EDUCATIONAL MATERIAL IN CYBER SECURITY

GameSS: Security Protocols

Sebastian Mödersheim

DTU Compute

WHO IS THIS MATERIAL FOR?

- Designers of protocols – of any distributed systems that need to protect their communication using cryptography
  - ★ e.g., websites, login/sign-in, registrations/updates, APIs, payment or keycards ...
- Students and security professionals who want to understand vulnerabilities and attacks against protocols, as well as how to systematically protect them
- Anybody who wants to use automatic tools to find attacks against protocols or to verify the absence of attacks
- Anybody who wants to use a simple concise and yet formally precise language to talk about the protocol and its security goals

WHO MADE THIS MATERIAL?

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WHAT ARE THE MAIN TAKEAWAYS FOR THIS CONTENT?

- You may easily overlook security problems if you are not precise about: what the system does, what the security goals are, and what the intruder can do.
- Even if you are precise on this, manual analysis can overlook problems. Tools can often find something you overlooked.
  - ★ In particular one should by default assume that participants could be dishonest and all dishonest people work together.
- You can often easily avoid a lot of problems by being explicit in messages about who is communicating and what the message is supposed to say (type-flaw attacks etc.)
- You can often easily make a system resilient against guessing attacks, even though users use weak passwords.

Mathematical Abstraction

- A clearly defined game
  - ★ "winnable" is a clearly defined
- Like in chess, it is still very complex for automated analysis
  - ★ astronomical or infinite size of search trees
  - ★ computers are sometimes better than humans at it...
- Mind the gap
  - ★ Be clear about the abstractions and assumptions made
  - ★ Separation of concerns

Overview

Protocol Security

"Logical Hacking" and Security Proofs

- What is an "attack"? (and what is not?)
- How can we automatically find attacks?
- How can we prove the security of a system?
  - ★ ... not just with respect to currently known attacks, but against any attacks!
  - ★ Is that even possible?
  - ★ Can we do that even automatically?
- How can we build systems that are secure?

This requires a precise definitions of

- the systems in questions
- its goals
- the assumptions (in particular, the intruder)

Overview of Problem Areas

Example: Alice wants to tell her bank to transfer 1000 Kr. to Bob.

- What are the involved goals?
  - ★ Authentication/Integrity
  - ★ Confidentiality/Privacy
- Involved Cryptographic Protocols: could be
  - ★ TLS
  - ★ The banking application
  - ★ Some login like MitID (also over TLS? Same session?)
- Implementation
  - ★ Crypto API
  - ★ All the non-crypto aspects, like parsing message formats.

Overview

Alice and Bob

Alice and Bob notation

- aka Message Sequence Charts
  aka Protocol Narrations
- popular informal notation for protocols

```
A -> B: {NA,A}pk(B)
B -> A: {NA,NB}pk(A)
A -> B: {NB}pk(B)
```

AnB

- A formal language based on Alice and Bob notation
  - ★ Defining the roles of the protocol and their initial knowledge
    - ▶ Indirectly defining the intruder's initial knowledge
    - ▶ Indirectly defining how agents execute the protocol
  - ★ Defining the security goals of the protocol
- OFMC: Open-Source Fixedpoint Model-Checker.
  - ★ Automatically finding attacks in protocols
  - ★ AnB is one input language for OFMC.

The Ctf challenges are done in AnB/OFMC: find a protocol for initial knowledge and goals that OFMC cannot attack anymore.

Example

Step-by-step development of a protocol for the following scenario:

- A (Alice) and B (Bob) want a secure connection with each other, but have no prior security relationship.
- There is a server s and both A and B each have with s a shared secret key $sk(A, s)$ and $sk(B, s)$, respectively.
- s should now help A and B establish a secure connection, i.e., a shared secret key KAB that they can use to communicate with each other.
- This only works if s is honest (why?)

First version

Protocol : *KeyExchange*
Types :
  Agent A, B, s;
  Symmetric_key KAB;
  Function sk;
Knowledge :
  A : $A, B, s, sk(A, s)$;
  B : $A, B, s, sk(B, s)$;
  s : $A, B, s, sk(A, s), sk(B, s)$;
Actions :
  $A \rightarrow s : A, B$
  $s \rightarrow A : KAB$
  $A \rightarrow B : KAB$
Goals :
  KAB secret between A, B, s
  A authenticates s on KAB
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- A, B are variables of type Agent: they can be instantiated with any agent name during the run of the protocol

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  - ★ ... including the intruder i
  - ★ The intruder can thus play the role of A or B

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- s is a constant of type Agent: there is only one agent called s who will play in all sessions

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  - ★ ... including the intruder i
  - ★ The intruder can thus play the role of A or B
- s is a constant of type Agent: there is only one agent called s who will play in all sessions
  - ★ the intruder cannot play the role of s
  - ★ s is thus a trusted third party

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- KAB is a variable of type symmetric key.
  - ★ The value will be freshly created during the protocol run.

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- KAB is a variable of type symmetric key.
  - ★ The value will be freshly created during the protocol run.
- sk is a user-defined function. We use it to model shared secret keys of two agents that are fixed before the protocol run.

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- It is necessary to specify an initial knowledge for every role of the protocol.
  - ★ It determines how agents send and receive messages

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  - ★ It determines how agents send and receive messages
- Typically everybody knows all agent names.

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- It is necessary to specify an initial knowledge for every role of the protocol.
  - ★ It determines how agents send and receive messages
- Typically everybody knows all agent names.
- A knows a secret key with the server: $sk(A, s)$
- B knows a secret key with the server: $sk(B, s)$
- s knows both $sk(A, s)$ and $sk(B, s)$

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- The idea of the protocol is to establish a fresh secret key KAB between A and B
  - ★ A and B initially do not have any key material with each other
  - ★ but both have a shared key with trusted third party s that can be used for establishing KAB.
- Question: why would this be impossible if we had an untrusted S instead of s?

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- The knowledge section also determines the initial knowledge of the intruder:
  - ★ Say $A = i$ and $B = b$ for agent i in role A and honest b in role B.
  - ★ Then the intruder gets the knowledge of A under this instantiation: $i, b, s, sk(i, s)$
  - ★ The intruder thus also has a shared secret key with s!
  - ★ That's only fair: the intruder should know enough to play a protocol role as a normal user.

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- The protocol starts by A contacting s stating the names of A and B
- Without crypto, there is no reliable information about senders and receivers.
- The intruder may intercept messages sent by honest agents, and insert arbitrary messages as if coming from any agent.
- A and B are not IP addresses, but unique identifiers (think domain name or user name/CPR).
- All agent names as public for now. Privacy: later lecture.

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- The server generates a fresh shared key KAB for A and B.
  - ★ The entity first using a non-agent variable is the creator.
- Here, KAB is sent in clear text to A. This obviously is not secure in an intruder-controlled network.
- In the last step A forwards the key to B (also in clear...)
- The server cannot directly send the key to both A and B, because a message can only have one recipient who has to be the sender of the next message

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- The secrecy goal: only A, B, and s may know the key.
- The authentication goals: later

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Running OFMC we get an attack:

```
SUMMARY:
  ATTACK_FOUND
GOAL:
  secrets

ATTACK TRACE:
i -> (s,1): x32,x31
(s,1) -> i: KAB(1)
i can produce secret KAB(1)

secret leaked: KAB(1)
```

First: try to associate attack steps with protocol steps

First version

$$
\begin{array}{lcll}
A & \to & s & : A, B \\
s & \to & A & : KAB \\
A & \to & B & : KAB
\end{array}
$$

```
i -> (s,1): x32,x31
(s,1) -> i: KAB(1)
i can produce secret KAB(1)
```

- OFMC uses internal variables like `x32` and `x31` for things the intruder can arbitrarily choose.
  - ★ Here, the intruder can choose any agent names for A and B
- `KAB(1)` means a fresh key that was generated by an honest agent – the number (1) is to make it unique.
- `(s,1)` means server in session 1 (sometimes an attack may involve several sessions/runs of the protocol)
- `i` is the intruder

1. Here the intruder contacts the server s posing as some agent `x32` (role A) who wants to talk to `x31` (role B).
2. The server generates a new key `KAB(1)` for `x32` and `x31` and sends it.
3. The intruder sees this key, violating secrecy.

How to Encrypt this?

```
A->s: A,B
s->A: {| KAB |}sk(A,s)
A->B: {| KAB |}sk(B,s)
```

```
ofmc: Protocol not executable:
At the following state of the knowledge:
...one cannot compose the
following message:
{|KAB|}sk(B,s)
sk(B,s)
|sk
```

- $\{|KAB|\}_{sk(A,s)}$ means symmetric encryption of KAB with key $sk(A,s)$.
- The server can do that, knowing $sk(A,s)$.
- However A cannot produce $\{|KAB|\}_{sk(B,s)}$ for B.
- OFMC rejects this specification since A cannot generate a message that the protocol tells her to send.
  - ★ In the error message you can see what OFMC tried: the message $\{|KAB|\}_{sk(B,s)}$ is not known to A, and neither is $sk(B,s)$ nor the entire function sk.

Second Version

```
A->s: A,B
s->A: {| KAB |}sk(A,s),
      {| KAB |}sk(B,s)
A->B: {| KAB |}sk(B,s)
```

```
GOAL:
  weak_auth

i -> (s,1): x32,x401
(s,1) -> i: {|KAB(1)|}_(sk(x32,s)),
            {|KAB(1)|}_(sk(x401,s))
i -> (x401,1): {|KAB(1)|}_(sk(x401,s))
```

- In the second version, s generates both encrypted messages.
  - ★ A cannot decrypt the second one, but she can forward it to B.
- This is now a meaningful specification, but OFMC finds an attack:

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  - ★ The intruder forwards the part for x401 as required in the protocol.

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  - ★ A cannot decrypt the second one, but she can forward it to B.
- This is now a meaningful specification, but OFMC finds an attack:
  - ★ The intruder again chooses two agent names, and the server generates encrypted keys for them.
  - ★ The intruder forwards the part for `x401` as required in the protocol.
  - ★ So how does this represent an attack?

Second Version

```
                                  GOAL: weak_auth
A->s: A,B                         ATTACK TRACE:
s->A: {| KAB |}sk(A,s),           i -> (s,1): x32,x401
      {| KAB |}sk(B,s)            (s,1) -> i: {|KAB(1)|}_(sk(x32,s)),
A->B: A,B,                                    {|KAB(1)|}_(sk(x401,s))
      {| KAB |}sk(B,s)            i -> (x401,1): x30,x401,
                                                 {|KAB(1)|}_(sk(x401,s))
```

- Adding the agent names in clear text to the messages allows to see what's going wrong:
  - ★ To s, the intruder claims to be x32
  - ★ To B (x401), the intruder claims to be x30
- Thus there is confusion between B and s as to who A is
  This violates the goal

  ```
  B authenticates s on A,KAB;
  ```

Second Version

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A->B: A,B,                                    {|KAB(1)|}_(sk(x401,s))
      {| KAB |}sk(B,s)            i -> (x401,1): x30,x401,
                                                 {|KAB(1)|}_(sk(x401,s))
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  - ★ To s, the intruder claims to be `x32`
  - ★ To B (`x401`), the intruder claims to be `x30`
- Thus there is confusion between B and s as to who A is
  This violates the goal

  `B authenticates s on A,KAB;`
- Suppose `x32=i`, then the intruder can see `KAB(1)`
  while B thinks he shares `KAB(1)` with `x30`.

Third Version

```
                                GOAL: weak_auth
A->s: A,B                       ATTACK TRACE:
s->A: {| B,KAB |}sk(A,s),       i -> (s,1): x401,x30
      {| A,KAB |}sk(B,s)        (s,1) -> i: {|x30,KAB(1)|}_(sk(x401,s)),
A->B: {| A,KAB |}sk(B,s)                    {|x401,KAB(1)|}_(sk(x30,s))
                                i -> (x401,1): {|x30,KAB(1)|}_(sk(x401,s)
```

- Third version adds the name of the other party to the encrypted message.
- There is an attack, but it is a bit hard to see what is wrong.
- Let us replace the variables in the attack trace with concrete agent names *a* and *b*.

Third Version

```
                                  GOAL: weak_auth
A->s: A,B                         ATTACK TRACE:
s->A: {| B,KAB |}sk(A,s),         i -> (s,1): a,b
      {| A,KAB |}sk(B,s)          (s,1) -> i: {|b,KAB(1)|}_(sk(a,s)),
A->B: {| A,KAB |}sk(B,s)                      {|a,KAB(1)|}_(sk(b,s))
                                  i -> (a,1): {|b,KAB(1)|}_(sk(a,s))
```

- Third version adds the name of the other party to the encrypted message.
- From s's point of view: role A is played by a, role B by b.

Third Version

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                                GOAL: weak_auth
A->s: A,B                       ATTACK TRACE:
s->A: {| B,KAB |}sk(A,s),       i -> (s,1): a,b
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                                i -> (a,1): {|b,KAB(1)|}_(sk(a,s))
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- From s's point of view: role A is played by a, role B by b.
- From a's point of view: role A is played by b, role B is played by a. This violates again the authentication goal between B and s.

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A->s: A,B
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      {| A,KAB |}sk(B,s)
A->B: {| A,KAB |}sk(B,s)
```

```
GOAL: weak_auth
ATTACK TRACE:
i -> (s,1): a,b
(s,1) -> i: {|b,KAB(1)|}_(sk(a,s)),
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```

- Third version adds the name of the other party to the encrypted message.
- From s's point of view: role A is played by a, role B by b.
- From a's point of view: role A is played by b, role B is played by a. This violates again the authentication goal between B and s.
- In many scenarios, it is a serious problem if the intruder can confuse agents about the role they play.

Fourth Version

```
A->s: A,B
s->A: {|A,B,KAB|}sk(A,s),
      {|A,B,KAB|}sk(B,s)
A->B: {|A,B,KAB|}sk(B,s)
```

```
GOAL: strong_auth
ATTACK TRACE:
i -> (s,1): a,b
(s,1) -> i: {|a,b,KAB(1)|}_(sk(a,s)),
            {|a,b,KAB(1)|}_(sk(b,s))
i -> (b,1): a,b,{|a,b,KAB(1)|}_(sk(b,s))
i -> (b,2): a,b,{|a,b,KAB(1)|}_(sk(b,s))
```

- Fourth version: in all encrypted messages we write both A and B–the ordering avoids the confusion.
  - ★ Alternative: have to tags `init` and `resp` to make clear which one is the initiator A and who is the responder B.

Fourth Version

```
A->s: A,B
s->A: {|A,B,KAB|}sk(A,s),
      {|A,B,KAB|}sk(B,s)
A->B: {|A,B,KAB|}sk(B,s)
```

```
GOAL: strong_auth
ATTACK TRACE:
i -> (s,1): a,b
(s,1) -> i: {|a,b,KAB(1)|}_(sk(a,s)),
            {|a,b,KAB(1)|}_(sk(b,s))
i -> (b,1): a,b,{|a,b,KAB(1)|}_(sk(b,s))
i -> (b,2): a,b,{|a,b,KAB(1)|}_(sk(b,s))
```

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  - ★ Alternative: have to tags `init` and `resp` to make clear which one is the initiator A and who is the responder B.
- In the attack, the intruder sends the last message a second time to b.
  - ★ For b, this is a completely new protocol run—note $(b, 1)$ vs. $(b, 2)$
  - ★ This is a replay attack: b is made to accept something a second time that was actually only said once by s.

