Online Quantitative Timed Pattern Matching with Semiring-Valued Weighted Automata

Masaki Waga[1,2,3]

National Institute of Informatics[1], SOKENDAI[2],
JSPS Research Fellow[3]

27 August 2019, FORMATS 2019

This work is partially supported by JST ERATO HASUO Metamathematics for Systems Design Project (No. JPMJER1603), by JSPS Grants-in-Aid No. 15KT0012 & 18J22498

Monitoring

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Why Monitoring?

Exhaustive formal method

(e.g. model checking, reachability analysis)

- The system is correct/incorrect for any execution
- We need system model (white box)
- Scalability is a big issue

Monitoring

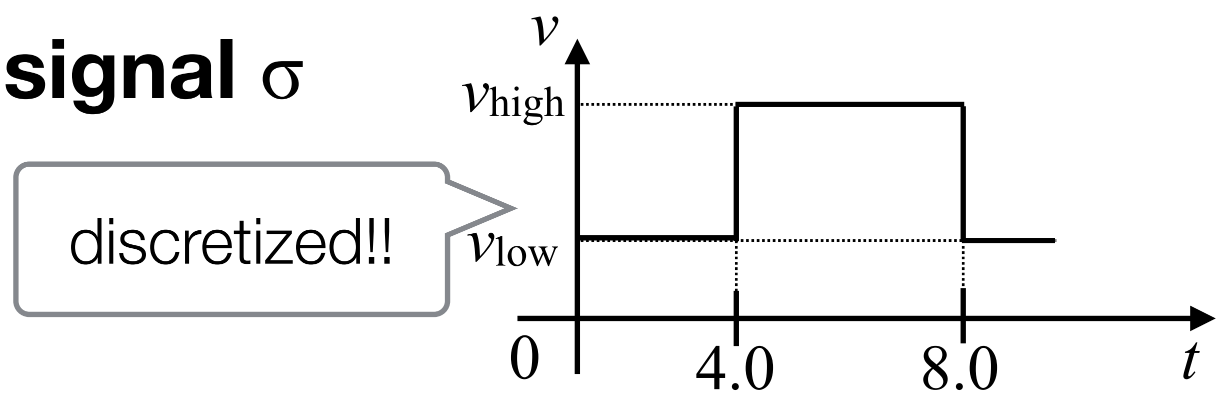
- The system is correct/incorrect for **the given** execution
  - **data-driven** analysis
- We do not need system model (black box is OK)
- Usually scalable

(Qualitative) timed pattern matching

[Ulus+, FORMATS'14]

Input

- **Finite-valued signal** σ
  - System ***log***
    - e.g.,



- **Real-time spec.** $\mathcal{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high for > 1 sec.

Output

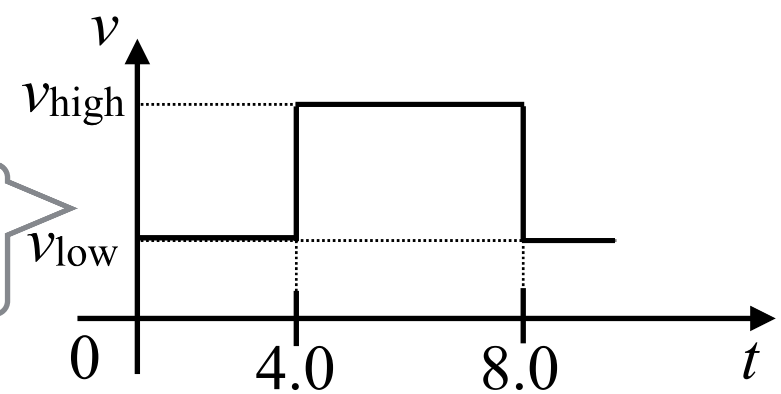
- **All** the subsignals σ([t,t′)) of the ***log*** satisfies the ***spec.***
  - e.g., σ([4.0,8.0)), σ([6.0,8.0)), σ([6.0,7.5)), …

(Qualitative) timed pattern matching

Input [Ulus+, FORMATS'14]

- **Finite-valued signal σ**
  - System ***log***
    - e.g.,

discretized!!



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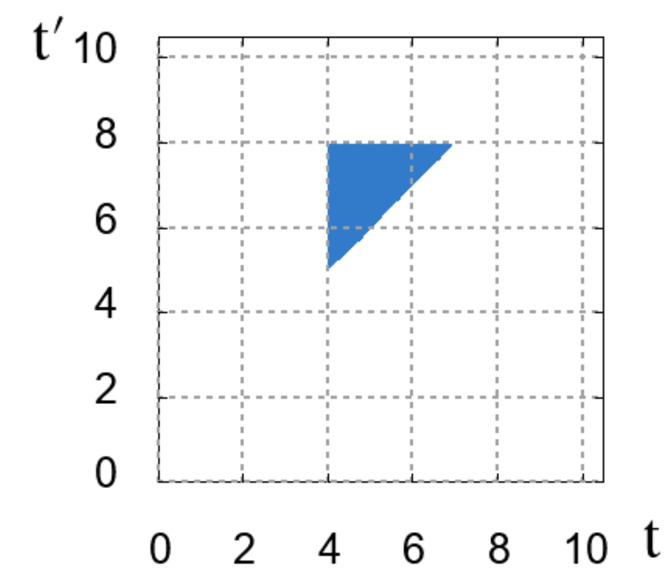

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M. Waga (NII)

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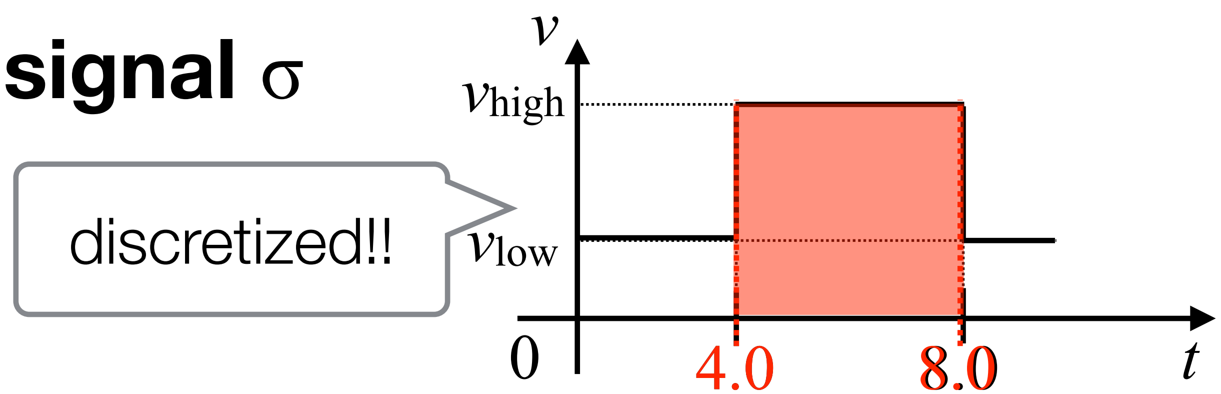

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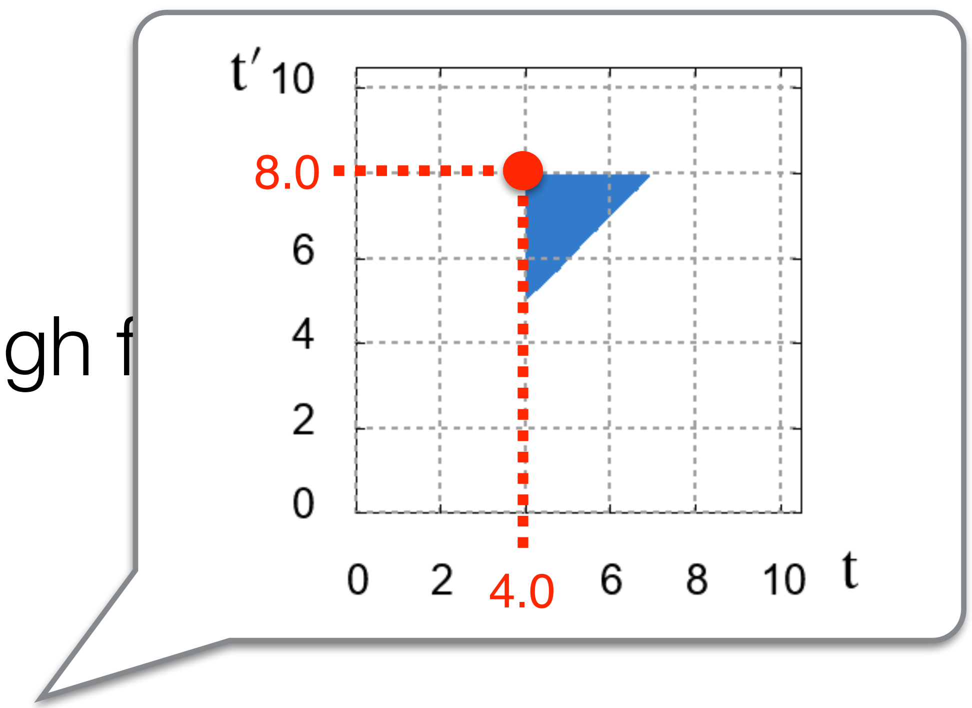

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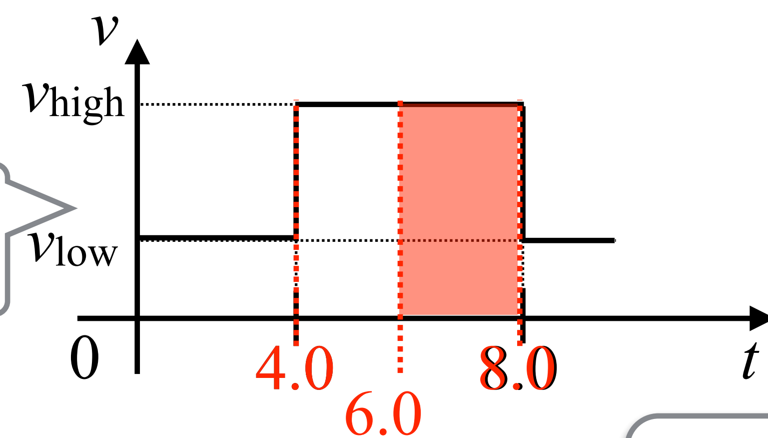

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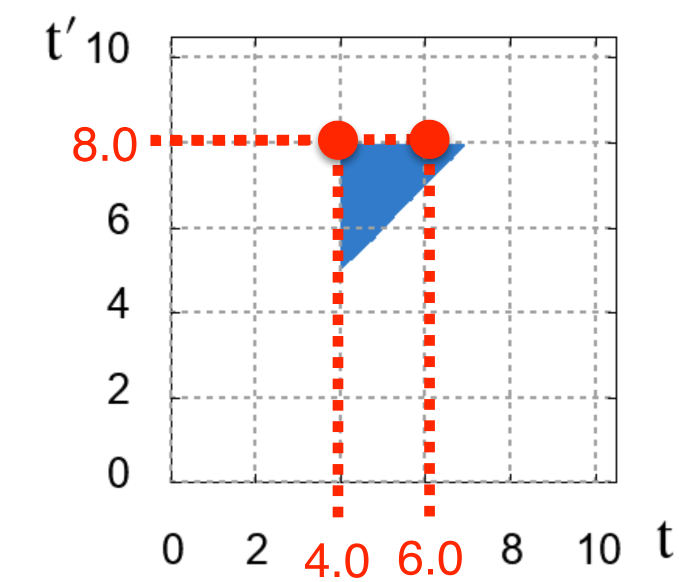

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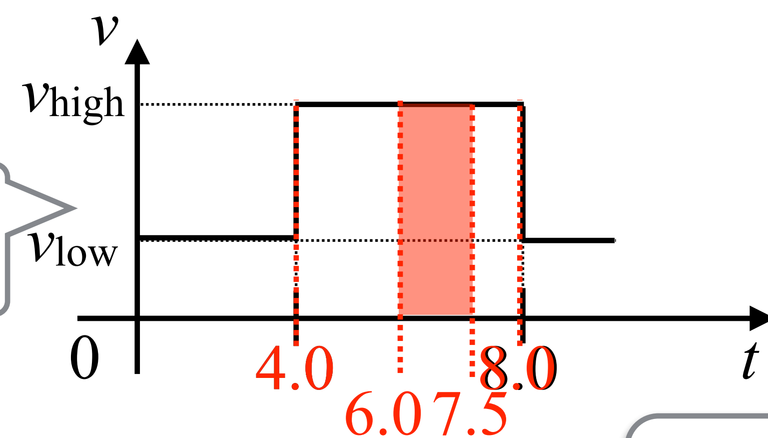

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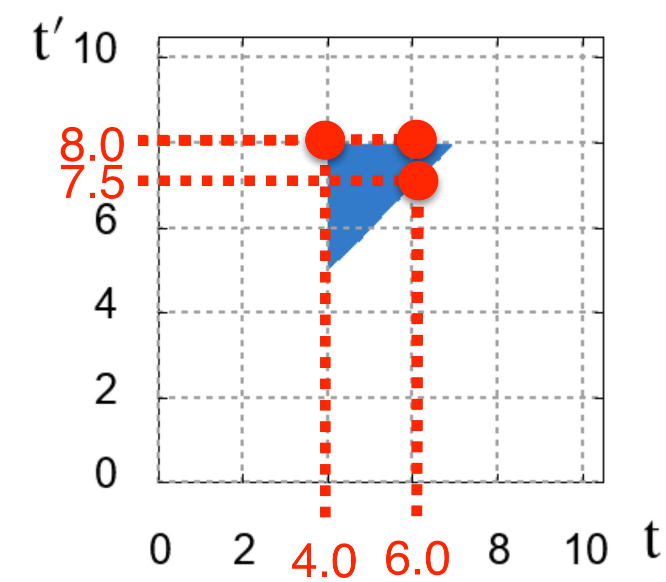

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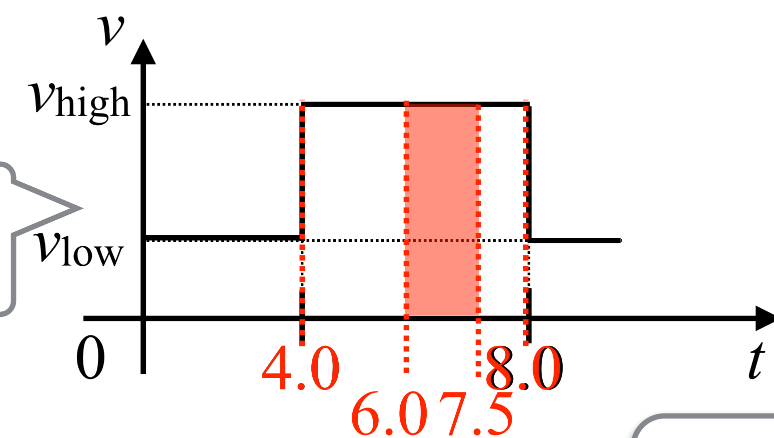

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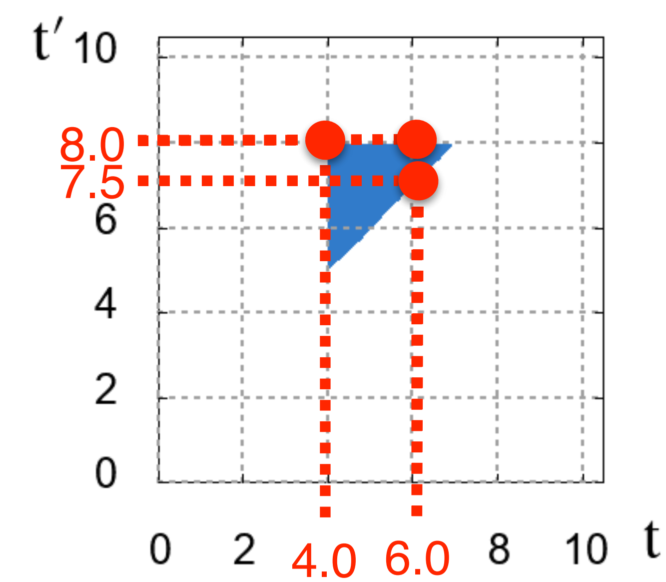

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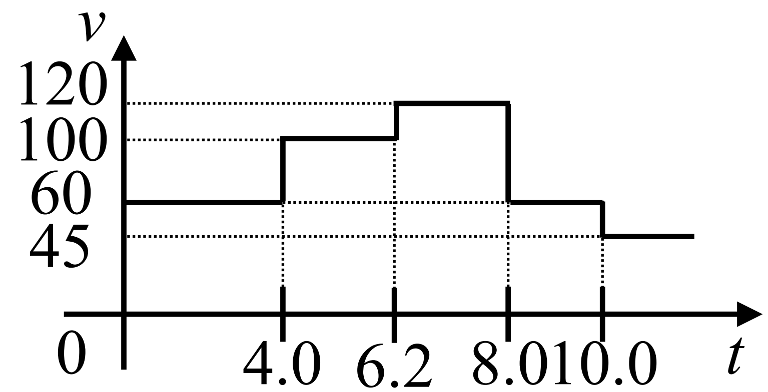
We want to know **how robustly** the spec. is satisfied!!

Quantitative timed pattern matching

Input [Bakhirkin+, FORMATS'17]

- ***Real*-valued piecewise-constant signal** σ
  - System ***log***
    - e.g.,



- **Real-time spec. with signal constraints** $\mathcal{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep **> 80** for > 1 sec.

Output

- **How robustly**, each subsignals $\sigma([t,t'))$ of the ***log***, satisfies the ***spec.***
  - e.g., $\mathcal{M}(\sigma, \mathcal{W})(2.0,4.0)$ = -20, $\mathcal{M}(\sigma, \mathcal{W})(6.5,7.8)$ = 40, …

satisfaction degree of $\mathcal{W}$ for $\sigma([2.0,4.0))$

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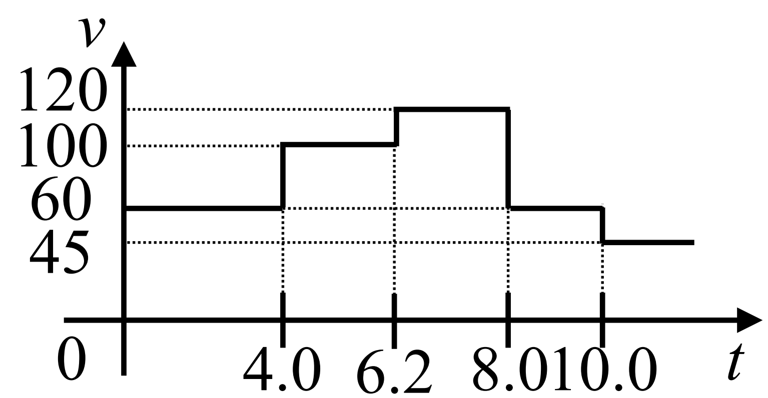

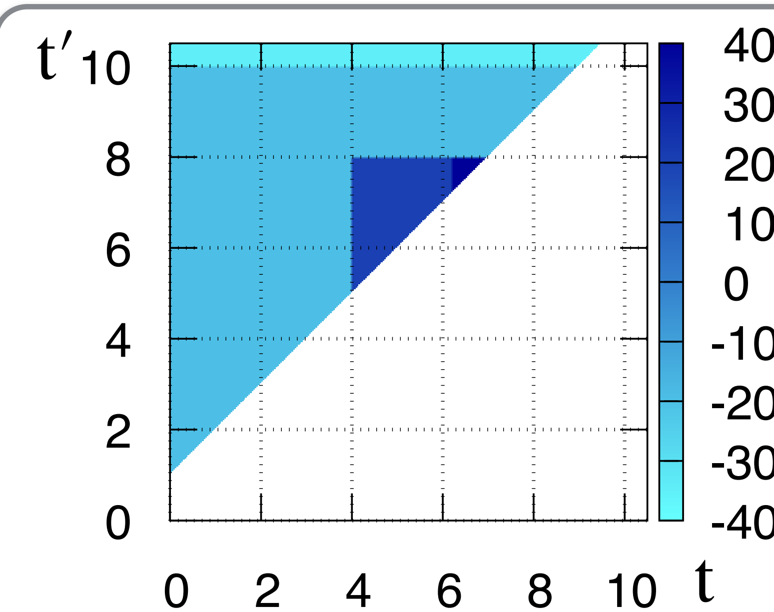

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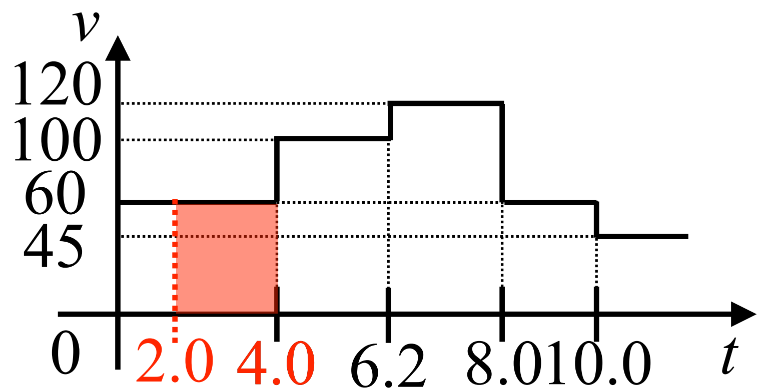

