Lecture 24: Network Security
Public Key Cryptography

COMP 332, Spring 2023

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Acknowledgements: materials adapted from Computer Networking: A Top Down Approach 7th edition: ©1996-2016, J.F Kurose and K.W. Ross, All Rights Reserved as well as from slides by Abraham Matta at Boston University, and some material from Computer Networks by Tannenbaum and Wetherall and Network Security Essentials by William Stallings.

Today

1. Announcements
   - Homework 8 due Wednesday, May 3 at 11:59p (no coding)
   - Homework 9 due Wednesday, May 10 at 11:59p (no written)
2. Network tools
   - ssh and scp
3. Public key cryptography
   - overview
   - RSA algorithm
4. Network security
   - authentication

What is network security?

Goal: enable secure communication over insecure channel

Confidentiality: use cryptography

- only sender, intended receiver understand message contents
  - sender encrypts message
  - receiver decrypts message

Authentication

- sender, receiver want to confirm identity of each other

Message integrity

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

Network Tools

SSH AND SCP

SSH: remotely connecting to a device

E.g., connect to your virtual machine from your host device

On your VM, start an ssh server

- sudo apt-get install openssh-server
- sudo service ssh restart
- (normally if you're connecting to a server you won't need to do as an ssh server is already running)

Connect

- ssh username@ip_address

```
vmanfredi@ ~ () $
> ssh vmanfred@129.133.177.177
The authenticity of host '129.133.177.177 (129.133.177.177)' can't be established.
ECDSA key fingerprint is SHA256:Tt5KAXugvAX3ZRgz9V54IeBTCYAFVG2iRRel4wobLpY.
Are you sure you want to continue connecting (yes/no)? yes
Warning: Permanently added '129.133.177.177' (ECDSA) to the list of known hosts.
vmanfred@129.133.177.177's password:
Welcome to Ubuntu 14.04.5 LTS (GNU/Linux 4.2.0-27-generic x86_64)
```

scp: copy files to/from another device

E.g., copy files to your virtual machine from your host device

Runs over ssh, so ssh server should be running

– may also want to check ports open on device

Copy

– scp file_to_copy username@ip_address:~/path_to_put_file

```
vmanfredi@ ~ () $
> scp run_tls_scrape.sh vmanfred@129.133.177.177:~
vmanfred@129.133.177.177's password:
Permission denied, please try again.
vmanfred@129.133.177.177's password:
run_tls_scrape.sh
                  100%  825     1.1MB/s   00:00
```

Public Key Cryptography

OVERVIEW

Problem

Symmetric key crypto requires sender, receiver share secret

- Q: how to agree on key in first place (particularly if never met)?

Public key cryptography

- 2 parties communicate without shared secret known in advance
  - radically different approach!
- applications
  - encryption and decryption
  - digital signatures
  - key exchange

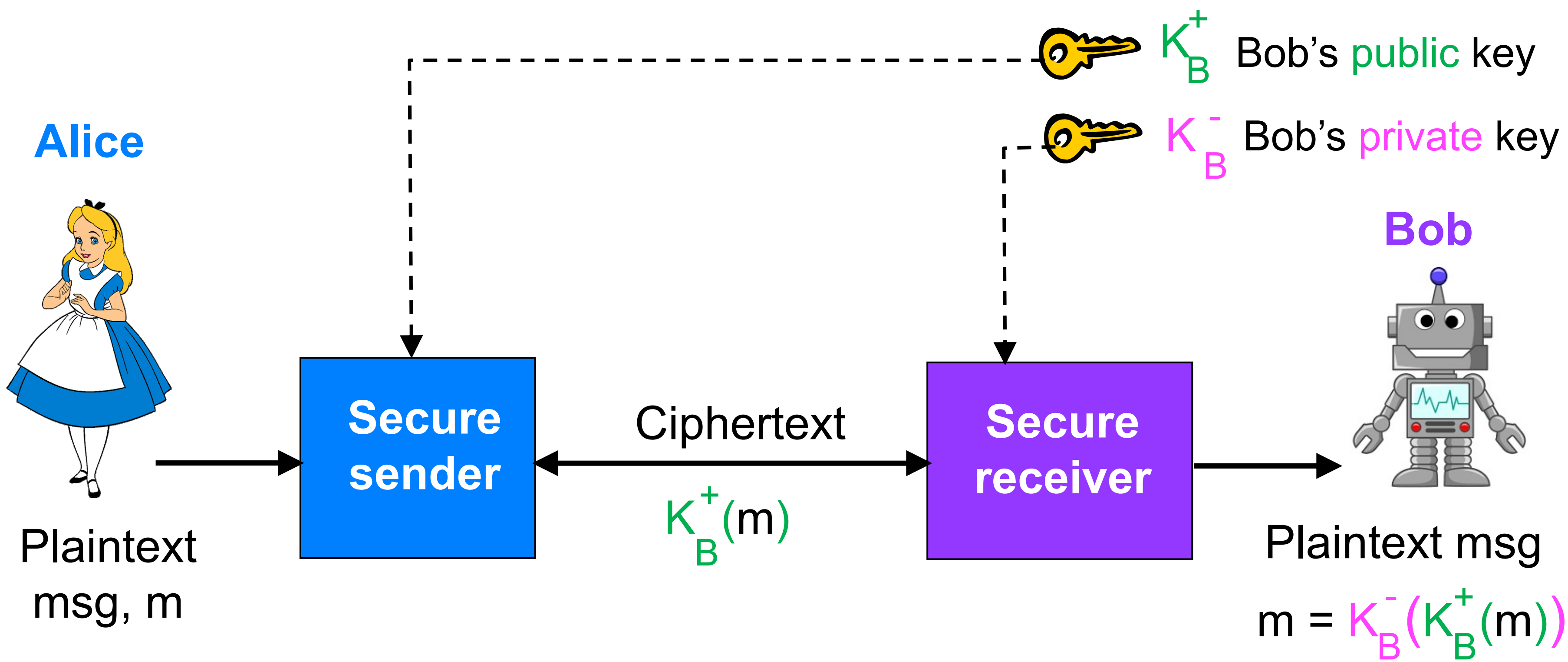
Most widely used public key cryptography algorithms

