Efficient TCTL Model Checking Algorithm for Timed Actos

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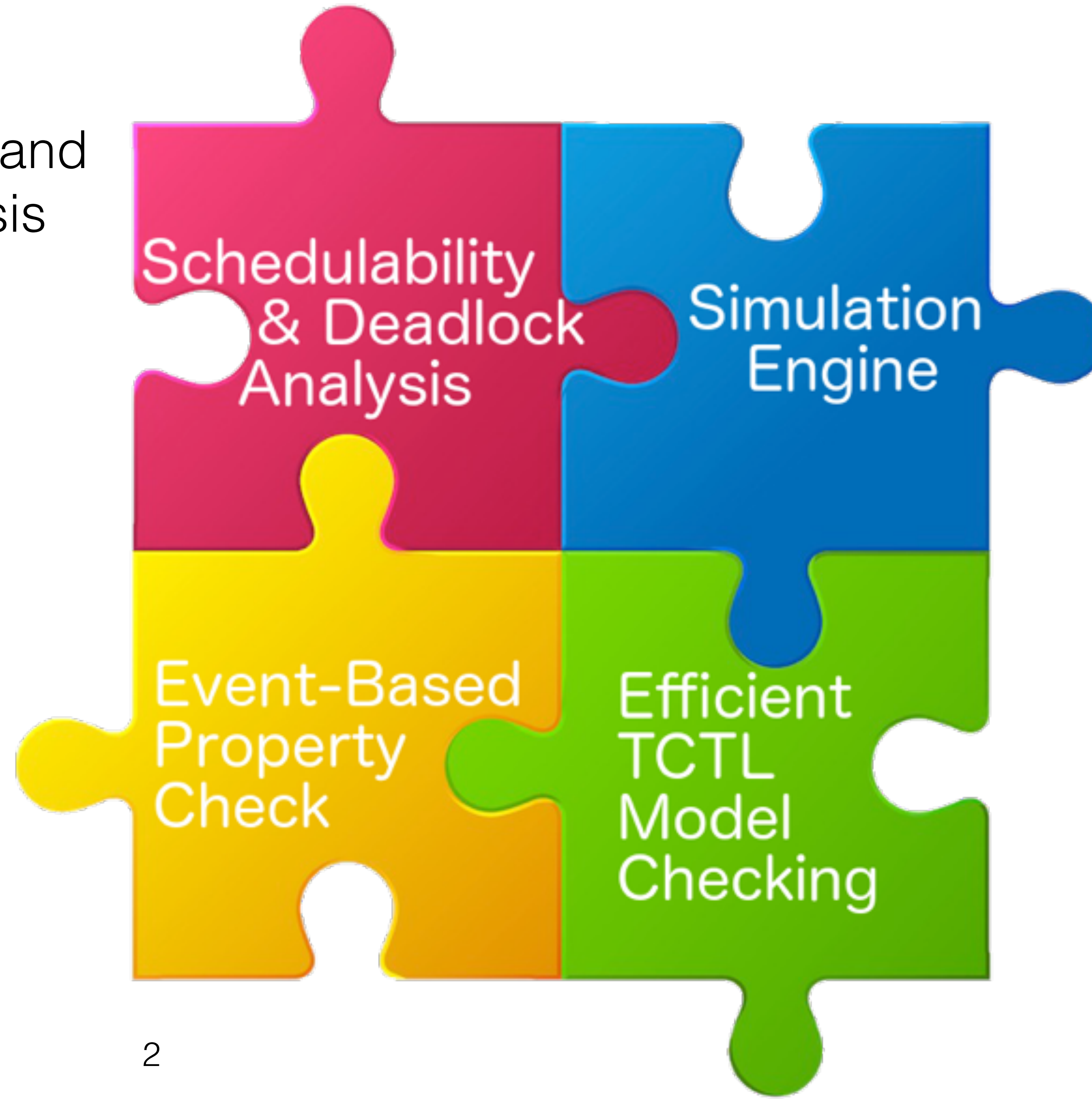
Analysis Support

- Floating Time Transition System for Schedulability and Deadlock-Freedom analysis
- Transforming to Erlang to simulate
- Event-Based Property Analysis using Simulation Engine of Timed Rebeca
- TCTL verification of Timed Rebeca models



Difficulties of TCTL Model Checking

- There is no efficient algorithm
- Only a subset of TCTL can be check efficiently
- Does having discrete time make it easier?