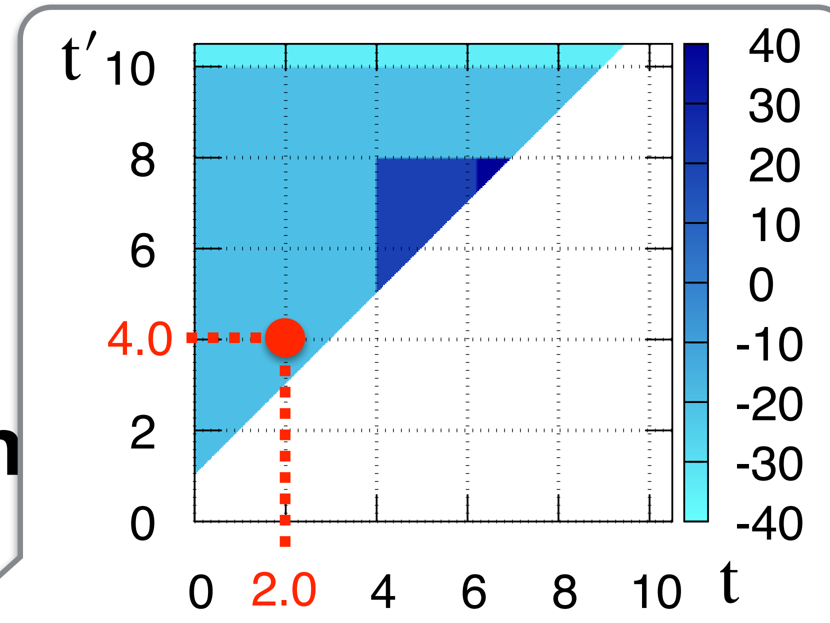

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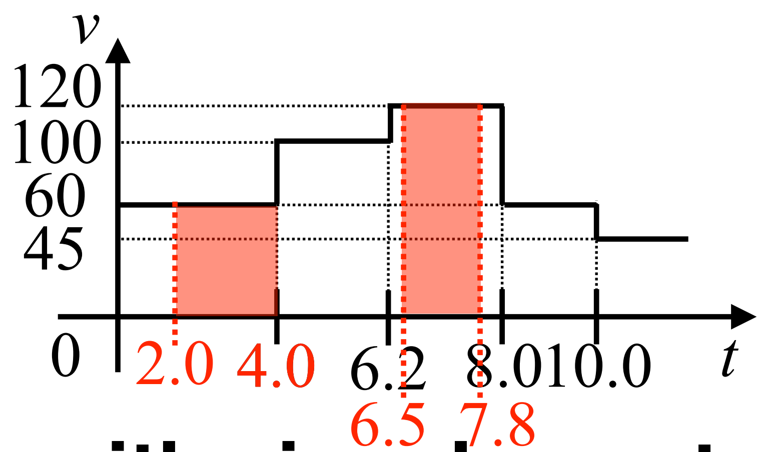

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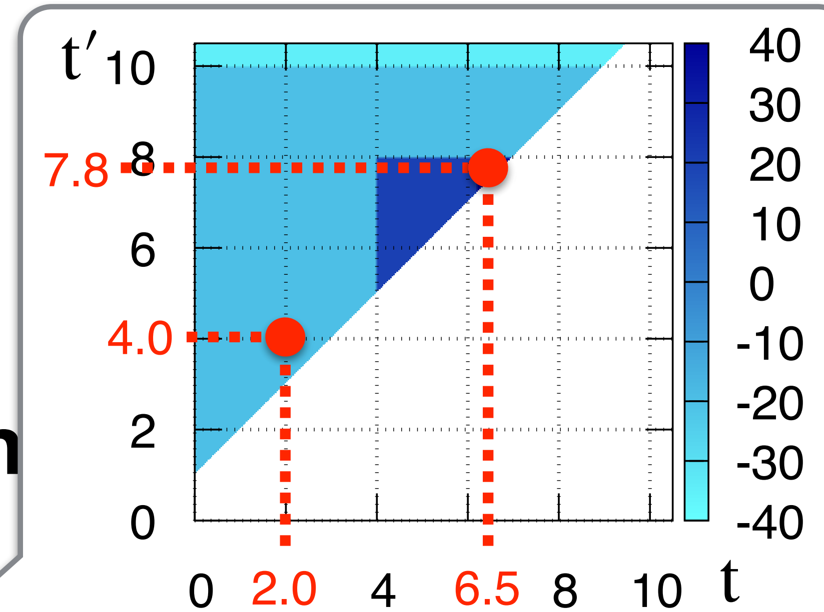

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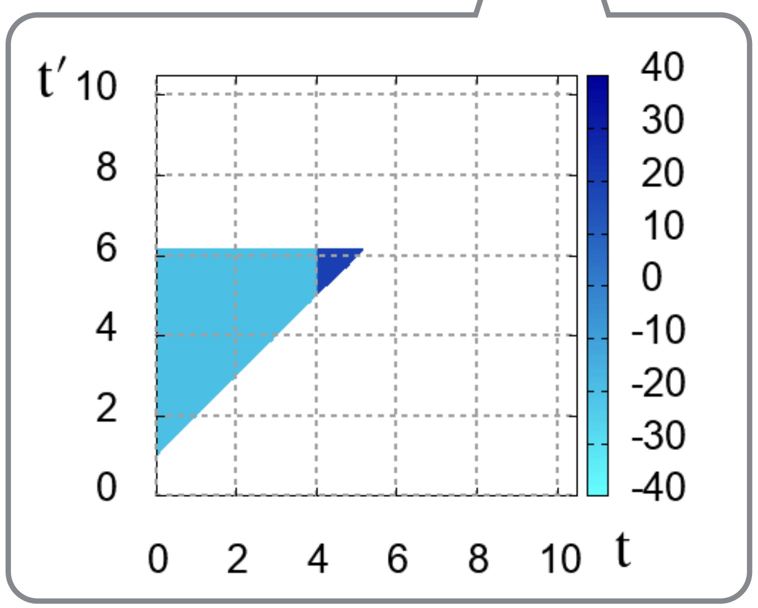
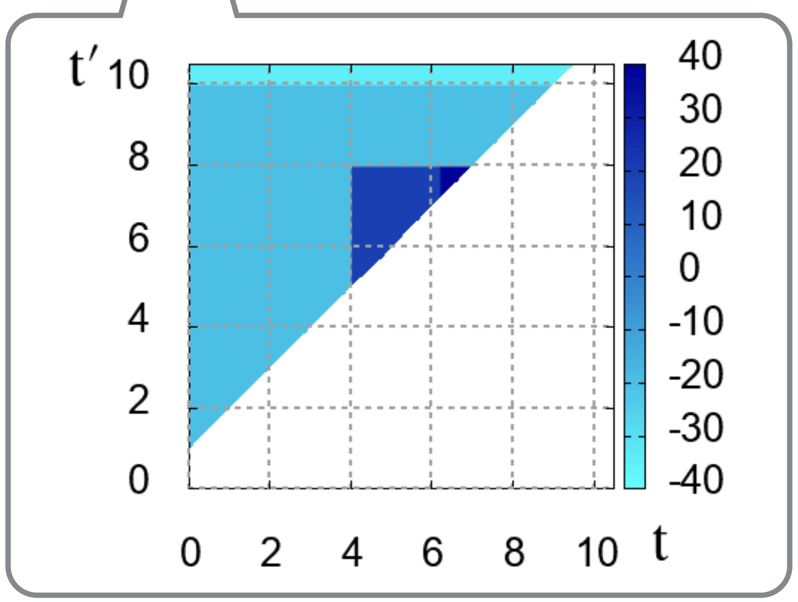
Online Pattern Matching

- After reading the prefix signal σ' of $\sigma = \sigma' \cdot \sigma''$, we obtain the partial result $\mathcal{M}(\sigma', \mathcal{W})$ of $\mathcal{M}(\sigma, \mathcal{W})$
  - Important in practice





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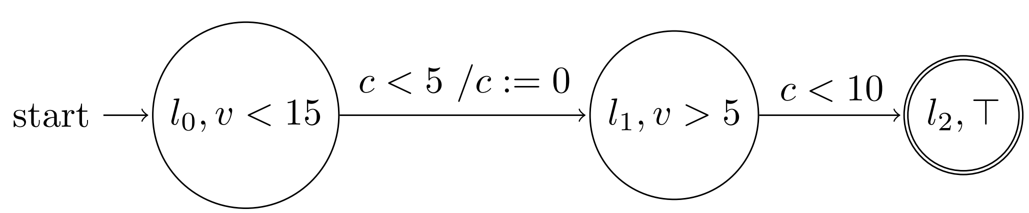
Timed symbolic weighted automata (TSWA)

- New formalism for spec.
  - Automata structure is good for online monitoring
- Generality of semiring (same as the usual WFA)



$$\kappa_r(u, (a_1 a_2 \ldots a_m)) = \inf_{i \in \{1,2,\ldots,n\}} \kappa_r(u, (a_i))$$

$$\kappa_r(\bigwedge_{i=1}^{n} (x_i \bowtie_i d_i), (a)) = \inf_{i \in \{1,2,\ldots,n\}} \kappa_r(x_i \bowtie_i d_i, (a)) \text{ where } \bowtie_i \in \{>, \geq, \leq, <\}$$

$$\kappa_r(x \succ d, (a)) = a(x) - d \quad \text{where } \succ \in \{\geq, >\}$$

$$\kappa_r(x \prec d, (a)) = d - a(x) \quad \text{where } \prec \in \{\leq, <\}$$

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

Contribution

- Introduced **timed symbolic weighted automata (TSWA)**
  - **TSWA:** timed automata with signal constraints (TSA)

    Automata structure

    \+ semiring-valued weight function

    Quantitative semantics

- Gave **online** algorithm for quantitative timed pattern matching

- Implementation + experiments → **Scalable**!!

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Related Works

	Qualitative	Quantitative
Offline	[Ulus+, FORMATS'14] (TRE)	[Bakhirkin+, FORMATS'17] (Signal RE)
Online	[Ulus+, TACAS'16], [Bakhirkin+, FORMATS'18] (TRE & TA)	**[Contribution] (TSWA)**

Only "Robust" Semantics
[Fainekos & Pappas, TCS'09]

↓

Any Semantics defined by **semiring-valued weight function**

Timed automata → Timed automata with **signal constraints**

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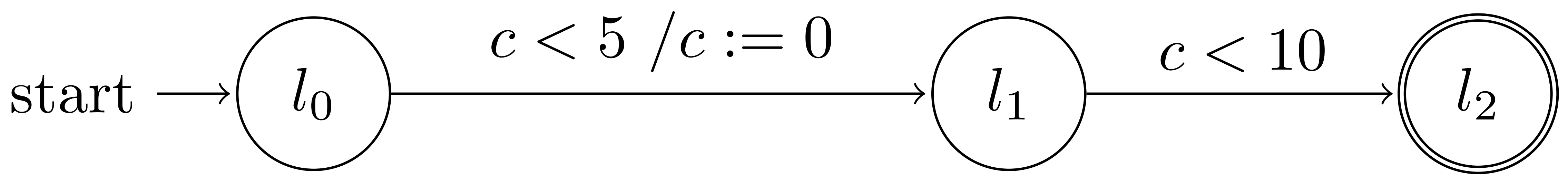
Outline

- Motivation + Introduction
- Technical Part
  - Timed symbolic weighted automata (TSWA)
    - TSWA: TA with signal constraints + weight function
  - Quantitative monitoring/timed pattern matching algorithm
    - Idea: zone construction with weight
- Experiments

TSWA: TA with signal constraints + weight function

Timed Automaton (TA)



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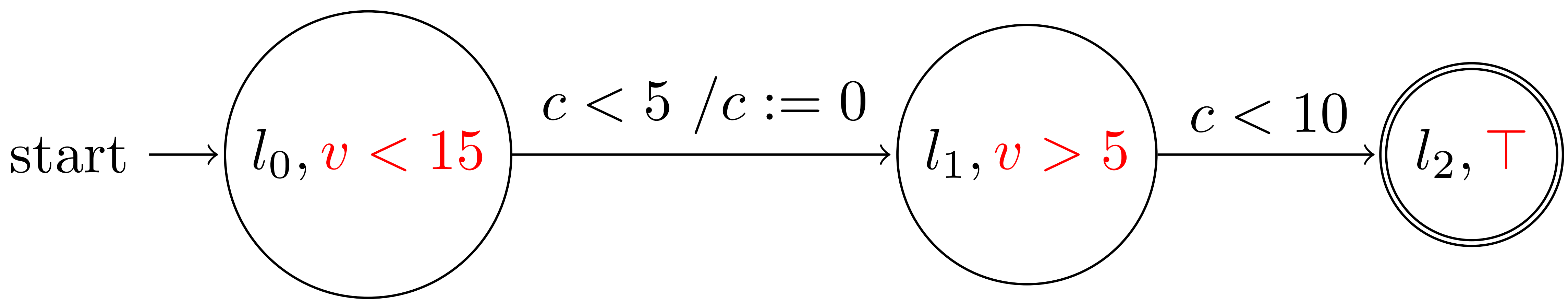
TSWA: TA with signal constraints + weight function

Timed Symbolic Automaton (TSA)



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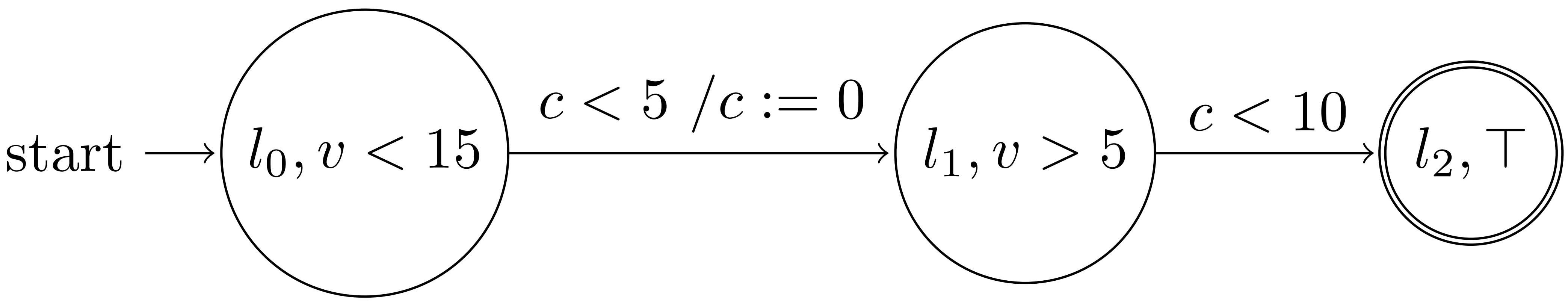
TSWA: TA with signal constraints + weight function

Timed Symbolic Weighted Automaton (TSWA)



+

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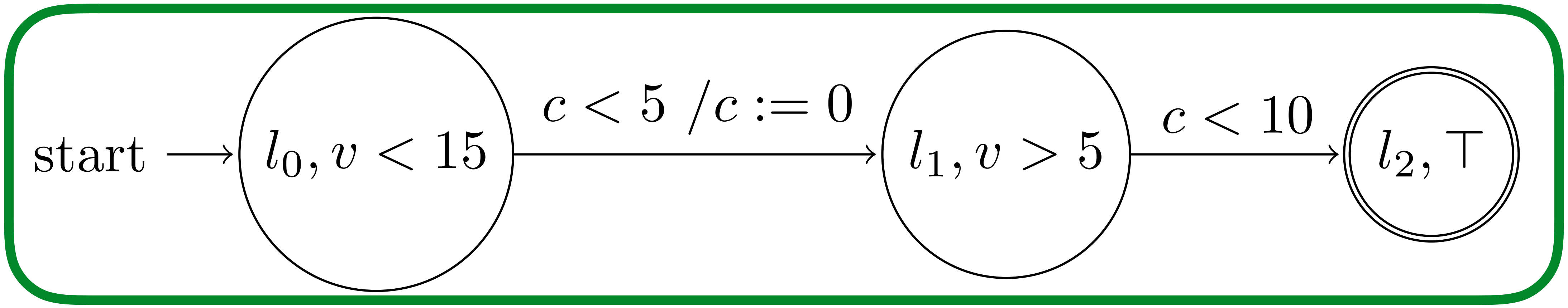
TSWA: TA with signal constraints + weight function

Timed Symbolic Weighted Automaton (TSWA)



Automata structure

+

Quantitative semantics

$$\kappa_r\big(u, (a_1 a_2 \dots a_m)\big) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(u, (a_i))$$

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Weight function

$$\kappa\colon \Phi(X, \mathbb{D}) \times (\mathbb{D}^X)^{\circledast} \to S$$

Constraints on signal values at the location

Sequence of signal values at the location

Semiring value

- $\kappa(\Lambda(l),u)$: weight for the stay at l with signal values u
- Semiring: set S with accumulating operators $\oplus$ and $\otimes$
- We can use any complete and idempotent semiring

Semantics: Weighted TTS

- l: location
- v: clock valuation
- t: absolute time
- u: sequence of signal values after the latest discrete transition

$$\rightarrow (l, v, t, u) \xrightarrow{3.0} (l, v+3, t+3, u \circ u') \xrightarrow{e} (l', v', t+3, \varepsilon)$$

$\kappa(\Lambda(l), u \circ u')$

$$(l, v, t, u) \xrightarrow{4.0} (l, v+4, t+4, u \circ u'') \xrightarrow{e} (l', v'', t+4, \varepsilon)$$

$\kappa(\Lambda(l), u \circ u'')$

⋮

continuous transitions

discrete transitions

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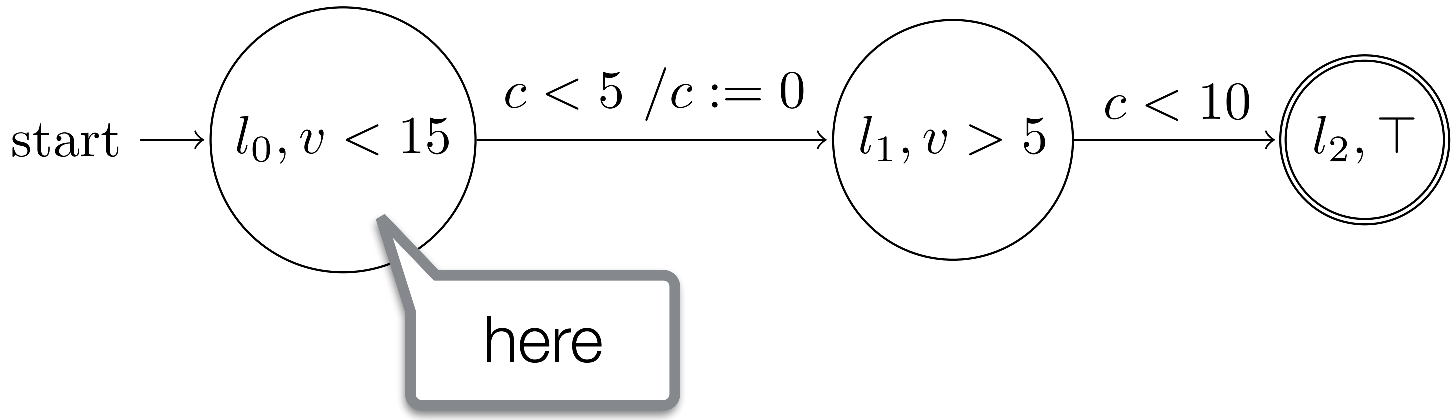
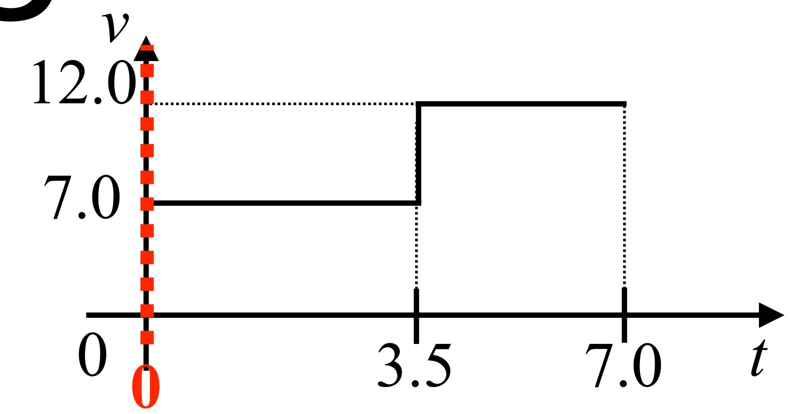
One path in Weighted TTS





→(l_0, c=0, 0,ε)

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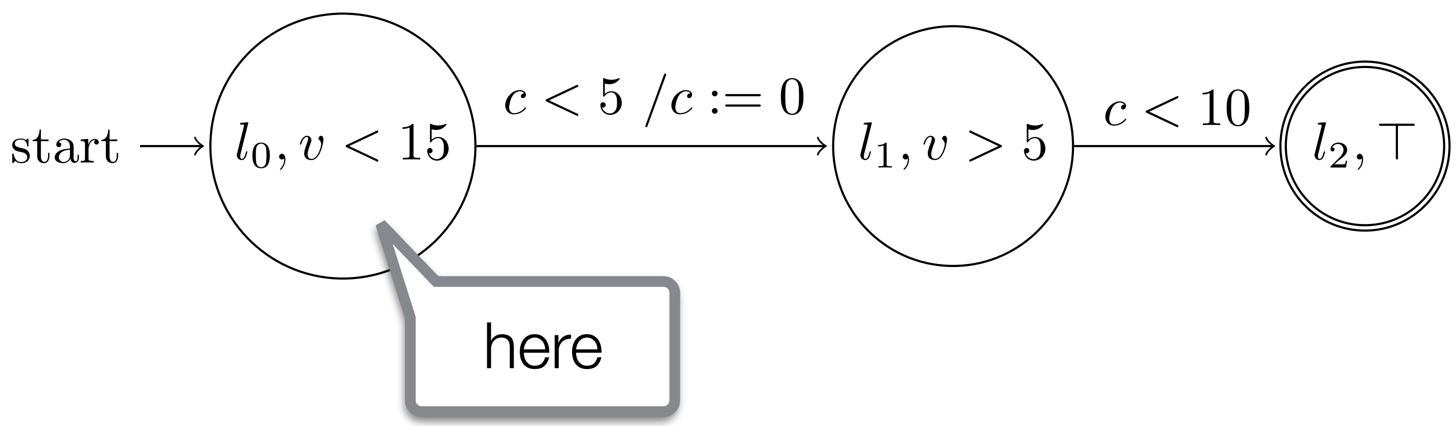
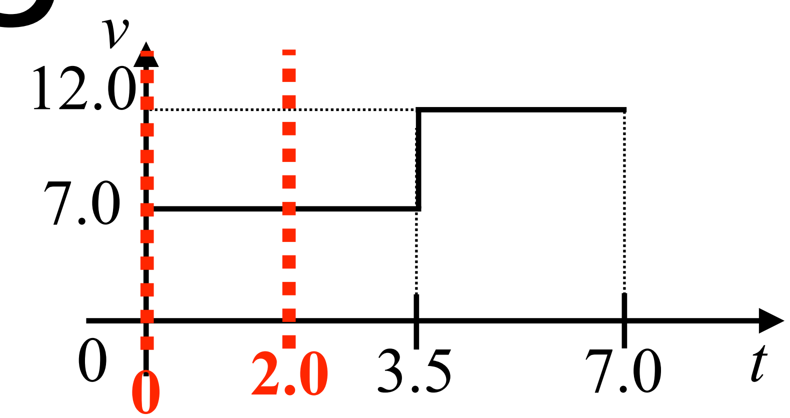
One path in Weighted TTS





$$\rightarrow (l_0,\ c{=}0,\ 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0,\ c{=}2,\ 2,\ \{v = 7\})$$

