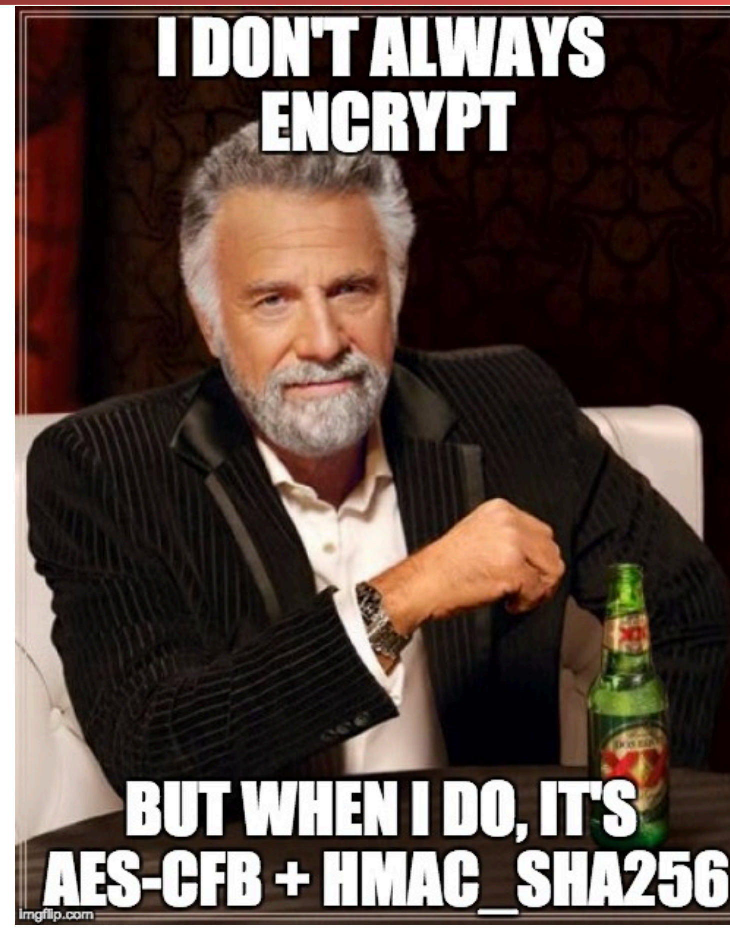
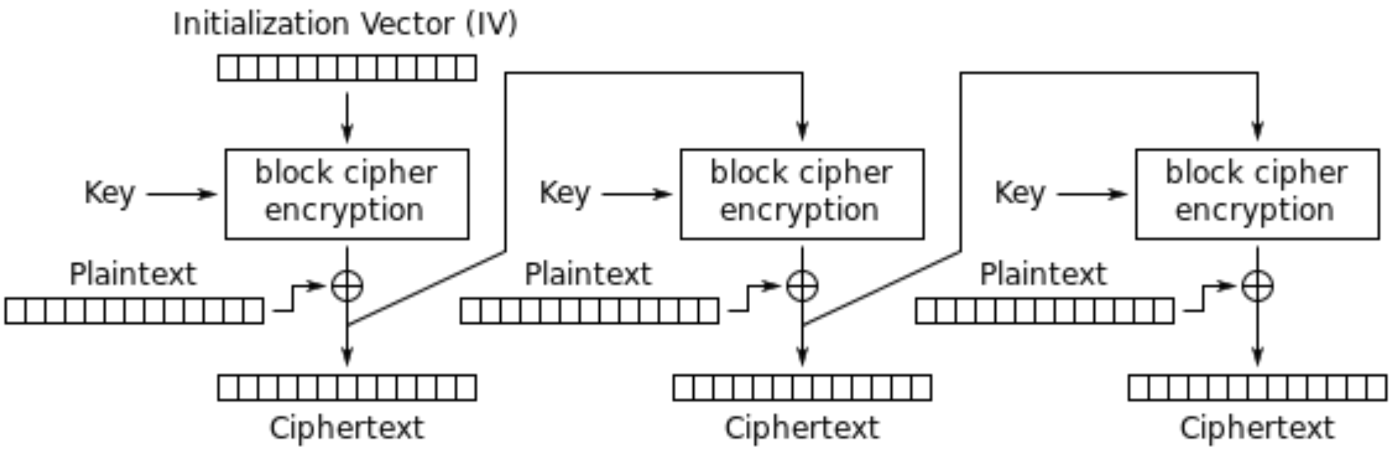
Crypto 2

