Time-Bounding Needham-Schroeder Public Key Exchange Protocol

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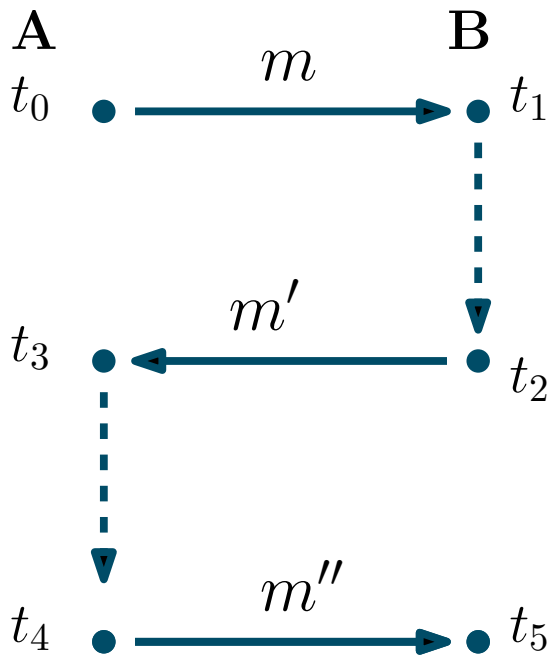
Cyber-Physical Security Protocols

Cyber-Physical Security Protocols are security protocols which rely on the **physical properties** in which its protocol sessions are carried out, such as:

- message transmission takes time
- processing requests takes time
- different transmission channels
- different transmission velocities
- physical and network distances between participants

Cyber-Physical Security Protocols

Example: **Distance Bounding Protocols**

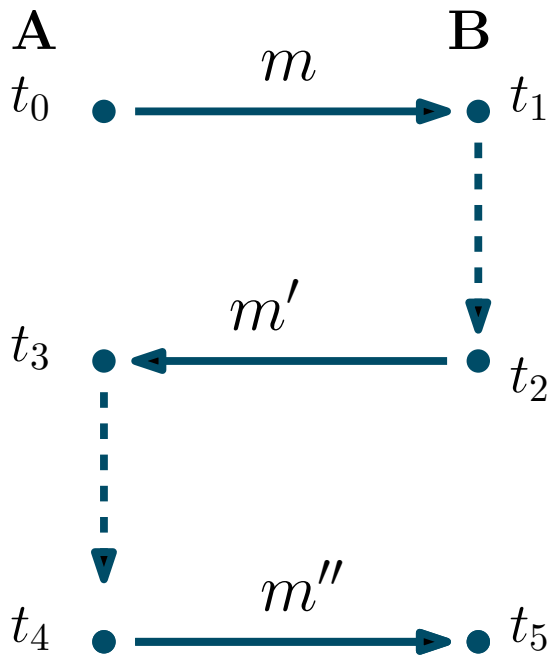


$t_3 - t_0$ is the response time

The round trip time of messages and the transmission velocity is taken into account to infer an upper bound of the distance between two agents.

Cyber-Physical Security Protocols

Example: **Distance Bounding Protocols**



If $t_3 - t_0 \leq R$ for a given **distance bounding time** R, then the verifier A grants the access to its resources to the prover B and sends a confirmation message.

Specification of Distance Bounding Protocols

Standard "Alice-Bob" notation needs to be refined.

$$\begin{aligned} A \longrightarrow B &: \ m \quad \text{at time} \ \ t_0 \\ B \longrightarrow A &: \ m' \quad \text{at time} \ \ t_1 \\ A \longrightarrow B &: \ m'' \quad \text{if} \ \ t_1 - t_0 \leq R \end{aligned}$$

Many **assumptions about time need to be formally specified**, including:

- time requirements for the fulfillment of a protocol session
- assumptions about the network, such as communication mediums and transmission velocities

Protocol verification

Following issues need to be addressed:

- which properties does the protocol ensure
- under which conditions
- against which intruders

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Moreover, the **standard Dolev-Yao intruder** should be ammended with time features in order to make **the physical properties of the system relevant**.

