Finding Security Vulnerabilities in a Network Protocol Using Formal Verification Methods

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Motivation

- Attacks on network protocols, taking advantage of built-in vulnerabilities, are not easy to identify
  - Rely on legitimate functionality of the protocol
  - May involve only a small number of messages
  - Identifying attacks is done mostly manually, by experts, in an ad hoc manner

Goals

- Develop **automatic** methods for identifying **attacks** in network protocols
- Using methods and tools for **formal verification of software and hardware**
  - **Model checking**

Model Checking [CE81,QS82]

An efficient procedure that receives:

- A finite-state model describing a system
- A temporal logic formula describing a property

It returns

yes, if the system has the property

no + Counterexample, otherwise

Mutual Exclusion Example

- Two process mutual exclusion with shared semaphore
- Each process has three states
  - Non-critical (N)
  - Trying (T)
  - Critical (C)
- Semaphore can be available (sem=1) or taken (sem=0)
- Initially both processes are in the Non-critical state and the semaphore is available --- $N_1 N_2 S_0$

- S_0 denotes sem=0
- S_1 denotes sem=1

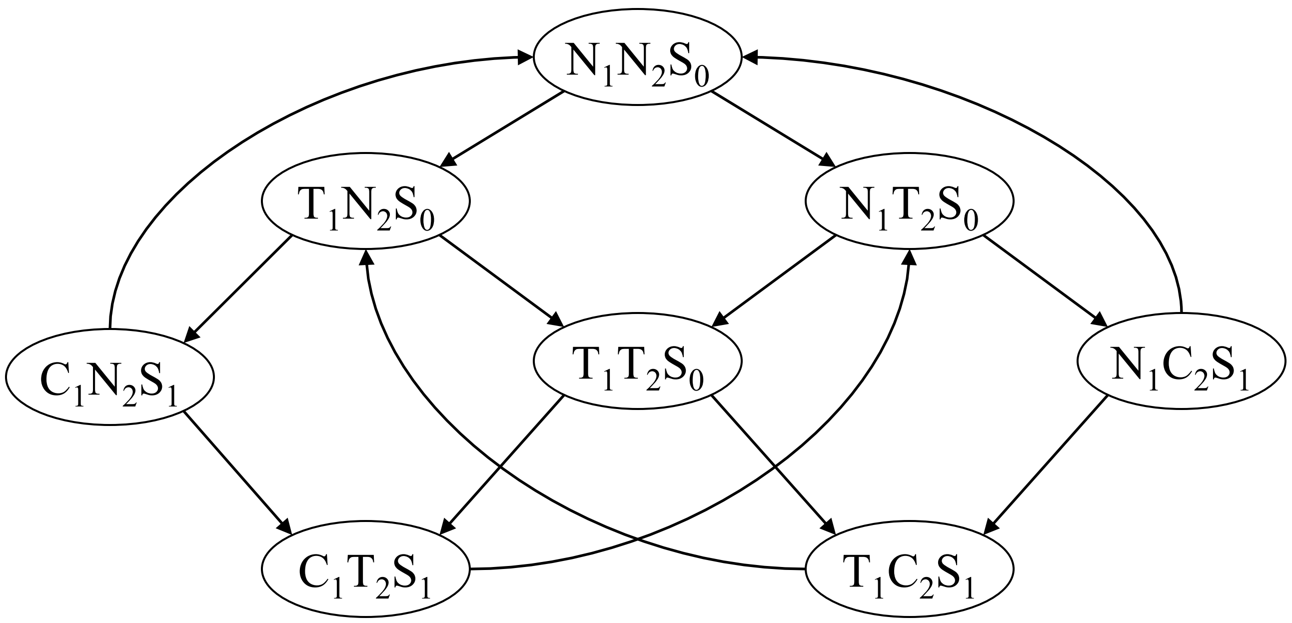
Mutual Exclusion Example

$P = P_1 \,||\, P_2$

```
Pi :: while (true) {
        if (vi == N)  vi = T;
        else if (vi == T && sem=1)
                        {vi = C; sem=0;}
        else if (vi == C) {vi = N; sem=1;}
     }
```

