

Verification of

Directed Acyclic Ad-Hoc Networks

Othmane
Rezine





Verification of

Directed Acyclic Ad-Hoc Networks

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Abdulla



Mohammed
Faouzi Atig



Othmane
Rezine





Ad-Hoc Networks

Directed Acyclic



Ad-Hoc Networks

Directed Acyclic



Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

Directed Acyclic



Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

Directed Acyclic

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*



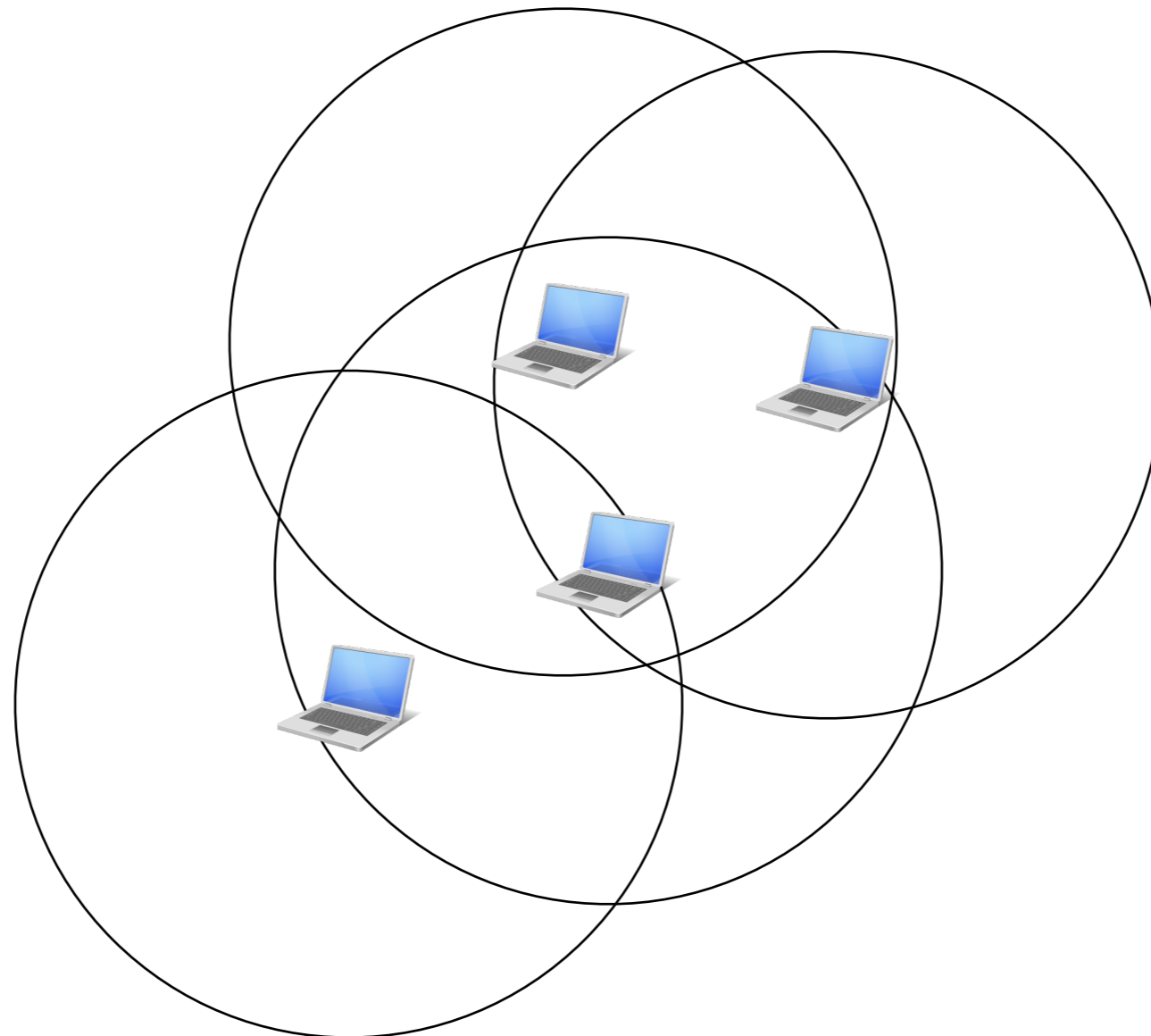
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*
- ▶ Radio Range



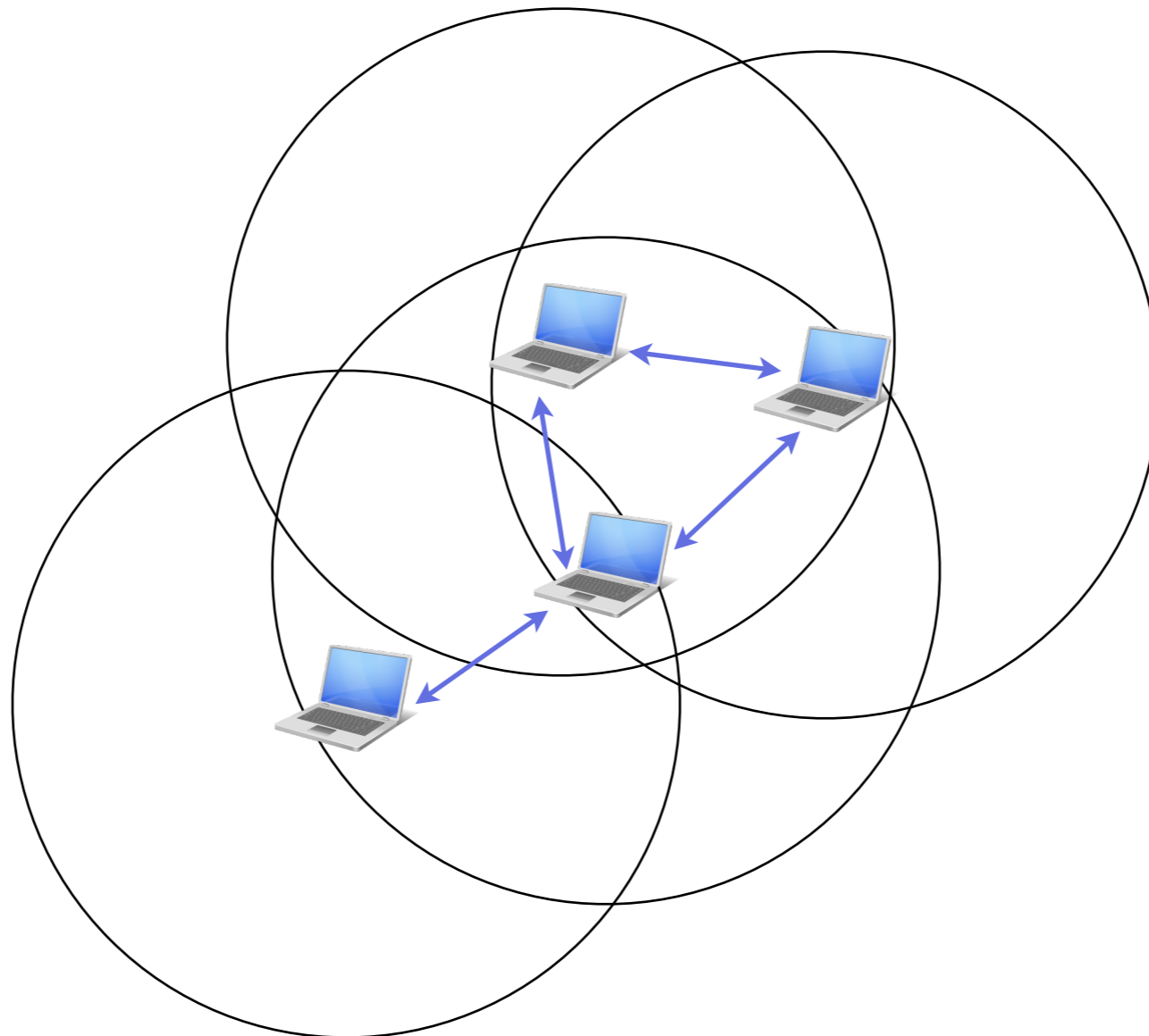
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*
- ▶ Radio Range
- ▶ Links / Topology



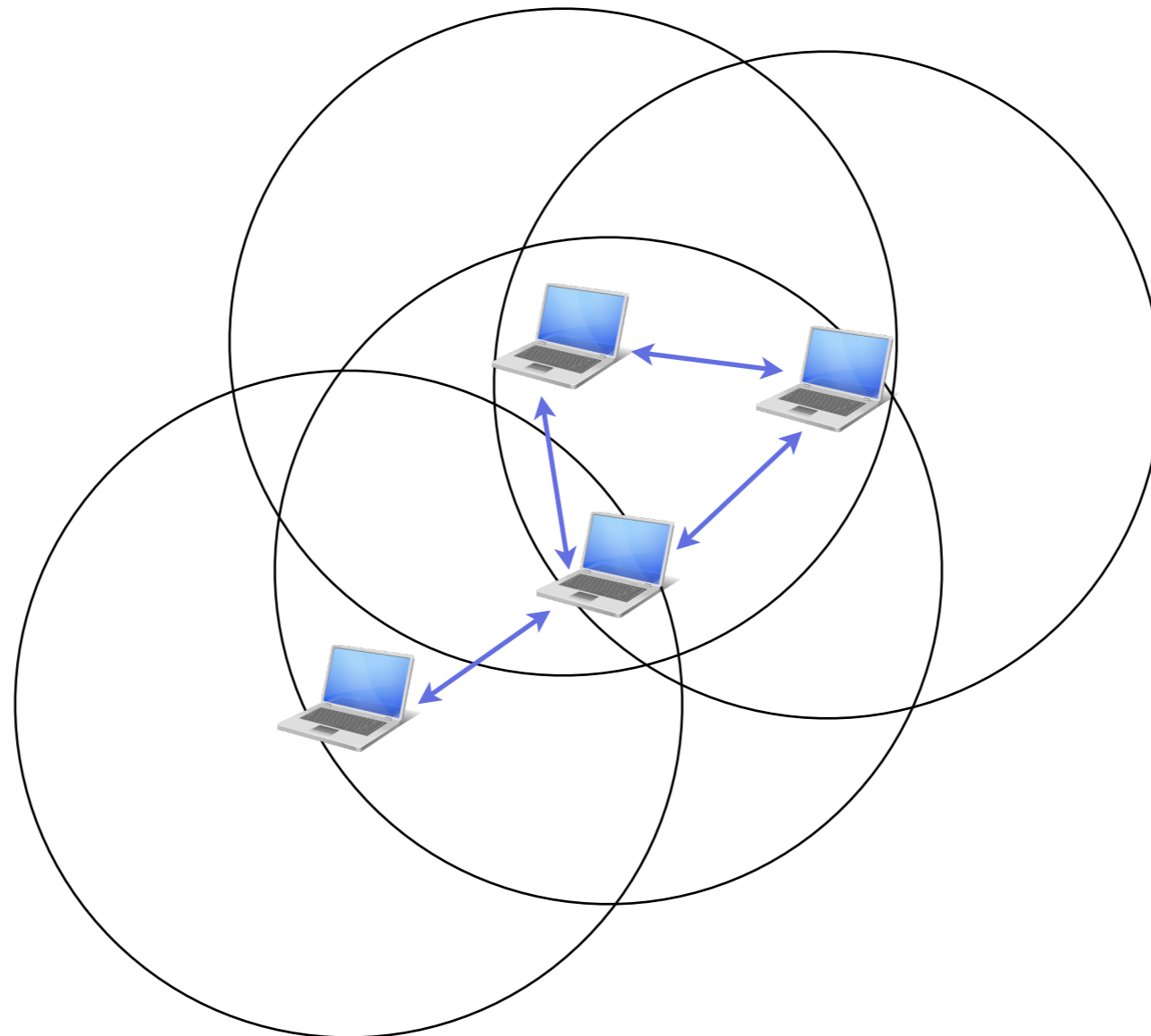
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*
- ▶ Radio Range
- ▶ Links / Topology
- ▶ Distributed management of the network



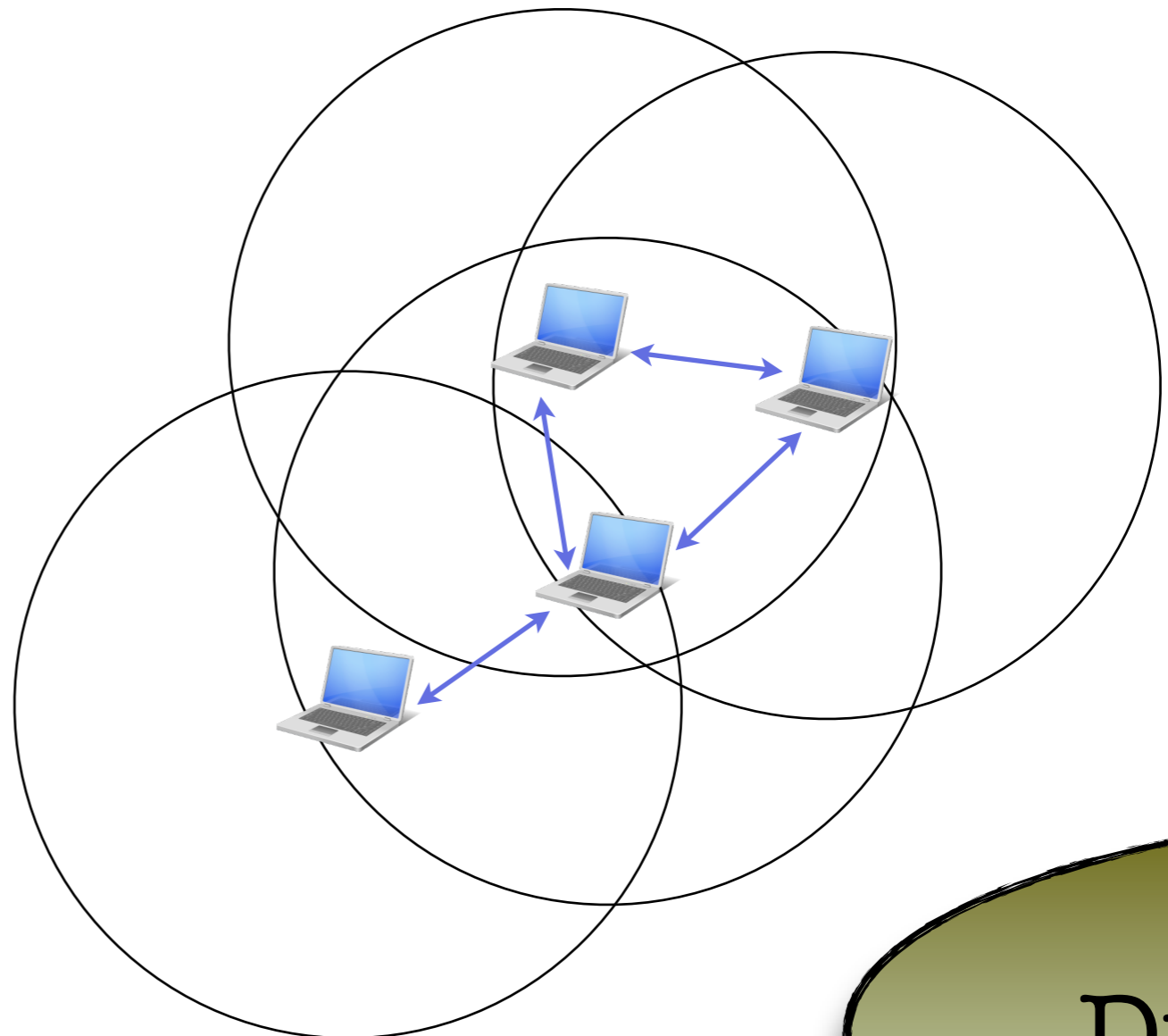
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*
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Direct

Ad-Hoc Networks

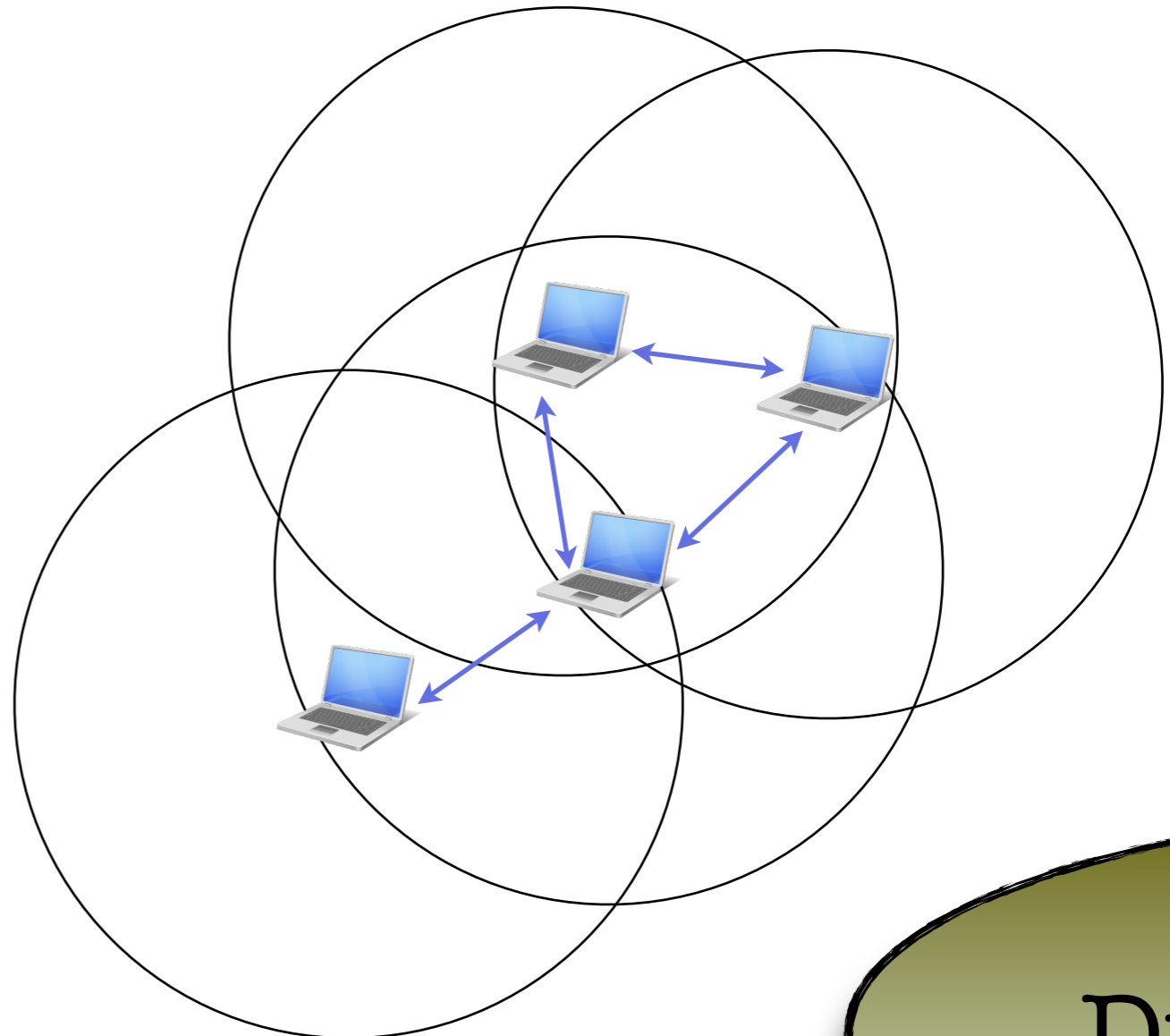
- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: *laptop*
- ▶ Radio Range
- ▶ Links / Topology
- ▶ Distributed management of the network

Applications

- ▶ Home area networks
- ▶ lack of telecom infrastructure



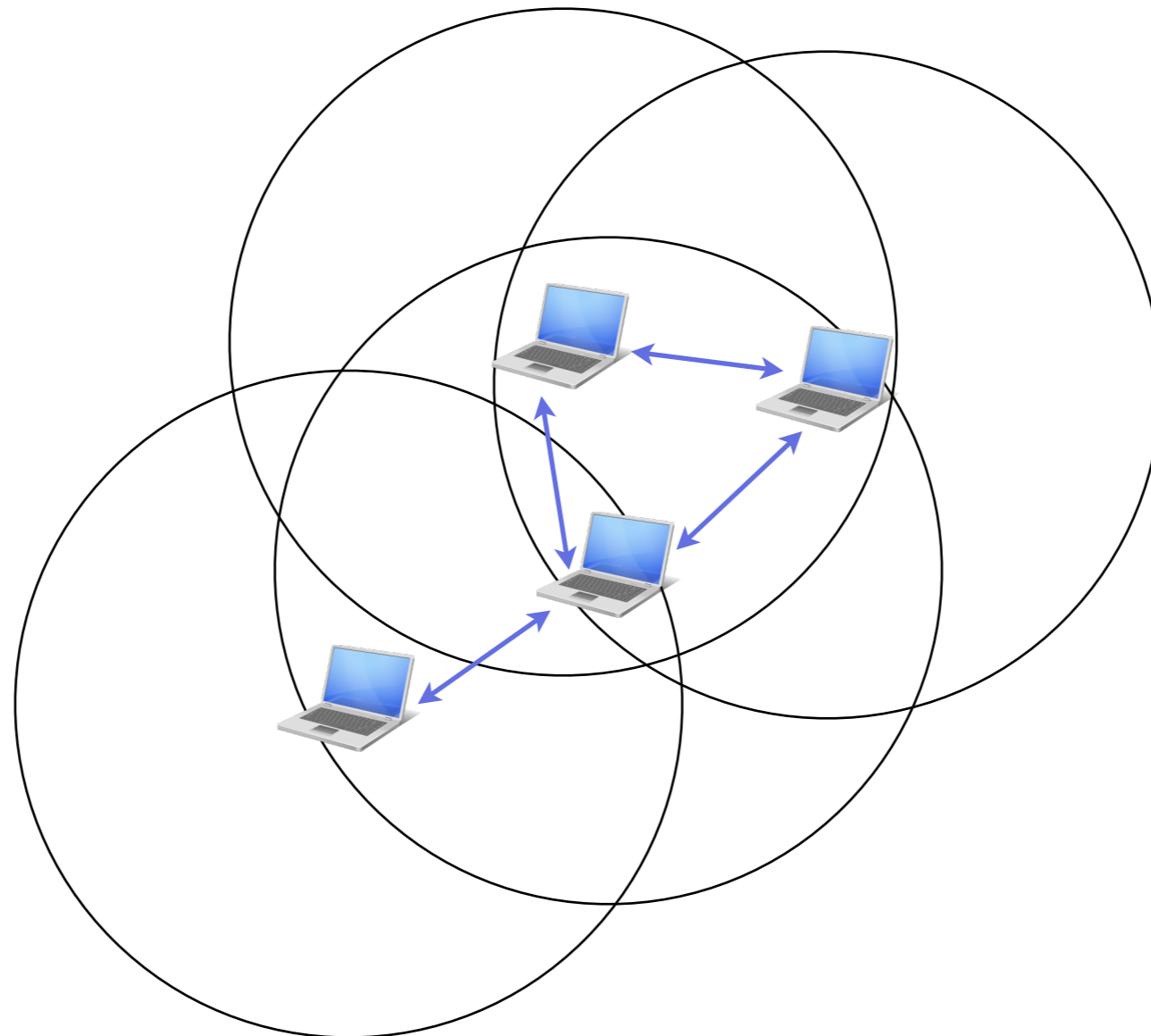
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Ad-Hoc Networks

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- ▶ Reachability



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- ▶ Radio Range
- ▶ Links / Topology
- ▶ Distributed management of the network



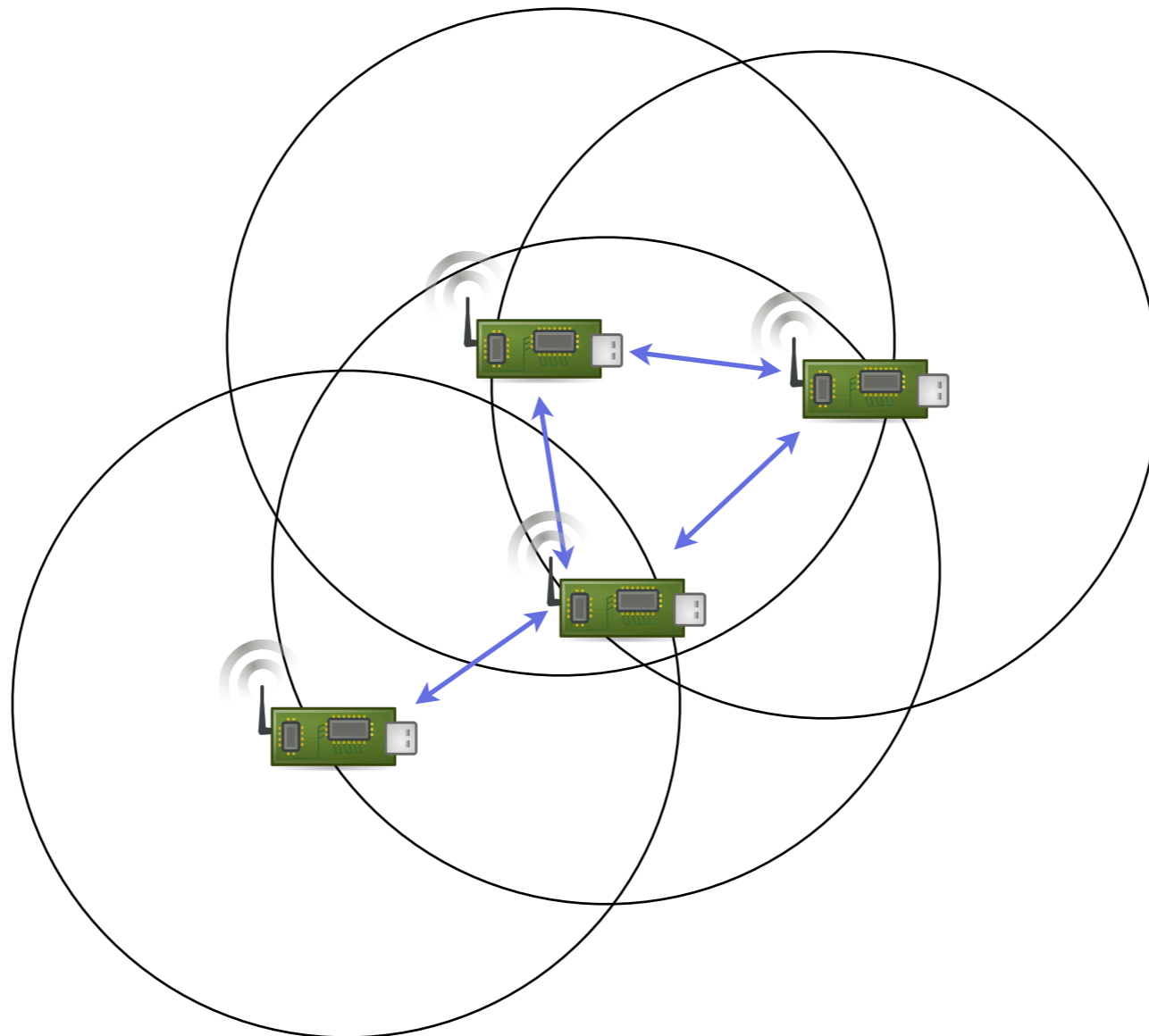
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Wireless nodes: ~~laptop~~ sensors
- ▶ Radio Range
- ▶ Links / Topology
- ▶ Distributed management of the network



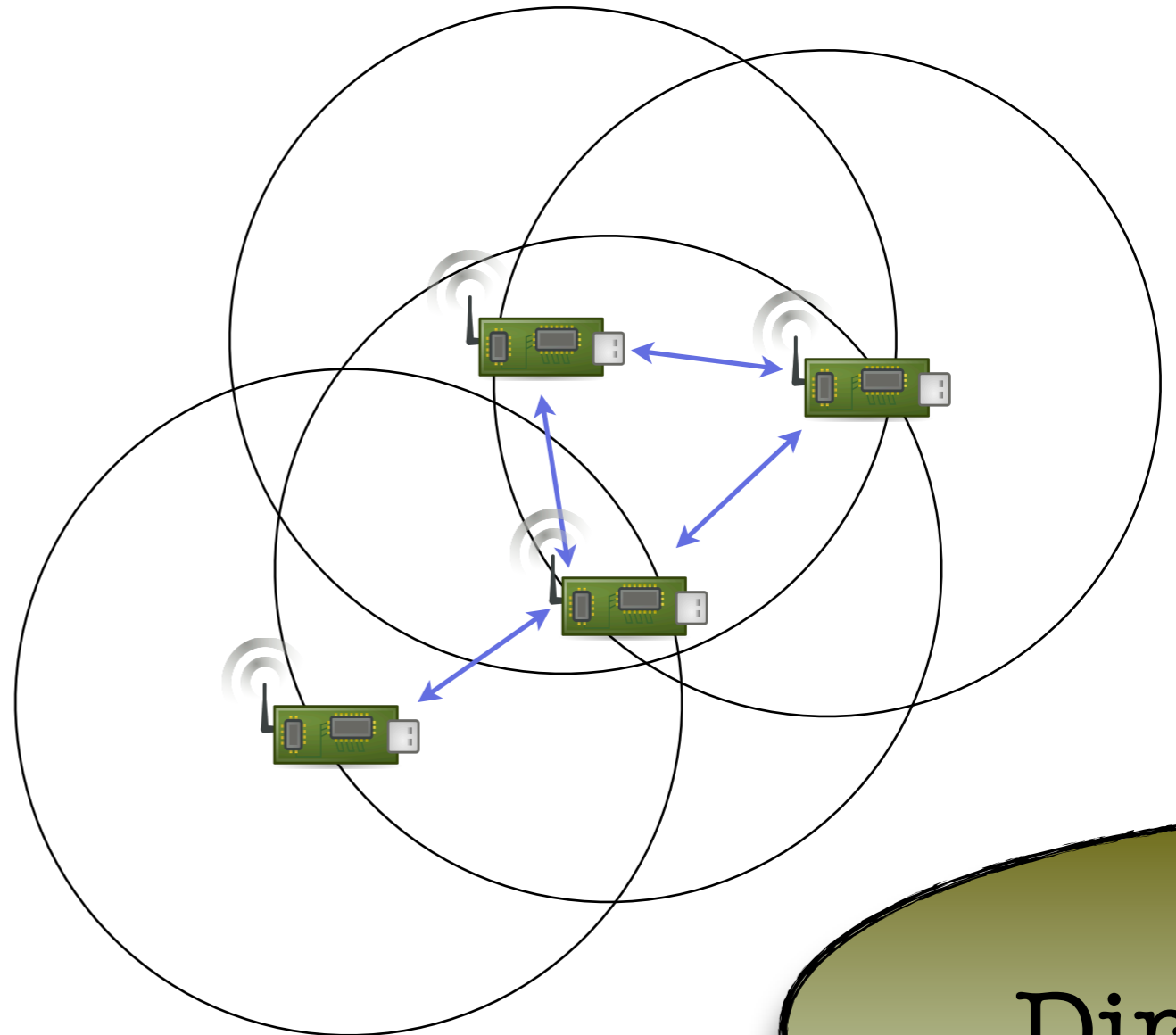
Direct

Ad-Hoc Networks

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- ▶ Wireless nodes: ~~laptop~~ sensors
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Direct

Ad-Hoc Networks

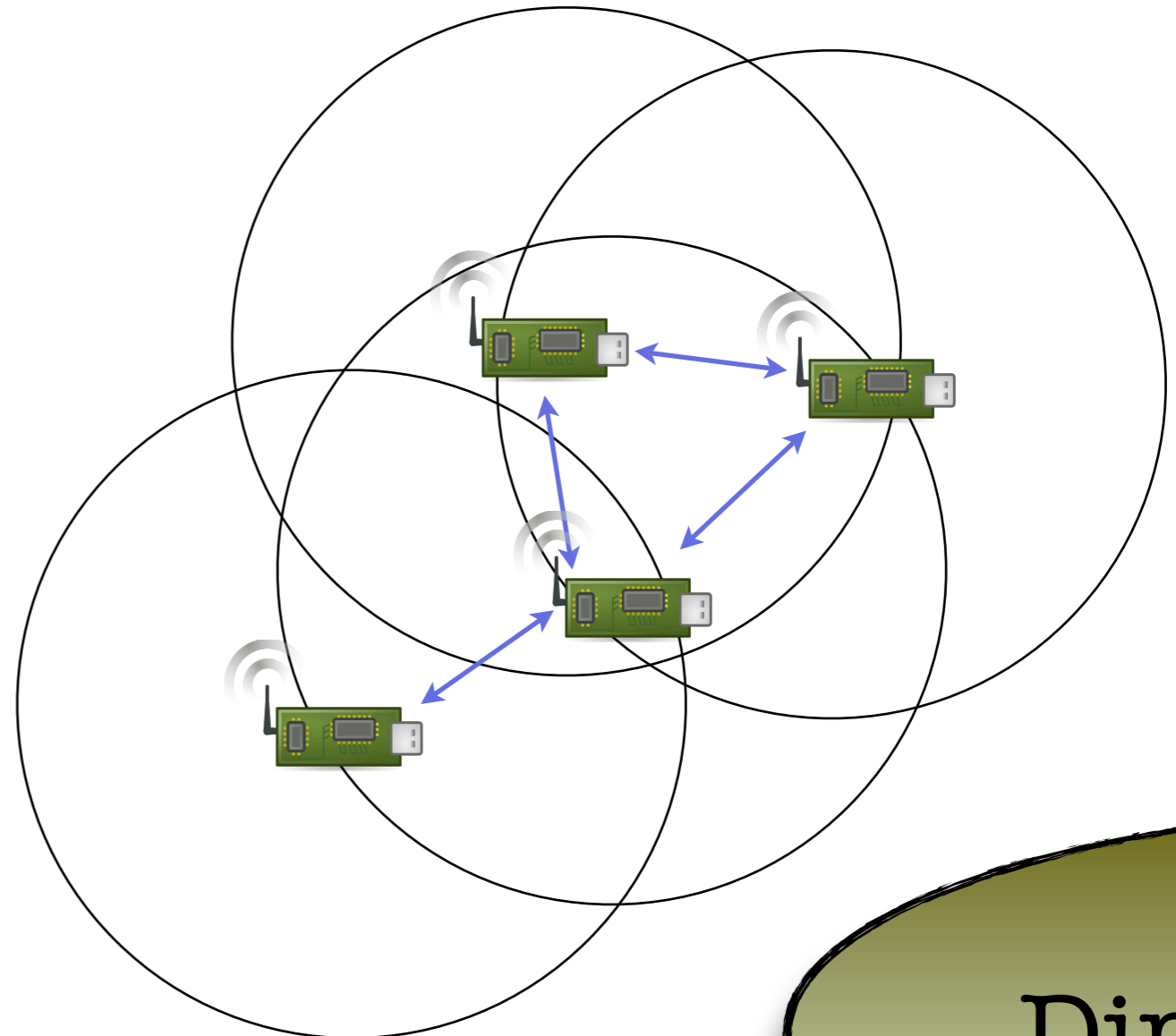
- ▶ Model
- ▶ Transition System
- ▶ Reachability

- ▶ Wireless nodes: ~~laptop~~ sensors
- ▶ Radio Range
- ▶ Links / Topology
- ▶ Distributed management of the network

Applications

Monitoring of

- ▶ Seismic activity
- ▶ Heat
- ▶ Pollution



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



G. Delzanno, A. Sangnier, G. Zavattaro
Parameterized verification of ad-hoc networks

CONCUR'10

Ad-Hoc Networks

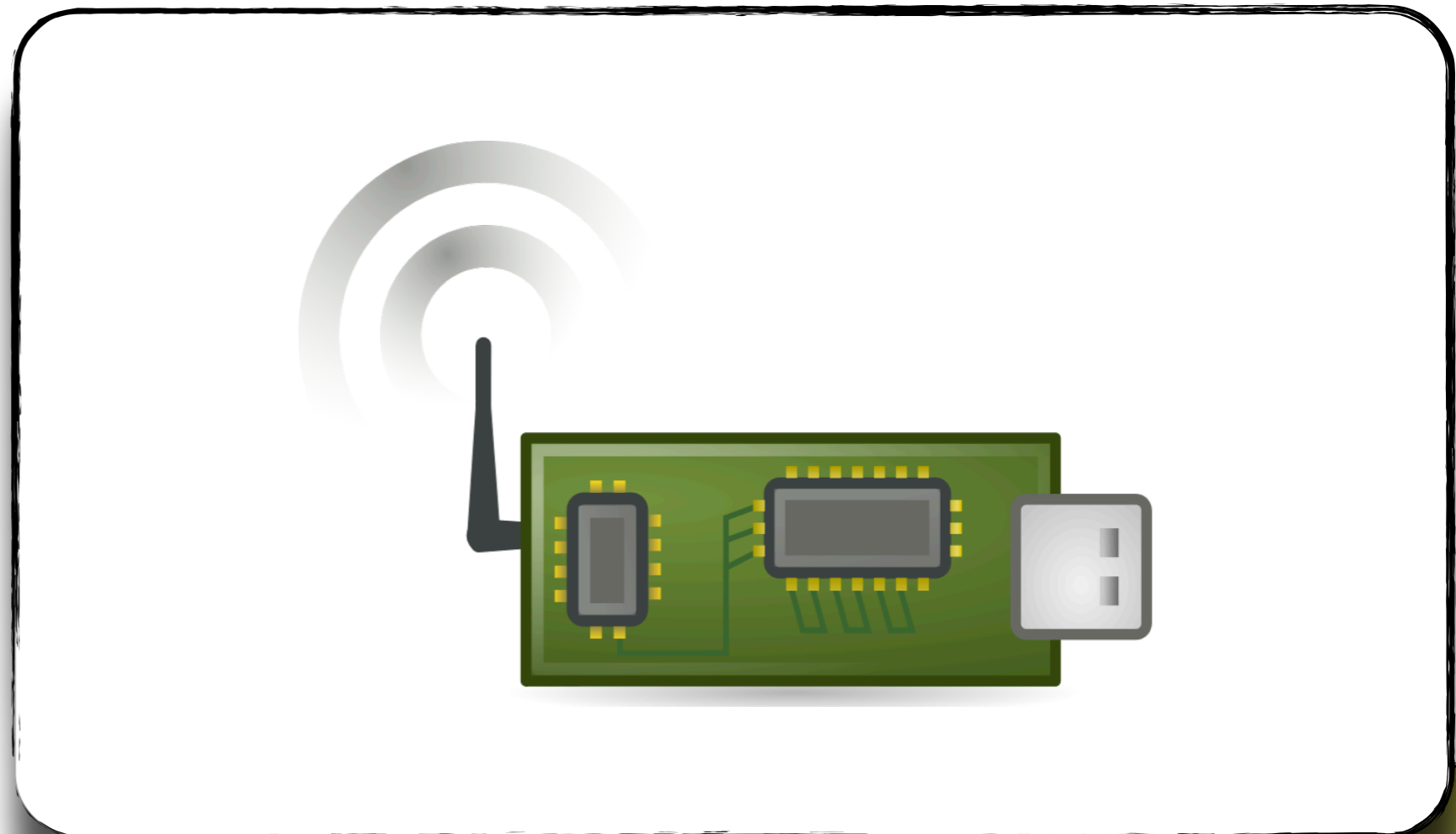
- ▶ Model
- ▶ Transition System
- ▶ Reachability



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CONCUR'10

Model



Direct

Ad-Hoc Networks

- ▶ Model
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- ▶ Reachability

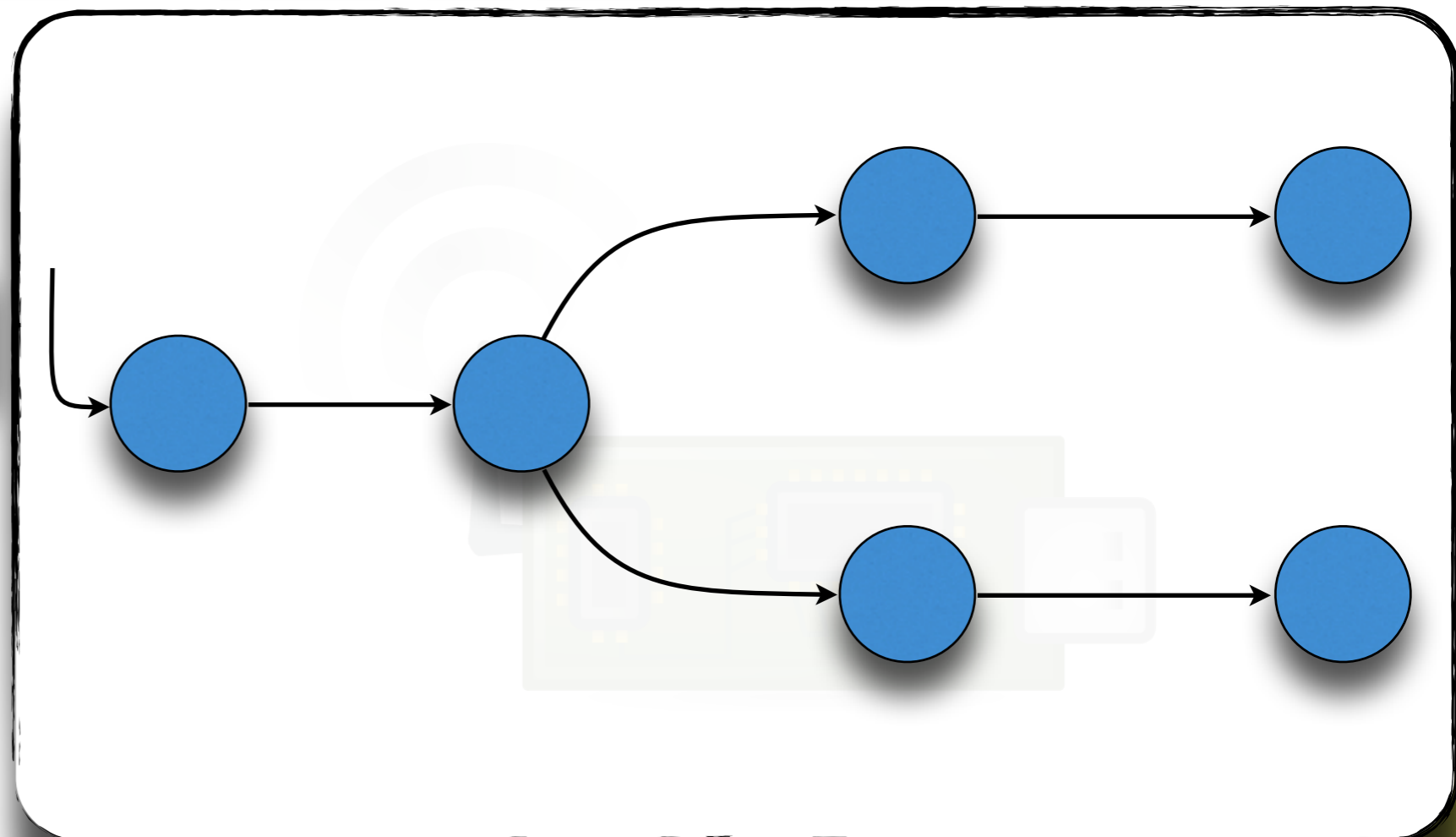


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Model

Node:
Process



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

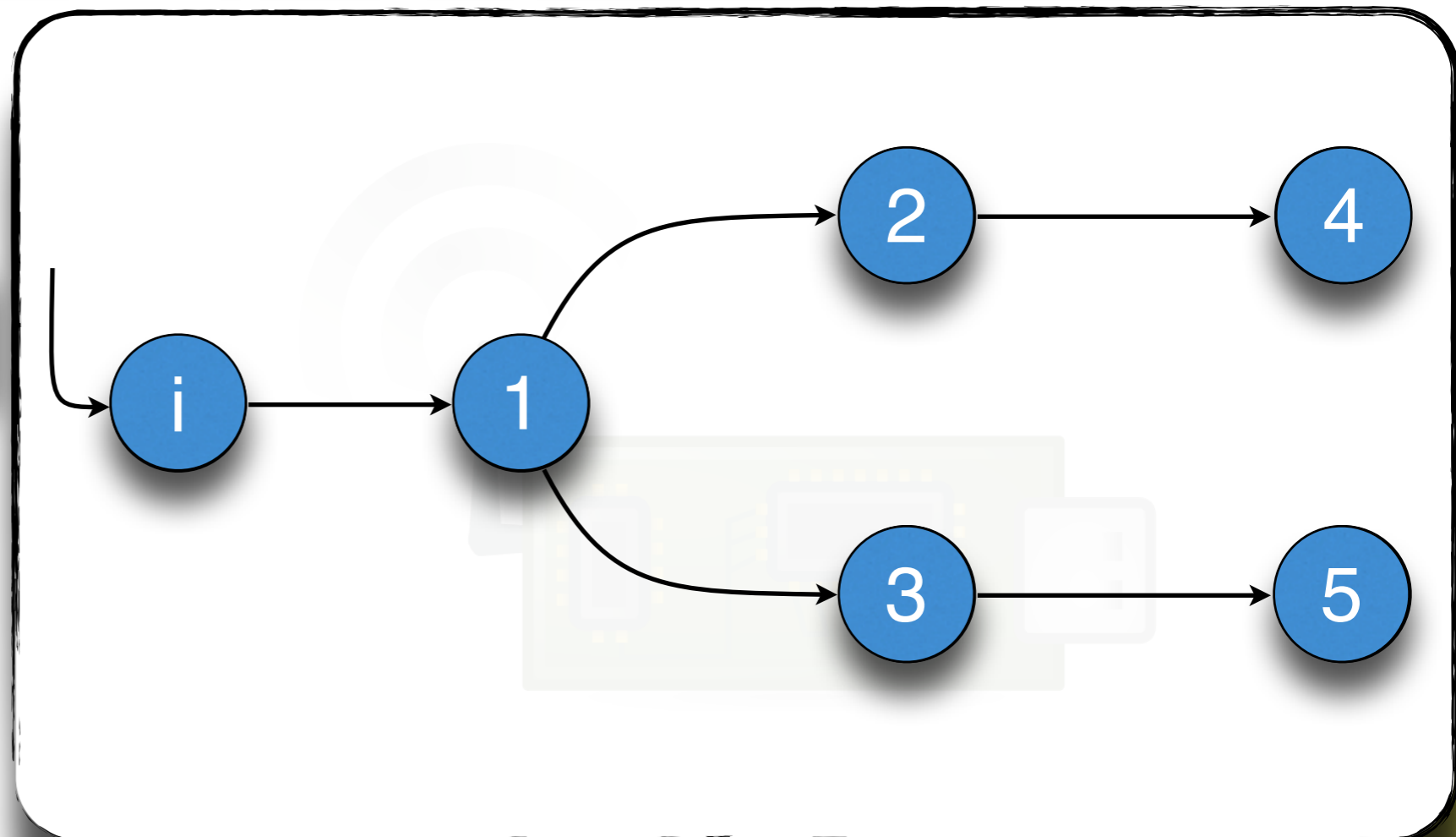


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Model

Node:
Process



Direct

Ad-Hoc Networks

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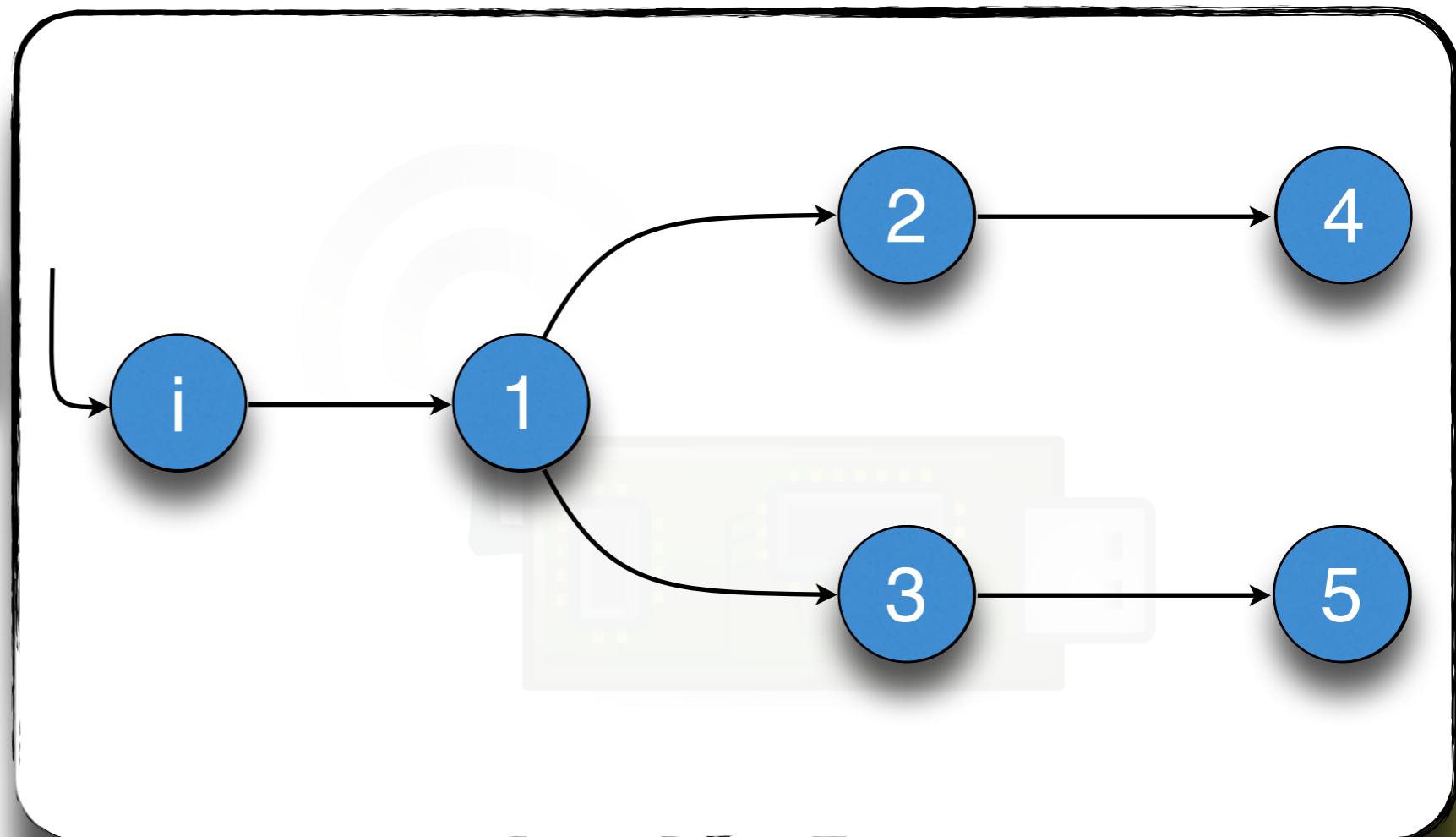
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Model

Node:
Process

Transitions:



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



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Parameterized verification of ad-hoc networks

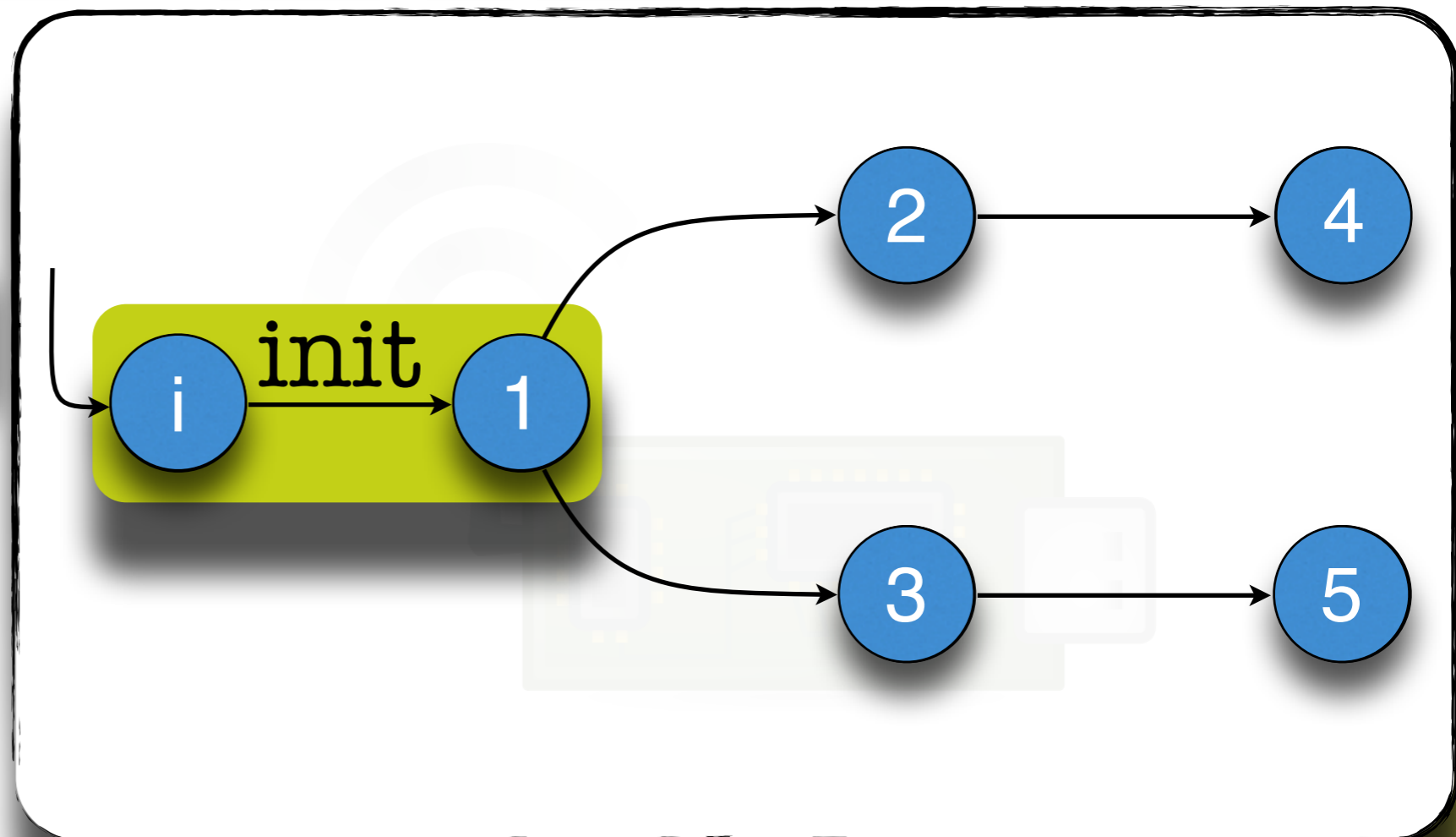
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Model

Node:
Process

Transitions:

▶ Local



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



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Parameterized verification of ad-hoc networks

CONCUR'10

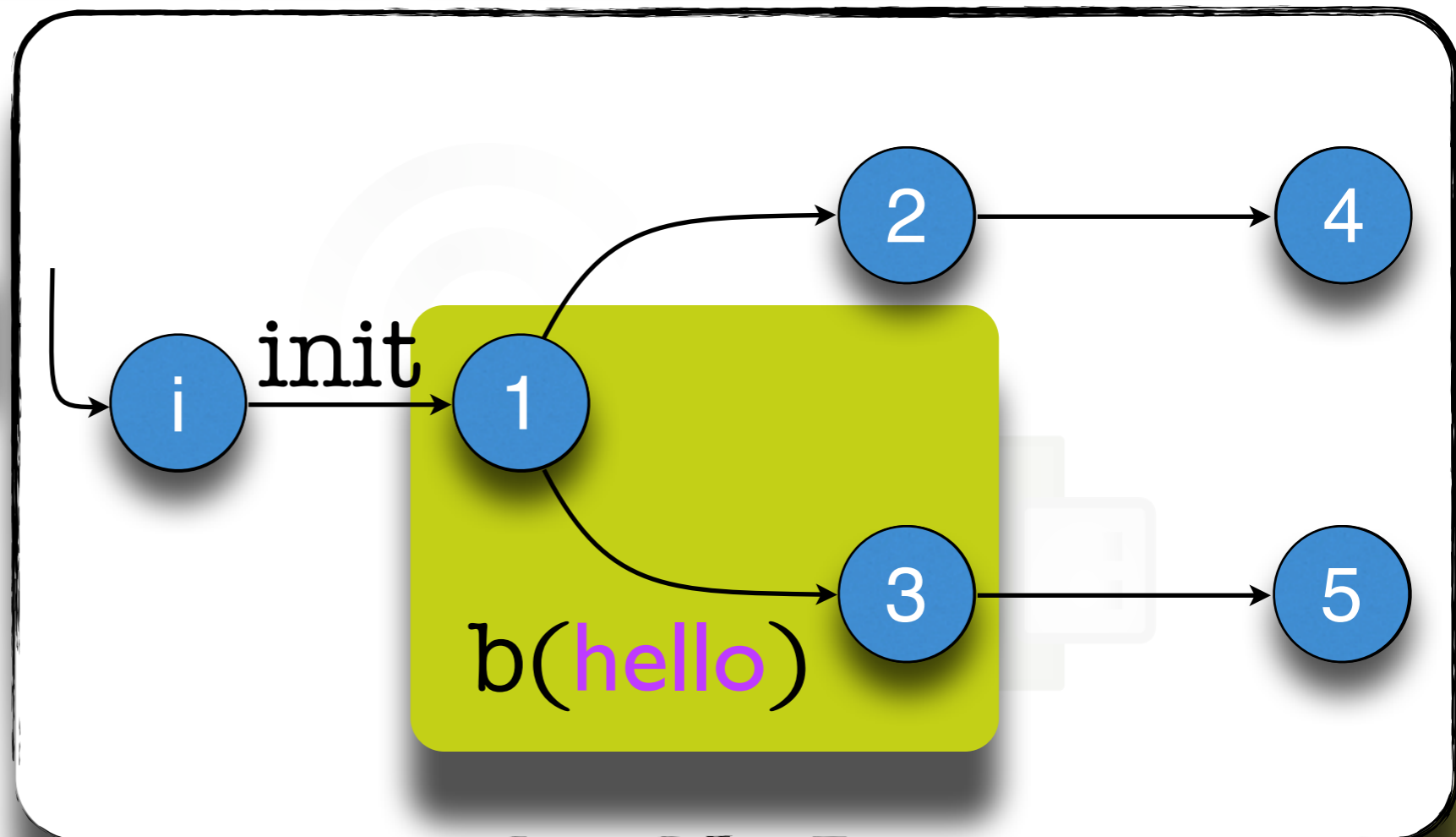
Model

Node:
Process

Transitions:

▶ Local

▶ Broadcast



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



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Parameterized verification of ad-hoc networks

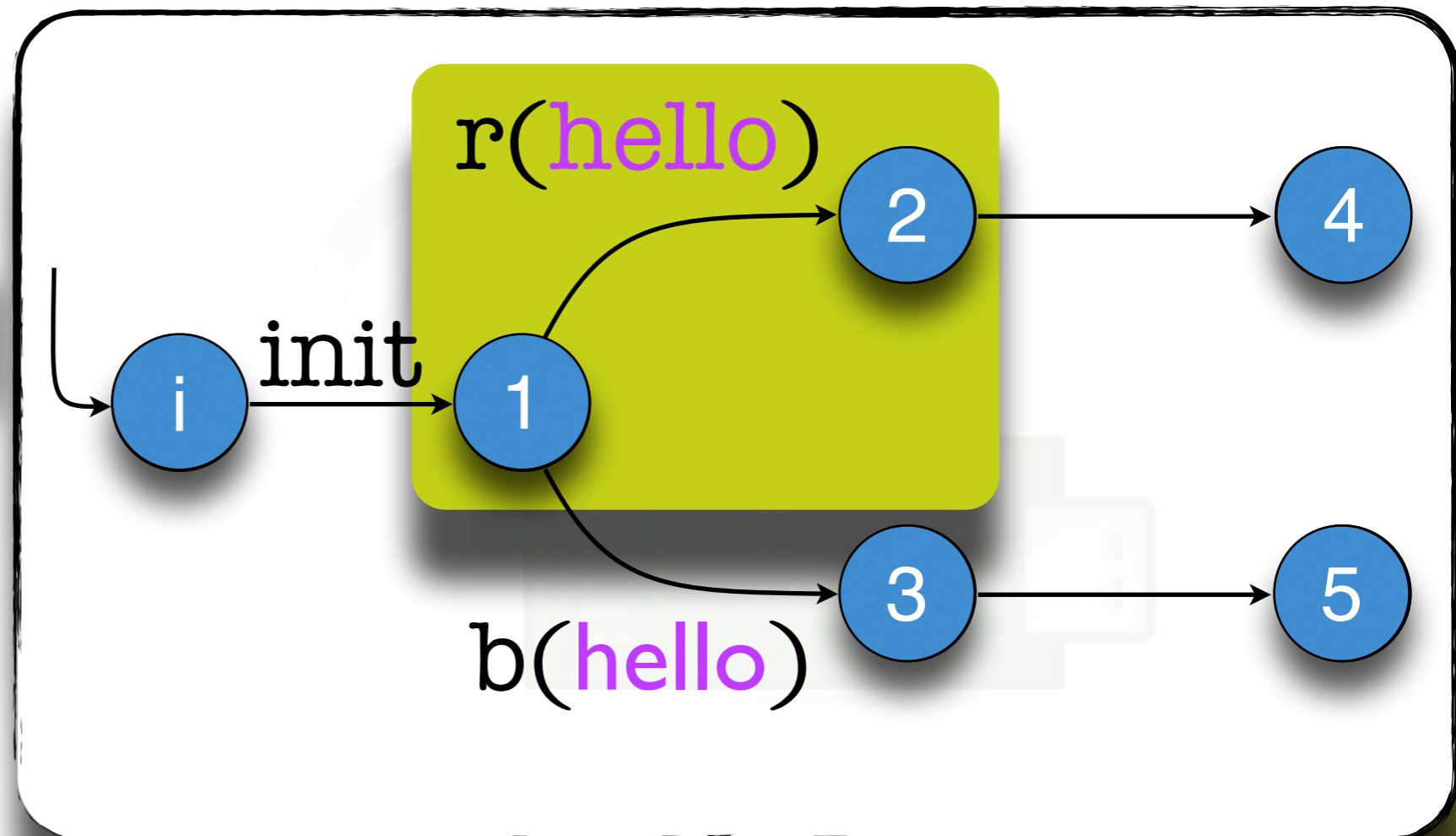
CONCUR'10

Model

Node:
Process

Transitions:

- ▶ Local
- ▶ Broadcast
- ▶ Receive



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



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Parameterized verification of ad-hoc networks

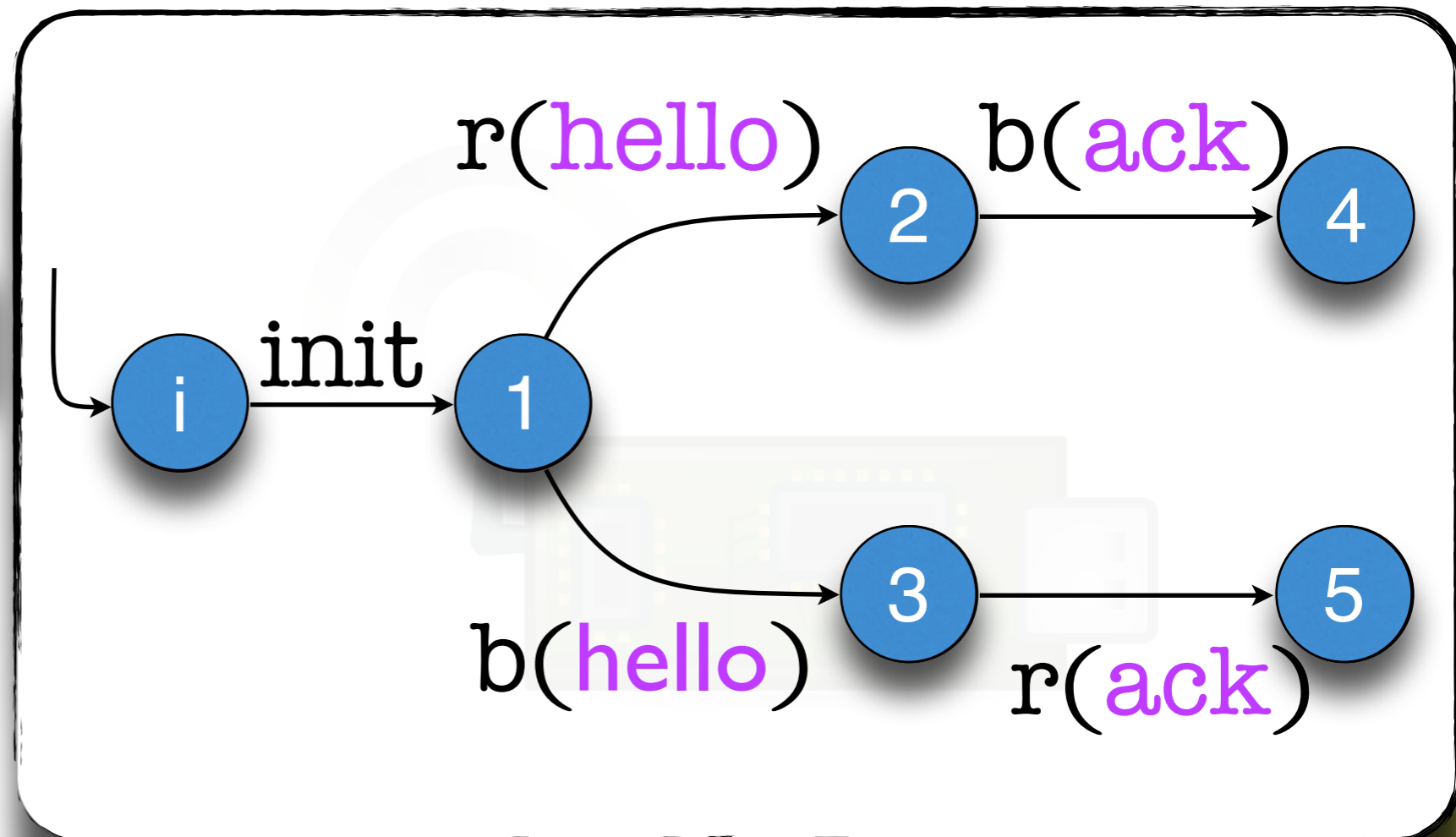
CONCUR'10

Model

Node:
Process

Transitions:

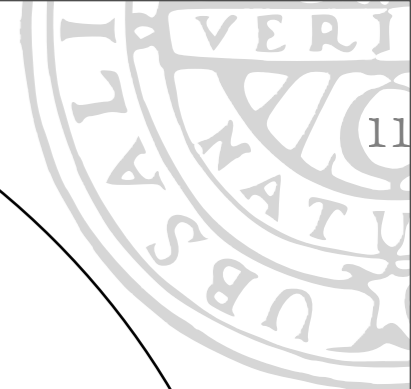
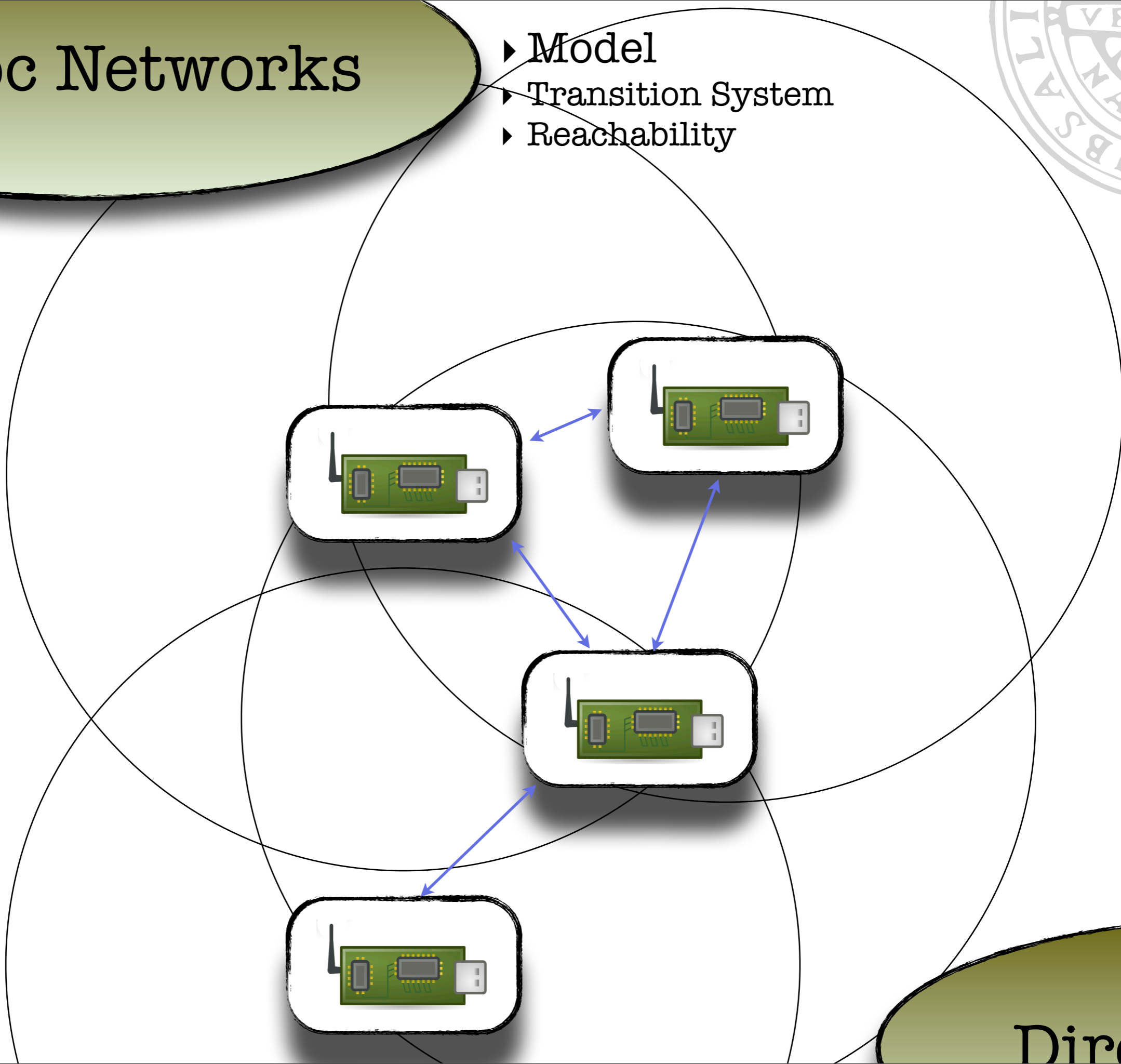
- ▶ Local
- ▶ Broadcast
- ▶ Receive



Direct

Ad-Hoc Networks

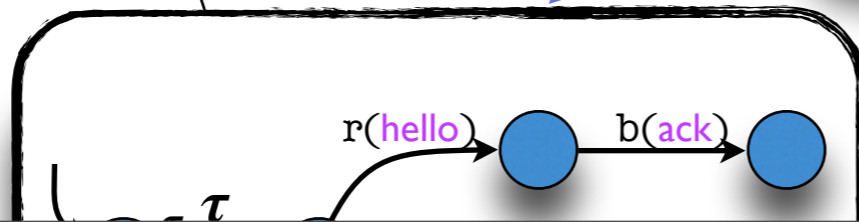
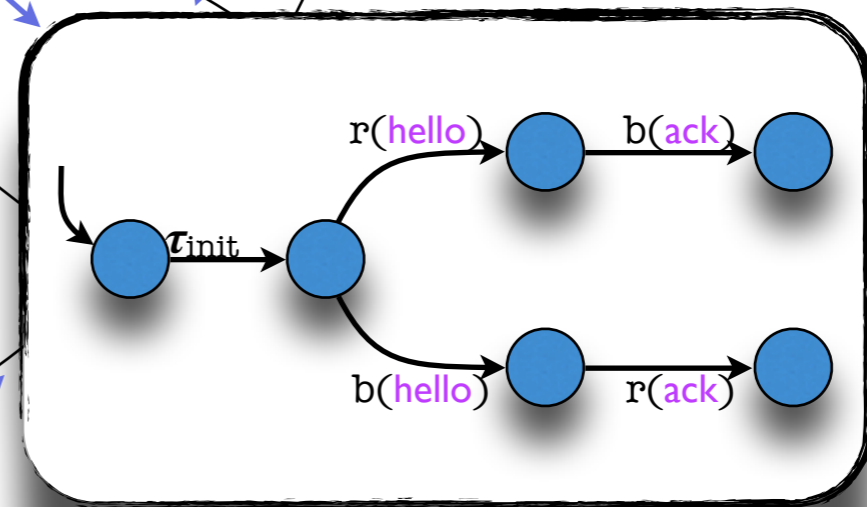
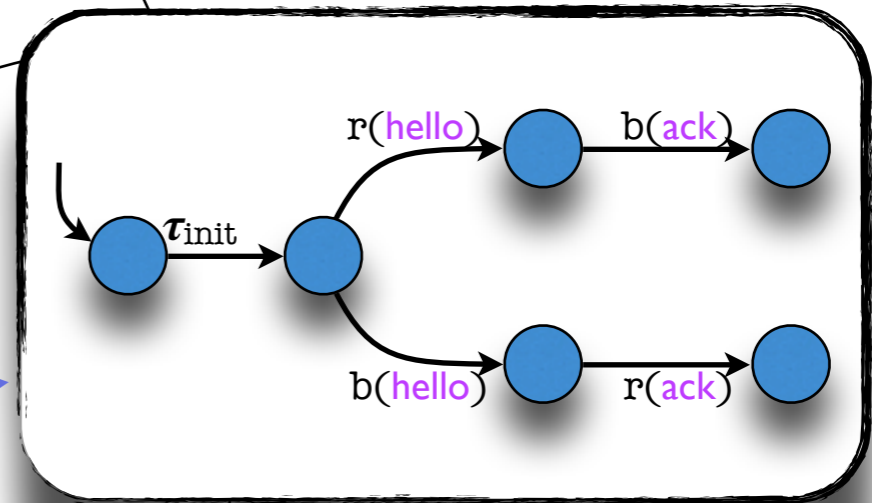
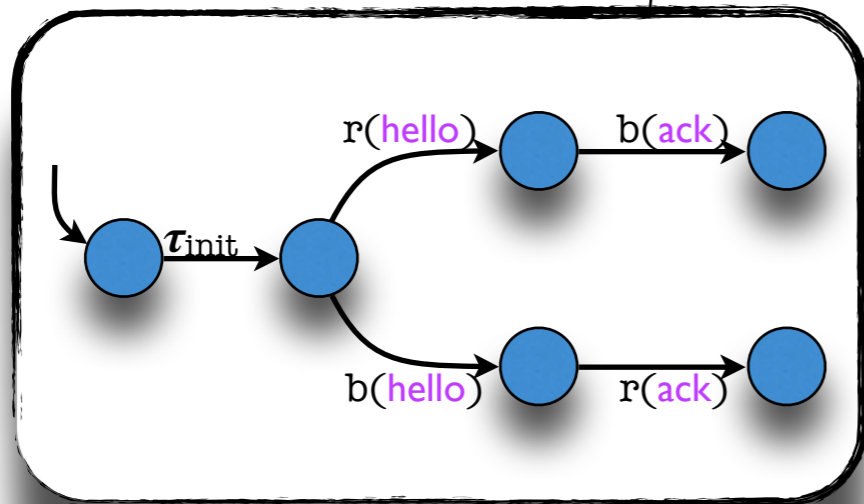
- ▶ Model
- ▶ Transition System
- ▶ Reachability



Direct

Ad-Hoc Networks

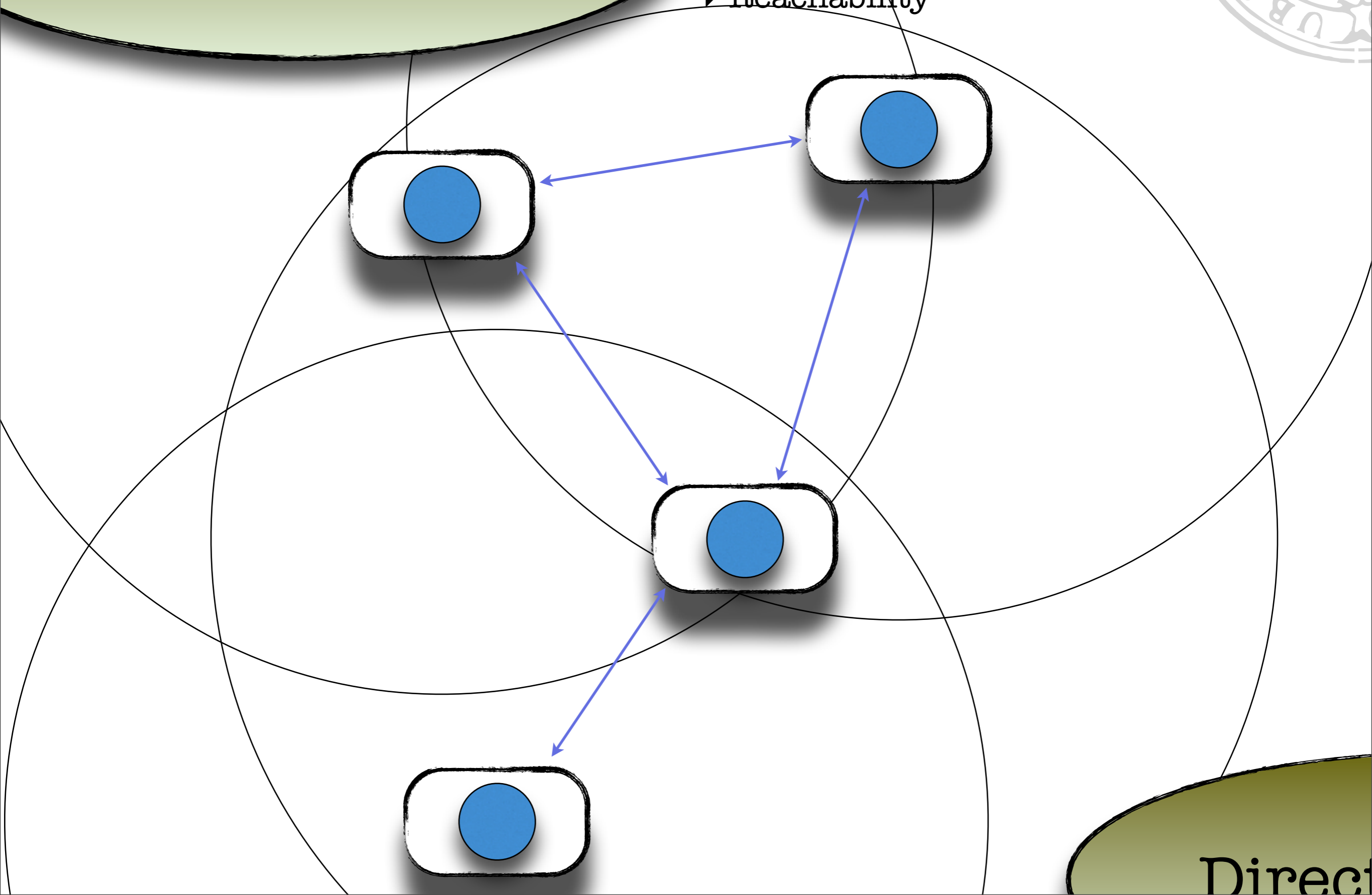
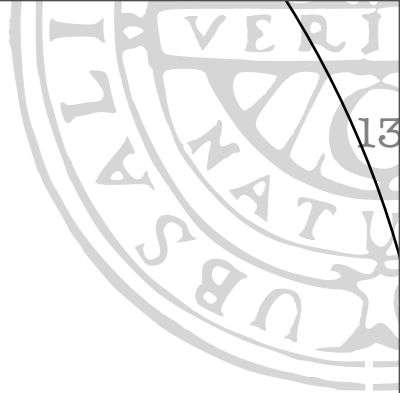
- ▶ Model
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Direct

Ad-Hoc Networks

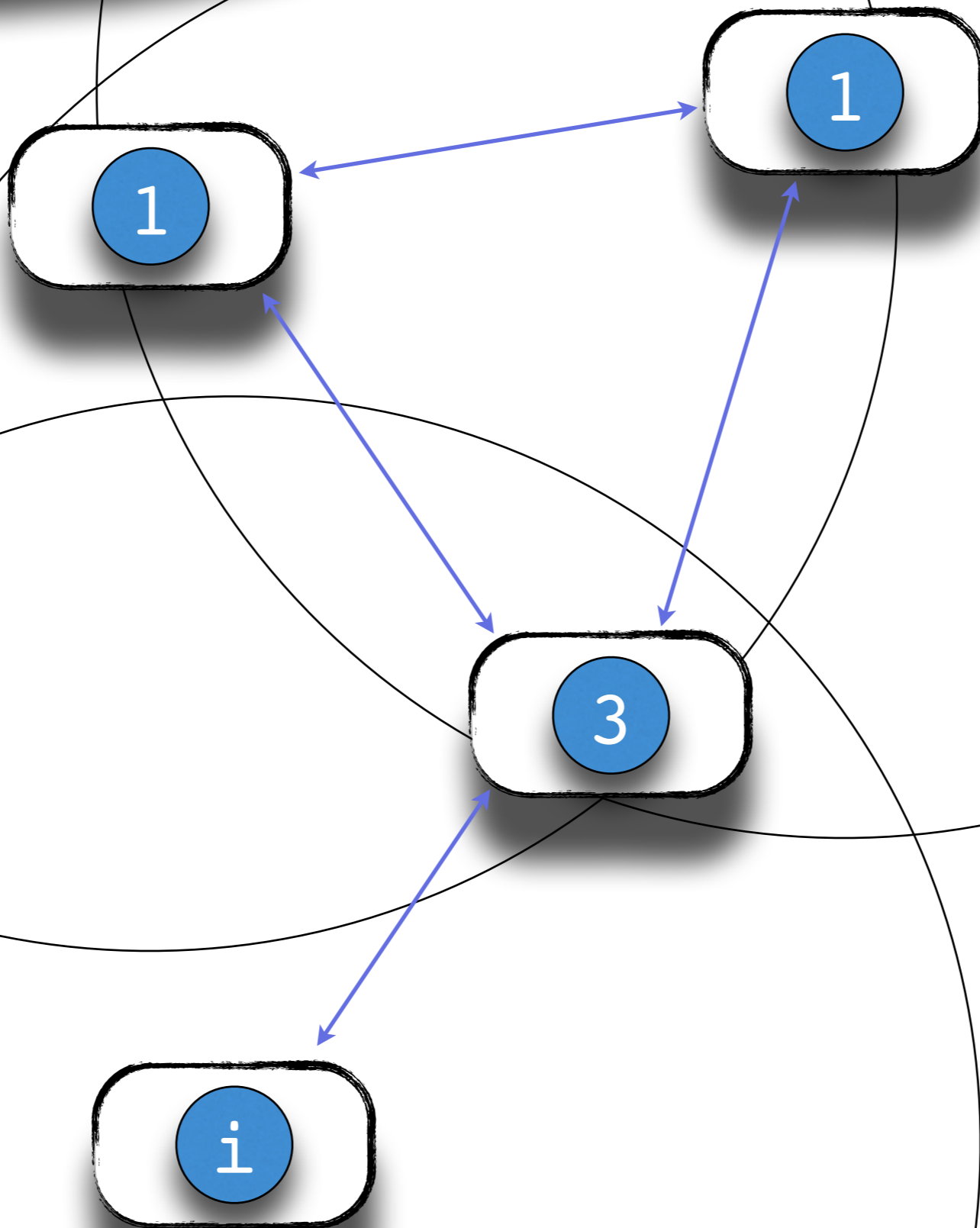
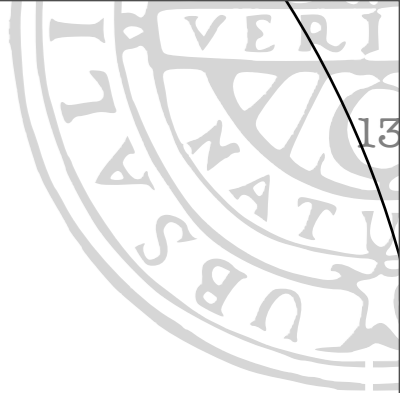
- ▶ Model
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Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Direct

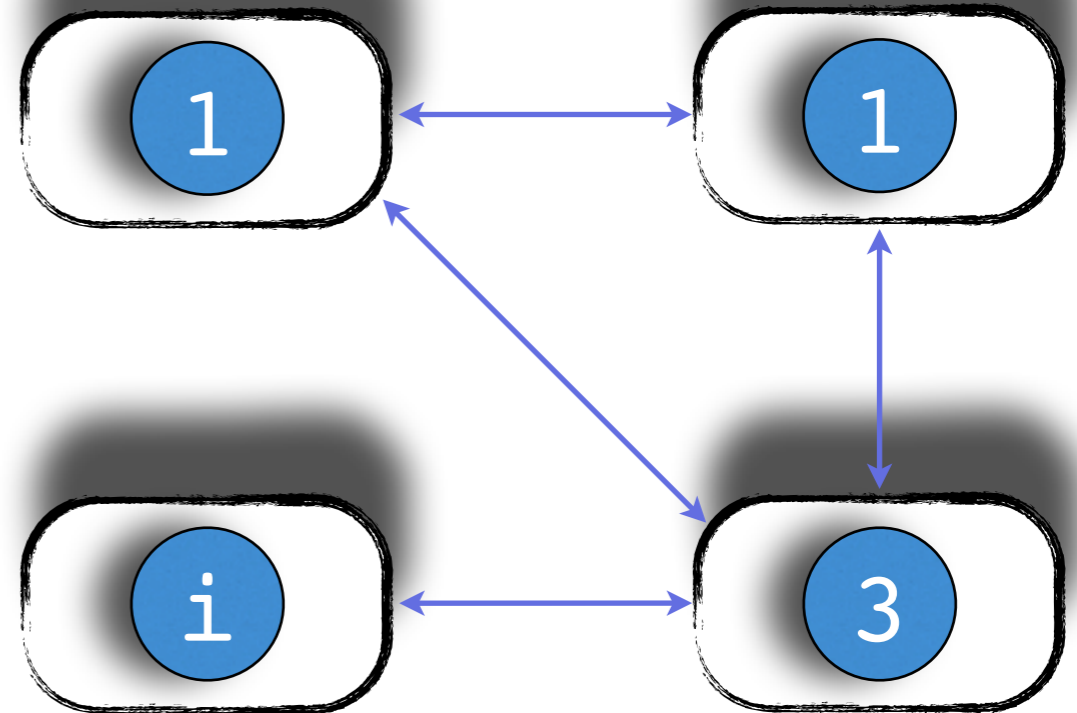
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Model

Node:
Process



Direct

Ad-Hoc Networks

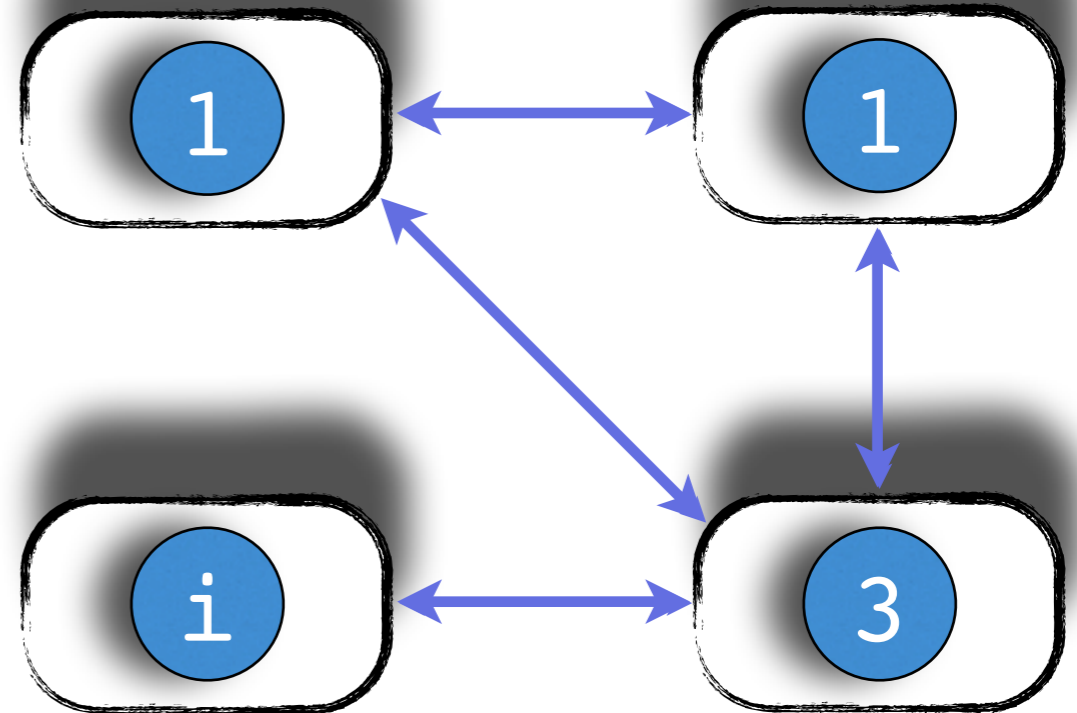
- ▶ Model
- ▶ Transition System
- ▶ Reachability



Model

Node:
Process

Topology:
Symmetric graph



Direct

Ad-Hoc Networks

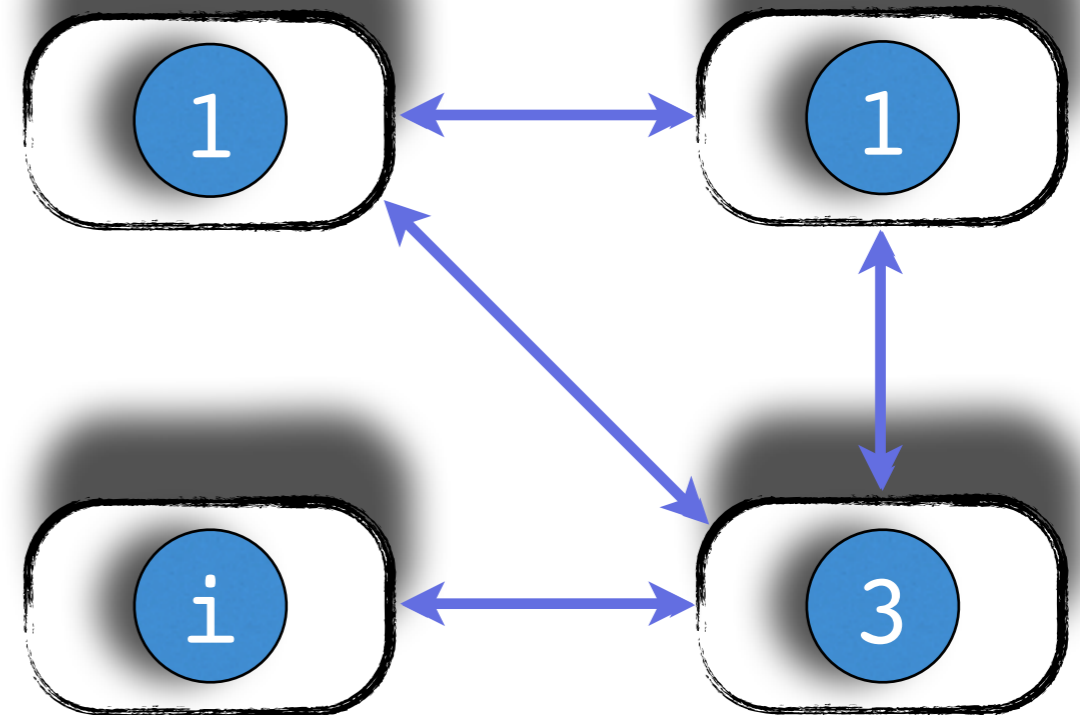
- ▶ Model
- ▶ Transition System
- ▶ Reachability

Model

Node:
Process

Topology:
Symmetric graph

Configuration:
Graph, state mapping



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



$\langle \Gamma, \longrightarrow \rangle$

Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

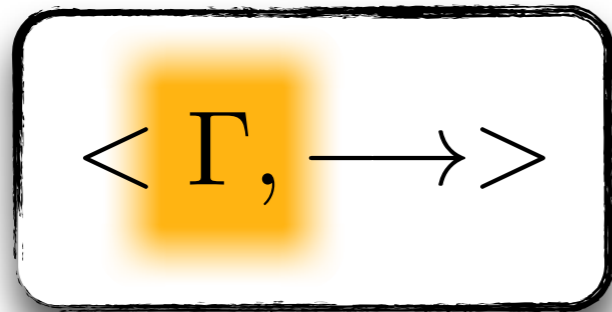


$\langle \Gamma, \longrightarrow \rangle$

Direct

Ad-Hoc Networks

- ▶ Model
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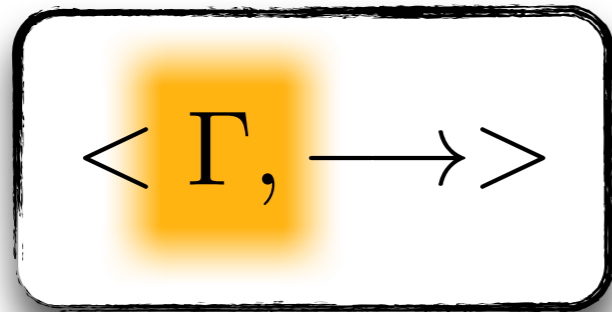


- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

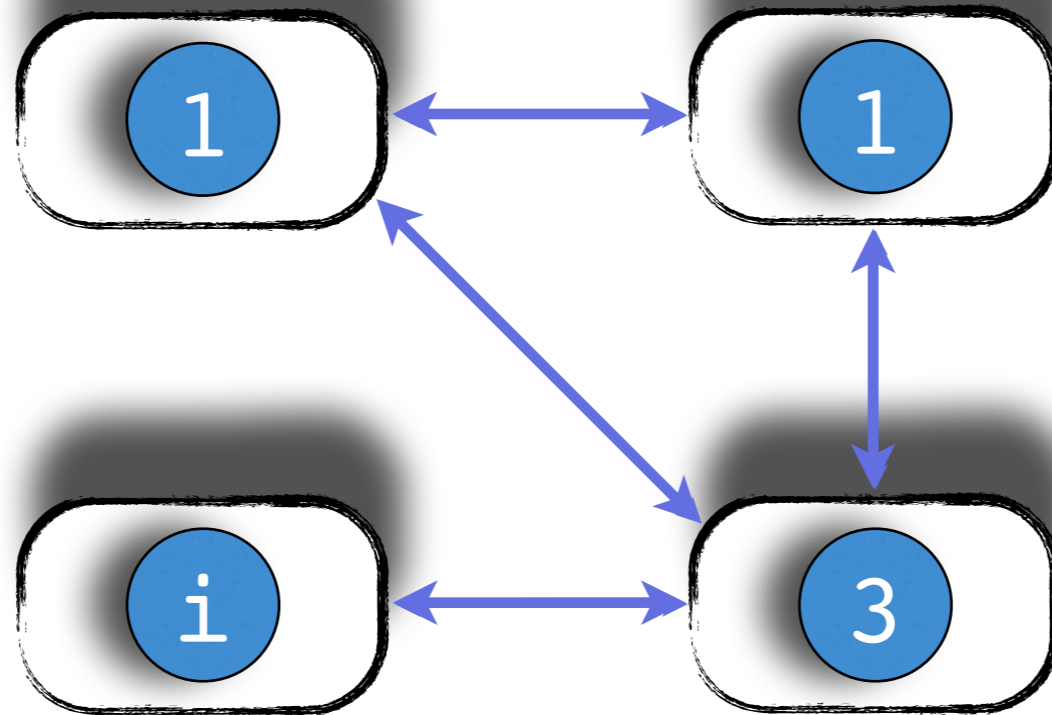


Ad-Hoc Networks

- ▶ Model
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- ▶ Reachability



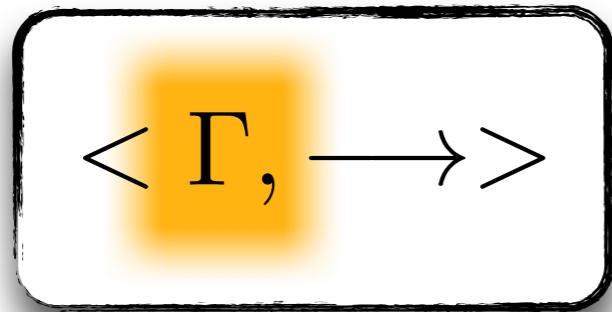
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace



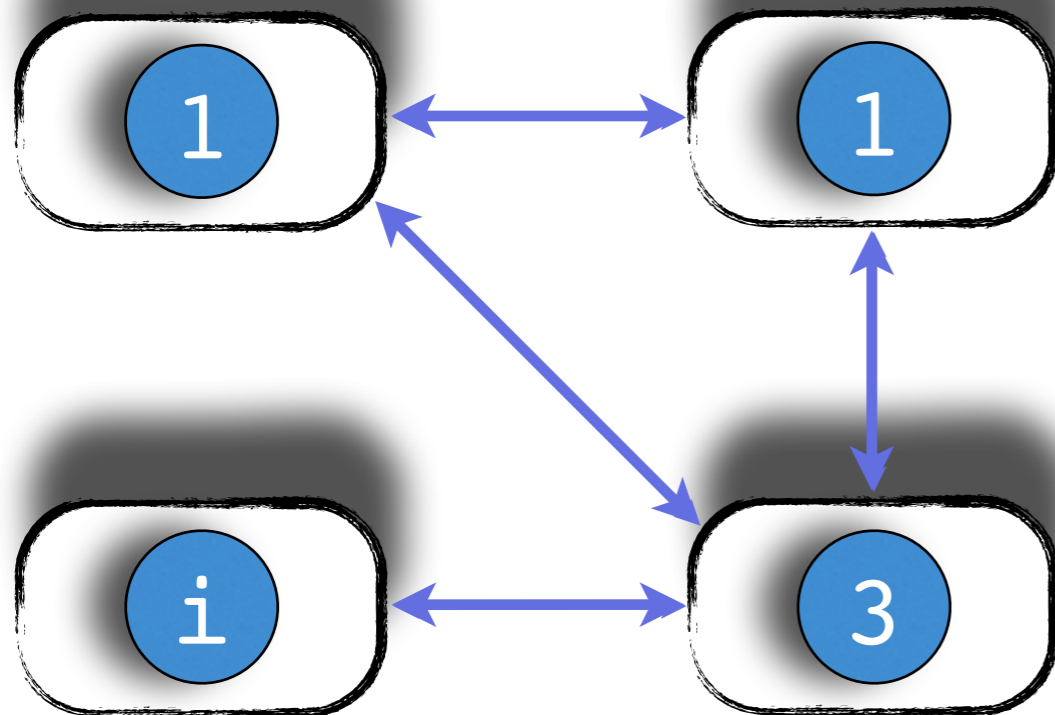
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

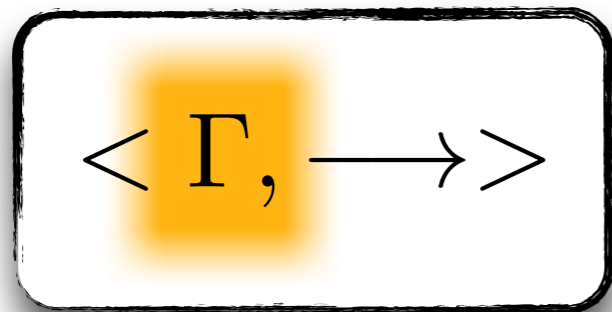


- ▶ Any Symmetric Graph

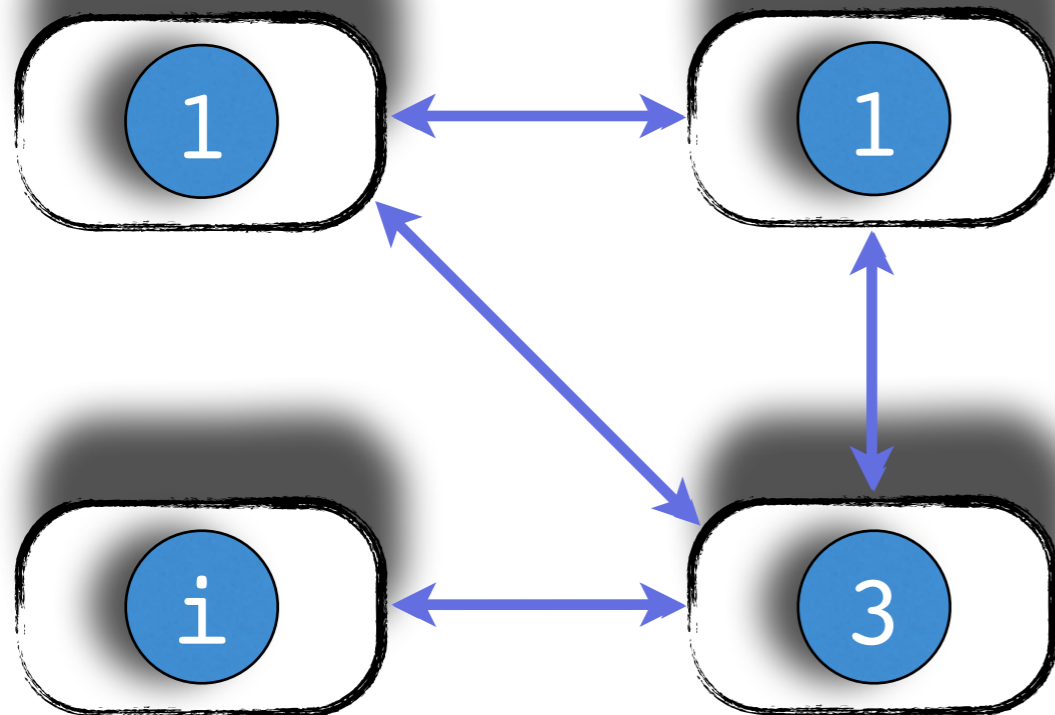
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

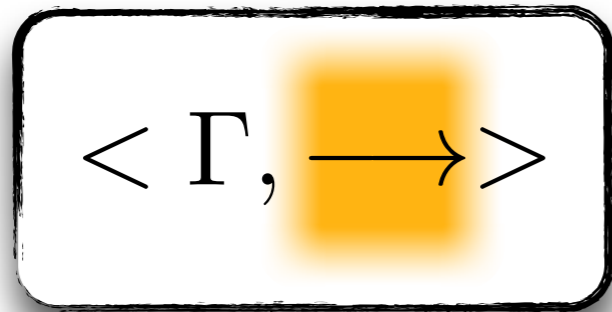


- ▶ Any Symmetric Graph
- ▶ Unbounded # of nodes

Direct

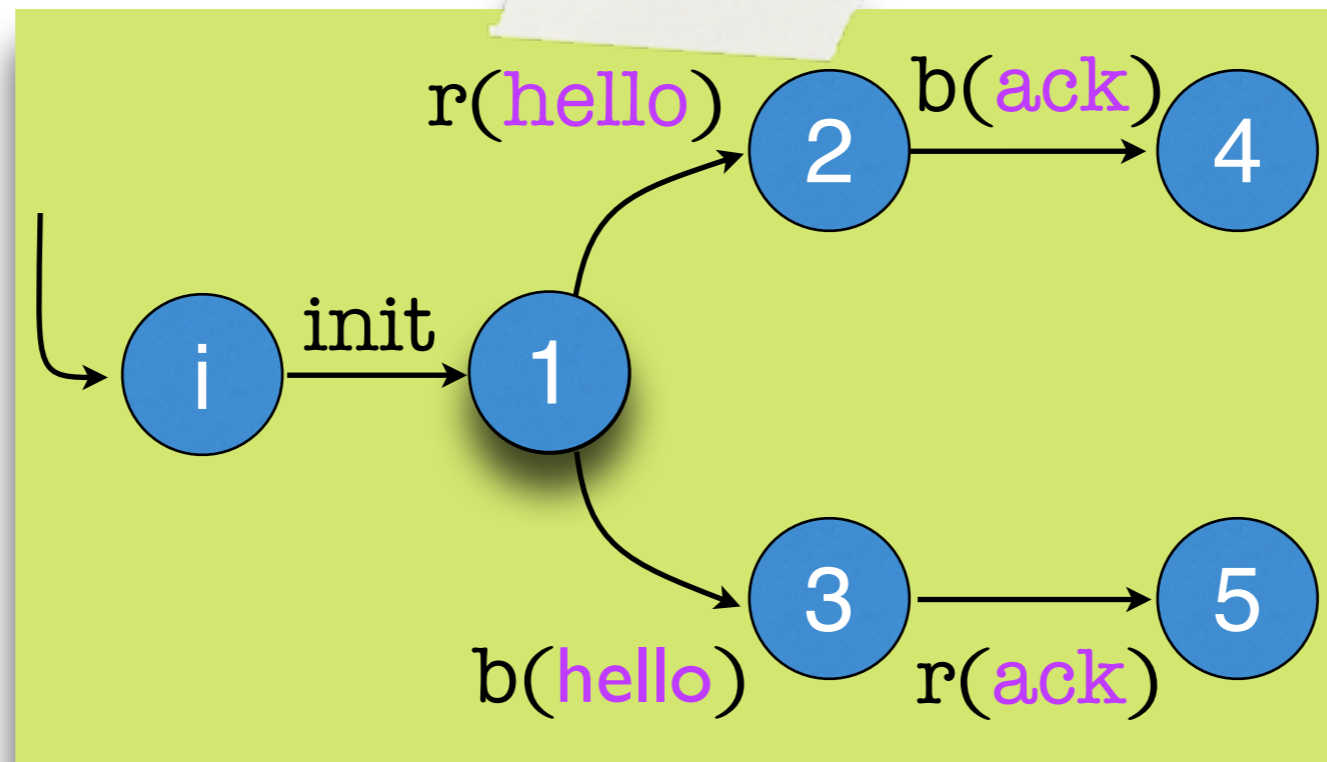
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



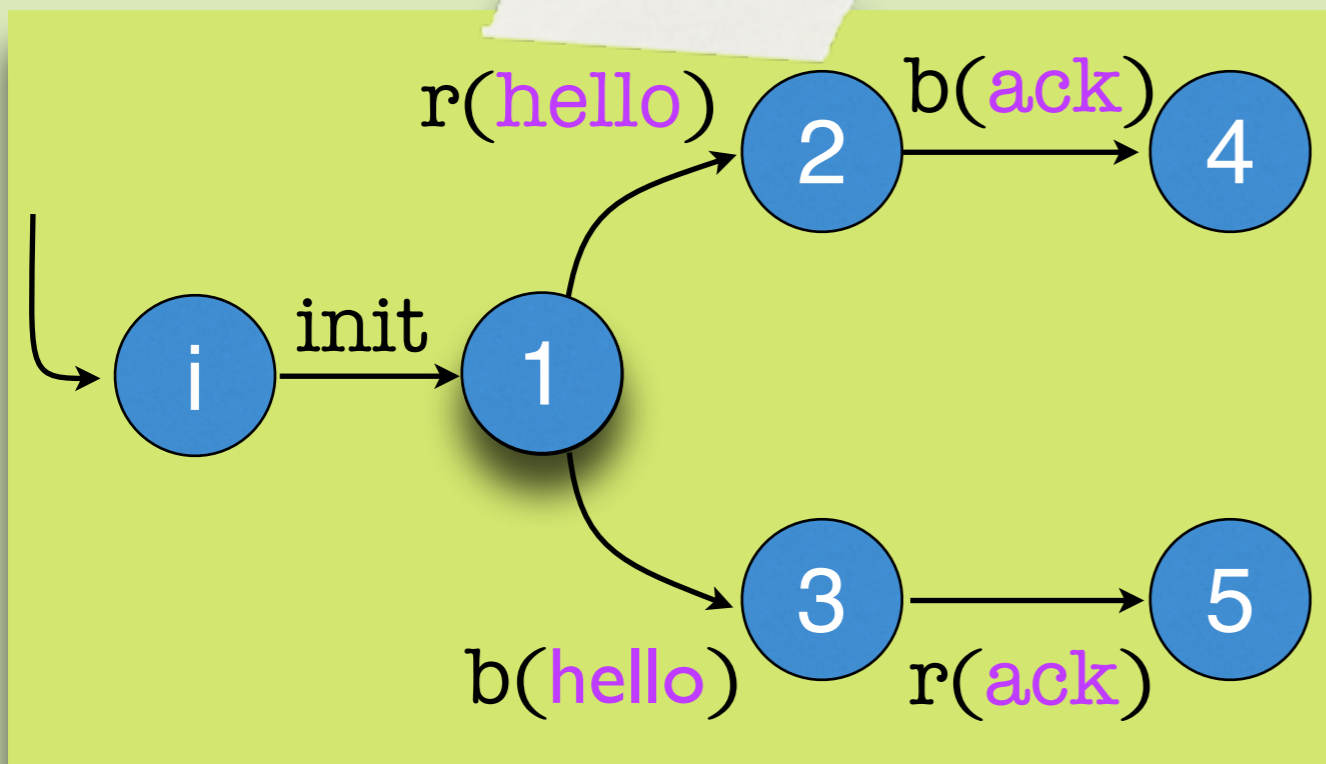
Ad-Hoc Networks

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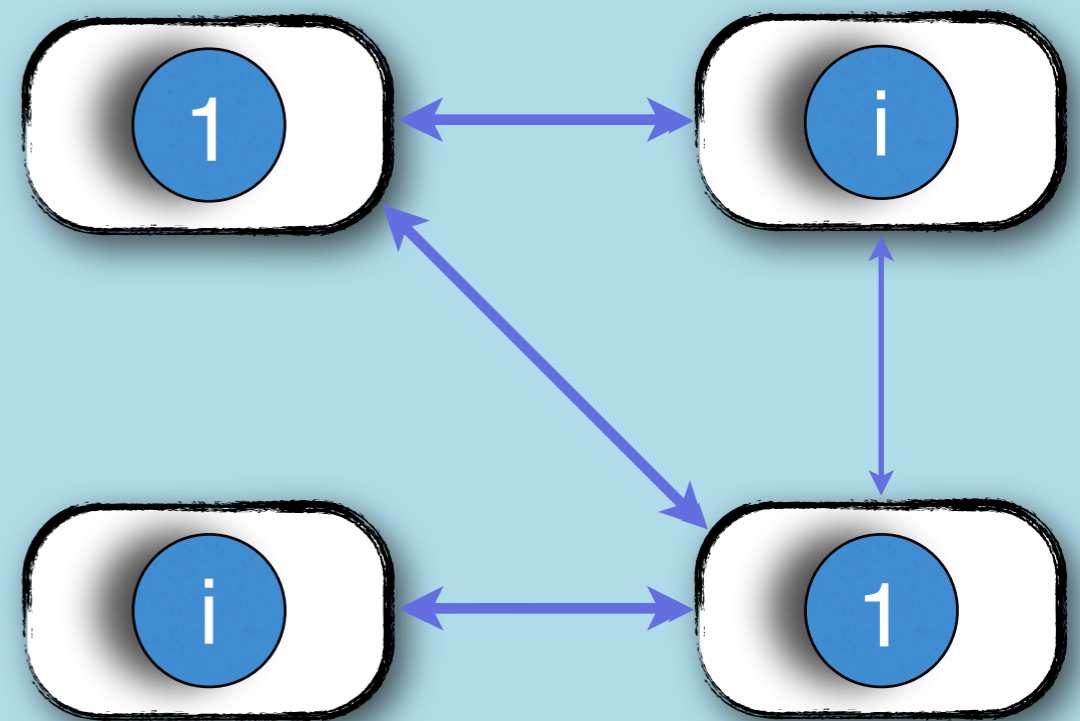
$\langle \Gamma, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



Configuration



Direct

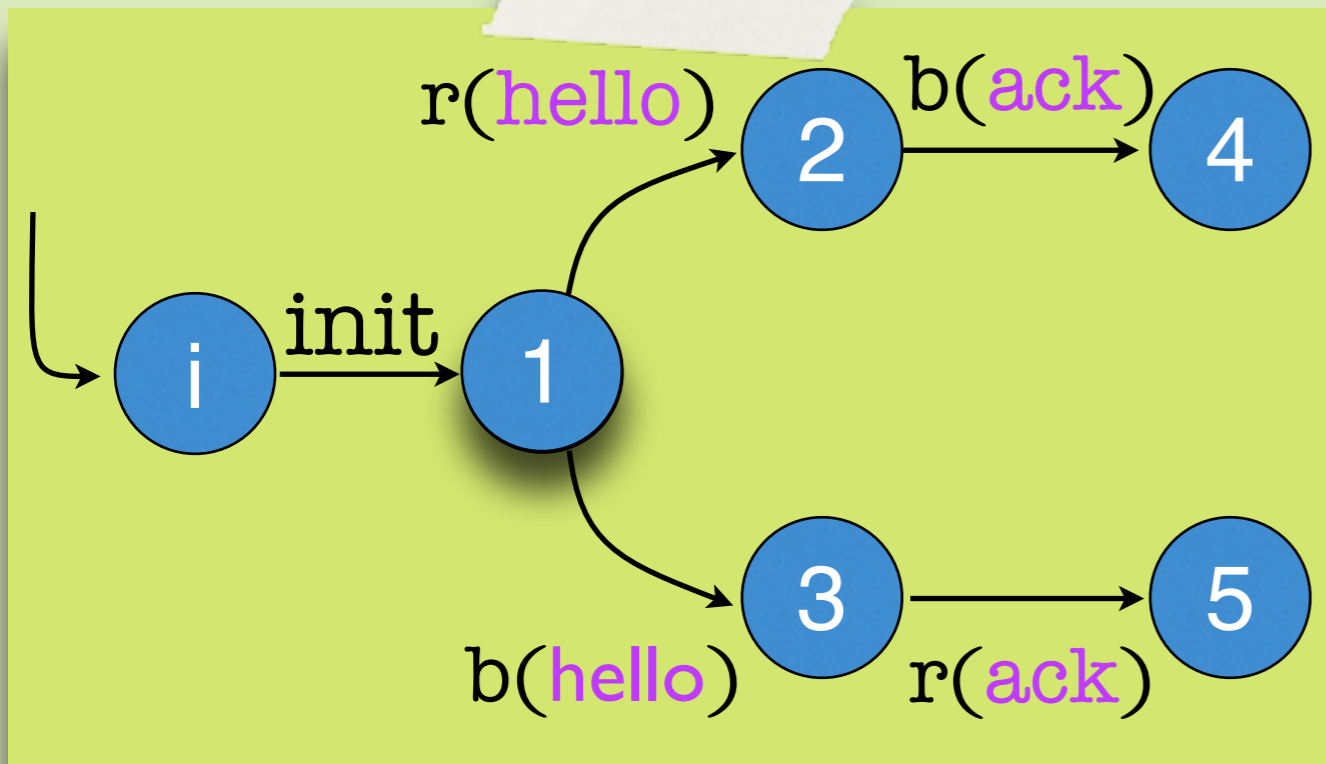
Ad-Hoc Networks

- ▶ Model
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$\langle \Gamma, \longrightarrow \rangle$

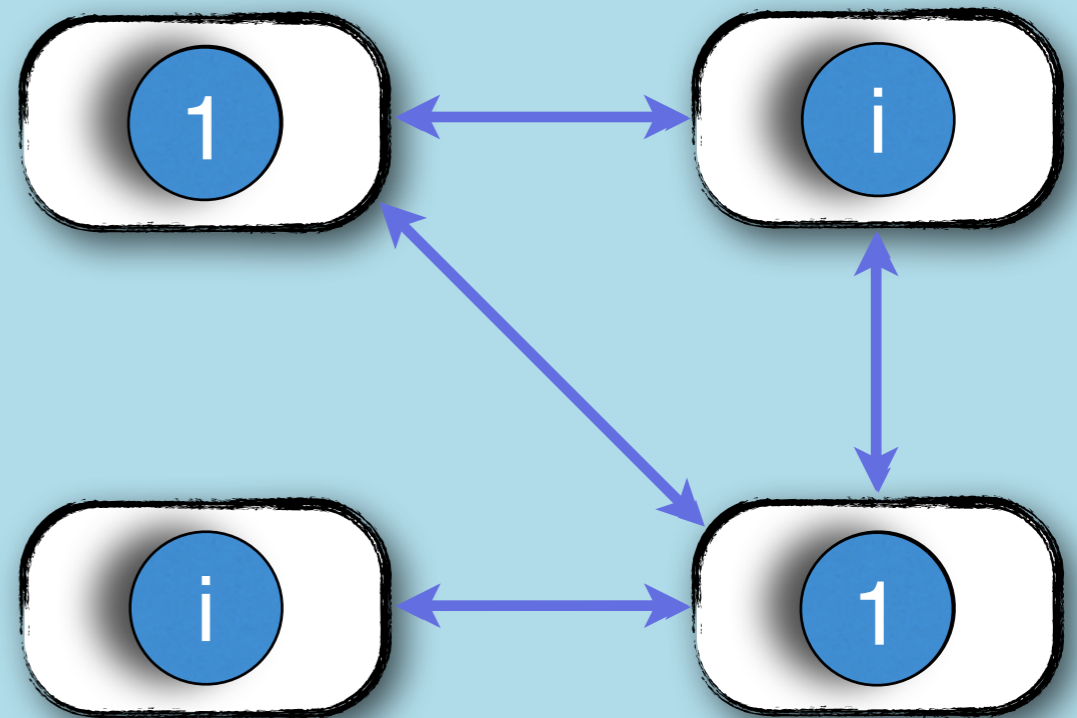
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



▶ local

Configuration



▶ local

Direct

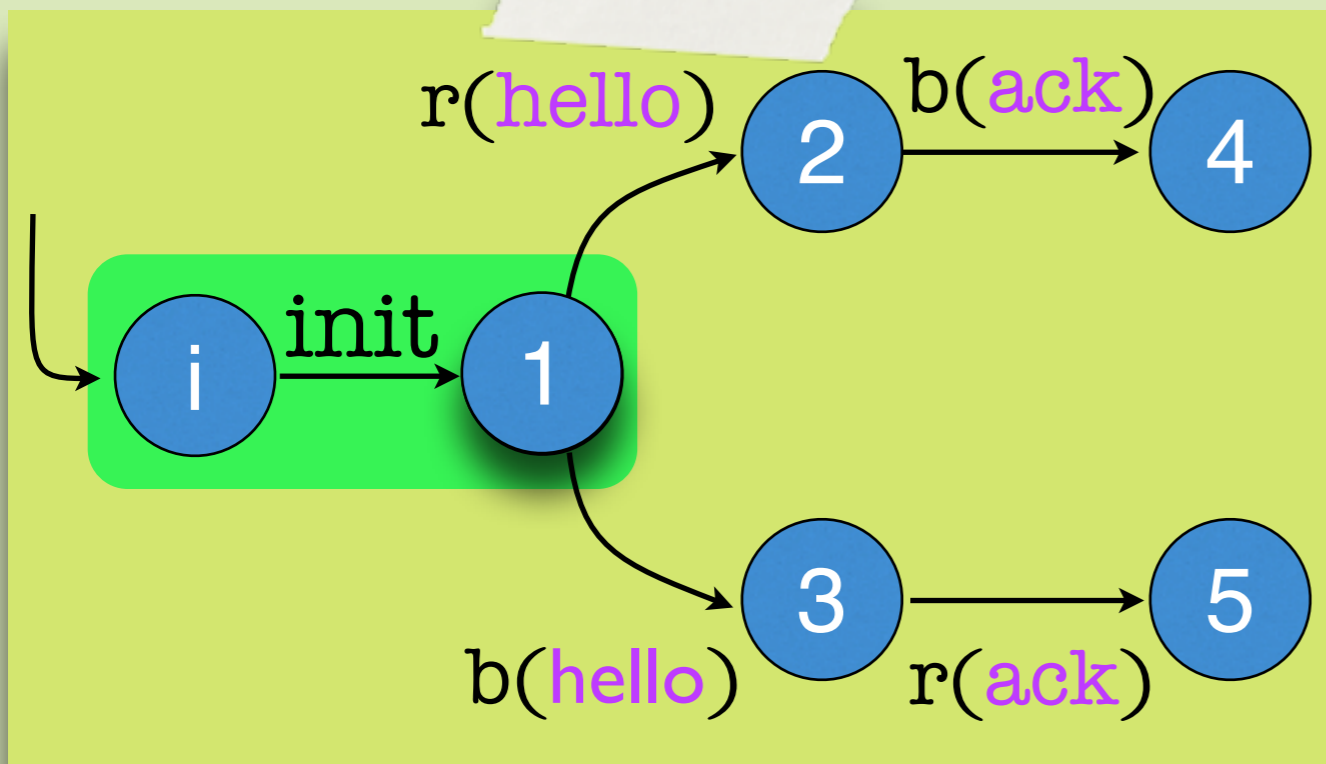
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

