CSE 484 / CSE M 584: Cryptography

Winter 2022

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Announcements

- Office Hours This Week: All virtual as we transition to hybrid next week
- Office Hours Next Week: TBD based on interest and needs, but possibly some hybrid / in person

Books – Not Required! But because people asked

- Real-World Cryptography by David Wong
  - I haven't read in detail, but looks very good
  - I could picture it becoming a required reading for future instances of this course
  - If get one book, I *think* this is the book I'd recommend

Books – Not Required! About Block Ciphers

- Differential Cryptanalysis of the Data Encryption Standard by Eli Biham
  - Amazing historical reference for block cipher design and cryptanalysis
  - Very detailed, but amazing if one wants to learn about historical block ciphers
- The Design of Rijndael: The Advanced Encryption Standard (AES) by Joan Daemen and Vincent Rijmen
  - About the new Advanced Encryption Standard
  - I haven't read but suspect it is awesome, but very detailed and very mathematical
- Cryptography Engineering by Ferguson, Schneier, and Kohno
  - 2010! (Based on earlier 2003 book.)
  - Well, I am a co-author, so I have read this book :P
  - Gentler introduction to block ciphers than above, more aligned with lectures
- Many other great books exist!

Fiction Books and Movies

- So many books and movies related to security over time!
- Maybe and Ed thread about them would be fun?
- Some may have content warnings; some may not represent our current understanding of inequities and harms and ethics…
- These are some that I remember, but please see above:
  - 1984 (So many parts way not okay today … but classic book about “Big Brother”)
  - QualityLand
  - Cory Doctorow’s books
  - Sneakers (movie)
  - Wargames (movie)

Brief Review

- Cryptography:
  - Layered approach (primitives, protocols, applications)
  - One big goal: Privacy
  - One big goal: Integrity
  - Other goals exist
- Kerckhoff's Principle
  - Algorithm public
  - Key to algorithm secret
- Randomness
  - Randomness problems can lead to security system problems

Brief Review

- Symmetric Setting: Communicants share symmetric key
- Asymmetric Setting: Communicants have public (shareable) key and secret (private) key

- So far, we are focused on the symmetric setting

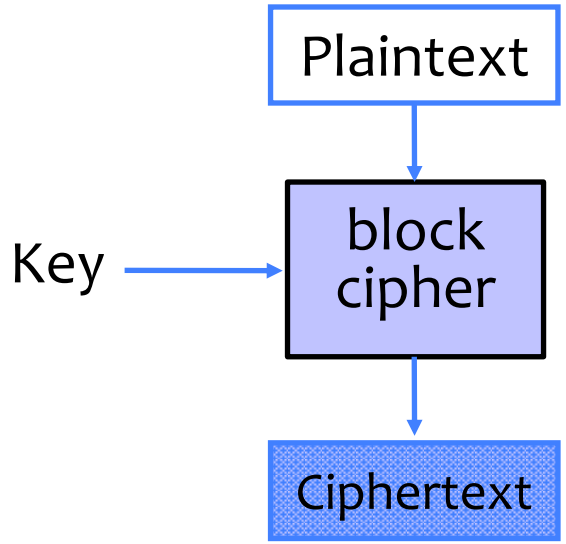
- One-time pad: perfect secrecy, but requires long keys and doesn't provide integrity
- Solution: a primitive (block or stream cipher) with a small key and that is designed to allow key reuse

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

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

Key = 00 Key = 01

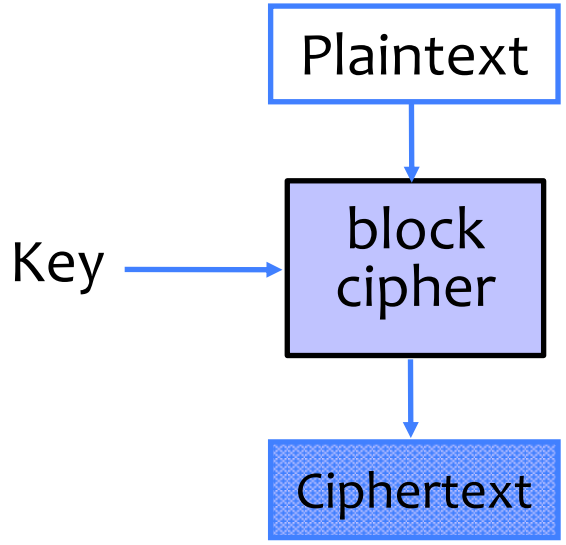
input	possible output	possible output	etc.
000	010	111	…
001	111	110	…
010	101	000	…
011	110	101	…
…	…		…
111	000	110	…

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

For K-bit key, 2^K possible 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

