CS 166: *Information Security*

Symmetric Key Crypto

Prof. Tom Austin
San José State University

Stream Ciphers & Block Ciphers

- Stream ciphers
  - –based on the one-time pad
- Block ciphers
  - –based on codebook ciphers

Symmetric Key Notation

Encrypt the *plaintext* `P` with the *key* `K` to produce the *ciphertext* `C`.

```
E(P,K) = C
```

Decrypt the ciphertext `C` with the key `K` to produce the plaintext `P`.

```
D(C,K) = P
```

Stream Ciphers

- Based on one time pad (OTP)
- Not provably secure
- More usable than OTP

One-Time Pad Review

Provably secure!

Plaintext:	0101 1010 0101 1011 0101
$\oplus$ **Key:**	1011 0010 1101 1001 0001
Ciphertext:	1110 1000 1000 0010 0100

One-Time Pad Review

Key is as long as the original message

Plaintext:	0101 1010 0101 1011 0101
⊕ **Key:**	1011 0010 1101 1001 0001
Ciphertext:	1110 1000 1000 0010 0100

Replacing the key with a keystream

Key: `1001 1110` → Keystream Generator

Keystream:

```
    1001 0011 1101 1000 ...
⊕
P:  0101 1010 0101 1011
------------------------
C:  1100 0001 1000 0011
```

Two Stream Ciphers

- A5/1
  - Based on shift registers
  - Used in GSM mobile phones
- RC4
  - Based on changing lookup table
  - Used many places

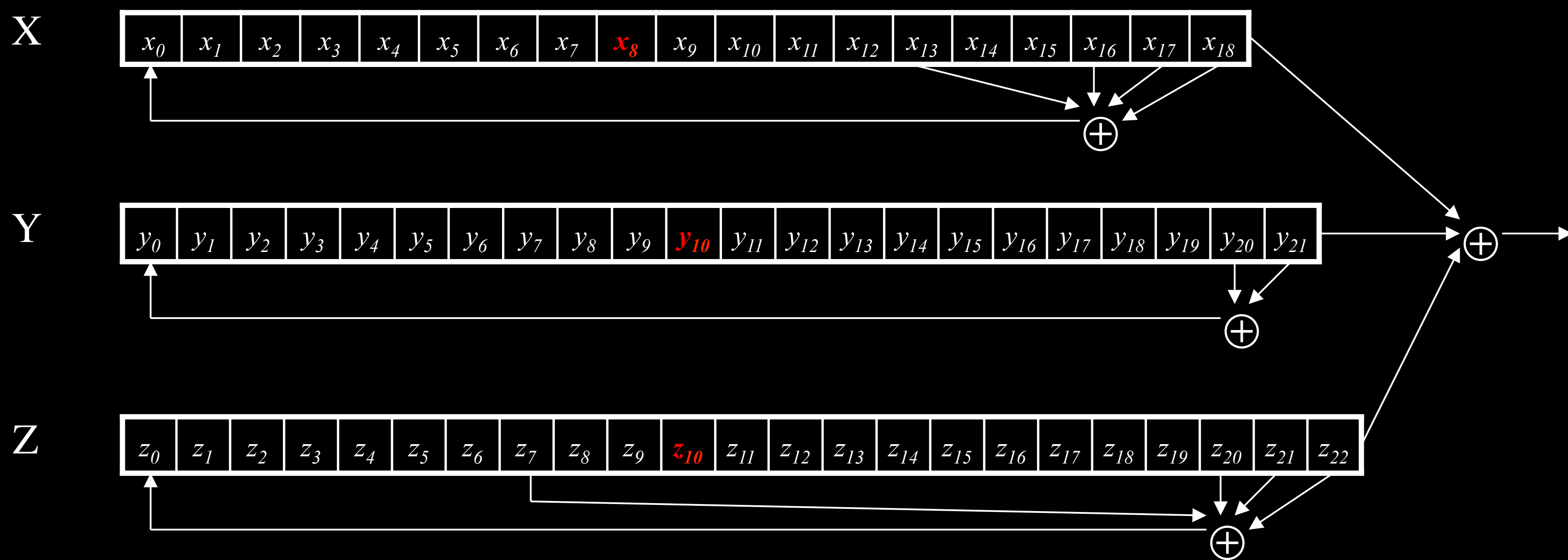
A5/1: Shift Registers

- Uses three *shift registers*
  - –Efficient in hardware
  - –Often slow if implemented in software
- The A5/1 shift registers:
  - –X: 19 bits ($x_0,x_1,x_2, \ldots,x_{18}$)
  - –Y: 22 bits ($y_0,y_1,y_2, \ldots,y_{21}$)
  - –Z: 23 bits ($z_0,z_1,z_2, \ldots,z_{22}$)

A5/1: Keystream

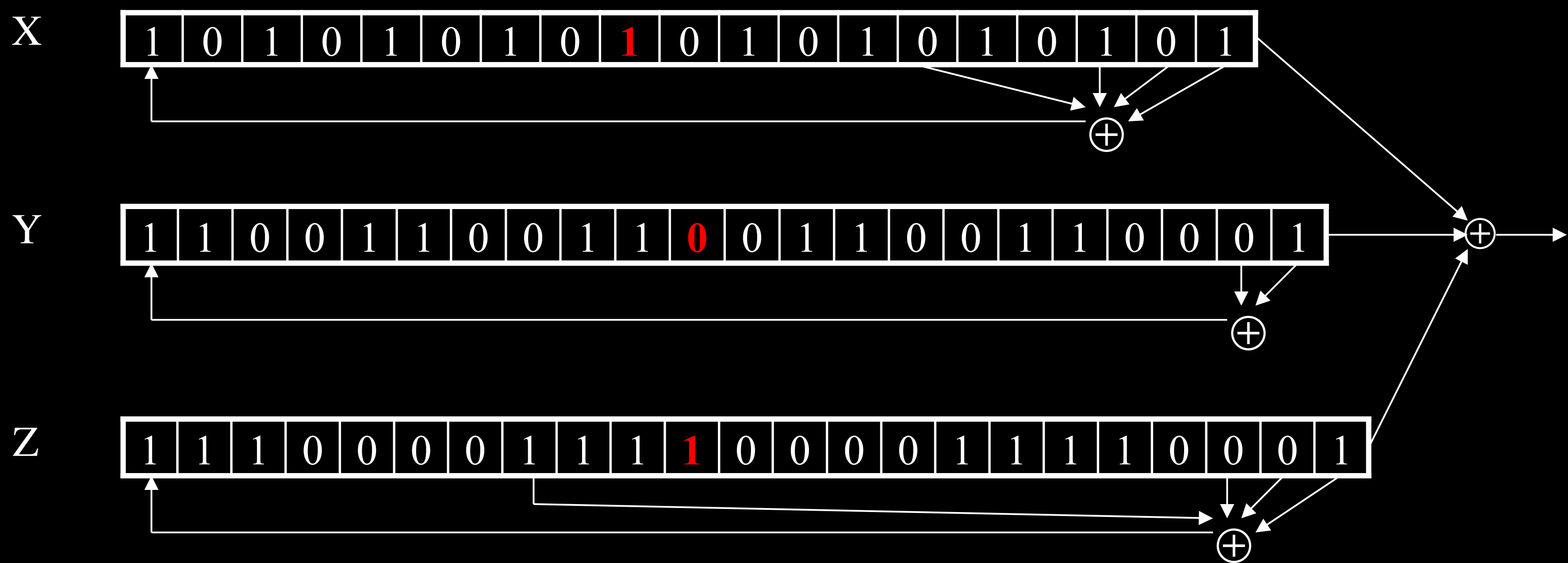
- At each step: m = maj(x_8, y_{10}, z_{10})
  - Examples: maj(0,1,0) = 0 and maj(1,1,0) = 1
- If $x_8 = m$ then X *steps*
  - $t = x_{13} \oplus x_{16} \oplus x_{17} \oplus x_{18}$
  - $x_i = x_{i-1}$ for i = 18,17,…,1 and $x_0 = t$
- If $y_{10} = m$ then Y *steps*
  - $t = y_{20} \oplus y_{21}$
  - $y_i = y_{i-1}$ for i = 21,20,…,1 and $y_0 = t$
- If $z_{10} = m$ then Z *steps*
  - $t = z_7 \oplus z_{20} \oplus z_{21} \oplus z_{22}$
  - $z_i = z_{i-1}$ for i = 22,21,…,1 and $z_0 = t$
- Keystream **bit** is $x_{18} \oplus y_{21} \oplus z_{22}$

A5/1



- Each variable here is a single bit
- Key is used as **initial fill** of registers
- Each register steps (or not) based on maj(x_8, y_{10}, z_{10})
- Keystream bit is XOR of rightmost bits of registers

A5/1



- In this example, $m = \mathrm{maj}(x_8, y_{10}, z_{10}) = \mathrm{maj}(1,0,1) = 1$
- Register X steps, Y does not step, and Z steps
- Keystream bit is XOR of right bits of registers
- Here, keystream bit will be $0 \oplus 1 \oplus 0 = 1$

Lab 3: A5/1 exercise

For the A5/1 cipher, on average how often

1. does the X register step?
2. does the Y register step?
3. does the Z register step?
4. do all 3 registers step?
5. do exactly 2 registers step?
6. does exactly 1 register step?
7. does no register step?

Shift Register Crypto

Efficient in hardware, but is often slow in software.

With faster processors, this approach is used less often.

Still useful for resource-constrained devices.

Rivest Cipher 4 (RC4)

- Stream cipher
- Used in wireless protocols
  - WEP, WPA, etc.
- Designed to be implemented efficiently in software.
- Uses a self-modifying lookup table
  - vs. A5/1 shift registers.
- Generates a ***byte*** at a time
  - vs. A5/1 bit at a time.