- RSA: Rivest, Shamir, Adelson (1978)
- Diffie-Hellman (1976)
- Elliptic Curve Cryptography (1985)

Public key cryptography at high level

Each user has its own public and private key pair

- K^+: public encryption key known to all
- K^-: private decryption key known only to receiver



Keys mathematically linked in special way

Requirements

1. Need $K_B^+(\cdot)$ and $K_B^-(\cdot)$ such that

$$K_B^-(K_B^+(m)) = m$$

2. Given public key K_B^+, should be impossible to compute private key K_B^-

Public Key Cryptography

RSA ALGORITHM

RSA: Rivest, Shamir, Adelson algorithm

Message

- bit pattern: can be uniquely represented by integer number
  - encrypting message is equivalent to encrypting number
- example
  - m = 10010001 uniquely represented by 145
  - encrypt m by encrypting 145 which gives new number, the ciphertext

Intuition

- security of RSA is based on hardness of prime factorization
  - easy to multiply 2 large prime numbers together, hard to factor result
- (elliptic curve cryptography uses elliptic curve discrete logarithms)

Recall

- x mod n: remainder of x when divided by n

Creating public/private key pair using RSA

1. Choose two large distinct prime numbers *p, q*
   – e.g., 1024 bits each

2. Compute $n=pq$, $z=(p-1)(q-1)$

3. Choose *e* ($<n$) such that no common factors with *z*
   – *e, z* are relatively prime

4. Choose *d* such that *ed-1* is exactly divisible by *z*
   – *ed* mod *z* = *1*

5. *Public* key is $\underbrace{(n,e)}_{K_B^+}$. *Private* key is $\underbrace{(n,d)}_{K_B^-}$.

Encryption and decryption

Given $\underbrace{(n,e)}_{K_B^+}$ and $\underbrace{(n,d)}_{K_B^-}$ as computed before

1. To encrypt message m (<n), compute

$$c = m^e \bmod n$$

2. To decrypt received bit pattern, c, compute

$$m = c^d \bmod n$$

Magic happens!

$$m = (\overbrace{m^e \bmod n}^{c})^d \bmod n$$

Why does RSA work?

Must show $c^d \bmod n = m$ where $c = m^e \bmod n$

$$
\begin{aligned}
c^d \bmod n &= (m^e \bmod n)^d \bmod n && \text{by substitution} \\
&= m^{ed} \bmod n && \text{by fact 1} \\
&= m^{(ed \bmod z)} \bmod n && \text{by fact 2} \\
&= m^1 \bmod n && \text{since } ed \bmod z = 1 \text{ by design} \\
&= m
\end{aligned}
$$

fact 1: $(a \bmod n)^d \bmod n \equiv a^d \bmod n$

fact 2: $a^b \bmod n = a^{(b \bmod z)} \bmod n$ where $n= pq$ and $z = (p-1)(q-1)$

Why is RSA secure?

Given Bob's public key (n,e)

- how hard is it to determine private key (n,d)?

(Relatively) easy

- compute $n=pq$ or $z=(p-1)(q-1)$

Hard

- find factors of $n=pq$ or $z=(p-1)(q-1)$ without knowing p or q
  - 2^{1024} bit # x 2^{1024} bit #
- prime factorization takes exponential time
  - no (non-quantum) efficient algorithm known

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Example

1. Choose two large prime numbers $p=17$, $q=11$

2. Compute

   $n = pq = 17x11 = 187$

   $z = (p-1)(q-1) = 16x10 = 160$

3. Choose $e=7$ ($<n$) that no common factors with z

4. Choose d such that $ed-1$ is exactly divisible by z

   $(ed -1) / z = 1$

   $(7d-1) / 160 = 1$

   $7d = 161$

   $d = 23$

5. *Public* key is $\underbrace{(n=187,e=7)}_{K_B^+}$. *Private* key is $\underbrace{(n=187,d=23)}_{K_B^-}$.

Another example

Bob chooses *p=5, q=7*. Then *n=35, z=24*.
e=5 (so *e, z* relatively prime).
d=29 (so *ed-1* exactly divisible by z).

Encrypting 8-bit messages

	bit pattern	m	m^e	$c = m^e \bmod n$
Encrypt	0000l010	12	248832	17

	c	c^d	$m = c^d \bmod n$
Decrypt	17	481968572106750915091411825223071697	12

Another important property

The following property will be very useful later for signatures

$$\underbrace{K_B^-(K_B^+(m))}_{\text{use public key first, followed by private key}} = m = \underbrace{K_B^+(K_B^-(m))}_{\text{use private key first, followed by public key}}$$

Result is the same!

Why can key application be re-ordered?

$$K_B^-(K_B^+(m)) = m = K_B^+(K_B^-(m))$$

Follows directly from modular arithmetic

$$(m^e \bmod n)^d \bmod n \equiv m^{ed} \bmod n$$
$$\equiv m^{de} \bmod n$$
$$\equiv (m^d \bmod n)^e \bmod n$$

RSA in practice

Exponentiation in RSA is computationally intensive

- e.g., symmetric key DES at least 100x faster than RSA
- use public key crypto to establish secure connection
  - then establish symmetric session key for encrypting data

Session key, K_S

- Bob and Alice use RSA to exchange symmetric key K_S
- once both have K_S, they use symmetric key cryptography

Generate ssh keys: ssh-keygen -t rsa

```
> ssh-keygen -t rsa
Generating public/private rsa key pair.
Enter file in which to save the key (/Users/vmanfredi/.ssh/id_rsa): test_pair
Enter passphrase (empty for no passphrase):
Enter same passphrase again:
Your identification has been saved in test_pair.
Your public key has been saved in test_pair.pub.
The key fingerprint is:
SHA256:YJ28K/kCn+dEvBpnkEm6BdbHvxpzbKZ4uQgpznWbdlQ vmanfredi@vmanfredis-MacBook-Pro-2.local
The key's randomart image is:
+---[RSA 2048]----+
|                 |
|     . + .       |
|    o = *        |
|   . = * oE      |
|    . = S..      |
|    .+ +.+ .     |
|  . =o=oO.*      |
| o o o=&=O       |
|  o  .***.       |
+----[SHA256]-----+
```

