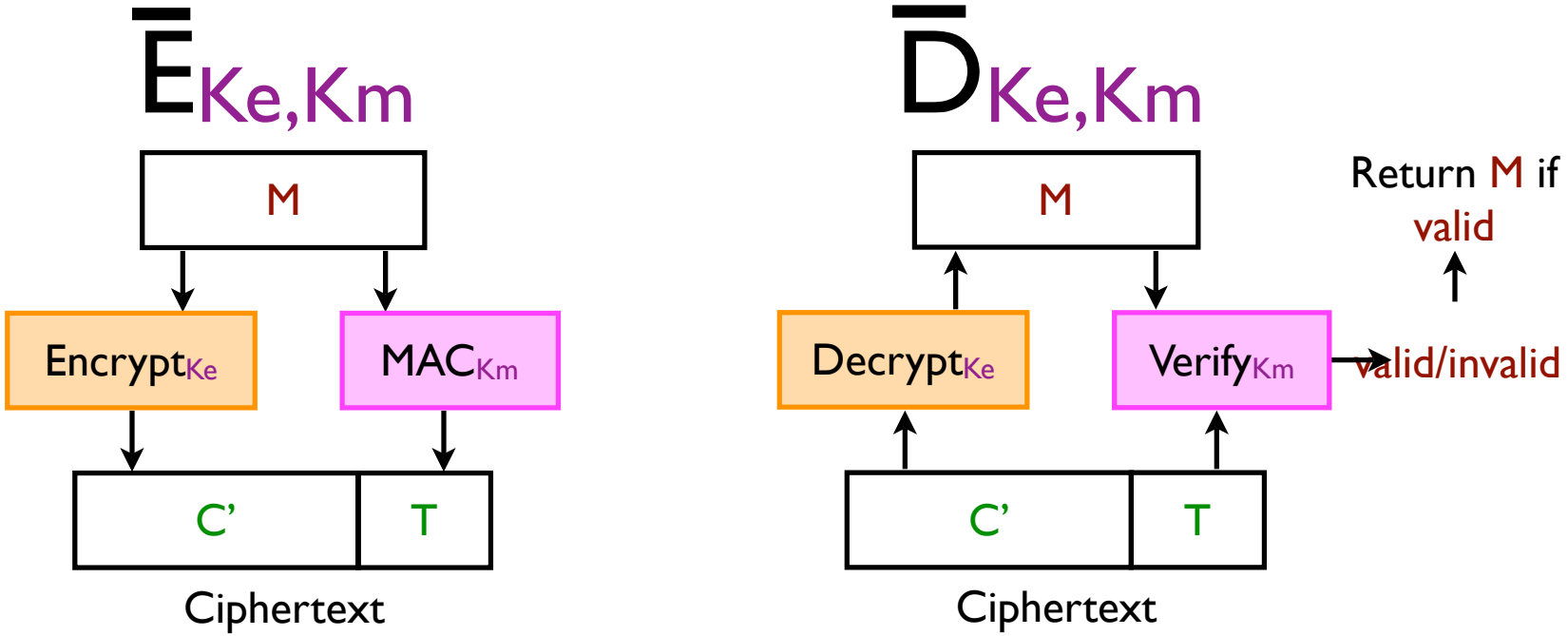
Authenticated encryption scheme

Recall: Often desire both privacy and integrity. (For SSH, SSL, IPsec, etc.)