RC4 Design

- Self-modifying lookup table always contains a permutation of the byte values 0,1,…,255.
- Key determines initial permutation
- At each step, RC4
  1. Swaps elements in current lookup table
  2. Selects a keystream byte from table

RC4 Initialization

- S[] is permutation of 0,1,...,255
- key[] contains N bytes of key

```
for i = 0 to 255
     S[i] = i
     K[i] = key[i (mod N)]
next i
j = 0
for i = 0 to 255
     j = (j + S[i] + K[i]) mod 256
     swap(S[i], S[j])
next i
i = j = 0
```

RC4 Keystream

- For each keystream byte, swap elements in table and select byte

```
i = (i + 1) mod 256
j = (j + S[i]) mod 256
swap(S[i], S[j])
t = (S[i] + S[j]) mod 256
keystreamByte = S[t]
```

- Use keystream bytes like a one-time pad
- **Note:** first 256 bytes should be discarded
  - Otherwise, related key attack exists

RC4 fading from popularity

- Used incorrectly in WEP
  - related key attack
- vulnerable to distinguishing attacks
  - random data distinguishable from RC4 encrypted data
- prohibited for TLS by RFC 7465

Death of Stream Ciphers?

- Popular in the past
  - Efficient in hardware
  - Speed was needed to keep up with voice, etc.
- Today, processors are fast
  - Software-based crypto is usually fast enough
- Future of stream ciphers?
  - Shamir declared “the death of stream ciphers”
  - May be greatly exaggerated…

Block Ciphers

Review of codebook ciphers

Word	Codeword
Apple	00123
Banana	11439
Citrus	92340
Cranberry	87642
Durian	58629
Orange	66793
Strawberry	88432
Watermelon	90210

Plaintext:

Apple Durian Orange

Ciphertext:

00123 58629 66793

Block Ciphers: Codebooks of Bytes

Input	Output
…	…
9E	CB
9F	80
A0	4F
A1	ED
A2	62
A3	9A
…	…

OK, they are a bit more complicated than that…

(Iterated) Block Cipher

- Plaintext and ciphertext consist of fixed-sized blocks
- Ciphertext obtained from plaintext by iterating a ***round function***
- Input to round function consists of ***key*** and ***output*** of previous round
- Usually implemented in software

Feistel Ciphers

- A *type* of cipher.
- Easy to reverse encryption.
  - i.e. you get decryption for free
- Most modern block ciphers are "Feistel-ish" if not strict Feistel ciphers.

Horst Feistel

Feistel Cipher: Encryption

- Split plaintext block into left and right halves:
  $P = (L_0,R_0)$
- For each round i = 1, 2, ..., n, compute

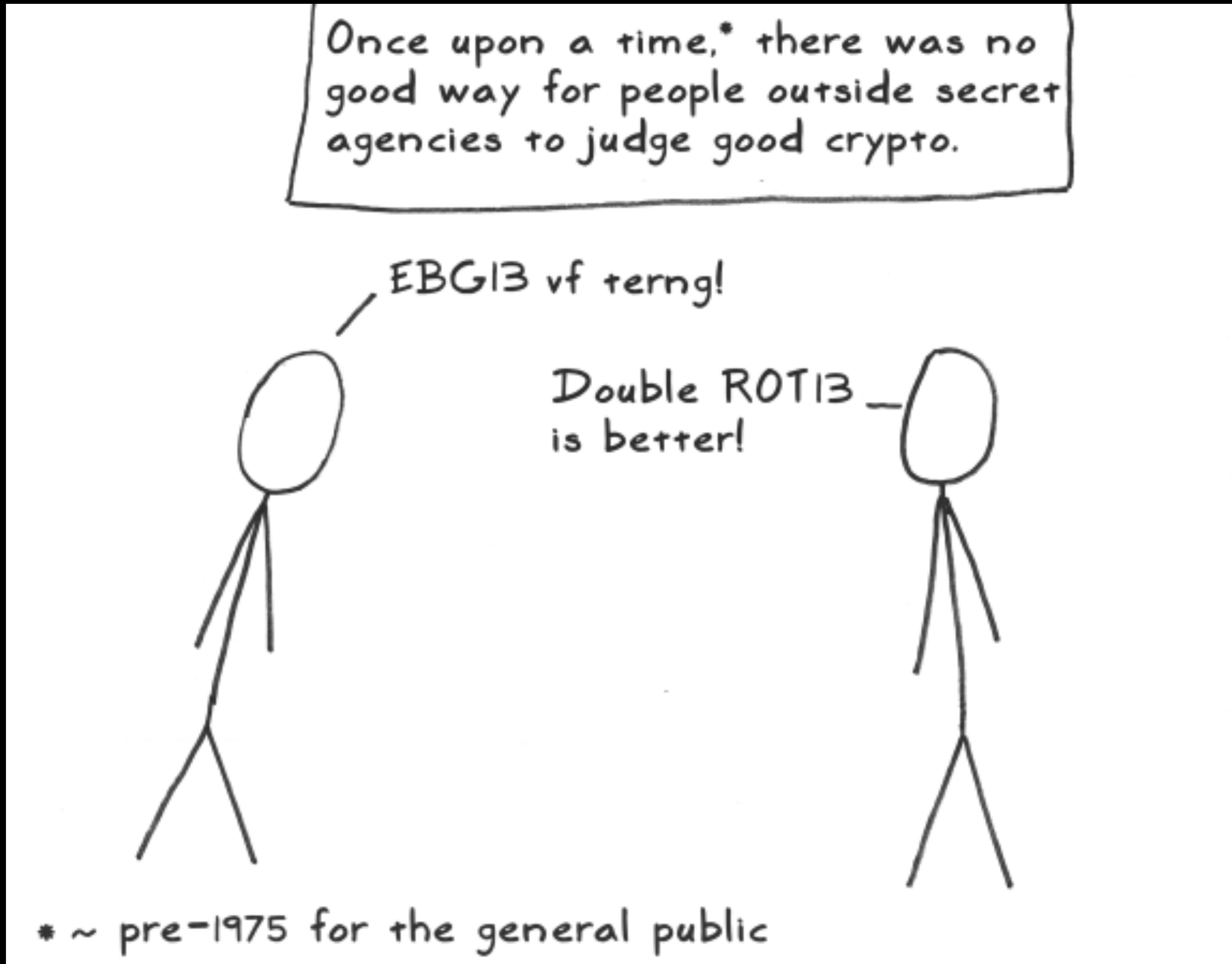
  $L_i = R_{i-1}$
  $R_i = L_{i-1} \oplus F(R_{i-1},K_i)$
  where F is **round function** and K_i is **subkey**
- Ciphertext: $C = (L_n,R_n)$

Feistel Cipher: Decryption

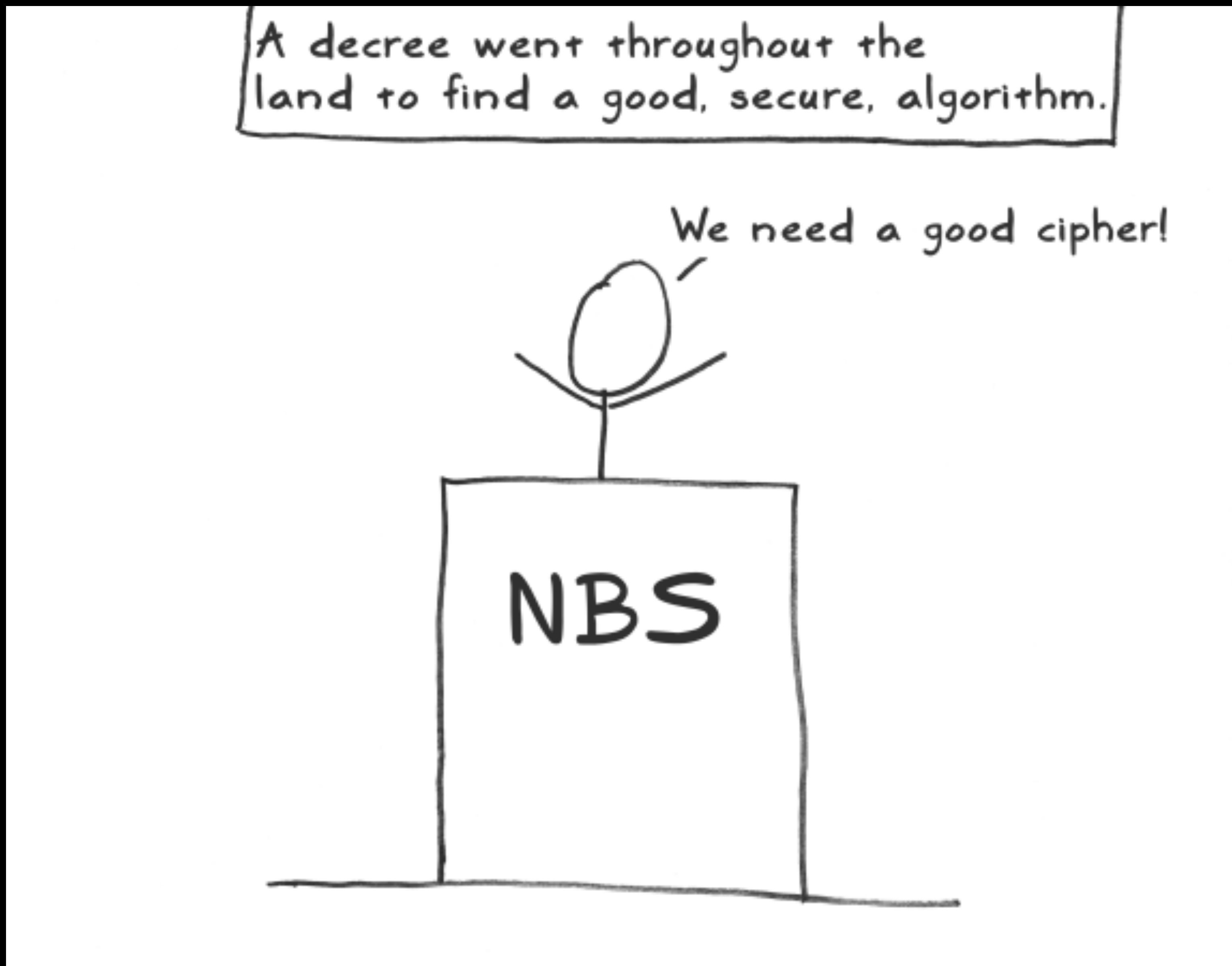
- Start with ciphertext $C = (L_n,R_n)$
- Each round $i = n,n-1,\ldots,1$, compute

