CS 352
Network Security: Introduction

CS 352, Lecture 25.1

http://www.cs.rutgers.edu/~sn624/352

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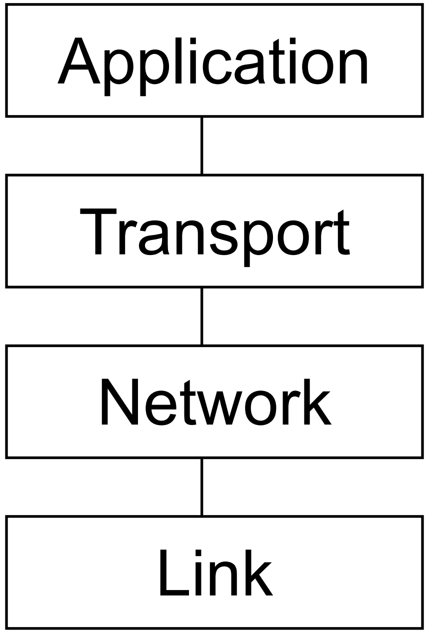
Security and the Network Stack



Security: cuts across all parts of the network stack!

Why network security?

- The Internet is used for all sorts of things
  - Banking and commerce
  - Interconnecting electronic voting machines
  - Interacting with the Government, your employer, school, …
  - Shopping online, including essentials like milk or groceries
  - Sometimes, even basic social interactions require the Internet!
- But malicious people share your network
  - People who want to snoop, pretend, steal
- “Attacks” can be passive or active
  - Sit and snoop (e.g., credit card info)
  - Actively target (e.g., phishing)

Some key aspects of network security

Confidentiality: only the sender and the intended receiver should understand the message contents

Integrity: sender, receiver want to ensure message not altered (in transit, or afterwards) without detection

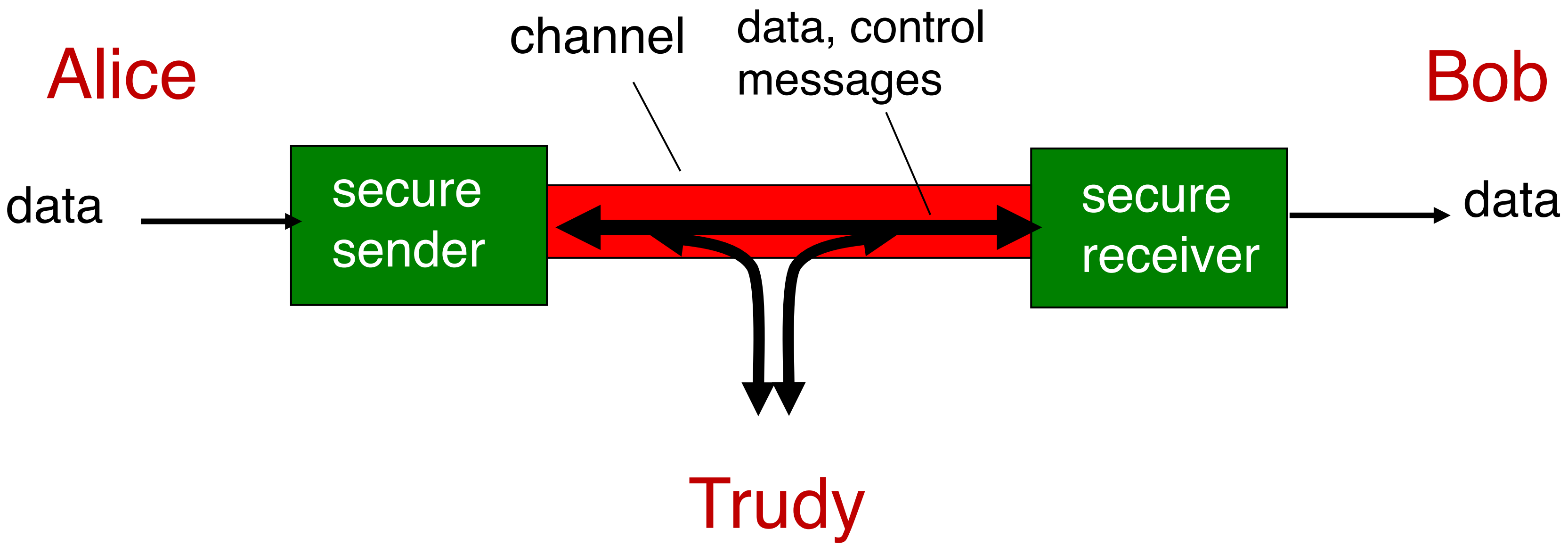
Authentication: confirm the identity of communicating parties

Non-repudiation: Once someone sends a message, or conducts a transaction, they can’t later deny the contents of that message

Availability: sender and receiver able to communicate at all

Friends and enemies: Alice, Bob, Trudy

- Two parties, Bob and Alice, want to communicate securely
  - Often used in network security examples
- Trudy (intruder) may intercept, delete, add messages



Who/what might Bob and Alice be?

