Online Quantitative Timed Pattern Matching with Semiring-Valued Weighted Automata

Masaki Waga

Kyoto University

12 May 2021, YR-OWLS

Based on the paper at FORMATS'19

Monitoring

Online Quantitative Timed Pattern Matching with Semiring-Valued Weighted Automata

Masaki Waga

Kyoto University

12 May 2021, YR-OWLS

Based on the paper at FORMATS'19

Safety Critical CPSs

Self-driving car crash in Arizona: Red light runner hits Waymo van

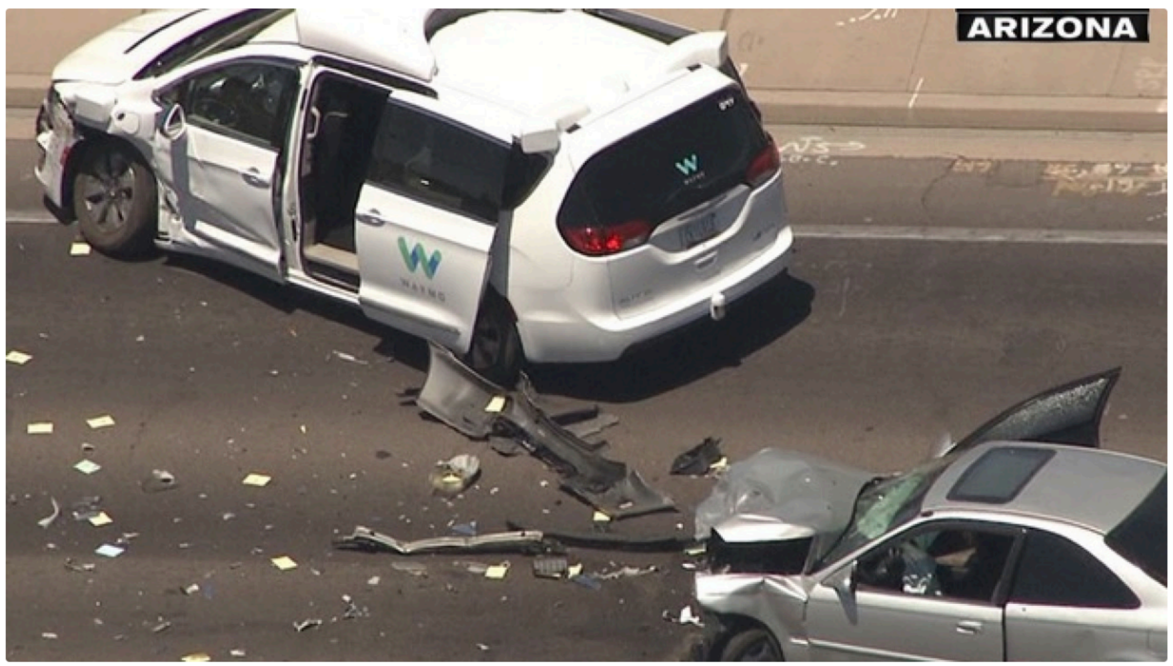


Photo by: Air15

BBC Sign in | News | Sport | Reel | Worklife | Travel | Future | M

NEWS

Home | Video | World | Asia | UK | Business | Tech | Science | Stories | Entertainment &

Technology

Tesla Model 3: Autopilot engaged during fatal crash

17 May 2019 Share

The Tesla Model 3 after the crash

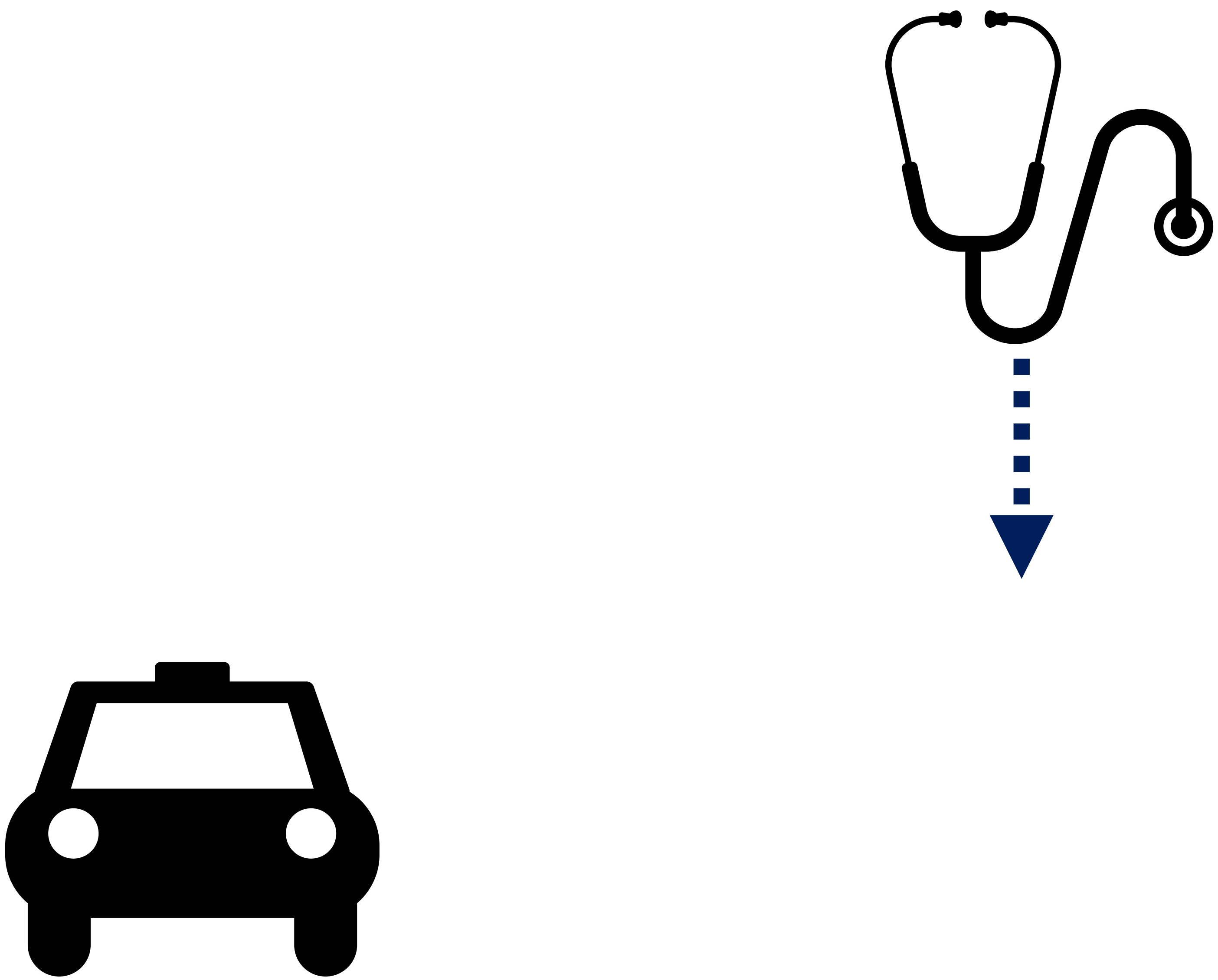
https://www.abc15.com/news/region-southeast-valley/chandler/waymo-car-involved-in-chandler-arizona-crash

https://www.bbc.com/news/technology-48308852

Monitoring

Specification:

No (RPM > 4000) for > 1 sec.

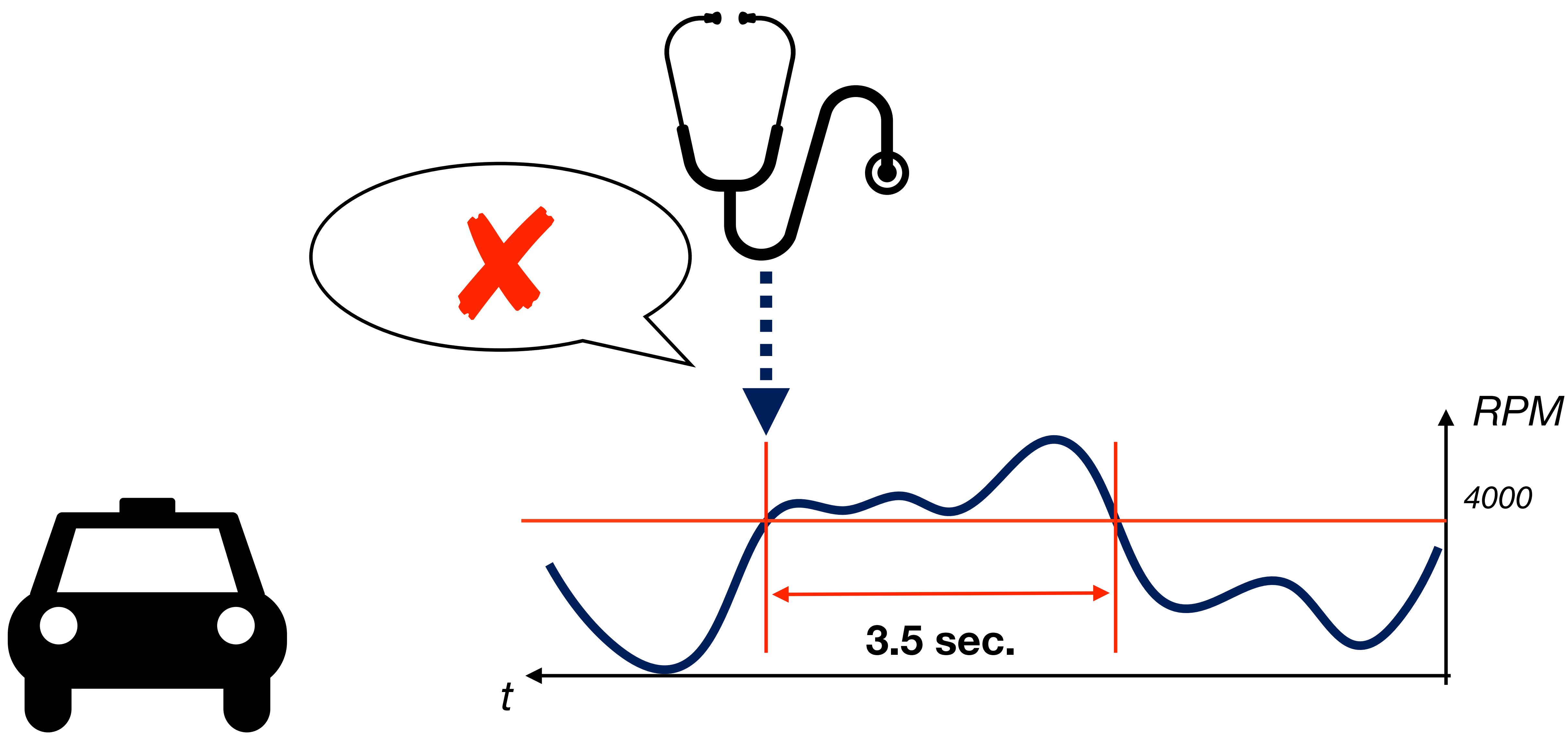


M. Waga (Kyoto U.)

Monitoring

Specification:

No (RPM > 4000) for > 1 sec.



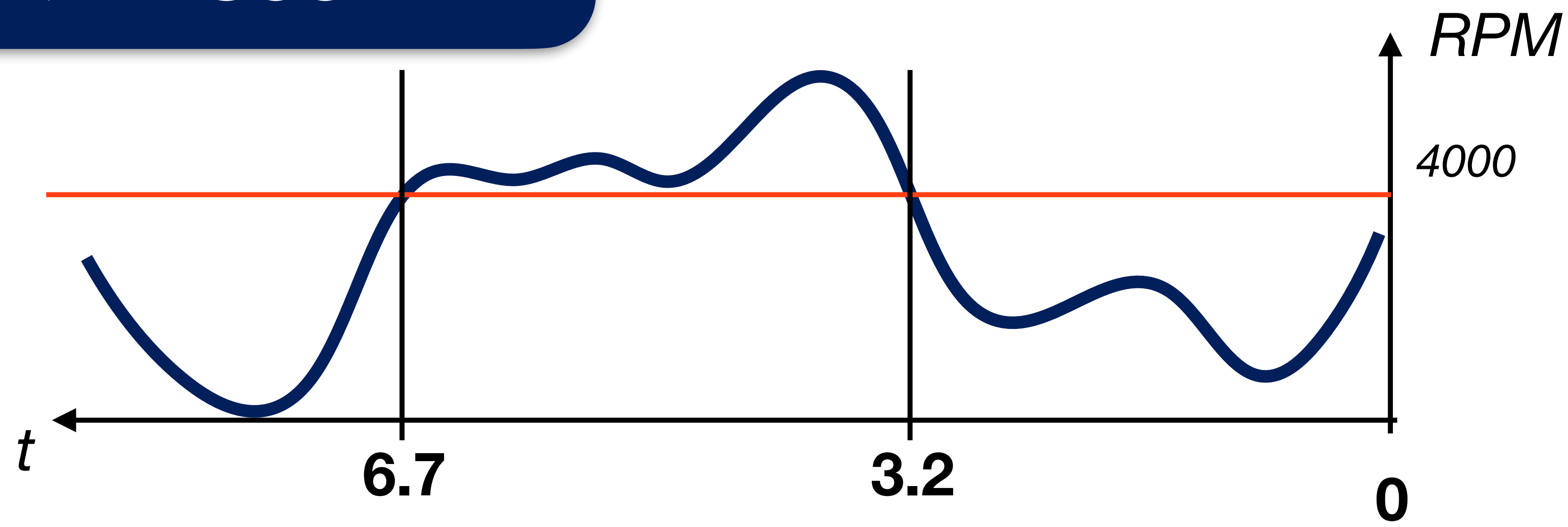
Timed Pattern Matching

[Ulus+, FORMATS'14]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals

Pattern Specification:
(RPM > 4000) for > 1 sec.



Timed Pattern Matching

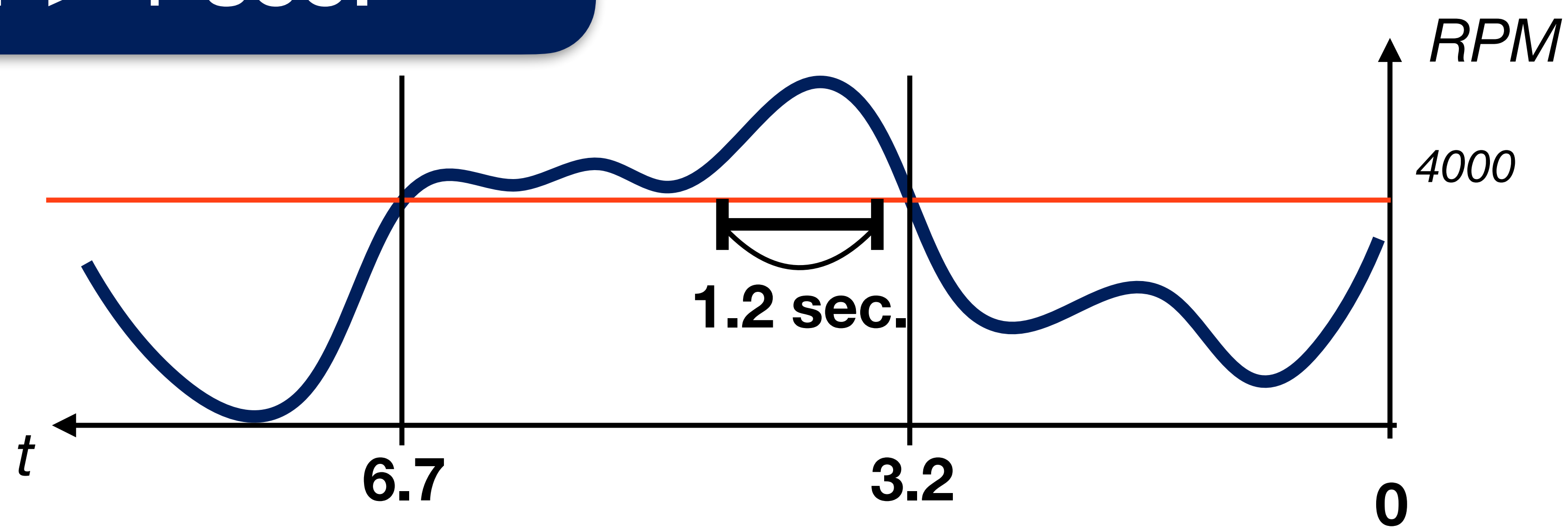
[Ulus+, FORMATS'14]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals

Pattern Specification:

(RPM > 4000) for > 1 sec.



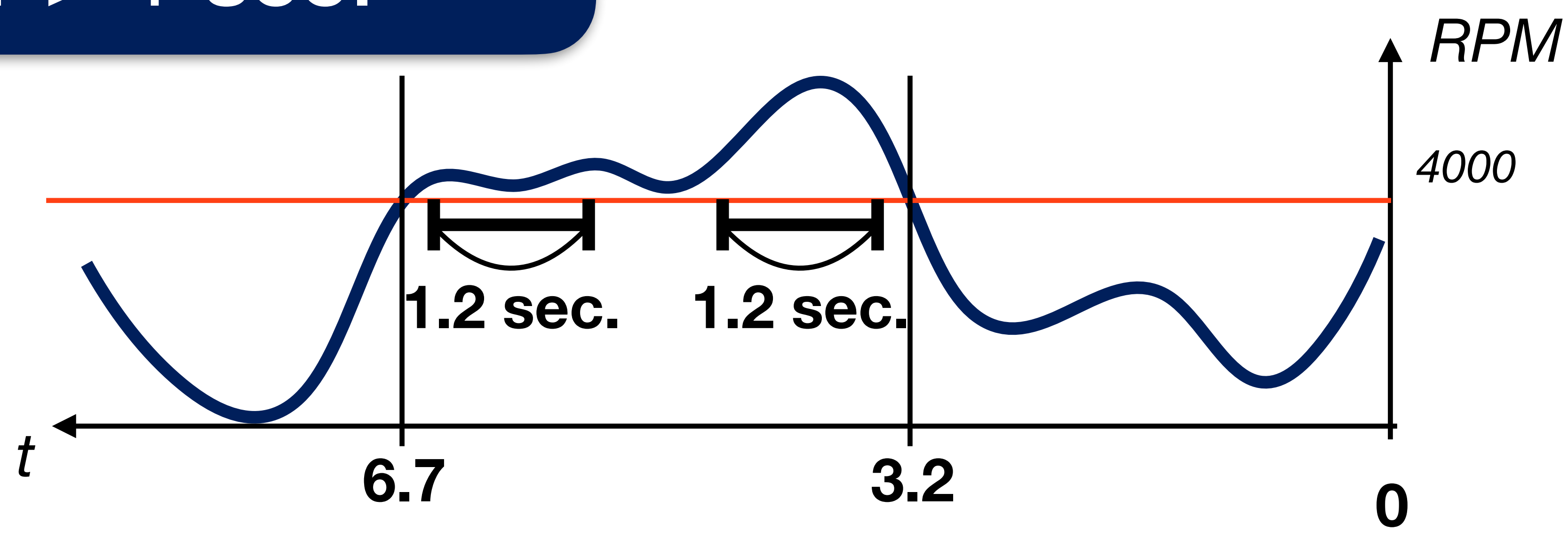
Timed Pattern Matching

[Ulus+, FORMATS'14]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals

Pattern Specification:
(RPM > 4000) for > 1 sec.



