CSE509: (Intro to) Systems Security

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Ciphers

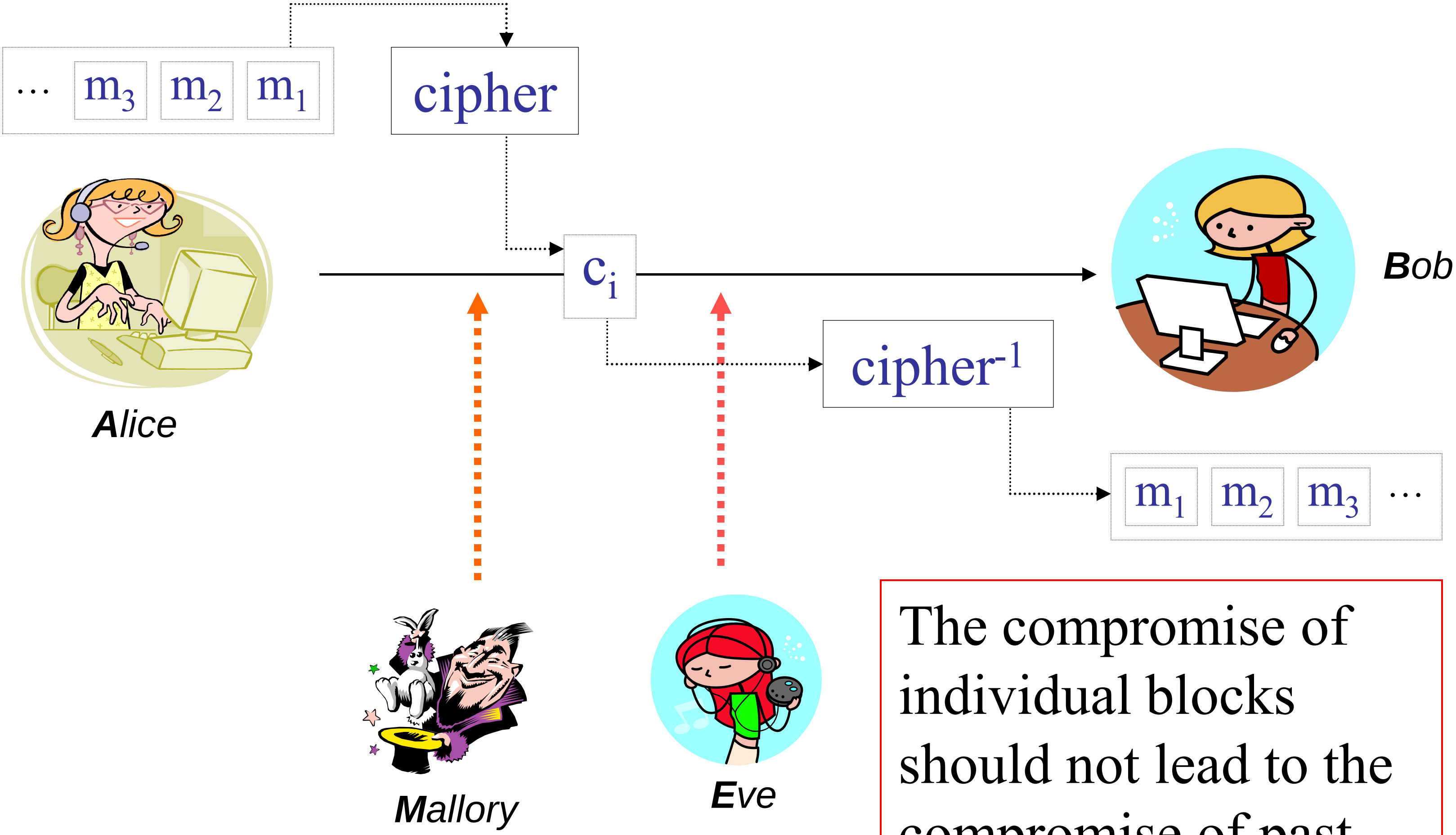
Ciphers

- Overview
- Naïve Usage
- Types of Ciphers

Ciphers???!