Initial state: $(v_1 == N, v_2 == N, sem=0)$

Mutual Exclusion Example

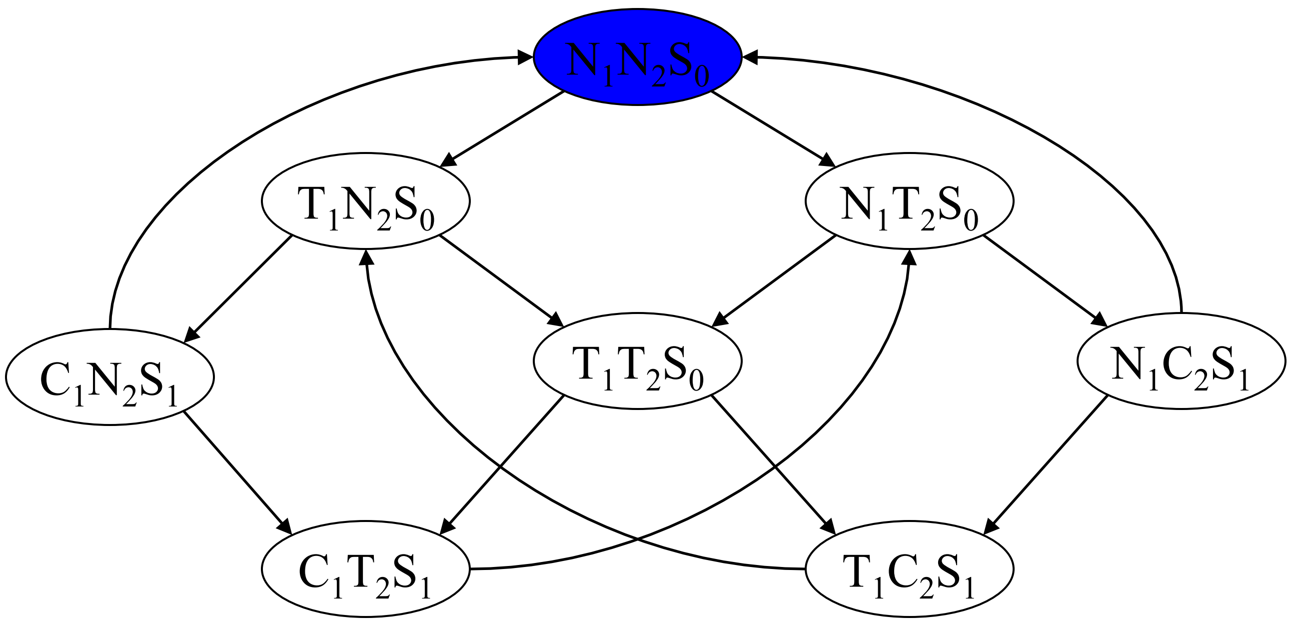


$$M \models AG\ \neg\ (C_1 \wedge C_2)$$

The two processes are never in their critical states at the same time

The state with $(C_1 \wedge C_2)$ is not reachable

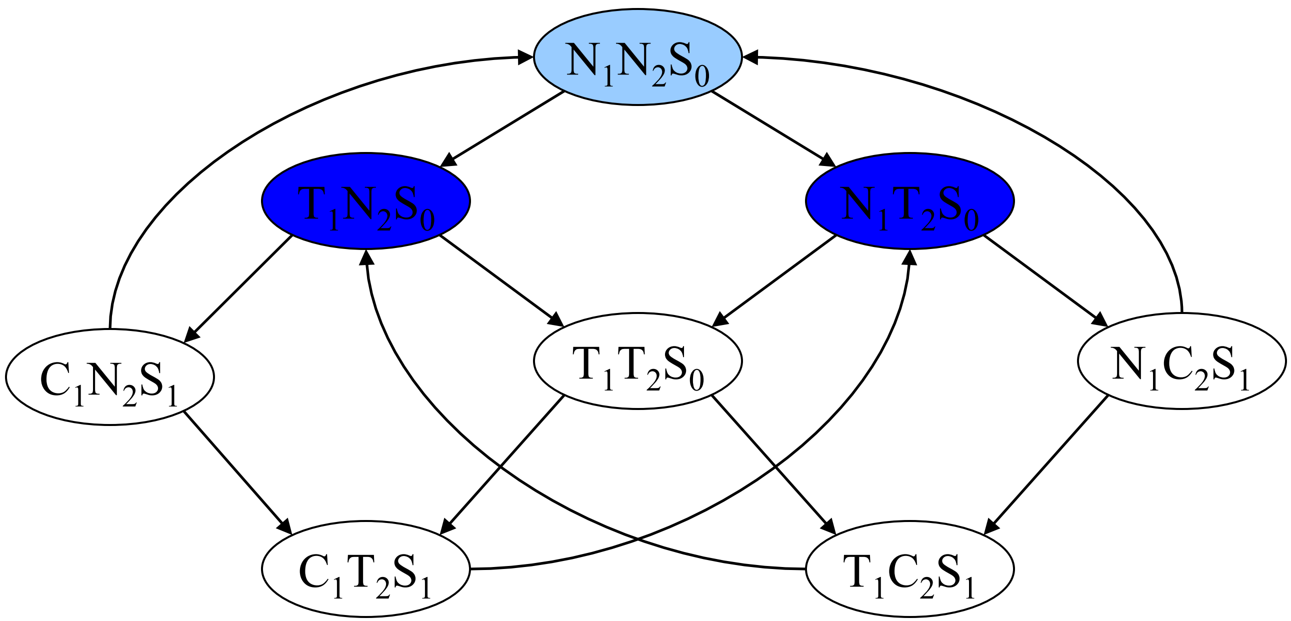
Mutual Exclusion Example



$$M \models AG \neg (C_1 \wedge C_2)$$

S_0

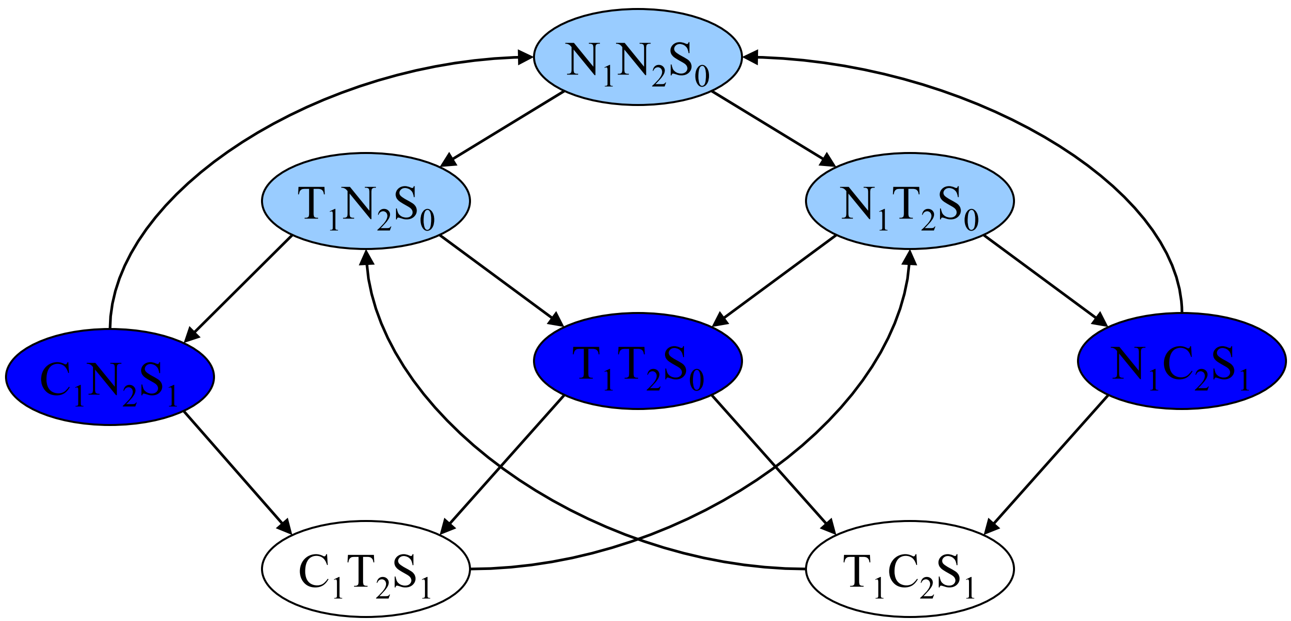
Mutual Exclusion Example



$$M \models AG \neg (C_1 \wedge C_2)$$

S_1

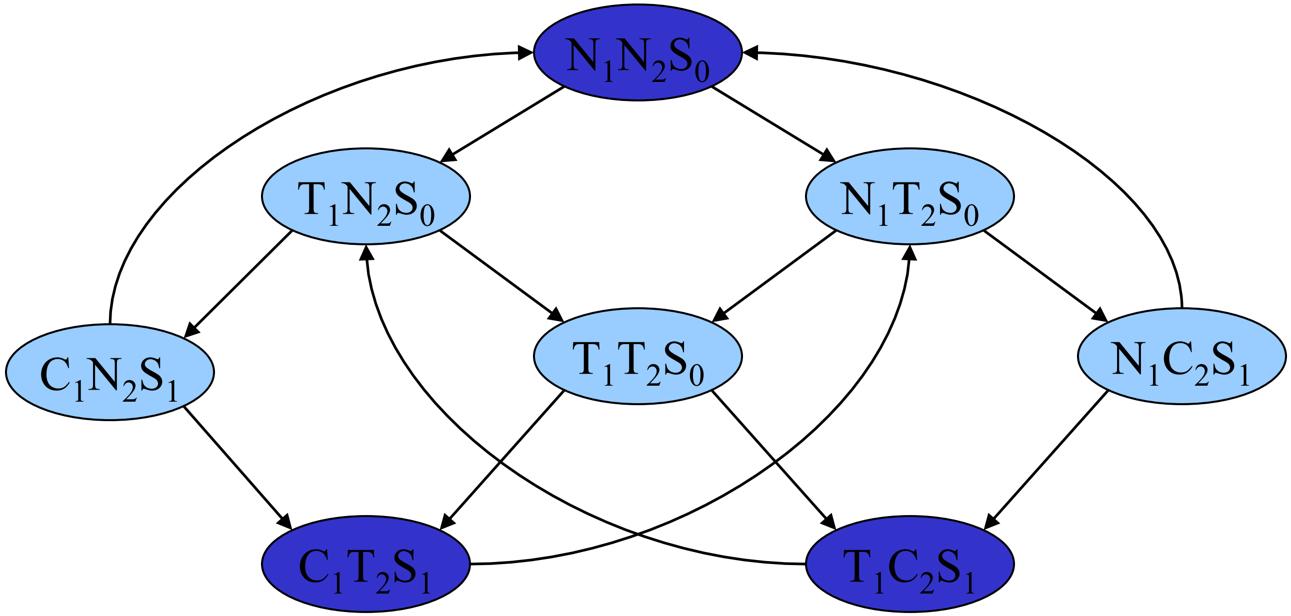