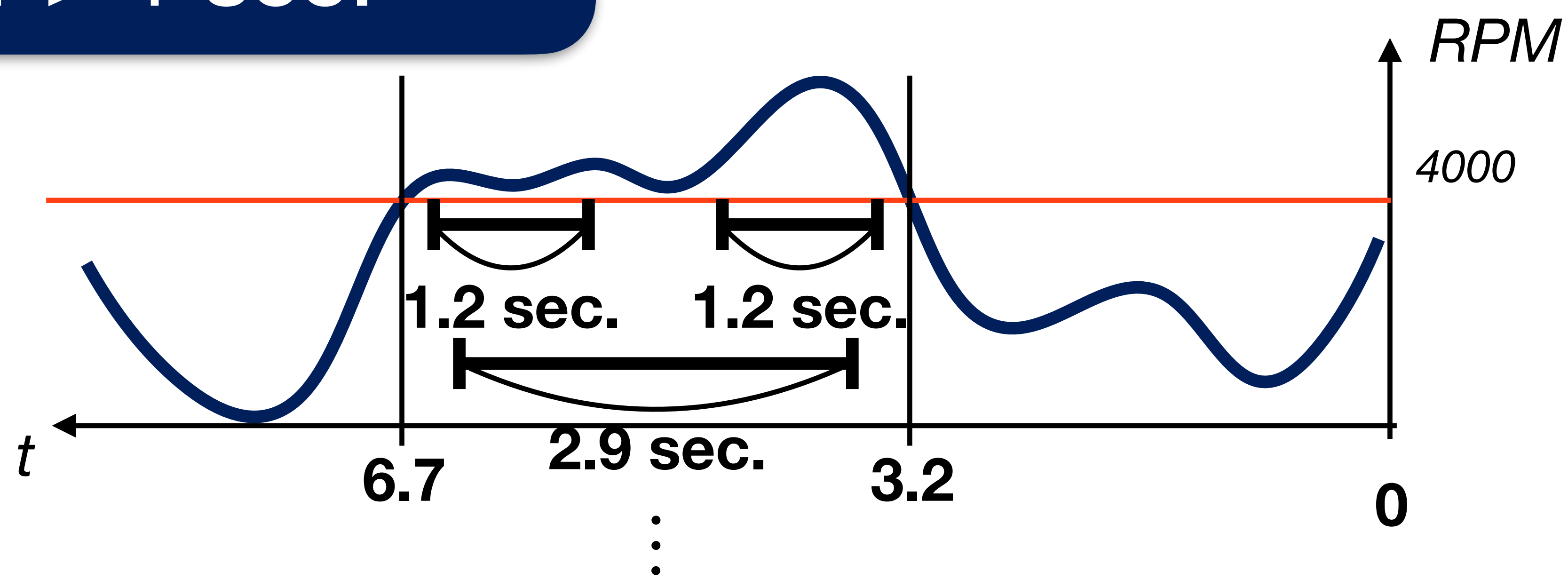
Timed Pattern Matching

[Ulus+, FORMATS'14]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals

Pattern Specification:
(RPM > 4000) for > 1 sec.



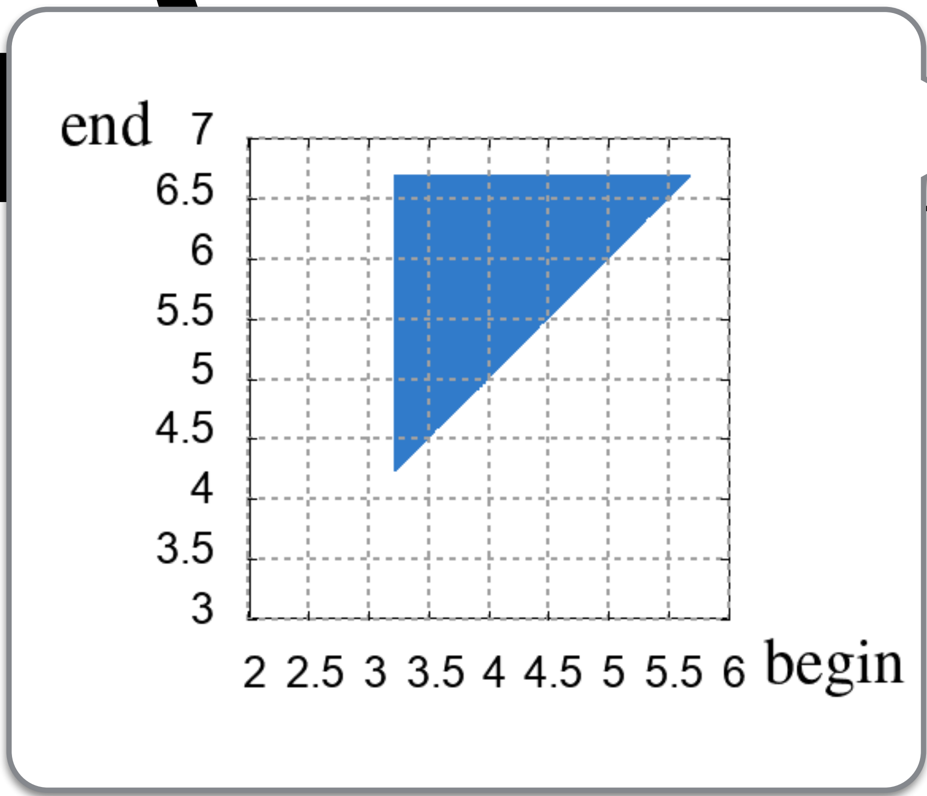
Timed Pattern Matching

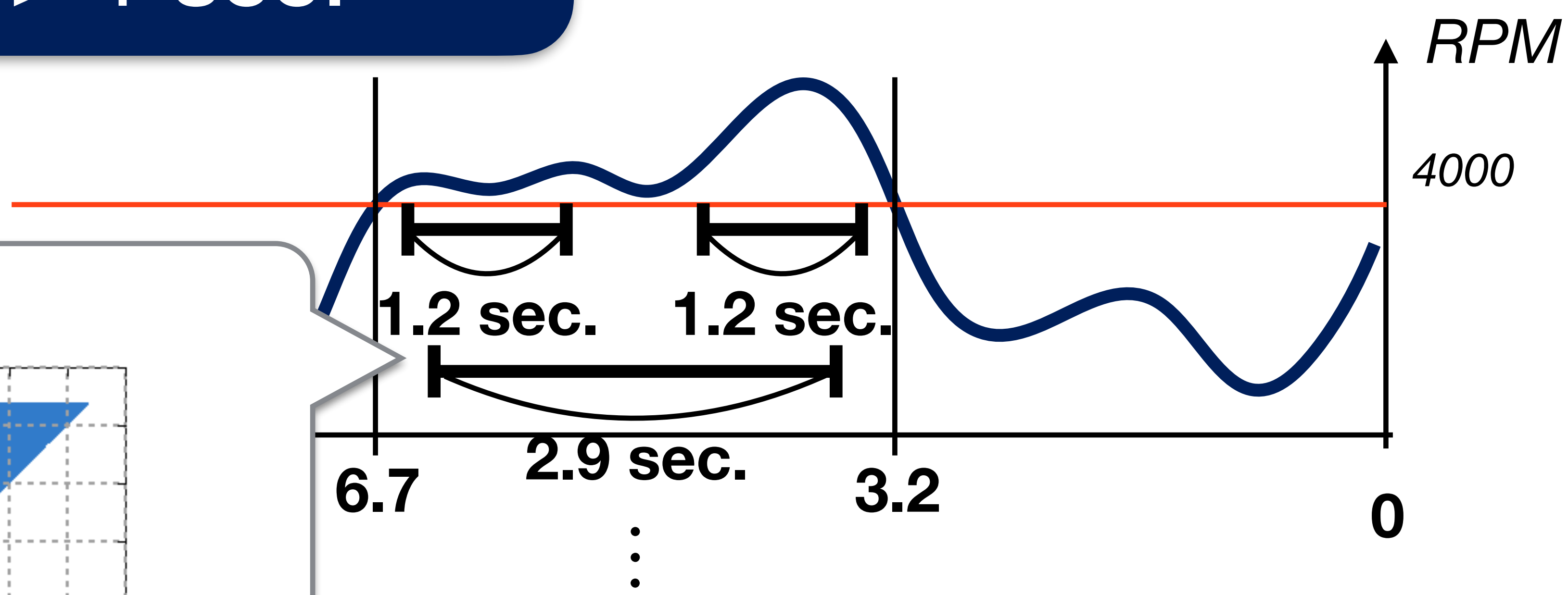
[Ulus+, FORMATS'14]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals

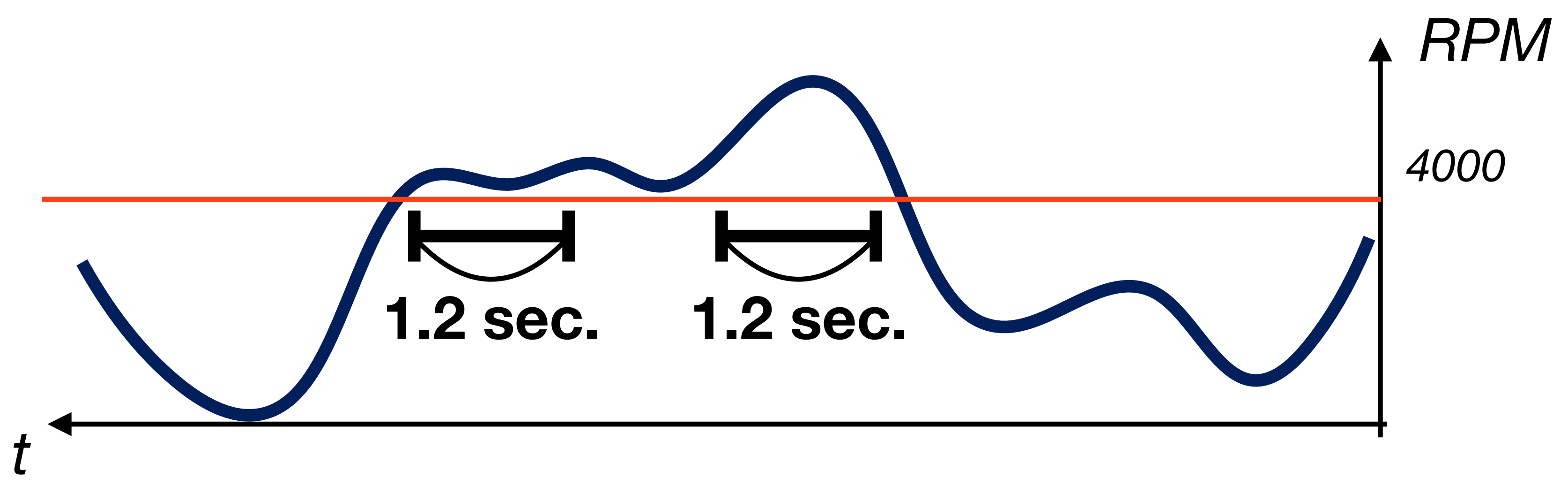
Pattern Specification:
(RPM > 4000) for > 1 sec.





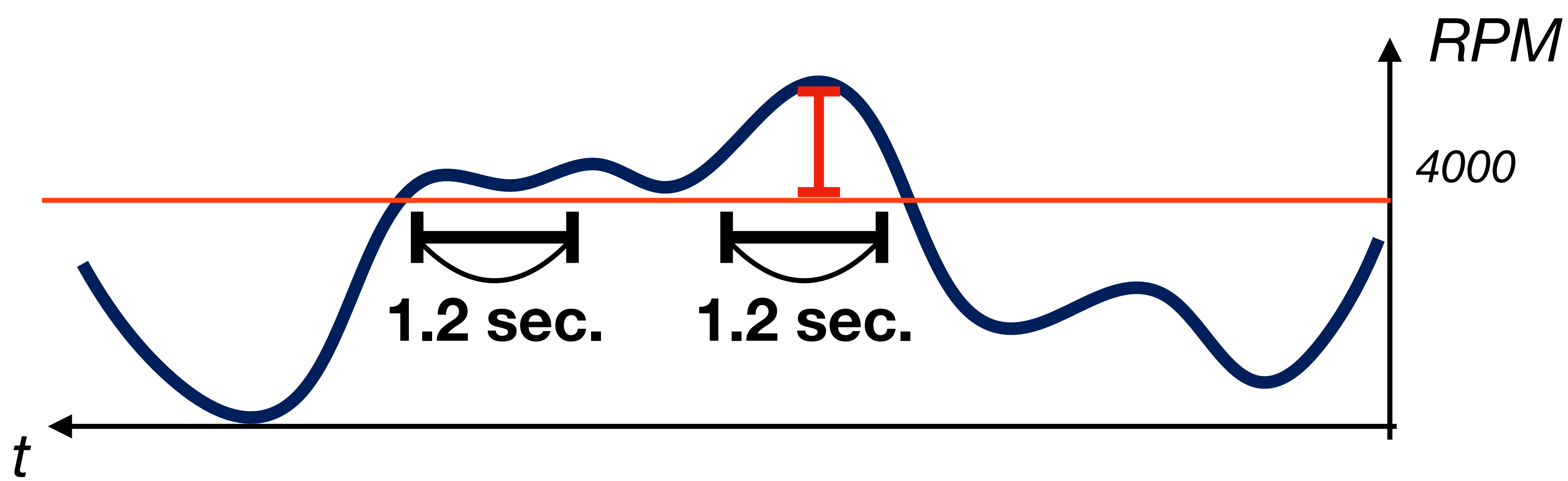
Qualitative → Quantitative

Pattern Specification:
(RPM > 4000) for > 1 sec.



Qualitative → Quantitative

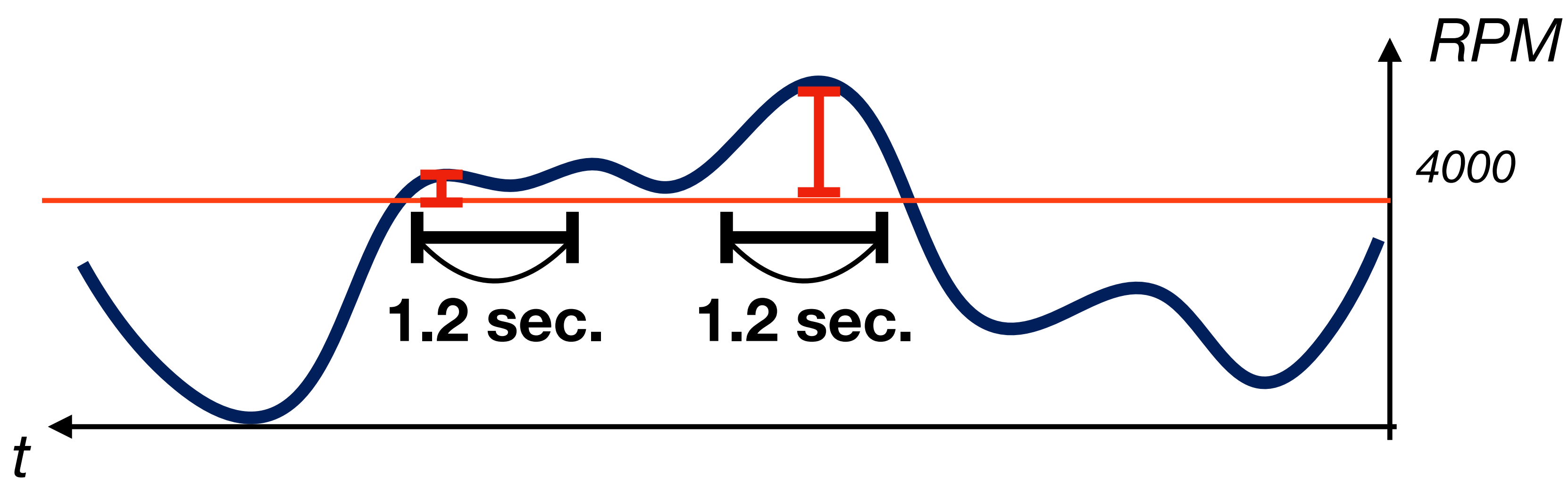
Pattern Specification:
(RPM > 4000) for > 1 sec.



Qualitative → Quantitative

Pattern Specification:

(RPM > 4000) for > 1 sec.



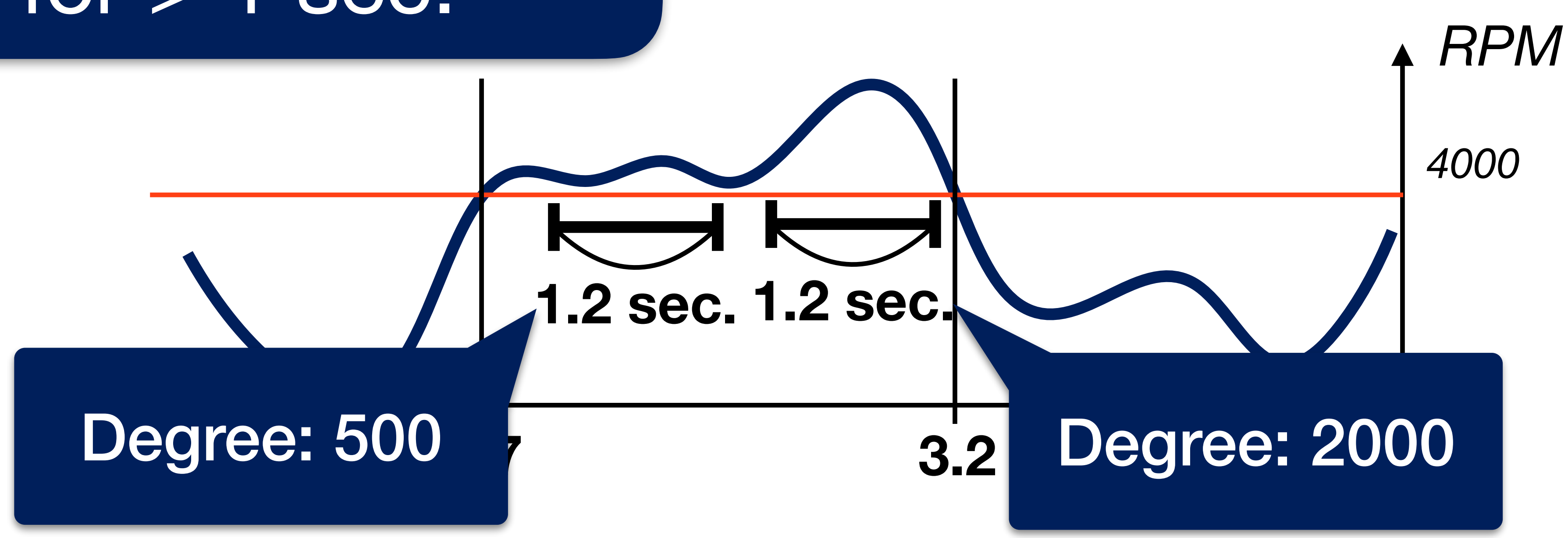
Quantitative Timed Pattern Matching

[Bakhirkin+, FORMATS'17]

Given: Signal and Pattern Spec.

Goal: Find all the matching intervals + ***satisfaction degree***

Pattern Specification:
(RPM > 4000) for > 1 sec.

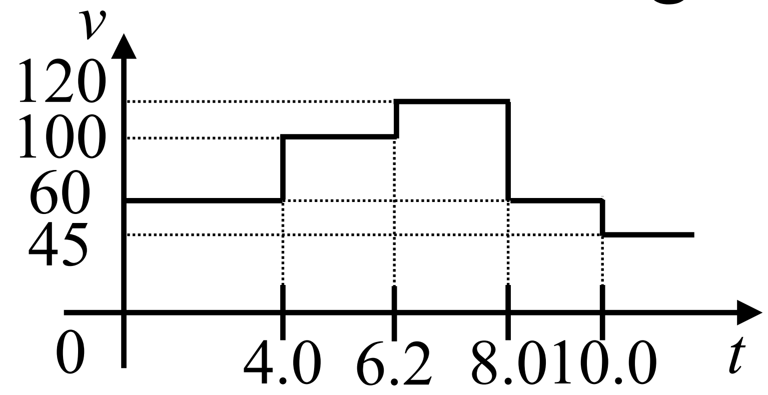


Quantitative Timed Pattern Matching

[Bakhirkin+, FORMATS'17]

Input

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



- **Pattern Specification** $\mathscr{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep **> 80** for > 1 sec.