Public key

```
  1 ssh-rsa AAAAB3NzaC1yc2EAAAADAQABAAABAQDYoldG09vq5zNjE3iO7l4fDMiRpD1rVl+cv0nts8PBCxyvvNhdP6ZTZucc
    Jx6AqH5S+4l7BV6nayW7oJ35OBPXX3TUwJcGUto2nFFjkfqEw9+1LZPiLumZ9433X17aKJ6FqHAUClbyAzm6E1e+TZIeMu3V
    I/7qbJP0XtBX5LYoBdiLDdXziMqf3/rTcThUCllyf3zFLzl6u9hgPqMLo+1BTgSqRV1roK4P7yQZD1LLpzLxjqfUfCOMHhi8
    pbYh+X3J/hKZ28hRFO7mYHuUM9zGqykAU+Ew9i9WSaQF+5K81lmEyCHtKN5xVAdXp1bLYrr1SVWydmXb+VE3gM6dZraJ vma
    nfredi@vmanfredis-MacBook-Pro-2.local
~
~
"test_pair.pub" 1L, 422C written
```

Private key


```
-----BEGIN RSA PRIVATE KEY-----
MIIEpAIBAAKCAQEA2KJXRtPb6uczYxN4ju5eHwzIkaQ9a1ZfnL9J7bPDwQscr7zY
XT+mU2bnHCcegKh+UvuJewVep2slu6Cd+TgT11901MCXBlLaNpxRY5H6hMPftS2T
4i7pmfeN919e2iiehahwFApW8gM5uhNXvk2SHjLt1SP+6myT9F7QV+S2KAXYiw3V
84jKn9/603E4VApZcn98xS85ervYYD6jC6PtQU4EqkVda6CuD+8kGQ9Sy6cy8Y6n
1HwjjB4YvKW2Ifl9yf4SmdvIURTu5mB7lDPcxqspAFPhMPYvVkmkBfuSvNZZhMgh
7SjecVQHV6dWy2K69UlVsnZl2/lRN4DOnWa2iQIDAQABAoIBAGJwQmB43LG9JWib
7GhmgHZzhKBJlW807HV5pspQqV8LAZoJofedeKLlW5c7X2zvI5fpnOs94WkKEzdT
IPWiOcHgKmKSsQ26kFXIamNobgHuT7UwZMaesp+4Edaai6tuUbpCc8tnd2K5fH3F
VFWxQfhfBBuaI7e6ZvDgNKP71ZoRV8b1HbiNA/JNyOdbVH2kqYFItxKGfovvpPyM
1xc0J/FHhthOgGPttVWX9d2K6yh6jq9WKOmIv2TaOo71TGn/RC5RgyDJTcJJ4PIV
s5iO9Vv6dV+aK6WHO8+45s/pXIkOLM+tqupylubwqy6hwSong4T0DAOU/B7bePec
3IOtAAECgYEA9SR5L+C2n7rbCxJlCYlIehXVpCATgk+fzJgrfTKMZLIZjrgIeBUJ
W+GAAFPqR0z7tKq6Jp0hISFWMTckAoPs+PzqHpG7P7daE6iNdu7TzupP1I8T3Ysq
B6K2OyGF1D//QBoyqTv5G26I3/5rN4Zm9GsDrTdo8+lTlWlQrsmUsAECgYEA4jqg
2YjGKame4x/zFSqdOZKhLZVqPiUbjoN1xL41fZP9M8Fu67aLAApaRbrkHnsUPRmS
T39YLo3orccvJb+3DVUO2g0KXhG0OgIbuqEFS1nmVrp+vWaSeqXz+g+cu8Ab/eRb
IaCH8u5fTXQmkG7TJuJfGFcCCBxTfCpttSi0hokCgYEAxxEWRBXj1zPimkwWtjbA
HzvJ4FyX2xMTvg24CxPYRBEIhgfWAMV8cxtcWWfLcJkIMT8OqTqh44hxuMeBO3Ws
IskmySood2ZKBHq0Xec1IurNZtvFEvvmZorwFnZzedd6TLC5gQoNkQQirFqq8Ez5
H/Qi6S98z80ircr21OknEAECgYBM9fL4bg4z6C9URu80GS4pgtdwIW9mOst4HQK4
bpjV4r11mO16JLx+xAbXx++I6wgEjSl3//NoywAH9kX0ypakY3ZM+bi4Lb+pKER0
pgieDLROdt1c44MbVE9+l0cTnBQpuEDEXM9C9pLXT5c69WjBxqrhJeBcD/7as7hk
s7dOOQKBgQDUvFn2tq+A/4cDqkWZxAZEhp1cHaGvg4ARm8hzLwAEFiKct8kgk5gm
+7ur7r/y4QSj9+DSihd/TXnui2LTX8YmAUgBJUUQs7B9muo2Gt++QtwVeKVuvRC5
LOMblm6EKnxJqR+SZKLdGhzC2nt2KbsQoyXk7Ew7cAuUji473q1JGQ==
-----END RSA PRIVATE KEY-----
```


```
~
"test_pair" 27L, 1679C written
```

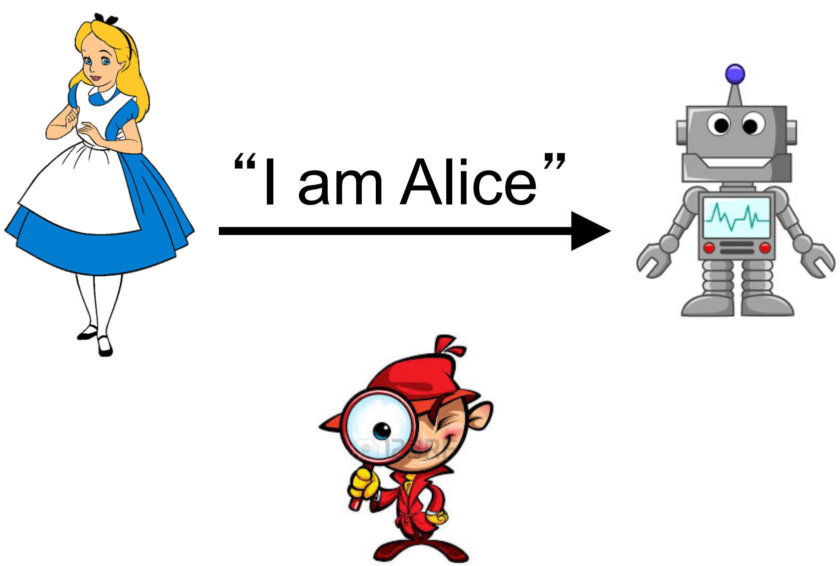
Network Security

AUTHENTICATION

Authentication

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap1.0: Alice says “I am Alice”