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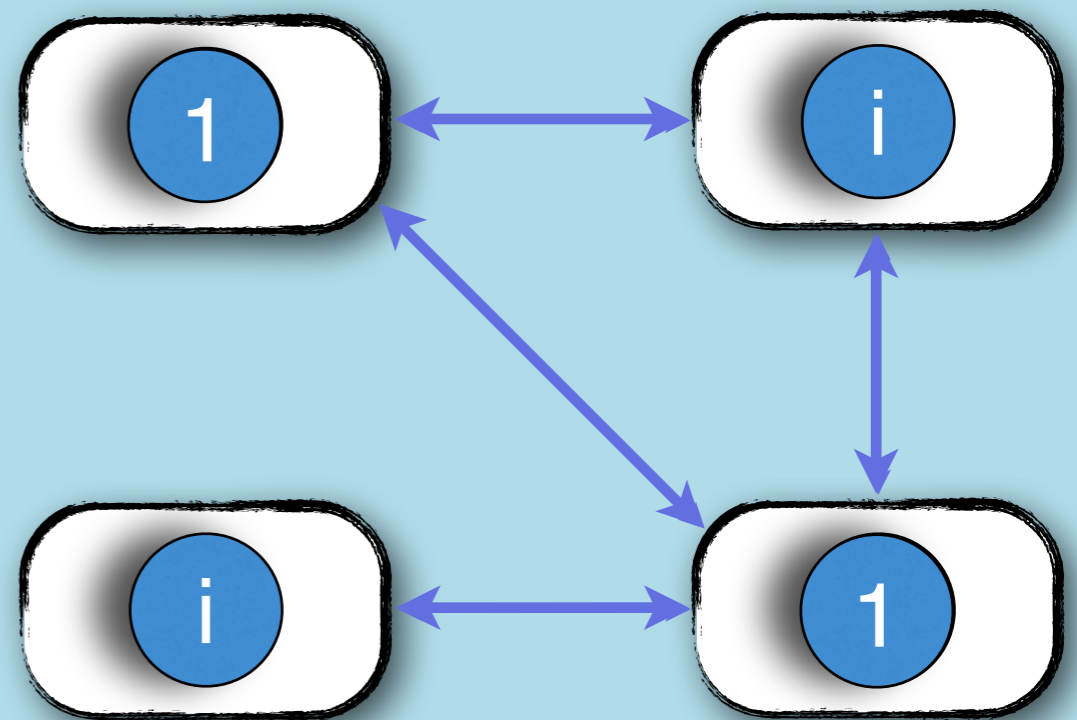
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



▶ local

Configuration



▶ local

Direct

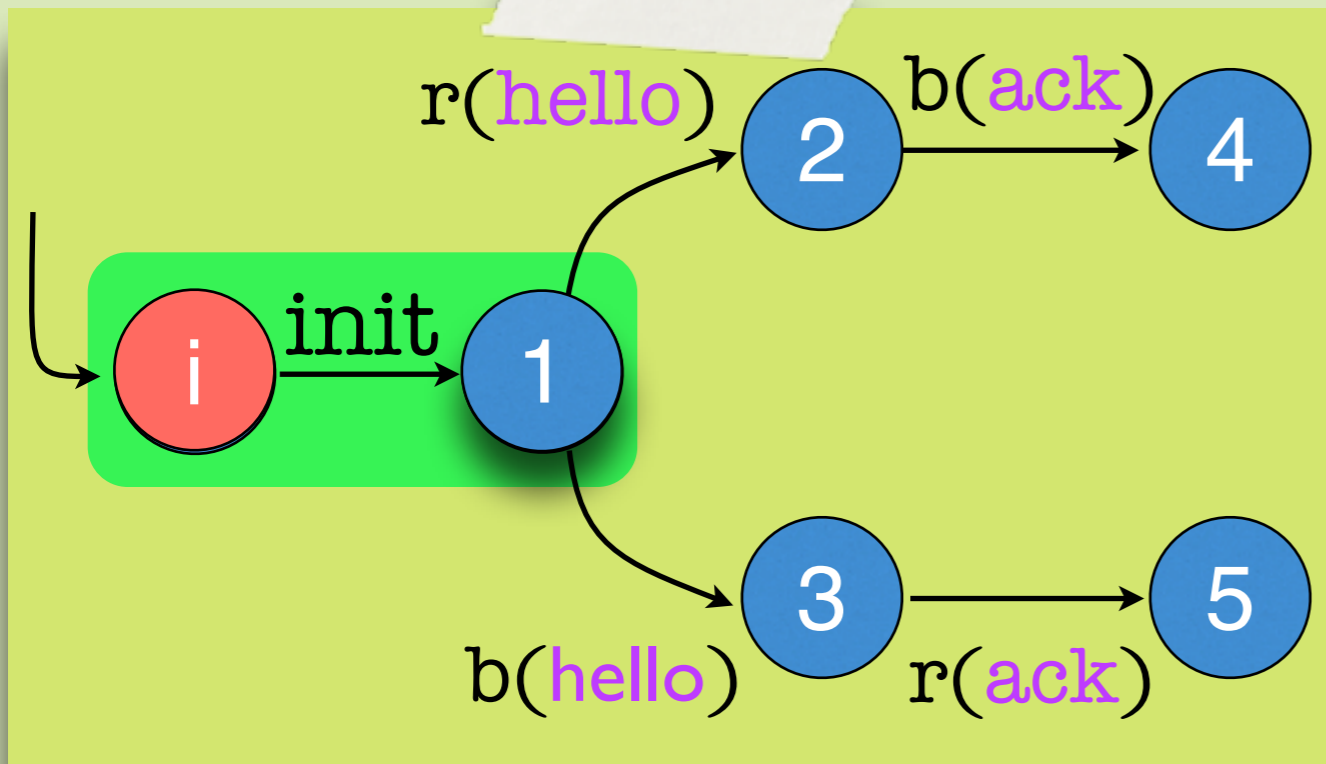
Ad-Hoc Networks

- ▶ Model
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$\langle \Gamma, \longrightarrow \rangle$

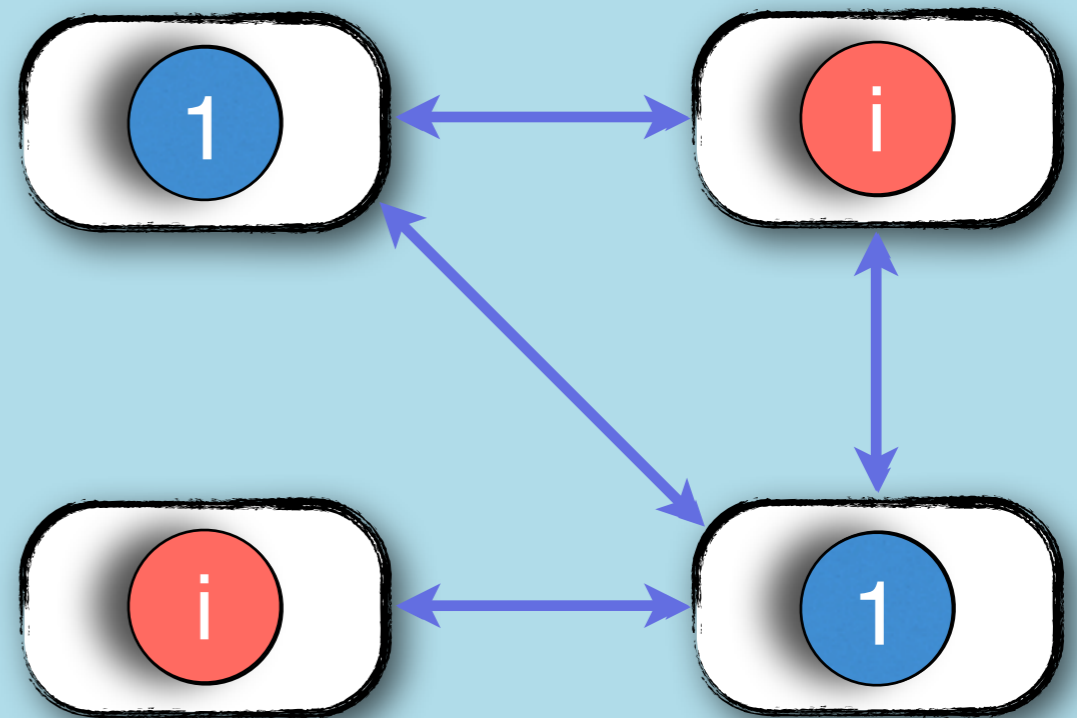
- ▶ Set of configurations
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Process



▶ local

Configuration



▶ local

Direct

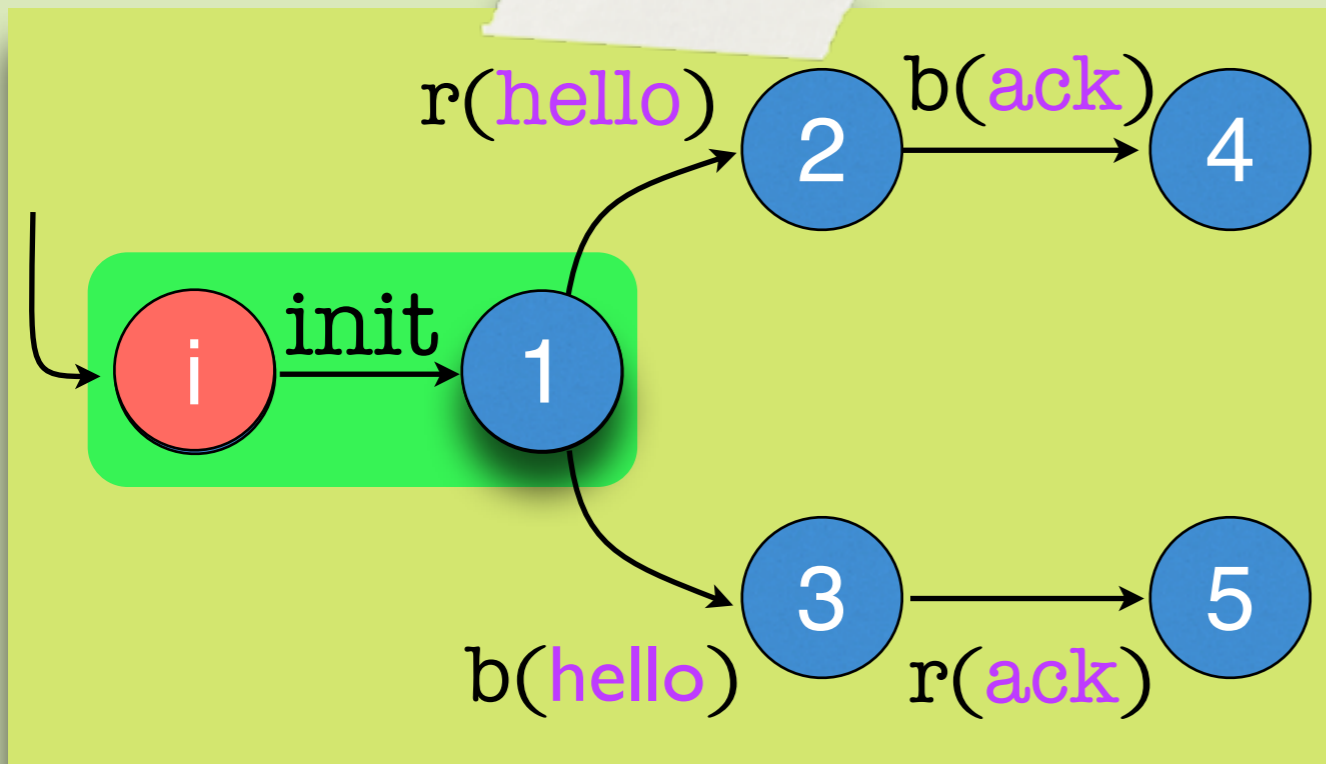
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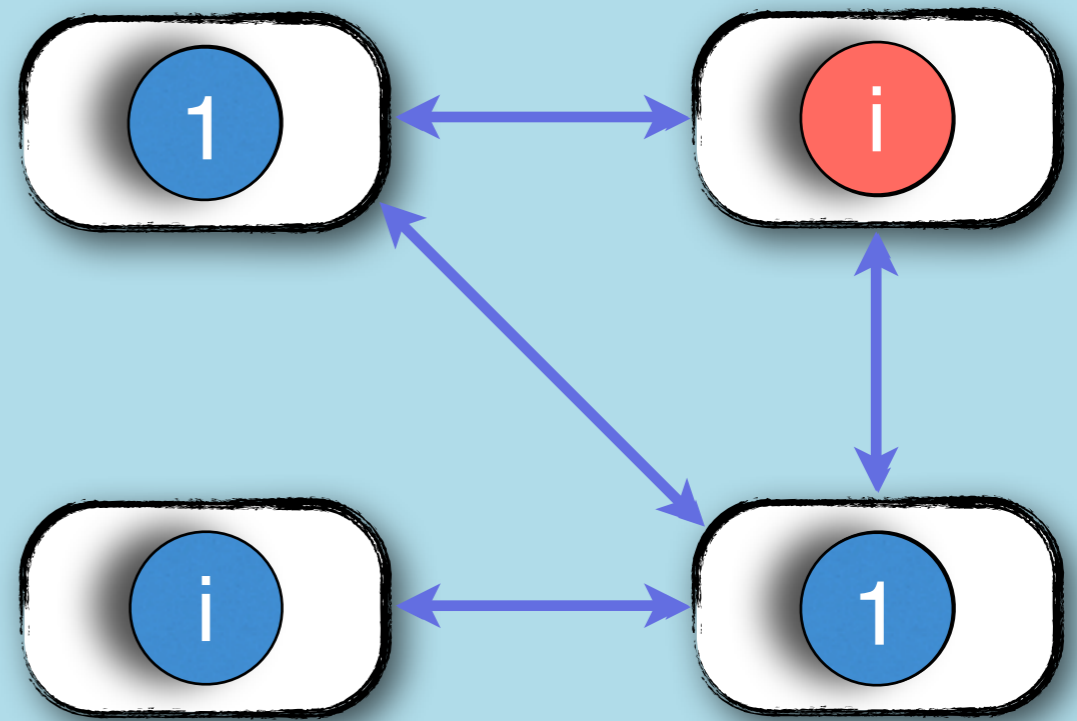
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



▶ local

Configuration



▶ local

Direct

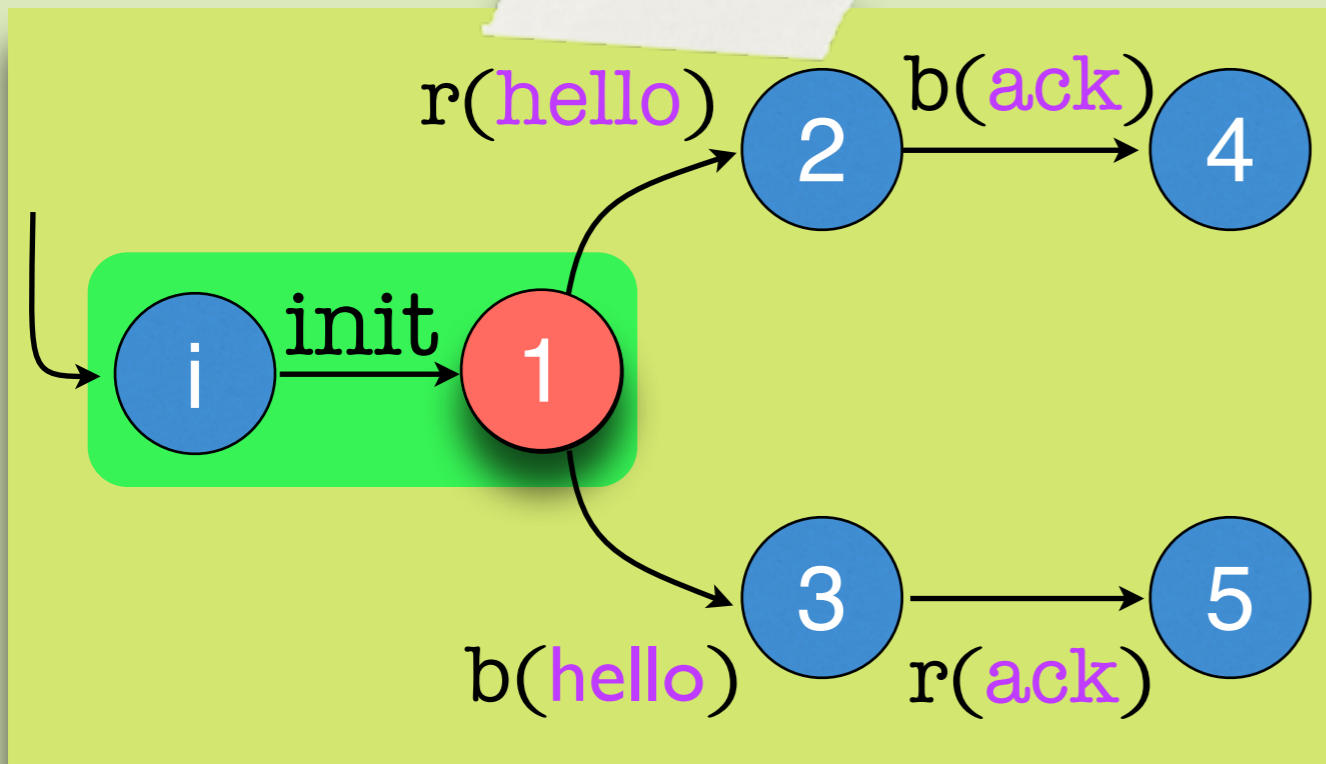
Ad-Hoc Networks

- ▶ Model
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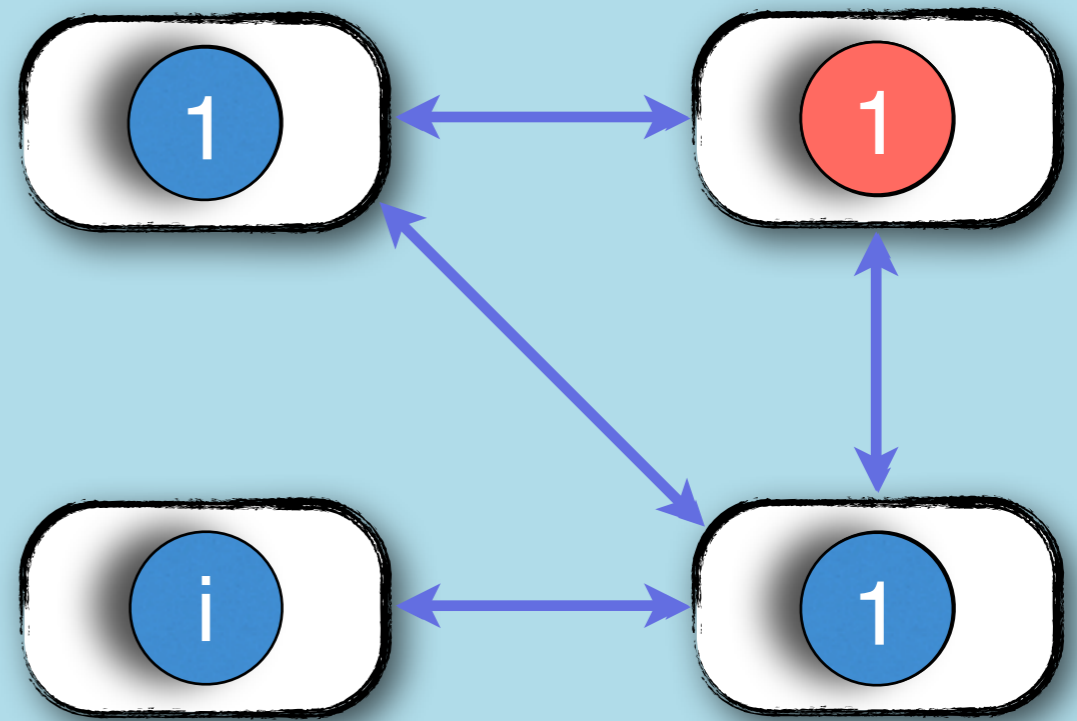
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



▶ local

Configuration



▶ local

Direct

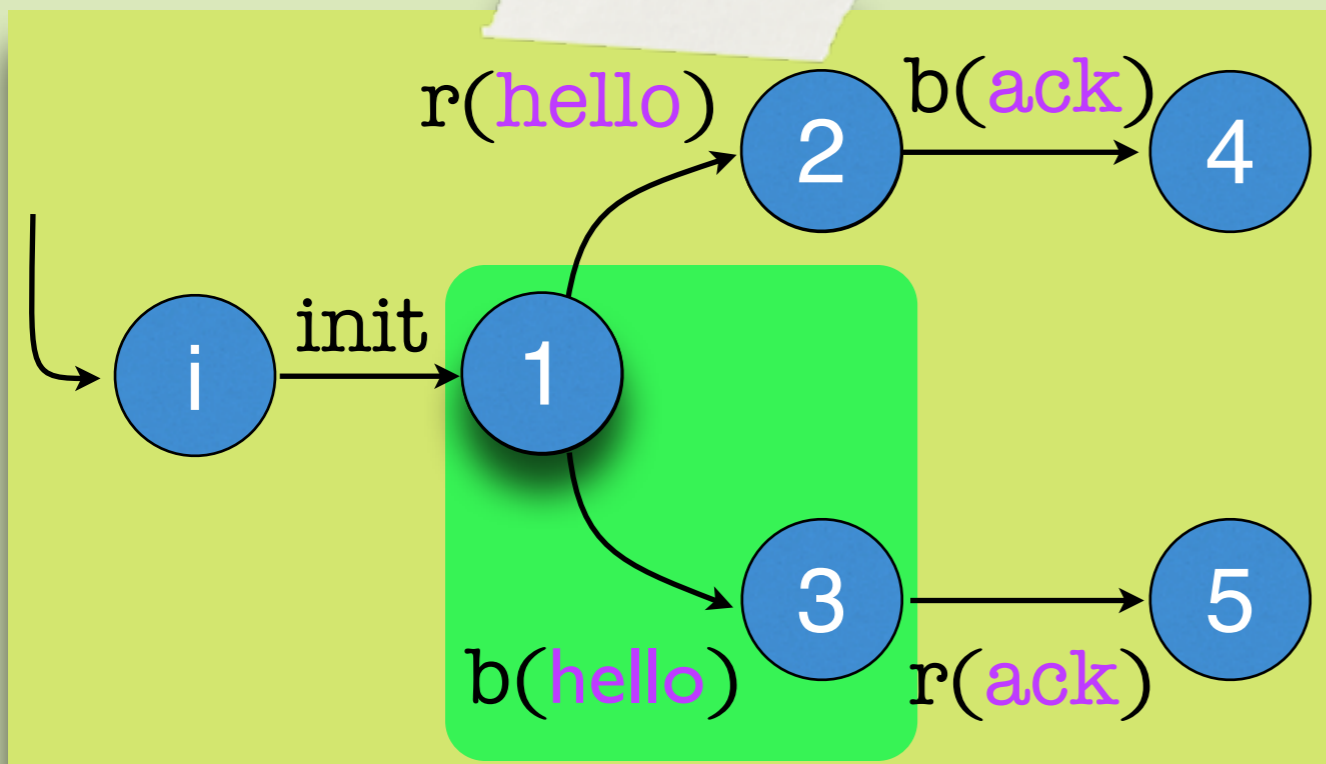
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- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

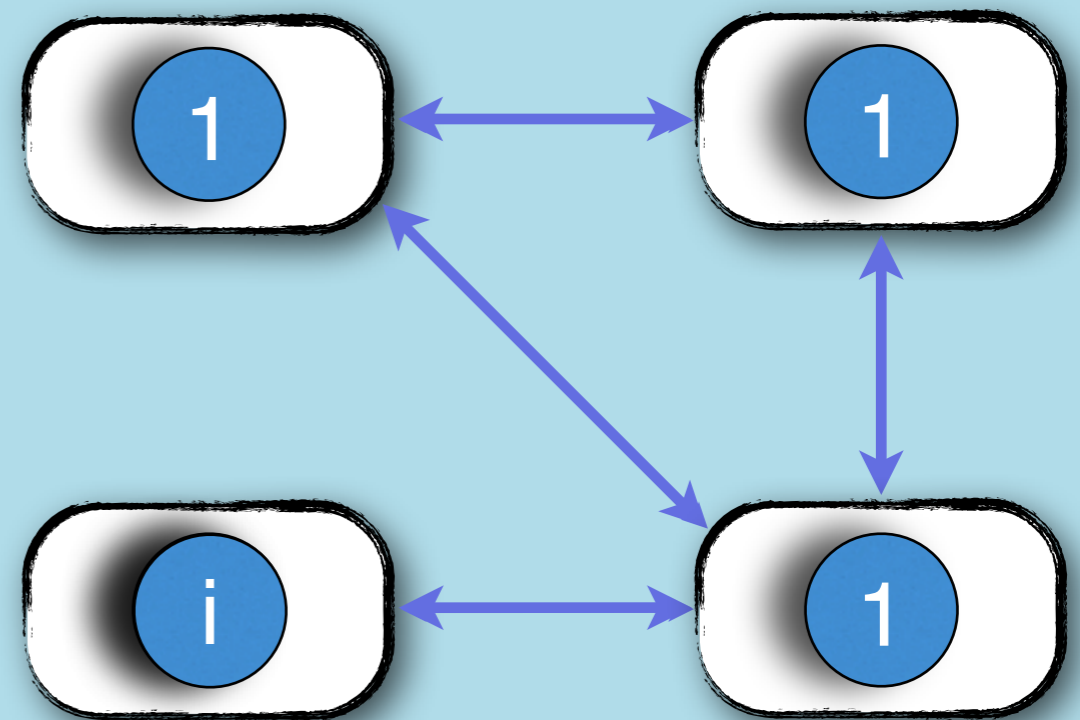
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast



Direct

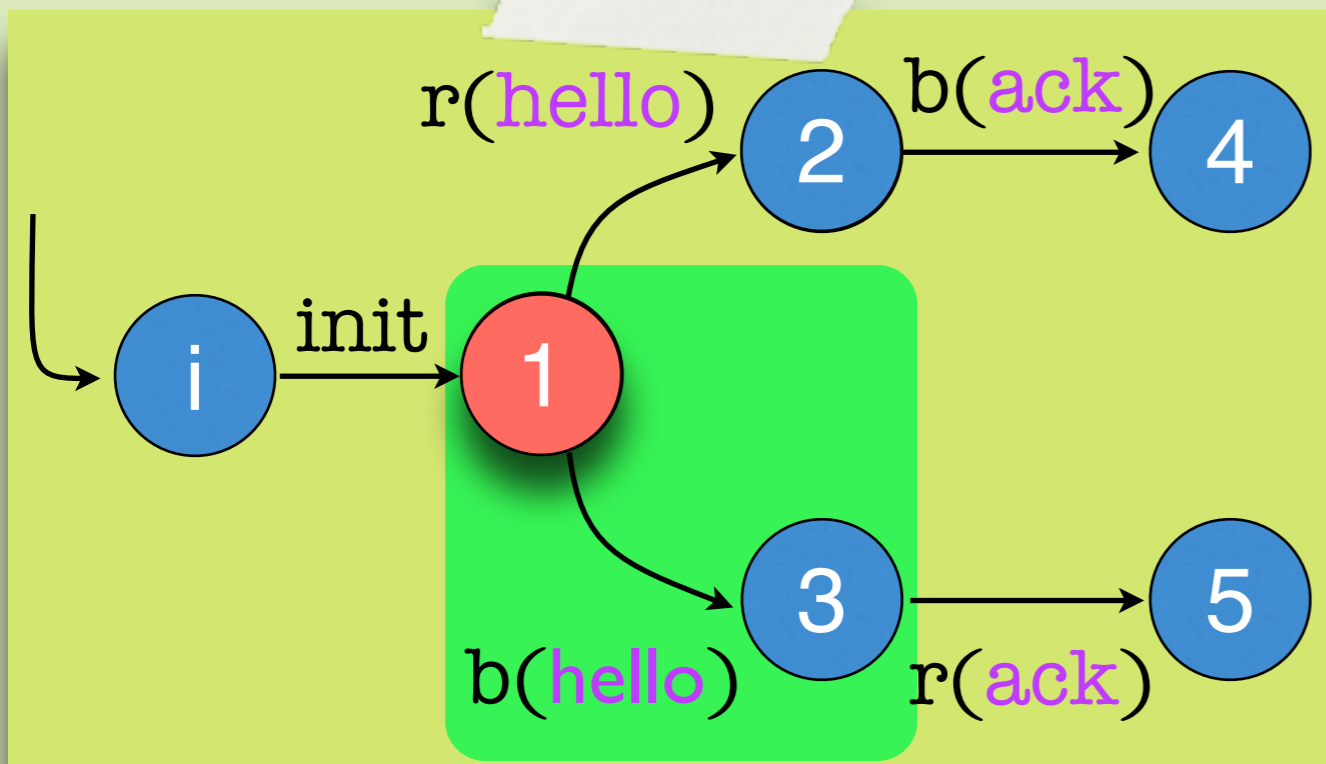
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

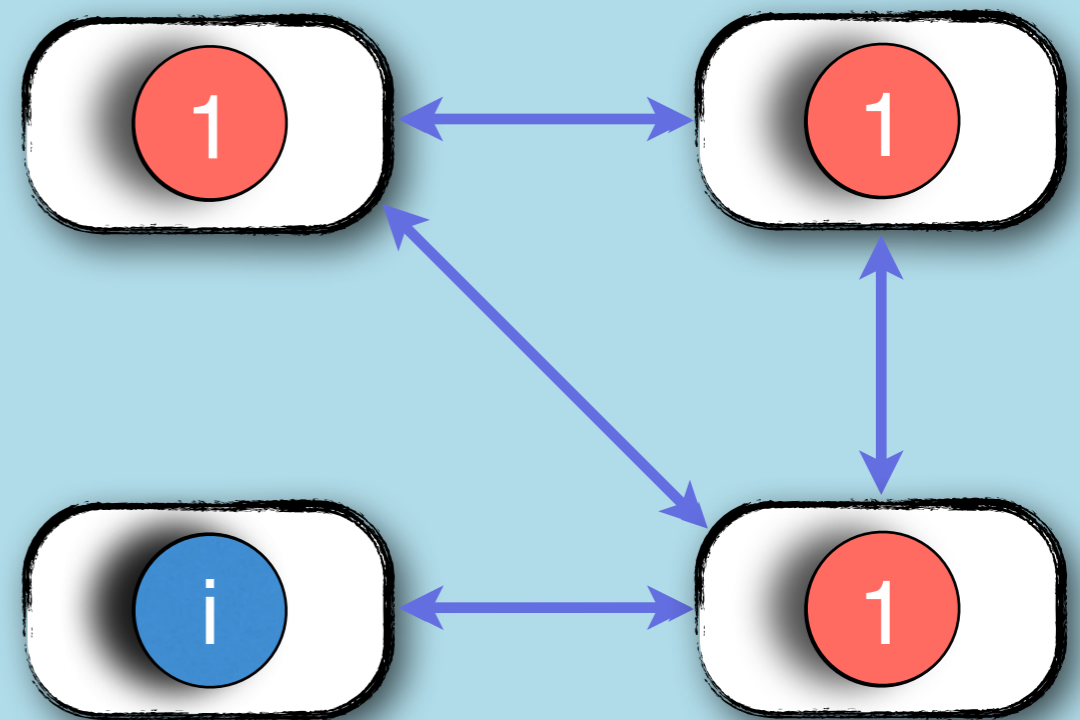
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast



Direct

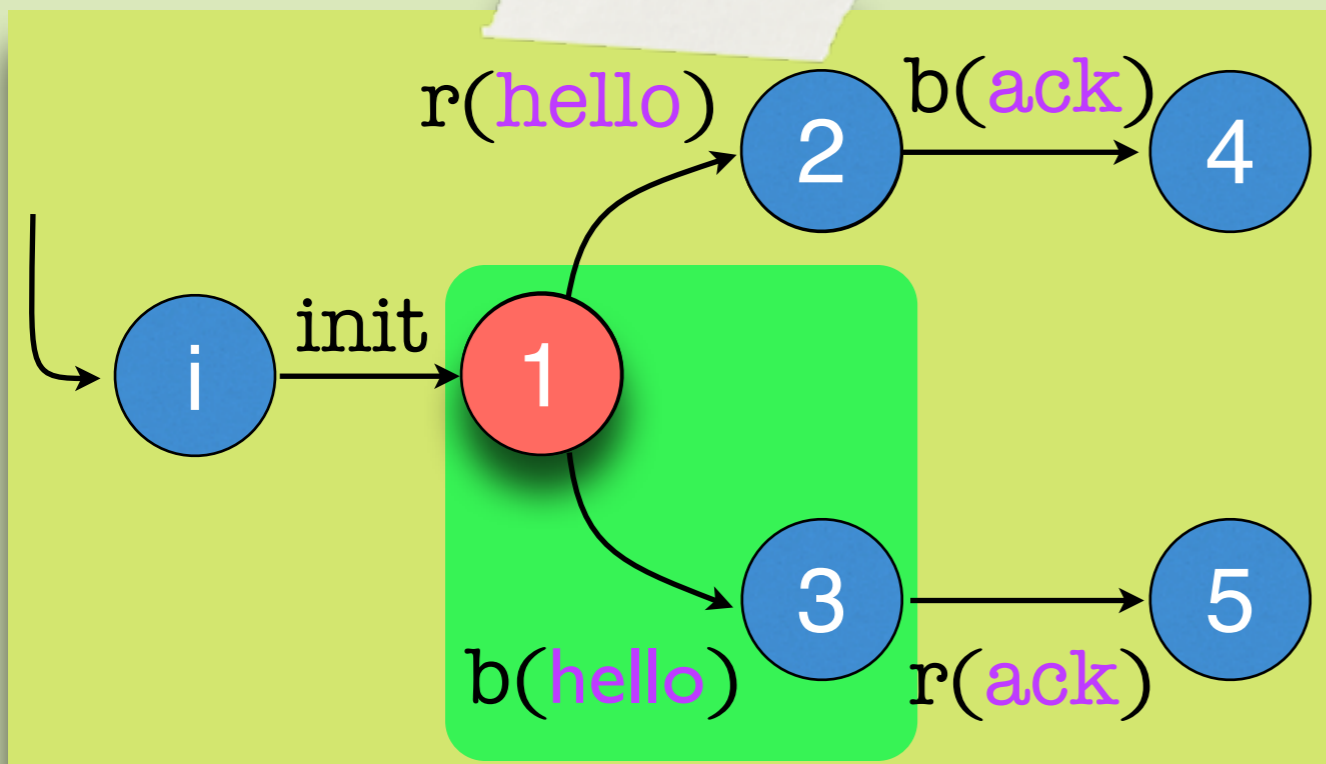
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process

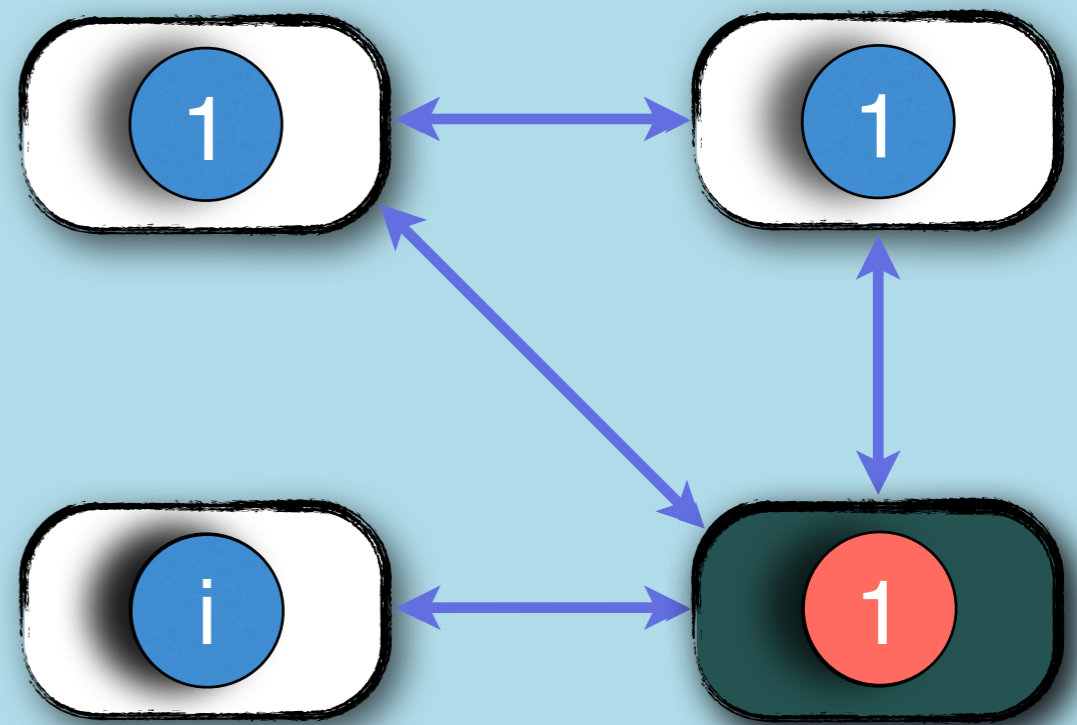


▶ local

▶ broadcast

▶ receive

Configuration



▶ local

▶ selective broadcast

broadcaster

Direct

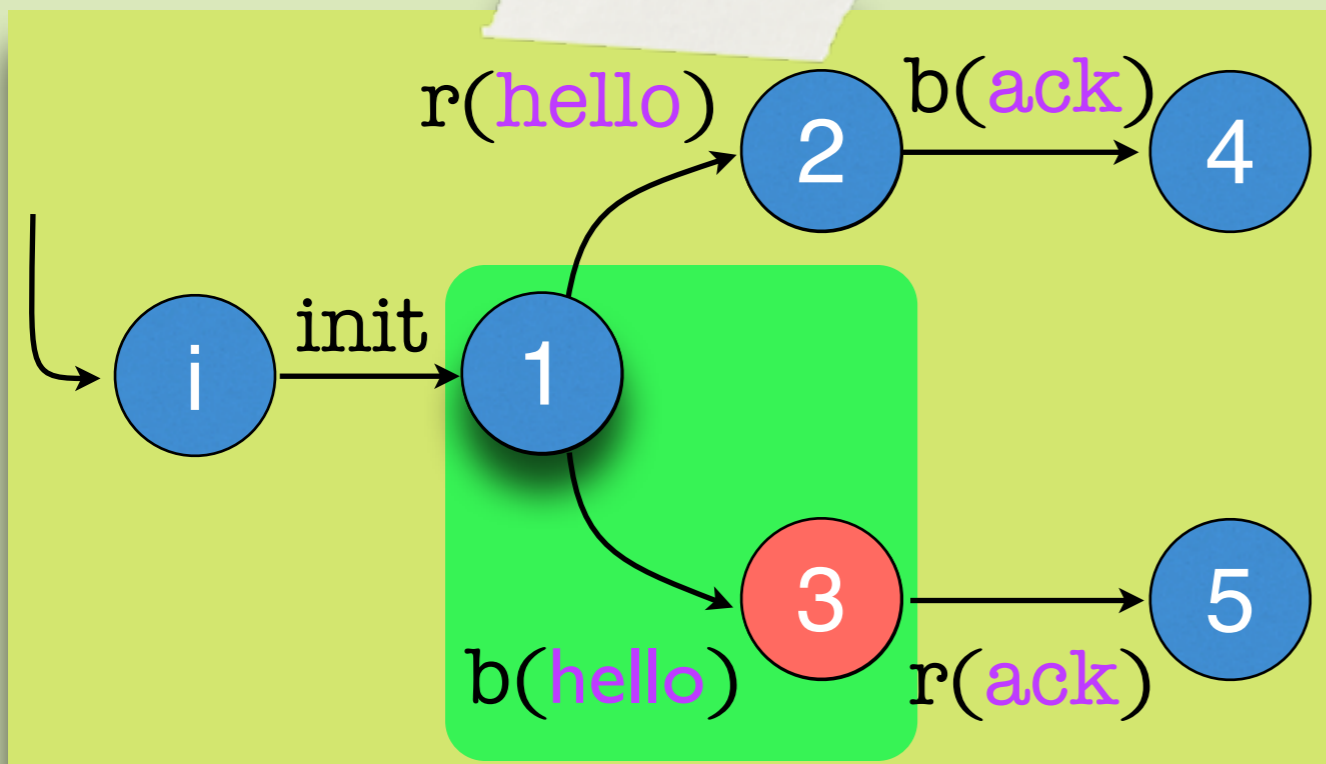
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

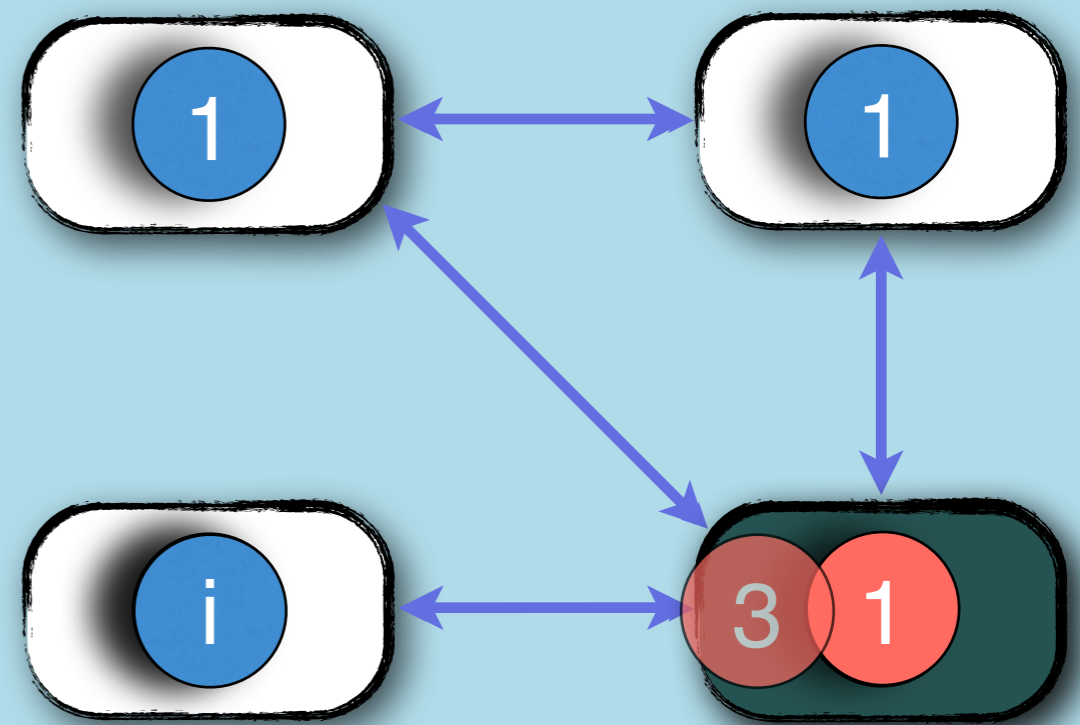
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast
- broadcaster

Direct

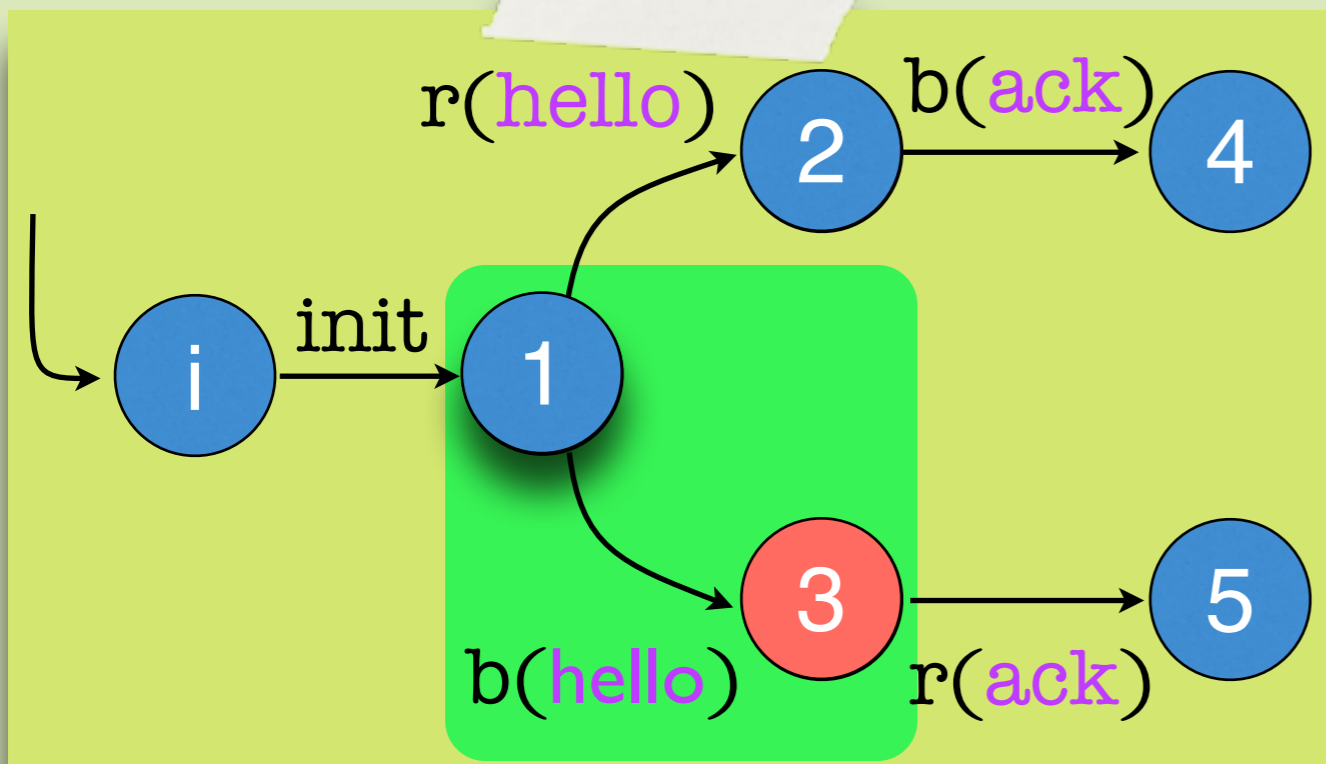
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

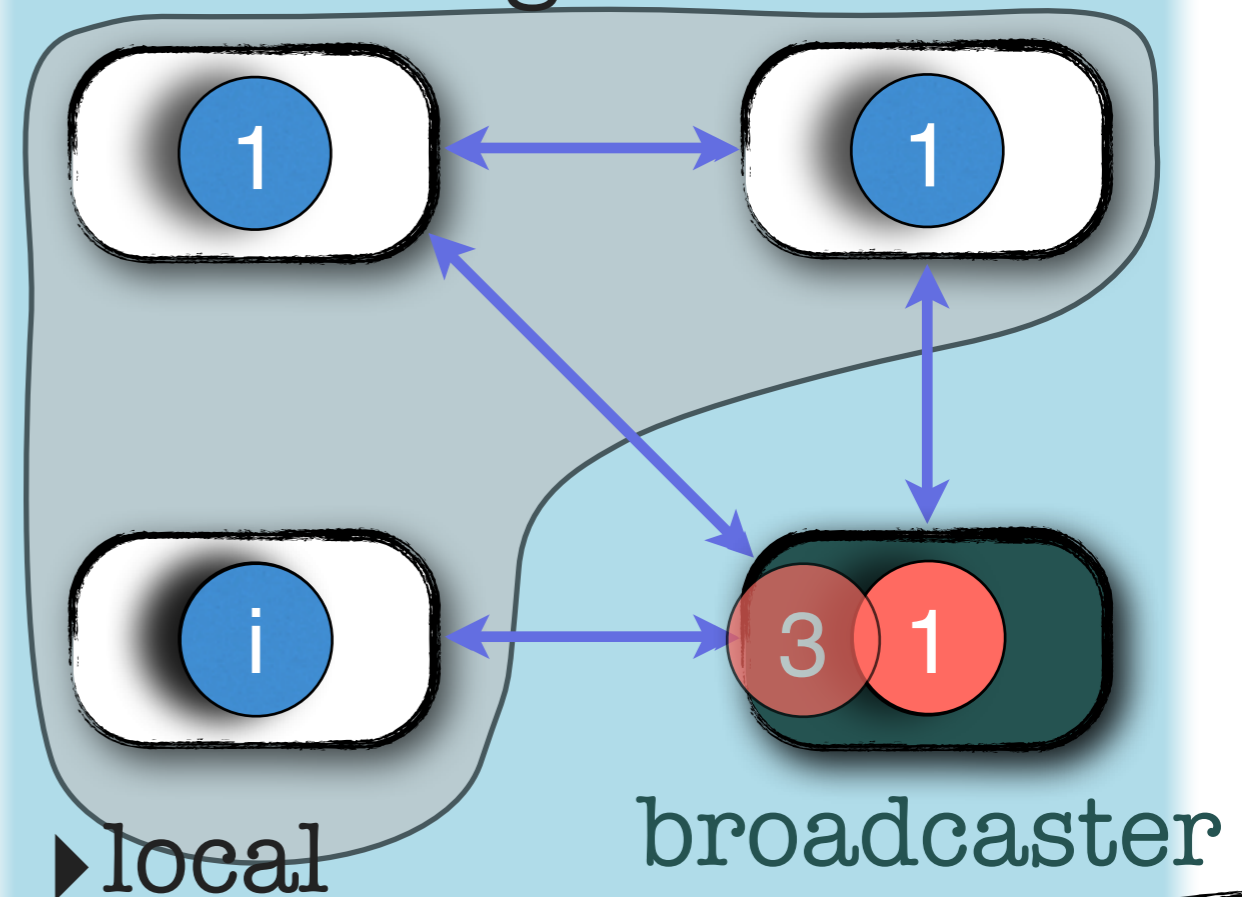
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast
- ▶ broadcaster

Direct

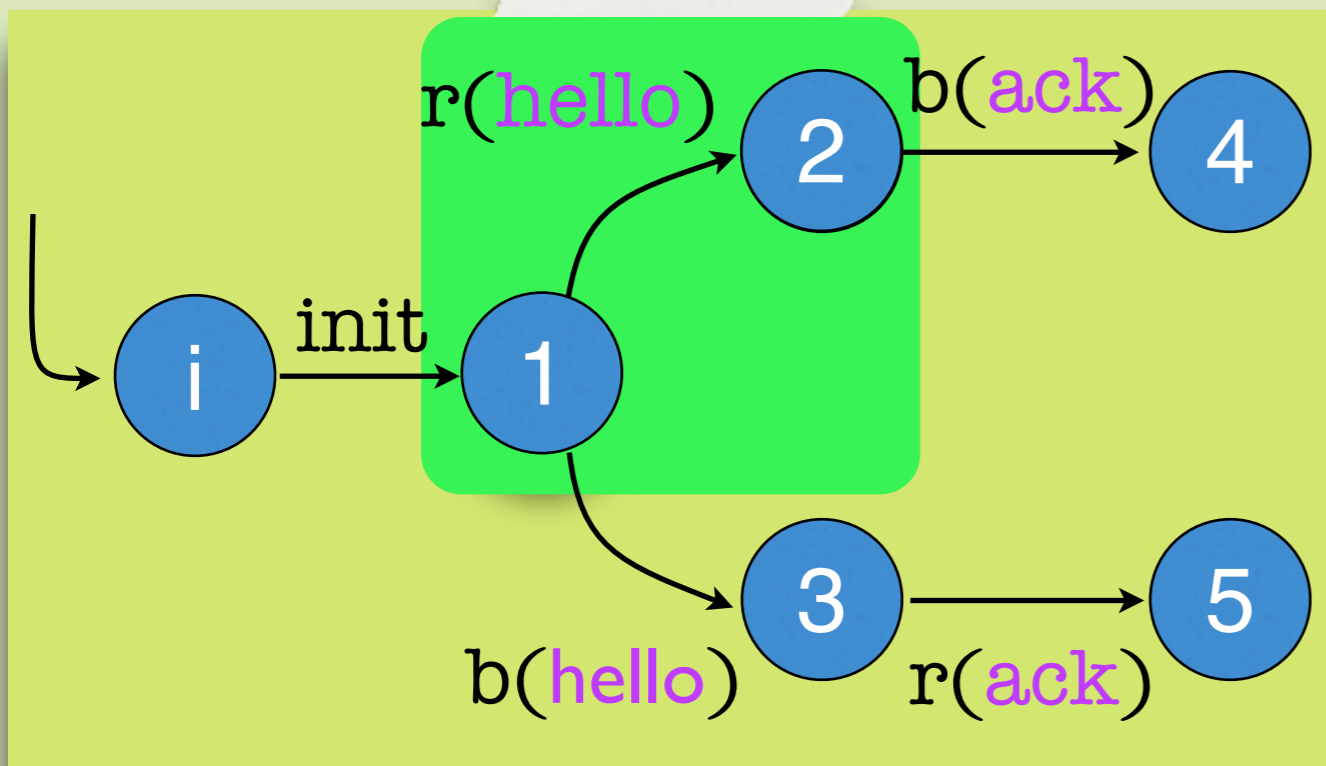
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$$\langle \Gamma, \longrightarrow \rangle$$

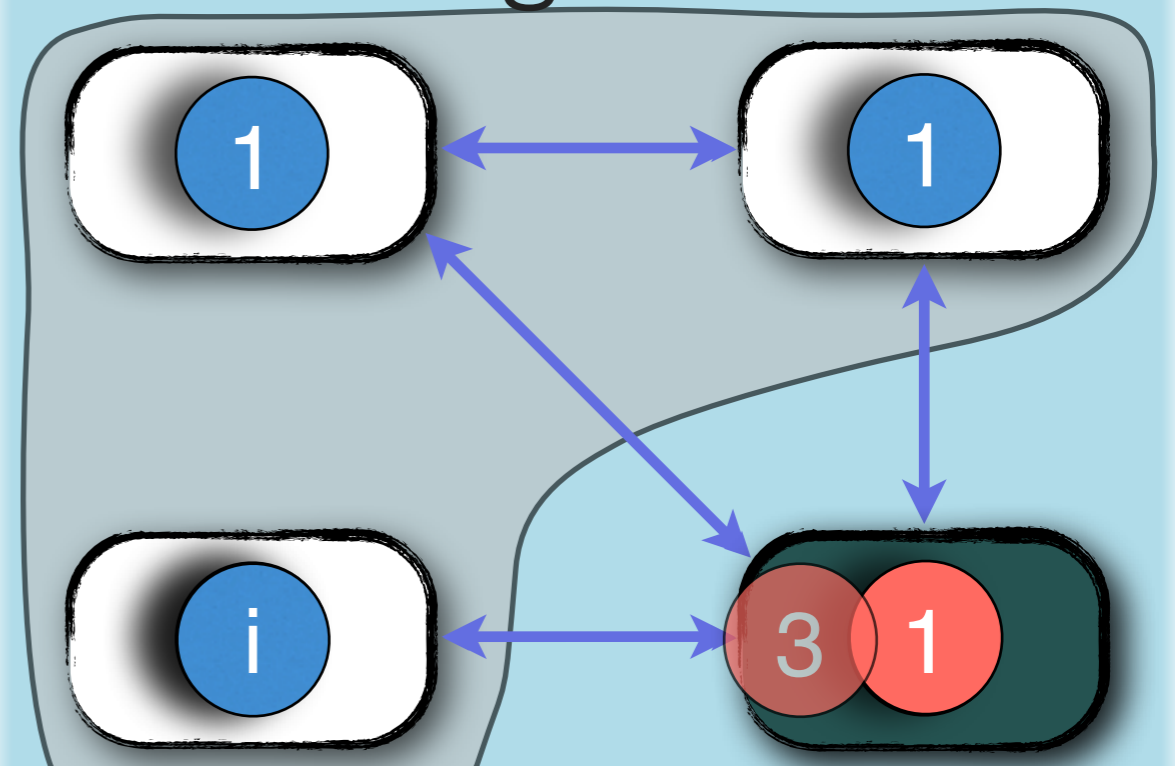
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast



Direct

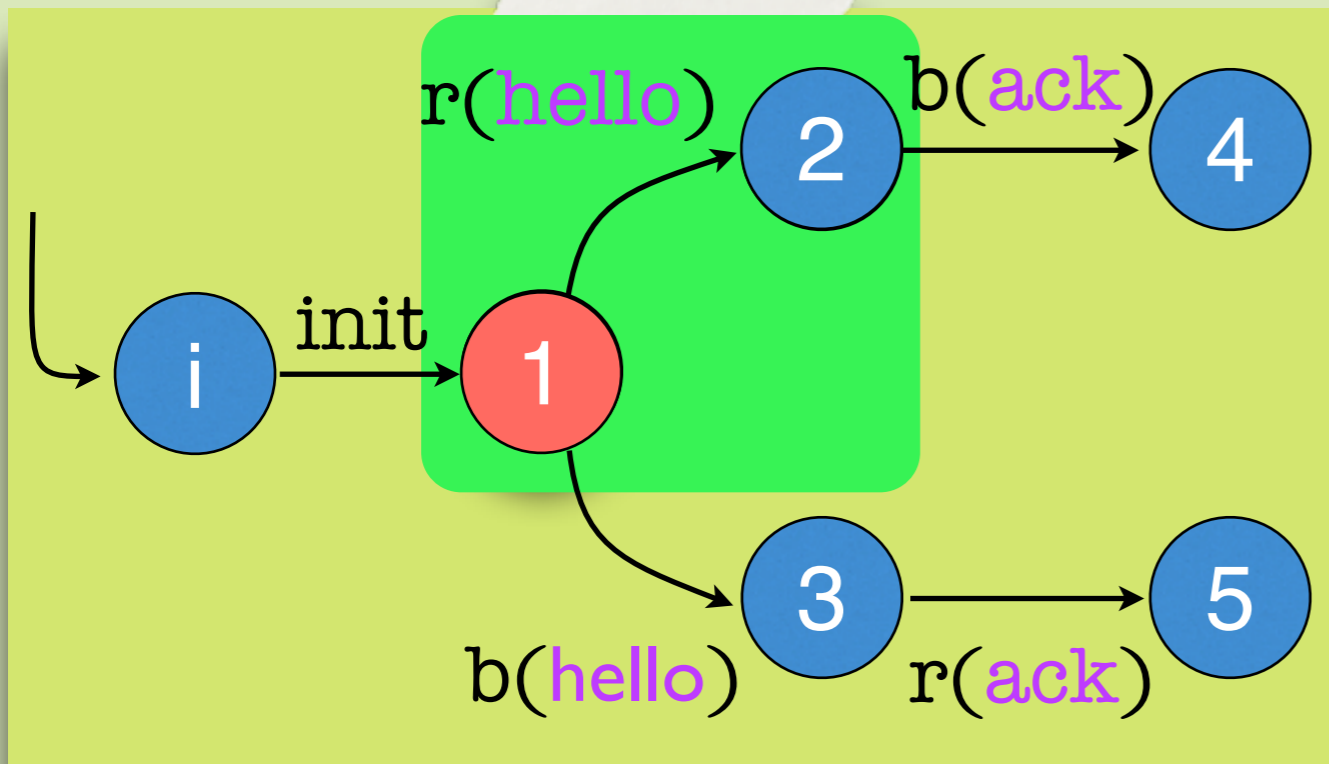
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$$\langle \Gamma, \longrightarrow \rangle$$

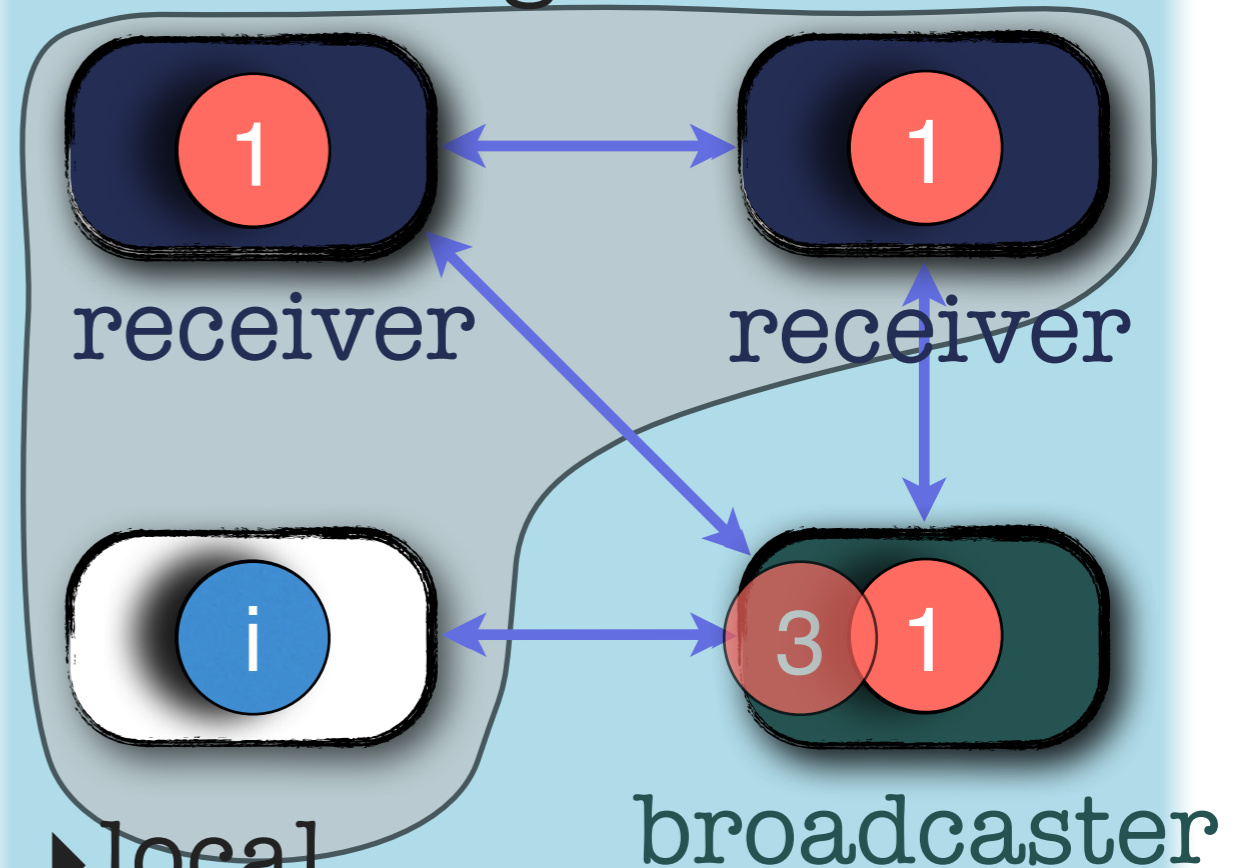
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast