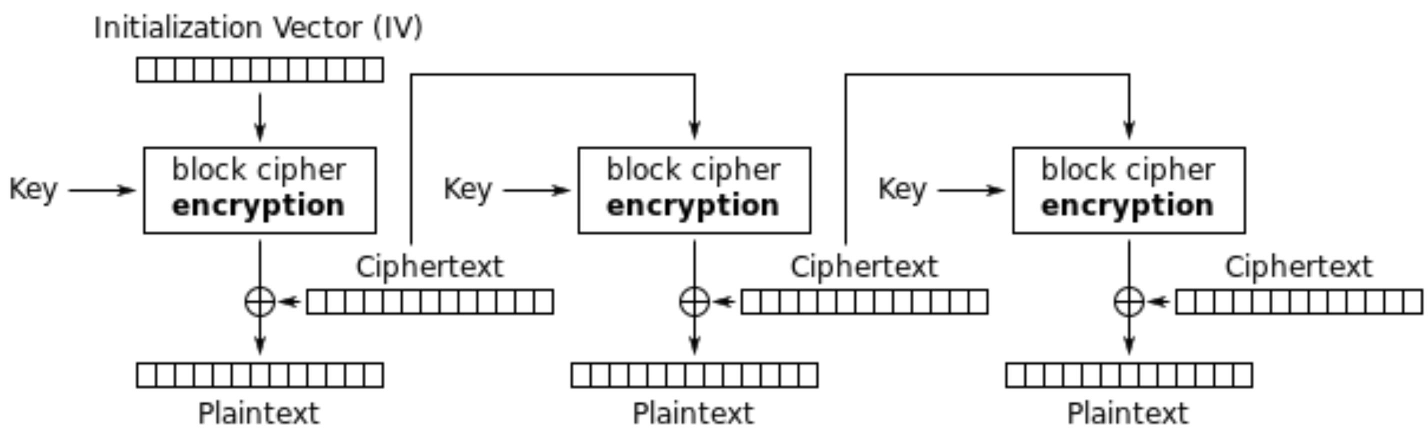

I DON'T ALWAYS ENCRYPT
BUT WHEN I DO, IT'S AES-CFB + HMAC_SHA256
imgflip.com

CFB Encryption



Cipher Feedback (CFB) mode encryption

CFB Decryption

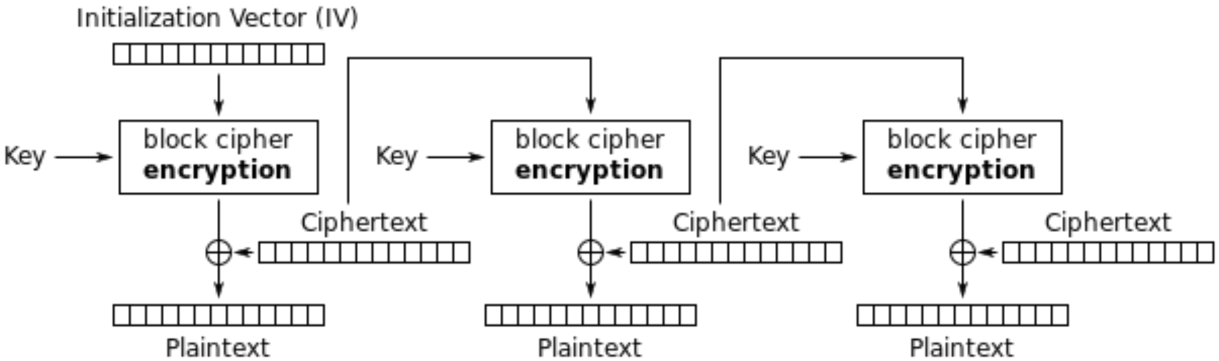


Cipher Feedback (CFB) mode decryption

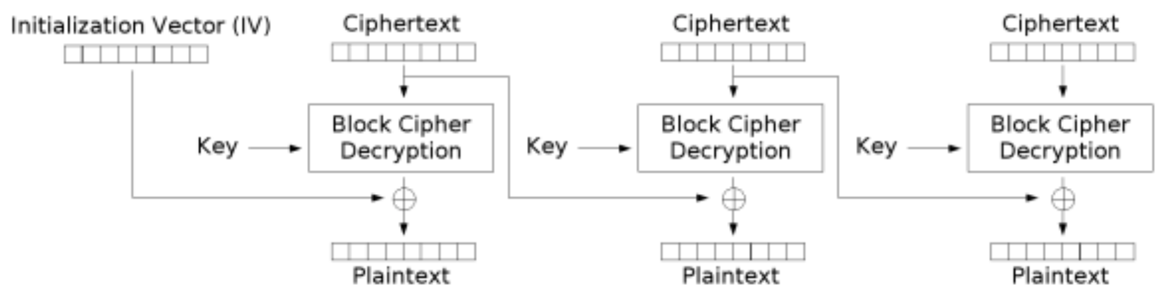
CFB doesn't need to pad...