Mutual Exclusion Example



$$M \models AG \neg (C_1 \wedge C_2)$$

S_2

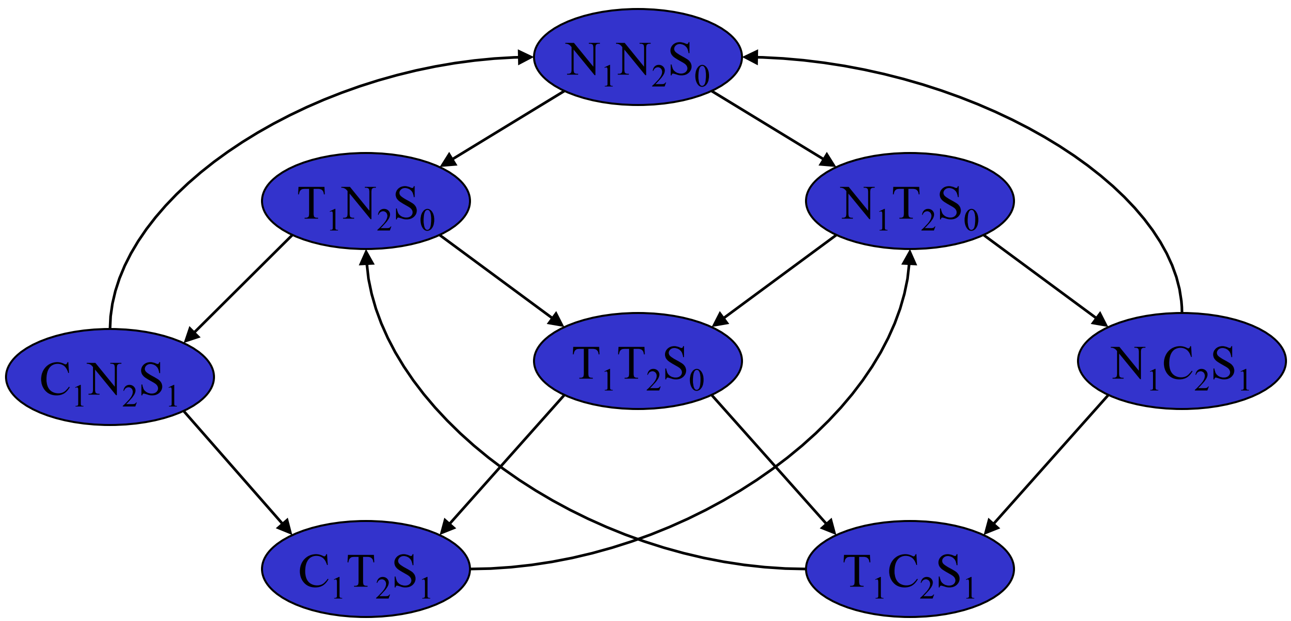
Mutual Exclusion Example



$$M \models AG \neg (C_1 \wedge C_2)$$

S_3

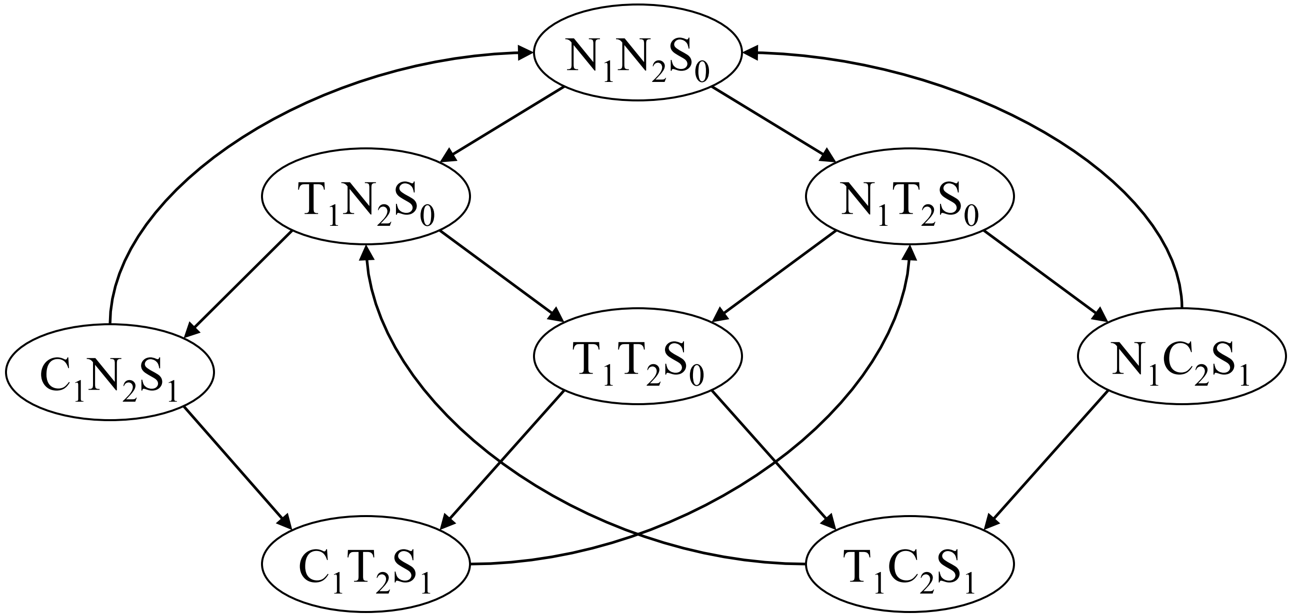
Mutual Exclusion Example



$$M \models AG \neg (C_1 \wedge C_2)$$

$$S_4 \subseteq S_0 \cup \ldots \cup S_3 \quad \surd$$

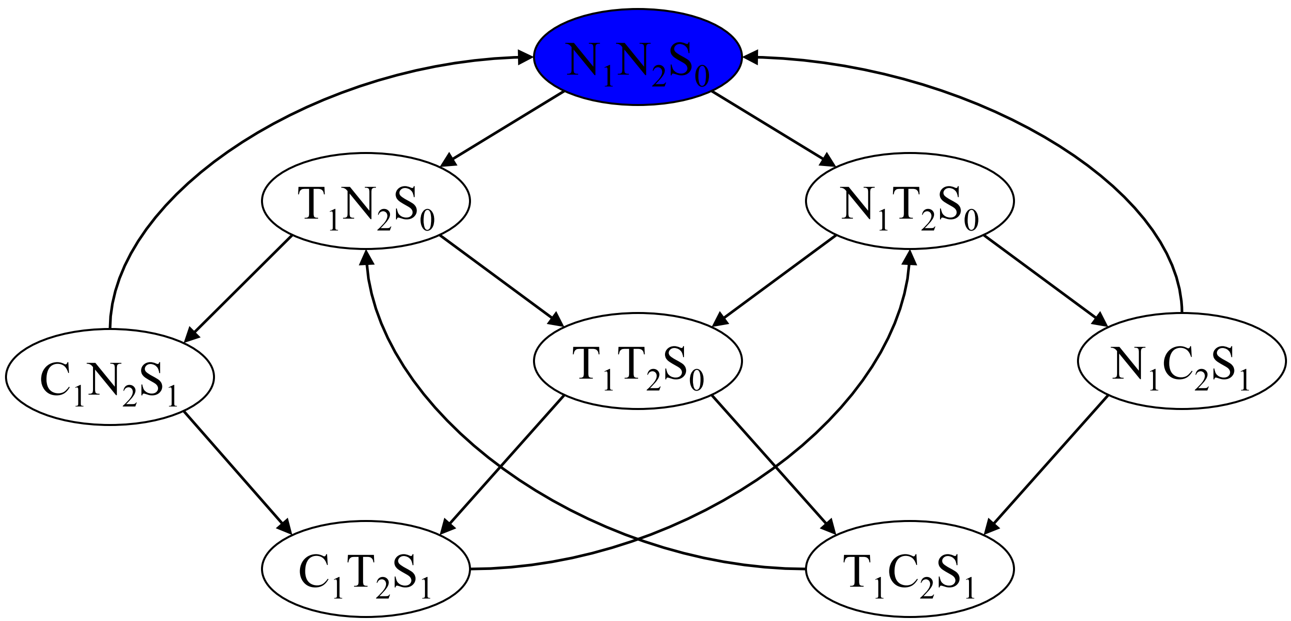
Mutual Exclusion Example



$$M \models AG \neg (T_1 \wedge T_2)$$

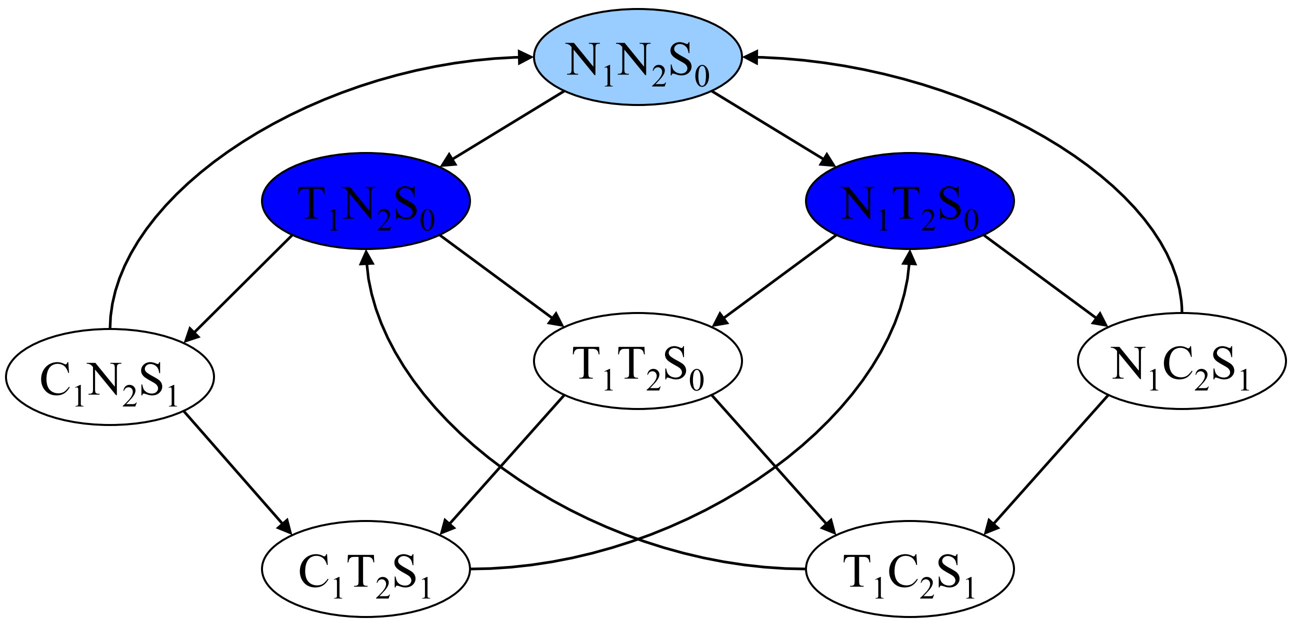
The two processes are never in their trying states at the same time

