Introduction to Information Security
14-741/18-631 Fall 2021
Unit 5: Lecture 1 & 2
Security Protocols

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This lecture's agenda

- **Outline**
  - Engineering principles for cryptographic protocols
    - Naming
    - Which primitives (schemes) to use
    - Timeliness
  - Kerberos example
- **Objective**
  - Expose you to the difficulties of secure communication protocol design
  - Convince you that crypto is a powerful tool, but it is easy to make design errors that render it useless
  - Give practical example of a secure communication protocol that you actually use every day

Security protocols

- **Entity authentication**
  - Proving identity to each other
- **Key exchange, establishment or agreement**
  - Establish a trusted session between two entities
  - Usually used to set up trusted communication channel providing secrecy and authenticity
- **Basis for**
  - Secure electronic commerce
  - Electronic voting
  - Time synchronization
- **We use the basic cryptographic primitives discussed before to design higher-level security properties**

Difficulties with security protocols

- **Combine a number of basic primitives**
  - Cryptography
  - Network communication
- **Individual primitives are generally working as expected, but interaction between primitives is generally Achilles' heel**

New concept: Nonces

- **NONCE = A number used only ONCE**
  - E.g., TCP ISN, CSRF token
  - More later this lecture
- **Can be implemented as**
  - **Counter**
    - Unique (non-repeating) but predictable
  - **Random number**
    - Unique and (hopefully) unpredictable
  - **Timestamps**
    - Unique (non-repeating) but predictable

Preparing for the worst

- **Always assume that the attacker can control at will the network where you want to deploy your secure communication protocol**

Active attackers

- **Or, what can Mallory do?**
  - Can eavesdrop on all protocol runs
  - Can **replay** messages at will
  - Can **inject** fabricated messages in the network
    - For instance fabricated from pieces of old messages
  - Can **modify** a principal's message
  - Can **initiate multiple parallel protocol sessions**
  - Can perform **guessing or exhaustive attack** on non-random (or poorly random) nonce

"Ideal" protocol wishlist

- **Efficient protocol**
  - Low computational overhead
    - Don't encrypt what you don't need to
  - Low communication overhead
    - Don't send unnecessary messages
- **Little client/server state**
- **As little trust as necessary**
- **As few assumptions as necessary**
  - Synchronized clocks?
  - Randomly selected nonces and initialization vectors?
  - Security of crypto primitives?
  - Authenticity or secrecy of keys

Ensure necessary security properties

Design principles for protocols

- Abadi and Needham:
  Prudent Engineering Practice for Cryptographic Protocols
- Following slides based on a lecture by Abadi, modified by us

Principle 1: Explicit communication

- Every message should say what it means: the interpretation of the message should depend only on its content
- It should be possible to write down an English sentence describing the content.

- This principle counteracts that messages are used out of context, prevent replay attacks, and intermixing of messages from concurrent sessions

The Denning-Sacco protocol (1982)

- Alice and Bob wants to exchange a secret key K_{AB}
- A trusted server (Trent) distributes public key certificates

The Denning-Sacco protocol

We write $\{m\}_K$ to mean encrypting/signing m using key K

A,B

Trent (trusted server)

Alice

Bob

The Denning-Sacco protocol

We write $\{m\}_K$ to mean encrypting/signing m using key K

A,B

CA,CB

Trent (trusted server)

Alice

Bob

The Denning-Sacco protocol

We write $\{m\}_K$ to mean encrypting/signing m using key K

A,B

CA,CB

Trent (trusted server)

Alice

$$CA,\ CB,\ \{T_A,\ K_{AB}, \{T_A,\ K_{AB}\}_{SK_A}\}_{PK_B}$$

Bob

Problem with Denning-Sacco

Trent (trusted server)

Bob's reasoning:
CA: Alice wants to share a key with me
After 1st decryption: K has been kept secret in transit
After 2st verification: K is computed by Alice
Alice must want to share this key K with me

Alice

$CA, CB, \{T, K, \{T, K\}_{SK_A}\}_{PK_B}$

Bob

Problem with Denning-Sacco

Trent (trusted server)

Bob's reasoning:

CA: Alice wants to share a key with me

After 1st decryption: K has been kept secret in transit

After 2st verification: K is computed by Alice

Alice must want to share this key K with me

?

$CA, CB, \{T, K, \{T, K\}_{SK_A}\}_{PK_B}$

Bob

Problem with Denning-Sacco

Charlie

Trent (trusted server)

Bob's reasoning:
CA: Alice wants to share a key with me
After 1st decryption: K has been kept secret in transit
After 2st verification: K is computed by Alice
Alice must want to share this key K with me

Alice

$CA, CB, \{T, K, \{T, K\}_{SK_A}\}_{PK_B}$

Bob

I can pretend to be Alice!