Direct

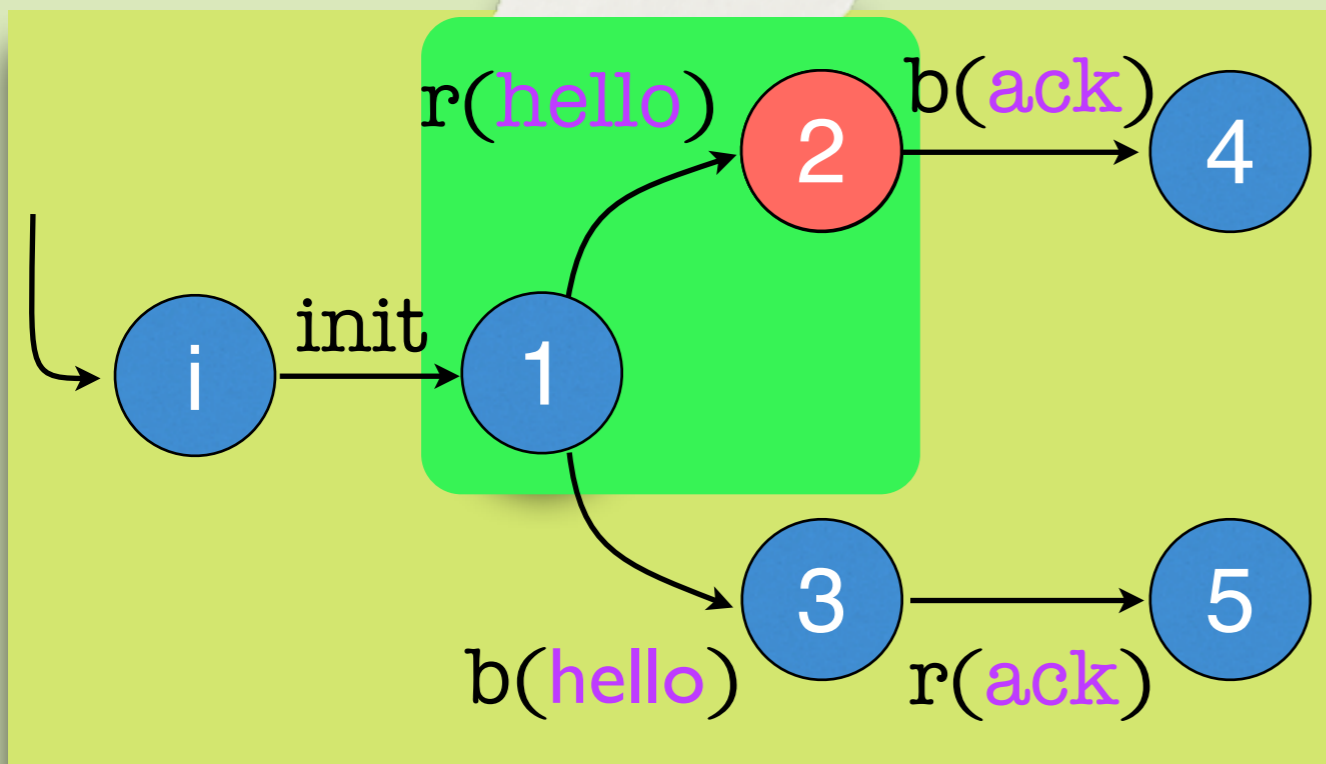
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

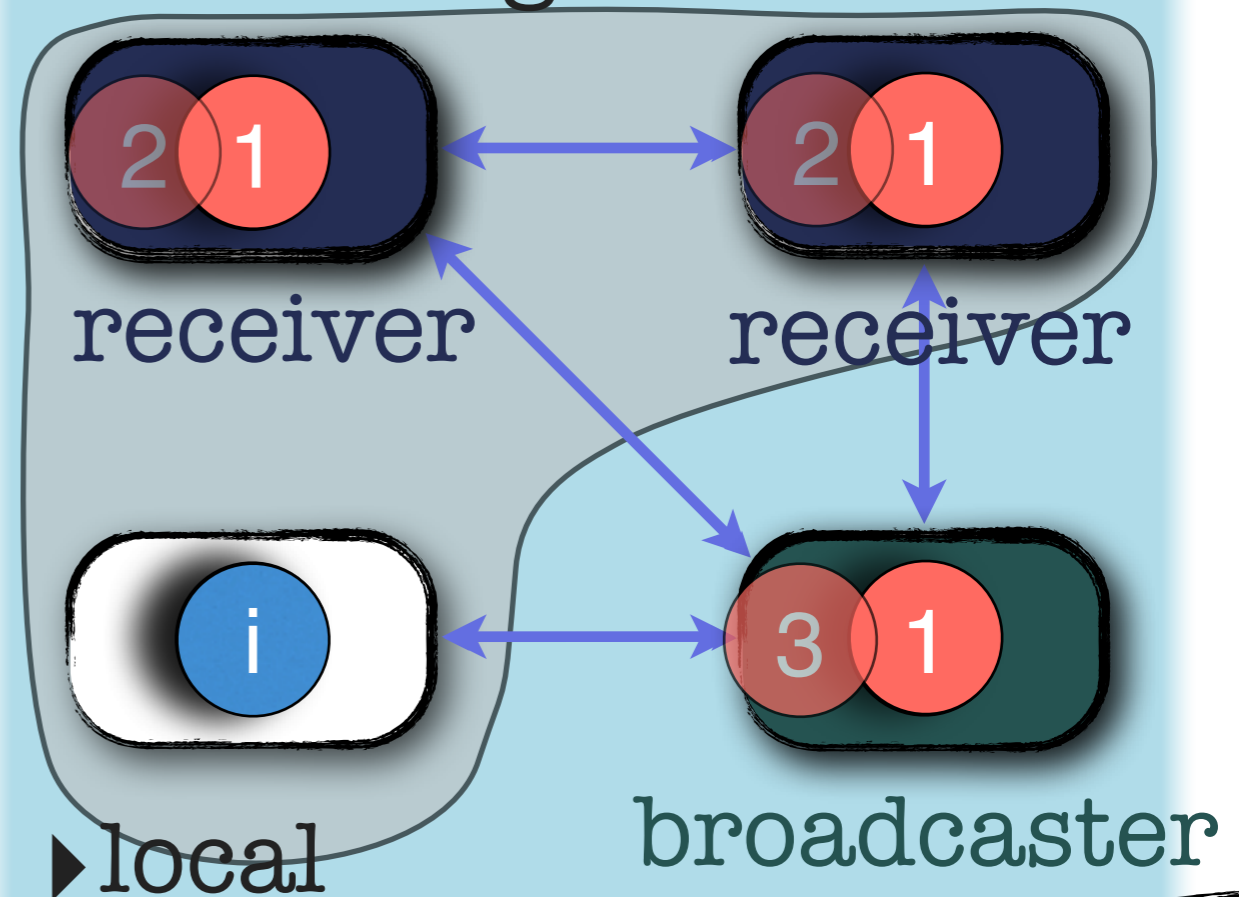
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
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Direct

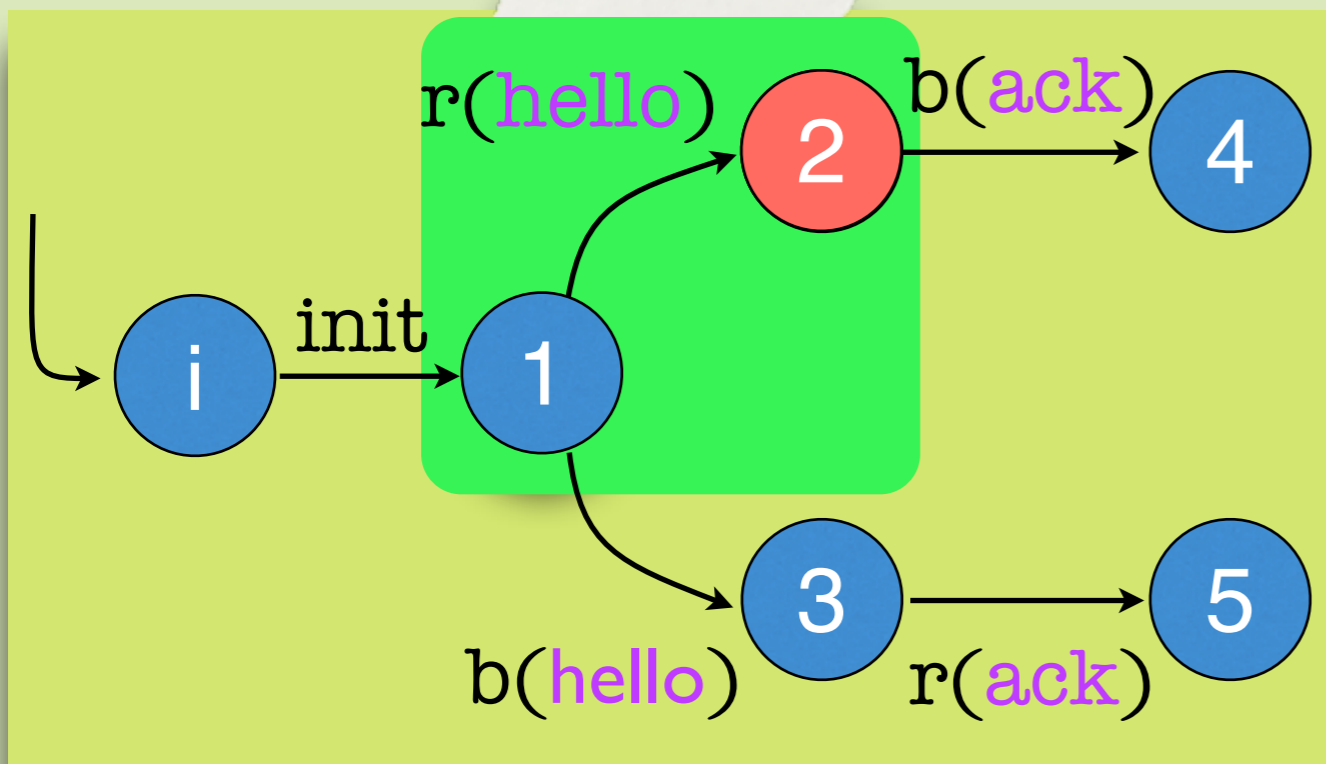
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

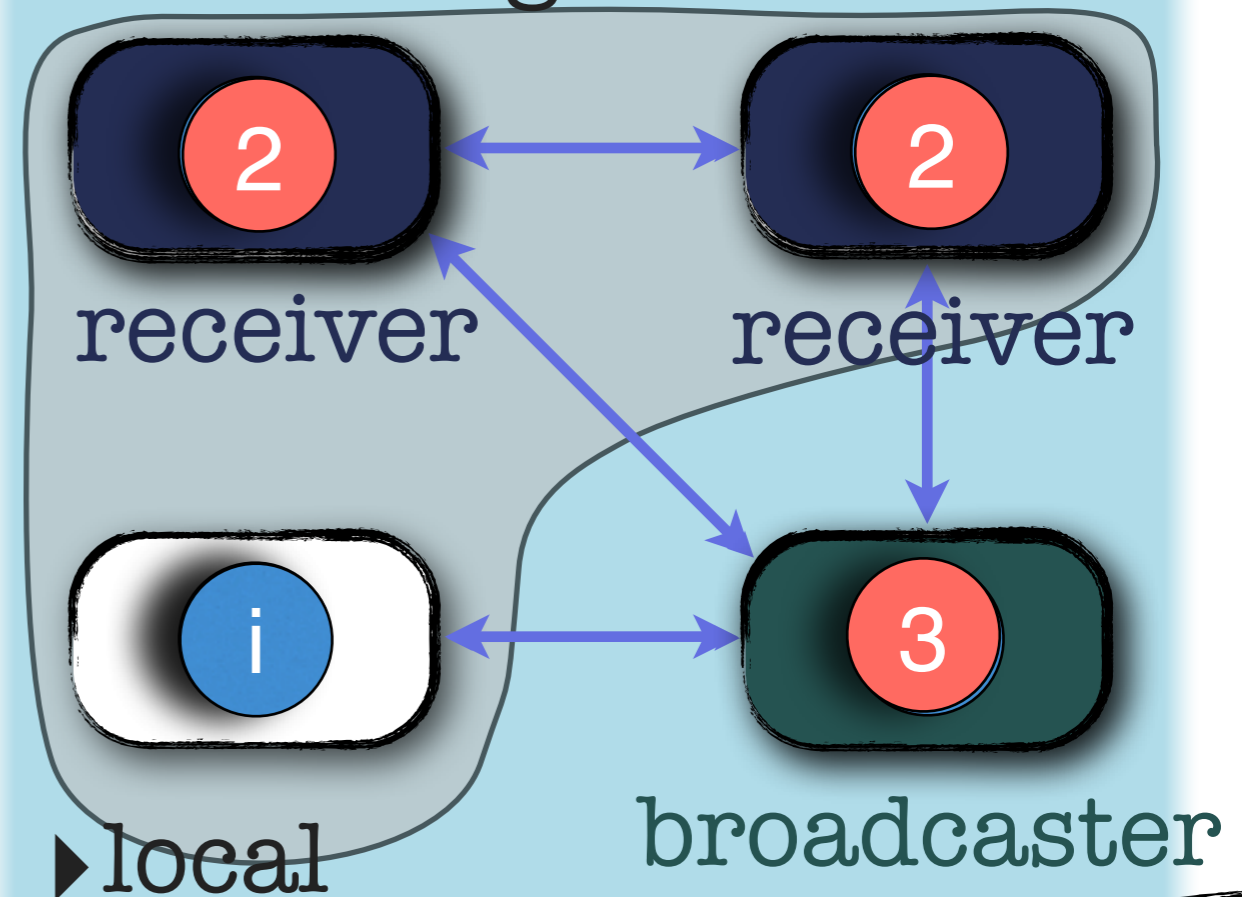
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



- ▶ local
- ▶ selective broadcast



Direct

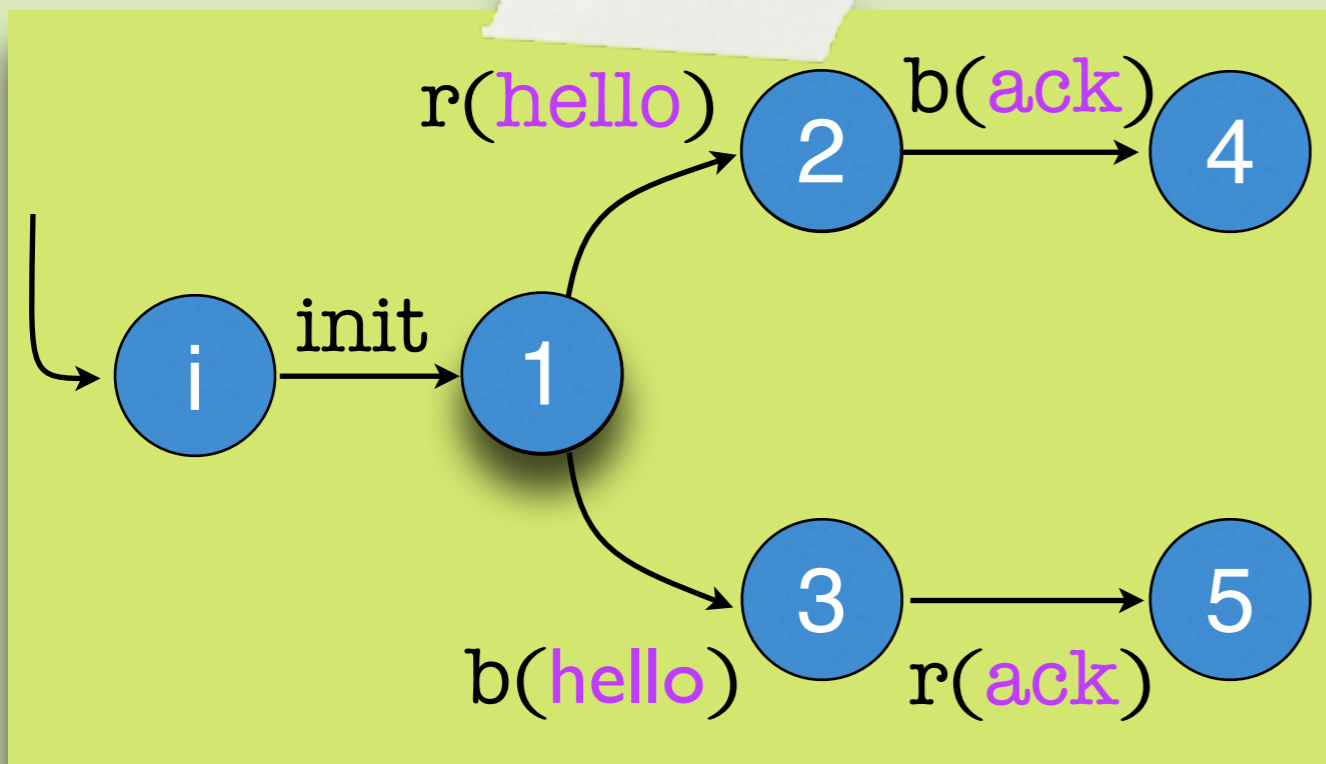
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

$\langle \Gamma, \longrightarrow \rangle$

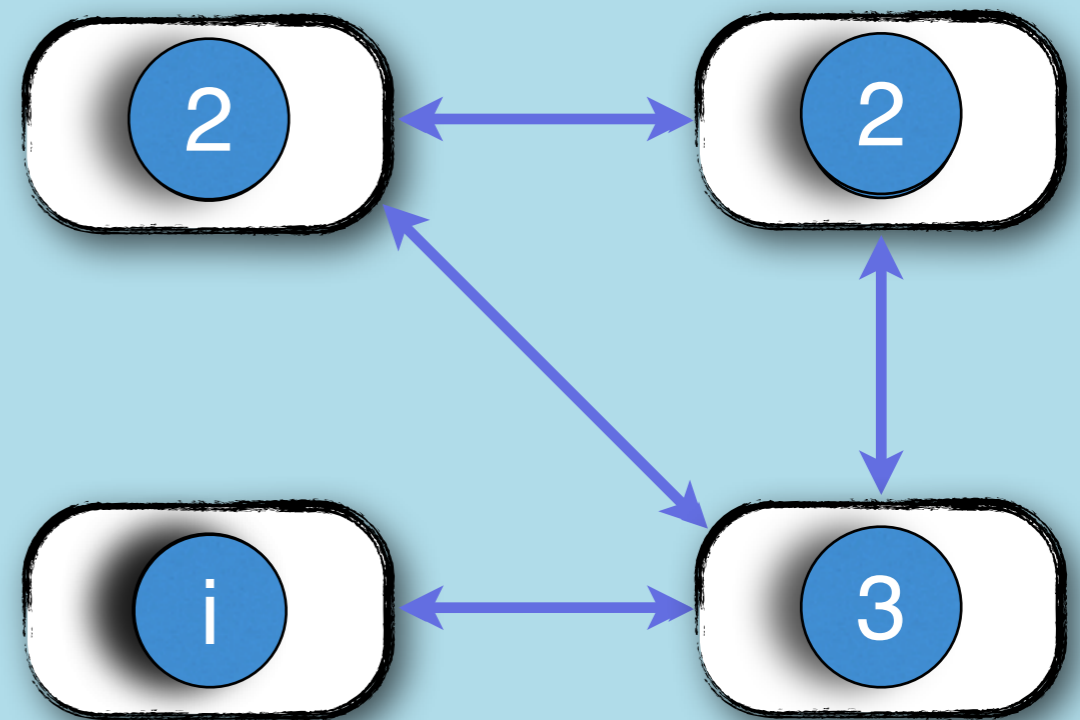
- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Process



- ▶ local
- ▶ broadcast
- ▶ receive

Configuration



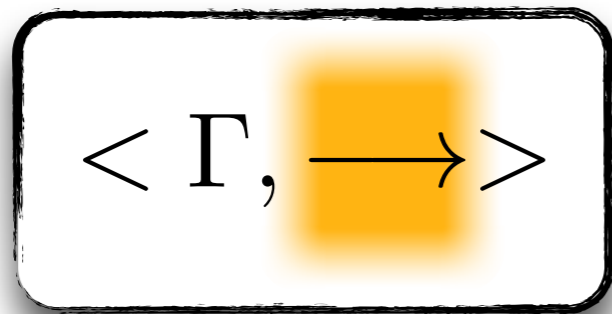
- ▶ local
- ▶ selective broadcast



Direct

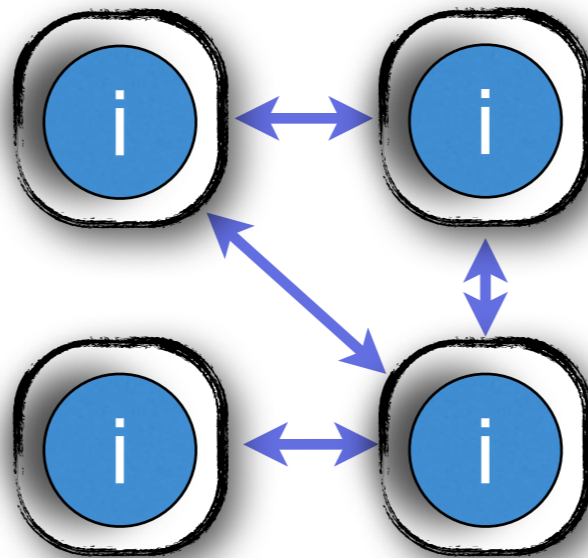
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

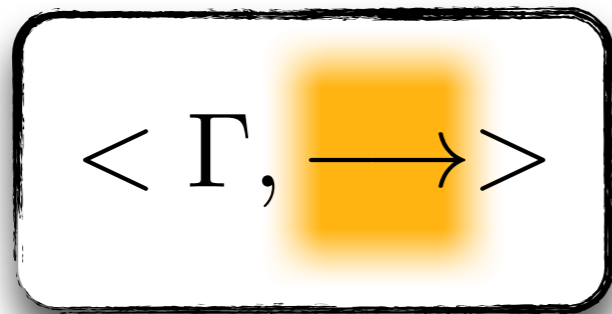
Conf



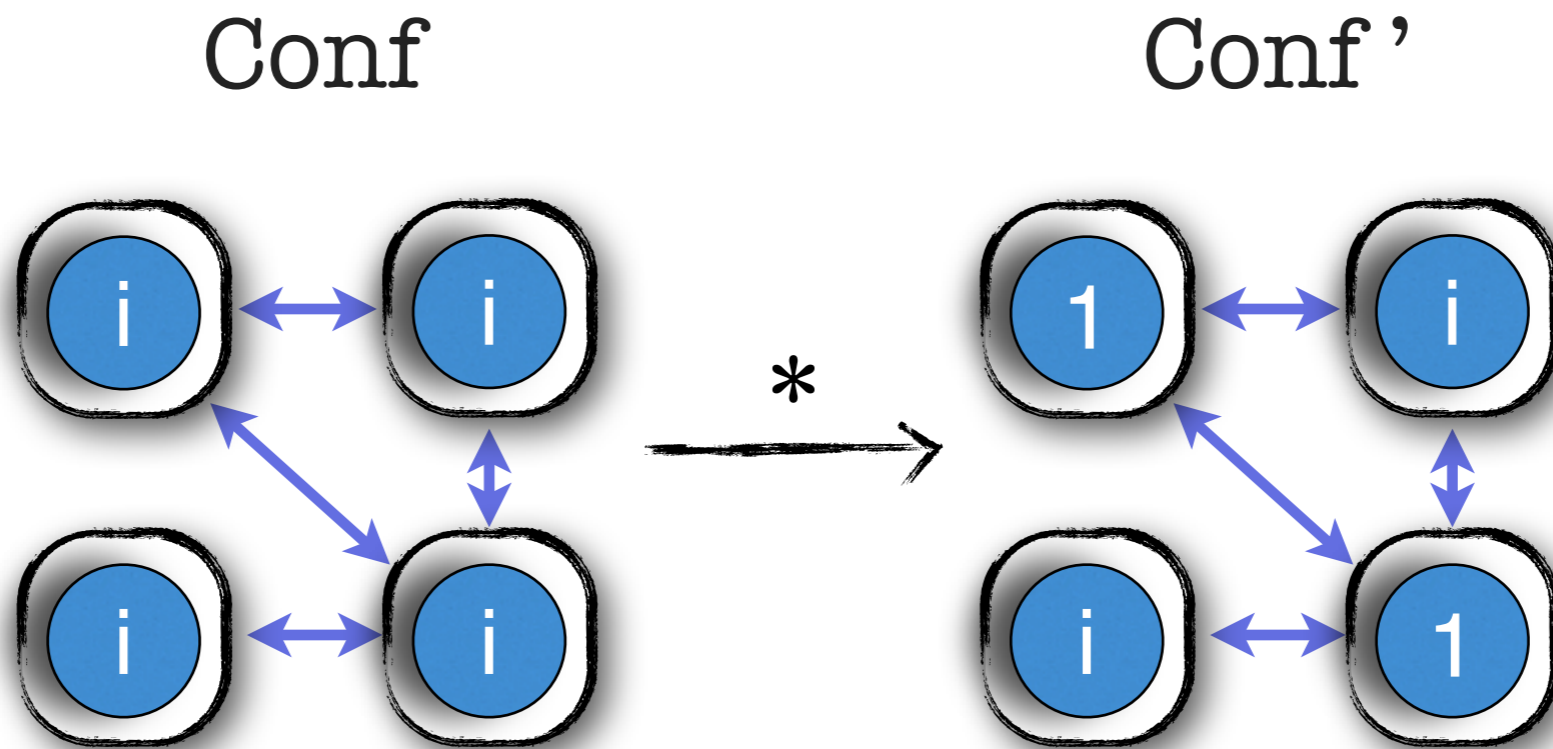
Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

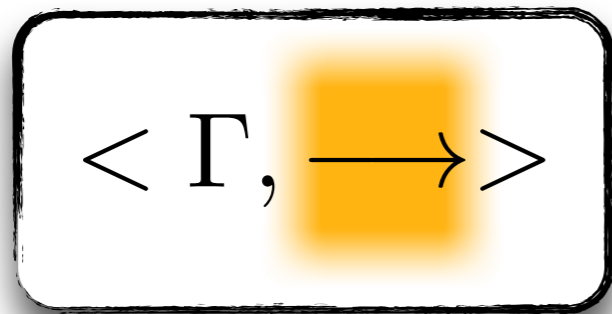


- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace



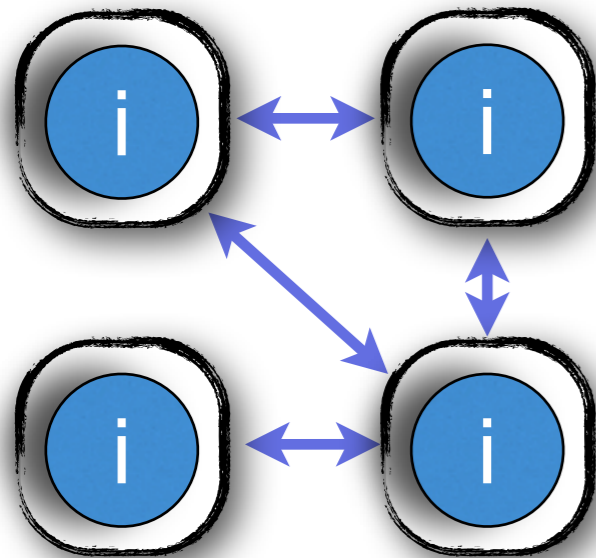
Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

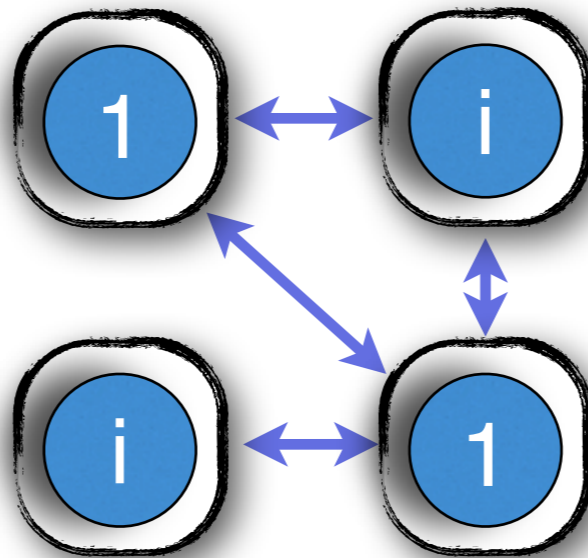


- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

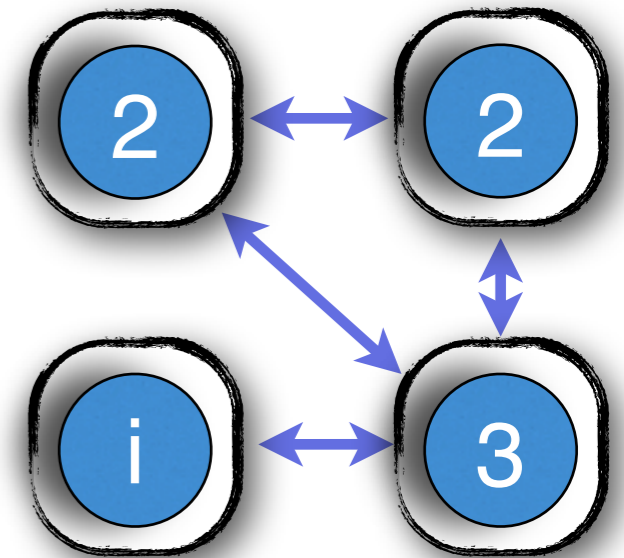
Conf



Conf'



Conf''



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

Given

Direct

Ad-Hoc Networks

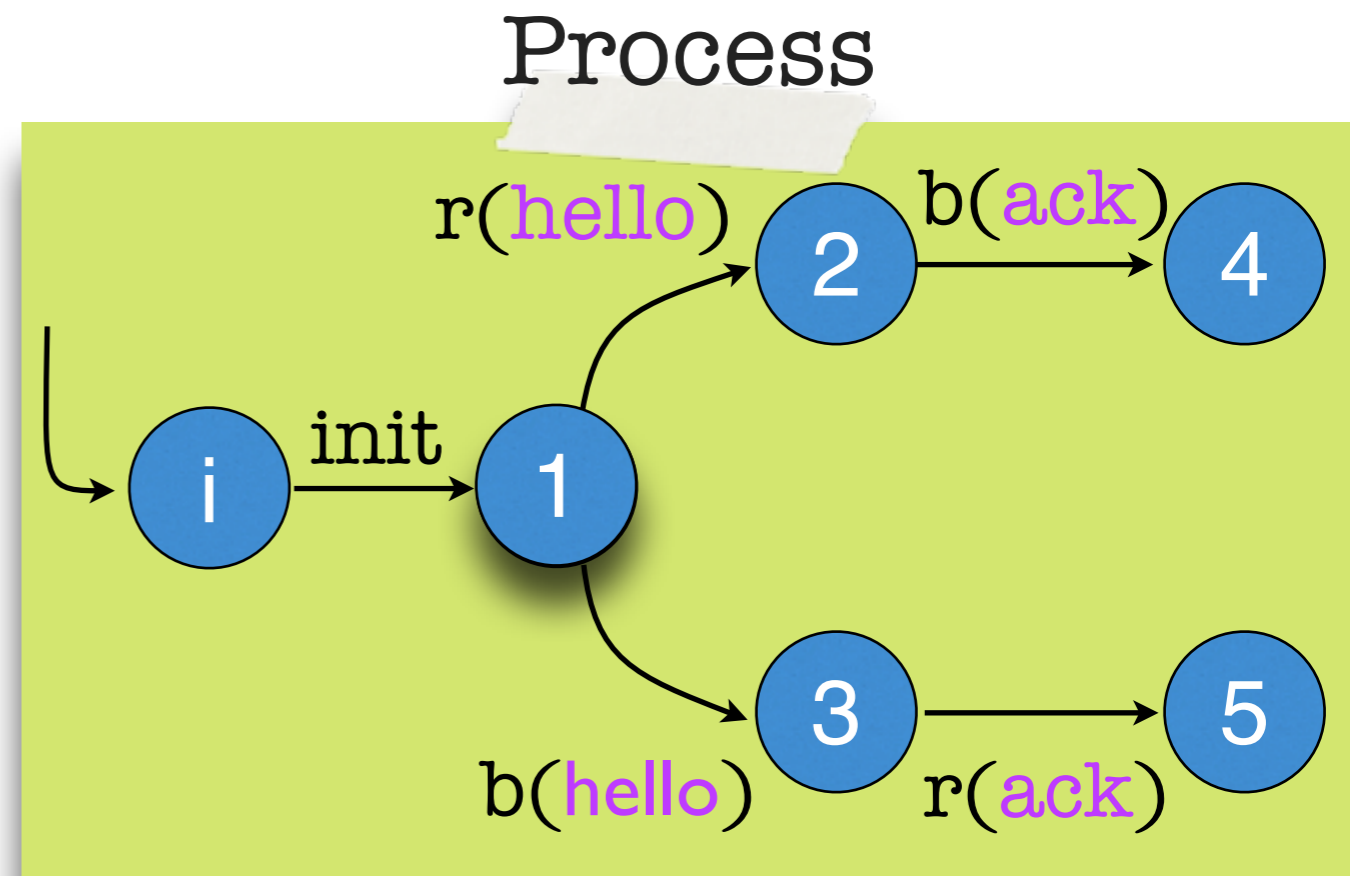
- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

▶ Process P

Given



Direct

Ad-Hoc Networks

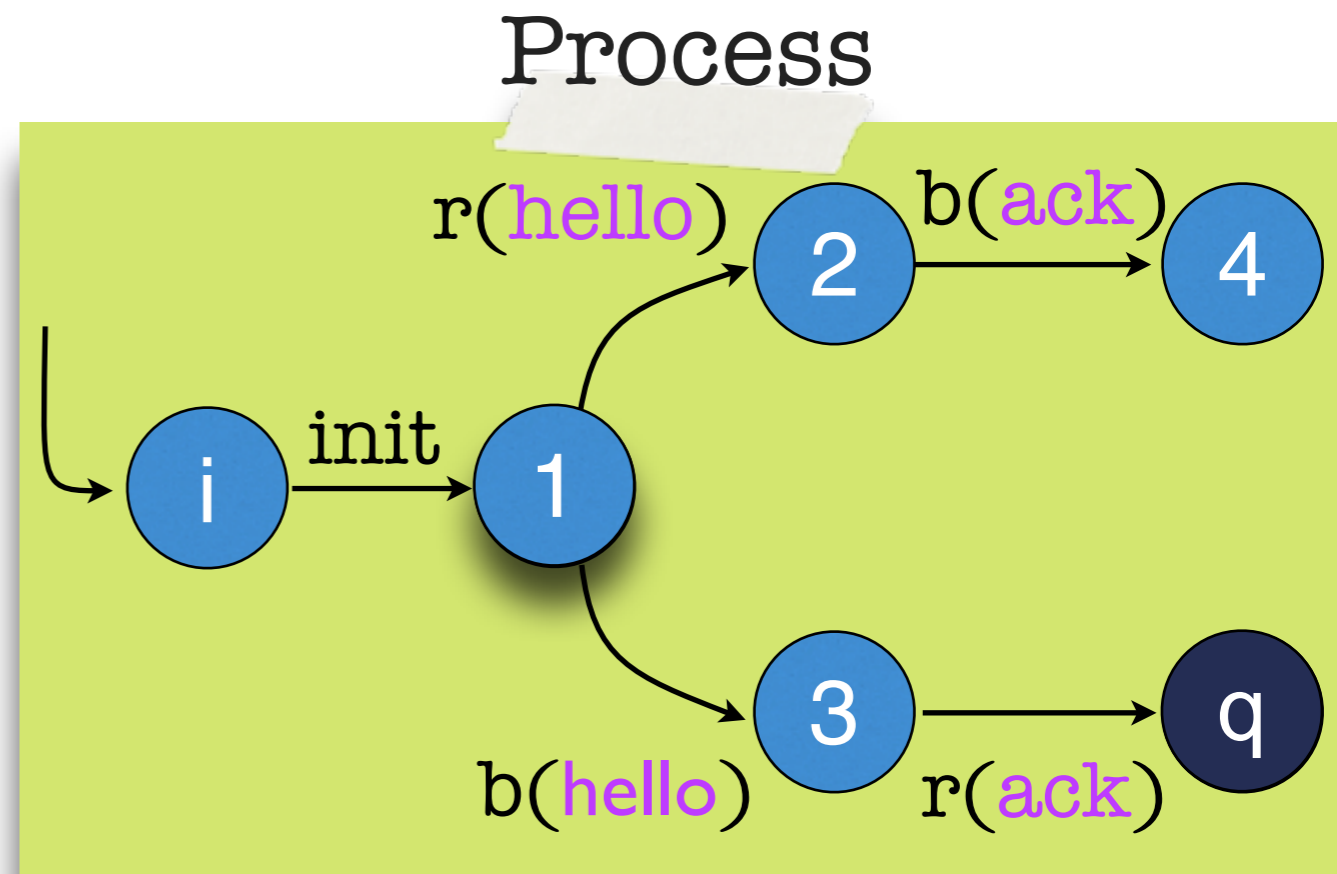
- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

Given

- ▶ Process P
- ▶ Control State q



Direct

Ad-Hoc Networks

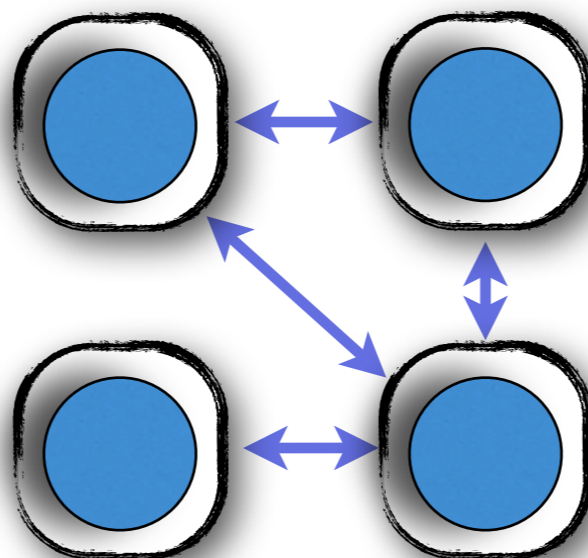
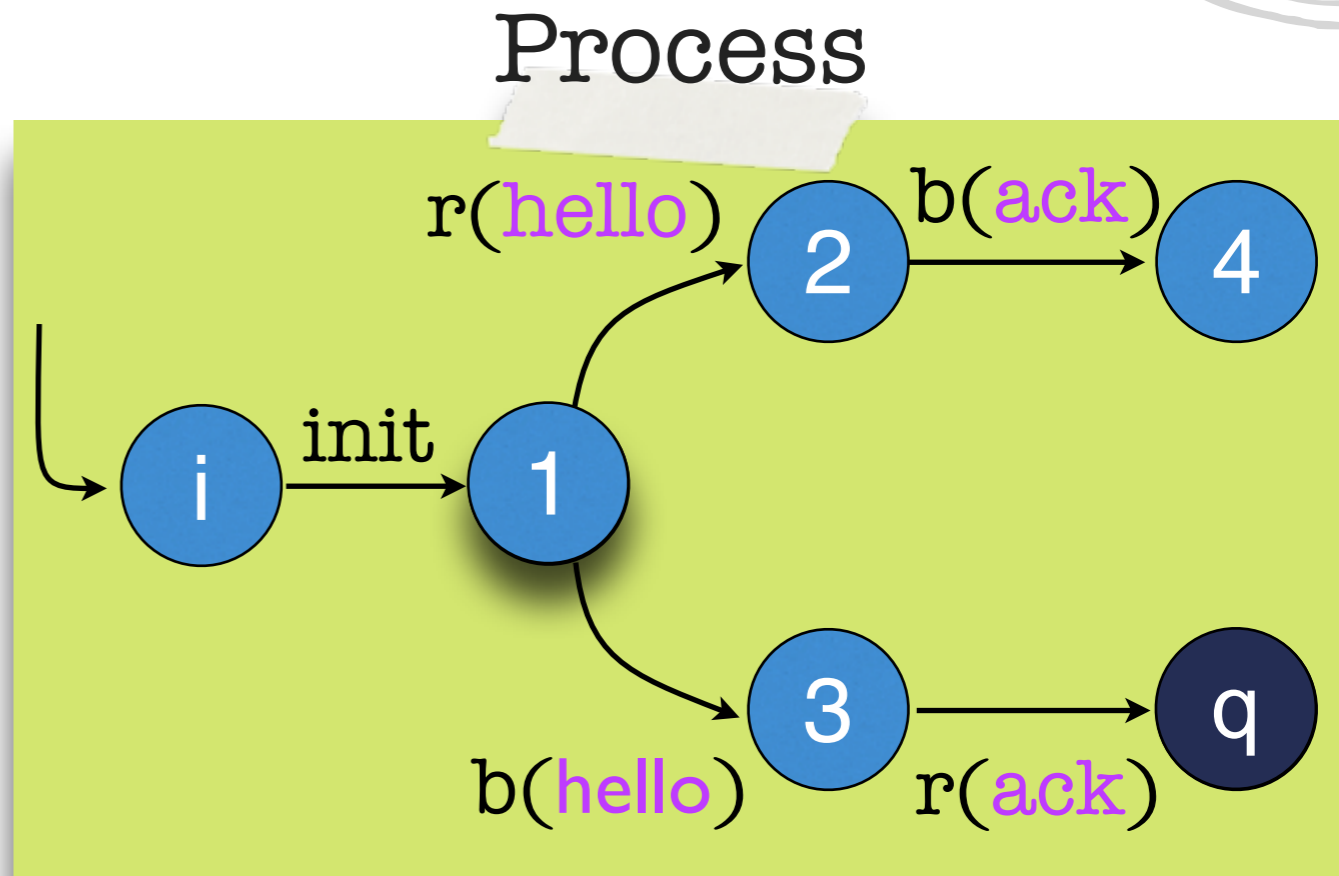
- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

- ▶ Process P
- ▶ Control State q

Given



Direct

Ad-Hoc Networks

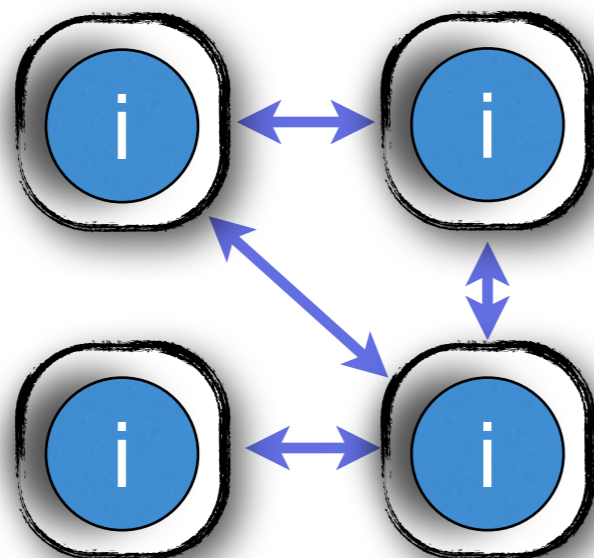
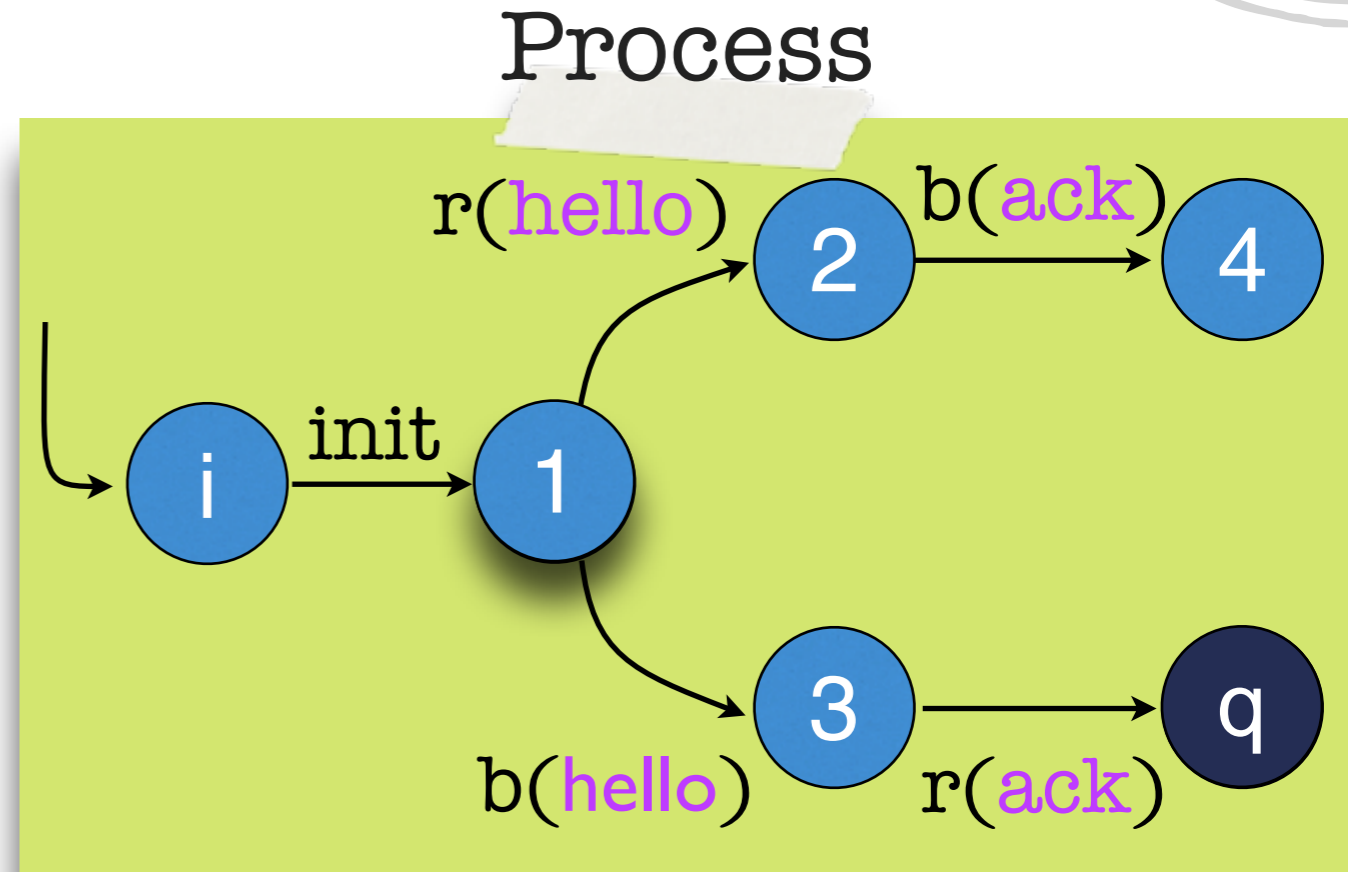
- ▶ Model
- ▶ Transition System
- ▶ Reachability



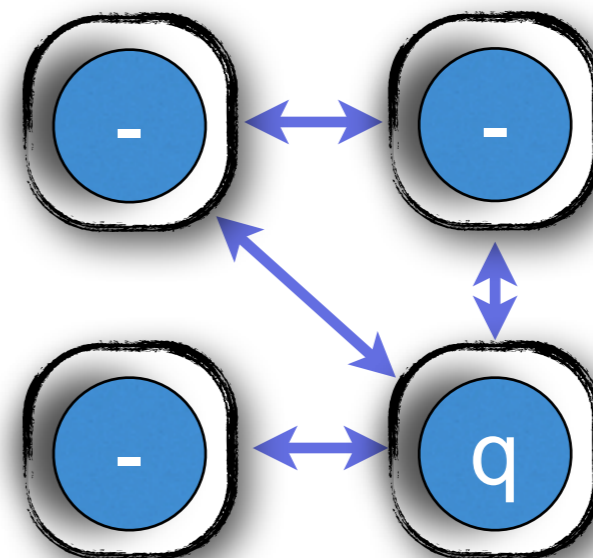
Control State Reachability (COVER)

- ▶ Process P
- ▶ Control State q

Given



*



Direct

Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability



Control State Reachability (COVER)

Undecidable

Direct



Ad-Hoc Networks

Directed Acyclic



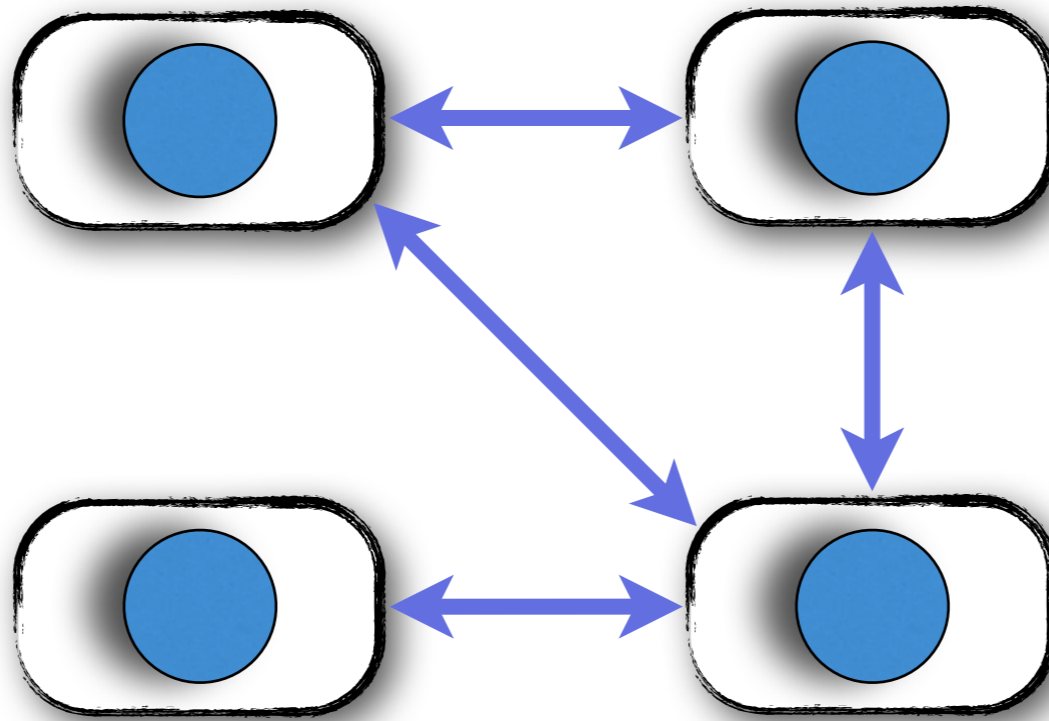
Ad-Hoc Networks

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

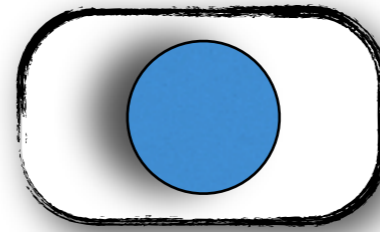
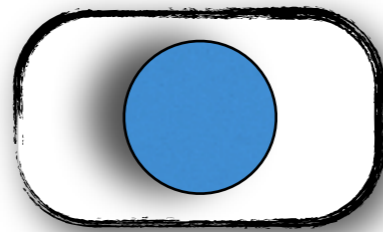
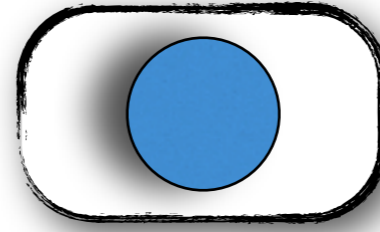
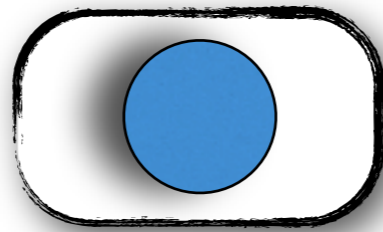
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



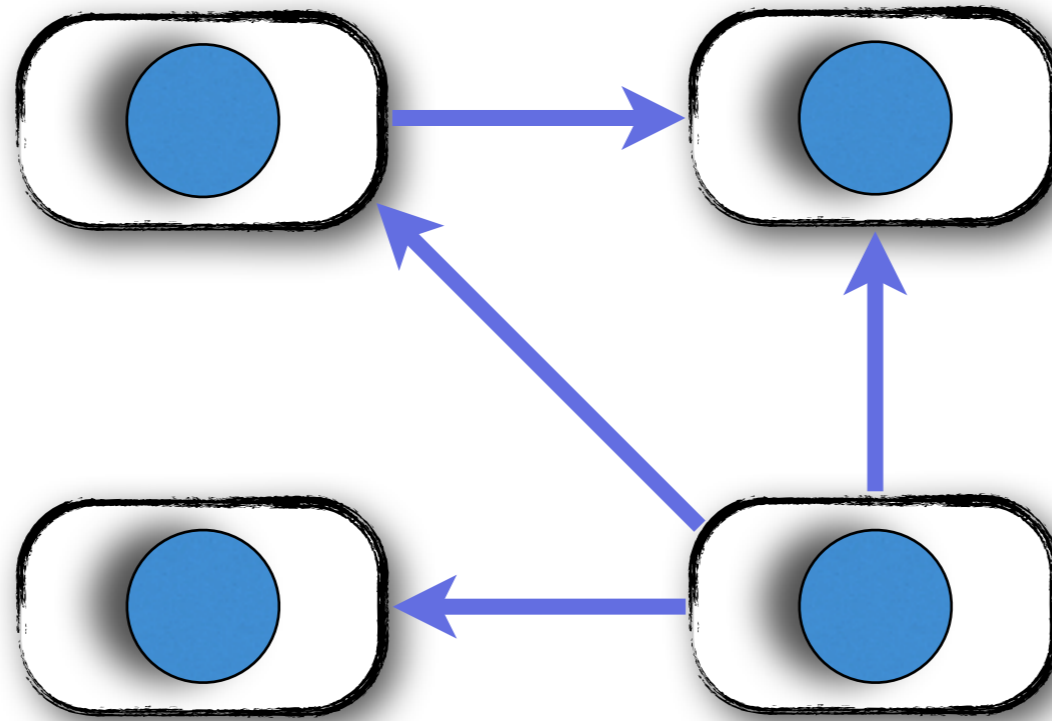
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability





Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Wireless Sensor Networks

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Wireless Sensor Networks

Phases:

sens₁

sens₂

sink

sens₃

Directed Acyclic

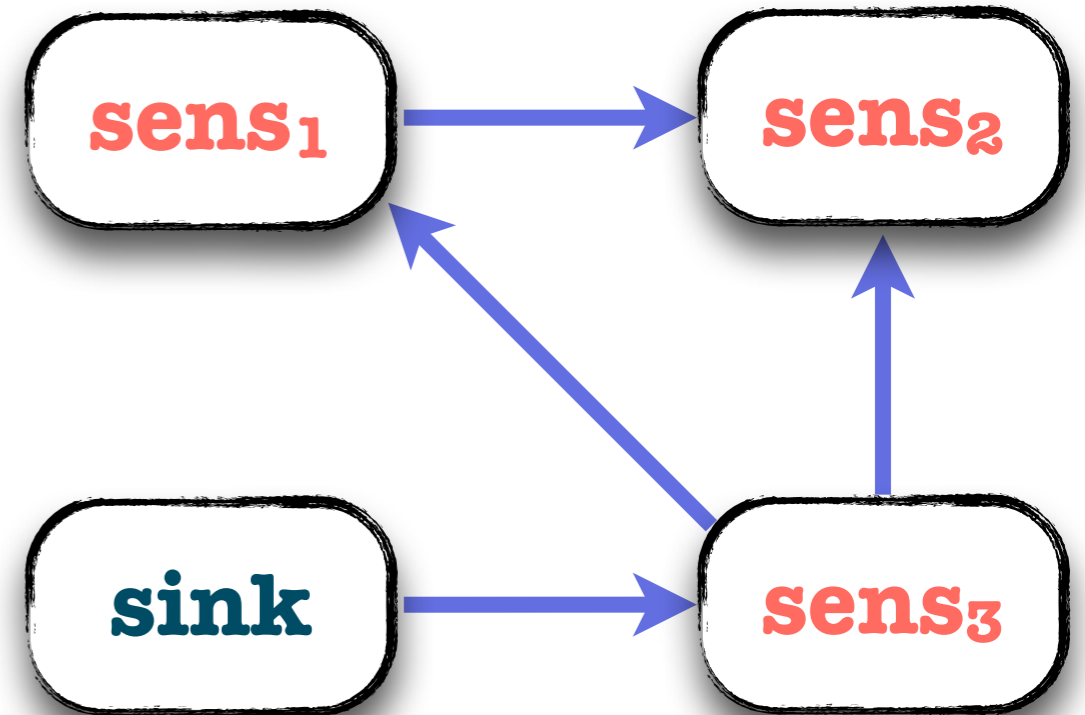
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Wireless Sensor Networks

Phases:

- Sink \rightarrow Sensors:
 - ▶ Data request
 - ▶ Software updates
- Sensors \rightarrow Sink:
Data collection.