Discrete vs. Continuous Time

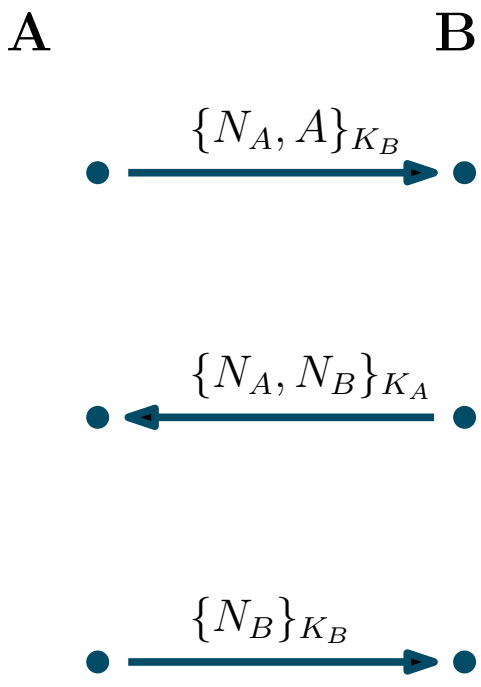
Protocol verification

Discrete Time Models	**Continuous Time Models**

We investigate how the models with **continuous time** relate to models with **discrete time** in protocol verification.

Cyber-Physical Security Protocols

Example: **Original (non-secure) Needham-Schroeder protocol**



Cyber-Physical Security Protocols

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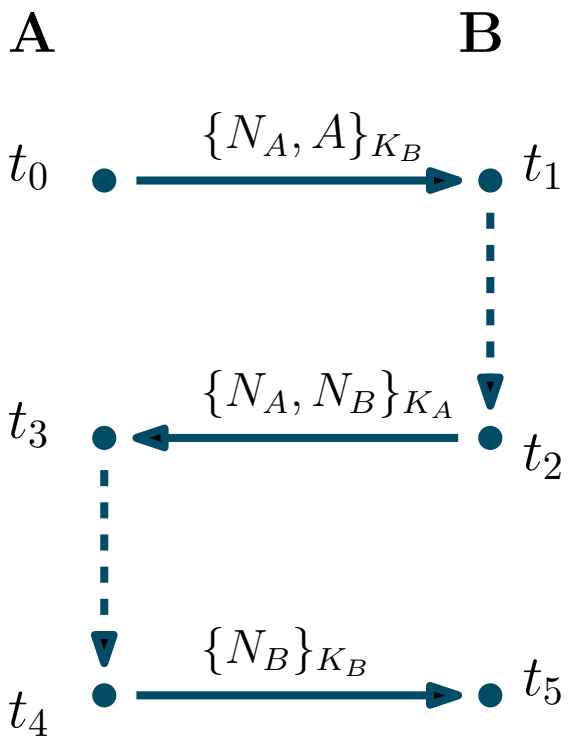

Can the protocol be fixed by means of **time**
(by some time requirements) ?

Time-Sensitive Features

We need to take into account **time-sensitive features** such as:

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- **network delays**
- participants' **processing time**
- protocol execution depends on the round trip time of messages by means of **measuring the response time**

Time-Sensitive Features

Network Delay

A and B communicate through network:

Message m sent at the moment t_0 is received at some **later moment** t_1, i.e. traversal of messages takes non-zero time $t_1 - t_0$.

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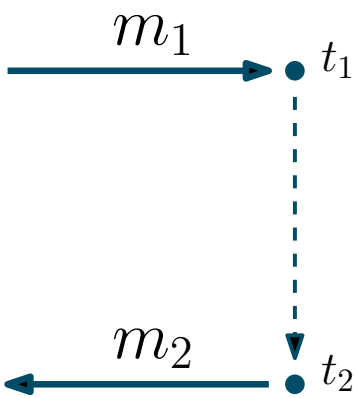
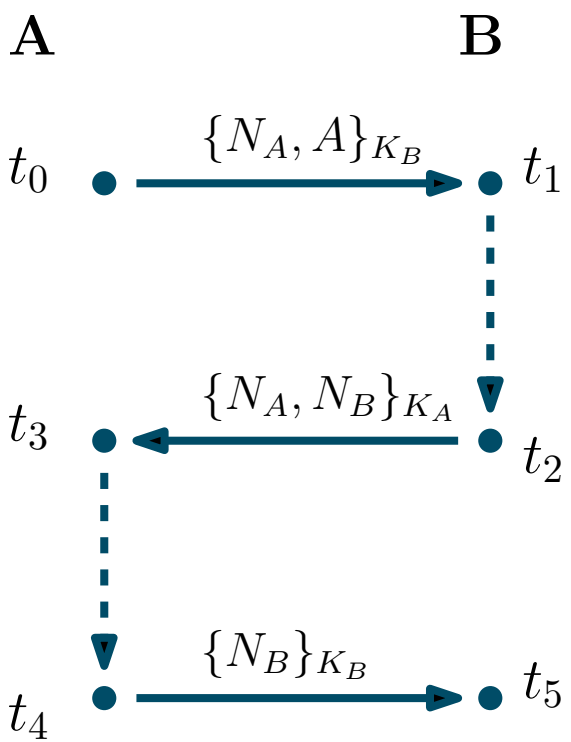


Processing Time

Message m_1 is received at the moment t_1.
Reply m_2 is sent at some **later moment** t_2.
That is, processing takes non-zero time $t_2 - t_1$.