Output

- **Function** assigning the satisfaction degree to each **subsignal** $\sigma([t,t'))$
  - e.g., $\mathscr{M}(\sigma, \mathscr{W})(2.0,4.0)$ = -20, $\mathscr{M}(\sigma, \mathscr{W})(6.5,7.8)$ = 40, …

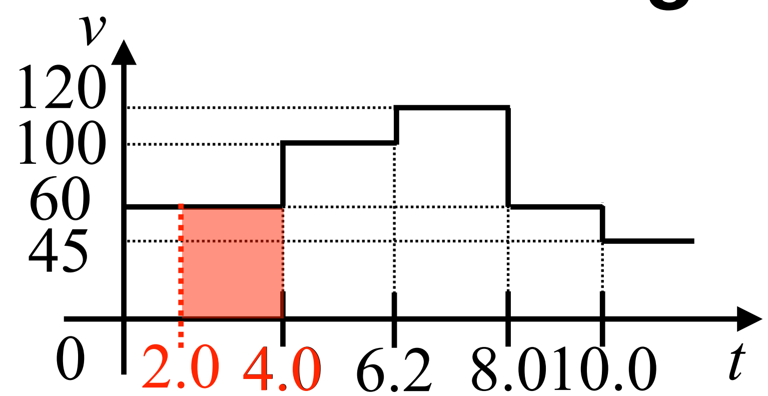
satisfaction degree of $\mathscr{W}$ for $\sigma([2.0,4.0))$

Quantitative Timed Pattern Matching

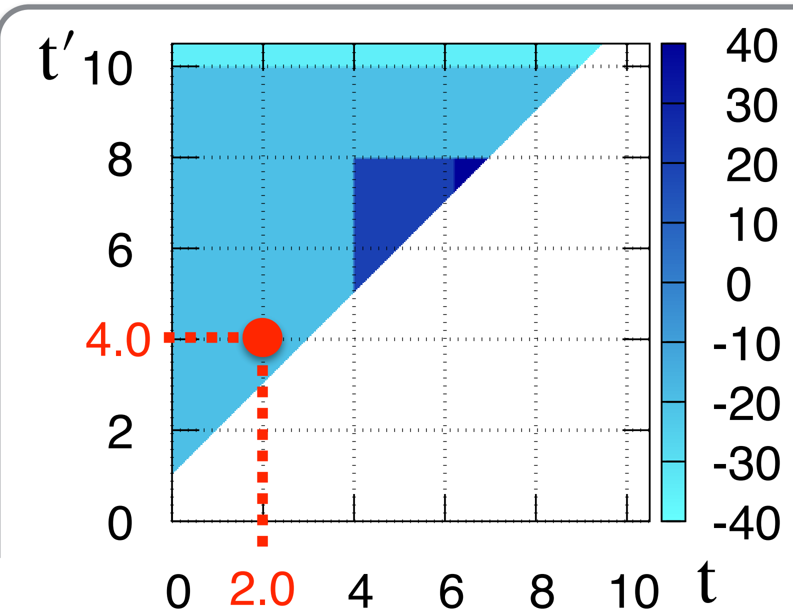
[Bakhirkin+, FORMATS'17]

Input

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



- **Pattern Specification $\mathscr{W}$**
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep **> 80** fo



Output

- **Function** assigning the satisfaction degr to each **subsignal** $\sigma([t,t'))$
  - e.g., $\mathscr{M}(\sigma, \mathscr{W})(2.0,4.0)$ = -20, $\mathscr{M}(\sigma, \mathscr{W})(6.5,7.8)$ = 40, …

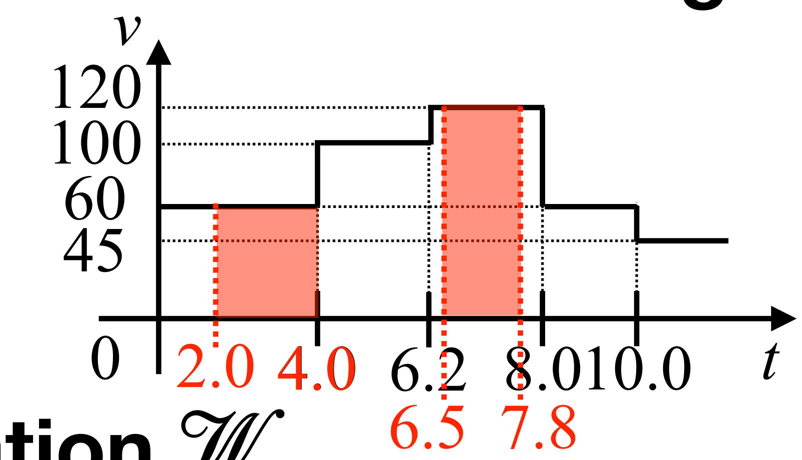
satisfaction degree of $\mathscr{W}$ for $\sigma([2.0,4.0))$

Quantitative Timed Pattern Matching

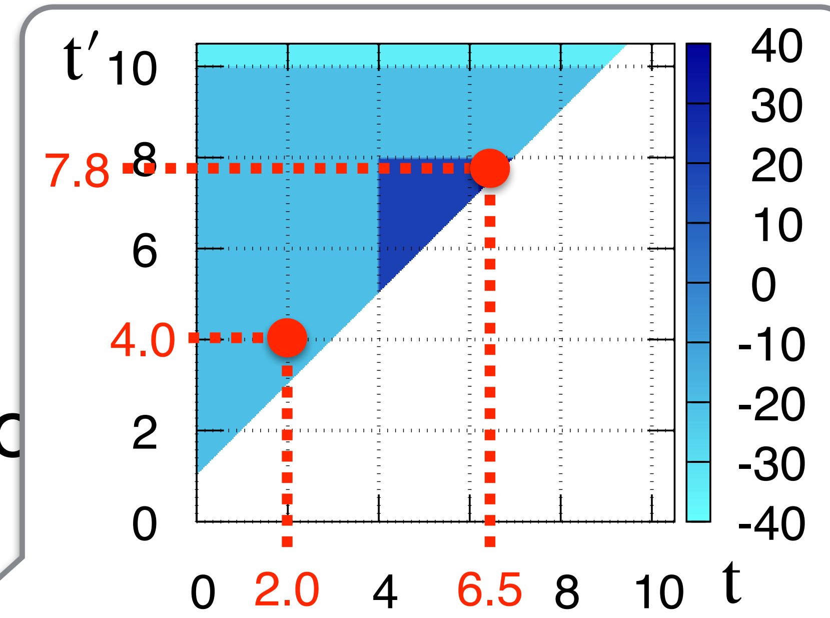
[Bakhirkin+, FORMATS'17]

Input

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



- **Pattern Specification** $\mathscr{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep **> 80** fo



Output

- **Function** assigning the satisfaction degr to each **subsignal** $\sigma([t,t'))$
  - e.g., $\mathscr{M}(\sigma, \mathscr{W})(2.0,4.0)$ = -20, $\mathscr{M}(\sigma, \mathscr{W})(6.5,7.8)$ = 40, …

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

Online Quantitative Timed Pattern Matching with Semiring-Valued Weighted Automata

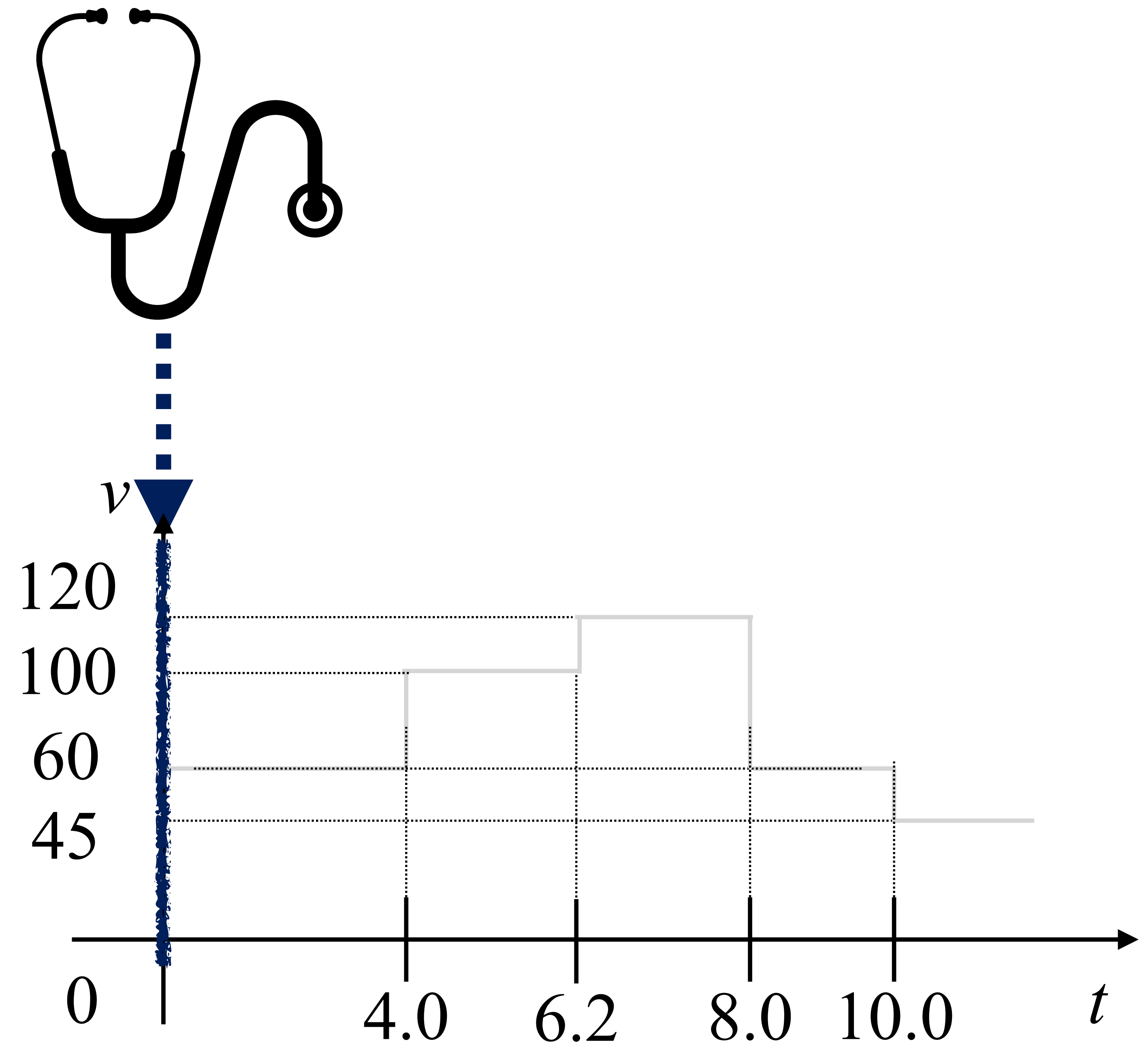
Masaki Waga

Kyoto University

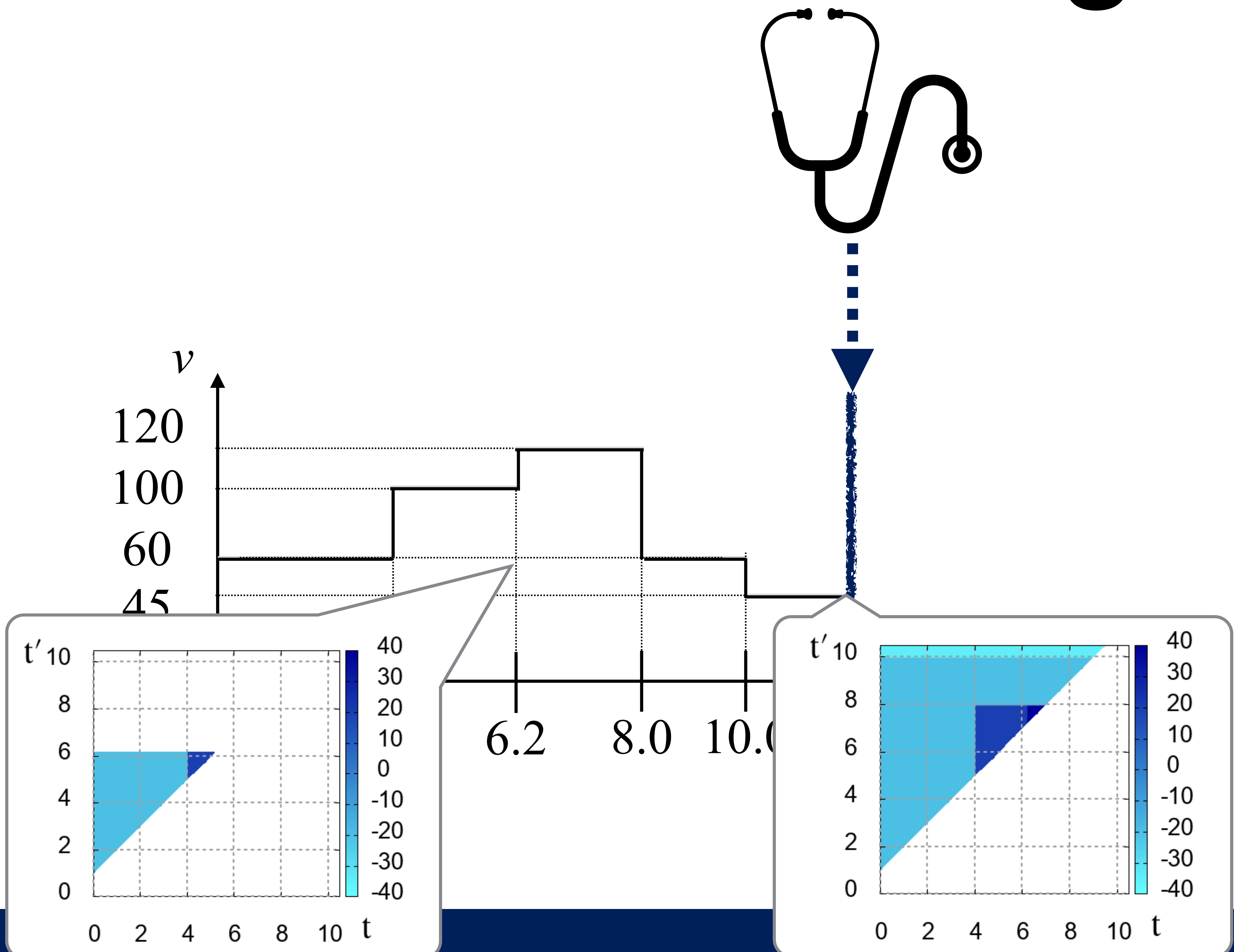
12 May 2021, YR-OWLS

Based on the paper at FORMATS'19

Online Pattern Matching



Online Pattern Matching



Online Quantitative Timed Pattern Matching with Semiring-Valued Weighted Automata

Masaki Waga

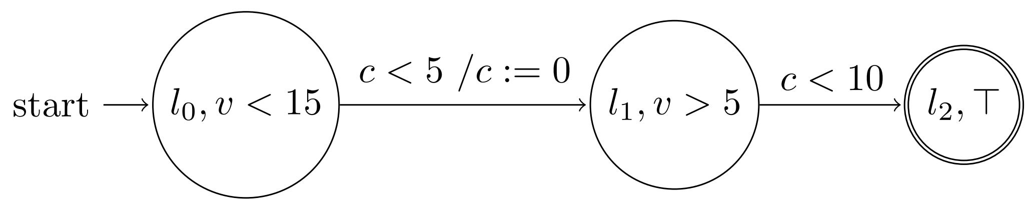
Kyoto University

12 May 2021, YR-OWLS

Based on the paper at FORMATS'19

Timed symbolic weighted automata (TSWA)

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



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

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

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

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

	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**!!

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**

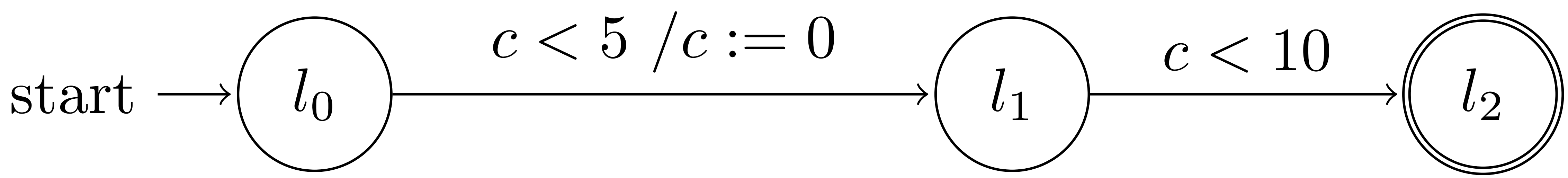
Timed automata → Timed automata with **signal constraints**

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

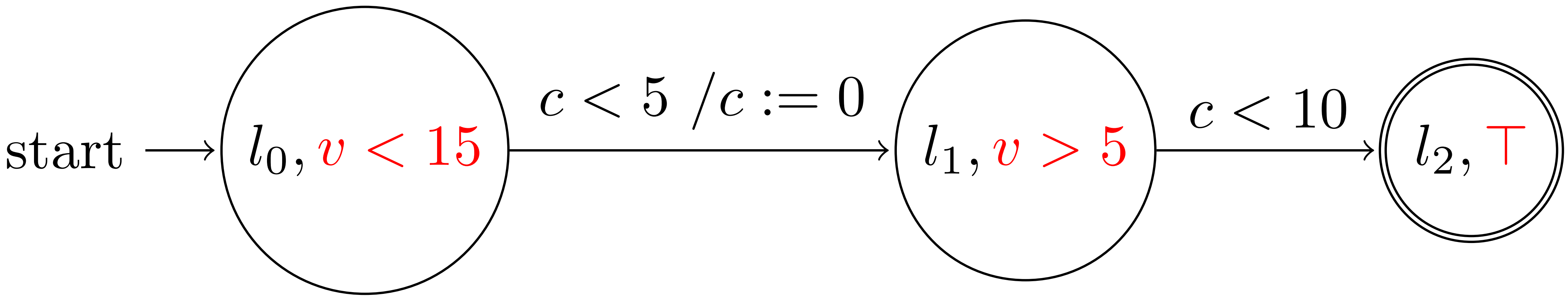
TSWA: TA with signal constraints + weight function

Timed Automaton (TA)



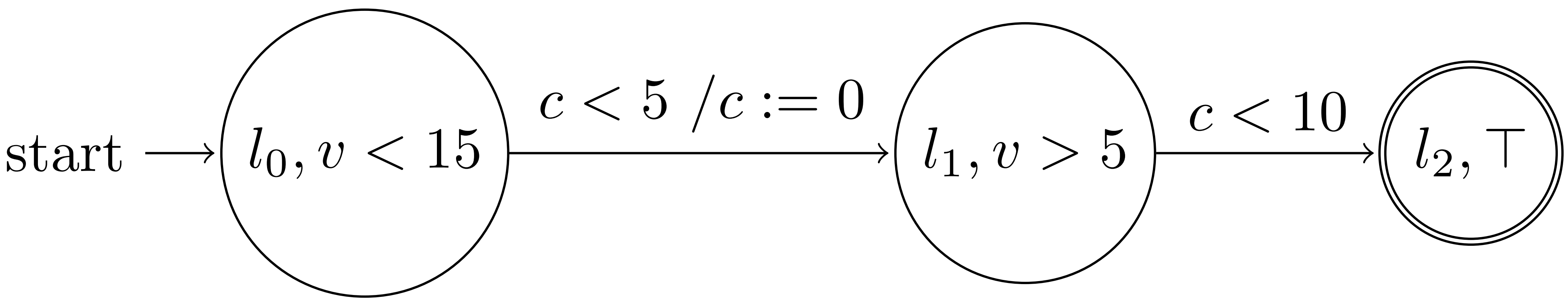
TSWA: TA with signal constraints + weight function

