Advanced Encryption Standard

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

Advanced Encryption Standard

- Used in:
  - IPSec
  - SSH
  - SSL/TLS
  - Wi-Fi (IEEE 802.11i)
  - VeraCrypt
  - etc…
- So common that, since 2008, Intel CPUs have specific "AES instruction"

Advanced Encryption Standard

- To date, it is **secure**
  - Some speculated attacks
    - Square attack
    - Impossible differential attack
    - Related key attack
  - But none better than brute-force

AES: Executive Summary

- **Block size:** 128 bits (others in Rijndael)
- **Key length:** 128, 192 or 256 bits (independent of block size in Rijndael)
- 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)

Key length comparison

- 56-64 bits
  - Short-term security
    - Few hours to days to crack it
- 112-128 bits
  - Long-term security
    - Several decades in the absence of Quantum Computers
- 256 bits
  - Long-term security
    - Several decades, even with Quantum Computers (with present quantum algorithms)

Key length comparison

- How big really is 2^{256}?
- $\cancel{2^{32}} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32}$
  - $2^{32} = 4,294,967,296$

- Let's assume you have a very powerful PC capable to compute 2^{32} guesses per second
  - We still need:

$2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32}$ sec

Key length comparison

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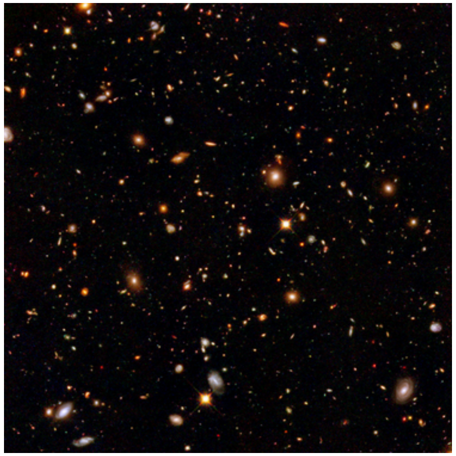
- $\cancel{2^{32}} * \cancel{2^{32}} * \cancel{2^{32}} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32}$
  - $2^{32} = 4{,}294{,}967{,}296$

- Let's assume 4B people on Earth help us finding the key…
- Let's assume we ask for help to 4B citizens of 4B planets in our Milky Way…

Key length comparison

- How big really is 2^{256}?
- $2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32}$
  - $2^{32} = 4{,}294{,}967{,}296$

- Let's ask help to 4B citizen of 4B planets in 4B galaxies!
- Ok! 16 billion galaxies…
- 64 Billion?
- 256 Billion galaxies!!!



Key length comparison

- How big really is 2^{256}?
- $2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32} * 2^{32}$
  - $2^{32} = 4{,}294{,}967{,}296$

- We still need $4{,}294{,}967{,}296$ seconds
- …more than 136 years…
- …and there are much less than 256B galaxies out there
- Maybe asking help to multiverses…

AES ByteSub

- Treat 128 bit block as 4x4 byte array

$$\begin{bmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{bmatrix} \longrightarrow \texttt{ByteSub} \longrightarrow \begin{bmatrix} b_{00} & b_{01} & b_{02} & b_{03} \\ b_{10} & b_{11} & b_{12} & b_{13} \\ b_{20} & b_{21} & b_{22} & b_{23} \\ b_{30} & b_{31} & b_{32} & b_{33} \end{bmatrix}.$$

- ByteSub is AES's "S-box"
- Can be viewed as nonlinear (but invertible) composition of two math operations

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 rows

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

AES MixColumn

- Invertible, linear operation applied to each column

$$\begin{bmatrix} a_{0i} \\ a_{1i} \\ a_{2i} \\ a_{3i} \end{bmatrix} \longrightarrow \texttt{MixColumn} \longrightarrow \begin{bmatrix} b_{0i} \\ b_{1i} \\ b_{2i} \\ b_{3i} \end{bmatrix} \quad \text{for } i = 0, 1, 2, 3$$

- Implemented as a (big) lookup table

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, since "$\oplus$" is its own inverse
- MixColumn is invertible (inverse is also implemented as a lookup table)
- Inverse of ShiftRow is easy (cyclic shift the other direction)
- ByteSub is invertible (inverse is also implemented as a lookup table)

A Few Other Block Ciphers

- Briefly…
  - IDEA
  - Blowfish
  - RC6
  - TEA

IDEA

- Invented by James Massey
  - One of the giants of modern crypto
- IDEA has 64-bit block, 128-bit key
- IDEA uses **mixed-mode arithmetic**
- Combine 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

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, so 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 $\oplus$ (XOR)
- Simple, easy to implement, fast, low memory requirement, etc.
- Possibly a "related key" attack
- 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?
  - If so, as impractical as a one-time pad!
- Encrypt each block independently?
- Is there any analog of codebook "additive"?
- 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 approach, but a bad idea
- 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:

EncryptDecrypt

$$C_0 = E(P_0, K) \qquad P_0 = D(C_0, K)$$
$$C_1 = E(P_1, K) \qquad P_1 = D(C_1, K)$$
$$C_2 = E(P_2, K) \ \ldots \qquad P_2 = D(C_2, K) \ \ldots$$