Time-Bounding Needham-Schroeder Protocol



If $t_3 - t_0 \leq R$ for a given **response bounding time** R, then A and sends to Bob the confirmation message $\{N_B\}_{K_B}$.

Time-Bounding Needham-Schroeder Protocol

The protocol is **secure** if the "accepted" N_A and N_B may never be revealed to somebody else except Alice and Bob.

For which response bounding time R is there an attack?

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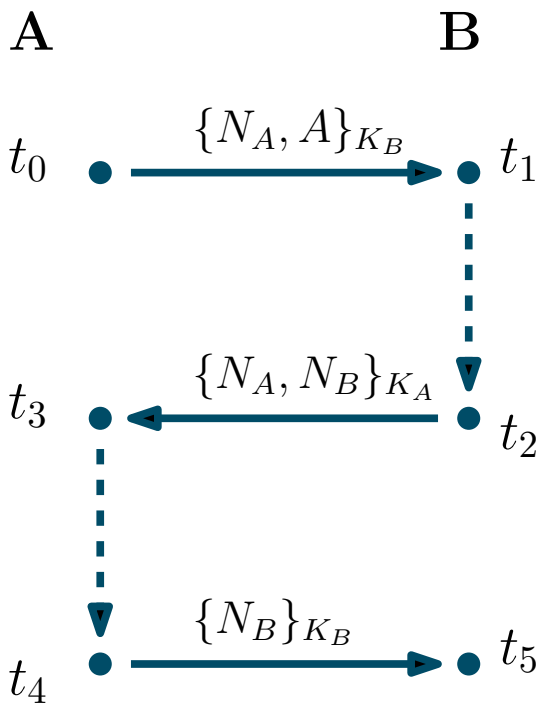
For which response bounding time R is there an attack?

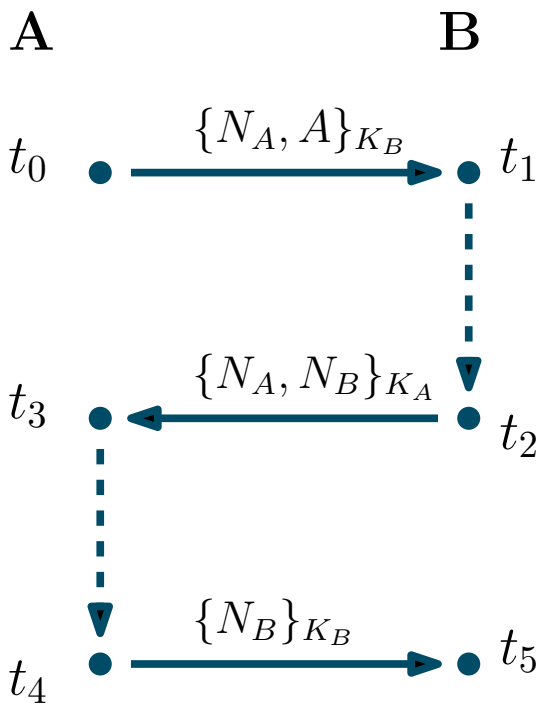
- We show that the answer depends on whether time is considered discrete or continuous.
- We show that the answer also depends on network delay and on internal processing time.

