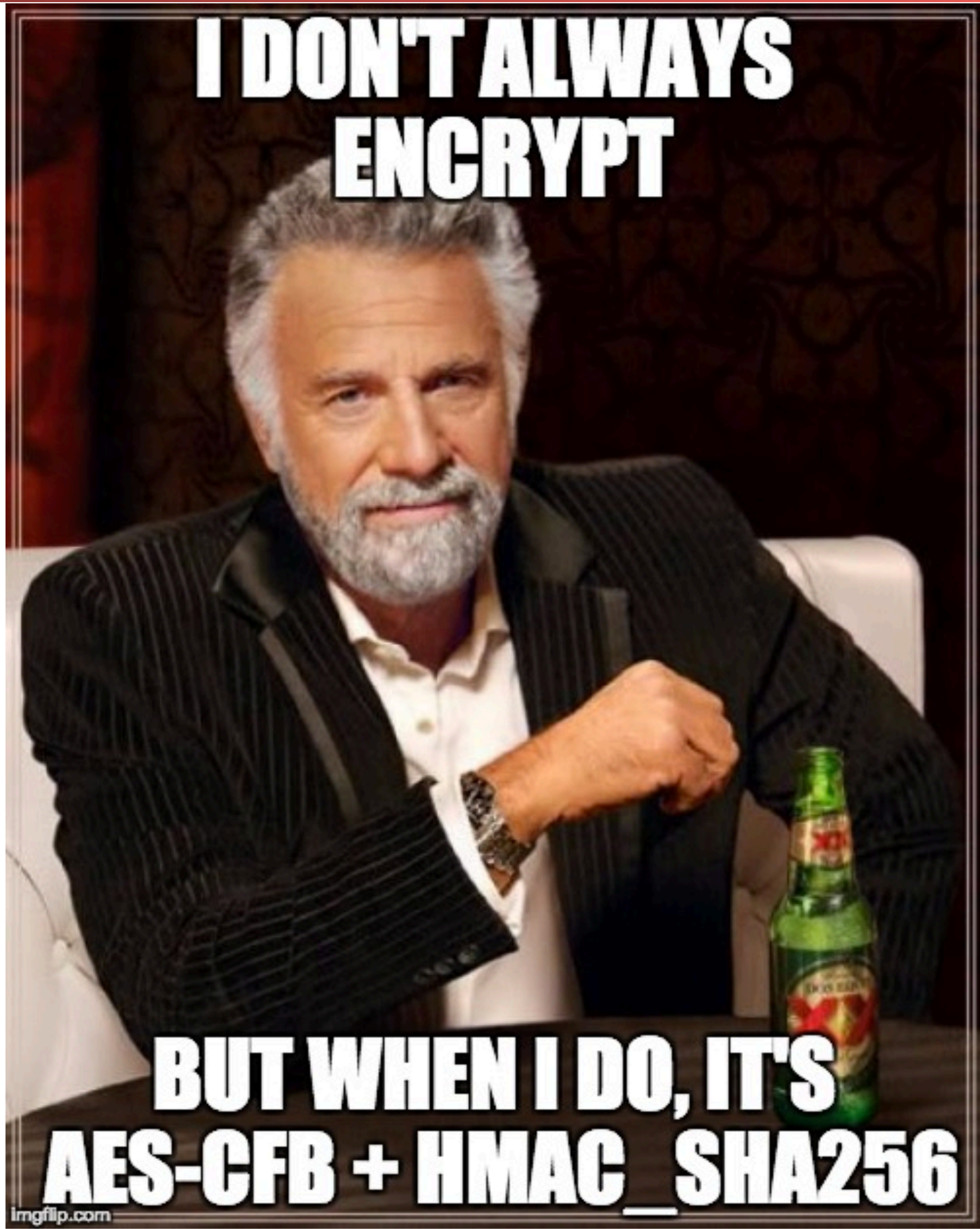
Crypto 2


I DON'T ALWAYS ENCRYPT
BUT WHEN I DO, IT'S AES-CFB + HMAC_SHA256
imgflip.com

Modern Encryption: Block cipher

- A function $\mathbf{E} : \{0, 1\}^b \times \{0, 1\}^k \rightarrow \{0, 1\}^b$. Once we fix the key **K** (of size **k** bits), we get:
- $\mathbf{EK} : \{0,1\}^b \rightarrow \{0,1\}^b$ denoted by $\mathbf{E_K(M) = E(M,K)}$.
  - (and also **D(C,K)**, **E(M,K)**'s inverse)
- Three properties:
  - Correctness:
    - $\mathbf{E_K(M)}$ is a permutation (bijective function) on b-bit strings
      - Bijective ⇒ invertible
  - Efficiency: computable in μsec's
  - Security:
    - For unknown **K**, "behaves" like a random permutation
- Provides a building block for more extensive encryption

DES (Data Encryption Standard)

- Designed in late 1970s
- Block size 64 bits, key size 56 bits
- NSA influenced two facets of its design
  - Altered some subtle internal workings in a mysterious way
  - Reduced key size 64 bits ⇒ 56 bits
    - Made brute-forcing feasible for attacker with massive (for the time) computational resources
- Remains essentially unbroken 40 years later!
  - The NSA's tweaking hardened it against an attack “invented” a decade later
- However, modern computer speeds make it completely unsafe due to small key size

Today's Go-To Block Cipher: AES (Advanced Encryption Standard)

- >20 years old, standardized >15 years ago...
- Block size 128 bits
- Key can be 128, 192, or 256 bits
  - 128 remains quite safe; sometimes termed "AES-128", paranoids use 256b
- As usual, includes encryptor and (closely-related) decryptor
  - How it works is beyond scope of this class…
    But if you are curious: http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html
- Not proven secure
  - But no known flaws
    - The NSA uses it for Top Secret communication with 256b keys:
      stuff they want to be secure ***for 40 years including possibly unknown breakthroughs***!
  - so we assume it is a secure block cipher

AES is also effectively free…

- Computational load is remarkably low
  - Partially why it won the competition:
    There were 3 really good finalists from a performance viewpoint:
    Rijndael (the winner), Twofish, Serpent
    One OK: RC6
    One ugggly: Mars
- On any given computing platform:
  Rinjdael was ***never*** the fastest
- But on every computing platform:
  Rinjdael was ***always*** the second fastest
  - The other two good ones always had a "this is the compute platform they are bad at"
- And now CPUs include dedicated AES support

How Hard Is It To Brute-Force 128-bit Key?

- 2^{128} possibilities – well, how many is that?
- Handy approximation: $2^{10} \approx 10^3$
- $2^{128} = 2^{10*12.8} \approx (10^3)^{12.8} \lesssim (10^3)^{13} \approx 10^{39}$