- Real humans ☺
- Web browser/server for electronic transactions
  - e.g., on-line purchases, or online banking
- DNS clients and servers
- Routers exchanging routing table updates
- Two mail clients

- Many other examples!

What might Trudy do?

- Eavesdrop: intercept messages
- Entity in the middle: actively insert messages into connection
- Impersonation: can fake (spoof) source address in packet (or any field in packet)
- Hijacking: “take over” ongoing connection by removing sender or receiver, inserting itself in place
- Denial of service: prevent service from being used by others (e.g., by overloading resources)

What we will learn in the next lectures

- Principles of network security
  - Primitives for confidentiality, authentication, integrity, non-repudiation
- How to apply these principles to secure:
  - An application: e-mail
  - Transport: TLS (Transport Layer Security for TCP)

Network security is a broad area

- Many exciting topics!
- Security for apps and transport protocols: e.g., QUIC
- Security at all layers: Network layer (e.g., IPSec, VPNs); Link layer (e.g., WPA)
- Security for protocols, e.g., DNSSEC, BGPSEC
- Operational security: how to secure a network
  - Firewalls, intrusion detection/prevention, data breach security, …
- Covering these and other topics in network & system security would require its own set of courses ☺

CS 352
Cryptography: Introduction

CS 352, Lecture 25.2

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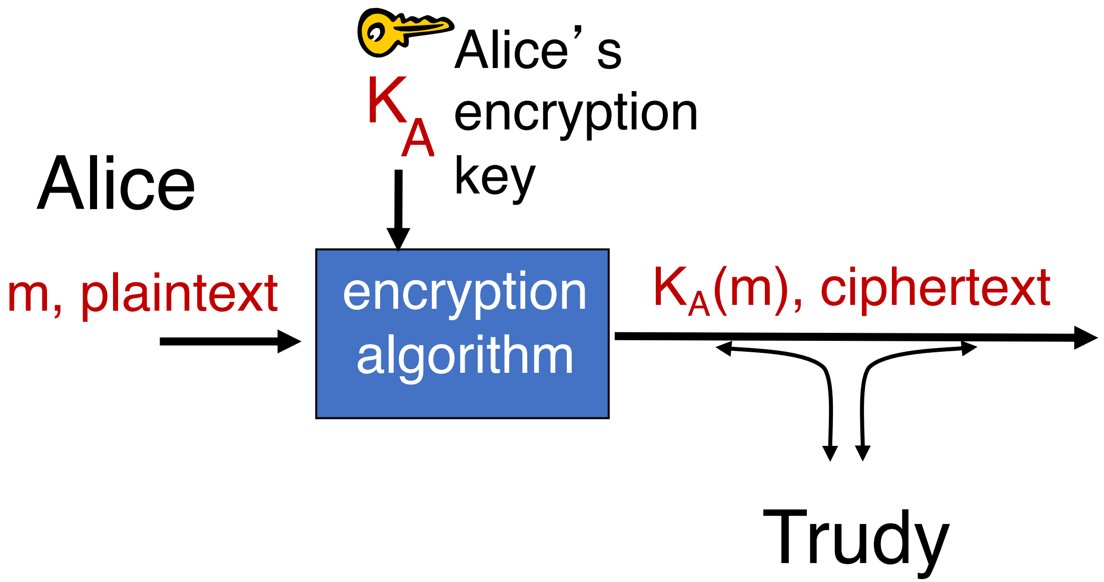
Confidentiality

- Confidentiality: only the sender and the intended receiver should understand the message contents
- How to achieve this goal?
  - Cryptography
- Sender encrypts a message, receiver decrypts it.
- An intermediate observer should just see random bytes!

Terminology of Cryptography



m: plaintext message

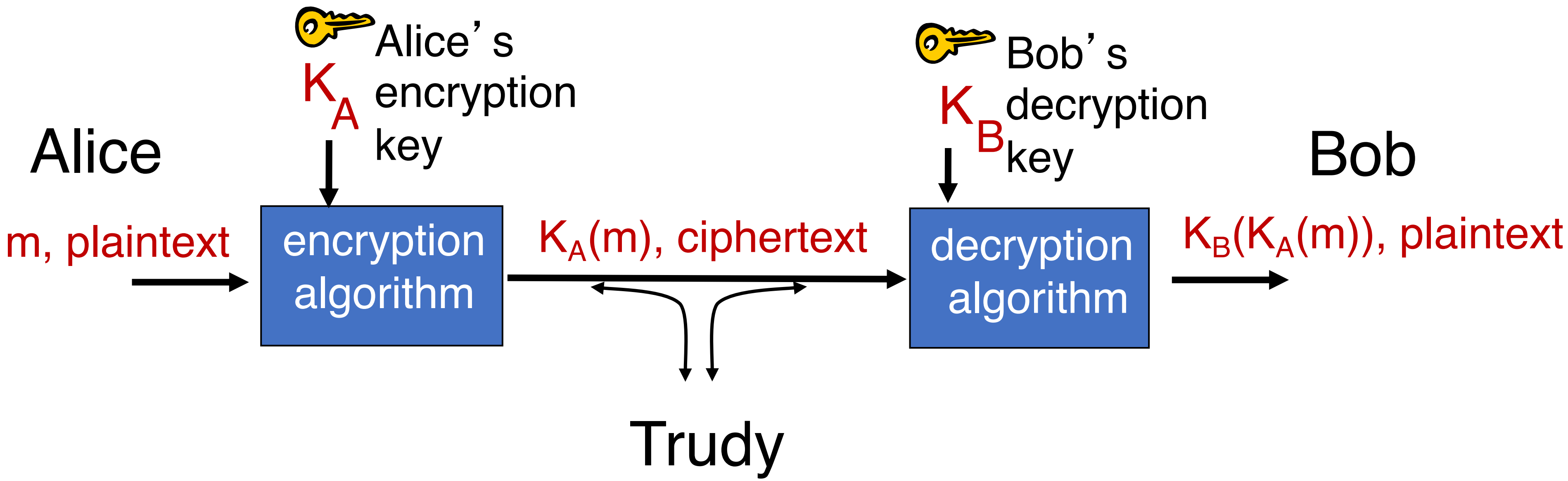
K_A, Alice's encryption key. Secret known only to Alice