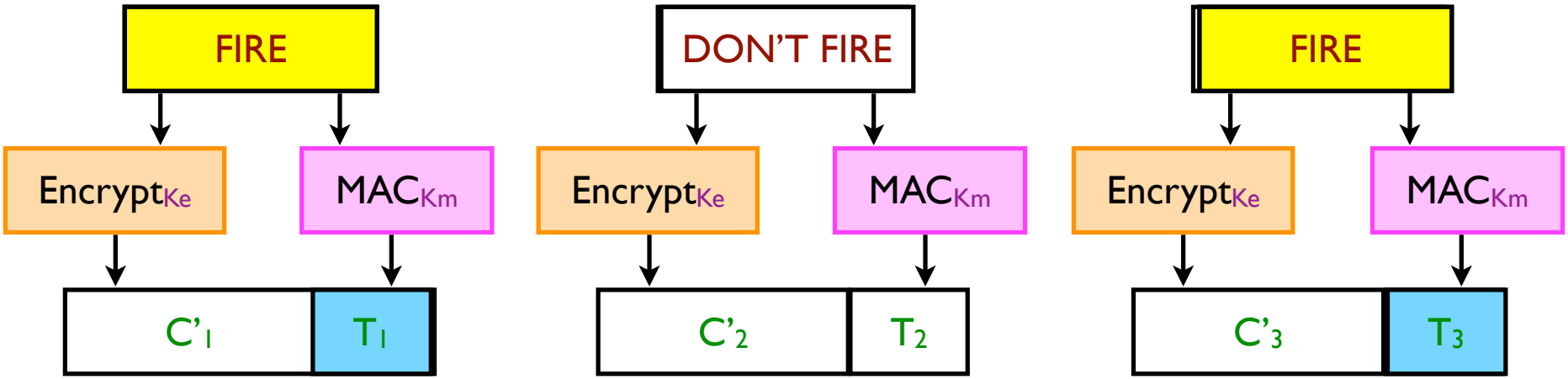
Some subtleties! Encrypt-and-MAC

Natural approach for authenticated encryption: Combine an encryption scheme and a MAC.



But insecure! [BN, Kra]

Assume Alice sends messages:

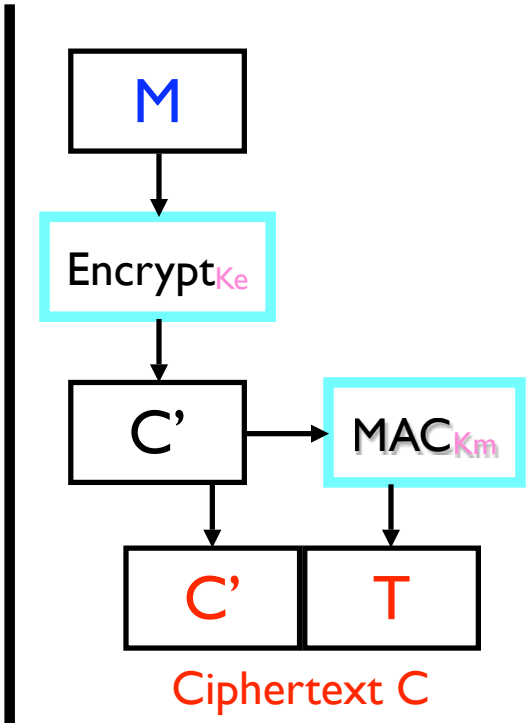


If $T_i = T_j$ then $M_i = M_j$

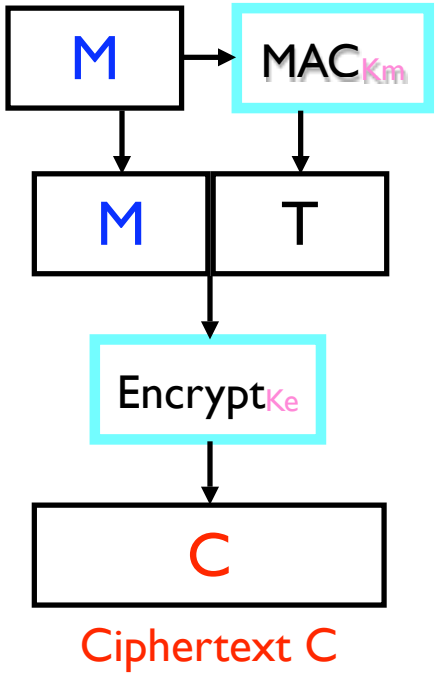
Adversary learns whether two plaintexts are equal.

Especially problematic when M_1, M_2, ... take on only a small number of possible values.

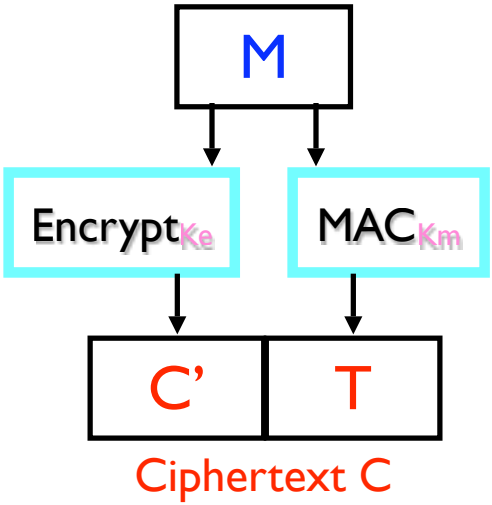
Results of [BN00,Kra01]



Encrypt-then-MAC



MAC-then-Encrypt



Encrypt-and-MAC

	Encrypt-then-MAC	MAC-then-Encrypt	Encrypt-and-MAC
Privacy	Strong (CCA)	Weak (CPA)	Insecure
Integrity	Strong (CTXT)	Weak (PTXT)	Weak (PTXT)