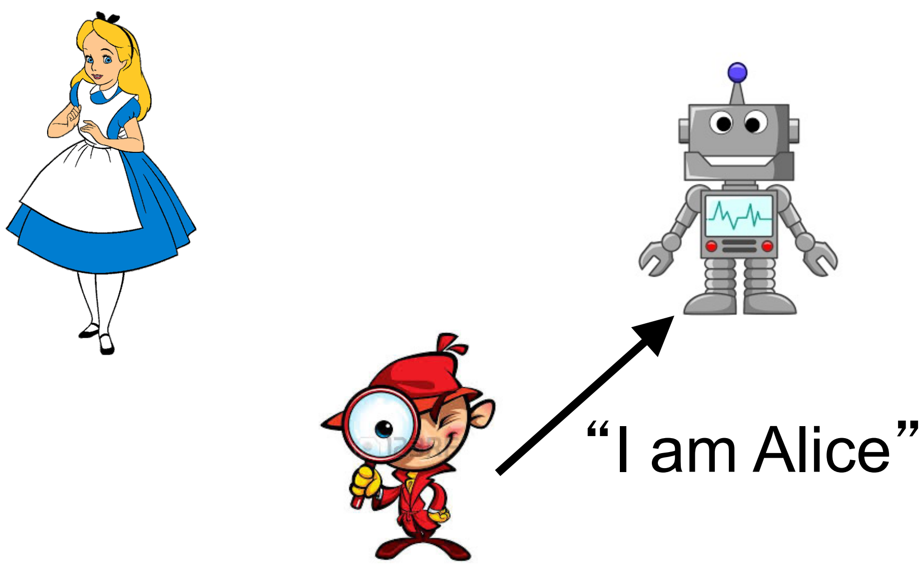


Failure scenario??

Authentication

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap1.0: Alice says “I am Alice”



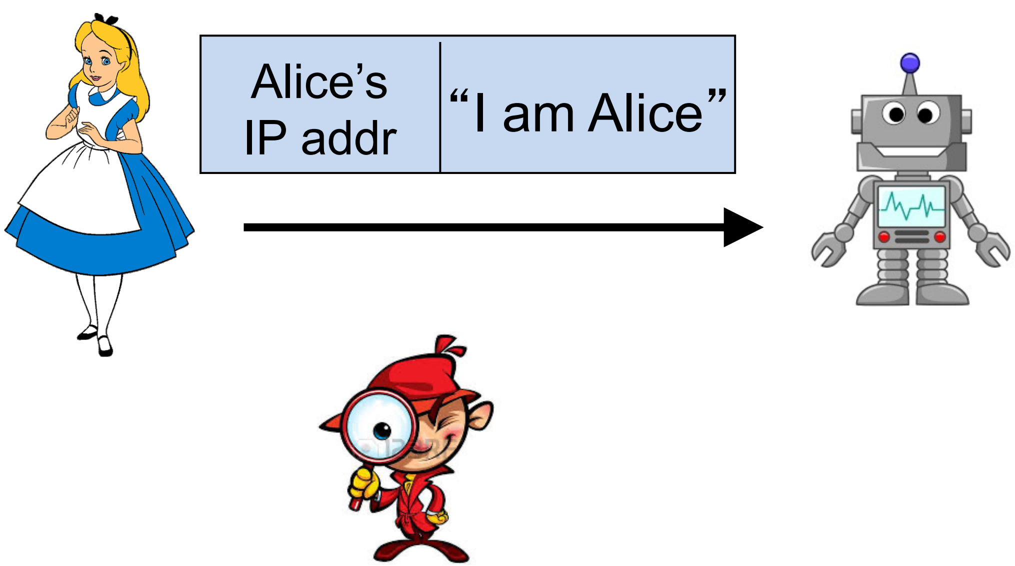
Failure scenario??

In network, Bob cannot see Alice, so Trudy simply declares herself to be Alice

Authentication: another try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap2.0: Alice says "I am Alice" in an IP packet containing her source IP address



Failure scenario??

Authentication: another try

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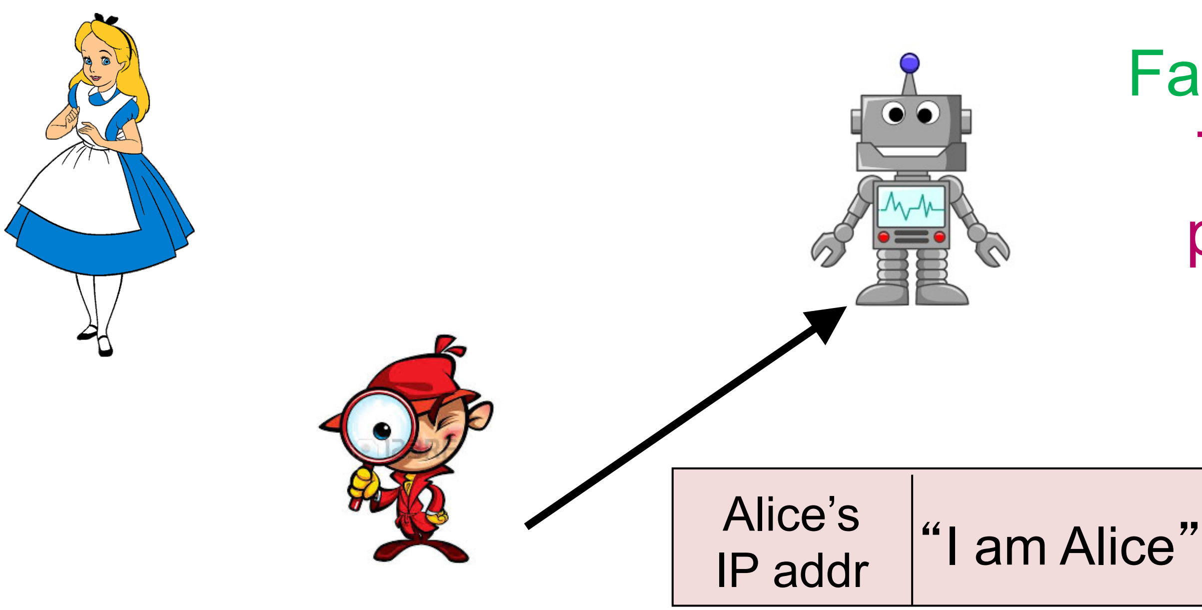