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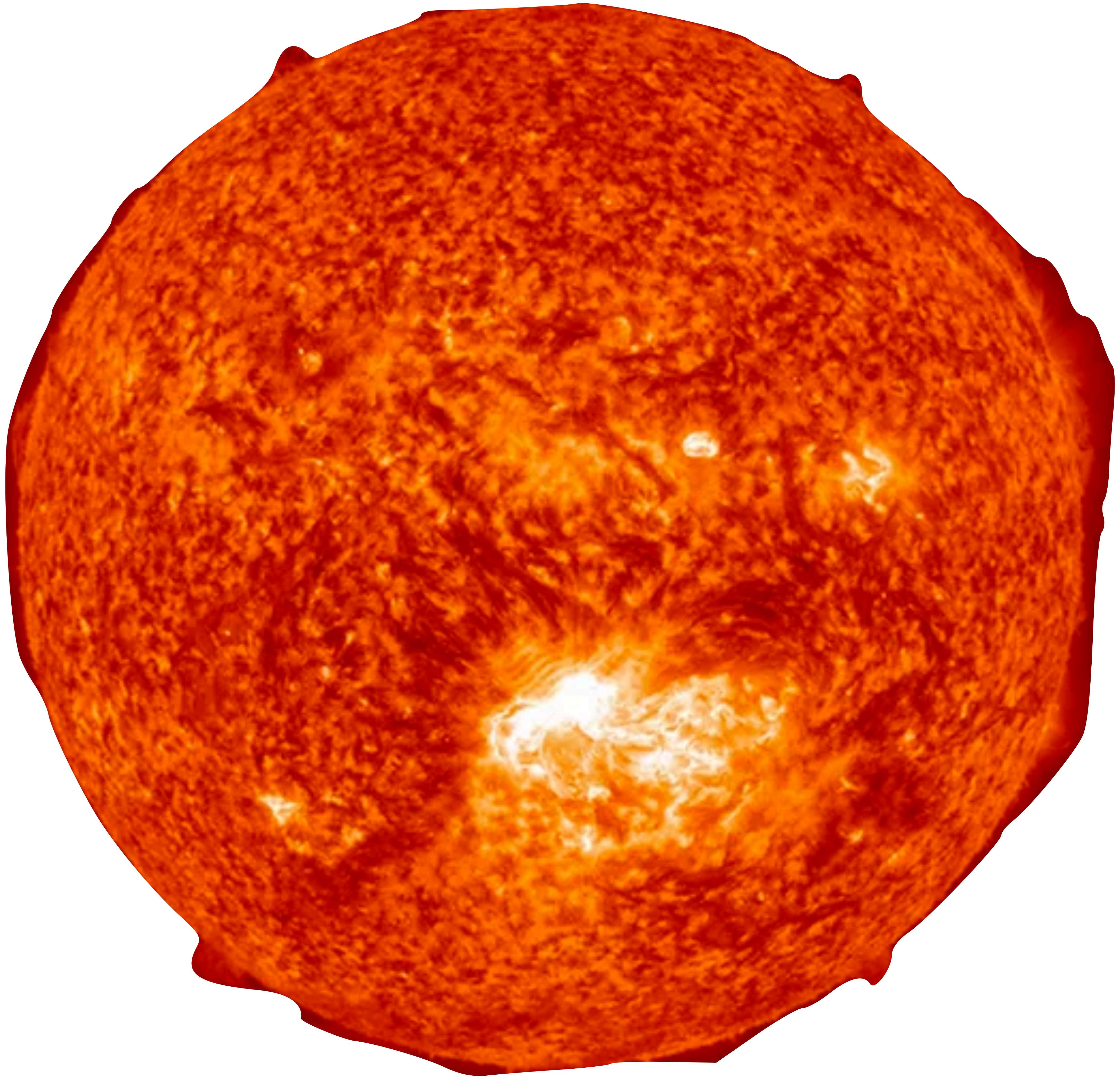
- Say we build massive hardware that can try 10^9 (1 billion) keys in 1 nanosecond (a billionth of a second)
  - So 10^{18} keys/sec
  - Thus, we'll need $\approx 10^{21}$ sec
- How long is that?
  - One year $\approx 3 \times 10^7$ sec
  - So need $\approx 3 \times 10^{13}$ years $\approx$ 30 trillion years

What about a 256b key in a year?

- Time to start thinking in ***astronomical*** numbers:
  - If each brute force device is $1mm^3$...
  - We will need 10^{52} of these things...
- 10^{43} cubic meters...
- Or the volume of ***7x10^{15} suns***!
  - Yes, 7 ***petasuns*** worth of sci-fi nanotech!
- Brute force is ***not a factor*** against modern block ciphers...
  IF the key is actually random!



Issues When Using the Building Block

- Block ciphers can only encrypt messages of a certain size
  - If **M** is smaller, easy, just pad it (more later)
  - If **M** is larger, can repeatedly apply block cipher
    - Particular method = a “block cipher mode”
    - Tricky to get this right!
- If same data is encrypted twice, attacker knows it is the same
  - Solution: incorporate a varying, known quantity (IV = “initialization vector”)

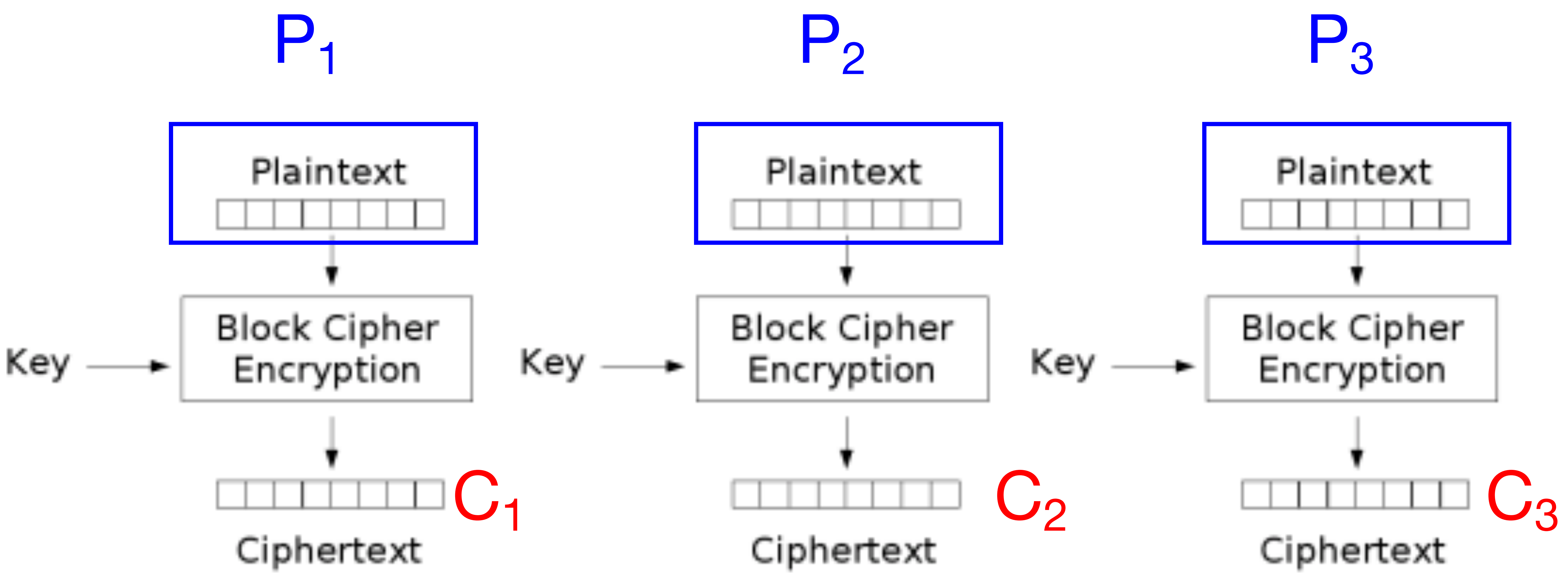
So enter "Modes of operation"

- We don't just run the block cipher on its own...
- But instead as part of a larger "Mode of Operation":
  - Combining the block cypher as the core of a larger function