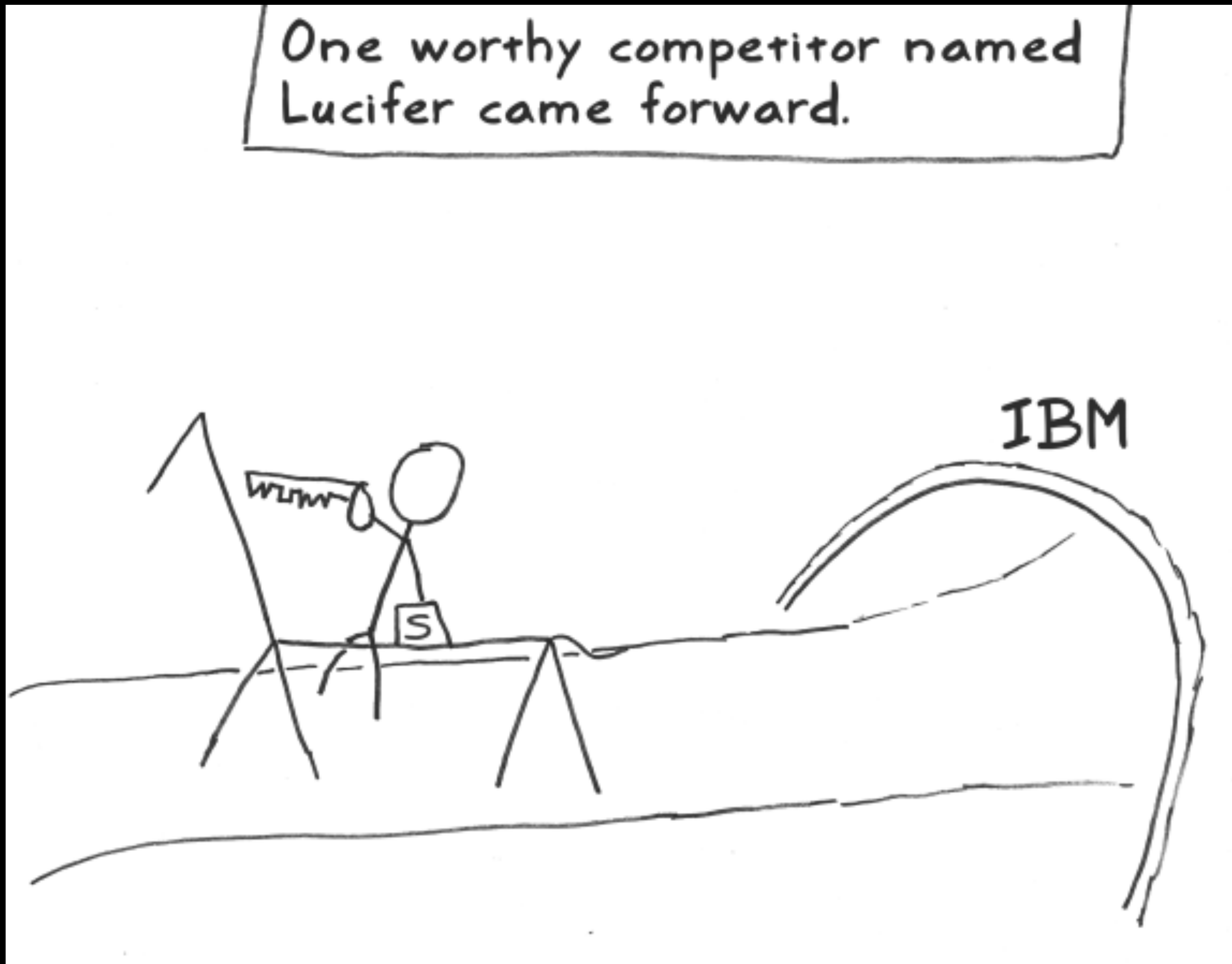
  $R_{i-1} = L_i$

  $L_{i-1} = R_i \oplus F(R_{i-1},K_i)$
- F is round function and K_i is subkey
- Plaintext: $P = (L_0,R_0)$



http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html


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

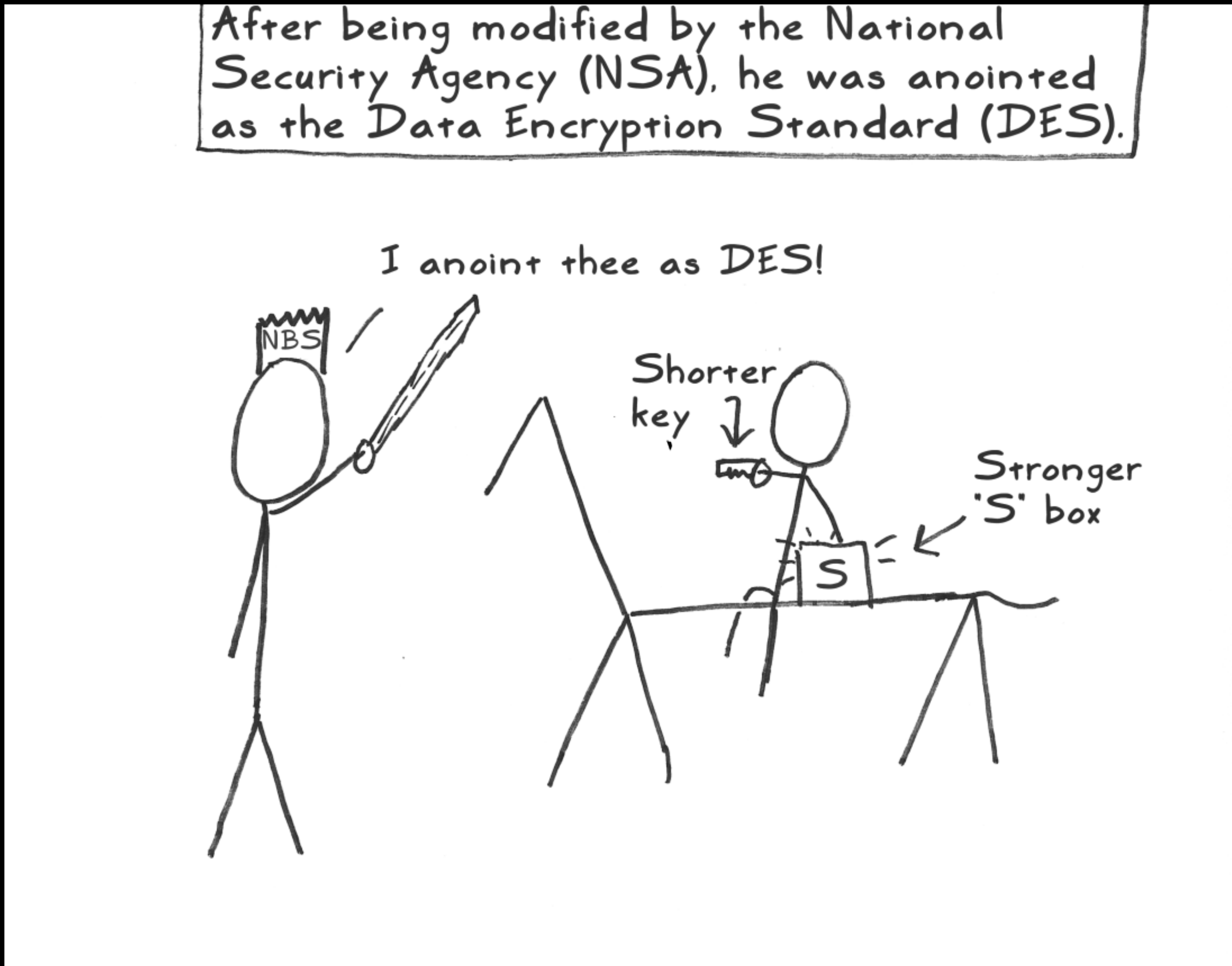

One worthy competitor named Lucifer came forward.
IBM
S

Data Encryption Standard (DES)

- **D**eveloped in 1970's
- Based on IBM's Lucifer cipher
- U.S. government standard

DES Controversy

- NSA secretly involved
  - changes made without explanation
- Key length reduced 128 to 56 bits
- Subtle changes to Lucifer algorithm