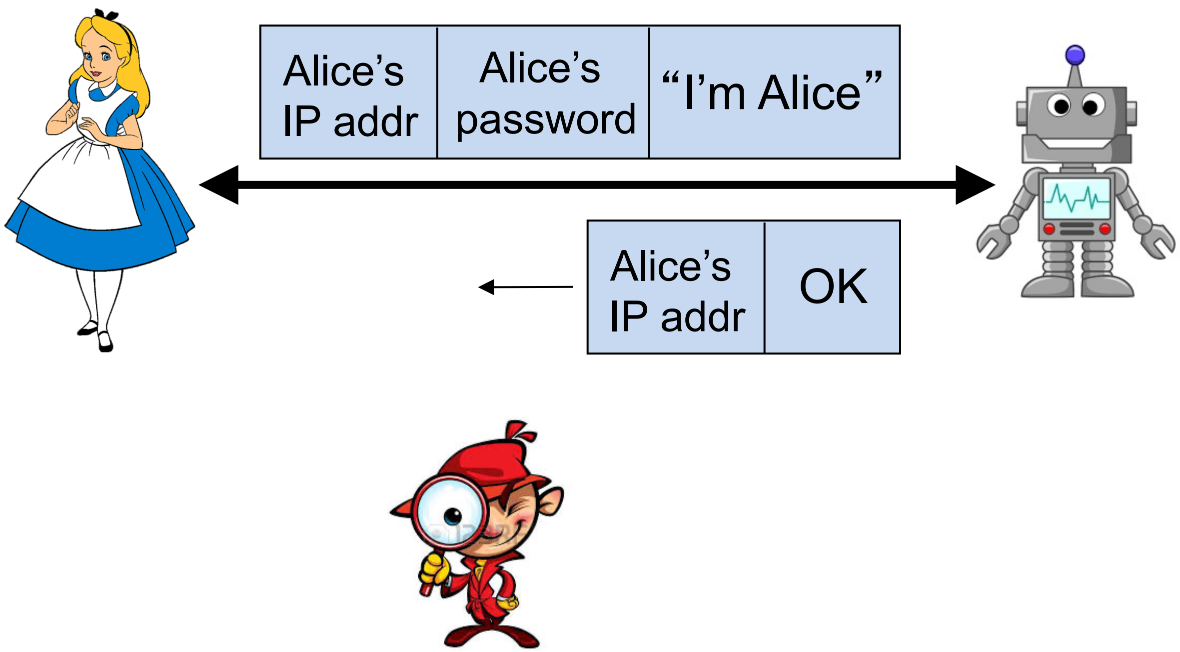
Failure scenario??

Trudy creates pkt "spoofing" Alice's addr

Authentication: another try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.0: Alice says "I am Alice" and sends her secret password to "prove" it

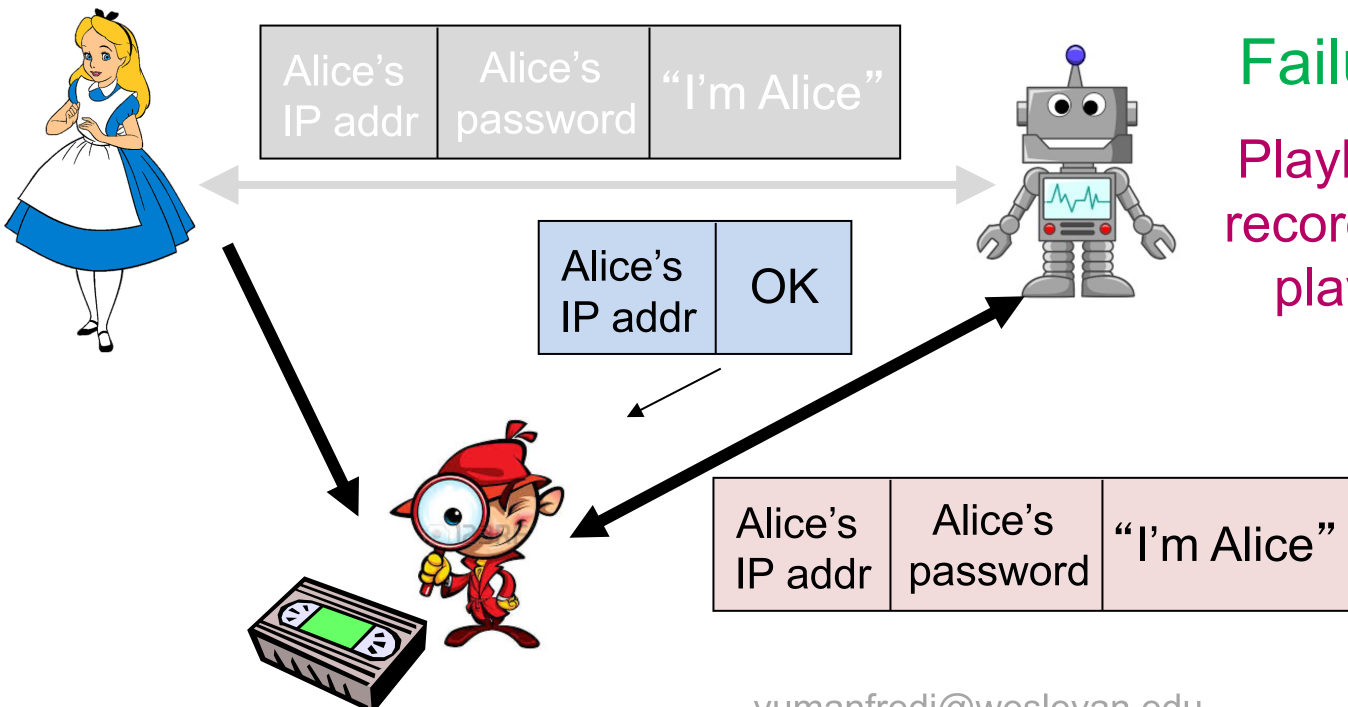


Failure scenario??