- 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

Error Propagation



Cipher Feedback (CFB) mode decryption



Cipher Block Chaining (CBC) mode decryption

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 $\approx 2^{n/2}$ 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*** selection 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 = 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 **T = MAC(M,K_{mac})**, send **C = E(M||T,$K_{encrypt}$)**
- Encrypt then MAC:
  - Compute **C = E(M,$K_{encrypt}$)**, **T = MAC(M,K_{mac})**, send **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:
    Nobody should be able to calculate **M** given **HMAC(M,K)** if they know **K** but don't know **M**
  - 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)** if they don't know **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

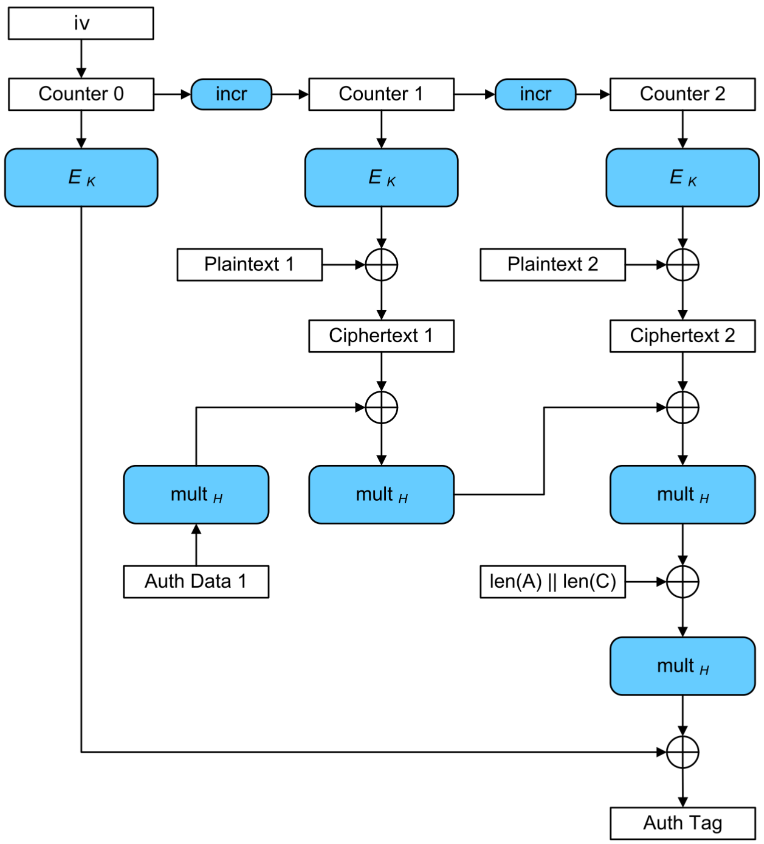
- Along with messages, can use for data at rest
  - E.g. laptop left in hotel, providing you don't store the key on the laptop
  - Can build an efficient data structure for this that doesn't require re-MAC'ing over entire disk image when just a few files change
- MACs in general provide no promise not 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!

GCM (Galios Counter Mode) AEAD Counter Mode

- ***E_k*** is just standard encryption
- ***$mult_h$*** is 128b multiplication over a special field
  - Not going into the details of the magic math because I don't understand it myself
- VERY fast mode of operation
  - Fully parallel encryption
  - Galios multiplication isn't parallelizeable but it is very light weight
    - Far lighter weight than HMAC-SHA256
- But a huge pitfall....
  - If you reuse the IV, not only do you lose confidentiality (like CTR mode)...
    You lose integrity as well!
  - Which wouldn't happen if you used CTR-HMAC-SHA256



A Lot Of Uses for Random Numbers...

