Moserware

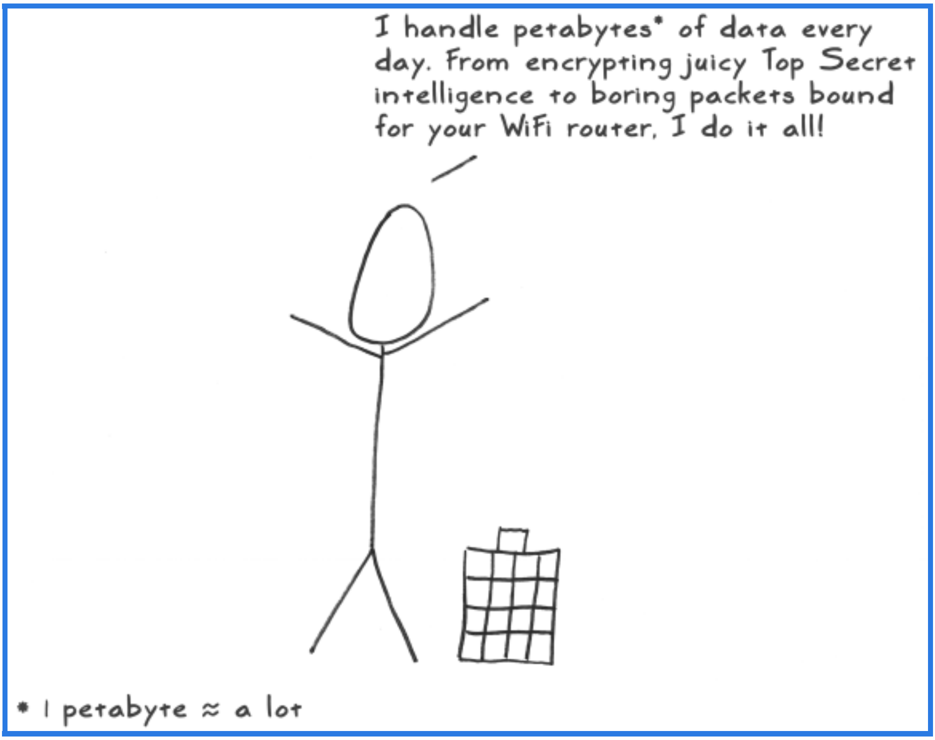
A Stick Figure Guide to the Advanced Encryption Standard (AES)

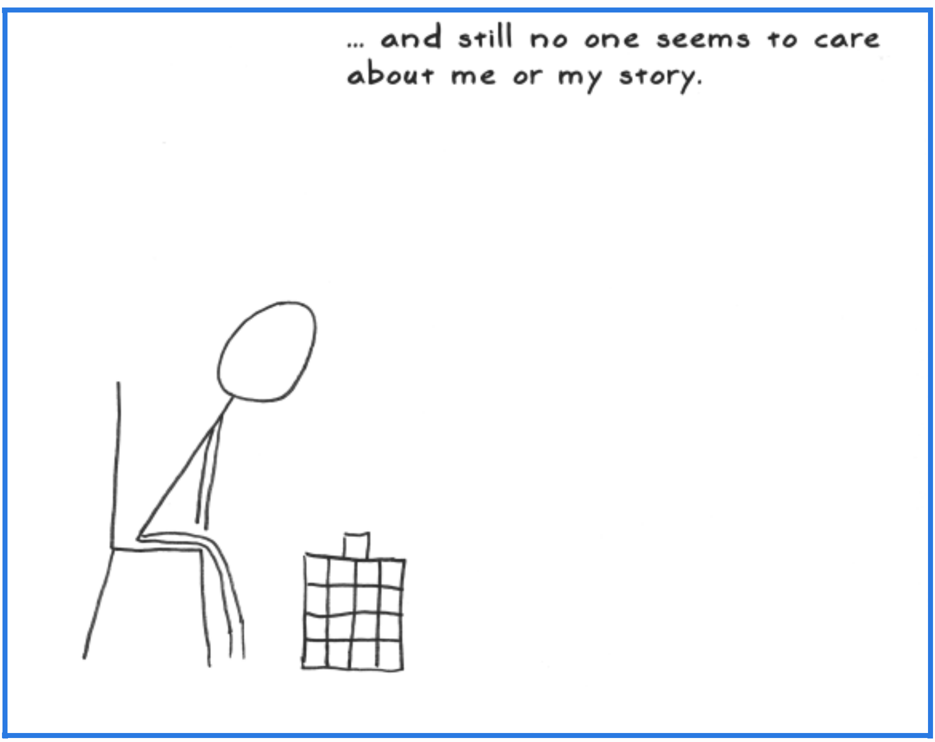
Sep 22, 2009

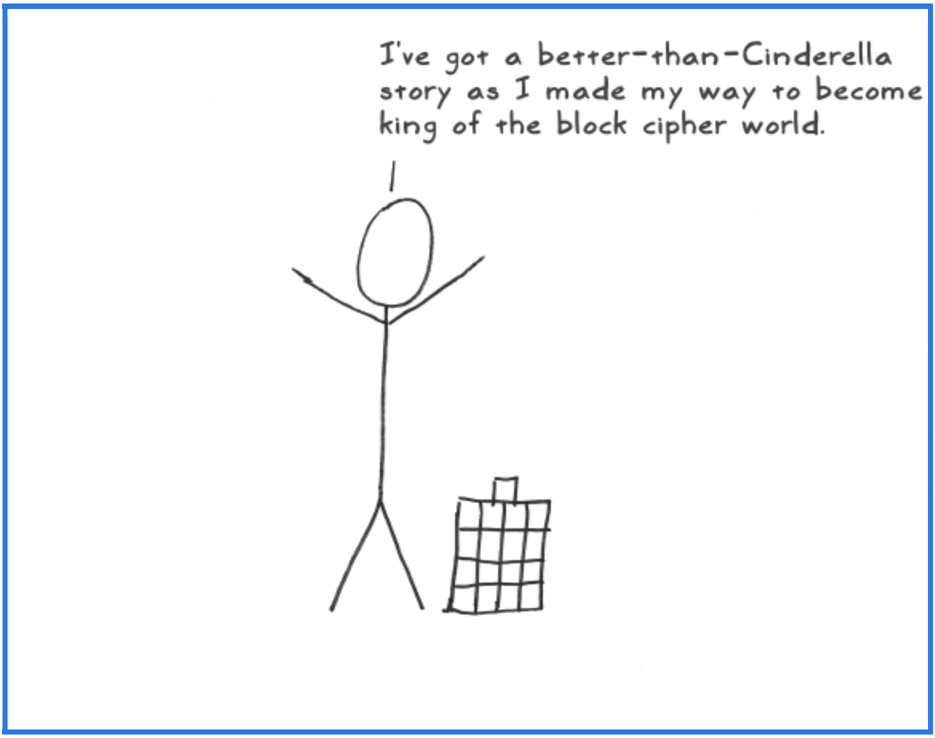
(A play in 4 acts. Please feel free to exit along with the stage character that best represents you. Take intermissions as you see fit. Click on the stage if you have a hard time seeing it. If you get bored, you can jump to the code. Most importantly, enjoy the show!)

Act 1: Once Upon a

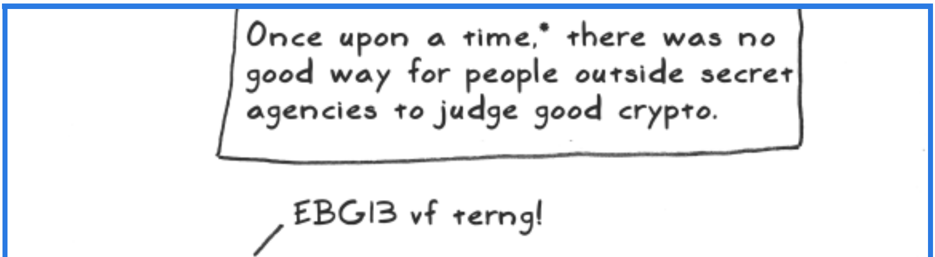
Time…

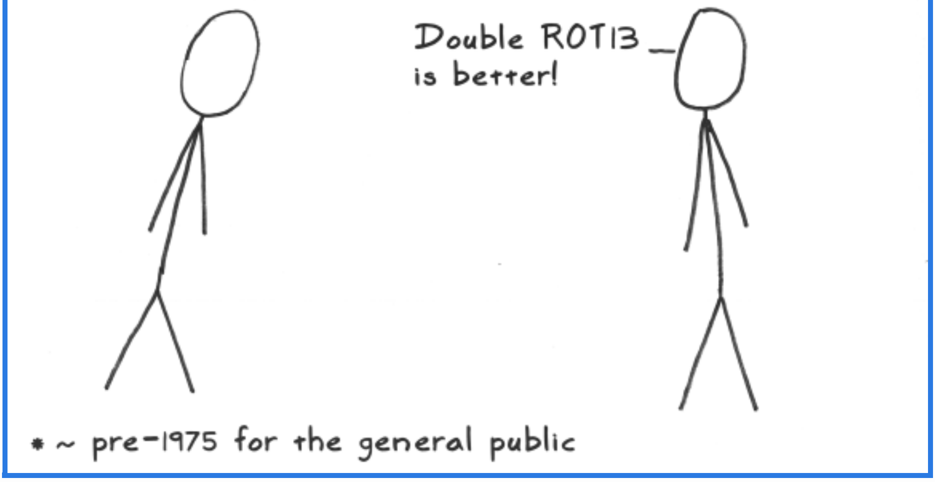

I handle petabytes* of data every day. From encrypting juicy Top Secret intelligence to boring packets bound for your WiFi router, I do it all!
* 1 petabyte ≈ a lot

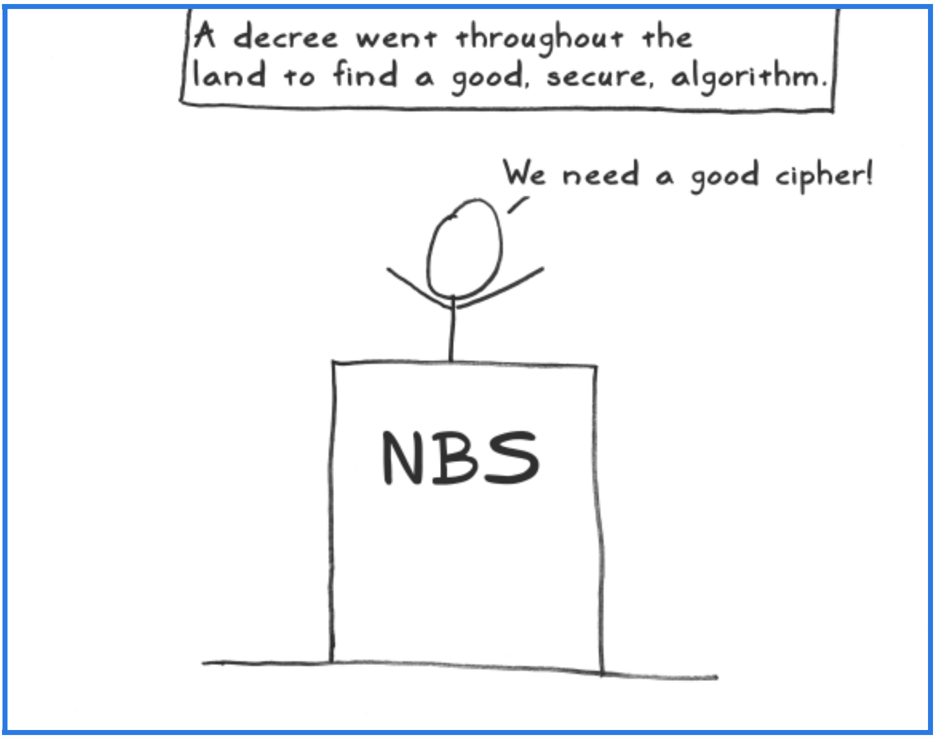

… and still no one seems to care about me or my story.

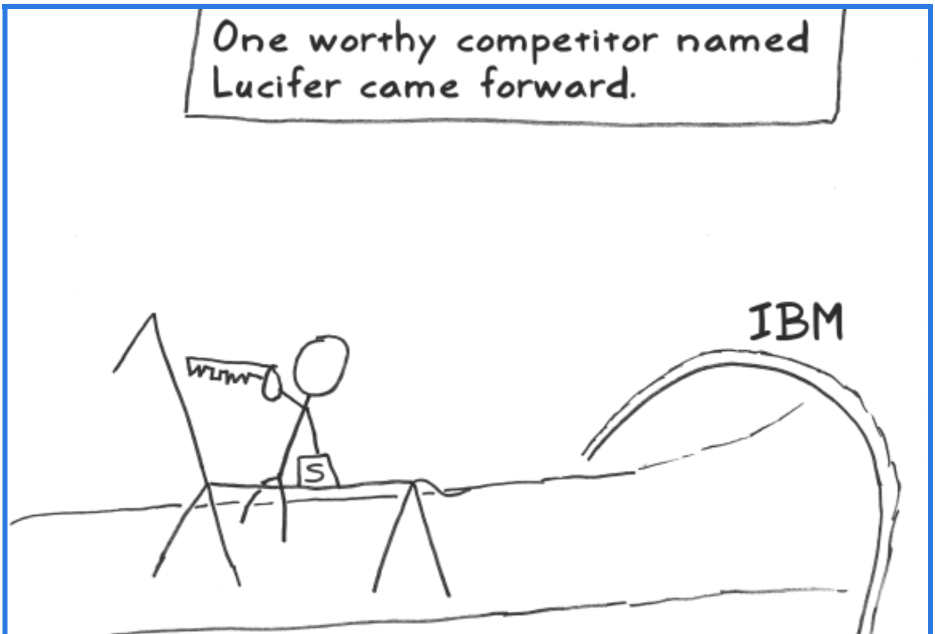

I've got a better-than-Cinderella story as I made my way to become king of the block cipher world.

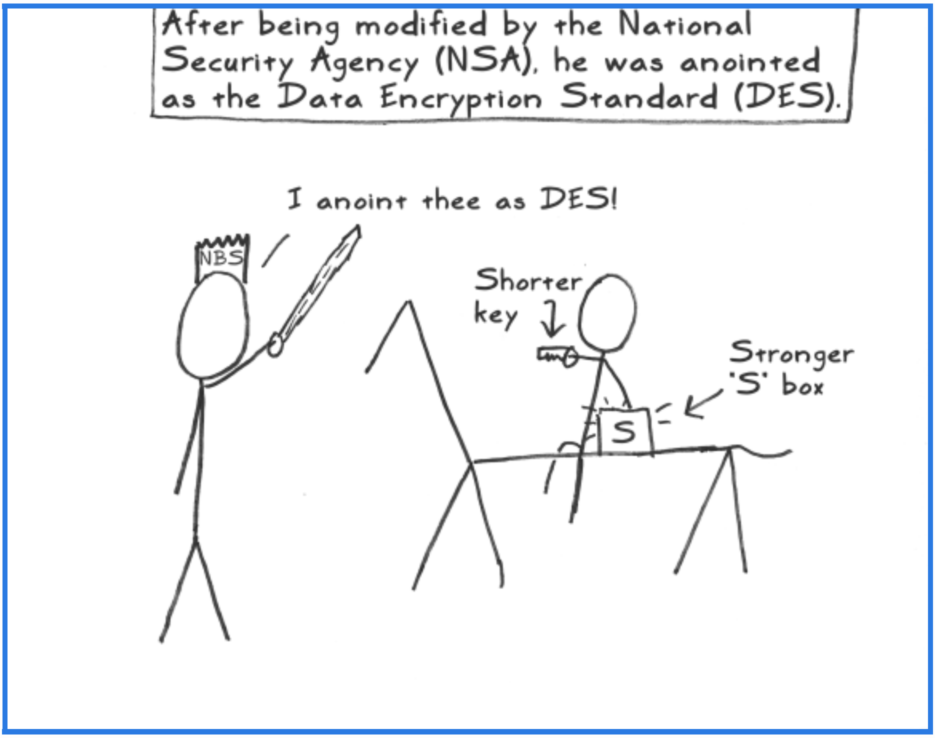

Whoa! You're still there. You want to hear it? Well let's get started...


Once upon a time,* there was no good way for people outside secret agencies to judge good crypto.
EBG13 vf terng!

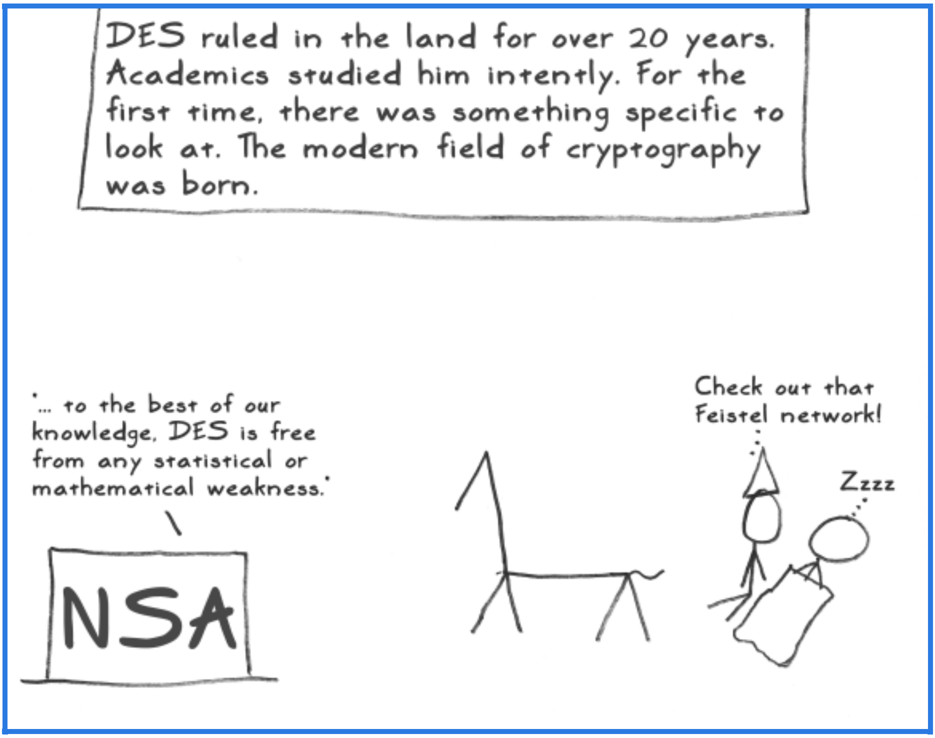

Double ROT13 is better!
* ~ pre-1975 for the general public


A decree went throughout the land to find a good, secure, algorithm.
We need a good cipher!
NBS