Authentication: another try

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap3.0: Alice says “I am Alice” and sends her secret password to “prove” it



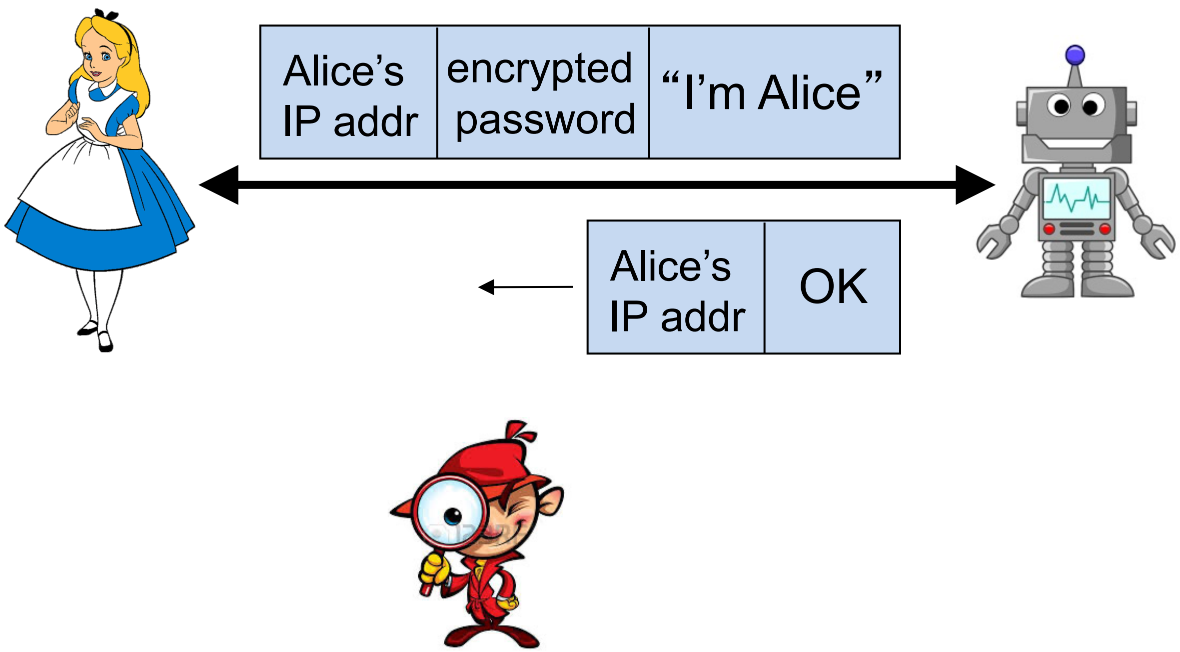
Failure scenario??

Playback attack: Trudy records Alice’s pkt, later plays it back to Bob

Authentication: yet another try

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap3.1: Alice says “I am Alice” and sends her encrypted secret password to “prove” it

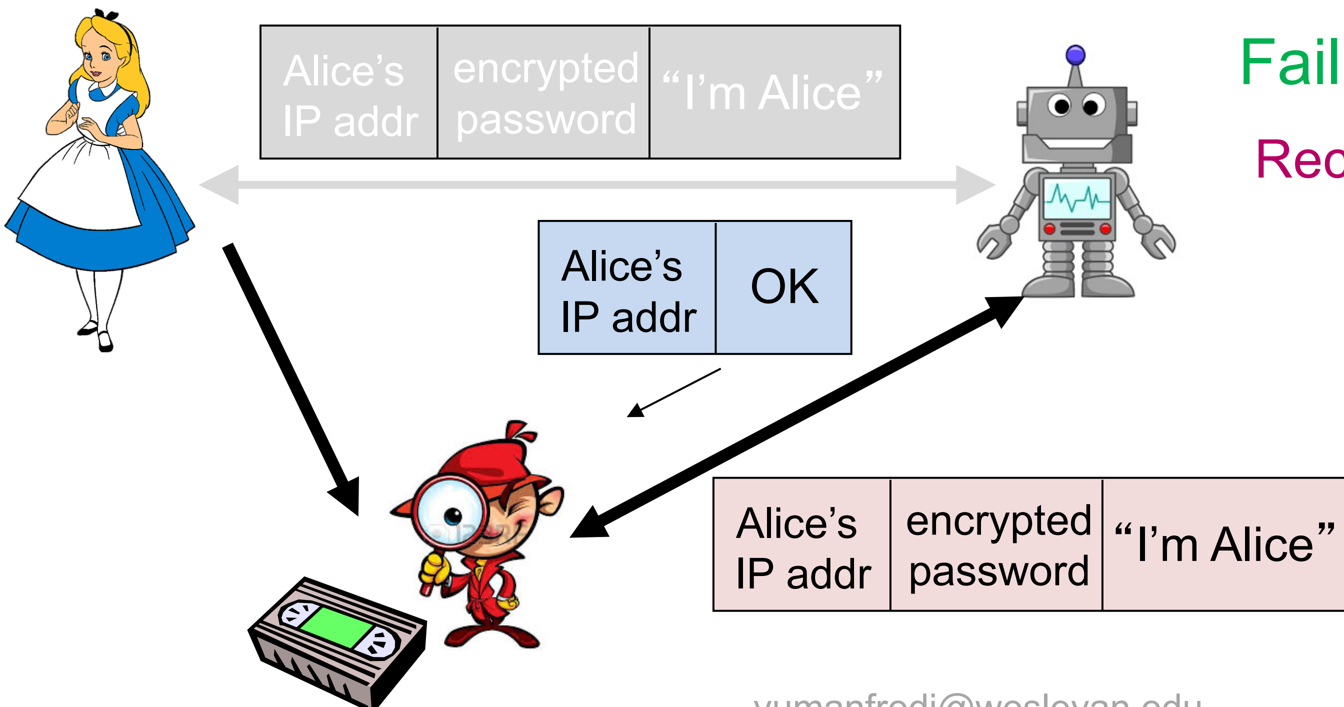


Failure scenario??