Fourth Version

```
A->s: A,B
s->A: {|A,B,KAB|}sk(A,s),
      {|A,B,KAB|}sk(B,s)
A->B: {|A,B,KAB|}sk(B,s)
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i -> (b,2): a,b,{|a,b,KAB(1)|}_(sk(b,s))
```

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- In the attack, the intruder sends the last message a second time to b.
  - ★ For b, this is a completely new protocol run—note $(b, 1)$ vs. $(b, 2)$
  - ★ This is a replay attack: b is made to accept something a second time that was actually only said once by s.
- Replay can often be exploited, for instance:
  - ★ a bank transfer that was ordered once is executed many times
  - ★ an agent is made to accept an old broken key

Fourth Version

```
A->s: A,B
s->A: {|A,B,KAB|}sk(A,s),
      {|A,B,KAB|}sk(B,s)
A->B: {|A,B,KAB|}sk(B,s)
```

```
GOAL: strong_auth
ATTACK TRACE:
i -> (s,1): a,b
(s,1) -> i: {|a,b,KAB(1)|}_(sk(a,s)),
            {|a,b,KAB(1)|}_(sk(b,s))
i -> (b,1): a,b,{|a,b,KAB(1)|}_(sk(b,s))
i -> (b,2): a,b,{|a,b,KAB(1)|}_(sk(b,s))
```

- Note `strong_auth` at `GOAL`: this appears in OFMC whenever the agreement on the names and data is correct, but something has been accepted more often than it was said (a replay attack).
- One can turn off the replay detection and just ask for the pure agreement by changing the goal to weak authentication:

```
A weakly authenticates s on B,KAB;
B weakly authenticates s on A,KAB;
```

Fourth Version

```
A->s: A,B
s->A: {|A,B,KAB|}sk(A,s),
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A->B: {|A,B,KAB|}sk(B,s)
```

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A->B: {|A,B,KAB|}sk(B,s)
```

- One can turn off the replay detection and just ask for the pure agreement by changing the goal to weak authentication:

```
A weakly authenticates s on B,KAB;
B weakly authenticates s on A,KAB;
```

- Then OFMC will output:

```
Open-Source Fixedpoint Model-Checker version 2024
Verified for 1 sessions
Verified for 2 sessions
^C
```

- Here `^C` means that I pressed Control-C to stop, because it will go on forever when no attack is found, checking more and more sessions.
- For the purposes of this course it is fine to step after two sessions, and you can do this in OFMC directly with the option `--numSess 2`

Fifth Version

```
Number NA,NB;
...
B->A: NB
A->s: A,B,NA,NB
s->A: {|A,B,KAB,NA,NB|}sk(A,s),
      {|A,B,KAB,NA,NB|}sk(B,s)
A->B: {|A,B,KAB,NA,NB|}sk(B,s)
```

```
SUMMARY:
  NO_ATTACK_FOUND
```

- The best way to solve replay is to use challenge response:
  - ★ Participants create a fresh random number like `NA` and `NB`.
  - ★ They are included in encrypted messages to prove that the encryption is not older than the fresh numbers.

Fifth Version

```
Number NA,NB;
...
B->A: NB
A->s: A,B,NA,NB
s->A: {|A,B,KAB,NA,NB|}sk(A,s),
      {|A,B,KAB,NA,NB|}sk(B,s)
A->B: {|A,B,KAB,NA,NB|}sk(B,s)
```

```
SUMMARY:
  NO_ATTACK_FOUND
```

- The best way to solve replay is to use challenge response:
  - ★ Participants create a fresh random number like `NA` and `NB`.
  - ★ They are included in encrypted messages to prove that the encryption is not older than the fresh numbers.
  - ★ We are done. However there is a better way to do this using Diffie-Hellman.

Sixth Version

```
Protocol: KeyExchange
Types: Agent A,B,s;
       Number X,Y,g,Payload;
       Function sk;
Knowledge: A: A,B,s,sk(A,s),g;
           B: A,B,s,sk(B,s),g;
           s: A,B,s,sk(A,s),sk(B,s),g;
Actions:
A->B: exp(g,X)
B->s: {| A,B,exp(g,X),exp(g,Y) |}sk(B,s)
s->A: {| A,B,exp(g,X),exp(g,Y) |}sk(A,s)
A->B: {| Payload |}exp(exp(g,X),Y)
Goals:
exp(exp(g,X),Y) secret between A,B;
Payload secret between A,B;
A authenticates B on exp(exp(g,X),Y);
B authenticates A on exp(exp(g,X),Y),Payload;
```

Sixth Version

```
A->B: exp(g,X)
B->s: {| A,B,exp(g,X),exp(g,Y) |}sk(B,s)
s->A: {| A,B,exp(g,X),exp(g,Y) |}sk(A,s)
A->B: {| Payload |}exp(exp(g,X),Y)
```

Diffie-Hellman:

- every agent generates a random X and Y
- they exchange $\exp(g, X) \mod p$ and $\exp(g, Y) \mod p$
  - ★ p is a large fixed prime number – we omit in OFMC
  - ★ g is a fixed generator of the group $\mathbb{Z}_p^\star$
  - ★ Both p and g are public
  - ★ we omit writing $\mod p$ in OFMC
- It is computationally hard to obtain X from $\exp(g, X) \mod p$
- However A and B have now a shared key $\exp(\exp(g, X), Y) \mod p = \exp(\exp(g, Y), X) \mod p$

Diffie-Hellman and ECDH

	Classic	
Group	$\mathbb{Z}_p^\star = \{1, \ldots, p-1\}$	
Group Op.	$\times : \mathbb{Z}_p^\star \times \mathbb{Z}_p^\star \to \mathbb{Z}_p^\star$ (Mult. modulo p)	
Generator	$g \in \mathbb{Z}_p^\star$	
Secrets	$X, Y \in \{1, \ldots, p-1\}$	
Half keys	$g^X := \underbrace{g \times \ldots \times g}_{X \text{ times}}$ $g^Y := \ldots$	
Full key	$(g^X)^Y = (g^Y)^X$	

Diffie-Hellman and ECDH

	Classic	Elliptic Curve (ECDH)
Group	$\mathbb{Z}_p^\star = \{1, \ldots, p-1\}$	Finite field $\mathbb{F}$ of order n
Group Op.	$\times : \mathbb{Z}_p^\star \times \mathbb{Z}_p^\star \to \mathbb{Z}_p^\star$ (Mult. modulo p)	$+ : \mathbb{F} \times \mathbb{F} \to \mathbb{F}$ (not quite so intuitive...)
Generator	$g \in \mathbb{Z}_p^\star$	g on curve
Secrets	$X, Y \in \{1, \ldots, p-1\}$	$X, Y \in \{1, \ldots, n-1\}$
Half keys	$g^X := \underbrace{g \times \ldots \times g}_{X \text{ times}}$	$X \cdot g := \underbrace{g + \ldots + g}_{X \text{ times}}$
	$g^Y := \ldots$	$Y \cdot g := \ldots$
Full key	$(g^X)^Y = (g^Y)^X$	$X \cdot Y \cdot g = Y \cdot X \cdot g$

Diffie-Hellman and ECDH

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Secrets	$X, Y \in \{1, \ldots, p-1\}$	$X, Y \in \{1, \ldots, n-1\}$
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Full key	$(g^X)^Y = (g^Y)^X$	$(g^X)^Y = (g^Y)^X$

Trick: write $\times$ for the group operation also in ECDH.

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Full key	$(g^X)^Y = (g^Y)^X$	$(g^X)^Y = (g^Y)^X$
Typical size	thousand of bits	hundreds of bits

Trick: write $\times$ for the group operation also in ECDH.

Sixth Version

```
A->B: exp(g,X)
B->s: {| A,B,exp(g,X),exp(g,Y) |}sk(B,s)
s->A: {| A,B,exp(g,X),exp(g,Y) |}sk(A,s)
A->B: {| Payload |}exp(exp(g,X),Y)
```

- Why is this version better than the fifth version?

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```

- Why is this version better than the fifth version?
  - ★ Both A and B contribute something fresh to the key
  - ★ The trusted party s does not even get to know the key
    - ▶ An honest but curious s cannot read messages between A and B.

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  - ★ Perfect Forward Secrecy: The intruder cannot read `Payload` even when learning `sk(A,s)` and `sk(B,s)` after the exchange.

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- Do we even need the trusted party s then?

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  - ★ Perfect Forward Secrecy: The intruder cannot read `Payload` even when learning `sk(A,s)` and `sk(B,s)` after the exchange.
- Do we even need the trusted party s then? Yes!
  - ★ `exp(g,X)` and `exp(g,Y)` are public
    - ▶ you may call them public keys (with X and Y the private keys)
  - ★ but they need to be authenticated (like public keys):
    - ▶ that `exp(g,X)` really comes from A
    - ▶ and `exp(g,Y)` really comes from B

Modeling Agents and Fixed Key-Infrastructures

- Normally variables (uppercase) like A,B,C,...
  - ★ can be played by any concrete (lowercase) agent like a,b,c,...,i
- Special agent: i – the intruder
- Honest agent: constant like s for a trusted server
  - ★ Cannot be instantiated (especially the intruder), fixed in all protocol runs
- Given key infrastructures: use functions e.g.
  - ★ sk(A,B) the shared key of A and B
  - ★ pw(A,B) the password of A at server B
  - ★ pk(A) the public key of A
    - ▶ inv(K) is the private key that belongs to public key K.
    - ▶ Note inv and exp are a built-in function (do not declare as a function).
  - ★ Give every role the necessary initial knowledge

AnB: Things to Note

- Identifiers that start with uppercase: variables (E.g., `A,B,KAB`)
- Identifiers that start with lowercase: constants and functions (E.g., `s,pre,sk`)
- One should declare a type for all identifiers; OFMC can search for *type-flaw* attacks when using the option `-untyped` (in which case all types are ignored).
- The (initial) knowledge of agents MUST NOT contain variables of any type other than `Agent`.
  - ★ For long-term keys, passwords, etc. use functions like $sk(A, B)$.
- Each variable that does not occur in the initial knowledge is freshly created during the protocol by the first agent who uses it.
  - ★ In the NSSK example, `A` creates `NA`, `s` creates `KAB`, `B` creates `NB`.

Message Term Algebra

for security protocols

Symbol	Arity	Meaning	Public
i	0	name of the intruder	yes
inv	1	private key of a given public key	no
crypt	2	asymmetric encryption in AnB: write $\{m\}_k$ for crypt(k, m)	yes
scrypt	2	symmetric encryption in AnB: write $\{\|m\|\}_k$ for scrypt(k, m)	yes
pair	2	pairing/concatenation in AnB: write m, n for pair(m, n)	yes
exp(·, ·)	2	exponentiation modulo fixed prime p	yes
$a, b, c, \ldots$	0	User-defined constants	User-def.
$f(\cdot)$	$\star$	User-defined function symbol f	User-def.

- Call Σ the set of all function symbols and Σ_p the public ones.
- Public functions can be applied by every agent
- inv is not public: the private key of a given public key.

Overview

The Dolev-Yao Intruder Model

- Black-box model of cryptography
  - ★ The intruder simply cannot break the crypto (or flip some bits)
  - ★ He can only use encryption/decryption algorithms with known keys like everybody else
- Kerckhoffs's principle:
  - ★ Encryption and decryption algorithms are not secret.
- Intruder controls entire communication medium. Realistic?
  - ★ Worst-case assumption (what is not secured may be infected)
- The intruder can act as a participant. Why that?
  - ★ Modeling a dishonest (or compromised) participant.
  - ★ Some attacks do not work when all participants are honest.

Intruder Deduction

The core of the Dolev-Yao model is a definition what the intruder can do with messages.

- We define a relation $M \vdash m$ where
  - ★ M is a set of messages
  - ★ m is a message

  expressing that the intruder can derive m, if his knowledge is M.

Example

$$M = \{\, k_1, \{\!|m_1|\!\}_{k_1}, m_2, \{\!|m_3|\!\}_{k_2} \,\}$$

Then we should have for instance:

- $M \vdash m_1$
- $M \vdash m_2$
- $M \not\vdash m_3$
- $M \vdash \{\!|\langle m_1, m_2 \rangle|\!\}_{k_1}$

Dolev-Yao Closure

We define $M \vdash t$ as a proof calculus with rules of the form

$$\frac{Premise_1 \quad \ldots \quad Premise_n}{Conclusion} \; Side\text{-}Condition$$

meaning:

- if we have proved all the premisses
- and the side-condition holds,
- then we have a proof of the conclusion.

The simplest rule is Axiom:

Axiom

$$\frac{}{M \vdash m} \text{ if } m \in M \text{ (Axiom)}$$

The intruder can derive every message m that is directly in his knowledge M.

Dolev-Yao Closure: Symmetric Crypto

Symmetric Cryptography

$$\frac{M \vdash m \quad M \vdash k}{M \vdash \{|m|\}_k}\ (\text{EncSym}) \qquad \frac{M \vdash \{|m|\}_k \quad M \vdash k}{M \vdash m}\ (\text{DecSym})$$

- The intruder can encrypt any message m he knows with any key k he knows.
- The intruder can decrypt any message $\{|m|\}_k$ to which he knows the decryption key k.

Example

$$M = \{\, k_1, \{|m_1|\}_{k_1}, m_2, \{|m_3|\}_{k_2} \,\}$$

$$\dfrac{\dfrac{}{M \vdash \{|m_1|\}_{k_1}}\ \text{Axiom} \qquad \dfrac{}{M \vdash k_1}\ \text{Axiom}}{M \vdash m_1}\ \text{DecSym}$$

Note: $M \nvdash m_3$

Infinity

Note that with the three rules given so far the set of derivable terms is already infinite:

Example

$$M = \{\, k_1, \{\!|m_1|\!\}_{k_1}, m_2, \{\!|m_3|\!\}_{k_2} \,\}$$

$$\dfrac{\dfrac{\dfrac{}{M \vdash m_2}\,\text{Axiom} \quad \dfrac{}{M \vdash k_1}\,\text{Axiom}}{M \vdash \{\!|m_2|\!\}_{k_1}}\,\text{EncSym} \quad \dfrac{}{M \vdash k_1}\,\text{Axiom}}{M \vdash \{\!|\{\!|m_2|\!\}_{k_1}|\!\}_{k_1}}\,\text{EncSym}$$

Dolev-Yao Closure: Concatenation

Concatenation

$$\frac{M \vdash m_1 \quad M \vdash m_2}{M \vdash \langle m_1, m_2 \rangle}\ (\text{Cat}) \qquad \frac{M \vdash \langle m_1, m_2 \rangle}{M \vdash m_i}\ (\text{Proj}_i)$$

- The intruder can concatenate and split messages.

Example

$$M = \{\, k_1, \{\!|\langle a, m_1 \rangle|\!\}_{k_1}, m_2, \{\!|m_3|\!\}_{k_2} \,\}$$

$$\dfrac{\dfrac{\dfrac{\dfrac{}{M \vdash \{\!|\langle a, m_1 \rangle|\!\}_{k_1}}\ \text{Axiom} \quad \dfrac{}{M \vdash k_1}\ \text{Axiom}}{M \vdash \langle a, m_1 \rangle}\ \text{DecSym}}{M \vdash m_1}\ \text{Proj}_2 \qquad \dfrac{}{M \vdash m_2}\ \text{Axiom}}{M \vdash \langle m_1, m_2 \rangle}\ \text{Cat}$$

Dolev-Yao Closure: Asymmetric Crypto

Asymmetric Cryptography

$$\frac{M \vdash m \quad M \vdash k}{M \vdash \{m\}_k}\ (\text{EncAsym}) \qquad \frac{M \vdash \{m\}_k \quad M \vdash \text{inv}(k)}{M \vdash m}\ (\text{DecAsym})$$

- The intruder can encrypt any message m he knows with any public key k he knows.
- The intruder can decrypt any message $\{m\}_k$ if he knows the private key $\text{inv}(k)$ to the public key k.

Example

$$M = \{\, k_1, \text{inv}(k_1), k_2, \{m_1\}_{k_1}, m_2, \{m_3\}_{k_2} \,\}$$

$$\dfrac{\dfrac{}{M \vdash \{m_1\}_{k_1}}\ \text{Axiom} \quad \dfrac{}{M \vdash \text{inv}(k_1)}\ \text{Axiom}}{M \vdash m_1}\ \text{DecAsym}$$

Note: $M \nvdash m_3$

Dolev-Yao Closure: Signatures

Signatures

$$\frac{M \vdash m \quad M \vdash \mathrm{inv}(k)}{M \vdash \{m\}_{\mathrm{inv}(k)}}\ (\mathrm{Sign}) \qquad \frac{M \vdash \{m\}_{\mathrm{inv}(k)}}{M \vdash m}\ (\mathrm{OpenSig})$$

- The intruder can sign any message m he knows with any private key $\mathrm{inv}(k)$ he knows.
- The intruder can open any message $\{m\}_{\mathrm{inv}(k)}$ that was signed with a private key $\mathrm{inv}(k)$.

Example

$$M = \{\, k_1, \mathrm{inv}(k_1), k_2, \{m_1\}_{\mathrm{inv}(k_2)}, m_2 \,\}$$

$$\dfrac{\dfrac{\dfrac{}{M \vdash \{m_1\}_{\mathrm{inv}(k_2)}}\ \mathrm{Axiom}}{M \vdash m_1}\ \mathrm{OpenSig} \qquad \dfrac{}{M \vdash \mathrm{inv}(k_1)}\ \mathrm{Axiom}}{M \vdash \{m_1\}_{\mathrm{inv}(k_1)}}\ \mathrm{Sign}$$

Dolev-Yao Closure: Public Functions

Public Functions

$$\frac{M \vdash m_1 \quad \ldots \quad M \vdash m_n}{M \vdash f(m_1, \ldots, m_n)} \text{ if } f \in \Sigma_p \text{ takes } n \text{ arguments} \quad \text{(Compose)}$$

- The intruder can apply any public function f to terms t_i that he knows.

Example

$$M = \{ k_1, k_2, \{\!|m_1|\!\}_{kdf(k_1,k_2)} \} \text{ where } kdf \text{ is public}$$

$$\dfrac{\dfrac{}{M \vdash \{\!|m_1|\!\}_{kdf(k_1,k_2)}}\ \text{Axiom} \quad \dfrac{\dfrac{}{M \vdash k_1}\ \text{Axiom} \quad \dfrac{}{M \vdash k_2}\ \text{Axiom}}{M \vdash kdf(k_1, k_2)}\ \text{Compose}}{M \vdash m_1}\ \text{DecSym}$$

Note: the rules EncSym, EncAsym, and Cat are just special cases of Compose.

Dolev-Yao Closure: Summary

Dolev-Yao rules

$$\frac{}{M \vdash m} \text{ if } m \in M \text{ (Axiom)}$$

$$\frac{M \vdash m_1 \quad \ldots \quad M \vdash m_n}{M \vdash f(m_1, \ldots, m_n)} \text{ if } f/n \in \Sigma_p \text{ (Compose)}$$

$$\frac{M \vdash \langle m_1, m_2 \rangle}{M \vdash m_i} \text{ (Proj}_i\text{)} \qquad \frac{M \vdash \{\!|m|\!\}_k \quad M \vdash k}{M \vdash m} \text{ (DecSym)}$$

$$\frac{M \vdash \{m\}_k \quad M \vdash \text{inv}(k)}{M \vdash m} \text{ (DecAsym)} \qquad \frac{M \vdash \{m\}_{\text{inv}(k)}}{M \vdash m} \text{ (OpenSig)}$$

The compose rule is for all public functions Σ_p, including $\{\!|\cdot|\!\}$. $\{\cdot\}$. $\langle \cdot, \cdot \rangle$

Example: Intruder Deduction

Example

$M = \{\ a, b, i, \mathsf{pk}(a), \mathsf{pk}(b), \mathsf{pk}(i), \mathsf{inv}(\mathsf{pk}(i)), \{\langle na, a\rangle\}_{\mathsf{pk}(i)}\}$

Can the intruder derive $\{\langle na, a\rangle\}_{\mathsf{pk}(b)}$?

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Overview

Needham-Schroeder Public-Key Protocol [1978]

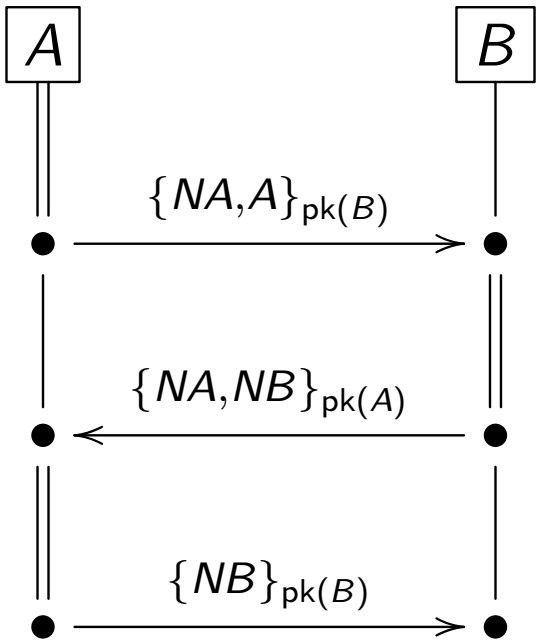
```
Protocol: NSPK