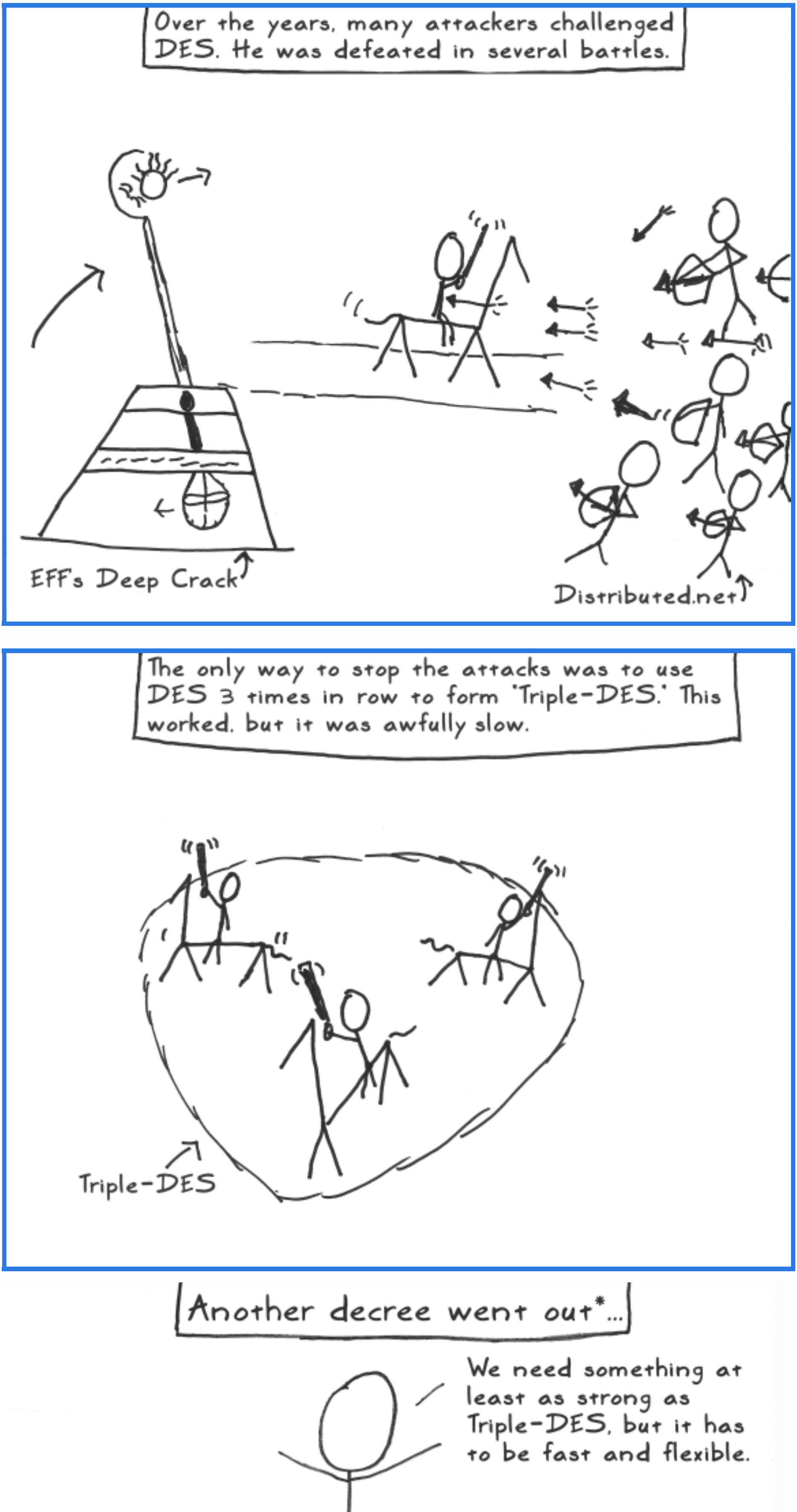

One worthy competitor named Lucifer came forward.
IBM
S

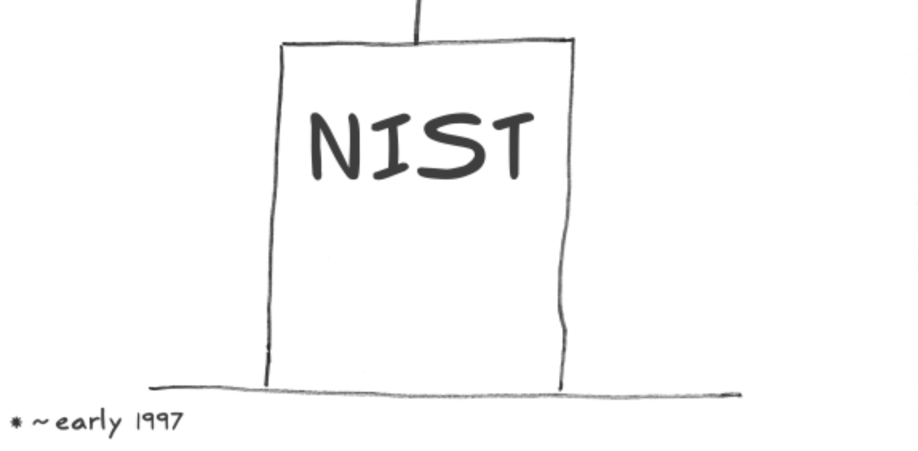


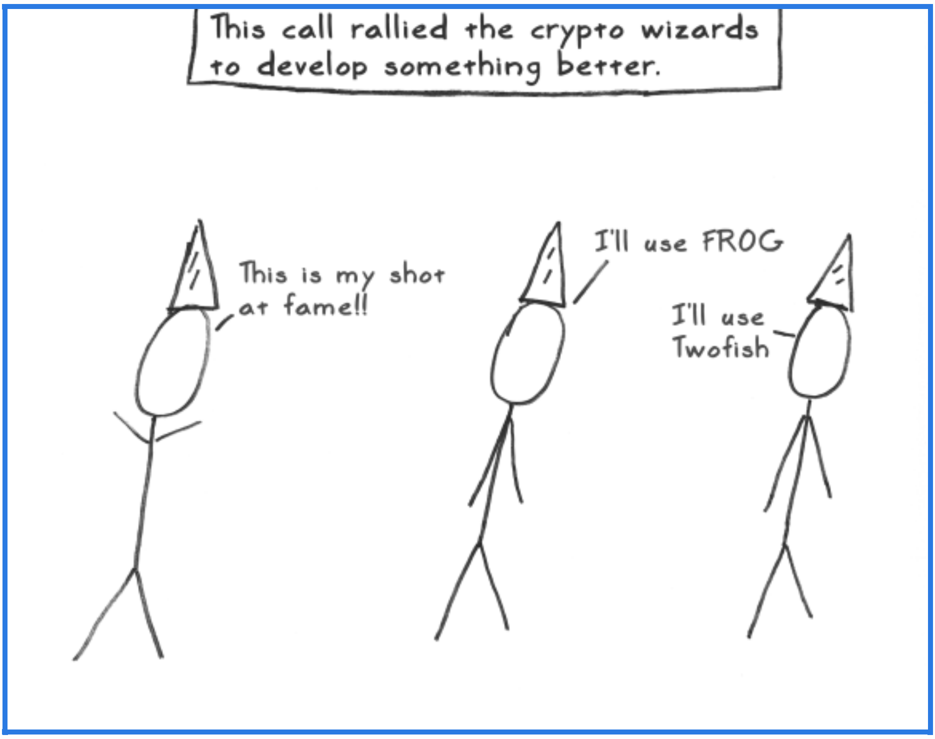
After being modified by the National Security Agency (NSA), he was anointed as the Data Encryption Standard (DES).
I anoint thee as DES!
NBS
Shorter key
Stronger 'S' box
S

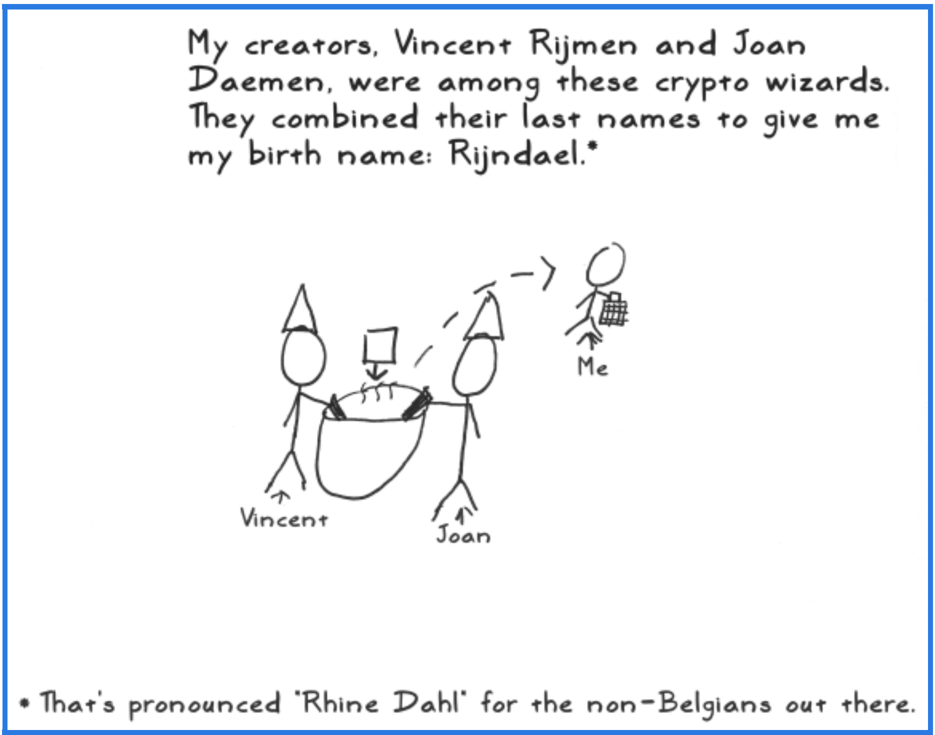


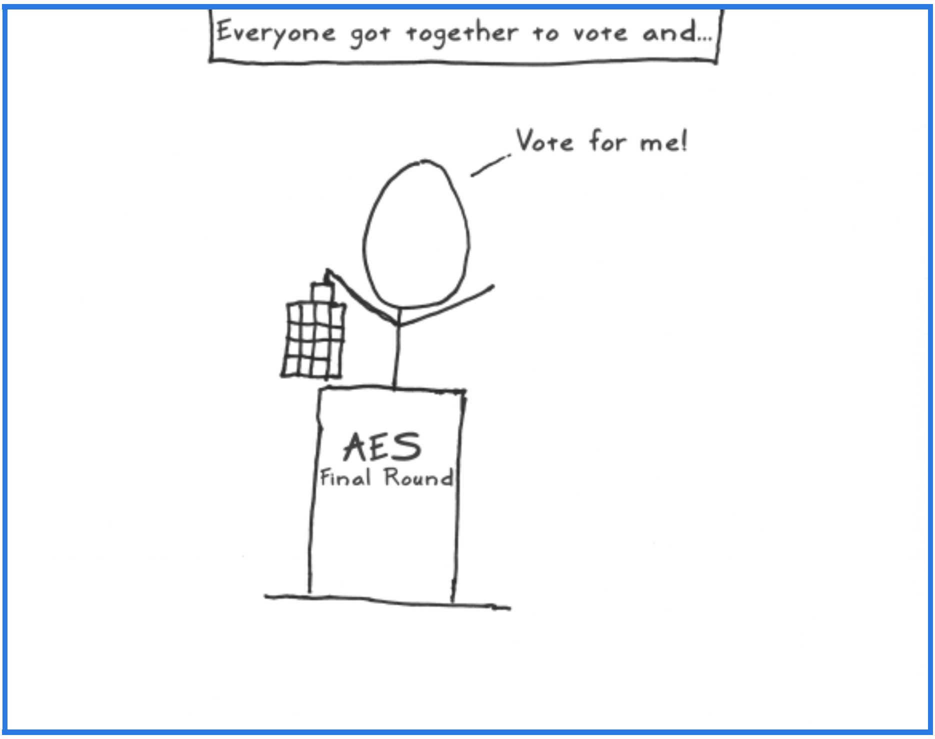
DES ruled in the land for over 20 years. Academics studied him intently. For the first time, there was something specific to look at. The modern field of cryptography was born.
"... to the best of our knowledge, DES is free from any statistical or mathematical weakness."
NSA
Check out that Feistel network!
Zzzz

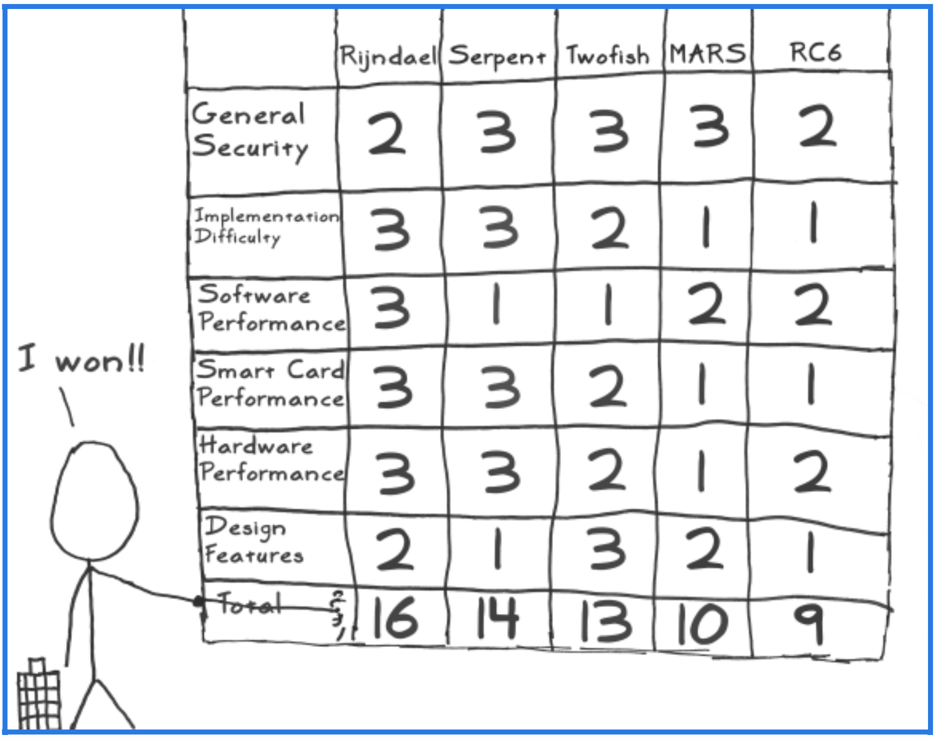

Over the years, many attackers challenged DES. He was defeated in several battles.
EFF's Deep Crack
Distributed.net
The only way to stop the attacks was to use DES 3 times in row to form "Triple-DES." This worked, but it was awfully slow.
Triple-DES
Another decree went out*...
We need something at least as strong as Triple-DES, but it has to be fast and flexible.

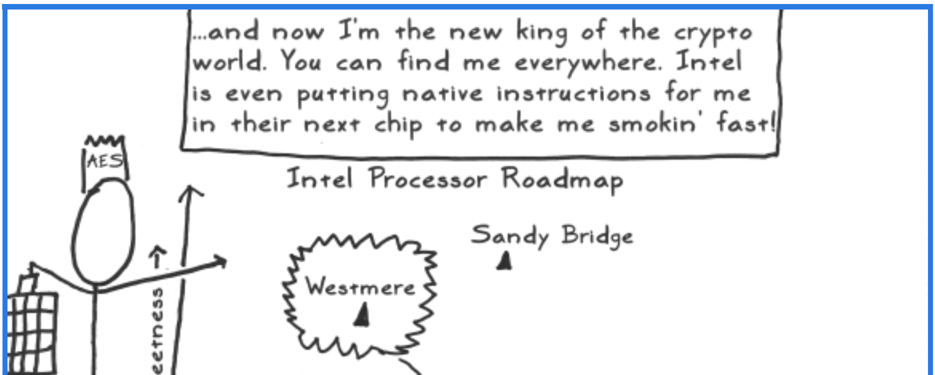

NIST
* ~early 1997

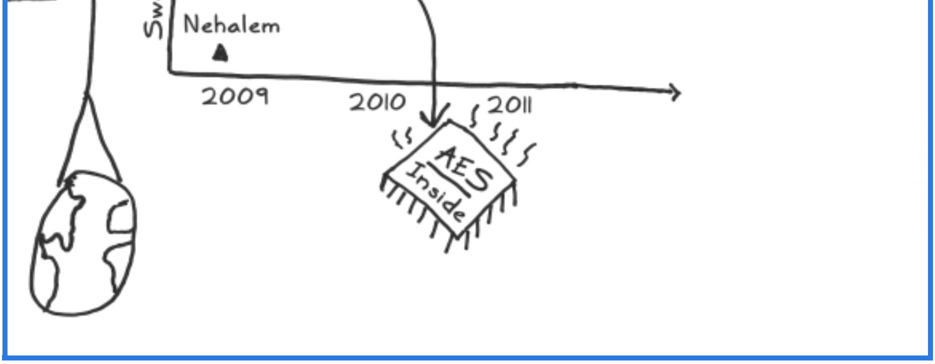

This call rallied the crypto wizards to develop something better.
This is my shot at fame!!
I'll use FROG
I'll use Twofish

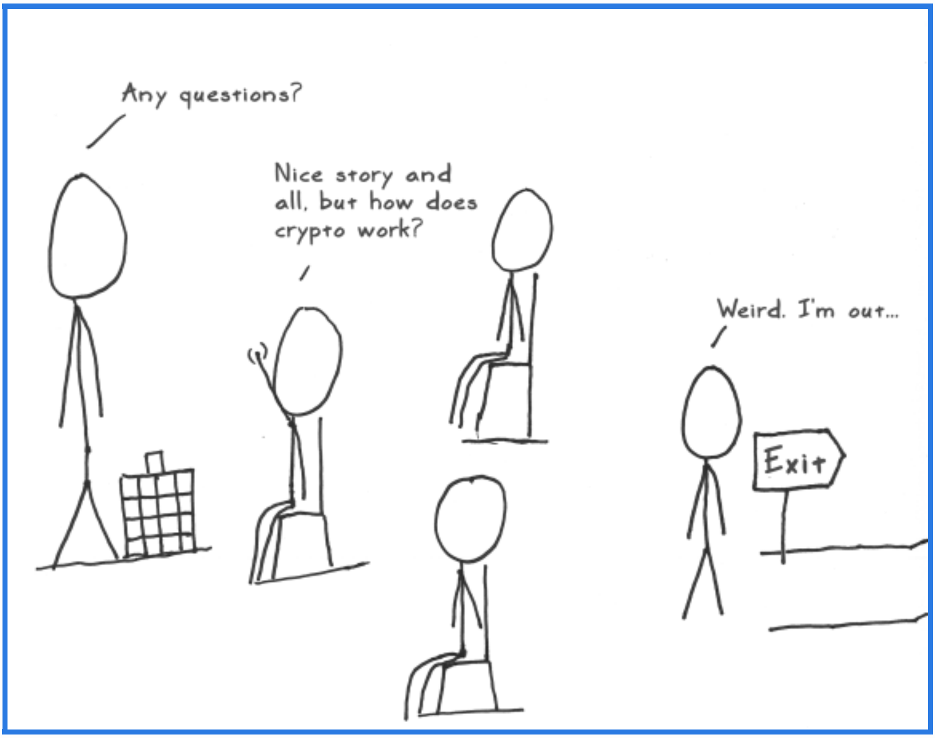

My creators, Vincent Rijmen and Joan Daemen, were among these crypto wizards. They combined their last names to give me my birth name: Rijndael.*
Me
Vincent
Joan
* That's pronounced "Rhine Dahl" for the non-Belgians out there.