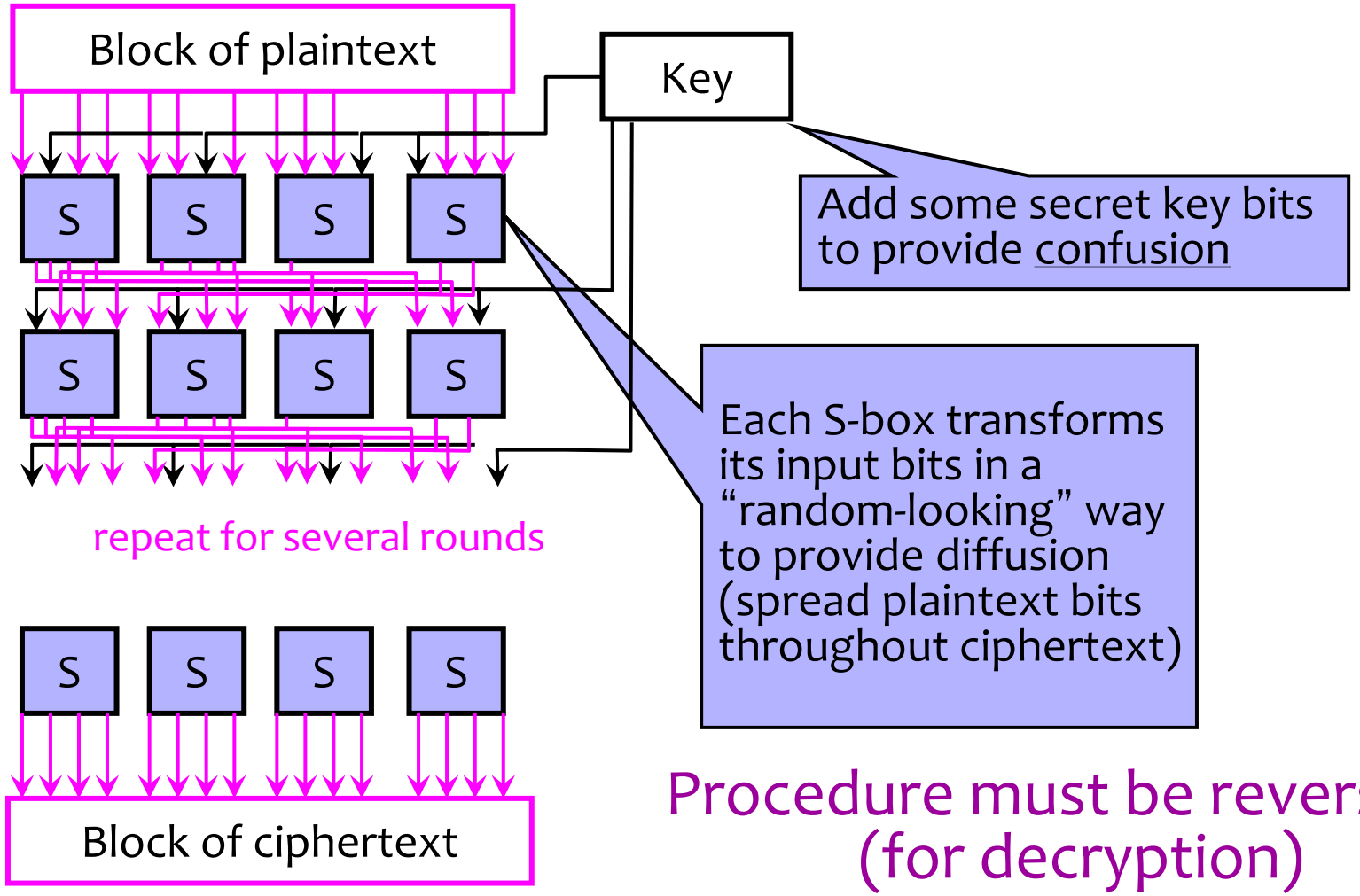


Block Cipher Security

- 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)



Procedure must be reversible (for decryption)

Standard Block Ciphers

- **DES: Data Encryption Standard**
  - Feistel structure: 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

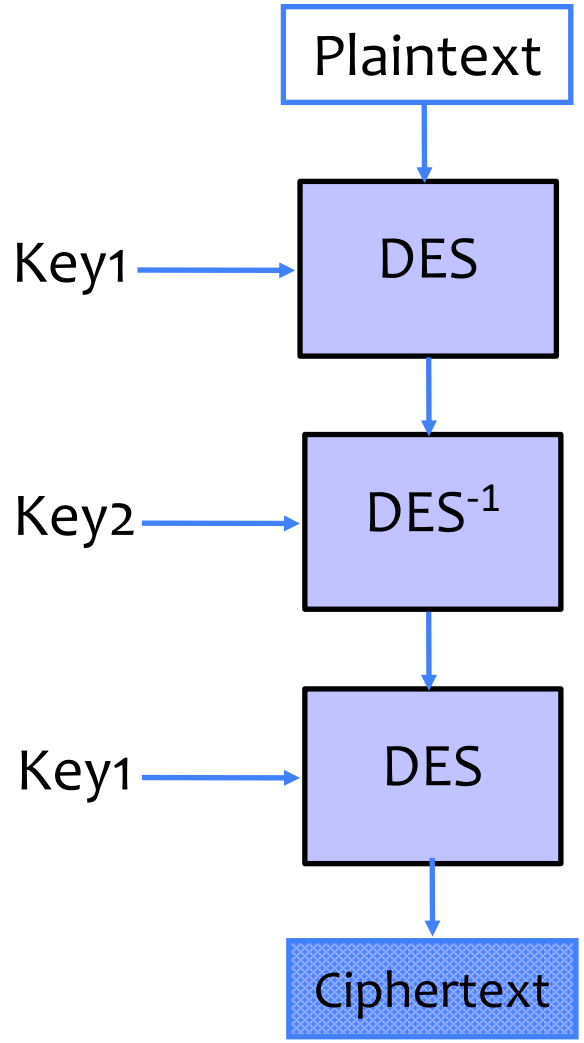
Key Size (bits)	Number of Alternative Keys	Time required at 1 encryption/μs	Time required at 10^6 encryptions/μs
32	$2^{32} = 4.3 \times 10^9$	$2^{31}\ \mu s = 35.8$ minutes	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	$2^{55}\ \mu s = 1142$ years	10.01 hours
128	$2^{128} = 3.4 \times 10^{38}$	$2^{127}\ \mu s = 5.4 \times 10^{24}$ 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)

End Review

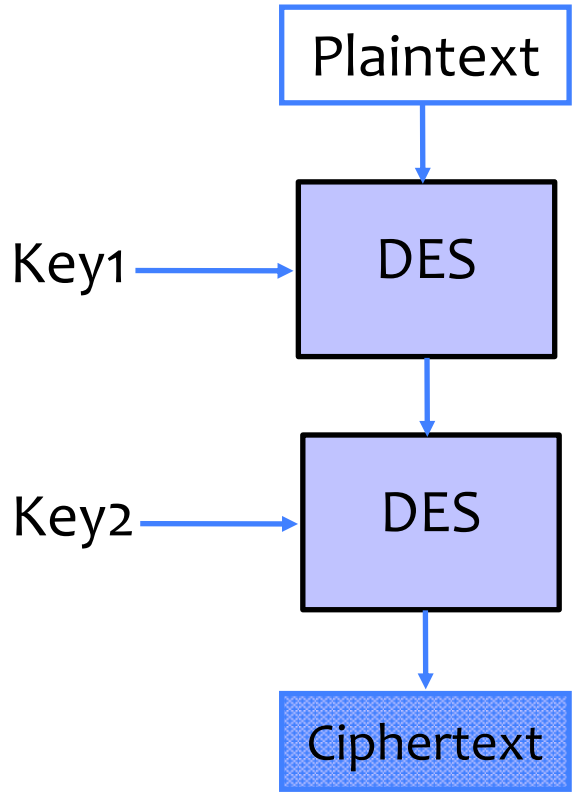
3DES

- 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 than that? → Breakout

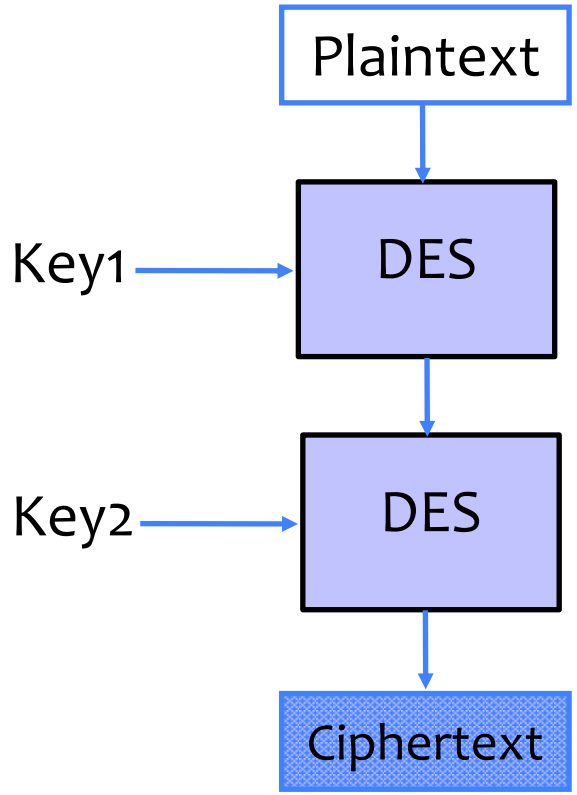


But wait… what about *2DES*?