Problem with Denning-Sacco

Charlie

Trent (trusted server)

Charlie's reasoning:

CA: Alice wants to share a key with me

After 1st decryption: K has been kept secret in transit

After 2st verification: K is computed by Alice

Alice must want to share this key K with me

$CA, CC, \{T, K, \{T, K\}_{SK_A}\}_{PK_C}$

Alice

$CA, CB, \{T, K, \{T, K\}_{SK_A}\}_{PK_B}$

Bob

I can pretend to be Alice!

Problem with Denning-Sacco

Charlie

Charlie's reasoning:

CA: Alice wants to share a key with me

After 1st decryption: K has been kept secret in transit

After 2st verification: K is computed by Alice

Alice must want to share this key K with me

Trent (trusted server)

B, C

CB,CC

$CA, CC, \{T, K, \{T, K\}_{SK_A}\}_{PK_C}$

Alice

$CA, CB, \{T, K, \{T, K\}_{SK_A}\}_{PK_B}$

Bob

I can pretend to be Alice!

Problem with Denning-Sacco

- Bob receives CA, CB, $\{T_A, K_{AB}, \{T_A, K_{AB}\}_{SK_A}\}_{PK_B}$ from Alice
- With SK_B, which he has, he can extract $\{T_A, K_{AB}\}_{SK_A}$
  - That is, the only thing that is used to prove Alice's identity!!!
- And now Bob can pose as Alice to anyone else (Charlie in our example below) as long as T_A is valid
- May look obvious, but it took 12 years to notice

Failure diagnosis

- **Optimistic use of crypto primitives**
- **Names are missing**
- **It is not possible to parse the message into the statement that represents its meaning**
- **Solution**
  - $A \rightarrow B$: $CA, CB, \{T_A, K_{AB}, \{\mathbf{A, B,}\ T_A, K_{AB}\}_{SK_A}\}_{PK_B}$
  - or any other unambiguous encoding of the meaning of the message

Principle 2: Appropriate action

- **The conditions for a message to be acted upon should be clearly set out so that someone reviewing a design may see whether they are acceptable or not.**
- **Said differently: Clearly state your assumptions!**
  - Be clear on how encryption is used, and the meaning of encryption
  - Be clear on how the timeliness of messages is proved, and on the meaning of temporal information in messages

Principle 3: Naming

- **If the identity of a principal is important for the meaning of a message, it is prudent to mention the principal’s name explicitly in the message**

The Woo-Lam protocol

- Alice wants to prove her presence to Bob
- Alice shares a key with Trent
- Alice doesn't share a key with Bob

The Woo-Lam protocol

Trent (trusted server)

Alice

A

Bob

The Woo-Lam protocol

Trent (trusted server)

Alice

A

N_B

Bob

The Woo-Lam protocol

Trent (trusted server)

Alice

A

N_B

$\{N_B\}_{K_{AT}}$

Bob

The Woo-Lam protocol

Trent (trusted server)