- Mechanisms for message security
    - But isn't everything ? ☺
- Fast ?
- Secure ?
- Suited for environment ?

Ciphers???!



… m_3 m_2 m_1

cipher

c_i

cipher^{-1}

m_1 m_2 m_3 …

Alice

Bob

Mallory

Eve

The compromise of individual blocks should not lead to the compromise of past communication !

Problems

- Using a cipher requires knowledge of threats in the environment in which it will be used
  - Is the set of possible messages small?
  - Do the messages exhibit regularities that remain after en-cipherment?
  - Can an active wire-tapper rearrange or change parts of the message?

Collision Attack: Birthday Attacks

- With 23 people in the same room chance of same birthday is over 50% !!!
- For **N** possible values expect a collision after seeing approx. **sqrt(N)** of them
- If $\mathbf{N=2^n}$ (**n**-bit key) after $\mathbf{2^{n/2}}$ ("birthday bound") messages a collision is expected !

Birthday Attack Deployed

- For **64**-bit key, after seeing **2^{32}** transactions Eve can find message sent with same key ! (how can she know ? Using keyed MAC of standard message header ?)
- Eve can then substitute old messages for new ones (e.g., reversing money transfers)

Collision Attack: Meet in the Middle

- Cousin of Birthday Attack

- $C = E_{K2}(E_{K1}(M))$
- This does not have 2n bit security !
- Why ?
- For a known (C,M) pair do this:
  - T: Build table $E_K(M)$ for all K
  - Compute $D_K(C)$ for all K and lookup in T
  - Takes 2^{n+1} steps only

Attack: Pre-computation

- If set of possible messages M is small
- Public key cipher f used
- Idea: pre-compute set of possible cipher-texts $f(M)$, build table $(m, f(m))$
- When cipher-text $f(m)$ appears, use table to find m
- Also called *forward searches*

Example

- Cathy knows Alice will send Bob one of two enciphered messages: BUY or SELL
- Using $public_B$, Cathy pre-computes

  $m_1 = \mathrm{E}_{\mathrm{public}_\mathrm{B}}(\text{“BUY”})$

  $m_2 = \mathrm{E}_{\mathrm{public}_\mathrm{B}}(\text{“SELL”})$
- Cathy sees Alice send Bob m_2
- Cathy knows Alice sent SELL

Another example: may not be obvious

- Digitized sound
  - Seems like far too many possible plaintexts
    - Initial calculations suggest $\mathbf{2^{32}}$ such plaintexts
  - Analysis of redundancy in human speech reduced this to about **100,000** ($\approx$ $\mathbf{2^{17}}$)
    - small enough to worry about pre-computation attacks

Mis-ordered Blocks

- Alice sends Bob message
  - Message is LIVE (11 08 21 04)
  - Enciphered message is 44 57 21 16
- Eve intercepts it, rearranges blocks
  - Now enciphered message is 16 21 57 44
- Bob gets enciphered message, deciphers it
  - He sees EVIL

Notes

- Signing each block won't stop it !
- Two approaches:
  - Crypto-hash the *entire* message and sign it
  - Place sequence numbers in each block of message, so recipient can tell intended order, then sign each block

Statistical Regularities

- If plaintext repeats, ciphertext may too
- Example using DES:
  - input (in hex):

    `3231` `3433 3635 3837` **`3231`** `3433 3635 3837`
  - corresponding output (in hex):

    `ef7c` `4bb2 b4ce 6f3b` **`ef7c`** `4bb2 b4ce 6f3b`
- Fix: cascade blocks together (chaining)
  - More details later

What These Mean

- Use of strong cryptosystems, well-chosen (or random) keys not enough to be secure
- Other factors:
  - Protocols directing use of cryptosystems
  - Ancillary information added by protocols
  - Implementation (not discussed here)
  - Maintenance and operation (not discussed here)