- Meet-in-the-middle attack

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), …

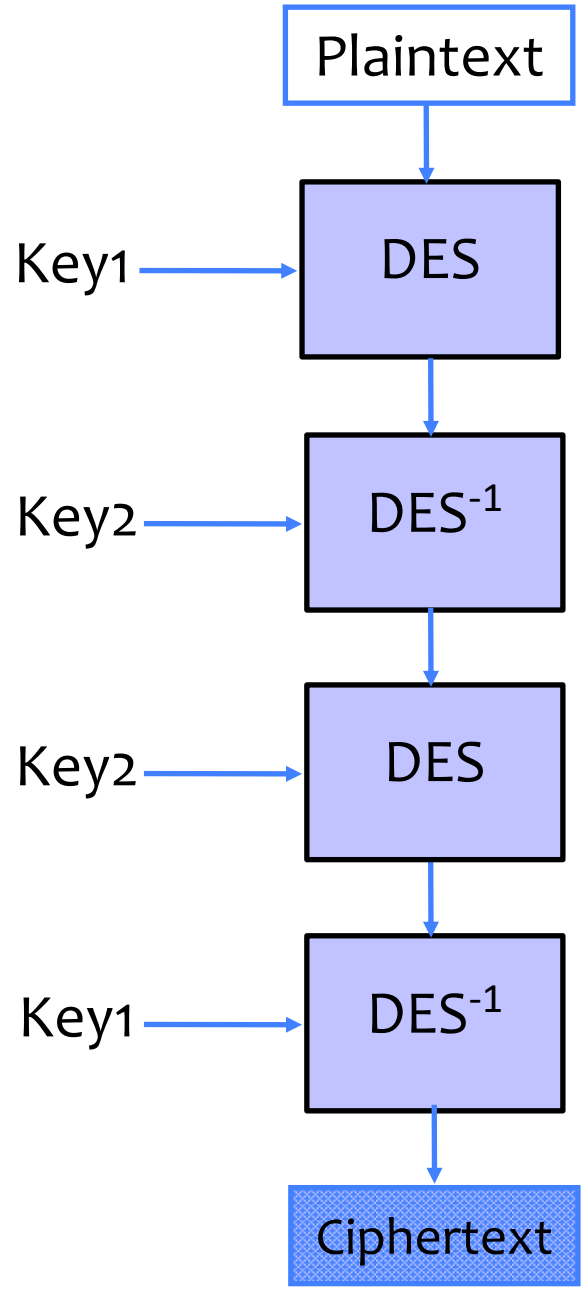


Defining the strength of a scheme

- *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)

4DES

- Paul Kocher's *JOKE* proposal
- If two-key 3DES is good, would two-key 4DES be even better



Standard Block Ciphers

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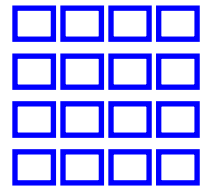
- **AES: Advanced Encryption Standard**
  - Federal standard as of 2001
    - NIST: National Institute of Standards & Technology
  - Based on the Rijndael algorithm
    - Selected via an open process
  - 128-bit blocks, keys can be 128, 192 or 256 bits

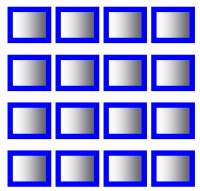
Encrypting a Large Message

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



128-bit plaintext

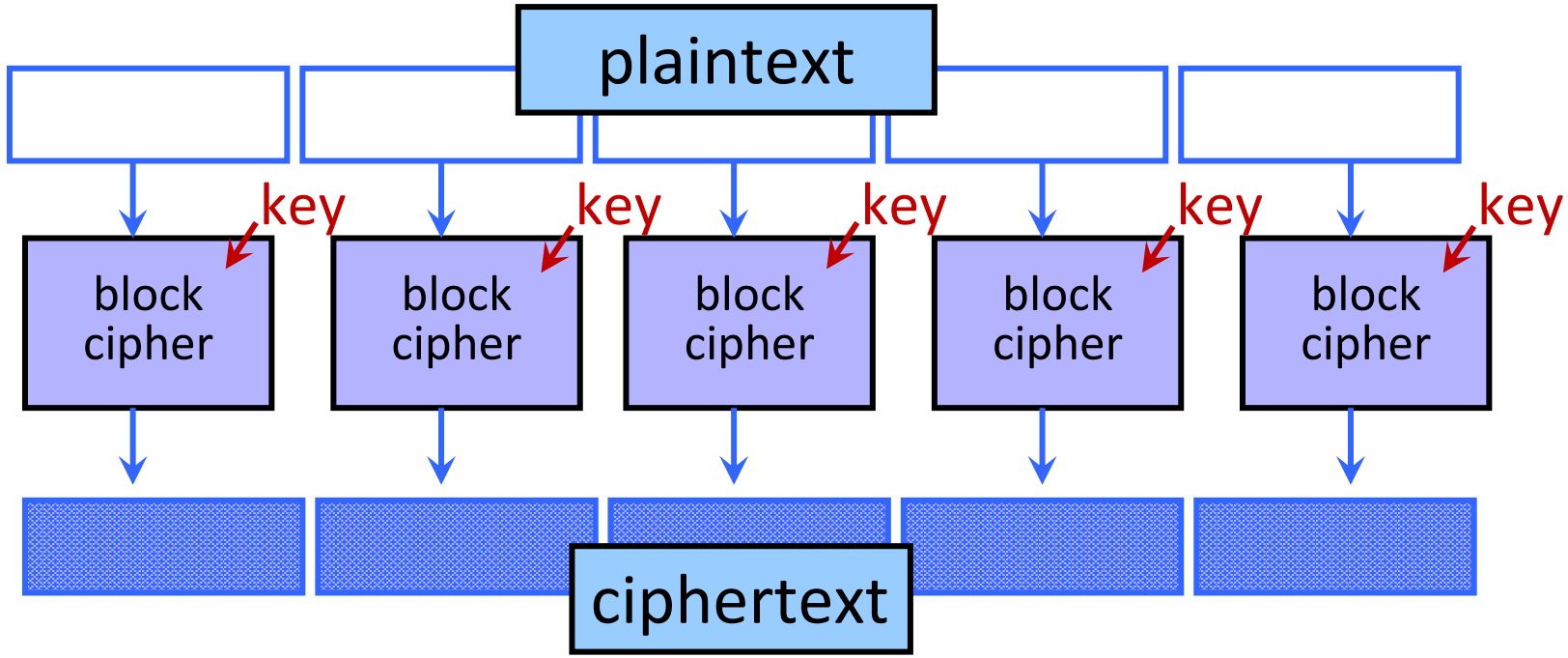
(arranged as 4x4 array of 8-bit bytes)



