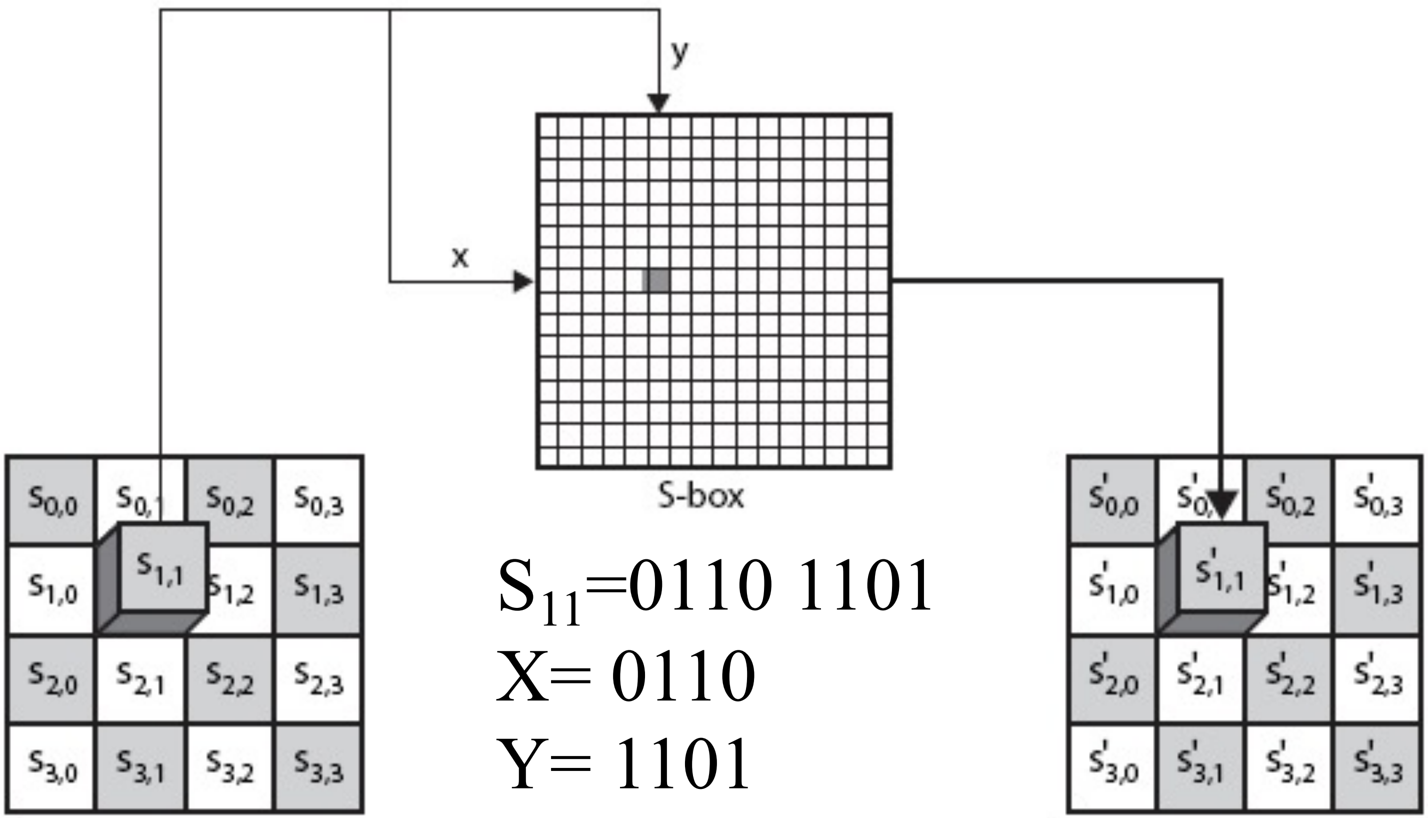
Four Steps in Each Round

- Substitute Bytes – single byte based
- Shift Rows – row-wise permutation
- Mix Columns – column-wise mixing
- Add Round Keys

AES: SubBytes() (S-Box)



S_{11}=0110 1101
X= 0110
Y= 1101

- A simple substitution of each byte
- Uses one table of 16x16 bytes containing a permutation of all 256 8-bit values