Electronic Code Book (ECB) mode

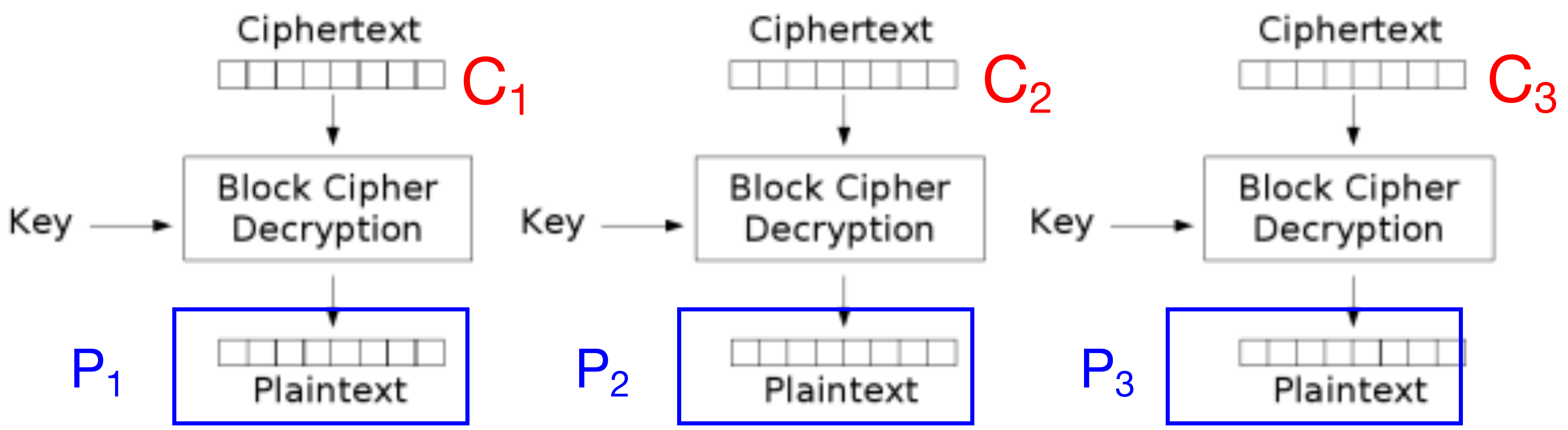
- Simplest block cipher mode
- Split message into b-bit blocks $\mathbf{P_1}$, $\mathbf{P_2}$, …
- Each block is enciphered independently, separate from the other blocks
  $\mathbf{C_i = E(P_i, K)}$
- Since key **K** is fixed, each block is subject to the same permutation
  - (As though we had a "code book" to map each possible input value to its designated output)

ECB Encryption



Electronic Codebook (ECB) mode encryption

ECB Decryption



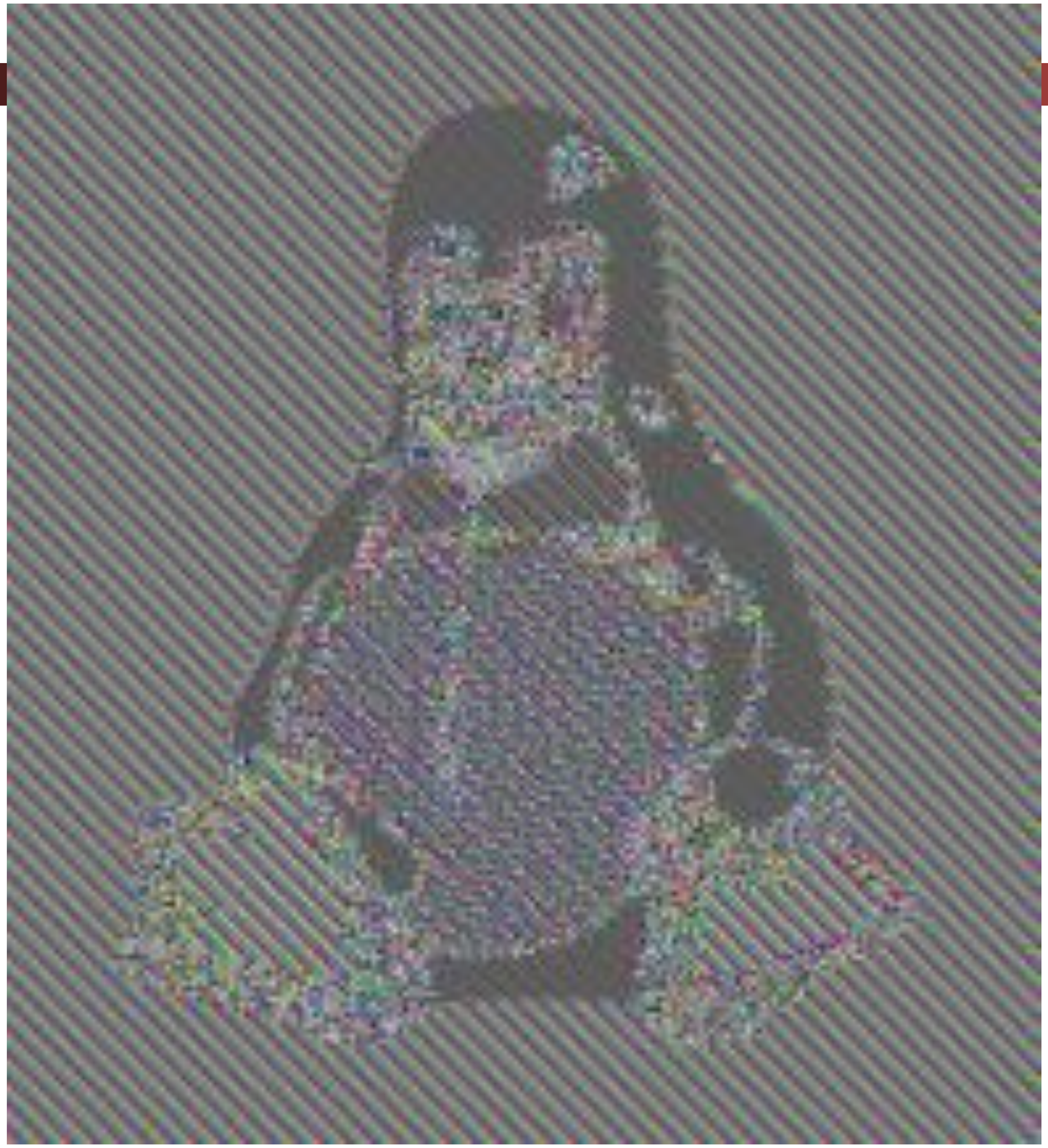
Electronic Codebook (ECB) mode decryption

Problem: Relationships between P_i's reflected in C_i's

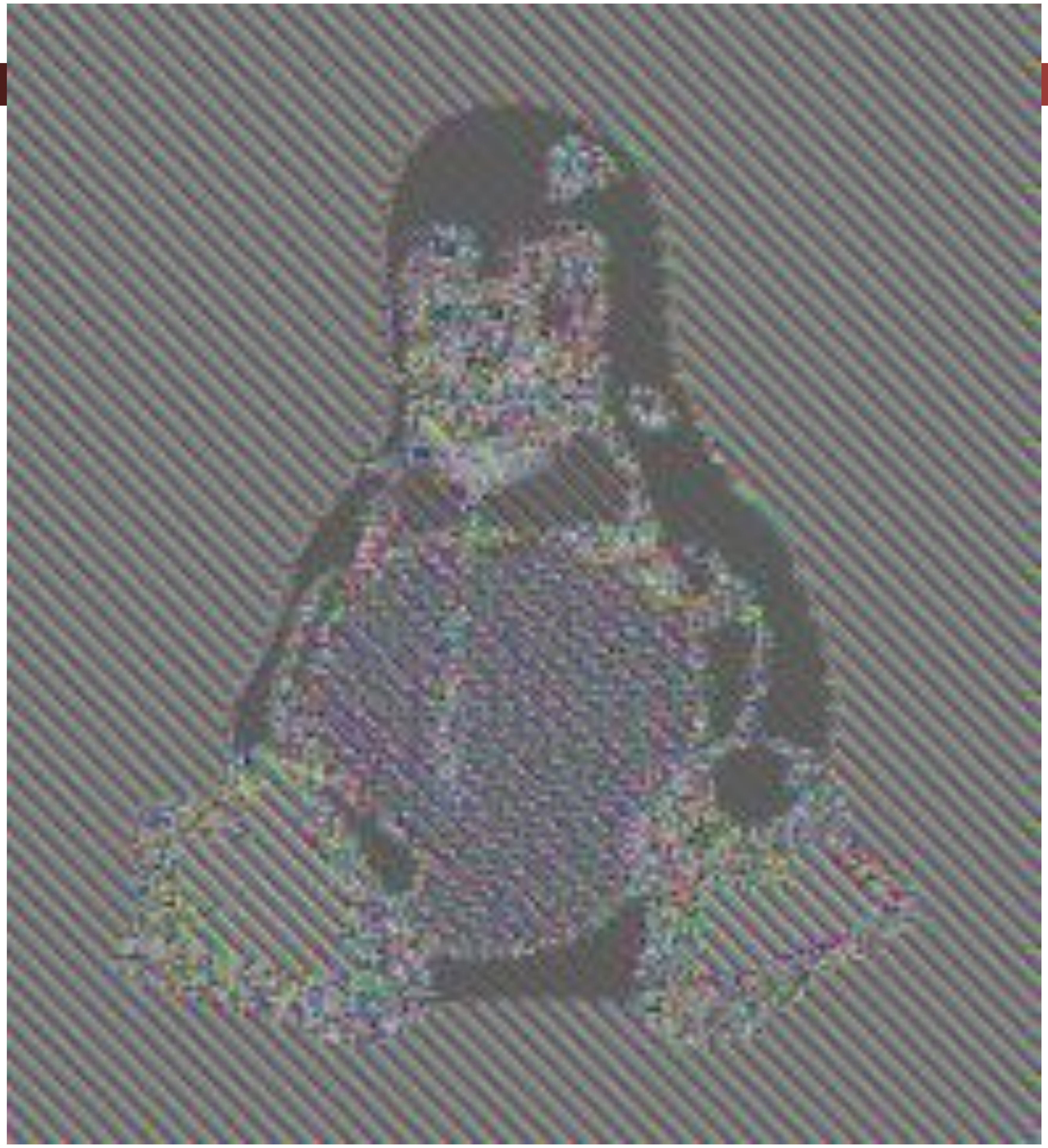
IND-CPA and ECB?