128-bit ciphertext

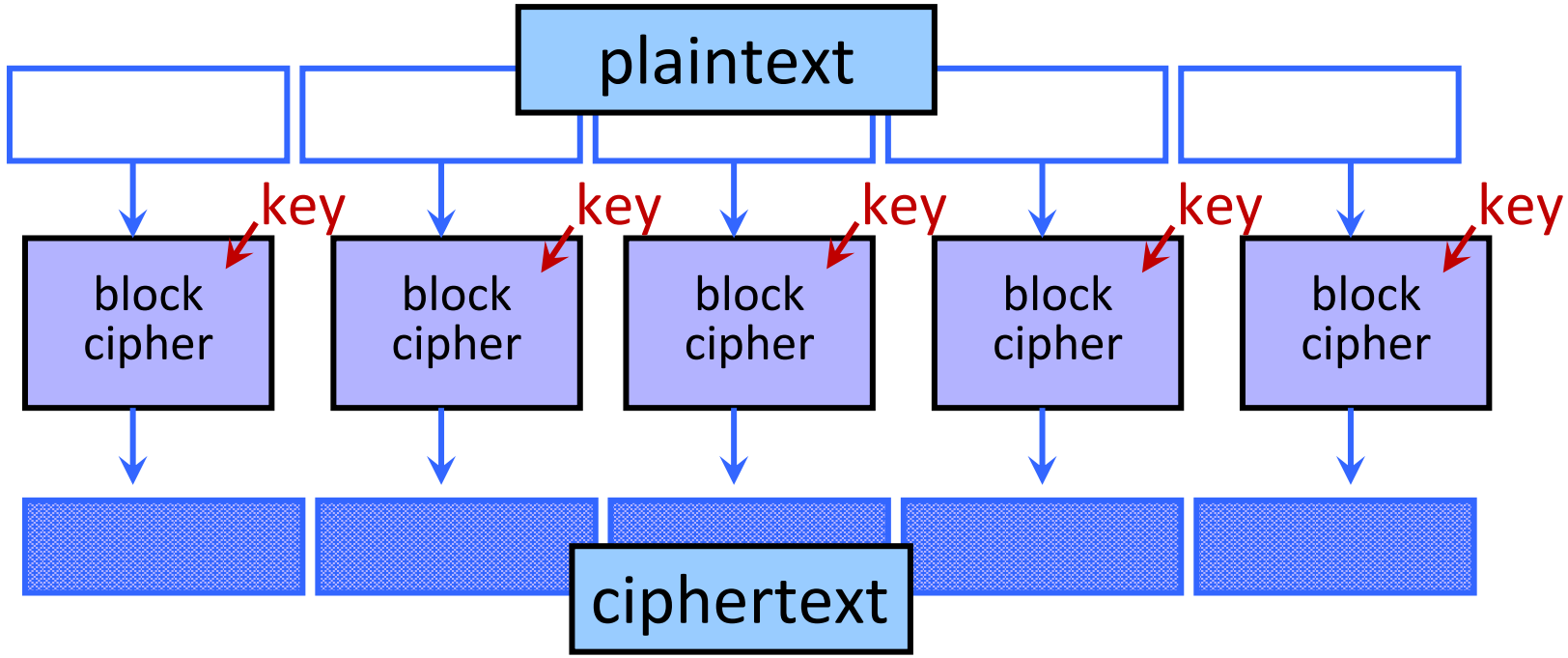
- What should we do?

Electronic Code Book (ECB) Mode



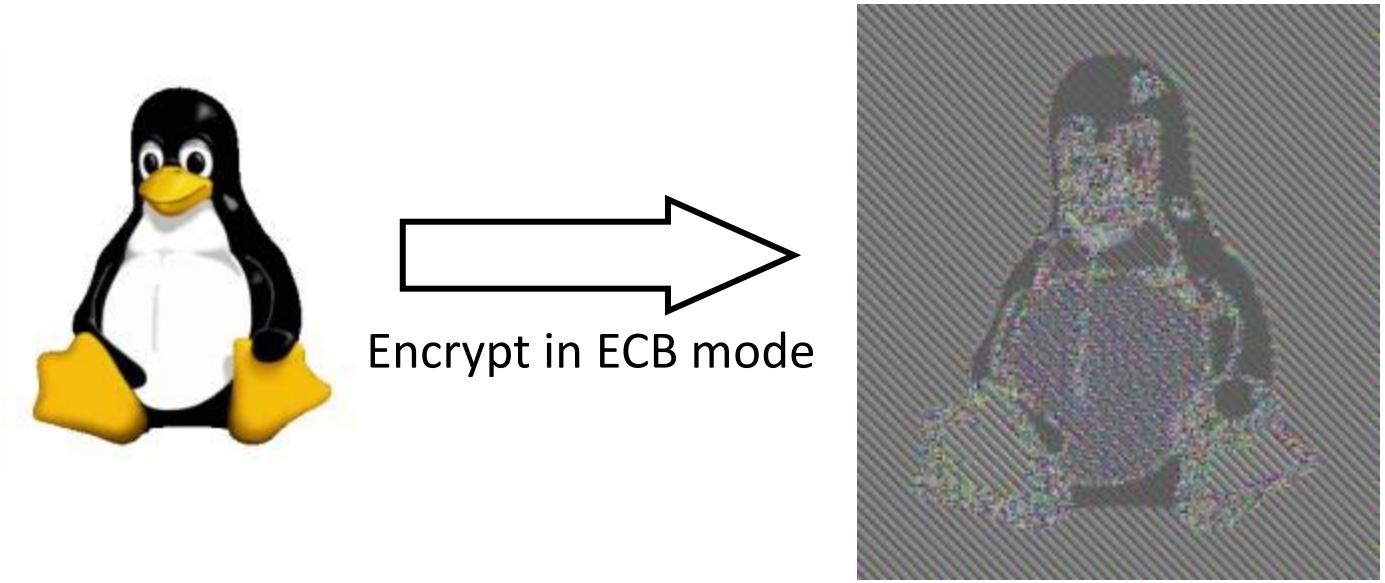
Canvas time!