Timed Symbolic Automaton (TSA)



TSWA: TA with signal constraints + weight function

Timed Symbolic Weighted Automaton (TSWA)



+

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

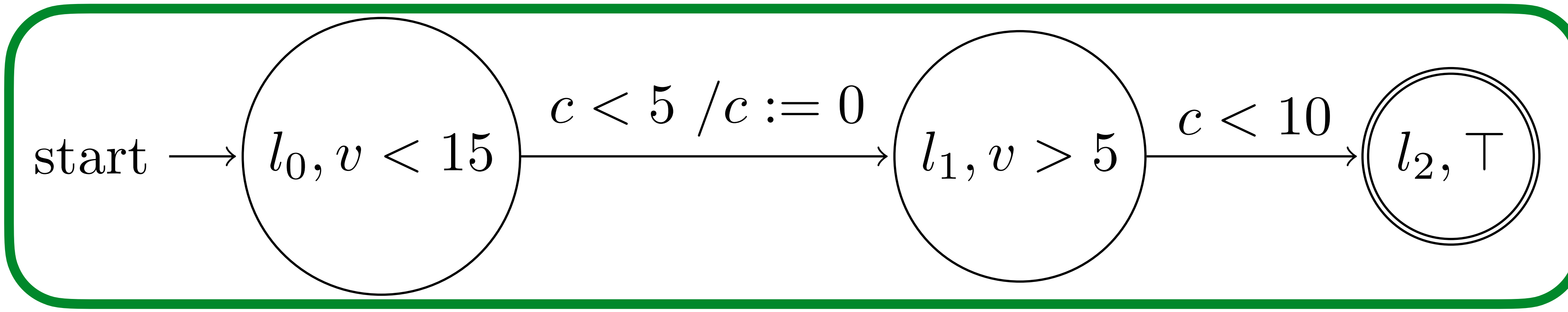
$$\kappa_r\Big(\bigwedge_{i=1}^{n} (x_i \bowtie_i d_i), (a)\Big) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(x_i \bowtie_i d_i, (a)) \text{ where } \bowtie_i \in \{>, \geq, \leq, <\}$$

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

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

TSWA: TA with signal constraints + weight function

Timed Symbolic Weighted Automaton (TSWA)



Automata structure

+

Quantitative semantics

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

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

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

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

Weight function

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

Constraints on signal values at the location

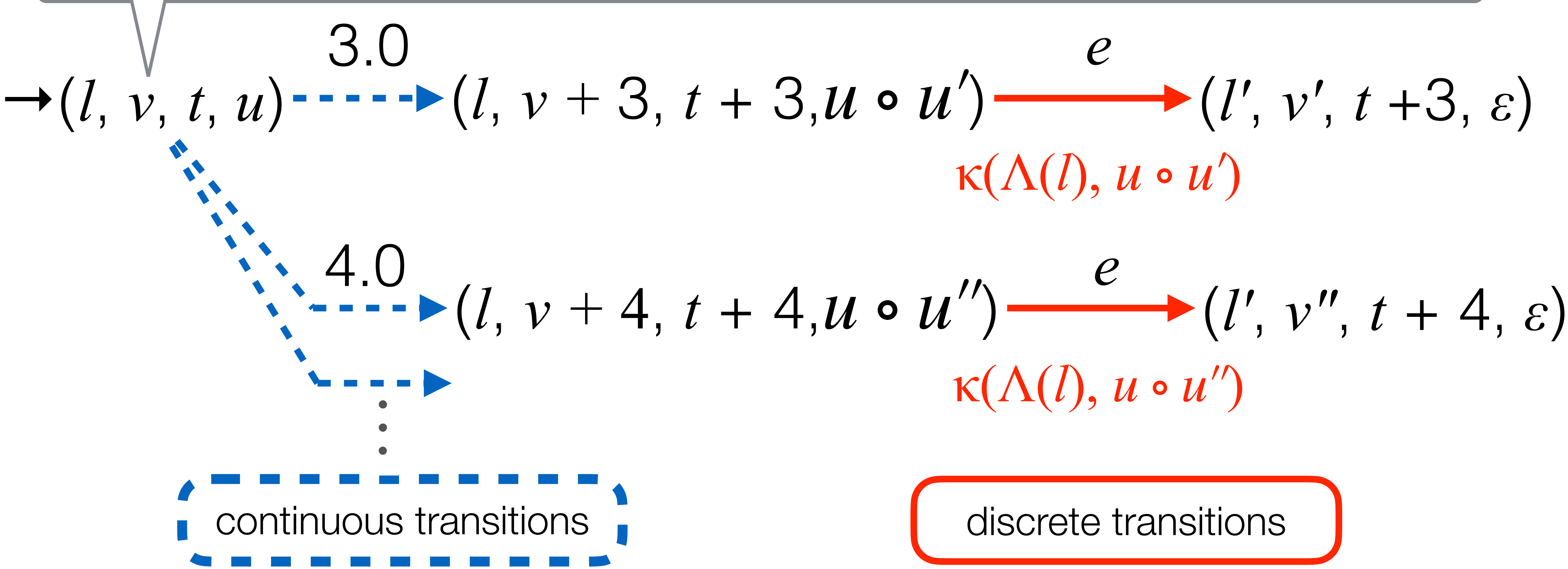
Sequence of signal values at the location

Semiring value

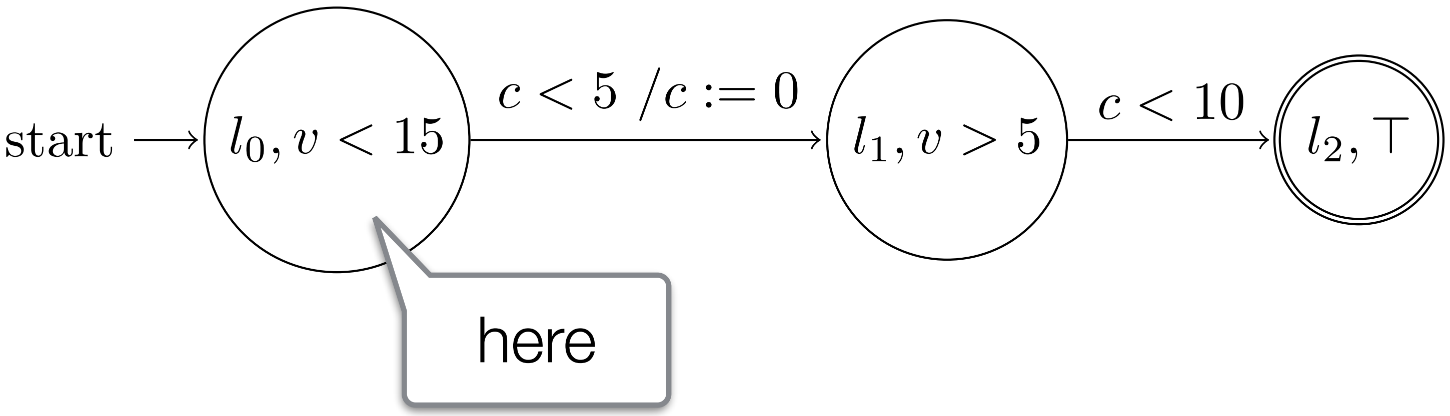
- $\kappa(\Lambda(l),u)$: weight for the stay at l with signal values u
- Semiring: set S with accumulating operators $\oplus$ and $\otimes$
- We can use any complete and idempotent semiring

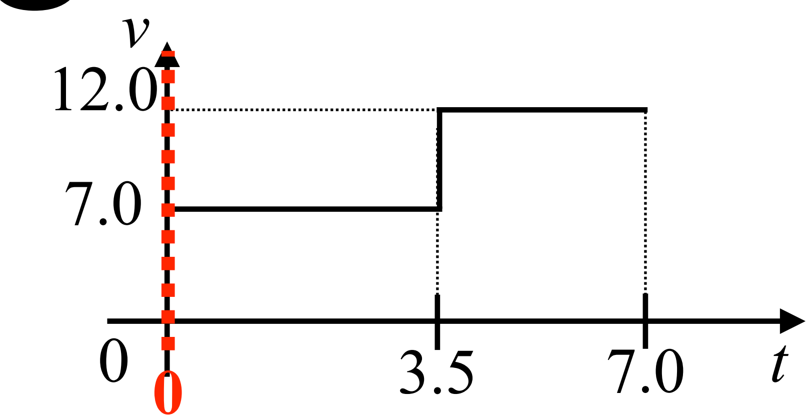
Semantics: Weighted TTS

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



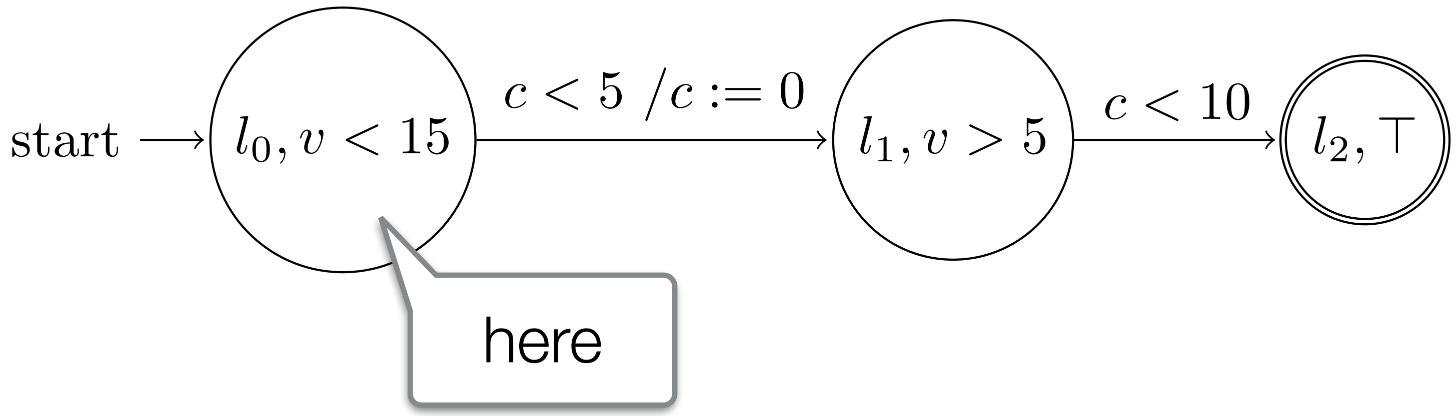
One path in Weighted TTS

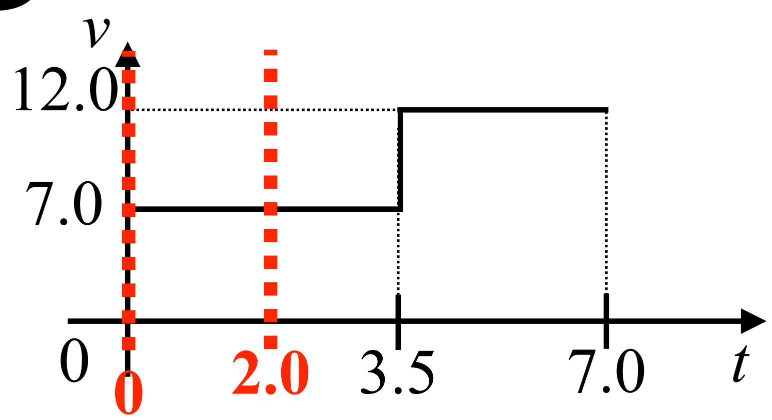




→(l_0, c=0, 0,ε)

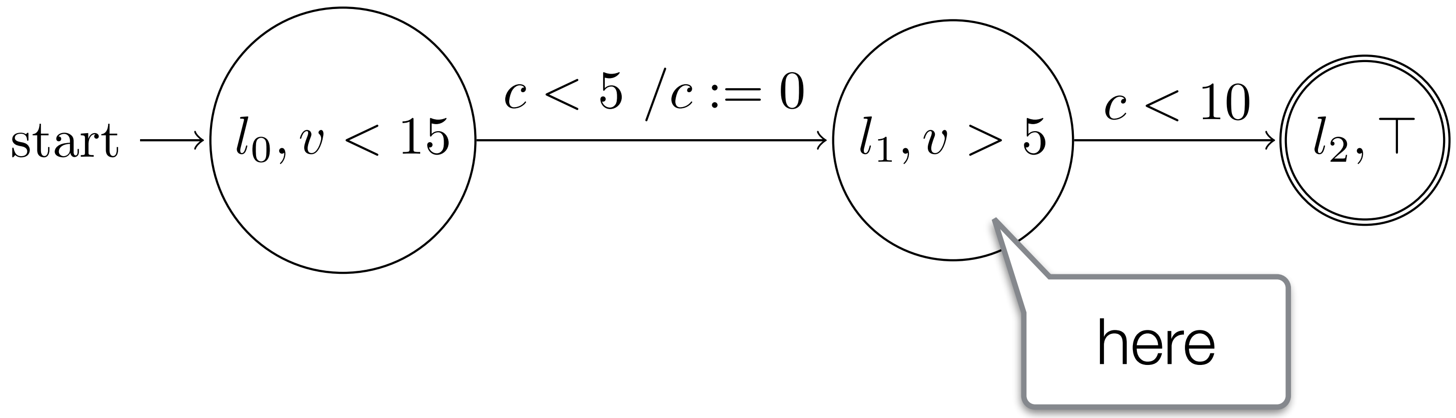
One path in Weighted TTS

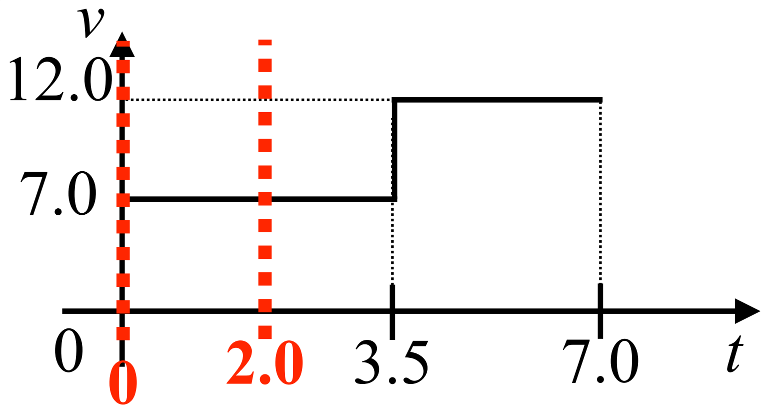




$\rightarrow (l_0, c{=}0, 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0, c{=}2, 2, \{v = 7\})$

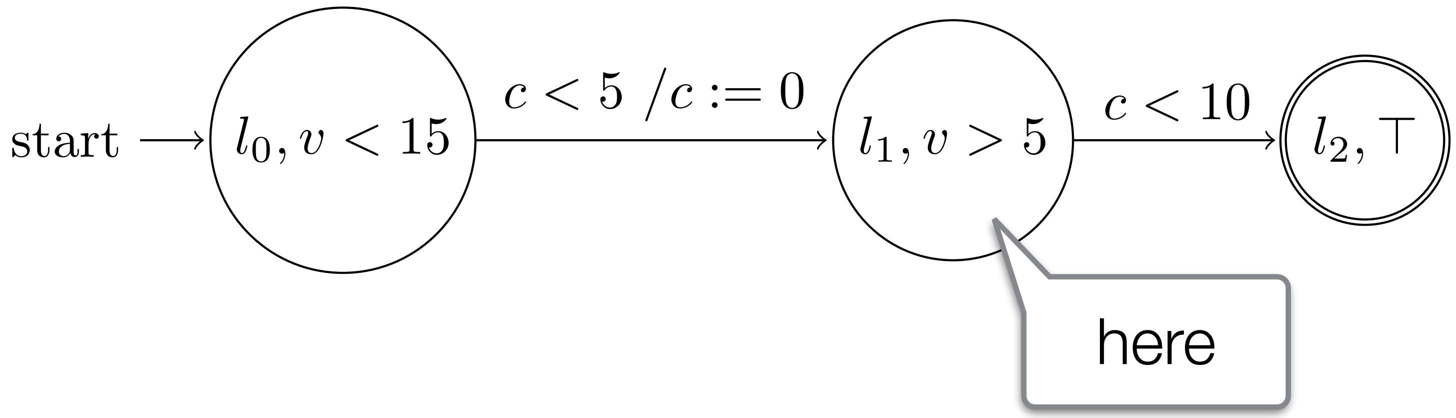
One path in Weighted TTS

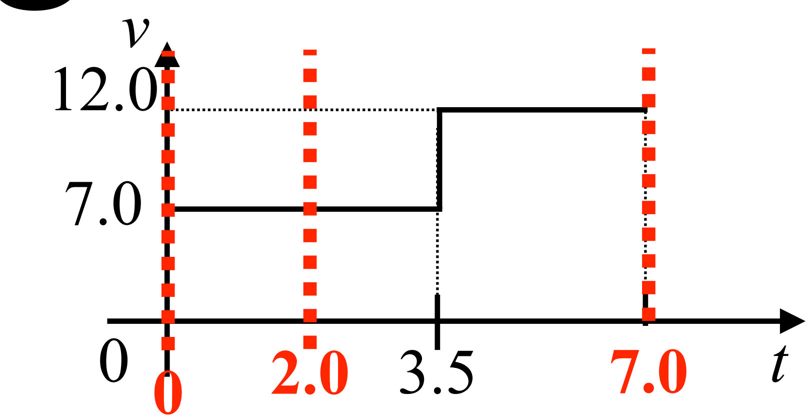




$$\rightarrow (l_0,\ c{=}0,\ 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0,\ c{=}2,\ 2,\ \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v=7\})]{e} (l_1,\ c{=}0,\ 2,\ \varepsilon)$$