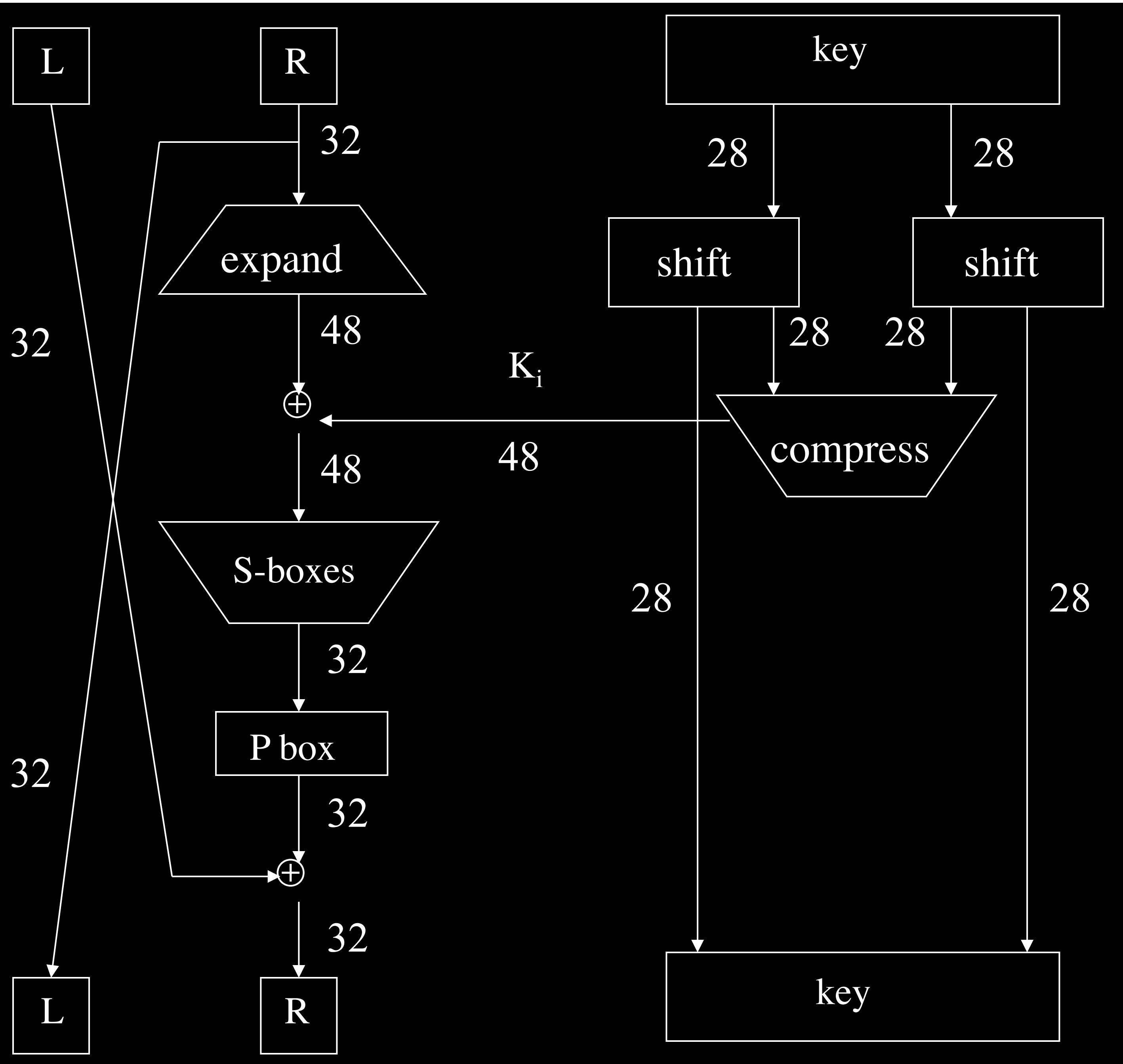

After being modified by the National Security Agency (NSA), he was anointed as the Data Encryption Standard (DES).
I anoint thee as DES!
NBS
Shorter key
Stronger "S" box
S

DES Numerology

- Feistel cipher with…
  - 64 bit block length
  - 56 bit key length
  - 16 rounds
  - 48 bits of key used each round (subkey)
- Each round is simple (for a block cipher)
- Security depends heavily on "S-boxes"
  - Each S-boxes maps 6 bits to 4 bits

Odds of guessing key: roughly the same as winning the lottery & getting struck by lightning the same day. [Schneier 1996]

One Round of DES



DES Expansion Permutation

- Input 32 bits

```
 0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
```

- Output 48 bits

```
31  0  1  2  3  4  3  4  5  6  7  8
 7  8  9 10 11 12 11 12 13 14 15 16
15 16 17 18 19 20 19 20 21 22 23 24
23 24 25 26 27 28 27 28 29 30 31  0
```

DES S-box

- 8 “substitution boxes” or S-boxes
- Each S-box maps 6 bits to 4 bits
- S-box number 1

input bits (0,5)

↓ input bits (1,2,3,4)

	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
00	1110	0100	1101	0001	0010	1111	1011	1000	0011	1010	0110	1100	0101	1001	0000	0111
01	0000	1111	0111	0100	1110	0010	1101	0001	1010	0110	1100	1011	1001	0101	0011	1000
10	0100	0001	1110	1000	1101	0110	0010	1011	1111	1100	1001	0111	0011	1010	0101	0000
11	1111	1100	1000	0010	0100	1001	0001	0111	0101	1011	0011	1110	1010	0000	0110	1101

DES P-box

- Input 32 bits

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31

- Output 32 bits

15	6	19	20	28	11	27	16	0	14	22	25	4	17	30	9
1	7	23	13	31	26	2	8	18	12	29	5	21	10	3	24

DES Subkey

- 56 bit DES key, numbered 0,1,2,…,55
- Left half key bits, `LK`

```
49 42 35 28 21 14  7
 0 50 43 36 29 22 15
 8  1 51 44 37 30 23
16  9  2 52 45 38 31
```

- Right half key bits, `RK`

```
55 48 41 34 27 20 13
 6 54 47 40 33 26 19
12  5 53 46 39 32 25
18 11  4 24 17 10  3
```

DES Subkey

- For rounds `i=1,2,...,16`
  - Let LK = (LK circular shift left by r_i)
  - Let RK = (RK circular shift left by r_i)
  - Left half of subkey K_i is of LK bits

```
13 16 10 23  0  4  2 27 14  5 20  9
22 18 11  3 25  7 15  6 26 19 12  1
```

  - Right half of subkey K_i is RK bits

```
12 23  2  8 18 26  1 11 22 16  4 19
15 20 10 27  5 24 17 13 21  7  0  3
```

DES Subkey

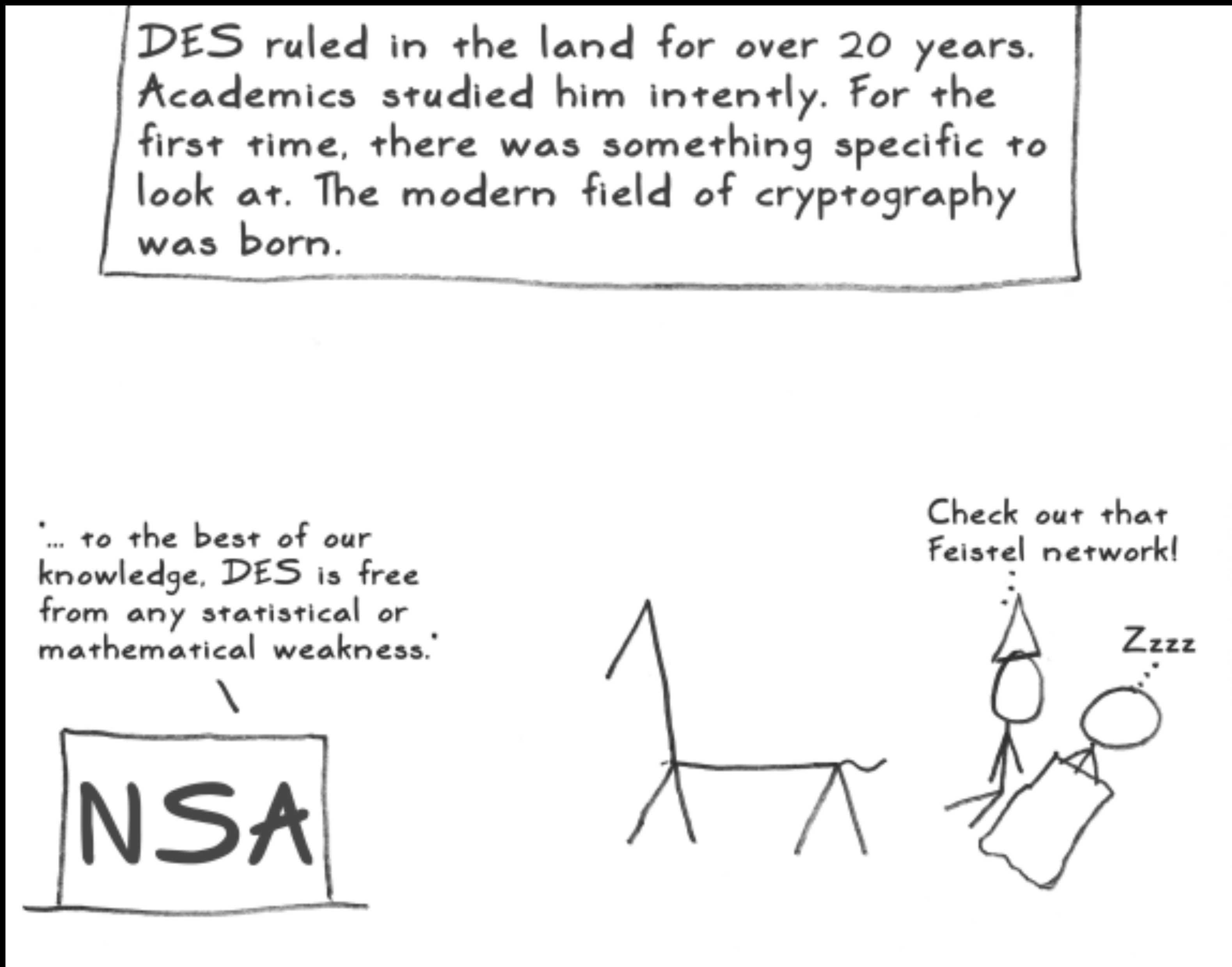
- For rounds 1, 2, 9 and 16 the shift r_i is 1, and in all other rounds r_i is 2
- Bits 8,17,21,24 of LK omitted each round
- Bits 6,9,14,25 of RK omitted each round
- **Compression permutation** yields 48 bit subkey K_i from 56 bits of LK and RK
- **Key schedule** generates subkey