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



[Wikipedia]

Zoom…

Move Fast and Roll Your Own Crypto

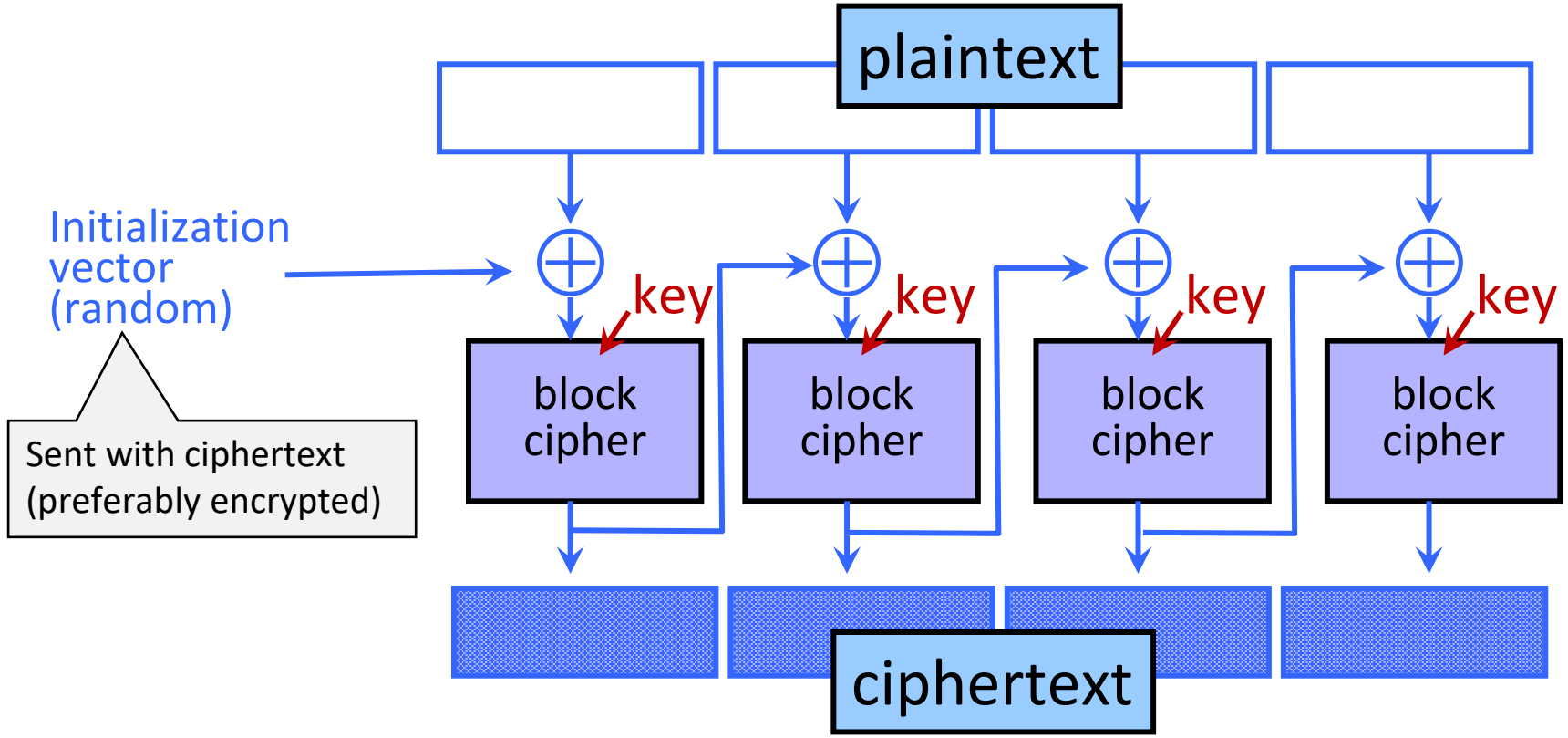
A Quick Look at the Confidentiality of Zoom Meetings

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.

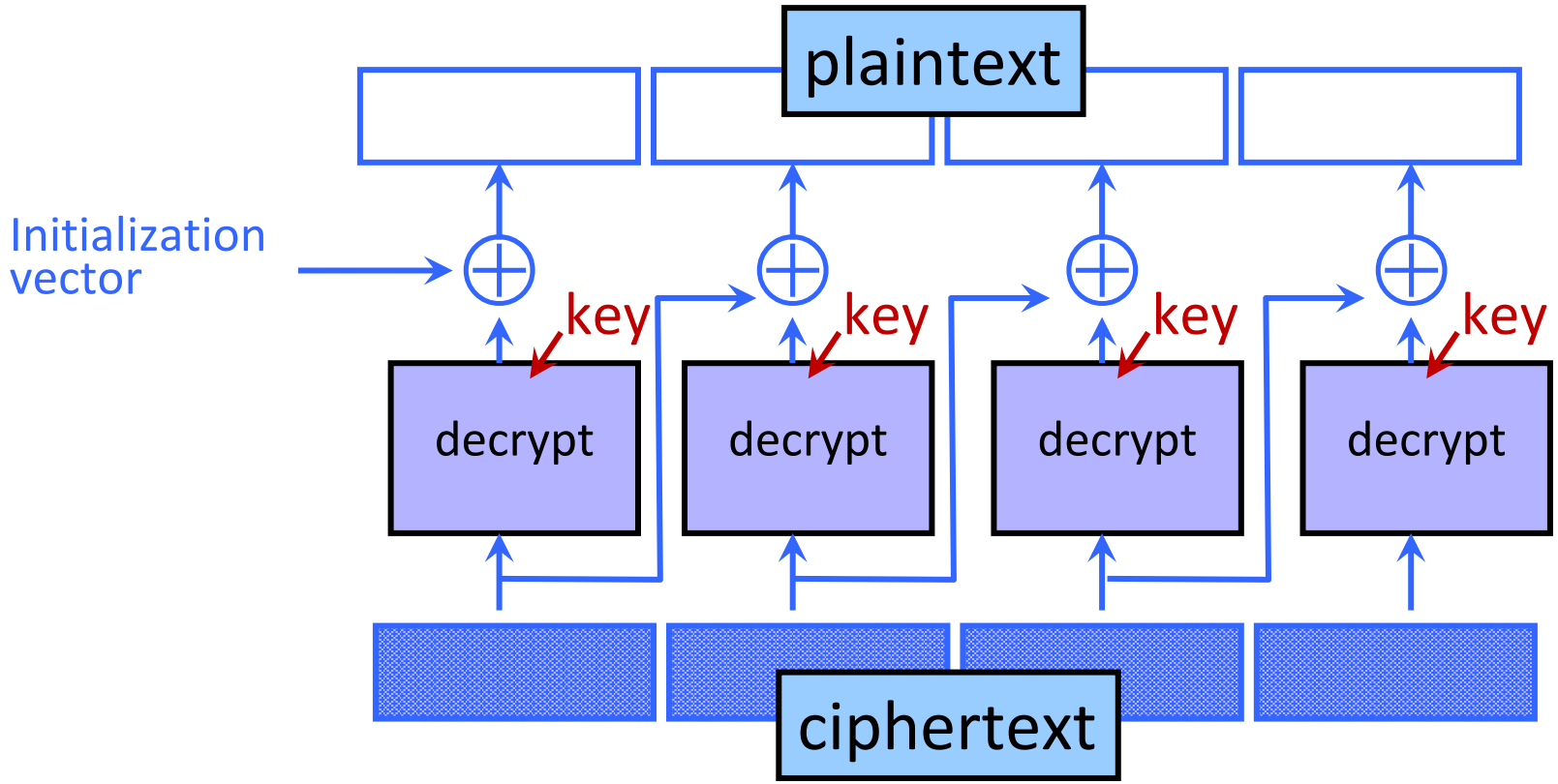
https://citizenlab.ca/2020/04/move-fast-roll-your-own-crypto-a-quick-look-at-the-confidentiality-of-zoom-meetings/