Mutual Exclusion Example



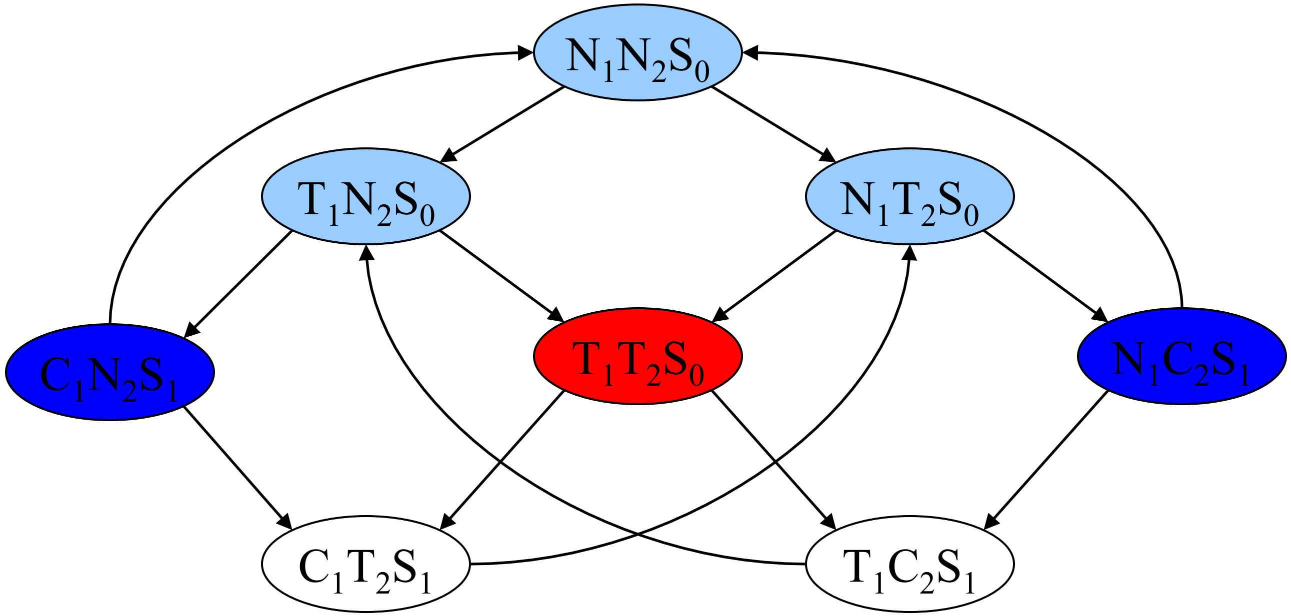
$$M \models AG \neg (T_1 \wedge T_2)$$

Mutual Exclusion Example



$$M \models AG \neg (T_1 \wedge T_2)$$

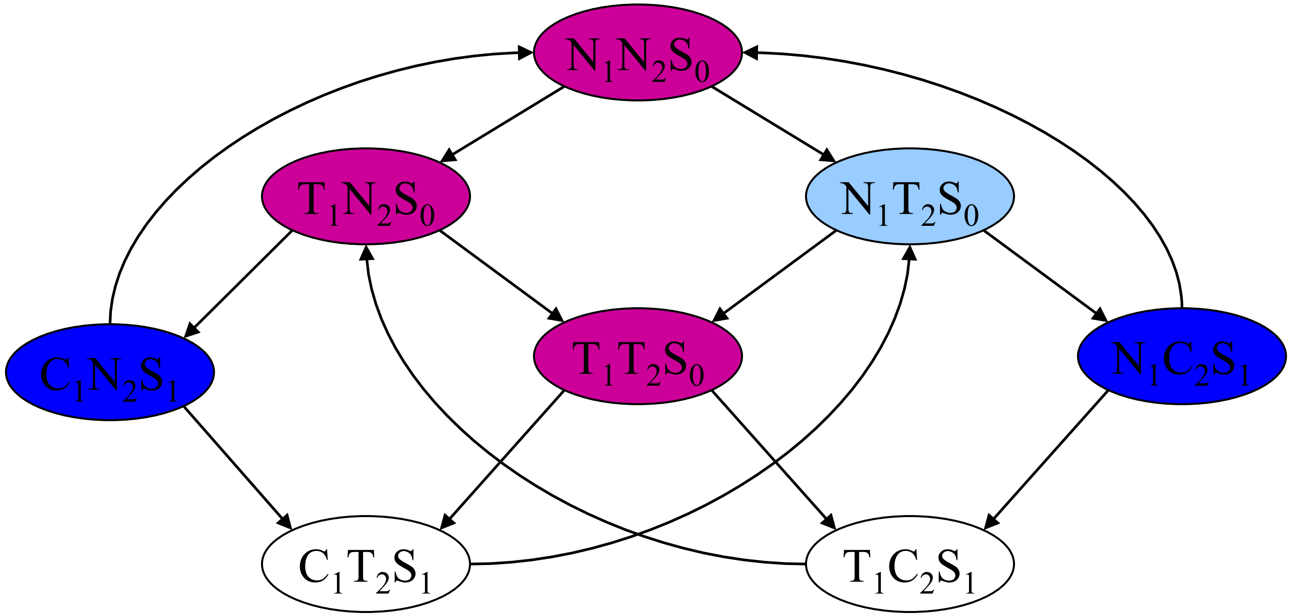
Mutual Exclusion Example



$$M \not\models AG\ \neg\ (T_1 \wedge T_2)$$

A violating state has been found

Mutual Exclusion Example



$$M \not\models AG \neg (T_1 \wedge T_2)$$

Model checking returns a counterexample

Our goals

To search **for attacks** using **model checking**

For this purpose, we define:

- **Model**
  - Represents the protocol's behaviors
  - Includes an **attacker** with predefined capabilities
- **Specification**
  - Specifies "**suspect**" states

Challenges

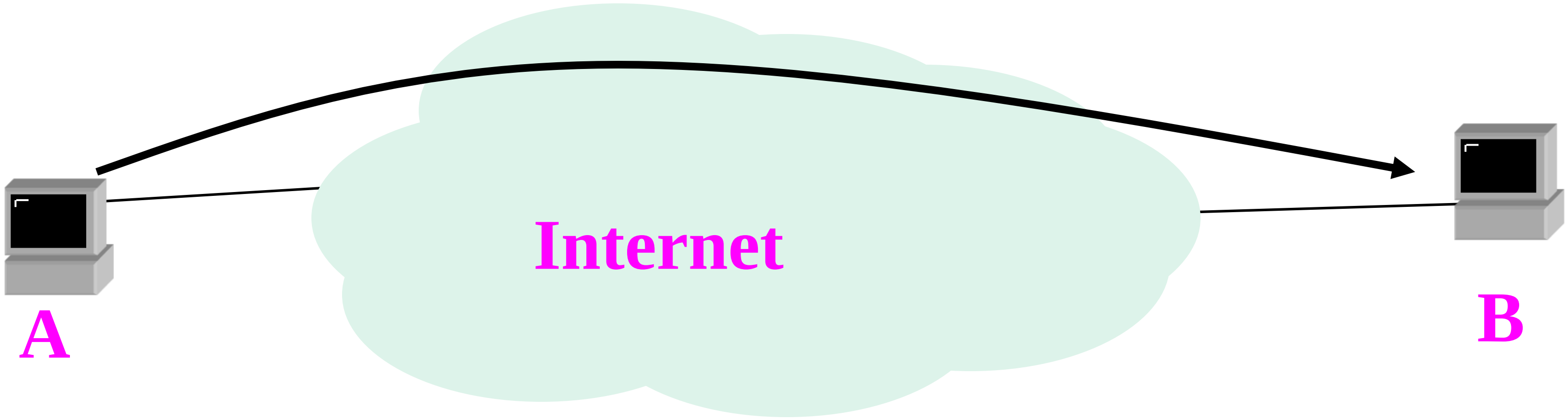
- Building a model which is
  - **Sufficiently detailed:** to enable identifying attacks based on the protocol's **functionality**
  - **Sufficiently reduced**: **feasible** for model checking tools
- Write **general specification** to identify different kinds of attacks with different techniques

Advantages of our approach

- We do not need to define an attack, but only its possible outcome.
  - Specifying suspect states requires less knowledge and efforts than defining an attack
  - May enable finding new attacks, unknown by now

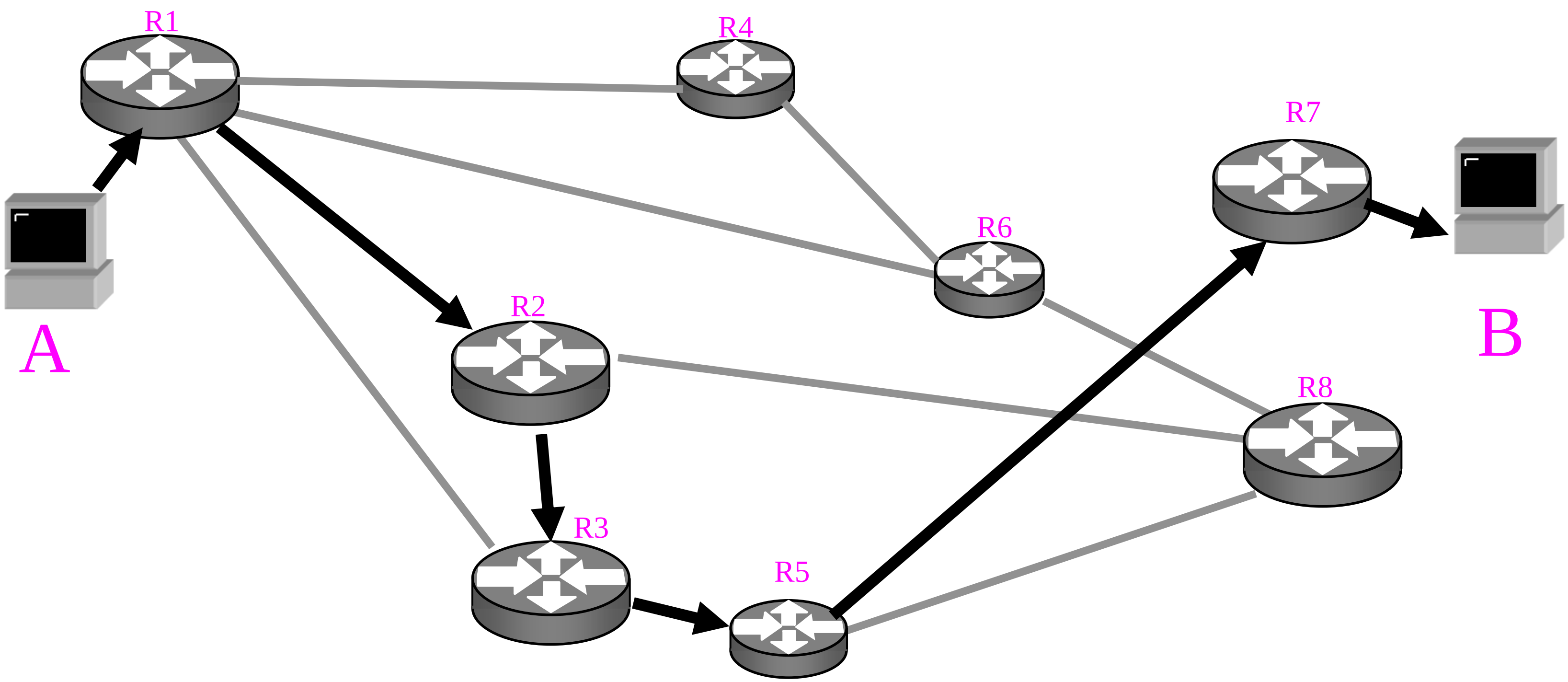
Routing in the Internet

- How do packets get from A to B in the Internet?