One path in Weighted TTS

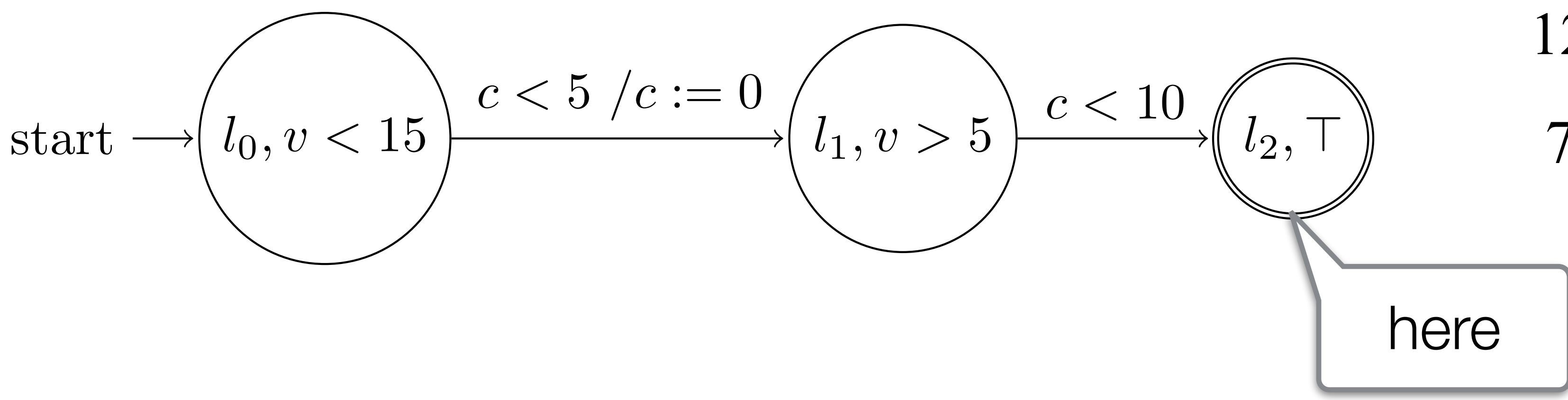


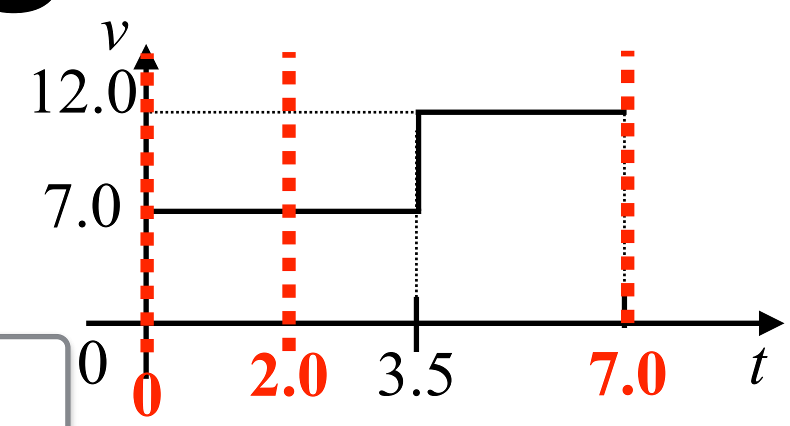


$$\to (l_0,\ c=0,\ 0, \varepsilon) \xrightarrow{2.0} (l_0,\ c=2,\ 2,\ \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v=7\})]{e} (l_1,\ c=0,\ 2,\ \varepsilon)$$

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

One path in Weighted TTS



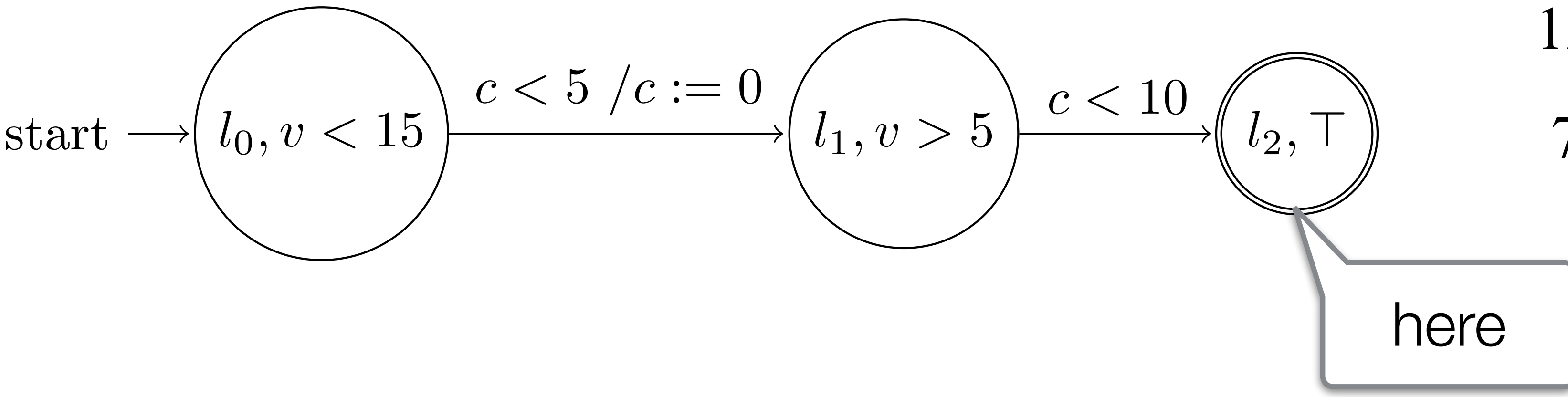


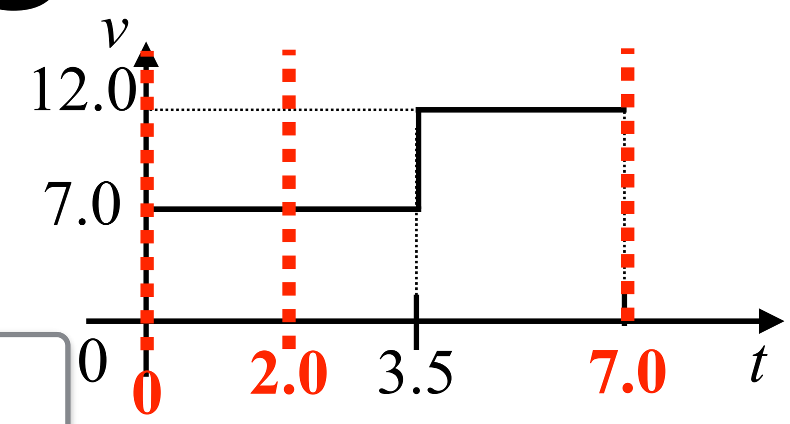
$$\rightarrow (l_0, c{=}0, 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0, c{=}2, 2, \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v=7\})]{e} (l_1, c{=}0, 2, \varepsilon)$$

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

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

One path in Weighted TTS



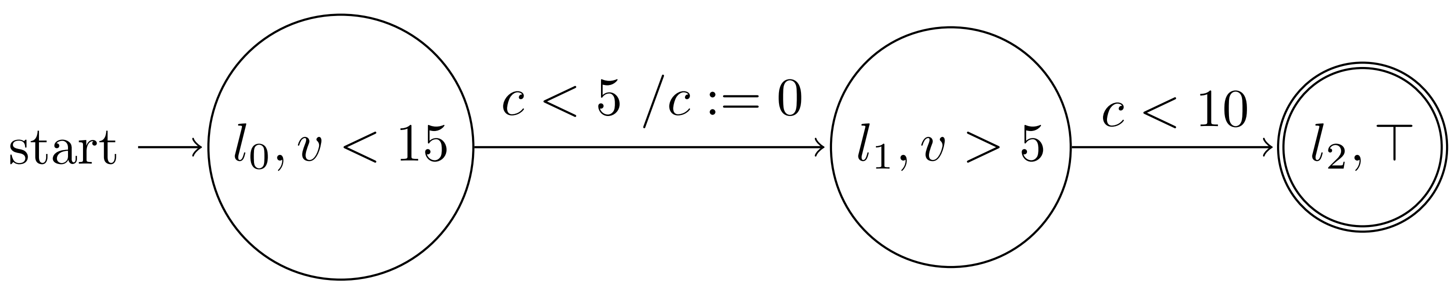


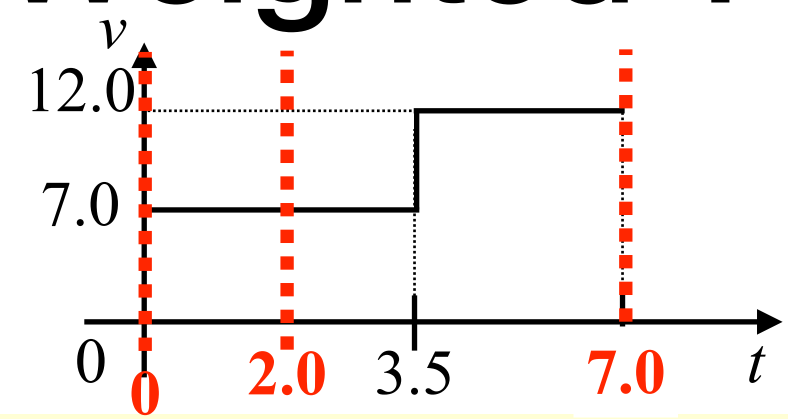
$$\to (l_0, c{=}0, 0, \varepsilon) \overset{2.0}{\dashrightarrow} (l_0, c{=}2, 2, \{v = 7\}) \xrightarrow[\kappa(v < 15,\ \{v{=}7\})]{e} (l_1, c{=}0, 2, \varepsilon)$$

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

	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





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

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

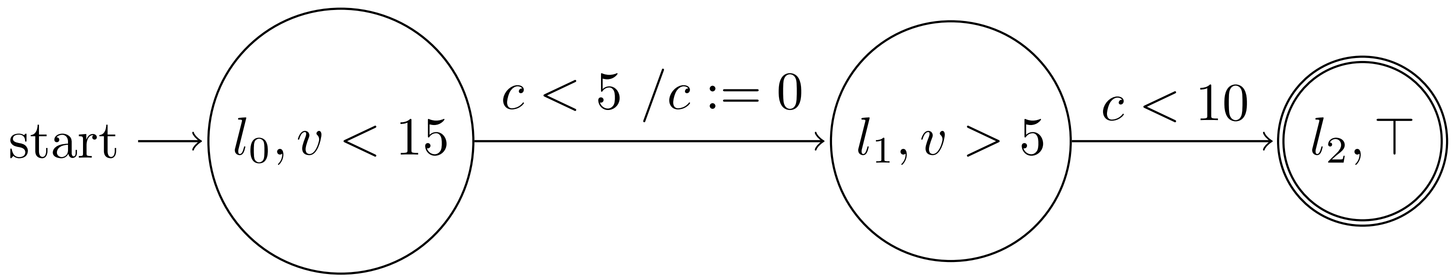
$\rightarrow (l_0, c{=}0, 0, \varepsilon) \xrightarrow{4.0} (l_0, c{=}4, 4, \{v = 7\}\{v = 12\}) \xrightarrow{e} (l_1, c{=}0, 4, \varepsilon) \xrightarrow{3.0} (l_1, c{=}3, 7, \{v = 12\}) \xrightarrow{e} (l_2, c{=}3, 7, \varepsilon)$

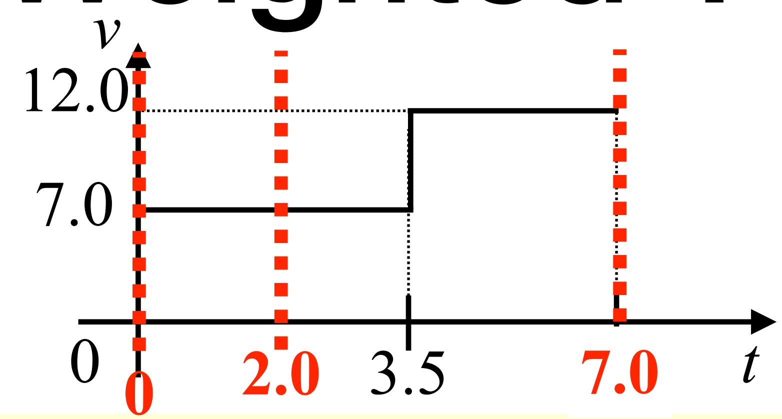
$\kappa(v < 15, \{v{=}7\}\{v{=}12\}) \otimes \kappa(v > 5, \{v{=}12\})$

⋮

	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





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

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

$\oplus$

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

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

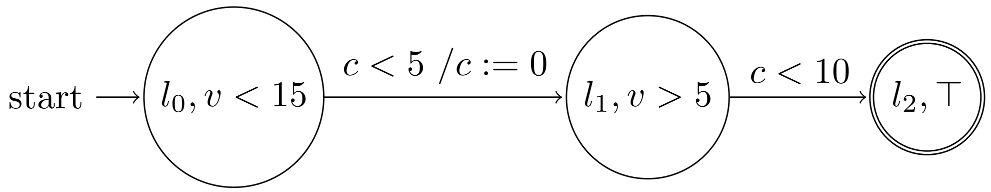
$\oplus$

⋮

	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)

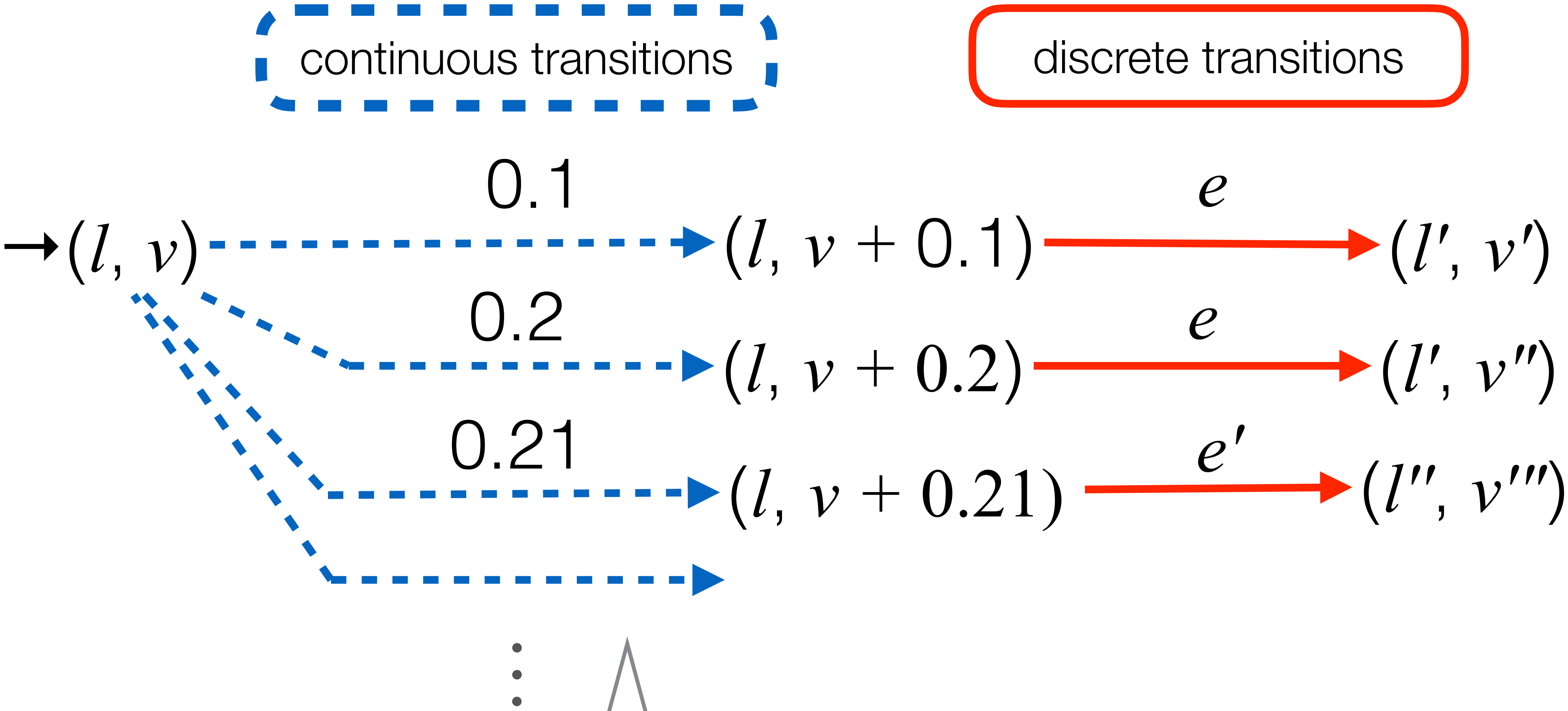
Semiring operations (⊗,⊕): how to accumulate weights

One-step semantics → semantics for a path/TSWA

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

Review: Reachability by zones



Infinitely many delays!!

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

Review: Reachability by zones

continuous transitions

discrete transitions

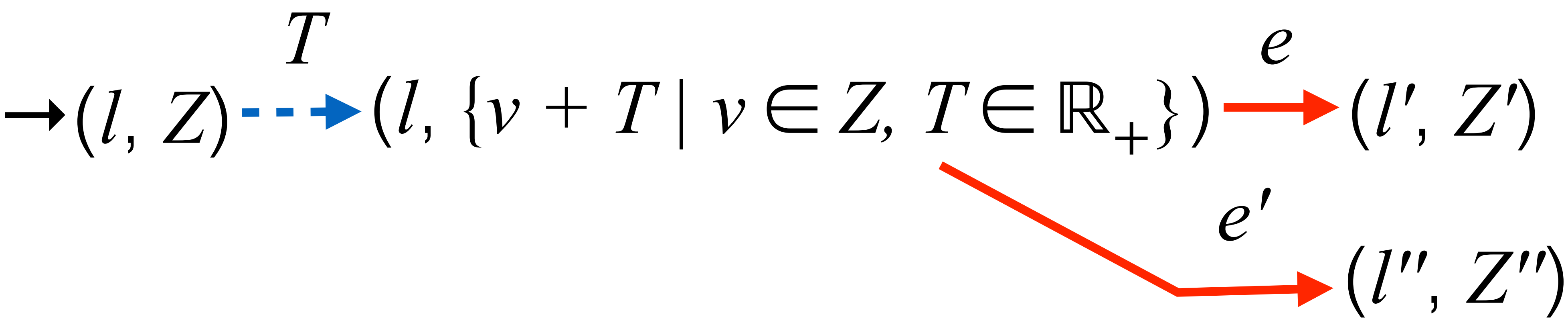
$$\to (l, \underline{\boldsymbol{Z}}) \xrightarrow{T} (l, \{v + T \mid v \in Z,\ T \in \mathbb{R}_+\}) \xrightarrow{e} (l', \underline{\boldsymbol{Z'}})$$

$$(l, \{v + T \mid v \in Z,\ T \in \mathbb{R}_+\}) \xrightarrow{e'} (l'', \underline{\boldsymbol{Z''}})$$

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

Observation: reachability is shortest distance over Boolean semiring!

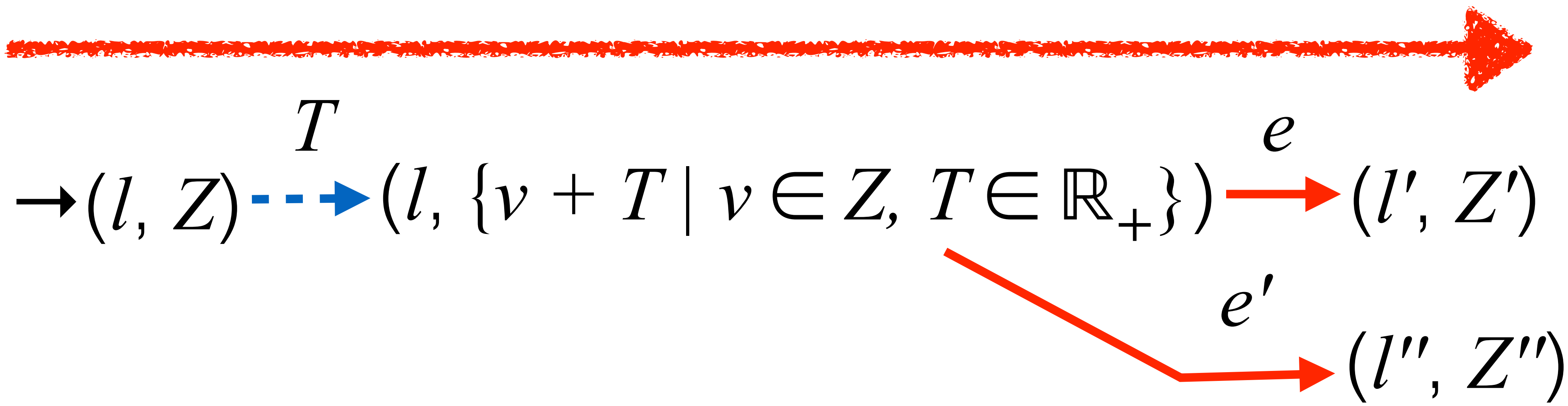
Observation: reachability is shortest distance over Boolean semiring!