K_A(m) is ciphertext: m encrypted with key K_A

Encryption transforms the message so that it's jumbled

Ideal: want K_A(m) to be uncorrelated with m (Trudy can't read the msg)

Terminology of Cryptography



K_B is Bob's decryption key, a secret known only to Bob

m' = $K_B(c)$, c decrypted with key K_B. $K_B(c)$ is plaintext

Want Bob to retrieve the same plaintext as the one sent by Alice

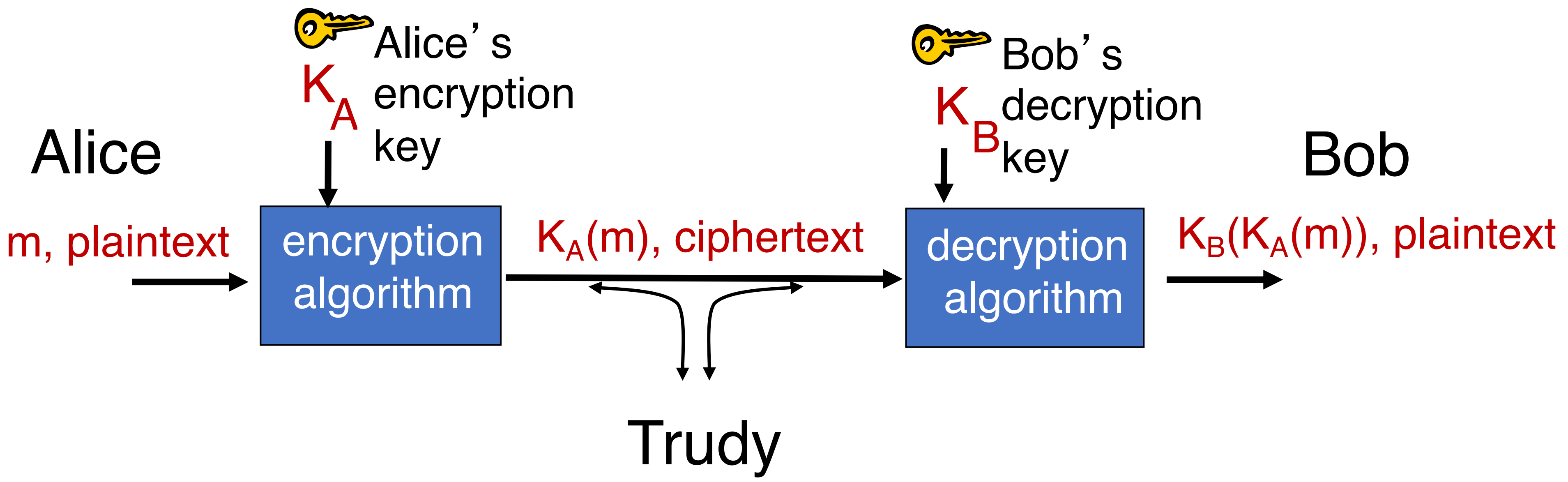
Want $m = K_B(K_A(m))$

Encryption and decryption algorithms are also called ciphers.

Algorithms and Keys

- Cryptography requires algorithms (for encryption and decryption) and keys (parameters fed to the algorithms)
- Cryptography practice: algorithms must be publicly known
  - Inspires trust that it works: obvious flaws found sooner
  - Openness fosters innovation: techniques can be improved by everyone
- On the other hand, keys are secret
  - Keys must be hard to guess, e.g., 128-bit, 256-bit, 1024-bit
- Analogy: everyone knows how your house lock works, and they use a similar design for their house lock
  - “Everyone uses the same lock, so it must be a reliable lock”
  - But only you know the combination for your lock

Two kinds of cryptography



- K_A and K_B are the same: symmetric key cryptography
  - Next module
- K_A and K_B are different: public key cryptography
  - Next lecture!