Alice

A

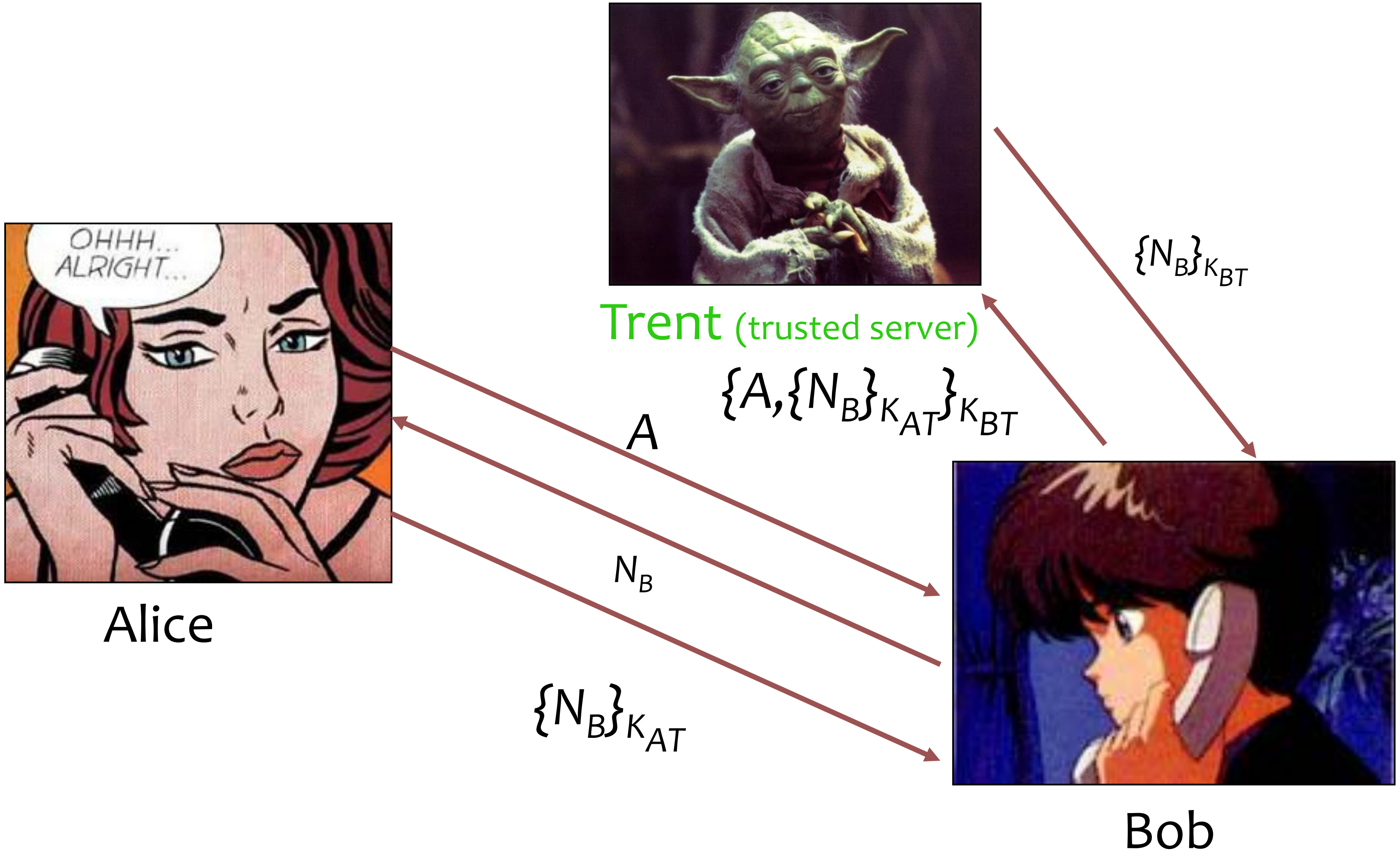
N_B

$\{N_B\}_{K_{AT}}$

$\{A,\{N_B\}_{K_{AT}}\}_{K_{BT}}$

Bob

The Woo-Lam protocol



The Woo-Lam protocol

Trent (trusted server)

Bob's reasoning:
A: Alice wants to talk to me
N_B: Challenge for Alice
After decryption: Blob = $\{N_B\}_{K_{AT}}$
Alice has encrypted N_B
I am talking to Alice

$\{N_B\}_{K_{BT}}$

$\{A, \{N_B\}_{K_{AT}}\}_{K_{BT}}$

Alice

A

N_B

Blob = $\{N_B\}_{K_{AT}}$

Bob

The Woo-Lam protocol

Bob's reasoning:
A: Alice wants to talk to me
N_B: Challenge for Alice
After decryption: Blob = $\{N_B\}_{K_{AT}}$
Alice has encrypted N_B
I am talking to Alice

Trent (trusted server)

$\{N_B\}_{K_{BT}}$

$\{M,\{N_B\}_{K_{MT}}\}_{K_{BT}}$

$\{A,\{N_B\}_{K_{AT}}\}_{K_{BT}}$

?

A

N_B

Blob = $\{N_B\}_{K_{MT}}$

Bob

The Woo-Lam protocol

Trent (trusted server)

A

M

Bob

The Woo-Lam protocol

Trent (trusted server)

A

M

N_B

N_B'

Bob

The Woo-Lam protocol

Trent (trusted server)

A

M

N_B

$N_B{}'$

$\{N_B\}_{K_{MT}}$

$\{N_B\}_{K_{MT}}$

Bob

The Woo-Lam protocol

Trent (trusted server)