Types: Agent A,B;
       Number NA,NB;
       Function pk,h

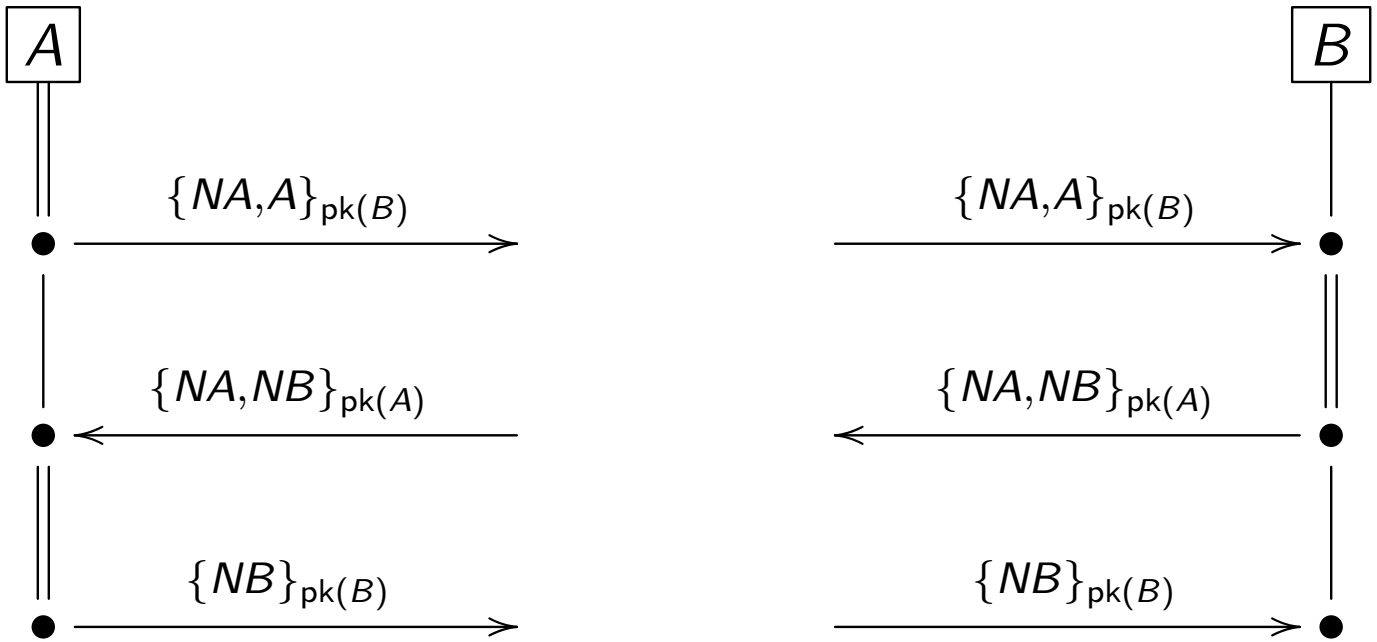
Knowledge: A: A,pk(A),inv(pk(A)),B,pk(B),h;
           B: B,pk(B),inv(pk(B)),A,pk(A),h
Actions:
A->B: {NA,A}(pk(B))   # A generates NA
B->A: {NA,NB}(pk(A))  # B generates NB
A->B: {NB}(pk(B))