Directed Acyclic

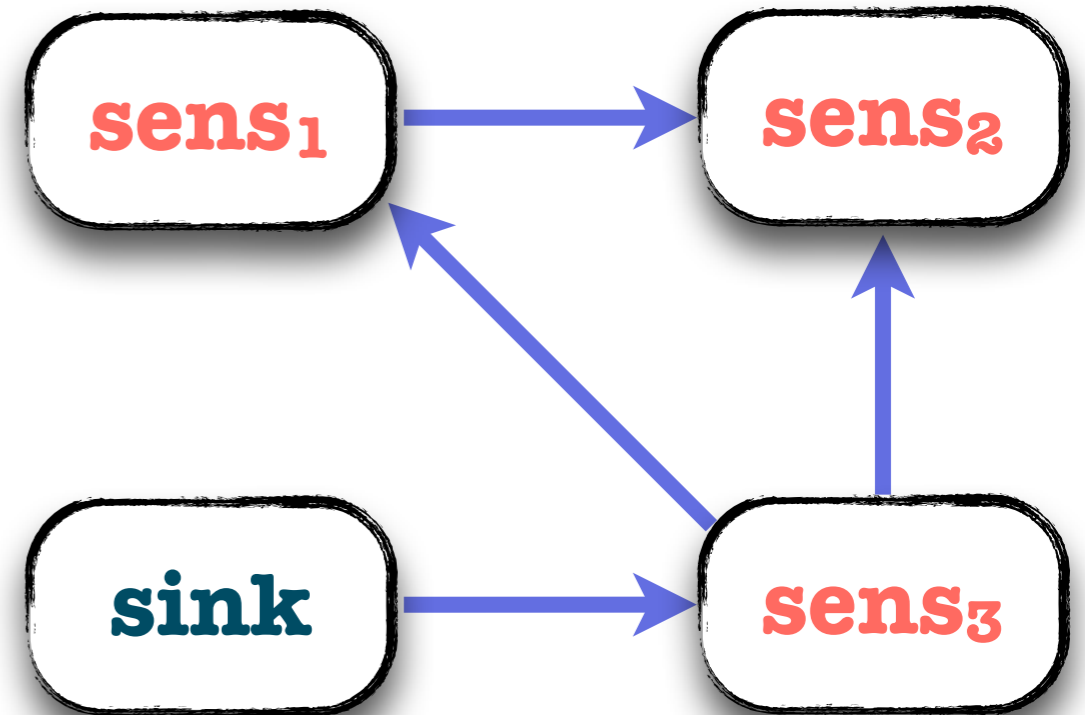
- ▶ Motivation
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Wireless Sensor Networks

Phases:

- Sink \rightarrow Sensors:
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Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Wireless Sensor Networks

Phases:

- Sink \rightarrow Sensors:
 - ▶ Data request
 - ▶ Software updates

- Sensors \rightarrow Sink:
Data collection.

sens₁

sens₂

sink

sens₃

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

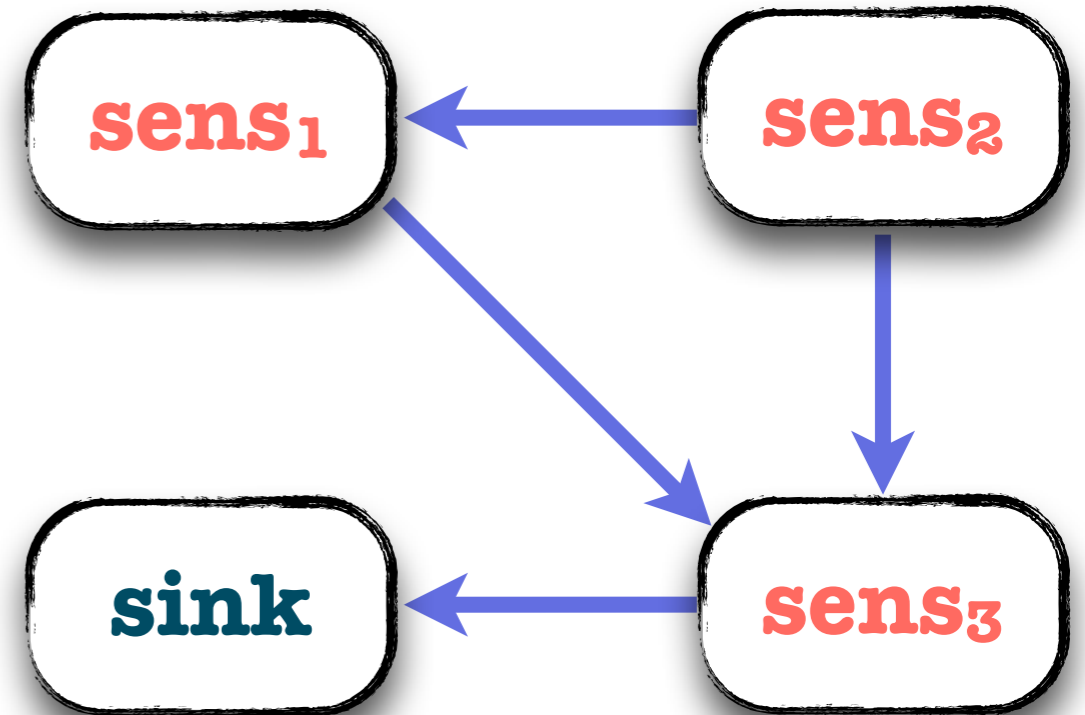


Wireless Sensor Networks

Phases:

- Sink \rightarrow Sensors:
 - ▶ Data request
 - ▶ Software updates

- Sensors \rightarrow Sink:
Data collection.



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

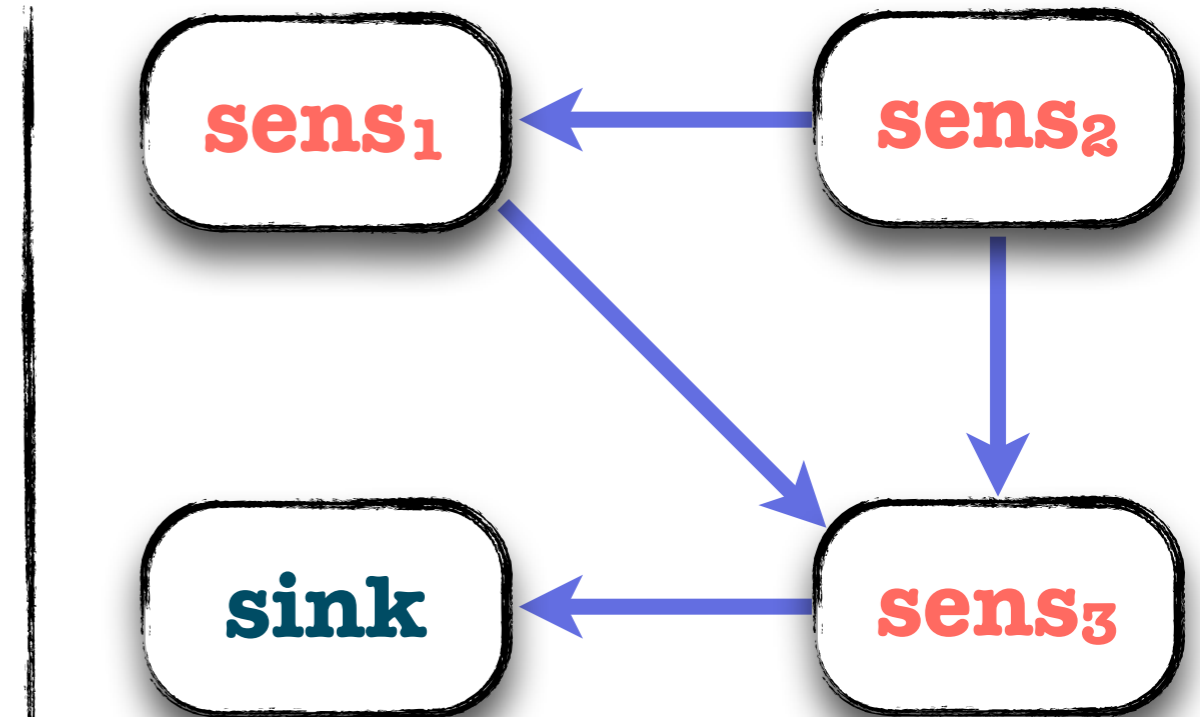


Wireless Sensor Networks

Phases:

- Sink \rightarrow Sensors:
 - ▶ Data request
 - ▶ Software updates

- Sensors \rightarrow Sink:
Data collection.



Root Discovery Protocol

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

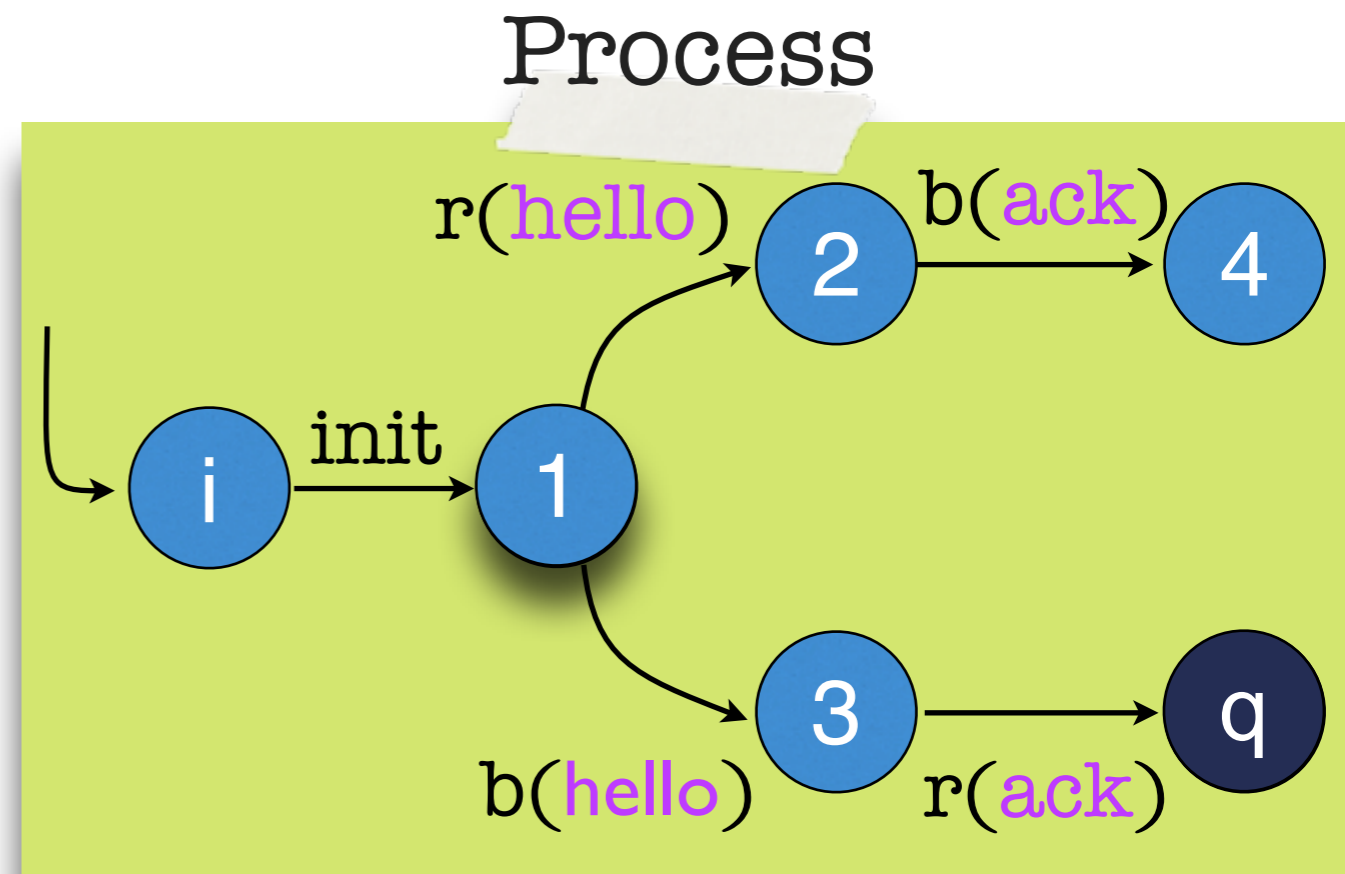
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Control State Reachability (COVER)

Given

- ▶ Process P
- ▶ Control State q



Directed Acyclic

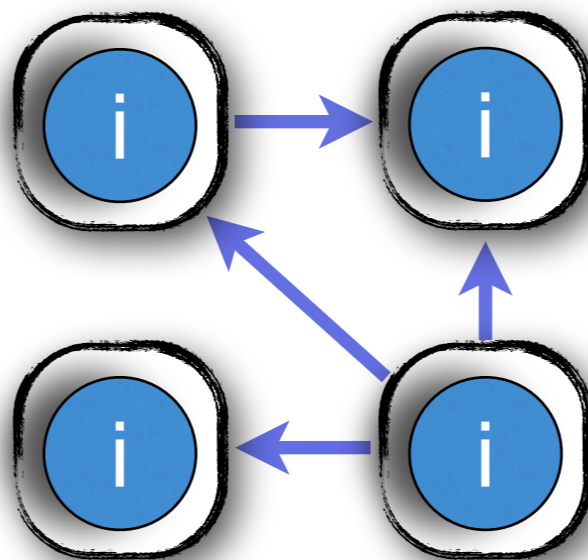
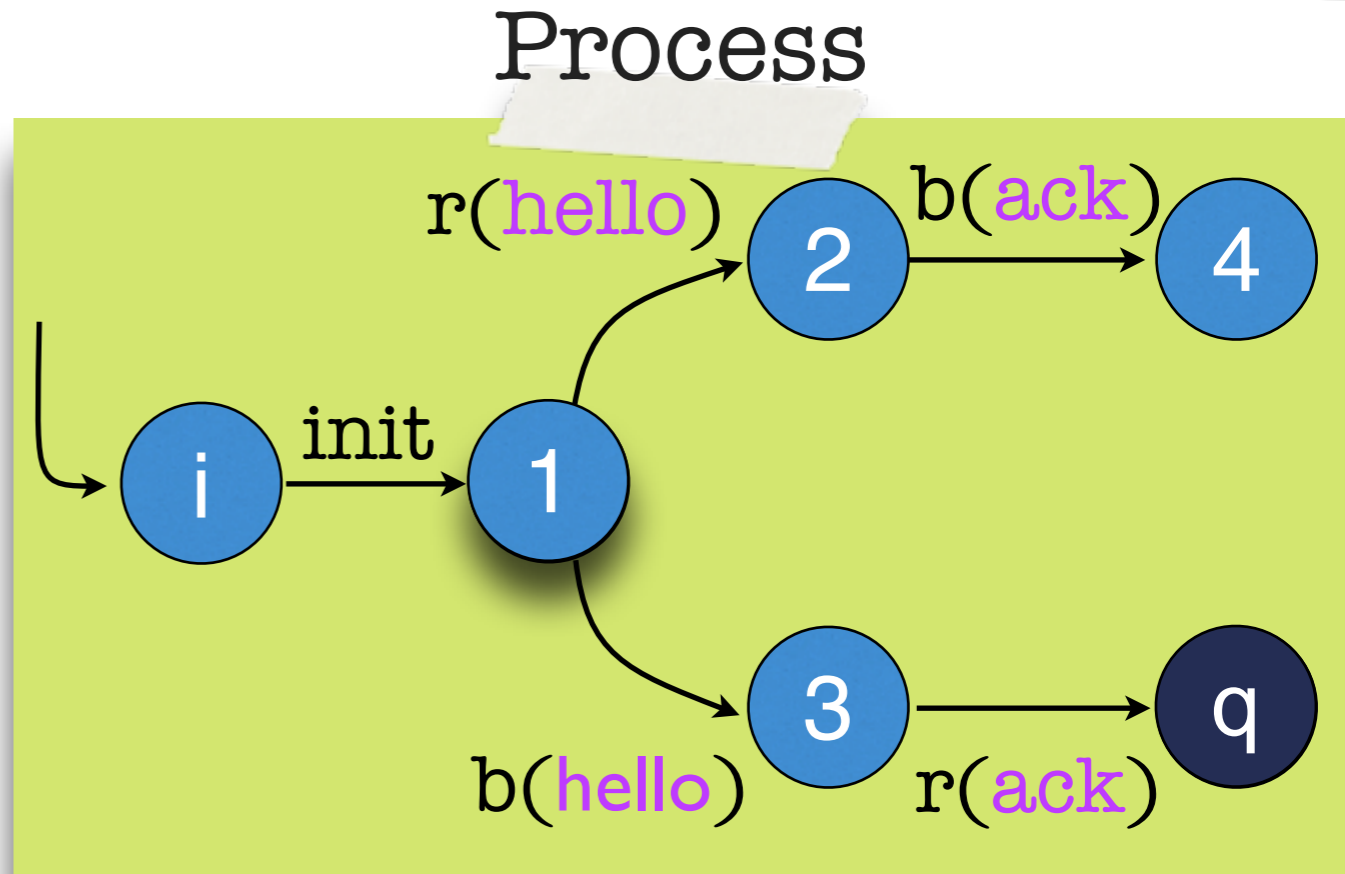
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Control State Reachability (COVER)

- ▶ Process P
- ▶ Control State q

Given



Directed Acyclic

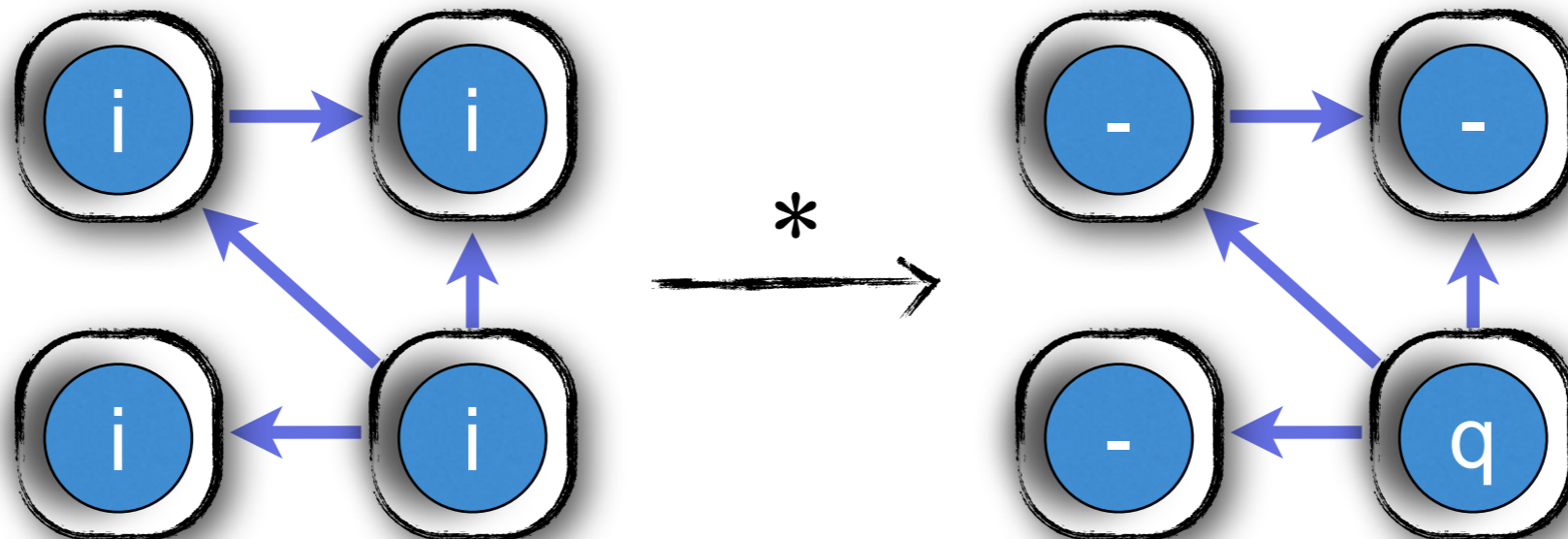
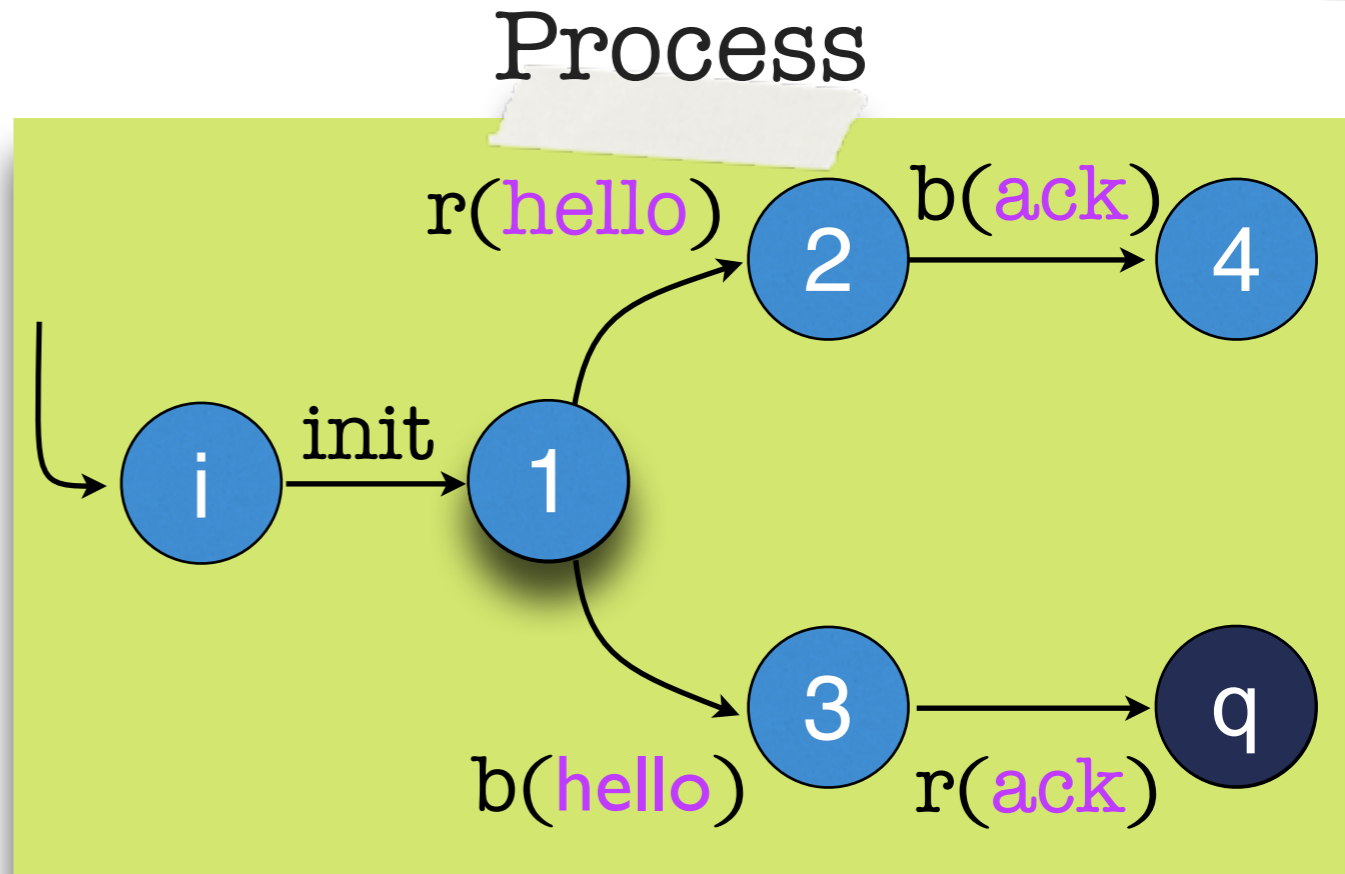
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Control State Reachability (COVER)

- ▶ Process P
- ▶ Control State q

Given





Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Control State Reachability (COVER)

Is still **Undecidable**

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Control State Reachability (COVER)

Is still **Undecidable**

Given A , B and T , is there k

$$T^k(L_A) \cap L_B \neq \emptyset$$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

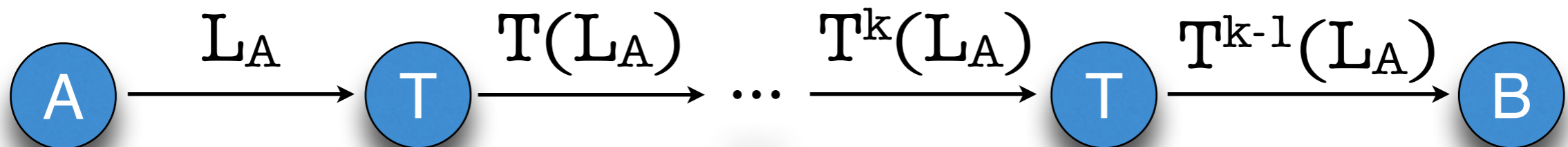


Control State Reachability (COVER)

Is still **Undecidable**

Given A , B and T , is there k

$$T^k(L_A) \cap L_B \neq \emptyset$$



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Control State Reachability (COVER)

Is still **Undecidable**



Directed Acyclic

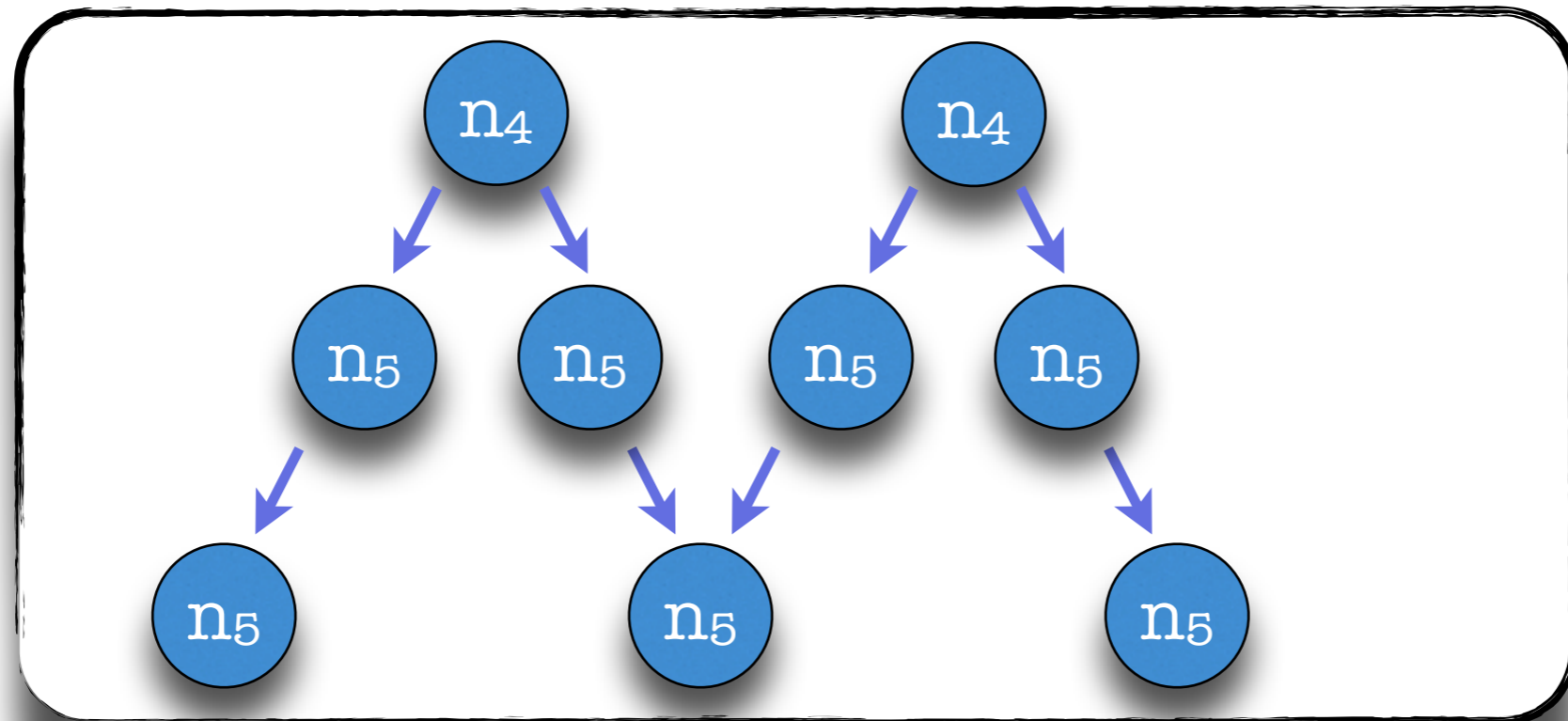
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Bounded Depth Control State Reachability

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Bounded Depth Control State Reachability

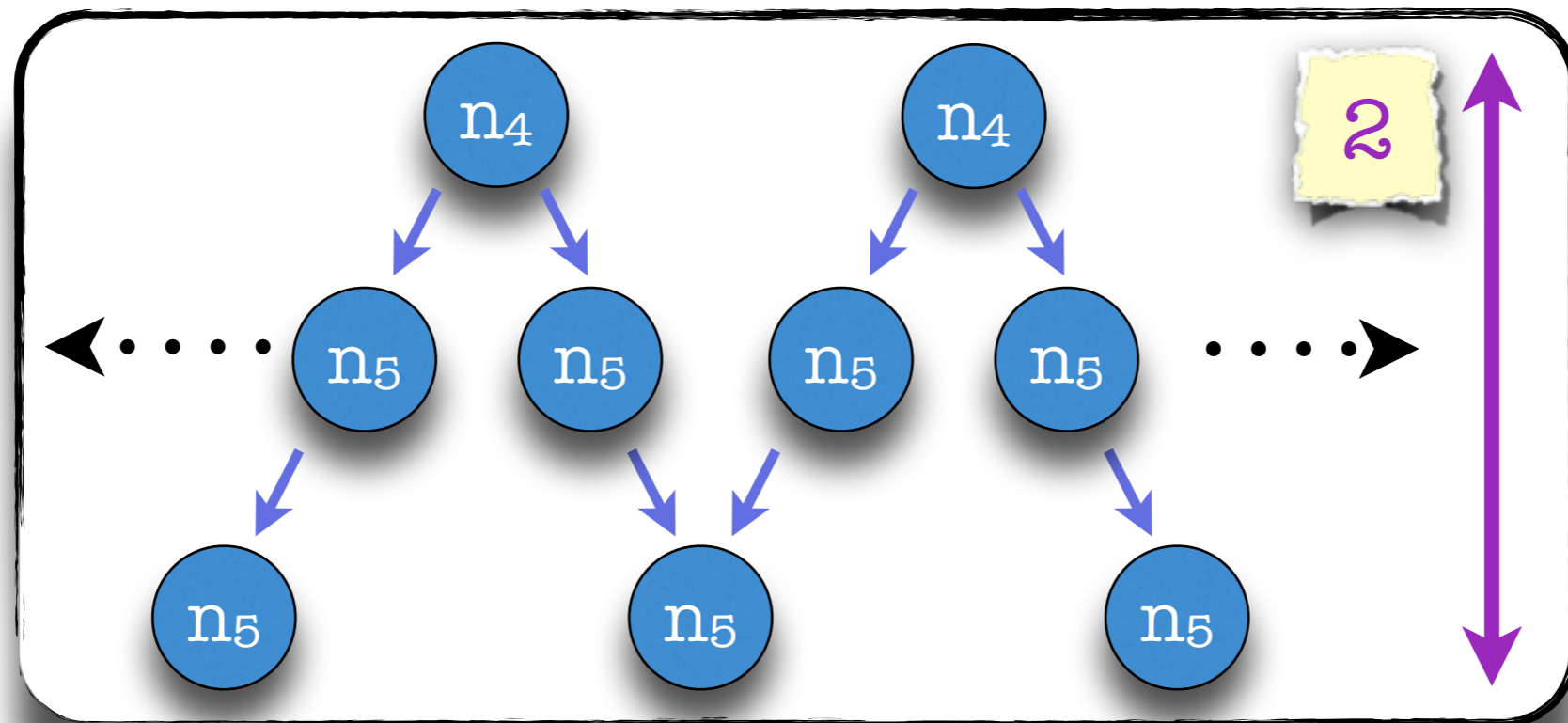


Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



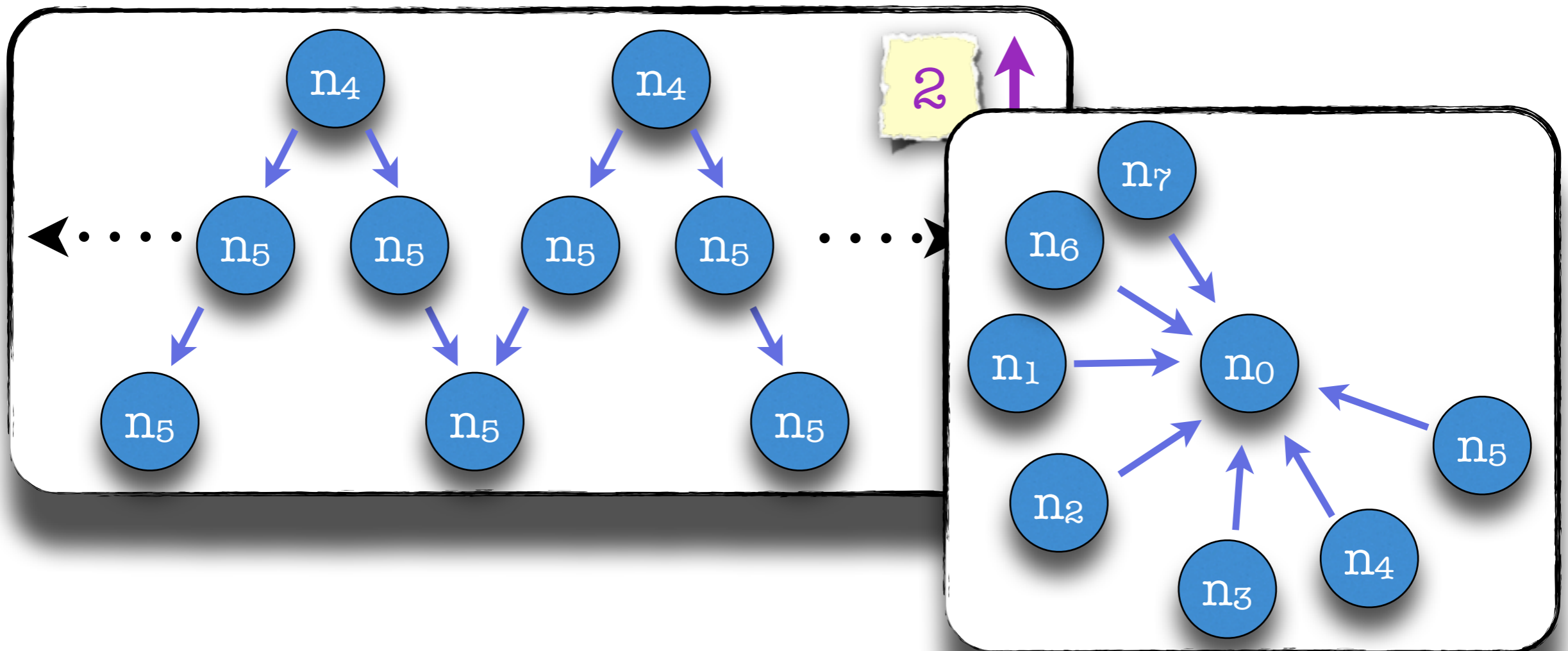
Bounded Depth Control State Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

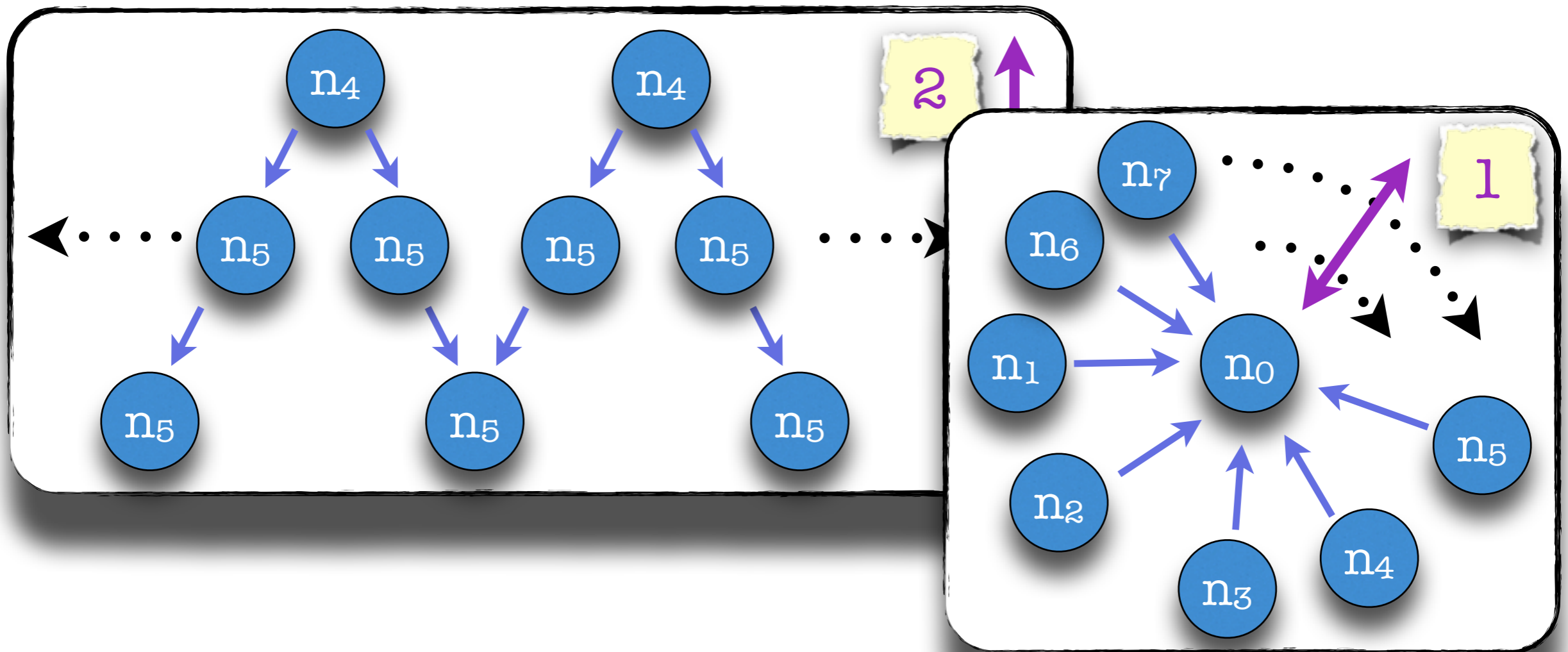
Bounded Depth Control State Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Bounded Depth Control State Reachability

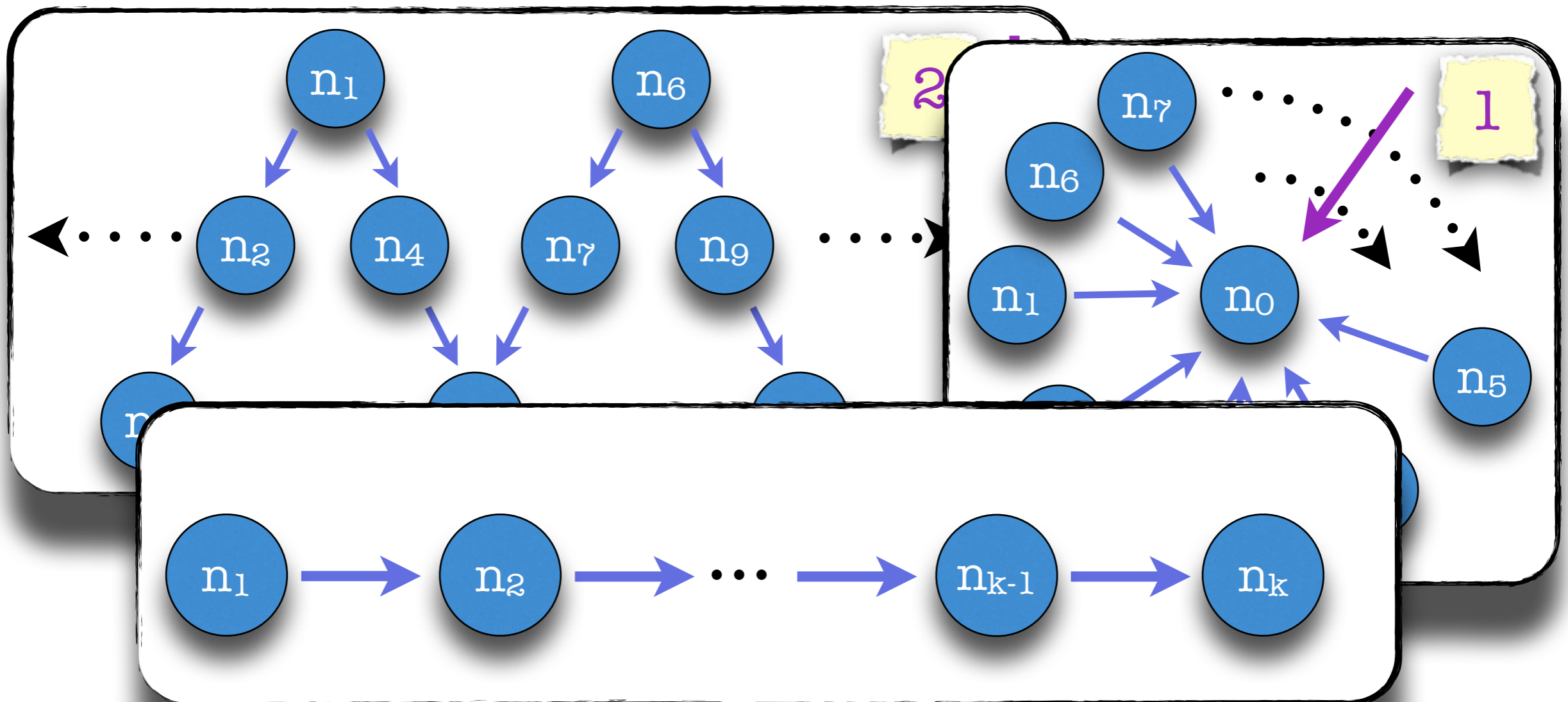


Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



Bounded Depth Control State Reachability

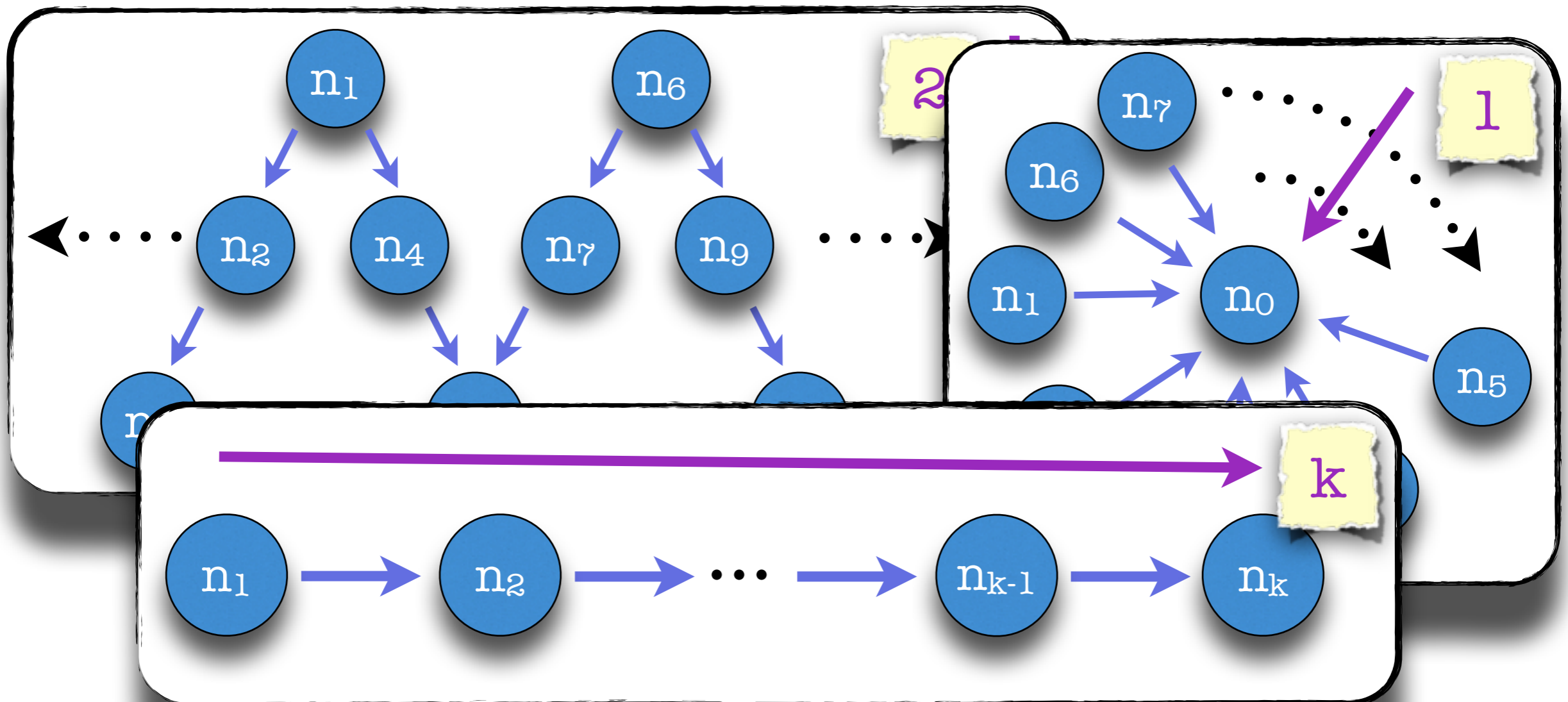


Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



k Bounded Depth Control State Reachability



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

k Bounded Depth Control State Reachability

Given

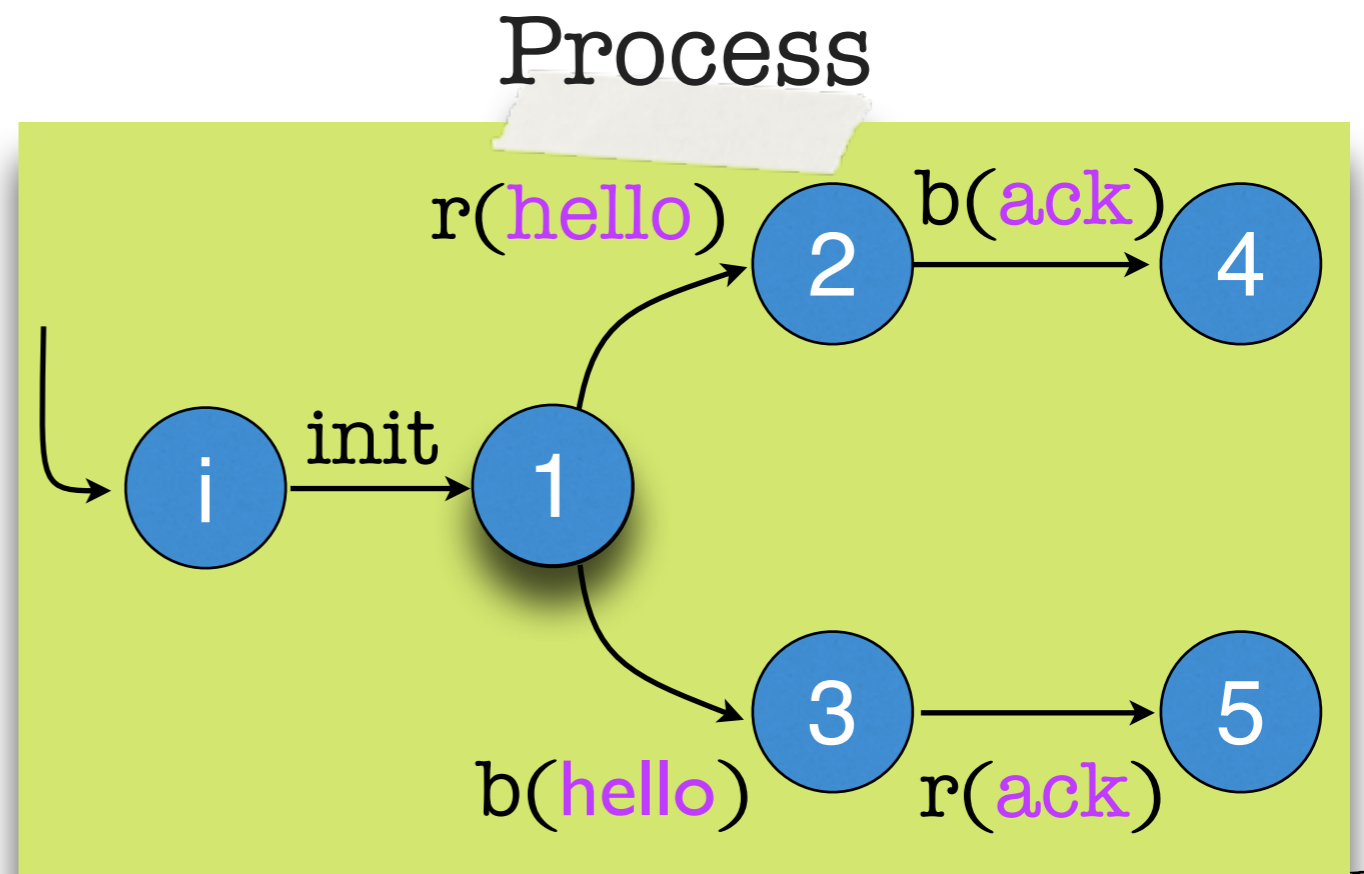
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

k Bounded Depth Control State Reachability

Given

▶ Process P



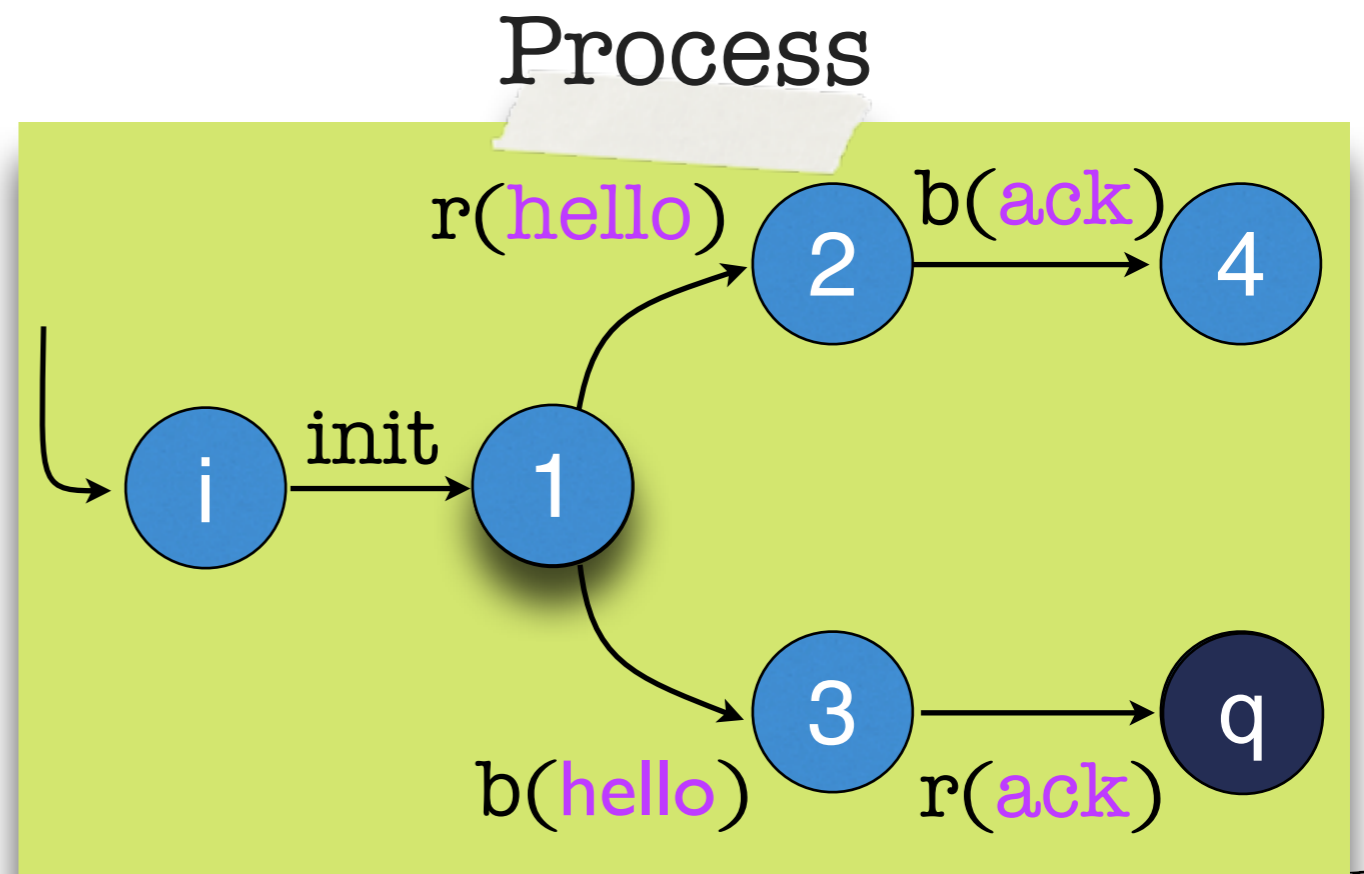
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

k Bounded Depth Control State Reachability

Given

- ▶ Process P
- ▶ Control State q



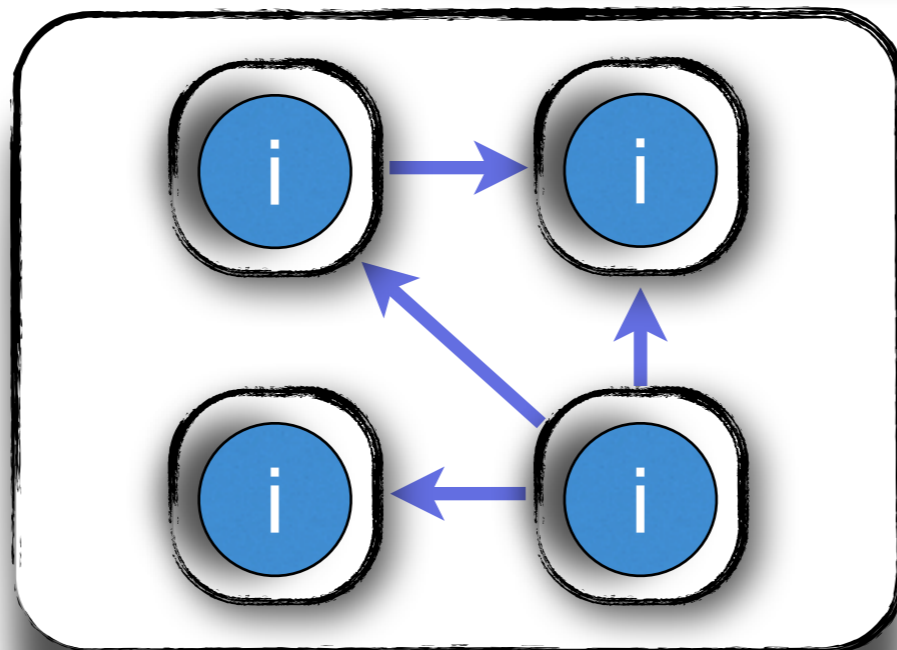
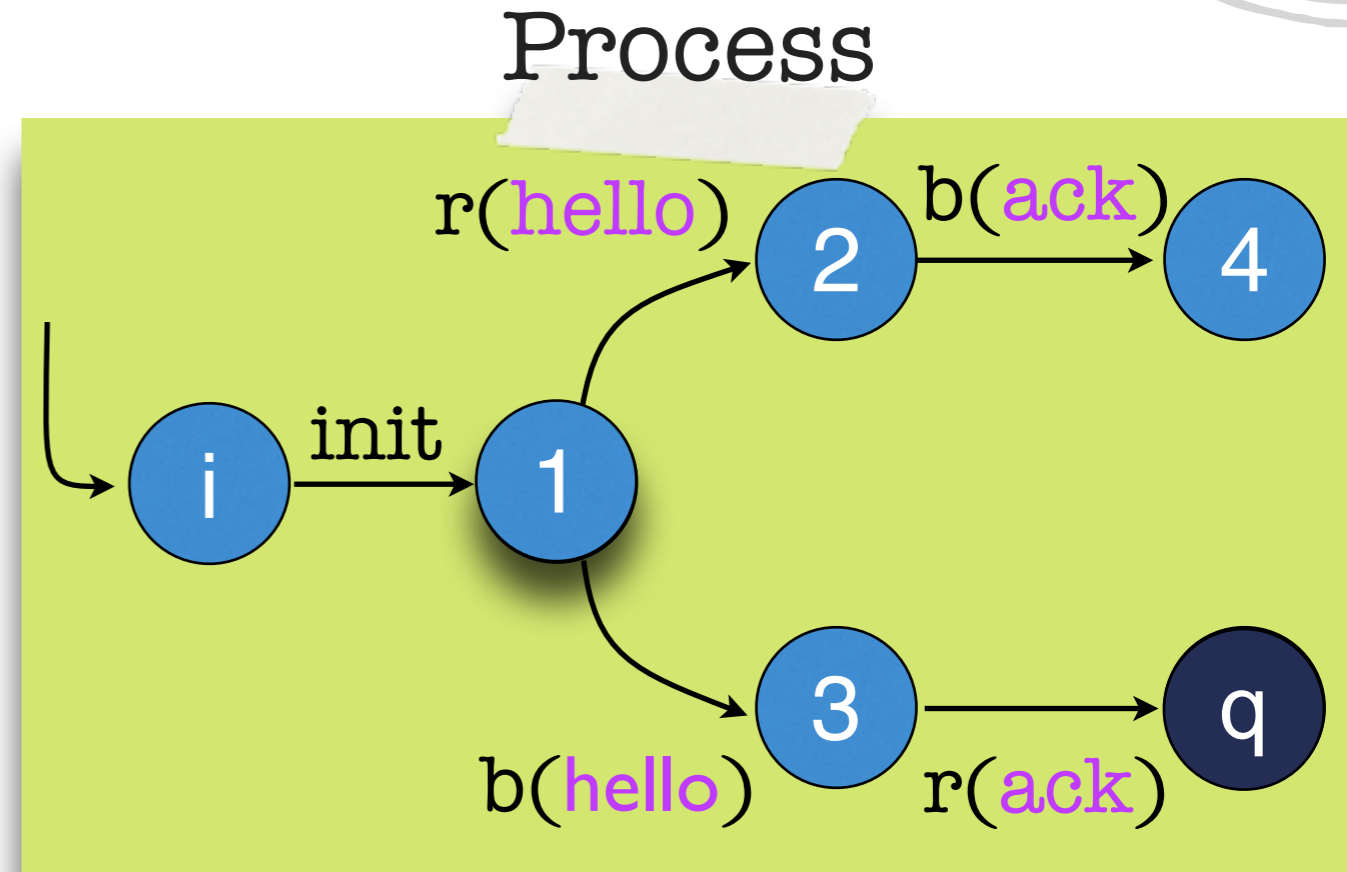
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



k Bounded Depth Control State Reachability (BOUNDED-COVER)

- Given
- ▶ Process P
 - ▶ Control State q



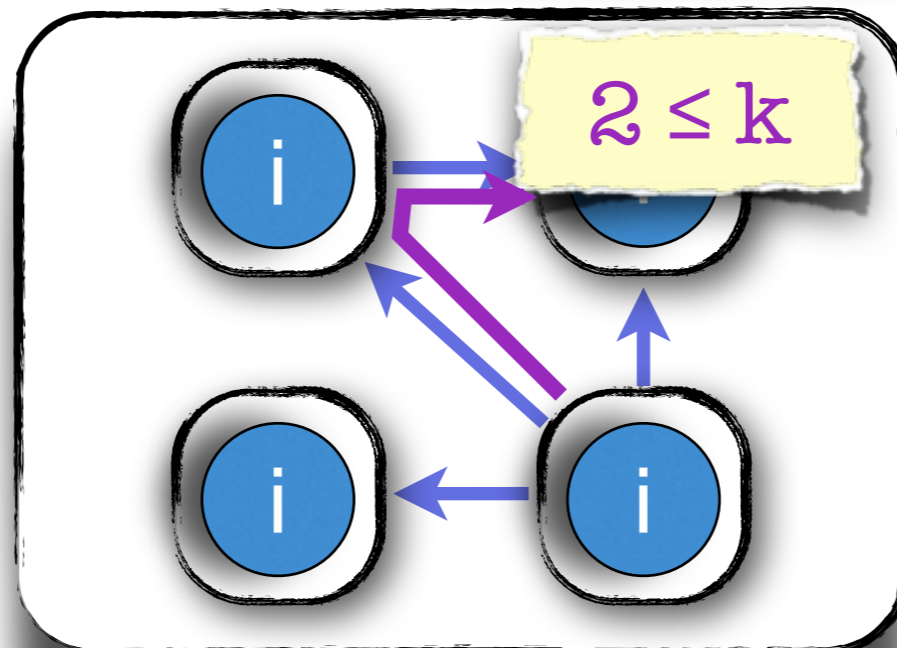
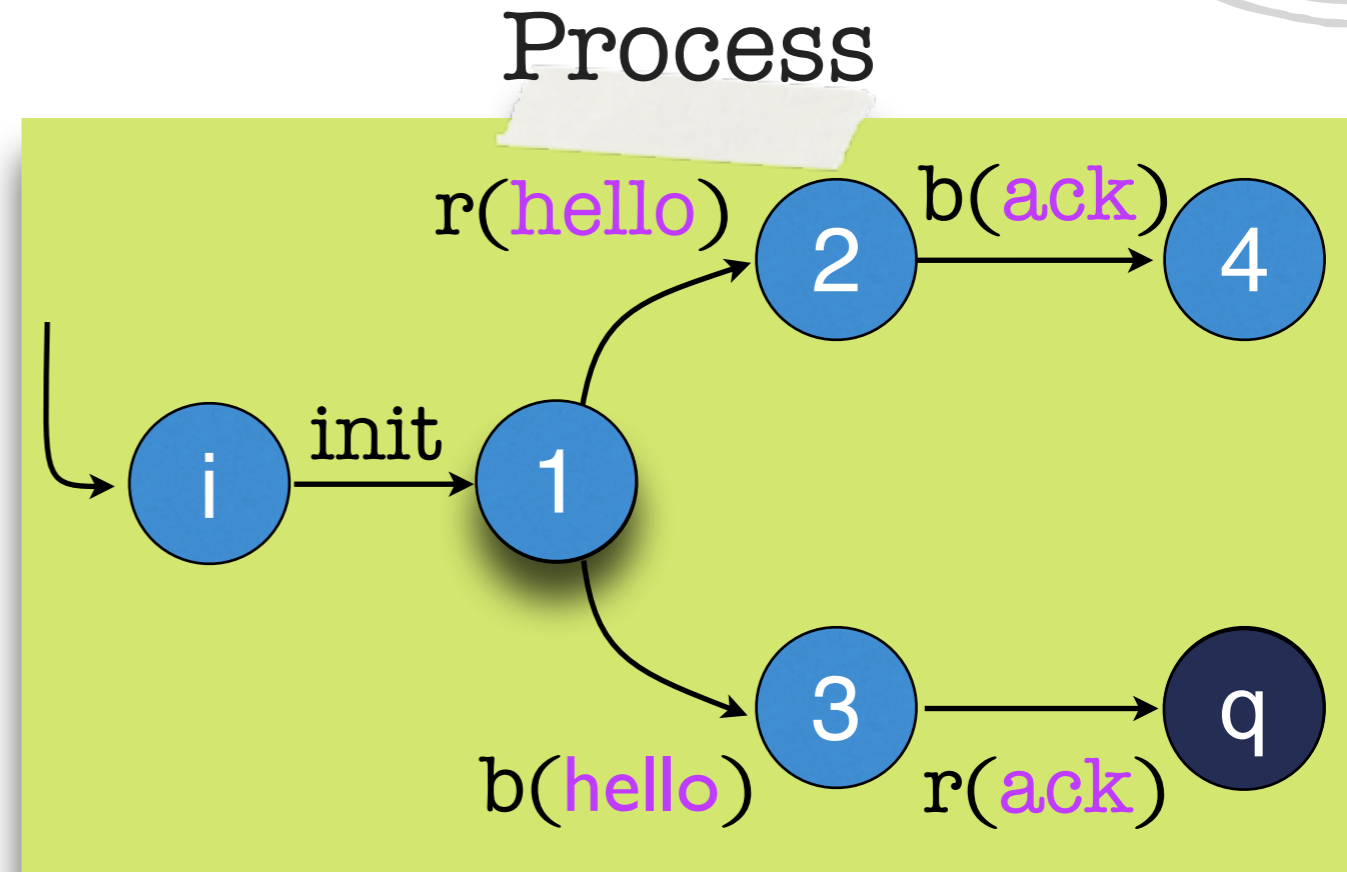
Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



k Bounded Depth Control State Reachability (BOUNDED-COVER)