Stream, Block Ciphers

- E encipherment function
  - $E_k(b)$ encipherment of message b with key k
  - In what follows, $m = b_1 b_2 \ldots$, each b_i of fixed length
- Block cipher
  - $E_k(m) = E_k(b_1)E_k(b_2) \ldots$
- Stream cipher
  - $k = k_1 k_2 \ldots$
  - $E_k(m) = E_{k1}(b_1)E_{k2}(b_2) \ldots$
  - If $k_1 k_2 \ldots$ repeats itself, cipher is *periodic* and the kength of its period is one cycle of $k_1 k_2 \ldots$

Examples

- Vigenère cipher
  - b_i = 1 character, $k = k_1 k_2 \ldots$ where k_i = 1 character
  - Each b_i enciphered using $k_{i \bmod \text{length}(k)}$
  - Stream cipher
- DES
  - b_i = 64 bits, k = 56 bits
  - Each b_i enciphered separately using k
  - Block cipher

Stream Ciphers

- Often (try to) implement one-time pad by xor'ing each bit of key with one bit of message
  - Example:

$$m = 00101$$
$$k = 10010$$
$$c = 10111$$

- But how to generate a good key?

Synchronous Stream Ciphers

- n-stage Linear Feedback Shift Register:
  - n bit register $r = r_0 \ldots r_{n-1}$
  - n bit "tap sequence" $t = t_0 \ldots t_{n-1}$
  - Use:
    - Use r_{n-1} as key bit
    - Compute $x = r_0 t_0 \oplus \ldots \oplus r_{n-1} t_{n-1}$
    - Shift r one bit to right, dropping r_{n-1}, x becomes r_0

Example

- 4-stage LFSR; $t = 1001$

r	k_i	*new bit computation*	*new r*
0010	0	01⊕00⊕10⊕01 = 0	0001
0001	1	01⊕00⊕00⊕11 = 1	1000
1000	0	11⊕00⊕00⊕01 = 1	1100
1100	0	11⊕10⊕00⊕01 = 1	1110
1110	0	11⊕10⊕10⊕01 = 1	1111
1111	1	11⊕10⊕10⊕11 = 0	0111
1110	0	11⊕10⊕10⊕11 = 1	1011

  - Key sequence has period of 15 (010001011101110)

NLFSR

- n-stage Non-Linear Feedback Shift Register: consists of
  - n bit register $r = r_0 \ldots r_{n-1}$
  - Use:
    - Use r_{n-1} as key bit
    - Compute $x = f(r_0, \ldots, r_{n-1})$; f is any function
    - Shift r one bit to right, dropping r_{n-1}, x becomes r_0

  Note same operation as LFSR but more general bit replacement function

Example

- 4-stage NLFSR; $f(r_0, r_1, r_2, r_3) = (r_0 \,\&\, r_2) \mid r_3$

r	k_i	*new bit computation*	*new r*
`1100`	`0`	`(1 & 0)	0 = 0`	`0110`
`0110`	`0`	`(0 & 1)	0 = 0`	`0011`
`0011`	`1`	`(0 & 1)	1 = 1`	`1001`
`1001`	`1`	`(1 & 0)	1 = 1`	`1100`
`1100`	`0`	`(1 & 0)	0 = 0`	`0110`
`0110`	`0`	`(0 & 1)	0 = 0`	`0011`
`0011`	`1`	`(0 & 1)	1 = 1`	`1001`

  - Key sequence has period of 4 (0011)

Eliminating Linearity

- NLFSRs not common
  - We don’t know how to design them to have long period
- Alternate approach: *output feedback mode*
  - For E encipherment function, k key, r register:
    - Compute $r' = E_k(r)$; key bit is rightmost bit of r'
    - Set r to r' and iterate, repeatedly enciphering register and extracting key bits, until message enciphered
  - Variant: use a counter that is incremented for each encipherment rather than a register
    - Take rightmost bit of $E_k(i)$, where i is number of encipherment