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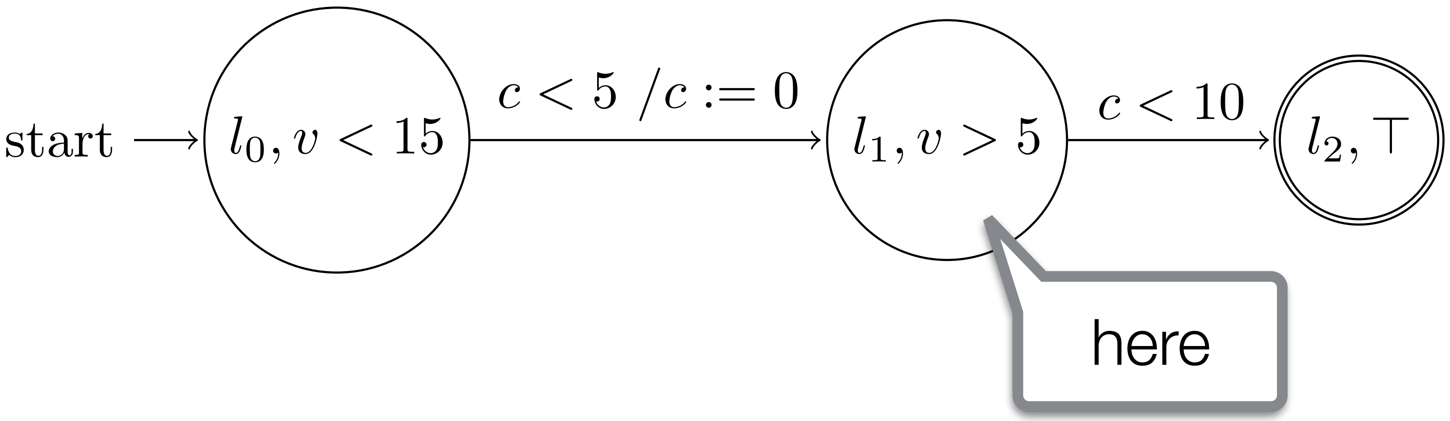
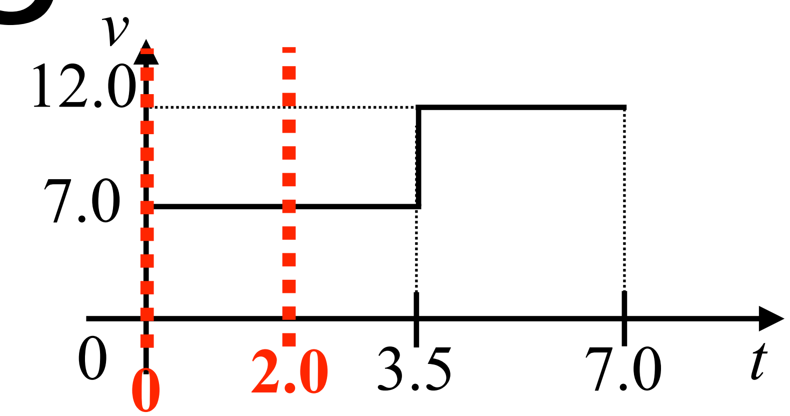
One path in Weighted TTS





$$\rightarrow (l_0,\ c{=}0,\ 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0,\ c{=}2,\ 2,\ \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v{=}7\})]{e} (l_1,\ c{=}0,\ 2,\ \varepsilon)$$

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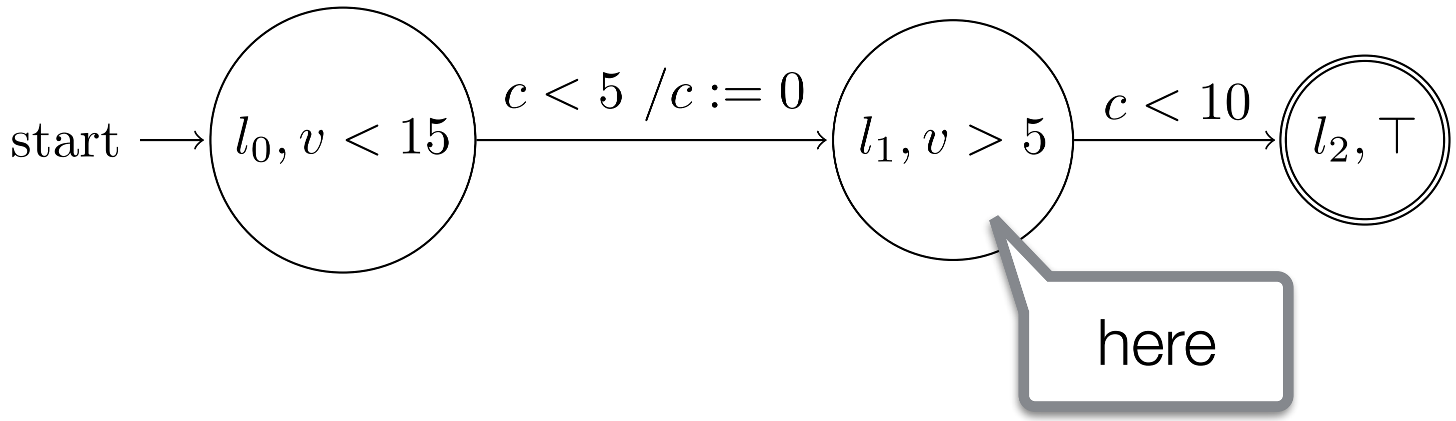

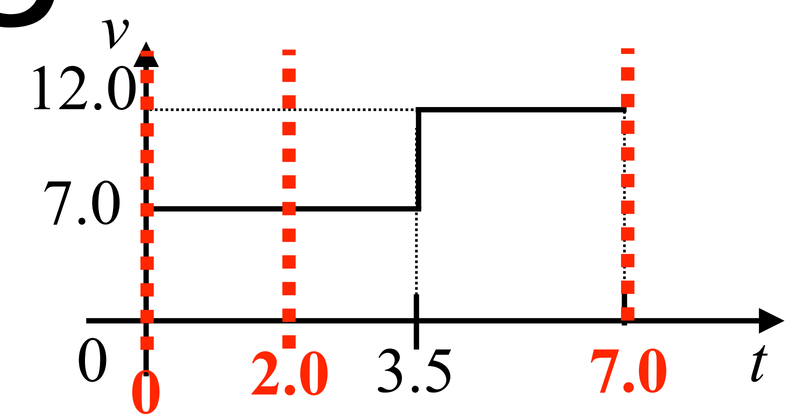

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$$\overset{5.0}{\dashrightarrow} (l_1, c=5, 7, \{v = 7\}\{v = 12\})$$

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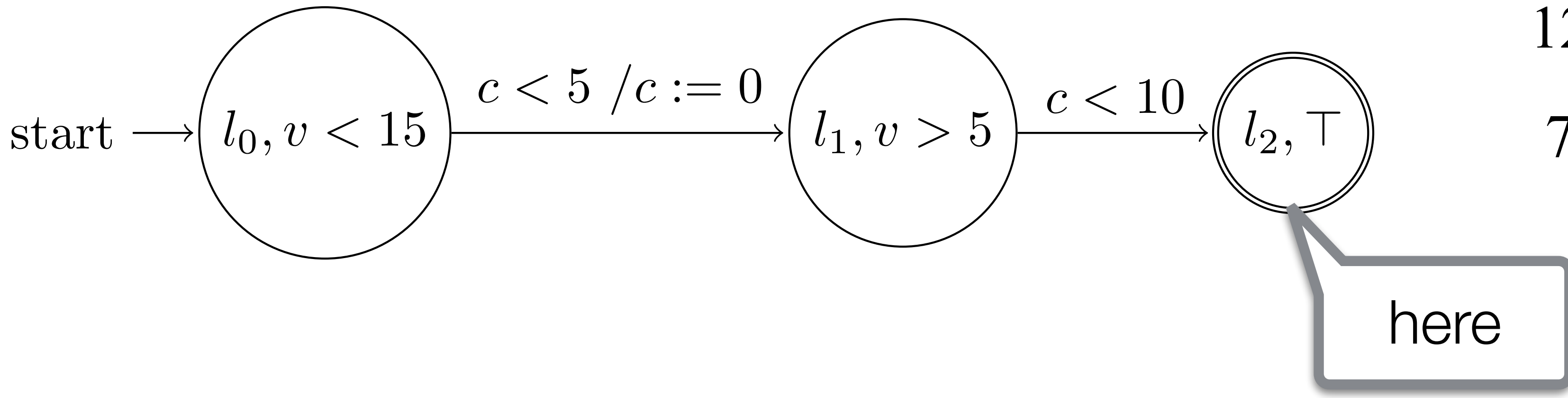
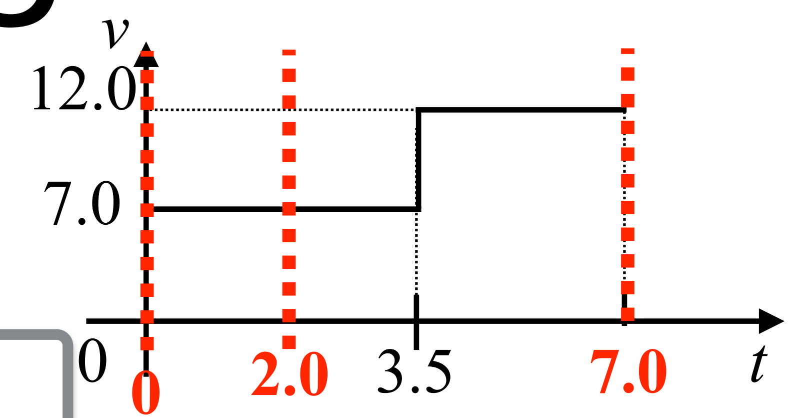
One path in Weighted TTS





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$$\overset{5.0}{\dashrightarrow} (l_1,\ c{=}5,\ 7,\ \{v = 7\}\{v = 12\}) \xrightarrow[\kappa(v > 5,\ \{v{=}7\}\{v{=}12\})]{e} (l_2,\ c{=}5,\ 7,\ \varepsilon)$$

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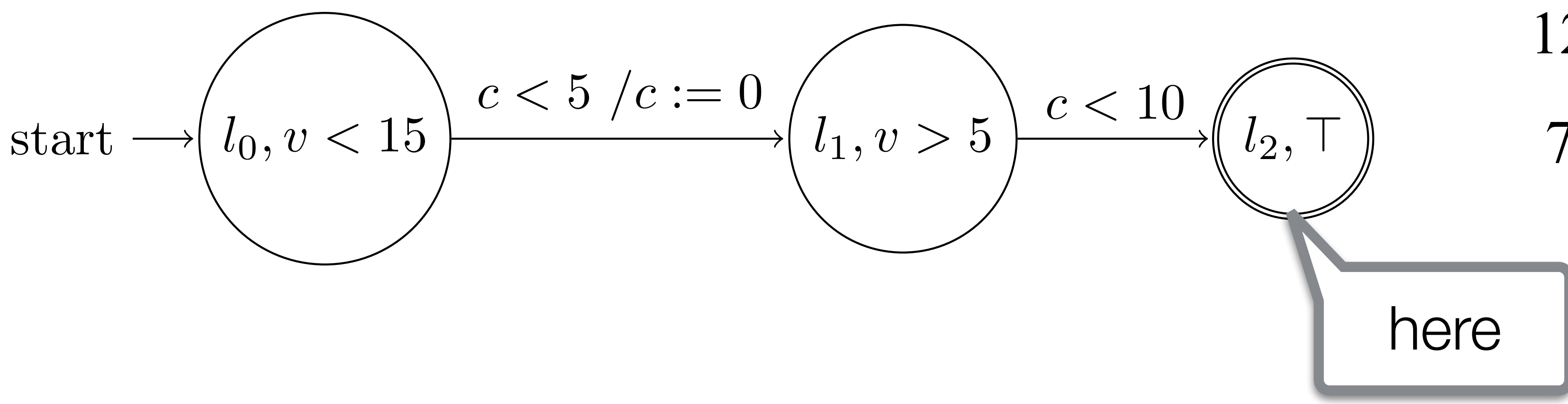
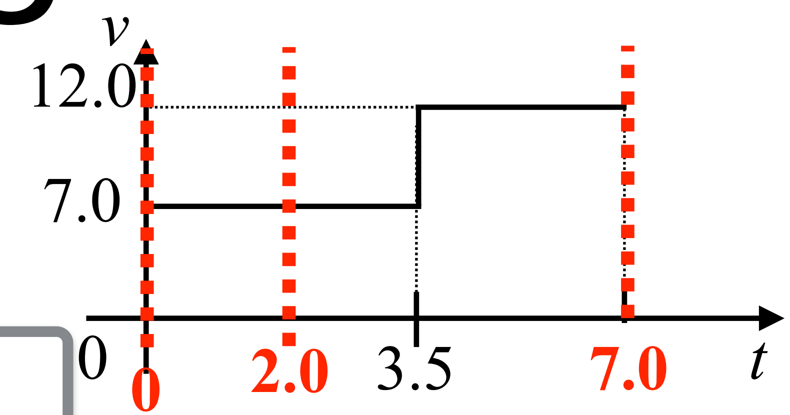
One path in Weighted TTS



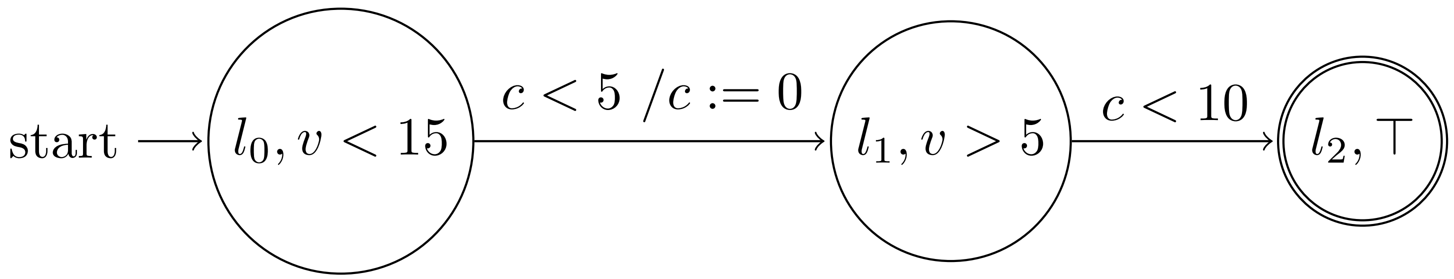


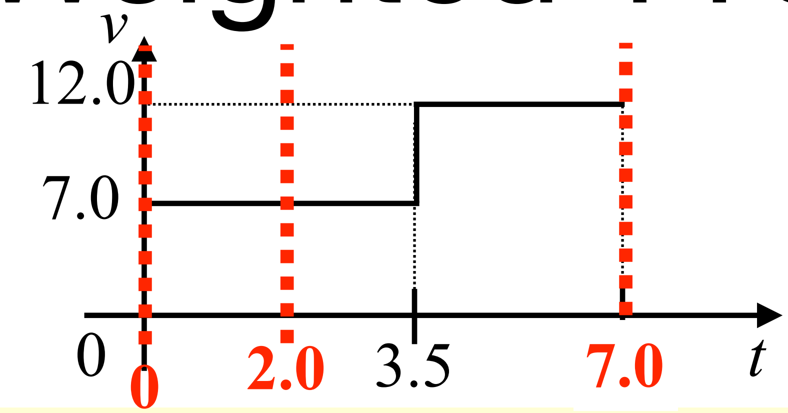
$$\to (l_0, c=0, 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0, c=2, 2, \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v=7\})]{e} (l_1, c=0, 2, \varepsilon)$$

$$\overset{5.0}{\dashrightarrow} (l_1, c=5, 7, \{v = 7\}\{v = 12\}) \xrightarrow[\kappa(v > 5,\ \{v=7\}\{v=12\})]{\otimes\ e} (l_2, c=5, 7, \varepsilon)$$

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

Accumulating paths in Weighted TTS





$\rightarrow (l_0, c=0, 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0, c=2, 2, \{v=7\}) \xrightarrow{e} (l_1, c=0, 3, \varepsilon) \overset{5.0}{\dashrightarrow} (l_1, c=5, 7, \{v=7\}\{v=12\}) \xrightarrow{e} (l_2, c=5, 7, \varepsilon)$

$\kappa(v < 15, \{v=7\}) \otimes \kappa(v > 5, \{v=7\}\{v=12\})$

$\rightarrow (l_0, c=0, 0, \varepsilon) \overset{4.0}{\dashrightarrow} (l_0, c=4, 4, \{v=7\}\{v=12\}) \xrightarrow{e} (l_1, c=0, 4, \varepsilon) \overset{3.0}{\dashrightarrow} (l_1, c=3, 7, \{v=12\}) \xrightarrow{e} (l_2, c=3, 7, \varepsilon)$

$\kappa(v < 15, \{v=7\}\{v=12\}) \otimes \kappa(v > 5, \{v=12\})$

⋮

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
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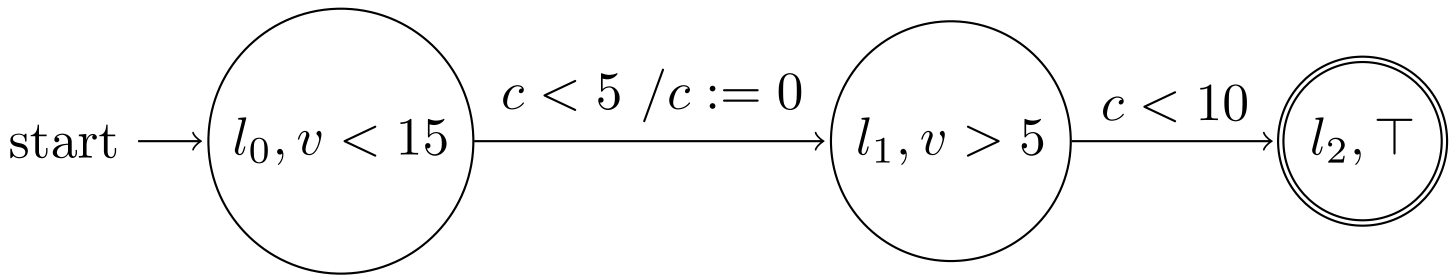
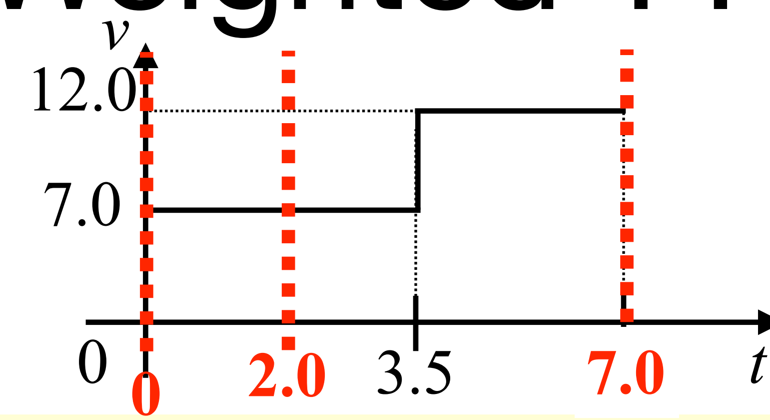
Accumulating paths in Weighted TTS





$\rightarrow (l_0, c{=}0, 0, \varepsilon) \xrightarrow{2.0} (l_0, c{=}2, 2, \{v = 7\}) \xrightarrow{e} (l_1, c{=}0, 3, \varepsilon) \xrightarrow{5.0} (l_1, c{=}5, 7, \{v = 7\}\{v = 12\}) \xrightarrow{e} (l_2, c{=}5, 7, \varepsilon)$

$\kappa(v < 15, \{v{=}7\}) \otimes \kappa(v > 5, \{v{=}7\}\{v{=}12\})$

$\oplus$

$\rightarrow (l_0, c{=}0, 0, \varepsilon) \xrightarrow{4.0} (l_0, c{=}4, 4, \{v = 7\}\{v = 12\}) \xrightarrow{e} (l_1, c{=}0, 4, \varepsilon) \xrightarrow{3.0} (l_1, c{=}3, 7, \{v = 12\}) \xrightarrow{e} (l_2, c{=}3, 7, \varepsilon)$

$\kappa(v < 15, \{v{=}7\}\{v{=}12\}) \otimes \kappa(v > 5, \{v{=}12\})$

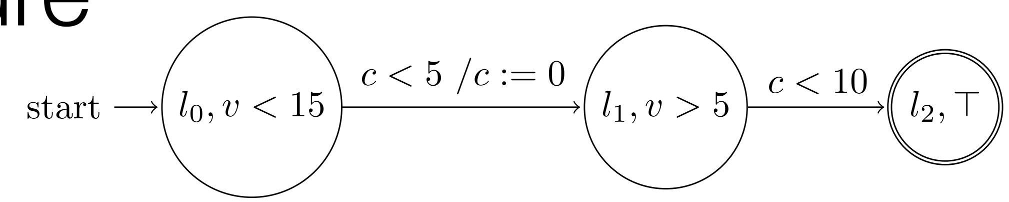
$\oplus$

⋮

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

Timed symbolic weighted automata (TSWA)

- **TSA**: the automata structure



- **Weight function** (κ): the one-step semantics (weight on each transition)
- **Semiring operations** (⊗,⊕): how to accumulate weights
  One-step semantics → semantics for a path/TSWA