Cipher Block Chaining (CBC) Mode: Encryption

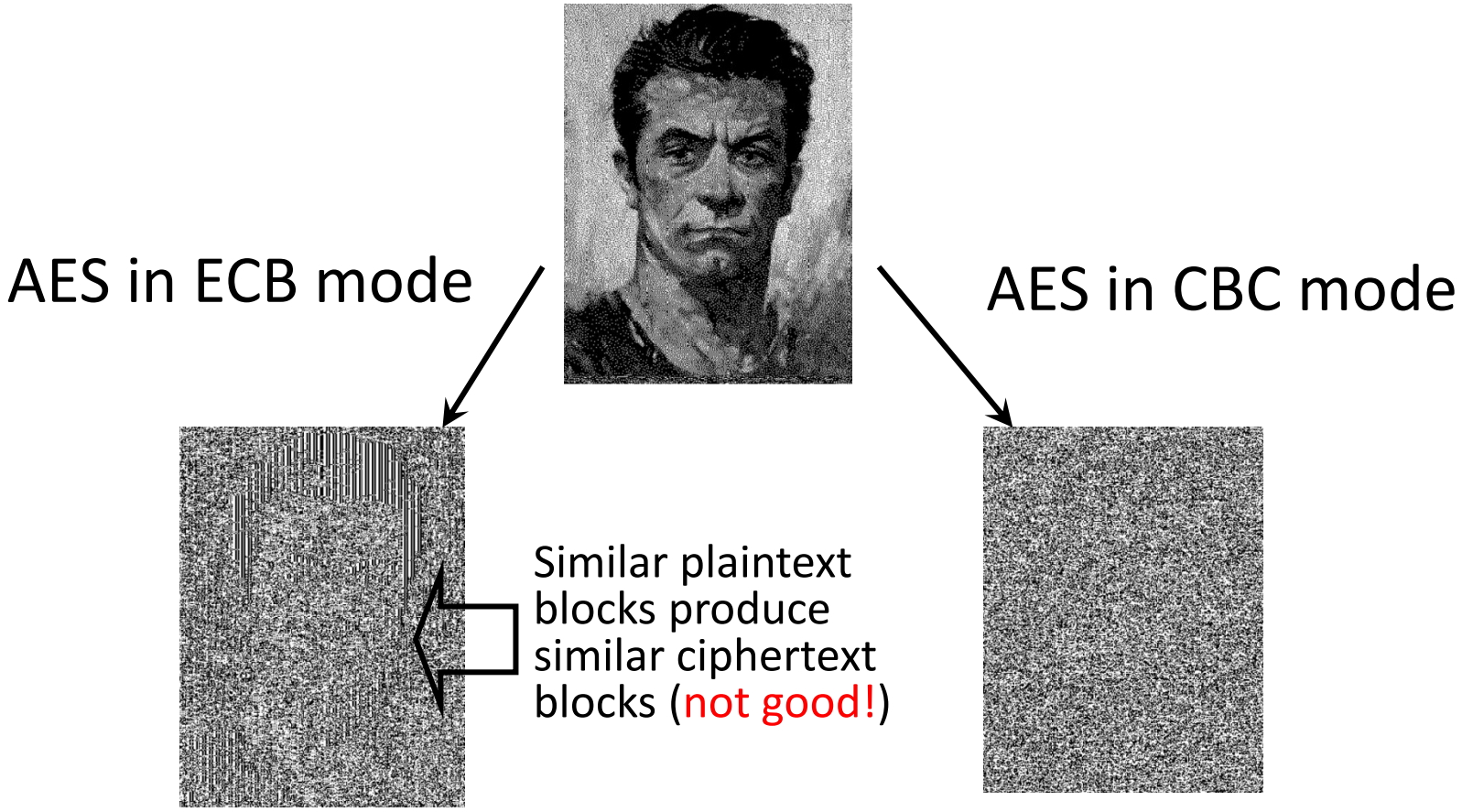


- Identical blocks of plaintext encrypted differently
- Last cipherblock depends on entire plaintext
  - Still does not guarantee integrity