Routing in the Internet

- Each router makes a **local** decision on how to forward a packet towards B

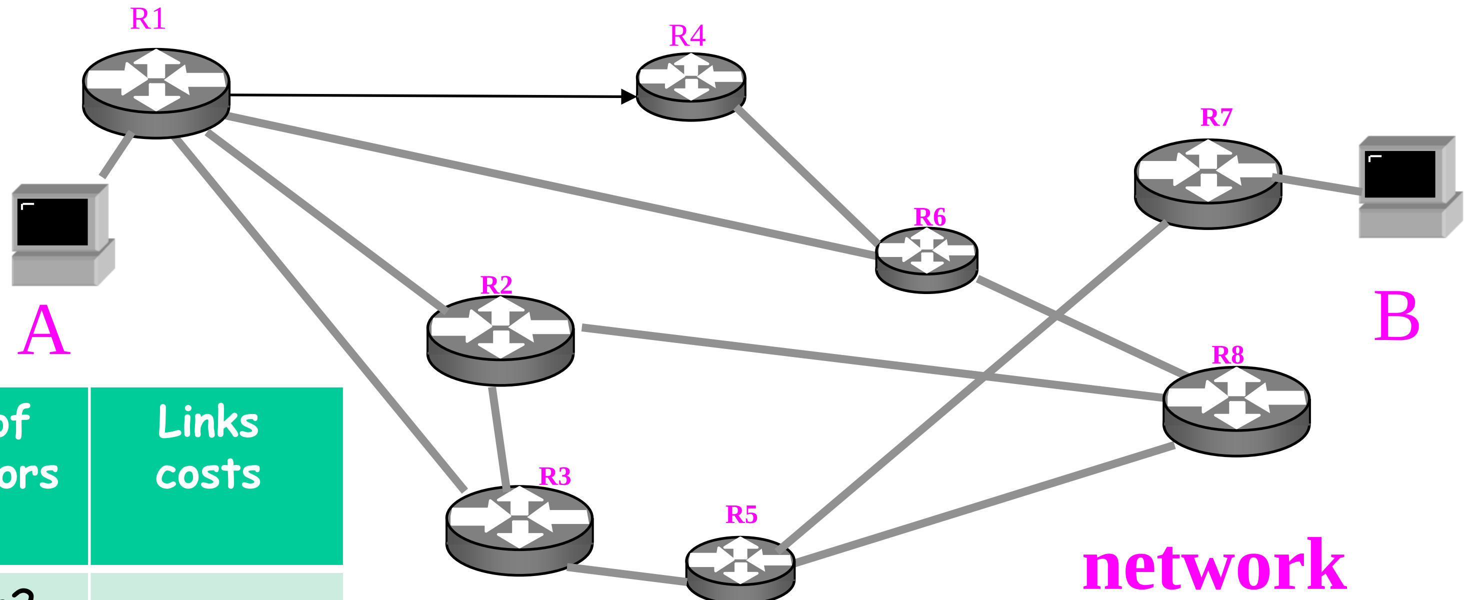


Research Focus - OSPF

- We focused on the **routing protocol**
  Open Shortest Path First (**OSPF**)
- OSPF is widely used for routing in the Internet
  - Finding attacks on OSPF is **significant**
- OSPF is a complex protocol
  - We may be able to derive insights from its modeling to modeling of other network protocols

OSPF

- Each router compiles a **database** of the most recent OSPF messages received from all routers in the network



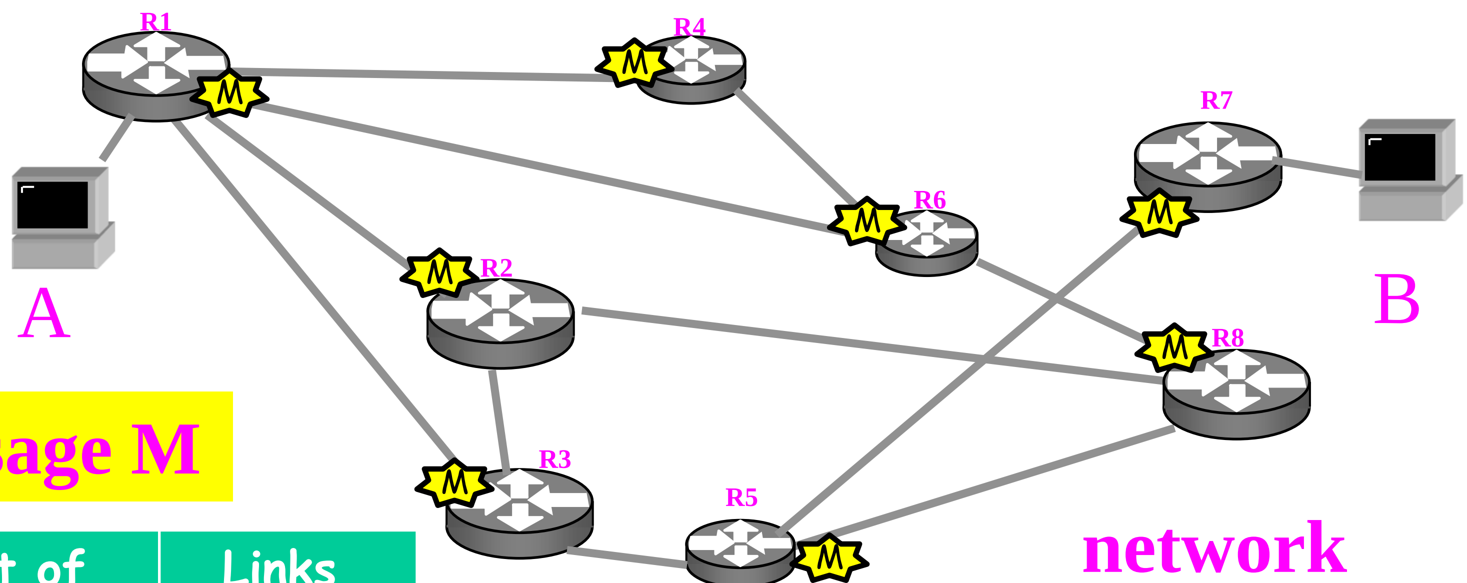
database

Originator	List of neighbors	Links costs
r1	r4,r6,r2, r3	…
r2	r3,r1,r8	…
…	…	…

Using this database a router obtains a complete view of the network topology

OSPF

- OSPF messages are **flooded** through the network

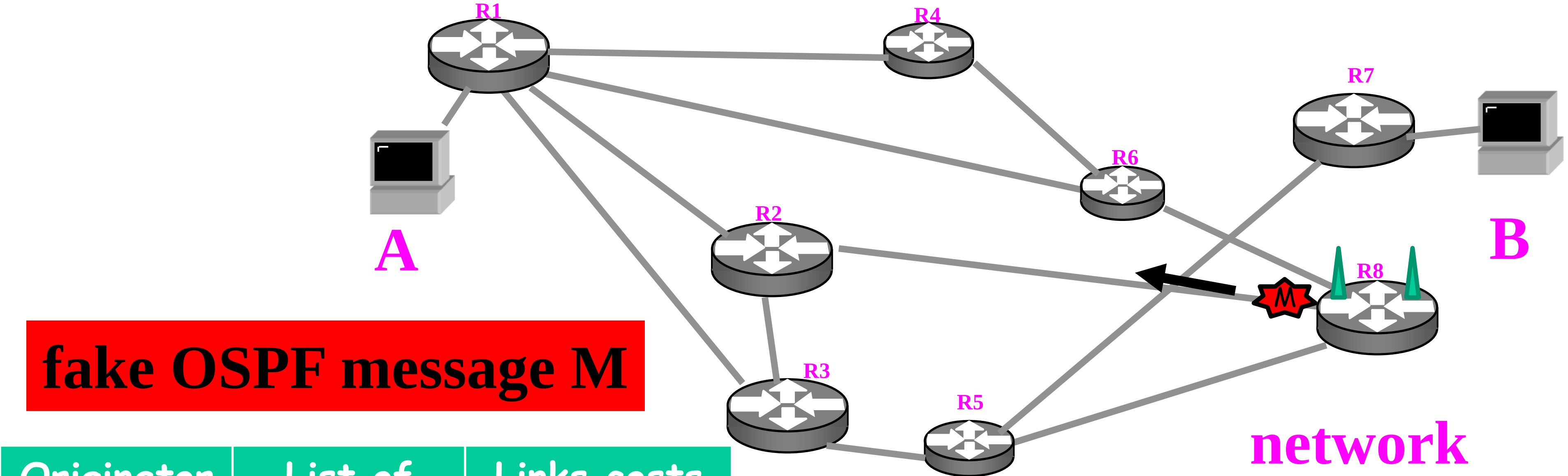


OSPF message M

Originator	List of neighbors	Links costs
r6	r4,r1,r8	...

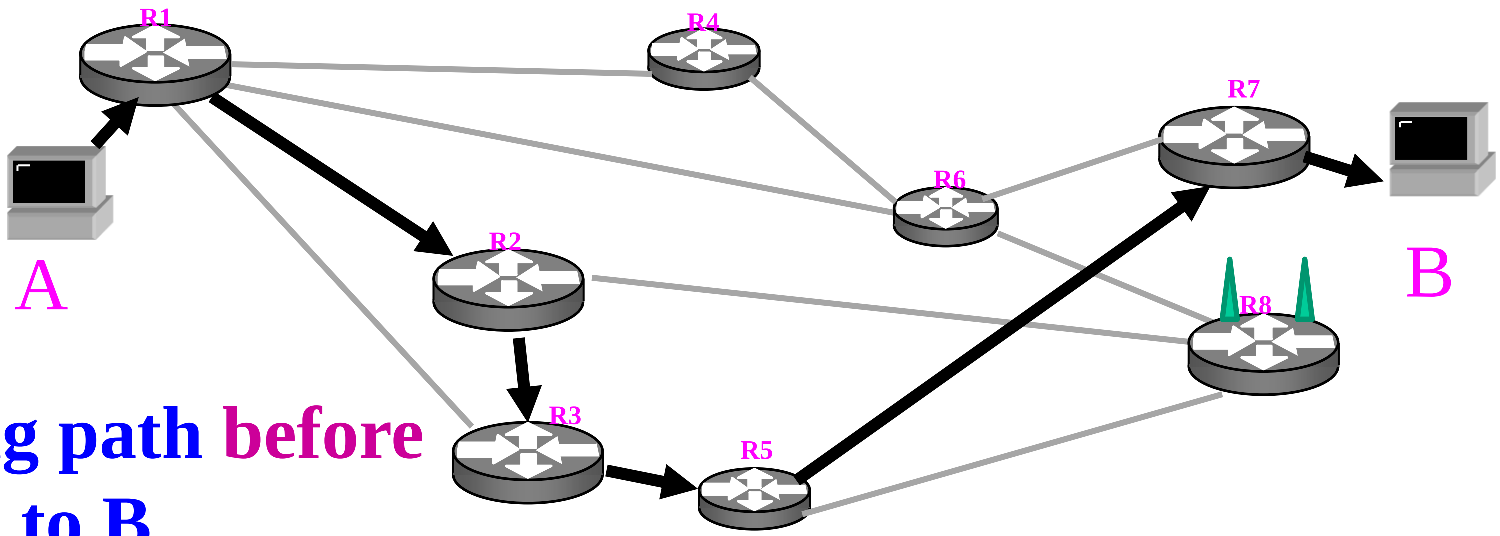
OSPF Attacks

- The goal of an OSPF **attacker** is to advertise **fake messages** on behalf of some other router(s) in the network.

