CSE P564: Computer Security and Privacy

More More Binary Exploitation (and Defenses)

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Paper discussion

AFL++: Combining Incremental Steps of Fuzzing Research

Pick one/more of the following to discuss

- Do approaches like patching out checksums (RedQueen) seem productive? Why or why not?
- Which configurable strategies for {scheduling, mutation} seem most or least valuable?
- “substitution with integers from a set of common interesting values” is an interesting insight about what humans know about programs. What other types of expert-human driven information helps with fuzzing?
- Why write a *paper* on AFL++?

Cryptography!

“If you think cryptography will solve your problem, you don't understand cryptography and you don't understand your problem”

- A cryptographer (its complicated)

“If you think cryptography will solve your problem, you don't understand cryptography and you don't understand your problem”

- A cryptographer (its complicated)

Probably either Jim Morris or Lampson or Needham

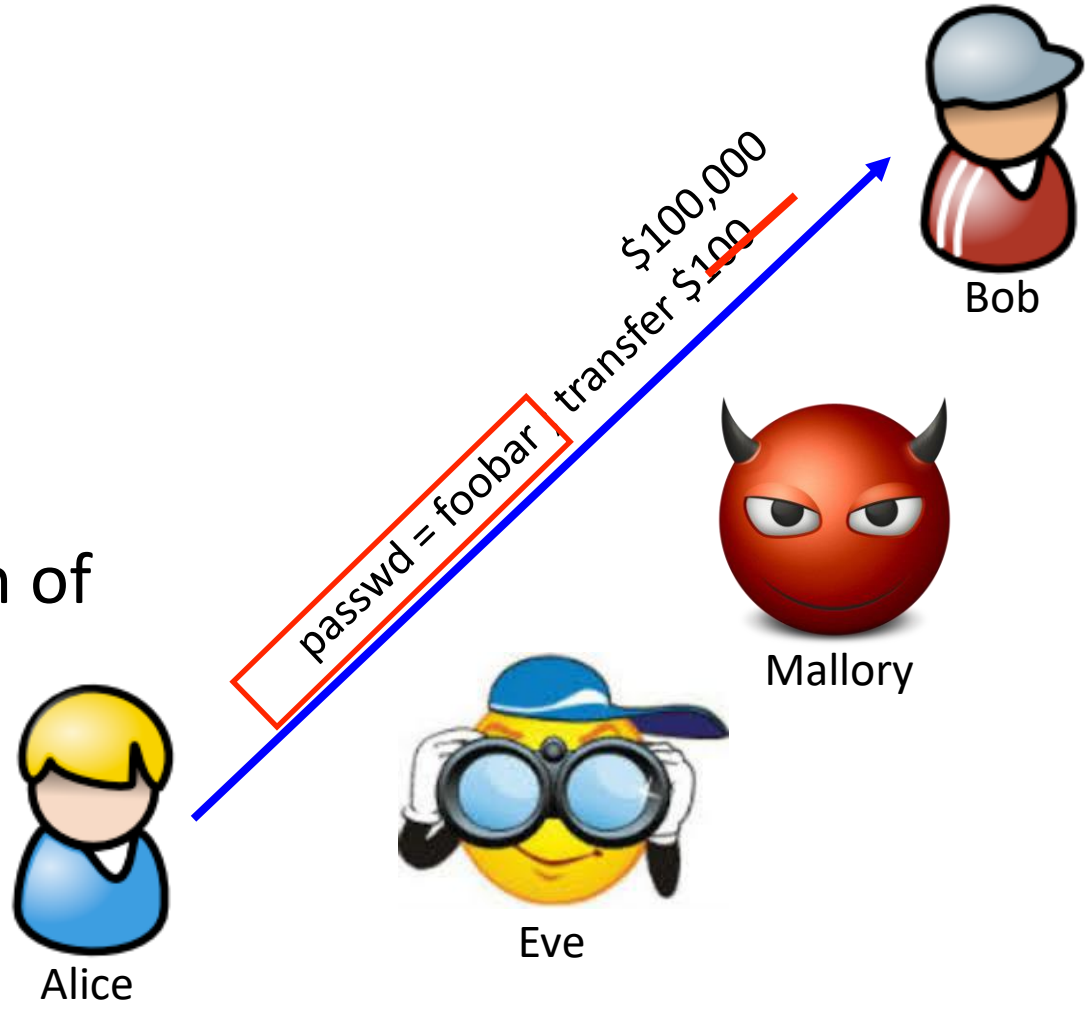
Common Communication Security Goals

Privacy of data:

Prevent exposure of information

Integrity of data:

Prevent modification of information

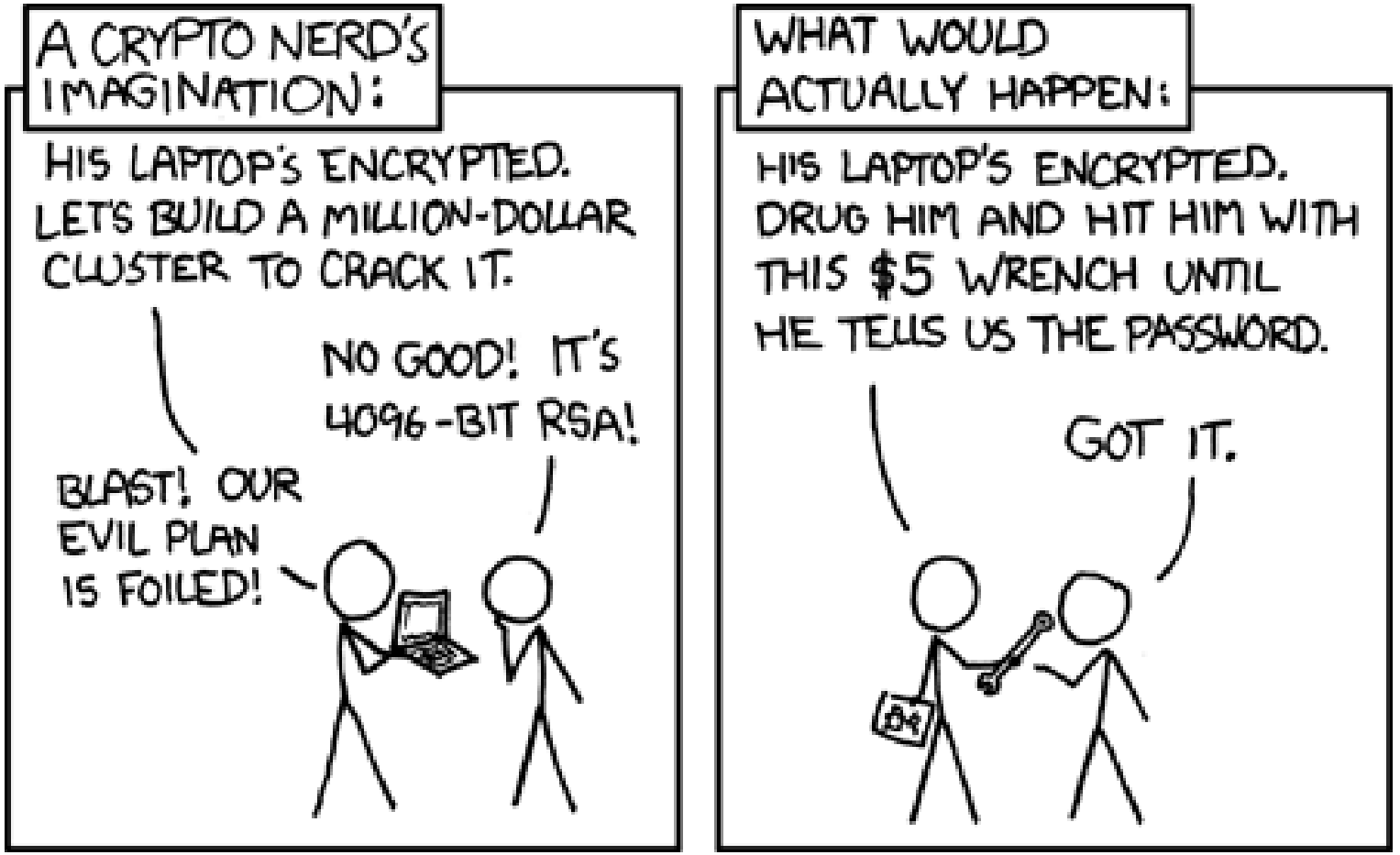


Recall Bigger Picture

- Cryptography only one small piece of a larger system
- Must protect entire system
  - Physical security
  - Operating system security
  - Network security
  - Users
  - Cryptography (following slides)
- Recall the weakest link

- Still, cryptography is a crucial part of our toolbox

Rubber-hose cryptanalysis: http://xkcd.com/538/

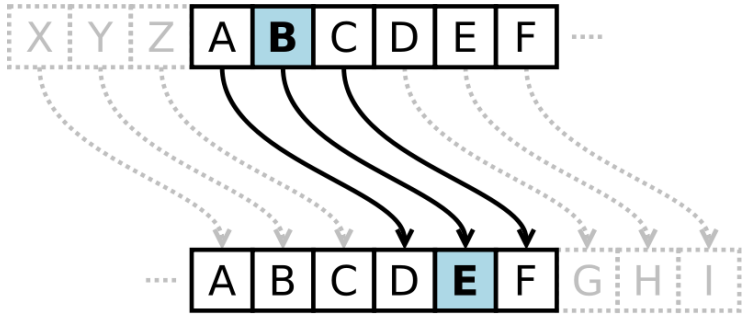


History of cryptography

- Substitution Ciphers
  - Caesar Cipher
- Transposition Ciphers
- Codebooks
- Machines

History: Caesar Cipher (Shift Cipher)

- Plaintext letters are replaced with letters fixed shift away in the alphabet.



a

- Example:
  - Plaintext: `The quick brown fox jumps over the lazy dog`
  - Key: Shift 3

    `ABCDEFGHIJKLMNOPQRSTUVWXYZ`

    `DEFGHIJKLMNOPQRSTUVWXYZABC`
  - Ciphertext: `WKHTX LFNEU RZQIR AMXPS VRYHU WKHOD CBGRJ`

History: Caesar Cipher (Shift Cipher)

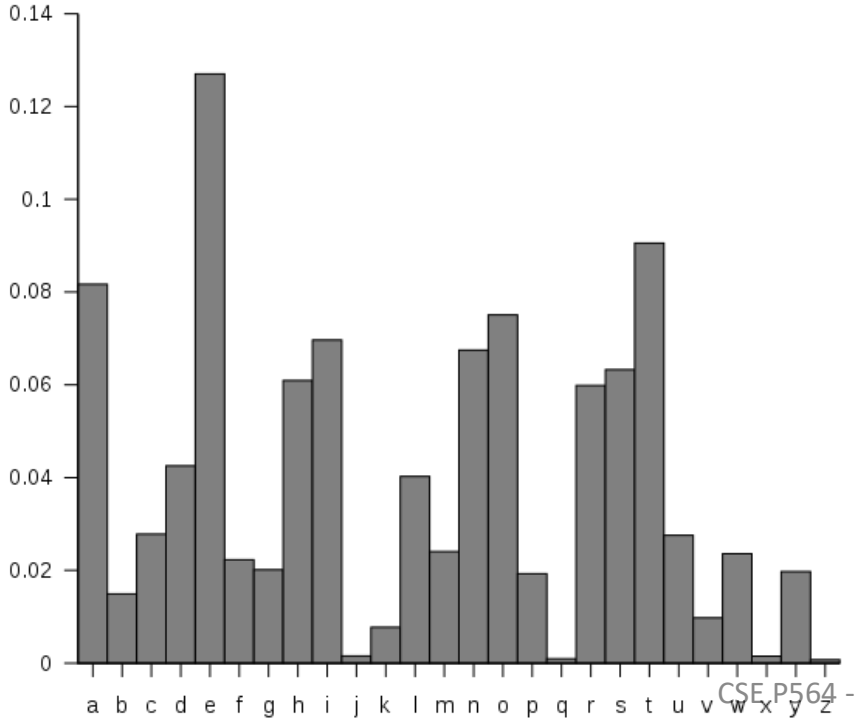
- ROT13: shift 13 (encryption and decryption are symmetric)
- What is the key space?
  - 26 possible shifts.
- How to attack shift ciphers?
  - Brute force.

History: Substitution Cipher

- Superset of shift ciphers: each letter is substituted for another one.
- One way to implement: Add a secret key
- Example:
  - Plaintext: ABCDEFGHIJKLMNOPQRSTUVWXYZ
  - Cipher: ZEBRASCDFGHIJKLMNOPQTUVWXY
- "State of the art" for thousands of years

History: Substitution Cipher

- What is the key space?
- How to attack?
  - Frequency analysis.