Time-Bounding Needham-Schroeder Protocol



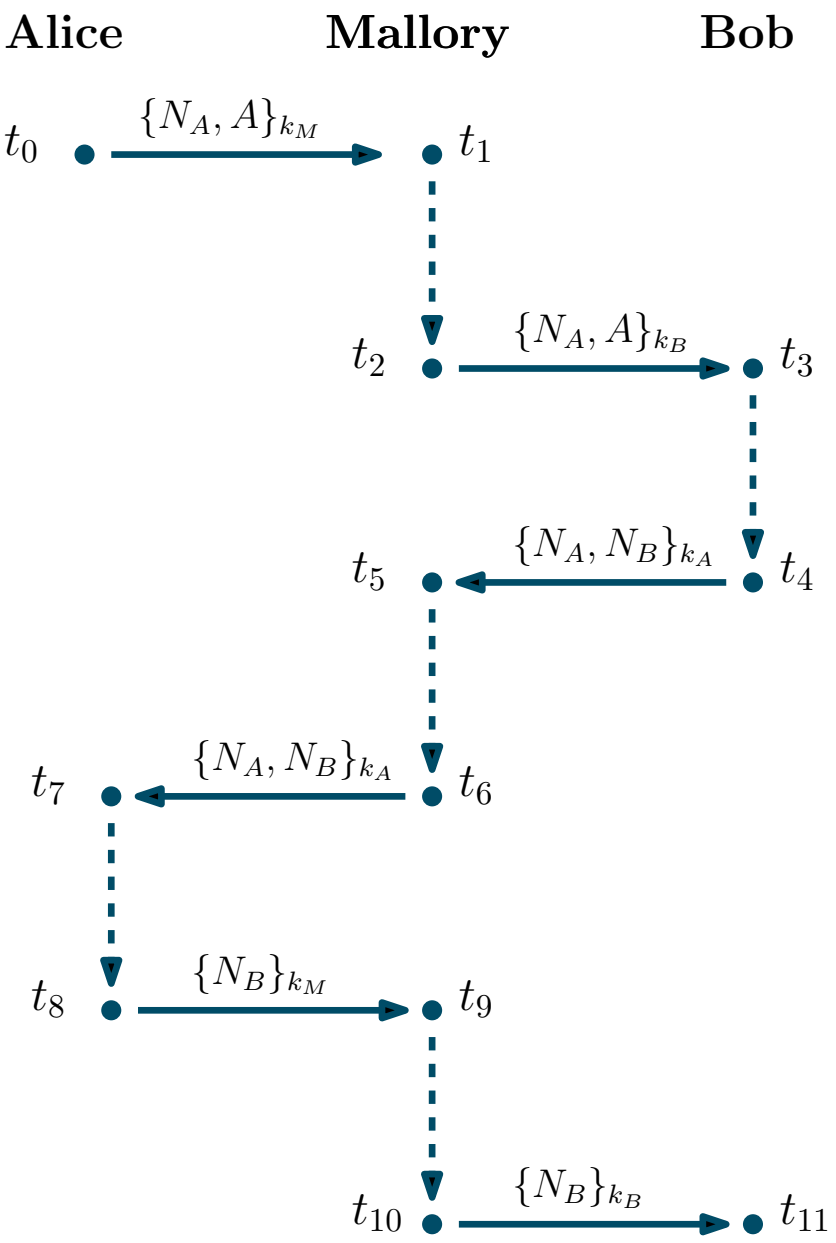
- The protocol is **safe** with an appropriate response bounding time R when using a model with discrete time : **no attack can be found.**

Time-Bounding Needham-Schroeder Protocol



- The protocol is **safe** with an appropriate response bounding time R when using a model with discrete time : **no attack can be found.**
- The protocol is **insecure** for any response bounding time R in the case of continuous time : **there is a timed version of Lowe attack.**