$\{M,\{N_B\}_{K_{MT}}\}_{K_{BT}}$

$\{A,\{N_B\}_{K_{MT}}\}_{K_{BT}}$

A

M

N_B

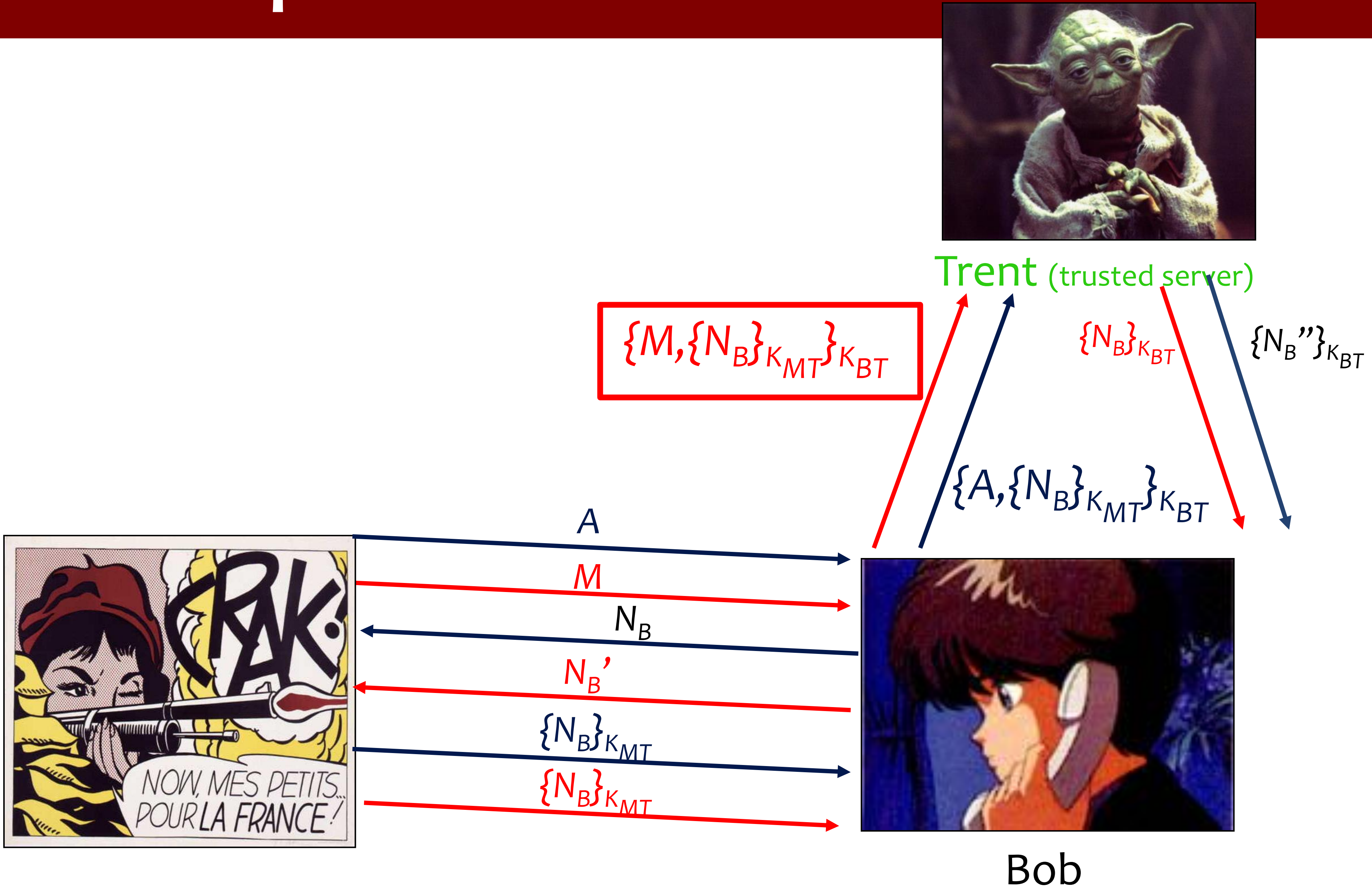
N_B'