- Of course not!
- **M,M'** is 2x the block length...
  - **M** = all 0s
  - **M'** = 0s for 1 block, 1s for the 2nd block
- This has catastrophic implications in the real world...

Original image, RGB values split into a bunch of b-bit blocks



Encrypted with ECB and interpreting ciphertext directly as RGB



Later (identical) message again encrypted with ECB

Building a Better Cipher Block Mode

- Ensure blocks incorporate more than just the plaintext to mask relationships between blocks. Done carefully, either of these works:
  - Idea #1: include elements of prior computation
  - Idea #2: include positional information
- Plus: need some initial randomness
  - Prevent encryption scheme from determinism revealing relationships between messages
  - Introduce initialization vector (IV):
    - IV is a public ***nonce***, a use-once unique value: Easiest way to get one is generate it randomly

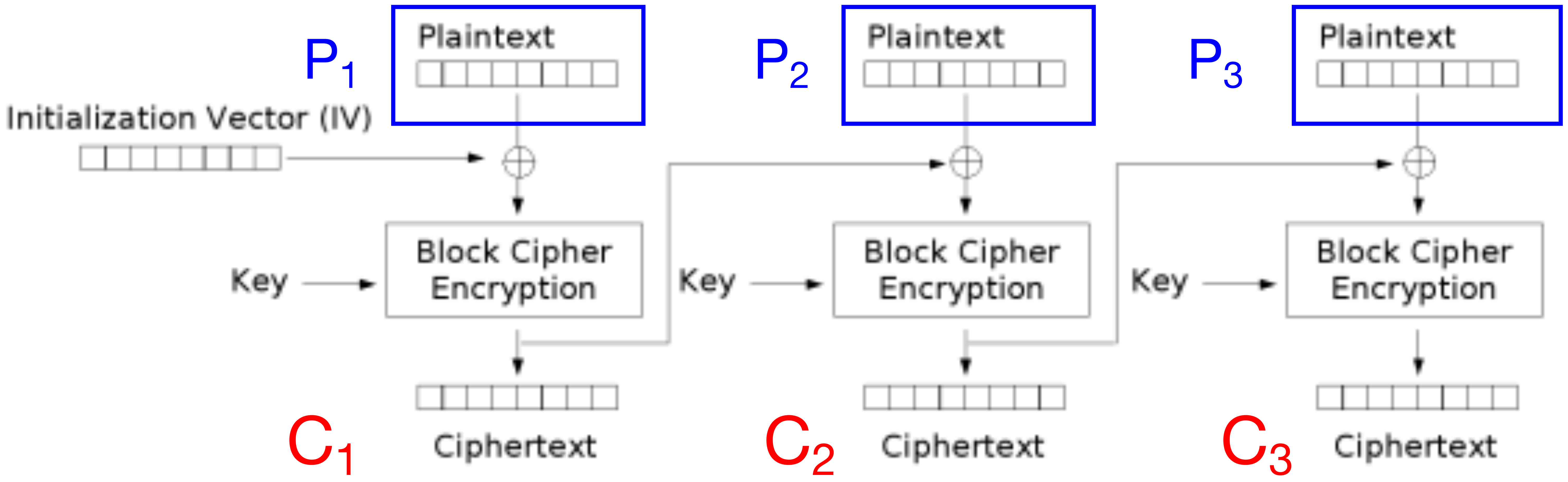
Nonces

- A ***nonce*** is a public use-once value
  - EG, as the initialization vector
- It is critical to ***never ever ever ever*** reuse a nonce
  - But if the nonce is 128b or greater, generate it randomly and you are good
- Depending on the algorithm, it can be mildly bad
  - Eh, you leak a little information...
- To catastrophic,
  CATASTROPHIC FAILURE!

CBC Encryption

E(Plaintext, K):

- If b is the block size of the block cipher, split the plaintext in blocks of size b: P_1, P_2, P_3,..
- Choose a random IV (do not reuse for other ***messages***)
- Now compute:



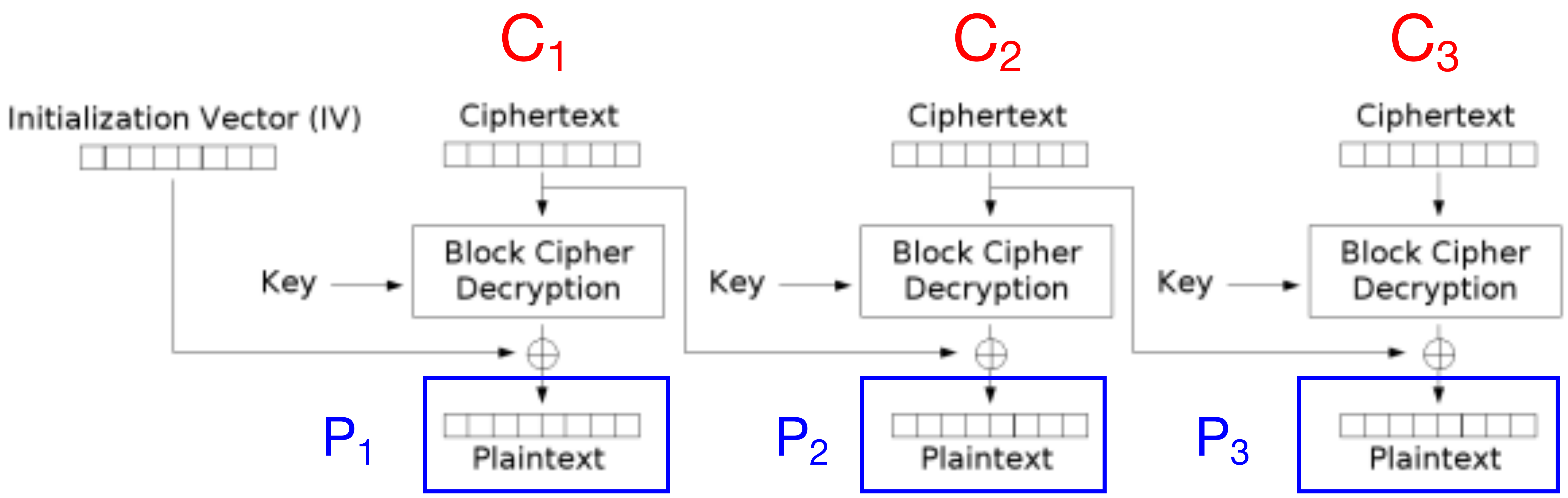
Cipher Block Chaining (CBC) mode encryption

- Final ciphertext is (IV, C_1, C_2, C_3). This is what Eve sees.