26! ~= 2^88

Bigrams:

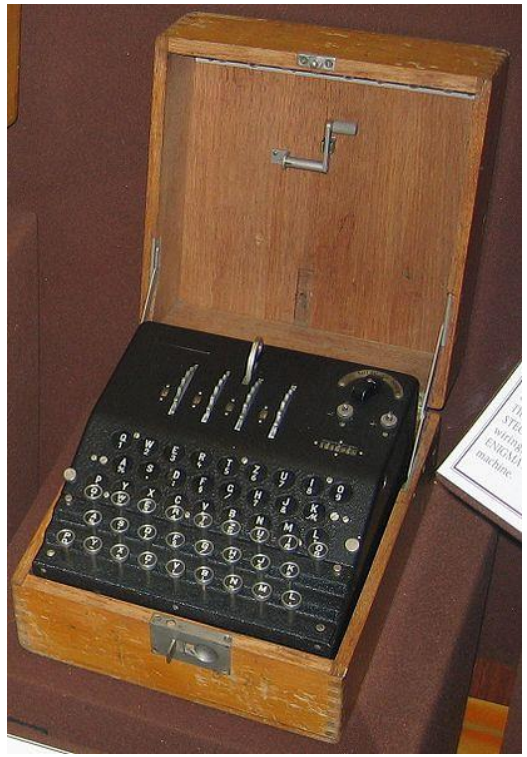
th 1.52%	en 0.55%	ng 0.18%
he 1.28%	ed 0.53%	of 0.16%
in 0.94%	to 0.52%	al 0.09%
er 0.94%	it 0.50%	de 0.09%
an 0.82%	ou 0.50%	se 0.08%
re 0.68%	ea 0.47%	le 0.08%
nd 0.63%	hi 0.46%	sa 0.06%
at 0.59%	is 0.46%	si 0.05%
on 0.57%	or 0.43%	ar 0.04%
nt 0.56%	ti 0.34%	ve 0.04%
ha 0.56%	as 0.33%	ra 0.04%
es 0.56%	te 0.27%	ld 0.02%

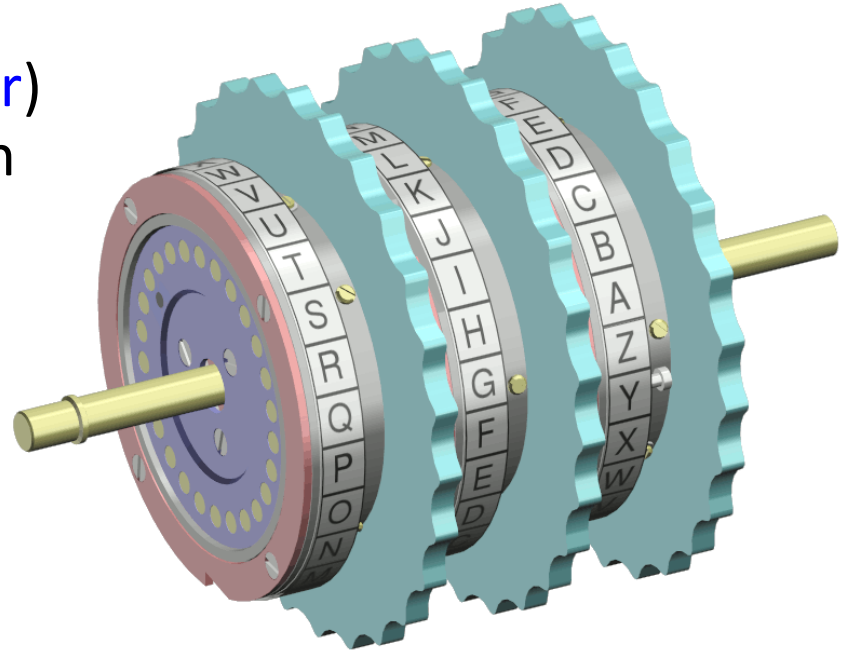
Trigrams:

1. the	6. ion	11. nce
2. and	7. tio	12. edt
3. tha	8. for	13. tis
4. ent	9. nde	14. oft
5. ing	10. has	15. sth

History: Enigma Machine

Uses rotors (substitution cipher) that change position after each key.





Key = initial setting of rotors

Key space?

26^n for n rotors

How Cryptosystems Work Today

- **Layered approach:** Cryptographic protocols (like “CBC mode encryption”) built on top of cryptographic primitives (like “block ciphers”)
- **Flavors of cryptography:** Symmetric (private key) and asymmetric (public key)
- Public algorithms (Kerckhoff’s Principle)
- Security proofs based on assumptions *(not this course)*

- Don’t go inventing your own! (If you just want to use some crypto in your system, use vetted libraries!)

The Cryptosystem Stack

- Primitives:
  - AES / DES / etc
  - RSA / ElGamal / Elliptic Curve (ed25519)
- Modes:
  - Block modes (CBC, ECB, CTR, GCM, …)
  - Padding structures
- Protocols:
  - TLS / SSL / SSH / tc
- Usage of Protocols:
  - Browser security
  - Secure remote logins

Kerckhoff's Principle

- Security of a cryptographic object should depend only on the secrecy of the secret (private) key.
- Security should not depend on the secrecy of the algorithm itself.

- Why? – Gradescope!
  - Why is this the right boundary to choose?
  - What is different between the protocol+algorithm vs the key?

- Foreshadow: Need for randomness – the key to keep private

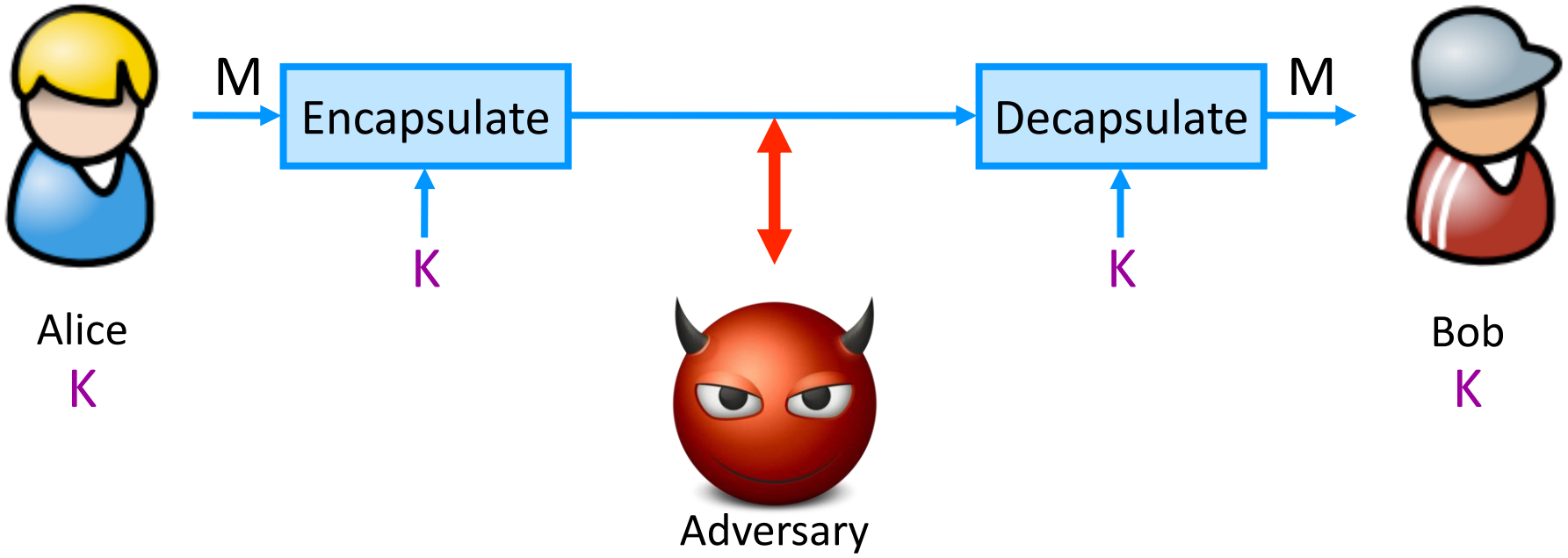
Flavors of Cryptography

- Symmetric cryptography
  - Both communicating parties have access to a shared random string K, called the key.

- Asymmetric cryptography
  - Each party creates a public key pk and a secret key sk.
  - *Hard concept to understand, and revolutionary! Inventors won Turing Award* ☺

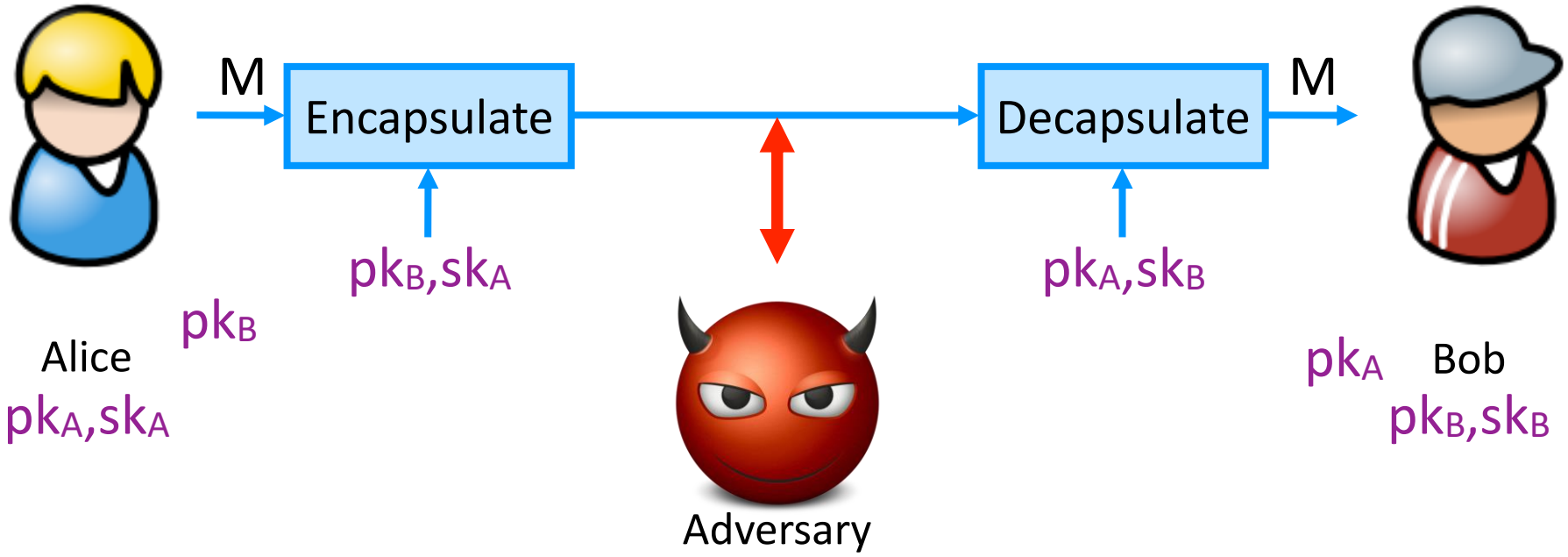
Symmetric Setting

Both communicating parties have access to a shared random string K, called the key.



Asymmetric Setting

Each party creates a public key pk and a secret key sk.



Properties of asymmetric cryptography

- We have a funny situation here:
  - Public keys are shared with everyone
  - Secret keys are not

- What is are some security properties we would want of:
  - Knowing a public key?
  - Encrypting a message with a secret key?

Public keys, Private keys, Secret keys…

- Secret key
  - The single key used in symmetric encryption
  - The non-public key in asymmetric
- Private keys
  - The non-public key in asymmetric
- Public key
  - The… public key in asymmetric
- Key
  - Generally means private/secret

Received April 4, 1977

A Method for Obtaining Digital Signatures and Public-Key Cryptosystems

R.L. Rivest, A. Shamir, and L. Adleman*

Abstract

An encryption method is presented with the novel property that publicly revealing an encryption key does not thereby reveal the corresponding decryption key. This has two important consequences:

1. Couriers or other secure means are not needed to transmit keys, since a message can be enciphered using an encryption key publicly revealed by the intended recipient. Only he can decipher the message, since only he knows the corresponding decryption key.
2. A message can be "signed" using a privately held decryption key. Anyone can verify this signature using the corresponding publicly revealed encryption key. Signatures cannot be forged, and a signer cannot later deny the validity of his signature. This has obvious applications in "electronic mail" and "electronic funds transfer" systems.

Flavors of Cryptography

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Flavors of Cryptography – Gradescope!

- Symmetric cryptography
  - Both communicating parties have access to a shared random string K, called the key.
  - Challenge: How do you privately share a key?
- Asymmetric cryptography
  - Each party creates a public key pk and a secret key sk.
  - Challenge: How do you validate a public key?

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  - Challenge: How do you validate a public key?
- Key building block: Randomness – something that the adversaries won't know and can't predict and can't figure out