CS 352
Symmetric Key Cryptography

CS 352, Lecture 25.3

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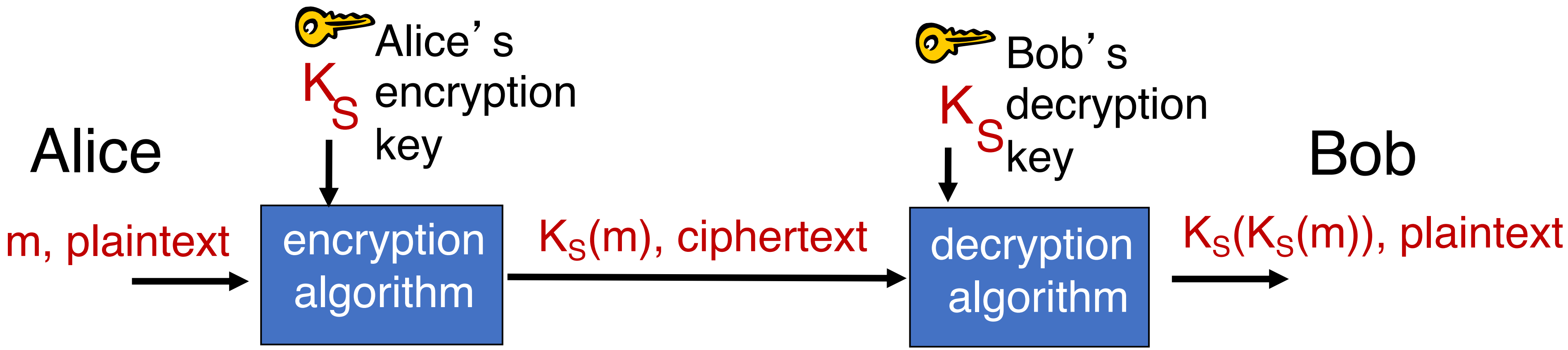
Symmetric Key Cryptography



- Alice and Bob use the same (symmetric) key, K_S
- Abuse notation: $K_S(m)$ at Alice's side is encryption, $K_S(c)$ at Bob's side is decryption
- $m = K_S(K_S(m))$
- Techniques of symmetric key crypto: substitution and permutation

Substitution-based ciphers

- Monoalphabetic cipher: substitute one letter for another
- Example 1: Caesar cipher. Replace each letter by letter shifted by some number of characters in the alphabet
  - Successor(2): a → c, b → d, …
  - Predecessor(3): a → x, b → y, c → z, d → a, …
- Example 2. Generic substitution mapping cipher

plaintext: abcdefghijklmnopqrstuvwxyz

↓ ↓

ciphertext: mnbvcxzasdfghjklpoiuytrewq

- Key: mapping from 26 letters to 26 letters

"Easy" to guess the key by observing the ciphertext alone. statistically analyze the language. Some letters are more common in plaintext than others, e.g., e and s are more common than k, j, or z

Substitution-based ciphers

- Example 3. Polyalphabetic ciphers. Use N monoalphabetic substitution ciphers with a pattern to cycle between them
- n substitution ciphers, $M_1,M_2,\ldots,M_n$
- Cycling pattern:
  - e.g., n=4: M_1,M_3,M_4,M_3,M_2; M_1,M_3,M_4,M_3,M_2; ..
- For each new plaintext symbol, use subsequent substitution pattern in cyclic pattern
  - Ciphertext for “dog”: substitute d from M_1, o from M_3, g from M_4
- Key: n substitution ciphers, and the cyclic pattern

Substitution-based ciphers

- Example 4. One-time pad.
  - XOR each bit of the plaintext with one bit of the shared key to generate the ciphertext: ciphertext[i] = message[i] ⊕ key-bits[i]
- Key: a truly random bit string, same size as the message, never reused, held secret, and shared ahead of time
  - Polyalphabetic cipher taken to an extreme: moving randomly through randomly-chosen substitution ciphers
- Statistically very hard to break:
  - All plaintexts are equally likely, since the key is truly random
  - Guessing one part of the plaintext reveals nothing about other parts
- Claude Shannon: a cipher that achieves “perfect secrecy”

Permutation-based ciphers

- Instead of substituting letters in the plaintext, we change their order
- Key: the new order. Convenient to use a word to induce an order

A	N	D	R	E	W
1	4	2	5	3	6
t	h	i	s	i	s
a	m	e	s	s	a
g	e	i	w	o	u
l	d	l	i	k	e
t	o	e	n	c	r
y	p	t	n	o	w

Say the key = ANDREW.
Sorted in alphabetical order, this is ADENRW.
We need to permute each 6-letter part of the message as follows:
1st letter of plaintext → 1st letter of ciphertext
2nd letter of plaintext → 4th letter of ciphertext
3rd letter of plaintext → 2nd letter of ciphertext, etc.