Everyone got together to vote and...
Vote for me!
AES
Final Round

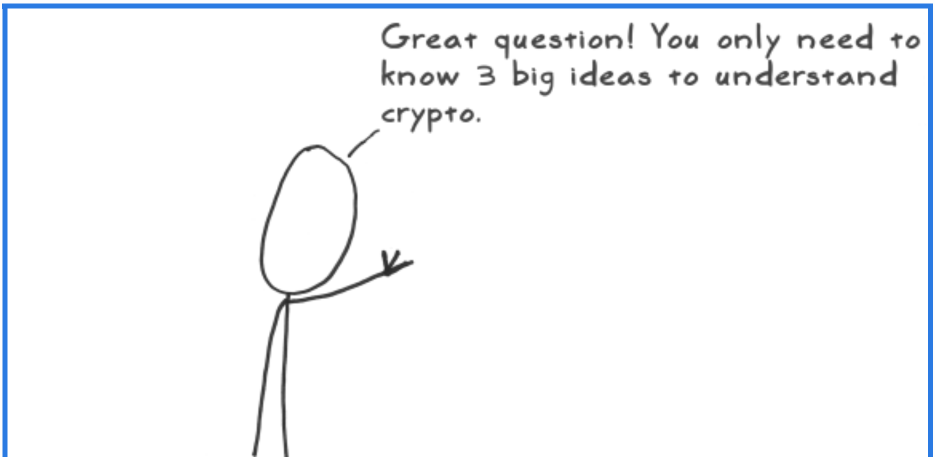

I won!!
Rijndael Serpent Twofish MARS RC6
General Security 2 3 3 3 2
Implementation Difficulty 3 3 2 1 1
Software Performance 3 1 1 2 2
Smart Card Performance 3 3 2 1 1
Hardware Performance 3 3 2 1 2
Design Features 2 1 3 2 1
~~Total~~ 16 14 13 10 9

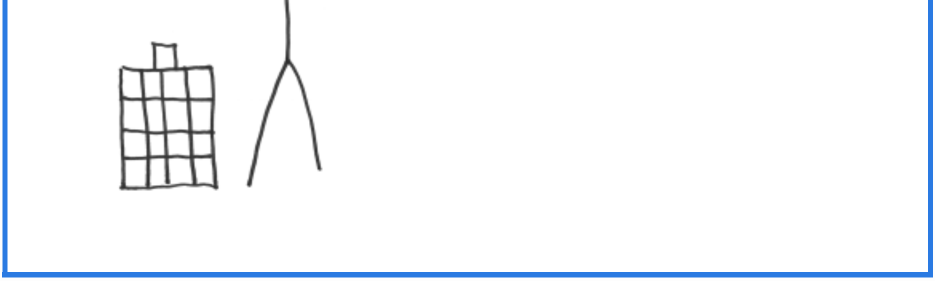

...and now I'm the new king of the crypto world. You can find me everywhere. Intel is even putting native instructions for me in their next chip to make me smokin' fast!
AES
Intel Processor Roadmap
Sandy Bridge
Westmere

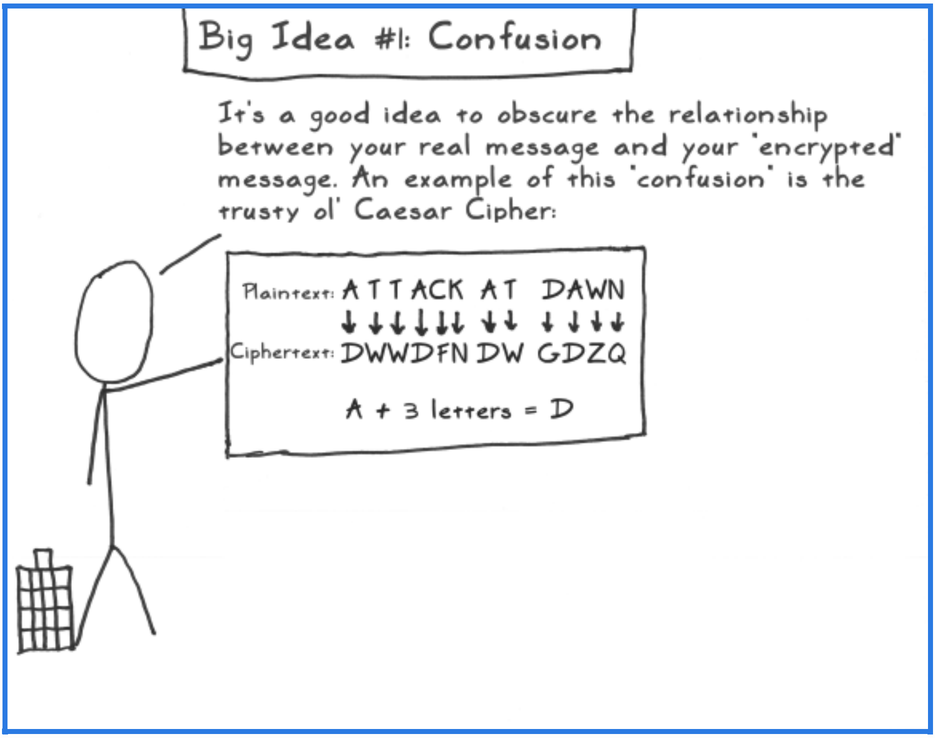




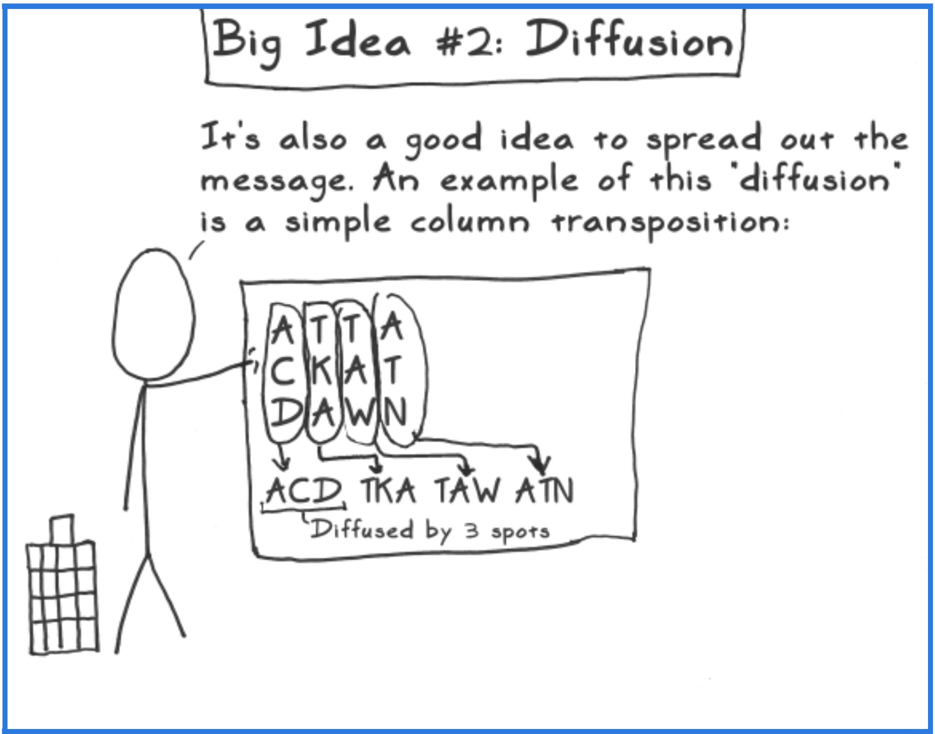
Act 2: Crypto Basics



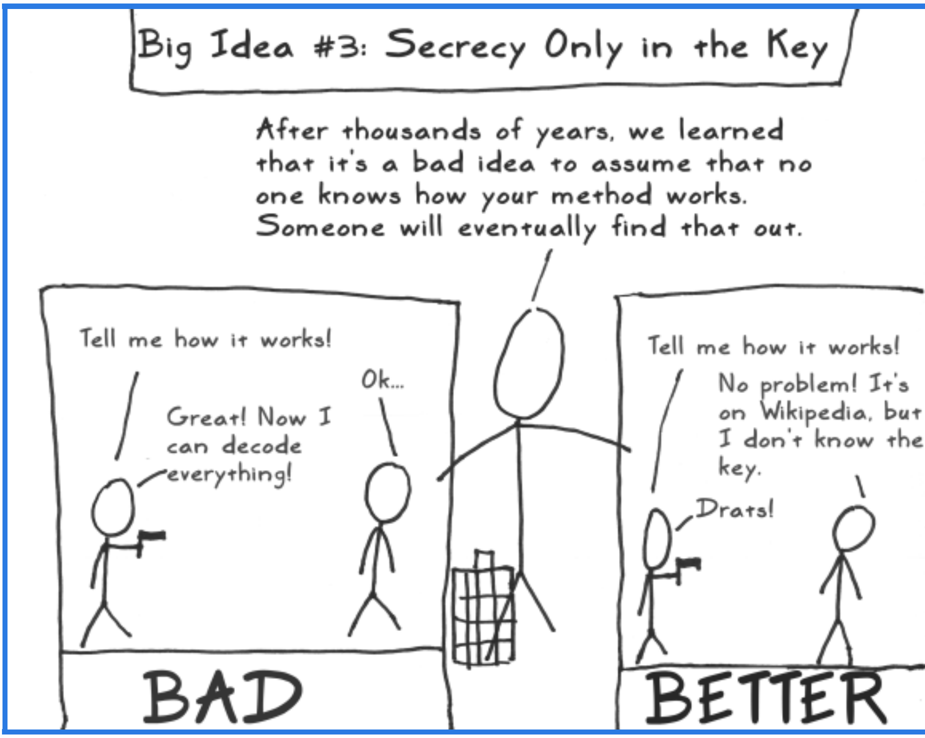


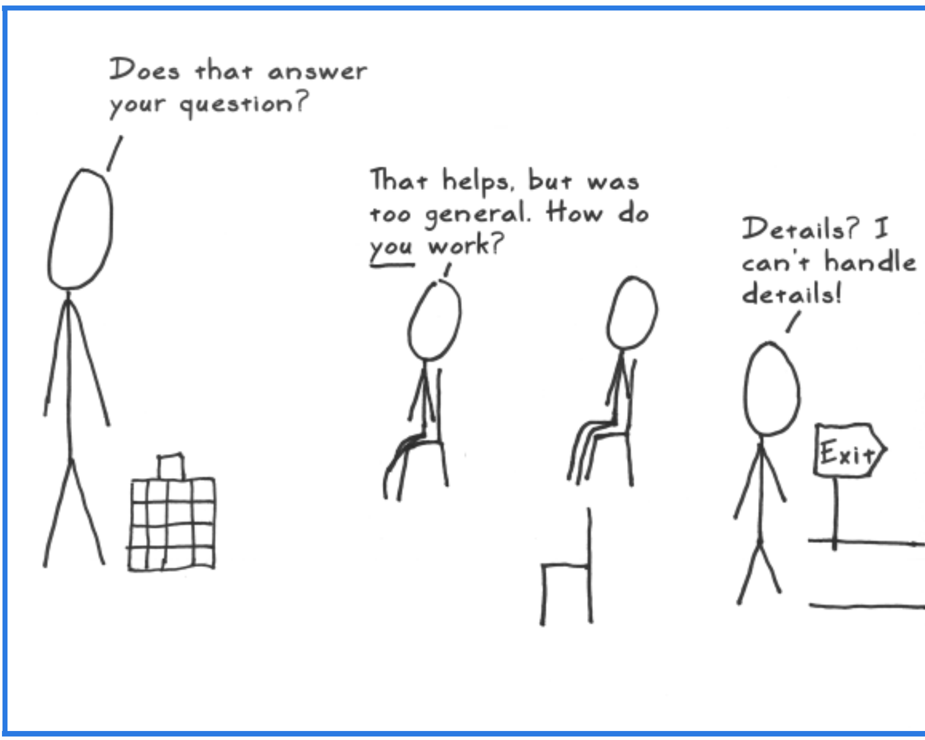


Big Idea #1: Confusion
It's a good idea to obscure the relationship between your real message and your 'encrypted' message. An example of this 'confusion' is the trusty ol' Caesar Cipher:
Plaintext: ATTACK AT DAWN
Ciphertext: DWWDFN DW GDZQ
A + 3 letters = D

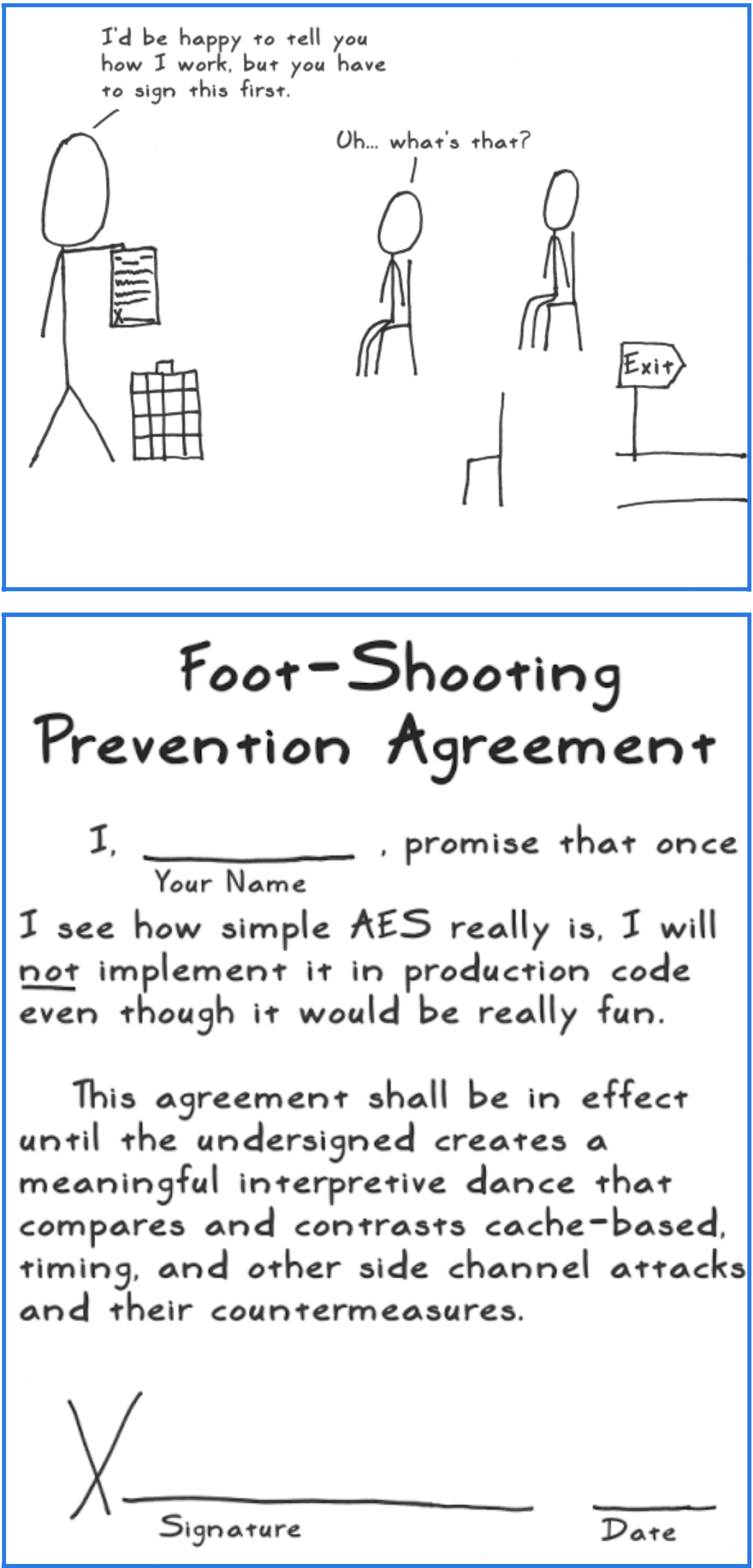


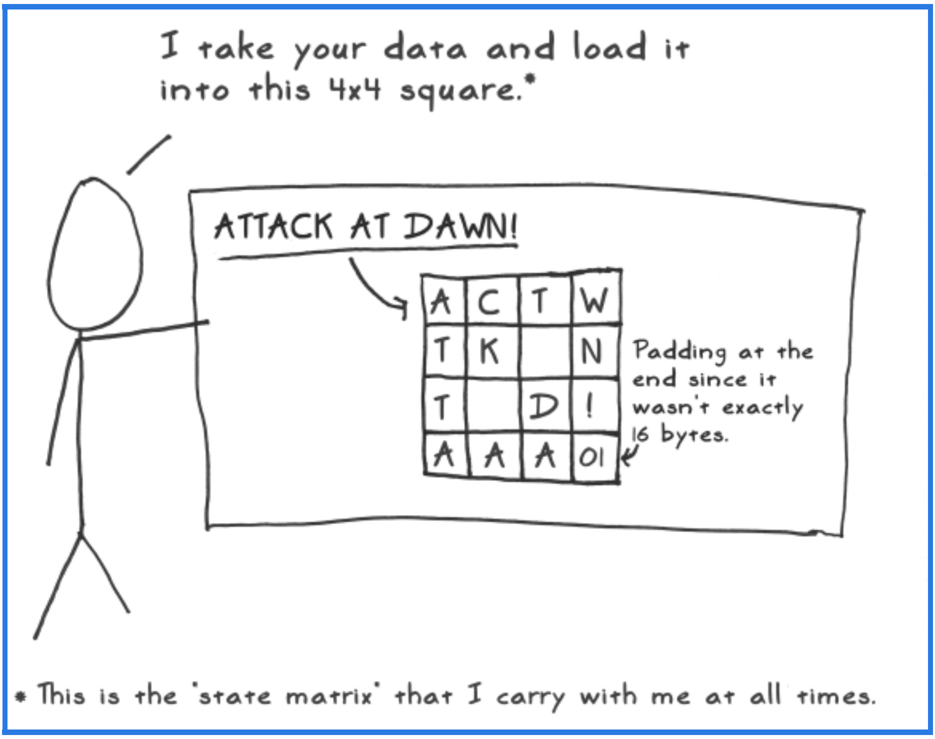
Big Idea #2: Diffusion
It's also a good idea to spread out the message. An example of this 'diffusion' is a simple column transposition:
ATTA
CKAT
DAWN
ACD TKA TAW ATN
Diffused by 3 spots

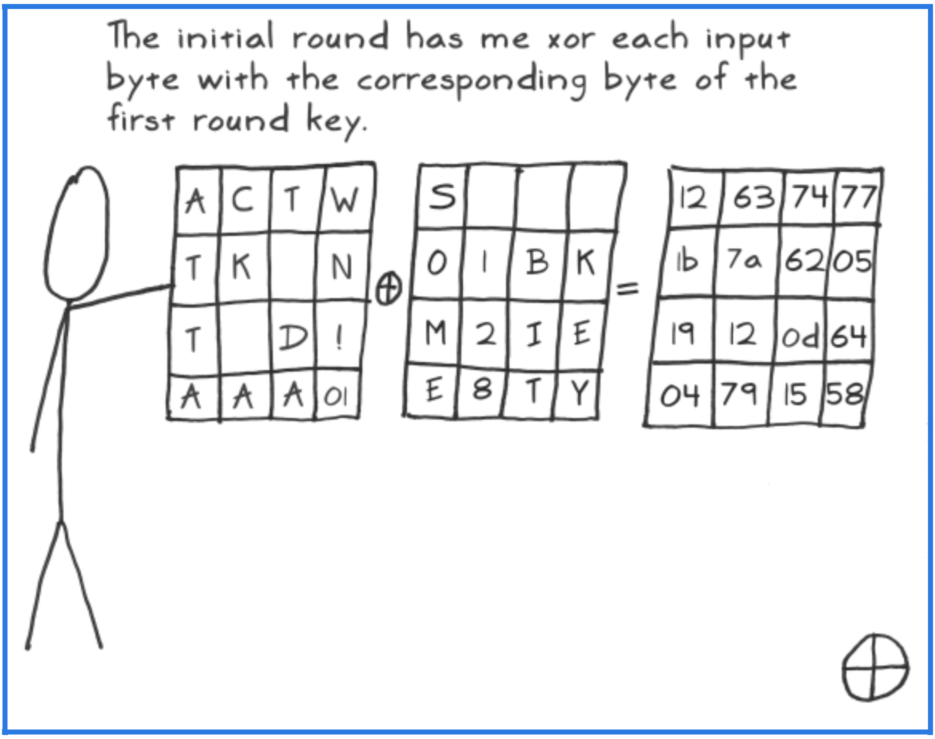


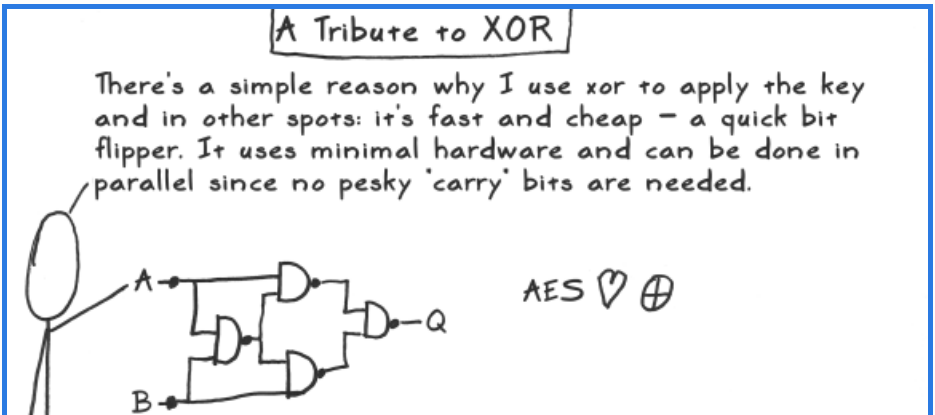


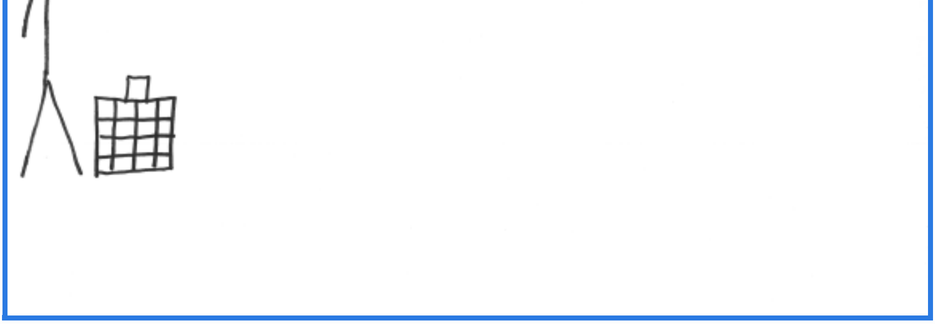
Act 3: Details

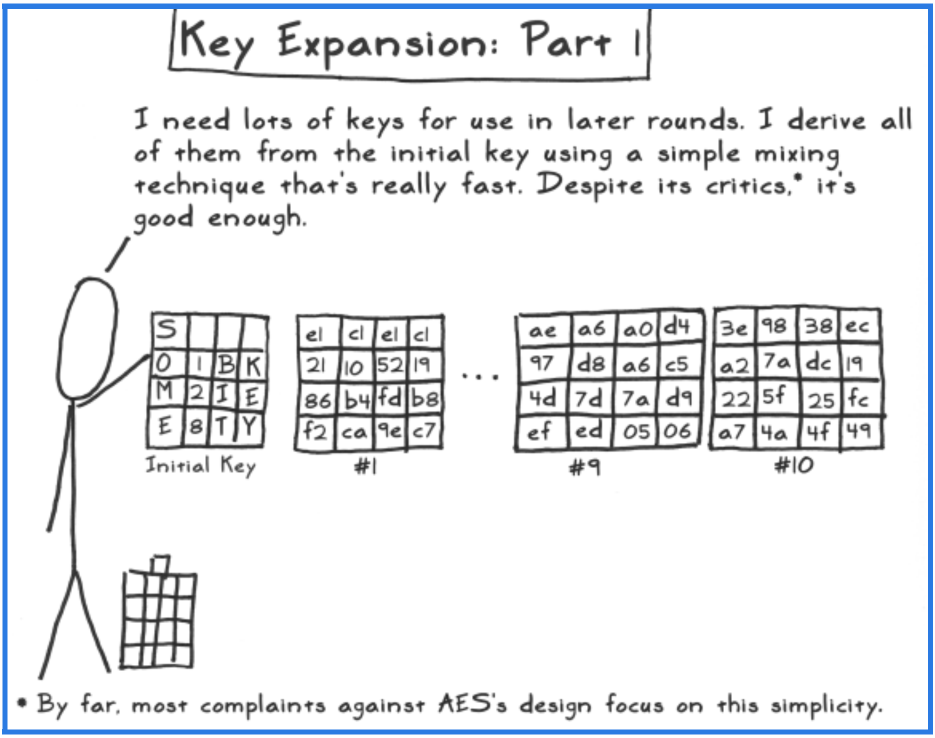

I'd be happy to tell you how I work, but you have to sign this first.
Uh... what's that?
Exit
Foot-Shooting Prevention Agreement
I, ____________ , promise that once
Your Name
I see how simple AES really is, I will not implement it in production code even though it would be really fun.
This agreement shall be in effect until the undersigned creates a meaningful interpretive dance that compares and contrasts cache-based, timing, and other side channel attacks and their countermeasures.
X
Signature
Date