Authentication: yet another try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.1: Alice says "I am Alice" and sends her encrypted secret password to "prove" it



Failure scenario??

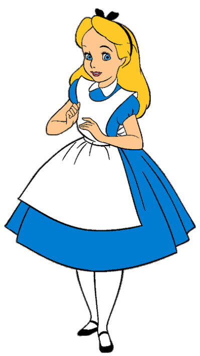
Record and playback still works!

Authentication: yet another try

Goal: avoid playback attack

Nonce*:* number, R, used only once-in-a-lifetime

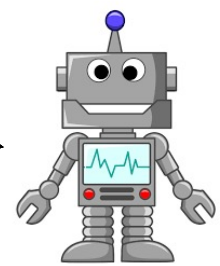
Protocol ap4.0: to prove Alice is “live”, Bob sends Alice R. Alice must return R, encrypted with shared secret key



“I am Alice”

R

$K_{A\text{-}B}(R)$



Failure scenario??
Drawbacks?

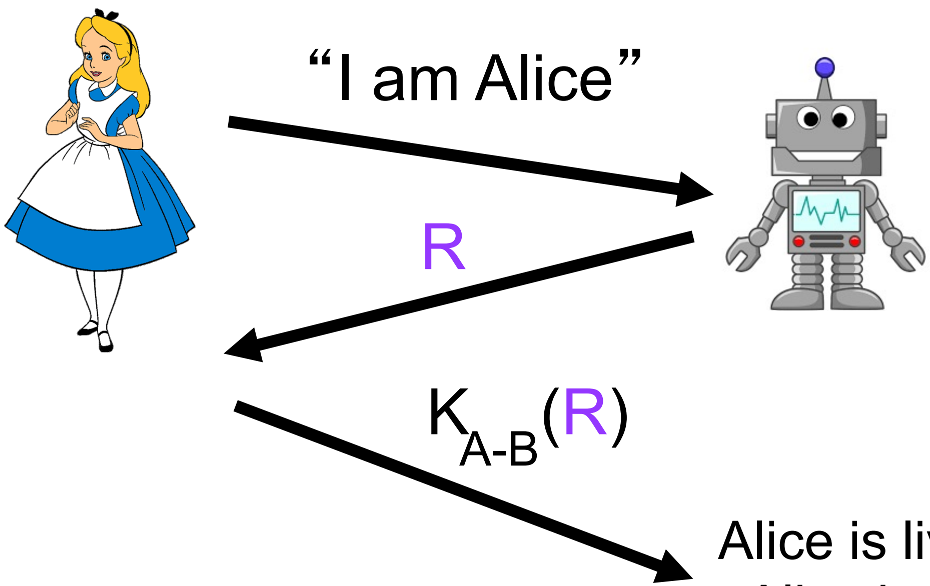
Alice is live, and only Alice knows key to encrypt nonce, so it must be Alice!

Authentication: yet another try

Goal: avoid playback attack

Nonce: number, R, used only once-in-a-lifetime

Protocol ap4.0: to prove Alice is “live”, Bob sends Alice R. Alice must return R, encrypted with shared secret key



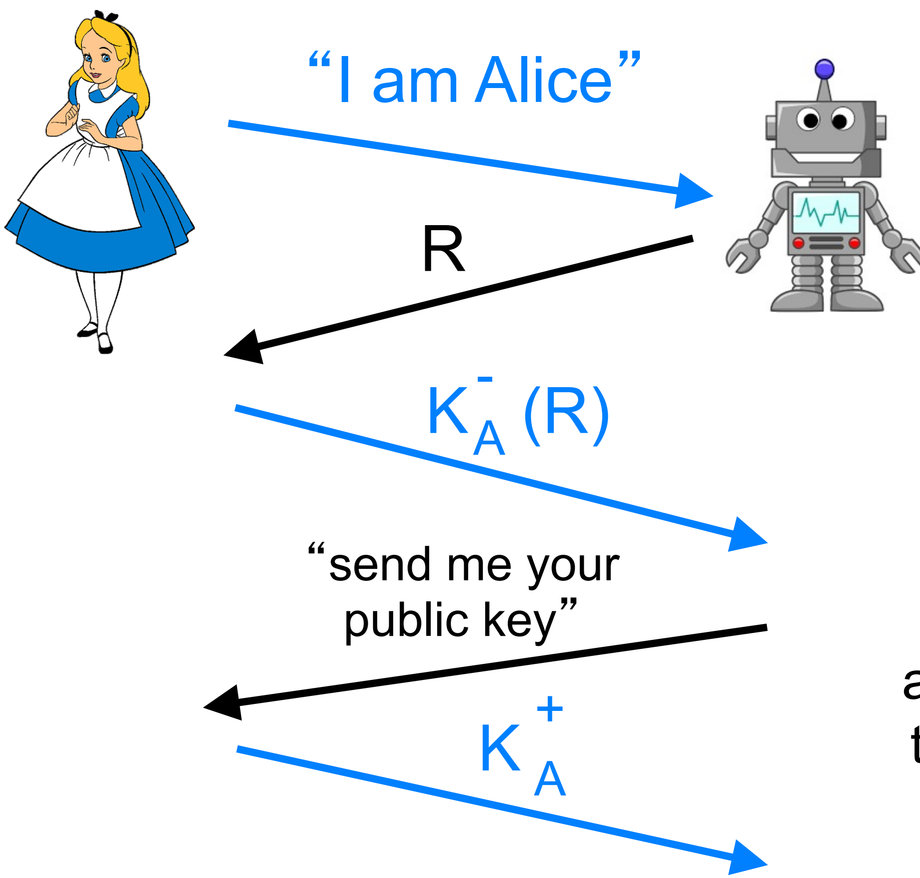
Failure scenario?? Drawbacks?

Requires shared symmetric key. Can we authenticate using public key techniques?

Alice is live, and only Alice knows key to encrypt nonce, so it must be Alice!