thisisamessageiwouldliketoencryptnow ➔ tiihssaesmsagioewullkdietecdnrytopnw

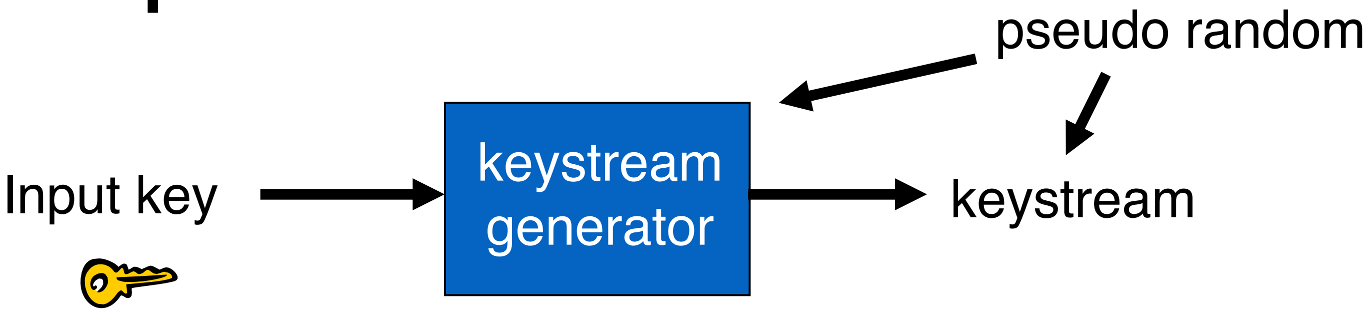
Possible to guess the key by analyzing structure of language and common letters.

Stream and Block Ciphers

Two types of symmetric ciphers

- Stream ciphers
  - Encrypt one bit at time, possibly with some dependence on prior bits
- Block ciphers
  - Break plaintext message in equal-size blocks
  - Encrypt each block as a unit, typically independently

Stream Ciphers



- Combine each bit of keystream with bit of plaintext to get one bit of ciphertext
- m(i) = ith bit of message, ks(i) = ith bit of keystream, c(i) = ith bit of ciphertext
- Encryption: $c(i) = ks(i) \oplus m(i)$ ($\oplus$ = XOR)
- Decryption: $m(i) = ks(i) \oplus c(i)$
- Very similar to one-time pad, except that the key is generated using a pseudorandom keystream generator

This strategy adopted by the RC4 cipher, deployed in early WiFi security standards (WEP and WPA); later deemed insecure

Block ciphers

- Message to be encrypted is processed in blocks of k bits (e.g., 64-bit blocks).
- Example block substitution cipher: 1-to-1 mapping is used to map k-bit block of plaintext to k-bit block of ciphertext

Example with k=3:

input	output
000	110
001	111
010	101
011	100

input	output
100	011
101	010
110	000
111	001

Ciphertext for 0 1 0 | 1 1 0 | 0 0 1 | 1 1 1?

101 000 111 001

Block ciphers

- How many possible k-bit block substitution ciphers exist?
  - There are 2^k values that are permuted amongst themselves: $2^k!$
  - k=3-bit inputs: 8! ➔ 40,320. Not that many.
  - But huge for k=64.
- Using a table for substitution is impractical
  - k=64: need 2^{64}-entry table; each entry has 64 bits
- Instead, use a function that simulates a randomly permuted table
- Some heavily used symmetric ciphers are block-based, e.g., AES

Summary of symmetric key ciphers so far

- Assume a pre-shared key between two communicating parties
- Key techniques: substitution and permutation
- Practical ciphers use a complex combination of the two
- Data Encryption Standard (DES)
  - Multiple iterations of substitution and permutation using a 56-bit key
- Advanced Encryption Standard (AES)
  - State of the art for symmetric key encryption. Hardware accelerated
  - A cool animation to understand the steps in AES: https://formaestudio.com/rijndaelinspector/archivos/Rijndael_Animation_v4_eng-html5.html

CS 352
Improving Symmetric Key Crypto

CS 352, Lecture 25.4

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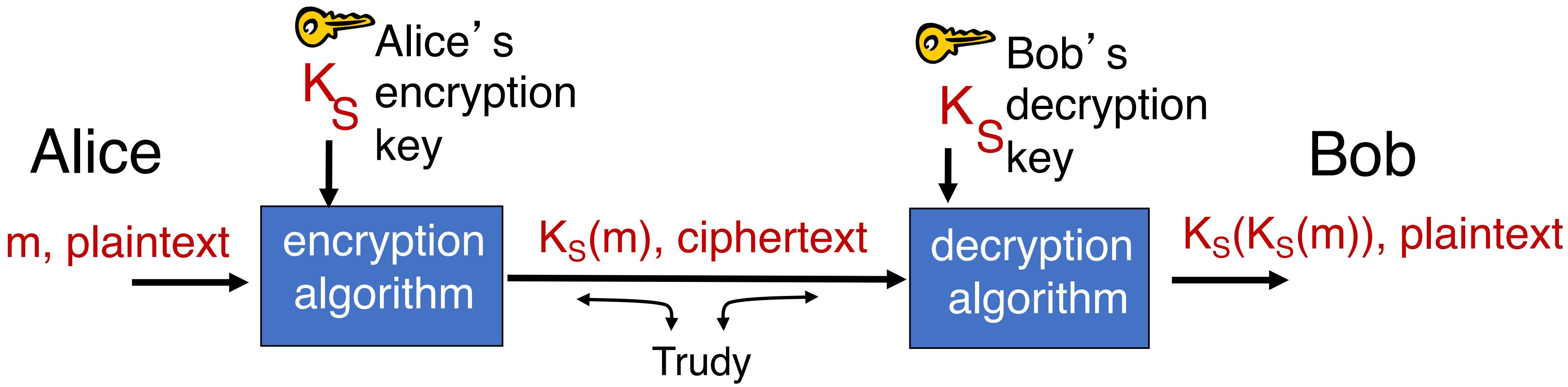
Review: Symmetric Key Cryptography