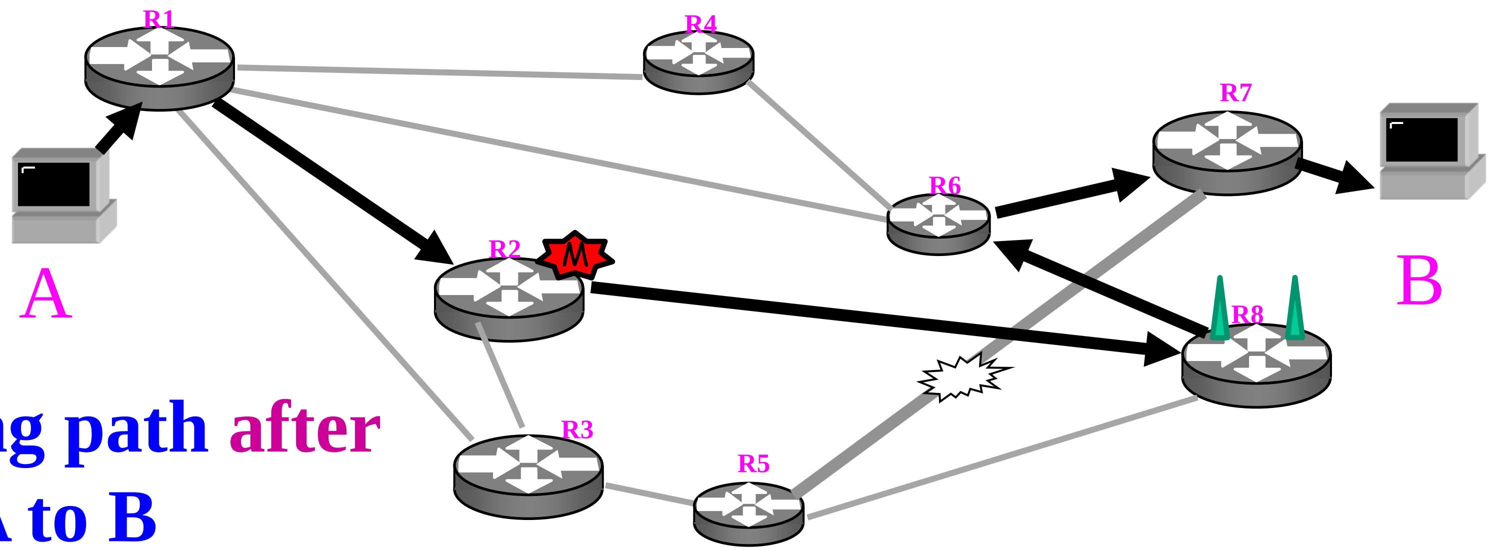


Originator	List of neighbors	Links costs
r5	r3,r8	…

OSPF Attacks



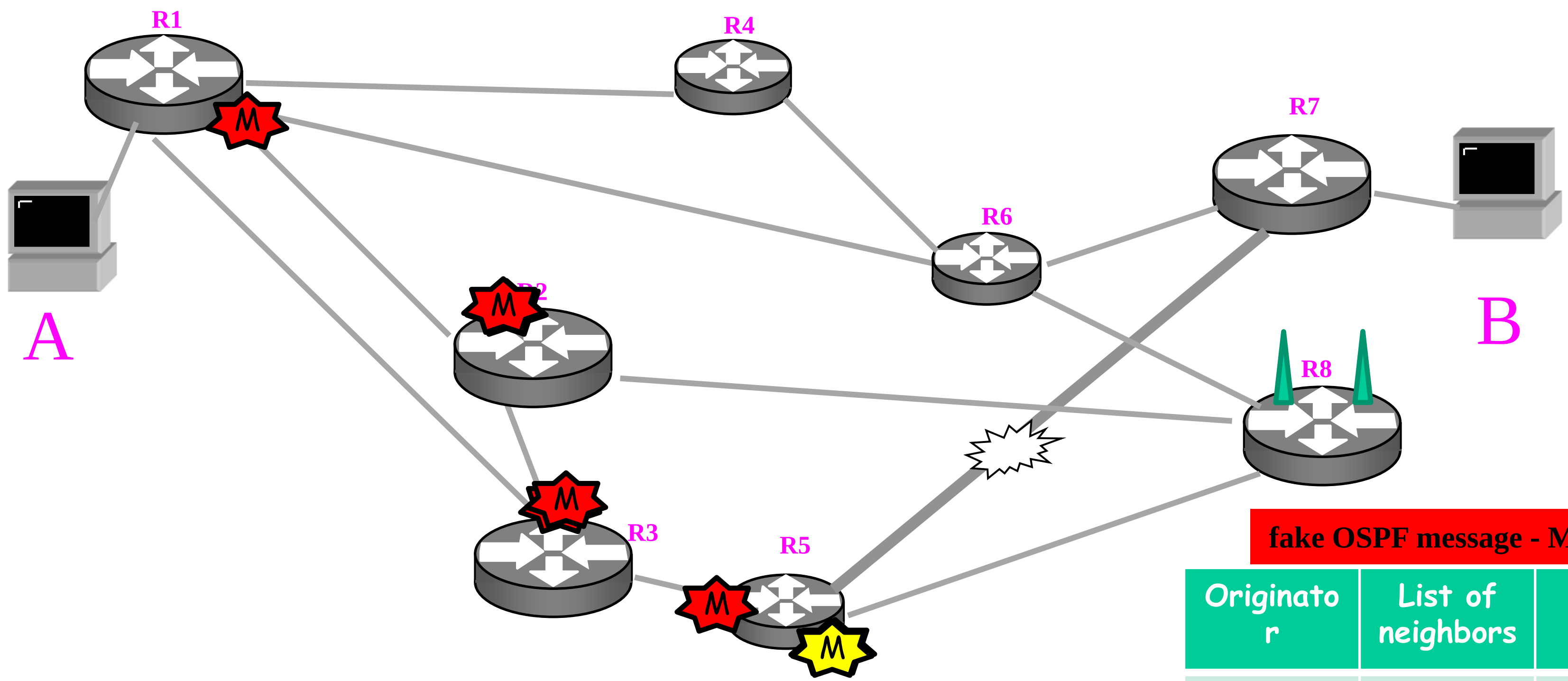
Routing path before from A to B



Routing path after from A to B

OSPF Fight Back Mechanism

When a router receives a message in its own name that it didn't originate, it sends a **fight back** message to all its neighbors



fake OSPF message - M		
Originato r	List of neighbors	Links costs
r5	r3,r8	…

The fight back message is supposed to revert the effect of the attack eventually

OSPF Attacks

- An **attack** is a **run** of the protocol that creates a **fake topology view** for some routers in the network
- An attack is called **persistent** if the **fake** topology view **remains** in some routers' databases
- We are interested in **finding persistent attacks**

OSPF Concrete Model

- A fixed network topology
- Router Model
  - Models a legitimate router
- Attacker Model
  - Models a malicious router
    - can send any **random message** to any **random destination** router
    - can **ignore** incoming messages.

In our model:

- Messages originated by the attacker are marked with a special flag **isFake**

- This flag is not part of the OSPF standard, and legitimate routers **do not make use of it**

- This flag **allows us to easily define the specifications** for the model

OSPF Concrete Model

- Our **formal model** for OSPF is a **finite state machine** with global states and transitions
- The model is a **simplified version** of OSPF, which includes the fight back mechanism

Specification

- A global state is considered **attacked** if:
  - Some router has a fake message in its database
  - No message resides in any router's queue

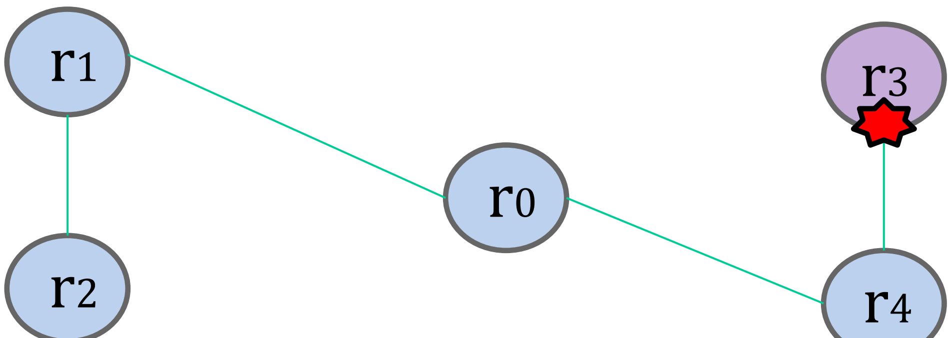
- An attacked state **defines the outcome** of a **successful persistent attack** regardless of a specific attack technique

Model Checking

- We implemented the model of OSPF in **C** , and used the **Bounded Model Checking** tool **CBMC** to find **persistent attacks** on OSPF
- A **counterexample** returned by CBMC is an **attack**