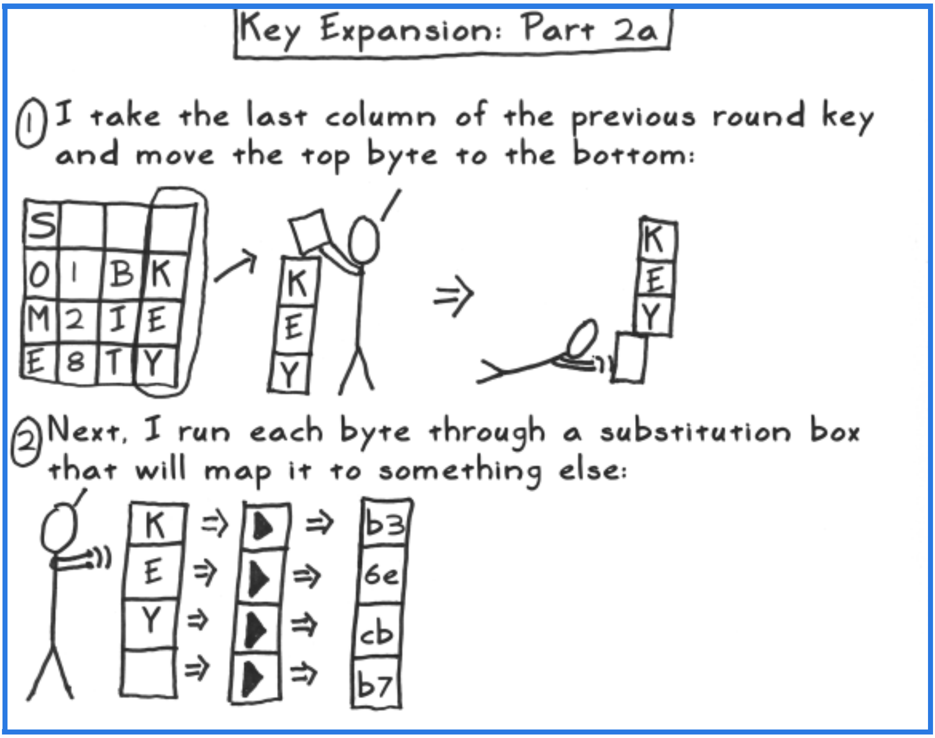

I take your data and load it into this 4x4 square.*
ATTACK AT DAWN!
A C T W
T K N
T D !
A A A 01
Padding at the end since it wasn't exactly 16 bytes.
* This is the 'state matrix' that I carry with me at all times.

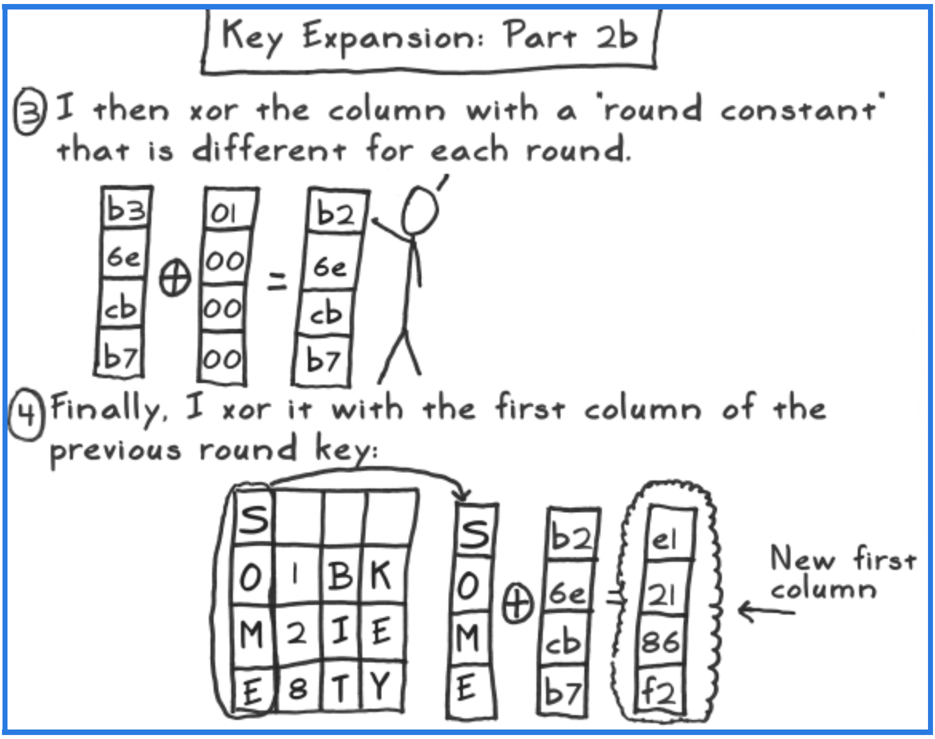

The initial round has me xor each input byte with the corresponding byte of the first round key.
A C T W
T K N
T D !
A A A 01
⊕
S
0 1 B K
M 2 I E
E 8 T Y
=
12 63 74 77
1b 7a 62 05
19 12 0d 64
04 79 15 58
⊕

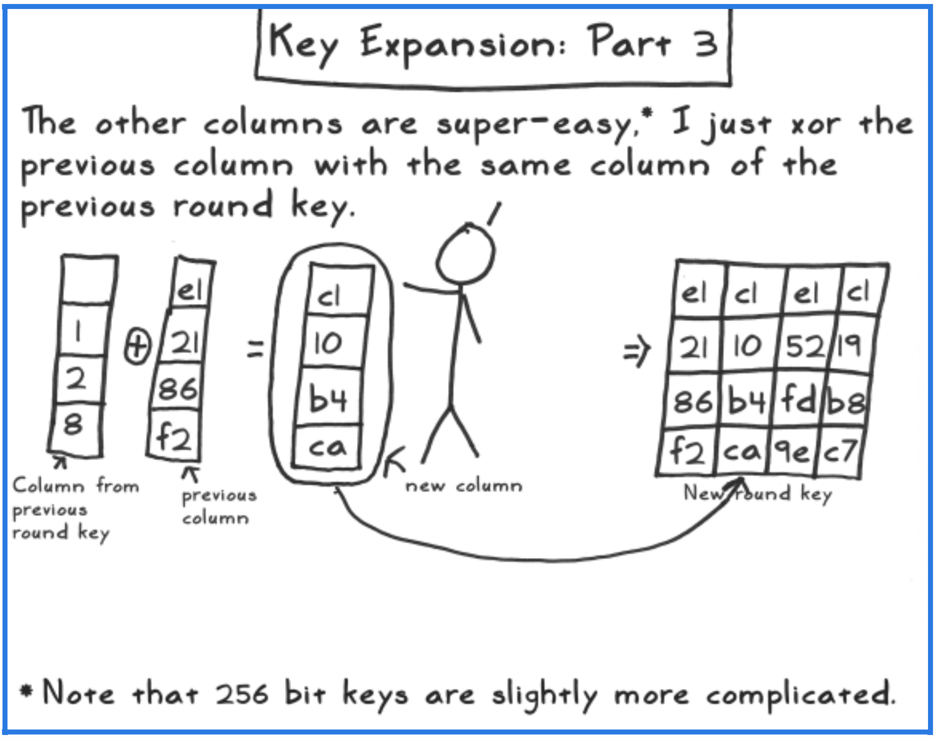

A Tribute to XOR
There's a simple reason why I use xor to apply the key and in other spots: it's fast and cheap – a quick bit flipper. It uses minimal hardware and can be done in parallel since no pesky 'carry' bits are needed.
A
B
Q
AES ♡ ⊕

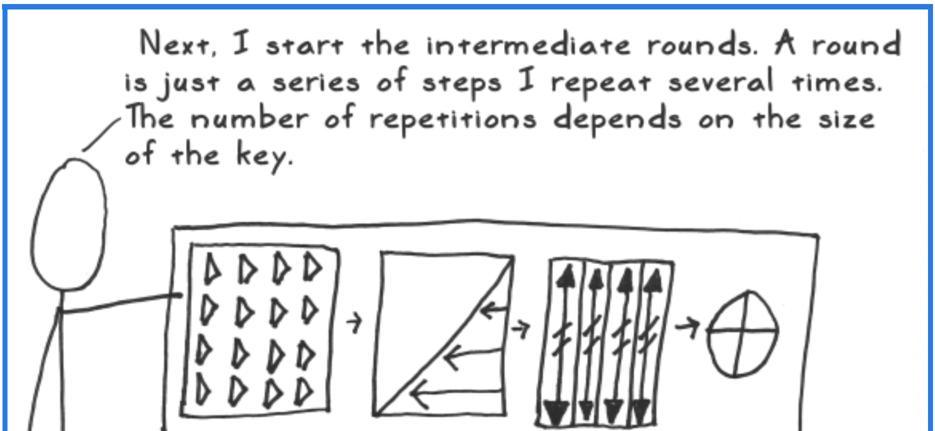


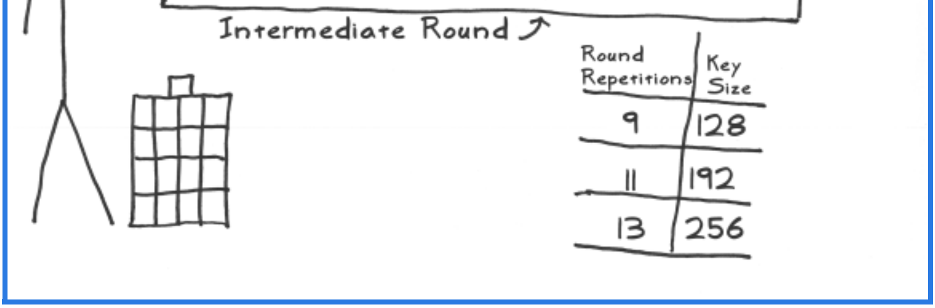

Key Expansion: Part 1
I need lots of keys for use in later rounds. I derive all of them from the initial key using a simple mixing technique that's really fast. Despite its critics,* it's good enough.
S
O 1 B K
M 2 I E
E 8 T Y
Initial Key
e1 c1 e1 c1
21 10 52 19
86 b4 fd b8
f2 ca 9e c7
#1
. . .
ae a6 a0 d4
97 d8 a6 c5
4d 7d 7a d9
ef ed 05 06
#9
3e 98 38 ec
a2 7a dc 19
22 5f 25 fc
a7 4a 4f 49
#10
* By far, most complaints against AES's design focus on this simplicity.

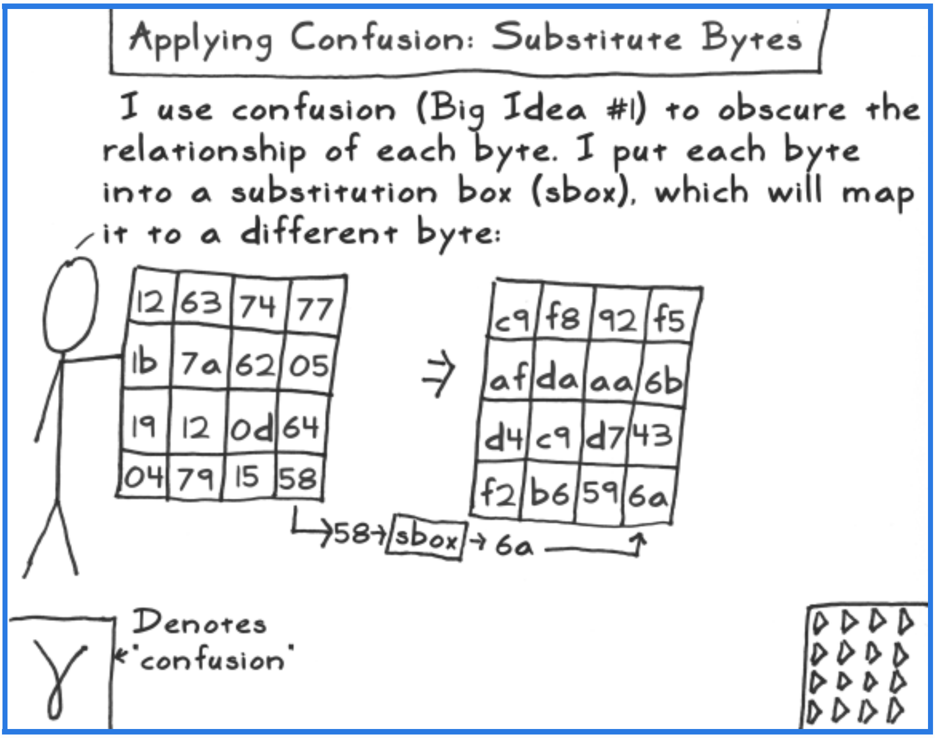

Key Expansion: Part 2a
① I take the last column of the previous round key and move the top byte to the bottom:
S
O 1 B K
M 2 I E
E 8 T Y
K
E
Y
K
E
Y
② Next, I run each byte through a substitution box that will map it to something else:
K
E
Y
b3
6e
cb
b7

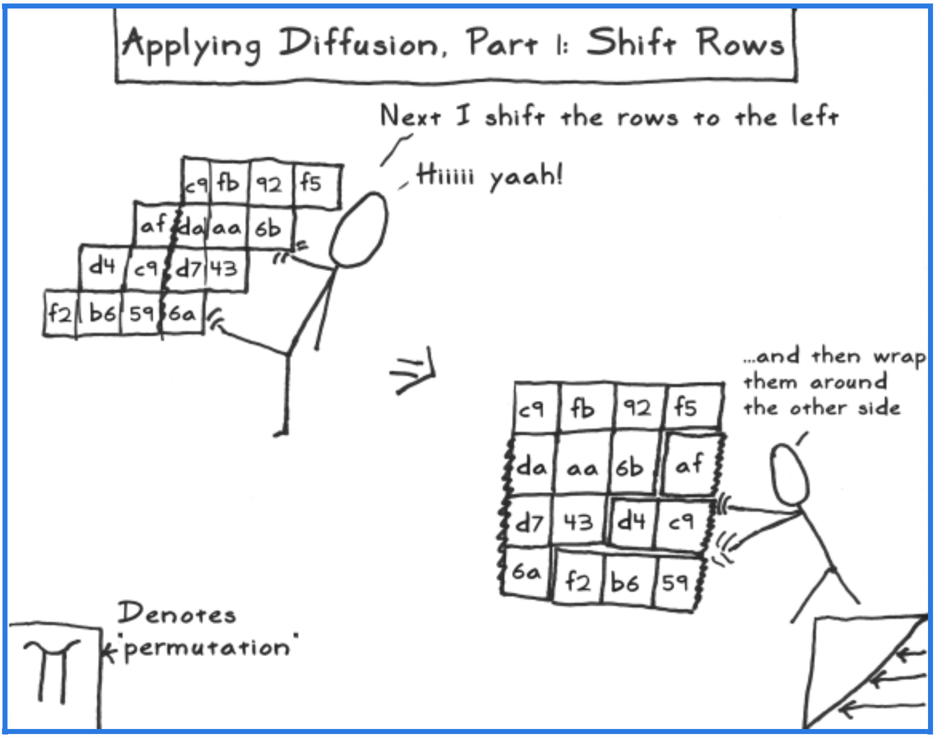

Key Expansion: Part 2b
③ I then xor the column with a 'round constant' that is different for each round.
b3 6e cb b7 ⊕ 01 00 00 00 = b2 6e cb b7
④ Finally, I xor it with the first column of the previous round key:
S O M E
S O M E ⊕ b2 6e cb b7 = e1 21 86 f2
New first column

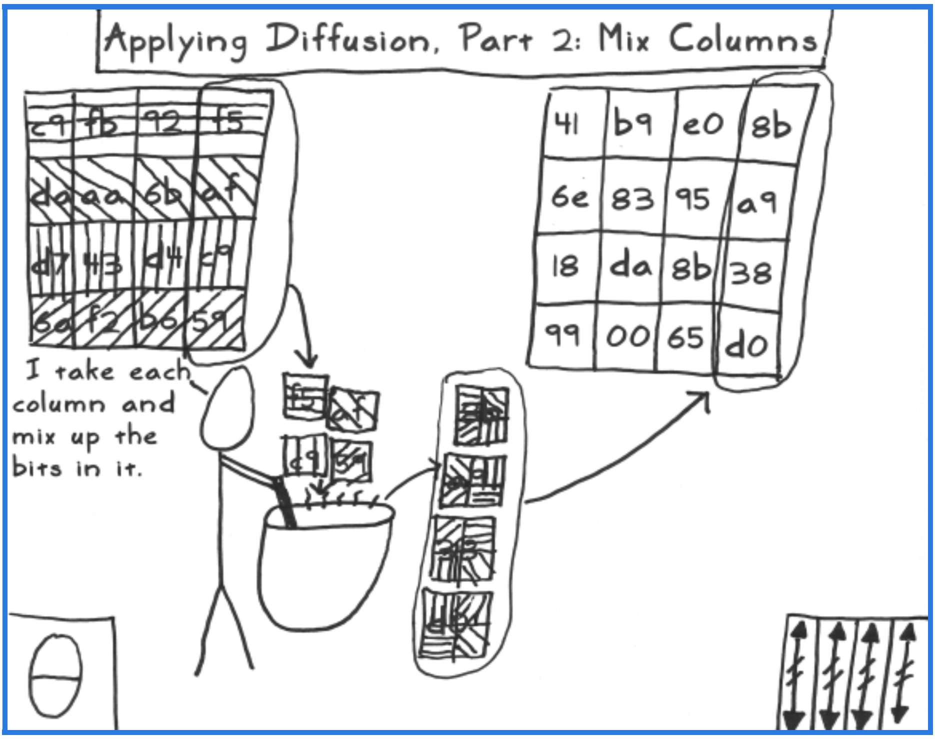

Key Expansion: Part 3
The other columns are super-easy,* I just xor the previous column with the same column of the previous round key.
1 2 8 ⊕ e1 21 86 f2 = c1 10 b4 ca
Column from previous round key
previous column
new column
e1 c1 e1 c1
21 10 52 19
86 b4 fd b8
f2 ca 9e c7
New round key
* Note that 256 bit keys are slightly more complicated.