Goals:
h(NA,NB) secret between A,B
```

NSPK as A Message Sequence Chart

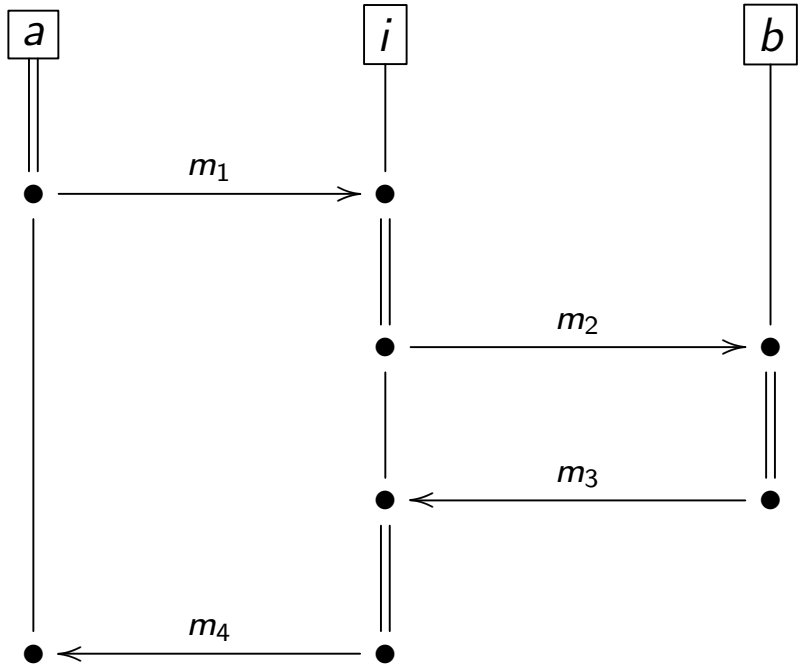


NSPK as Roles / Strands



- For each Role of the protocol, a program that sends and receives messages (over possibly insecure network)
- Strand: concrete execution of a role: all variables (here A, B, NA, NB) instantiated with concrete values
  - ★ or a prefix thereof (an agent might not finish)

Attacks

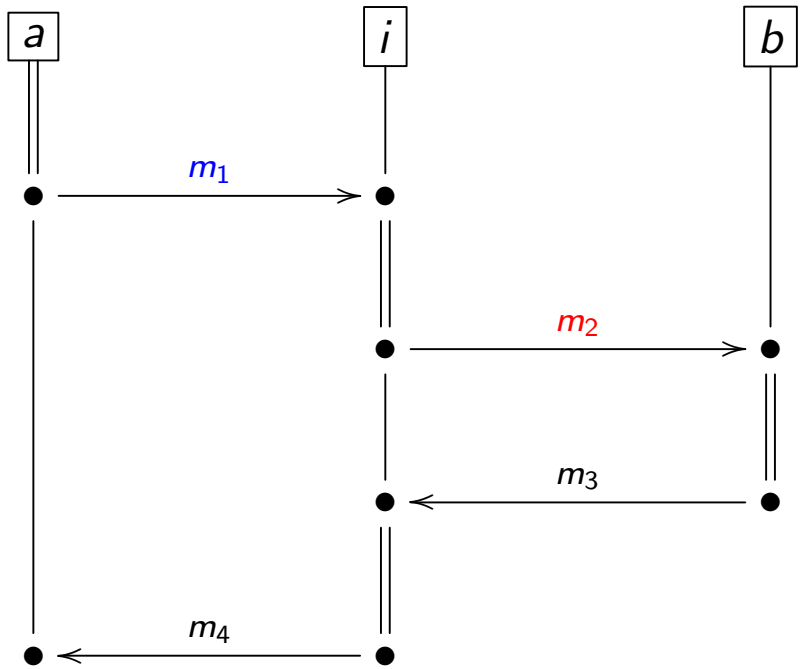


An attack is a strand space where the following conditions are met:

- Messages sent by honest agents are received by i
- Messages received by honest agents are sent by i who can compose the message from the messages he has received so far.

- The successful completion violates a goal of the protocol.

Attacks



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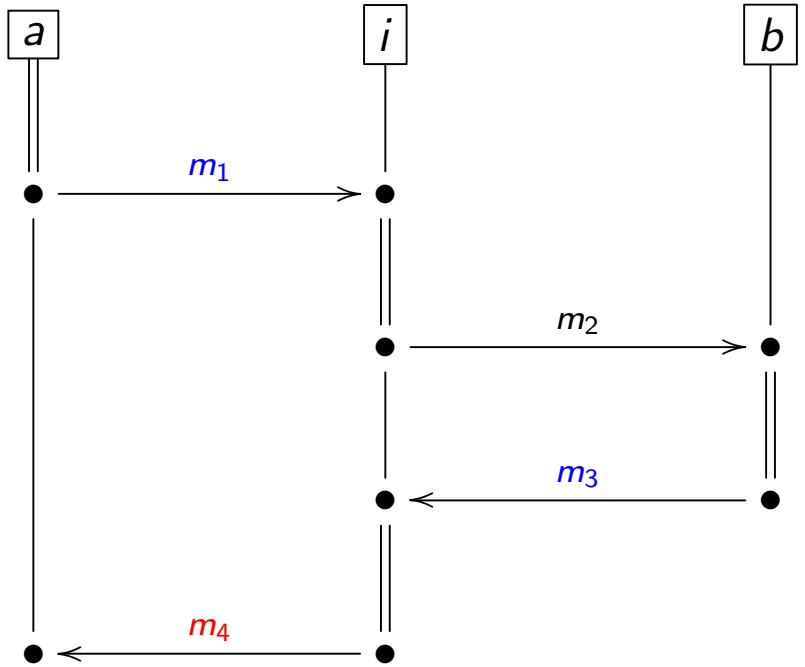

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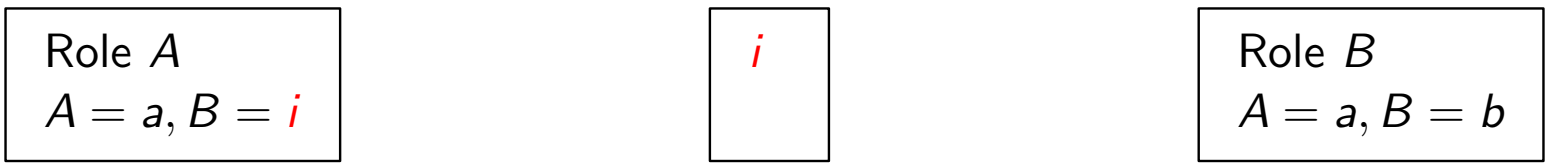
- Messages sent by honest agents are received by i
- Messages received by honest agents are sent by i who can compose the message from the messages he has received so far.
  - ★ In the example: $\{m_1\} \vdash m_2$ and $\{m_1, m_3\} \vdash m_4$.
- The successful completion violates a goal of the protocol.

An Attack on NSPK [Lowe 1996]

Protocol roles like A and B can be instantiated arbitrarily by honest agents like a and b, as well as by the dishonest i (intruder).



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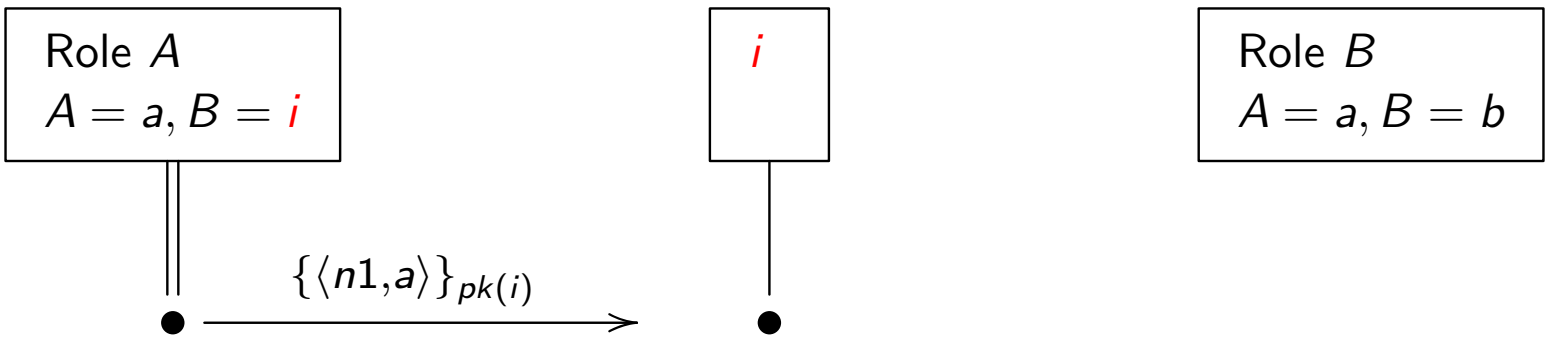

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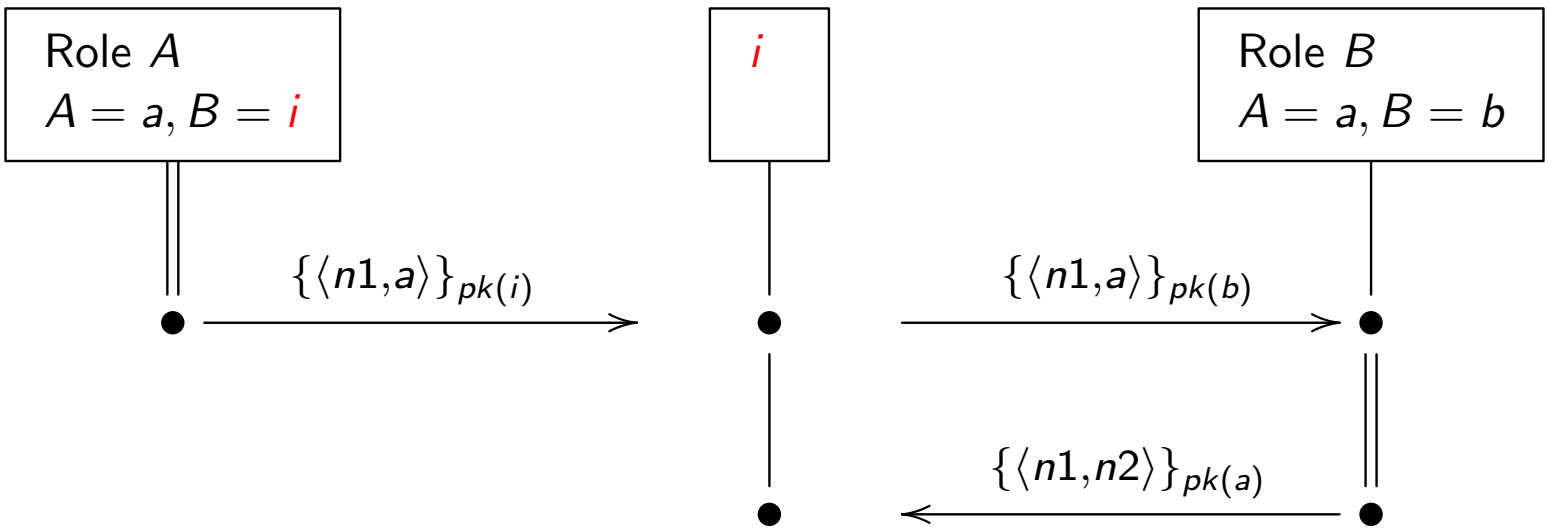

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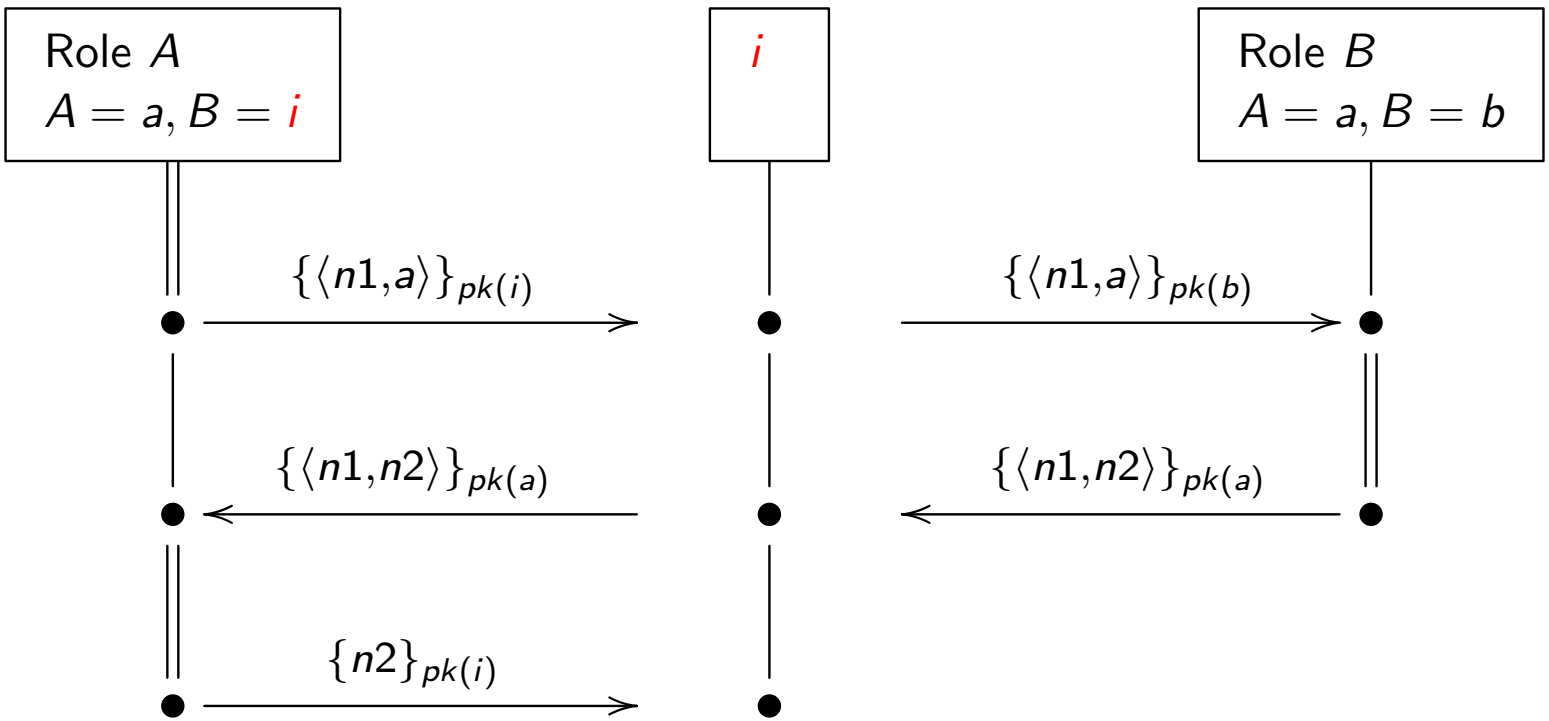

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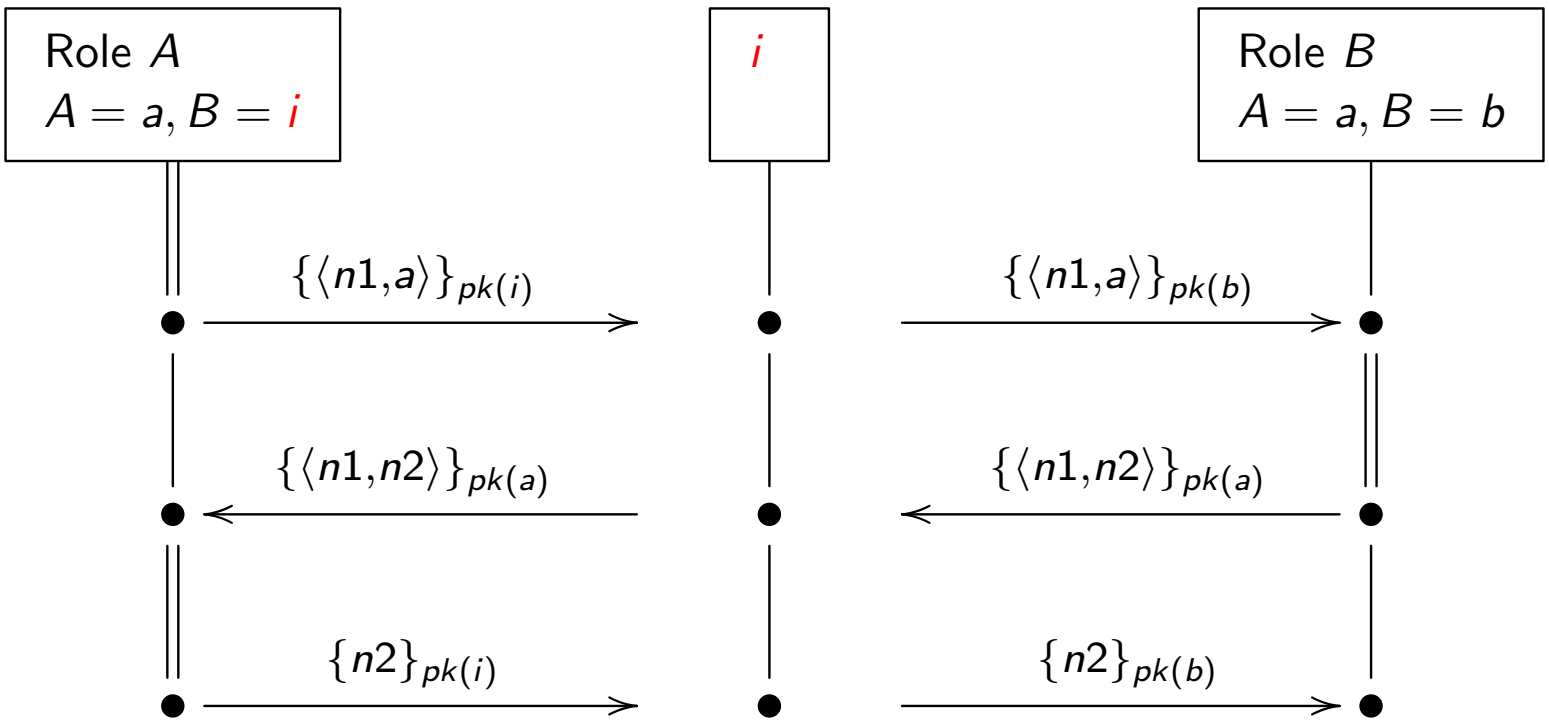

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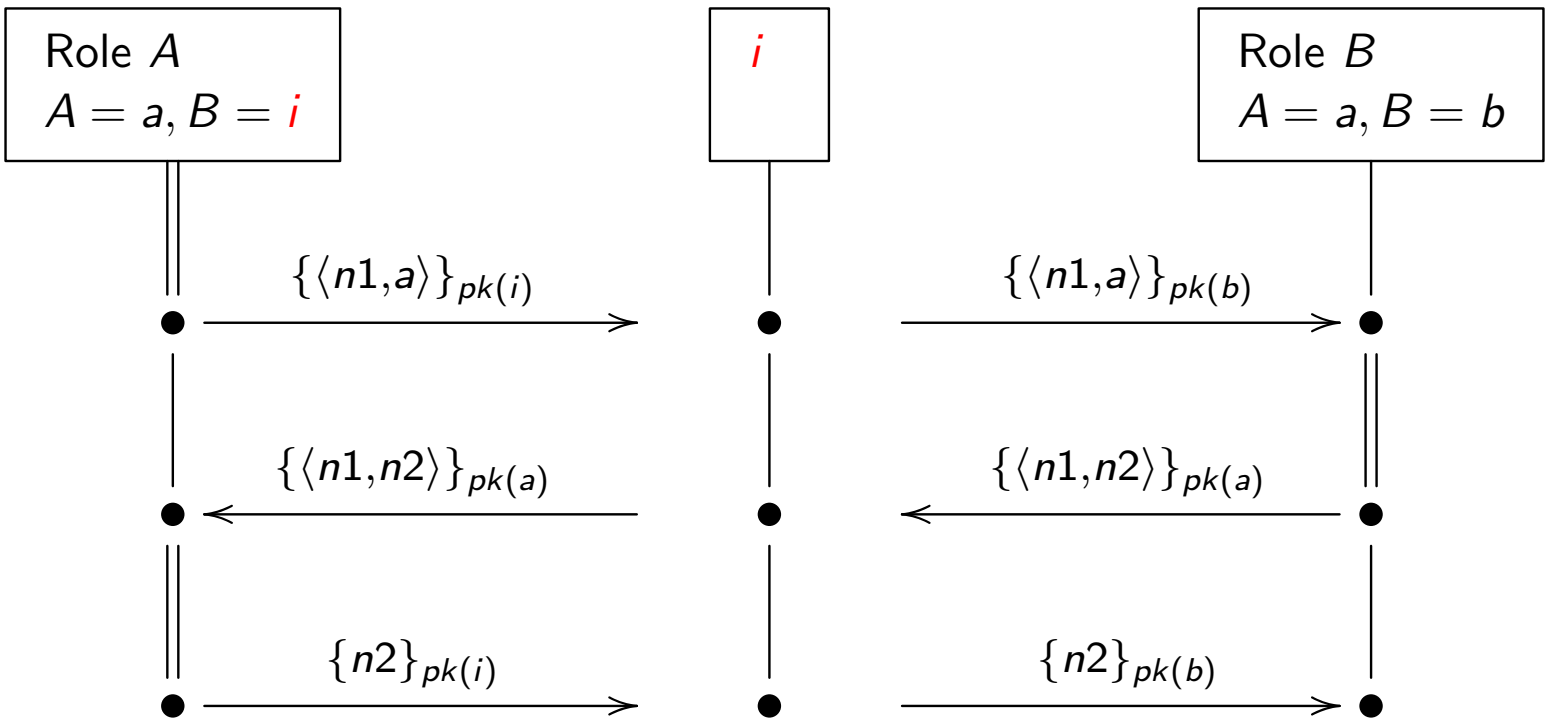