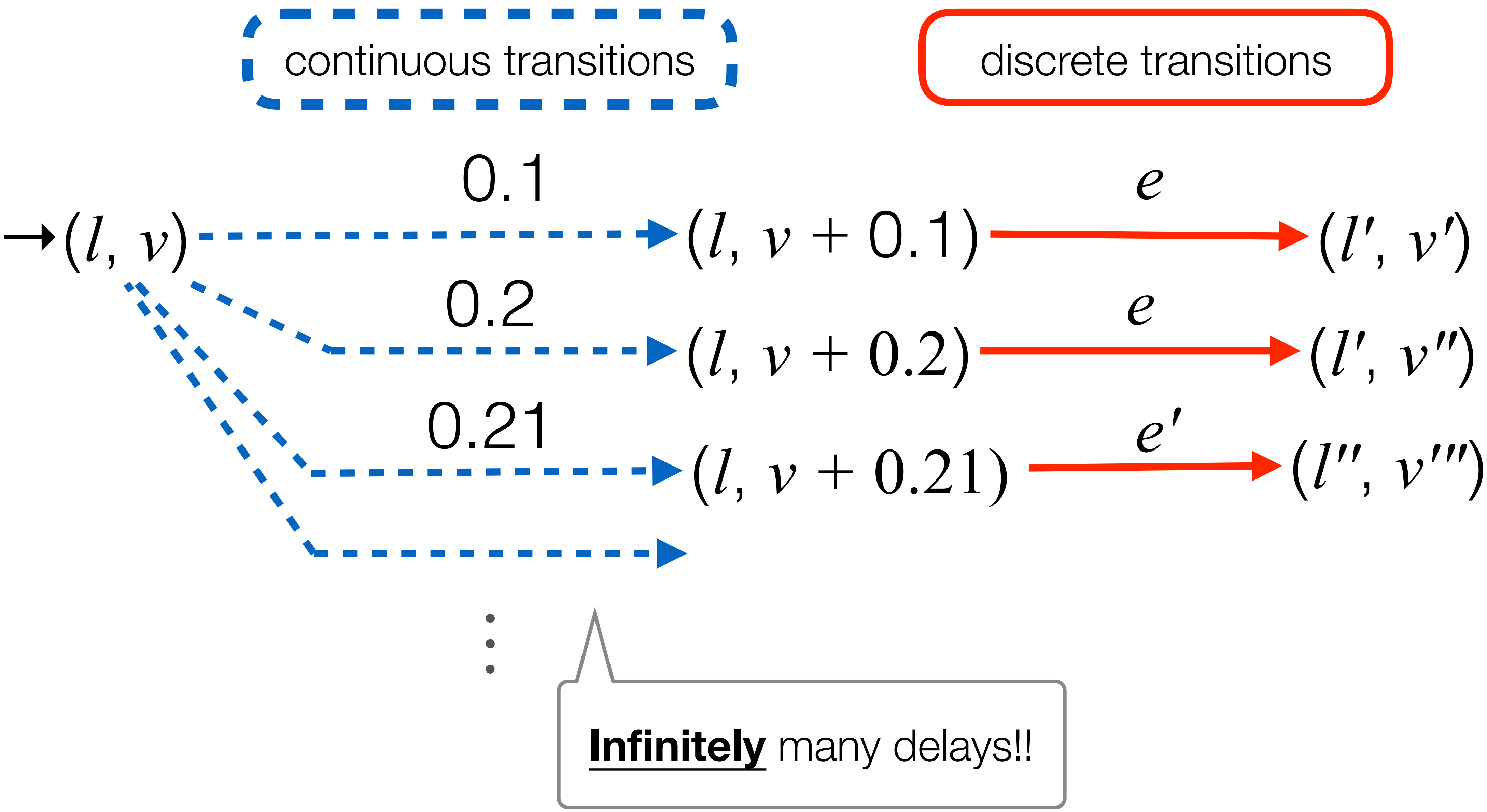
M. Waga (NII)

Outline

- Motivation + Introduction
- Technical Part
  - Timed symbolic weighted automata (TSWA)
    - TSWA: TA with signal constraints + weight function
  - Quantitative monitoring/timed pattern matching algorithm
    - Idea: zone construction with weight
- Experiments

M. Waga (NII)

Review: Reachability by zones



Infinitely many reachable states!! → symbolic analysis by **zones**

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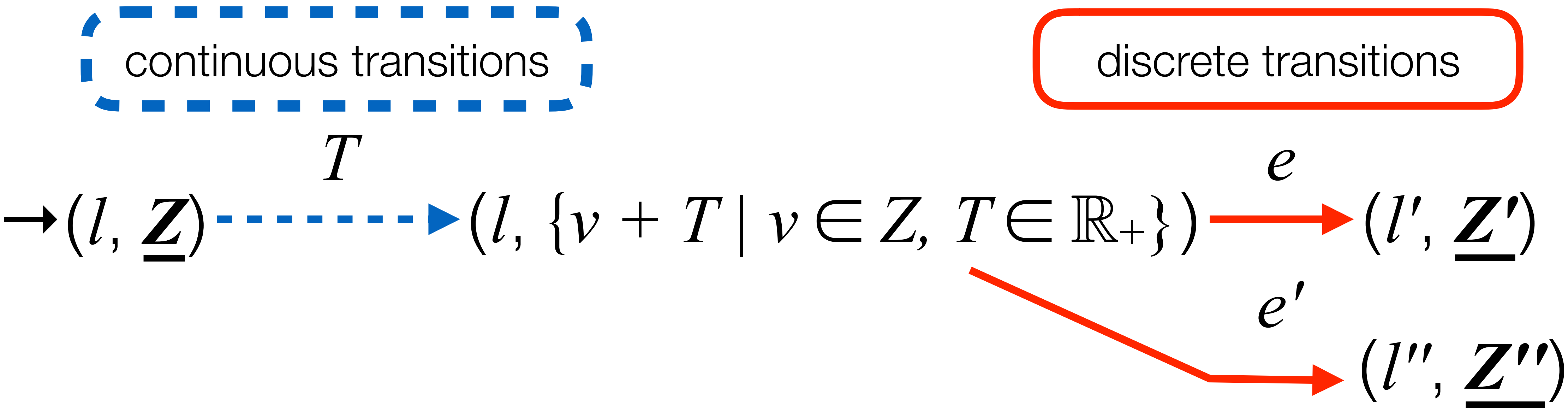
Review: Reachability by zones



- Zone Z symbolically represents **infinitely many** clock valuations!!

Infinitely many reachable states!! → symbolic analysis by **zones**

M. Waga (NII)

Observation: reachability is shortest distance over Boolean semiring!

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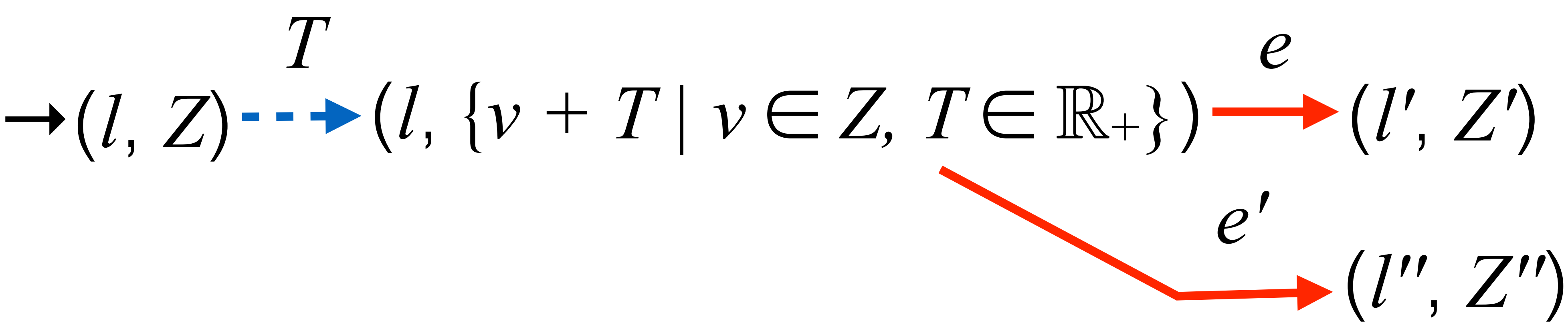
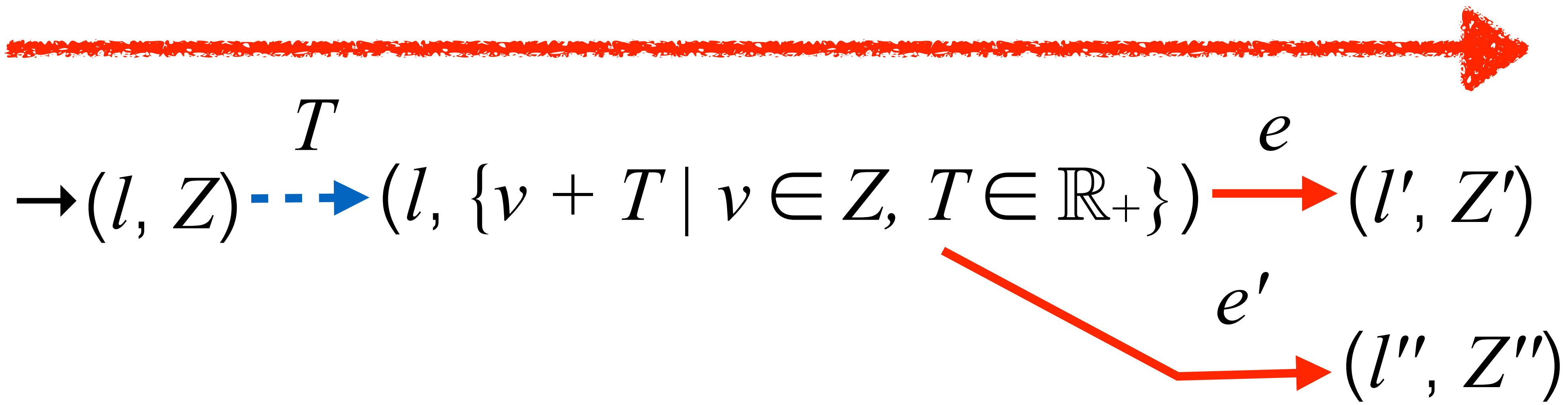


M. Waga (NII)

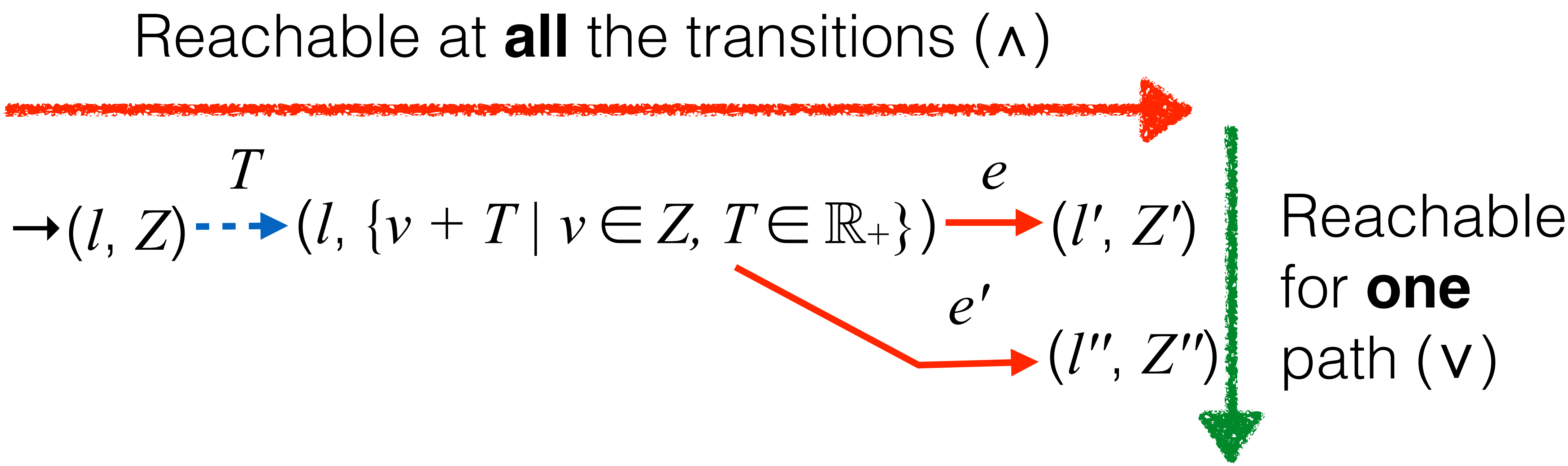
Observation: reachability is shortest distance over Boolean semiring!

Reachable at **all** the transitions (∧)



M. Waga (NII)

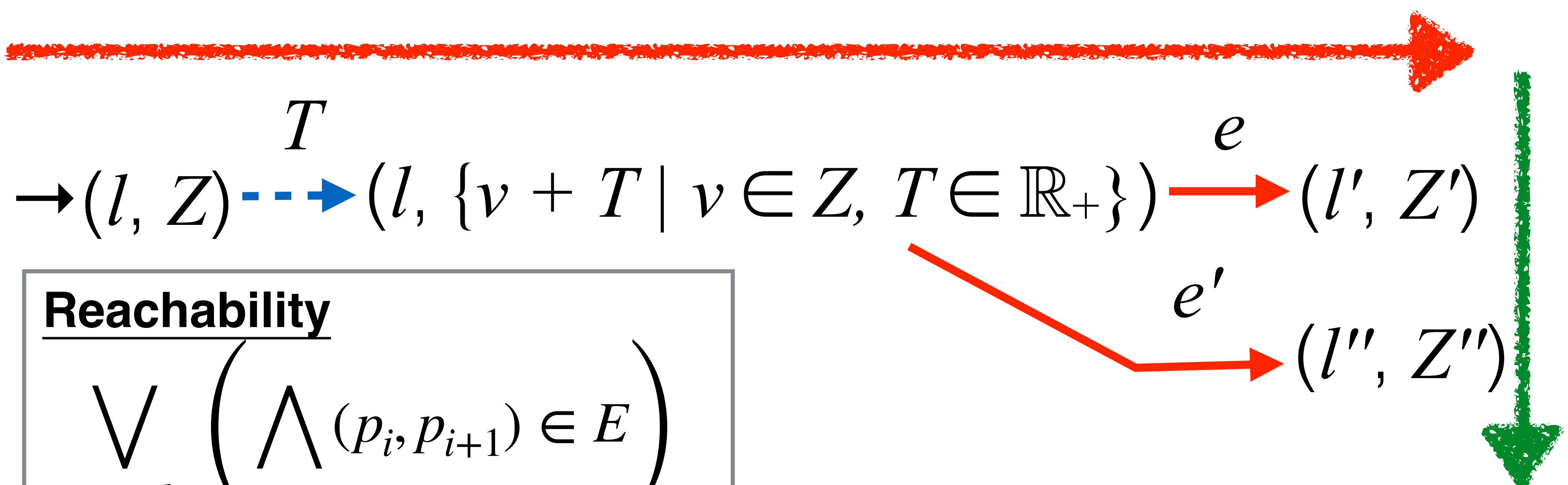
Observation: reachability is shortest distance over Boolean semiring!



M. Waga (NII)

Observation: reachability is shortest distance over Boolean semiring!

Reachable at **all** the transitions (∧)



Reachable for **one** path (∨)

Reachability

$$\bigvee_{p \in Paths} \left(\bigwedge_i (p_i, p_{i+1}) \in E \right)$$

M. Waga (NII)

Observation: reachability is shortest distance over Boolean semiring!

Reachable at **all** the transitions (∧)

$$\rightarrow (l, Z) \overset{T}{\dashrightarrow} (l, \{v + T \mid v \in Z, T \in \mathbb{R}_+\}) \overset{e}{\rightarrow} (l', Z')$$

$$(l, \{v + T \mid v \in Z, T \in \mathbb{R}_+\}) \overset{e'}{\rightarrow} (l'', Z'')$$

Reachable for **one** path (∨)

Reachability

$$\bigvee_{p \in Paths} \left(\bigwedge_i (p_i, p_{i+1}) \in E \right)$$

Shortest Distance (for semiring)

$$\bigoplus_{p \in Paths} \left(\bigotimes_i w(p_i, p_{i+1}) \right)$$

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	∨	sup	inf
$\otimes$	∧	inf	+

M. Waga (NII)

Observation: reachability is shortest distance over Boolean semiring!

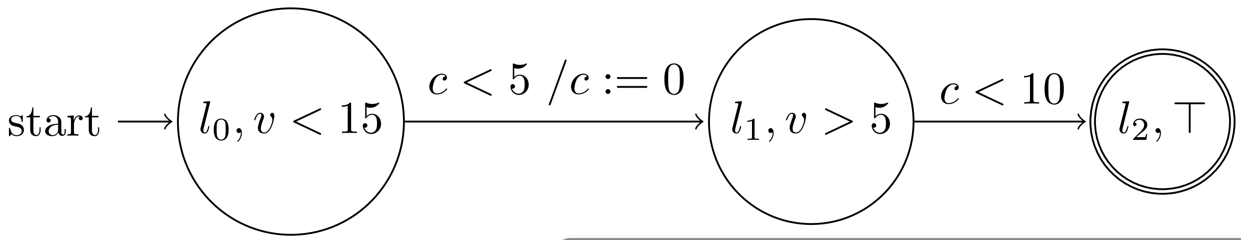
Qualitative [Bakhirkin+, FORMATS'18]

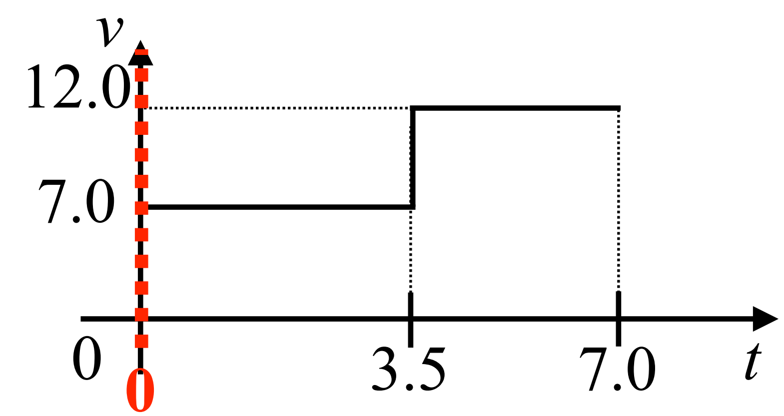
TA —zone constr.→ zone graph (with Boolean weight) —reachability checking (Boolean shortest distance)→ reachability (qualitative semantics)

Quantitative [Contribution]

TSWA —zone constr.→ zone graph with semiring weight —semiring shortest distance→ quantitative semantics

Zone construction with weight





- T: absolute time

This is OK for monitoring

- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ $(= 7.0)$

$\rightarrow (l_0, c = T = 0, \varepsilon)$

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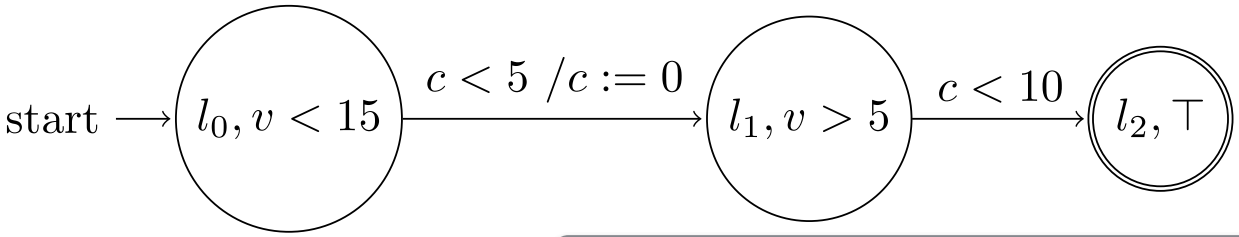
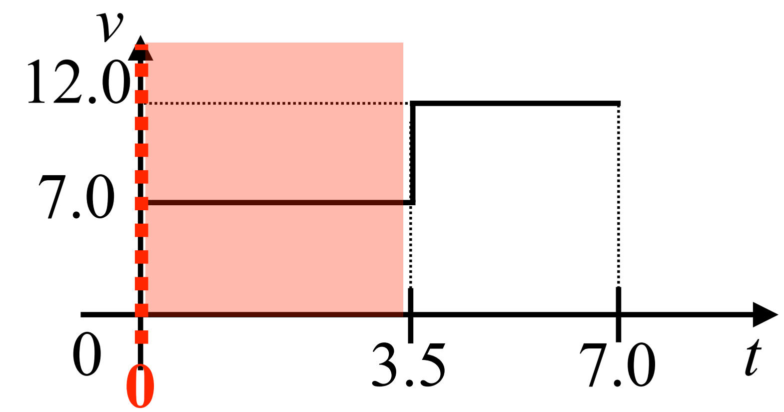
Zone construction with weight





- T: absolute time

This is OK for monitoring

- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ $(= 7.0)$

$$\rightarrow (l_0, c = T = 0, \varepsilon) \dashrightarrow (l_0, 0 < c = T < 3.5, \{v = 7\})$$

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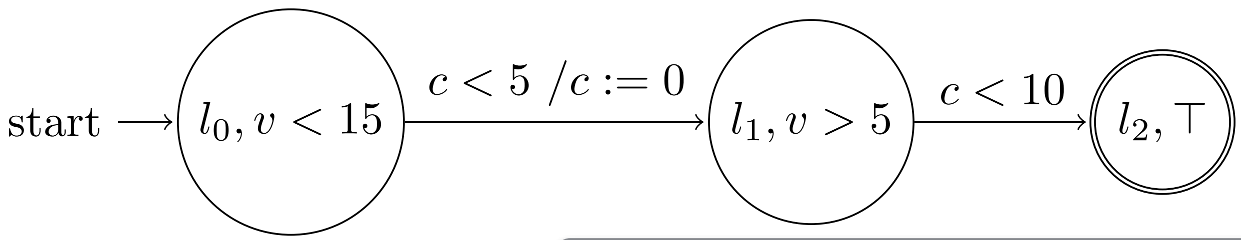
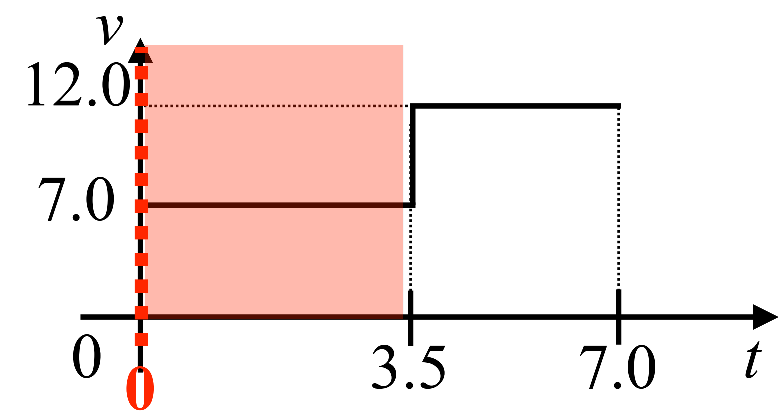
Zone construction with weight





This is OK for monitoring

- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

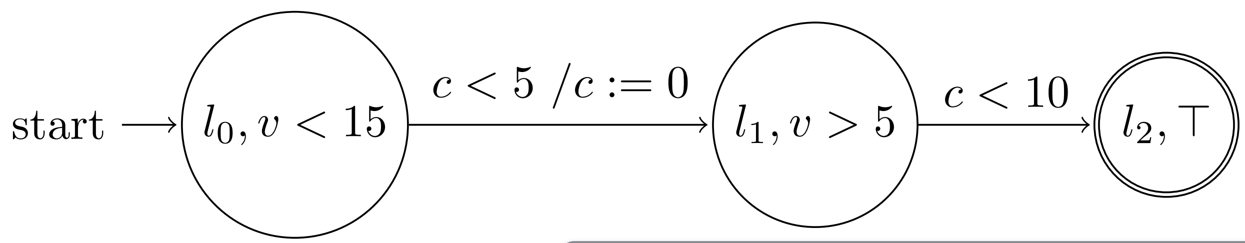
$\rightarrow (l_0, c = T = 0, \varepsilon)$ - - - → $(l_0, 0 < c = T < 3.5, \{v = 7\})$