Example of Attacks on OSPF

Attack #1

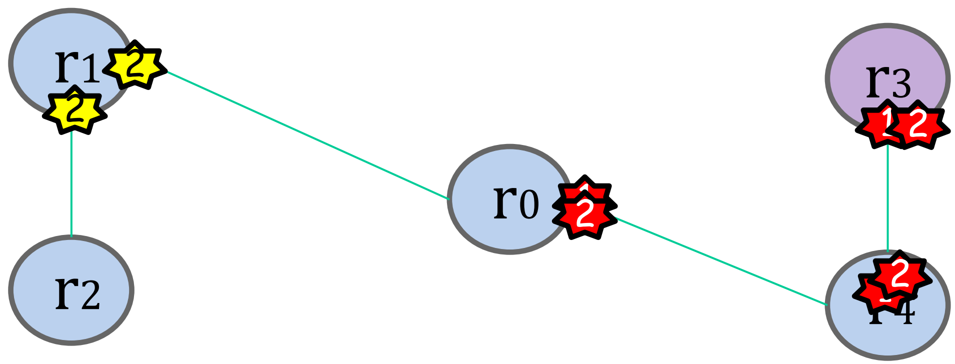


- The attacker (r3) originates a fake message:

dest = r2, orig = r4

Example of Attacks on OSPF

Attack #2

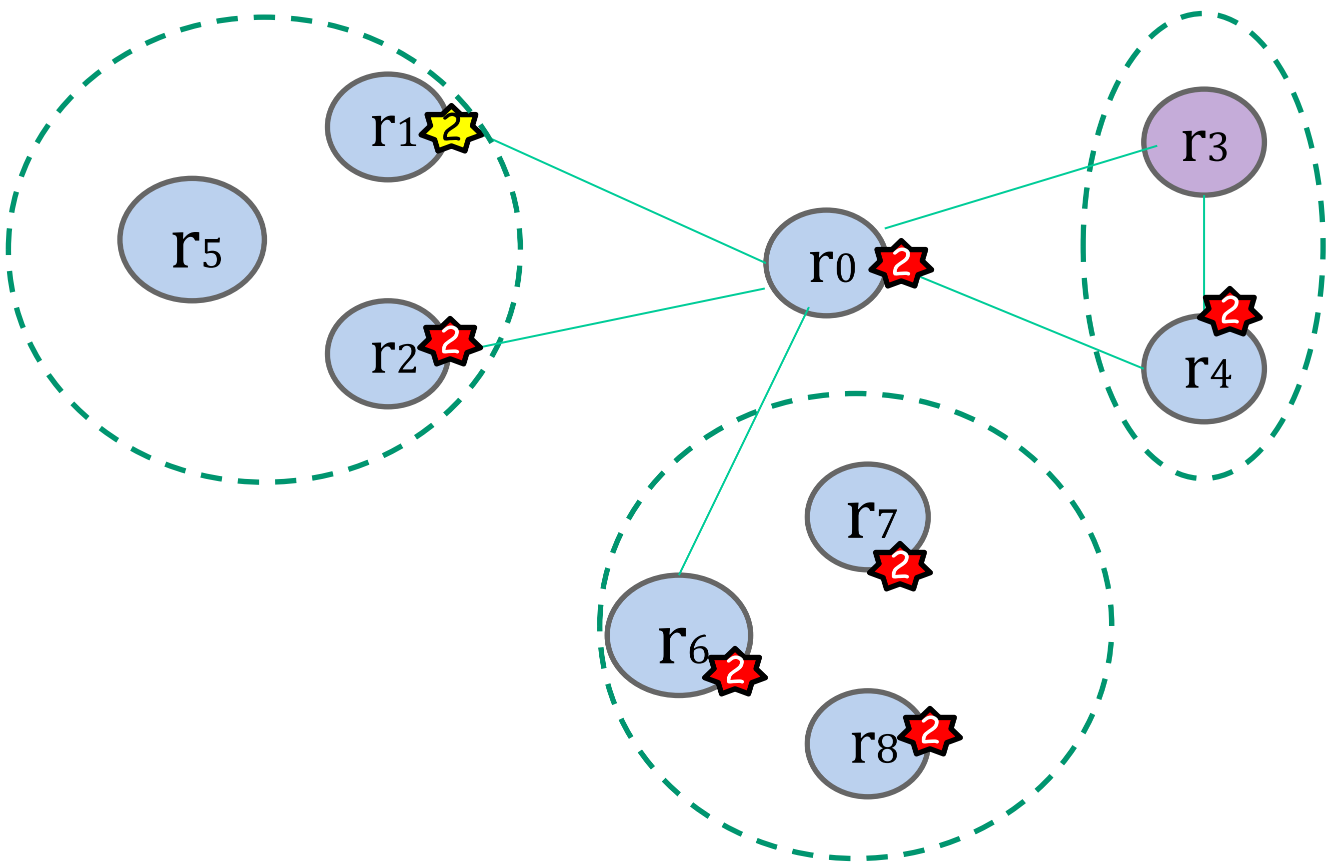


- The attacker (r3) sends two fake messages:

m1 = (dest = r4, orig = r1, sequence_number = 1)

m2 = (dest = r4, orig = r1, sequence_number = 2)

Another demonstration of attack #2 on a different topology



Concrete Model - Problems

- **state explosion problem**
  - Models that can be handled are very small in size and hence **restricted in their topologies and functionality**
  - We would like to **extend** our search for attacks to **larger and more complex topologies**

Abstract Model

- We are interested in **general** attacks
  - insensitive to most of the topology's details
  - **can be applied in a family of topologies**

- We define an abstract model which:
  - represents a family of concrete models
  - under-approximates each member in the family.

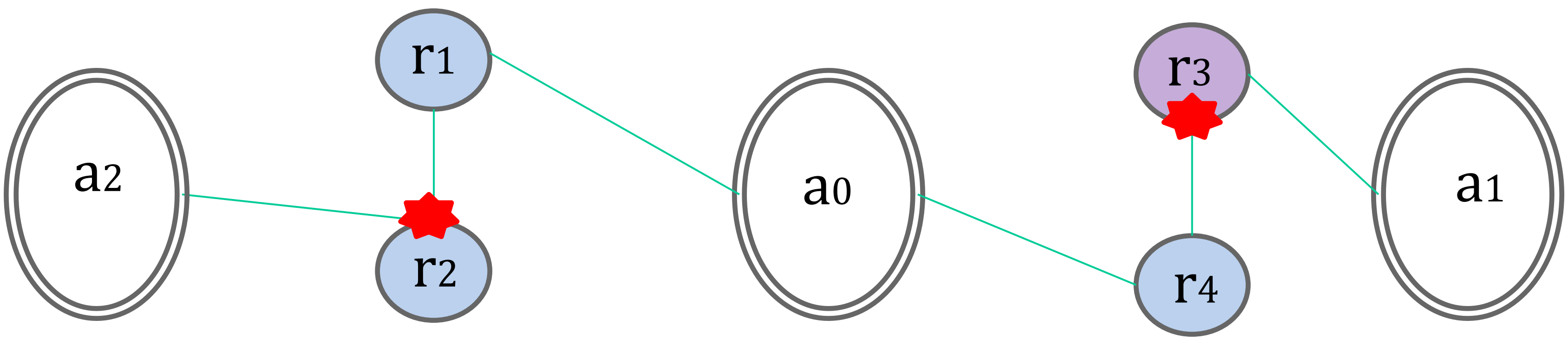
Abstract Model

- The abstract model consists of an **abstract topology** and an **abstract protocol**
- We defined several levels of **abstract components**
- An abstract topology may also contain some un-abstracted routers
- The **attacker** is always an **un-abstracted** router

Main Property of the Abstract Model

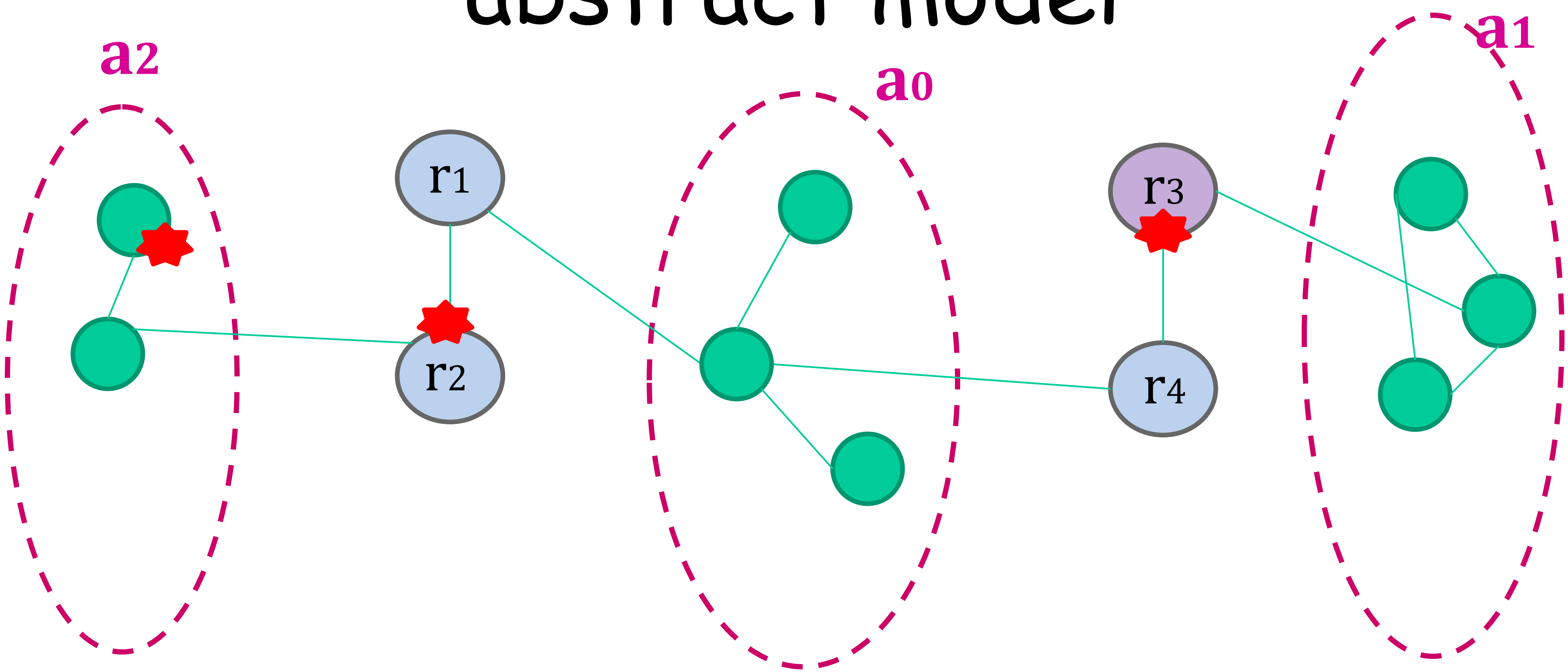
- If an attack is found on an abstract network, then **there is a corresponding attack** on **each one** of the concrete networks represented by it.