The Secure Shell (SSH) protocol is designed to provide:

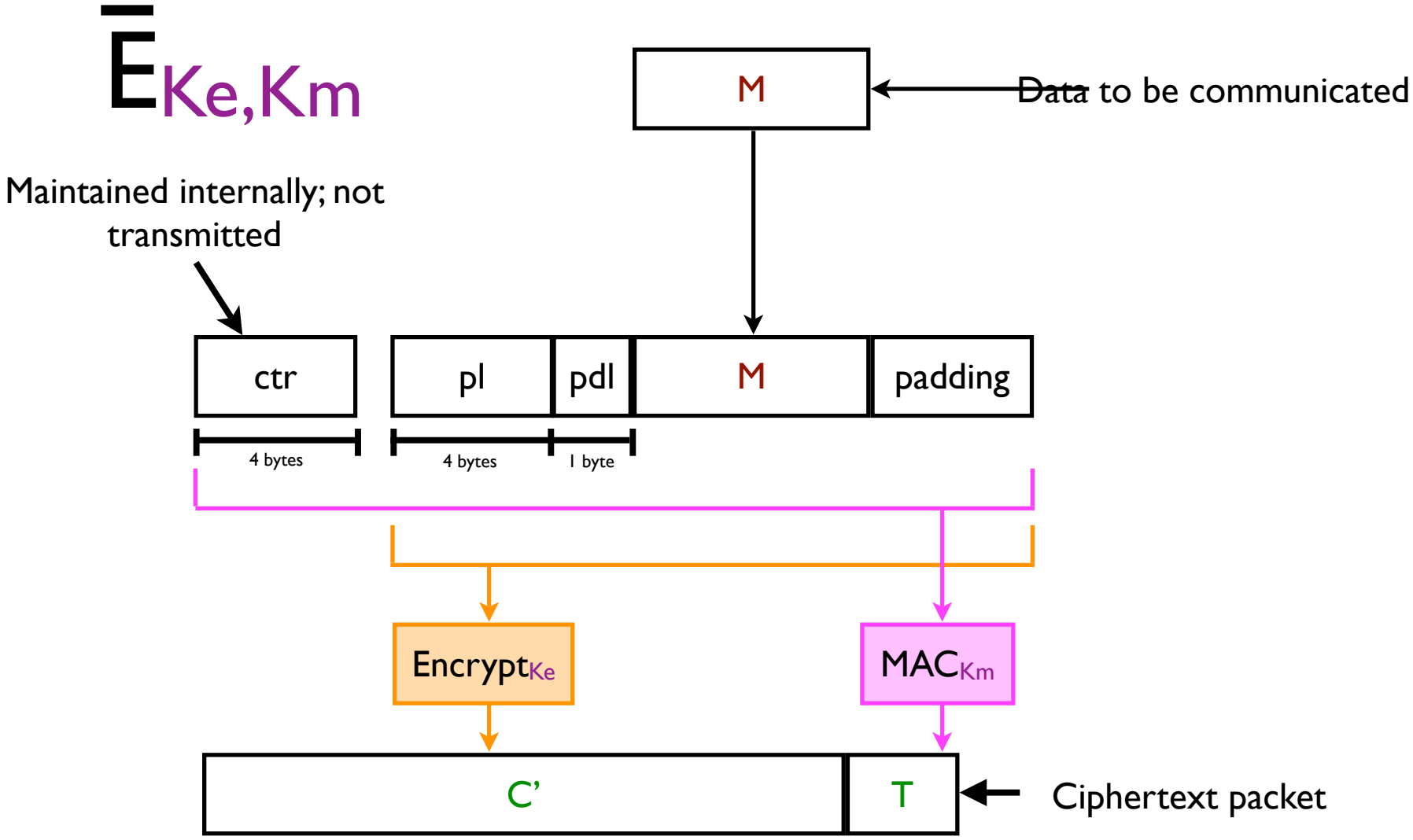
- Secure remote logins.
- Secure file transfers.

Where security includes:

- Protecting the privacy of users' data.
- Protecting the integrity of users' data.