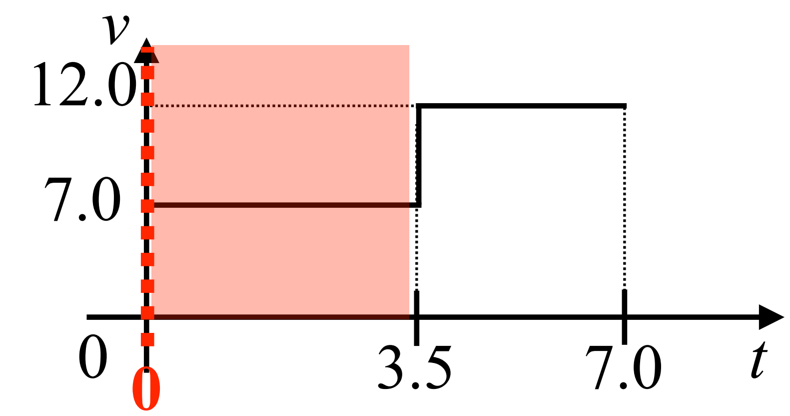
$\kappa(v < 15, \{v=7\})$ ↓

$(l_1, 0 = c < T < 3.5, \varepsilon)$

M. Waga (NII)

Zone construction with weight





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- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ $(= 7.0)$

$\rightarrow (l_0, c = T = 0, \varepsilon)$ ⇢ $(l_0, 0 < c = T < 3.5, \{v = 7\})$

$\kappa(v < 15, \{v = 7\})$ ↓

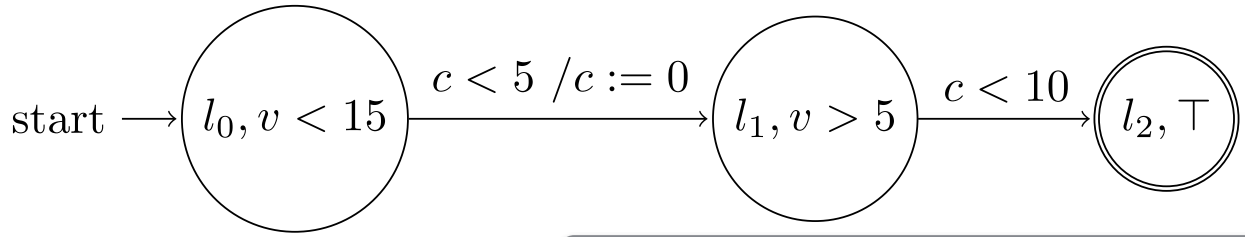
$(l_1, 0 = c < T < 3.5, \varepsilon)$

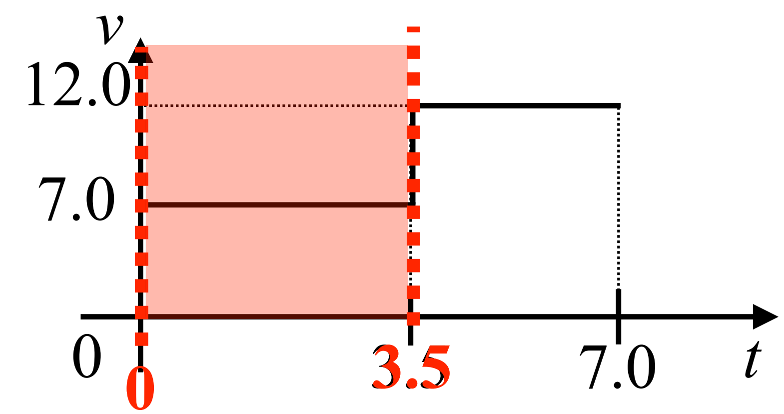
⇣

$(l_1, 0 < c < T < 3.5, \{v = 7\})$

M. Waga (NII)

Zone construction with weight





- T: absolute time
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This is OK for monitoring

$\rightarrow (l_0, c = T = 0, \varepsilon)$ ⇢ $(l_0, 0 < c = T < 3.5, \{v = 7\})$

$\kappa(v < 15, \{v=7\})$ ↓

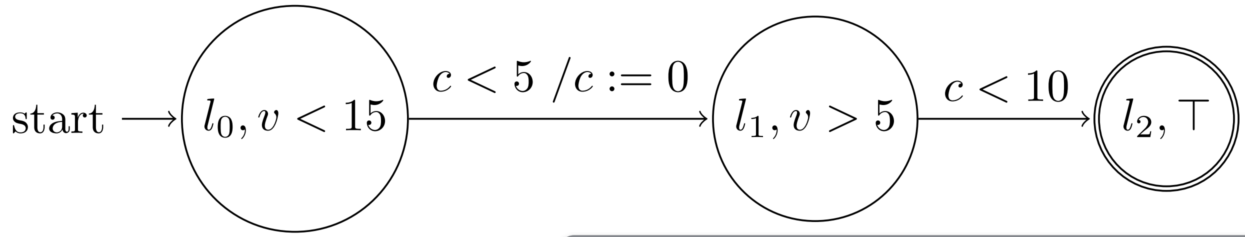
$(l_1, 0 = c < T < 3.5, \varepsilon)$

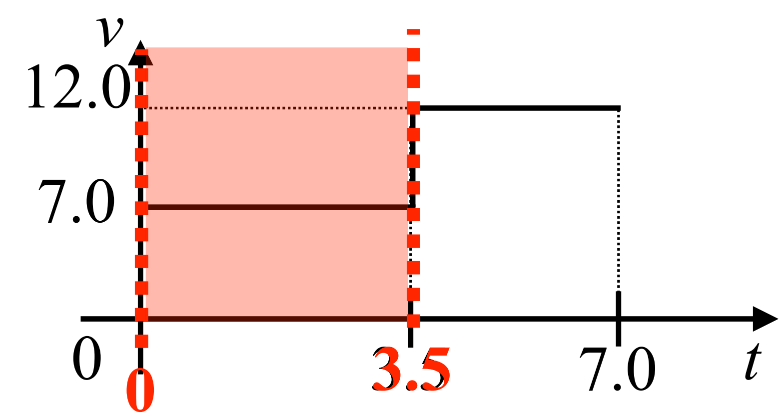
⇣

$(l_1, 0 < c < T < 3.5, \{v = 7\})$

M. Waga (NII)

Zone construction with weight





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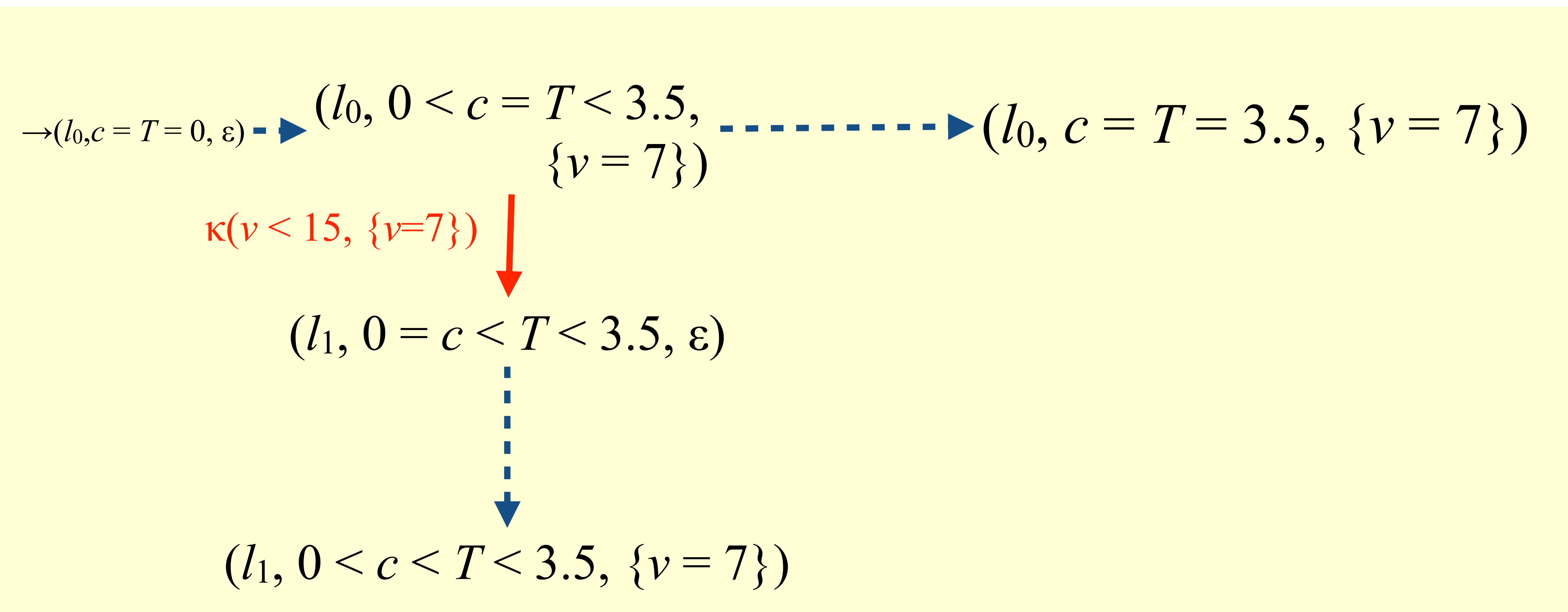

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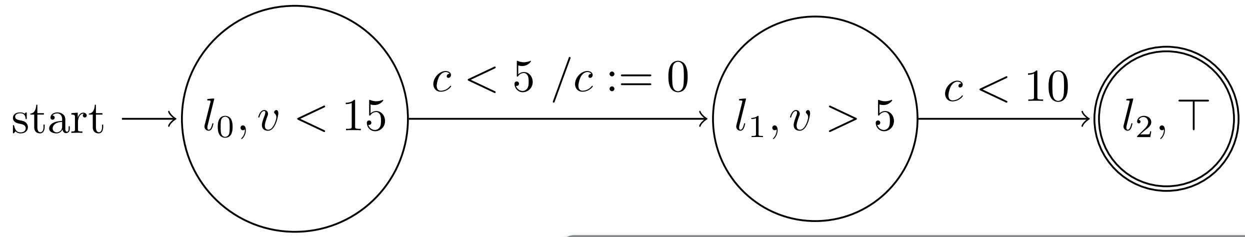
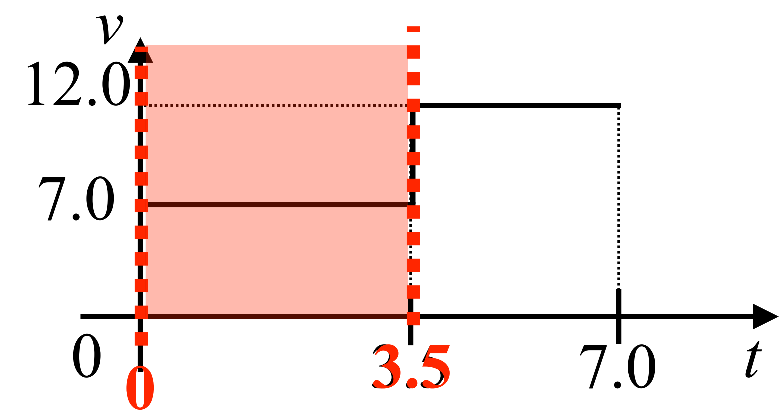
Zone construction with weight





- T: absolute time

This is OK for monitoring

- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ $(= 7.0)$

$\rightarrow (l_0, c = T = 0, \varepsilon)$ ⇢ $(l_0, 0 < c = T < 3.5, \{v = 7\})$ ⇢ $(l_0, c = T = 3.5, \{v = 7\})$

$\kappa(v < 15, \{v = 7\})$ ↓

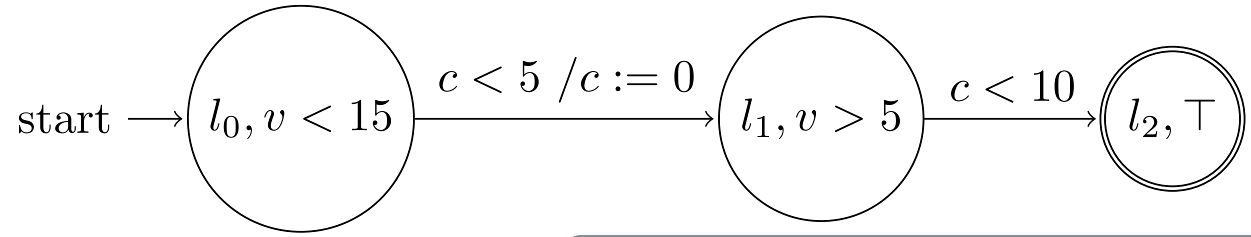
$(l_1, 0 = c < T < 3.5, \varepsilon)$

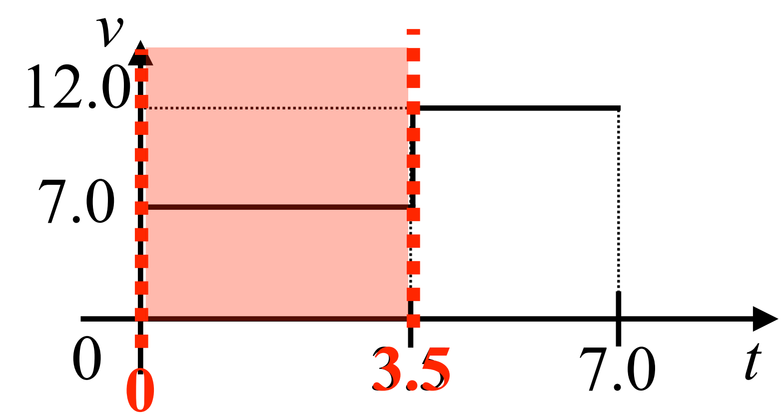
↓

$(l_1, 0 < c < T < 3.5, \{v = 7\})$ ⇢ $(l_1, 0 < c < T = 3.5, \{v = 7\})$

M. Waga (NII)

Zone construction with weight





- T: absolute time — This is OK for monitoring
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

$\rightarrow (l_0, c = T = 0, \varepsilon)$ ⇢ $(l_0, 0 < c = T < 3.5, \{v = 7\})$ ⇢ $(l_0, c = T = 3.5, \{v = 7\})$

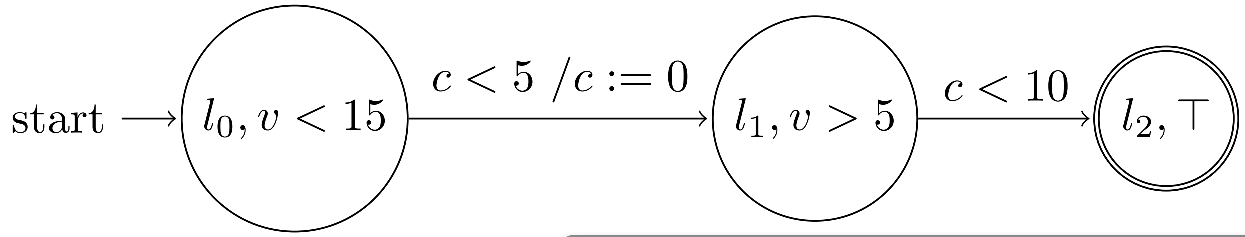
$\kappa(v < 15, \{v=7\})$ ↓ $(l_1, 0 = c < T < 3.5, \varepsilon)$

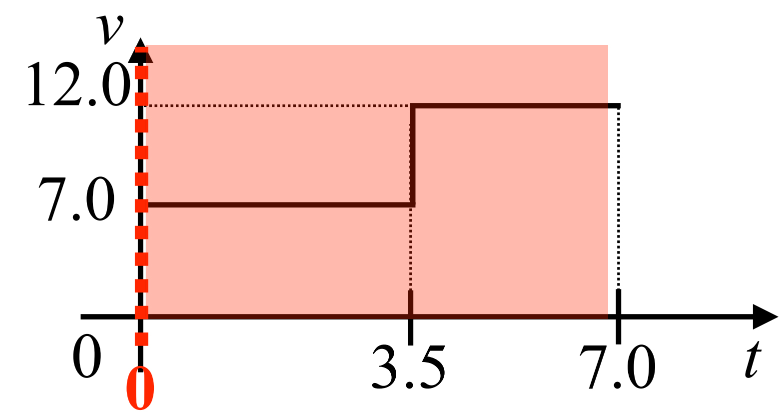
$\kappa(v < 15, \{v=7\})$ ↓ $(l_1, c = 0 < T = 3.5, \varepsilon)$

$(l_1, 0 = c < T < 3.5, \varepsilon)$ ⇣ $(l_1, 0 < c < T < 3.5, \{v = 7\})$ ⇢ $(l_1, 0 < c < T = 3.5, \{v = 7\})$

M. Waga (NII)

Zone construction with weight





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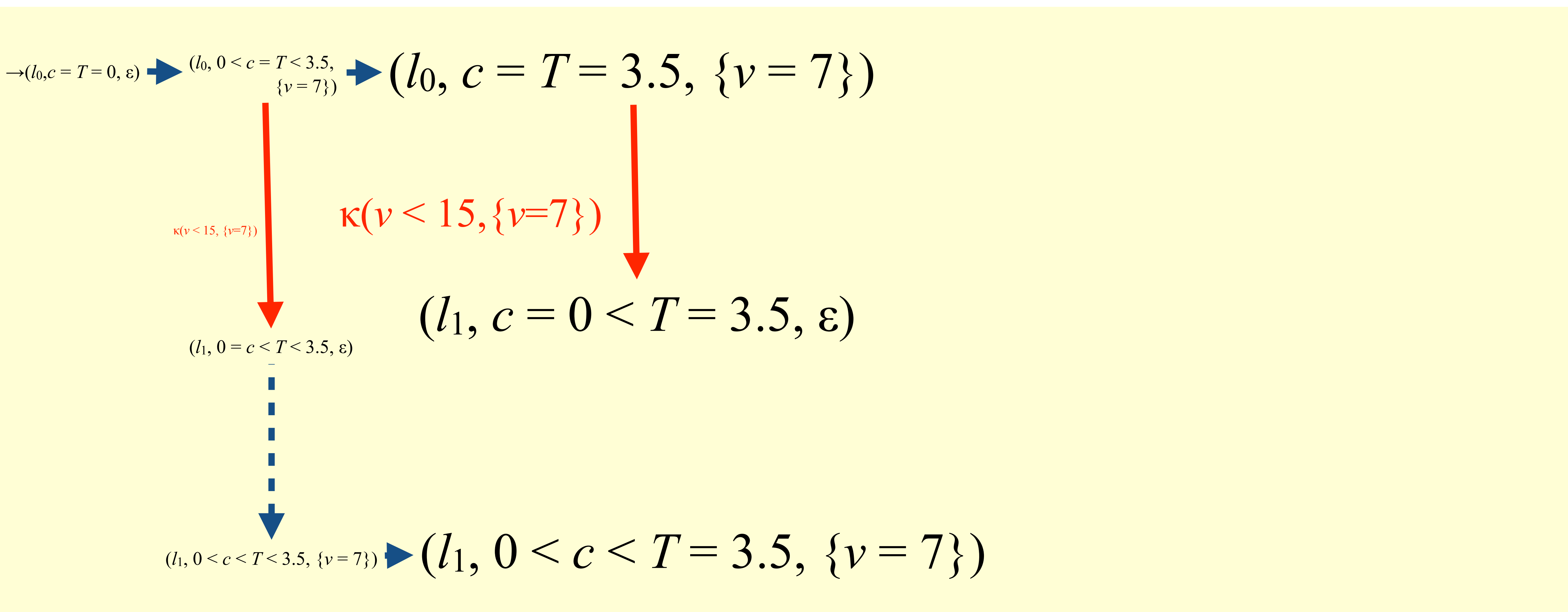
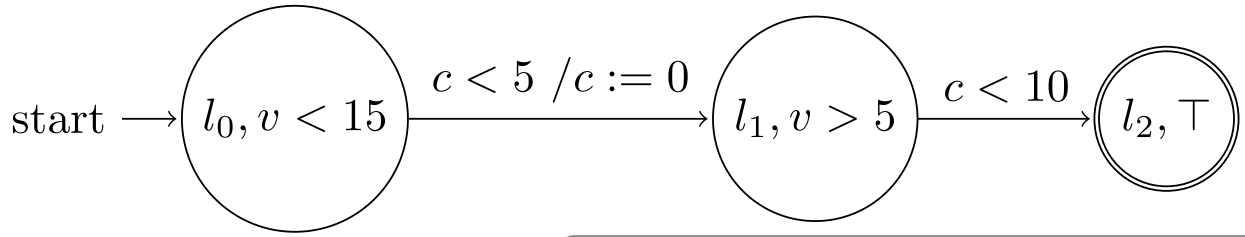
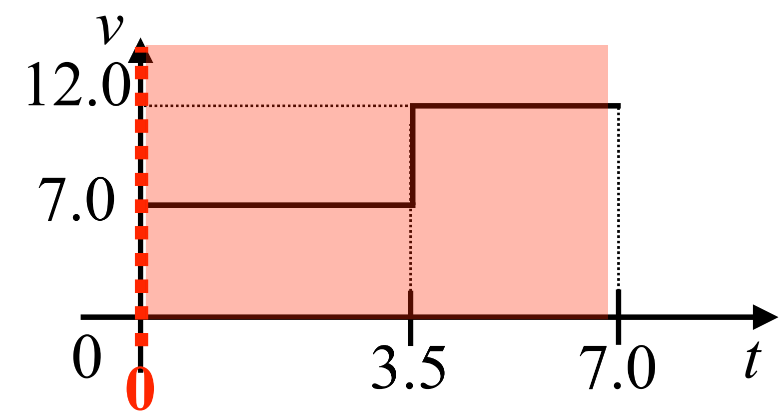