  - Duration transition graph (DTG) is a good alternative

Semantics Of Timed Rebeca in Timed Transition System

- The tuple $TTS = (S, s_0, Act, \rightarrow, AP, L)$ is the timed transition system of a Timed Rebeca model where:
  - S is a set of states $\left(\prod_{i \in \mathcal{I}} (V_{s,i}, B_{s,i}, pc_{s,i}, res_{s,i}), now_s\right)$
  - Act is a set of actions $\bigcup_{i \in \mathcal{I}} ((\mathcal{I} \times i \times \mathcal{M}_i) \times \mathbb{N} \times \mathbb{N}) \cup \{\tau\} \cup \mathbb{N}$
  - Three types of transitions
    - Taking an event
    - Internal transition
    - progress of time

Simple Timed Rebeca Model

```
reactiveclass RC1 (3) {
 knownrebecs {
  RC2 r2;
 }
 RC1() {
  self.m1();
 }
 msgsrv m1() {
  delay(2);
  r2.m2();
  delay(2);
  r2.m3();
  self.m1() after (10);
 }
}
```

```
reactiveclass RC2 (4) {
 knownrebecs {
  RC1 r1;
 }
 RC2() { }
 msgsrv m2() { }

 msgsrv m3() { }
}

main {
 RC1 r1(r2):();
 RC2 r2(r1):();
}
```

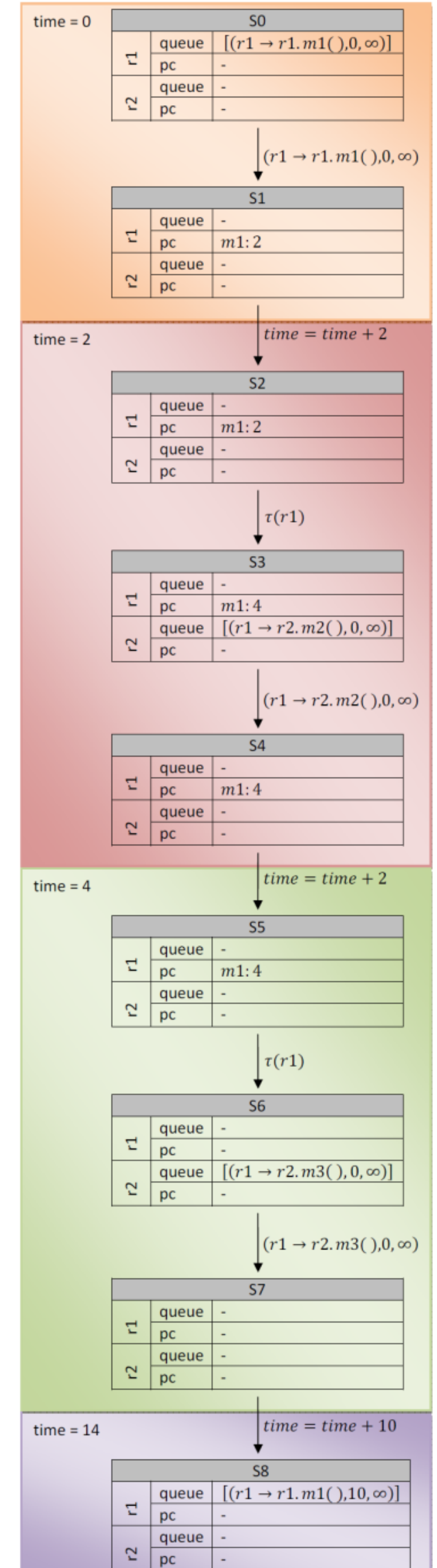
Simple Timed Rebeca Model

```
reactiveclass RC1 (3) {
 knownrebecs {
  RC2 r2;
 }
 msgsrv m1() {
  delay(2);
  r2.m2();
  delay(2);
  r2.m3();
  self.m1() after (
 }
}
```

```
reactiveclass RC2 (4) {
 knownrebecs {
  RC1 r1;
 }
 RC2() { }
 msgsrv m2() { }
 () { }
 ();
 ();
```

Line number as program counter

```
  msgsrv m1() {
1     delay(2);
2     r2.m2();
3     delay(2);
4     r2.m3();