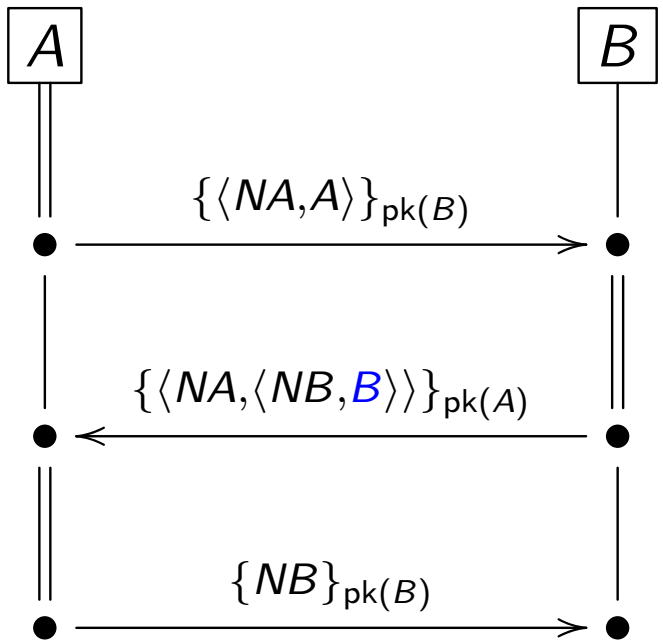


What went wrong?

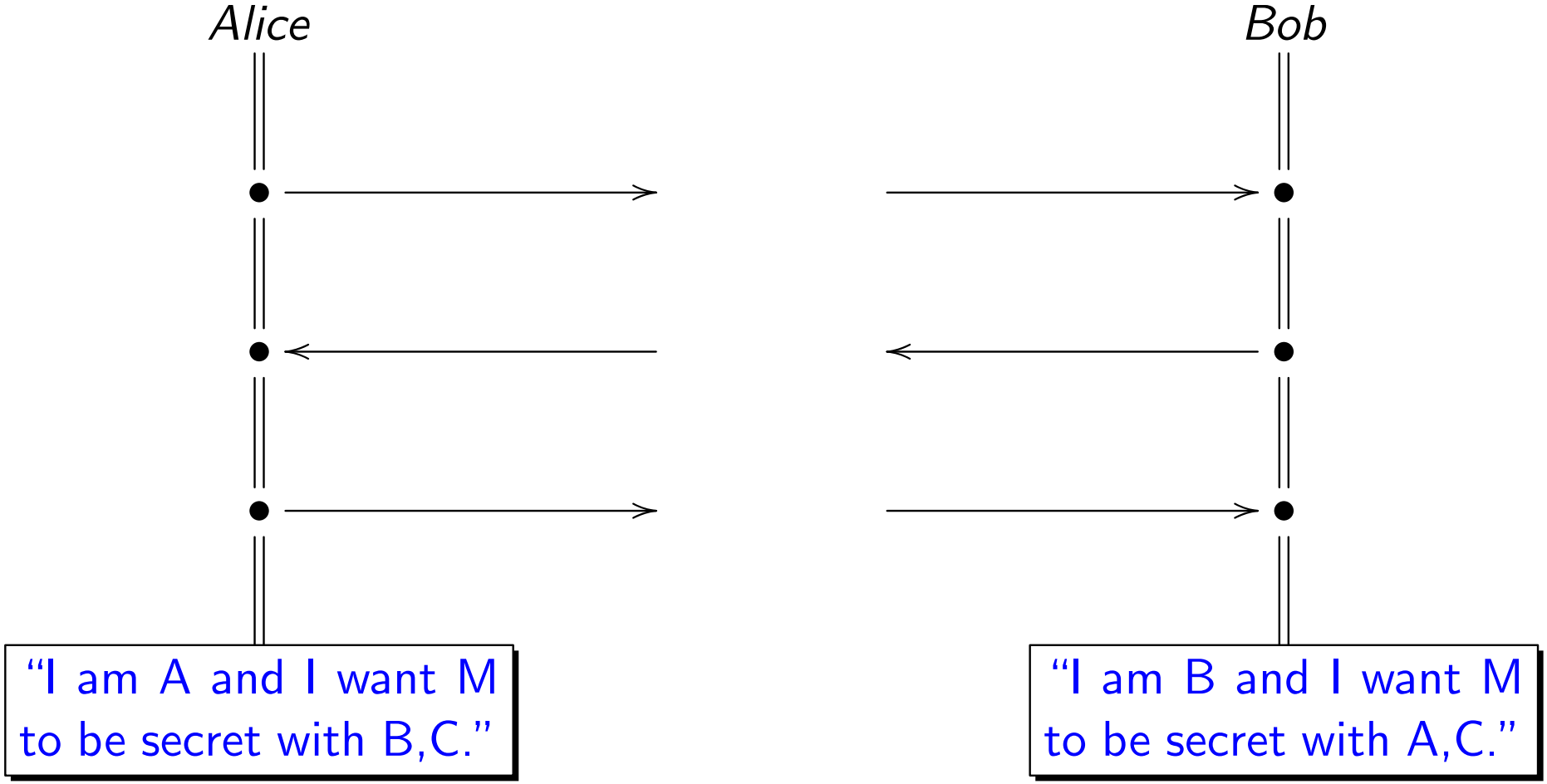
Nothing in the message $\{n1, n2\}_{\mathsf{pk}(a)}$ says who created it.

Needham-Schroeder Public Key protocol with Lowe's Fix (NSL) (Lowe, 1996)



- At least the previous attack is no longer possible anymore.
- Is the protocol now secure?

Secrecy: `M secret between A,B,C`



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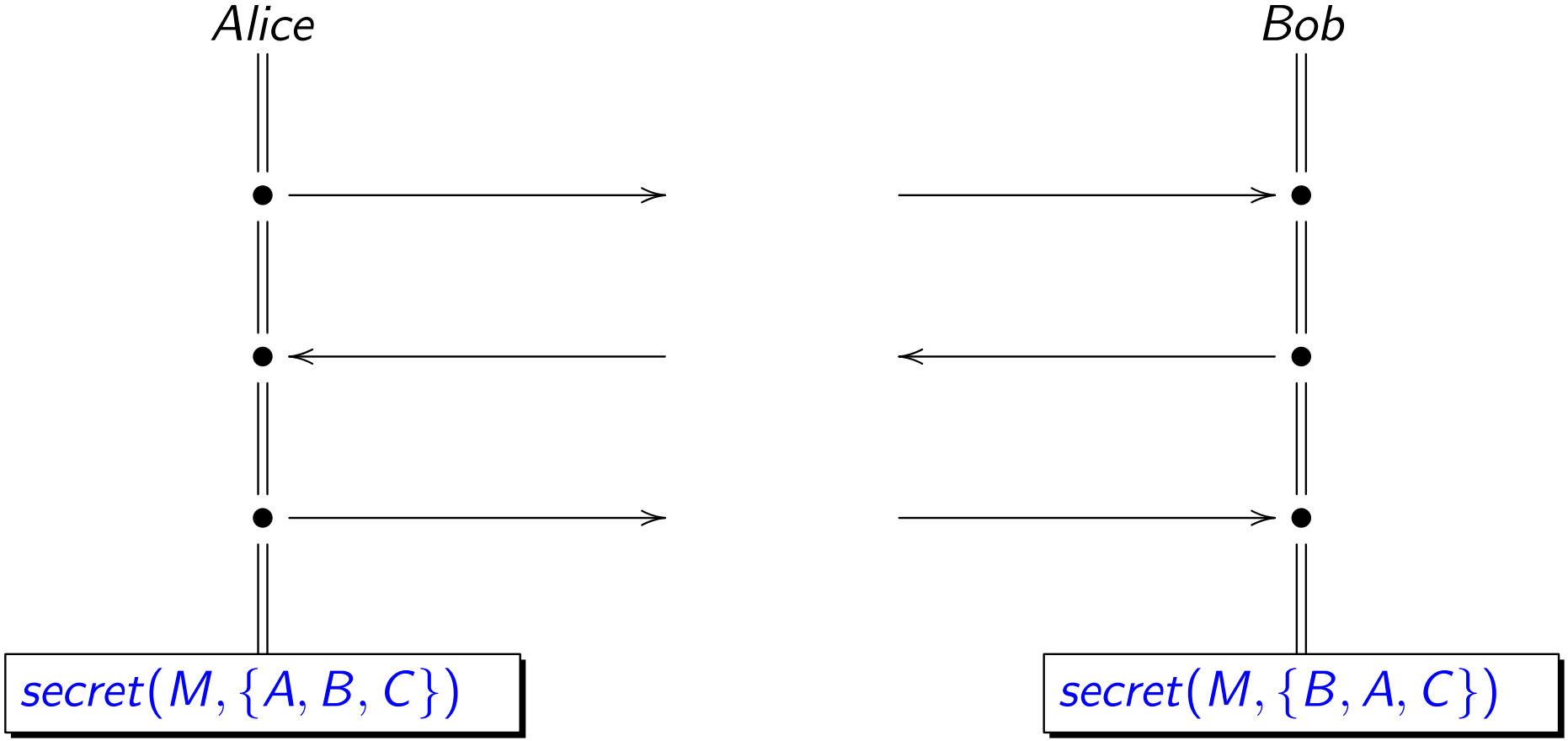
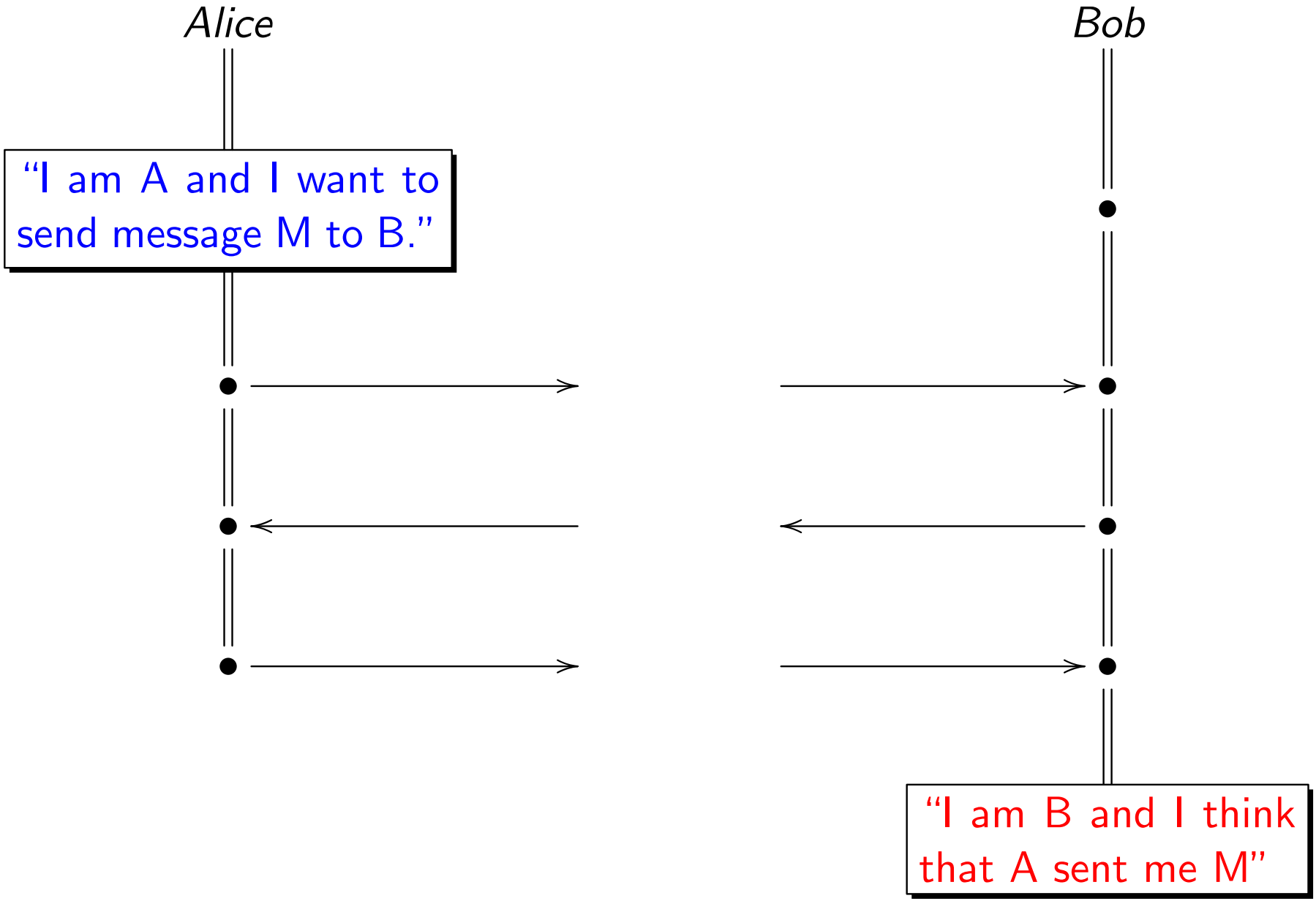


Attack: secret(M,Set), intruder knows M and is not a member of the Set.

Formalization: Weak Authentication



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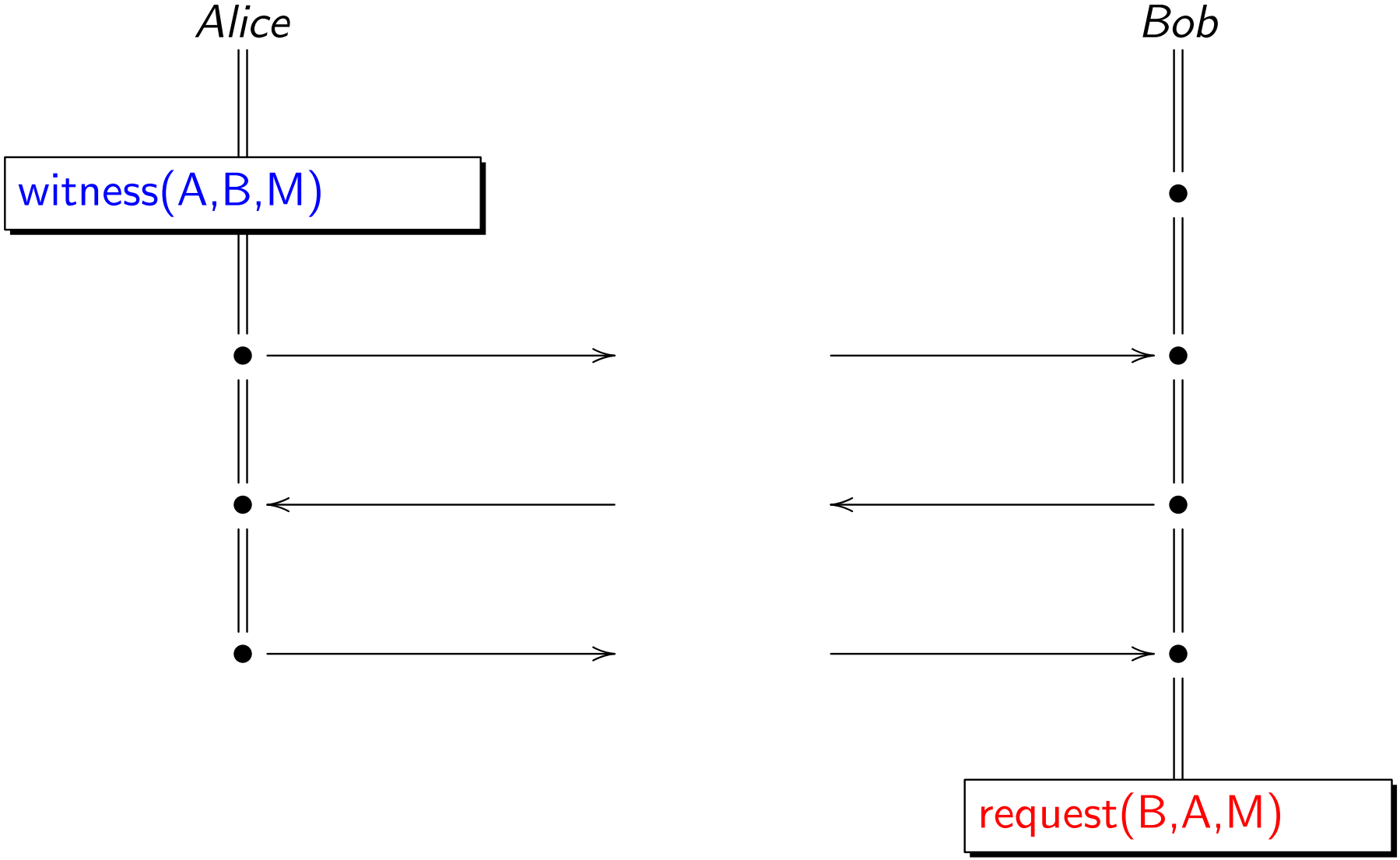

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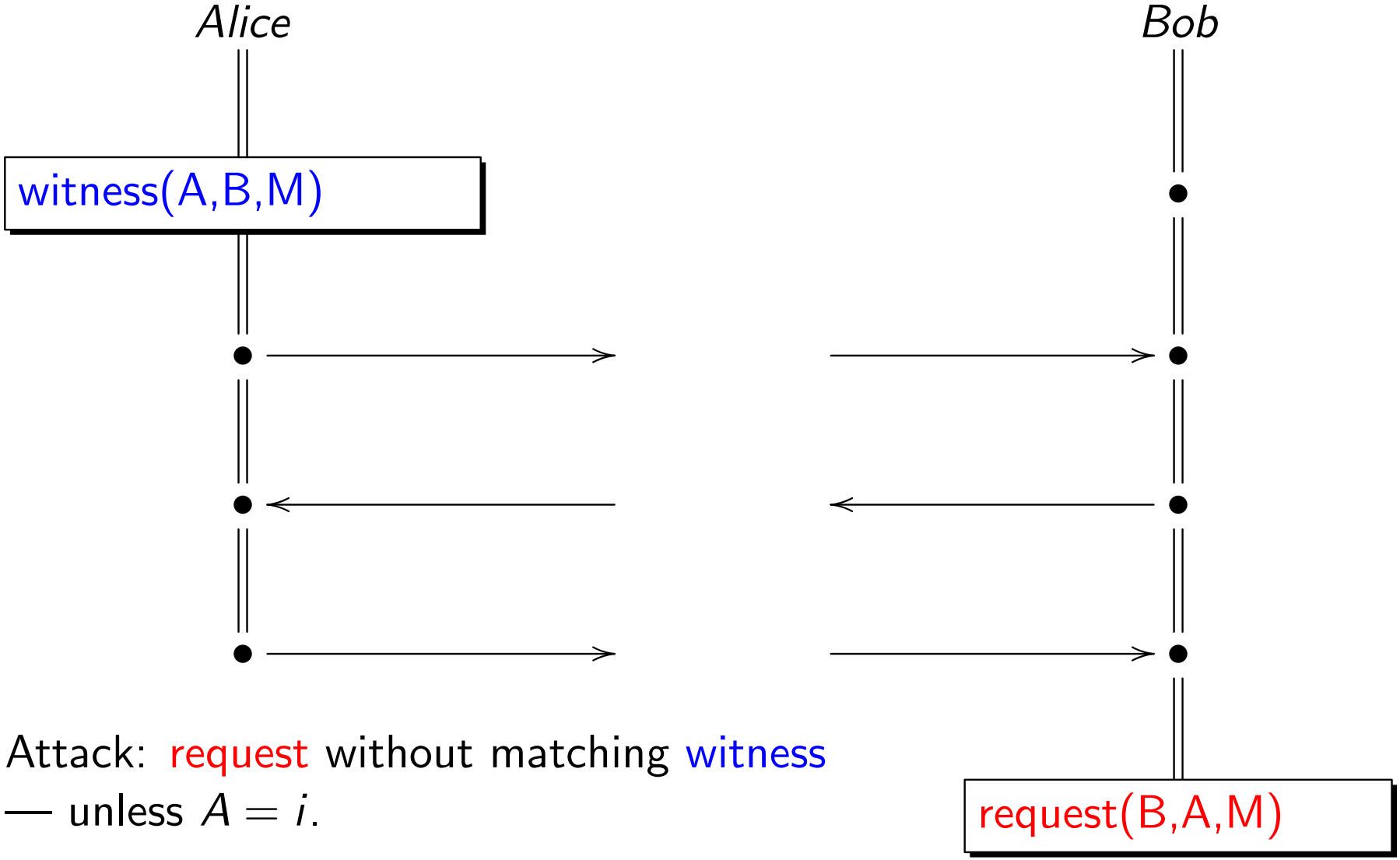
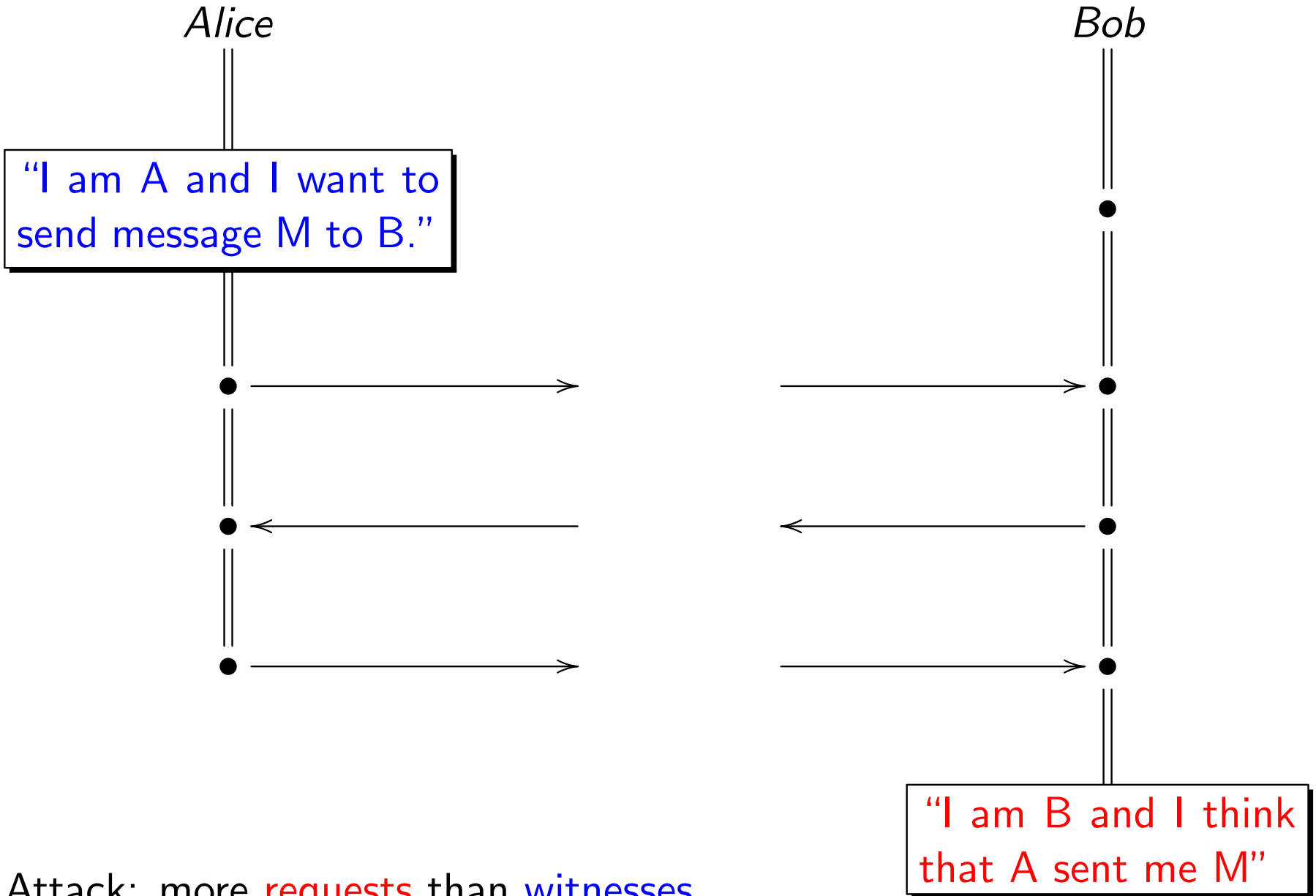


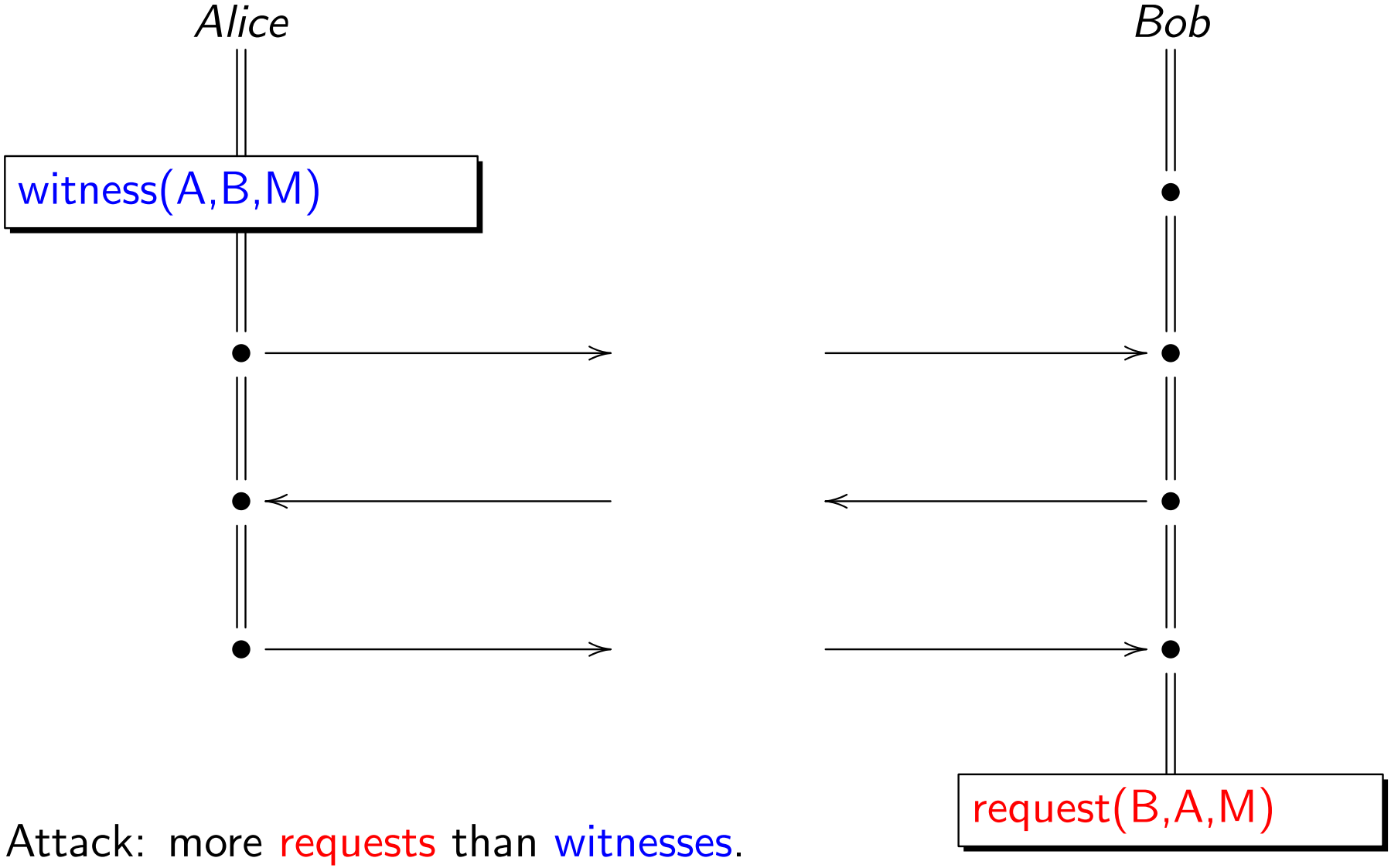
Attack: request without matching witness
— unless $A = i$.

Formalization: Strong Authentication



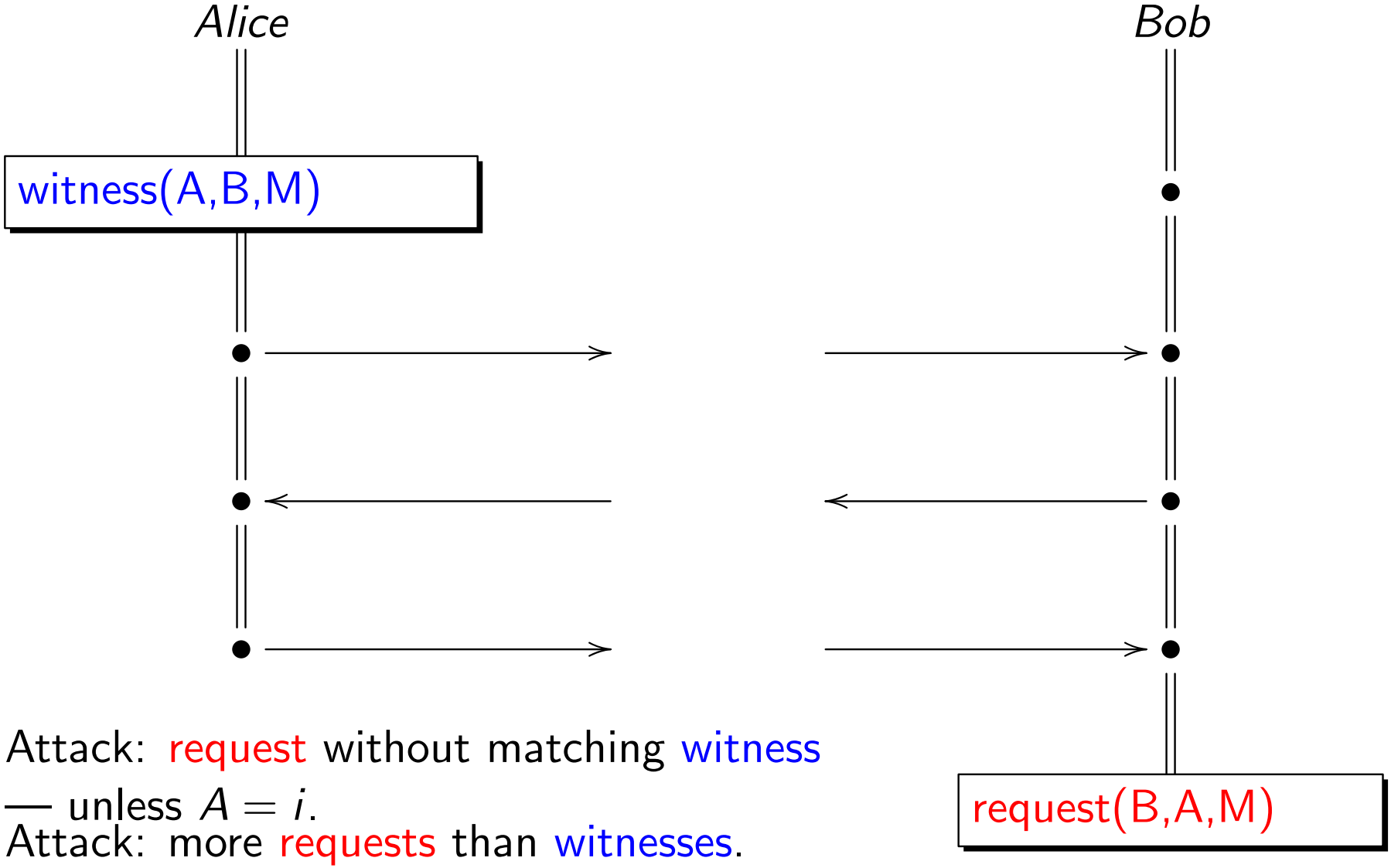
Attack: more requests than witnesses.

Formalization: Strong Authentication



Attack: more requests than witnesses.

Formalization: Strong Authentication



Attack: request without matching witness
— unless $A = i$.
Attack: more requests than witnesses.

Capture the Flag!

Capture the Flag with AnB/OFMC

ctf here works as follows:

- Given: an AnB file on which OFMC finds an attack
- You obtain the flag if you upload an AnB file that
  - ★ has the same `Knowledge` section
  - ★ the same `Goal` section
  - ★ it only augments the `Types` section
  - ★ OFMC does not find an attack within two sessions in the untyped model
- Thus what you can change in the AnB file is:
  - ★ The name of the protocol (but that's irrelevant)
  - ★ You can introduce further numbers, keys, ... in the `Types` section
  - ★ You can arbitrarily change the message exchange in the `Actions` section