$\{N_B\}_{K_{MT}}$

$\{N_B\}_{K_{MT}}$

Bob

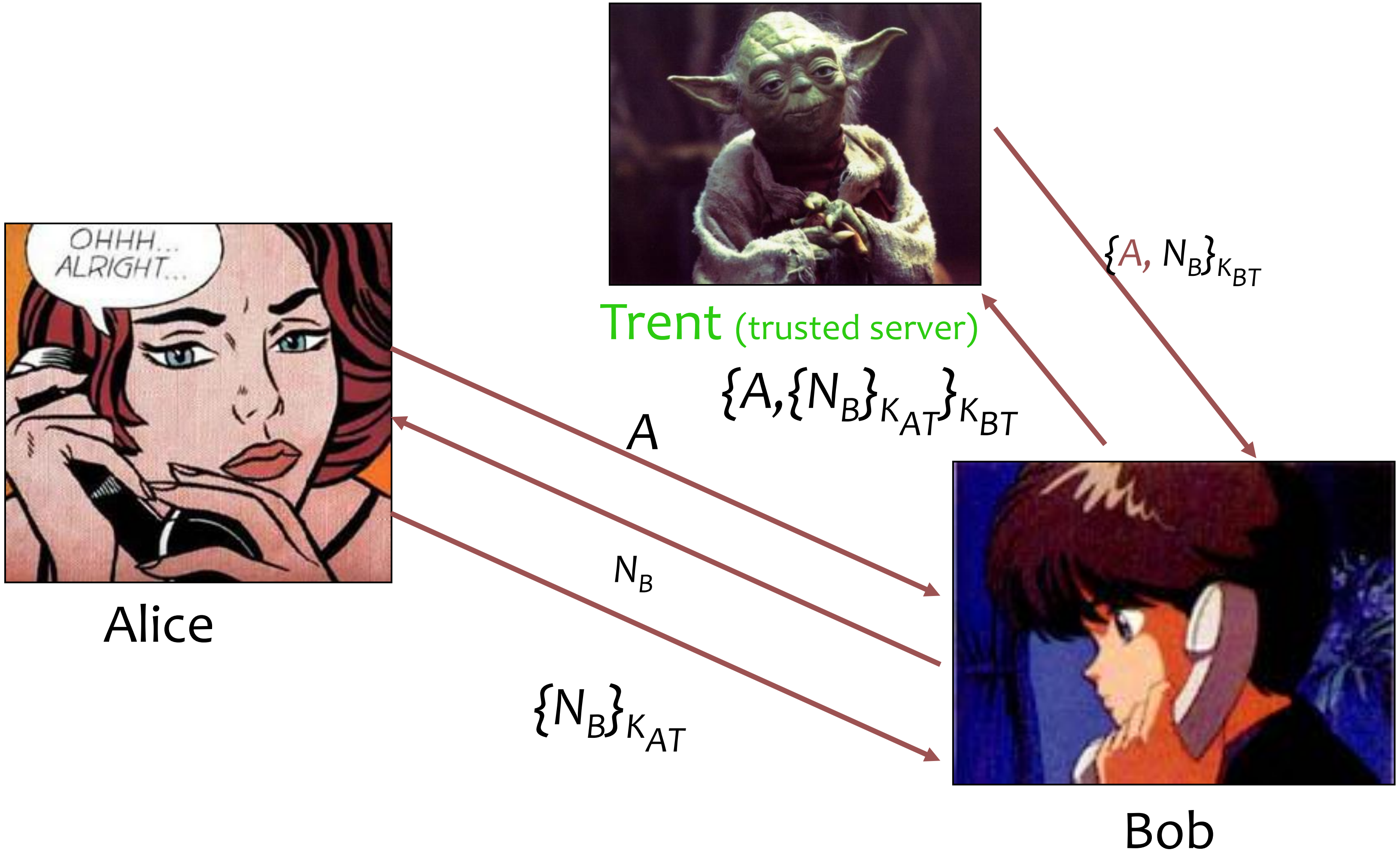
The Woo-Lam protocol



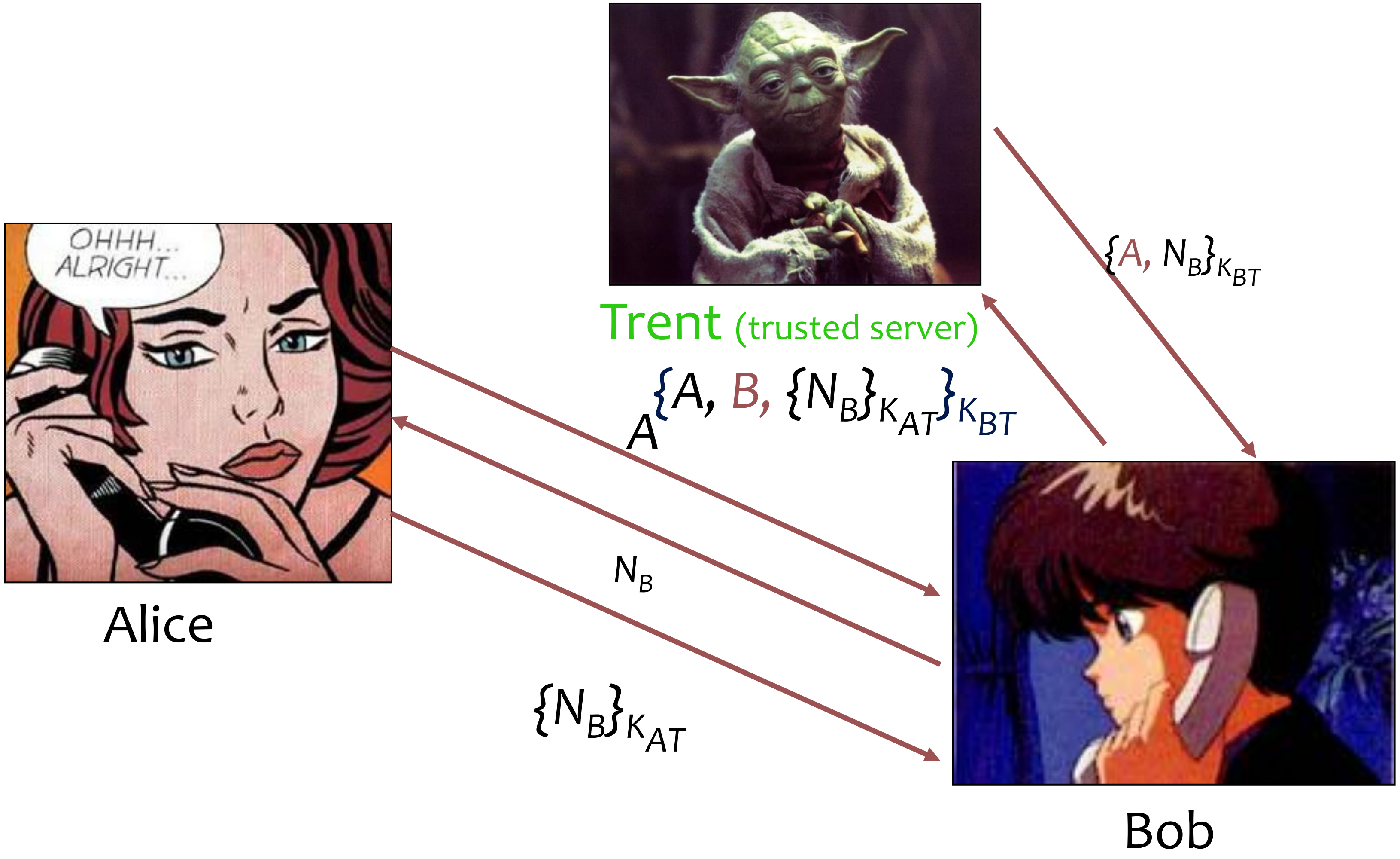
Diagnosis

- **Mallory can convince Bob that Alice is present**
- **This is because nothing ties the identity to the nonce!**
  - Trent's response doesn't mention Alice by name
  - Nonce are good for ensuring freshness but not always for association

Solution


OHHH... ALRIGHT...
Trent (trusted server)
Alice
Bob
A
N_B
$\{N_B\}_{K_{AT}}$
$\{A, \{N_B\}_{K_{AT}}\}_{K_{BT}}$
$\{A, N_B\}_{K_{BT}}$

Solution


OHHH... ALRIGHT...
Trent (trusted server)
A
{A, B, {N_B}_{K_AT}}_{K_BT}
{A, N_B}_{K_BT}
N_B
{N_B}_{K_AT}
Alice
Bob

Optimization

Trent (trusted server)

$\{A, N_B\}_{K_{BT}}$

$A, B, \{N_B\}_{K_{AT}}$

Alice

A

N_B

$\{N_B\}_{K_{AT}}$

Bob

Other principles

- **Other principles concern**
  - encryption
  - timeliness
  - trust
  - secrecy
- **The principles serve to**
  - simplify protocols
  - simplify formal analysis
  - avoid many mistakes

Uses of encryption

- **Secrecy**
- **Authentication: a principal proves ownership of a key by encrypting a known message with that key**
- **Bind together parts of a message**
  - $\{N_A, N_B\}_{K_{AT}}$ is different from $\{N_A\}_{K_{AT}}\{N_B\}_{K_{AT}}$
- **Produce random numbers**

Kerberos protocol

- **Famous authentication protocol using trusted server and “tickets”**
- **Used when logging into andrew**
  (outside of WebISO…)

Kerberos protocol

A, B

Trent (trusted server)

Alice

Bob

Kerberos protocol

Trent (trusted server)

A, B

$\{T_T, L, K_{AB}, B, \{T_T, L, K_{AB}, A\}_{K_{BT}}\}_{K_{AT}}$

Alice

Bob

Kerberos protocol

A, B

Trent (trusted server)