M. Waga (NII)

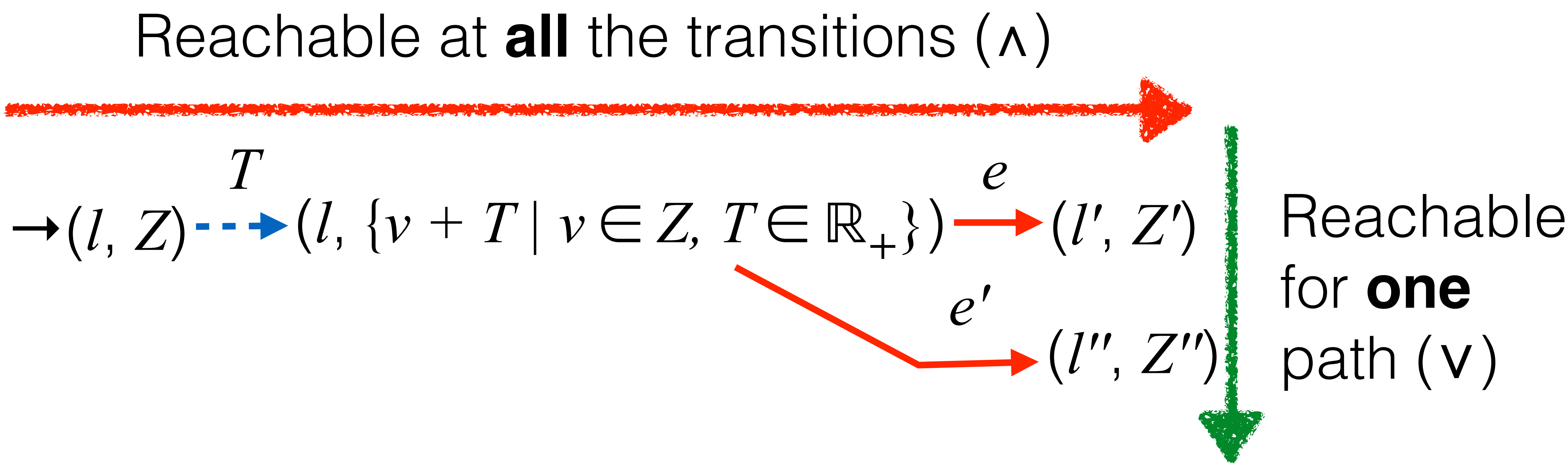
Observation: reachability is shortest distance over Boolean semiring!

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 (∧)

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

$\overset{e'}{\rightarrow} (l'', Z'')$

Reachable for **one** path (∨)

Reachability

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

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	$+$

Observation: reachability is shortest distance over Boolean semiring!

Qualitative [Bakhirkin+, FORMATS'18]

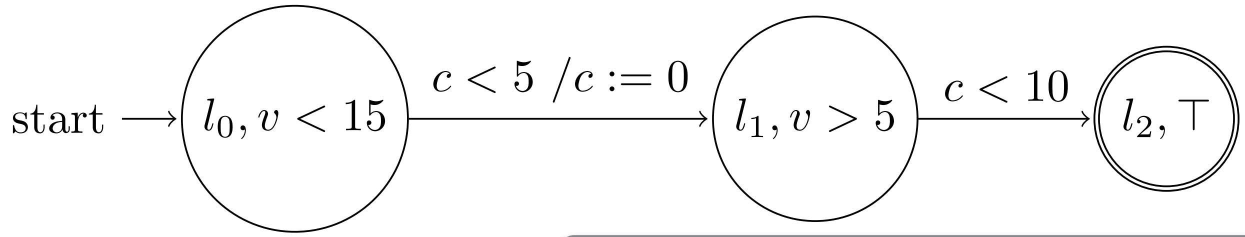
TA —zone constr.→ zone graph (with Boolean weight) —reachability checking (Boolean shortest distance)→ reachability (qualitative semantics)

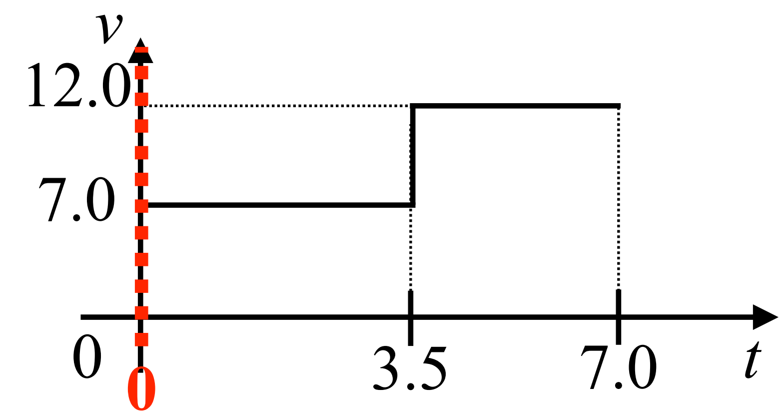
↓

Quantitative [Contribution]

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

Zone construction with weight



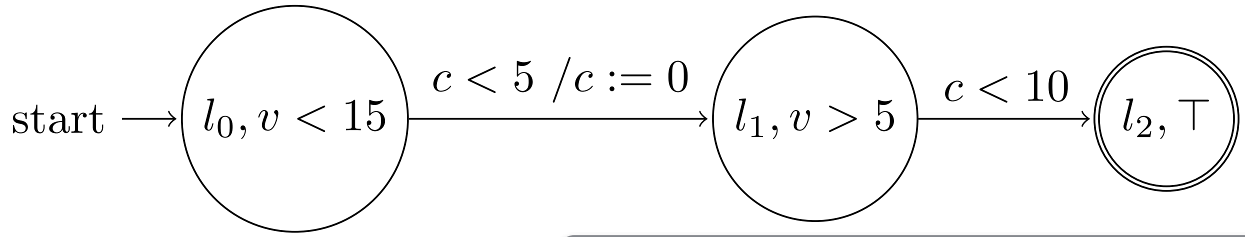


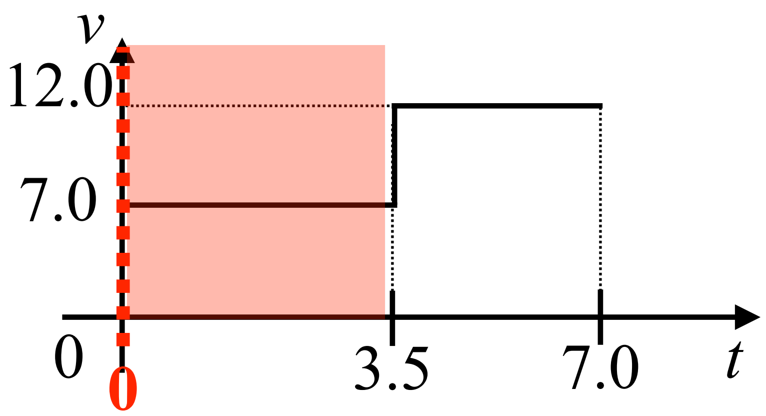
- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

This is OK for monitoring

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

Zone construction with weight





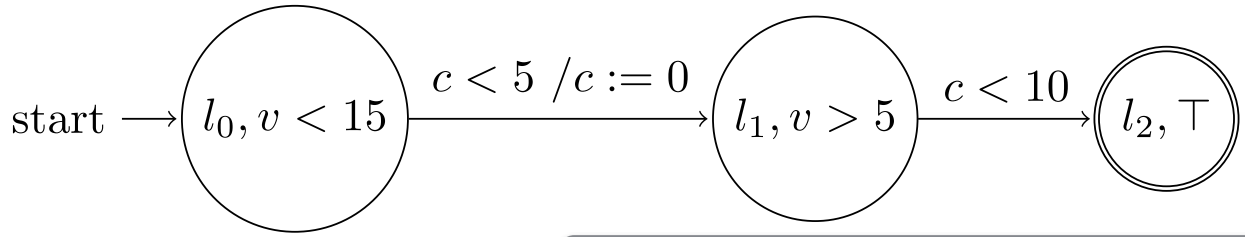
- T: absolute time

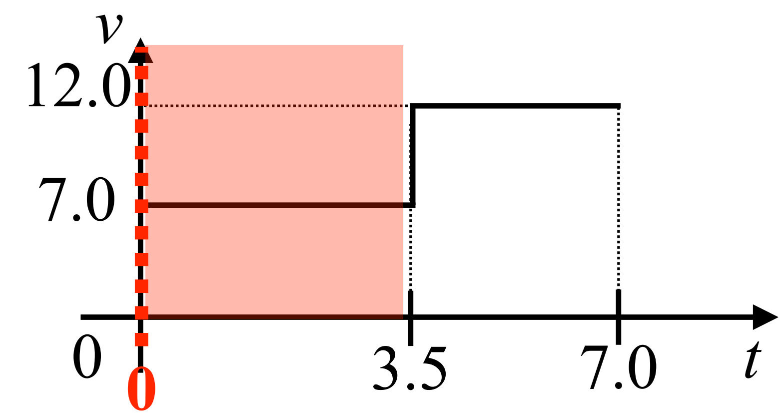
This is OK for monitoring

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

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

Zone construction with weight





- T: absolute time

This is OK for monitoring

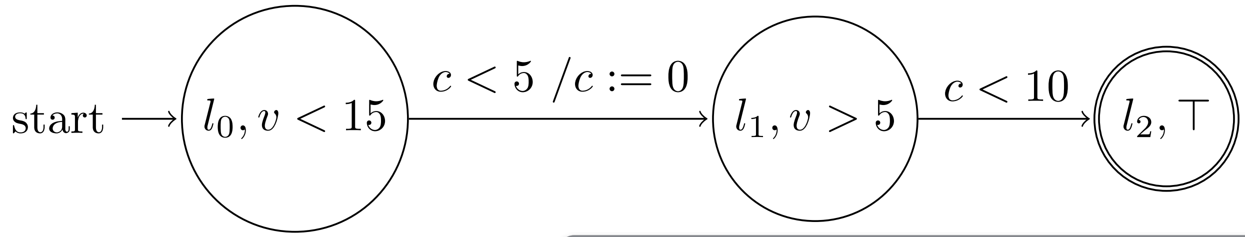
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ $(= 7.0)$

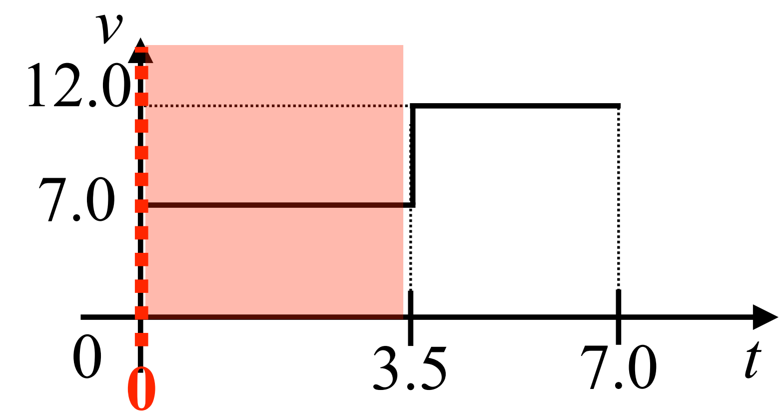
$\rightarrow (l_0, c = T = 0, \varepsilon)$ - - - → $(l_0, 0 < c = T < 3.5, \{v = 7\})$

$\kappa(v < 15, \{v=7\})$ ↓

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

Zone construction with weight





- T: absolute time

This is OK for monitoring

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

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

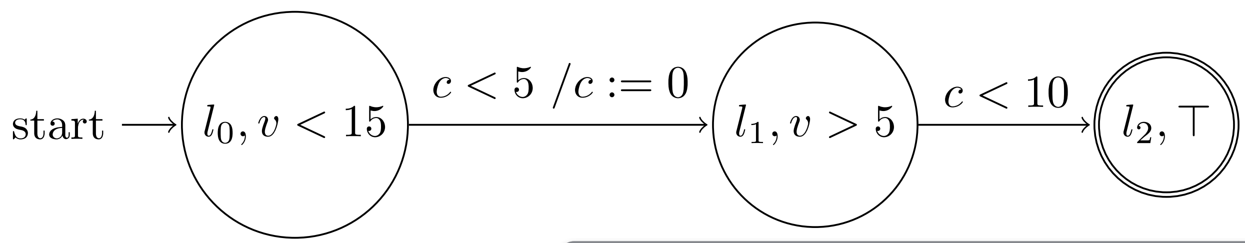
↓ $\kappa(v < 15, \{v=7\})$

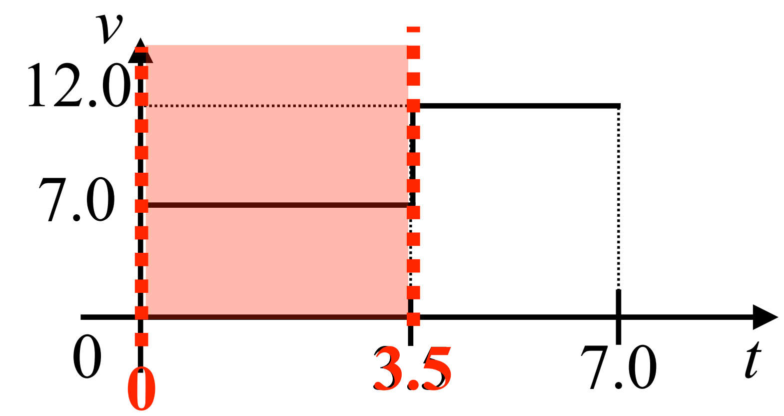
$(l_1, 0 = c < T < 3.5, \varepsilon)$

⇣

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

Zone construction with weight





- T: absolute time

This is OK for monitoring

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

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

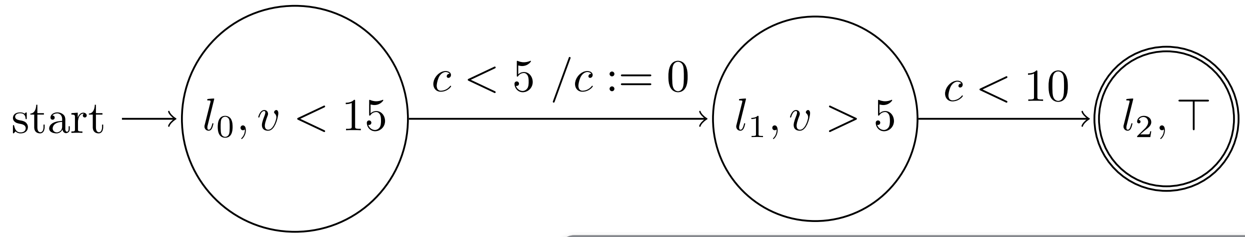
$\kappa(v < 15, \{v=7\})$ ↓

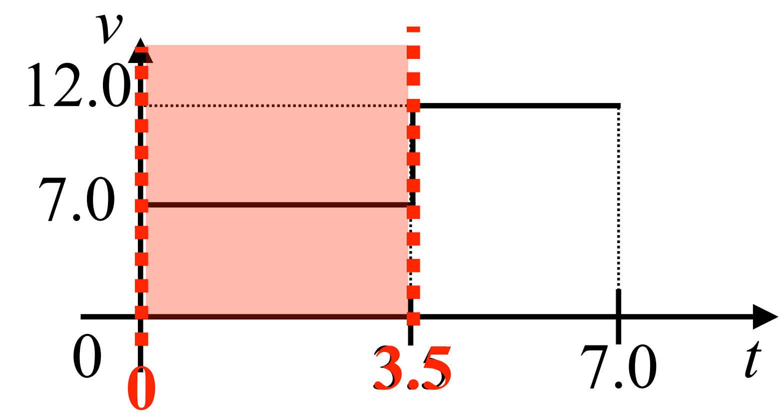
$(l_1, 0 = c < T < 3.5, \varepsilon)$

↓

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

Zone construction with weight





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

This is OK for monitoring

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

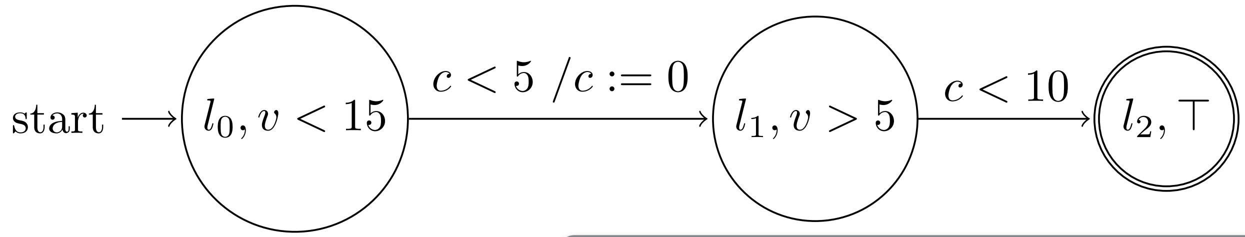
$\kappa(v < 15, \{v=7\})$ ↓

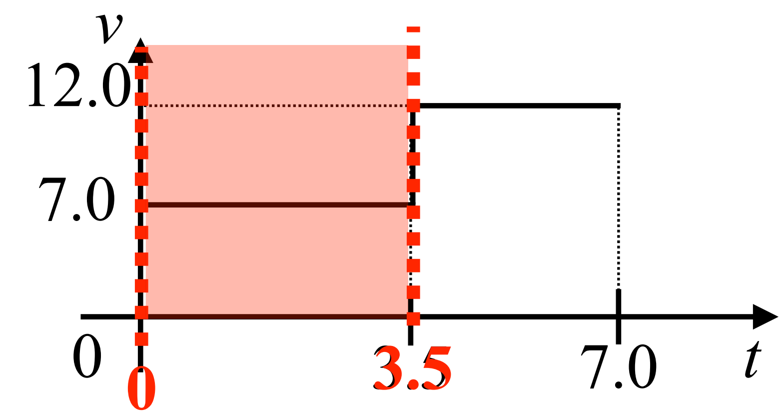
$(l_1, 0 = c < T < 3.5, \varepsilon)$

⇣

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

Zone construction with weight





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

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

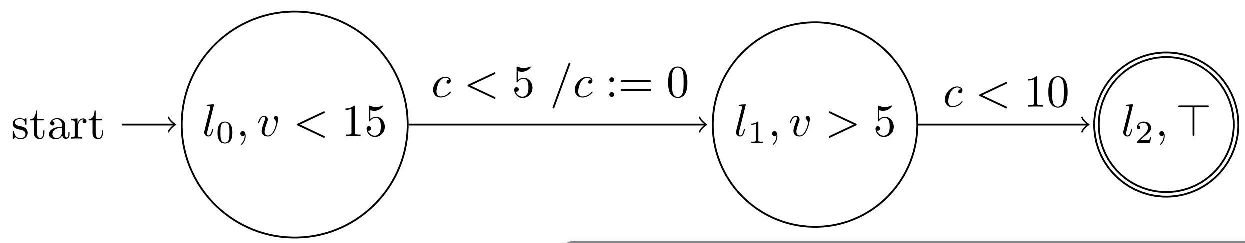
$\kappa(v < 15, \{v{=}7\})$ ↓

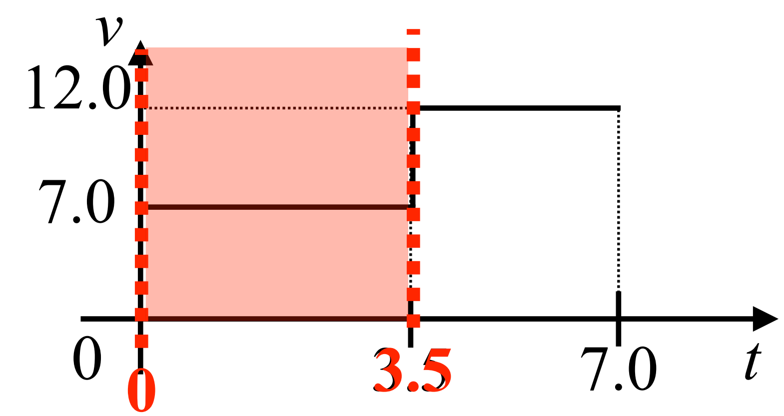
$(l_1, 0 = c < T < 3.5, \varepsilon)$

⇣

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

Zone construction with weight





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

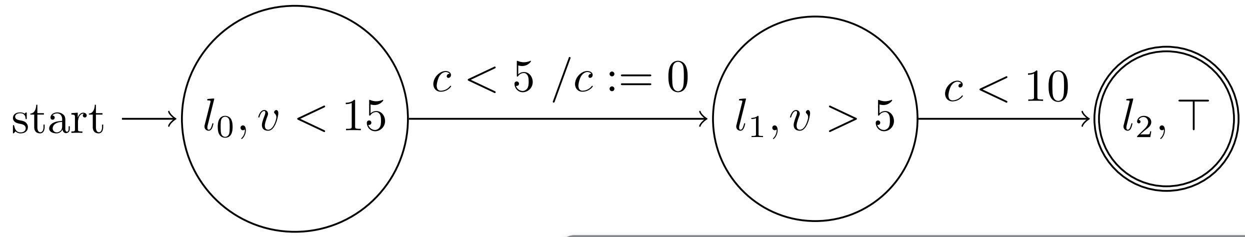
$\rightarrow (l_0, c = T = 0, \varepsilon)$ ⇢ $(l_0, 0 < c = T < 3.5, \{v = 7\})$ ⇢ $(l_0, c = T = 3.5, \{v = 7\})$