Attack on Time-Bounding Needham-Schroeder Protocol

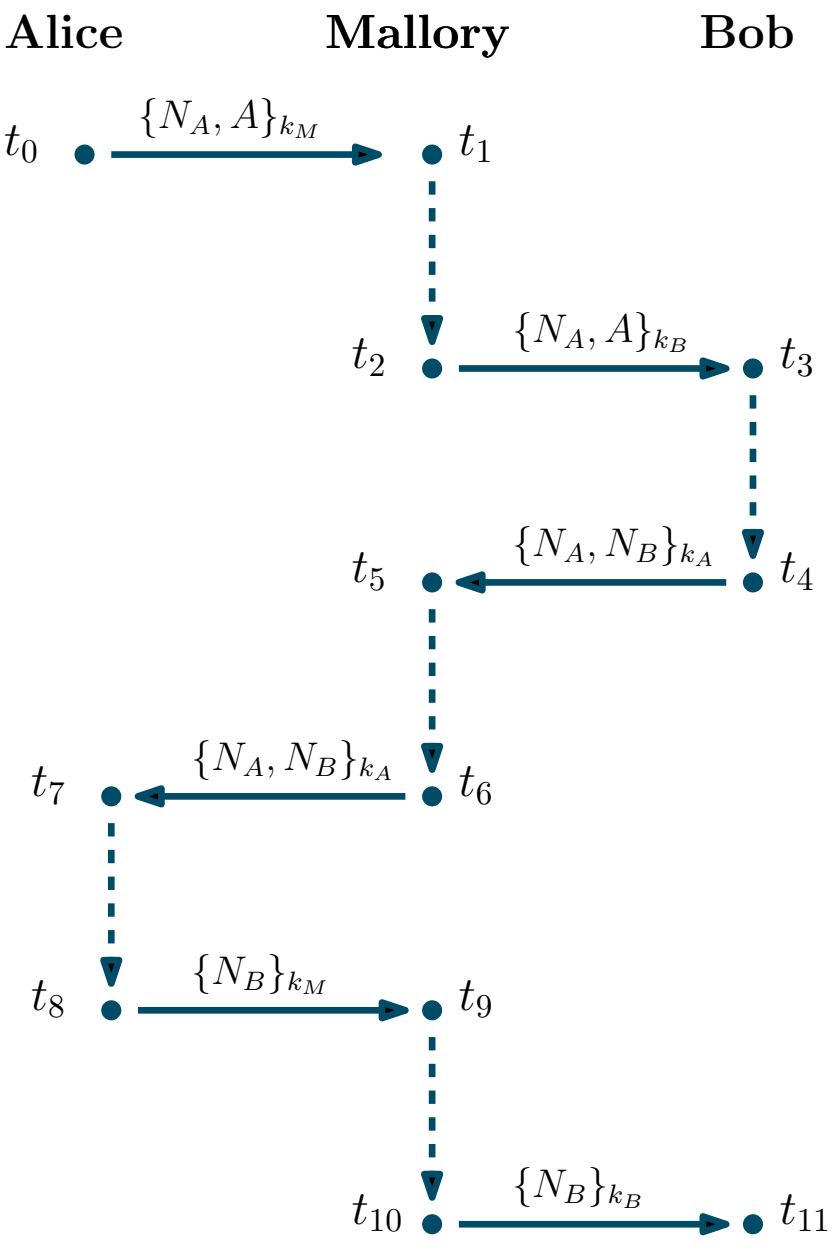


Lowe-style attack

Mallory forces Bob to believe that he communicated with Alice, and that only Alice learned Bob's nonce N_B.

Actually, Bob communicated with Mallory, and Mallory learned N_B.

Attack on Time-Bounding Needham-Schroeder Protocol



Lowe-style attack

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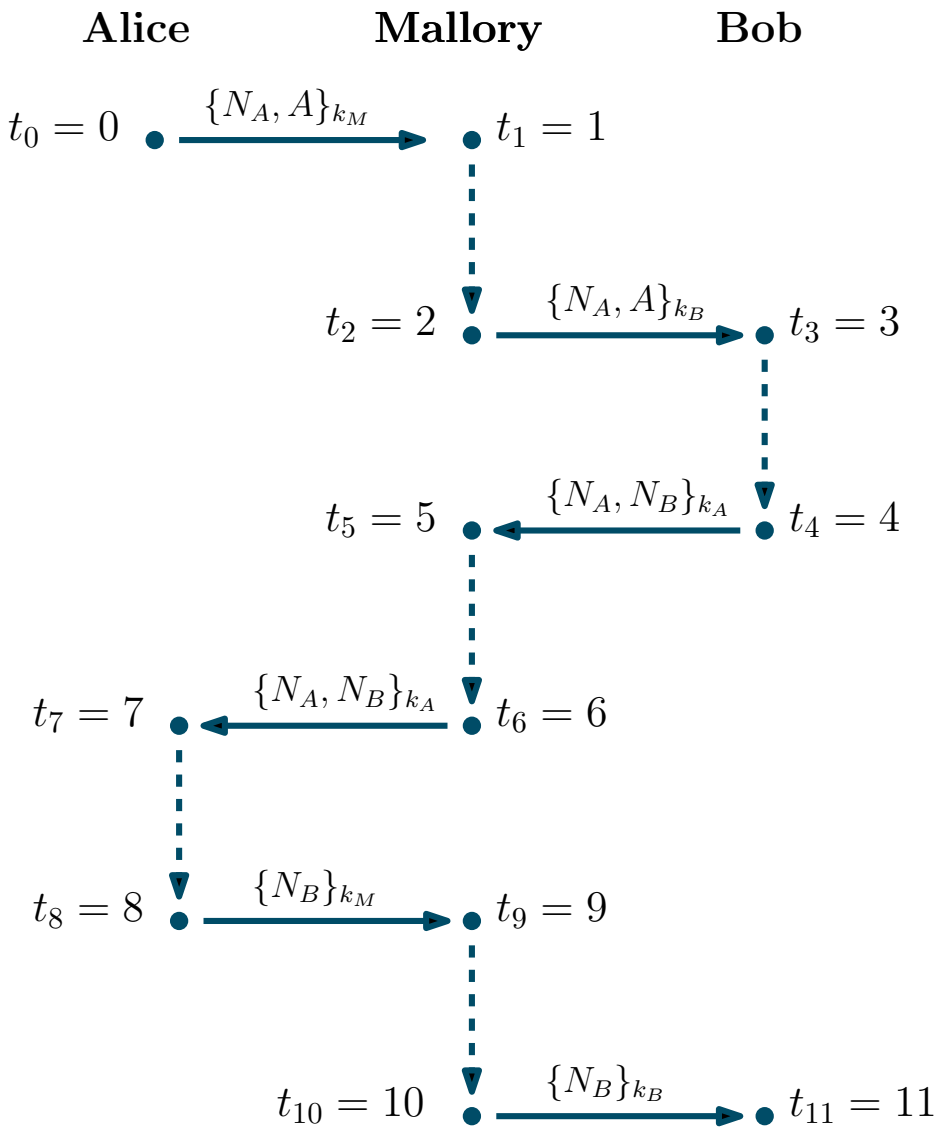
Actually, Bob communicated with Mallory, and Mallory learned N_B.