Self-Synchronous Stream Cipher

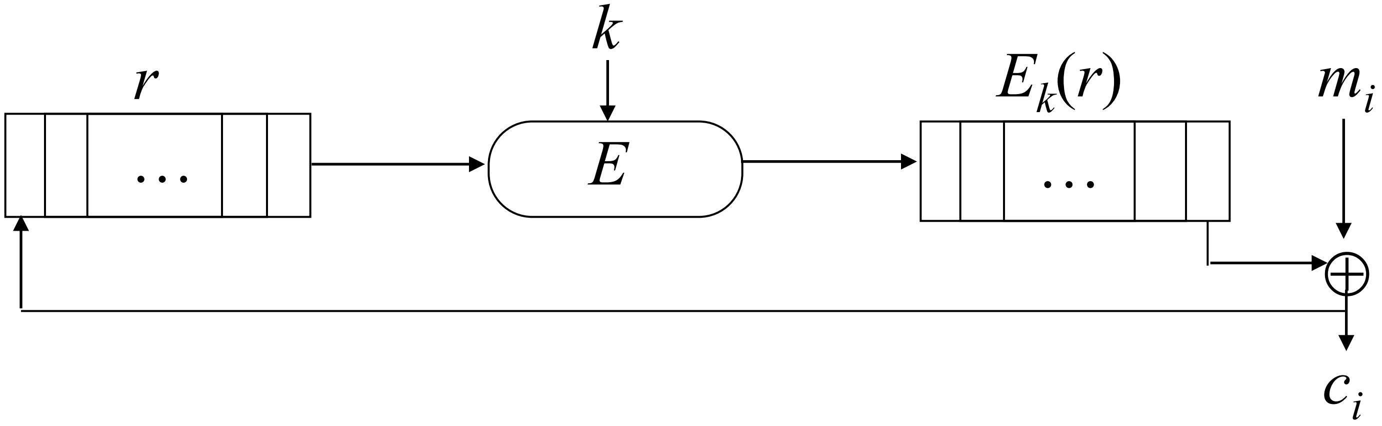
- Take key from message itself (*autokey*)
- Example: Vigenère, key drawn from plaintext
  - *key* `XTHEBOYHASTHEBA`
  - *plaintext* `THEBOYHASTHEBAG`
  - *ciphertext* `QALFPNFHSLALFCT`
- Problem:
  - Statistical regularities in plaintext show in key
  - Once you get any part of the message, you can decipher more

Another Example

- Take key from ciphertext (*autokey*)
- Example: Vigenère, key drawn from ciphertext
  - *key* `XQXBCQOVVNGNRTT`
  - *plaintext* `THEBOYHASTHEBAG`
  - *ciphertext* `QXBCQOVVNGNRTTM`
- Problem:
  - Attacker gets key along with ciphertext, so deciphering is trivial

Variant

- Cipher feedback mode: 1 bit of ciphertext fed into *n* bit register
  - Self-healing property: if ciphertext bit received incorrectly, it and next *n* bits decipher incorrectly; but after that, the ciphertext bits decipher correctly
  - Need to know *k*, *E* to decipher ciphertext



Block Ciphers

- Encipher, decipher multiple bits at once
- Each block enciphered independently
- Problem: identical plaintext blocks produce identical ciphertext blocks
  - Example: two database records
    - `MEMBER: HOLLY INCOME $100,000`
    - `MEMBER: HEIDI INCOME $100,000`
  - Encipherment:
    - `ABCQZRME GHQMRSIB CTXUVYSS RMGRPFQN`
    - `ABCQZRME ORMPABRZ CTXUVYSS RMGRPFQN`

Solution: CBC

- Insert information about block's position into the plaintext block, then encipher.
- *Cipher block chaining mode (CBC)*:
  - Exclusive-or current plaintext block with previous ciphertext block:
    - $c_0 = E_k(m_0 \oplus I)$
    - $c_i = E_k(m_i \oplus c_{i-1})$ for i > 0

    where I is the initialization vector

Solution: CTR

- *Counter mode (CTR)*:
  - – Key constructed by encrypting block counter
    - $k_{\mathrm{i}} = E_k(unique\_nonce||i)$
    - $c_{\mathrm{i}} = m_{\mathrm{i}} \oplus k_{\mathrm{i}}$

    e.g. unique_nonce=(message number)
  - – Question: why do we need the *nonce* ?
  - – Careful: <u>never</u> use same (*k,nonce*) pair !!!