AES S-Box

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

The column is determined by the least significant nibble, and the row by the most significant nibble. For example, the value $9a_{16}$ is converted into $b8_{16}$.

itution

Example:

EA	04	65	85
83	45	5D	96
5C	33	98	B0
F0	2D	AD	C5

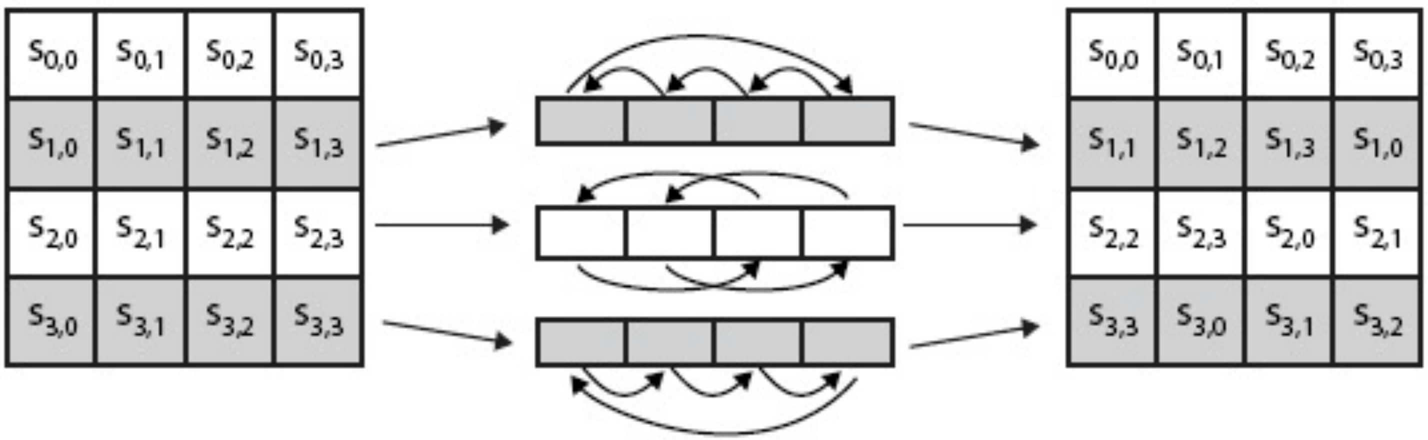
→

87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

Shift Rows

- A circular byte shift in each row
  - 1st row is unchanged
  - 2nd row does 1 byte circular shift to left
  - 3rd row does 2 byte circular shift to left
  - 4th row does 3 byte circular shift to left
- Decrypt does shifts to right

AES: ShiftRows()