- The key foundation for all modern cryptographic systems is often not encryption but these "random" numbers!
- So many times you need to get something random:
  - A random cryptographic key
  - A random initialization vector
  - A "nonce" (use-once item)
  - A unique identifier
  - Stream Ciphers
- If an attacker can ***predict*** a random number things can catastrophically fail

Breaking Slot Machines

- Some casinos experienced unusual bad "luck"
  - The suspicious players would wait and then all of a sudden try to play
- The slot machines have ***predictable*** pRNG
  - Which was based on the current time & a seed
- So play a little...
  - With a cellphone watching
  - And now you know when to press "spin" to be more likely to win
- Oh, and this ***never*** effected Vegas!
  - ***Evaluation standards*** for Nevada slot machines specifically designed to address this sort of issue

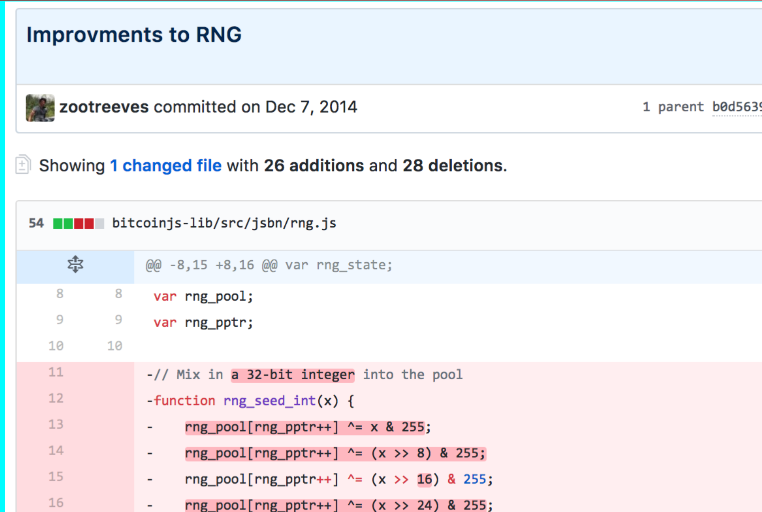
BRENDAN KOERNER SECURITY 02.06.17 07:00 AM

RUSSIANS ENGINEER A BRILLIANT SLOT MACHINE

IN EARLY JUNE 2014, accountants at the Lumiere Place Casino in St. Louis noticed that several of their slot machines had—just for a couple of days—gone haywire. The government-approved software that powers such machines gives the house a fixed mathematical edge, so that casinos can be certain of how much they'll earn over the long haul—say, 7.129 cents for every dollar played. But on June 2 and 3, a number of Lumiere's machines had spit out far more money than they'd consumed, despite not awarding any major jackpots, an aberration known in industry parlance as a

Breaking Bitcoin Wallets

- blockchain.info supports "web wallets"
  - Javascript that protects your Bitcoin
- The private key for Bitcoin needs to be random
  - Because otherwise an attacker can spend the money
- An "Improvment" [sic] to the RNG reduced the entropy (the actual randomness)
  - Any wallet created with this improvment was brute-forceable and could be stolen



TRUE Random Numbers

- True random numbers generally require a physical process
- Common circuit is an unusable ring oscillator built into the CPU
  - It is then sampled at a low rate to generate true random bits which are then fed into a pRNG on the CPU
- Other common sources are human activity measured at very fine time scales
  - Keystroke timing, mouse movements, etc
    - "Wiggle the mouse to generate entropy for a key"
  - Network/disk activity which is often human driven
- More exotic ones are possible:
  - Cloudflare has a wall of lava lamps that are recorded by a HD video camera which views the lamps through a rotating prism: It is just one source of the randomness

Combining Entropy

- Many physical entropy sources are biased
  - Some have significant biases: e.g. a coin that flips "heads" 90% of the time!
  - Some aren't very good: e.g. keystroke timing at a microsecond granularity
- The general procedure is to combine various sources of entropy
- The goal is to be able to take multiple crappy sources of entropy
  - Measured in how many bits:
    A single flip of a fair coin is 1 bit of entropy
  - And combine into a value where the entropy is the minimum of the sum of all entropy sources (maxed out by the # of bits in the hash function itself)
  - **N-1** bad sources and **1** good source -> good pRNG state

Pseudo Random Number Generators (aka Deterministic Random Bit Generators)

- Unfortunately one needs a ***lot*** of random numbers in cryptography
  - More than one can generally get by just using the physical entropy source
- Enter the pRNG or DRBG
  - If one knows the state it is entirely predictable
  - If one doesn't know the state it should be indistinguishable from a random string
- Three operations
  - Instantiate: (aka Seed) Set the internal state based on the real entropy sources
  - Reseed: Update the internal state based on both the previous state and ***additional entropy***
    - The big different from a simple stream cipher
  - Generate: Generate a series of random bits based on the internal state
    - Generate can also optionally add in additional entropy
- **instantiate(entropy)**
  reseed(entropy)
  generate(bits, {optional entropy})