Authentication: a final try

Protocol ap5.0: use nonce and public key cryptography



Bob computes

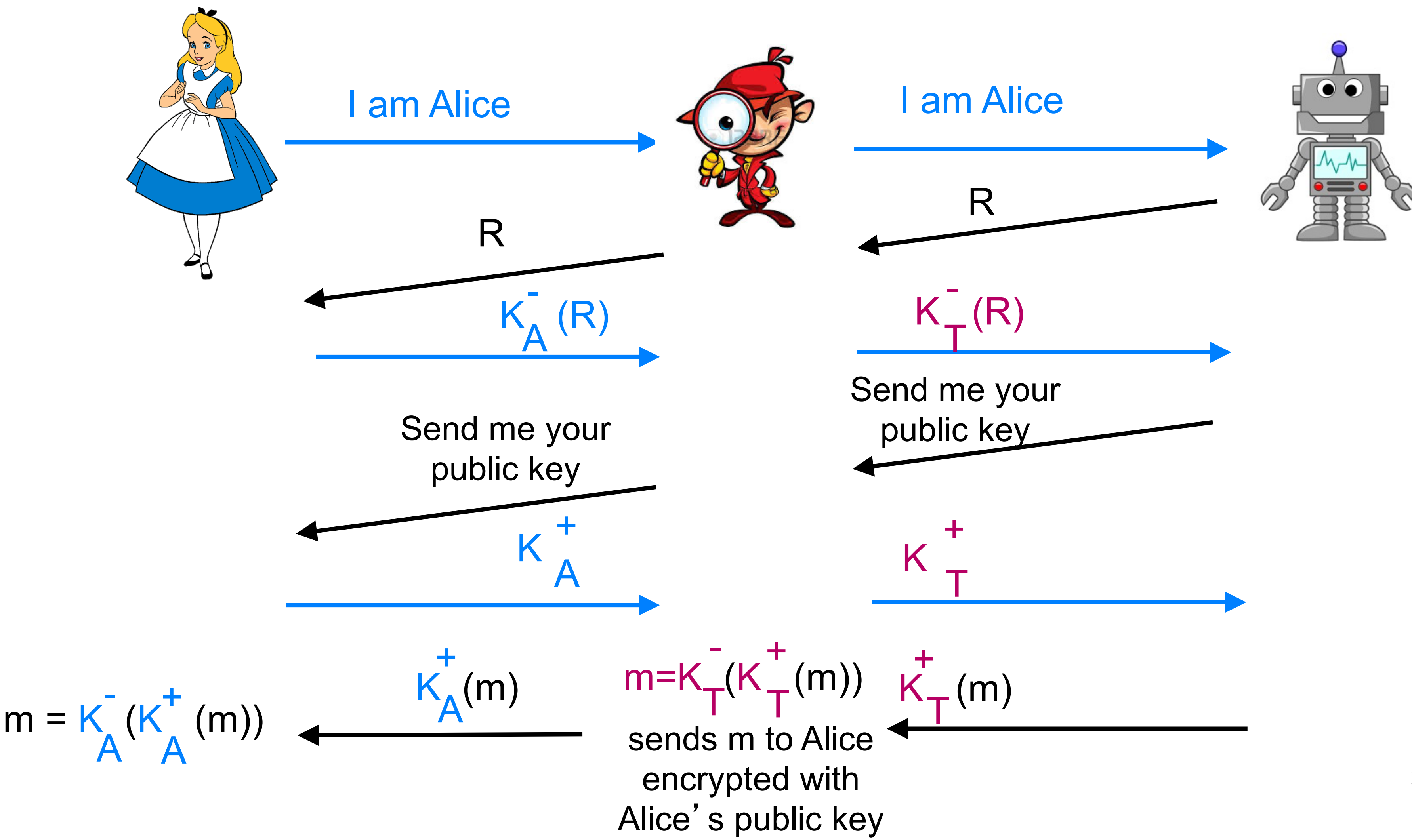
$$K_A^+(K_A^-(R)) = R$$

and knows only Alice could have the private key that encrypted R such that this holds true

ap5.0 security hole

Man-in-the-middle Attack

– Trudy poses as Alice (to Bob) and as Bob (to Alice)



ap5.0 security hole

Man-in-the-middle Attack

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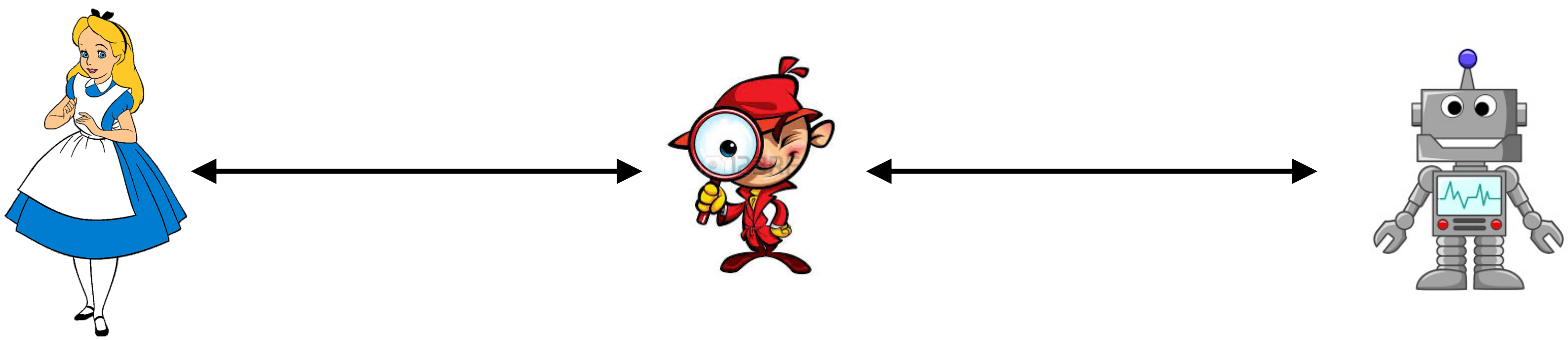

Difficult to detect

- Bob receives everything that Alice sends, and vice versa
  - e.g., so Bob, Alice can meet one week later and recall conversation!
- problem is that Trudy receives all messages as well!