Detour: Randomness

Ingredient: Randomness

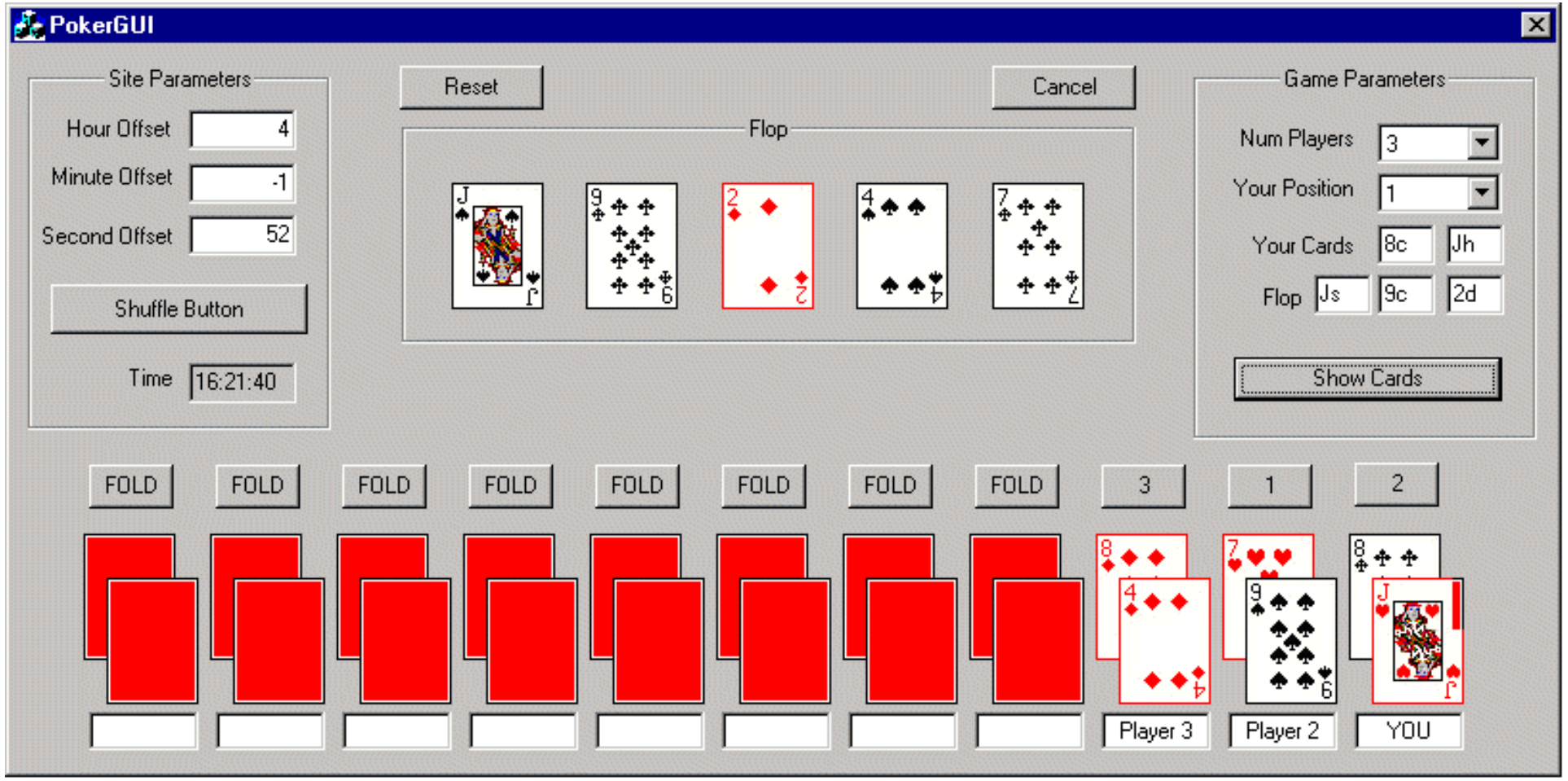
- Many applications (especially security ones) require randomness
- Explicit uses:
  - Generate secret cryptographic keys
  - Generate random initialization vectors for encryption
- Other “non-obvious” uses:
  - Generate passwords for new users
  - Shuffle the order of votes (in an electronic voting machine)
  - Shuffle cards (for an online gambling site)

C's rand() Function

- C has a built-in random function: `rand()`
- Don't use `rand()` for security-critical applications!
  - Given a few sample outputs, you can predict subsequent ones

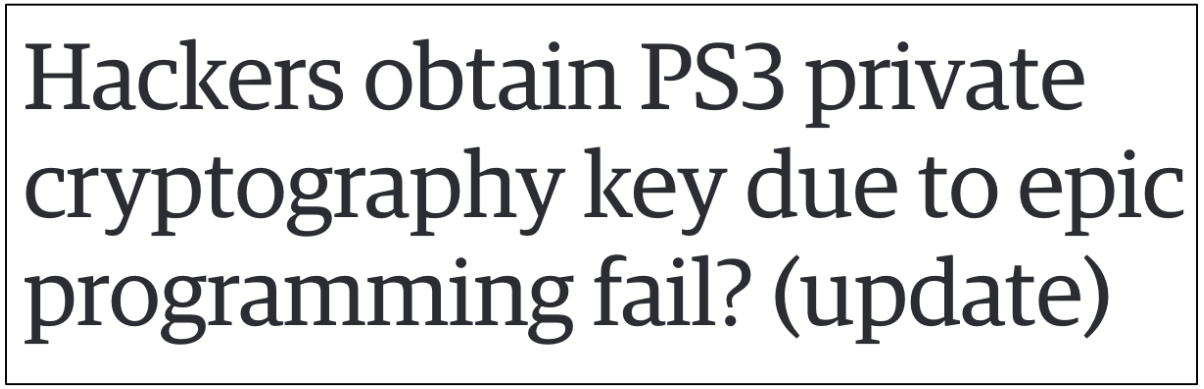
```
unsigned long int next = 1;


/* rand:return pseudo-random integer in 0-32767 */
int rand(void) {
        next = next * 1103515245 + 12345;
        return (unsigned int)(next/65536) % 32768;
}


/* srand:set seed for rand() */
void srand(unsigned int seed) {
        next = seed;
}
```


A World of Action!
Help
Suggestions
Fold in Turn
$0
jonnyboy
brute
Fold
Check
Bet ($5)
mamajoe
RickG
Options
Sit Out
Leave
584330
mamajoe: Hey guys, Big B is in!
Dealer Text



More details: "How We Learned to Cheat at Online Poker: A Study in Software Security"
https://web.archive.org/web/20120301022831/http://www.cigital.com/papers/download/developer_gambling.php

PS3 and Randomness



http://www.engadget.com/2010/12/29/hackers-obtain-ps3-private-cryptography-key-due-to-epic-programm/

- 2010/2011: Hackers found/released private root key for Sony's PS3
- Key used to sign software – now can load any software on PS3 and it will execute as "trusted"
- Due to bad random number: same "random" value used to sign all system updates

A recent example: keypair

https://securitylab.github.com/advisories/GHSL-2021-1012-keypair/

- keypair is a JS library for generating (asymmetric) keypairs

The output from the Lehmer LCG is encoded incorrectly. The specific line with the flaw is:

```
b.putByte(String.fromCharCode(next & 0xFF))
```

The definition of putByte is

```
[…]putByte = function(b) { this.data += String.fromCharCode(b); };
```

Since we are masking with 0xFF, we can determine that 97% of the output from the LCG are converted to zeros. The only outputs that result in meaningful values are outputs 48 through 57, inclusive.

The impact is that each byte in the RNG seed has a 97% chance of being 0 due to incorrect conversion. When it is not, the bytes are 0 through 9.

How might we get “good” random numbers?

Obtaining Pseudorandom Numbers

- For security applications, want "cryptographically secure pseudorandom numbers"
- Libraries include cryptographically secure pseudorandom number generators (CSPRNG)

Obtaining Pseudorandom Numbers

- Linux:
  - /dev/random – blocking (waits for enough entropy)
  - /dev/urandom – nonblocking, possibly less entropy (??)
  - `getrandom()` – by default, blocking

- Internally:
  - Entropy pool gathered from multiple sources
    - e.g., mouse/keyboard/network timings

- Challenges with embedded systems, saved VMs

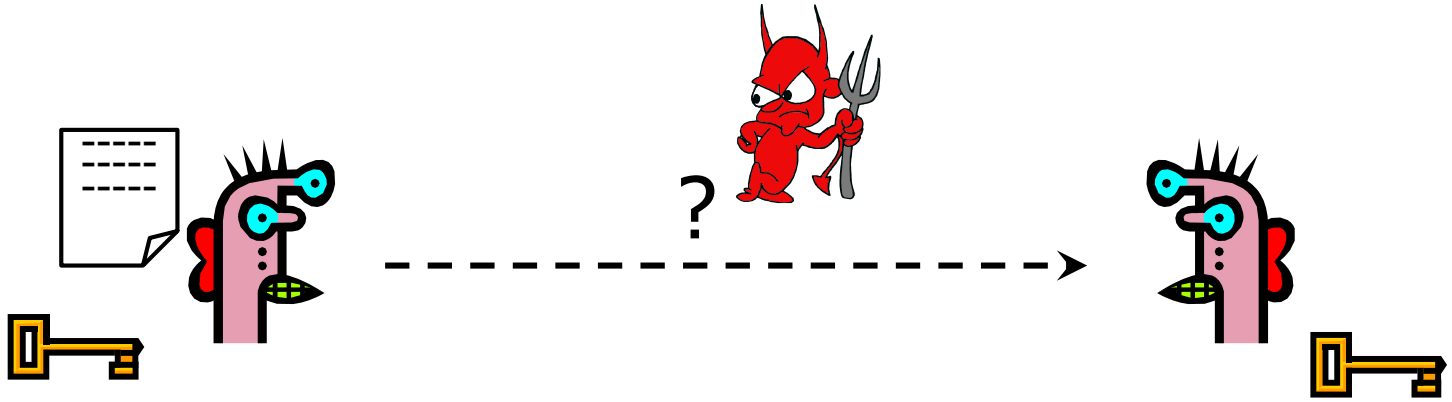
Obtaining *Random* Numbers

- Better idea:
  - AMD/Intel's on-chip random number generator
    - RDRAND

- Hopefully no hardware bugs!
  - https://arstechnica.com/gadgets/2019/10/how-a-months-old-amd-microcode-bug-destroyed-my-weekend/
  - Or only a few bugs?

Back to encryption

Confidentiality: Basic Problem



Given (Symmetric Crypto): both parties know the same secret.

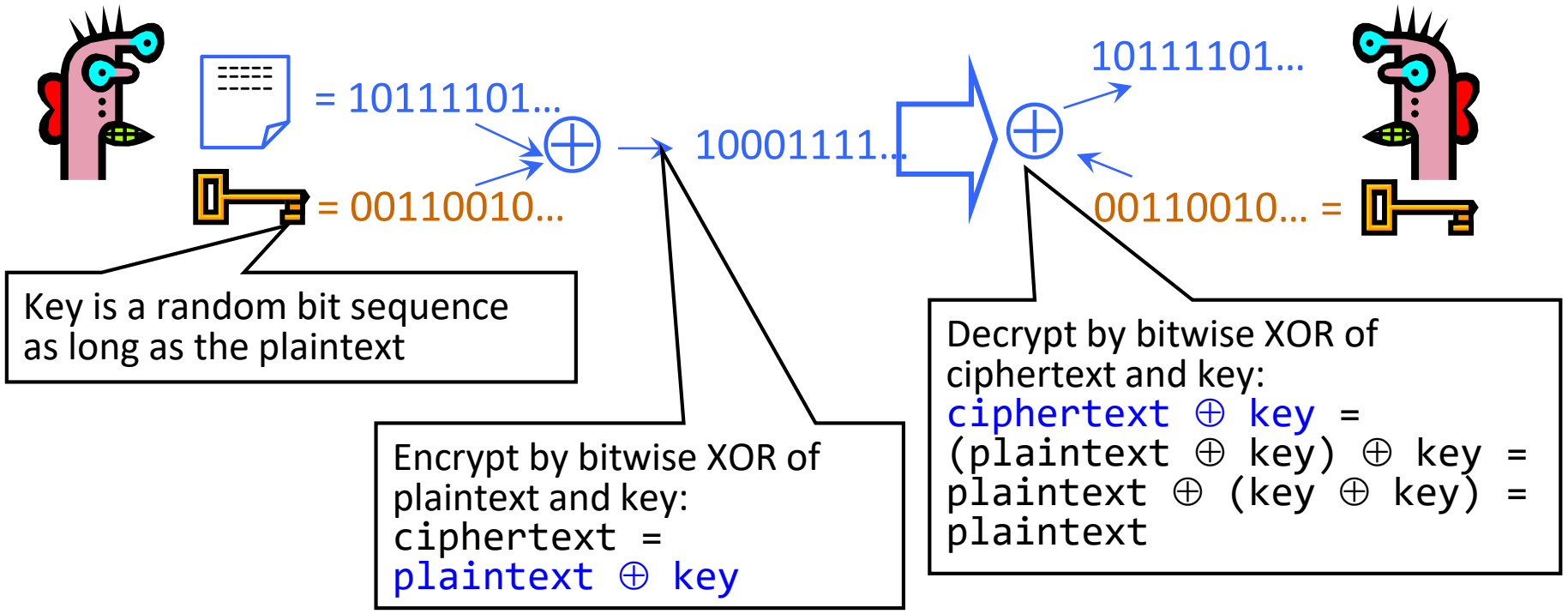
Goal: send a message confidentially.

Ignore for now: How is this achieved in practice??

One weird bit-level trick

- XOR!
  - Just XOR with a random bit!
- Why?
  - Uniform output
  - Independent of ‘message’ bit

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, 1949)

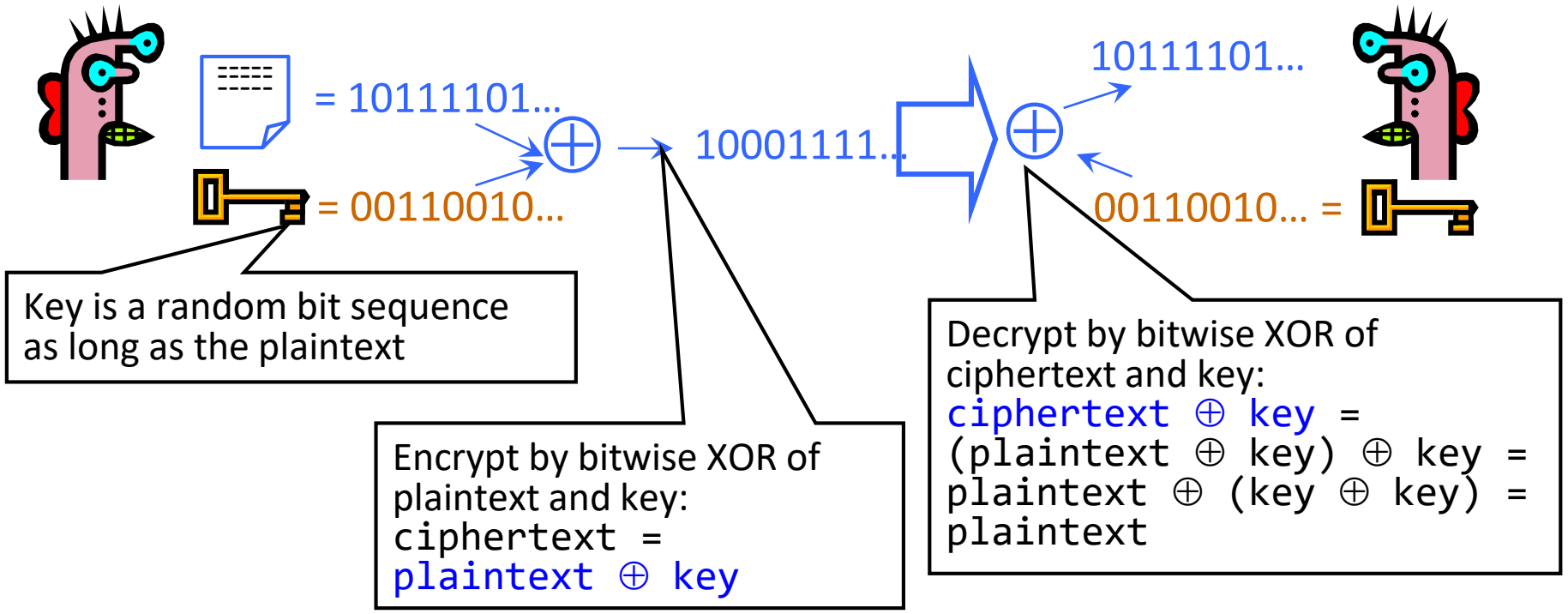
Advantages of One-Time Pad

- 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 sender communicate the key to receiver?