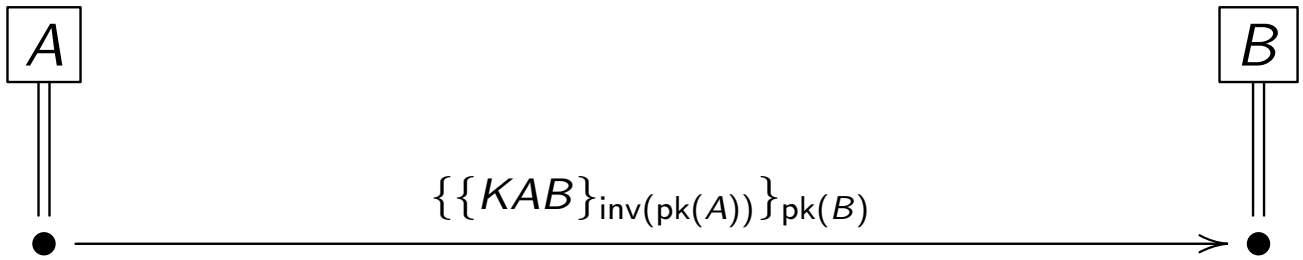
Capture the Flag!

The slides up to this point are sufficient for solving the following challenges:

- ctf1.AnB
- ctf2.AnB
- ctf3.AnB

Overview

A Common Mistake...



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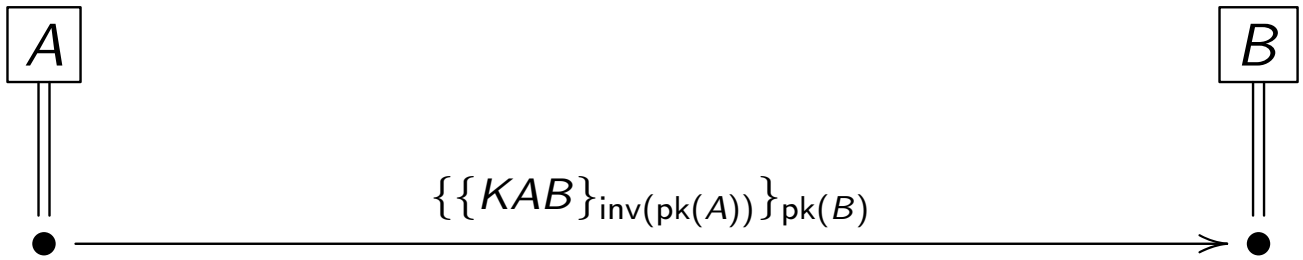
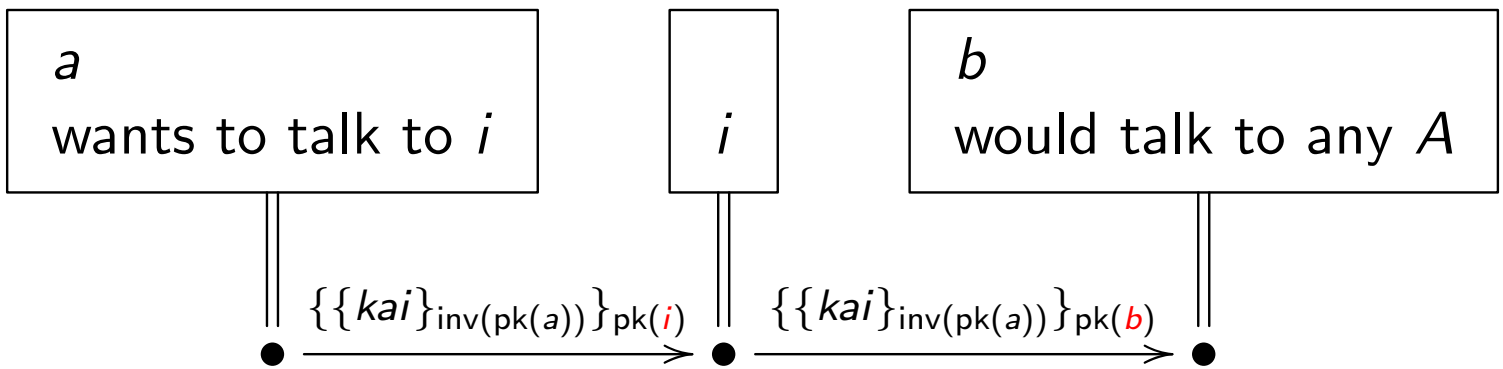


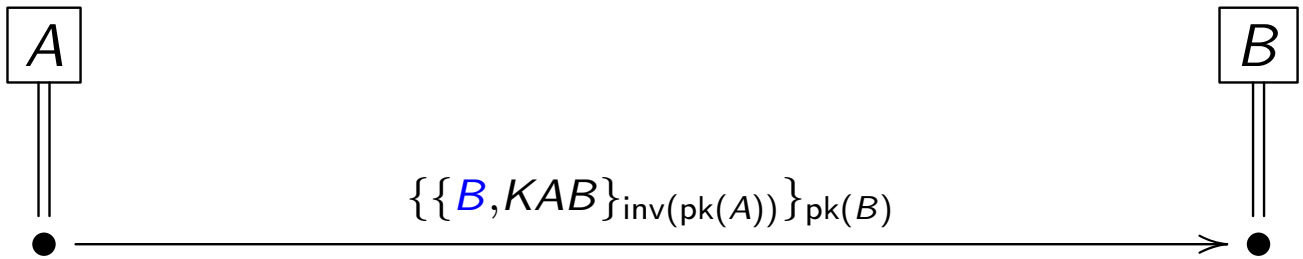
Attack:



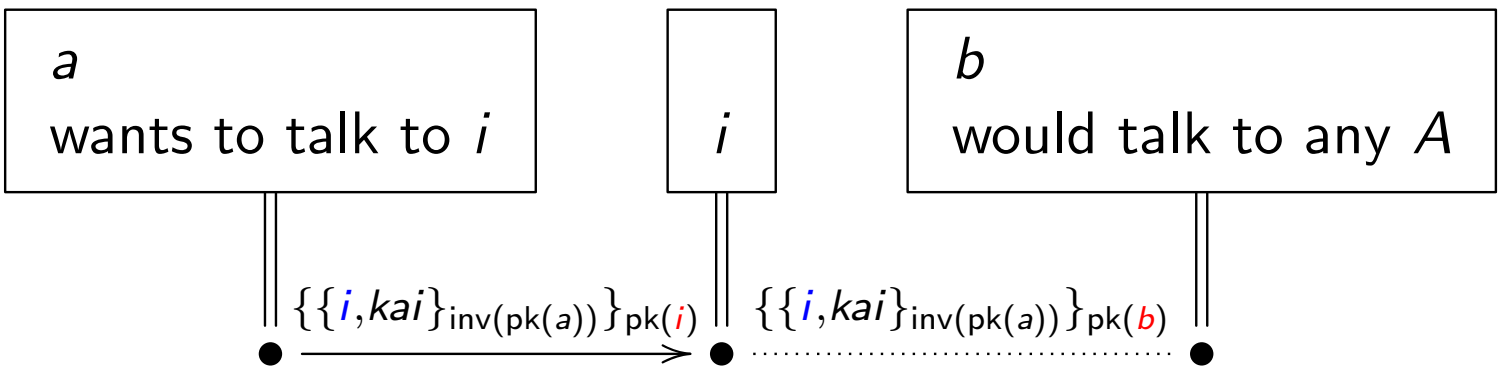
- a thinks: *kai* is a secure session key with *i* ✓
- b thinks: *kai* is a secure session key with *a* ✗
  - ★ the intruder knows *kai* and *a* may not even know *b*.

A Common Mistake...

Include the name of the intended recipient in the signature:



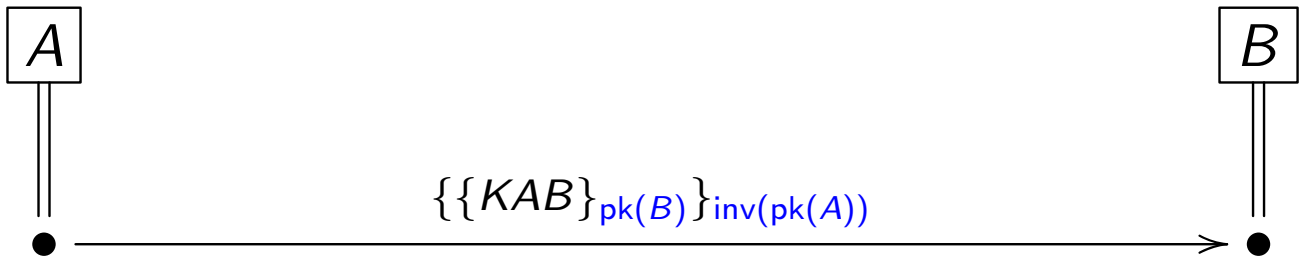
The attack does not work anymore:



- Always be clear what the messages mean!

An Alternative Solution

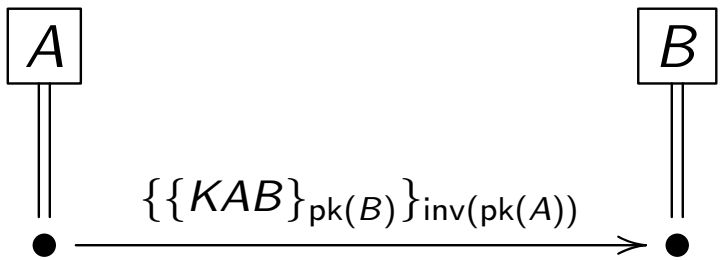
What about first encrypting and then signing?

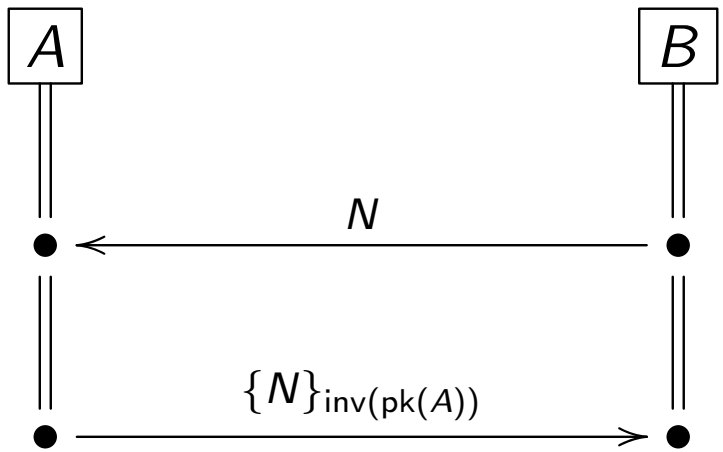


- Indeed, this also prevents the attack.[1]
- This violates, however, a common recommendation:
  - ★ Do not design protocols where users must sign encrypted data.
  - ★ Why not?

[1] Actually, OFMC by default uses the property that $\{\{M\}_K\}_{inv(K)} = M$ so for $A = B$, there is an attack... but let's forget that property for now.

Mind the Environment

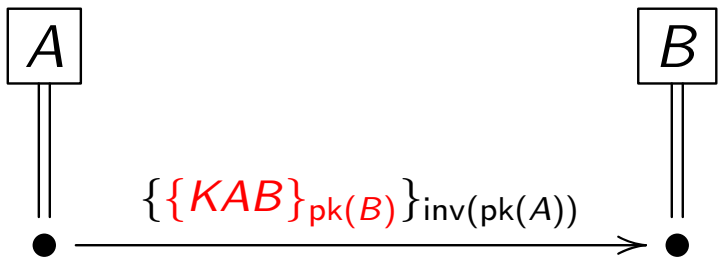


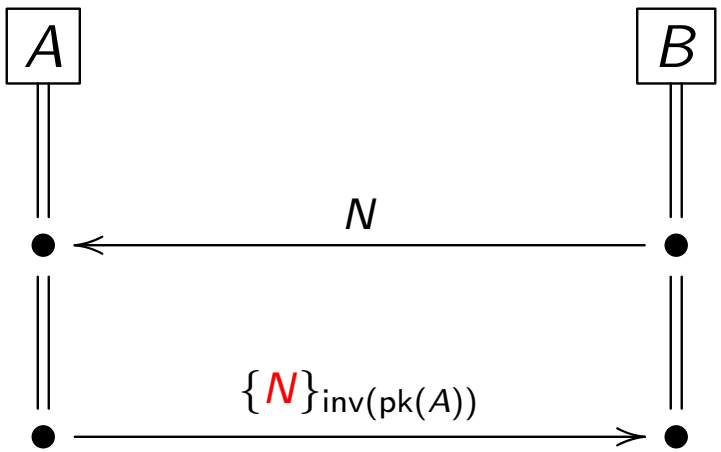


Terrible protocol design:

- while each of these protocols is secure in isolation

Mind the Environment

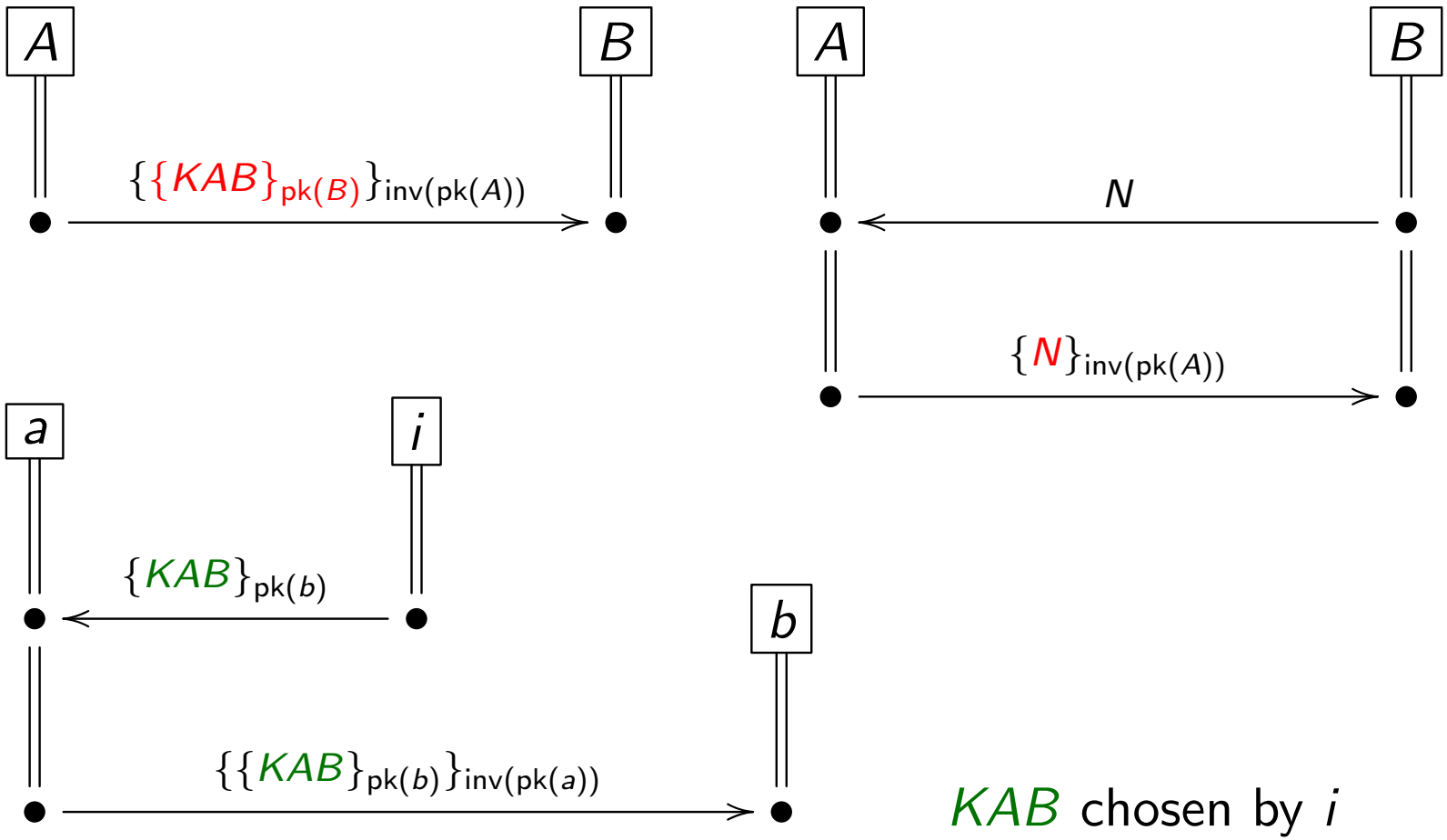




Terrible protocol design:

- while each of these protocols is secure in isolation
- together they break because the signed messages don't say what they mean...

Mind the Environment



KAB chosen by *i*

Attack/Confusion: *a* runs right protocol, *b* runs left protocol.
This is called a type flaw attack.

Classics: Otway-Rees [1987]