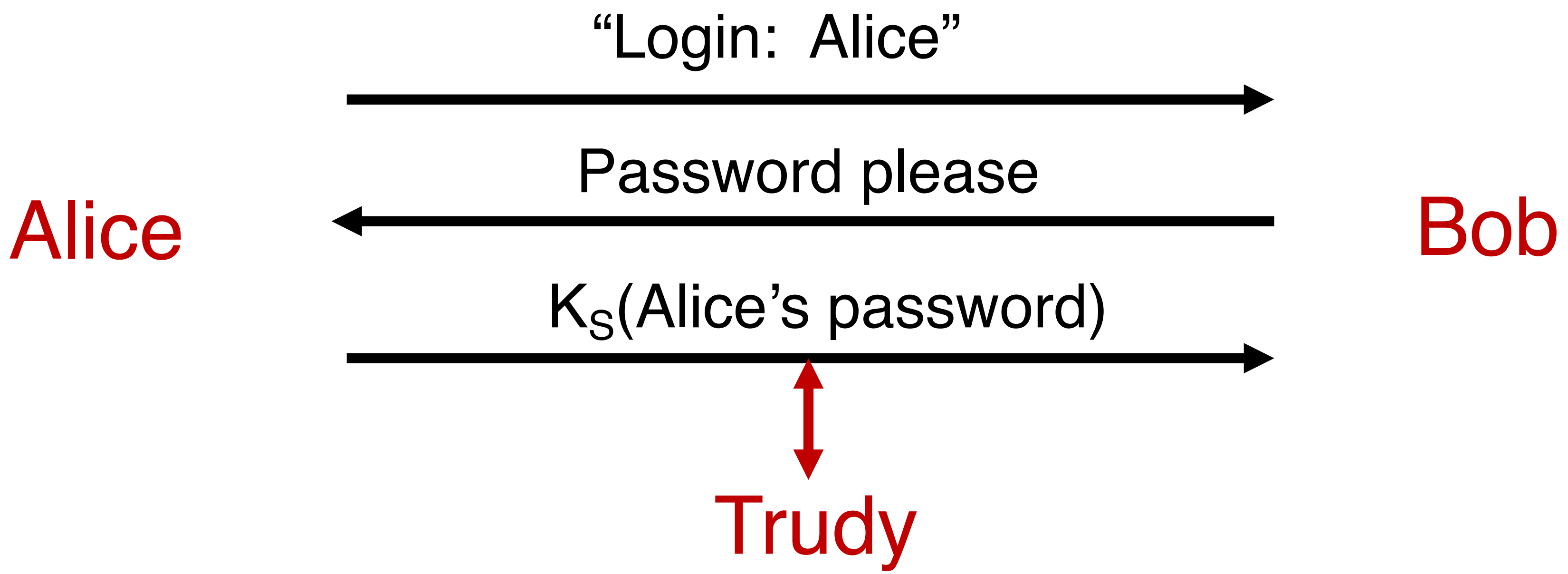
- Shared key at both ends, K_S
- Algorithms are typically easy to understand and implement
- Achieves confidentiality: harder for Trudy to break ciphertext
- However, fails to provide integrity, authentication, and non-repudiation
- Requires a pre-shared key between Alice and Bob