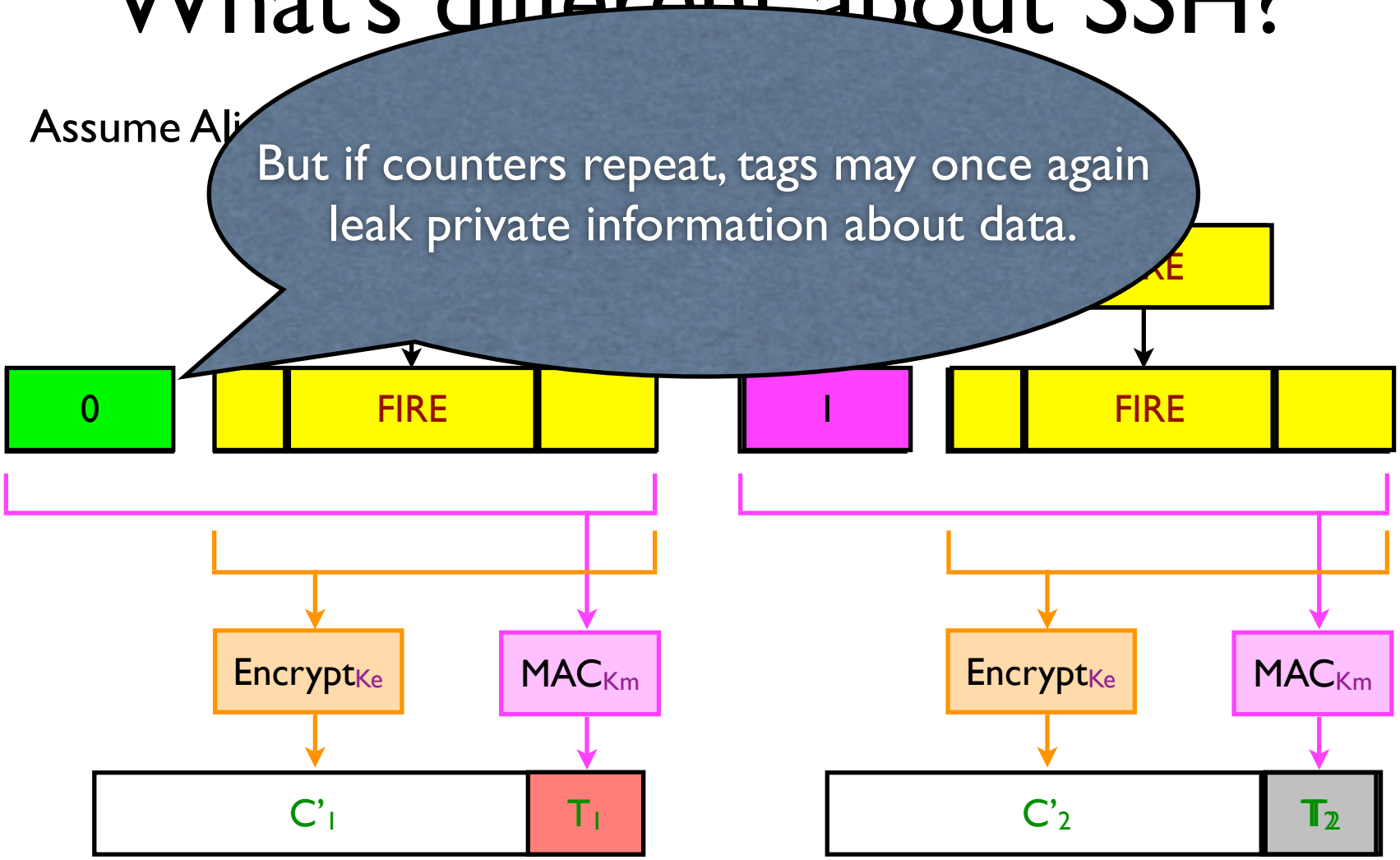
OpenSSH is included in the default installations of OS X and many Linux distributions.

Authenticated encryption in SSH



What's different about SSH?

Assume Ali



Then the tags T_1 and T_2 will be different with high probability.

Next

- A bit more context...

Improved se

- RFIDs in car ke
  - RFIDs in car ke
  - Result: Car ja

boingboing
A Directory Of Wonderful Things

Biometric car lock defeated by cutting off owner's finger

POSTED BY CORY DOCTOROW, MARCH 31, 2005 7:53 AM | PERMALINK

Andrei sez, "'Malaysia car thieves steal finger.' This is what security visionaries Bruce Schneier and Ross Anderson have been warning about for a long time. Protect your $75,000 Mercedes with biometrics and you risk losing whatever body part is required by the biometric mechanism."

> ...[H]aving stripped the car, the thieves became frustrated when they wanted to restart it. They found they again could not bypass the immobiliser, which needs the owner's fingerprint to disarm it.
>
> They stripped Mr Kumaran naked and left him by the side of the road - but not before cutting off the end of his index finger with a machete.