87	F2	4D	97
EC	6E	4C	90
4A	C3	46	E7
8C	D8	95	A6

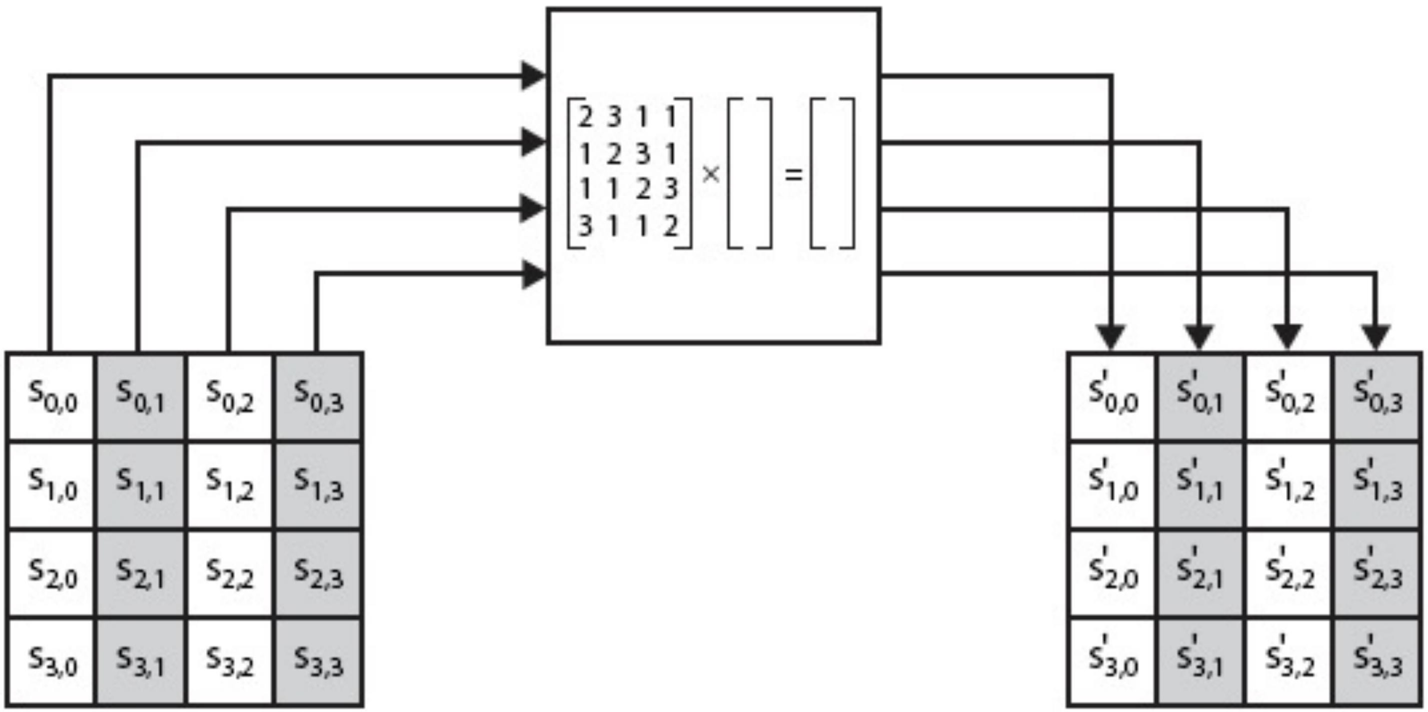
→

87	F2	4D	97
6E	4C	90	EC
46	E7	4A	C3
A6	8C	D8	95

Mix Columns

- Each column is processed separately
- Each byte is replaced by a value dependent on all 4 bytes in the column

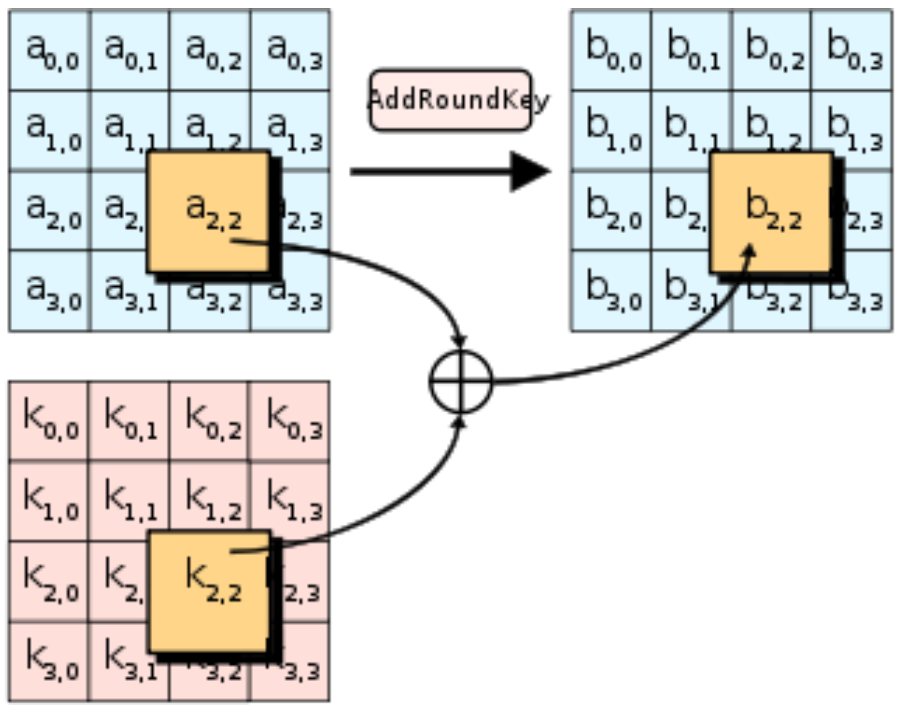
AES: MixColumns()