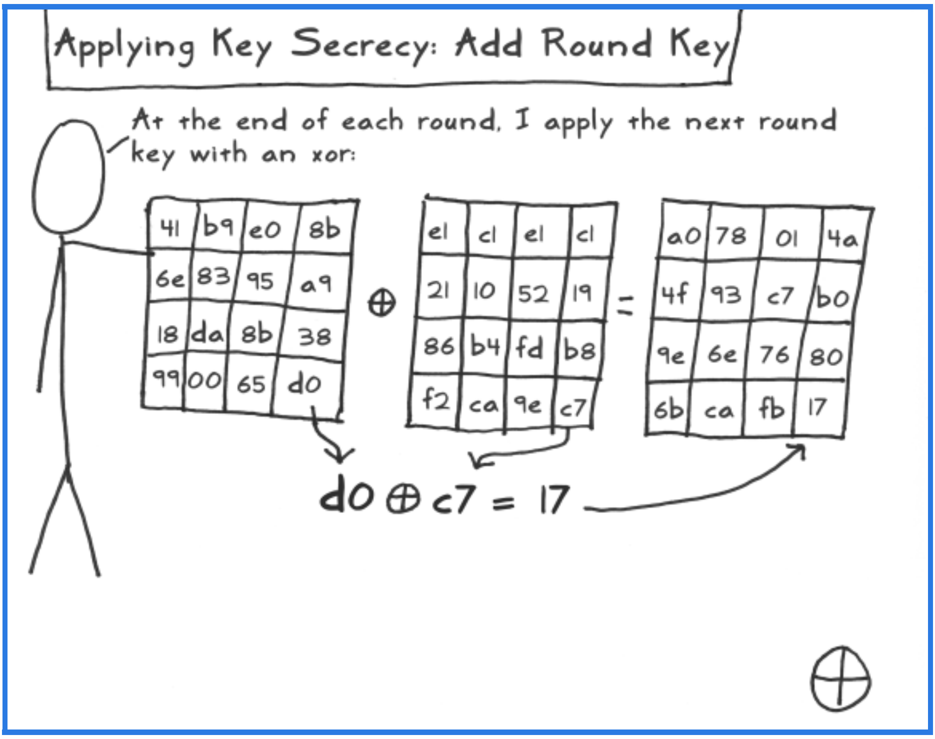

Next, I start the intermediate rounds. A round is just a series of steps I repeat several times. The number of repetitions depends on the size of the key.

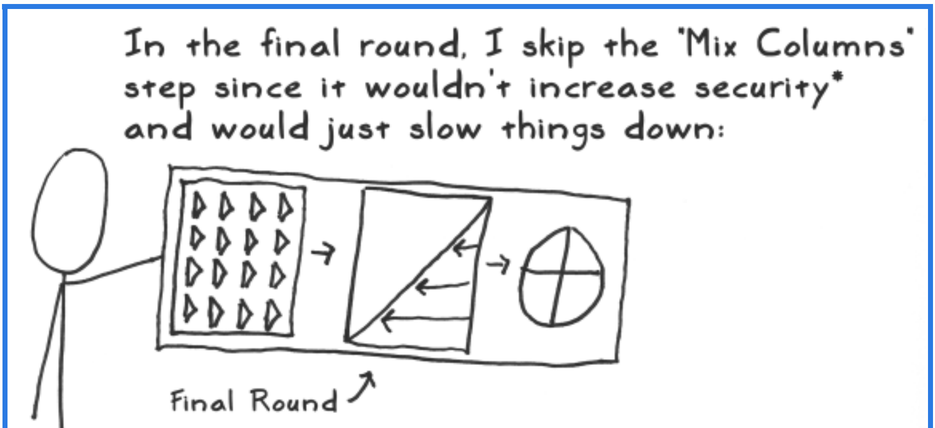

Intermediate Round
Round Repetitions
Key Size
9
128
11
192
13
256


Applying Confusion: Substitute Bytes
I use confusion (Big Idea #1) to obscure the relationship of each byte. I put each byte into a substitution box (sbox), which will map it to a different byte:
12 63 74 77
1b 7a 62 05
19 12 0d 64
04 79 15 58
c9 f8 92 f5
af da aa 6b
d4 c9 d7 43
f2 b6 59 6a
58
sbox
6a
Denotes 'confusion'

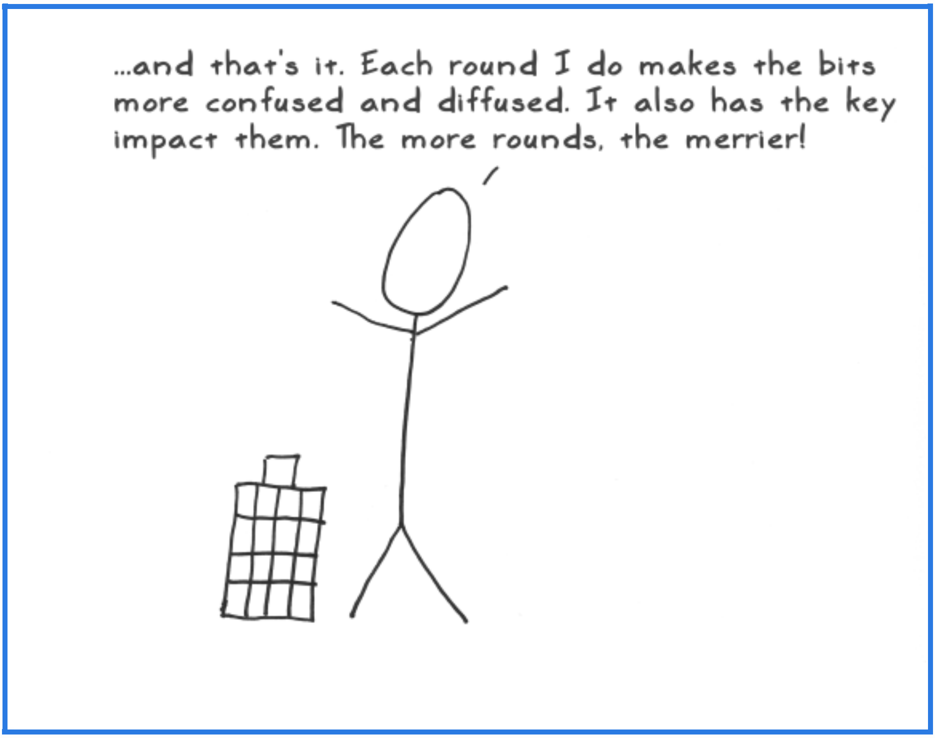

Applying Diffusion, Part 1: Shift Rows
Next I shift the rows to the left
Hiiiii yaah!
c9 fb 92 f5
af da aa 6b
d4 c9 d7 43
f2 b6 59 6a
...and then wrap them around the other side
c9 fb 92 f5
da aa 6b af
d7 43 d4 c9
6a f2 b6 59
Denotes 'permutation'


Applying Diffusion, Part 2: Mix Columns
I take each column and mix up the bits in it.
41 b9 e0 8b
6e 83 95 a9
18 da 8b 38
99 00 65 d0

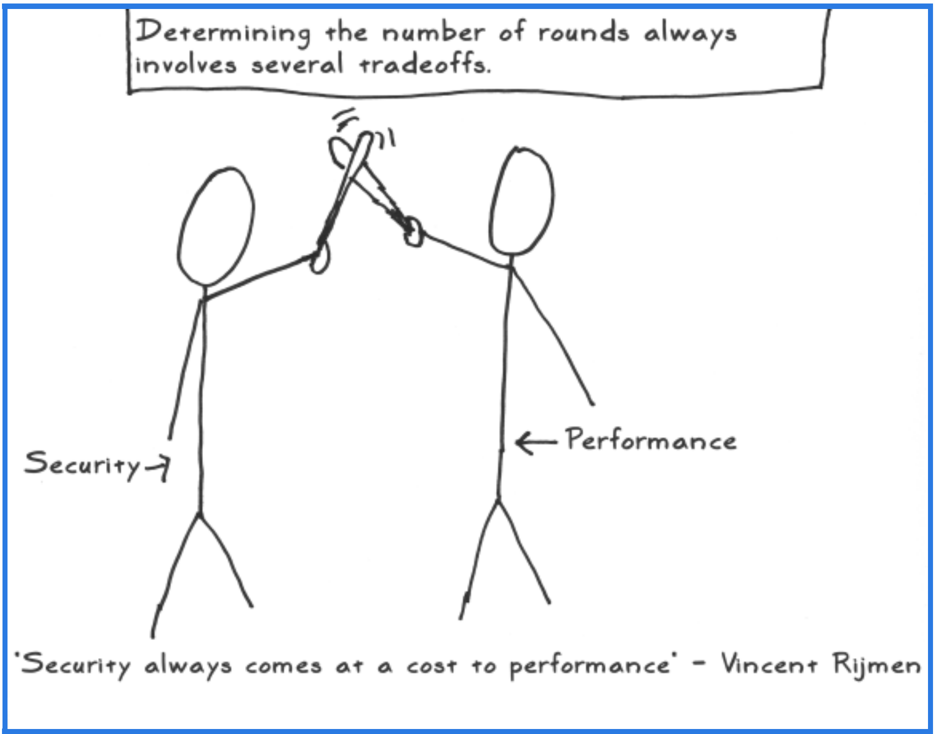

Applying Key Secrecy: Add Round Key
At the end of each round, I apply the next round key with an xor:
41 b9 e0 8b
6e 83 95 a9
18 da 8b 38
99 00 65 d0
e1 c1 e1 c1
21 10 52 19
86 b4 fd b8
f2 ca 9e c7
a0 78 01 4a
4f 93 c7 b0
9e 6e 76 80
6b ca fb 17
d0 ⊕ c7 = 17


In the final round, I skip the "Mix Columns" step since it wouldn't increase security* and would just slow things down:
Final Round

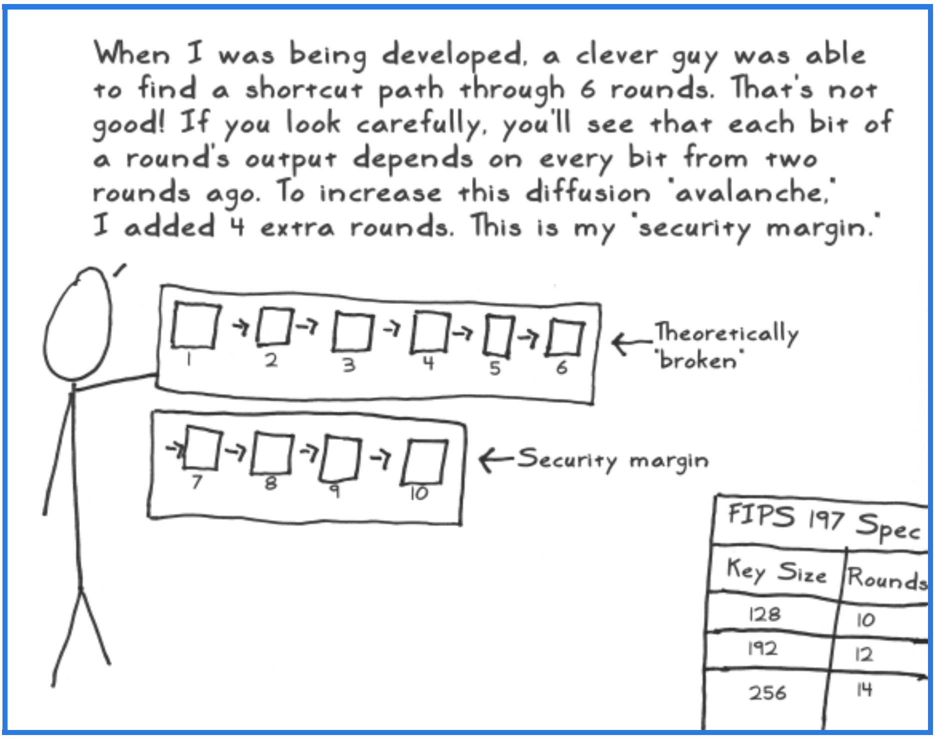
*The diffusion it would provide wouldn't go to the next round.

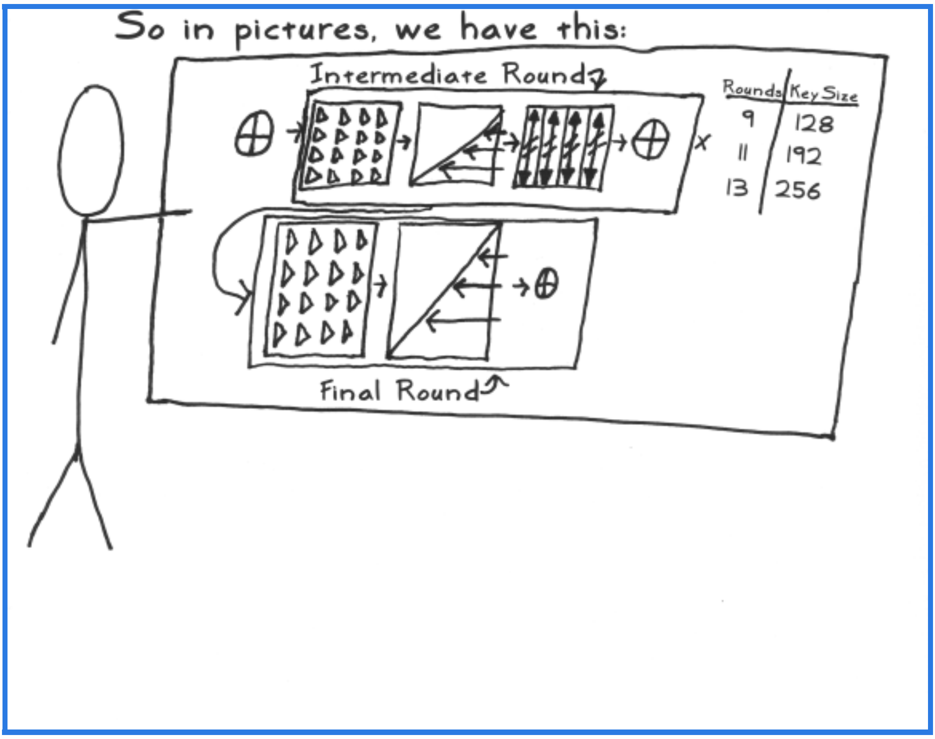


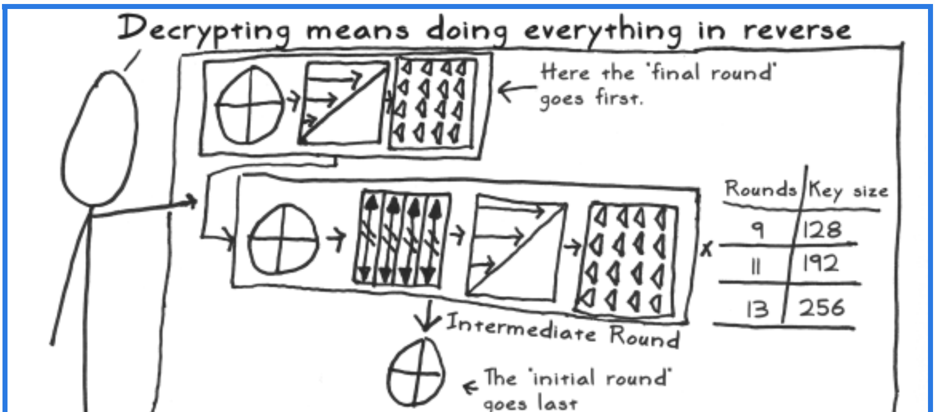
...and that's it. Each round I do makes the bits more confused and diffused. It also has the key impact them. The more rounds, the merrier!

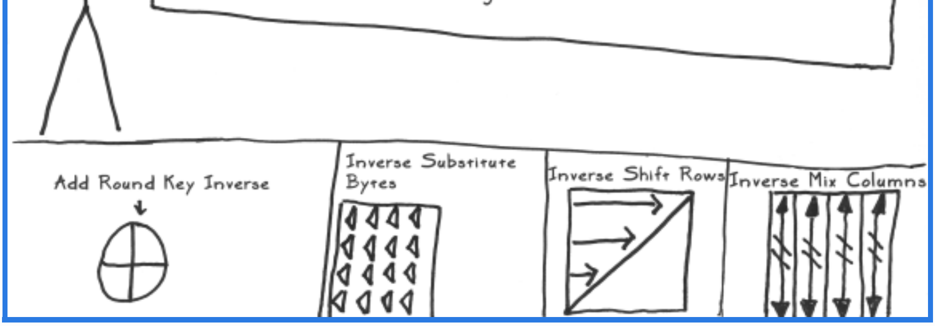


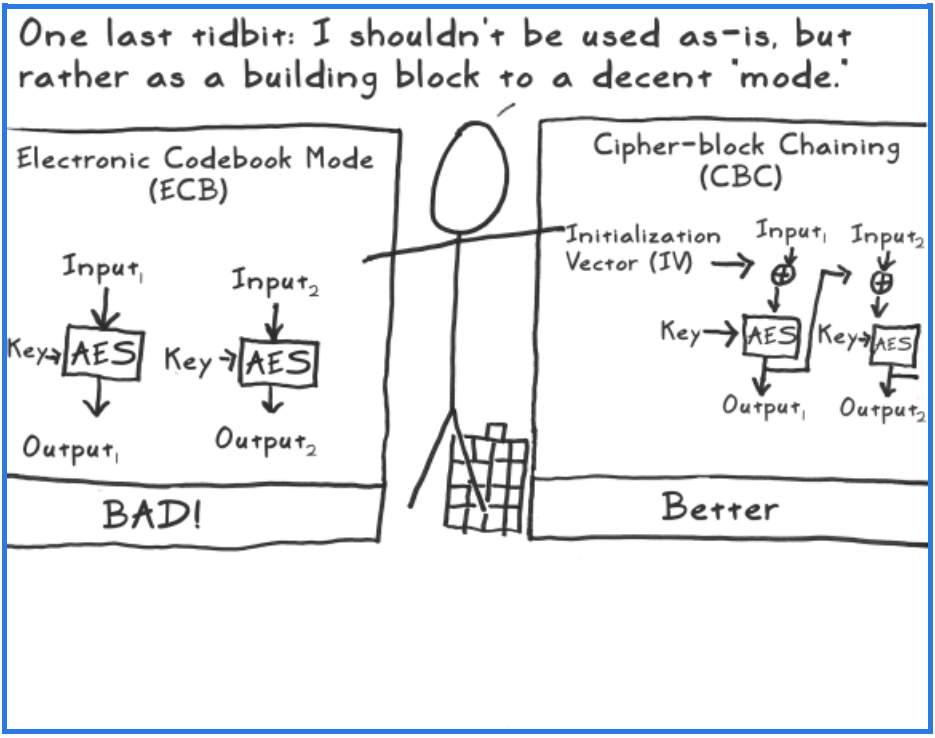
Determining the number of rounds always involves several tradeoffs.
Security
Performance
'Security always comes at a cost to performance' - Vincent Rijmen