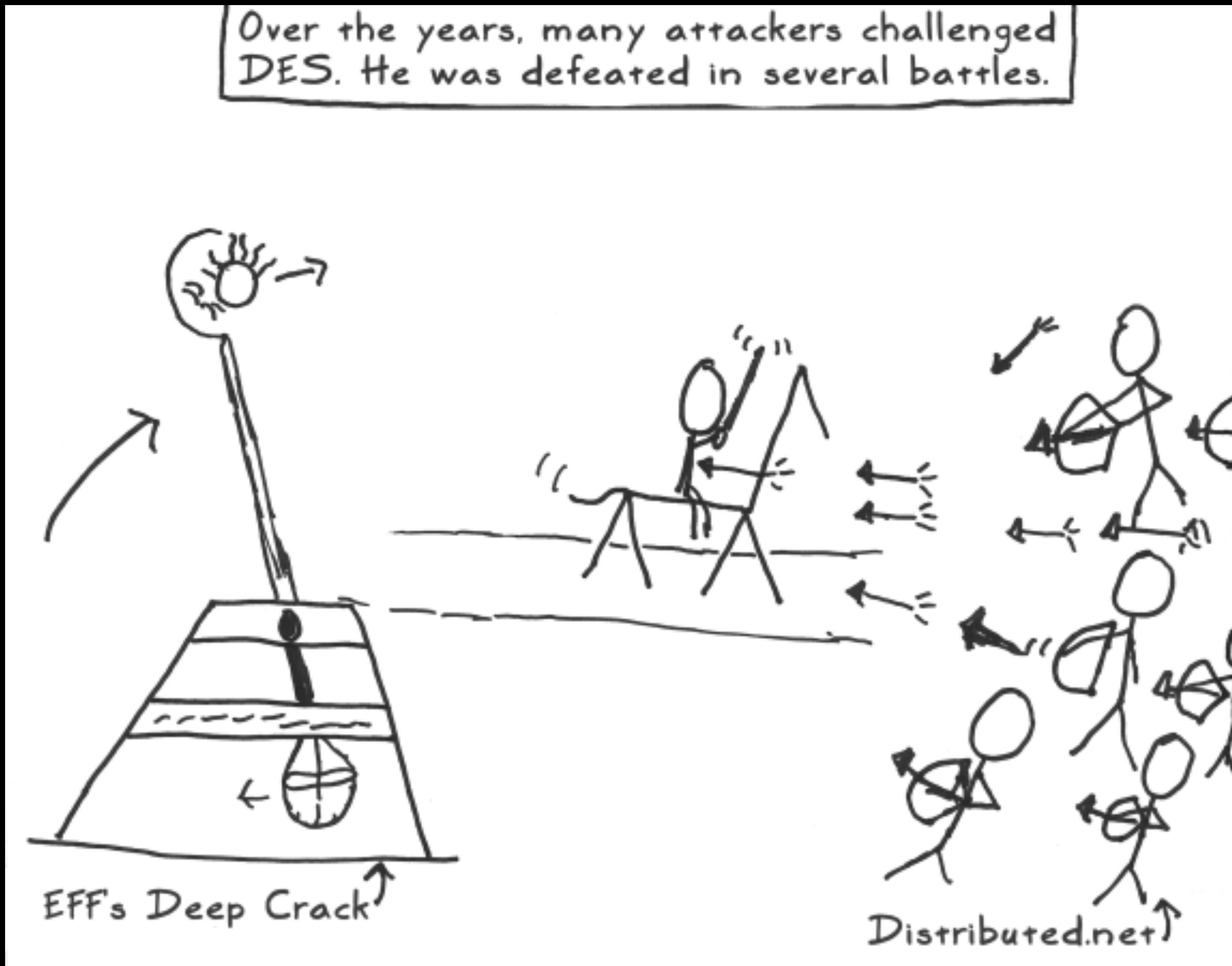
DES Last Word (Almost)

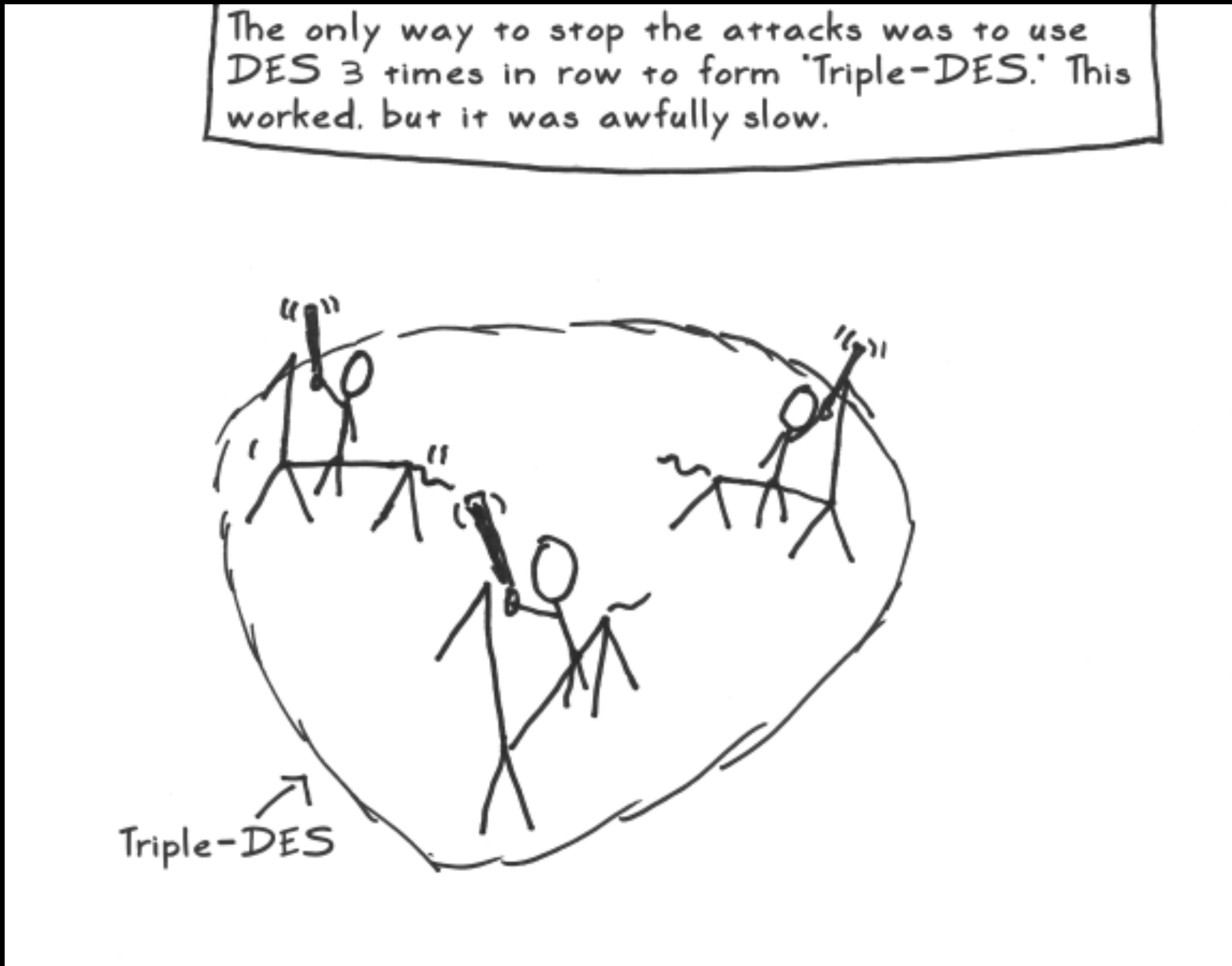
- Initial permutation before round 1
- Halves swapped after last round
- Final permutation applied to (R_{16}, L_{16})
- None of this serves security purpose

Security of DES

- Security depends heavily on S-boxes
  - Everything else in DES is linear
- Thirty+ years of intense analysis has revealed no “back door”
- Attacks, essentially exhaustive key search
- **Inescapable conclusions**
  - Designers knew what they were doing
  - Way ahead of their time


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

Block Cipher Notation

- P = plaintext block
- C = ciphertext block
- Encrypt P with key K to get ciphertext C
  - $C = E(P, K)$
- Decrypt C with key K to get plaintext P
  - $P = D(C, K)$
- Note: $P = D(E(P, K), K)$ and $C = E(D(C, K), K)$
  - But $P \neq D(E(P, K_1), K_2)$ and $C \neq E(D(C, K_1), K_2)$ when $K_1 \neq K_2$

Triple DES

- Today, 56 bit DES key is too small
  - Exhaustive key search is feasible
- But DES is everywhere, so what to do?
- **Triple DES** or **3DES** (112 bit key)
  - $C = E(D(E(P,K_1),K_2),K_1)$
  - $P = D(E(D(C,K_1),K_2),K_1)$
- Why Encrypt-Decrypt-Encrypt with 2 keys?
  - Backward compatible: $E(D(E(P,K),K),K) = E(P,K)$
  - And 112 bits is enough

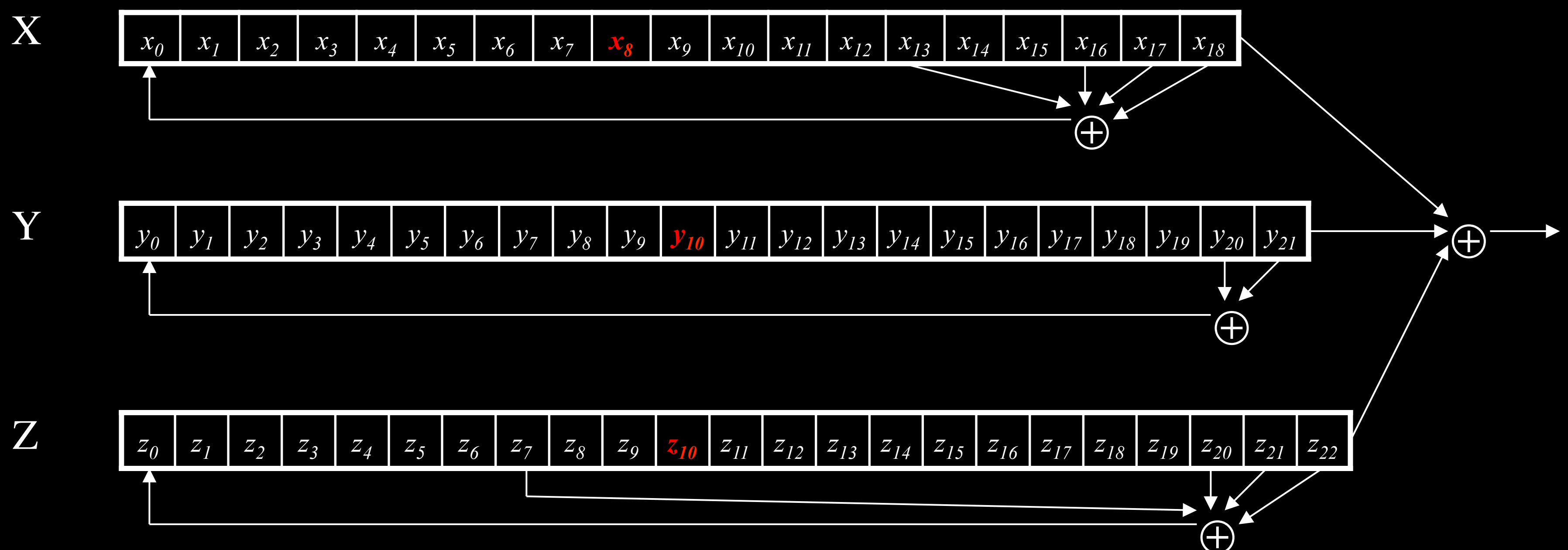
Alternate Strategy to 3DES

- Why not $C = E(E(P,K),K)$?
  - Trick question: it's still just 56 bit key
- Why not $C = E(E(P,K_1),K_2)$?
- A (semi-practical) **known plaintext** attack exists