M. Waga (NII)

Zone construction with weight





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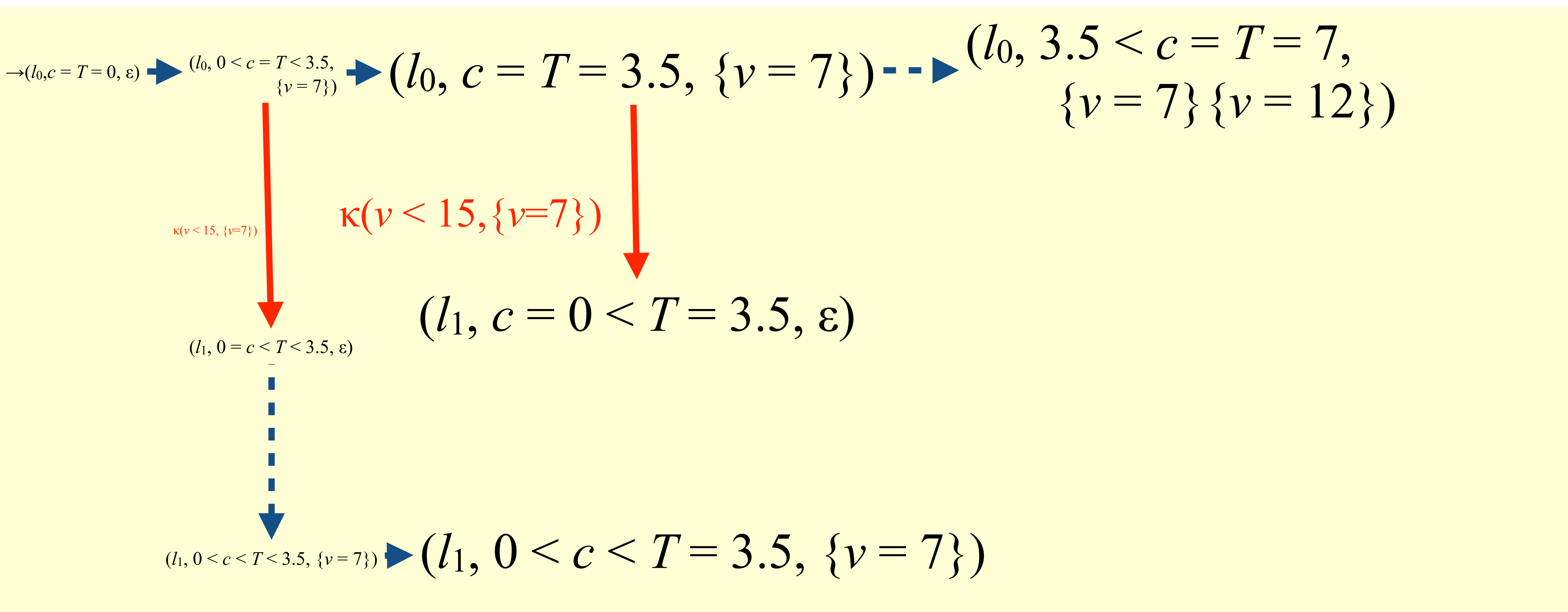
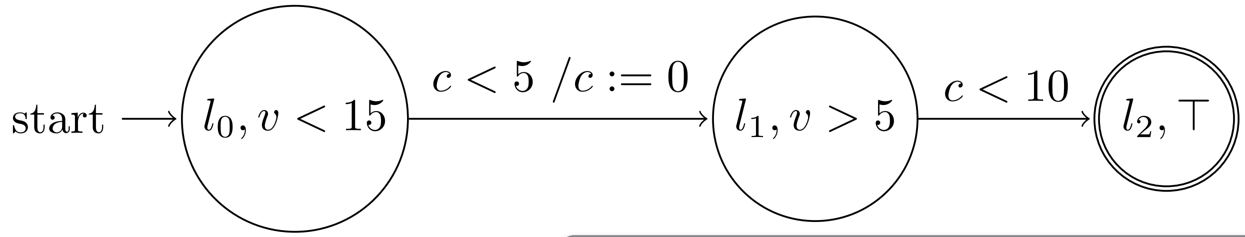
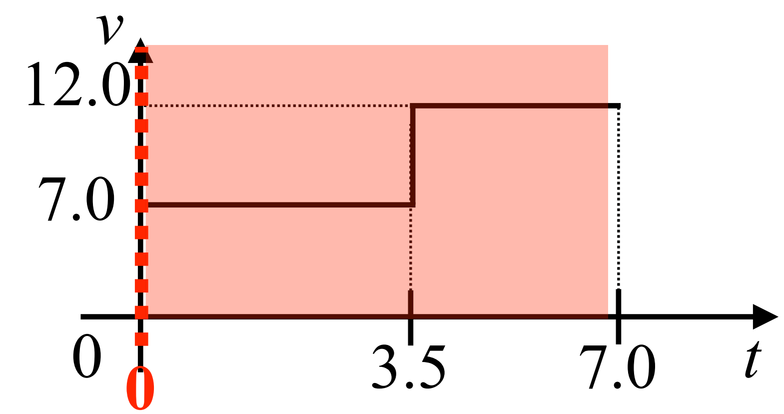


M. Waga (NII)

Zone construction with weight





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$\kappa(v < 15, \{v=7\})$

$\kappa(v < 15, \{v=7\})$

$(l_1, 0 = c < T < 3.5, \varepsilon)$

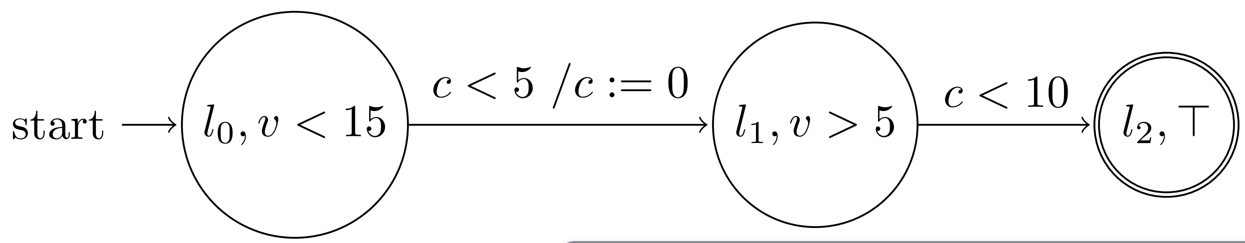
$(l_1, c = 0 < T = 3.5, \varepsilon)$

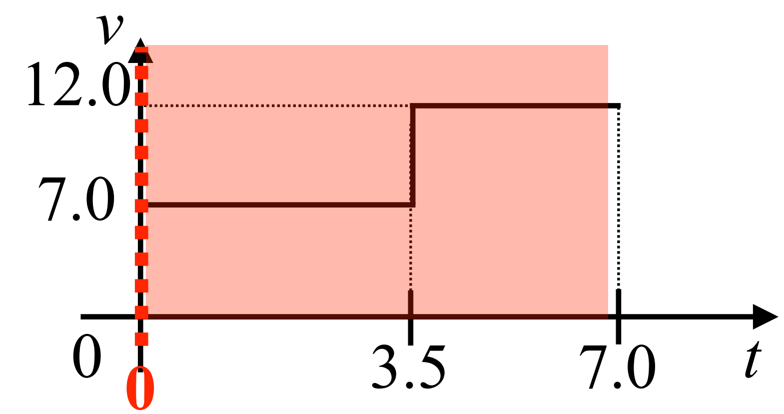
$(l_1, 0 < c < T \in (3.5, 7), \{v = 12\})$

$(l_1, 0 < c < T < 3.5, \{v = 7\})$ → $(l_1, 0 < c < T = 3.5, \{v = 7\})$

M. Waga (NII)

Zone construction with weight





- T: absolute time

This is OK for monitoring

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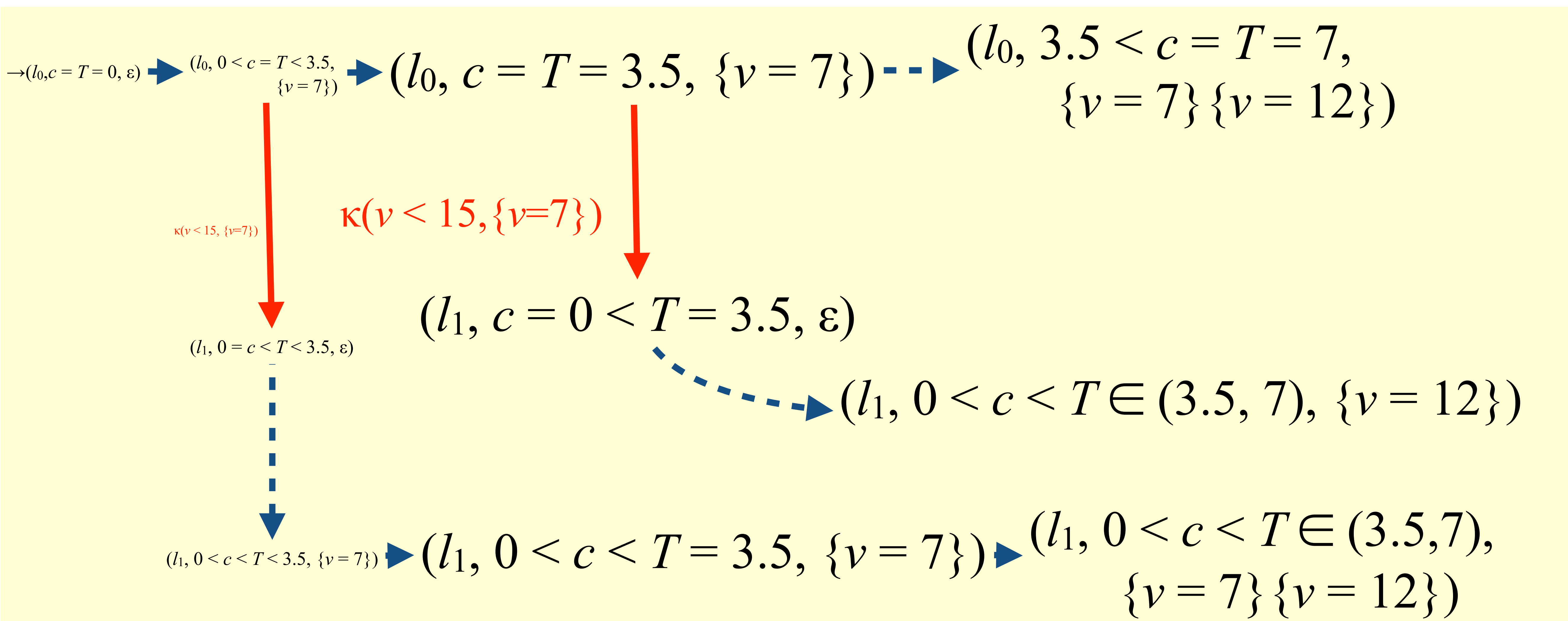
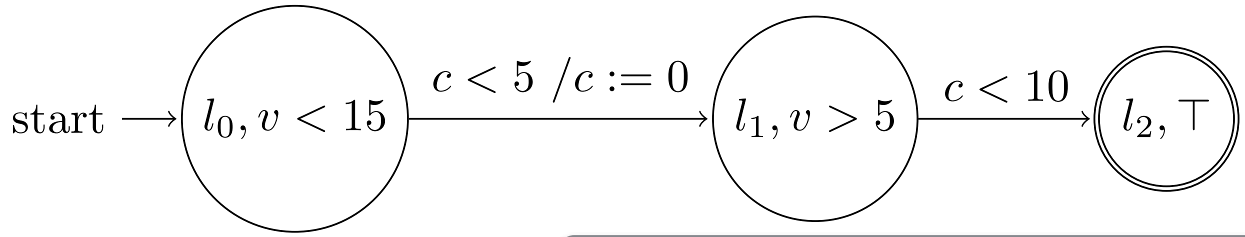
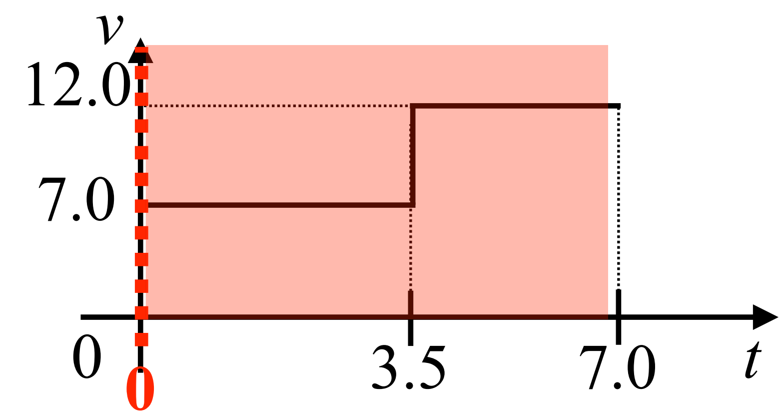


Zone construction with weight





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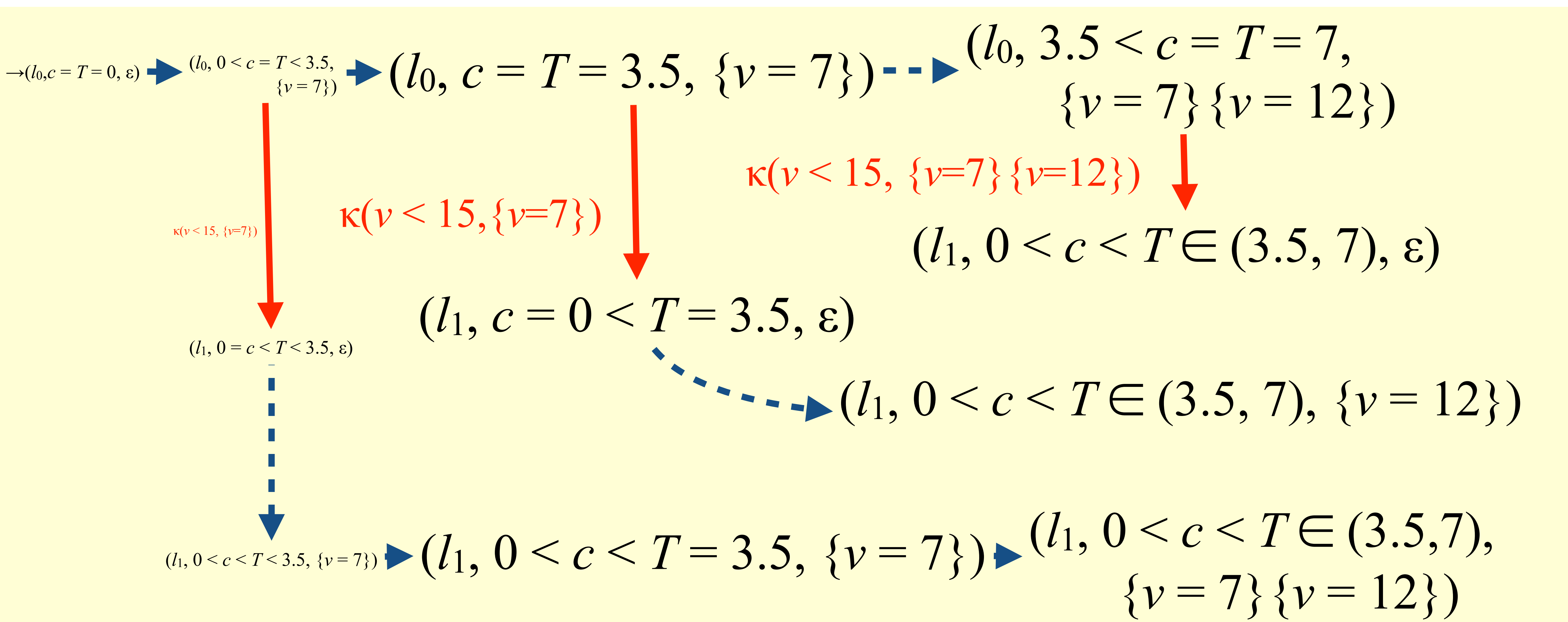
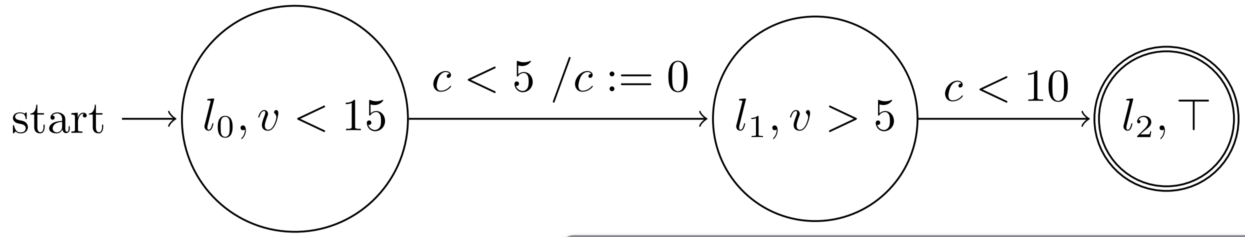
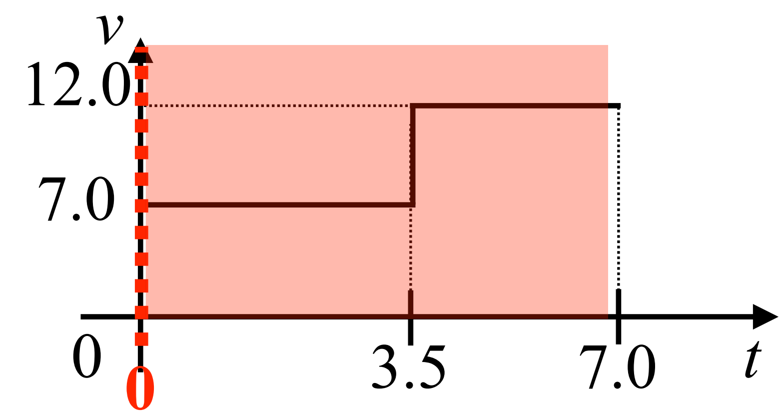


M. Waga (NII)

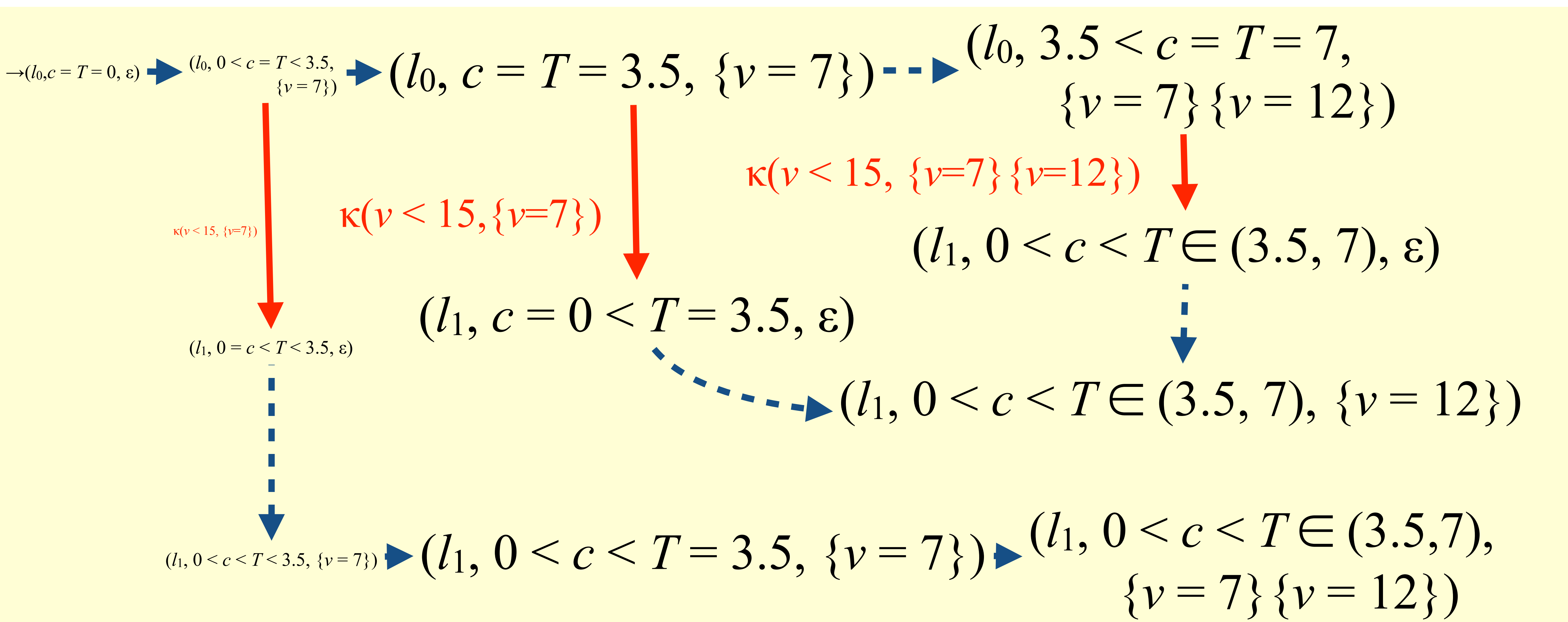
Zone construction with weight





- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

This is OK for monitoring



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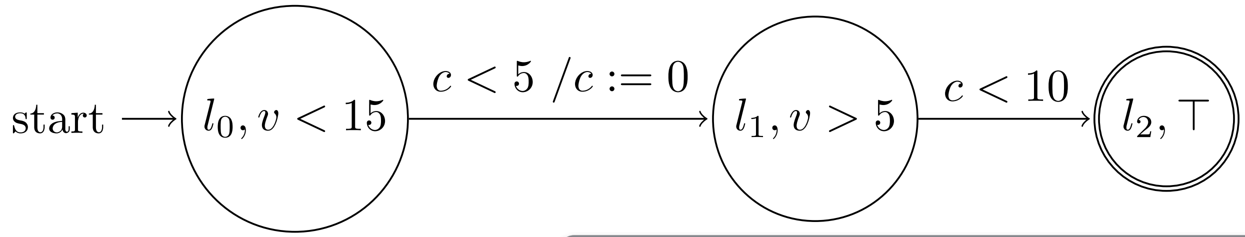
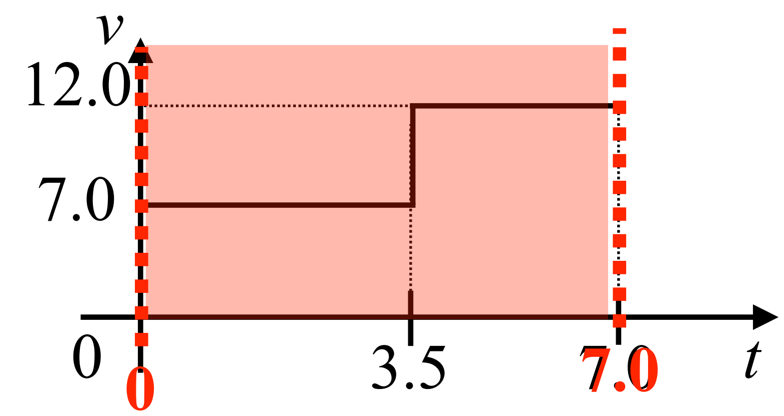
Zone construction with weight