Problems with the One-Time Pad?

- Gradescope!
- What potential security problems do you see with the one-time pad?
- (Try not to look ahead and next slides)
- Recall two key goals of cryptography: confidentiality and integrity
  - Assume we are sending the message over an untrusted medium
  - Remember our different adversaries!

One-Time Pad - Reminder



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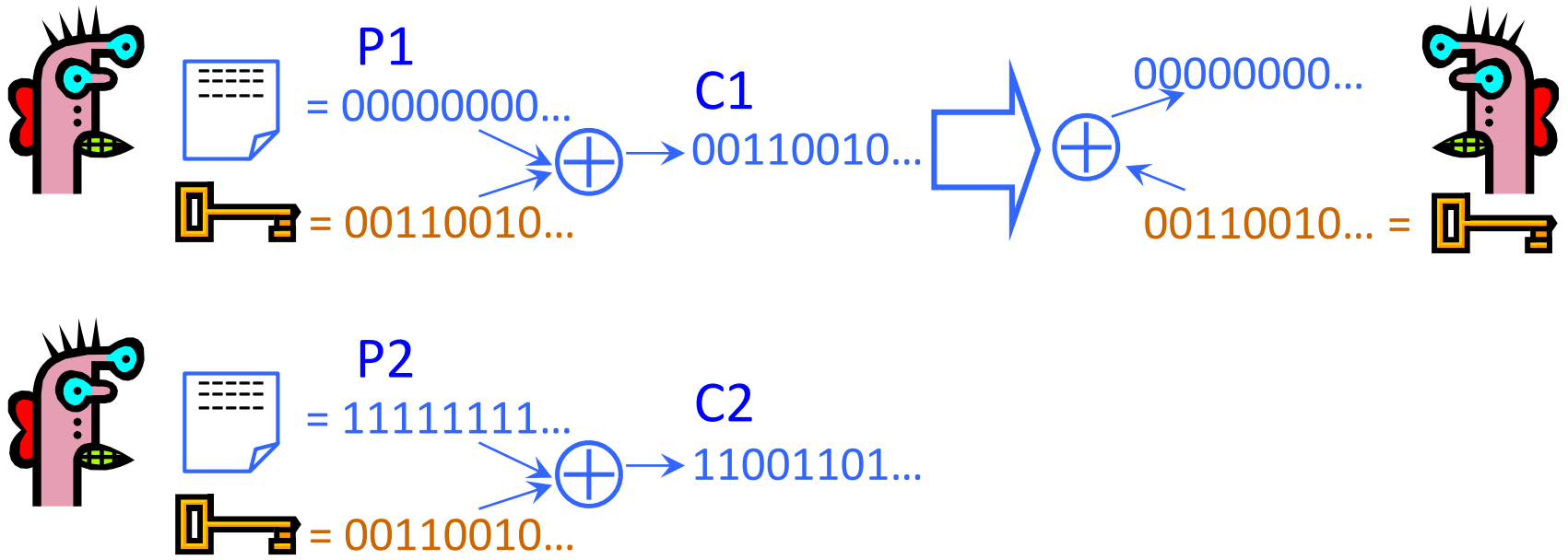
Dangers of Reuse



Learn relationship between plaintexts

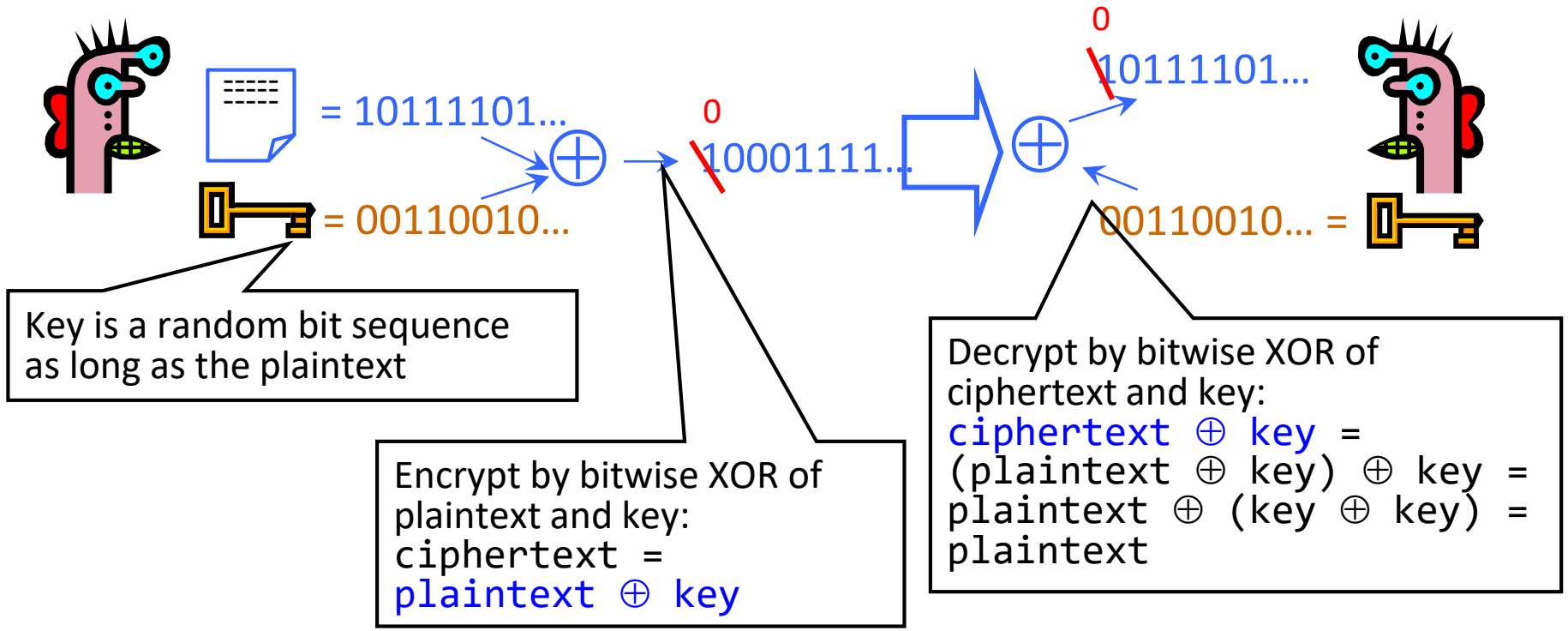
C1⊕C2 = (P1⊕K)⊕(P2⊕K) =

(P1⊕P2)⊕(K⊕K) = P1⊕P2

Problems with One-Time Pad

- (1) Key must be as long as the plaintext
  - Impractical in most realistic scenarios
  - Still used for diplomatic and intelligence traffic
- **(2) Insecure if keys are reused**
  - **Attacker can obtain XOR of plaintexts**

Integrity?


= 10111101…
= 00110010…
Key is a random bit sequence as long as the plaintext
0
10001111…
Encrypt by bitwise XOR of plaintext and key:
ciphertext = plaintext ⊕ key
0
10111101…
00110010… =
Decrypt by bitwise XOR of ciphertext and key:
ciphertext ⊕ key = (plaintext ⊕ key) ⊕ key = plaintext ⊕ (key ⊕ key) = plaintext

Problems with One-Time Pad

- (1) Key must be as long as the plaintext
  - Impractical in most realistic scenarios
  - Still used for diplomatic and intelligence traffic
- (2) Insecure if keys are reused
  - Attacker can obtain XOR of plaintexts
- **(3) Does not guarantee integrity**
  - **One-time pad only guarantees confidentiality**
  - **Attacker cannot recover plaintext, but can easily change it to something else**

Reducing Key Size

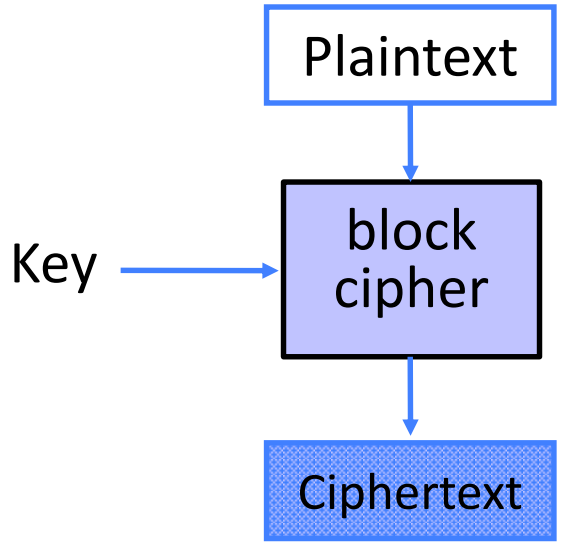
- What to do when it is infeasible to pre-share huge random keys?
  - When one-time pad is unrealistic…
- Use special cryptographic primitives: block ciphers, stream ciphers
  - Single key can be re-used (with some restrictions)
  - Not as theoretically secure as one-time pad

What if we try something simple?

- Alice and Bob synchronize their clocks perfectly, then generate OTPs
- Hash(time)
- Hash(time, key)

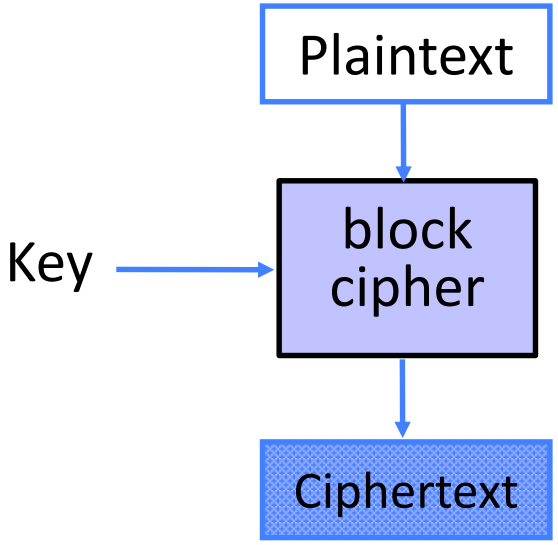
Block Ciphers

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



Keyed Permutation

- Not just shuffling of input bits!
  - Suppose plaintext = “111”.
  - Then “111” is not the only possible ciphertext!
- Instead:
  - **Permutation of possible outputs**
  - Use secret key to pick a permutation



Keyed Permutation

input	possible output	possible output	etc.
000	010	111	…
001	111	110	…
010	101	000	…
011	110	101	…
…	…		…
111	000	110	…

Key = 00
Key = 01

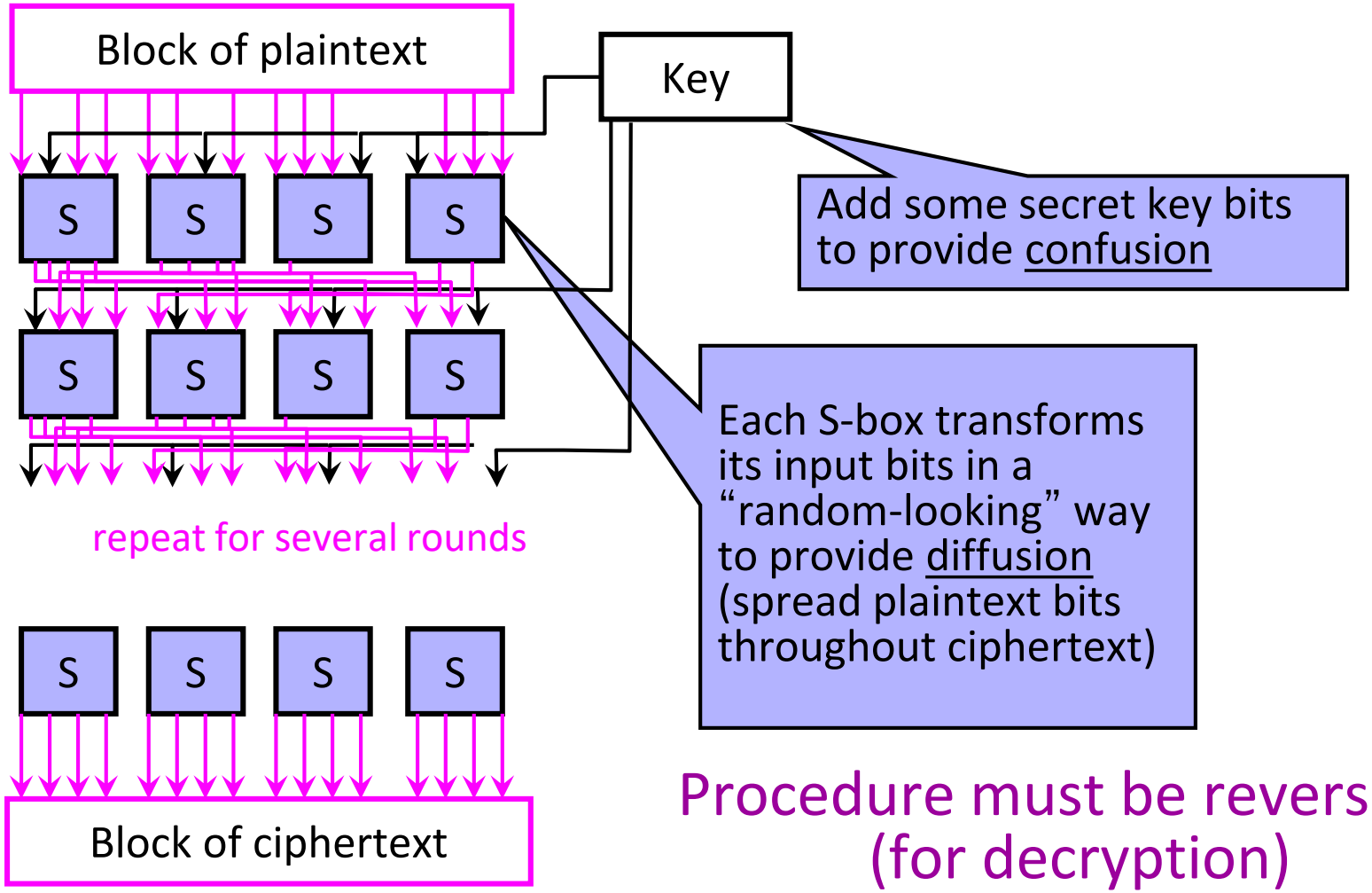
For N-bit input, $2^N!$ possible permutations
For K-bit key, 2^K possible keys

Block Cipher Security

- Result should look like a random permutation on the inputs
  - Recall: not just shuffling bits. N-bit block cipher permutes over 2^N inputs.