- Given
- ▶ Process P
 - ▶ Control State q



Directed Acyclic

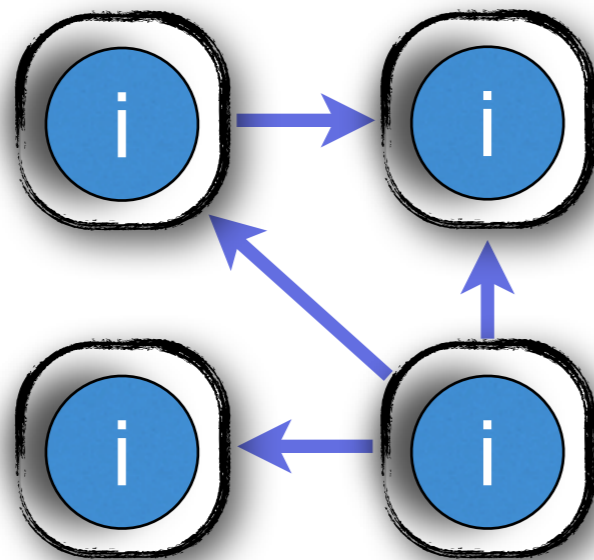
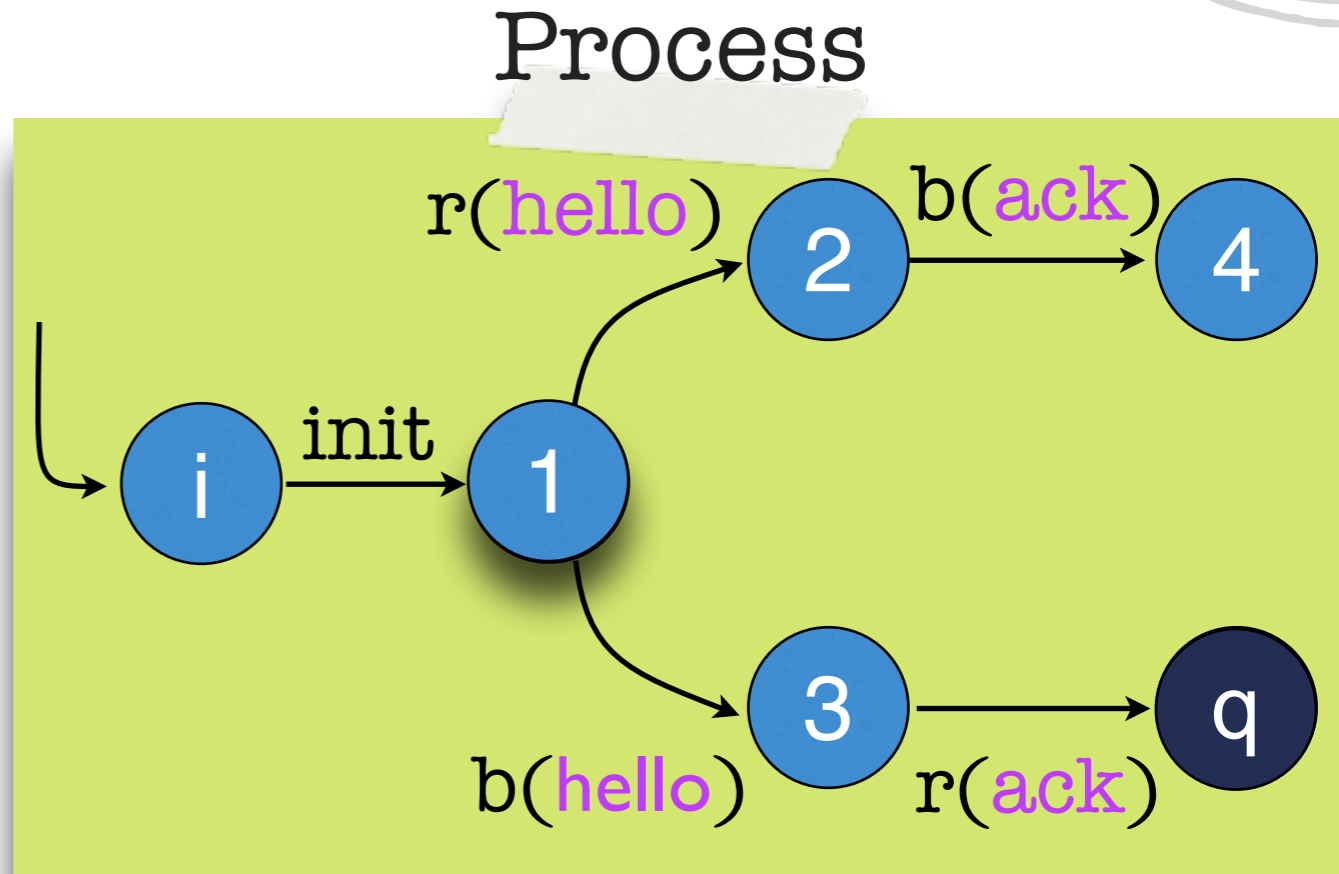
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



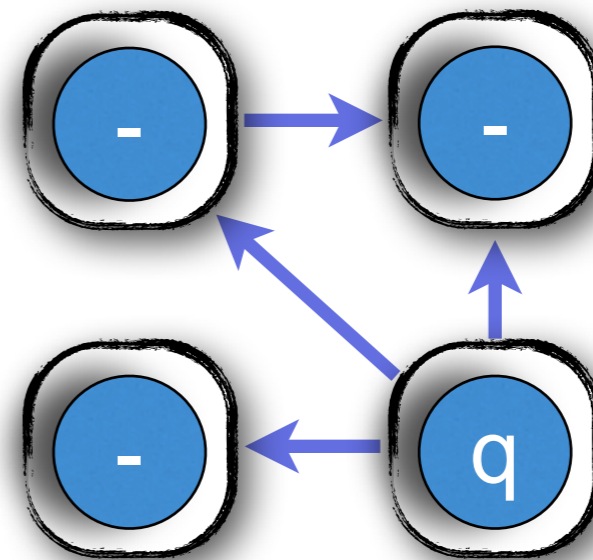
k Bounded Depth Control State Reachability (BOUNDED-COVER)

- ▶ Process P
- ▶ Control State q

Given



$*$



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

(BOUNDED-COVER)

DECIDABLE

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

(2) Reduce **(BOUNDED-COVER)** **(TREE-BOUNDED-COVER)**

(3) Define an ordering on configurations

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order
- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



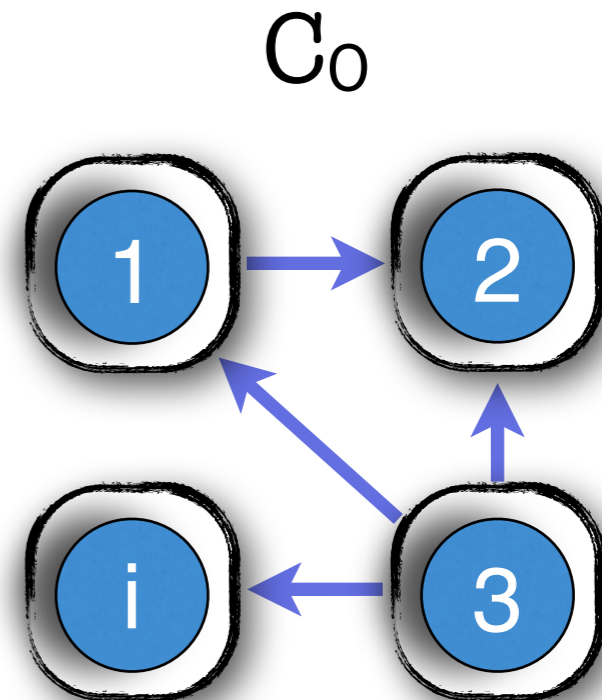
(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

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- ▶ \sqsubseteq is a Well-Quasi Order
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Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

▶ \sqsubseteq is a Well-Quasi Order

▶ \longrightarrow : Monotonic wrt. \sqsubseteq

$\forall (C_i)_{i \geq 0}: C_0, C_1, C_2, \dots$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

▶ \sqsubseteq is a Well-Quasi Order

▶ \longrightarrow : Monotonic wrt. \sqsubseteq

$\forall (C_i)_{i \geq 0}: C_0, C_1, C_2, \dots$

$\exists i < j; C_i \sqsubseteq C_j$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order

- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order

- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

C_3

\sqcup

$C_1 \longrightarrow C_2$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

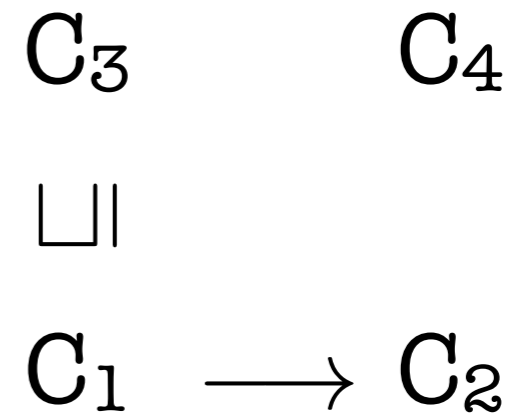
Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order

- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

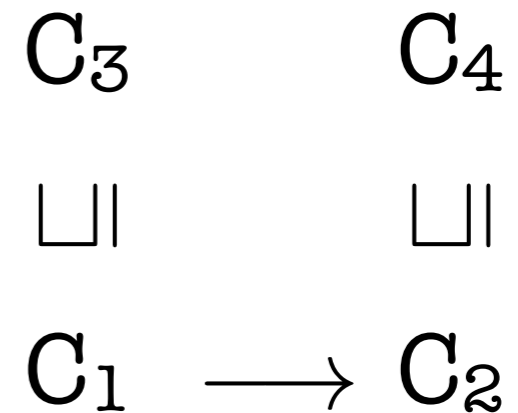
Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order

- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order

- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

$$C_3 \longrightarrow C_4$$

$$\sqcup \quad \sqcup$$

$$C_1 \longrightarrow C_2$$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order
- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

WSTS framework Algorithm:

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order
- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

WSTS framework Algorithm:

- ▶ Symbolic Representation of Infinite Sets

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

Pre-requisites

- ▶ \sqsubseteq is a Well-Quasi Order
- ▶ \longrightarrow : Monotonic wrt. \sqsubseteq

WSTS framework Algorithm:

- ▶ Symbolic Representation of Infinite Sets
- ▶ Backward Analysis

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(1) The WSTS framework

(2) Reduce **(BOUNDED-COVER)** **(TREE-BOUNDED-COVER)**

(3) Define an ordering on configurations

Directed Acyclic

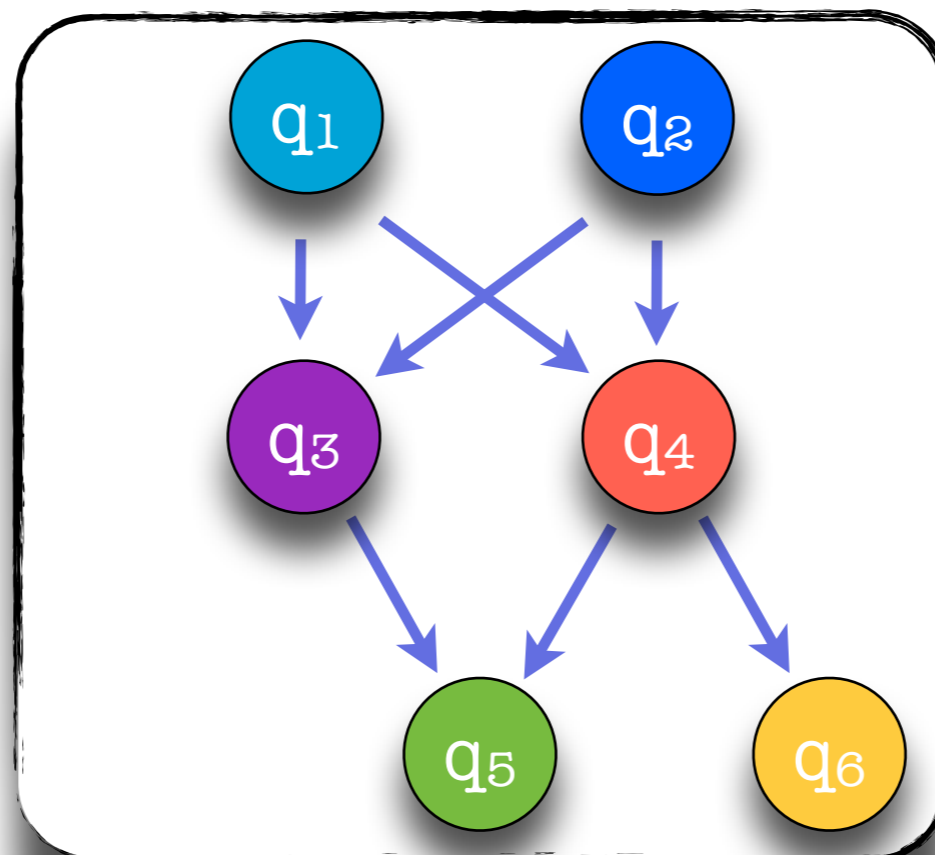
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce **(BOUNDED-COVER) (TREE-BOUNDED-COVER)**



Directed Acyclic

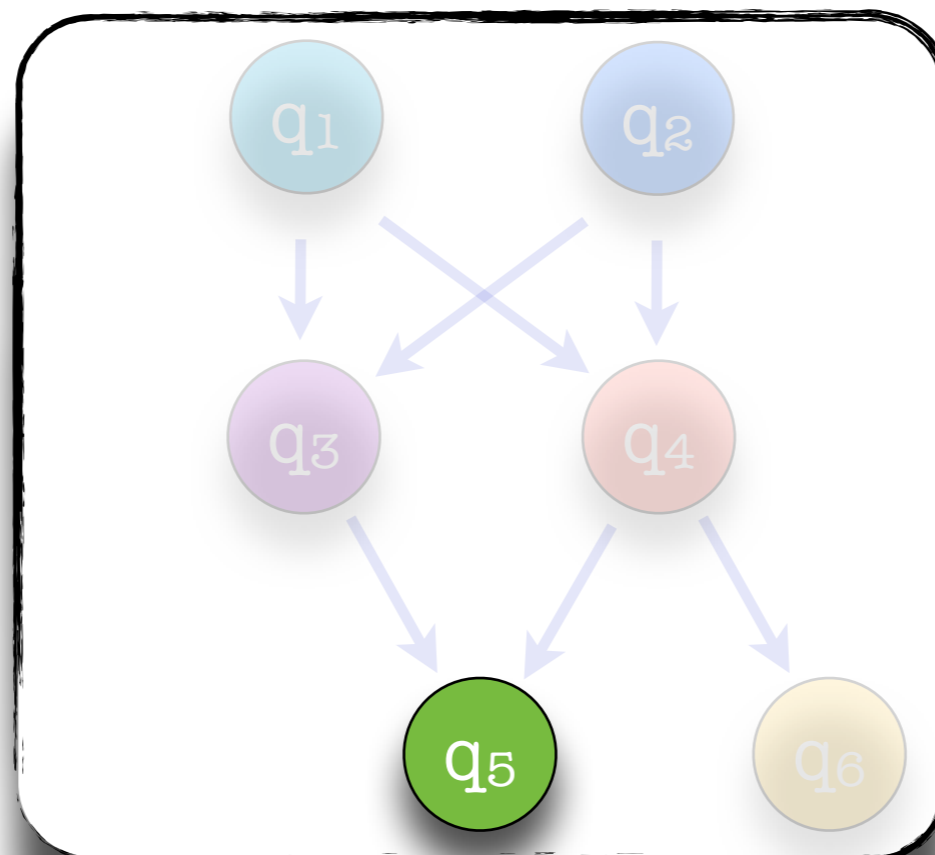
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce **(BOUNDED-COVER) (TREE-BOUNDED-COVER)**



Directed Acyclic

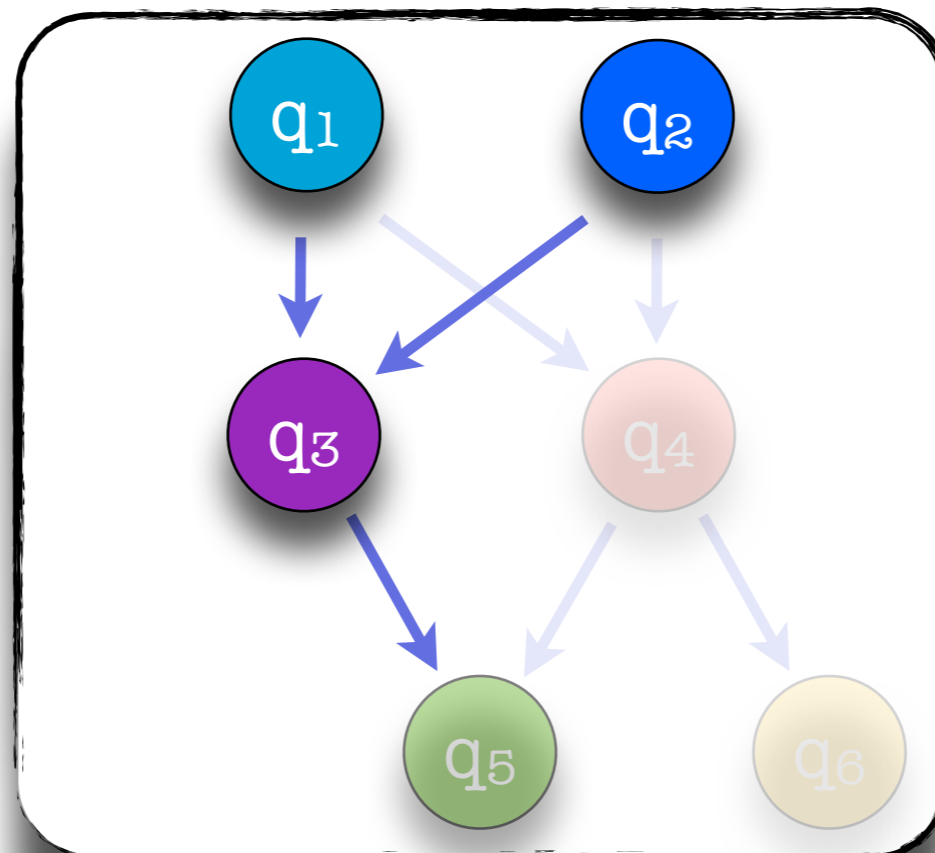
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce **(BOUNDED-COVER) (TREE-BOUNDED-COVER)**



Directed Acyclic

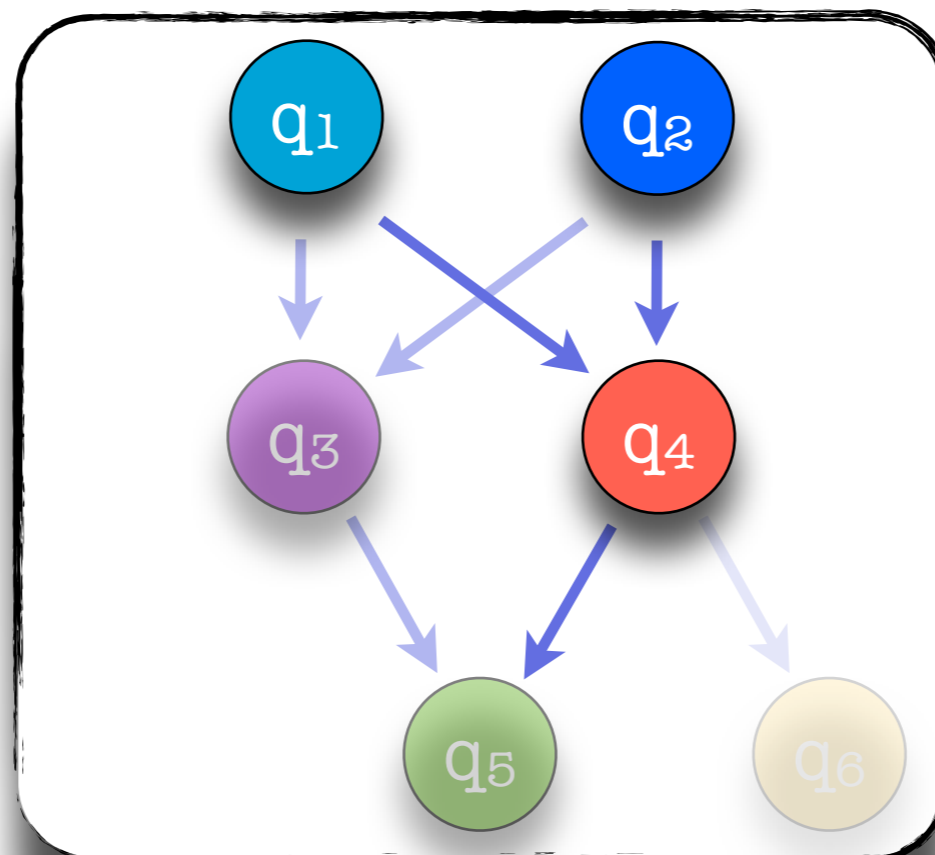
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- ▶ Reachability
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce **(BOUNDED-COVER) (TREE-BOUNDED-COVER)**



Directed Acyclic

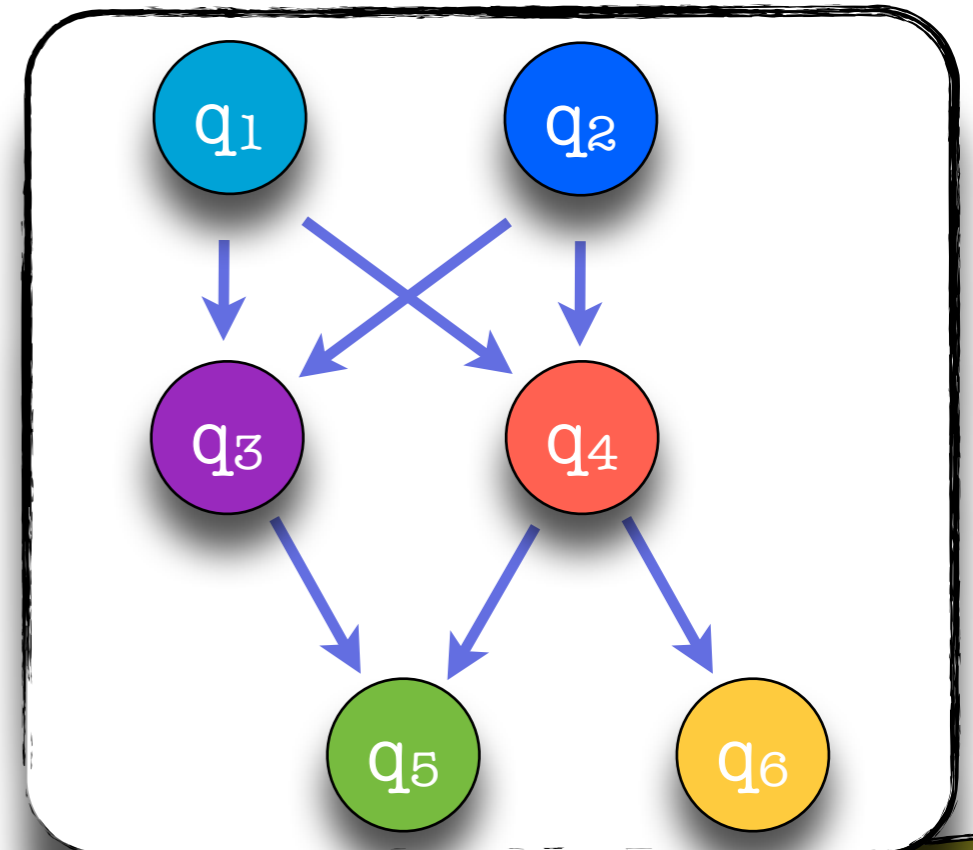
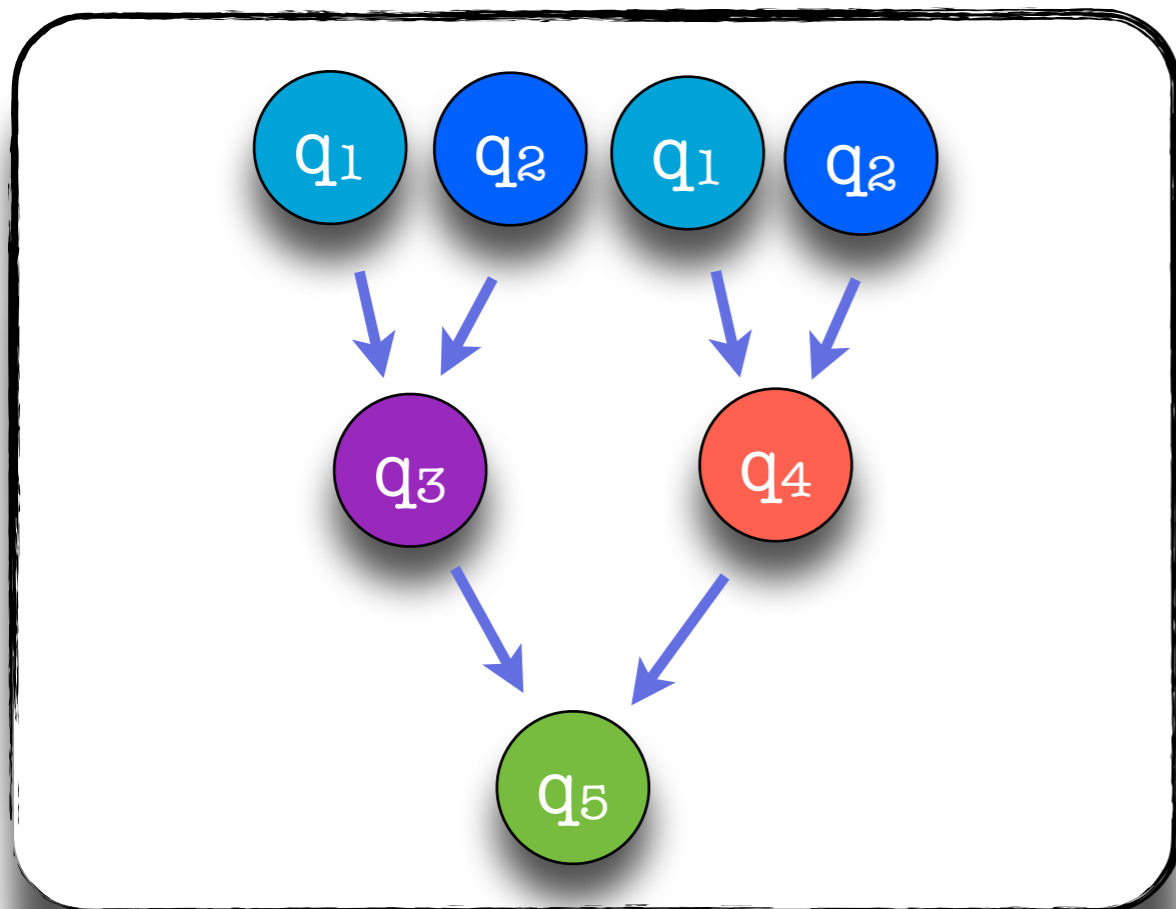
- ▶ Motivation
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- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



Directed Acyclic

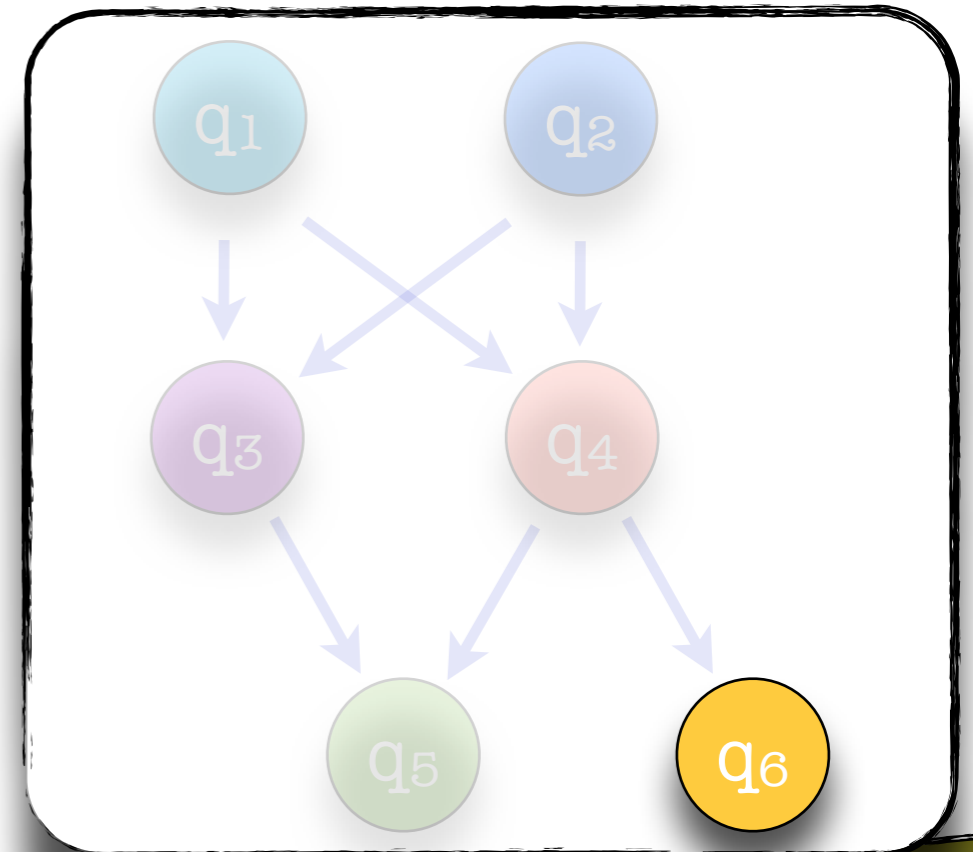
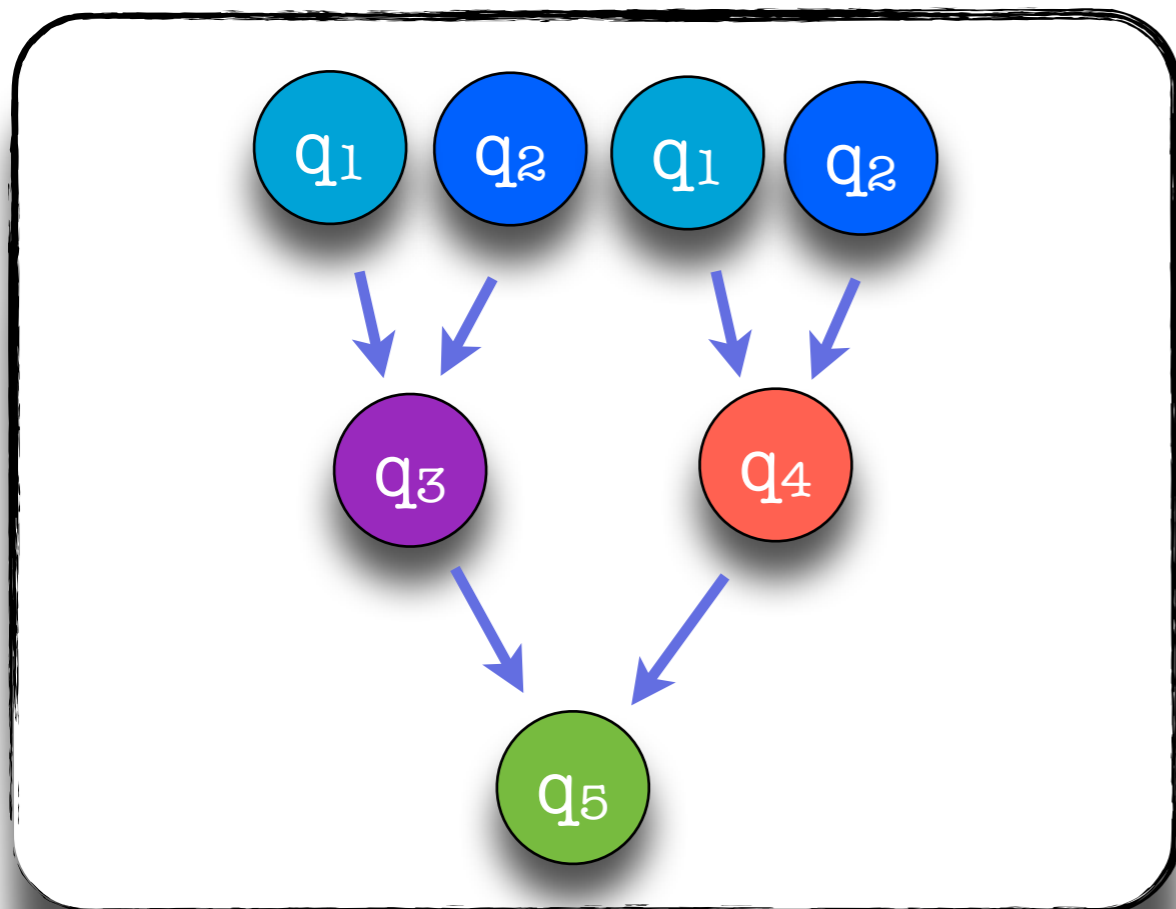
- ▶ Motivation
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



Directed Acyclic

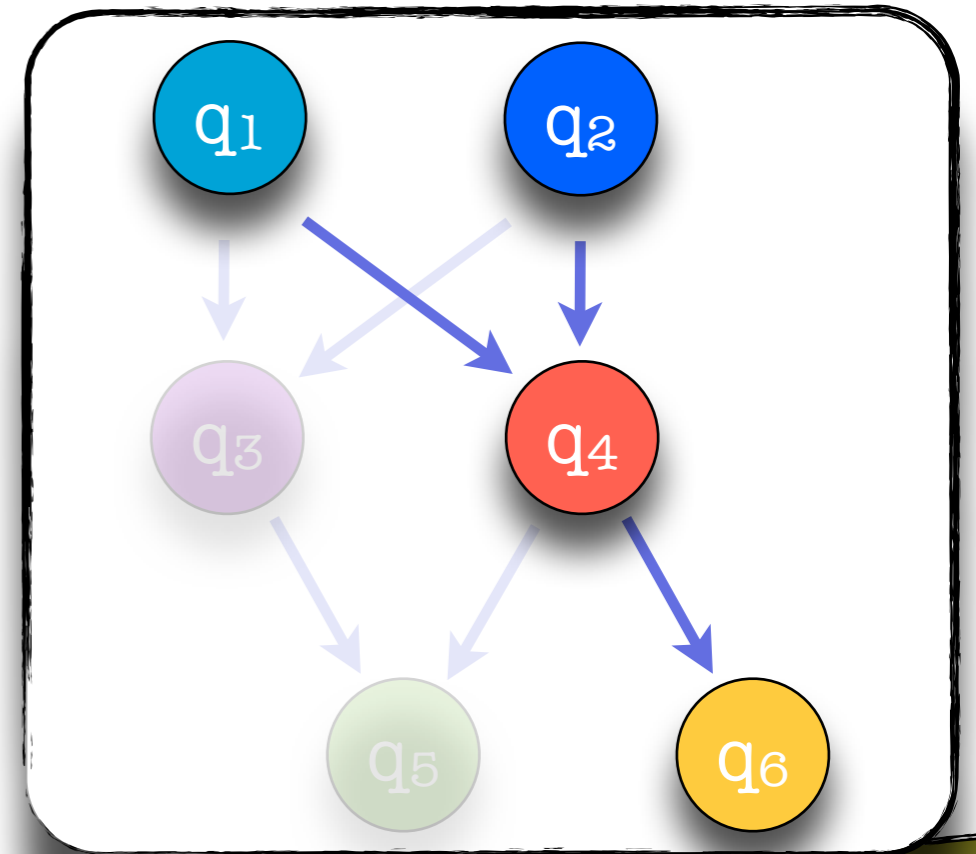
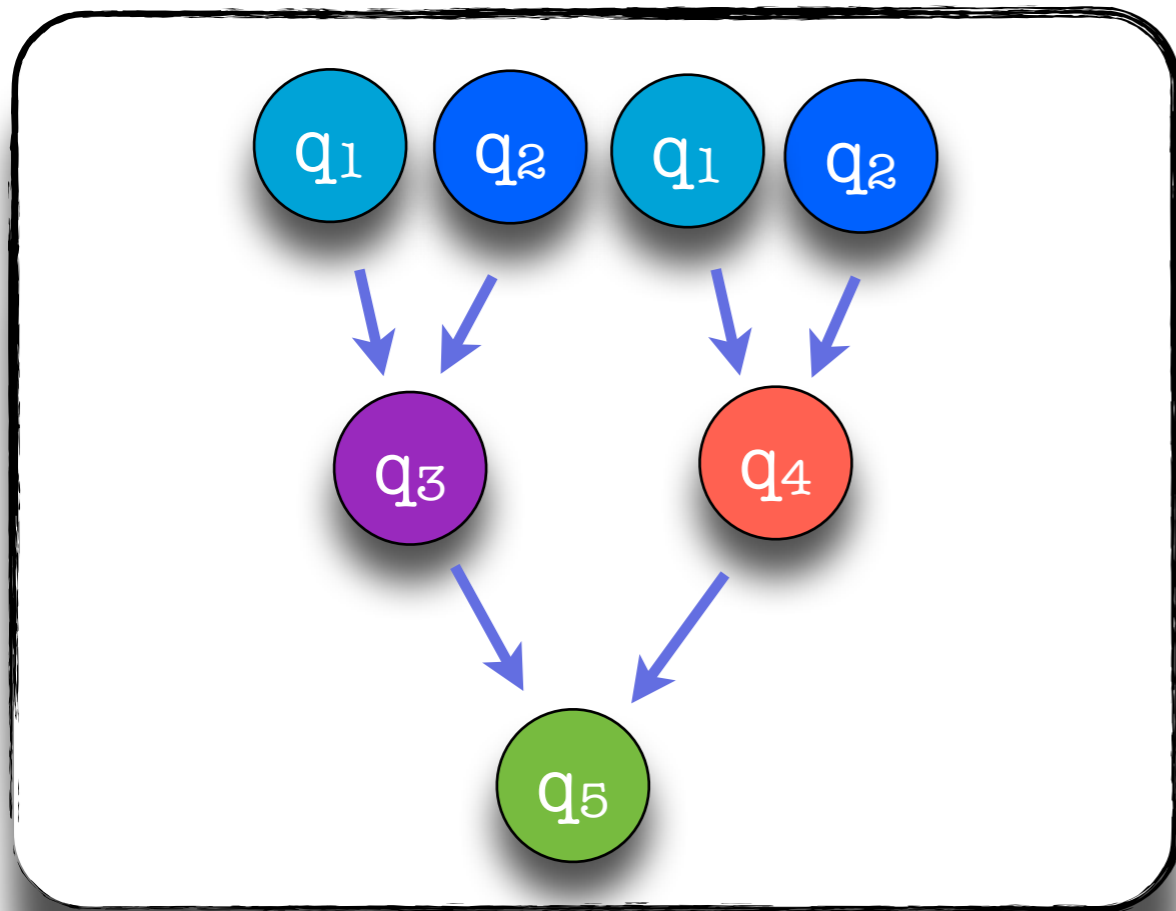
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- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



Directed Acyclic

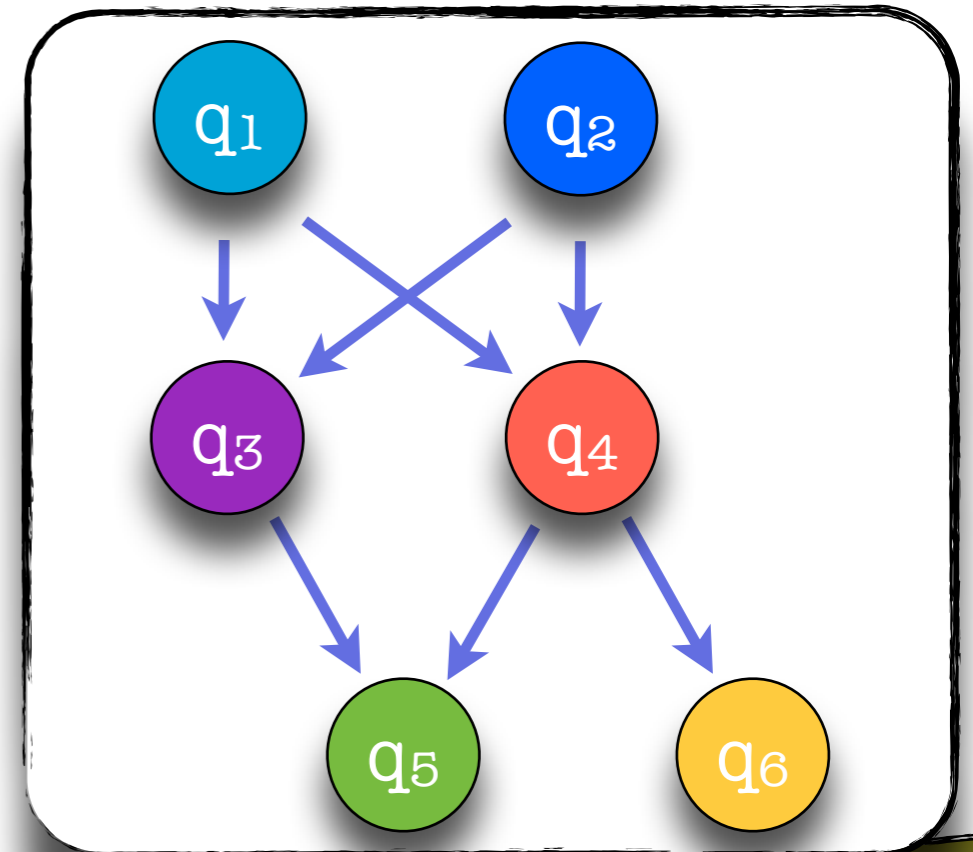
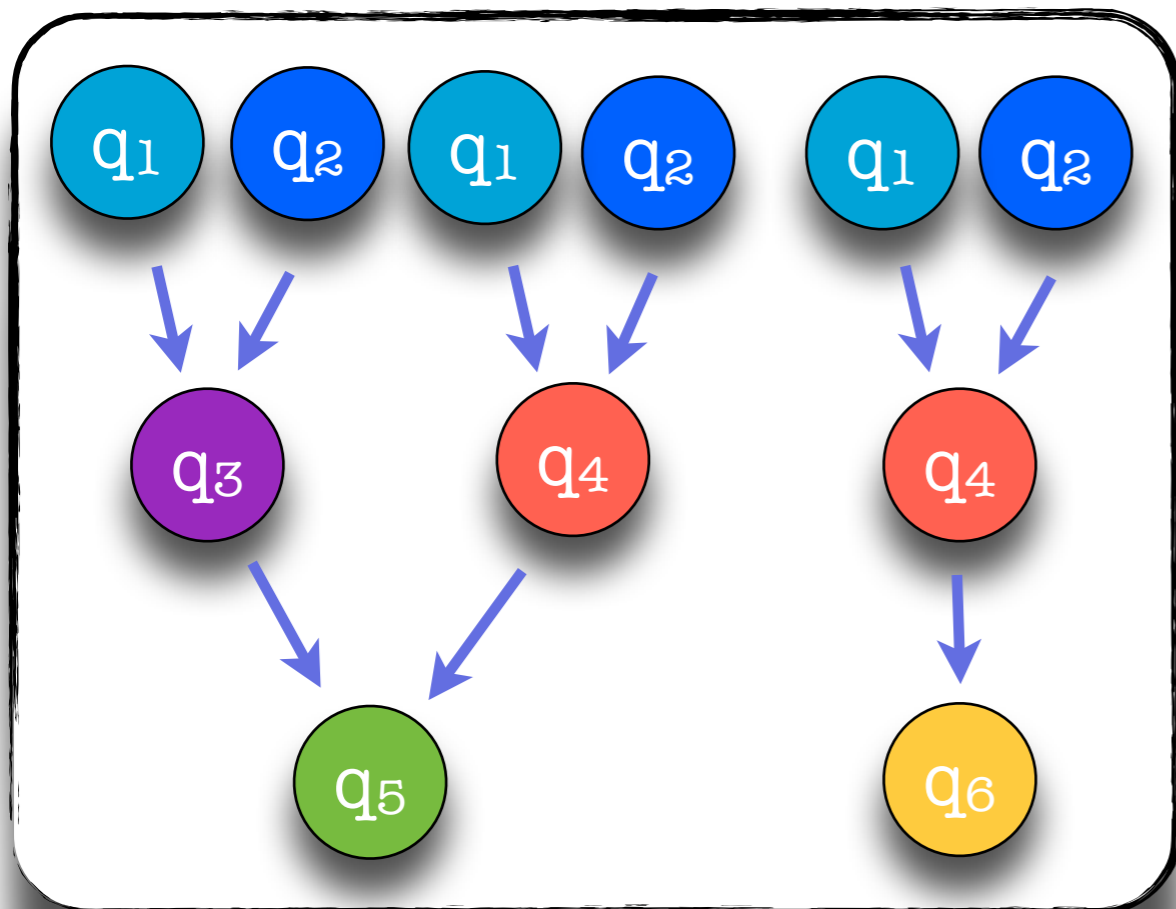
- ▶ Motivation
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



Directed Acyclic

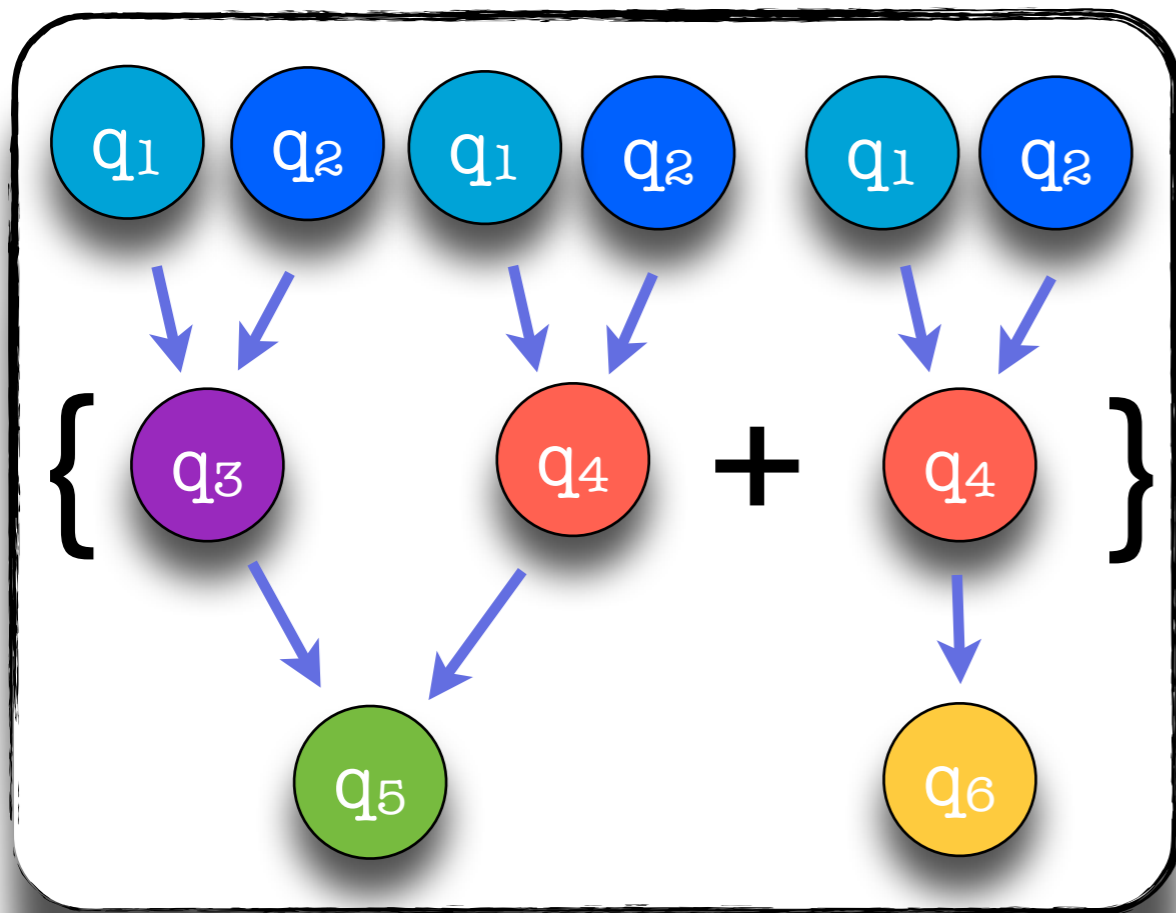
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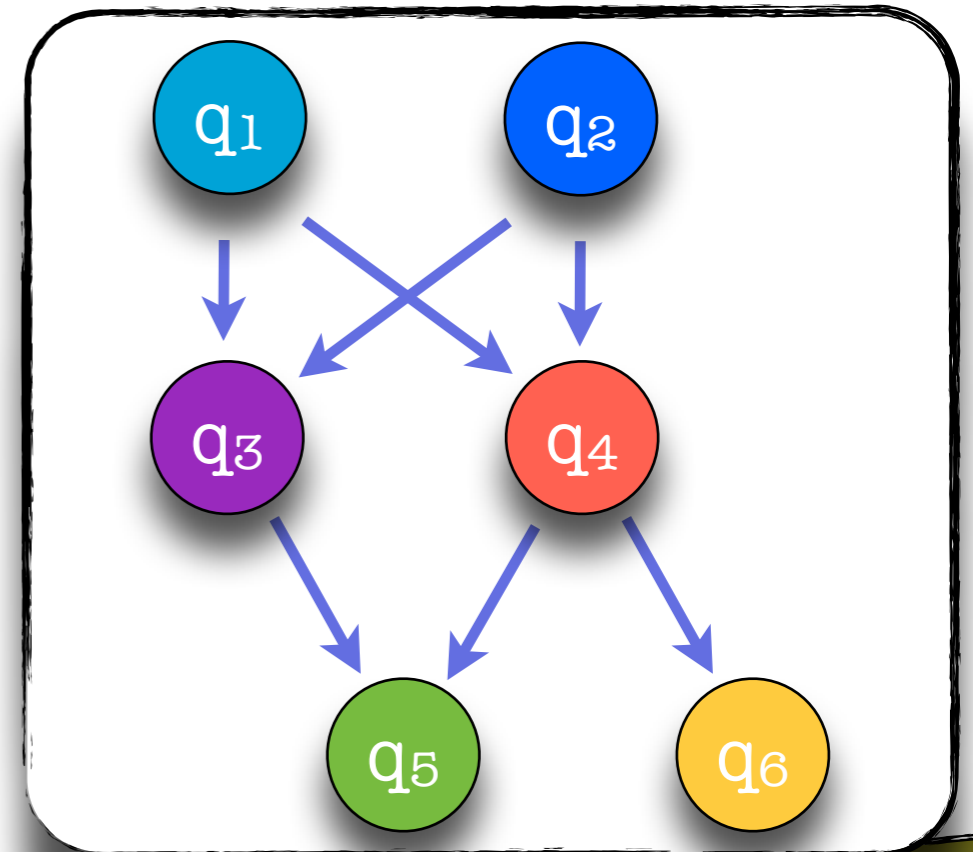
(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



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Directed Acyclic

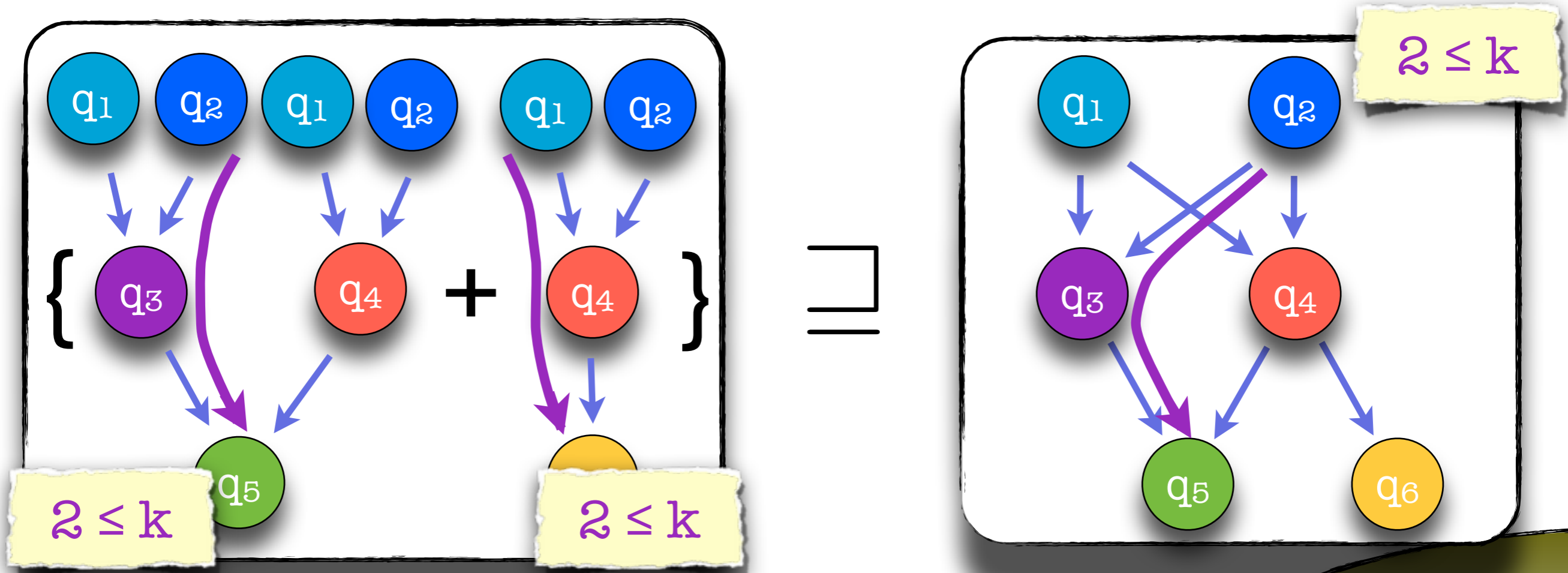
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- ▶ Reachability
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(2) Reduce (BOUNDED-COVER) (TREE-BOUNDED-COVER)



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

- (1) The WSTS framework
- (2) Reduce **(BOUNDED-COVER) (TREE-BOUNDED-COVER)**
- (3) Define an ordering on configurations

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



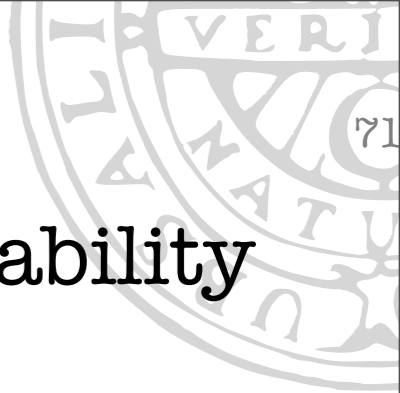
(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations

Directed Acyclic

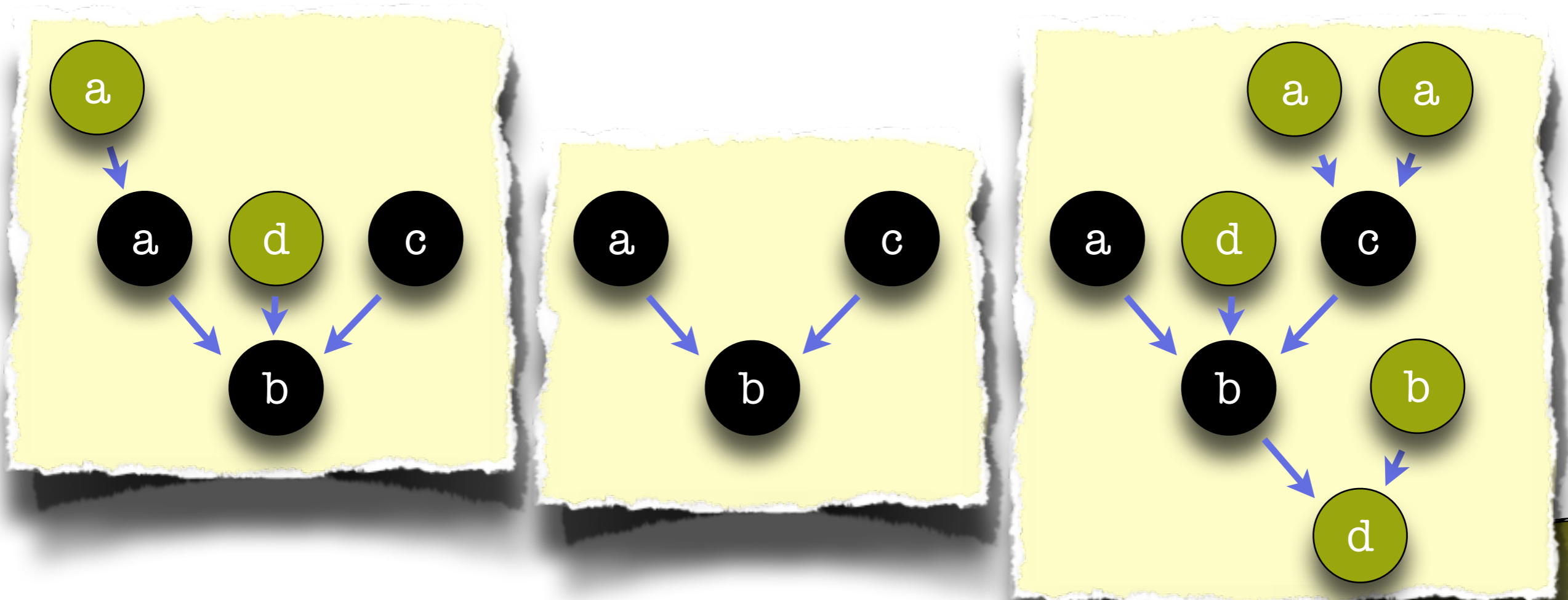
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

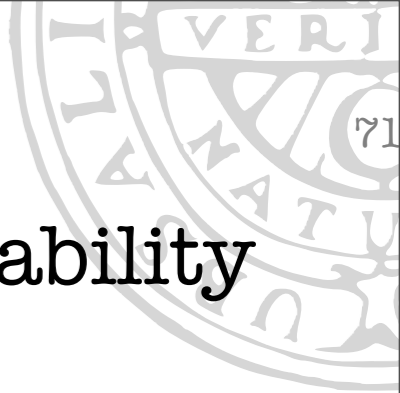
Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