```
A->B:  M,A,B,{|NA,M,A,B|}sk(A,s)
B->s:  M,A,B,{|NA,M,A,B|}sk(A,s),
                {|NB,M,A,B|}sk(B,s)
s->B:  M,A,B,{|NA,KAB|}sk(A,s),
                {|NB,KAB|}sk(B,s)
B->A:  M,A,B,{|NA,KAB|}sk(A,s)
```

- Actually secure in default typed mode.
- Use option `--untyped` to get an attack (or remove type declaration for KAB):

```
ATTACK TRACE:
(x401,1) -> i: M(1),x401,x25,{|NA(1),M(1),x401,x25|}_(sk(x401,s))
i -> (x401,1): M(1),x401,x25,{|NA(1),M(1),x401,x25|}_(sk(x401,s))
```

The Problem

$$M, A, B, \{|NA, M, A, B|\}_{\mathsf{sk}(A,s)}$$
$$\ldots$$
$$M, A, B, \{|NA, \ KAB \ \ |\}_{\mathsf{sk}(A,s)}$$

- Suppose that in the implementation, the structure M, A, B has the same length in bits as KAB
- i can replay the former message in place of the latter

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- i can replay the former message in place of the latter
  - ★ the recipient will accept M, A, B as the new session key.
  - ★ M, A, B is known to the intruder.
- Designers must make message formats sufficiently different whenever they mean something different!
- Actually, most implementations will use more than just string concatenation to structure messages.

Structuring Messages

Real-world Example: TLS 1.3 Handshake