Attempting authentication with symmetric key crypto

An example: Login system

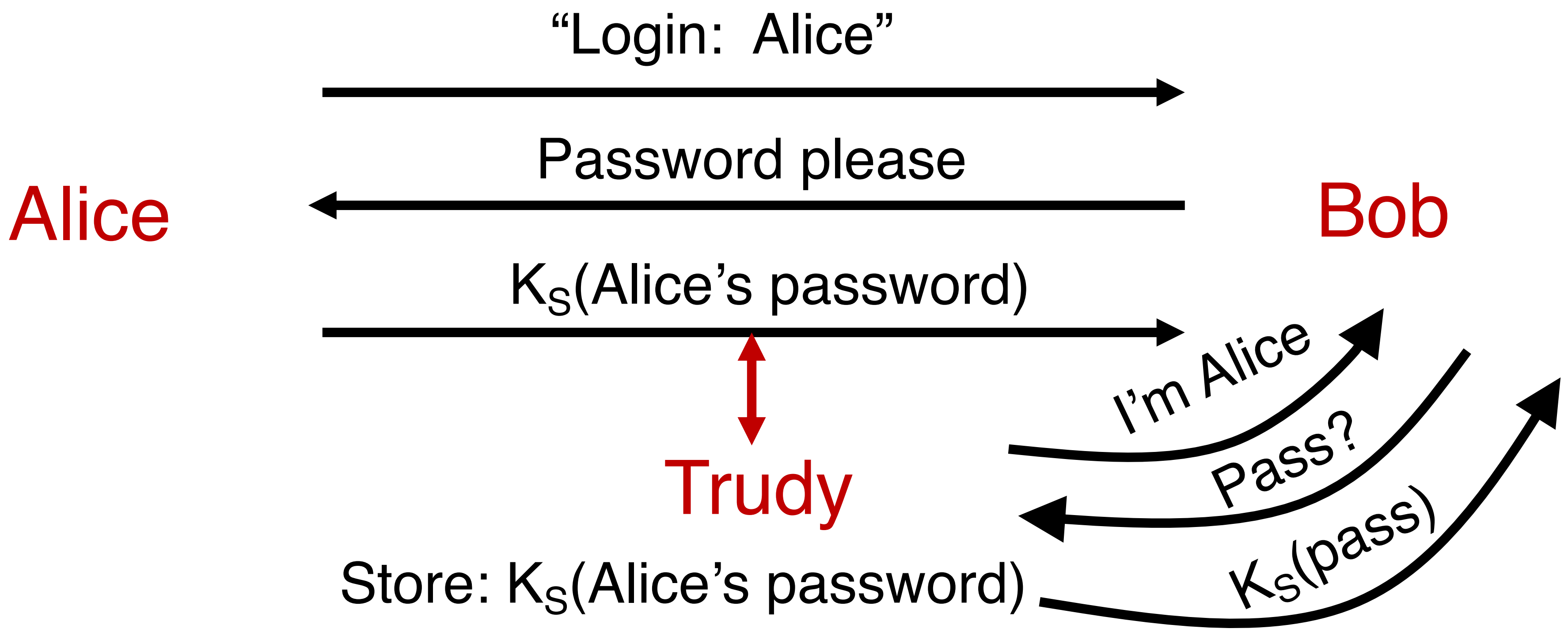
- Bob runs a login server to provide access to protected resources
- Alice must present a password to login
- Exchange of password implemented using symmetric key cryptography on top of block ciphers

Simple authentication strategy



- Alice's password is encrypted, and hence protected from Trudy
- Assuming Bob is trusted, Bob can decrypt the password using the shared secret key K_S

However, subject to replay attack



- Trudy can store the observed ciphertext K_S(password), and replay it later to gain access to Bob's server

Preventing replay attacks

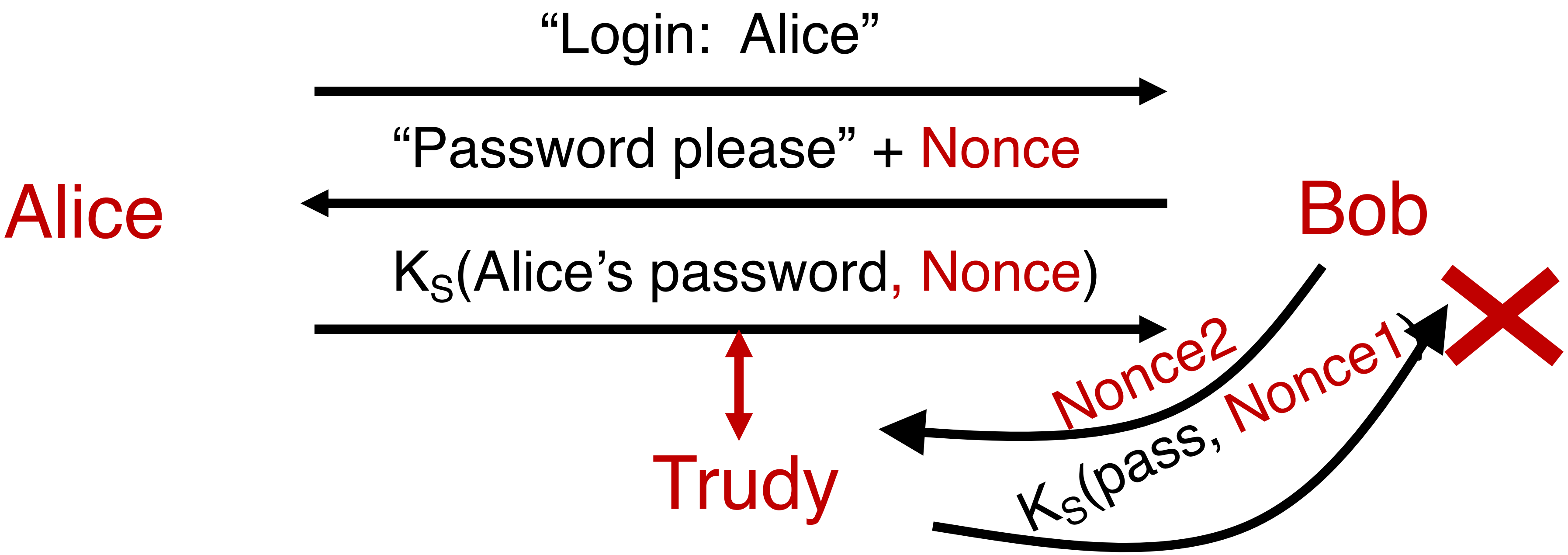
- Key idea: Vary the ciphertext for the same plaintext sent at different times.