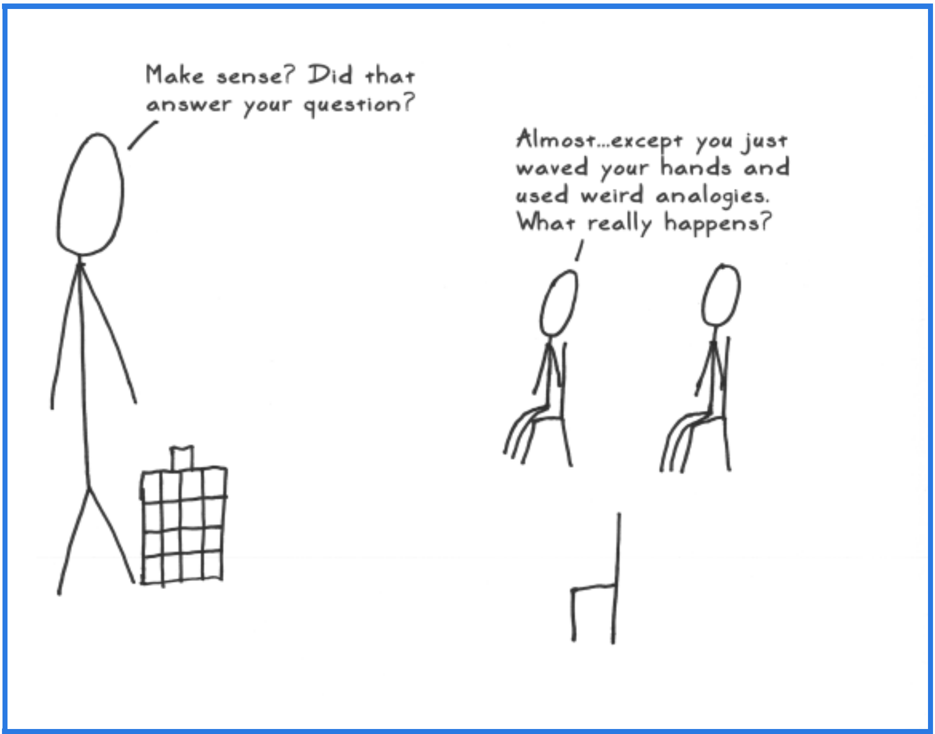

When I was being developed, a clever guy was able to find a shortcut path through 6 rounds. That's not good! If you look carefully, you'll see that each bit of a round's output depends on every bit from two rounds ago. To increase this diffusion 'avalanche,' I added 4 extra rounds. This is my 'security margin.'
1 2 3 4 5 6
Theoretically 'broken'
7 8 9 10
Security margin
FIPS 197 Spec
Key Size | Rounds
128 | 10
192 | 12
256 | 14

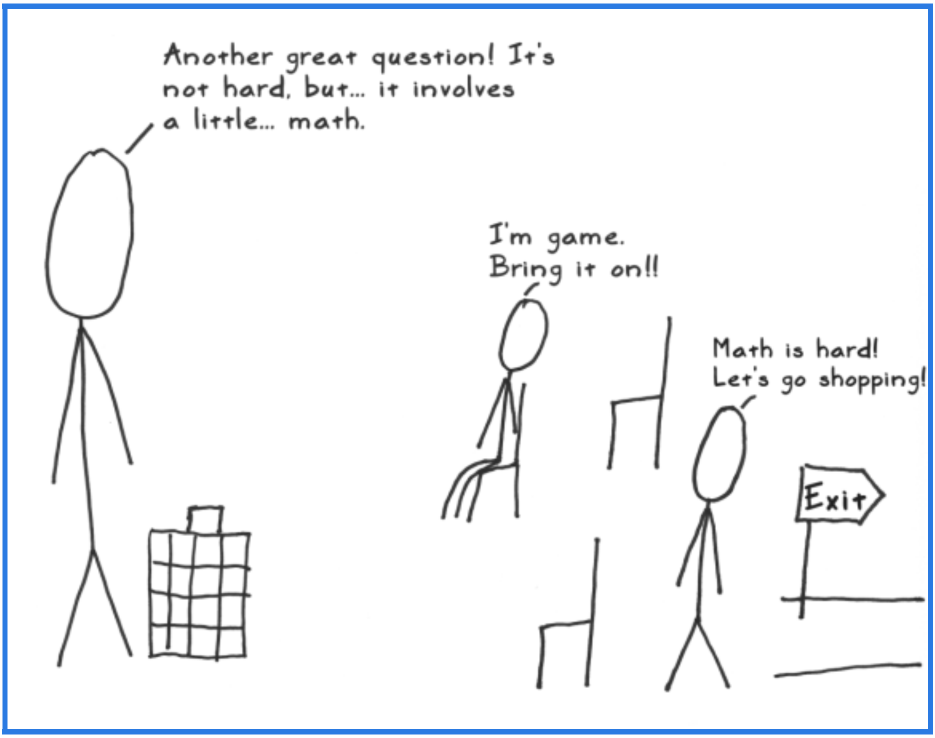

So in pictures, we have this:
Intermediate Rounds
x
Rounds | Key Size
9 | 128
11 | 192
13 | 256
Final Round


Decrypting means doing everything in reverse
Here the 'final round' goes first.
Rounds | Key size
9 | 128
11 | 192
13 | 256
x
Intermediate Round
The 'initial round' goes last

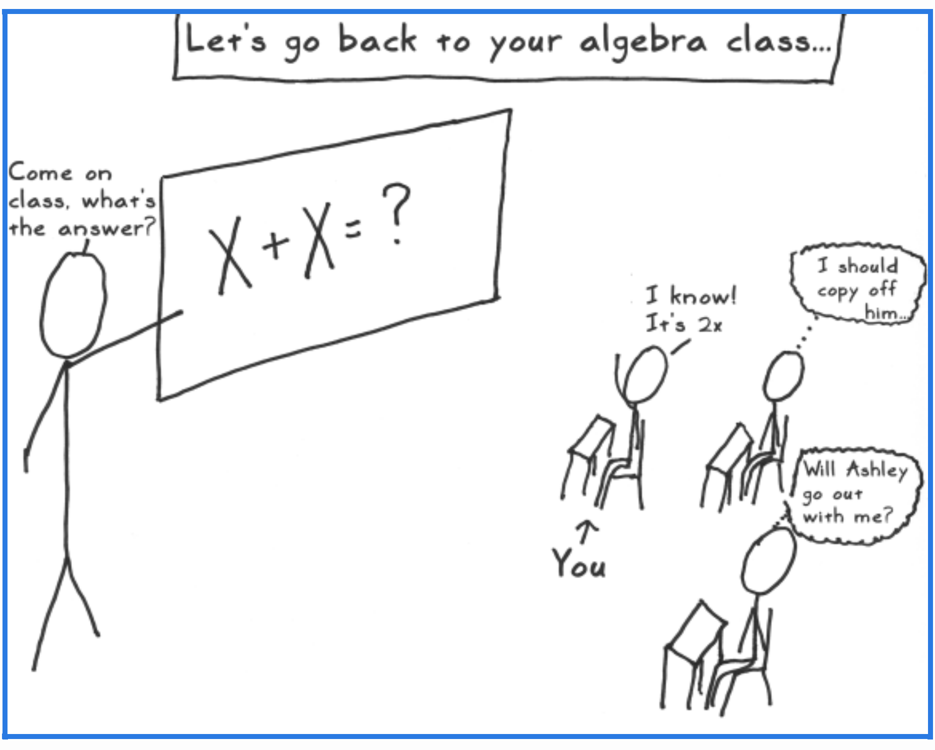

Add Round Key Inverse
Inverse Substitute Bytes
Inverse Shift Rows
Inverse Mix Columns

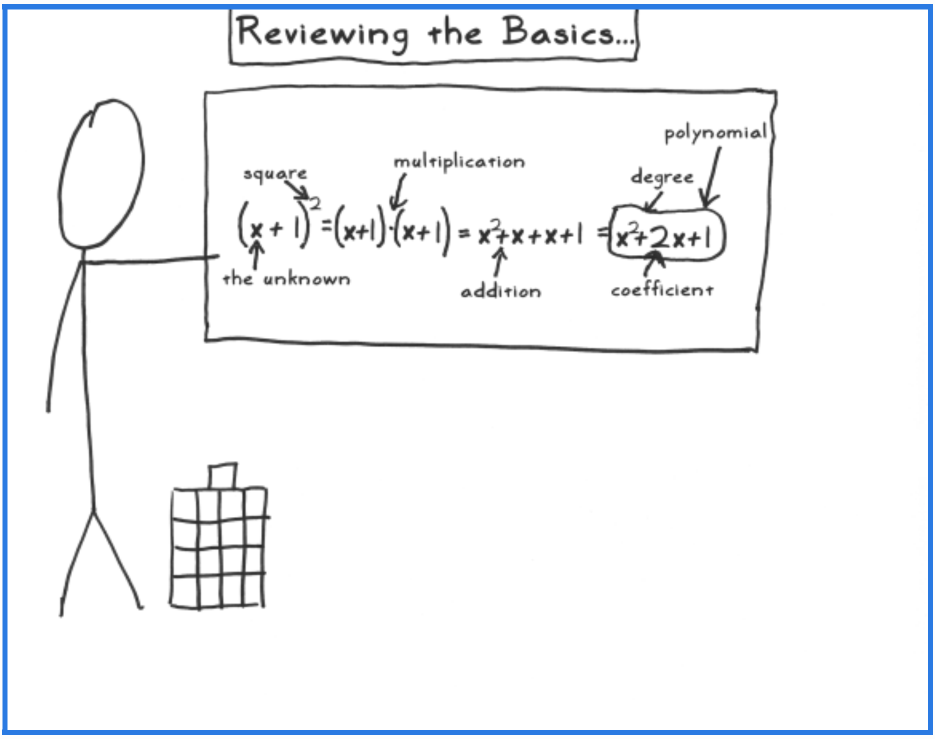

One last tidbit: I shouldn't be used as-is, but rather as a building block to a decent 'mode.'
Electronic Codebook Mode (ECB)
Input$_1$
Key
AES
Output$_1$
Input$_2$
Key
AES
Output$_2$
BAD!
Cipher-block Chaining (CBC)
Initialization Vector (IV)
Input$_1$
Key
AES
Output$_1$
Input$_2$
Key
AES
Output$_2$
Better

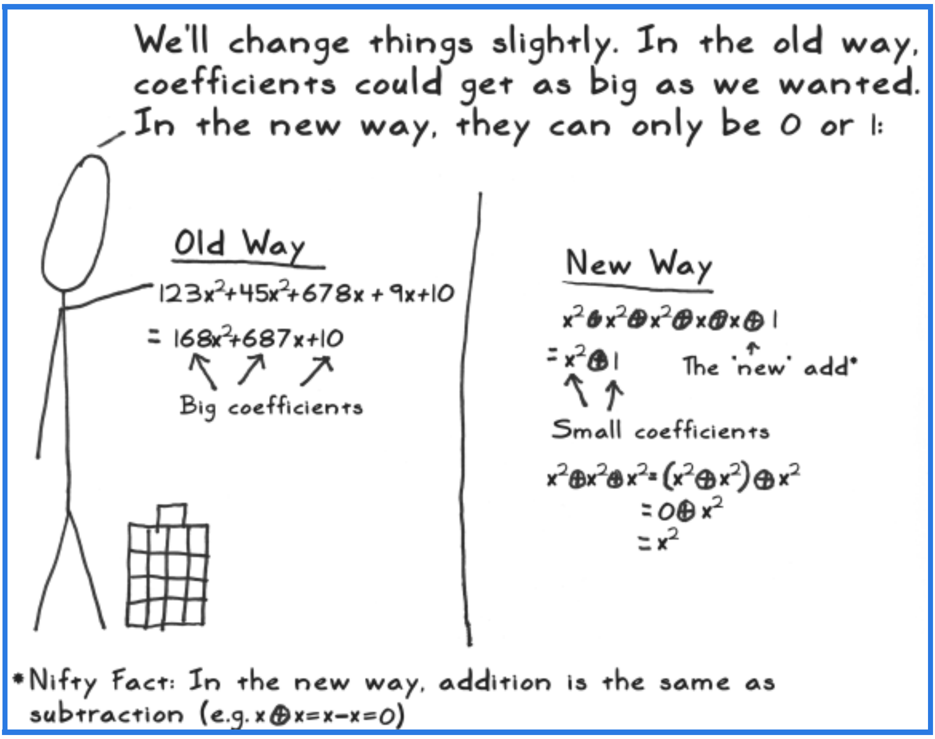

Make sense? Did that answer your question?
Almost...except you just waved your hands and used weird analogies. What really happens?

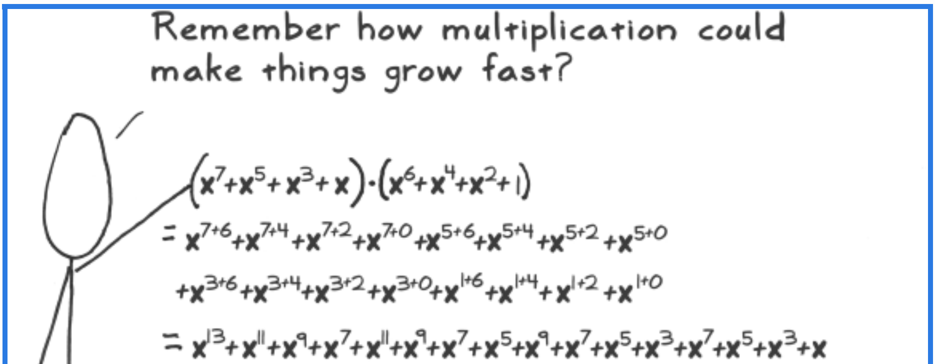

Another great question! It's not hard, but... it involves a little... math.
I'm game. Bring it on!!
Math is hard! Let's go shopping!
Exit

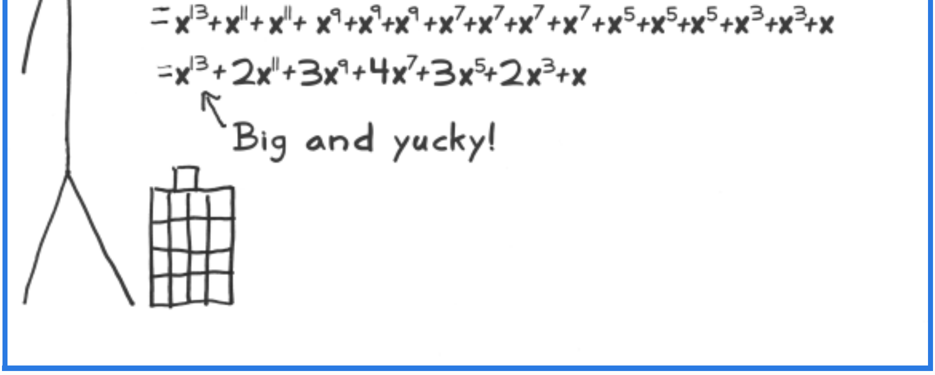
Act 4: Math!

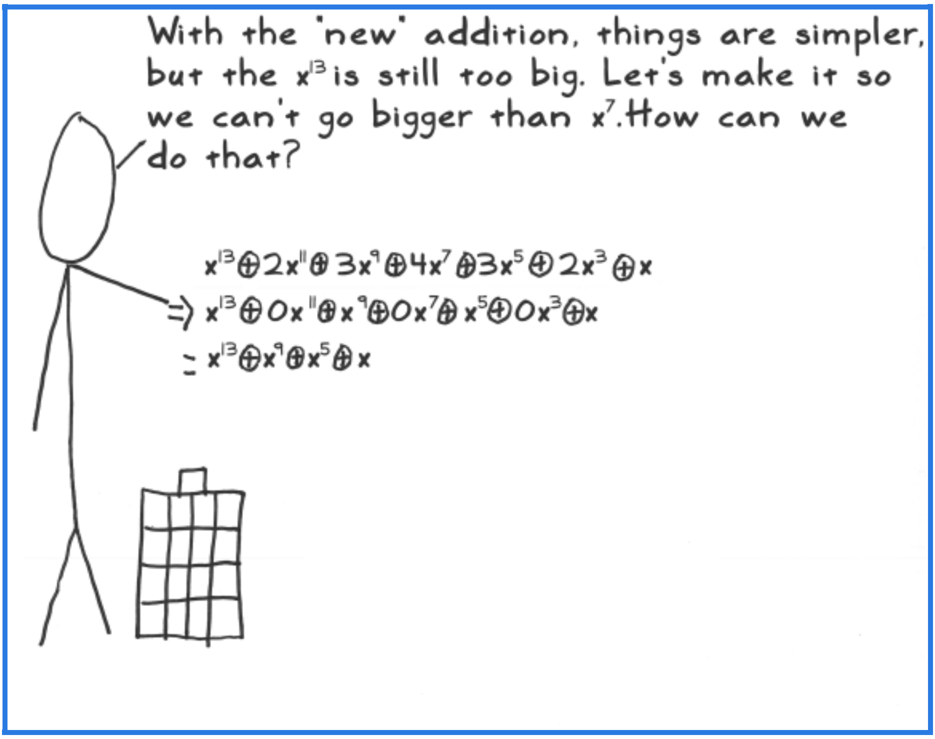

Let's go back to your algebra class...
Come on class, what's the answer?
X+X=?
I know! It's 2x
I should copy off him...
Will Ashley go out with me?
You

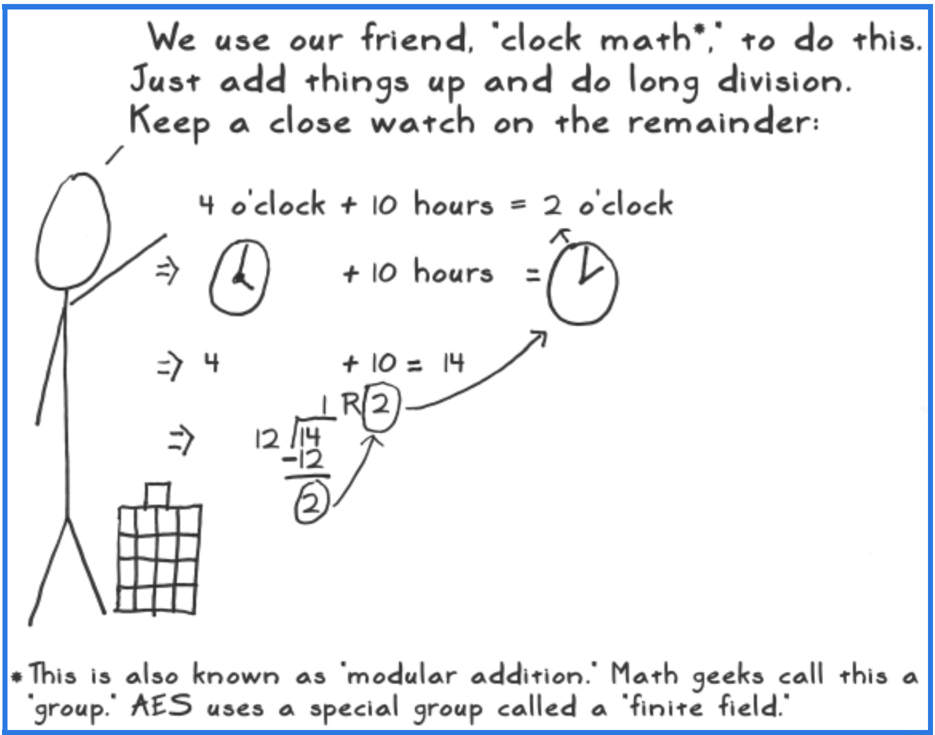

Reviewing the Basics...
polynomial
square
multiplication
degree
$(x+1)^2=(x+1)\cdot(x+1)=x^2+x+x+1=x^2+2x+1$
the unknown
addition
coefficient

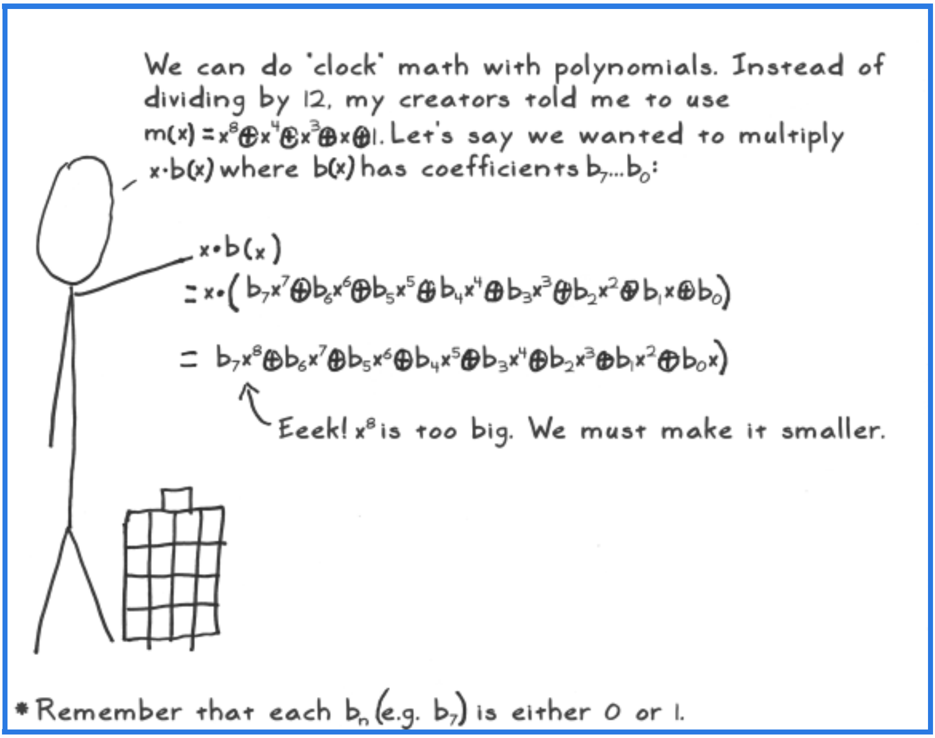

We'll change things slightly. In the old way, coefficients could get as big as we wanted. In the new way, they can only be 0 or 1:
Old Way
$123x^2+45x^2+678x+9x+10$
$=168x^2+687x+10$
Big coefficients
New Way
$x^2\oplus x^2\oplus x^2\oplus x\oplus x\oplus 1$
$=x^2\oplus 1$
The 'new' add*
Small coefficients
$x^2\oplus x^2\oplus x^2=(x^2\oplus x^2)\oplus x^2$
$=0\oplus x^2$
$=x^2$
*Nifty Fact: In the new way, addition is the same as subtraction (e.g. $x\oplus x=x-x=0$)