- 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 Substitution-Permutation design)



Procedure must be reversible (for decryption)

Standard Block Ciphers

- **DES: Data Encryption Standard**
  - Feistel network: builds invertible function using non-invertible ones
  - Invented by IBM, issued as federal standard in 1977
  - 64-bit blocks, 56-bit key + 8 bits for parity

DES and 56 bit keys

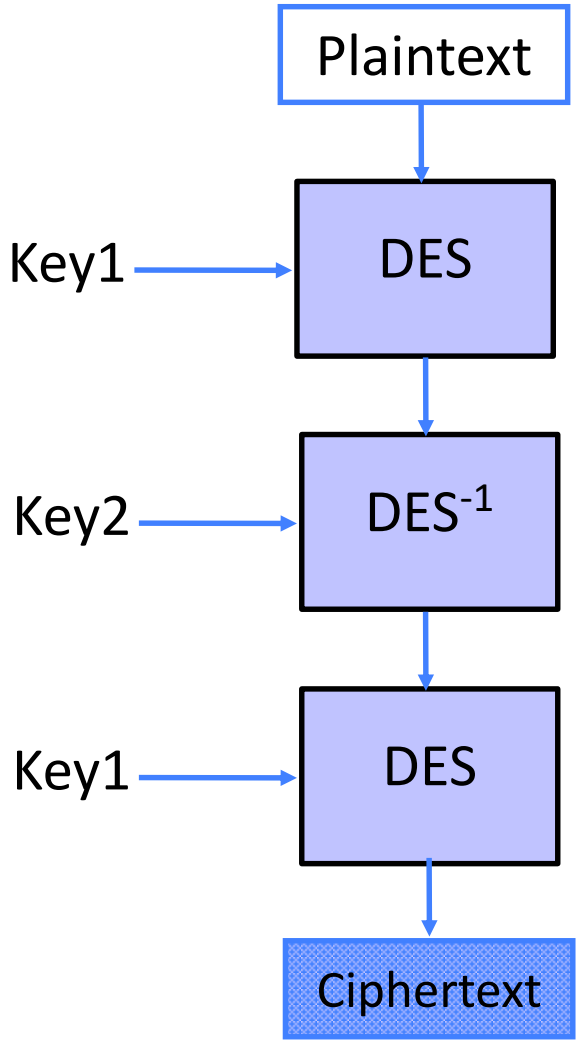
- 56 bit keys are quite short

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

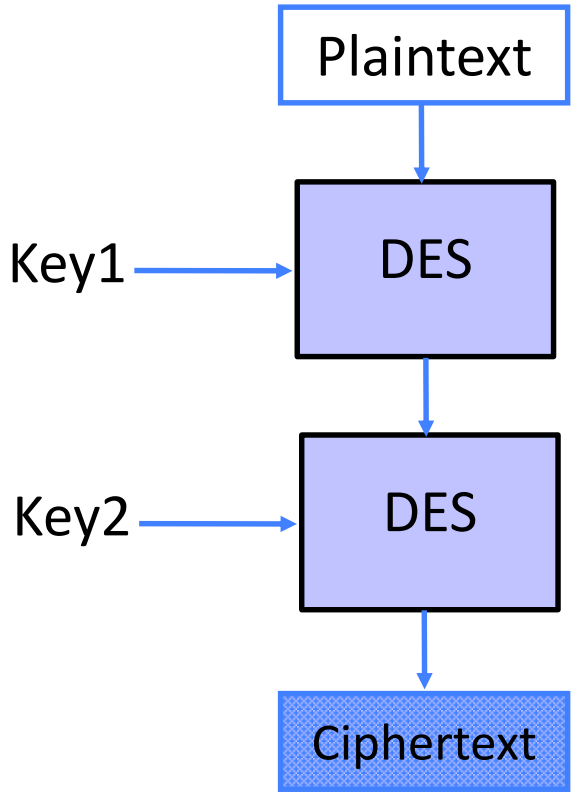
3DES

- Two-key 3DES increases security of DES by doubling the key length

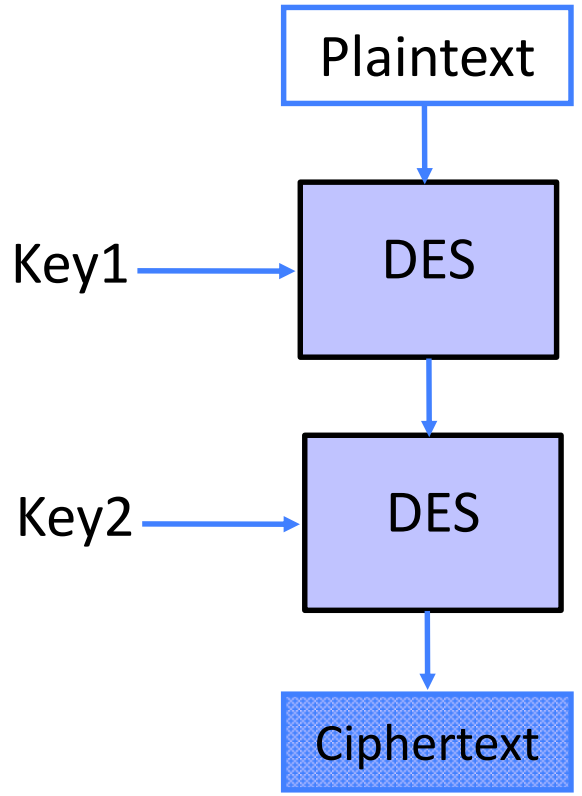


But wait… what about *2DES*?

- Suppose you are given plaintext-ciphertext pairs (P1,C1), (P2,C2), (P3,C3)
- Suppose Key1 and Key2 are each 56-bits long
- Can you figure out Key1 and Key2 if you try all possible values for both (2^{112} possibilities) → Yes
- Can you figure out Key1 and Key2 more efficiently than that? → Discuss!

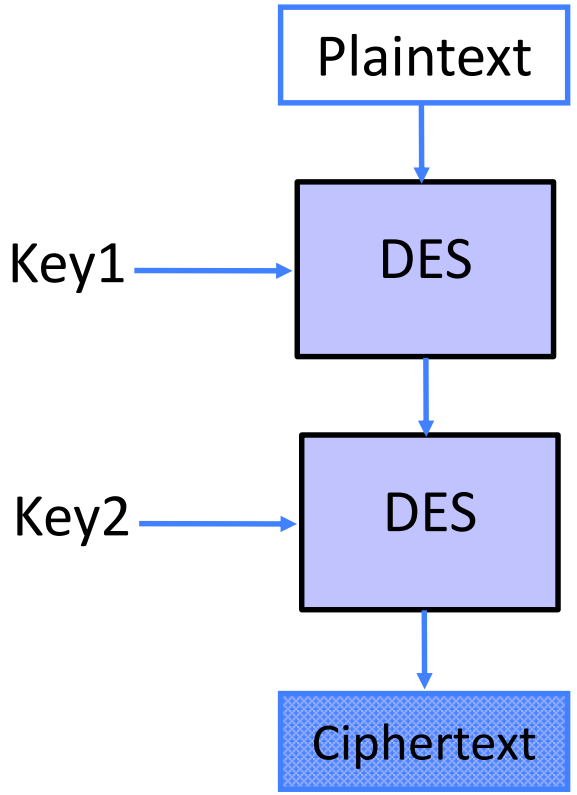


Meet-in-the-middle



Meet-in-the-Middle Attack

- Guess 2^{56} values for Key1, and create a table from P1 to a middle value M1 for each key guess ($M1^{G1}$, $M1^{G2}$, $M1^{G3}$, …)
- Guess 2^{56} values for Key2, and create a table from C1 to a middle value M'1 for each key guess ($M'1^{G1}$, $M'1^{G2}$, $M'1^{G3}$, …)
- Look for collision in the middle values → if only one collision, found Key1 and Key2; otherwise repeat for (P2,C2), …



Defining the strength of a scheme

- *Effective Key Strength*
  - Amount of ‘work’ the adversary needs to do
- DES: 56-bits
  - 2^56 encryptions to try ‘all keys’
- 2DES: 57-bits
  - 2*(2^56) encryptions = 2^57
- 3DES: 112-bits (or sometimes 80-bits)
  - Meet-in-the-middle + more work = 2^112 (for 3 keys, e.g. K1, K2, K3)
  - Various attacks = 2^80 (for 2 keys, e.g. K1, K2, K1)

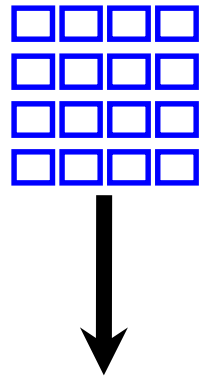
Standard Block Ciphers

- **DES: Data Encryption Standard**
  - Feistel Network: builds invertible function using non-invertible ones
  - Invented by IBM as “Lucifer”, issued as federal standard in 1977
  - 64-bit blocks, 56-bit key + 8 bits for parity

- **AES: Advanced Encryption Standard**
  - Substitution-Permutation structure
  - New federal standard as of 2001
    - NIST: National Institute of Standards & Technology
  - Based on the Rijndael algorithm
    - Selected via an open process
  - 128-bit blocks, keys can be 128, 192 or 256 bits

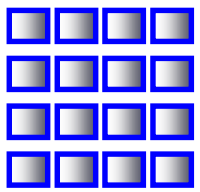
Encrypting a Large Message

- So, we've got a good block cipher, but our plaintext is larger than 128-bit block size



128-bit plaintext

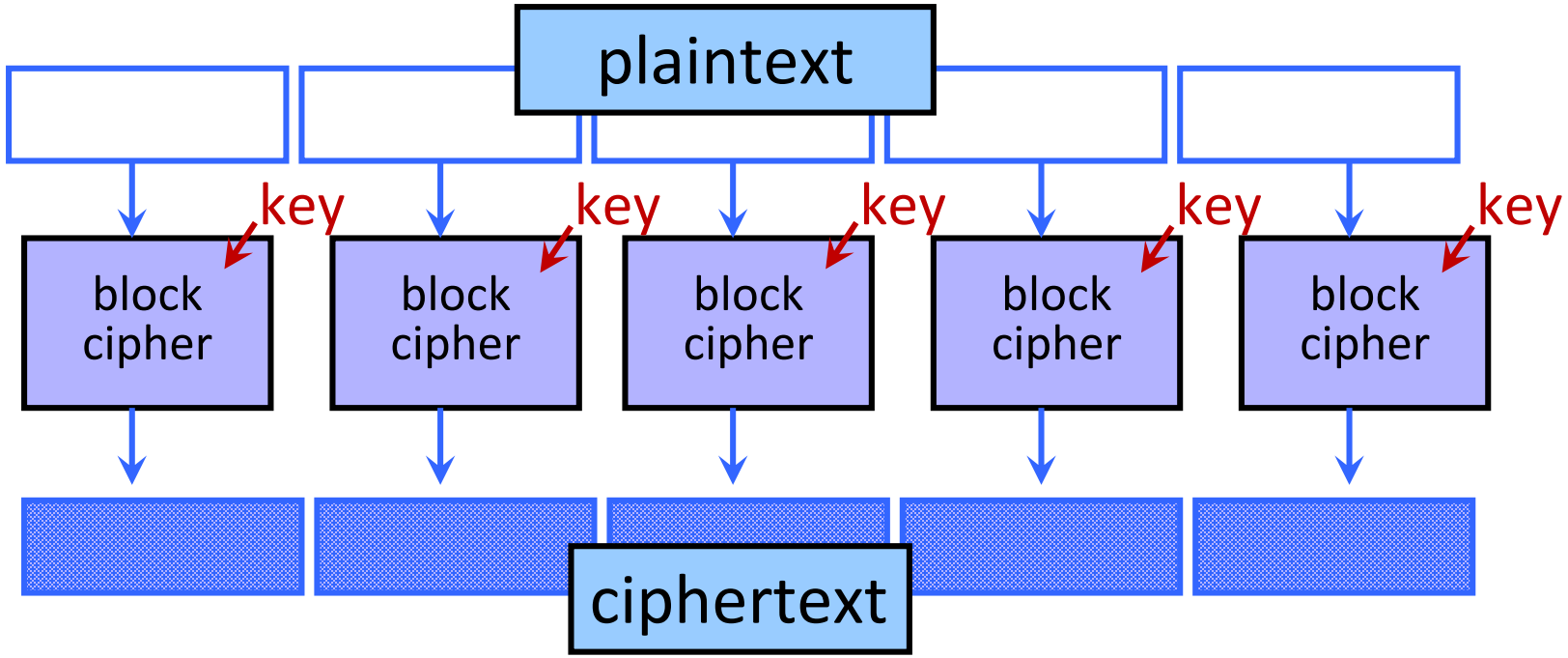
(arranged as 4x4 array of 8-bit bytes)