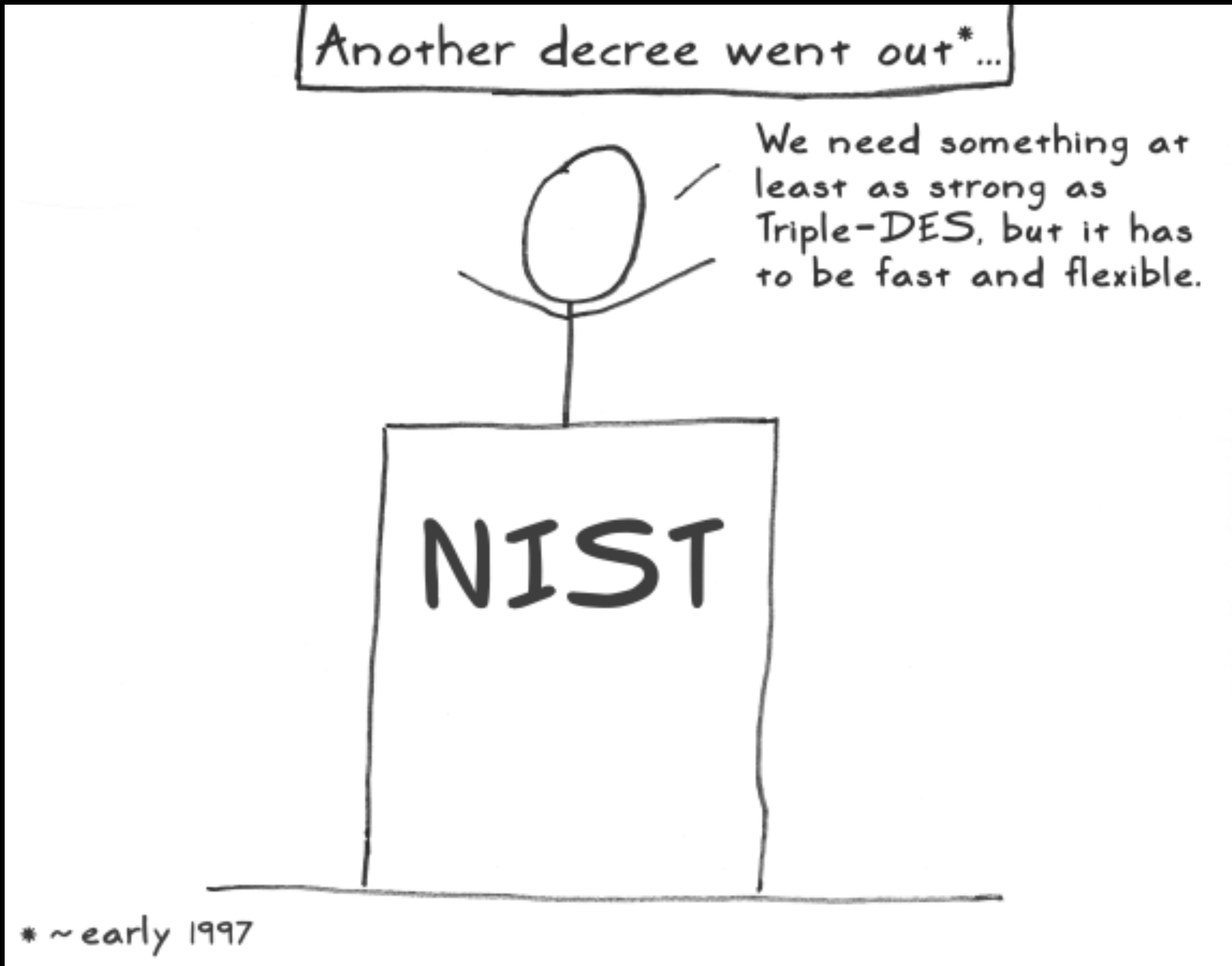
Known Plaintext Attack AgainstAlternate 3DES

- Pre-compute table of $E(P,K_1)$ for every possible key K_1
  - resulting table has 2^{56} entries.
- For each possible K_2 compute $D(C,K_2)$ until a match in table is found.
- When match is found, have:
  $E(P,K_1) = D(C,K_2)$
- Result gives us keys: $C = E(E(P,K_1),K_2)$
- Worst case to break? $2^{56} + 2^{56} = 2^{57}$

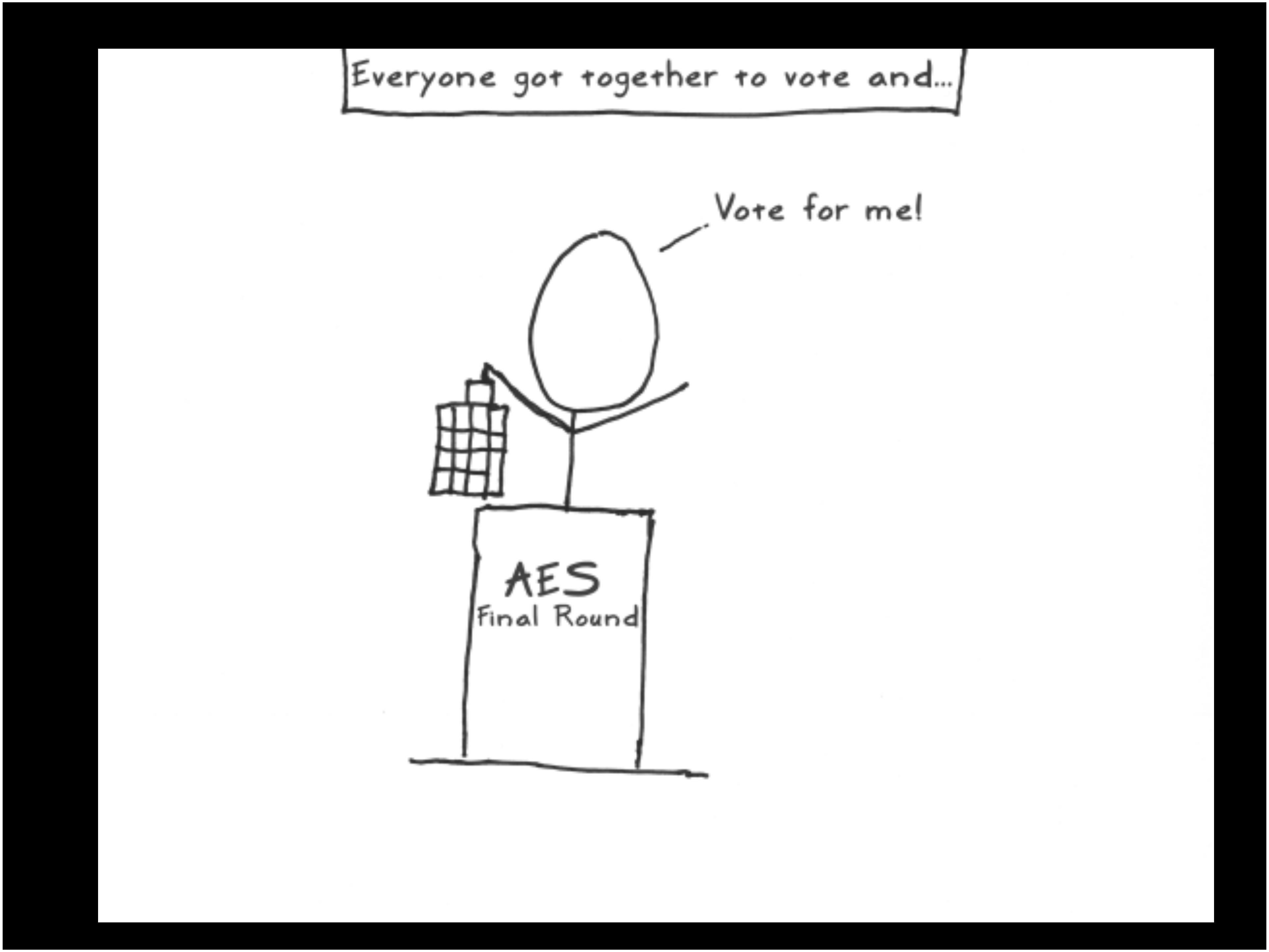
REVIEW: A5/1 lab

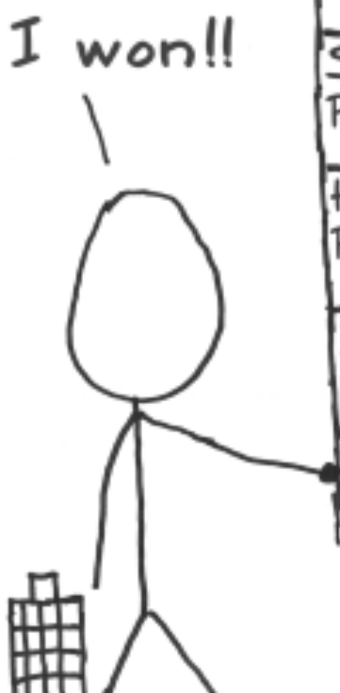


- Each variable here is a single bit
- Key is used as **initial fill** of registers
- Each register steps (or not) based on maj(x_8, y_{10}, z_{10})
- Keystream bit is XOR of rightmost bits of registers