- 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 digs Bob. Trudy digs Tom.`

- Assuming 64-bit blocks and 8-bit ASCII:

$P_0 =$ "`Alice di`", $P_1 =$ "`gs Bob. `",

$P_2 =$ "`Trudy di`", $P_3 =$ "`gs Tom. `"

- Ciphertext: C_0, C_1, C_2, C_3
- Trudy cuts and pastes: C_0, C_3, C_2, C_1
- Decrypts as

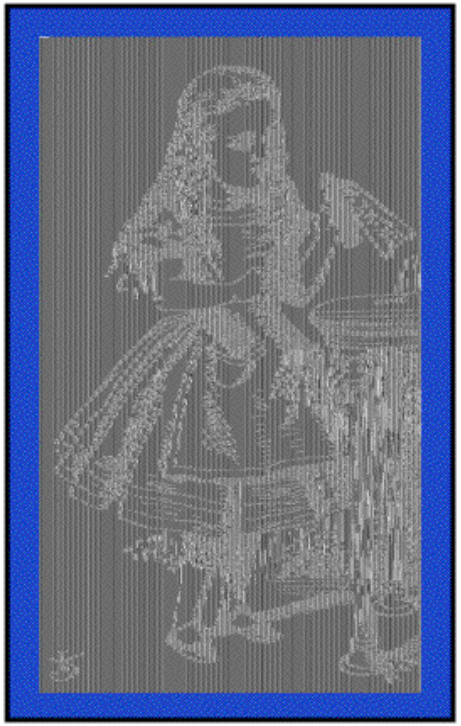
  `Alice digs Tom. Trudy digs Bob.`

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!

Cipher Block Chaining (CBC) Mode

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

EncryptionDecryption

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

$C_1 = E(C_0 \oplus P_1, K),$ $P_1 = C_0 \oplus D(C_1, K),$

$C_2 = E(C_1 \oplus P_2, K),\ldots$ $P_2 = C_1 \oplus D(C_2, K),\ldots$

- Analogous to classic codebook with additive

CBC Mode

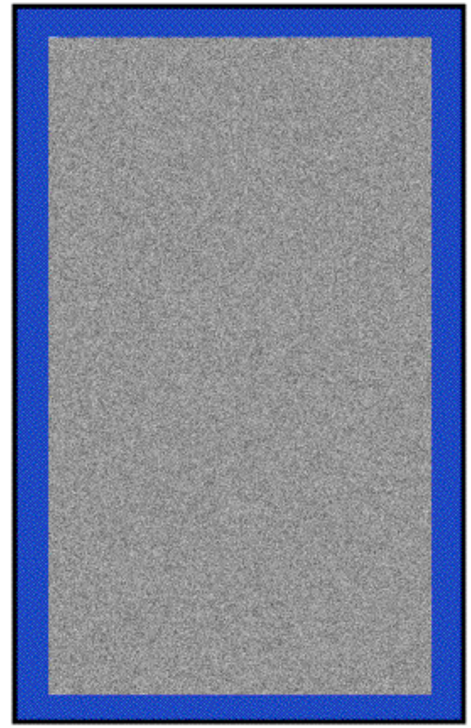
- Identical plaintext blocks yield different ciphertext blocks — this is very good!
- But what about errors in transmission?
  - If C_1 is garbled to, say, G then

    $$P_1 \neq C_0 \oplus D(G, K),\ P_2 \neq G \oplus D(C_2, K)$$

  - But $P_3 = C_2 \oplus D(C_3, K),\ P_4 = C_3 \oplus D(C_4, K),\ \ldots$
  - 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 **Decryption**

$$C_0 = P_0 \oplus E(IV, K),$$
$$C_1 = P_1 \oplus E(IV+1, K),$$
$$C_2 = P_2 \oplus E(IV+2, K),\ldots$$

$$P_0 = C_0 \oplus E(IV, K),$$
$$P_1 = C_1 \oplus E(IV+1, K),$$
$$P_2 = C_2 \oplus E(IV+2, K),\ldots$$

- Note: CBC also works for random access
    - But there is a significant limitation…

Integrity

Data Integrity

- **Integrity**— detect unauthorized writing (i.e., detect unauthorized mod 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., 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
  - The MAC serves as a cryptographic checksum for data

MAC Computation

- MAC computation (assuming N blocks)

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

  $C_1 = E(C_0 \oplus P_1, K)$,

  $C_2 = E(C_1 \oplus P_2, K), \ldots$

  $C_{N-1} = E(C_{N-2} \oplus P_{N-1}, K) = MAC$

- Send $IV, P_0, P_1, \ldots, P_{N-1}$ and MAC
- Receiver does same computation and verifies that result agrees with MAC
- Both sender and receiver must know K

Does a MAC work?

- Suppose Alice has 4 plaintext blocks
- Alice computes

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

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

  $C_0 = E(IV \oplus P_0, K)$, $C_1 = E(C_0 \oplus X, K)$,

$C_2 = E(C_1 \oplus P_2, K)$, $C_3 = E(C_2 \oplus P_3, K) = \mathit{MAC} \neq \text{MAC}$

- It works since error <u>propagates</u> into **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…)