$\{T_T, L, K_{AB}, B, \{T_T, L, K_{AB}, A\}_{K_{BT}}\}_{K_{AT}}$

Alice

$\{T_T, L, K_{AB}, A\}_{K_{BT}}, \{A, T_A\}_{K_{AB}}$

Bob

Kerberos protocol

Trent (trusted server)

A, B

$\{T_T, L, K_{AB}, B, \{T_T, L, K_{AB}, A\}_{K_{BT}}\}_{K_{AT}}$

Alice

$\{T_T, L, K_{AB}, A\}_{K_{BT}}, \{A, T_A\}_{K_{AB}}$

$\{T_A+1\}_{K_{AB}}$

Bob

Kerberos protocol

1. $A \rightarrow T$: *A, B*
2. $T \rightarrow A$: $\{T_T, L, K_{AB}, B, \{T_T, L, K_{AB}, A\}_{K_{BT}}\}_{K_{AT}}$
3. $A \rightarrow B$: $\{T_T, L, K_{AB}, A\}_{K_{BT}}, \{A, T_A\}_{K_{AB}}$
4. $B \rightarrow A$: $\{T_A+1\}_{K_{AB}}$

- Message 2 requires encryption, K_{AB} needs to remain secret, T should sign message as a proof of authenticity
- Double encryption proves to B in message 3 that A must have successfully decrypted message 2
- 2nd encryption in message 3 proves knowledge of K_{AB}

Timeliness/Freshness (1/3)

- **Principle 6: Be clear as to what properties you assume of nonces.**
  - Freshness?
  - Unique value?
  - Value unpredictable?
  - Association with (e.g., a key, principle?)

The Wide-Mouthed Frog protocol

- **Revocation is difficult, much easier to do if key has limited lifetime**
  - Expires automatically, has to be explicitly renewed
- **Protocol used to deliver a key with an “expiry date”**

(illustration by Jonathan Lambert)

Let me handle all your timestamping needs!

The Wide-Mouthed Frog protocol

$\{T_A, B, K_{AB}\}_{K_{AT}}$

Trent (trusted server)

Alice

Bob

The Wide-Mouthed Frog protocol

$\{T_A, B, K_{AB}\}_{K_{AT}}$

Trent (trusted server)

$\{T_T, A, K_{AB}\}_{K_{BT}}$

Alice

T_T is not associated with Alice

Bob

- Trent only puts T_T in the message if K_{AB} is fresh
- If T_T is fresh, Alice must have shared K_{AB} recently

Attacking the frog

Trent (trusted server)

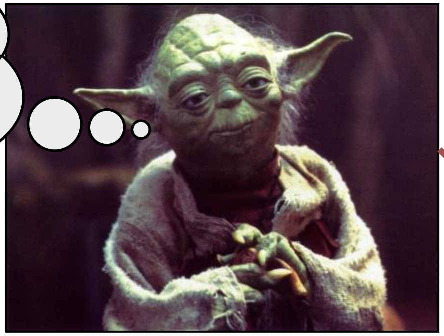
$\{T_T, A, K_{AB}\}_{K_{BT}}$

Bob

$\{T_T, A, K_{AB}\}_{K_{BT}}$

Attacking the frog

Bob is talking to me,
I am replying to Alice



Trent (trusted server)

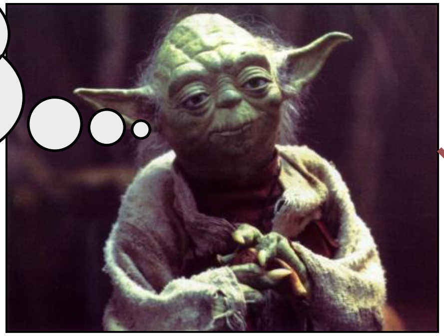
$\{T_T, A, K_{AB}\}_{K_{BT}}$

Bob

$\{T_T, A, K_{AB}\}_{K_{BT}}$

Attacking the frog

Bob is talking to me,
I am replying to Alice



Trent (trusted server)

$\{T_T, A, K_{AB}\}_{K_{BT}}$

$\{T_T, A, K_{AB}\}_{K_{BT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

Bob

Attacking the frog

Trent (trusted server)

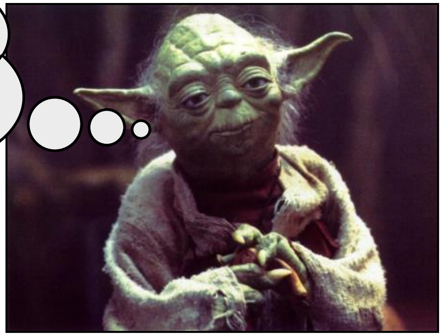
$\{T_T, A, K_{AB}\}_{K_{BT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