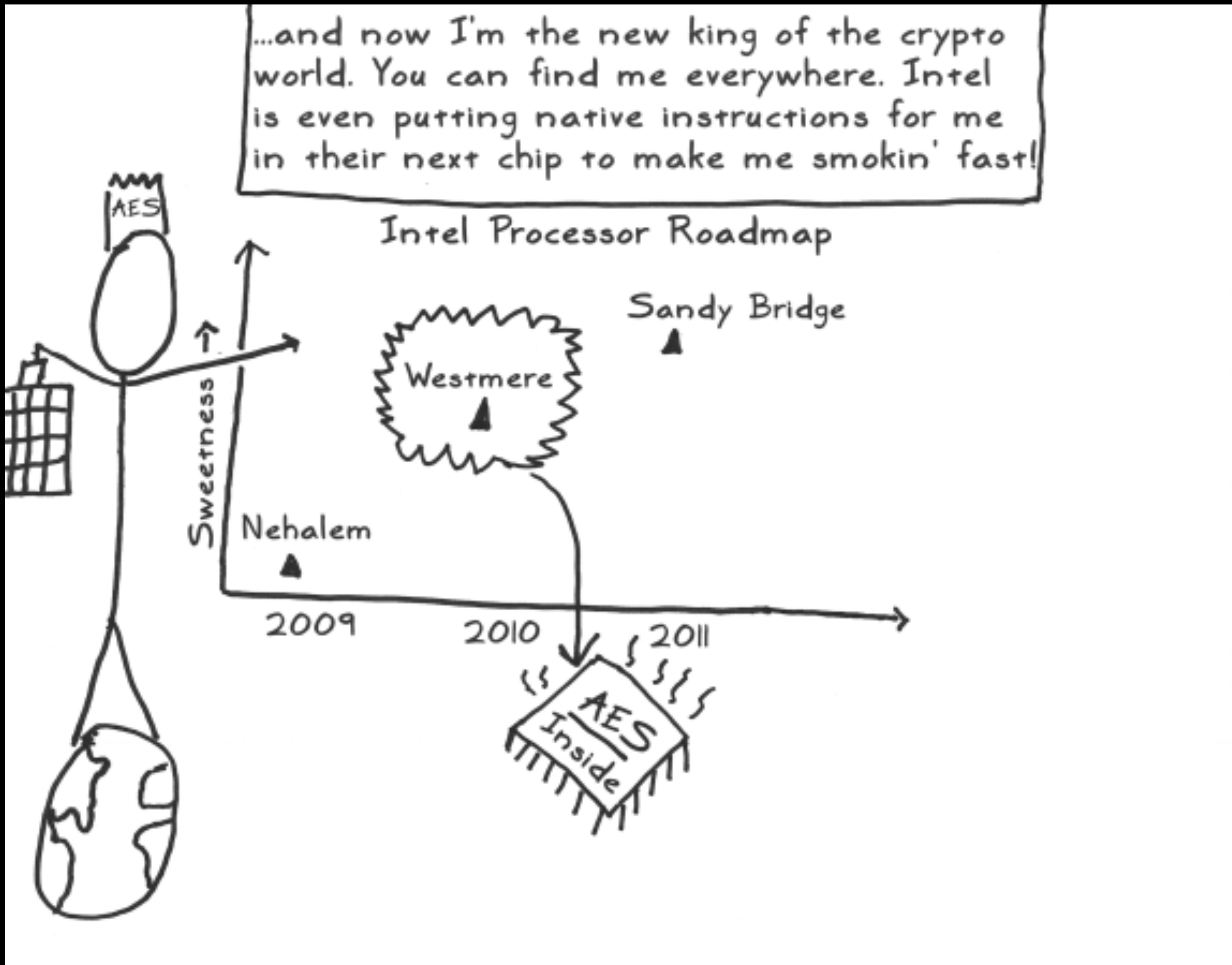

Another decree went out*...
We need something at least as strong as Triple-DES, but it has to be fast and flexible.
NIST
* ~early 1997


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


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



	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
Sweetness
Nehalem
Westmere
Sandy Bridge
2009
2010
2011
AES
Inside

Advanced Encryption Standard (AES)

- Replacement for DES
- AES competition (late 90's)
  - NSA openly involved
  - Transparent process
  - Many strong algorithms proposed
  - Rijndael Algorithm ultimately selected (pronounced like "Rhine Doll")
- Iterated block cipher (like DES)
- Not a Feistel cipher (unlike DES)

AES Overview

- **Block size:** 128 bits (others in Rijndael)
- **Key length:** 128, 192 or 256 bits (independent of block size)
- 10 to 14 rounds (depends on key length)
- Each round uses 4 functions (3 “layers”)
  - ByteSub (nonlinear layer)
  - ShiftRow (linear mixing layer)
  - MixColumn (nonlinear layer)
  - AddRoundKey (key addition layer)

AES ByteSub

- Treat 128 bit block as 4x6 byte array

$$\begin{matrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{matrix} \xrightarrow{\text{ByteSub}} \begin{matrix} b_{00} & b_{01} & b_{02} & b_{03} \\ b_{10} & b_{11} & b_{12} & b_{13} \\ b_{20} & b_{21} & b_{22} & b_{23} \\ b_{30} & b_{31} & b_{32} & b_{33} \end{matrix}$$

- ByteSub is AES's "S-box"
  - details next slide
- Can be viewed as either
  1. a nonlinear (but invertible) composition of 2 math operations; or
  2. a lookup table

AES "S-box"

Last 4 bits of input

First 4 bits of input

	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	00	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
6	d0	ef	aa	fb	43	4d	33	85	45	f9	02	7f	50	3c	9f	a8
7	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
8	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
9	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a	e0	32	3a	0a	49	06	24	5c	c2	d3	ac	62	91	95	e4	79
b	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	08
c	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d	70	3e	b5	66	48	03	f6	0e	61	35	57	b9	86	c1	1d	9e
e	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

AES ShiftRow

cyclic shift - linear operation

$$\begin{matrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{matrix} \xrightarrow{\text{ShiftRow}} \begin{matrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{11} & a_{12} & a_{13} & a_{10} \\ a_{22} & a_{23} & a_{20} & a_{21} \\ a_{33} & a_{30} & a_{31} & a_{32} \end{matrix}$$

AES MixColumn

- invertible
- linear
- applied to each column
- implemented as lookup table

$$\begin{bmatrix} a_{0i} \\ a_{1i} \\ a_{2i} \\ a_{3i} \end{bmatrix} \xrightarrow{\text{MixColumn}} \begin{bmatrix} b_{0i} \\ b_{1i} \\ b_{2i} \\ b_{3i} \end{bmatrix} \qquad \text{for } 1 = 0, 1, 2, 3$$

AES AddRoundKey

- XOR subkey with block

$$\begin{bmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{bmatrix} \oplus \begin{bmatrix} k_{00} & k_{01} & k_{02} & k_{03} \\ k_{10} & k_{11} & k_{12} & k_{13} \\ k_{20} & k_{21} & k_{22} & k_{23} \\ k_{30} & k_{31} & k_{32} & k_{33} \end{bmatrix} = \begin{bmatrix} b_{00} & b_{01} & b_{02} & b_{03} \\ b_{10} & b_{11} & b_{12} & b_{13} \\ b_{20} & b_{21} & b_{22} & b_{23} \\ b_{30} & b_{31} & b_{32} & b_{33} \end{bmatrix}$$

Block Subkey

- RoundKey (subkey) determined by **key schedule** algorithm

AES Decryption

- To decrypt, process must be invertible
- Inverse of MixAddRoundKey is easy
  - $\oplus$ is its own inverse
- MixColumn is invertible
  - inverse also implemented as a lookup table
- Inverse of ShiftRow is easy
  - cyclic shift the other direction
- ByteSub is invertible
  - inverse also implemented as a lookup table

A Few Other Block Ciphers

- Briefly…
  - IDEA
  - Blowfish
  - RC6
- More detailed…
  - TEA

IDEA

- **I**nternational **D**ata **E**ncryption **A**lgorithm
- Invented by James Massey
  - One of the giants of modern crypto
- 64-bit block, 128-bit key
- Uses **mixed-mode arithmetic**
- Combines different math operations
  - IDEA the first to use this approach
  - Frequently used today

Blowfish

- Blowfish encrypts 64-bit blocks
- Key is variable length, up to 448 bits
- Invented by Bruce Schneier
- Almost a Feistel cipher

$$R_i = L_{i-1} \oplus K_i$$
$$L_i = R_{i-1} \oplus F(L_{i-1} \oplus K_i)$$

- The round function F uses 4 S-boxes
  - Each S-box maps 8 bits to 32 bits
- **Key-dependent S-boxes**
  - S-boxes determined by the key

RC6

- Invented by Ron Rivest
- Variables
  - Block size
  - Key size
  - Number of rounds
- An AES finalist
- Uses **data dependent rotations**
  - Unusual for algorithm to depend on plaintext
- Possibly NSA's algorithm of choice
  [Jacob Appelbaum 2014]

Time for TEA

- Tiny Encryption Algorithm (TEA)
- 64 bit block, 128 bit key
- Assumes 32-bit arithmetic
- Number of rounds is variable
  - 32 is considered secure
- Uses “weak” round function
  - large number of rounds required

TEA Encryption

Assuming 32 rounds:

```
(K[0],K[1],K[2],K[3]) = 128 bit key
(L,R) = plaintext (64-bit block)
delta = 0x9e3779b9
sum = 0
for i = 1 to 32
    sum += delta
    L += ((R<<4)+K[0])^(R+sum)^((R>>5)+K[1])
    R += ((L<<4)+K[2])^(L+sum)^((L>>5)+K[3])
next i
ciphertext = (L,R)
```

TEA Decryption

Assuming 32 rounds:

```
(K[0],K[1],K[2],K[3]) = 128 bit key
(L,R) = ciphertext (64-bit block)
delta = 0x9e3779b9
sum = delta << 5
for i = 1 to 32
    R -= ((L<<4)+K[2])^(L+sum)^((L>>5)+K[3])
    L -= ((R<<4)+K[0])^(R+sum)^((R>>5)+K[1])
    sum -= delta
next i
plaintext = (L,R)
```

TEA Comments

- **Almost** a Feistel cipher
  - Uses + and - instead of ⊕ (XOR)
- Simple
- Easy to implement
- Fast
- Low memory requirement
- Possibly a “related key” attack

TEA Variations

- eXtended TEA (XTEA)
  - eliminates related key attack
  - slightly more complex
- Simplified TEA (STEA)
  - insecure version
  - used as an example for cryptanalysis

Block Cipher Modes

Multiple Blocks

- How to encrypt multiple blocks?
- Do we need a new key for each block?
  - As bad as (or worse than) a one-time pad!
- Encrypt each block independently?
- Make encryption depend on previous block?
  - That is, can we “chain” the blocks together?
- How to handle partial blocks?
  - We won’t discuss this issue

Modes of Operation

- Many modes: we discuss 3 most popular
- Electronic Codebook (**ECB**) mode
  - Encrypt each block independently
  - Most obvious, but has a serious weakness
- Cipher Block Chaining (**CBC**) mode
  - Chain the blocks together
  - More secure than ECB, virtually no extra work
- Counter Mode (**CTR**) mode
  - Block ciphers acts like a stream cipher
  - Popular for random access

ECB Mode

- Notation: C = E(P,K)
- Given plaintext $P_0, P_1, \ldots, P_m, \ldots$
- Most obvious way to use a block cipher:

Encrypt	**Decrypt**
$C_0 = E(P_0, K)$	$P_0 = D(C_0, K)$
$C_1 = E(P_1, K)$	$P_1 = D(C_1, K)$
$C_2 = E(P_2, K)$ …	$P_2 = D(C_2, K)$ …

- For fixed key K, this is "electronic" version of a codebook cipher (without additive)
  - With a different codebook for each key

ECB Cut and Paste

- Suppose plaintext is

  `Alice luvs Bob. Trudy luvs Joe.`
- Assuming 64-bit blocks and 8-bit ASCII:

  P_0 = "`Alice lu`", P_1 = "`vs Bob. `",

  P_2 = "`Trudy lu`", P_3 = "`vs Joe. `"
- Ciphertext: C_0,C_1,C_2,C_3
- Trudy cuts and pastes: C_0,C_3,C_2,C_1
- Decrypts as

  `Alice luvs Joe. Trudy luvs Bob.`

ECB Weakness

- Suppose $P_i = P_j$
- Then $C_i = C_j$ and Trudy knows $P_i = P_j$
- This gives Trudy some information, even if she does not know P_i or P_j
- Trudy might know P_i
- Is this a serious issue?