CBC Decryption

D(Ciphertext, K):

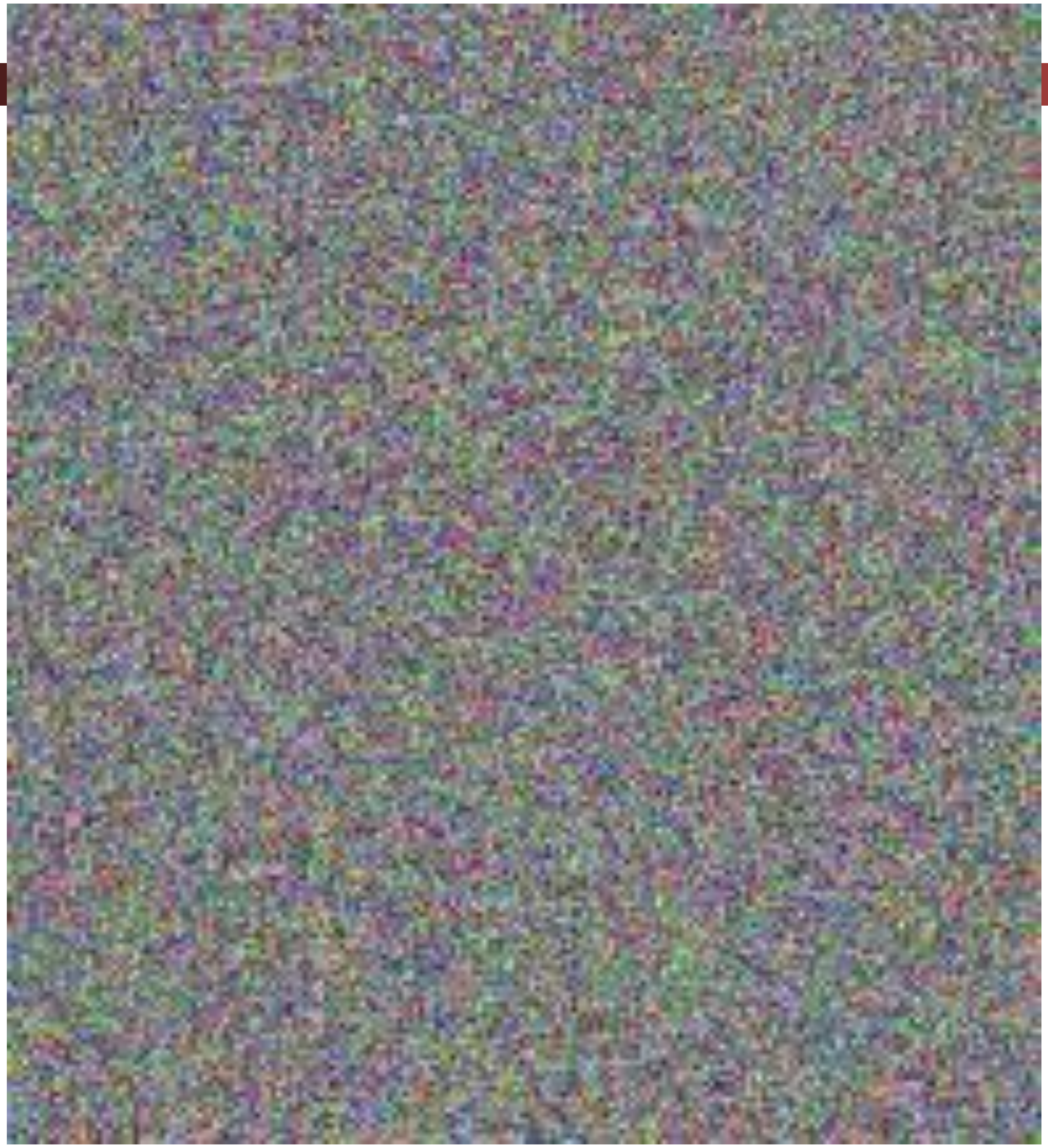
- Take IV out of the ciphertext
- If b is the block size of the block cipher, split the ciphertext in blocks of size b: C_1, C_2, C_3, …
- Now compute this:



Cipher Block Chaining (CBC) mode decryption

- Output the plaintext as the concatenation of P_1, P_2, P_3, ...

Original image, RGB values split into a bunch of b-bit blocks



Encrypted with CBC: Should be indistinguishable from random noise

CBC Mode...

- Widely used
- Issue: sequential encryption, can't parallelize encryption
  - ***Must*** finish encrypting block b before starting b+1
  - But you can parallelize decryption
- Parallelizable alternative: CTR (Counter) mode
- Security: If no reuse of nonce, both are provably secure (IND-CPA) assuming the underlying block cipher is secure

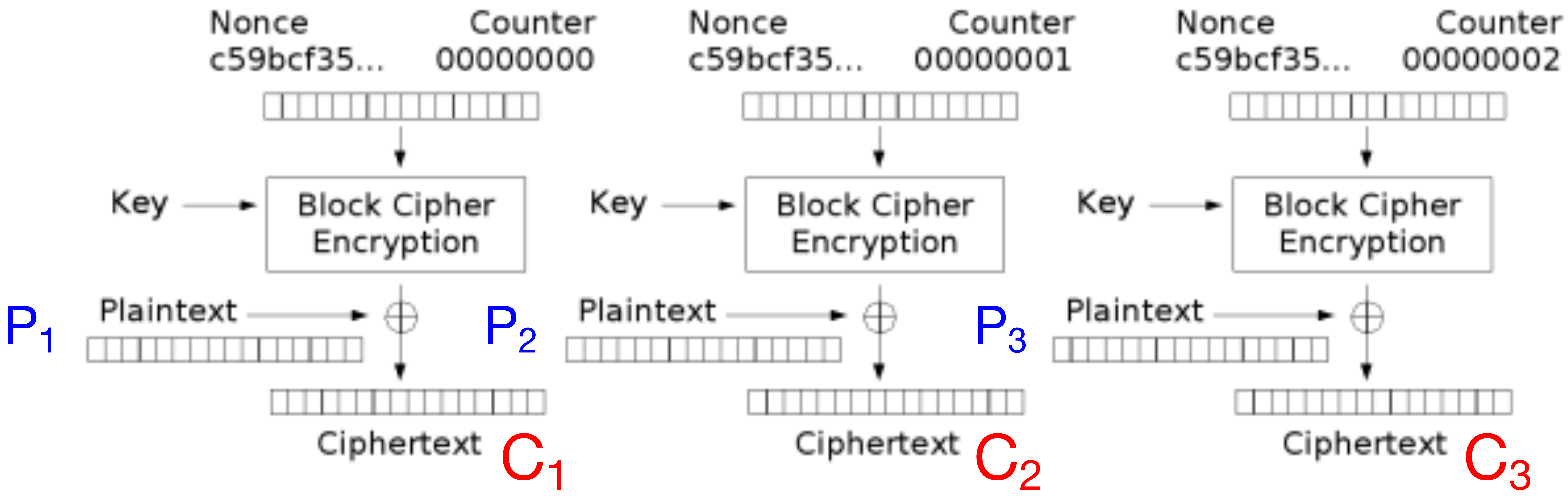
And padding…

- What happens if length(**M**) % BlockSize != 0?
  - Need to "Pad" to add bits
- Two main options:
  - Send the length at the start of the message…
    - And then who cares what you add on at the end
  - Use a padding scheme that you can add on to the end…
- EG, PKCS#7:
  - If M % BlockSize == Blocksize - 1: Pad with 0x01
  - If M % BlockSize == Blocksize - 2: Pad with 0x02 0x02