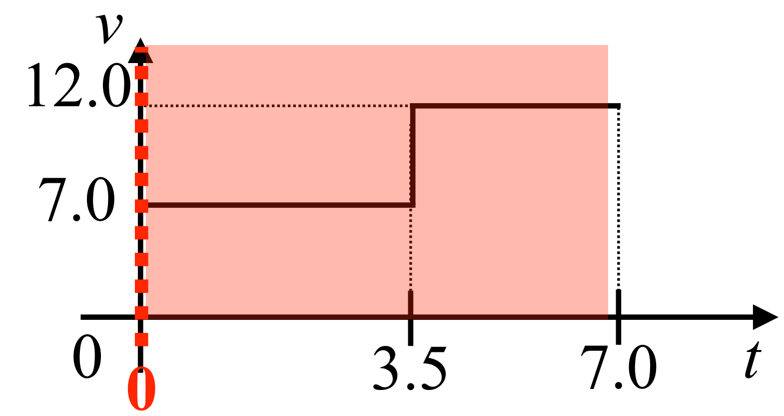
$(l_0, 0 < c = T < 3.5, \{v = 7\})$ —$\kappa(v < 15, \{v=7\})$→ $(l_1, 0 = c < T < 3.5, \varepsilon)$

$(l_0, c = T = 3.5, \{v = 7\})$ —$\kappa(v < 15, \{v=7\})$→ $(l_1, c = 0 < T = 3.5, \varepsilon)$

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

Zone construction with weight





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

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

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

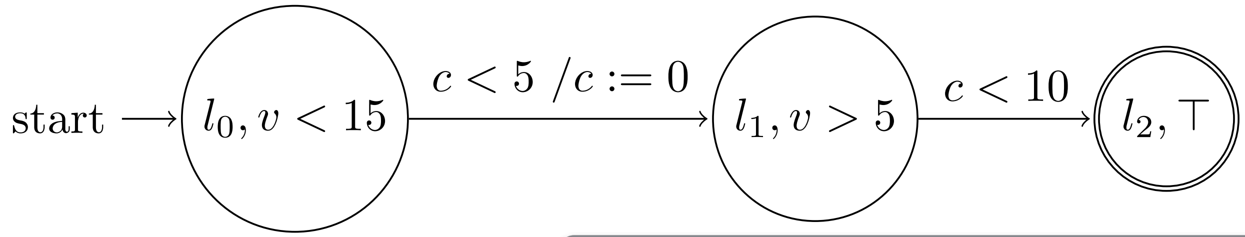
$\kappa(v < 15, \{v=7\})$

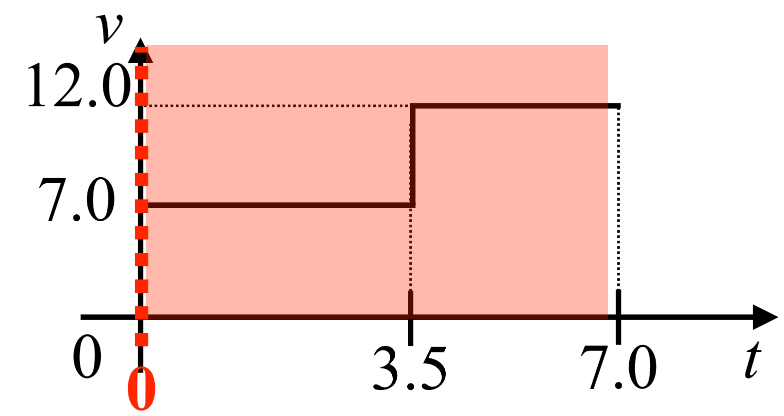
$(l_1, c = 0 < T = 3.5, \varepsilon)$

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

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

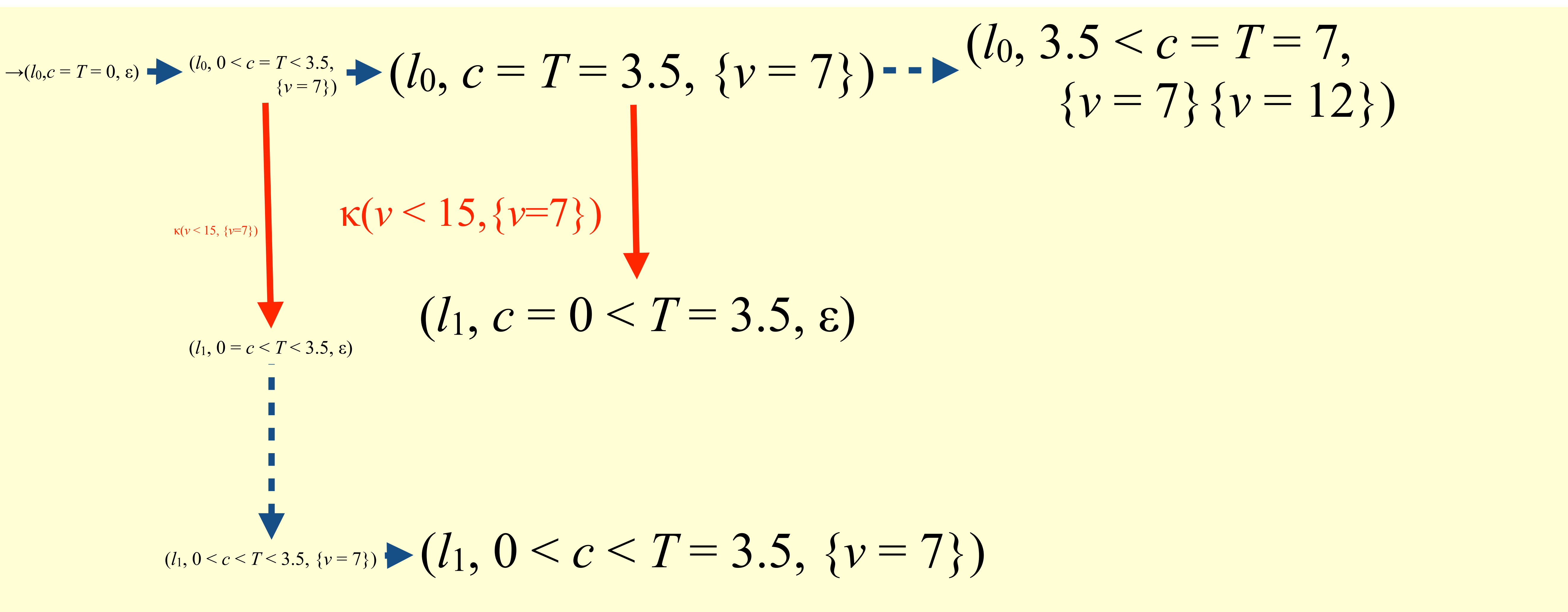
Zone construction with weight



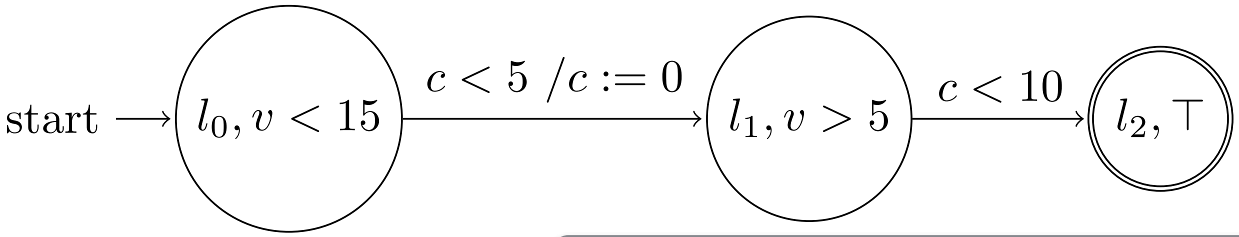


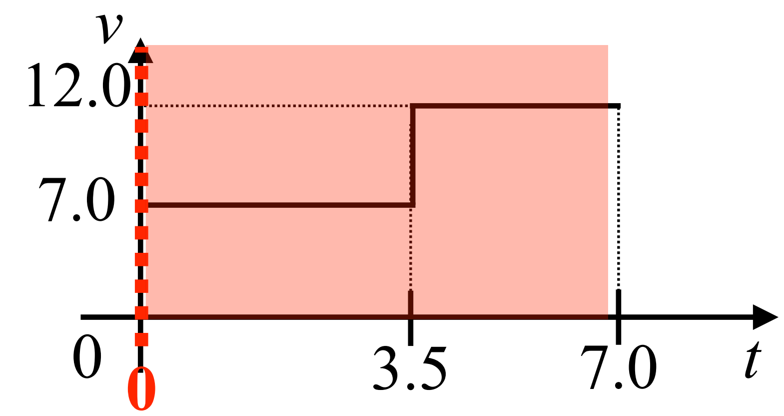
This is OK for monitoring

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

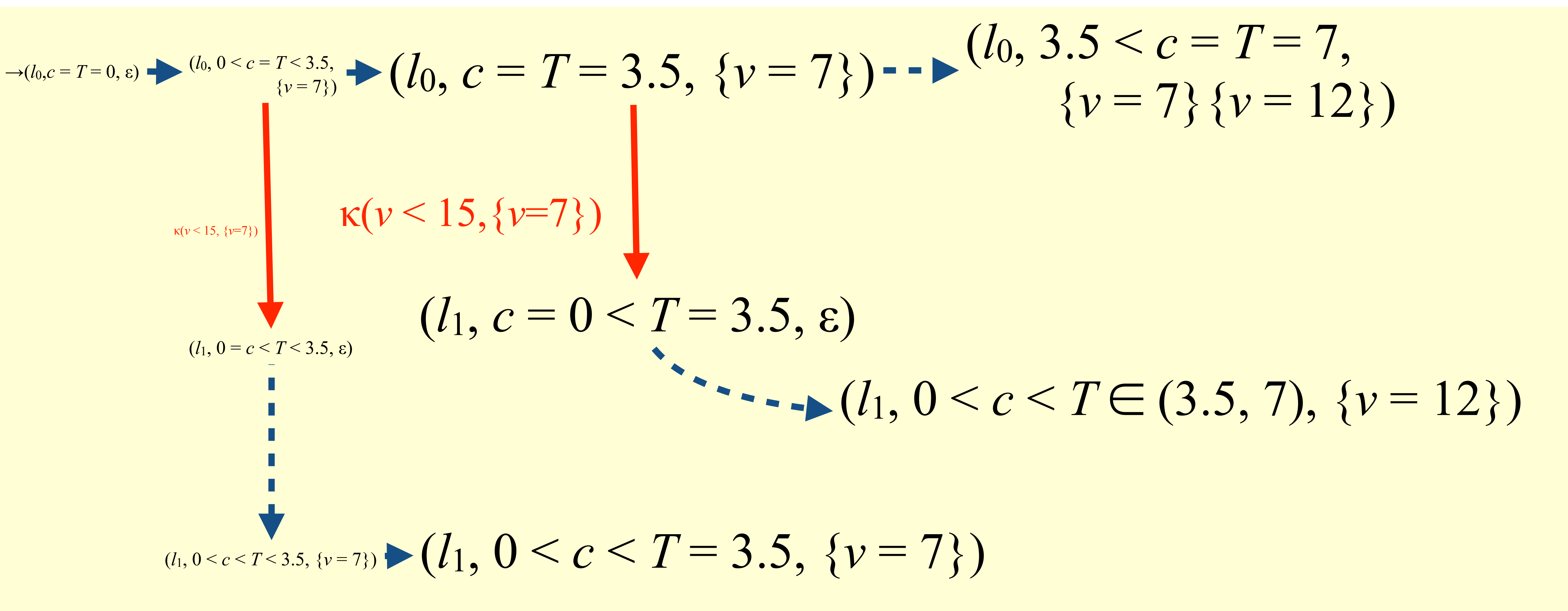


Zone construction with weight



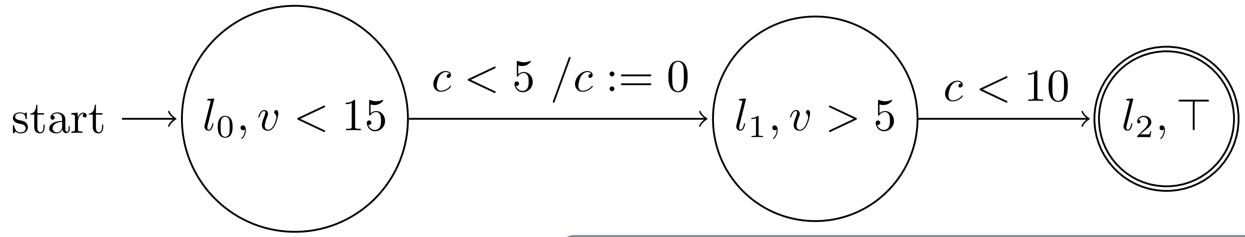


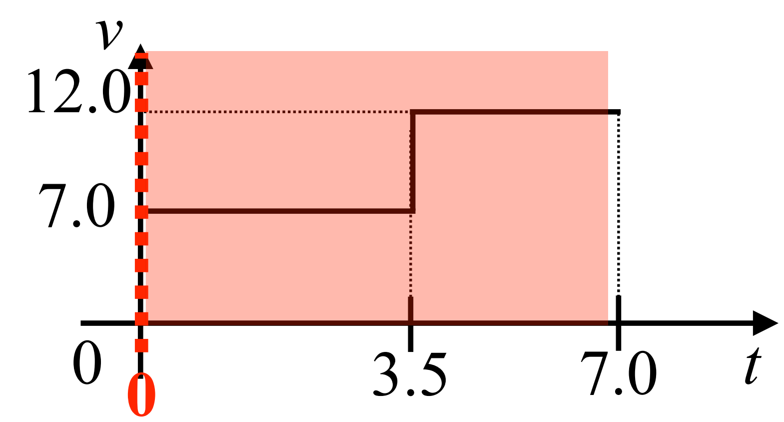
- T: absolute time — This is OK for monitoring
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)



M. Waga (Kyoto U.)

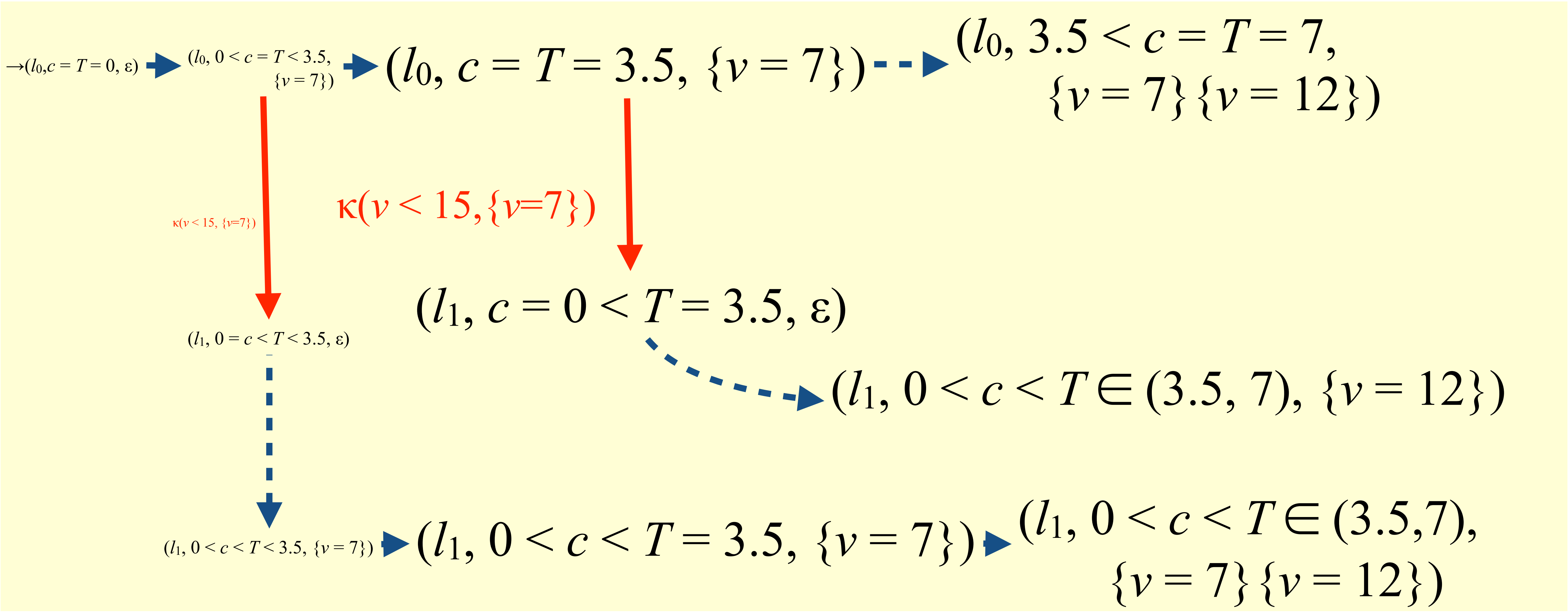
Zone construction with weight





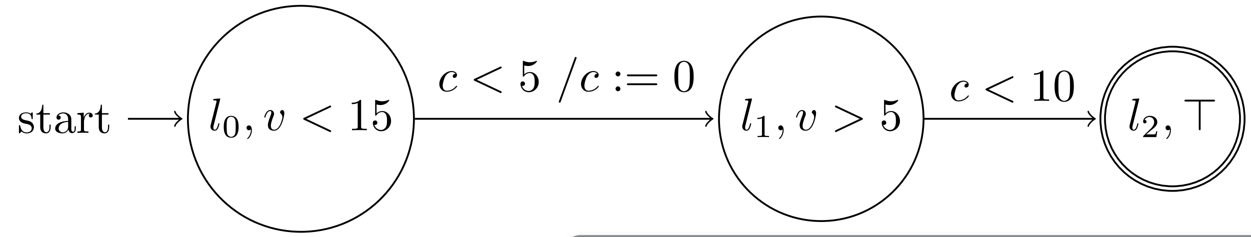
- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