Add Round Key

- XOR state matrix with 128-bits of the round key
- Inverse for decryption is identical since XOR is own inverse, just with correct round key
- Designed to be as simple as possible

AES: AddRoundKey()



Implementation Aspects of AES

- Can be efficiently implemented even on 8-bit CPU
  - Byte substitution works on bytes using a table of 256 entries
  - Shift rows is simple byte shifting
  - Add round key works on byte XORs
  - Mix columns requires more complicated operations (matrix multiply) on byte values, but can be simplified to use a table lookup and XORs.
  - Observe that each step is invertible, so decryption given key bits is straightforward
  - All operations can be combined into XOR and table lookups -hence very fast & efficient

Private-Key Cryptography

- Traditional **private/secret/single key** cryptography uses **one** key
- Shared by both sender and receiver
- If this key is disclosed communications are compromised
- Also is **symmetric**, parties are equal
- Hence does not protect sender from receiver forging a message & claiming is sent by sender

Public-Key Cryptography

- Probably most significant advance in the 3000 year history of cryptography
- Uses **two** keys – a public & a private key
- **Asymmetric** since parties are **not** equal
- Uses clever application of number theoretic concepts to function
- Complements **rather than** replaces private key crypto

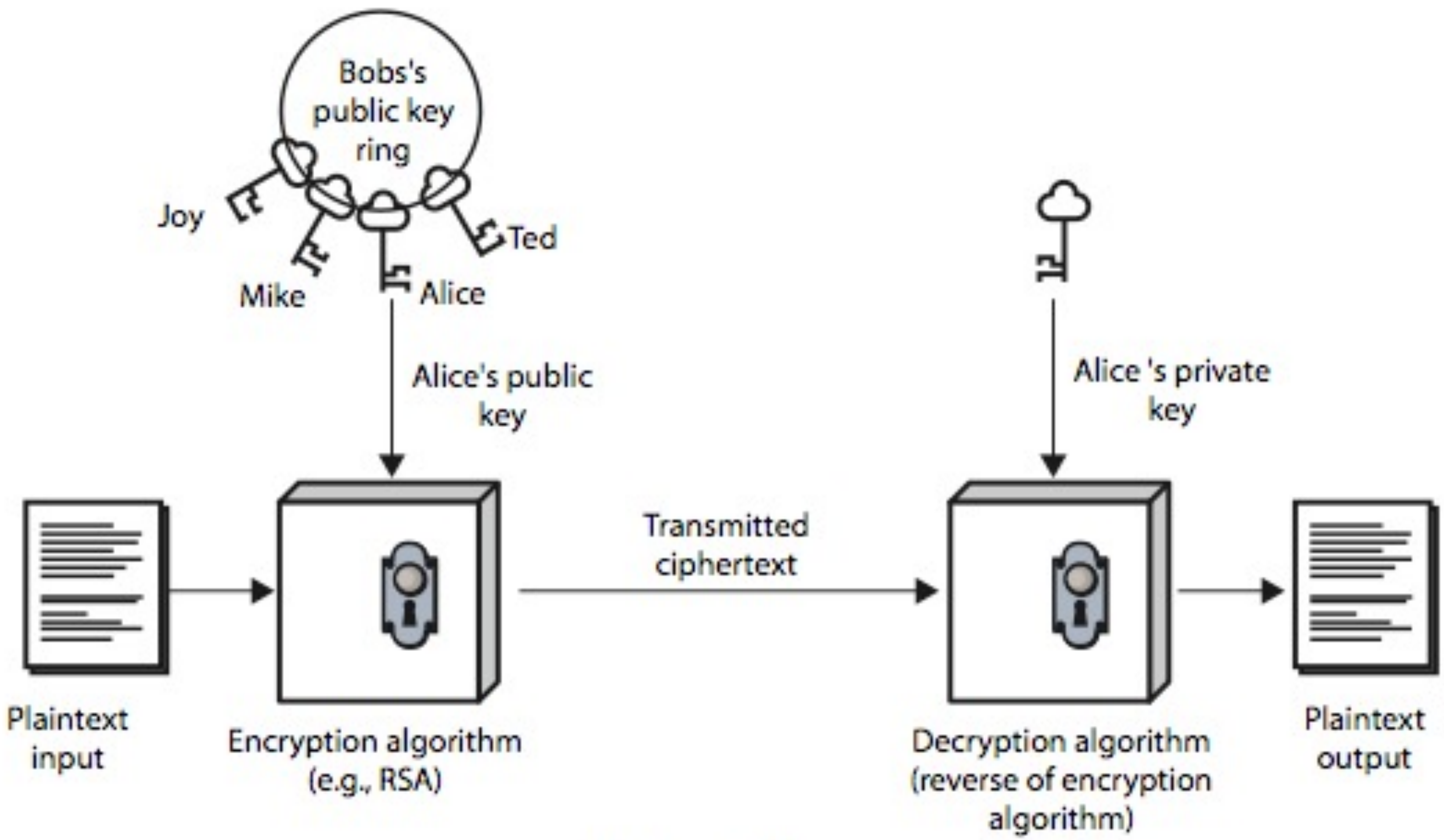
Why Public-Key Cryptography?