  ….
  - If M % BlockSize == 0: Pad a ***full block*** with the block size (so for AES 0x20 0x20…)

CTR Mode Encryption

(Nonce = Same as IV)

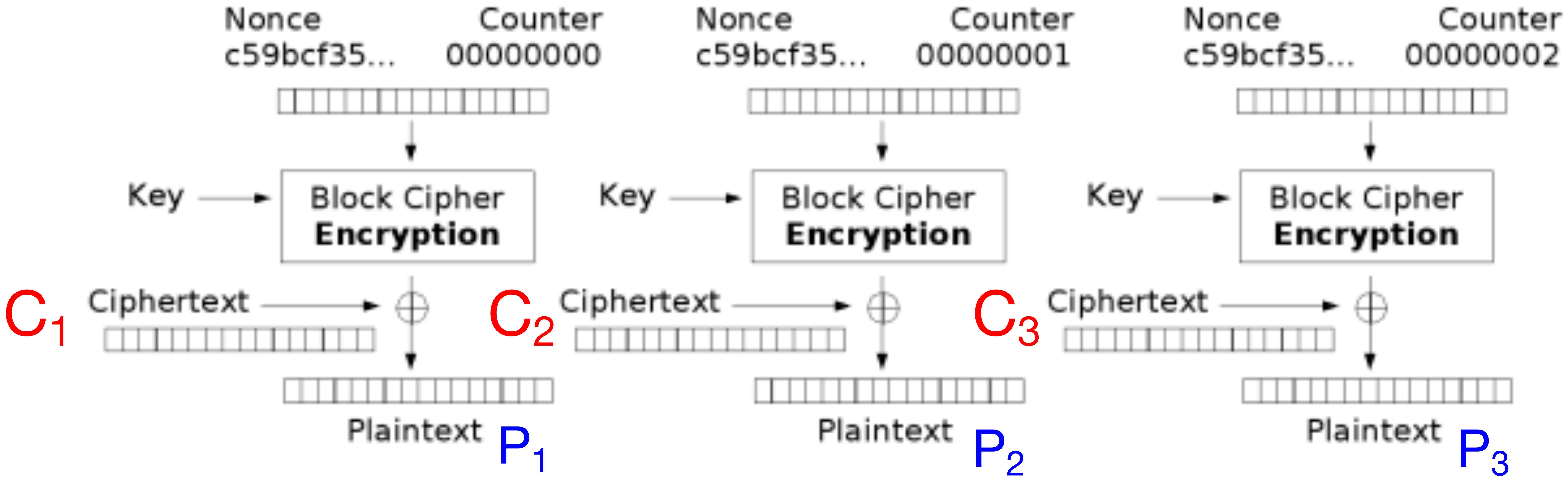


Counter (CTR) mode encryption

Important that nonce/IV does not repeat across different encryptions.

Choose at random!

Counter Mode Decryption



Counter (CTR) mode decryption

Note, CTR decryption uses block cipher's ***encryption***, **not** decryption

Thoughts on CTR mode...

- CTR mode is actually a stream cipher (more on those later):
  - You no longer need to worry about padding which is nice
- CTR mode is fully parallelizeable for encryption as well as decryption
  - In high performance applications you can always just throw more compute and encrypt faster

NEVER EVER EVER use CTR Mode! (Well, if you are paranoid…)

- What happens if you reuse the IV in CBC...
  - Its bad but not catastrophic:
    you fail IND-CPA but the damage may be tolerable:
    - **M = {A,A,B}**
      M' = {A,B,B}
      Adversary can see that the first part of M and M' are the same, but not the later part
- What happens if you reuse the IV in CTR mode?
  - It is ***exactly*** like reusing a one-time pad!
- An example of a system which fails badly...
  - CTR mode is ***theoretically*** as secure as CBC when used properly...
  - But when it is misused it fails catastrophically:
    Personal bias: I believe we need systems that are still robust ***when implemented incorrectly***

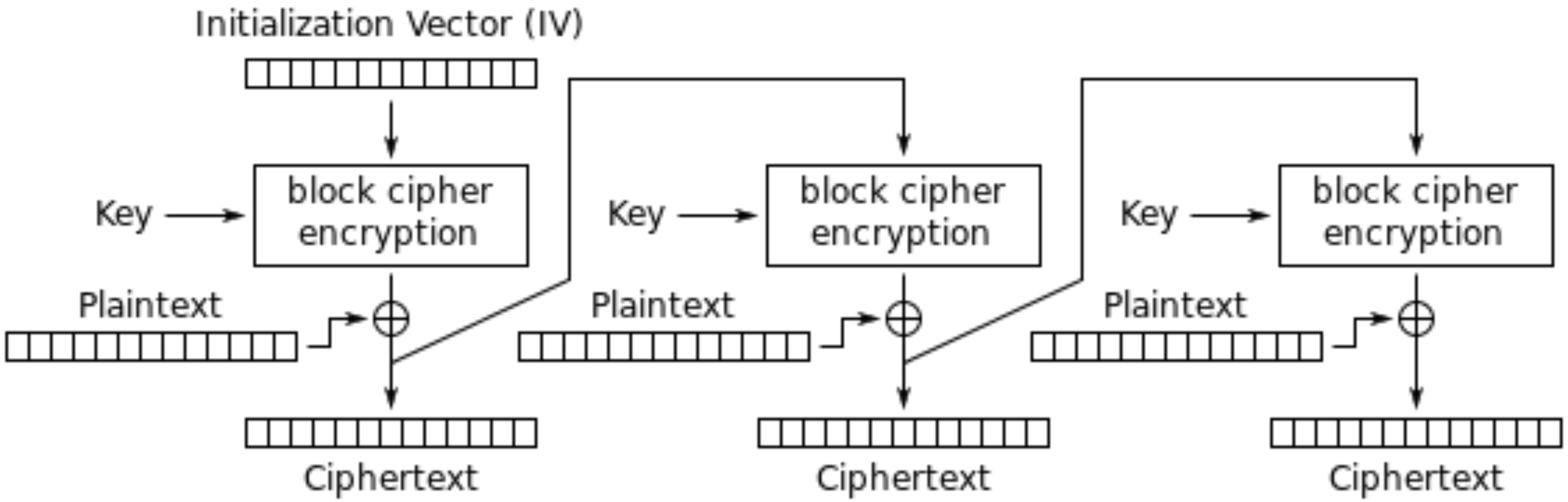
This was the summer 61A exam mistake!

- They used a python AES library
  - A bad library for a whole host of reasons but...
- When they invoked CTR mode encryption...
  - They never specified an IV...
    Just assuming the library would use a RANDOM IV
  - Nope, library defaults to a 0 IV
- And since multiple different versions of the exam are all encrypted with the same key...
- ***ALL SECURITY WAS LOST!***

What To Use Then?