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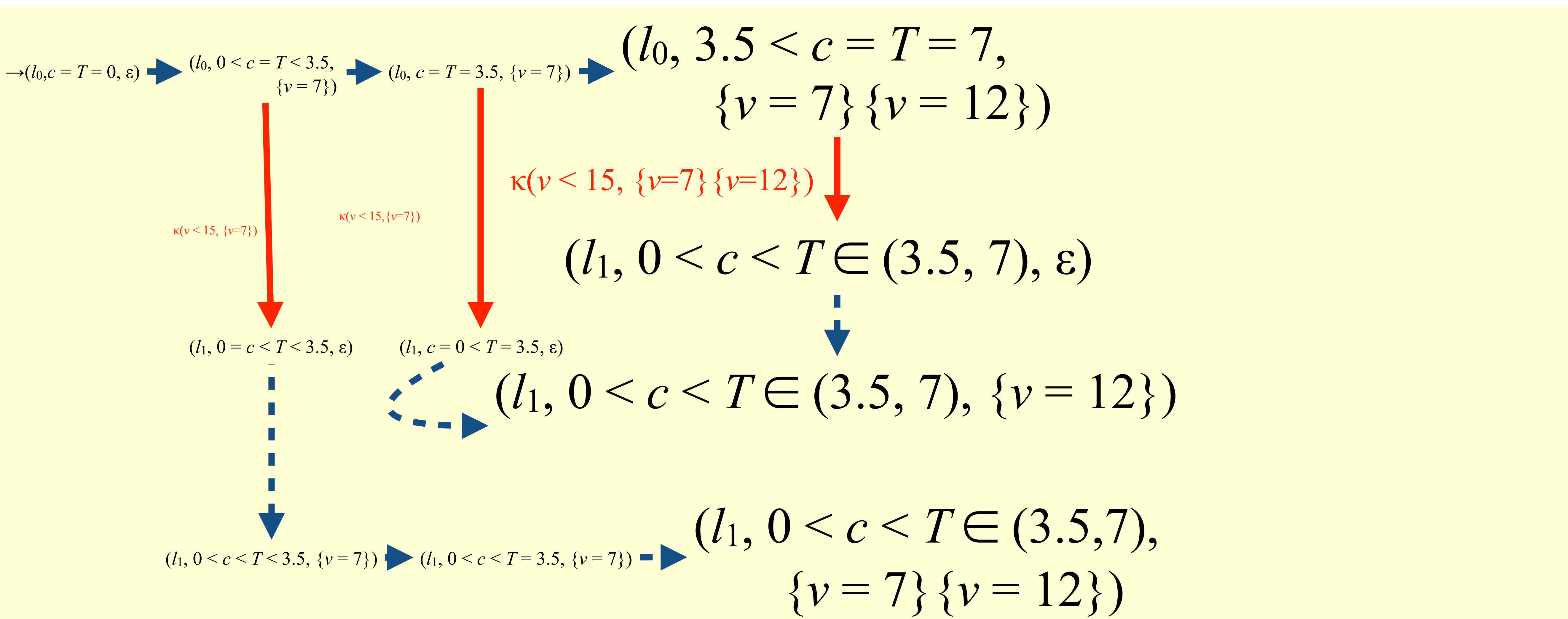
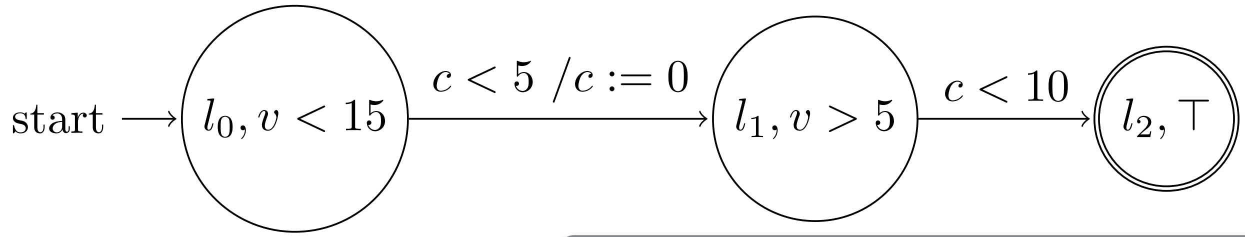
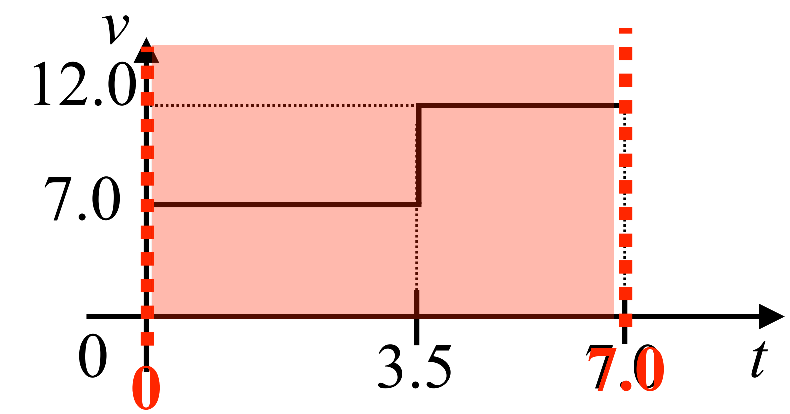


M. Waga (NII)

Zone construction with weight





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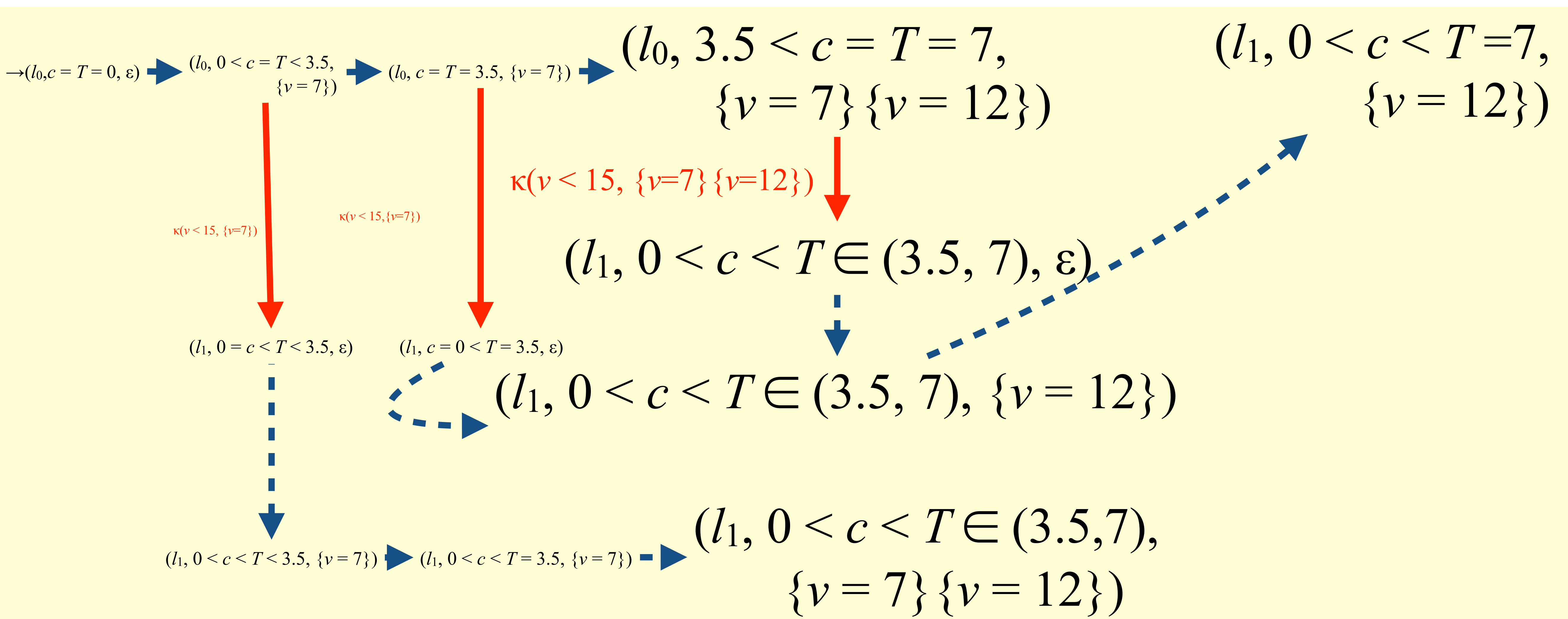

M. Waga (NII)

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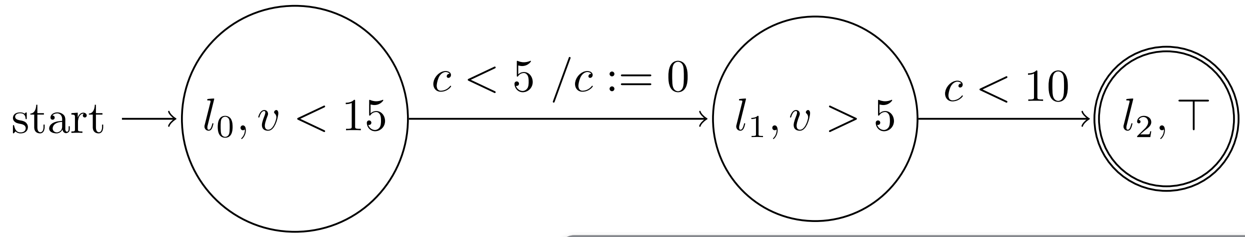

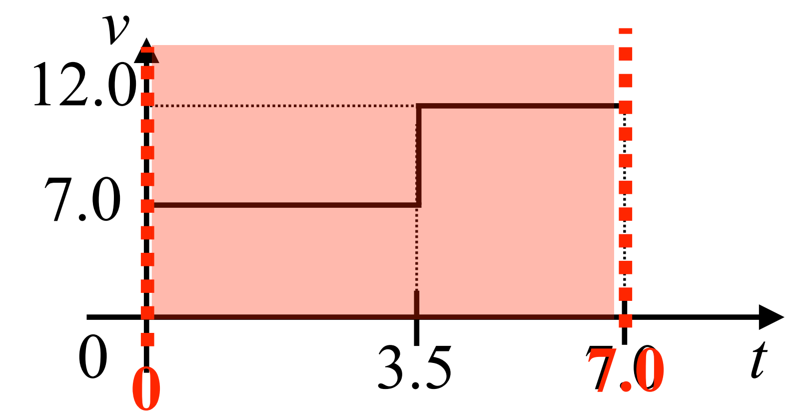

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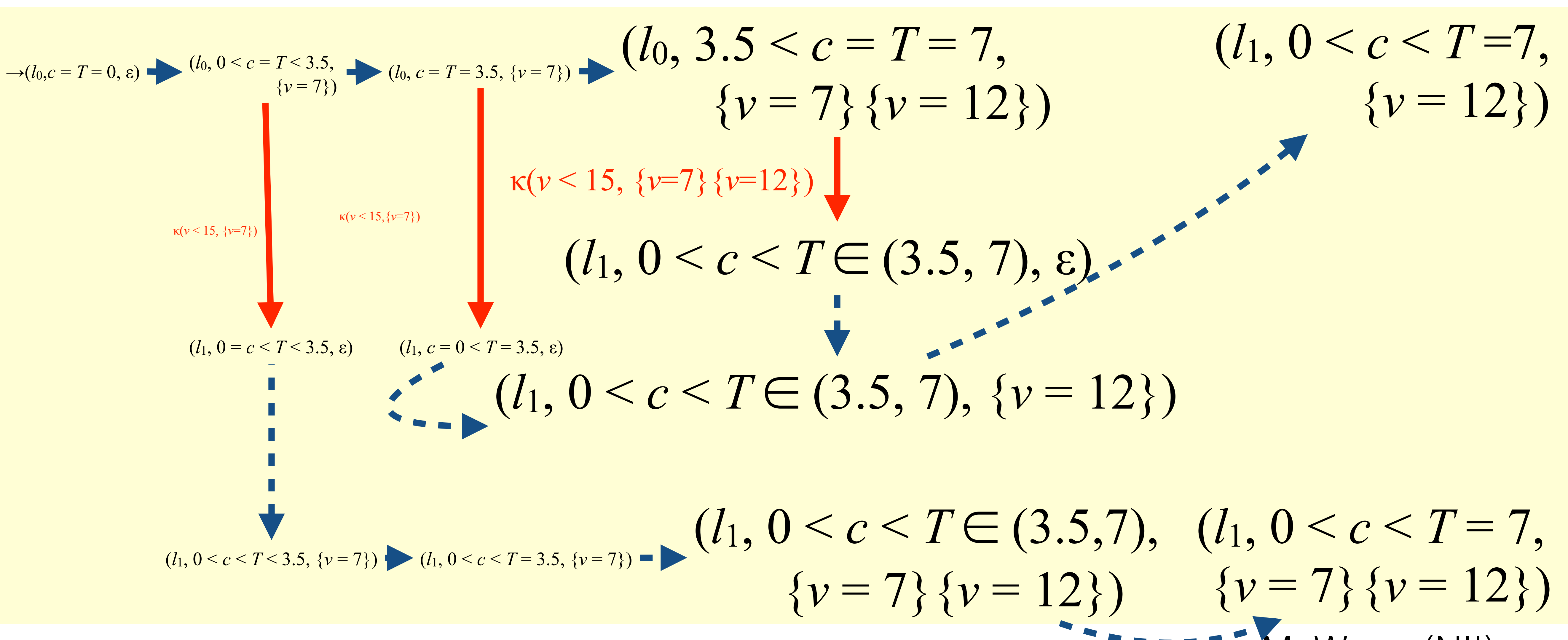
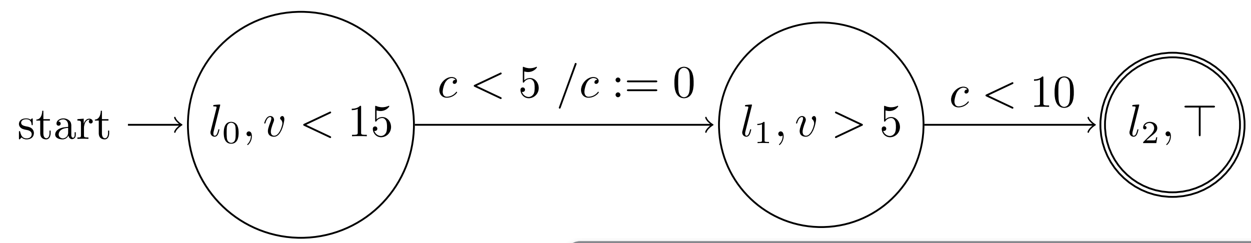
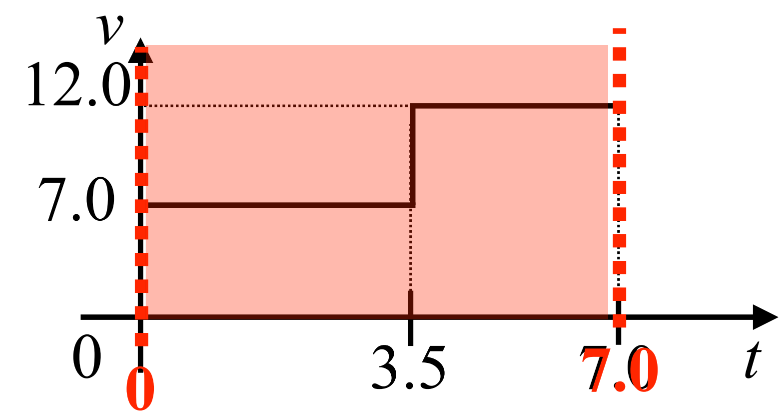


Zone construction with weight





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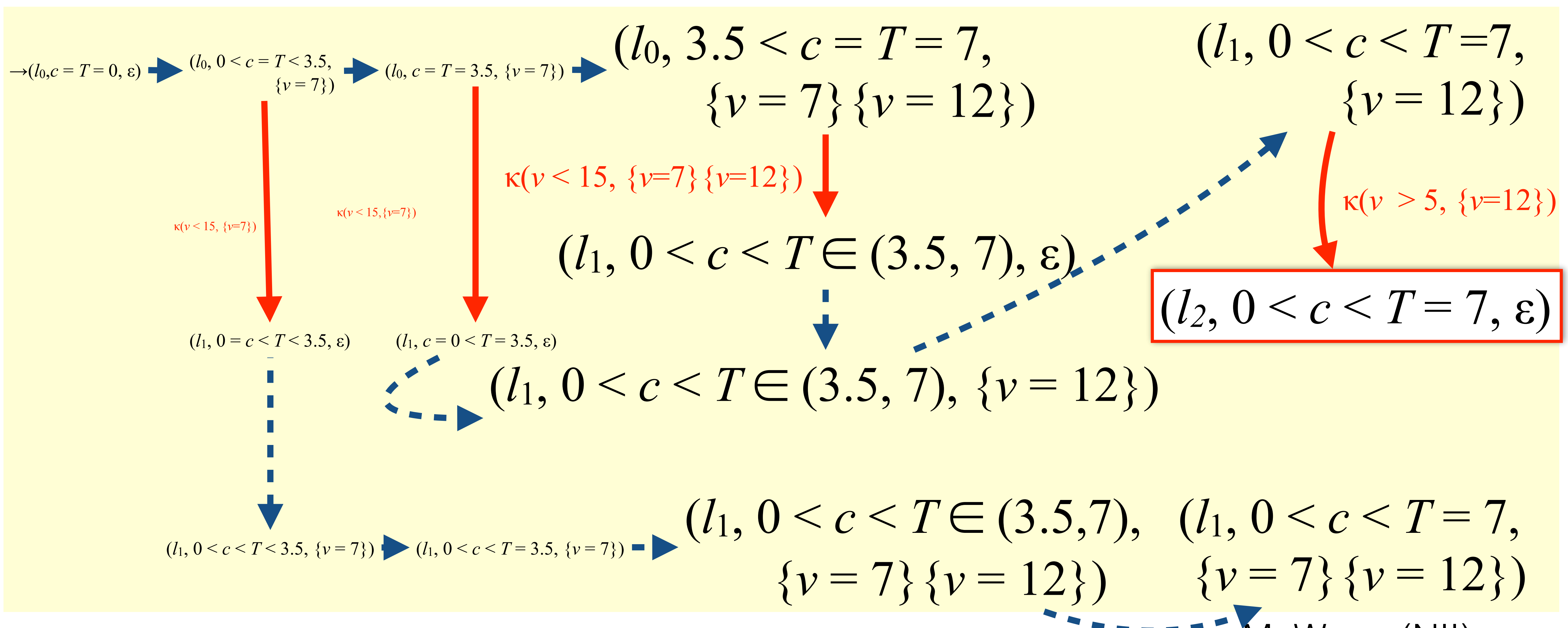
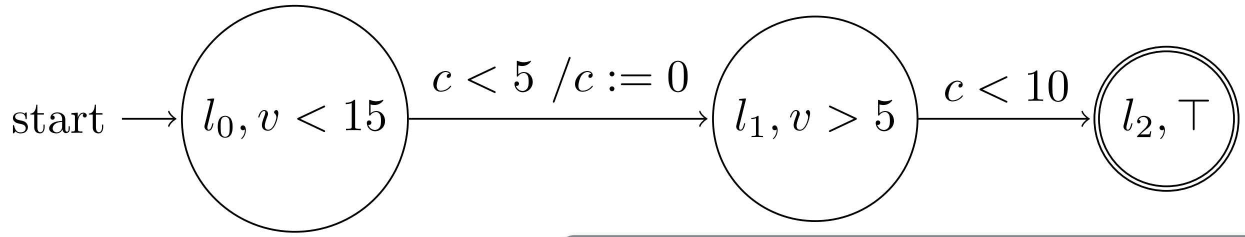
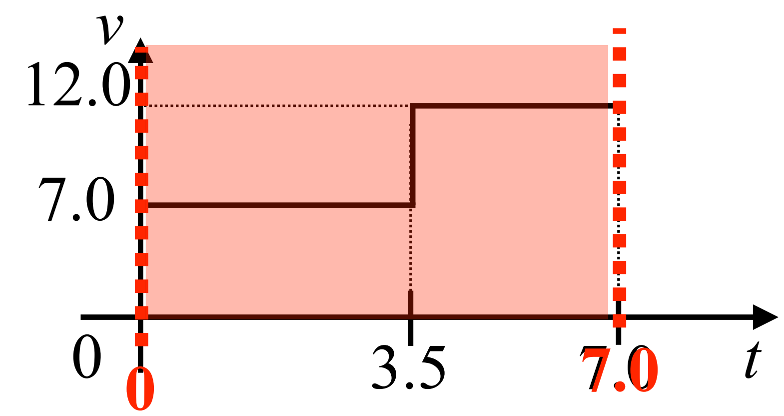


Zone construction with weight





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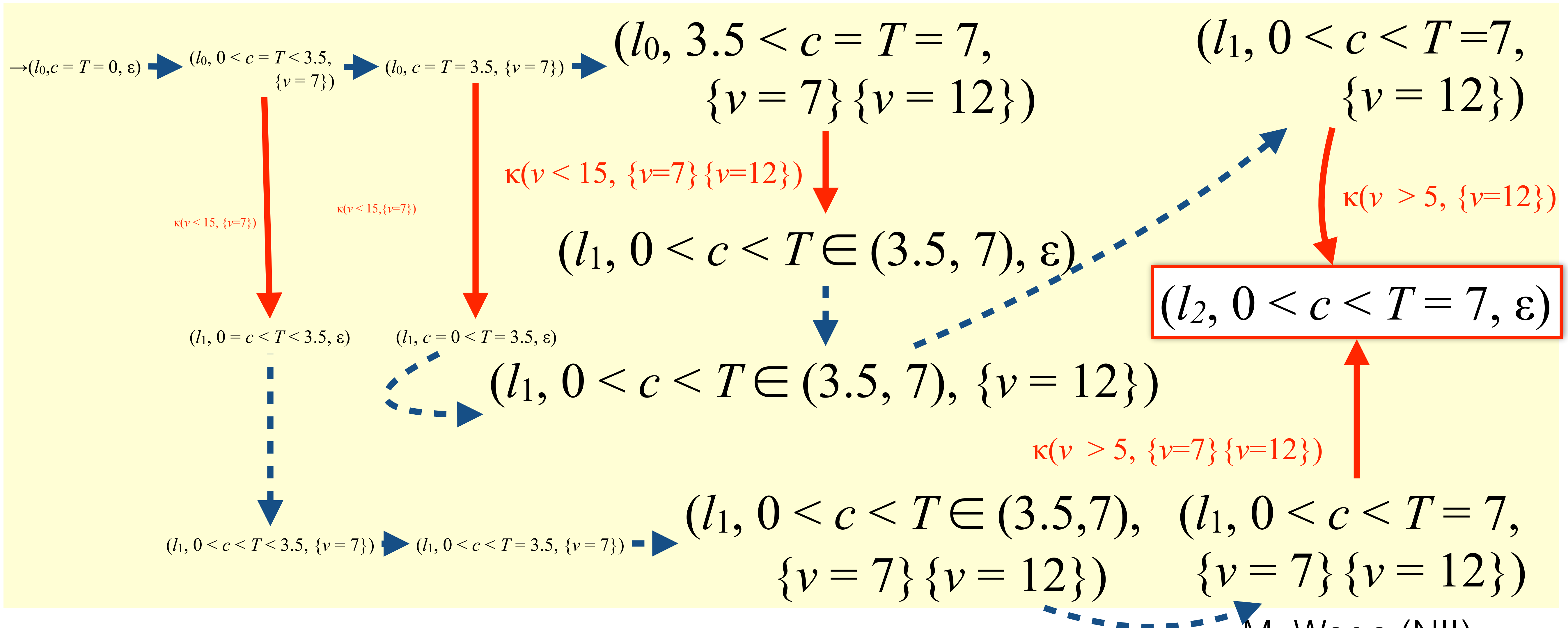

Main Theorem: Correctness

Thm.
The shortest distance in the zone graph with weight is same as the shortest distance in the weighted TTS for any complete and idempotent semiring.