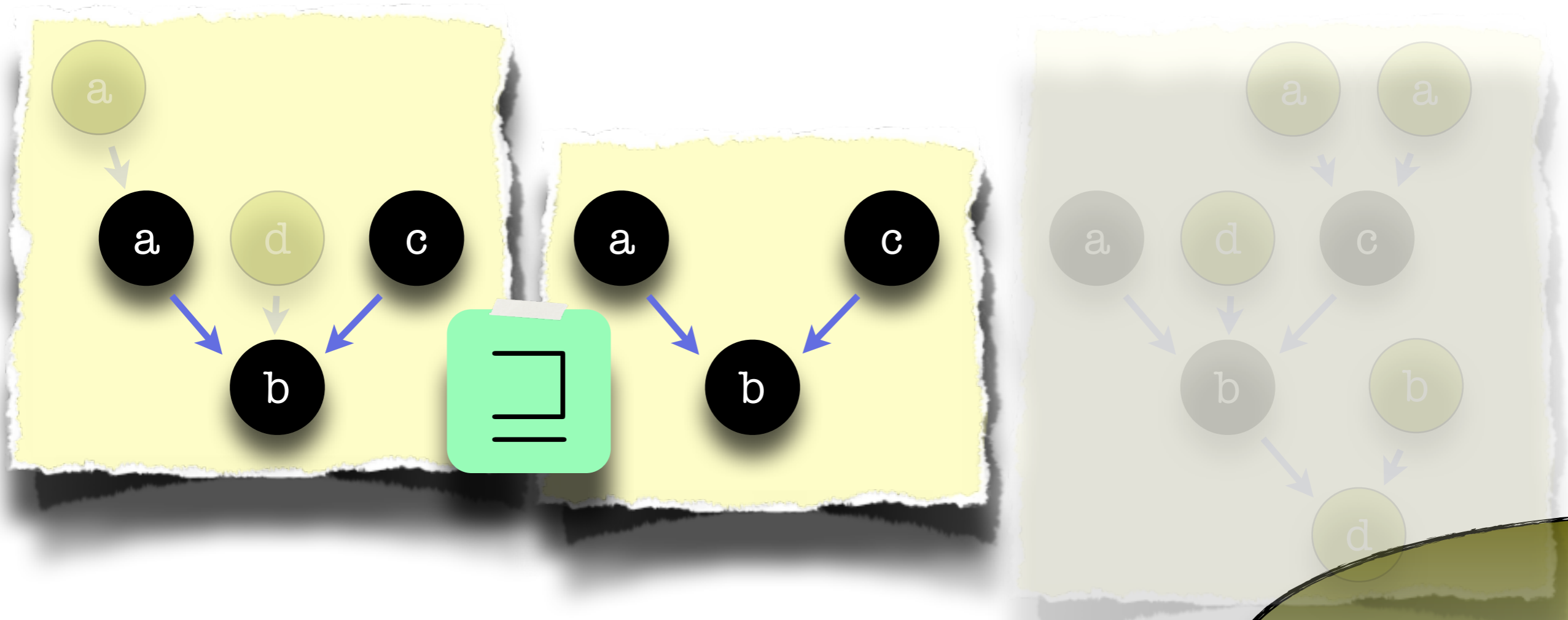
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

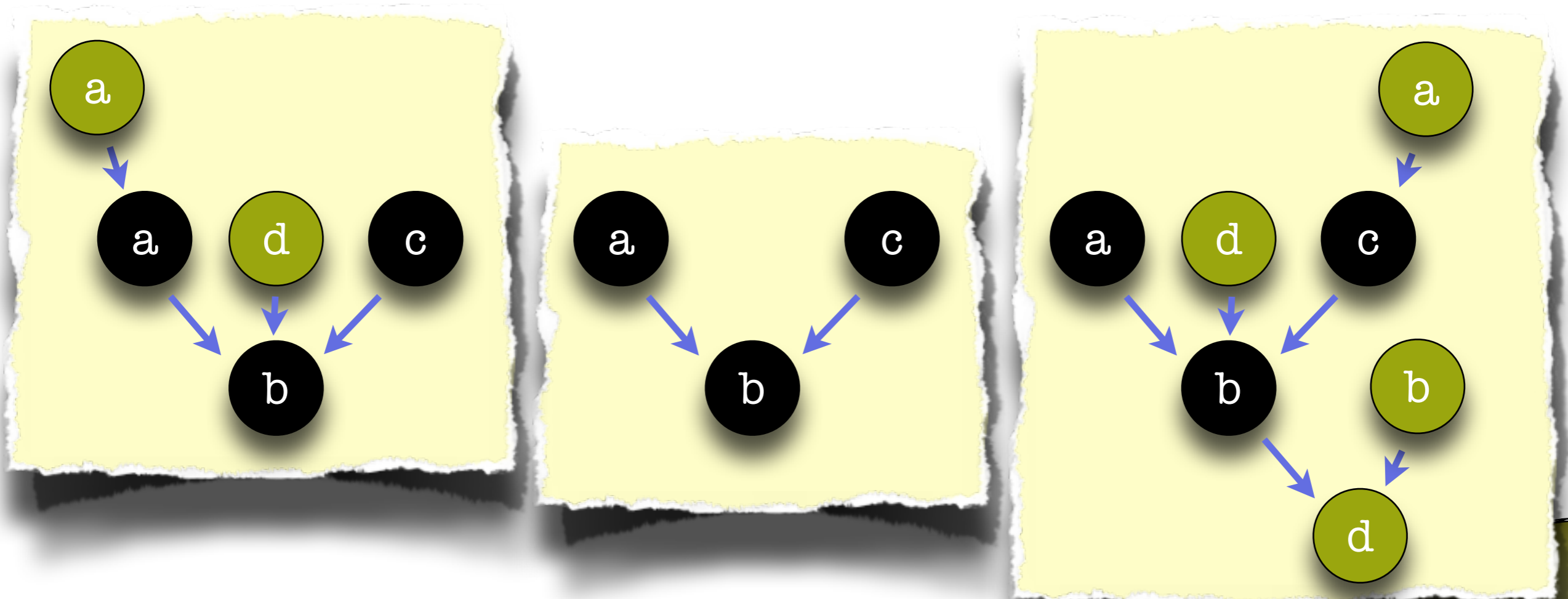
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

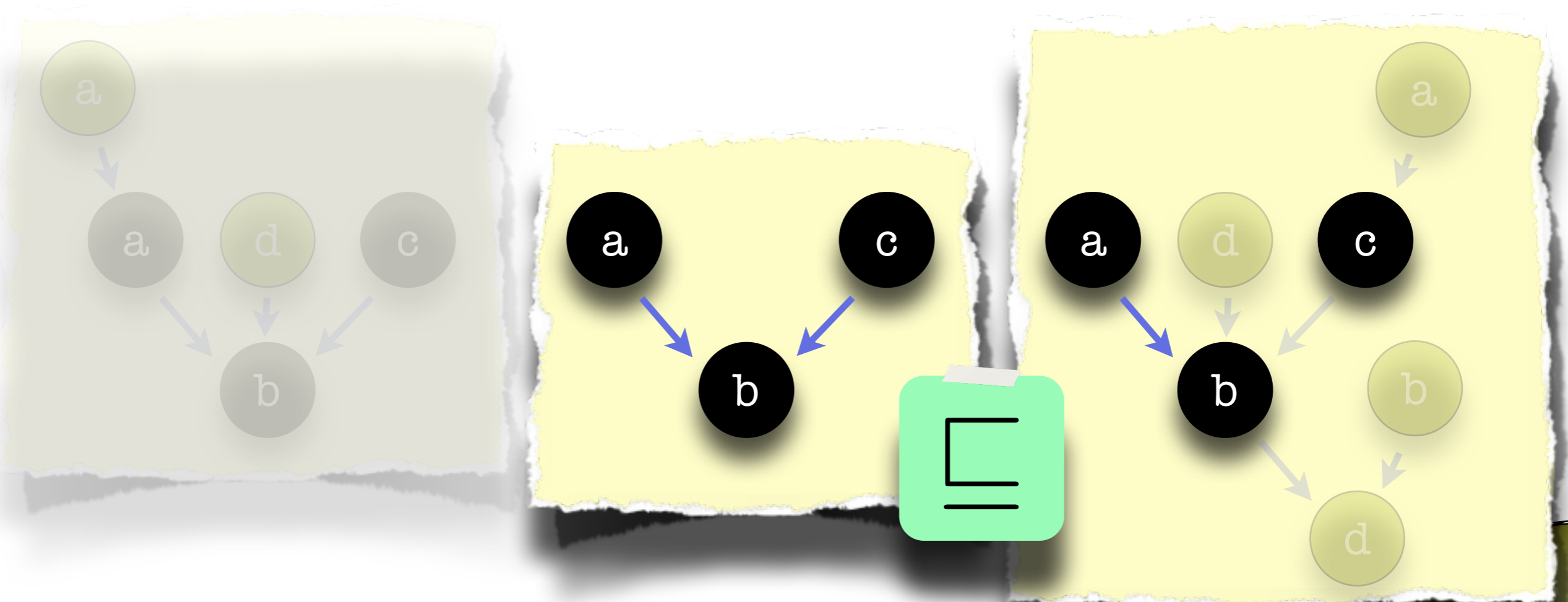
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

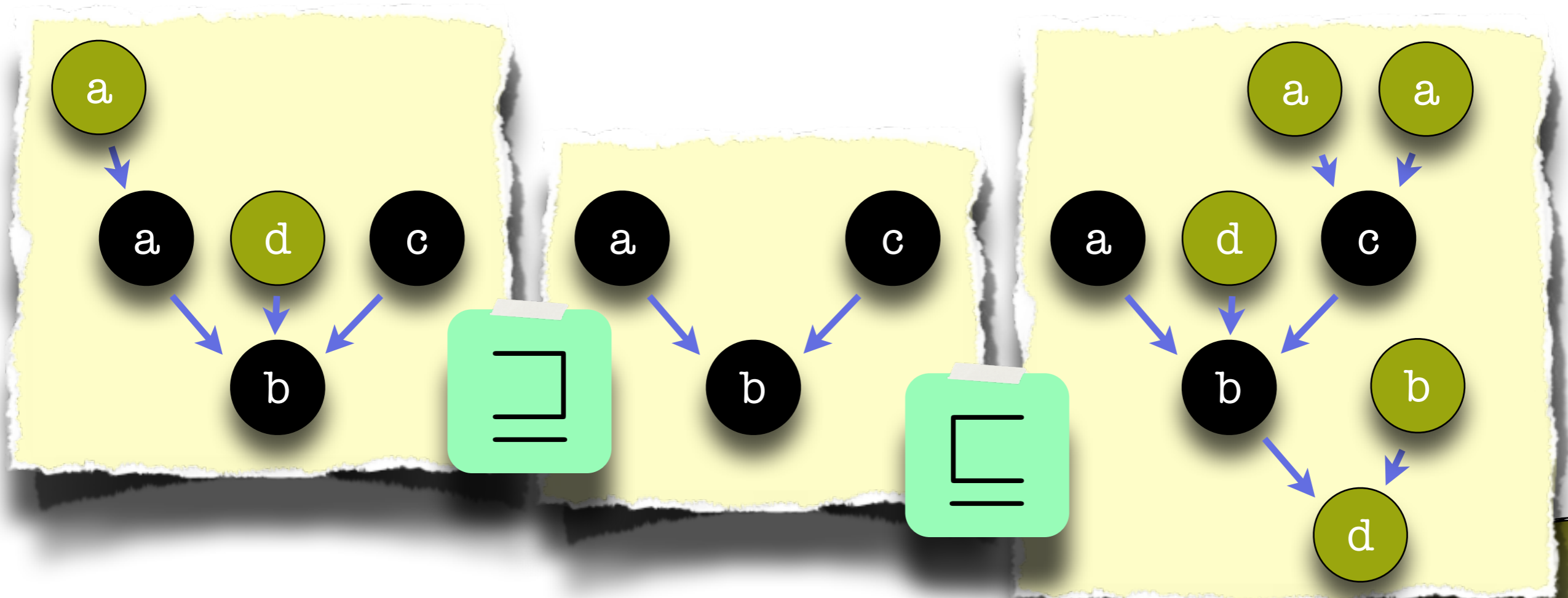
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- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

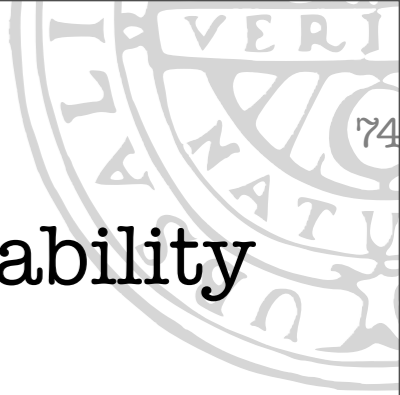
Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

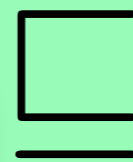
Theory of Well Structured Transition Systems

(3) Define an ordering on configurations

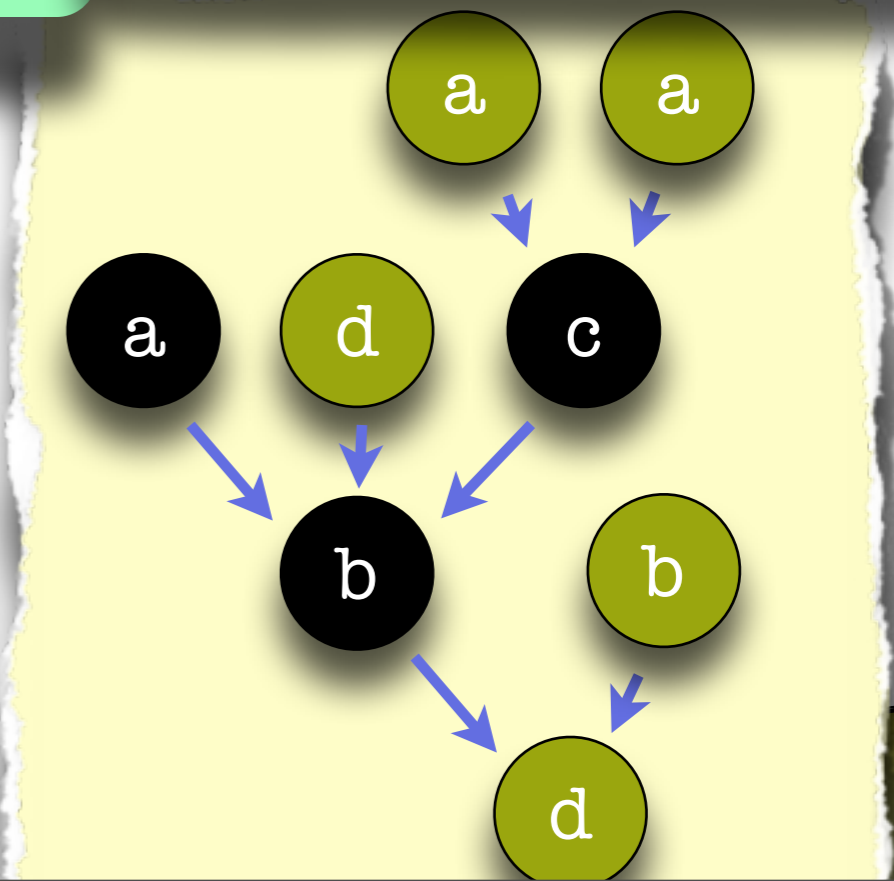
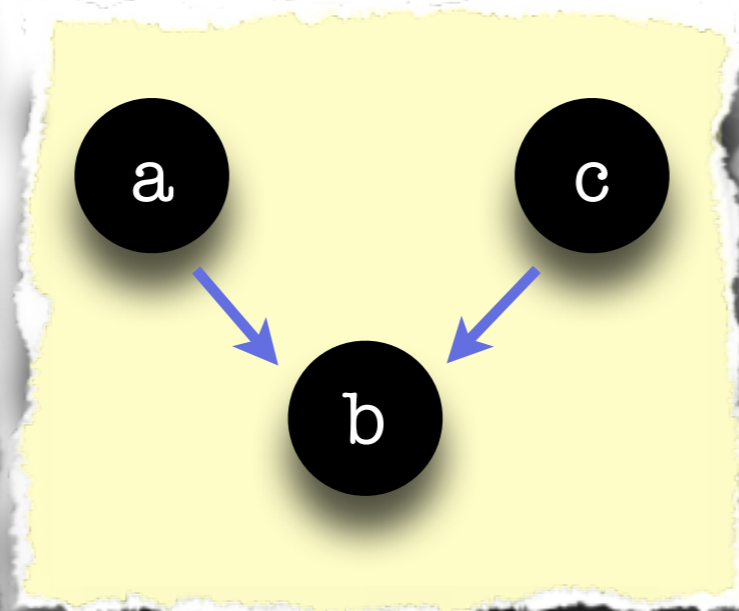
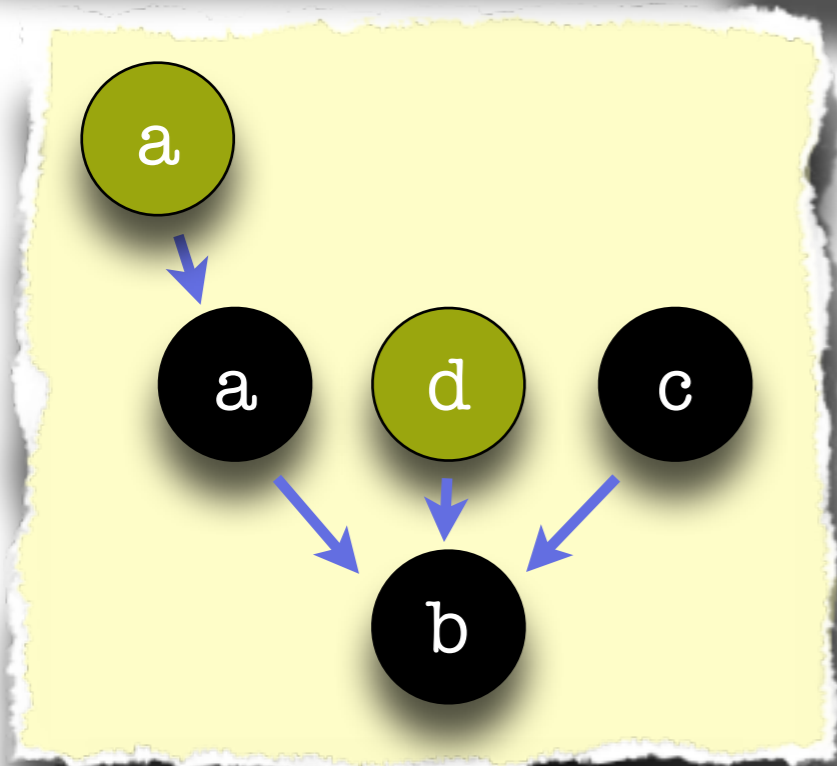
$\langle b, [a[a], d, c] \rangle$



$\langle b, [a, c] \rangle$



$\langle d, [b[a, d, c[a^2]], b] \rangle$



Directed Acyclic

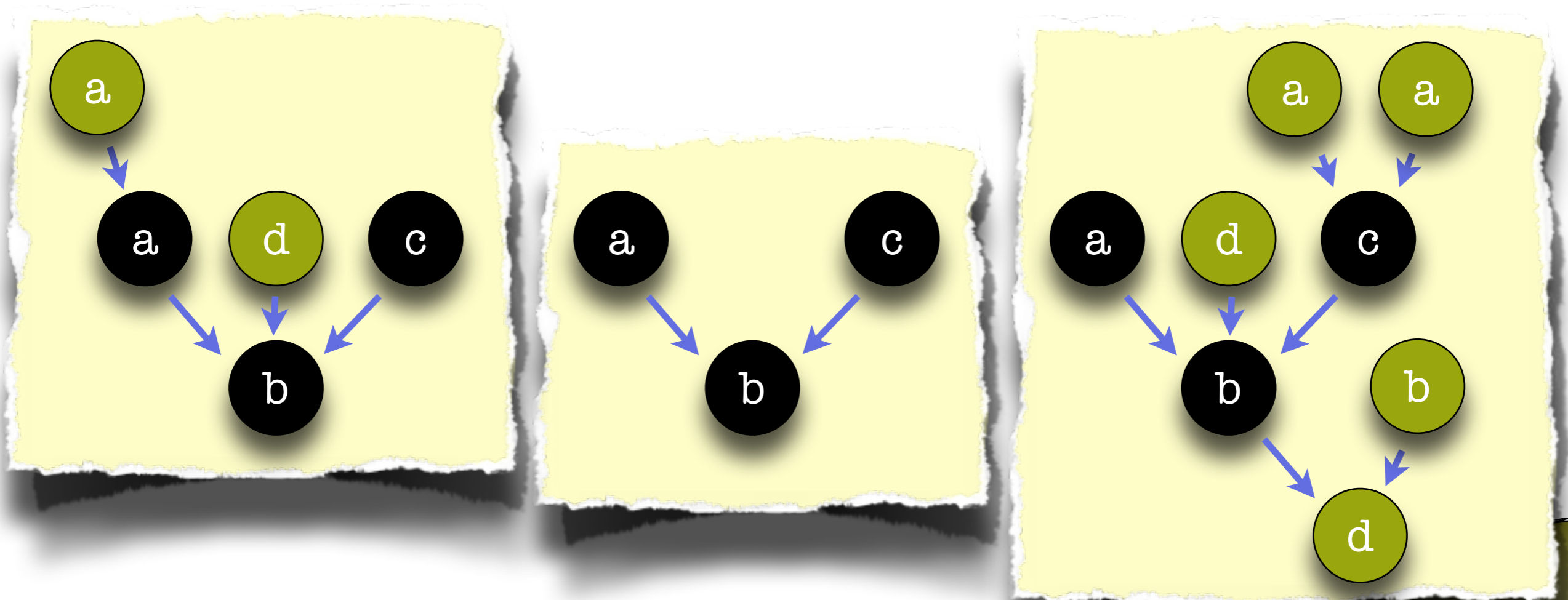
- ▶ Motivation
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations



Directed Acyclic

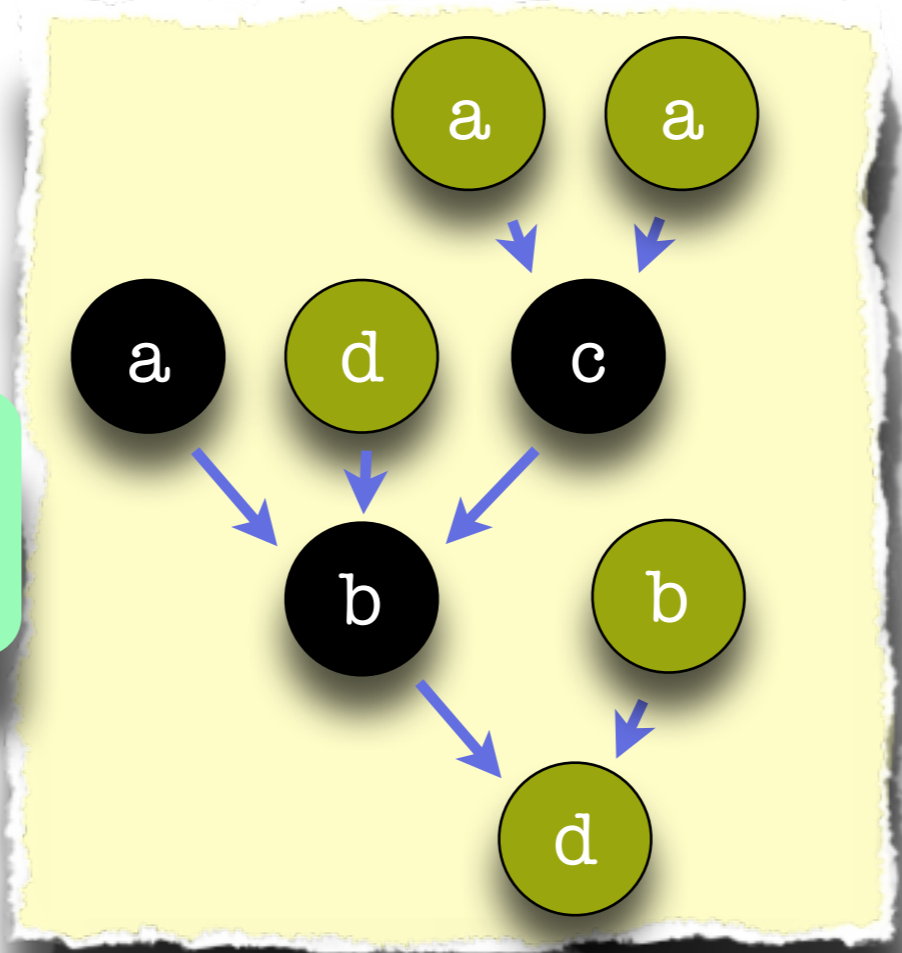
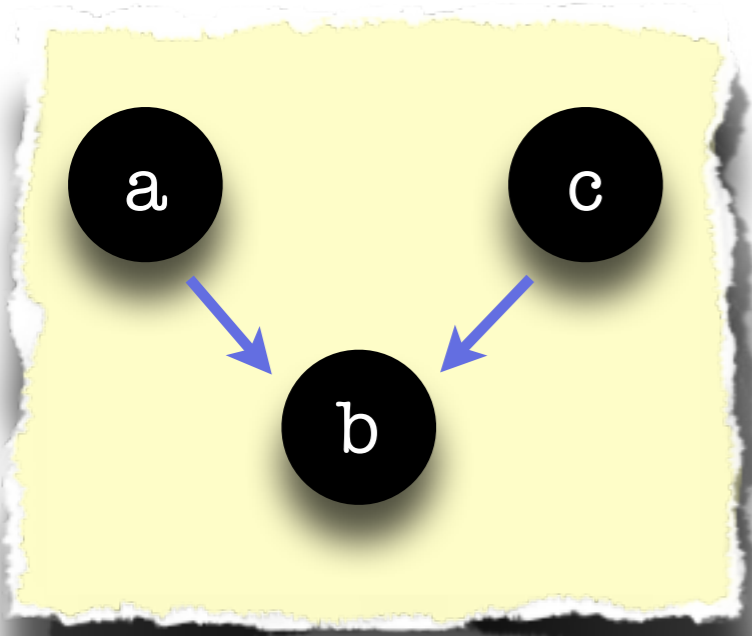
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity



Directed Acyclic

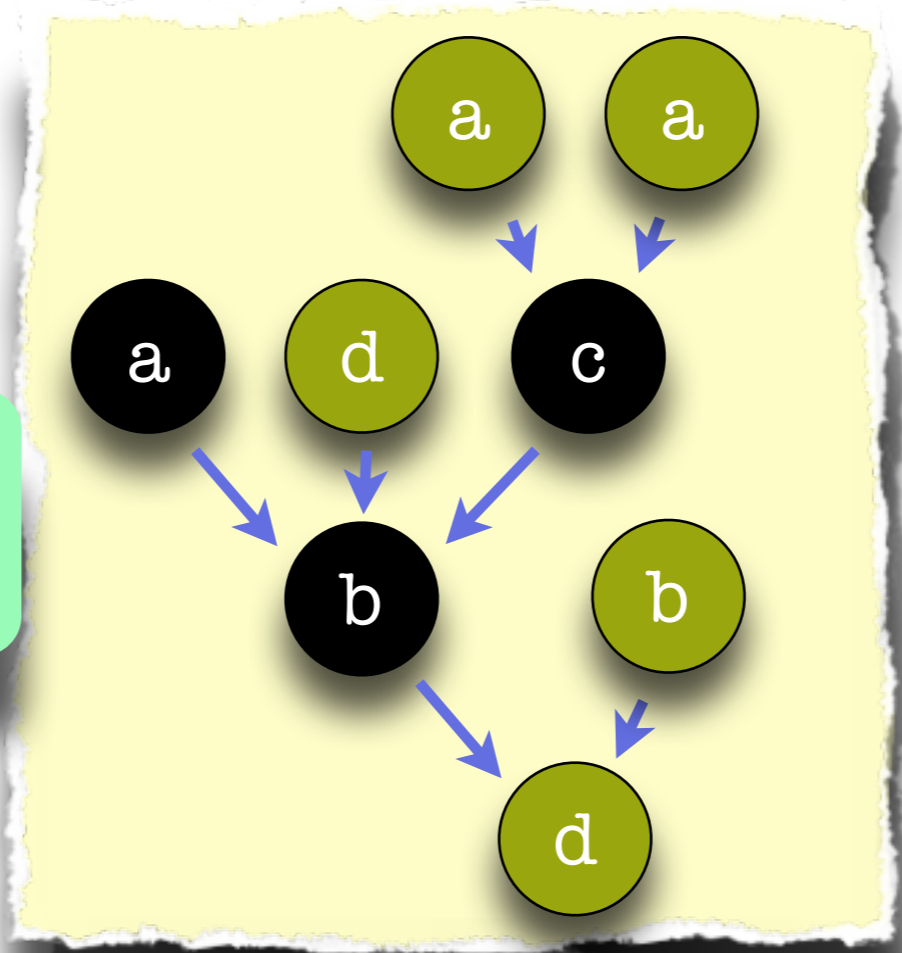
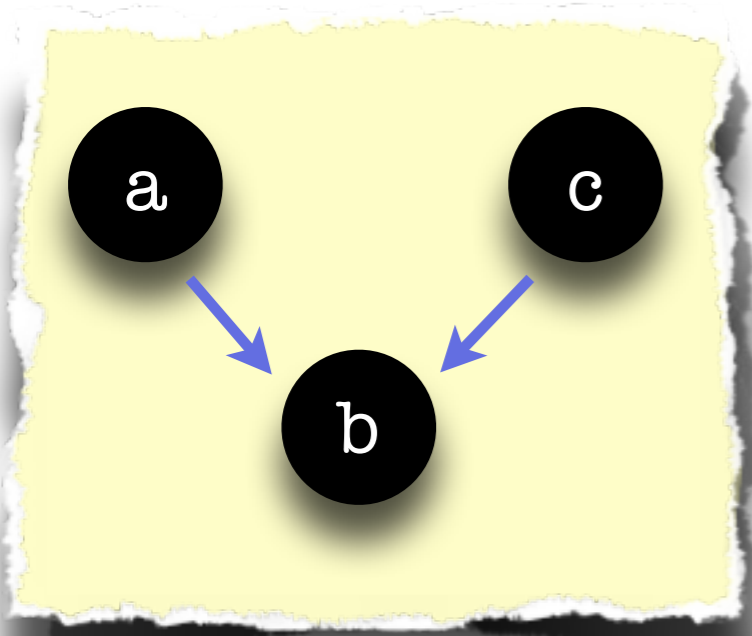
- ▶ Motivation
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(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity



$$C_1 \sqsubseteq C_2$$

Directed Acyclic

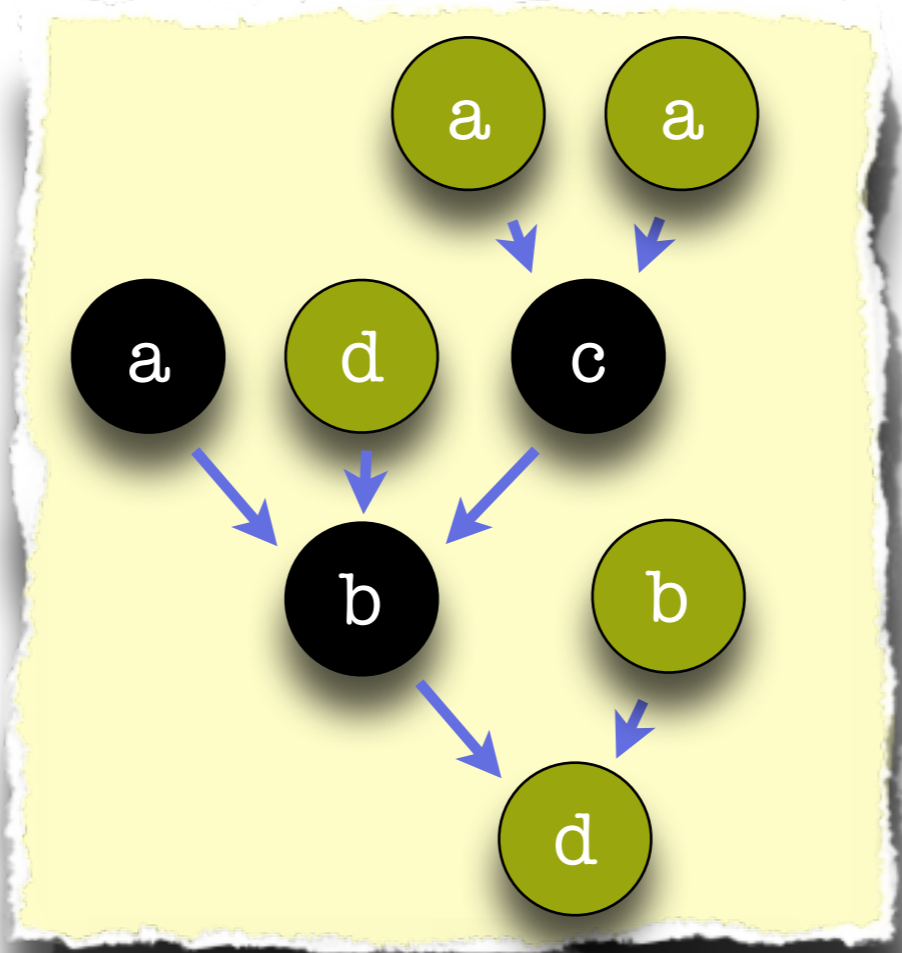
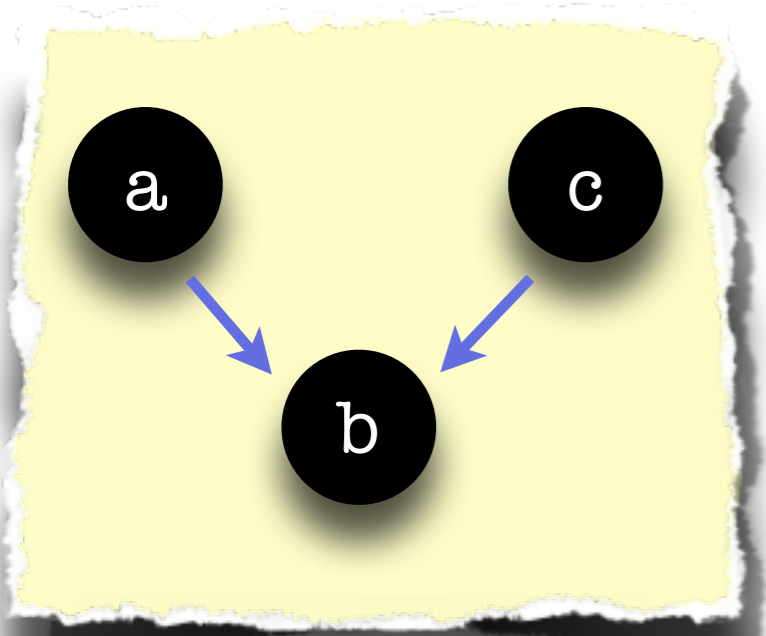
- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability



(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity



$$C_1 \sqsubseteq C_2$$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

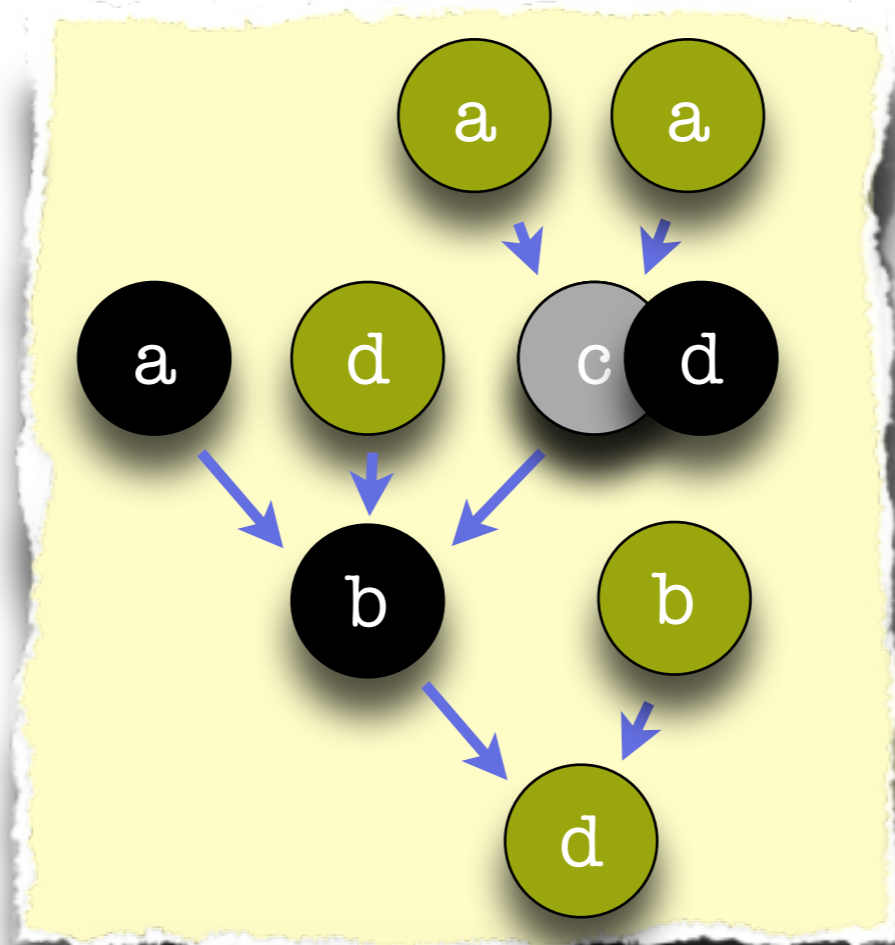
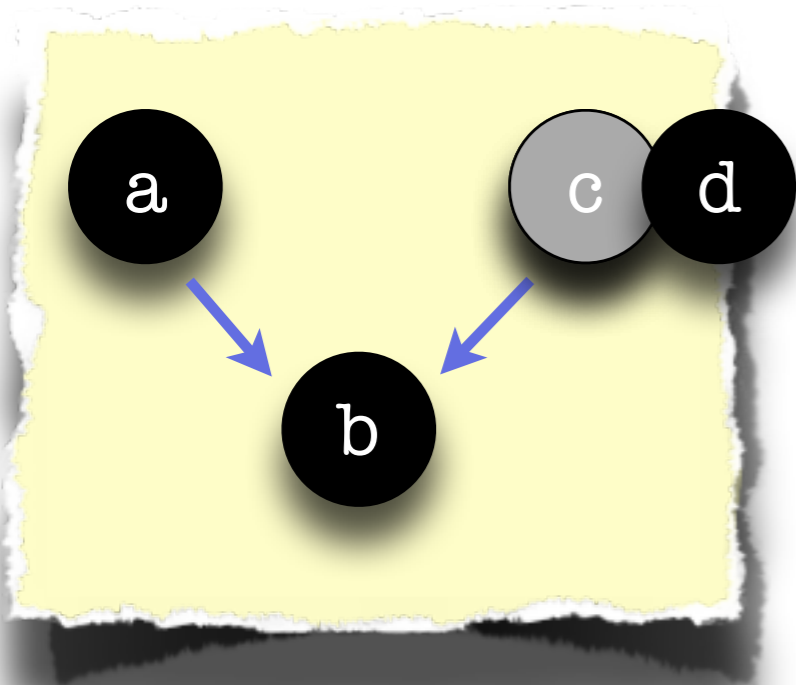


(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity

- ▶ Broadcast: $c \rightarrow d$



$$C_1 \sqsubseteq C_2$$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

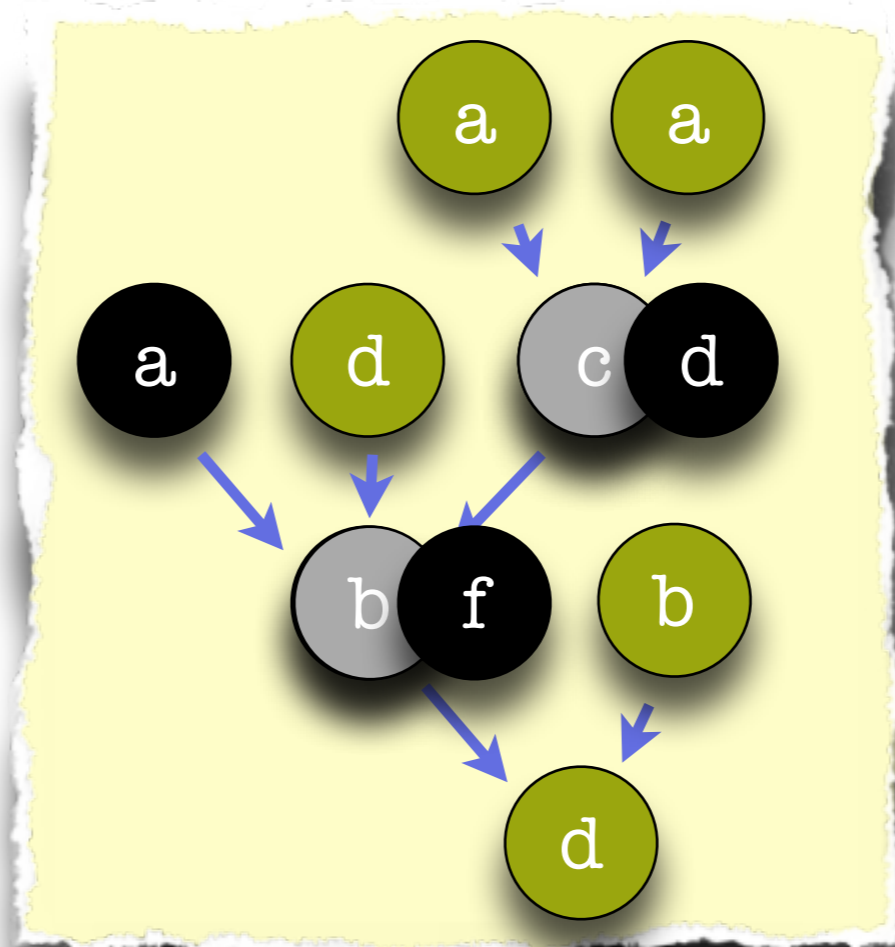
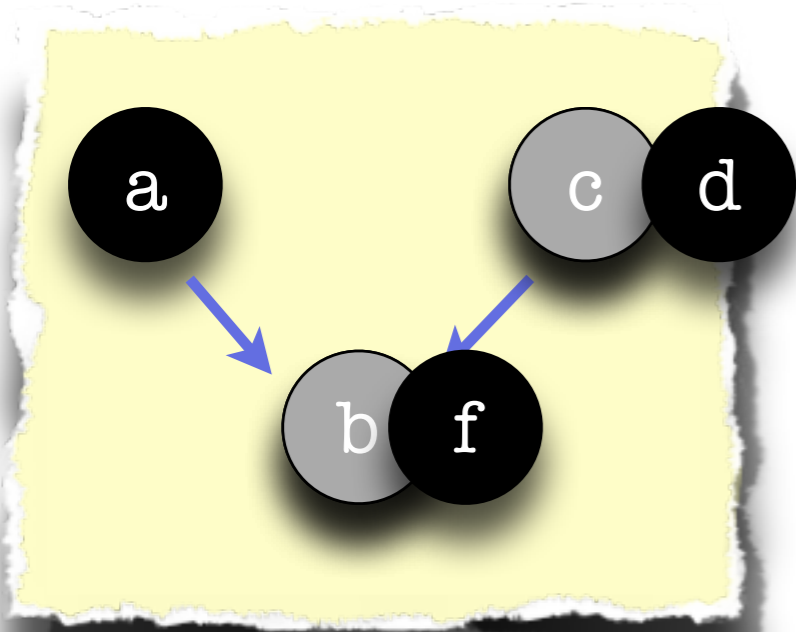


(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity

- ▶ Broadcast: $c \rightarrow d$
- ▶ Receive: $b \rightarrow f$



$$C_1 \sqsubseteq C_2$$

Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

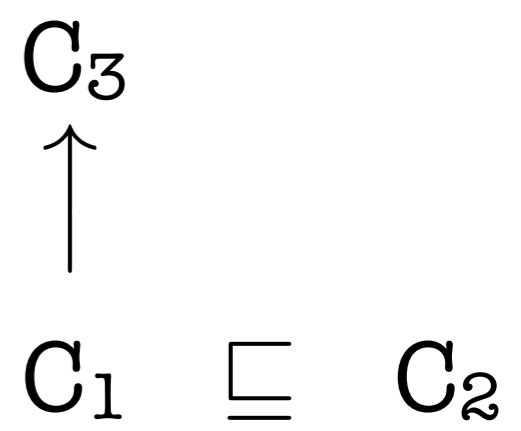
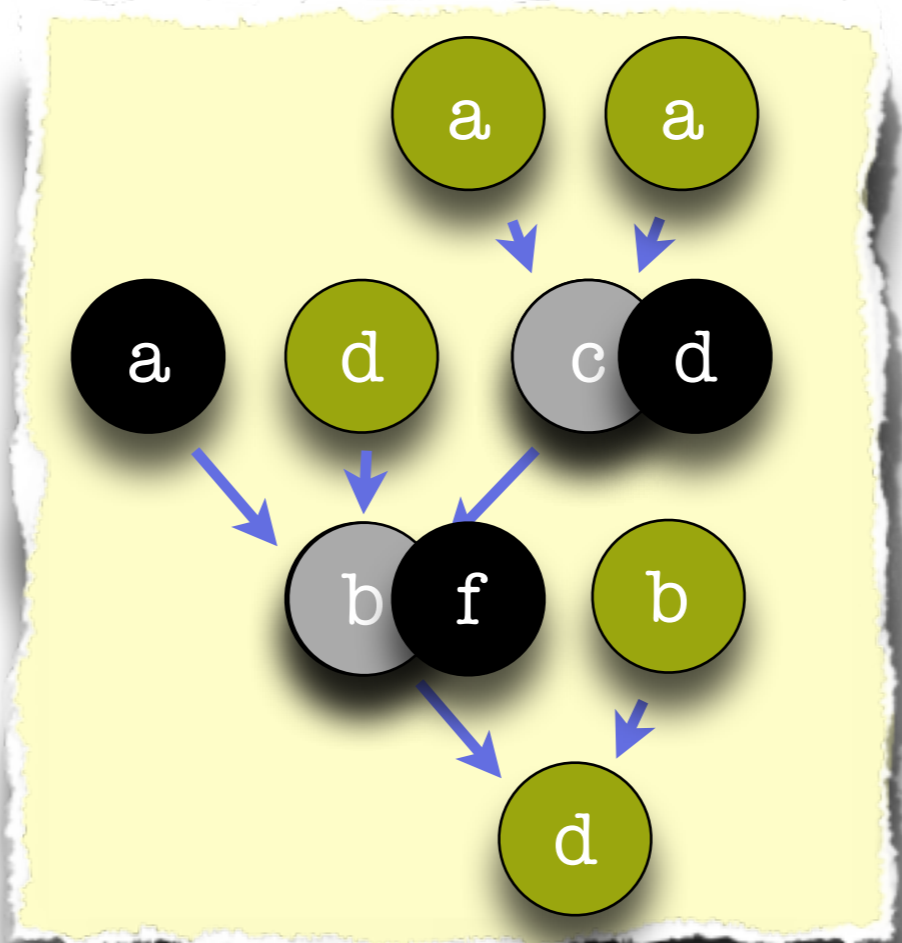
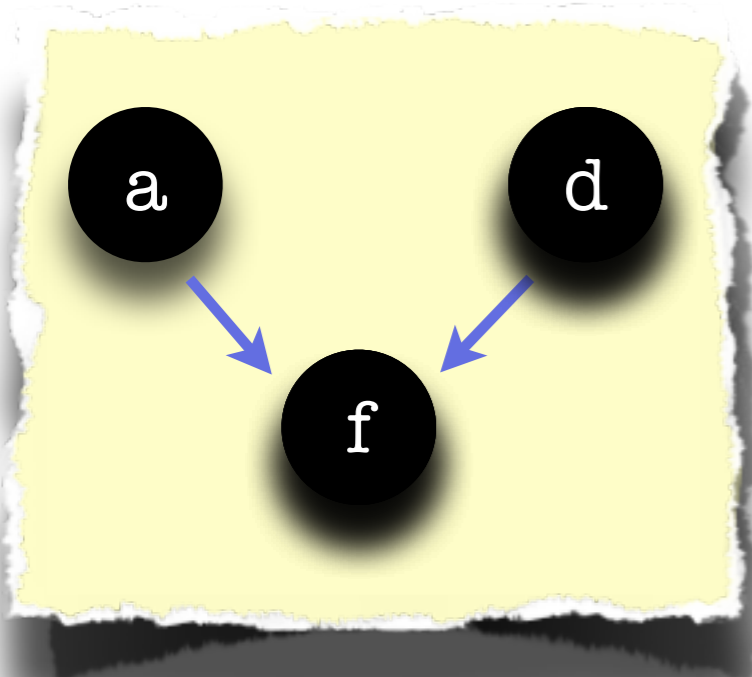


(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity

- ▶ Broadcast: $c \rightarrow d$
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Directed Acyclic

- ▶ Motivation
- ▶ Reachability
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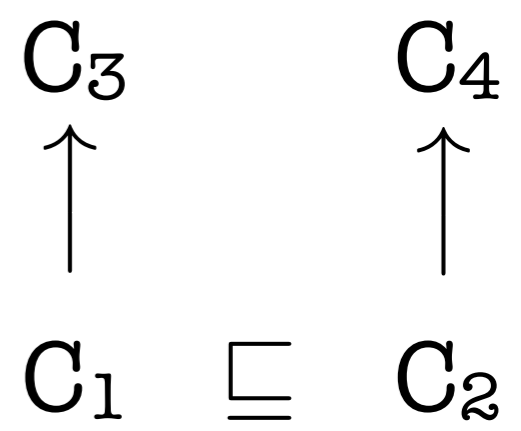
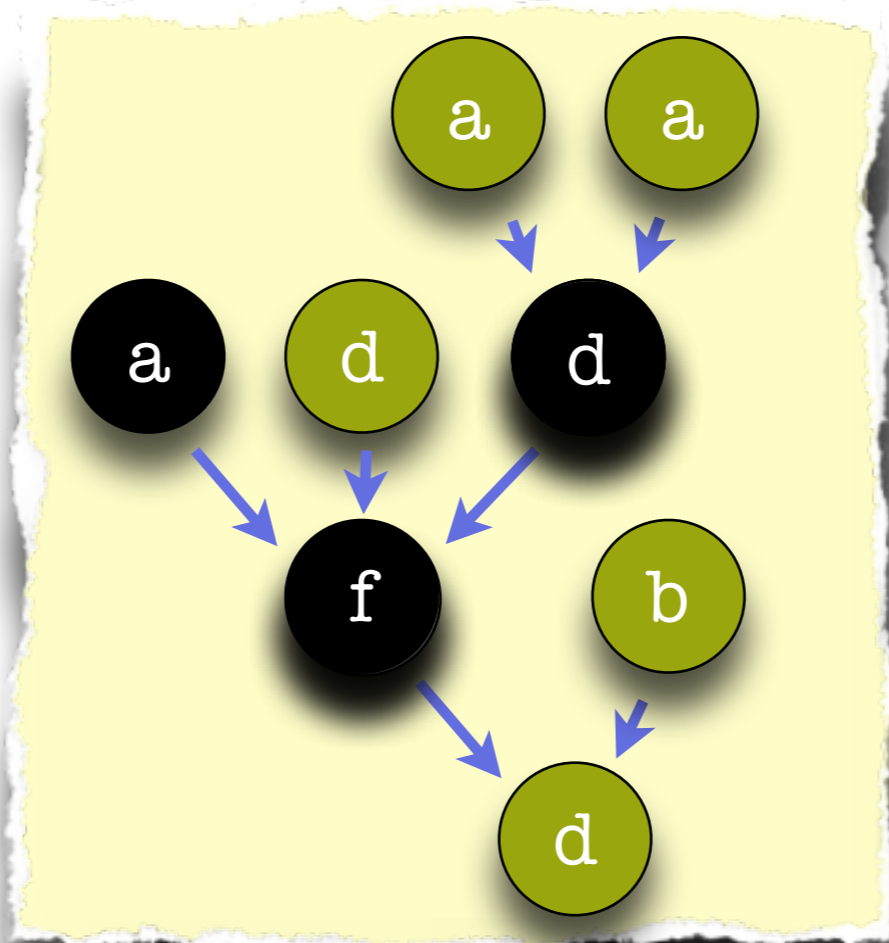
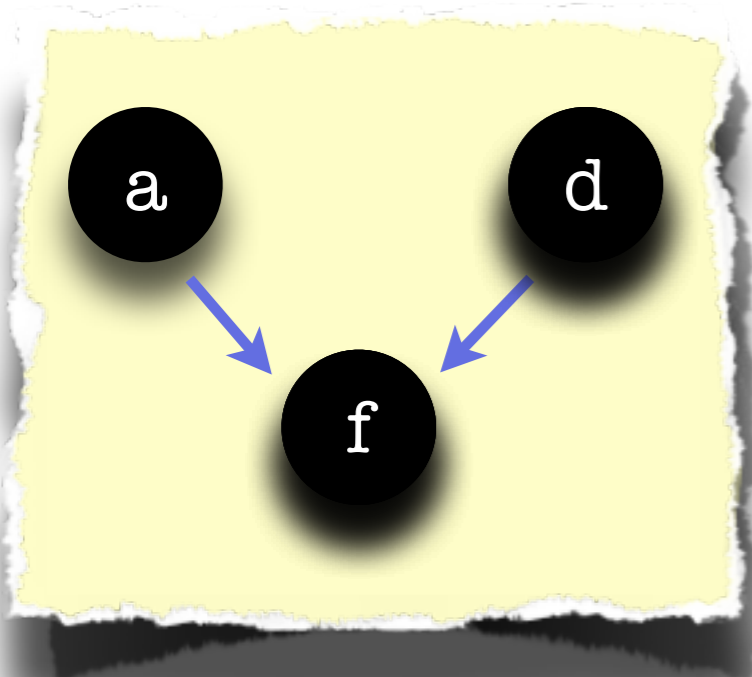


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Theory of Well Structured Transition Systems

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Directed Acyclic

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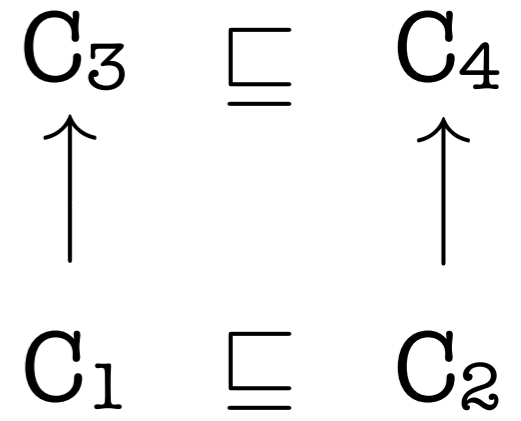
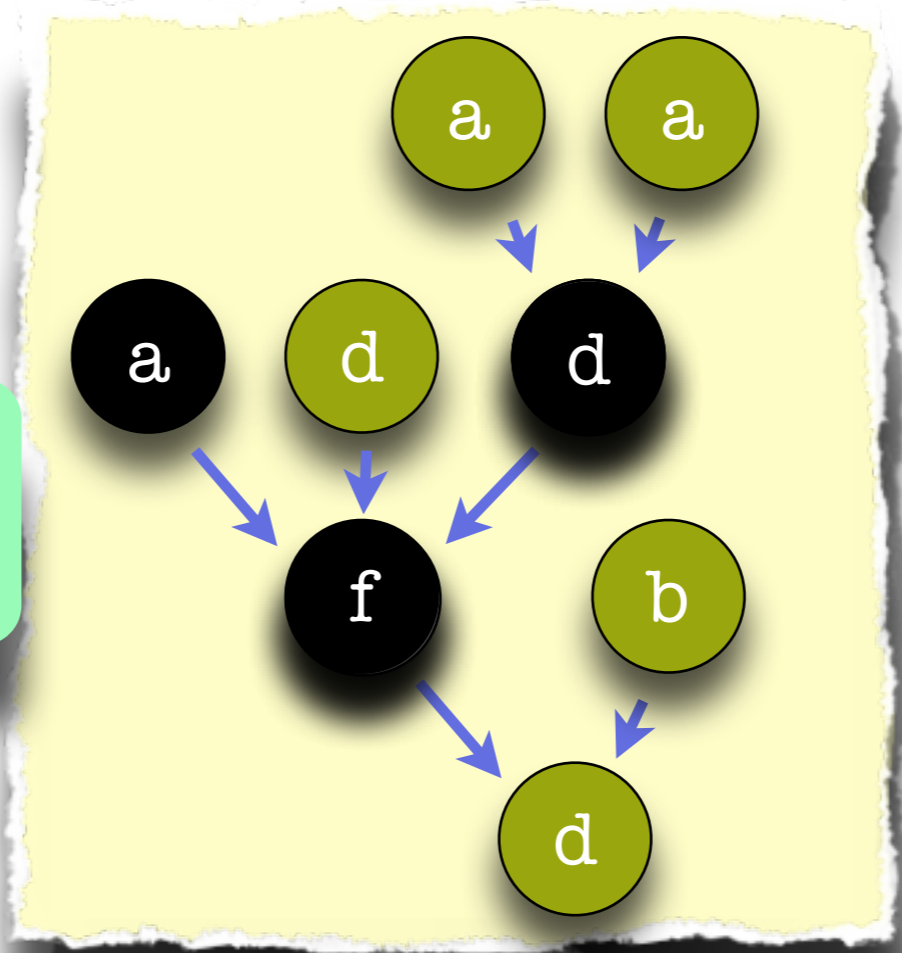
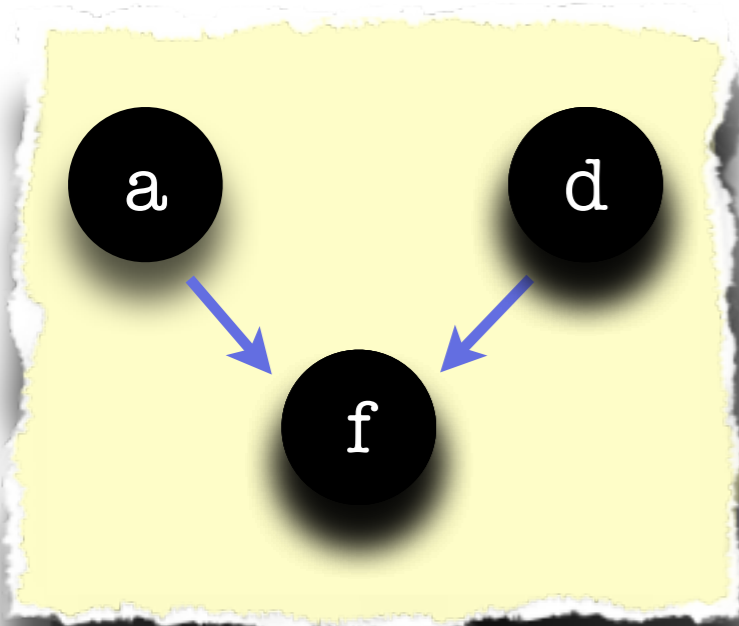


(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

(3) Define an ordering on configurations: Monotonicity

- ▶ Broadcast: $c \rightarrow d$
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Directed Acyclic

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

(BOUNDED-COVER) DECIDABLE

Theory of Well Structured Transition Systems

- (1) The WSTS framework
- (2) Reduce **(BOUNDED-COVER)** **(TREE-BOUNDED-COVER)**
- (3) Define an ordering on configurations