Under which time conditions is the attack possible?

Attack on Time-Bounding Needham-Schroeder Protocol

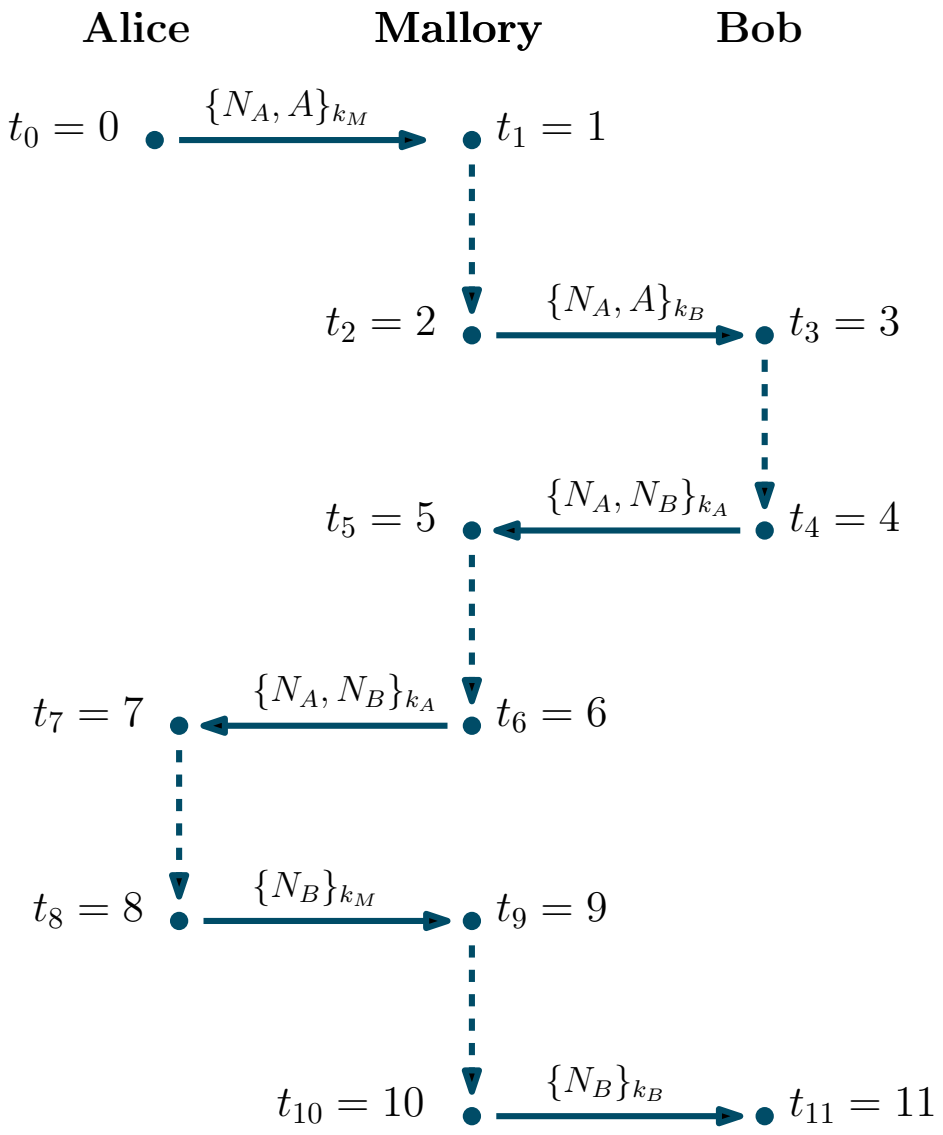


Lowe-style attack

Discrete time model

Since both network delay and processing take at least 1 time unit, attack can be performed only for response bounding time $R \geq 7$.