5     self.m1() after (10);
  }
```


time = 0
S0
r1 queue [(r1 → r1.m1(),0,∞)]
pc -
r2 queue -
pc -
(r1 → r1.m1(),0,∞)
S1
r1 queue -
pc m1: 2
r2 queue -
pc -
time = time + 2
time = 2
S2
r1 queue -
pc m1: 2
r2 queue -
pc -
τ(r1)
S3
r1 queue -
pc m1: 4
r2 queue [(r1 → r2.m2(), 0, ∞)]
pc -
(r1 → r2.m2(),0,∞)
S4
r1 queue -
pc m1: 4
r2 queue -
pc -
time = time + 2
time = 4
S5
r1 queue -
pc m1: 4
r2 queue -
pc -
τ(r1)
S6
r1 queue -
pc -
r2 queue [(r1 → r2.m3(), 0, ∞)]
pc -
(r1 → r2.m3(),0,∞)
S7
r1 queue -
pc -
r2 queue -
pc -
time = time + 10
time = 14
S8
r1 queue [(r1 → r1.m1(),10,∞)]
pc -
r2 queue -
pc -

```
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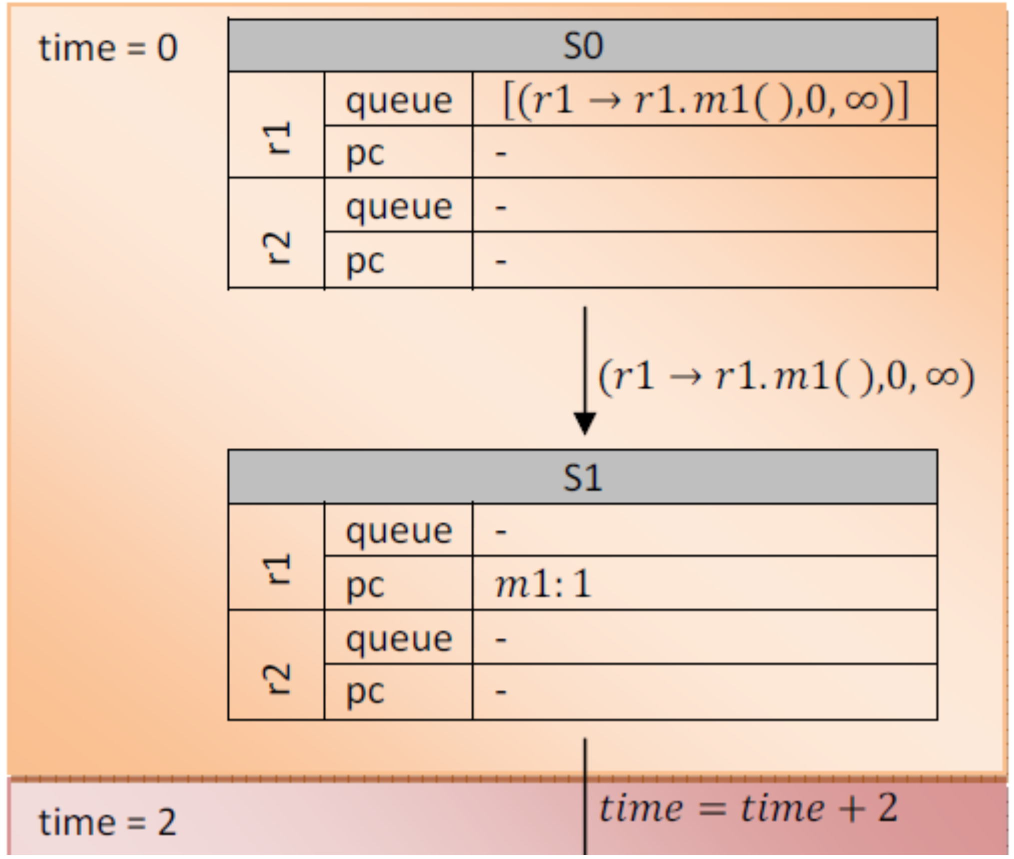