CBC Mode: Decryption

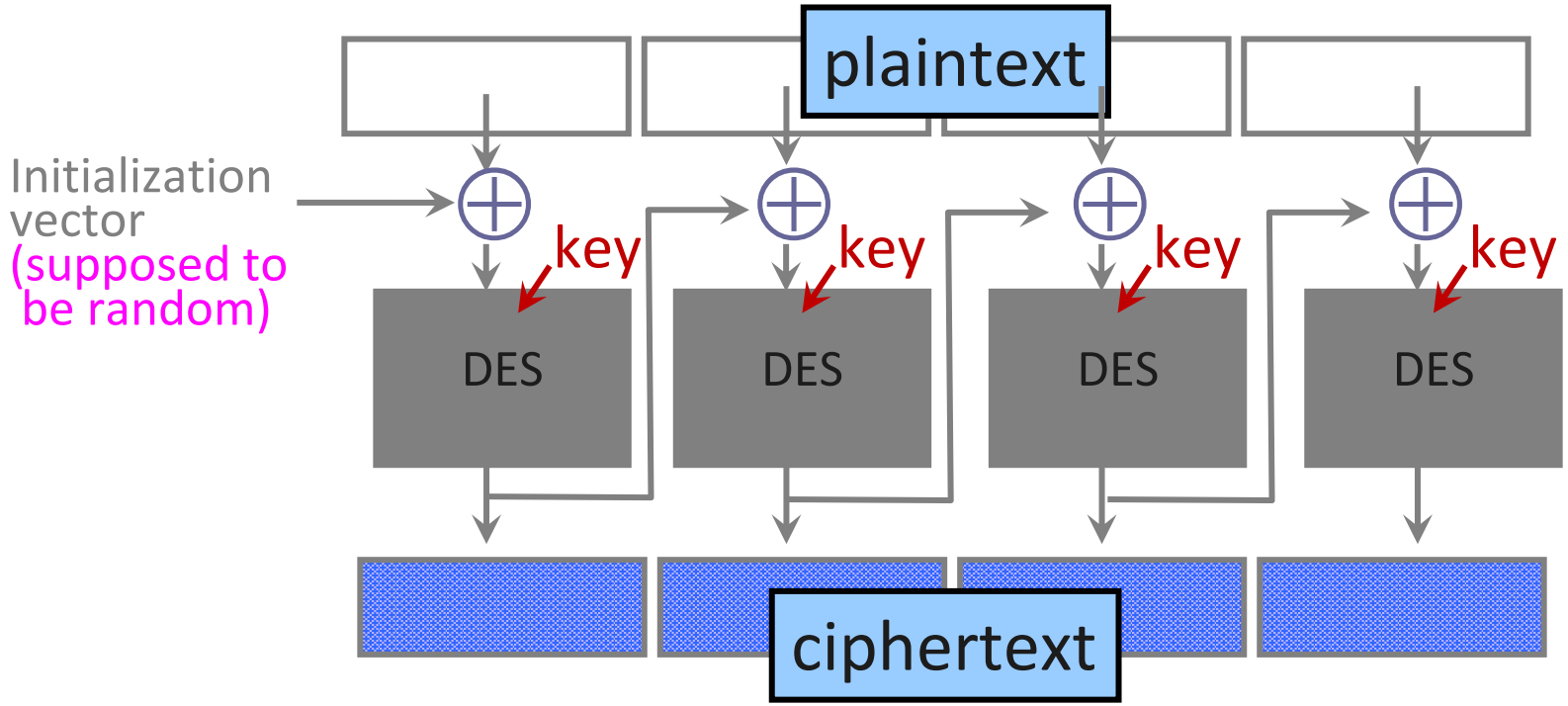


ECB vs. CBC



[Picture due to Bart Preneel]

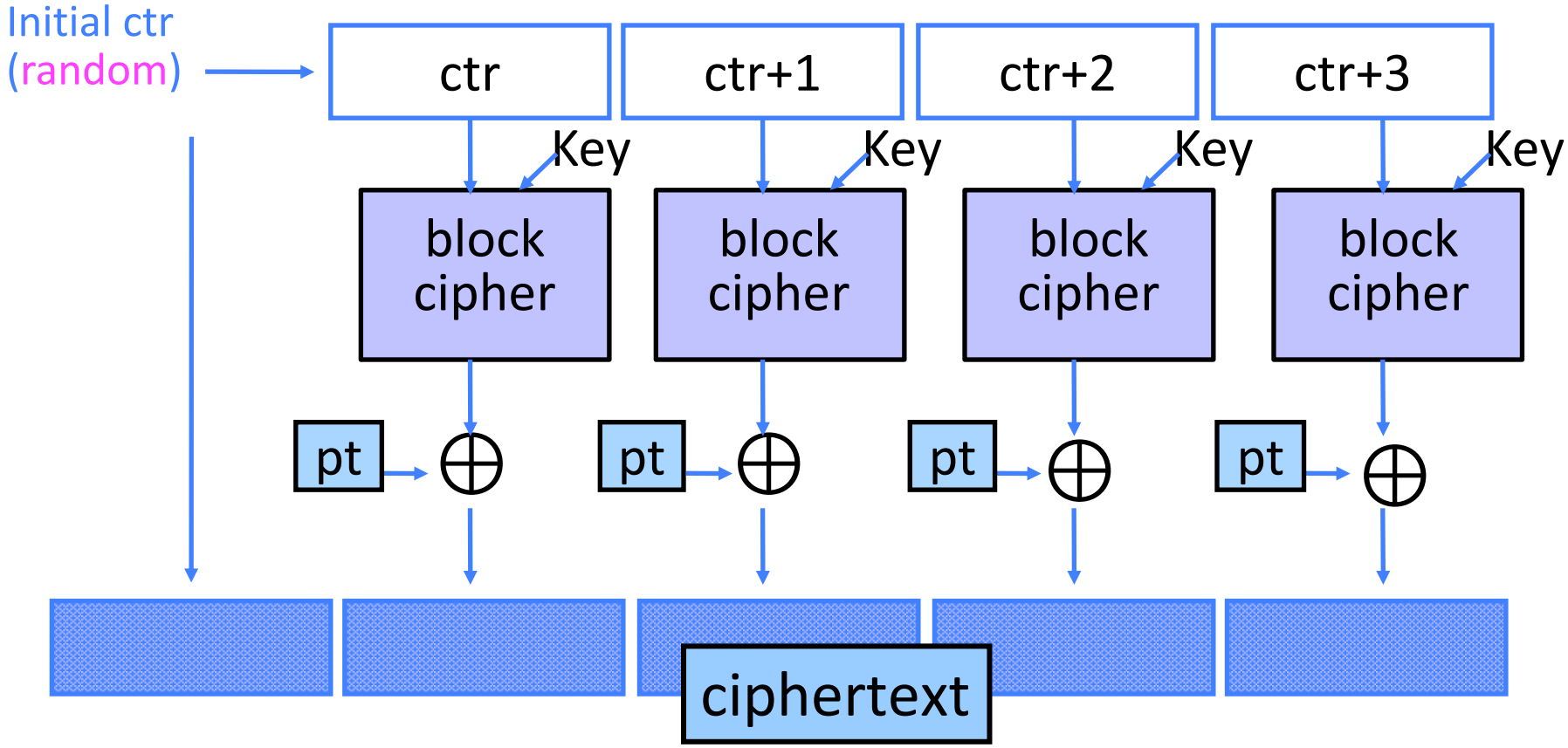
Initialization Vector Dangers



Found in the source code for Diebold voting machines:

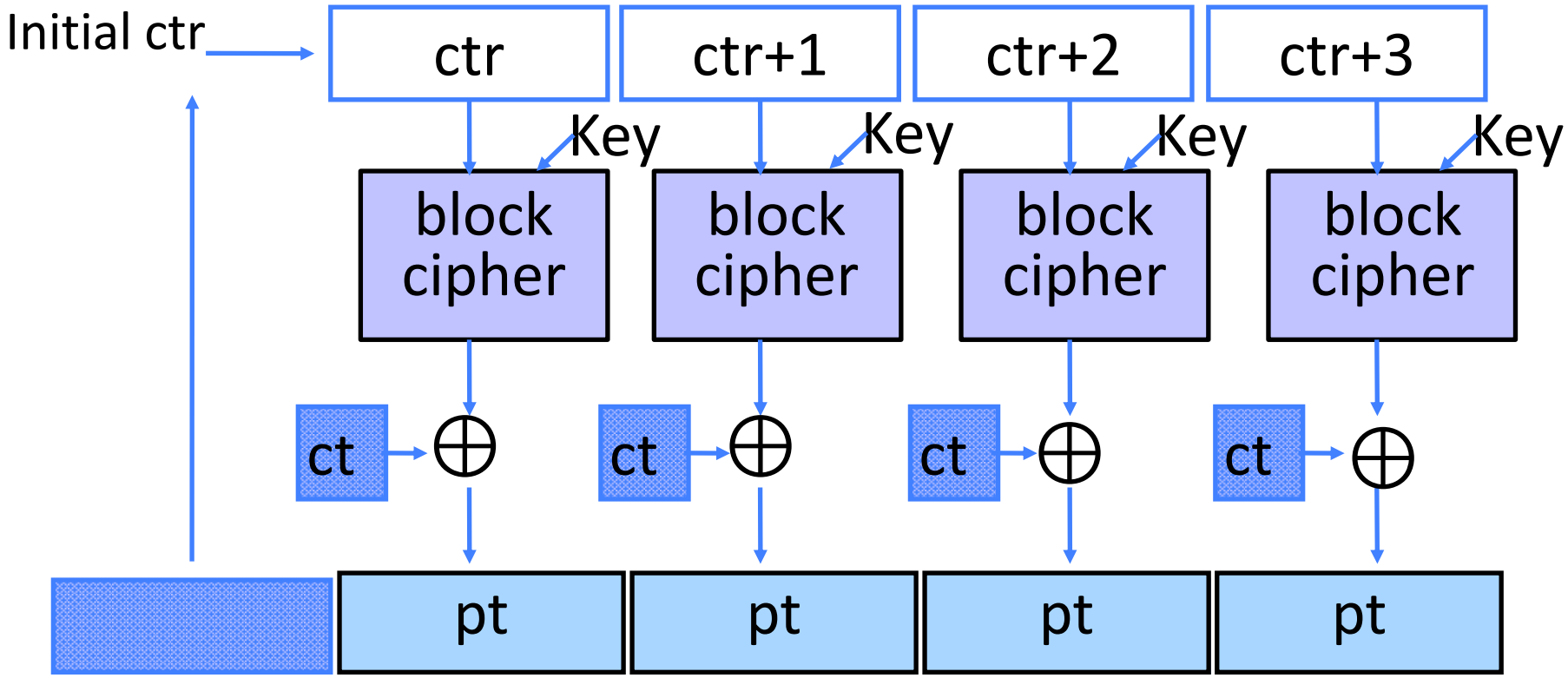
```
DesCBCEncrypt((des_c_block*)tmp, (des_c_block*)record.m_Data,
        totalSize, DESKEY, NULL, DES_ENCRYPT)
```

Counter Mode (CTR): Encryption



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

Counter Mode (CTR): Decryption



Ok, so what mode do I use?

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

- Good modes:
  - GCM - Galois/Counter Mode
  - CTR (sometimes)
  - Even ECB is fine in “the right circumstance” ← so much packed into “the right circumstances” however, so best to avoid

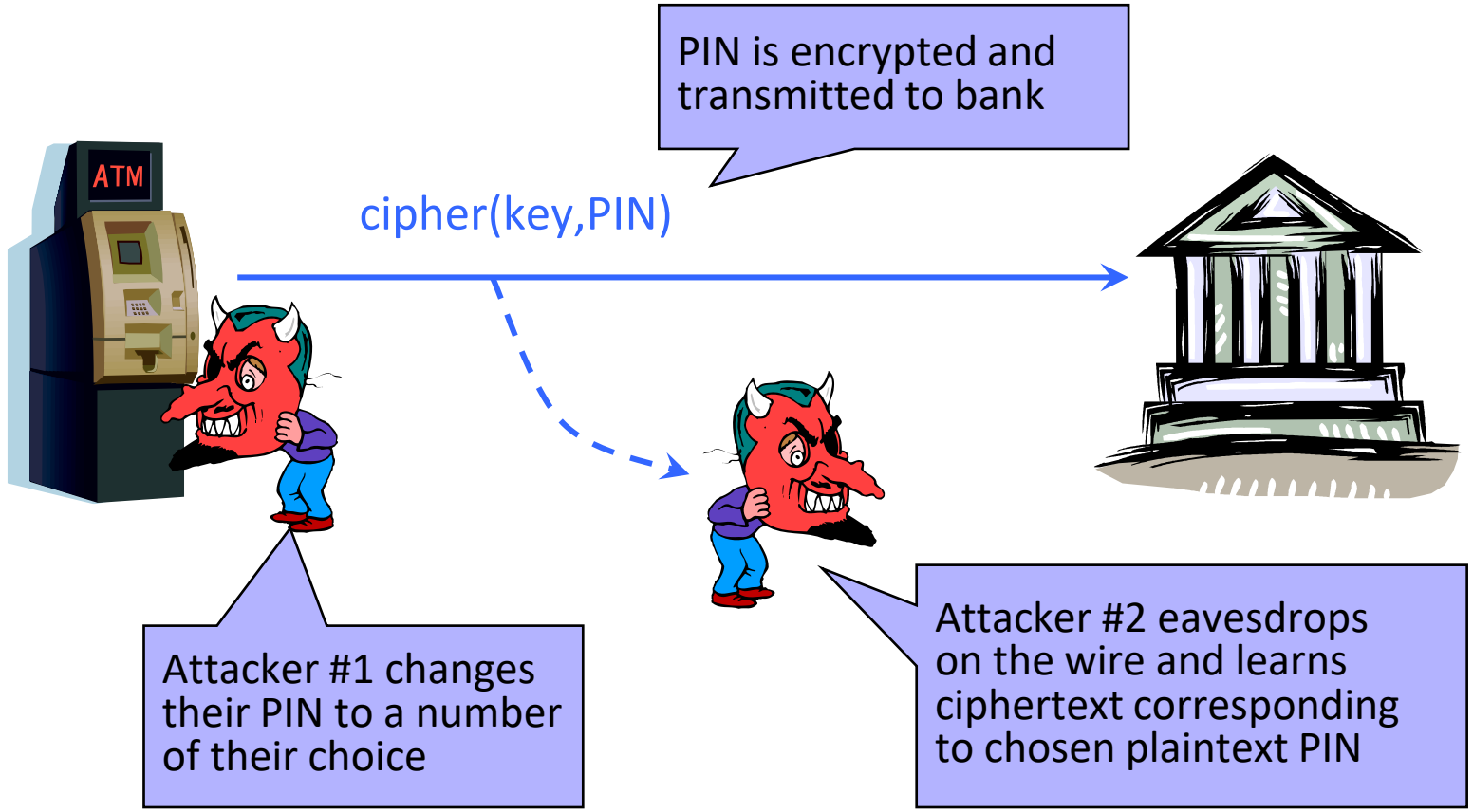
When is an Encryption Scheme “Secure”?

- 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

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, they cannot verify their 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