Attack on Time-Bounding Needham-Schroeder Protocol



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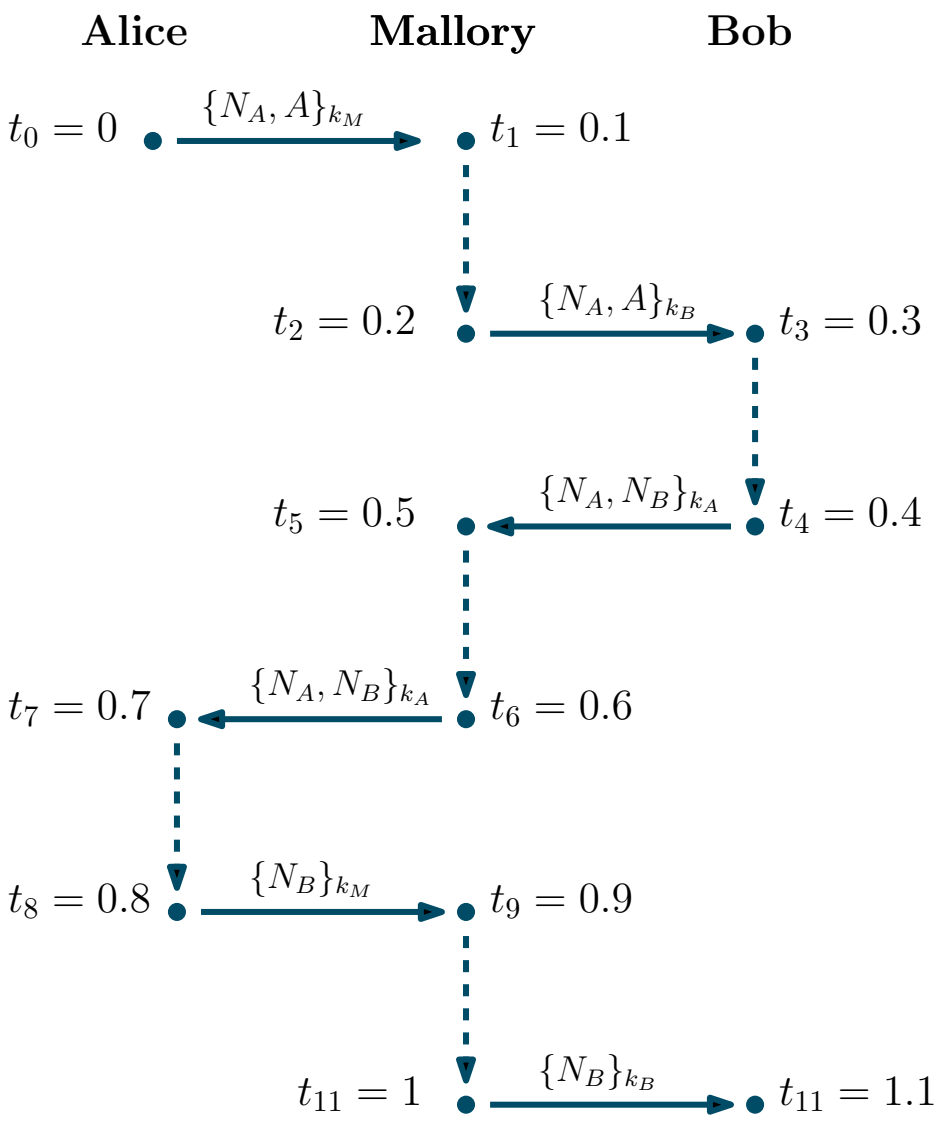
There is **no attack** for $R < 7$.

Attack on Time-Bounding Needham-Schroeder Protocol



Lowe-style attack

Continuous time model

Attack is possible for every response bounding time

$$R > 0$$

Discrete vs. Continuous Time

The existance of the attack depends on whether time is considered discrete or continuous.

No rescaling of discrete time units removes this issue:

For **any discretisation of time**, such as days, seconds or any other infinitesimal time unit, there is a protocol, for which

- **there exists an attack with continuous time**, and
- **no attack is possible in the discrete case**.

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- **there exists an attack with continuous time**, and
- **no attack is possible in the discrete case**.

Between moments t_i and t_j only a finite number of acts can happen within discrete time, whereas an **unbounded number of timed events** are possible within continuous time.