```
enum { client_hello(1),
       server_hello(2),
       new_session_ticket(4),
       ...
} HandshakeType;

struct {
  HandshakeType msg_type;    /* handshake type */
  uint24 length;             /* remaining bytes in message */
  select (Handshake.msg_type) {
    case client_hello:          ClientHello;
    case server_hello:          ServerHello;
    ...
  };
} Handshake;

uint16 ProtocolVersion;
opaque Random[32];
uint8 CipherSuite[2];    /* Cryptographic suite selector */

struct {
  ProtocolVersion legacy_version = 0x0303;    /* TLS v1.2 */
  Random random;
  opaque legacy_session_id<0..32>;
  CipherSuite cipher_suites<2..2^16-2>;
  opaque legacy_compression_methods<1..2^8-1>;
  Extension extensions<8..2^16-1>;
} ClientHello;
```

Structuring Messages

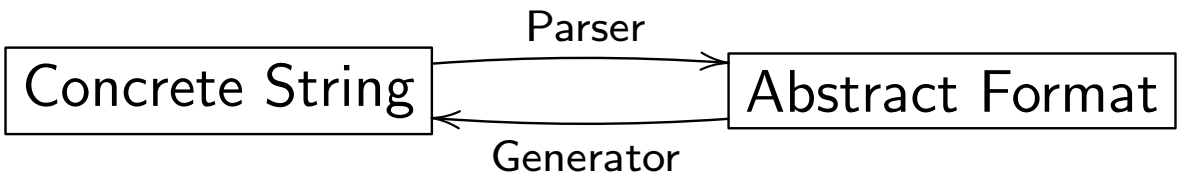
Concrete syntax of message formats, e.g.:

- Record data types (like TLS)
- XML
- JSON
- ...

Abstract syntax of message formats:

- A new function symbol for each message format, e.g. $client\_hello(random, cipher\_suites, extensions)$
- The arguments are simply messages (can be random numbers, agent names, encrypted messages,...)
- The function symbol represents abstractly that there is some concrete way to structure the data.

Concrete and Abstract syntax connected by a parser and a generator:



Crypto API

For concrete implementations, we assume a crypto-library:

- `String scrypt(String key, String msg)`
  implements a symmetric encryption (like AES)
- `String dscrypt(String key, String cipher)`
  implements the corresponding decryption algorithm
  will fail if `cipher` is not the result of an encryption with `key`.
- Similar functions for other cryptographic primitives.

We expect that $\texttt{dscrypt}(\texttt{k}, \texttt{scrypt}(\texttt{k}, \texttt{m})) = \texttt{m}$.

Cryptographic soundness results:

- Roughly: by cryptanalysis the intruder cannot achieve anything that he could not achieve by calls of the crypto-API.
- Can be shown under some restrictions and hardness assumptions e.g. [Abadi & Rogaway] [Backes et al.]

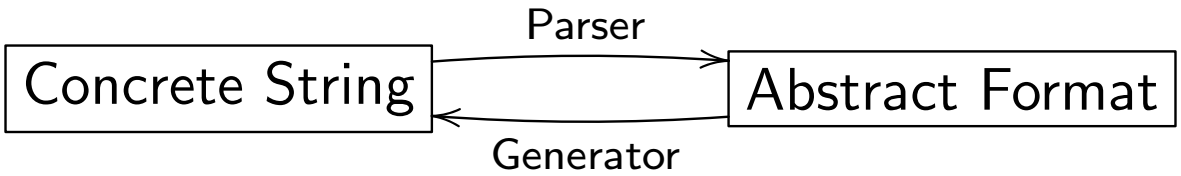
Non-Crypto API

Similarly, we assume a non-crypto-library:
For every format $f(t_1, \ldots, t_n)$:

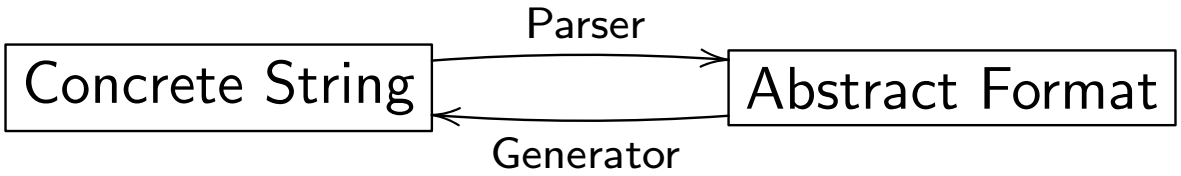
- A corresponding data-type `F` that has fields for $t_1, \ldots, t_n$
- `F parseF(String s)` that tries to parse the given string for this format and return a corresponding data structure.
- `String generate(F form)` that generates a string from the given data structure.

We expect that

- $\texttt{parseF}(\texttt{generate}(\texttt{form})) = \texttt{form}$
  for every object `form` of datatype `F`
- $\texttt{generate}(\texttt{parseF}(\texttt{s})) = \texttt{s}$
  for every string `s` where `parseF(s)` does not fail.



Soundness



Desirable properties:

- Unambiguous: For a concrete string there is at most one way to parse it for a format.
- Disjointness: No string can be parsed for more than one format.

A soundness result for the non-crypto API [M.&Katsoris]:

- Similar to the result for soundness of the crypto API
- Roughly: by string manipulation the intruder cannot achieve anything that he could not achieve by calls of the non-crypto-API.
- Requires that formats are unambiguous and pairwise disjoint, and soundness of crypto.

Formats for Otway Rees

Consider again the Otway-Rees protocol – without the cleartext messages for simplicity:

```
A->B: {|NA,M,A,B|}sk(A,s)
B->s: {|NA,M,A,B|}sk(A,s),
      {|NB,M,A,B|}sk(B,s)
s->B: {|NA,KAB|}sk(A,s),
      {|NB,KAB|}sk(B,s)
B->A: {|NA,KAB|}sk(A,s)
```

Uses two different message formats:

- NA, M, A, B of type number,number,agent,agent.
- NA, KAB of type nonce,symkey.

We could define two data-formats for this:

- f1(N, M, A, B) with four arguments
- f2(N, K) with two arguments

Formats for Otway Rees

```
A->B: {|f1(NA,M,A,B)|}sk(A,s)
B->s: {|f1(NA,M,A,B)|}sk(A,s),
      {|f1(NB,M,A,B)|}sk(B,s)
s->B: {|f2(NA,KAB)|}sk(A,s),
      {|f2(NB,KAB)|}sk(B,s)
B->A: {|f2(NA,KAB)|}sk(A,s)
```

Notes:

- The intruder can construct and deconstruct `f1` and `f2` like concatenations.

Formats in OFMC

```
Types: Format f1,f2;
       ...
Knowledge: A: A,B,sk(A,s);
           B: B,A,sk(B,s);
           s: A,B,sk(A,s),sk(B,s)
Actions:
A->B: M,A,B,{|f1(NA,M,A,B)|}sk(A,s)
B->s: M,A,B,{|f1(NA,M,A,B)|}sk(A,s),{|f1(NB,M,A,B)|}sk(B,s)
s->B: M,{|f2(NA,KAB)|}sk(A,s),{|f2(NB,KAB)|}sk(B,s)
B->A: M,{|f2(NA,KAB)|}sk(A,s)
Goals:...
```

- Formats are automatically in the knowledge of every agent, thus also the intruder can apply them.
- Formats are transparent: if the intruder knows `f1(NB,M,A,B)` then also `NB,M,A,B`.

Formats for Otway Rees

```
A->B: {|f1(NA,M,A,B)|}sk(A,s)
B->s: {|f1(NA,M,A,B)|}sk(A,s),
      {|f1(NB,M,A,B)|}sk(B,s)
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```

Does using formats prevent all type-flaw attacks on Otway-Rees?

Formats for Otway Rees

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A->B: {|f1(NA,M,A,B)|}sk(A,s)
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Does using formats prevent all type-flaw attacks on Otway-Rees?

- The intruder can still construct and send messages like
  `{| f1(a,b,i,b) |}sk(i,s)`
- This message is called ill-typed because it contains agents where numbers are expected
- It would actually still be accepted by the server.

Formats for Otway Rees

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A->B: {|f1(NA,M,A,B)|}sk(A,s)
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- The intruder can still construct and send messages like `{| f1(a,b,i,b) |}sk(i,s)`
- This message is called ill-typed because it contains agents where numbers are expected
- It would actually still be accepted by the server.
- Idea: the intruder cannot really exploit this, because nobody would accidentally read this as an `f2` message for instance.

Message Patterns

- We now give a result for protocols that are resistant to type flaws – a notion we need to define.
- For that, we first define what sub-message patterns are.

Definition (Sub-Message-Patterns)

The sub-message patterns $SMP(P)$ of a protocol P are the least set

- that contains all the protocol messages
- for every message $f(t_1, \ldots, t_n) \in SMP(P)$ also the sub-messages $t_1, \ldots, t_n$ are in $SMP(P)$.
- for every message of the form $\{m\}_k \in SMP(P)$ also $\mathrm{inv}(k) \in SMP(P)$.

For simplicity, every pair m_1, m_2 can directly be considered as two messages m_1 and m_2.
Finally, rename all variables such that every two distinct messages $s, t \in SMP(P)$ have no variables in common.

Example: Otway-Rees

Messages of the protocol:

```
M,A,B,{|f1(NA,M,A,B)|}sk(A,s),
M,A,B,{|f1(NA,M,A,B)|}sk(A,s),
{|f1(NB,M,A,B)|}sk(B,s),
M,{|f2(NA,KAB)|}sk(A,s),{|f2(NB,KAB)|}sk(B,s),
M,{|f2(NA,KAB)|}sk(A,s)
```

Subterms:

```
f1(NA,M,A,B)
f2(NA,KAB)
sk(A,s),NA,M,A,B
```

Example: Otway-Rees

Renaming (and removing duplicates)

$SMP(Otway - Rees) = \{$

```
M_1,A_1,B_1,
{|f1(NA_2,M_2,A_2,B_2)|}sk(A_2,s),
{|f1(NB_3,M_3,A_3,B_3)|}sk(B_3,s),
{|f2(NA_4,KAB_4)|}sk(A_4,s),
{|f2(NB_5,KAB_5)|}sk(B_5,s),
f1(NA_6,M_6,A_6,B_6)
f2(NA_7,KAB_7)
sk(A_8,s),
NA_9
```

$\}$.

Type-Flaw Resistance

Type-Flaw Resistance

A protocol is called type-flaw resistant if the following holds:

- Take any two elements s and t of the message patterns that are not variables
- If s and t can be unified then s and t have the same type.

Example: Otway-Rees

We have to check only messages that are not variables themselves:

1. {|f1(NA_2,M_2,A_2,B_2)|}sk(A_2,s),
2. {|f1(NB_3,M_3,A_3,B_3)|}sk(B_3,s),
3. {|f2(NA_4,KAB_4)|}sk(A_4,s),
4. {|f2(NB_5,KAB_5)|}sk(B_5,s),
5. f1(NA_6,M_6,A_6,B_6)
6. f2(NA_7,KAB_7)
7. sk(A_8,s),

Example: Otway-Rees

We have to check only messages that are not variables themselves:

1. {|f1(NA_2,M_2,A_2,B_2)|}sk(A_2,s),
2. {|f1(NB_3,M_3,A_3,B_3)|}sk(B_3,s),
3. {|f2(NA_4,KAB_4)|}sk(A_4,s),
4. {|f2(NB_5,KAB_5)|}sk(B_5,s),
5. f1(NA_6,M_6,A_6,B_6)
6. f2(NA_7,KAB_7)
7. sk(A_8,s),

The only pairs of unifiable messages are:

- 1. and 2.
- 3. and 4.

These are all type-correct. Thus type-flaw resistant!

Counter-Example: Original Otway-Rees

The original protocol without formats:

1. {|NA_2,M_2,A_2,B_2|}sk(A_2,s),
2. {|NB_3,M_3,A_3,B_3)|}sk(B_3,s),
3. {|NA_4,KAB_4|}sk(A_4,s),
4. {|NB_5,KAB_5|}sk(B_5,s),
5. sk(A_7,s),

For instance, 1. and 3. have a unifier

- NA_2=NA_4, (M_2,A_2,B_2)=KAB_4, A_2=B_3
- This violates our notion of type-flaw resistance, so the following theorem about type-flaw resistant protocols does not apply.
- Note that the entire concatenation M_2,A_2,B_2 is here a single message that can be unified with KAB.
  - ★ This may or may not work in a real implementation...

A Typing Result

Theorem

Given an attack against a type-flaw resistant protocol. Then there is a well-typed attack against the protocol, i.e., where the intruder sends no ill-typed messages. [Hess & M.], extending [Arapinis & Duflot]

- As a consequence, it is sound to restrict the intruder model to well-typed messages for type-flaw resistant protocols.
- This often cuts a lot "garbage" from the analysis in many questions.
- This comes at a low price: clear messages are good engineering practice anyway!

Summary: Typing

For secure implementations:

- Use a well-established crypto library
  - ★ Do not cook up your own stuff (unless you are a cryptographer)
  - ★ Make sure you understand the requirements and guarantees of the library and its functions, and what they achieve
- Mind the things that are not crypto:
  - ★ Define precise formats
  - ★ Check they are unambiguous and pairwise disjoint
  - ★ Write parsers and generators that do not suffer from buffer overflows and the like
- Ensure that all subterms of different types are distinguishable
  - ★ Use the formats for that
  - ★ Do use crypto on raw data like $\{N\}_{\mathsf{inv}(k)}$.
- Verify your abstract design with a tool like OFMC to find logical flaws – in the typed model.

Capture the Flag!

Related to the typing are the following ctf challenges:

- ctf4.AnB
- ctf5.AnB

Overview

Guessing Attacks

Example: a Variant of Microsoft-ChapV2

```
Protocol: PW
Types: Agent A,B;
       Number NB;
       Function pw,h;
Knowledge:
  A: A,B,pw(A,B),h;
  B: A,B,pw(A,B),h;
Actions:
  B->A: NB
  A->B: h(pw(A,B),NB)
Goals:
B authenticates A on NB
```

What if `pw(A,B)` has low entropy?

Low Entropy Passwords

- Low entropy passwords
  - ★ e.g. natural language words
  - ★ short

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- Use D for a brute-force attack on an observed message:

Observed message	$nb, h(pw(a, b), nb)$	
Construct	$nb, h(\ guess\ , nb)$	for every $guess \in D$

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Construct	$nb, h(\ guess\ , nb)$	for every $guess \in D$

- When $pw(a,b) = guess$ for some guess, the constructed and the observed message are identical, and the intruder has found out $pw(a,b)$.

Guessing Attacks in OFMC

```
B->A: NB
A->B: h(pw(A,B),NB)
Goals:
B authenticates A on NB
pw(A,B) guessable secret between A,B
```

Gives attack:

```
GOAL:
  guesswhat

ATTACK TRACE:
i -> (x20,1): x206
(x20,1) -> i: h(pw(x20,x25),x206)
i can produce secret h(guessPW,x206)

secret leaked: h(guessPW,x206)
```

Guessing Attacks in OFMC

Implementation in OFMC:

- Say $pw(A, B)$ is specified as a guessable secret between A and B.
- Let $guessPW$ be a constant known to the intruder.
- Check every message sent by an honest agent if it contains $pw(A, B)$.
  - ★ Example: outgoing message $h(pw(A, B), NA)$
  - ★ Then declare $h(guessPW, NA)$ as a secret between A and B.
  - ★ If the intruder is able to violate this secrecy goal, then he can make a guessing attack.
- Additionally, if the password is used for symmetric encryption, then guessing the key is sufficient:
  - ★ Example: $\{\!|m|\!\}_{h(pw(A,B),NA)}$
  - ★ Then also $h(guessPW, NA)$ is a secret between A and B.

Capture the Flag!

The last flag is now waiting to be caught:

- ctf6.AnB

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