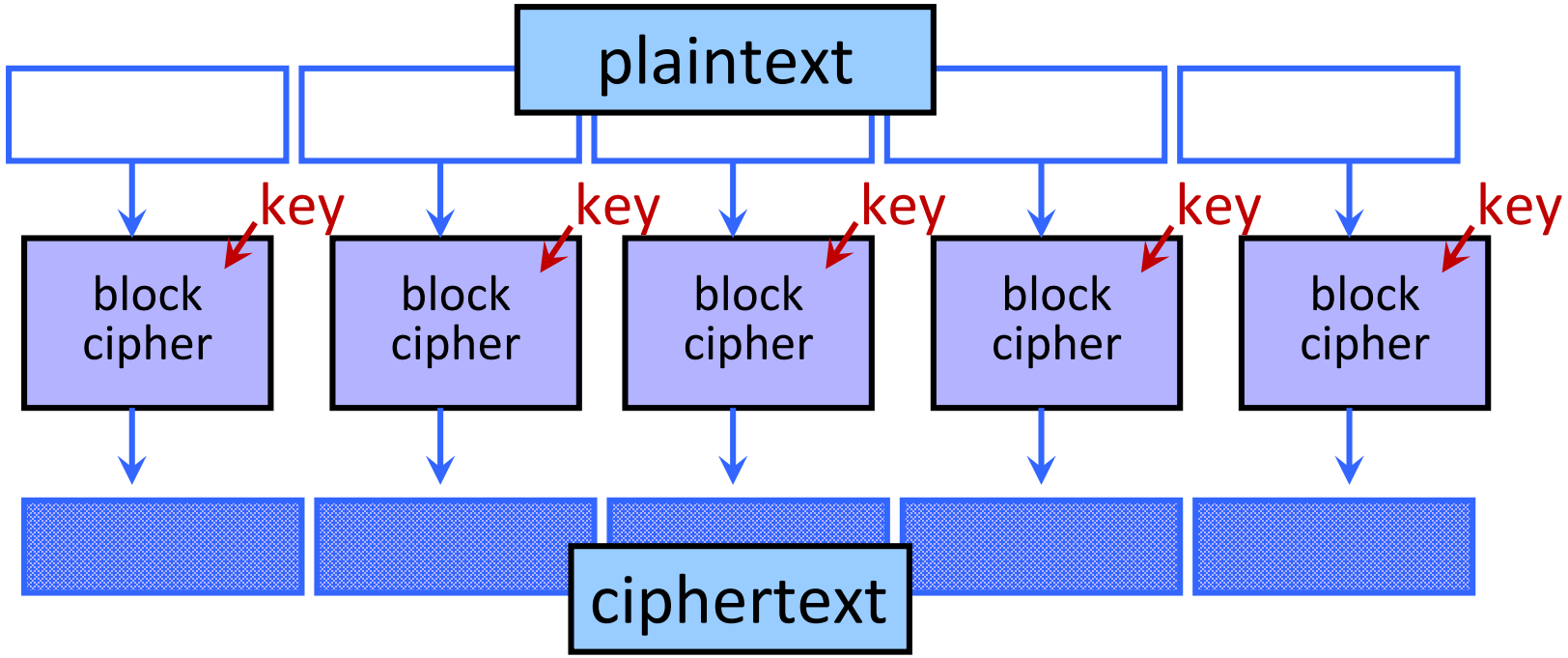
128-bit ciphertext

- What should we do?

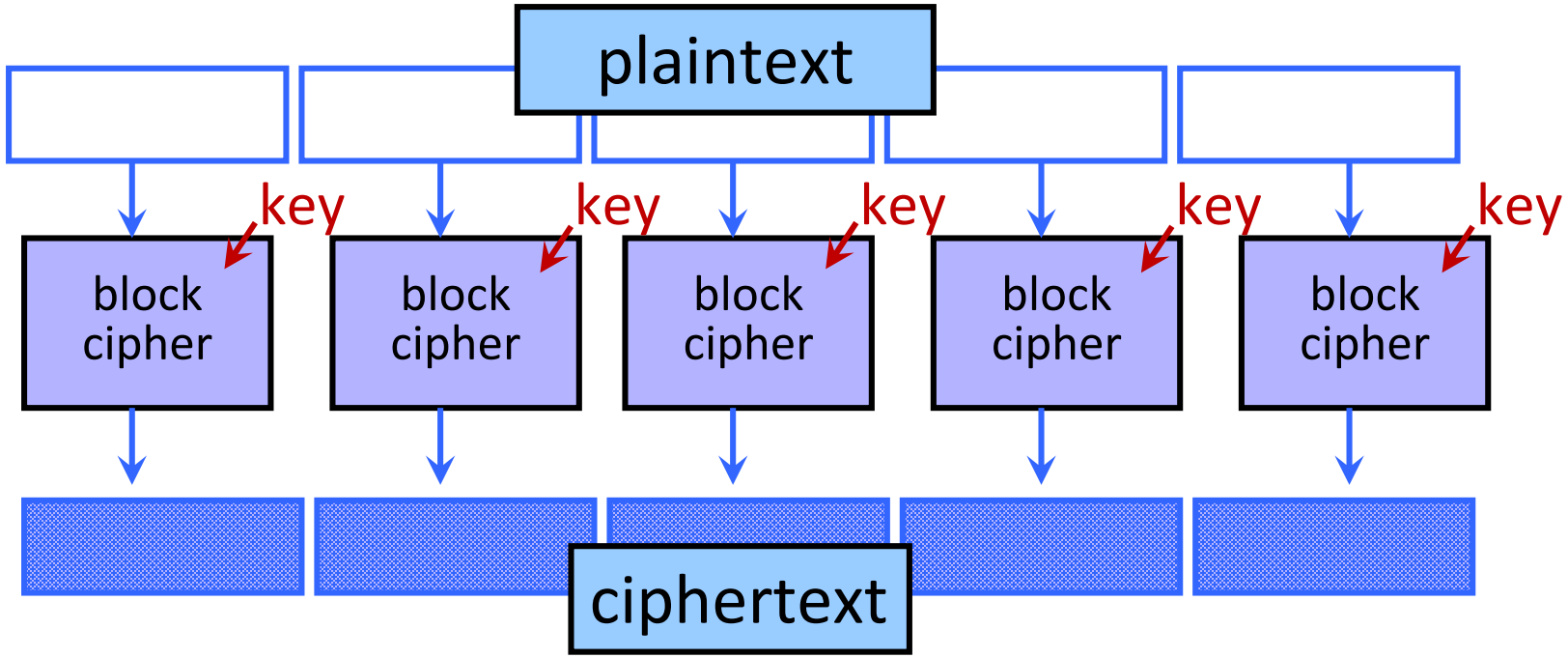
Electronic Code Book (ECB) Mode



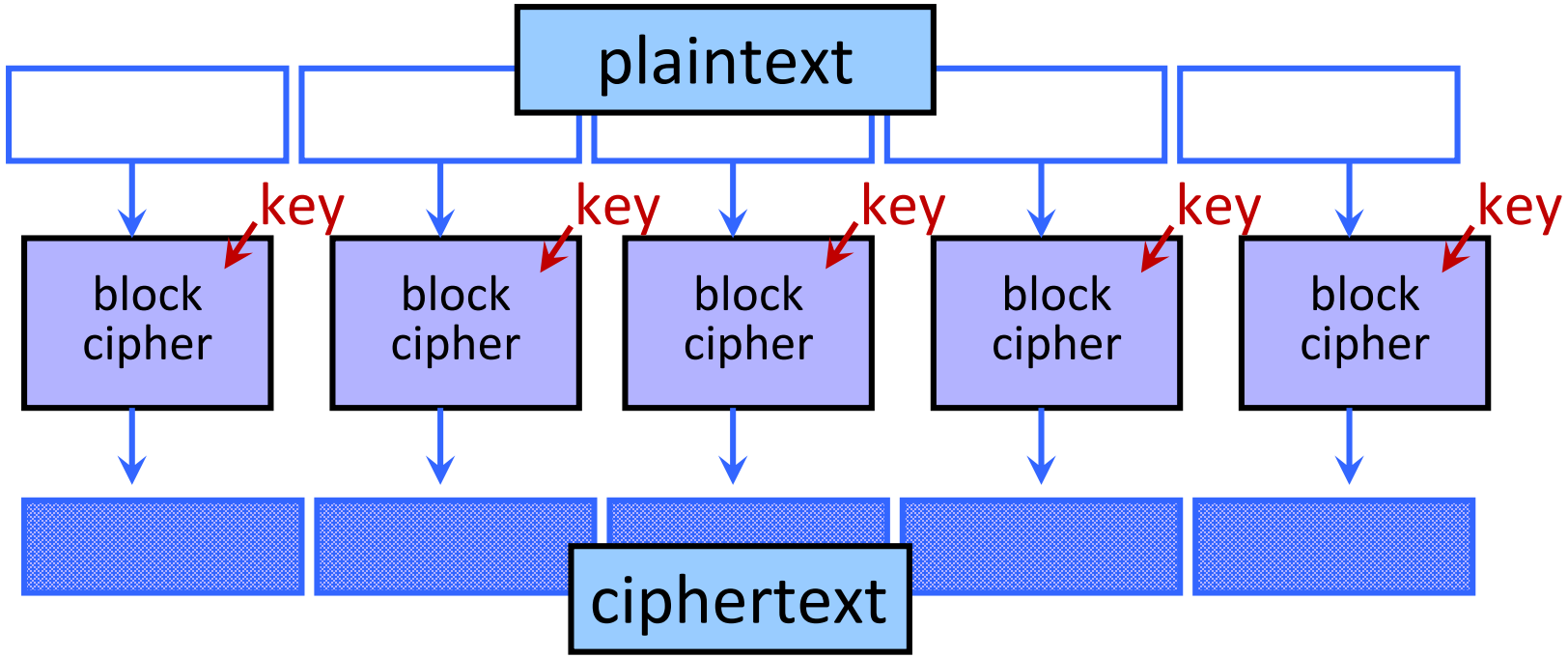
Electronic Code Book (ECB) Mode



Canvas: What properties of ECB aren't great?