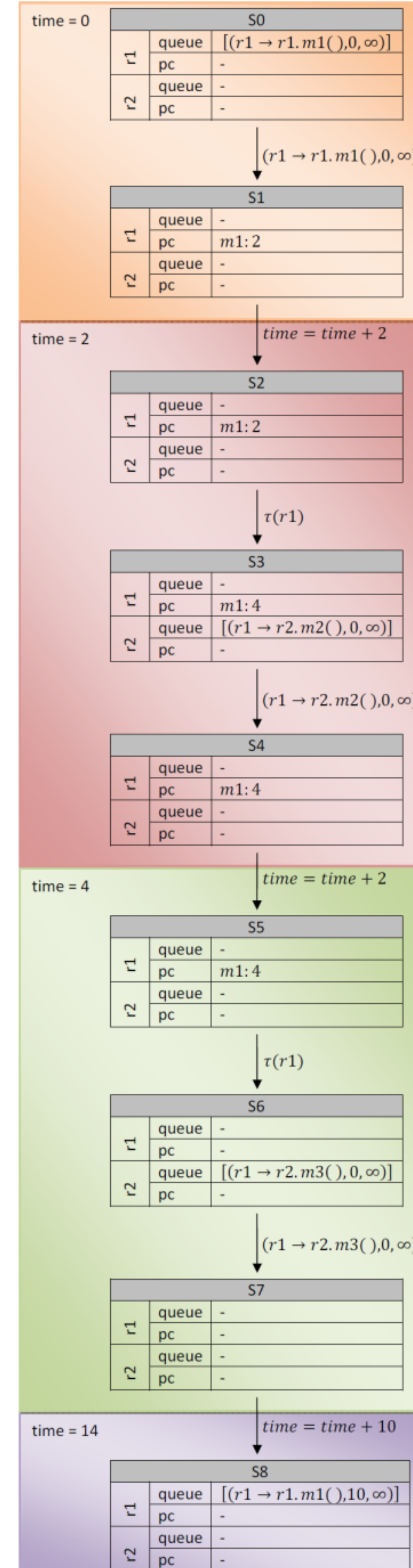

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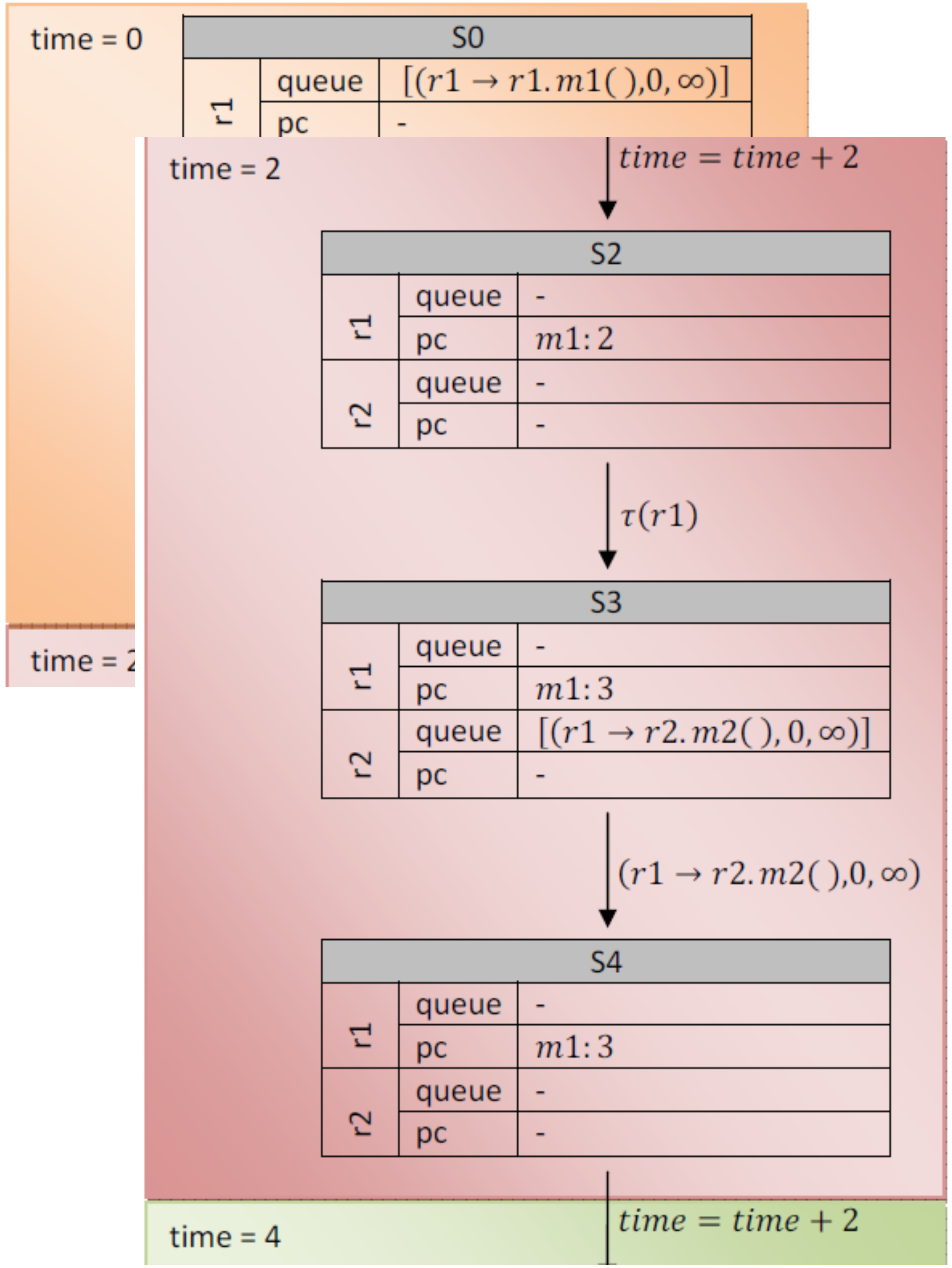

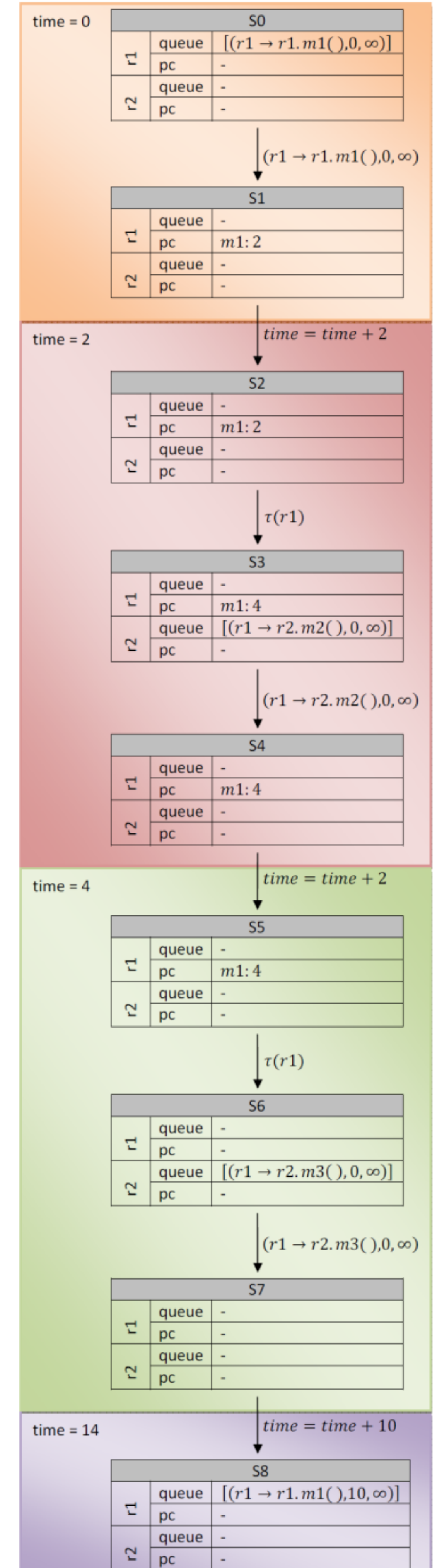

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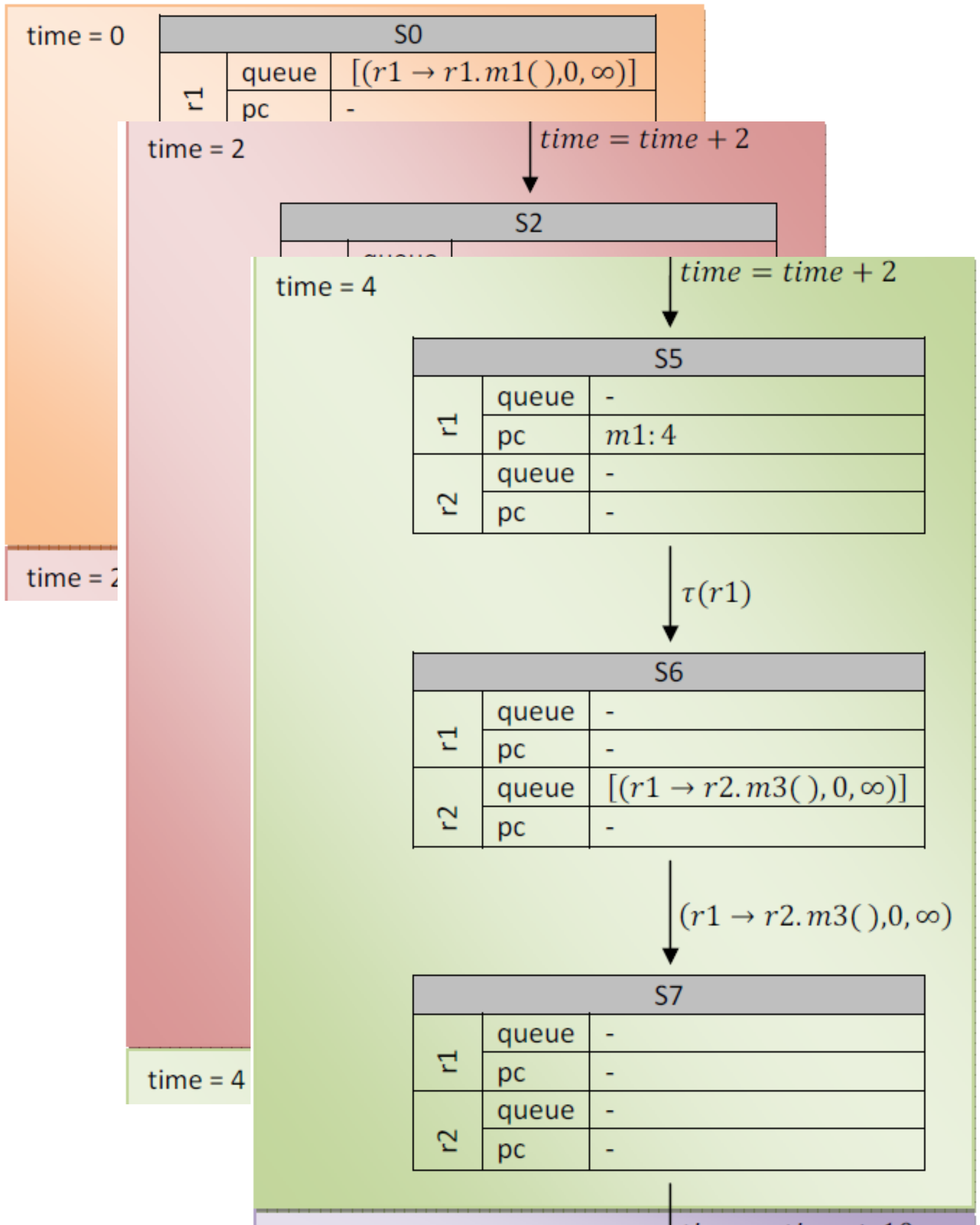
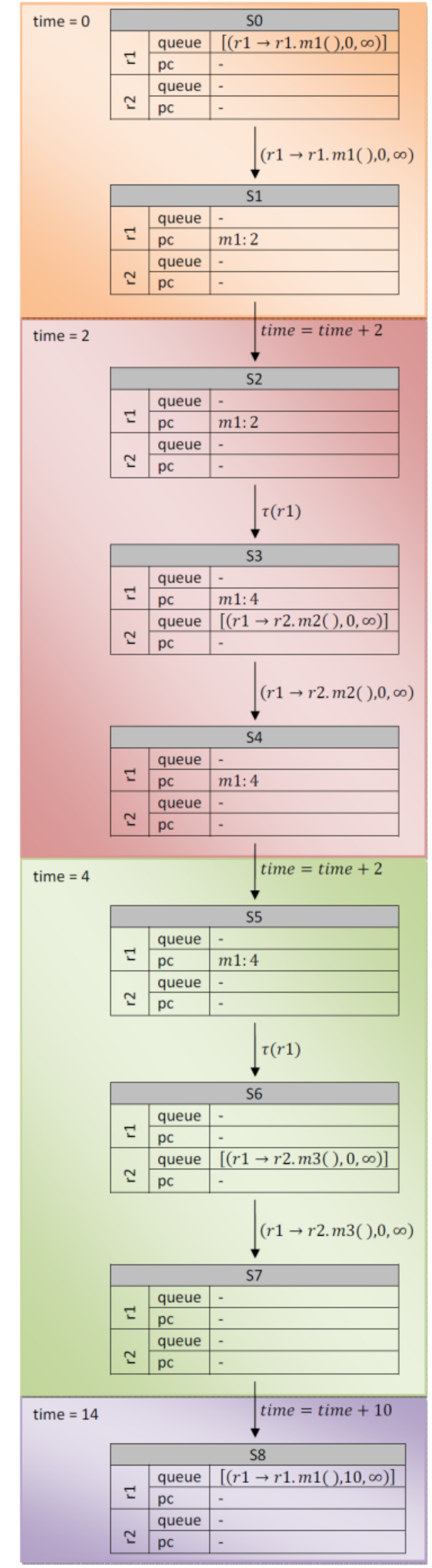
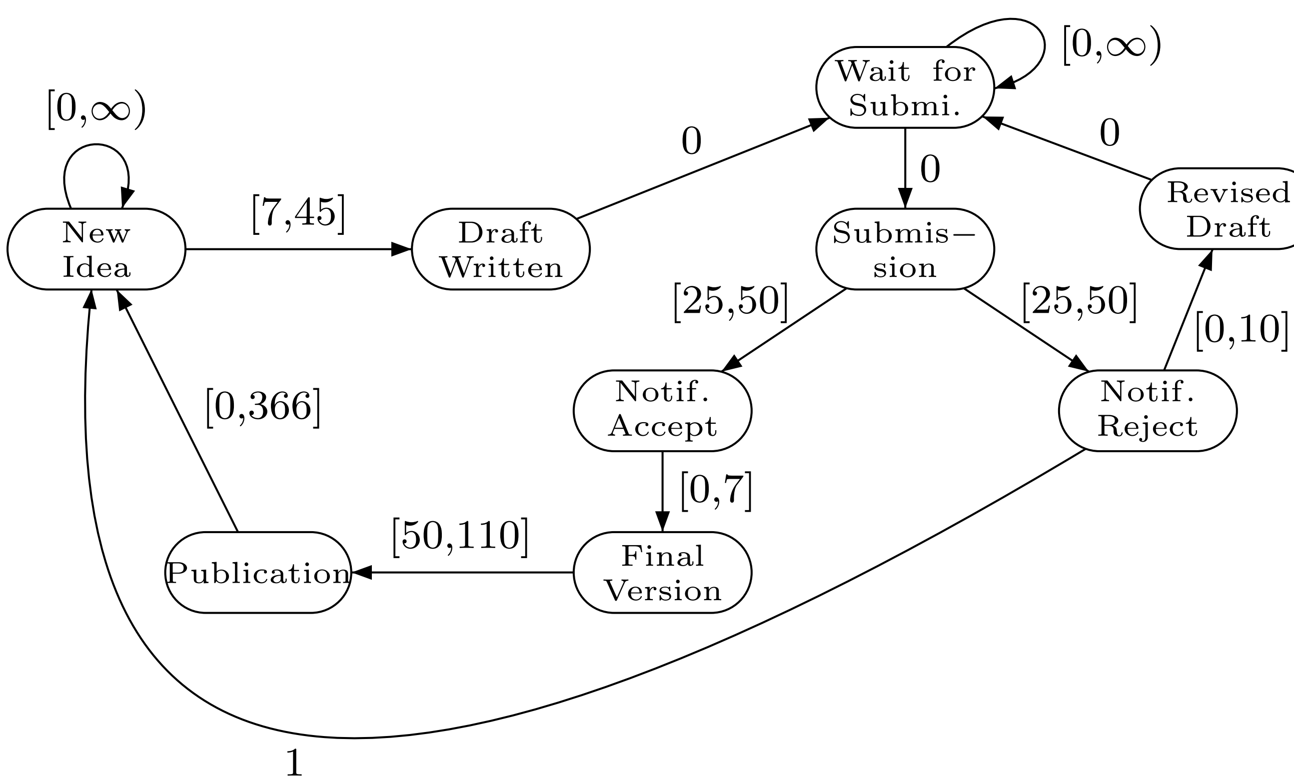


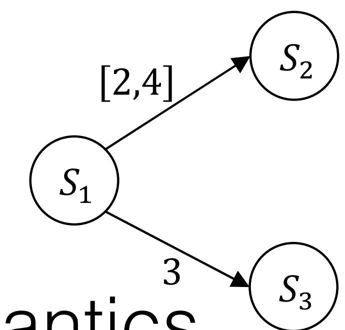


Duration Transition Graph

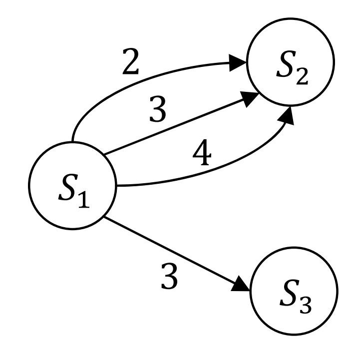
- Example of a DTG



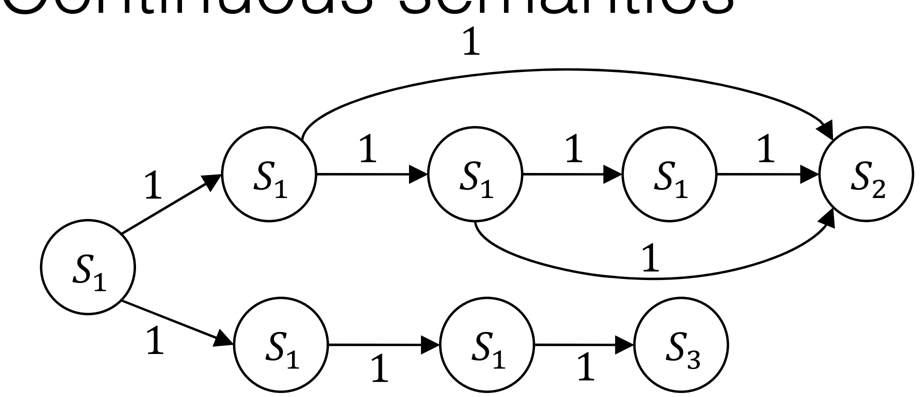
- Two different semantics



- Jump semantics



- Continuous semantics



TCTL Model Checking for DTG

- There is a polynomial time model checking algorithm for TCTL<> properties but model checking of $TCTL_=$ is NP-Complete
- Combination of CTL model checking and shortest/ longest path search
  - Try to find a set of states which satisfy a given TCTL formula without any timed constraint
  - Check timed constraints

How the Algorithm Works for $\exists \Phi_1 \mathbf{U}^{\leq c} \Phi_2$

- Assume $DTG^{sub}_{\mathcal{M}} = (S', s'_0, Act, \rightarrow', AP', L')$ as a reduced version of $DTG_{\mathcal{M}}$ which satisfies $\exists \Phi_1 \mathbf{U} \Phi_2$

- Any state s in $DTG^{sub}_{\mathcal{M}}$ satisfies the time version of the formula if and only if there is path from s to state s' such that the length of path is less than the time constraint.