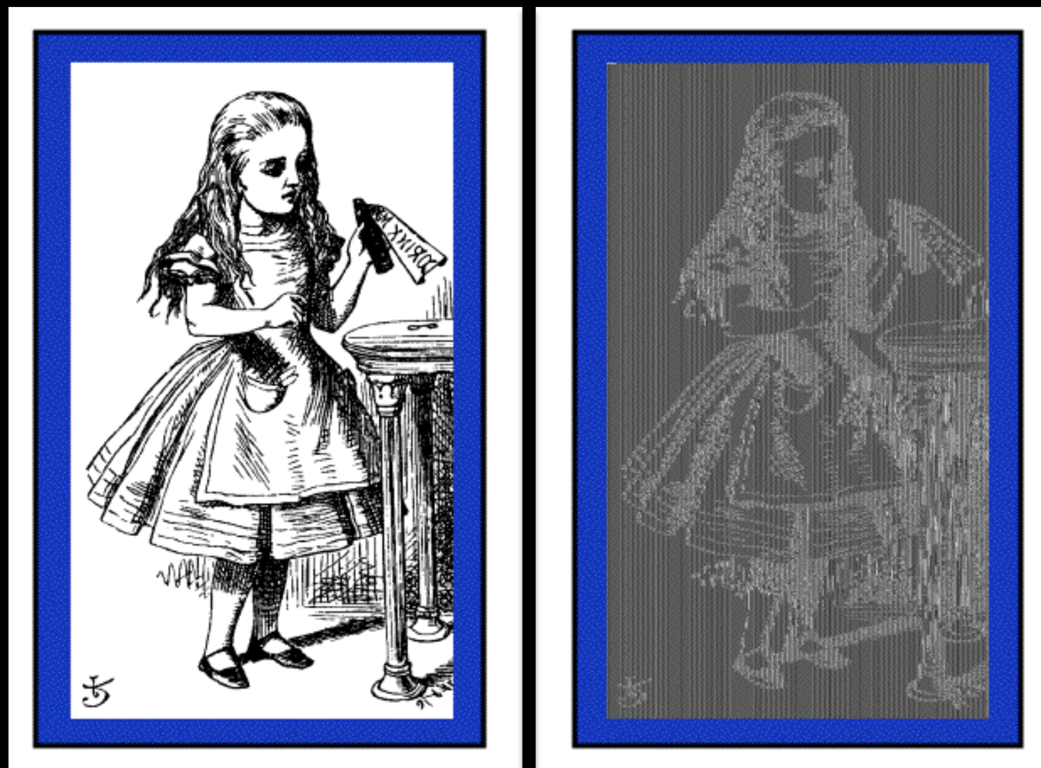
Alice Hates ECB Mode

- Alice's uncompressed image, and ECB encrypted (TEA)

- Why does this happen?
- Same plaintext yields same ciphertext!

Alice Hates ECB Mode

- Alice’s uncompressed image, and ECB encrypted (TEA)



- Why does this happen?
- Same plaintext yields same ciphertext!

CBC Mode

- Blocks are "chained" together
- A random initialization vector, or IV, is required to initialize CBC mode
- IV is random, but not secret

Encryption

$$C_0 = E(IV \oplus P_0, K),$$
$$C_1 = E(C_0 \oplus P_1, K),$$
$$C_2 = E(C_1 \oplus P_2, K), \ldots$$

Decryption

$$P_0 = IV \oplus D(C_0, K),$$
$$P_1 = C_0 \oplus D(C_1, K),$$
$$P_2 = C_1 \oplus D(C_2, K), \ldots$$

- Analogous to classic codebook *with additive*

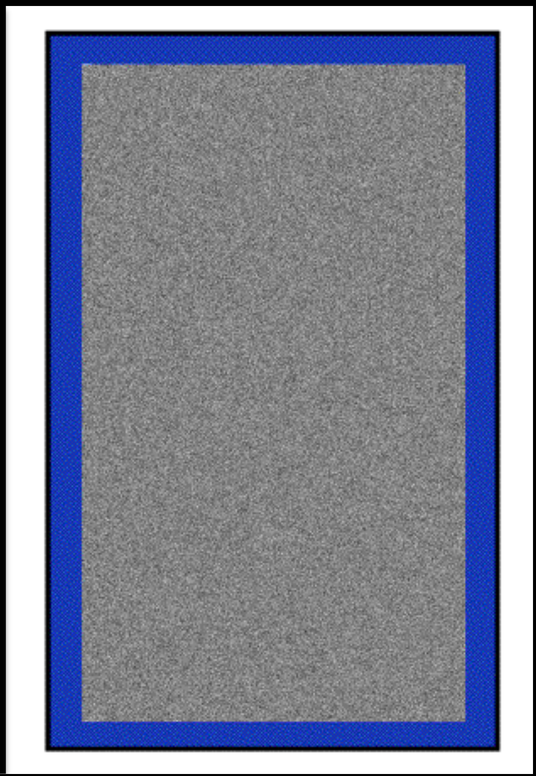
CBC Mode

- Identical plaintext blocks yield different ciphertext blocks
- If C_1 is garbled to, say, G then

  $P_1 \neq C_0 \oplus D(G, K)$, $P_2 \neq G \oplus D(C_2, K)$
- But $P_3 = C_2 \oplus D(C_3, K)$, $P_4 = C_3 \oplus D(C_4, K)$,…
- Automatically recovers from errors!
- Cut and paste is still possible, but more complex (and will cause garbles)

Alice Likes CBC Mode

- Alice's uncompressed image, Alice CBC encrypted (TEA)



- Why does this happen?
- Same plaintext yields different ciphertext!

Counter Mode (CTR)

- CTR is popular for random access
- Use block cipher like a stream cipher

Encryption

$C_0 = P_0 \oplus E(IV, K),$

$C_1 = P_1 \oplus E(IV+1, K),$

$C_2 = P_2 \oplus E(IV+2, K), \ldots$

Decryption

$P_0 = C_0 \oplus E(IV, K),$

$P_1 = C_1 \oplus E(IV+1, K),$

$P_2 = C_2 \oplus E(IV+2, K), \ldots$

Integrity

Data Integrity

- **Integrity** — detect unauthorized writing (i.e., modification of data)
- Example: Inter-bank fund transfers
  - Confidentiality may be nice, integrity is critical
- Encryption provides **confidentiality**
  - prevents unauthorized disclosure
- Encryption alone does **not** provide integrity
  - One-time pad, ECB cut-and-paste, etc.

MAC

- Message Authentication Code (MAC)
  - Used for data **integrity**
  - Integrity **not** the same as confidentiality
- MAC is computed as **CBC residue**
  - That is, compute CBC encryption, saving only final ciphertext block, the MAC

MAC Computation

- MAC computation (assuming N blocks)

$C_0 = E(IV \oplus P_0, K)$,
$C_1 = E(C_0 \oplus P_1, K)$,
$C_2 = E(C_1 \oplus P_2, K), \ldots$
$C_{N-1} = E(C_{N-2} \oplus P_{N-1}, K) = MAC$

- MAC sent with IV and plaintext
- Receiver does same computation and verifies that result agrees with MAC
- Note: receiver must know the key K

Does a MAC work?

- Suppose Alice has 4 plaintext blocks
- Alice computes

  $\mathbf{C_0} = E(IV \oplus P_0, K)$, $\mathbf{C_1} = E(\mathbf{C_0} \oplus P_1, K)$,

  $\mathbf{C_2} = E(\mathbf{C_1} \oplus P_2, K)$, $\mathbf{C_3} = E(\mathbf{C_2} \oplus P_3, K) = \mathbf{MAC}$
- Alice sends IV, P_0, P_1, P_2, P_3 and **MAC** to Bob
- Suppose Trudy changes P_1 to X
- Bob computes

  $\mathbf{C_0} = E(IV \oplus P_0, K)$, $\boldsymbol{C_1} = E(\mathbf{C_0} \oplus X, K)$,

  $\boldsymbol{C_2} = E(\boldsymbol{C_1} \oplus P_2, K)$, $\boldsymbol{C_3} = E(\boldsymbol{C_2} \oplus P_3, K) = \boldsymbol{MAC'} \neq \mathbf{MAC}$
- That is, error propagates into the MAC
- Trudy can't make ***MAC'*** == **MAC** without K

Confidentiality and Integrity

- Encrypt with one key, MAC with another key
- Why not use the same key?
  - Send last encrypted block (MAC) twice?
  - This cannot add any security!
- Using different keys to encrypt and compute MAC works, even if keys are related
  - But, twice as much work as encryption alone
  - Can do a little better – about 1.5 "encryptions"
- Confidentiality and integrity with same work as one encryption is a research topic

Uses for Symmetric Crypto

- Confidentiality
  - Transmitting data over insecure channel
  - Secure storage on insecure media
- Integrity (MAC)
- Authentication protocols (later…)
- Anything you can do with a hash function (upcoming chapter…)

Lab: Alternate CTR mode

- Suppose we use encrypt using the following formula:

  $$C_i = P_i \oplus E(K, IV+i)$$

- Is this secure? Why or why not?
  - If so, how does this relate to CTR mode?
  - If not, what type of attacks would be a concern?