Specification of Cyber-Physical Security Protocols

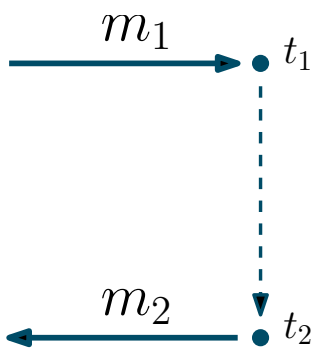
Lower bounds for passing messages and processing requests

a - strict lower bound for passing messages
b - strict lower bound for processing messages

Network Delay

Traversal of messages is greater then a :

$$t_1 - t_0 > a$$



Processing Time

Internal processing is greater then b :

$$t_2 - t_1 > b$$

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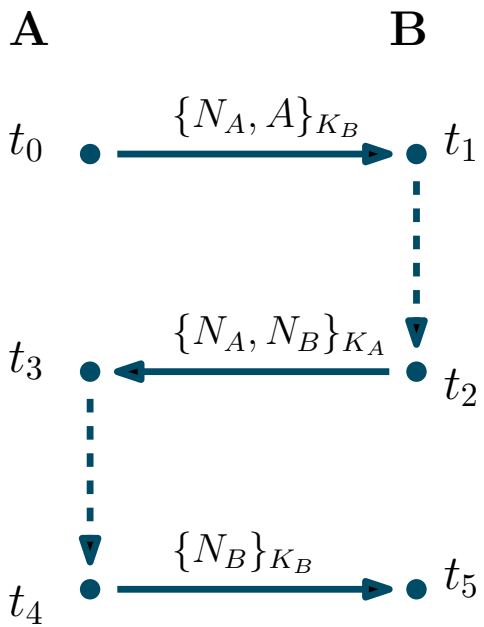

For which R the protocol is safe?
For which R there is an attack?

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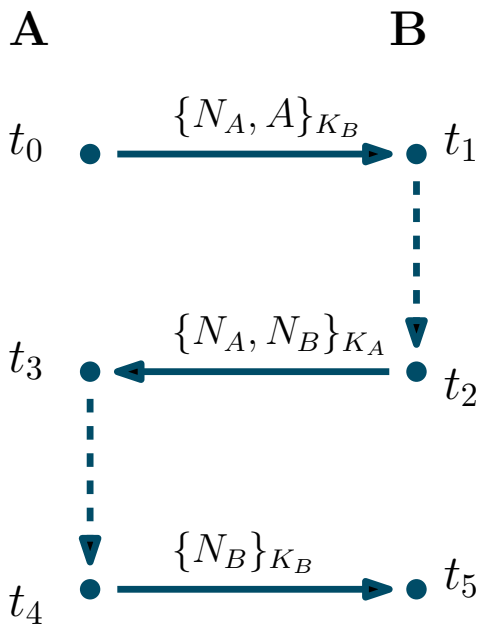

For which R the protocol is safe?
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Given explicit lower bounds we can provide precise results.

Time-Bounding Needham-Schroeder Protocol

Lower bounds for passing messages and processing requests

a - strict lower bound for passing messages
b - strict lower bound for processing messages

In case $a > 0$ or $b > 0$, for non-negative integers a, b,

- For **discrete time**, there is **no Dolev-Yao attack** on the time-bounding Needham-Schroeder protocol with response bounding time $R < 4a + 3b + 7$.
- For **continuous time**, there is **no Dolev-Yao attack** on the time-bounding Needham-Schroeder protocol with the response bounding time $R < 4a + 3b$.

Discrete vs. Continuous Time

Protocol verification

Discrete Time Models	**Continuous Time Models**

There is a difference !

There are protocols for which there is no attack in the discrete time model, but there is an attack in the continuous time model.

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One should be aware of this difference in **cyber-physical security protocol verification**.

Complexity results

Planning Problem \ Reachability Problem		
Balanced actions	Untimed system	**PSPACE-complete** [Kanovich et al., FAST'10]
	System with discrete time	**PSPACE-complete** [Kanovich et al.,RTA'12]
	System with real time	**PSPACE-complete** new
Actions not necessarily balanced		**Undecidable**

Though the nonce updates cause a potentially infinite number of states, the PSPACE membership is given for the timed systems with **fresh values (nonces)**.

Future Work

- Investigating the power of our intruder model:
  how much damage can be done under which conditions
- Alternative Intruder and Protocol Models
  e.g. agents allowed to move, not static
- Implementation of our model in automated tools e.g. Maude:
  verifying cyber-physical protocols
- Specification of asynchronous systems
  Time synchronization mechanisms
  Network Time Protocols
- Analysis of security protocols
  e.g. timestamps, timing channels

Related Work

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- Kanovich, Okada, Scedrov. Specifying real-time finite-state systems in linear logic, 1998.
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- Brands, Chaum. Distance-bounding protocols, 1993.
- Meadows, Poovendran, Pavlovic, Chang, Syverson. Distance bounding protocols: Authentication logic analysis and collusion attacks, 2007.
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- Malladi, Bruhadeshwar, Kothapalli. Automatic analysis of distance bounding protocols, 2010.