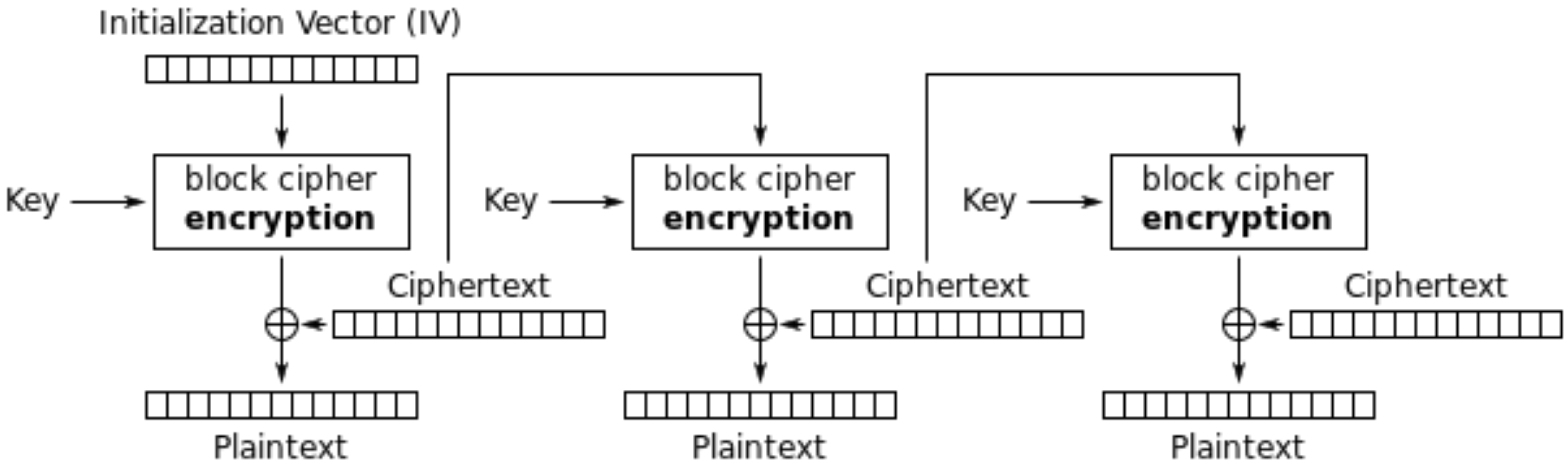
- What if you want a cipher mode where you don't need to pad (like CTR mode)?
  - But you want the robust to screwup properties of CBC mode?
- Idea: lets do it CTR-like (xor plaintext with block cipher output), but...
- Instead of the next block input being an incremented counter...
  have the next block be the previous ciphertext
- Still lacks integrity however, we'll fix that next time...

CFB Encryption



Cipher Feedback (CFB) mode encryption

CFB Decryption



Cipher Feedback (CFB) mode decryption

CFB doesn't need to pad...

- Since the encryption is XORed with the plaintext...
  - You can end on a "short" block without a problem
  - So more convenient than CBC mode
- But similar security properties as CBC mode
  - Sequential encryption, parallel decryption
  - Same error propagation effects
  - Effectively the same for IND-CPA
- But a bit worse if you reuse the IV

Mallory the Manipulator

- Mallory is an active attacker
  - Can introduce new messages (ciphertext)
  - Can “replay” previous ciphertexts
  - Can cause messages to be reordered or discarded
- A “Man in the Middle” (MITM) attacker
  - Can be much more powerful than just eavesdropping

Encryption Does Not Provide Integrity

- Simple example: Consider a block cipher in CTR mode...
- Suppose Mallory knows that Alice sends to Bob "Pay Mal $0100". Mallory intercepts corresponding C
  - M = "Pay Mal $0100". C = "r4ZC#jj8qThMK"
  - $M_{10..13}$ = "0100". $C_{10..13}$ = "ThMK"
- Mallory wants to replace some bits of C...

Encryption Does Not Provide Integrity

- Mallory computes
  - “0100” $\oplus$ $C_{10..13}$
    - Tells Mallory that section of the counter XOR:
      Remember that CTR mode computes $E_k(IV||CTR)$ and XORs it with the corresponding part of the message
  - $C'_{10..13}$ = "9999" $\oplus$ “0100” $\oplus$ $C_{10..13}$
- Mallory now forwards to Bob a full $C' = C_{0..9}||C'_{10..13}||C_{14...}$
- Bob will decrypt the message as "Pay Mal $9999"...
  - For a CTR mode cipher, Mallory can in general replace any ***known*** message M with a message M' of equal length!

Integrity and Authentication

- Integrity: Bob can confirm that what he's received is exactly the message M that was originally sent
- Authentication: Bob can confirm that what he's received was indeed generated by Alice
- Reminder: for either, confidentiality may-or-may-not matter
  - E.g. conf. not needed when Mozilla distributes a new Firefox binary
- Approach using symmetric-key cryptography:
  - Integrity via MACs (which use a shared secret key **K**)
  - Authentication arises due to confidence that only Alice & Bob have **K**
- Approach using public-key cryptography (later on):
  - "Digital signatures" provide both integrity & authentication together
- Key building block: cryptographically strong hash functions

Hash Functions

- Properties
  - Variable input size
  - Fixed output size (e.g., 256 bits)
  - Efficient to compute
  - Pseudo-random (mixes up input extremely well):
    A single bit changes on the input and ~1/2 the bits should change on the output
- Provides a "fingerprint" of a document
  - E.g. "**`shasum -a 256 <exams/mt1-solutions.pdf`**" prints
    `0843b3802601c848f73ccb5013afa2d5c4d424a6ef477890ebf8db9bc4f7d13d`

Cryptographically Strong Hash Functions

- A collision occurs if **x≠y** but **Hash(x) = Hash(y)**
  - Since input size > output size, collisions do happen
- A cryptographically strong **Hash(x)** provides three properties:
  - One-way: **h = Hash(x)** easy to compute, but not to invert.
    - Intractable to find ***any*** **x'** s.t. **Hash(x') = h**, for a given **h**
    - Also termed “preimage resistant”

H(🐮) =

Cryptographically Strong Hash Functions

- The other two properties of a cryptographically strong **Hash(x)**:
  - Second preimage resistant: given **x**, intractable to find **x'** s.t. **Hash(x) = Hash(x')**
  - Collision resistant: intractable to find any **x**, **y** s.t. **Hash(x)** = **Hash(y)**
- Collision resistant $\Longrightarrow$ Second preimage resistant
  - We consider them separately because given Hash might differ in how well it resists each
  - Also, the Birthday Paradox means that for n-bit Hash, finding **x-y** pair takes only ≈ $2^{n/2}$ hashes
    - Vs. potentially 2^n tries for **x'**: **Hash(x) = Hash(x')** for given **x**
- Plus a hash function should look "random"
  - A "PRF" or Pseudo-Random Function

Cryptographically Strong Hash Functions, con’t

- Some contemporary hash functions
  - MD5: 128 bits
    - broken – lack of collision resistance
    - Collisions for the heck of it: https://shells.aachen.ccc.de/~spq/md5.gif
      An MD5 "hash quine": an animated GIF that shows its own hash
  - SHA-1: 160 bits broken spring 2017, but was known to be weak yet still used...
  - SHA-256/SHA-384/SHA-512: 256, 384, 512 bits in the SHA-2 family, at least not currently broken
  - SHA-3: New standard! Yayyy!!!! (Based on Keccak, again 256b, 384b, and 512b options)
- Provide a handy way to unambiguously refer to large documents
  - If hash can be securely communicated, provides integrity
    - E.g. Mozilla securely publishes SHA-256(new FF binary)
    - Anyone who fetches binary can use “`cat binary | shasum -a 256`” to confirm it’s the right one, untampered
- Not enough by themselves for integrity, since functions are completely known – Mallory can just compute revised hash value to go with altered message

SHA-256...

- SHA-256/SHA-384 are two parameters for the SHA-2 hash algorithm, returning 256b or 384b hashes
  - Works on blocks with a truncation routine to make it act on sequences of arbitrary length
- Is vulnerable to a ***length-extension attack***: **s** is secret
  - Mallory knows **len(s)**, **H(s)**
  - Mallory can use this to calculate **H(s||M)** for an **M** of Mallory's construction
    - Works because ***all the internal state*** at the point of calculating **H(s||...)** is derivable from **H(s)** and **len(s)**
- New SHA-3 standard (Keccak) does not have this property

Stupid Hash Tricks: Sample A File...