Attacking the frog

Alice is talking to me,
I am replying to Bob



Trent (trusted server)

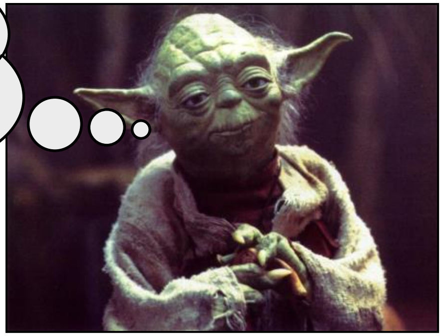
$\{T_T, A, K_{AB}\}_{K_{BT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

Attacking the frog

Alice is talking to me,
I am replying to Bob



Trent (trusted server)

$\{T_T, A, K_{AB}\}_{K_{BT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

$\{T_T'', A, K_{AB}\}_{K_{BT}}$

$\{T_T', B, K_{AB}\}_{K_{AT}}$

Attacking the frog

Alice is talking to me,
I am replying to Bob

$\{T_T'', A, K_{AB}\}_{K_{BT}}$

Mallory can keep the key K_{AB} valid for as long as she wants… Which eventually can be useful if she manages to steal the key!

$\{T_T', B, K_{AB}\}_{K_{AT}}$

Failure diagnosis

- **Need to be careful about association!**
- **Possible solutions**
  - Have Trent keep a list of current/recent working keys and timestamps
  - Do not change T_A into T_T?
    - Lead to other problems?

Timeliness/Freshness (2/3)

- **Principle 7: The use of a predictable quantity (such as time or the value of a counter) can serve in guaranteeing freshness. But if a predictable quantity is to be effective, it should be protected so that an intruder cannot simulate a challenge and later replay a response.**

Predictability of nonces

- **Simple clock synchronization protocol**

Alice

A, N_A

$\{T_T, N_A\}_{K_{AT}}$

Trent (trusted server)

Predictability of nonces

A, N_A →

← $\{T_T, N_A\}_{K_{AT}}$

Trent (trusted server)

Alice

A, N_A →

← $\{T_T, N_A\}_{K_{AT}}$

Diagnosis

- **If N_A is predictable**
  - Possible for Mallory to set the value of Alice's clock back
- **Solutions**
  - Make N_A random

In-class exercise

- **Modify the protocol messages so that N_A doesn't need to be unpredictable**
  - E.g., implemented as a counter
- **Assume**
  - Alice and Trent share a secret key K_{AT}
  - The counter never overflows
  - The second message stays the same

Alice

A, N_A

$\{T_T, N_A\}_{K_{AT}}$

Trent (trusted server)

Solution

Timeliness/Freshness (3/3)

- Freshness: use vs. generation
- Principle 9: A key may have been used recently for example to encrypt a nonce, yet be quite old, and be possibly compromised. Recent use does not make the key look any better than it would otherwise

The Needham-Schroeder protocol

1. $A \rightarrow T$: A, B, N_A
2. $T \rightarrow A$: $\{N_A, B, K_{AB}, \{K_{AB}, A\}_{K_{BT}}\}_{K_{AT}}$
3. $A \rightarrow B$: $\{K_{AB}, A\}_{K_{BT}}$
4. $B \rightarrow A$: $\{N_B\}_{K_{AB}}$
5. $A \rightarrow B$: $\{N_B+1\}_{K_{AB}}$

1. $M \rightarrow B$: $\{K_{AB}, A\}_{K_{BT}}$
2. $B \rightarrow M$: $\{N_B\}_{K_{AB}}$
3. $M \rightarrow B$: $\{N_B+1\}_{K_{AB}}$

- Does A obtain freshness for key K_{AB}?
- Does B obtain freshness for key K_{AB}?

How to stay out of trouble

- **Keep your protocols simple (KISS)**
  - Remember the Saltzer Schroeder principles for access control… they sometimes apply to other fields!
- **Be suspicious of clever optimizations**
- **Be explicit**
  - include sufficient proofs of freshness
  - include sufficient names
  - do not count on context
  - use evident classifications
- **Interpreting a message should be a simple matter of parsing (no context should be needed)**
- **Cryptography helps, but is not the whole story**

Take away slide

- **Designing correct security protocols is extremely challenging**
- **Subtle flaws can result in a vulnerable protocol**
- **Often unsatisfied assumption results in vulnerability**
- **Promising research direction**
  - automated protocol verification