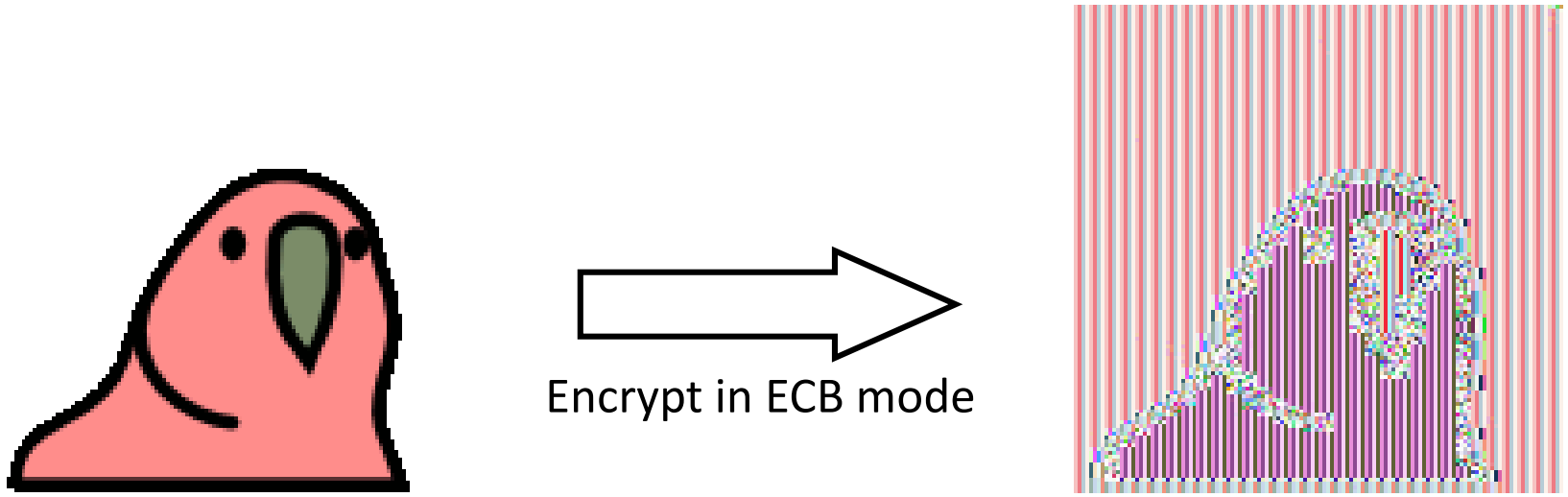


Electronic Code Book (ECB) Mode



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

Information Leakage in ECB Mode



Oops

Move Fast and Roll Your Own Crypto

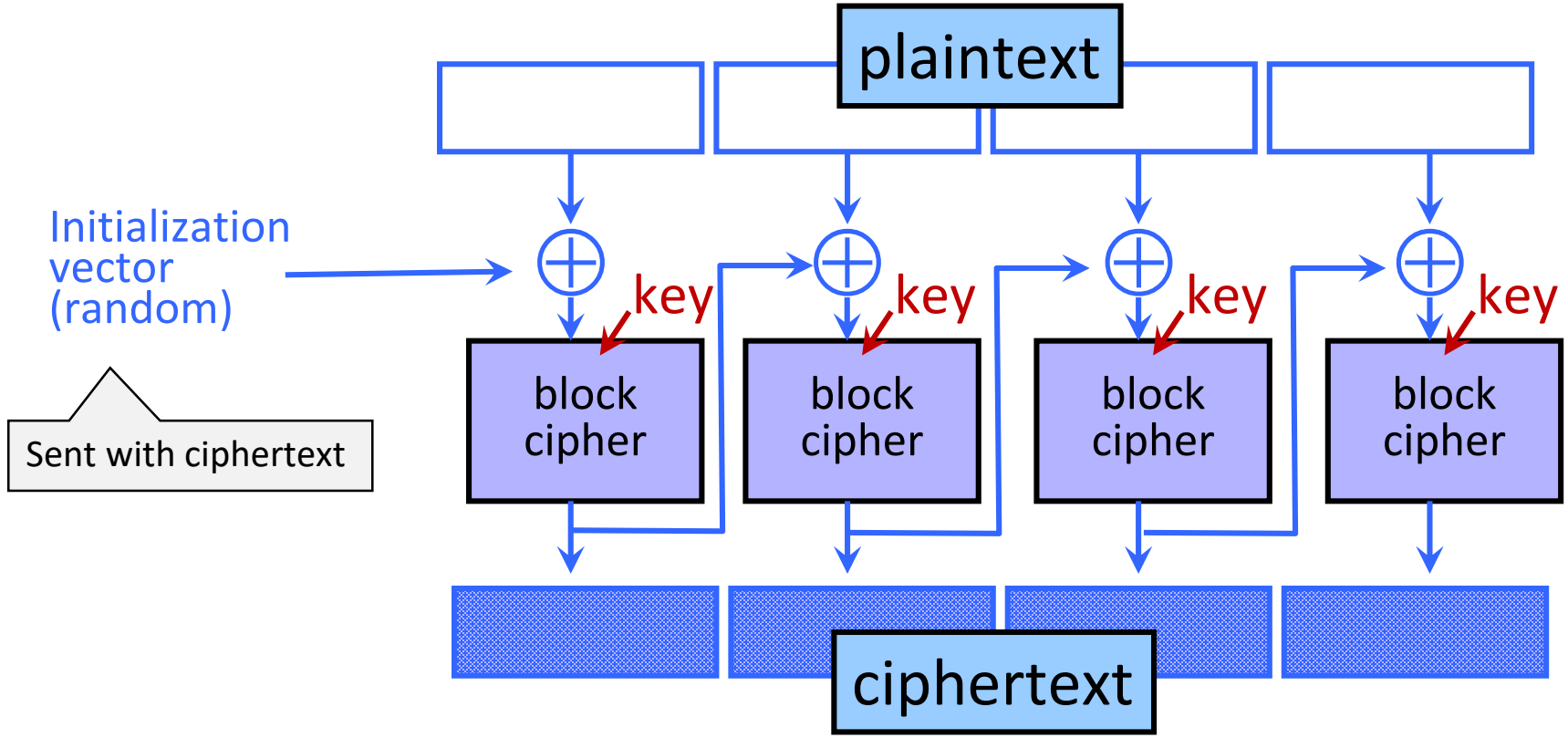
A Quick Look at the Confidentiality of Zoom Meetings

By Bill Marczak and John Scott-Railton April 3, 2020

- Zoom documentation claims that the app uses "AES-256" encryption for meetings where possible. However, we find that in each Zoom meeting, a single AES-128 key is used in ECB mode by all participants to encrypt and decrypt audio and video. The use of ECB mode is not recommended because patterns present in the plaintext are preserved during encryption.

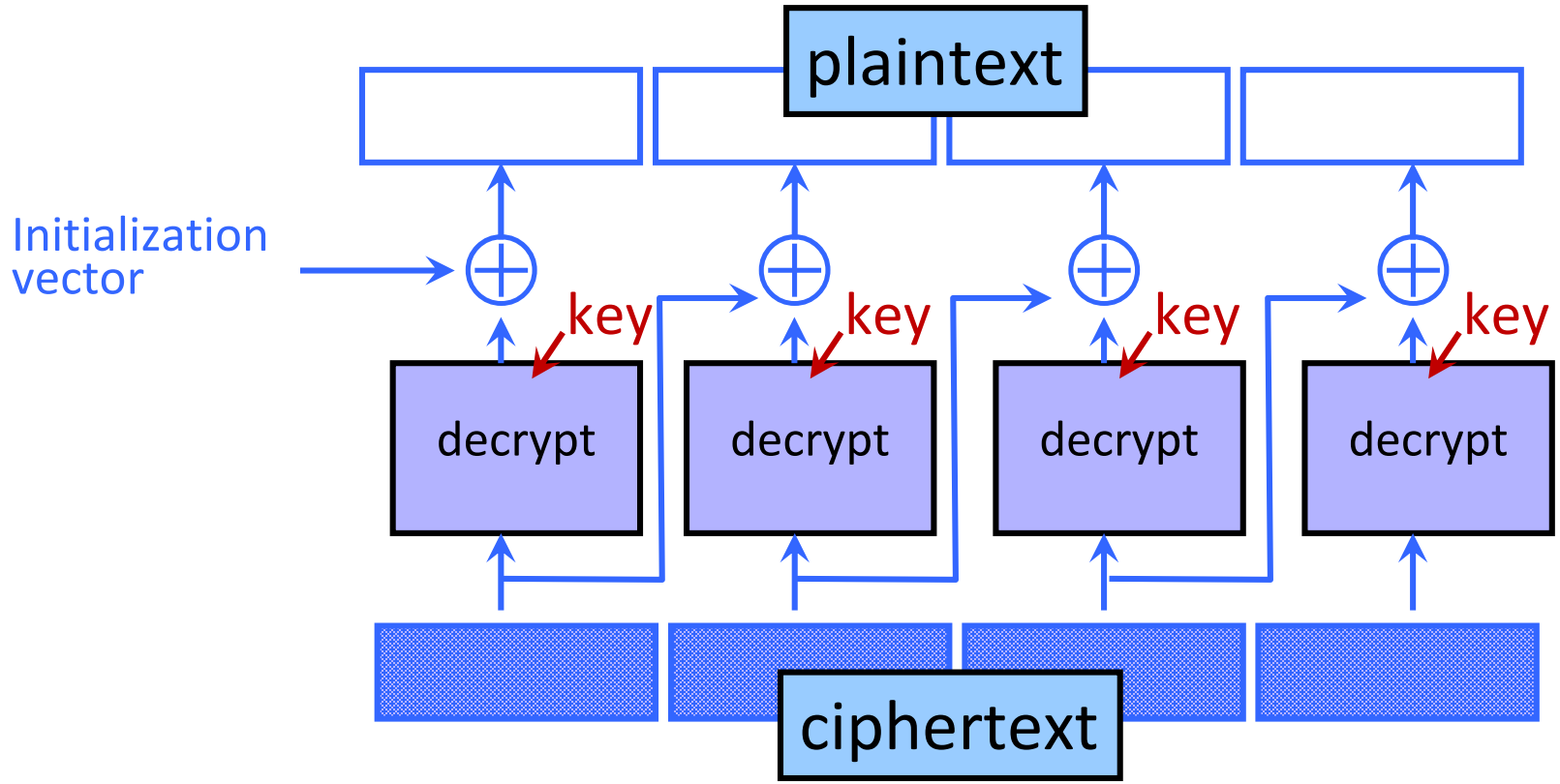
https://citizenlab.ca/2020/04/move-fast-roll-your-own-crypto-a-quick-look-at-the-confidentiality-of-zoom-meetings/

Cipher Block Chaining (CBC) Mode: Encryption

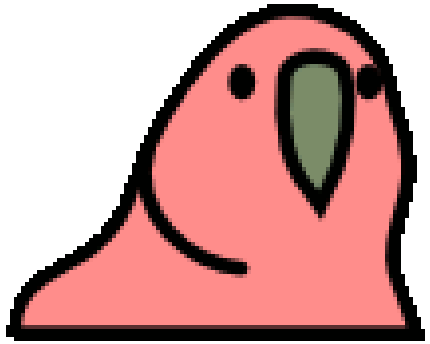


- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption



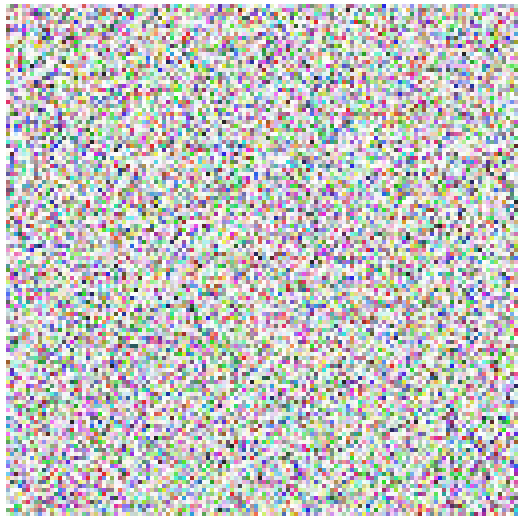
ECB vs. CBC



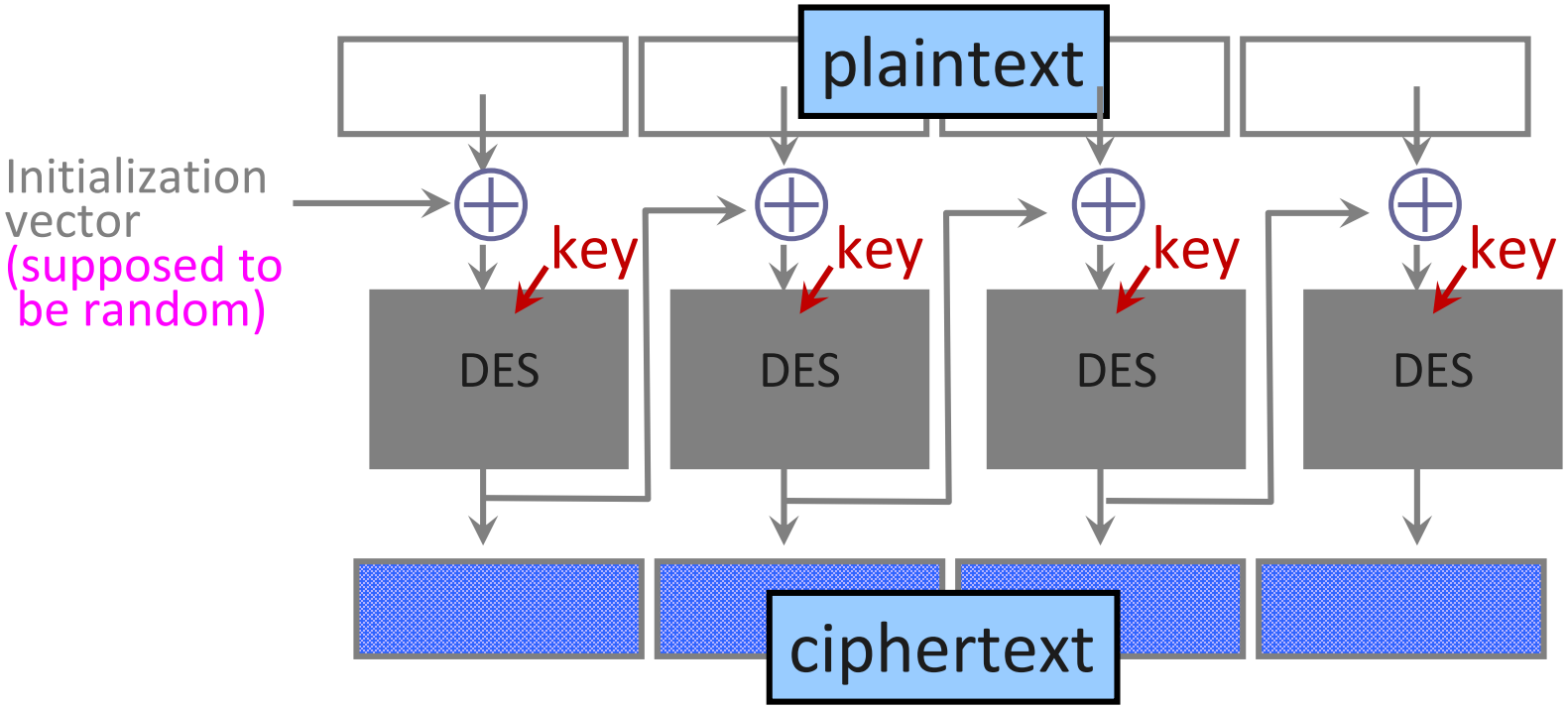
AES in ECB mode

AES in CBC mode

Similar plaintext blocks produce similar ciphertext blocks (not good!)