- Make the ciphertext depend on a one-time value, randomly chosen by Bob.
  - e.g., a random number generated by Bob

- Nonce: a “number used once only”

- Alice must combine the password with the nonce before encryption

Challenge-Response with Nonce



- The nonce changes each authentication attempt
- Trudy cannot reply an earlier ciphertext to produce a valid password
- The nonce is different, so the expected ciphertext is different
- Nonces don't have to be confidential

Protecting against general replay attacks

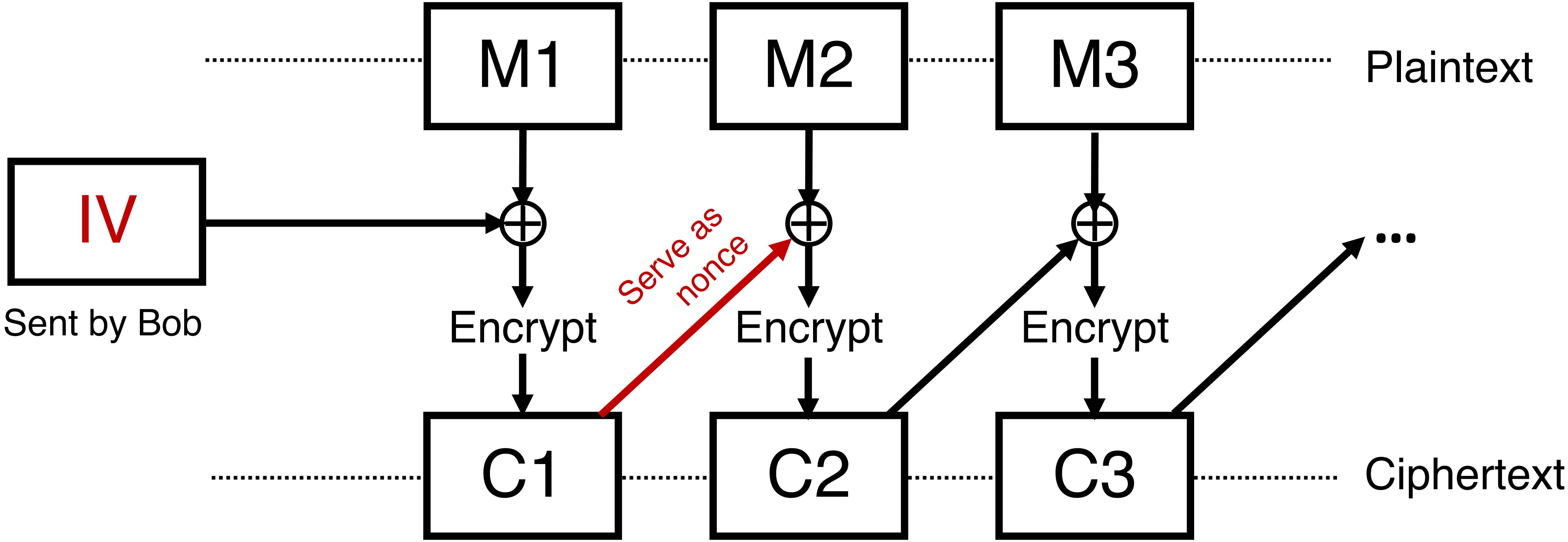
Generally, repeated ciphertext is bad

- Real network protocols often have repeated plaintext
  - e.g., the same web page content for the login screen
  - e.g., application headers, like HTTP/1.1 GET
  - The problem is more general: not just about repeating passwords!
- If the same plaintext shows up as the same ciphertext repeatedly, that can be used to break the cipher
- Example: Block substitution ciphers: finding the mapping for one part of one block means other ciphertext can be reversed to guess plaintext of other blocks, and so on…
- Idea: Can we use nonces for all messages?
  - Yes!

However, naïve nonces are inefficient!

- Suppose nonce is used as follows:
  - Alice performs K_S(message ⊕ nonce) before transmitting
  - If Alice must send N bits of plaintext, Bob must send N bits of nonce
  - Doubles the number of bits exchanged overall!
- Want to generate nonces automatically & randomly @ Alice, but still have Bob agree on the nonces. How?
- Cipher block chaining: use the previous ciphertext as a nonce for the next plain text block
- The first block uses an Initialization Vector (IV): only first nonce is sent explicitly by Bob

Cipher block chaining: encryption @ Alice



C1 depends on the first nonce, IV, not just the plaintext M1

Agreeing on a shared key

How to agree on a shared secret key?

- In reality: two parties may meet in person or communicate "out of band" to exchange shared key
- Often, communicating parties may never meet in person
  - It's very common not to meet someone you talk to over the Internet
  - Amazon? Your bank?
- And what if the shared secret is stolen?
  - Must exchange keys securely again!
- Q: how to exchange keys securely over an insecure network?

Next lecture: Public key cryptography