Ad-Hoc Networks

- ▶ Model
- ▶ Transition System
- ▶ Reachability

- ▶ Motivation
- ▶ Reachability
- ▶ Bounded Depth Reachability

Directed Acyclic



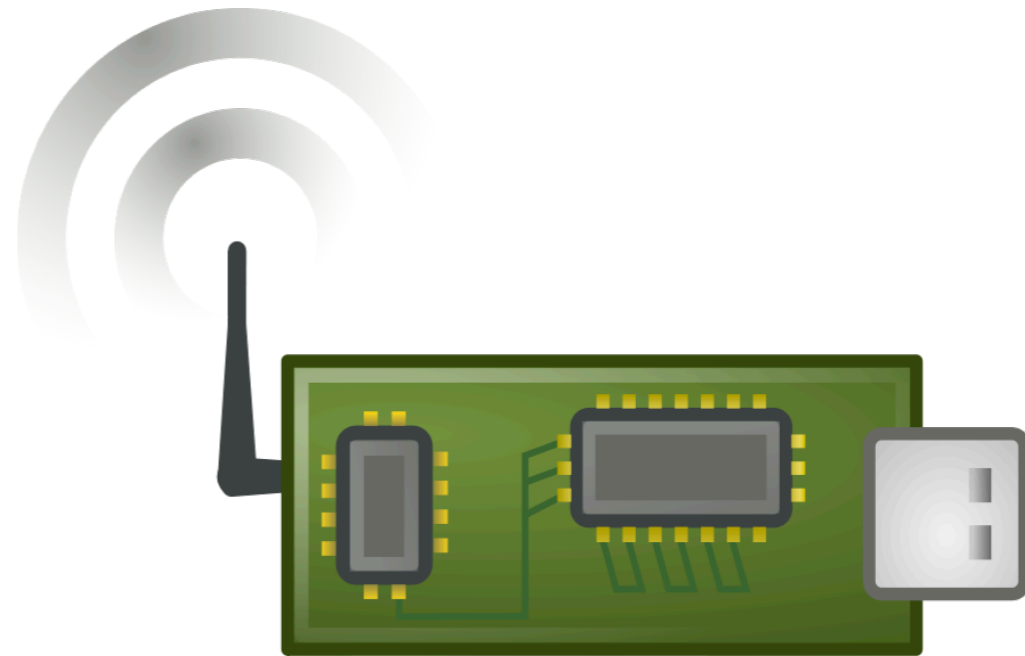
CURRENT WORK

Dynamic Communicating Automata

Dynamic Communicating Automata



Model

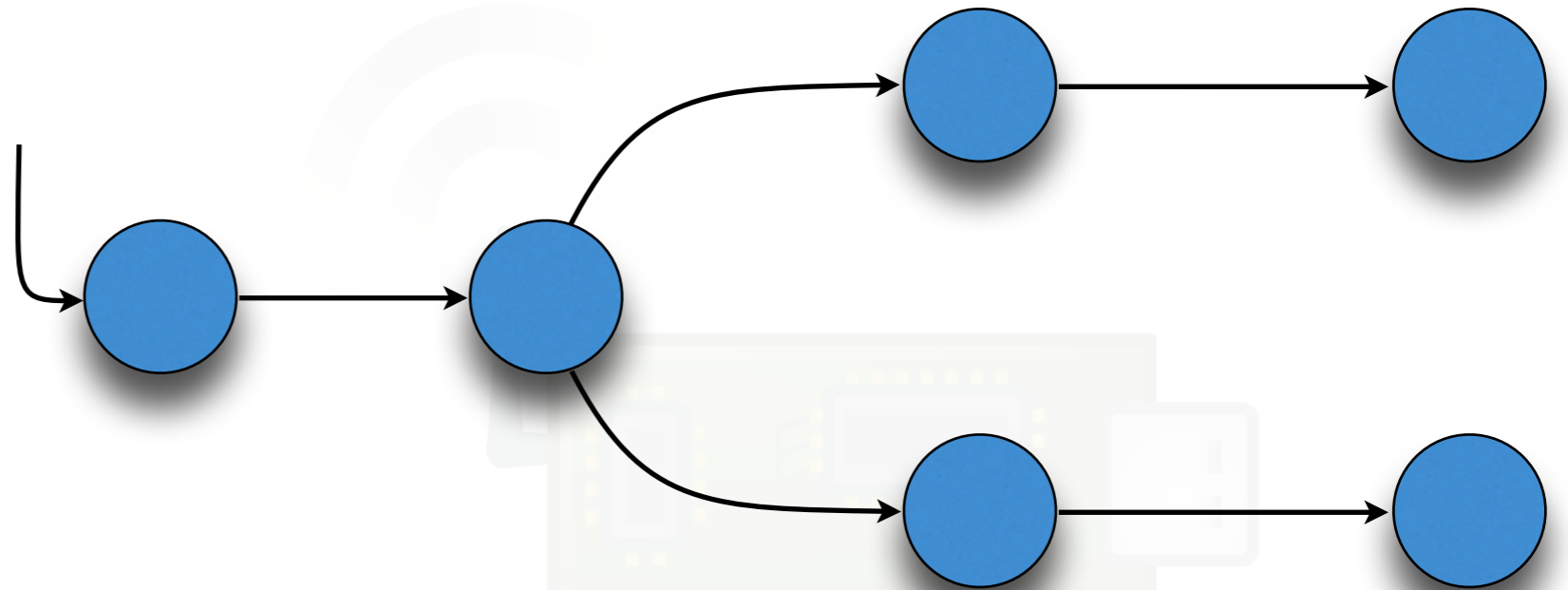


Dynamic Communicating Automata



Model

Node:
Process

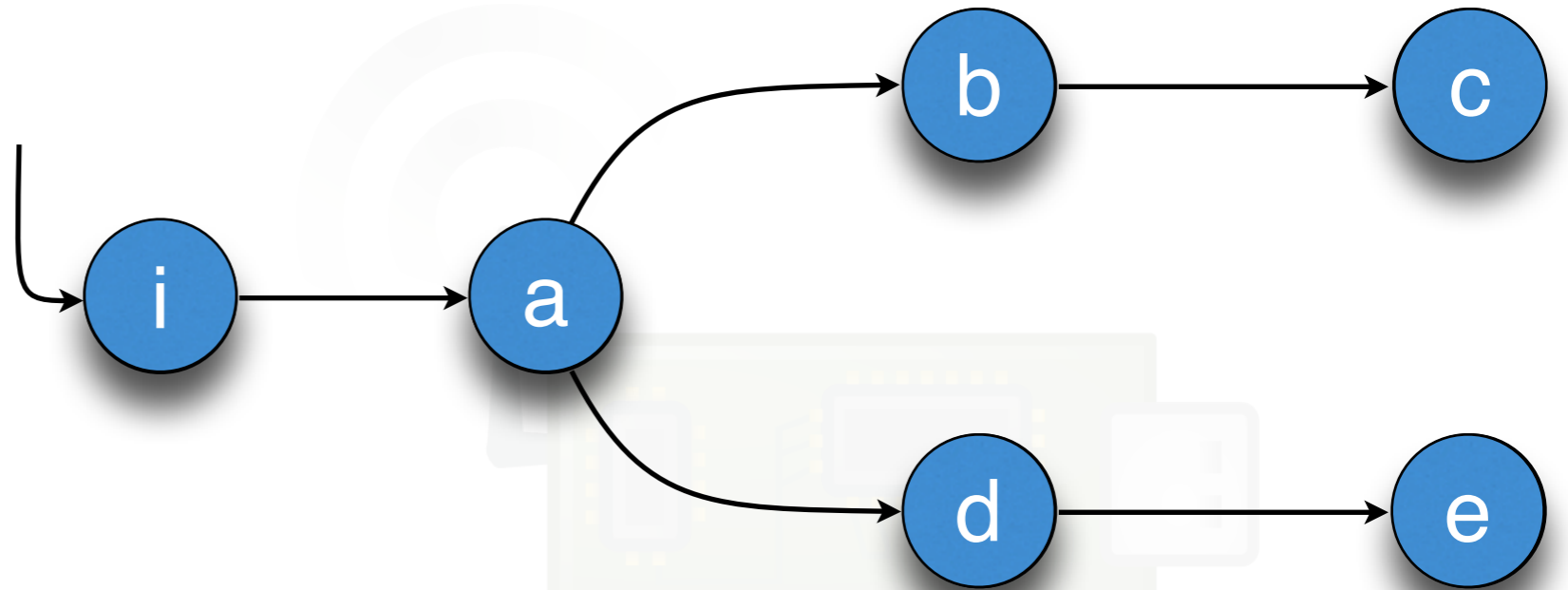


Dynamic Communicating Automata



Model

Node:
Process



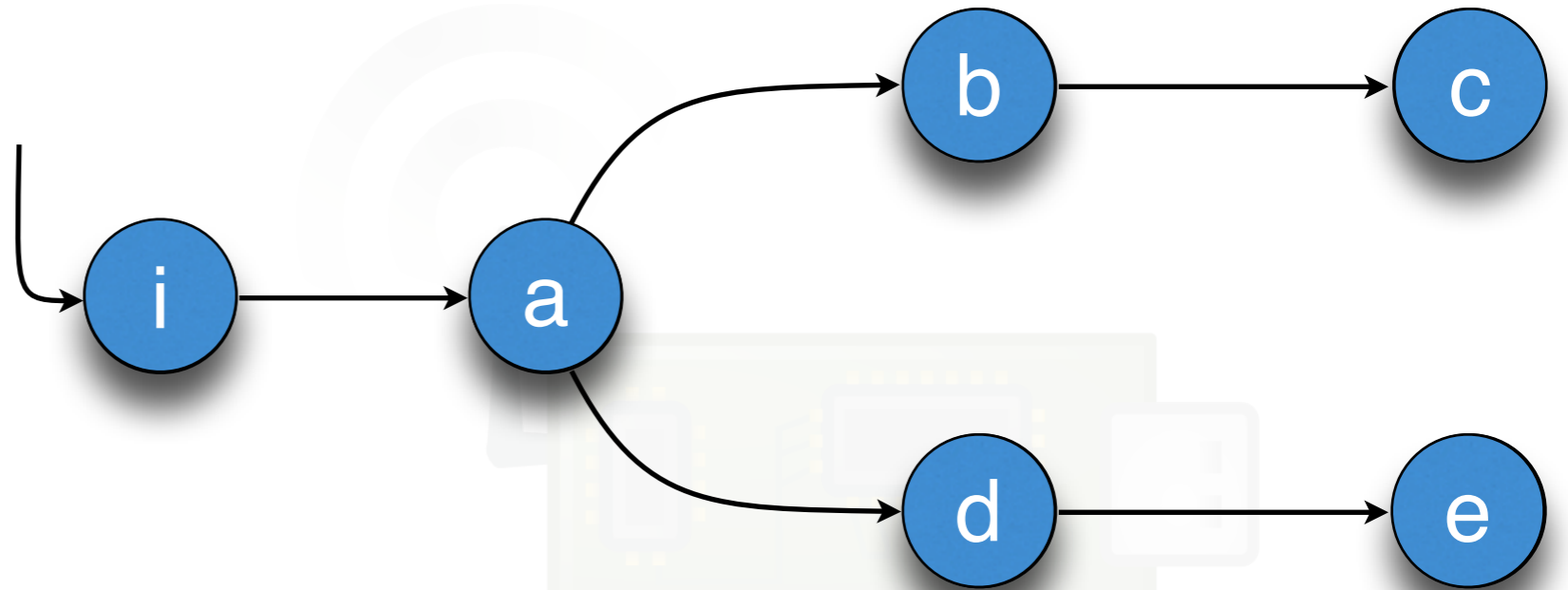
Dynamic Communicating Automata



Model

Node:
Process

Id = 1



Dynamic Communicating Automata

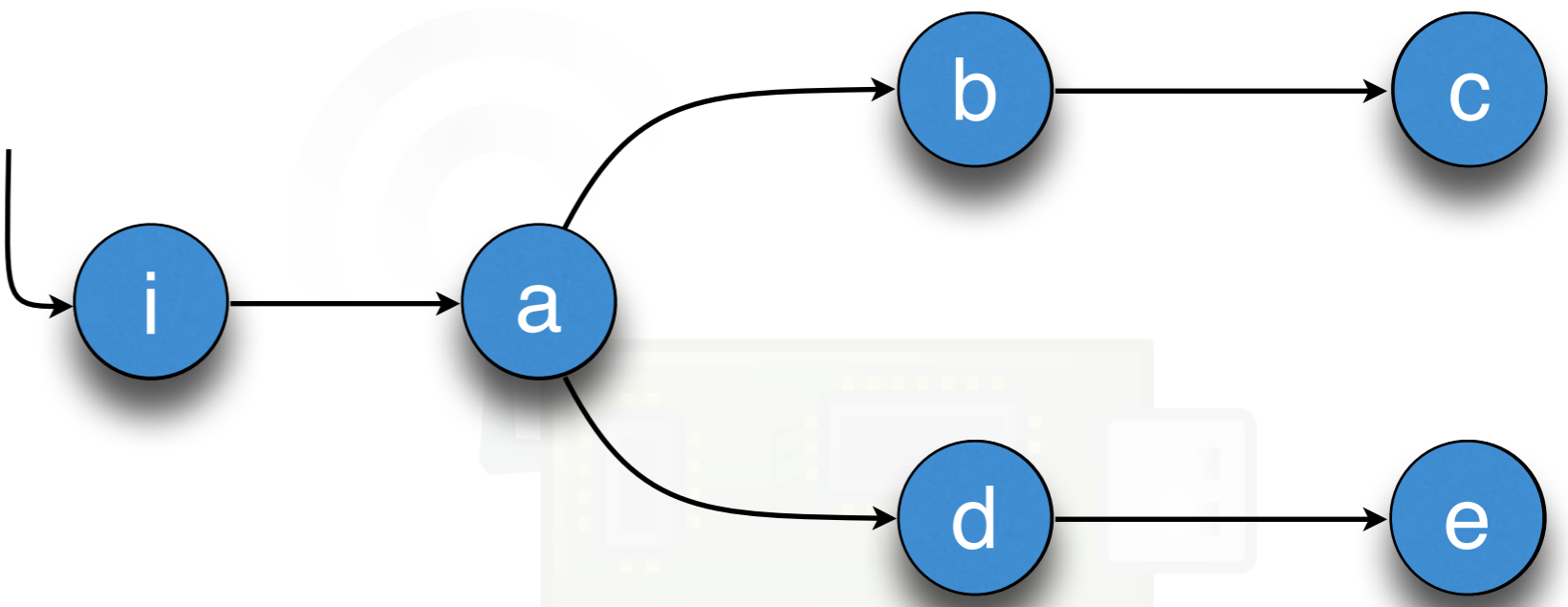


Model

Node:
Process

Id = 1

Reg = {
x:null,
y:3,
z:null



Dynamic Communicating Automata



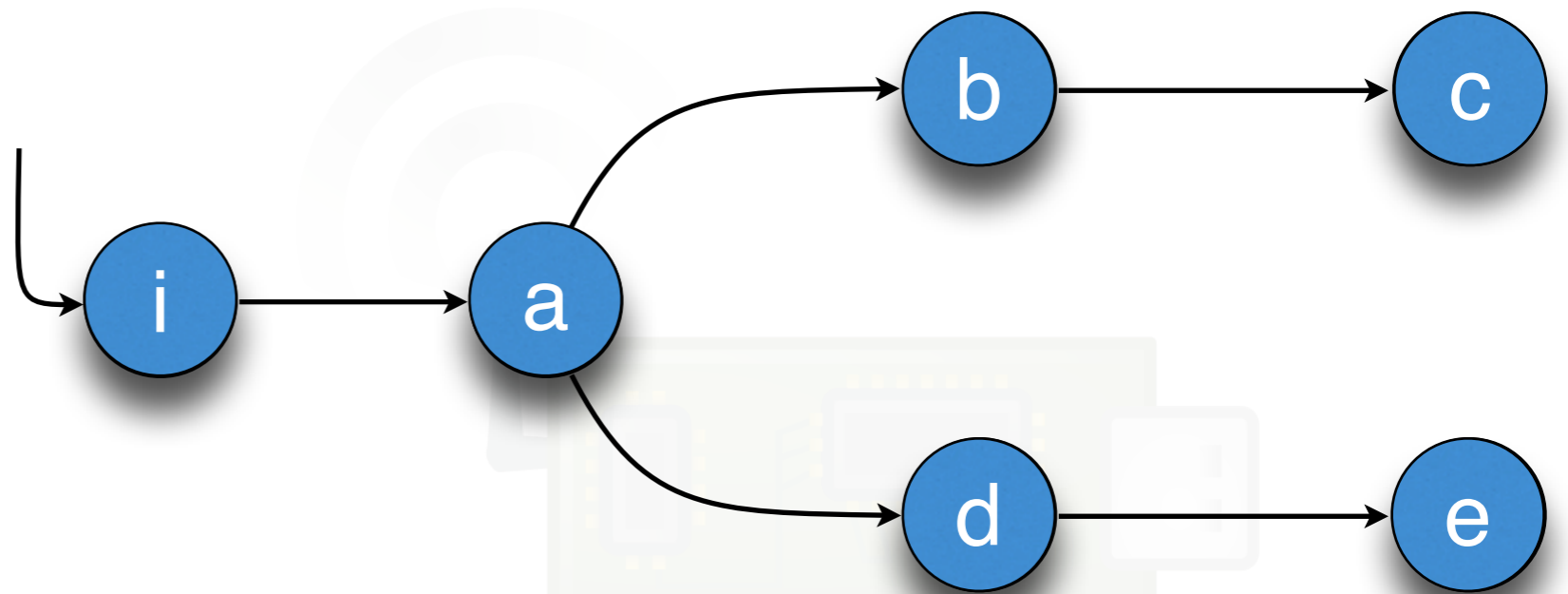
Model

Node:
Process

Transitions:

Id = 1

Reg = {
x:null,
y:3,
z:null



Dynamic Communicating Automata

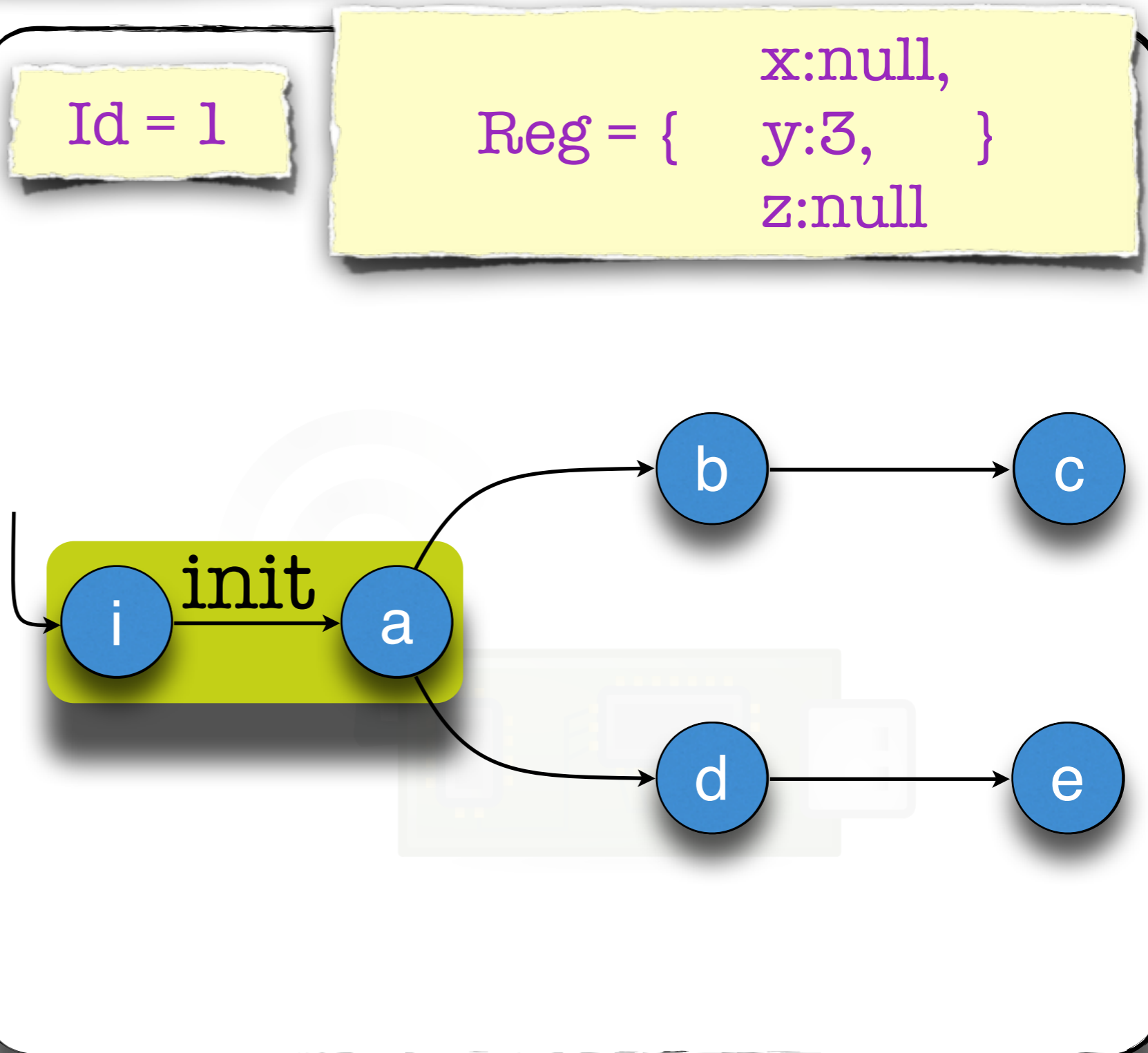


Model

Node:
Process

Transitions:

▶ Local



Dynamic Communicating Automata



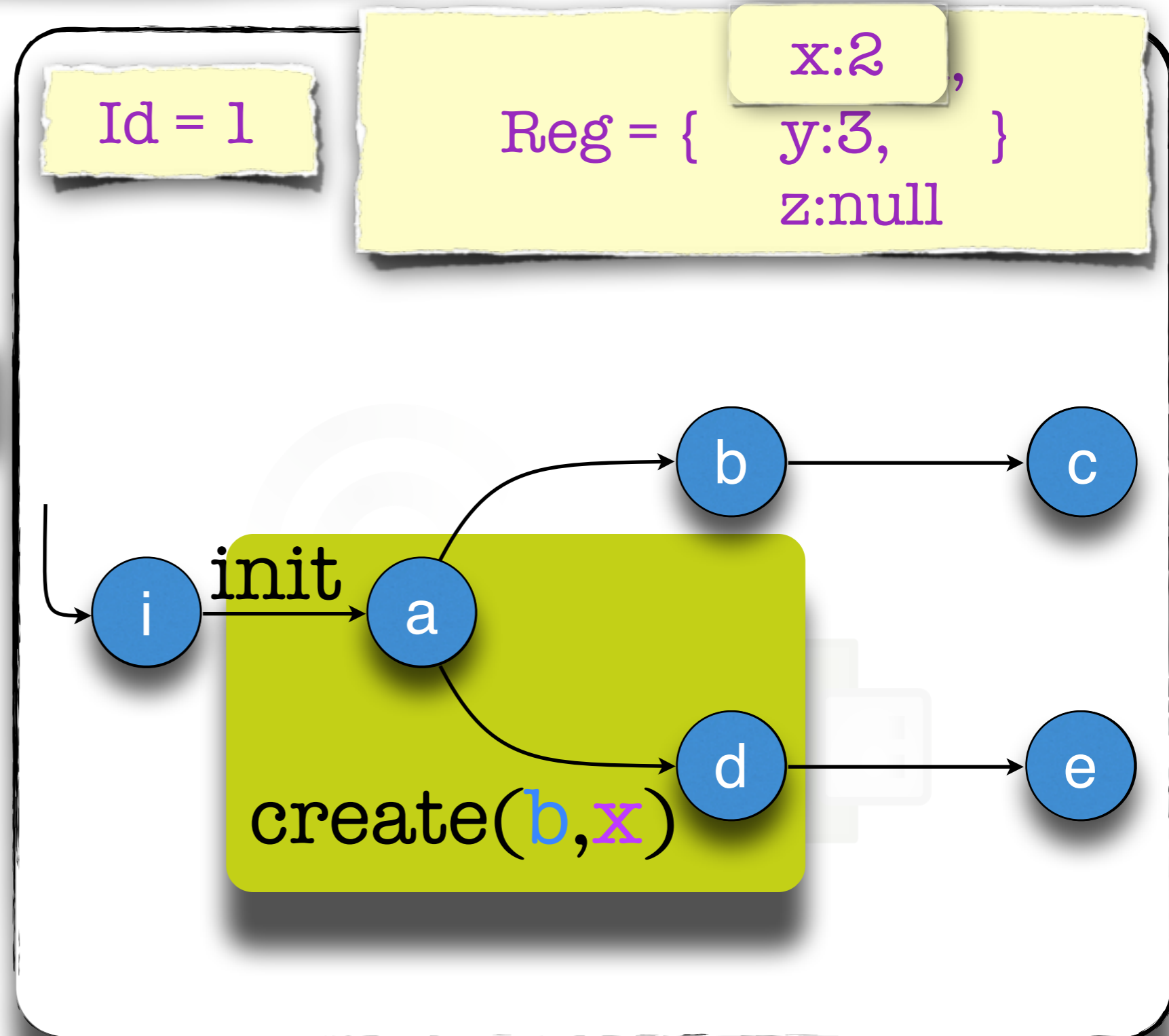
Model

Node:
Process

Transitions:

▶ Local

▶ Create (q,to_x)



Dynamic Communicating Automata

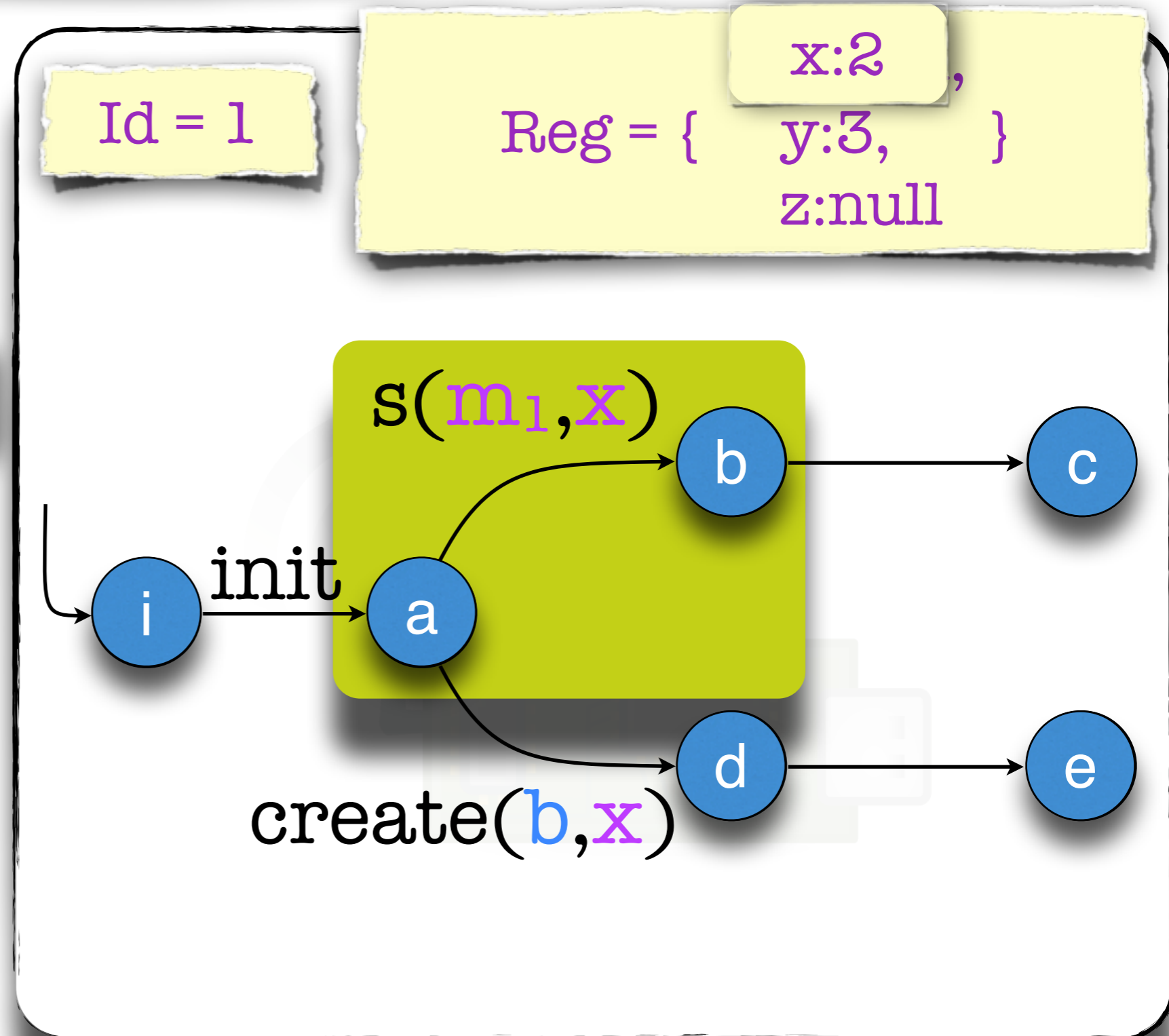


Model

Node:
Process

Transitions:

- ▶ Local
- ▶ Create (q,to_x)
- ▶ Send (m,to_x)



Dynamic Communicating Automata

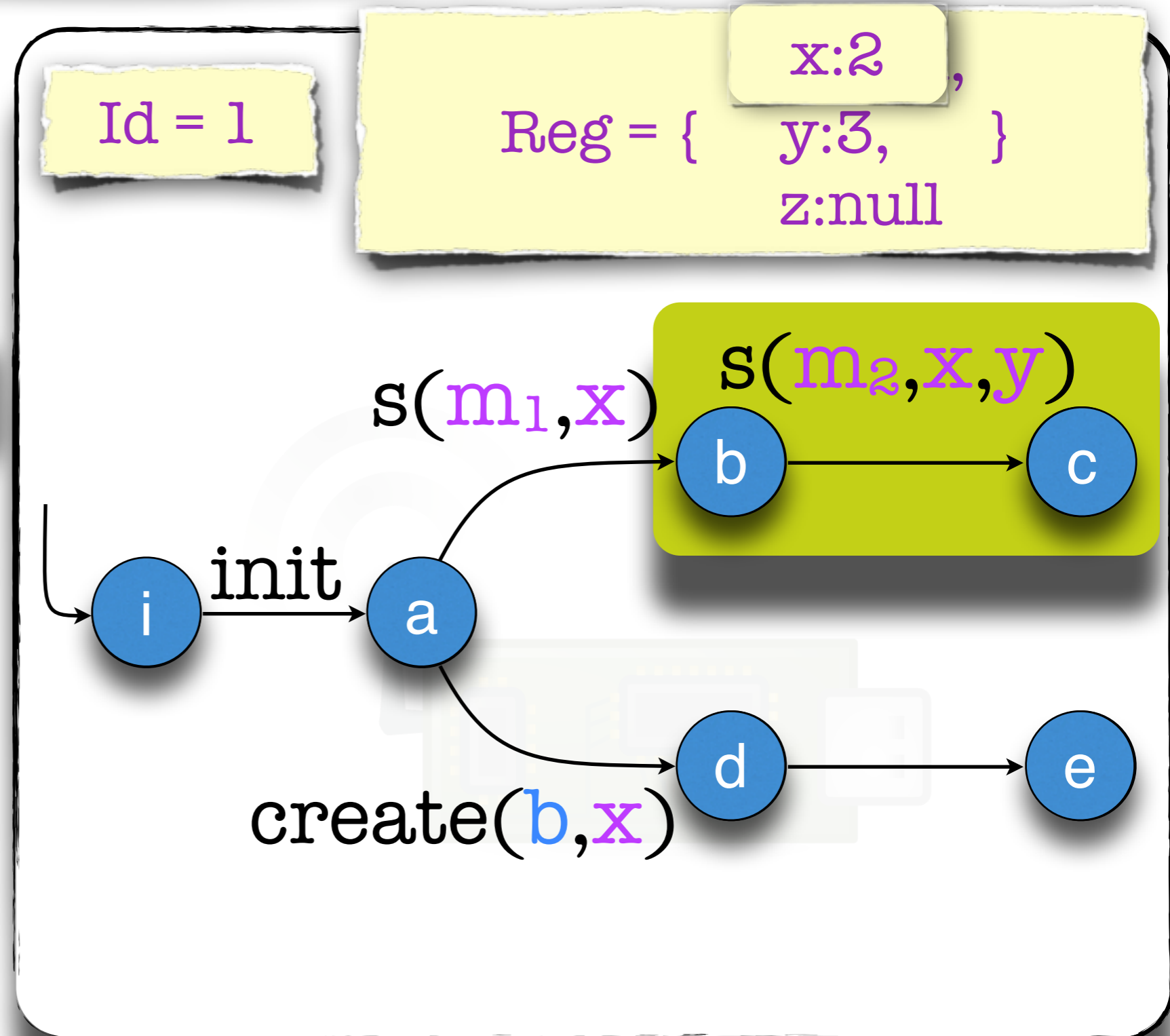


Model

Node:
Process

Transitions:

- ▶ Local
- ▶ Create (q,to_x)
- ▶ Send (m,to_x)
- ▶ Send (m,to_x,with_y)



Dynamic Communicating Automata

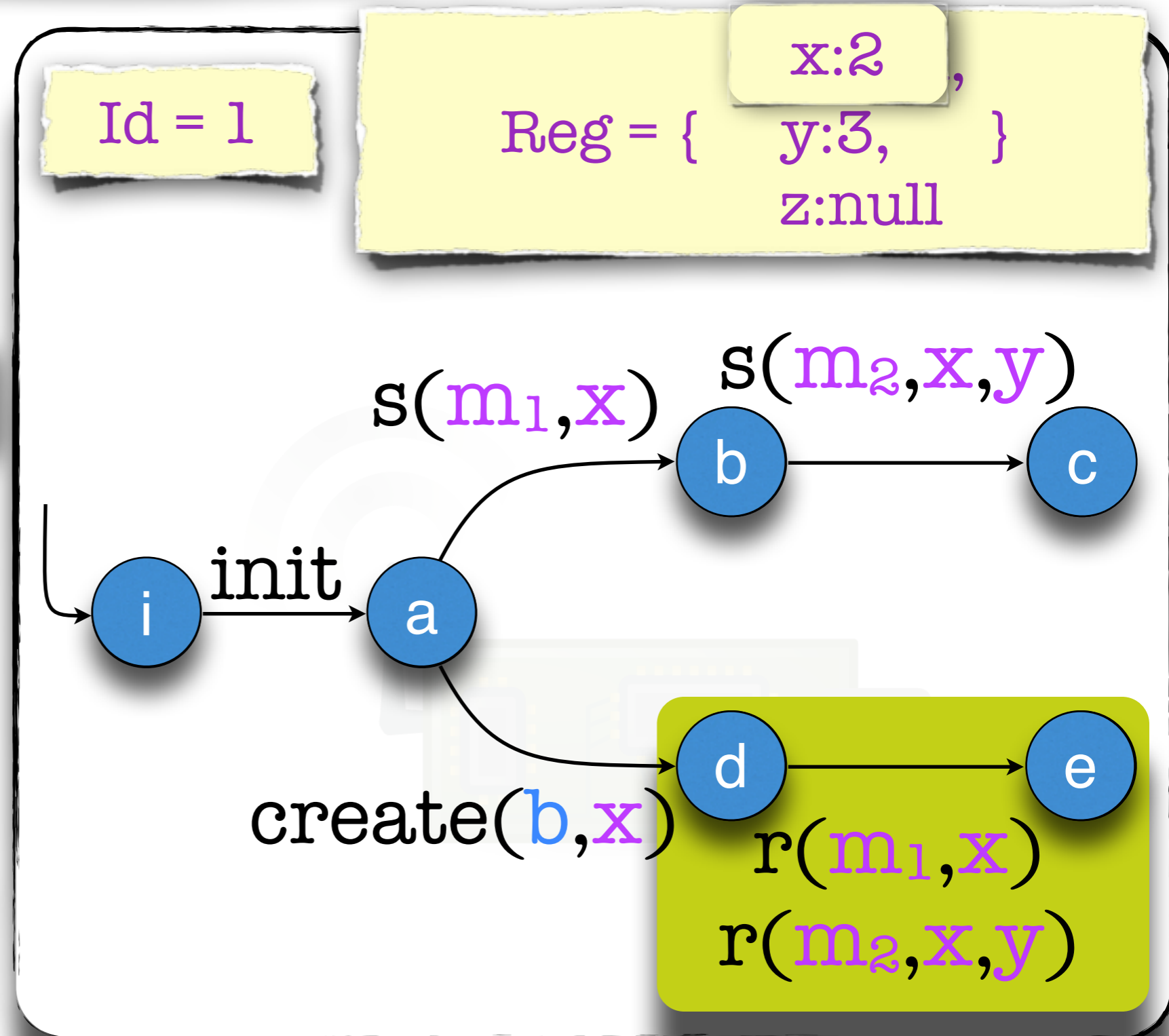


Model

Node:
Process

Transitions:

- ▶ Local
- ▶ Create (q,to_x)
- ▶ Send (m,to_x)
- ▶ Send (m,to_x,with_y)
- ▶ Recv (m,fr_x)
- ▶ Recv (m,fr_x,with_y)



Dynamic Communicating Automata

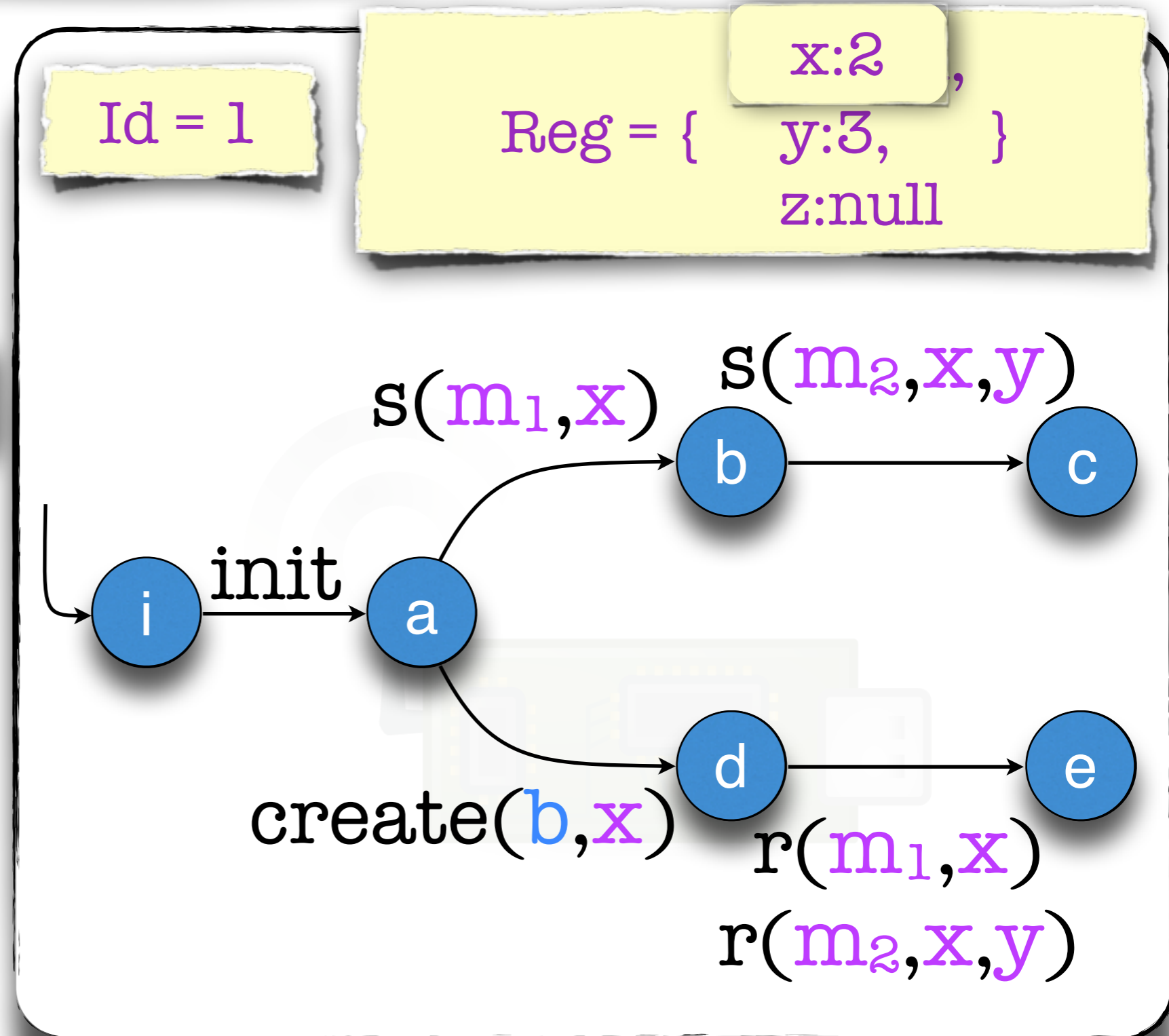


Model

Node:
Process

Transitions:

- ▶ Local
- ▶ Create (q,to_x)
- ▶ Send (m,to_x)
- ▶ Send (m,to_x,with_y)
- ▶ Recv (m,fr_x)
- ▶ Recv (m,fr_x,with_y)



Dynamic Communicating Automata

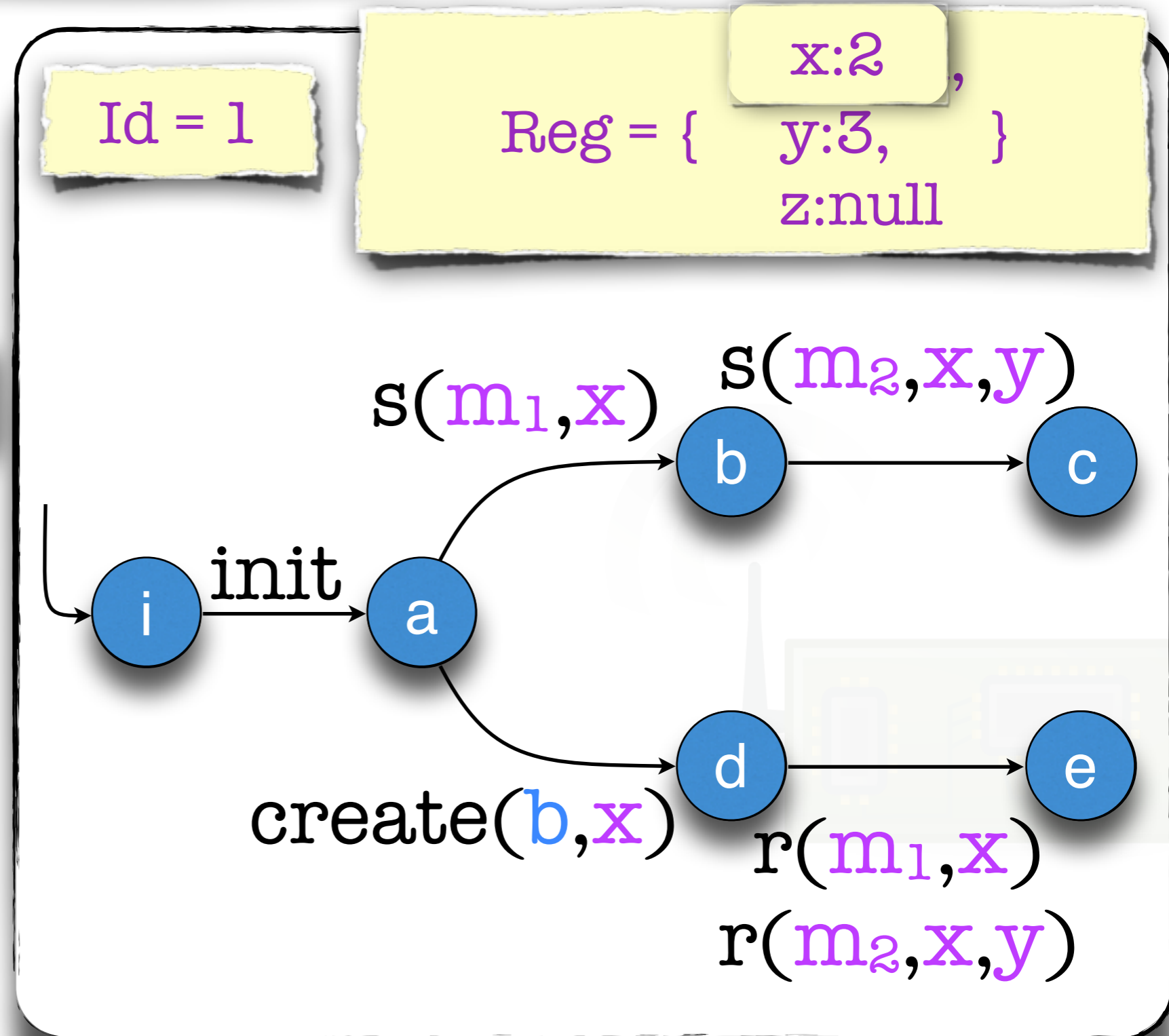


Model

Node:
Process

Transitions:

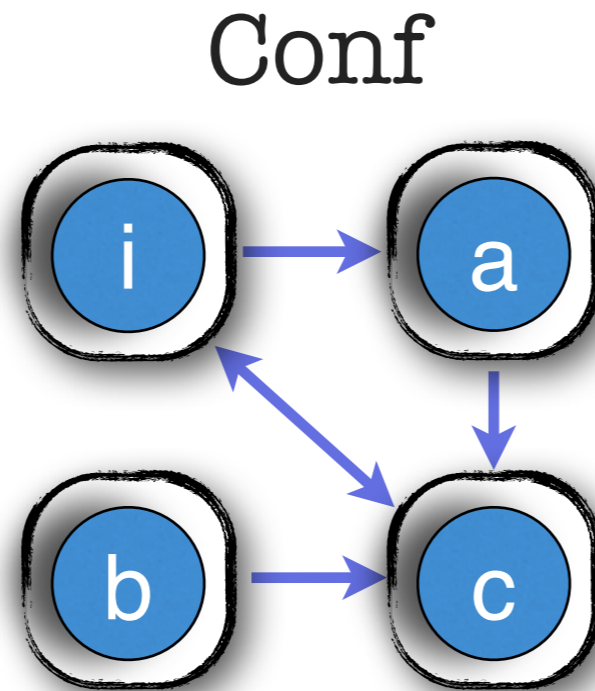
- ▶ Local
- ▶ Create (q,to_x)
- ▶ Send (m,to_x)
- ▶ Send (m,to_x,with_y)
- ▶ Recv (m,fr_x)
- ▶ Recv (m,fr_x,with_y)



Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

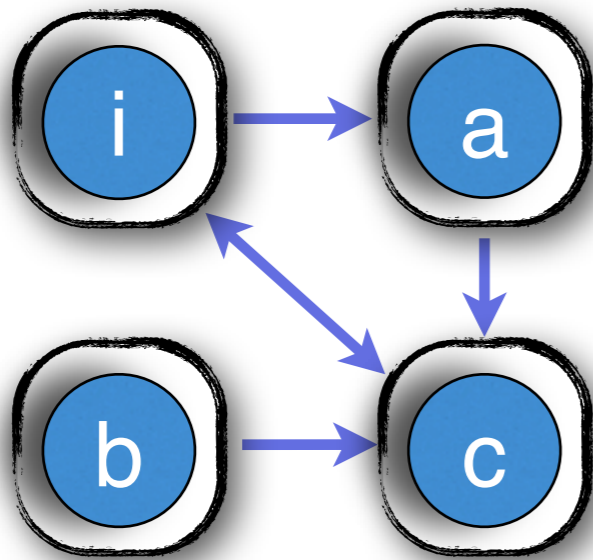


Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Conf



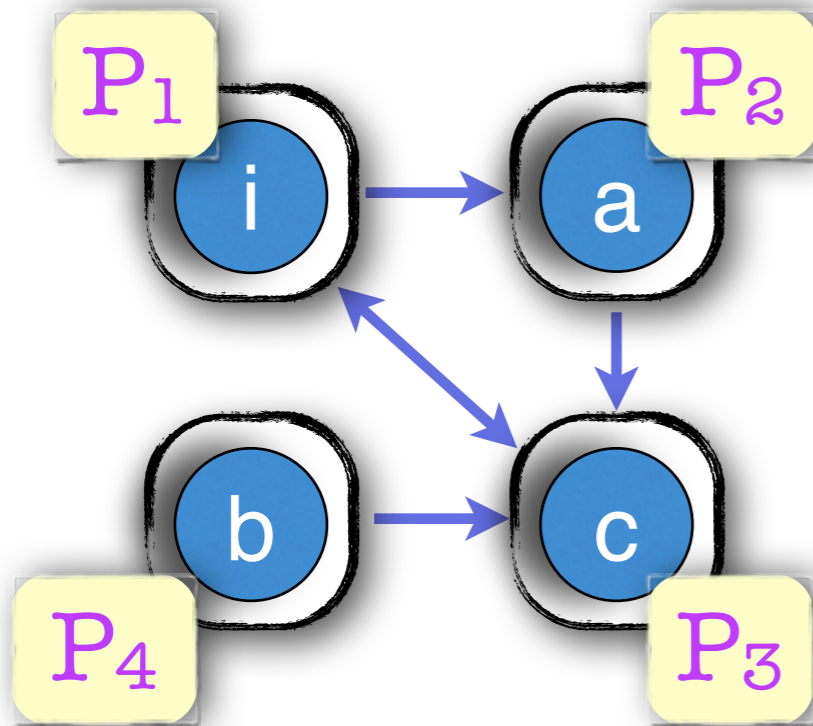
$\langle P, Id, S, R \rangle$

Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Conf



$\langle P, Id, S, R \rangle$

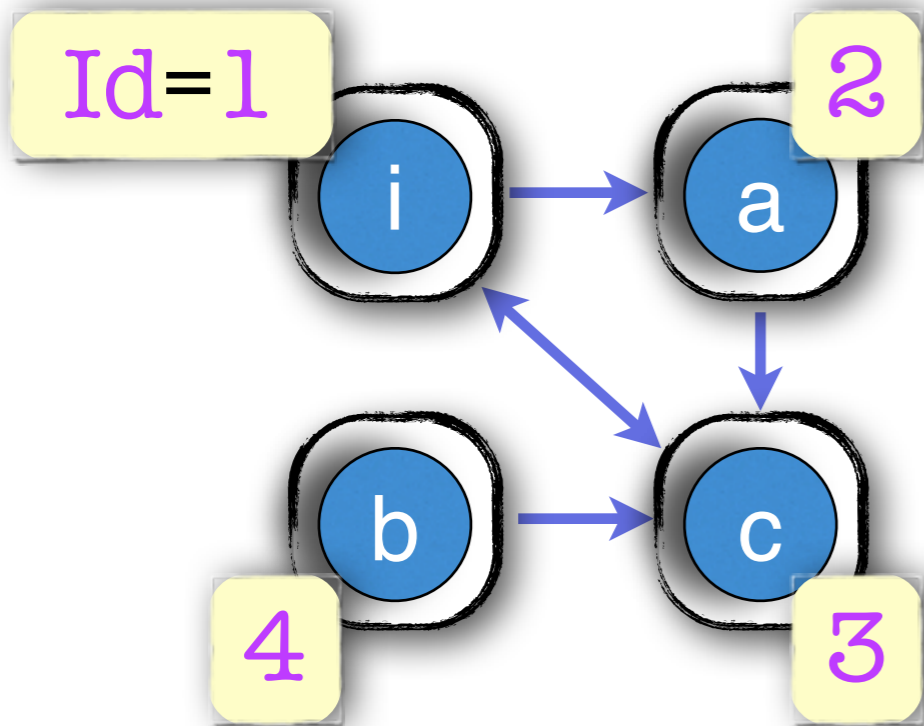
Dynamic Communicating Automata



$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Conf



$\langle P, \text{Id}, S, R \rangle$

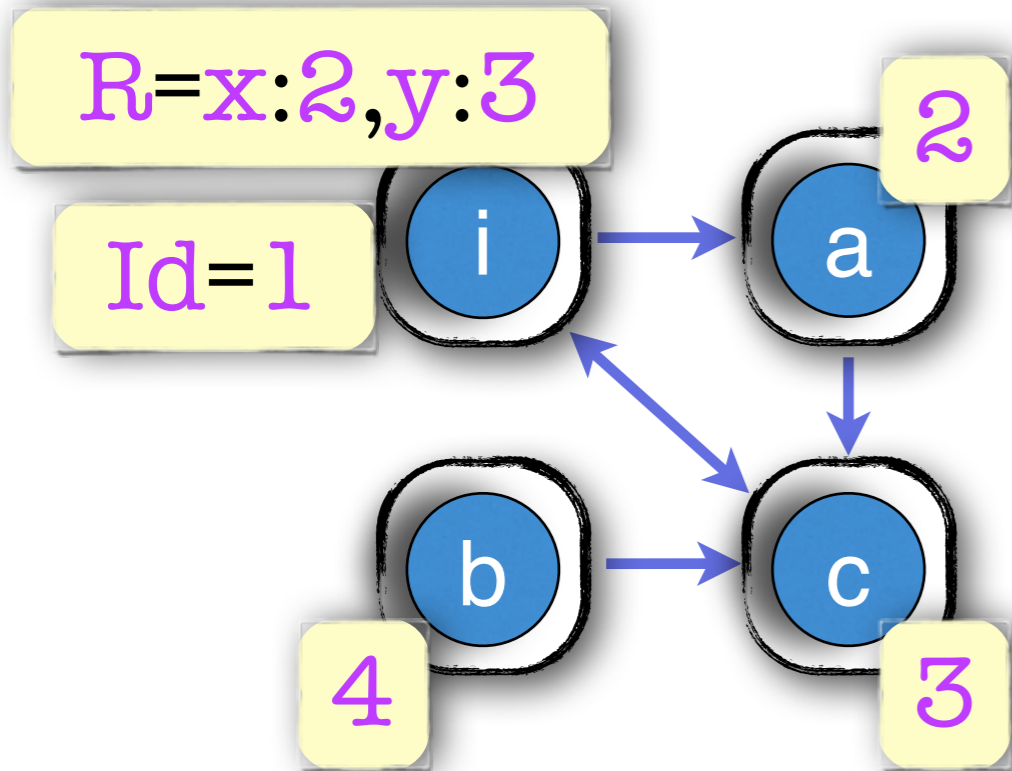
Dynamic Communicating Automata



$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Conf



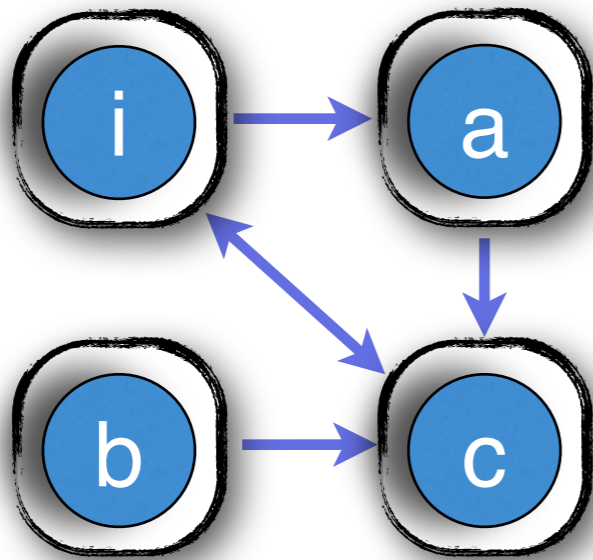
$\langle P, Id, S, R \rangle$

Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of configurations
- ▶ Transition Relation
- ▶ Trace

Conf



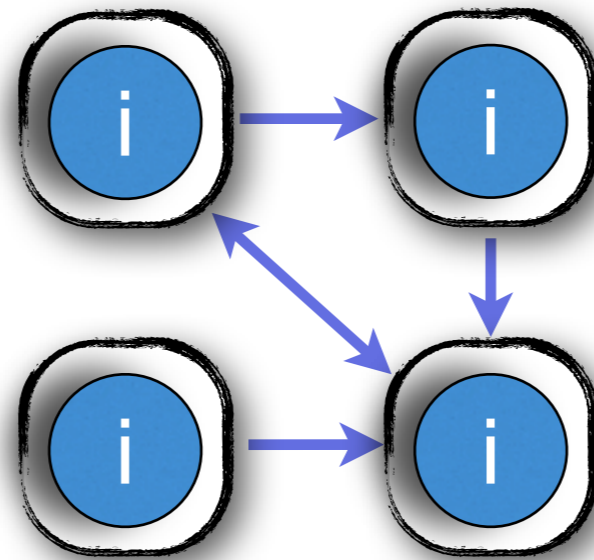
$\langle P, Id, S, R \rangle$

Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace

Initial Conf



Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace

Initial Conf

{  }

Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace



Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace

▶ Local actions



Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace



- ▶ Local actions
- ▶ Process Creation

Dynamic Communicating Automata

$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace



- ▶ Local actions
- ▶ Process Creation
- ▶ Message & Reg passing
(Rendez-vous communication)

Dynamic Communicating Automata



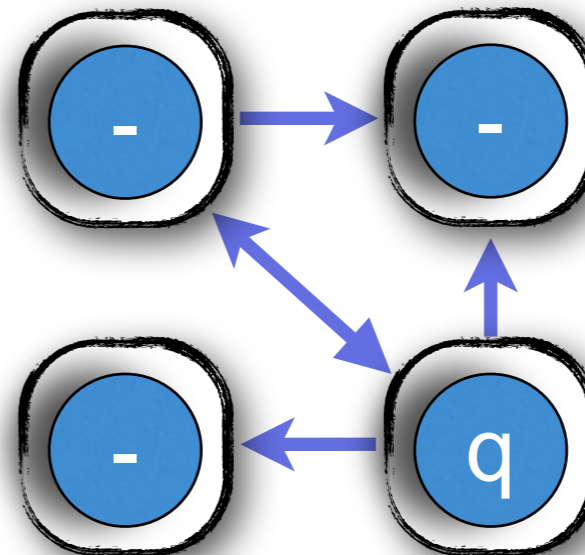
$\langle \Gamma, \Gamma_0, \longrightarrow \rangle$

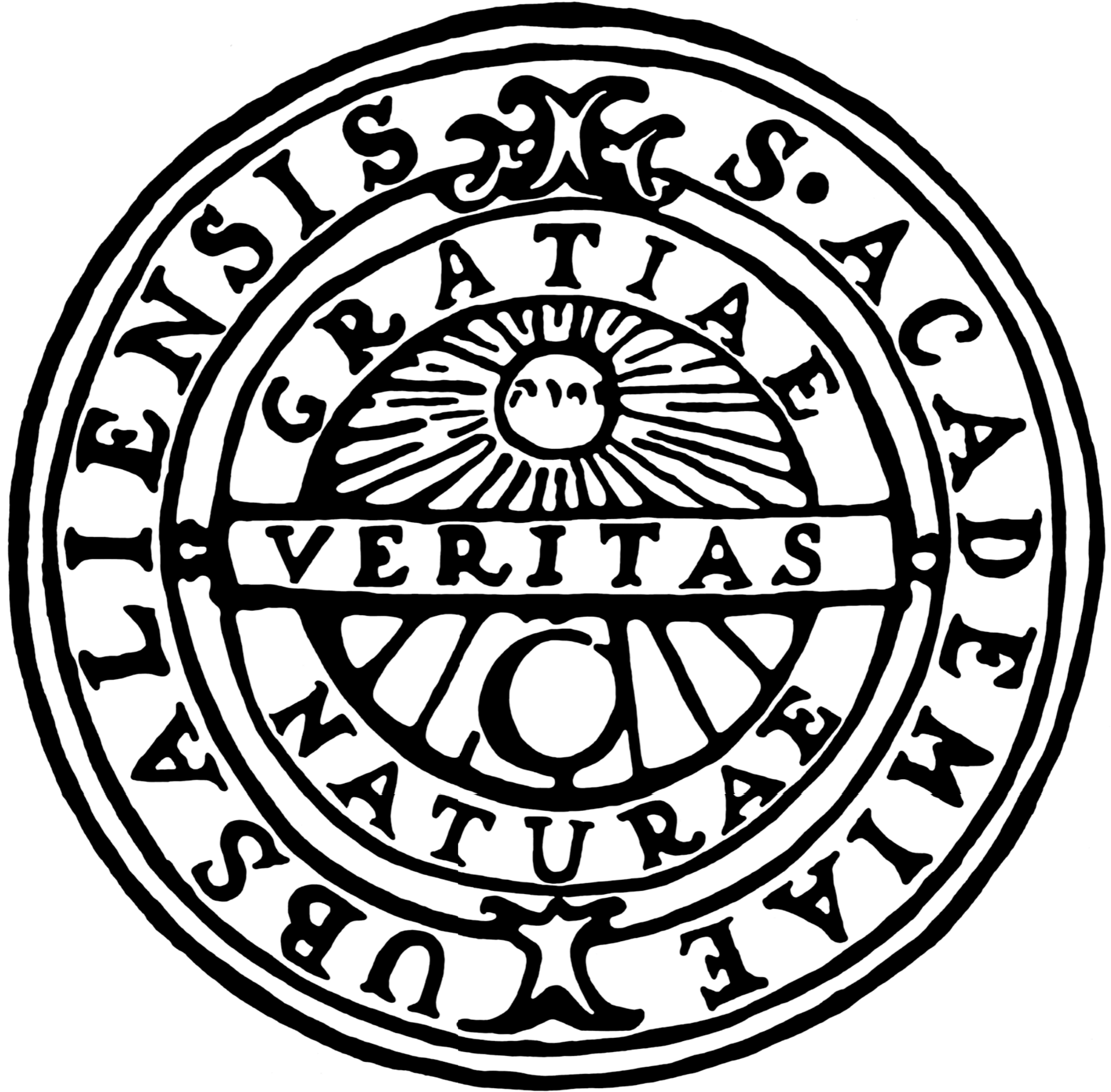
- ▶ Set of initial configurations
- ▶ Transition Relation
- ▶ Trace

Initial Conf



Reachable Conf





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GRATIA FAVORATA
VERITAS
SANTISSIMA TRINITAS