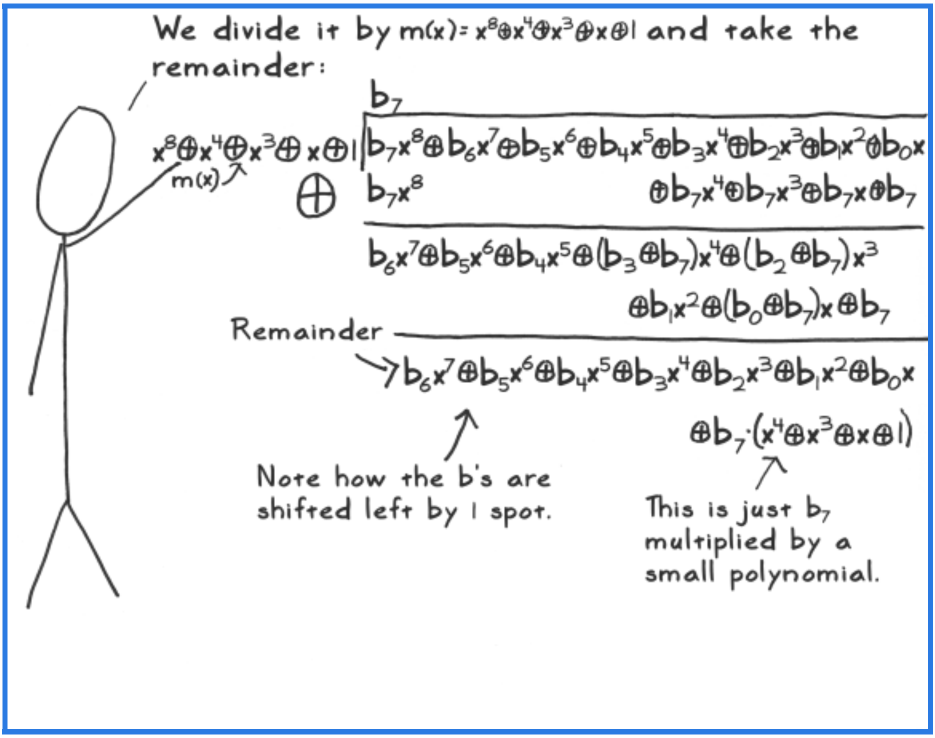

Remember how multiplication could make things grow fast?
$(x^7+x^5+x^3+x)\cdot(x^6+x^4+x^2+1)$
$=x^{7+6}+x^{7+4}+x^{7+2}+x^{7+0}+x^{5+6}+x^{5+4}+x^{5+2}+x^{5+0}$
$+x^{3+6}+x^{3+4}+x^{3+2}+x^{3+0}+x^{1+6}+x^{1+4}+x^{1+2}+x^{1+0}$
$=x^{13}+x^{11}+x^9+x^7+x^{11}+x^9+x^7+x^5+x^9+x^7+x^5+x^3+x^7+x^5+x^3+x$

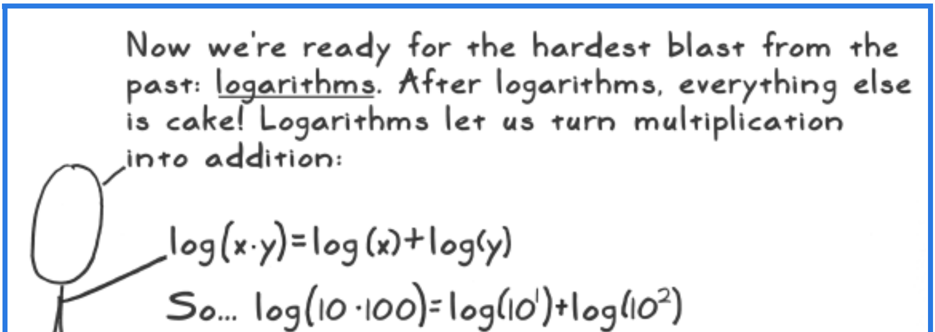

$=x^{13}+x^{11}+x^{11}+x^9+x^9+x^9+x^7+x^7+x^7+x^7+x^5+x^5+x^5+x^3+x^3+x$
$=x^{13}+2x^{11}+3x^9+4x^7+3x^5+2x^3+x$
Big and yucky!


With the 'new' addition, things are simpler, but the x^{13} is still too big. Let's make it so we can't go bigger than x^7. How can we do that?
$x^{13} \oplus 2x^{11} \oplus 3x^9 \oplus 4x^7 \oplus 3x^5 \oplus 2x^3 \oplus x$
$\Rightarrow x^{13} \oplus 0x^{11} \oplus x^9 \oplus 0x^7 \oplus x^5 \oplus 0x^3 \oplus x$
$= x^{13} \oplus x^9 \oplus x^5 \oplus x$


We use our friend, "clock math*," to do this. Just add things up and do long division. Keep a close watch on the remainder:
4 o'clock + 10 hours = 2 o'clock
+ 10 hours =
$\Rightarrow 4 + 10 = 14$
$12 \overline{)14}$ 1 R 2
-12
2
* This is also known as 'modular addition.' Math geeks call this a 'group.' AES uses a special group called a 'finite field.'


We can do 'clock' math with polynomials. Instead of dividing by 12, my creators told me to use $m(x) = x^8 \oplus x^4 \oplus x^3 \oplus x \oplus 1$. Let's say we wanted to multiply $x \cdot b(x)$ where $b(x)$ has coefficients $b_7 \ldots b_0$:
$x \cdot b(x)$
$= x \cdot (b_7x^7 \oplus b_6x^6 \oplus b_5x^5 \oplus b_4x^4 \oplus b_3x^3 \oplus b_2x^2 \oplus b_1x \oplus b_0)$
$= b_7x^8 \oplus b_6x^7 \oplus b_5x^6 \oplus b_4x^5 \oplus b_3x^4 \oplus b_2x^3 \oplus b_1x^2 \oplus b_0x)$
Eeek! x^8 is too big. We must make it smaller.
* Remember that each b_n (e.g. b_7) is either 0 or 1.


We divide it by $m(x) = x^8 \oplus x^4 \oplus x^3 \oplus x \oplus 1$ and take the remainder:
b_7
$x^8 \oplus x^4 \oplus x^3 \oplus x \oplus 1$
$b_7x^8 \oplus b_6x^7 \oplus b_5x^6 \oplus b_4x^5 \oplus b_3x^4 \oplus b_2x^3 \oplus b_1x^2 \oplus b_0x$
m(x)
$\oplus$
$b_7x^8 \oplus b_7x^4 \oplus b_7x^3 \oplus b_7x \oplus b_7$
$b_6x^7 \oplus b_5x^6 \oplus b_4x^5 \oplus (b_3 \oplus b_7)x^4 \oplus (b_2 \oplus b_7)x^3 \oplus b_1x^2 \oplus (b_0 \oplus b_7)x \oplus b_7$
Remainder
$b_6x^7 \oplus b_5x^6 \oplus b_4x^5 \oplus b_3x^4 \oplus b_2x^3 \oplus b_1x^2 \oplus b_0x \oplus b_7 \cdot (x^4 \oplus x^3 \oplus x \oplus 1)$
Note how the b's are shifted left by 1 spot.
This is just b_7 multiplied by a small polynomial.


Now we're ready for the hardest blast from the past: logarithms. After logarithms, everything else is cake! Logarithms let us turn multiplication into addition:
$\log(x \cdot y) = \log(x) + \log(y)$
So... $\log(10 \cdot 100) = \log(10^1) + \log(10^2)$

$$= 2 + 1 = 3$$

In reverse:

$$\log^{-1}(1) = 10^{1} = 10$$
$$\log^{-1}(2) = 10^{2} = 100$$
$$\log^{-1}(3) = 10^{3} = 1{,}000$$

$$\Rightarrow 10 \cdot 100 = 1{,}000$$

We can use logarithms in our new world. Instead of using 10 as the base, we can use the simple polynomial of $x \oplus 1$ and watch the magic unravel.*

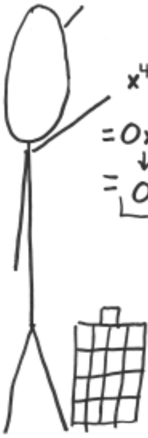
$$(x \oplus 1)^{1} = x \oplus 1$$
$$(x \oplus 1)^{2} = (x \oplus 1)(x \oplus 1) = x^{2} \oplus x \oplus x \oplus 1 = x^{2} \oplus 1$$
$$(x \oplus 1)^{3} = (x \oplus 1)^{2} \cdot (x \oplus 1) = x^{3} \oplus x^{2} \oplus x \oplus 1$$

So...

$$\log_{x \oplus 1}(x \oplus 1) = 1, \ \log_{x \oplus 1}(x^{2} \oplus 1) = 2, \ \log_{x \oplus 1}(x^{3} \oplus x^{2} \oplus x \oplus 1) = 3$$

*If you keep multiplying by $(x \oplus 1)$ and then take the remainder after dividing by $m(x)$, you'll see that you generate all possible polynomial below x^{8}. This is very important!

Why bother with all of this math?* Encryption deals with bits and bytes, right? Well, there's one last connection: a 7^{th} degree polynomial can be represented in exactly 1 byte since the new way uses only 0 or 1 for coefficients:

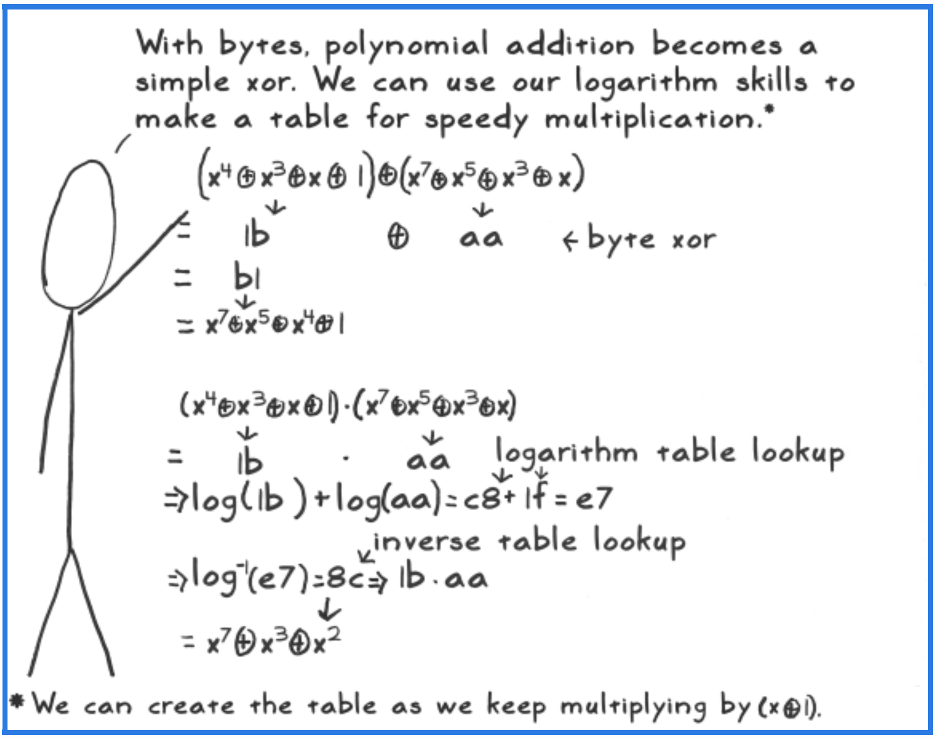


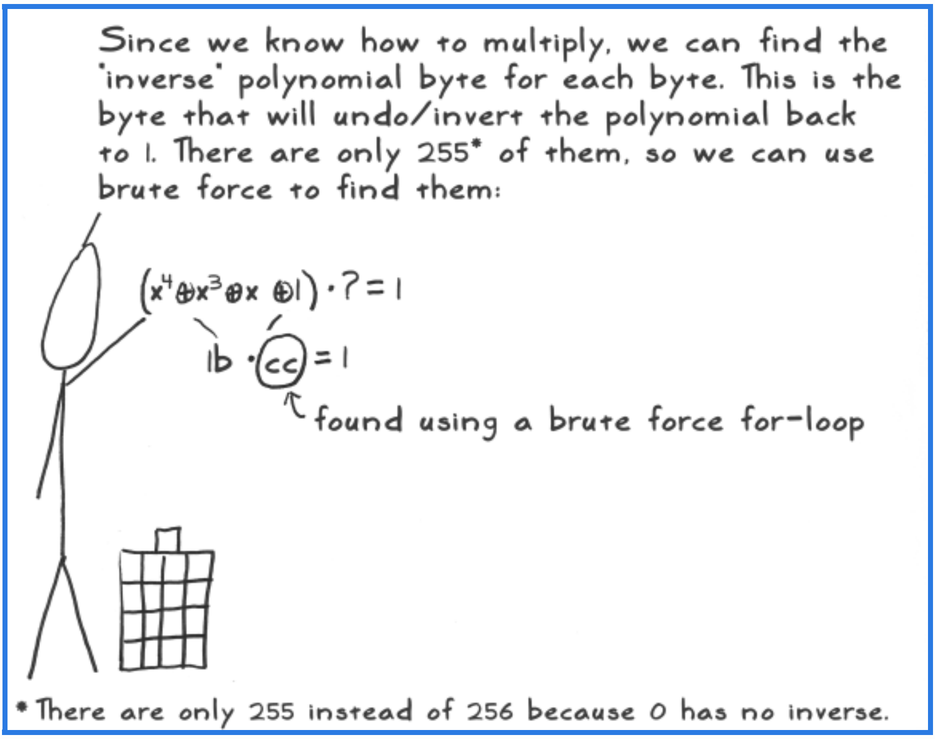
$$x^{4} \oplus x^{3} \oplus x \oplus 1$$
$$= 0x^{7} \oplus 0x^{6} \oplus 0x^{5} \oplus 1x^{4} \oplus 1x^{3} \oplus 0x^{2} \oplus 1x \oplus 1$$
$$= \underbrace{0\ 0\ 0\ 1}_{1}\ \underbrace{1\ 0\ 1\ 1}_{1011_2 = 11_{10} = b_{16}}$$

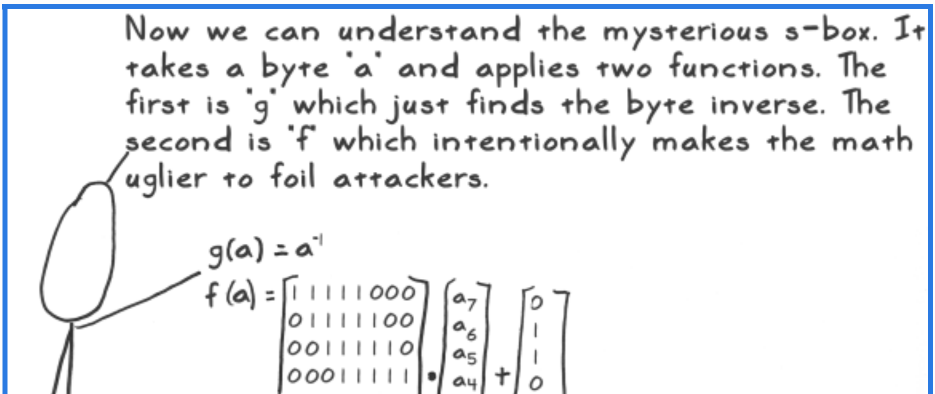
$1011_2 = 11_{10} = b_{16}$ ← hexadecimal

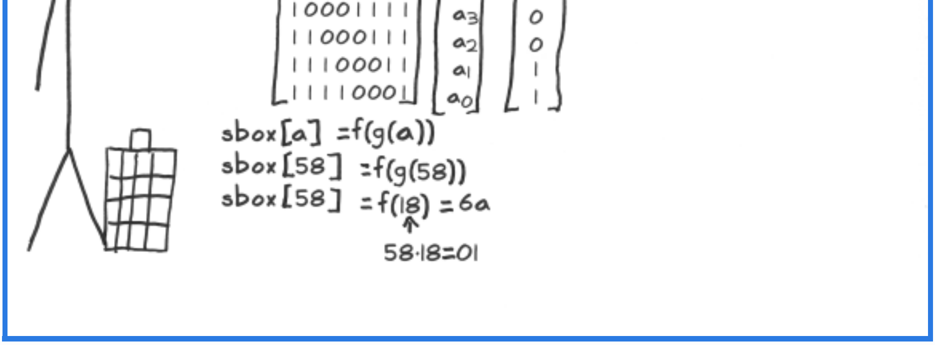
$= 1b$ ↖ A single byte!!

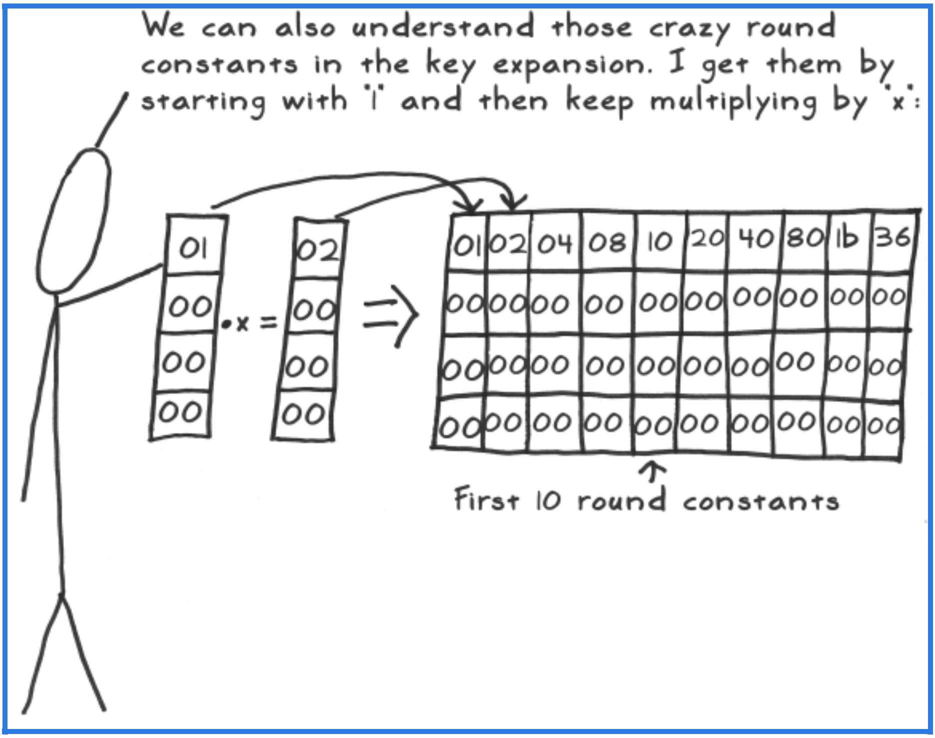
*Although we'll work with bytes from now on, the math makes sure everything works out.