- This can be checked using $O(n^2)$ algorithm

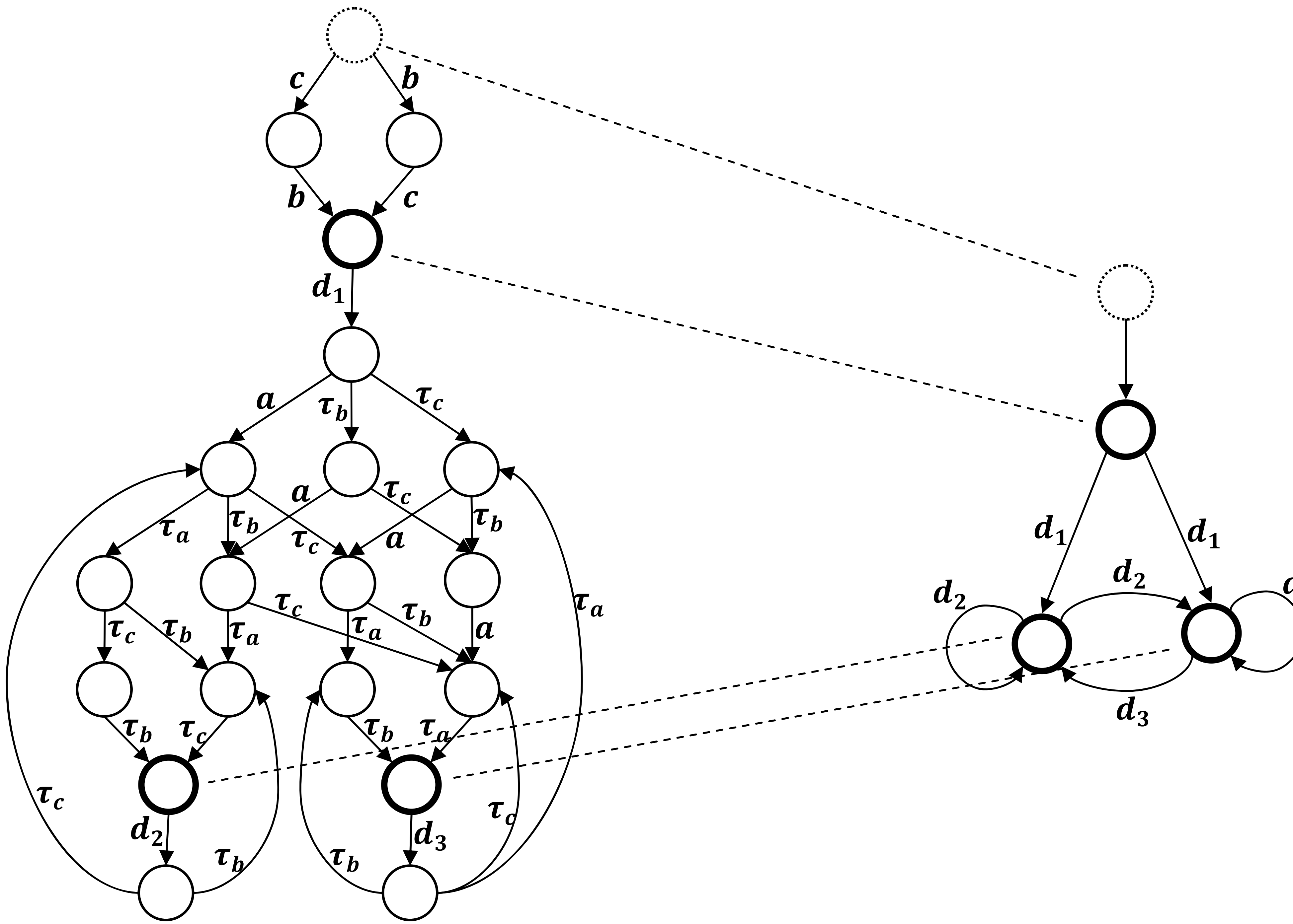
$TCTL_{<>}$ Model Checking of Timed Rebeca Models

- TTS of a Timed Rebeca model is a DTG
  - All the transitions are assumed to be internal transitions (no action label) with zero time duration
  - Progress-of-Time transitions are assumed as transitions with tight duration
- Model checking Timed Rebeca models against $TCTL_{<>}$ properties is possible in $O(n^2)$

A New Reduction Technique

- There are some transient states in the state space (Residual time is zero in transient states)
- Transient behavior is not interested in some systems
  - It is possible to eliminate transient states from the state space
  - The overhead of reduction must be smaller than the gain of model checking on smaller state space

Example of How Reduction Technique Works



Cost Free Reduction Technique!