Properties for the pRNG

- Can a pRNG be truly random?
  - No. For seed length **s**, it can only generate at most **2^s** distinct possible sequences.
- A cryptographically strong pRNG "looks" truly random to an attacker
  - Attacker ***cannot distinguish*** it from a random sequence:
    If the attacker can tell a sufficiently long bitstream was generated by the pRNG instead of a truly random source it isn't a good pRNG

Prediction and Rollback Resistance

- A pRNG should be predictable only if you know the internal state
  - It is this predictability which is why its called "pseudo"
- If the attacker does not know the internal state
  - The attacker should not be able to distinguish a truly random string from one generated by the pRNG
- It ***should*** also be rollback-resistant
  - Even if the attacker finds out the state at time T, they should not be able to determine what the state was at T-1
  - More precisely, if presented with two random strings, one truly random and one generated by the pRNG at time T-1, the attacker should not be able to distinguish between the two
  - Rollback resistance isn't specifically required in a pRNG...
    But it should be

Why "Rollback Resistance" is Essential

- Assume attacker, at time T, is able to obtain all the internal state of the pRNG
  - How? E.g. the pRNG screwed up and instead of an IV, released the internal state, or the pRNG is bad...
- Attacker observes how the pRNG was used
  - T_{-1} = Random Session key
    T_0 = Nonce/IV
- Now if the pRNG doesn't resist rollback, and the attacker gets the state at T_0, attacker can know the session key! And we are back to...

More on Seeding and Reseeding

- Seeding should take all the different physical entropy sources available
  - If one source has 0 entropy, it ***must not*** reduce the entropy of the seed
  - We can shove a whole bunch of low-entropy sources together and create a high-entropy seed
- Reseeding ***adds*** in even more entropy
  - **F(internal_state, new material)**
  - Again, even if reseeding with 0 entropy, it ***must not*** reduce the entropy of the seed

Probably the best pRNG/DRBG: HMAC_DRBG

- Generally believed to be the best
  - ***Accept no substitutes***!
- Two internal state registers, ***V*** and ***K***
  - Each the same size as the hash function's output
- ***V*** is used as (part of) the data input into HMAC, while ***K*** is the key
- If you can break this pRNG you can ***either break the underlying hash function*** or ***break a significant assumption about how HMAC works***
  - Yes, security proofs sometimes are a very good thing and actually do work
  - So as long as the security proof for HMAC is correct, the security proof for HMAC_DRBG is correct!

HMAC_DRBG Generate

- The basic generation function
- Remarks:
  - It requires one HMAC call per blocksize-bits of state
  - Then two more HMAC calls to update the internal state
- Prediction resistance:
  - If you can distinguish new **K** from random when you don't know old **K**:
    You've distinguished HMAC from a random function!
    Which means you've either broken the hash or the HMAC construction
- Rollback resistance:
  - If you can learn old **K** from new **K** and **V**:
    You've reversed the hash function!

```
function hmac_drbg_generate (state, n) {
  tmp = ""
  while(len(tmp) < N){
     state.v = hmac(state.k,state.v)
     tmp = tmp || state.v
  }
  // Update state with no input
  state.k = hmac(state.k, state.v || 0x00)
  state.v = hmac(state.k, state.v)
  // Return the first N bits of tmp
  return tmp[0:N]
}
```

HMAC_DRBG Update

- Used instead of the "no-input update" when you have additional entropy on the generate call
- Used standalone for both instantiate (**state.k = state.v = 0**) and reseed (keep **state.k** and **state.v**)
- Designed so that even if the attacker controls the input but doesn't know **k**: The attacker should not be able to predict the new **k**

```
function hmac_drbg_update (state, input) {
  state.k = hmac(state.k, state.v || 0x00
                          || input)
  state.v = hmac(state.k, state.v)
  state.k = hmac(state.k, state.v || 0x01
                          || input)
  state.v = hmac(state.k, state.v)
}
```

Generating ***true*** random numbers

- Modern CPUs have true random number generators
  - Sample a noisy circuit at a low rate or similar tricks
- These sources are biased...
  - They are also ***slow***
- So use this as an entropy source to feed a pRNG on the chip
  - Now you can get random numbers quickly
- Very fast
- Vulnerable to tampering!
  - You can't actually test that the pRNG circuit is 100% correct without adding paths that could potentially sabotage the pRNG circuit
  - Sabotage that can reduce effective entropy to 32b are possible