Example of an Abstract Attack on OSPF in the Abstract Model

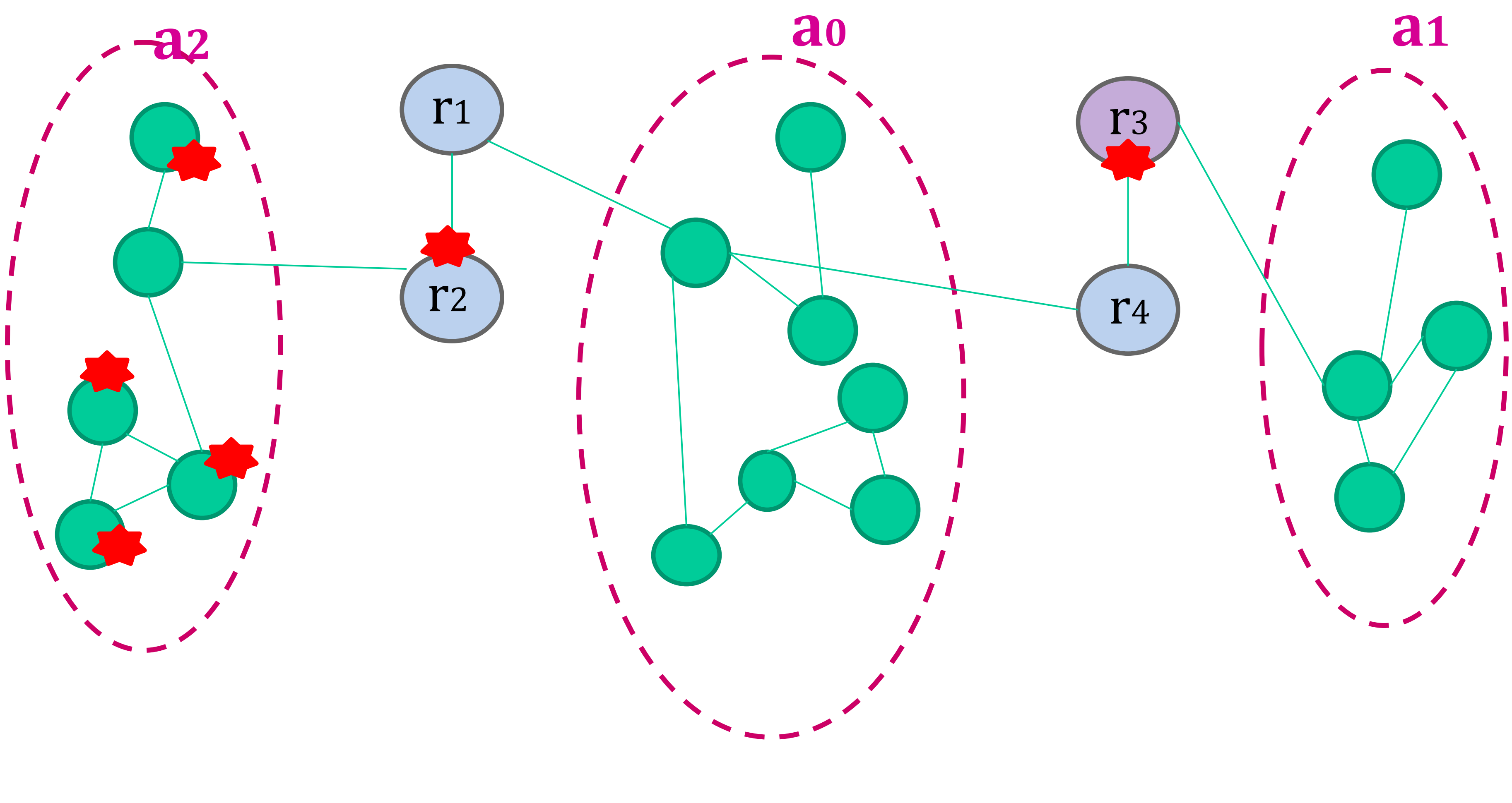


- The attacker sends a fake message with: dest=2, orig=4

Example of an attack in a concrete instantiation of the abstract model

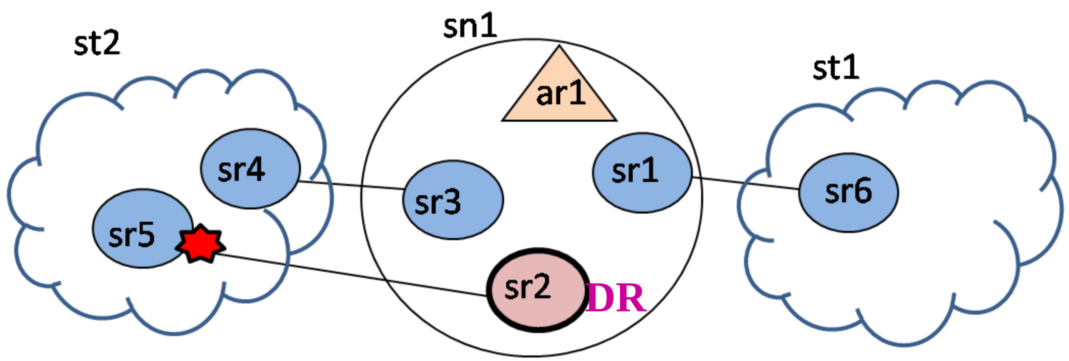


Example of a similar attack on another possible instantiation of the abstract model



Examples of attacks on OSPF in the abstract model

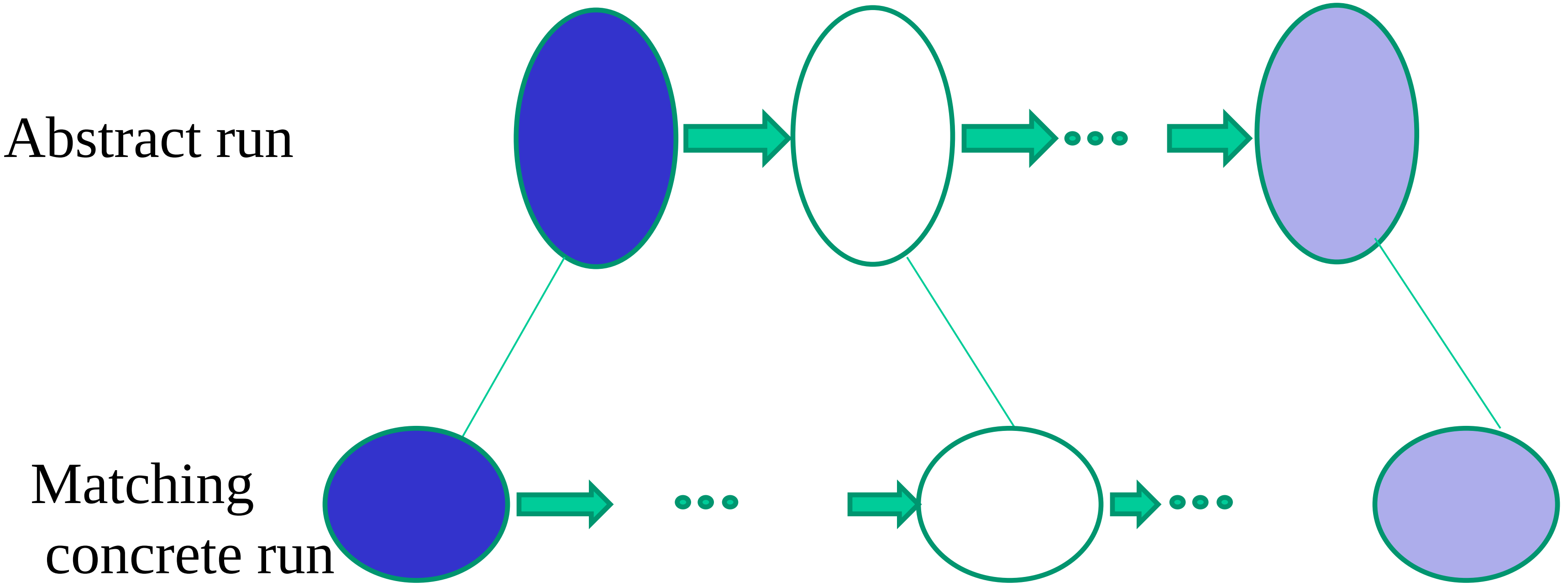
- Attack # 2



  - The attacker (designated router) originates a fake message on behalf of sr1: m = (dest = sr5; orig = sr1; seq = 1; isFake = T)

Correctness of Our Method

- Lemma
  - For each abstract transition on the abstract topology, there is a corresponding concrete finite run on each matching concrete topology



Correctness of Our Method

- Theorem
  - An abstract attack found on an abstract topology T_A, has a corresponding attack on each matching concrete topology T_C.

- Exposed OSPF vulnerabilities:
    - a message is opened only by its destination
    - the flooding procedure does not flood a message back to its source
  - As a result, a fake message in the name of router r might be sent through r
  - If the attacker plays the role of a designated router, then by ignoring messages it can stop message flooding, including fight back messages

Conclusion

- We automatically found attacks on small concrete models
- We automatically found general attacks on small abstract models
- The general attacks are applicable to huge networks, with possibly thousands of routers
  - No model checker can be applied directly to such networks

Conclusion

- We developed a novel technique for parameterized networks suitable for finding a counterexample (in our case an attack) on each member of the family

Thank You