- Timed Rebeca models must be checked to be Zeno free
- It can be checked by using DFS search to detect cycles without progress-of-time states
    - Timed model is discrete in Timed Rebeca

Algorithm 1: *ZenoFree*(s) analyzes the model for Zeno-freedom.

Input: State s of a timed transition system T
Output: The part of T reachable from s is Zeno-free or not

$visited \leftarrow \emptyset$
forall the *state* $s' \in Successors(s)$ **do**
  if $s' \notin visited$ **then**
    $visited \leftarrow visited \cup \{s'\}$
    $recStack(s') \leftarrow true$
    if $ZenoFree(s') = false$ **then**
      return $false$
    $recStack(s') \leftarrow false$
  else
    if $recStack(s') = true \wedge now(s') = now(s)$ **then**
      return $false$
return $true$

Cost Free Reduction Technique!

- Reduction technique requires BFS traversal to figure out the set of next level progress-of-time states of each state
- Combination of BFS and DFS is required
  - Explore the states among two consequent progress-of-time states by bounded-DFS
  - Then go to the next level

Algorithm 2: *BoundedZenoCheck*(s) makes sure that there is no cycle among reachable states from s to *npts*(s). Also sets the nearest progress-of-time states of all the reachable states from s to *npts*(s).

```
Input: State s of a timed transition system
Output: The bounded reachable part of the transition
        system is Zeno-free or not
visited ← ∅
forall the state s′ ∈ Successors(s) do
    if s′ ∉ visited then
        visited ← visited ∪ {s′}
        if s′ is progress-of-time then
            //DFS has reached one of its boundaries
            npts(s) ← npts(s) ∪ {s′}
        else
            if now(s) = now(s′) then
                recStack(s′) ← true
                childsNPTS ← BoundedZenoCheck(s′)
                recStack(s′) ← false
                if childsNPTS = ∅ then
                    return ∅
                else
                    npts(s) ← npts(s) ∪ childsNPTS
            else
                //Back-edge is detected
                npts(s) ← npts(s) ∪ npts(s′)
    else
        if recStack(s′) = true then
            //There is cycle which shows Zeno behavior
            return ∅
return npts(s)
```

Algorithm 3: *FTS*($TTS_{\mathcal{M}}$) creates the corresponding FTS of a given TTS or returns $\emptyset$ in the case of Zeno behavior in the model.

```
Input: Timed transition system
       TTS_M = (S, s_0, Act, →, AP, L)
Output: Folded timed transition system of M
S′ ← {s_0}
Act′ ← ∅
↪ ← ∅
AP′ ← AP
L′ ← L
openBorderStates ← {s_0}
nextLevelStates ← ∅
repeat
    while openBorderStates ≠ ∅ do
        remove s from openBorderStates
        NPTS ← BoundedZenoCheck(s)
        if NPTS = ∅ then
            return ∅
        else
            nextLevelStates ← nextLevelStates ∪ NPTS
            S′ ← S′ ∪ NPTS
            foreach s′ ∈ NPTS do
                ↪ ← ↪ ∪ {(s, act′, s′)}
                Act′ ← Act′ ∪ {act′}
    openBorderStates ← nextLevelStates
    nextLevelStates ← ∅
until openBorderStates ≠ ∅
return (S′, s_0, Act′, ↪, AP, L)
```

More Than Smaller State Space

- Using reduction technique, we are able to efficiently check the model for $TCTL_=$ properties

- There is a pseudo-polynomial algorithm for finding exact path among two nodes of the graph

  - Preprocessing a graph to uniforms the weights of edges by an $O(W^2\, n^3)$ algorithm

  - Looking for exact path by an $O(|k|\, min\{|k|,w\}\, n^2)$ algorithm

Polynomial Algorithm for Model Checking of $TCTL_{=}$ Properties

- All the weights in TTS are positive integers, so there is no need for an $O(W^2\ n^3)$ relaxation algorithm
- In model checking problem, “k” related to the maximum bound number which is used in $TCTL_{=}$ formula
  - In many cases “k” can be assumed as an small constant
  - The complexity of finding exact path is reduced to $O(|k|^2\ n^2)= O(n^2)$

Experimental Results

- Four different models are used
- 90% reduction in the state space size in some cases

Problem	Size	State Space Size	Reduced State Space Size	Percentage of Reduction
Ticket Service	**2 customers**	77	10	87%
	3 customers	360	39	89%
	4 customers	1825	184	90%
	5 customers	10708	1045	90%
	6 customers	73461	6996	90%
	7 customers	581962	54019	91%
WSAN	-	1920	818	57%
Yarn	-	533	172	68%
8x8 NoC	-	74192	6068	92%

Conclusion

- We can model check Timed Rebeca models against $TCTL_{<>}$ properties in polynomial time.
- A combination of checking for Zeno freedom and reduction technique is proposed
  - Reducing the state space size without overhead
- We propose an approach which works for model checking of wide range of $TCTL_{=}$ formulas in polynomial time

Thank you