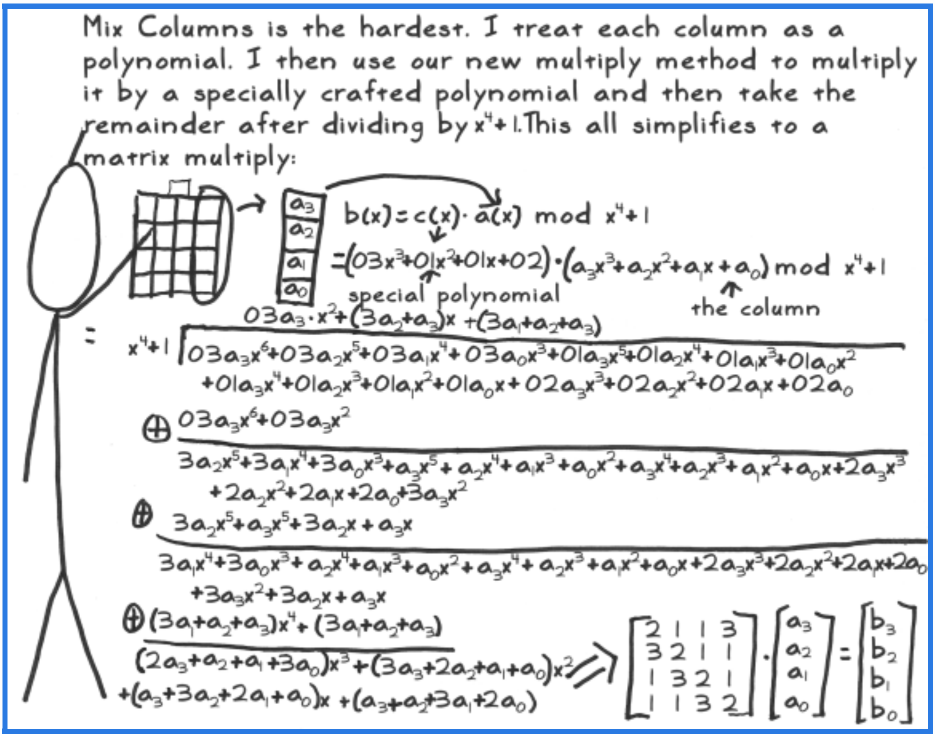

With bytes, polynomial addition becomes a simple xor. We can use our logarithm skills to make a table for speedy multiplication.*
$(x^4 \oplus x^3 \oplus x \oplus 1) \oplus (x^7 \oplus x^5 \oplus x^3 \oplus x)$
$= 1b \oplus aa$
← byte xor
$= b1$
$= x^7 \oplus x^5 \oplus x^4 \oplus 1$
$(x^4 \oplus x^3 \oplus x \oplus 1) \cdot (x^7 \oplus x^5 \oplus x^3 \oplus x)$
$= 1b \cdot aa$
logarithm table lookup
$\Rightarrow \log(1b) + \log(aa) = c8 + 1f = e7$
inverse table lookup
$\Rightarrow \log^{-1}(e7) = 8c \Rightarrow 1b \cdot aa$
$= x^7 \oplus x^3 \oplus x^2$
* We can create the table as we keep multiplying by $(x \oplus 1)$.

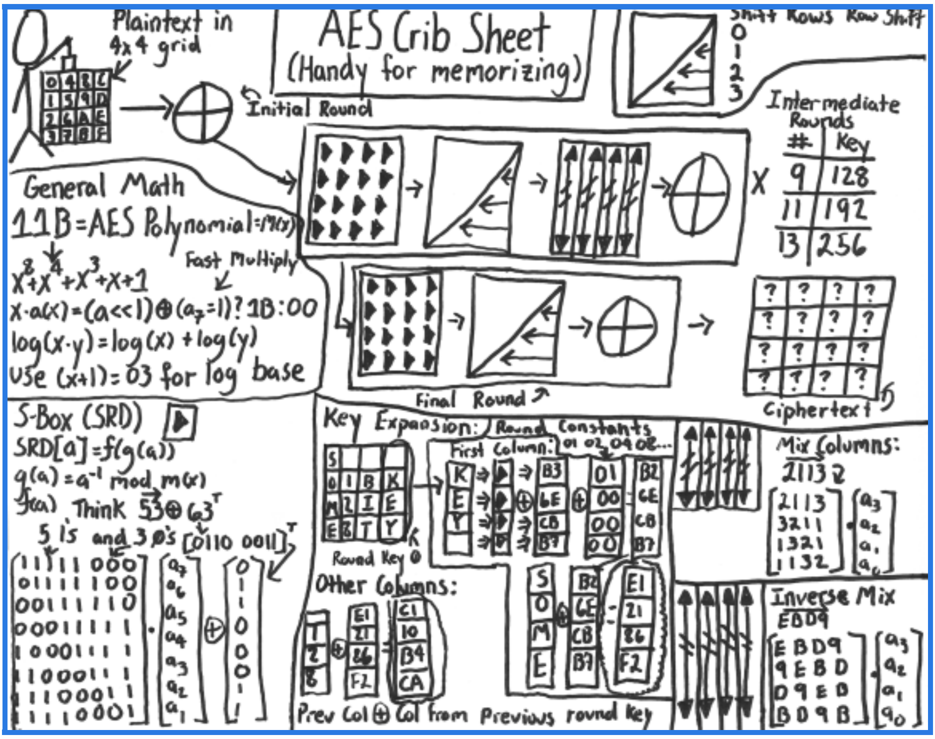

Since we know how to multiply, we can find the 'inverse' polynomial byte for each byte. This is the byte that will undo/invert the polynomial back to 1. There are only 255* of them, so we can use brute force to find them:
$(x^4 \oplus x^3 \oplus x \oplus 1) \cdot ? = 1$
$1b \cdot cc = 1$
found using a brute force for-loop
* There are only 255 instead of 256 because 0 has no inverse.

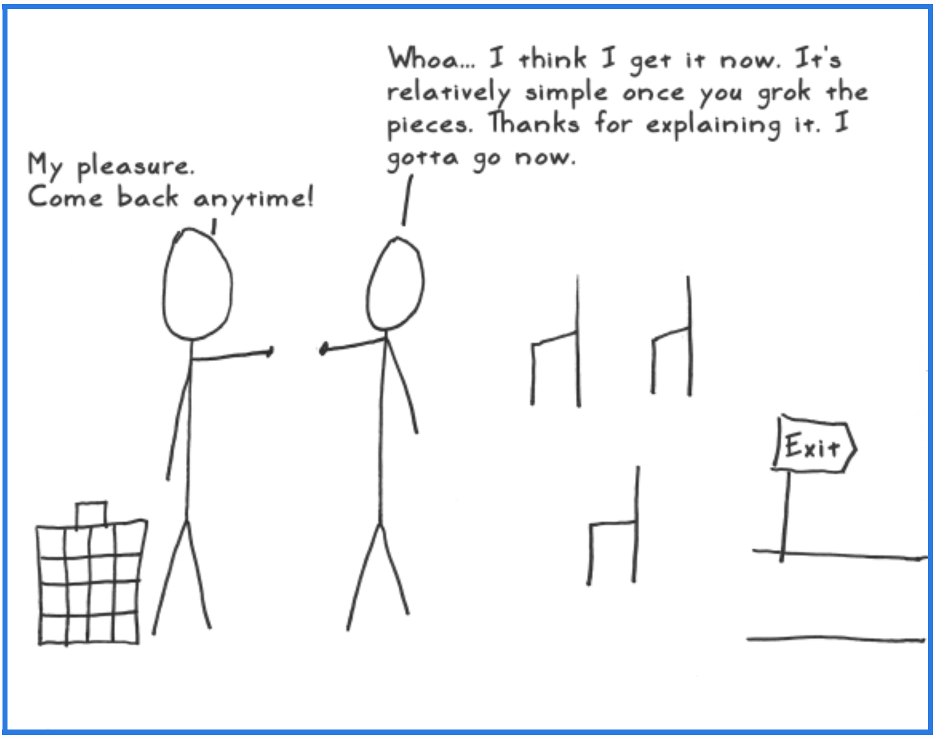

Now we can understand the mysterious s-box. It takes a byte 'a' and applies two functions. The first is 'g' which just finds the byte inverse. The second is 'f' which intentionally makes the math uglier to foil attackers.
$g(a) = a^{-1}$
$f(a) = \begin{bmatrix} 11111000 \\ 01111100 \\ 00111110 \\ 00011111 \end{bmatrix} \cdot \begin{bmatrix} a_7 \\ a_6 \\ a_5 \\ a_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$

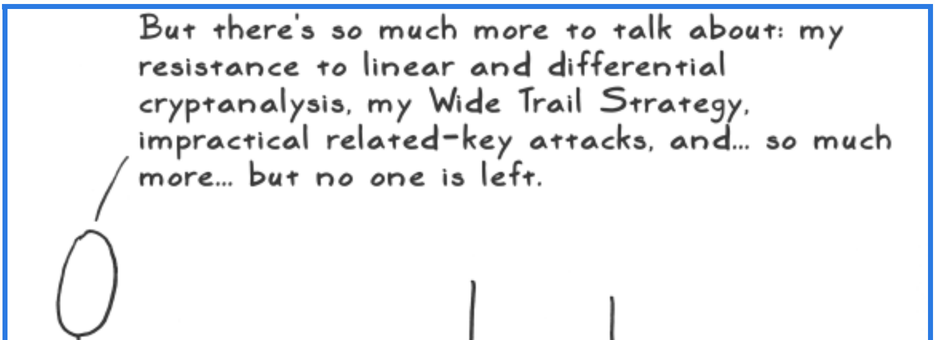

10001111 | a_3 | 0
11000111 | a_2 | 0
11100011 | a_1 | 1
11110001 | a_0 | 1
sbox[a] =f(g(a))
sbox[58] =f(g(58))
sbox[58] =f(18) =6a
58·18=01

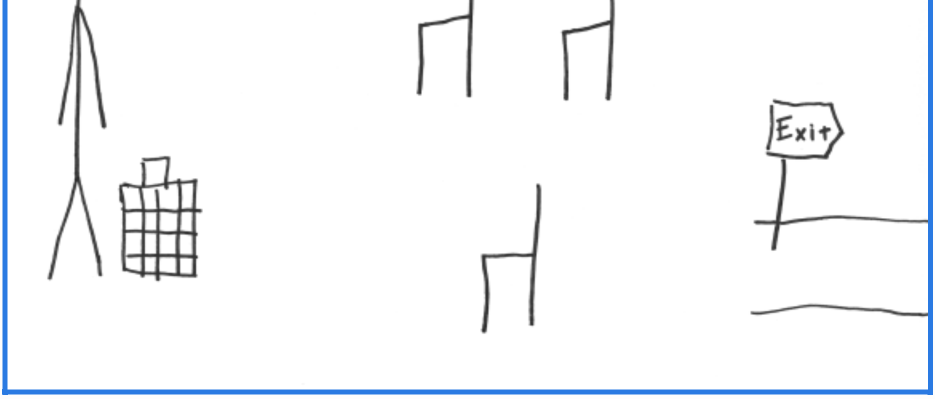

We can also understand those crazy round constants in the key expansion. I get them by starting with '1' and then keep multiplying by 'x':
01 00 00 00 •x = 02 00 00 00
01 02 04 08 10 20 40 80 1b 36
00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00
First 10 round constants

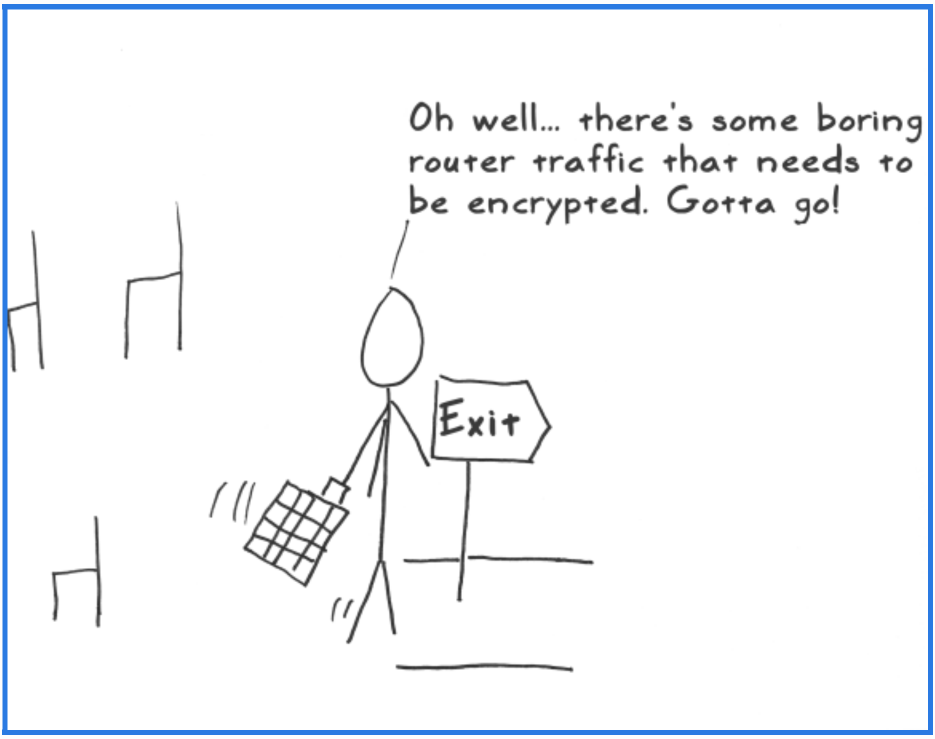

Mix Columns is the hardest. I treat each column as a polynomial. I then use our new multiply method to multiply it by a specially crafted polynomial and then take the remainder after dividing by x^4+1. This all simplifies to a matrix multiply:
a_3 a_2 a_1 a_0
$b(x)=c(x)\cdot a(x) \bmod x^4+1$
$=(03x^3+01x^2+01x+02)\cdot(a_3x^3+a_2x^2+a_1x+a_0) \bmod x^4+1$
special polynomial
the column
$03a_3\cdot x^2+(3a_2+a_3)x+(3a_1+a_2+a_3)$
$= x^4+1 \,\overline{)\, 03a_3x^6+03a_2x^5+03a_1x^4+03a_0x^3+01a_3x^5+01a_2x^4+01a_1x^3+01a_0x^2}$
$+01a_3x^4+01a_2x^3+01a_1x^2+01a_0x+02a_3x^3+02a_2x^2+02a_1x+02a_0$
$\oplus\ 03a_3x^6+03a_3x^2$
$3a_2x^5+3a_1x^4+3a_0x^3+a_3x^5+a_2x^4+a_1x^3+a_0x^2+a_3x^4+a_2x^3+a_1x^2+a_0x+2a_3x^3$
$+2a_2x^2+2a_1x+2a_0+3a_3x^2$
$\oplus\ 3a_2x^5+a_3x^5+3a_2x+a_3x$
$3a_1x^4+3a_0x^3+a_2x^4+a_1x^3+a_0x^2+a_3x^4+a_2x^3+a_1x^2+a_0x+2a_3x^3+2a_2x^2+2a_1x+2a_0$
$+3a_3x^2+3a_2x+a_3x$
$\oplus\ (3a_1+a_2+a_3)x^4+(3a_1+a_2+a_3)$
$(2a_3+a_2+a_1+3a_0)x^3+(3a_3+2a_2+a_1+a_0)x^2$
$+(a_3+3a_2+2a_1+a_0)x+(a_3+a_2+3a_1+2a_0)$
$\Rightarrow \begin{bmatrix}2&1&1&3\\3&2&1&1\\1&3&2&1\\1&1&3&2\end{bmatrix}\cdot\begin{bmatrix}a_3\\a_2\\a_1\\a_0\end{bmatrix}=\begin{bmatrix}b_3\\b_2\\b_1\\b_0\end{bmatrix}$

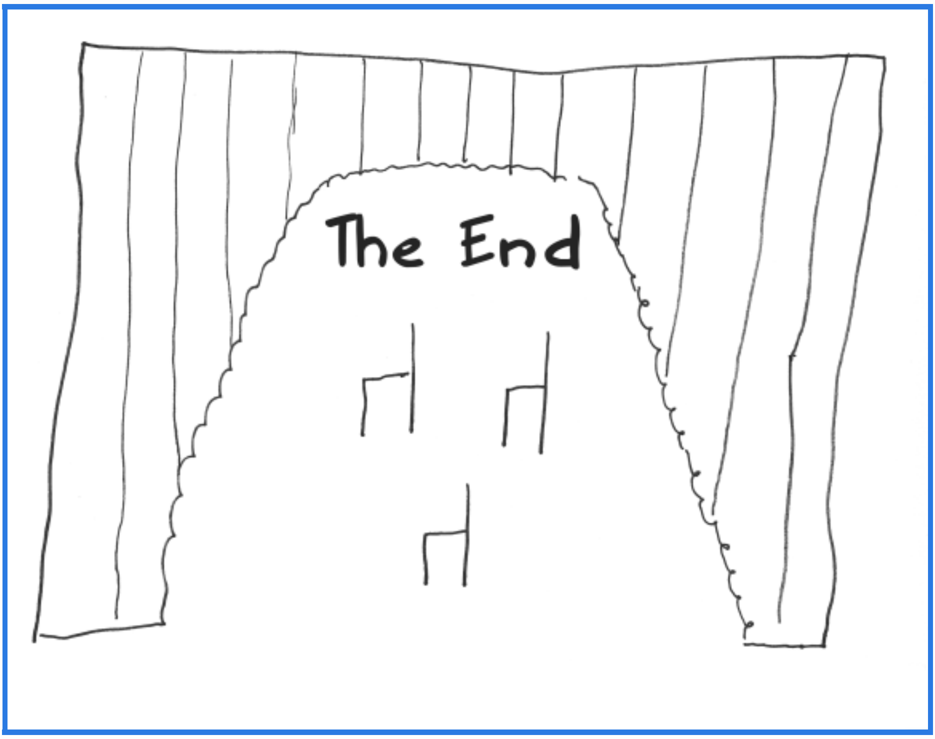

Plaintext in 4x4 grid
AES Crib Sheet
(Handy for memorizing)
Shift Rows Row Shift
0
1
2
3
Initial Round
Intermediate Rounds
Key
9 128
11 192
13 256
General Math
11B=AES Polynomial=m(x)
Fast Multiply
x^8+x^4+x^3+x+1
x·a(x)=(a<<1)⊕(a7=1)?1B:00
log(x·y)=log(x)+log(y)
Use (x+1)=03 for log base
Final Round
Ciphertext
S-Box (SRD)
SRD[a]=f(g(a))
g(a)=a^-1 mod m(x)
f(a) Think 53⊕63^T
5 1's and 3 0's [0110 0011]^T
Key Expansion:
Round Constants
First Column:
01 02 04 08...
Round Key 0
Other Columns:
Prev Col ⊕ Col from Previous round key
Mix Columns:
2113
Inverse Mix
EBD9
Exit


Whoa... I think I get it now. It's relatively simple once you grok the pieces. Thanks for explaining it. I gotta go now.
My pleasure.
Come back anytime!
Exit


But there's so much more to talk about: my resistance to linear and differential cryptanalysis, my Wide Trail Strategy, impractical related-key attacks, and... so much more... but no one is left.

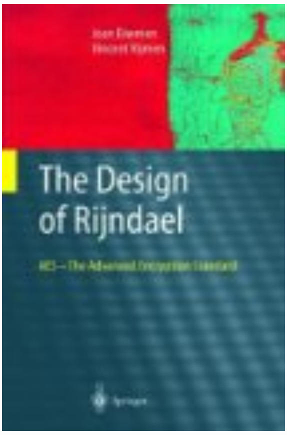

Exit


Oh well... there's some boring router traffic that needs to be encrypted. Gotta go!
Exit


The End

Epilogue

I created a heavily-commented AES/Rijndael implementation to go along with this post and put it on GitHub. In keeping with the Foot-Shooting Prevention Agreement, it shouldn't be used for production code, but it should be helpful in seeing exactly where all the numbers came from in this play. Several resources were useful in creating this:



- The Design of Rijndael is *the* book on the subject, written by the Rijndael creators. It was helpful in understanding specifics, especially the math (although some parts were beyond me). It's also where I got the math notation and graphical representation in the left and right corners of the scenes describing the layers (SubBytes, ShiftRows, MixColumns, and AddRoundKey).
- The FIPS-197 specification formally defines AES and provides a good overview.
- The Puzzle Palace, especially chapter 9, was helpful while creating Act 1. For more on how the NSA modified DES, see this.

- More on Intel's (and now AMD) inclusion of native AES instructions can be found here and in detail here. - Other helpful resources include Wikipedia, Sam Trenholme's AES math series, and this animation.

Please leave a comment if you notice something that can be better explained.

Update #1: Several scenes were updated to fix some errors mentioned in the comments.
Update #2: By request, I've created a slide show presentation of this play in both PowerPoint and PDF formats. I've licensed them under the Creative Commons Attribution License so that you can use them as you see fit. If you're teaching a class, consider giving extra credit to any student giving a worthy interpretive dance rendition in accordance with the Foot-Shooting Prevention Agreement.