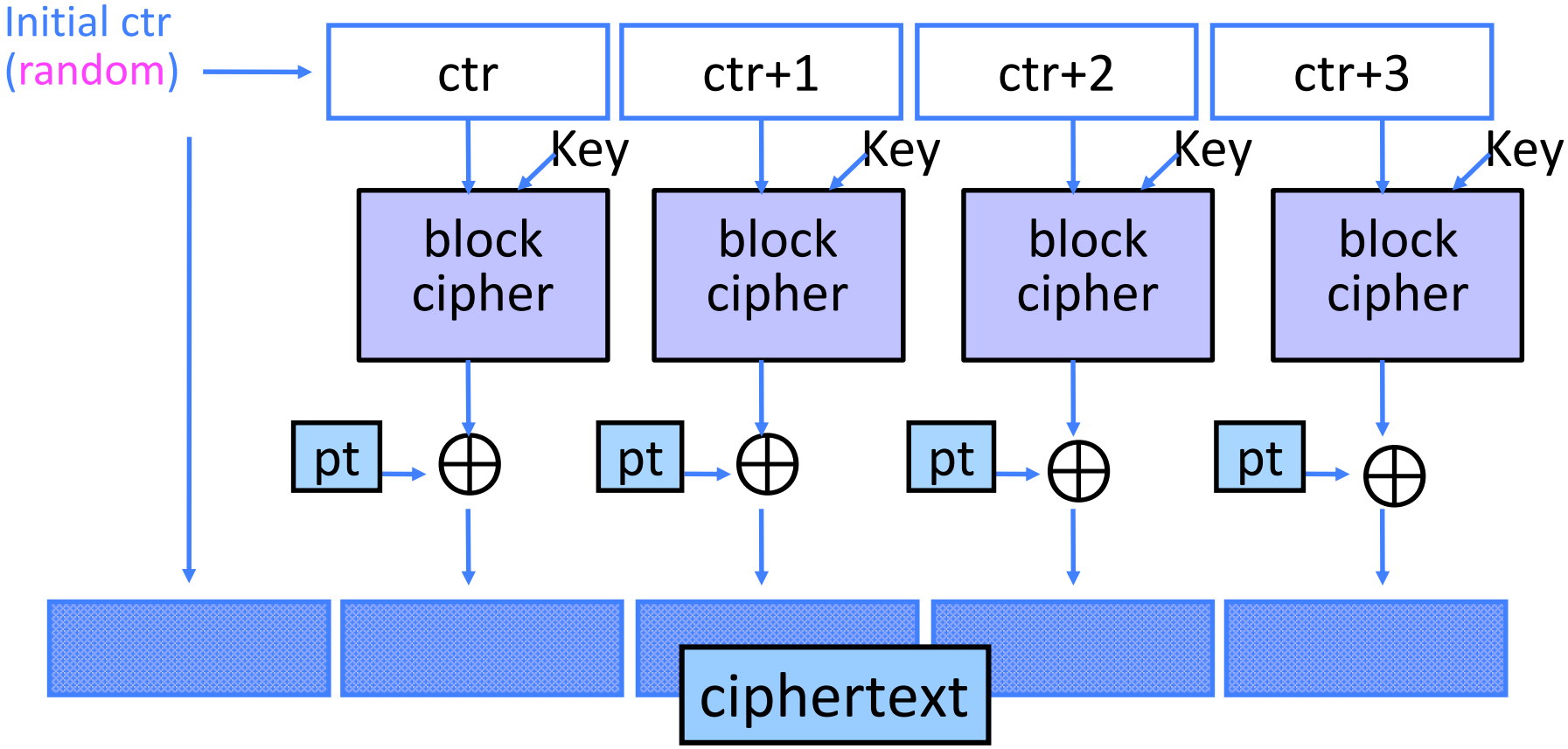
Initialization Vector Dangers



Found in the source code for Diebold voting machines:

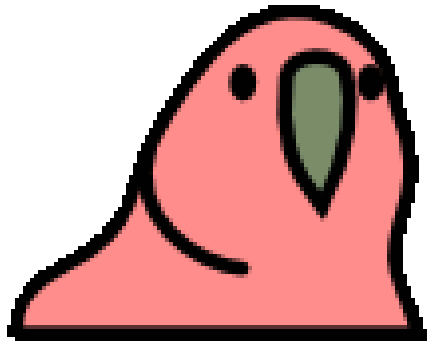
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
        totalSize, DESKEY, NULL, DES_ENCRYPT)
```

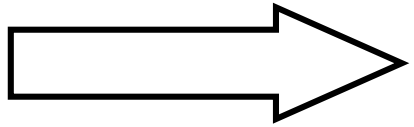
Counter Mode (CTR): Encryption



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

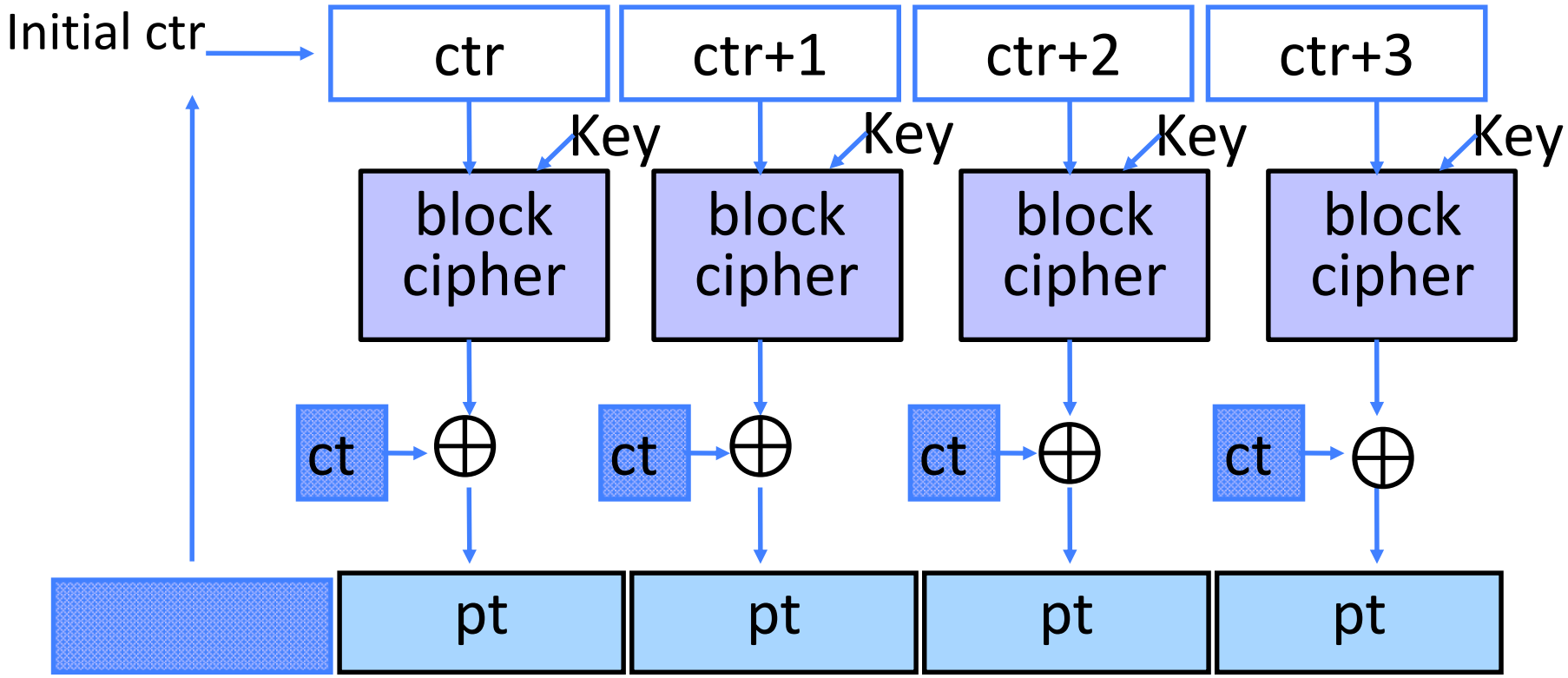
Information Leakage in CTR Mode (poorly)





Encrypt in CTR mode:
But with the same counter for each frame!

Counter Mode (CTR): Decryption



Ok, so what mode do I use?

- Don’t choose a mode, use established libraries ☺

- Modes that might be good:
  - GCM-SIV - Galois/Counter Mode + more
  - CCM – CTR + CBC-MAC (we’ll get to that next time)
  - CTR (sometimes its fine!)

- AES-128 is standard (AES-256 is… fine)
  - Be concerned if something says “AES 1024”…

https://research.kudelskisecurity.com/2022/05/11/practical-bruteforce-of-aes-1024-military-grade-encryption/

When is an Encryption Scheme “Secure”?

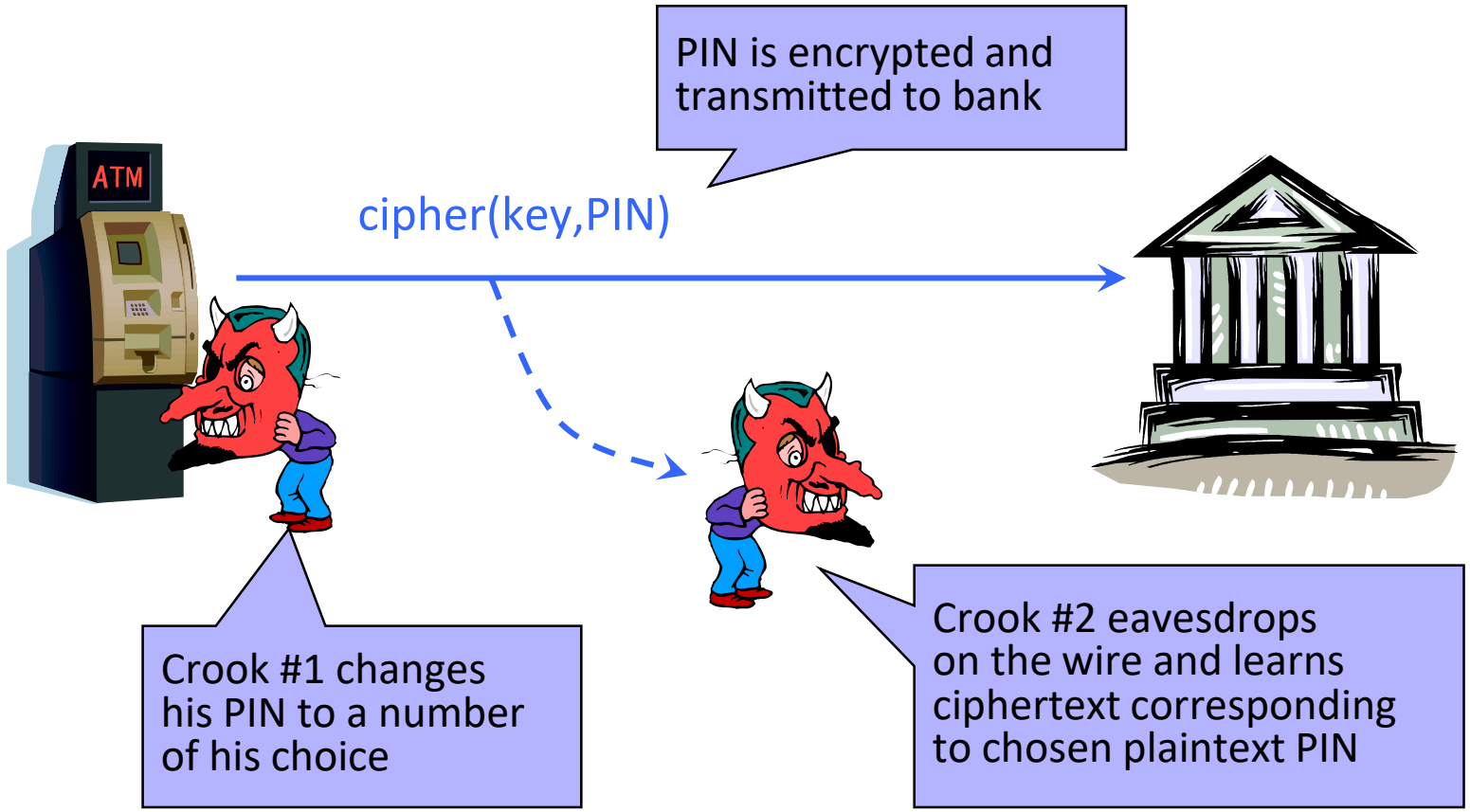
- Hard to recover the key?
  - What if attacker can learn plaintext without learning the key?

- Hard to recover plaintext from ciphertext?
  - What if attacker learns some bits or some function of bits?

How Can a Cipher Be Attacked?

- Attackers knows ciphertext and encryption algorithm
  - What else does the attacker know? Depends on the application in which the cipher is used!
- Ciphertext-only attack
- KPA: Known-plaintext attack (stronger)
  - Knows some plaintext-ciphertext pairs
- CPA: Chosen-plaintext attack (even stronger)
  - Can obtain ciphertext for any plaintext of choice
- CCA: Chosen-ciphertext attack (very strong)
  - Can decrypt any ciphertext except the target

Chosen Plaintext Attack



… repeat for any PIN value

Thinking about formality

- Confidentiality?
  - How about *indistinguishability*
  - Given:
    - Message M
    - Encrypt(M,k) or Encrypt(random,k)
      - At random
  - Can you tell the difference better than 50/50?

The shape of the formal approach

- INDistinguishability under Chosen Plaintext Attack
  - IND-CPA
- Formalized *cryptographic game*

- Adversary submits pairs of *plaintexts* (M_a, M_b)
  - Gets back ONE of the *ciphertexts* (C_x)

- Adversary must guess which ciphertext this is (C_a or C_b)
  - If they can do better than 50/50, they win

Very Informal Intuition

Minimum security requirement for a modern encryption scheme

- Security against chosen-plaintext attack (CPA)
  - Ciphertext leaks no information about the plaintext
  - Even if the attacker correctly guesses the plaintext, he cannot verify his guess
  - Every ciphertext is unique, encrypting same message twice produces completely different ciphertexts
    - Implication: encryption must be randomized or stateful
- Security against chosen-ciphertext attack (CCA)
  - Integrity protection – it is not possible to change the plaintext by modifying the ciphertext