- BlackHat Dude claims to have 150M records stolen from Equifax...
  - How can I as a reporter verify this?
- Idea: If I can have the hacker select 10 ***random*** lines...
  - And in selecting them also say something about the size of the file...
  - Voila! Verify those lines and I now know he's not full of BS
- Can I use hashing to write a small script which the BlackHat Dude can run?
  - Where I can easily verify that the 10 lines were sampled at random, and can't be faked?

Sample a File


```
#!/usr/bin/env python
import hashlib, sys
hashes = {}

for line in sys.stdin:
    line = line.strip()
    for x in range(10):
        tmp = "%s-%i-nickrocks" % (line, x)
        hashval = hashlib.sha256(tmp)
        h = hashval.digest()
        if x not in hashes or hashes[x][0] > h:
            hashes[x] = (h, hashval, tmp)

for x in range(10):
    h, hashval, val = hashes[x]
    print "%s=\"%s\"" % (hashval.hexdigest(), val)
```

Why does this work?

- For each x in range 0-9...
  - Calculates **H(line||x)**
  - Stores the lowest hash matching so far
- Since the hash appears random...
  - Each iteration is an ***independent*** sample from the file
  - The expected value of H(line||x) is a function of the size of the file: More lines, and the value is smaller
- To fake it...
  - Would need to generate fake lines, ***and see if the hash is suitably low***
  - Yet would need to make sure these fake lines semantically match!
    - Thus you can't just go "John Q Fake", "John Q Fakke", "Fake, John Q", etc...

Message Authentication Codes (MACs)

- Symmetric-key approach for integrity
  - Uses a shared (secret) key **K**
- Goal: when Bob receives a message, can confidently determine it hasn't been altered
  - In addition, whomever sent it must have possessed **K**
    (⇒ message authentication, sorta...)
- Conceptual approach:
  - Alice sends **{M, T}** to Bob, with tag **T = MAC(K, M)**
    - Note, **M** could instead be **C =** $\mathbf{E_K}$**'(M)**, but not required
  - When Bob receives **{M', T'}**, Bob checks whether **T' = MAC(K, M')**
    - If so, Bob concludes message untampered, came from Alice
    - If not, Bob discards message as tampered/corrupted

Requirements for Secure MAC Functions

- Suppose MITM attacker Mallory intercepts Alice's **{M, T}** transmission …
  - … and wants to replace **M** with altered **M***
  - … but doesn't know shared secret key **K**
- We have secure integrity if MAC function
  T = MAC(M, K) has two properties:
  - Mallory can't compute **T* = MAC(M*, K)**
    - Otherwise, could send Bob **{M*, T*}** and fool him
  - Mallory can't find **M**** such that **MAC(M**, K) = T**
    - Otherwise, could send Bob **{M**, T}** and fool him
- These need to hold even if Mallory can observe many **{M_i, T_i}** pairs, including for **M_i**'s she chose

MAC then Encrypt or Encrypt then MAC

- You should ***never*** use the same key for the MAC and the Encryption
  - Some MACs will break completely if you reuse the key
  - Even if it is ***probably*** safe (eg, AES for encryption, HMAC for MAC) its still a bad idea
- MAC then Encrypt:
  - Compute $\mathbf{T = MAC(M,K_{mac})}$, send $\mathbf{C = E(M||T,K_{encrypt})}$
- Encrypt then MAC:
  - Compute $\mathbf{C = E(M,K_{encrypt})}$, $\mathbf{T = MAC(C,K_{mac})}$, send $\mathbf{C||T}$
- Theoretically they are the same, but...
  - Once again, its time for ...

HTTPS Authentication in Practice

- When you log into a web site, it sets a "cookie" in your browser
  - All subsequent requests include this cookie so the web server knows who you are
- If an attacker can get your cookie...
  - They can impersonate you on the "Secure" site
- And the attacker can create multiple tries
  - On a WiFi network, inject a bit of JavaScript that repeatedly connects to the site
  - While as a man-in-the-middle to manipulate connections

The TLS 1.0 "Lucky13" Attack: "F-U, This is Cryptography"

- HTTPS/TLS uses MAC then Encrypt
  - With CBC encryption
- The Lucky13 attack changes the cipher text in an attempt to discover the state of a byte
  - But can't predict the MAC
  - The TLS connection retries after each failure so the attacker can try multiple times
    - Goal is to determine the status each byte in the authentication cookie which is in a known position
- It detects the ***timing*** of the error response
  - Which is different if the guess is right or wrong
    - Even though the underlying algorithm was "***proved***" secure!
- So always do Encrypt then MAC since, once again, it is more mistake tolerant

The best MAC construction: HMAC

- Idea is to turn a hash function into a MAC
  - Since hash functions are often much faster than encryption
  - While still maintaining the properties of being a cryptographic hash
- Reduce/expand the key to a single hash block
- XOR the key with the i_pad
  - 0x363636... (one hash block long)
- Hash ((K ⊕ i_pad) || message)
- XOR the key with the o_pad
  - 0x5c5c5c...
- Hash ((K ⊕ o_pad) || first hash)

```
function hmac (key, message) {
    if (length(key) > blocksize) {
        key = hash(key)
    }
    while (length(key) < blocksize) {
       key = key || 0x00
    }
    o_key_pad = 0x5c5c... ⊕ key
    i_key_pad = 0x3636... ⊕ key
    return hash(o_key_pad ||
                hash(i_key_pad || message))
}
```

Why This Structure?

- i_pad and o_pad are slightly arbitrary
  - But it is necessary for security for the two values to be different
    - So for paranoia chose very different bit patterns
- Second hash prevents appending data
  - Otherwise attacker could add more to the message and the HMAC and it would still be a valid HMAC for the key
    - Wouldn't be a problem with the key at the ***end*** but at the start makes it easier to capture intermediate HMACs
- Is a Pseudo Random Function if the underlying hash is a PRF
  - AKA if you can break this, you can break the hash!

```
function hmac (key, message) {
    if (length(key) > blocksize) {
        key = hash(key)
    }
    while (length(key) < blocksize) {
       key = key || 0x00
    }
    o_key_pad = 0x5c5c... ⊕ key
    i_key_pad = 0x3636... ⊕ key
    return hash(o_key_pad ||
                hash(i_key_pad || message))
}
```

Great Properties of HMAC...

- It is still a hash function!
  - So all the good things of a cryptographic hash:
    An attacker or even the recipient shouldn't be able to calculate **M** given **HMAC(M,K)**
  - An attacker who doesn't know **K** can't even verify if **HMAC(M,K) == M**
    - Very different from the hash alone, and potentially very useful:
      Attacker can't even brute force try to find **M** based on **HMAC(M,K)**!
- Its probably safe if you screw up and use the same key for both MAC and Encrypt
  - Since it is a different algorithm than the encryption function...
  - ***But you shouldn't do this anyway***!

Considerations when using MACs

- Along with messages, can use for data at rest
  - E.g. laptop left in hotel, providing you don't store the key on the laptop
  - Can build an efficient data structure for this that doesn't require re-MAC'ing over entire disk image when just a few files change
- MACs in general provide no promise not to leak info about message
  - Compute MAC on ciphertext if this matters
  - Or just use HMAC, which ***does*** promise not to leak info if the underlying hash function doesn't
- ***NEVER*** use the same key for MAC and Encryption...
  - Known "FU-this-is-crypto" scenarios reusing an encryption key for MAC in some algorithms when its the same underlying block cipher for both

Plus AEAD Encryption Modes...

- The latest block cipher modes are "AEAD":
  - Authenticated Encryption with Additional Data
- Provides both integrity ***and*** confidentiality over the data
  - With ***integrity*** also provided for the "Additional Data"
- Used right, these are great
  - Assuming you use a library...
- Used wrong...
  - The AEAD modes are built for "performance", which means parallelization, which means CTR mode, which means IV reuse is a disaster!