All of them work!!

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

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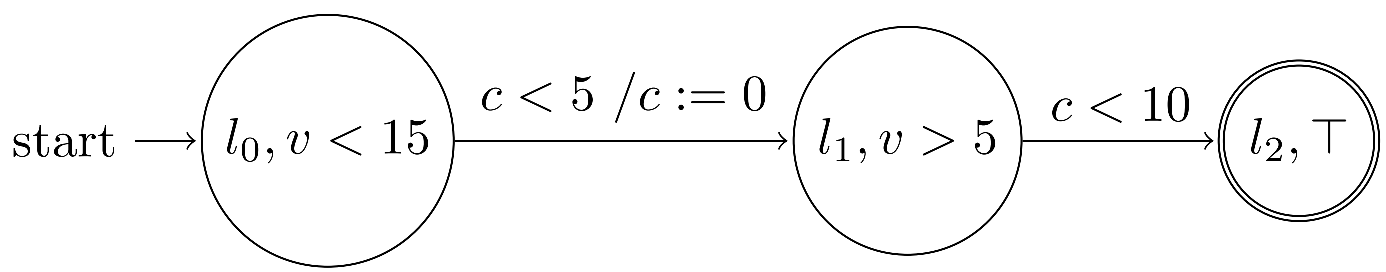
Local Conclusion: Zone Construction with Weight

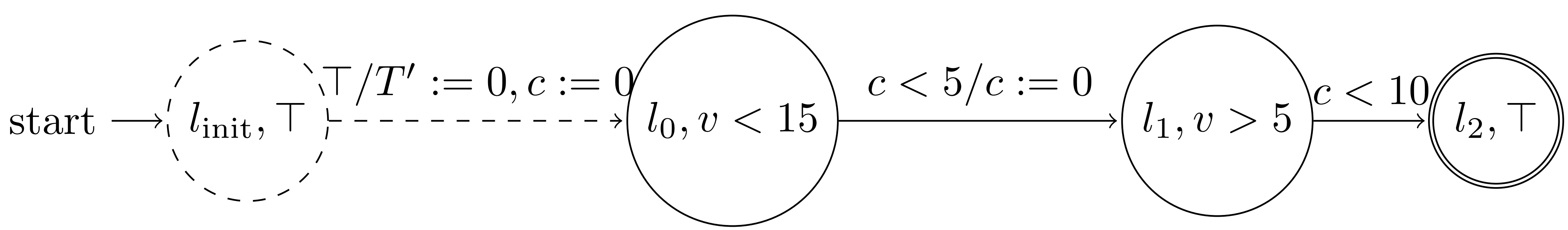
- The construction is basically same as the usual zone construction
- Weights are same as weighted TTS
- The state space is **finite** thanks to **zones** and **finite horizon** of the input signal

Matching Automata for Pattern Matching

[Bakhirkin+, FORMATS’18]



- Add l_{init} to wait for the beginning of the matching
- Add clock variable T’ for the beginning of the matching



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Outline

- Motivation + Introduction
- Technical Part
  - Timed symbolic weighted automata (TSWA)
    - TSWA: TA with signal constraints + weight function
  - Quantitative monitoring/timed pattern matching algorithm
    - Idea: zone construction with weight
- Experiments

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Environment of Experiments

- **Semirings**: sup-inf ($\mathbb{R} \cup \{\pm \infty\}$, sup, inf) and **tropical** ($\mathbb{R} \cup \{+ \infty\}$, inf, +)
- Used 3 original benchmarks (automotive):
  - Inspired by ST-Lib [Kapinski+, SAE Technical Paper'16]
- **Overshoot**: $|v_{\mathrm{ref}} - v|$ gets large after v_{ref} changed
  - Only matches the sub-signals of **length < 150 time units**
- **Ringing**: $v(t) - v(t\text{-}10)$ gets positive and negative repeatedly
  - Only matches the sub-signals of **length < 80 time units**
- **Overshoot (unbounded)**: $|v_{\mathrm{ref}} - v|$ gets large after v_{ref} changed
  - No such *bounded*
- Amazon EC2 c4.large instance / Ubuntu 18.04 LTS (64 bit)
  - 2.9 GHz Intel Xeon E5-2666 v3, 2 vCPUs, 3.75 GiB RAM

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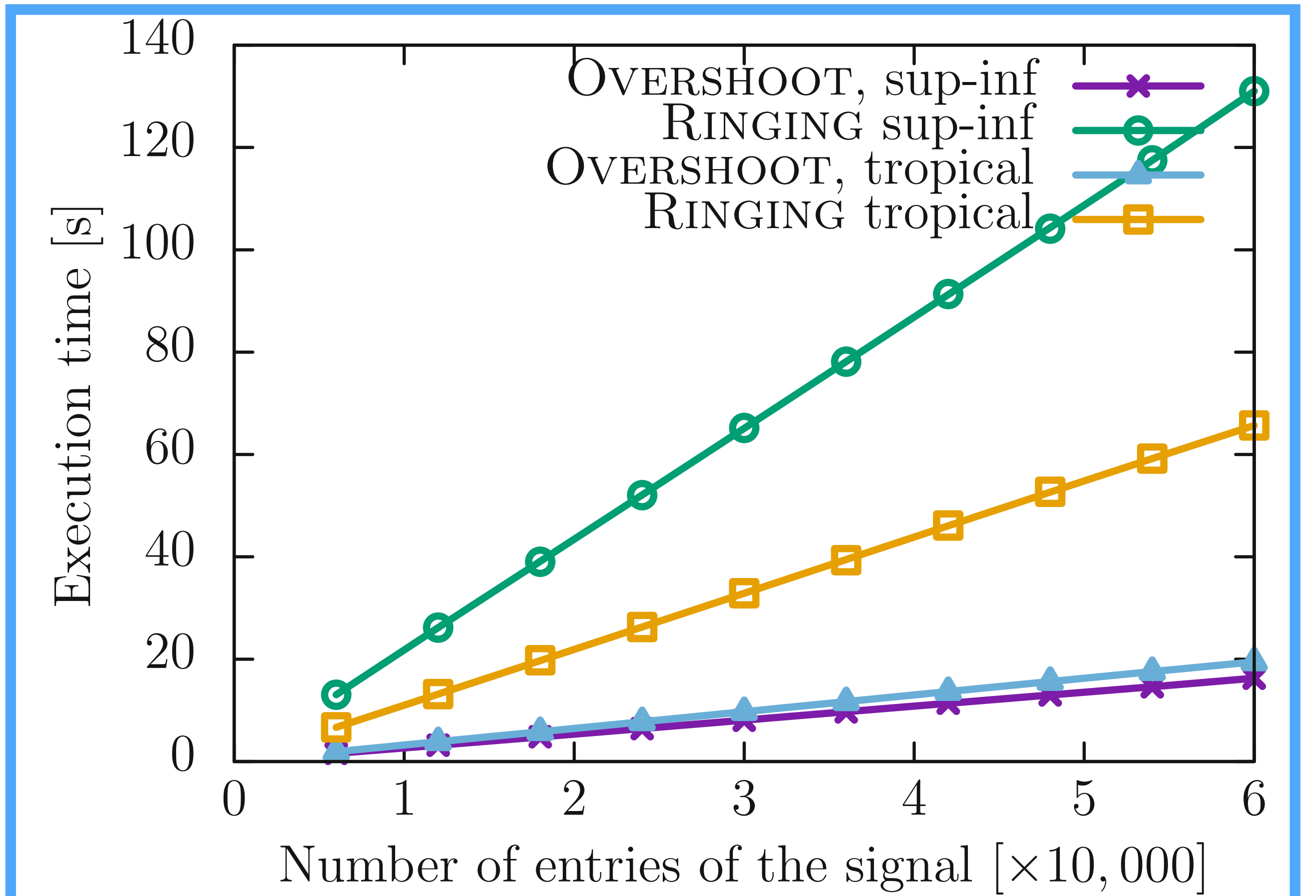
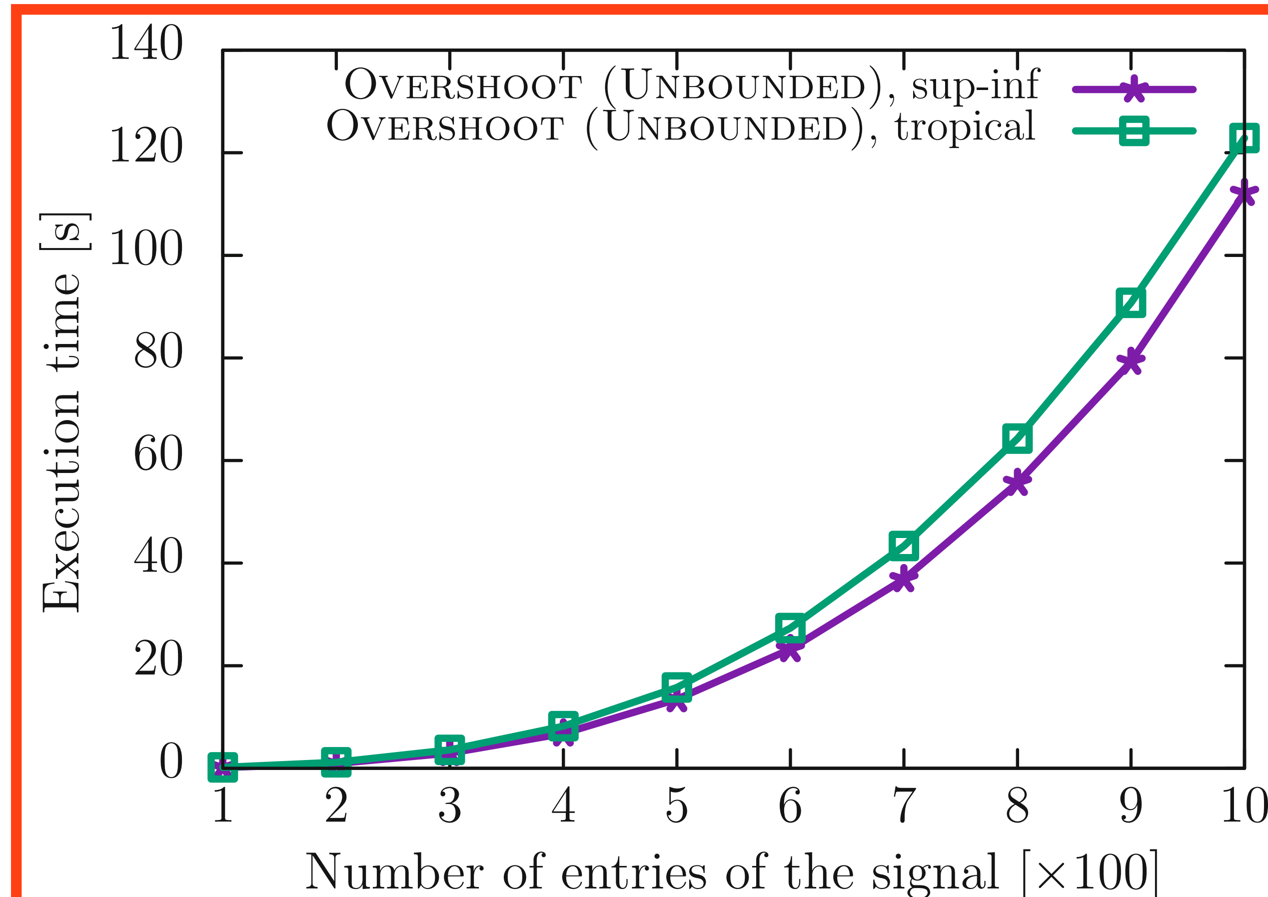
Execution Time

Bounded



Unbounded



- Execution time is **linear** for the bounded spec.
  - 1,000 entries / 1 or 2 sec.
- Execution time explodes for the unbounded spec.

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Conclusion

- Introduced timed symbolic weighted automata **(TSWA)**
  - **TSWA**: TA with signal constraints + weight function
- Gave quantitative monitoring/timed pattern matching algorithm
  - **Idea**: zone construction with weight
- Implementation + experiments
  - **scalable** for bounded specifications

Appendix

Example: "Robust" Semantics

Weight Function: minimum distance from the threshold

$$\kappa_r\bigl(u,(a_1 a_2 \dots a_m)\bigr) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(u,(a_i))$$

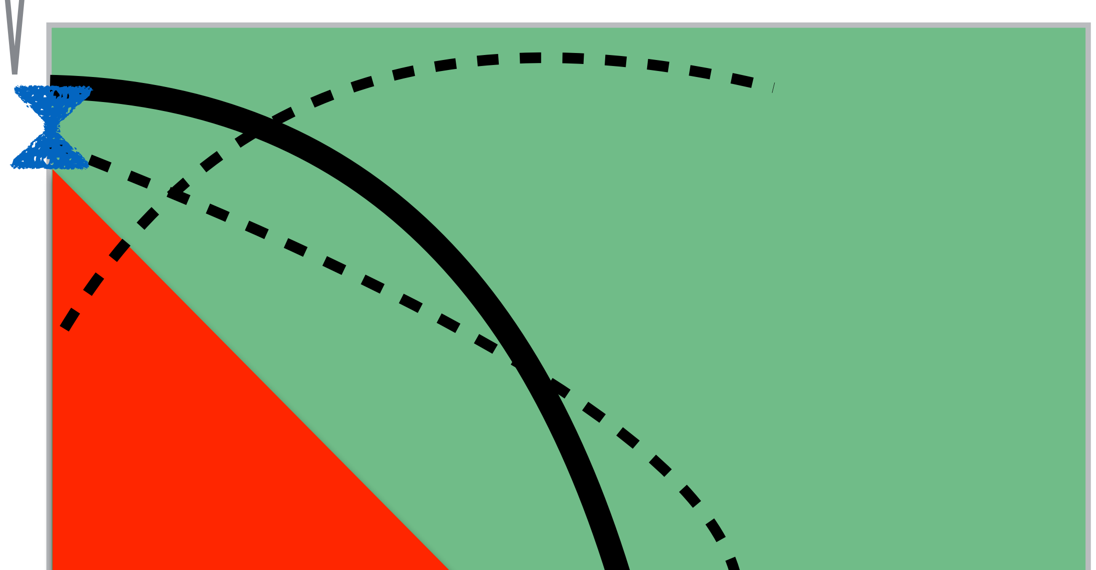
$$\kappa_r\Bigl(\bigwedge_{i=1}^{n}(x_i \bowtie_i d_i),(a)\Bigr) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(x_i \bowtie_i d_i,(a)) \text{ where } \bowtie_i \in \{>,\geq,\leq,<\}$$

$$\kappa_r(x \succ d,(a)) = a(x) - d \quad \text{where } \succ \in \{\geq,>\}$$

$$\kappa_r(x \prec d,(a)) = d - a(x) \quad \text{where } \prec \in \{\leq,<\}$$

Robustness

Semiring: sup-inf semiring



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Example: "Robust" Semantics

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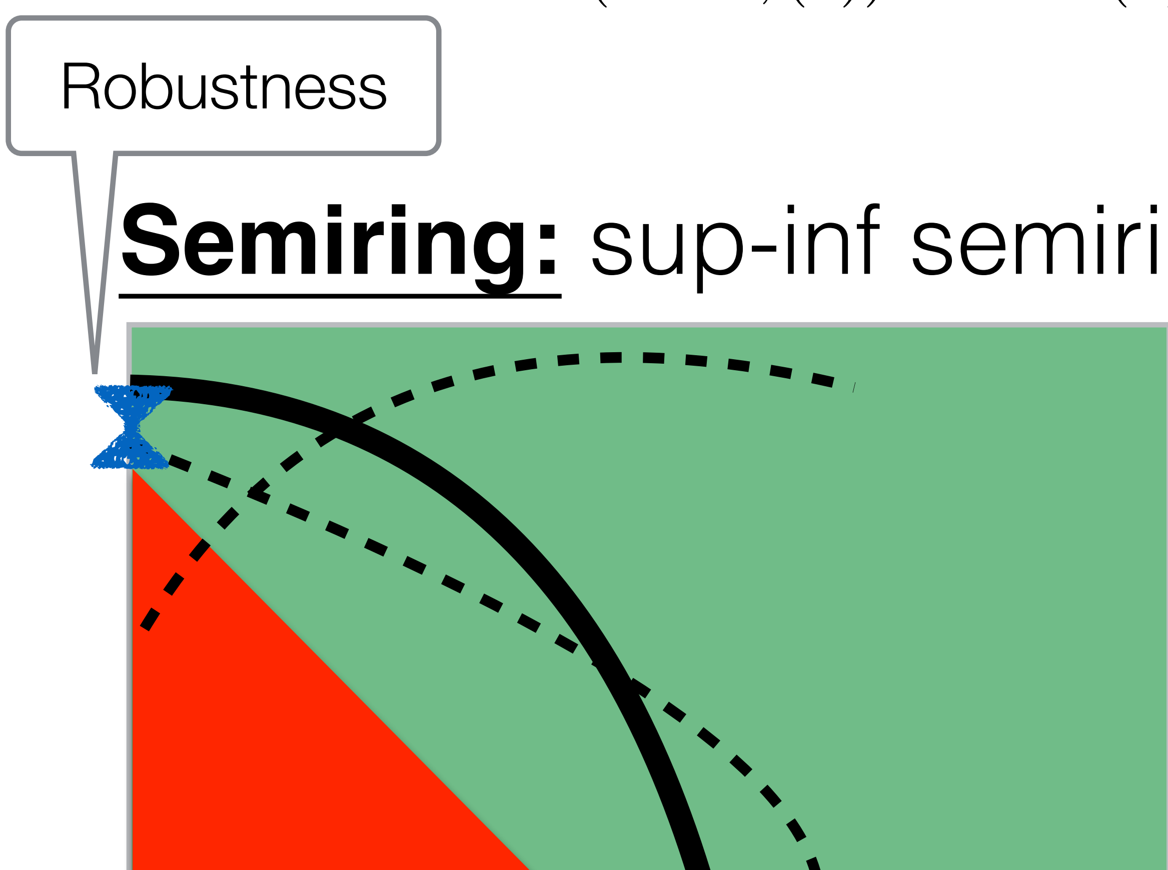
Semiring: sup-inf semiring



	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

Insights: Zone Construction with Weight

- The construction is basically same as the usual zone construction
- The state space is **finite** thanks to **zones** and **finite horizon** of the input signal
- The weight is **constant** because the signal is **piecewise-constant**

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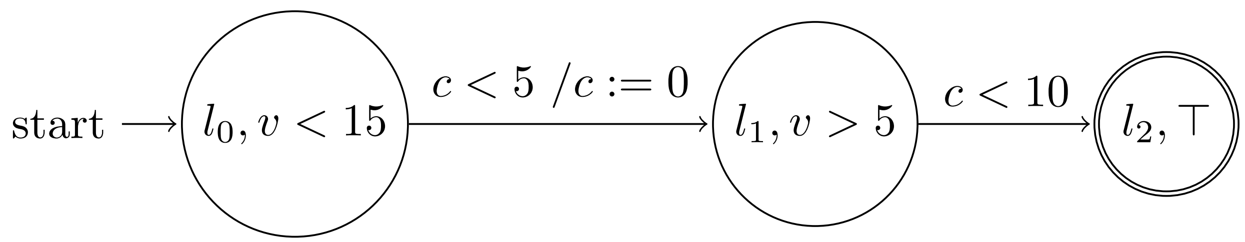
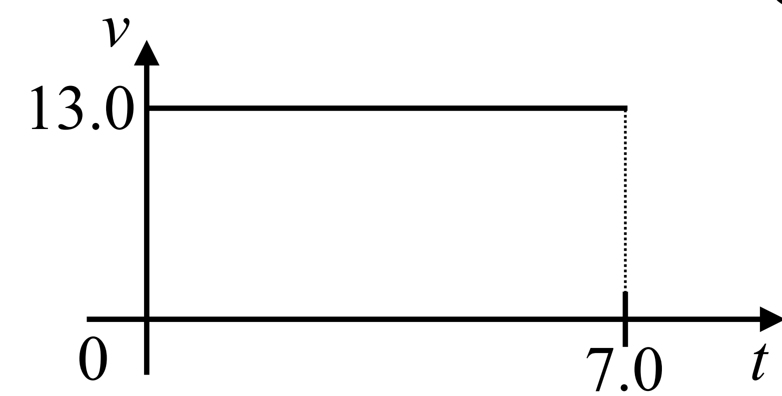
Comparison of the semiring





$\rightarrow (l_0, c{=}0, 0, \varepsilon)$ ⇢ $(l_0, c{=}2, 2, \{v = 7\})$ → $(l_1, c{=}0, 3, \varepsilon)$ ⇢ $(l_1, c{=}5, 7, \{v = 7\}\{v = 12\})$ → $(l_2, c{=}5, 7, \varepsilon)$

$\kappa(v < 15, \{v{=}13\}) = 2 \quad \otimes \quad \kappa(v > 5, \{v{=}13\}) = 8$

Sup-inf semiring

$2 \otimes 8 = \inf(2, 8) = 2$

Tropical semiring

$2 \otimes 8 = 2 + 8 = 10$

	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$