- Developed to address two key issues:
  - **key distribution** – how to have secure communications in general without having to trust a key distribution center with your key
  - **Digital signatures** – how to verify a message comes intact from the claimed sender
- Public invention due to Diffie & Hellman at Stanford University in 1976
  - known earlier in classified community

Public-Key Cryptography

- **Public-key/two-key/asymmetric** cryptography involves the use of **two** keys:
  - a **public-key**, which may be known by anybody, and can be used to **encrypt messages**, and **verify signatures**
  - a **private-key**, known only to one party, used to **decrypt messages**, and **sign** (create) **signatures**
- **Asymmetric** because
  - those who encrypt messages or verify signatures **cannot** decrypt messages or create signatures

Public-Key Cryptography



(a) Encryption

Public-Key Characteristics

- Public-Key algorithms rely on two keys where:
  - when the relevant (en/decrypt) key is known it is computationally easy to en/decrypt messages
  - it is computationally infeasible to find decryption key, knowing only algorithm & encryption key

Diffie & Hellman Key Exchange

- Alice and Bob want to share a secret (e.g., a key) in an open channel.

- Assume they agree on two numbers n and g
- g is primitive root mod (n)
  - For each $p < n$ s.t. p is coprime to n, there is an a such that

    $g^a = p \bmod (n)$
- These g and n do not have to be kept secret

Alice

- Chooses a large random number x
- Calculates

$$X = g^x \bmod (n)$$

- Sends X, g, and n to Bob.

Bob

- Chooses a large random number y
- Calculates

$$Y = g^y \bmod (n)$$

- Sends Y to Alice.

- Alice calculates

$$k = Y^x \bmod (n)$$

- Bob calculates

$$k' = X^y \bmod (n)$$

The Key

- $k' = k$ is the shared key

$$k = Y^x \bmod (n) = (g^y)^x \bmod (n) = g^{yx} \bmod (n)$$

$$k' = X^y \bmod (n) = (g^x)^y \bmod (n) = g^{xy} \bmod (n)$$

No efficient classical algorithm for computing general discrete logarithms.

- Nobody can calculate k given
  n, g, X, and Y

Example

- Alice and Bob get public numbers
  - $n = 23$, $g = 9$
- Alice and Bob compute public values
  - $X = 9^4 \bmod 23 = 6561 \bmod 23 = 6$
  - $Y = 9^3 \bmod 23 = 729 \bmod 23 = 16$
- Alice and Bob exchange public numbers

Example

- Alice and Bob compute symmetric keys
  - $k_a = 16^4 \bmod 23 = 9$
  - $k_b = 6^3 \bmod 23 = 9$
- Alice and Bob now can talk securely!

Diffie-Hellman Limitations

- Only Alice and Bob know k
- Good for only one session
- Used if you only want a symmetric key
- Can't be sure connected to the same person
- No authentication