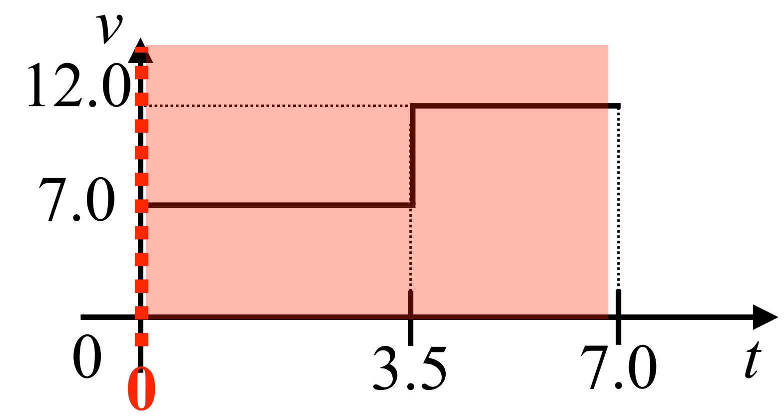
This is OK for monitoring



M. Waga (Kyoto U.)

Zone construction with weight

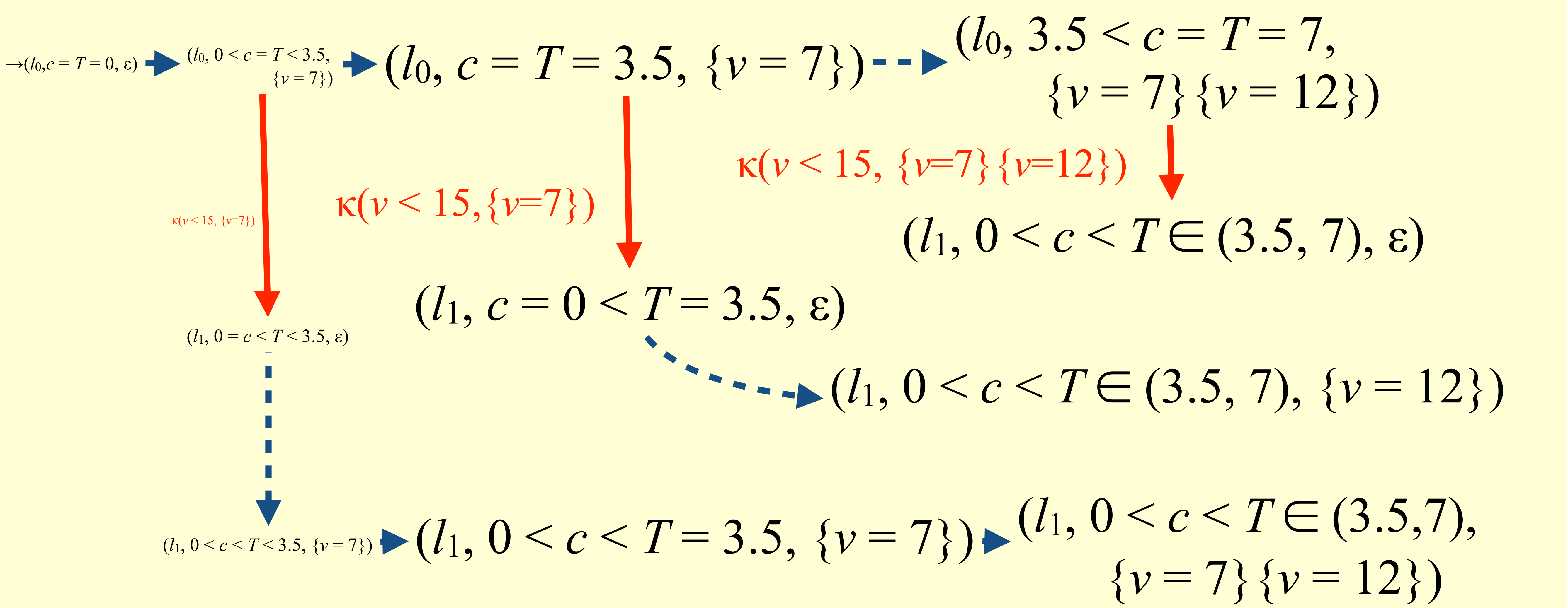




- T: absolute time

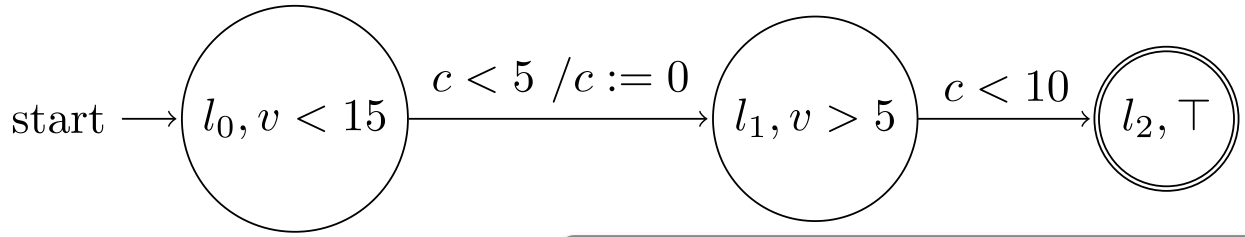
This is OK for monitoring

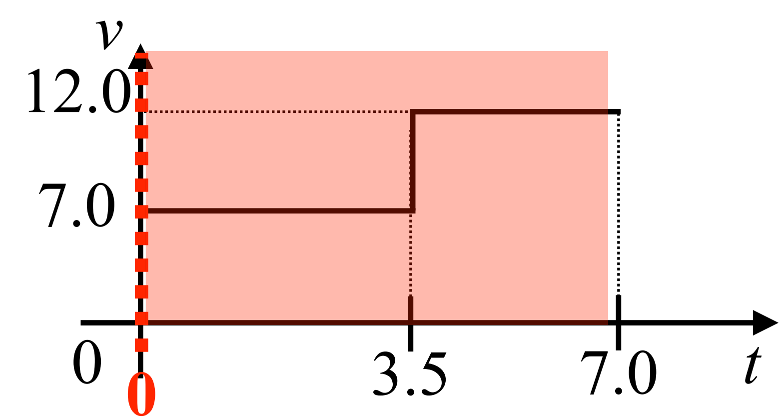
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)



M. Waga (Kyoto U.)

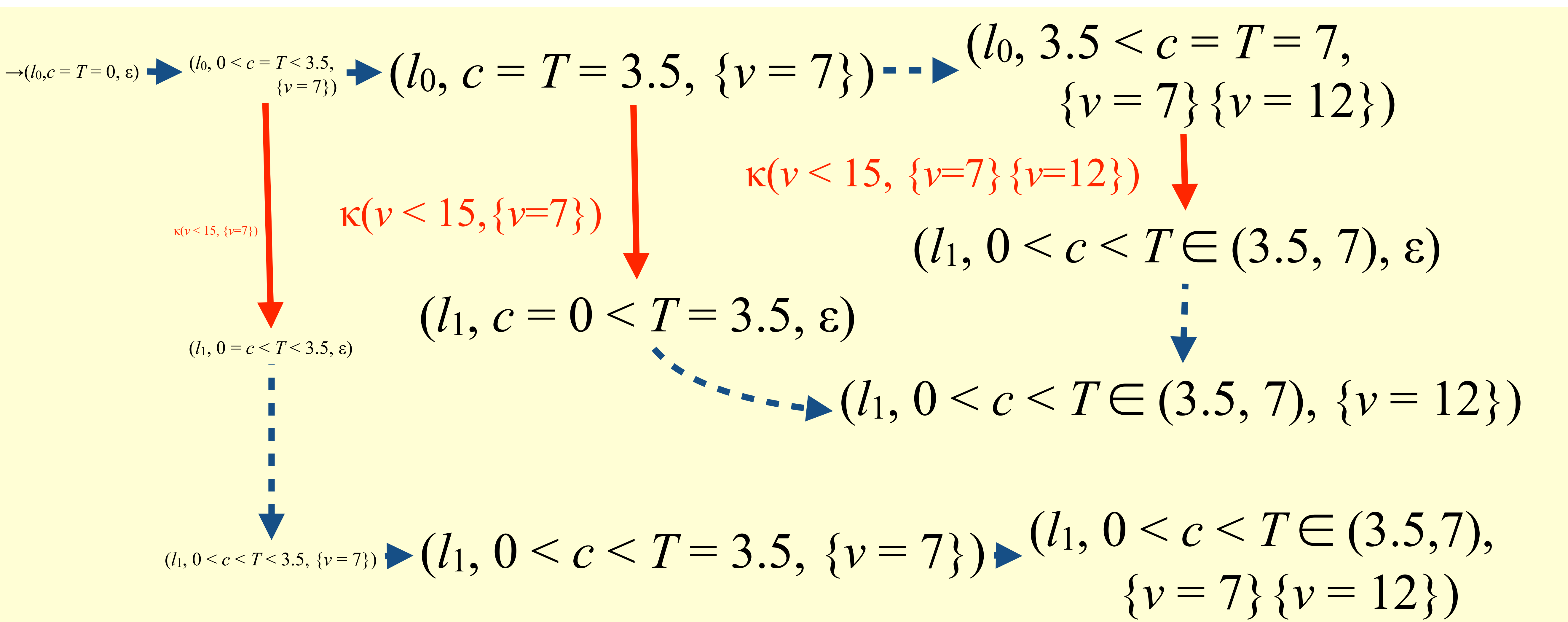
Zone construction with weight



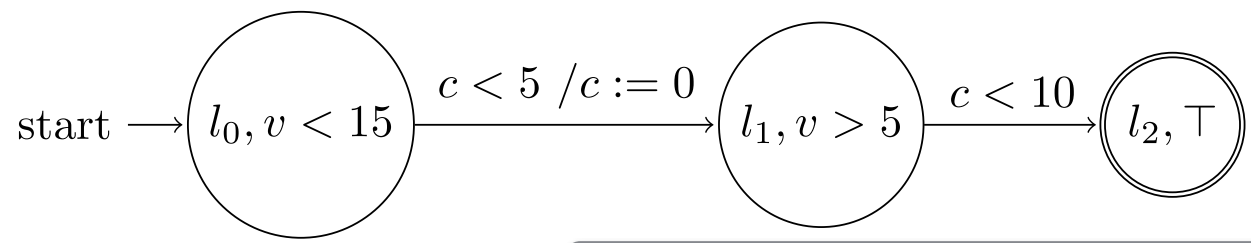


This is OK for monitoring

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

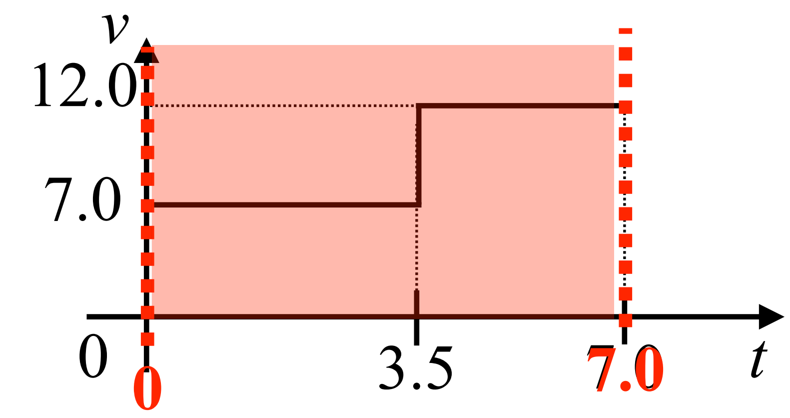


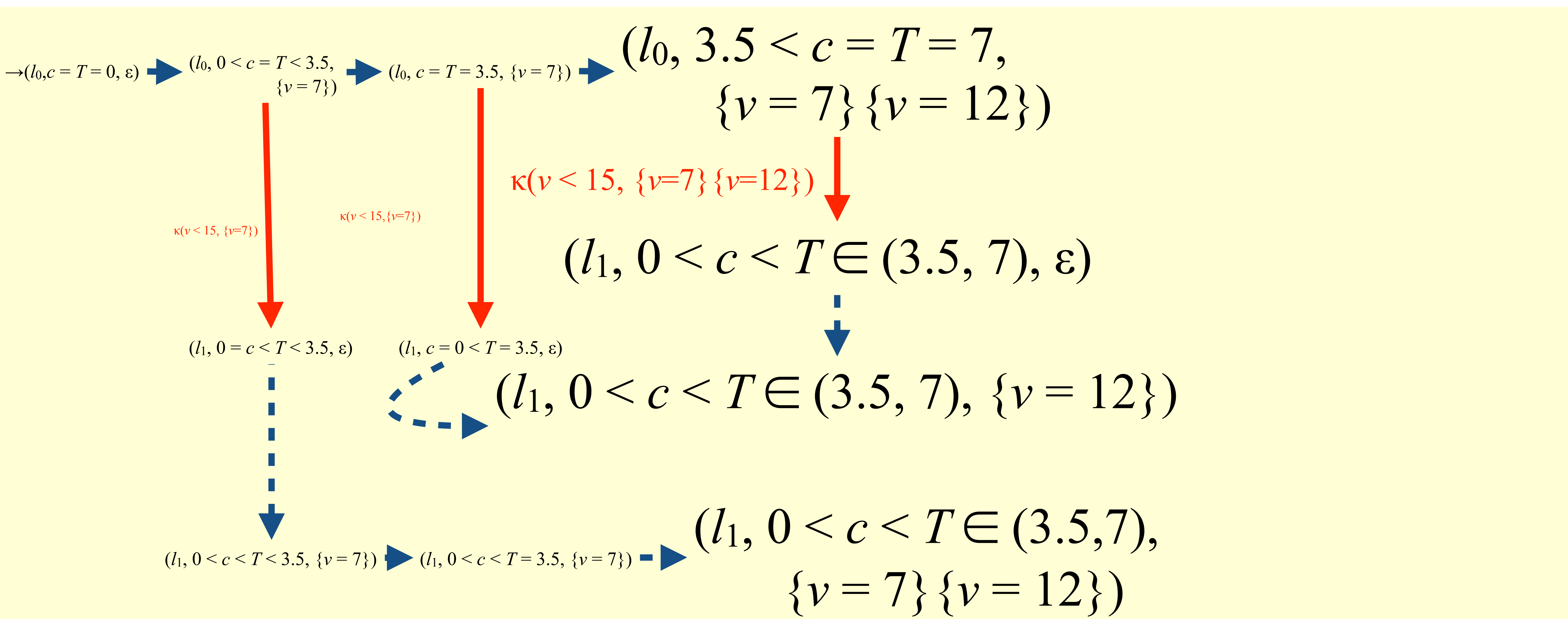
Zone construction with weight



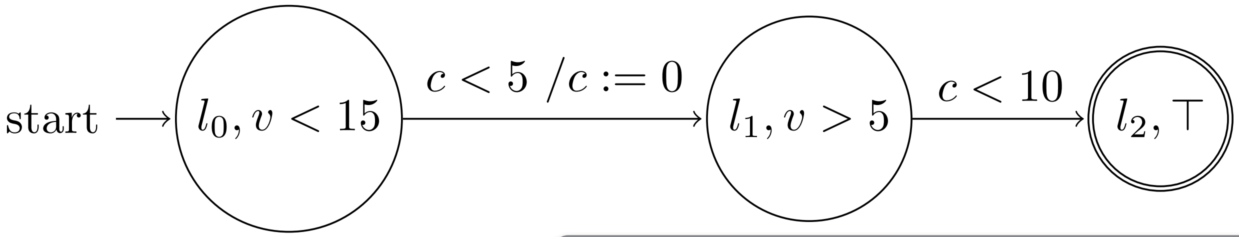
This is OK for monitoring

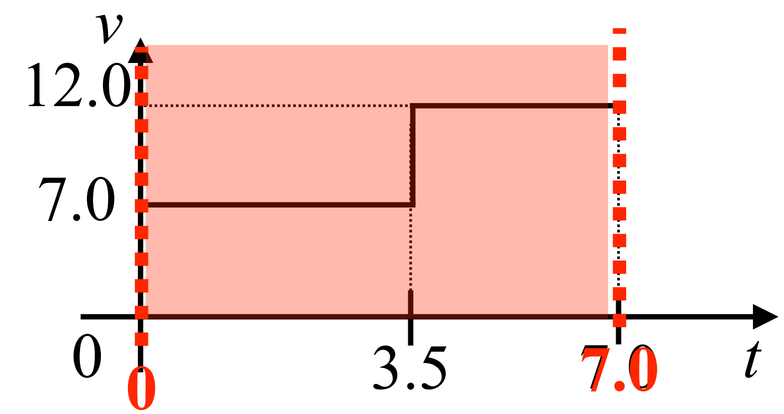
- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)





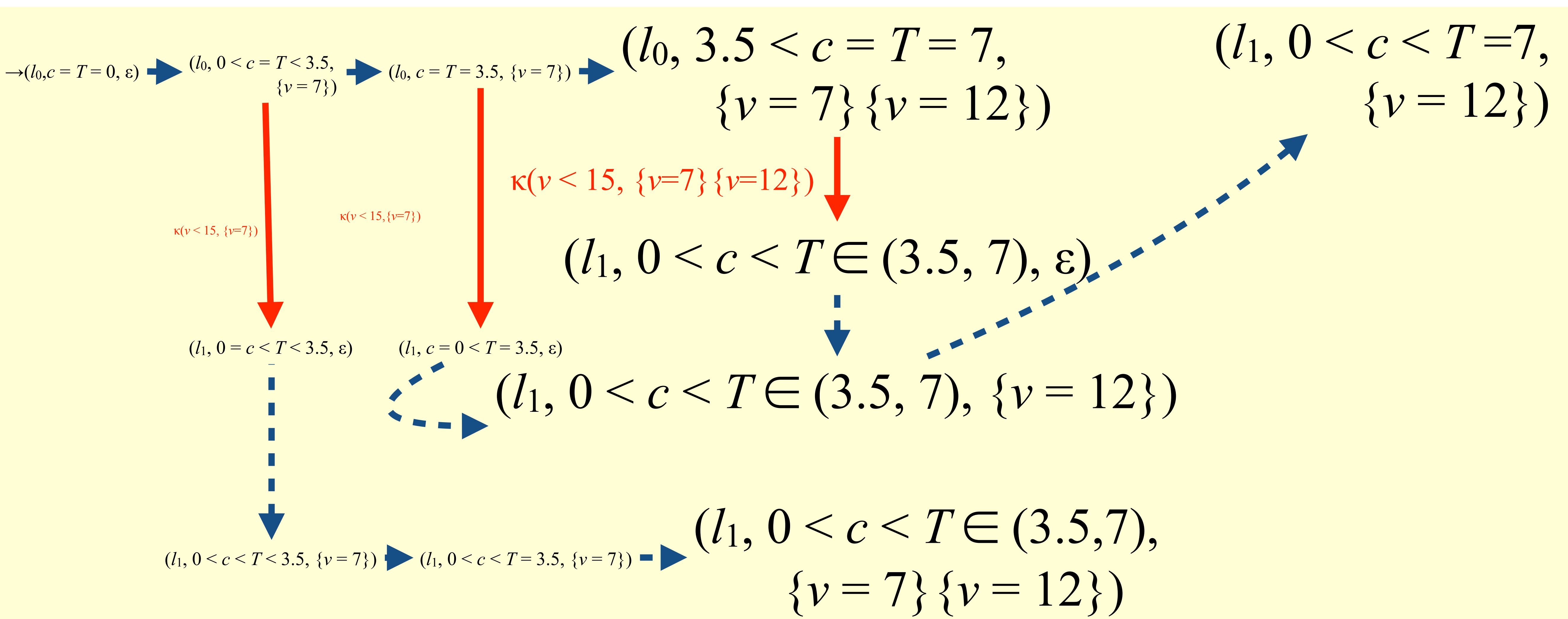
Zone construction with weight



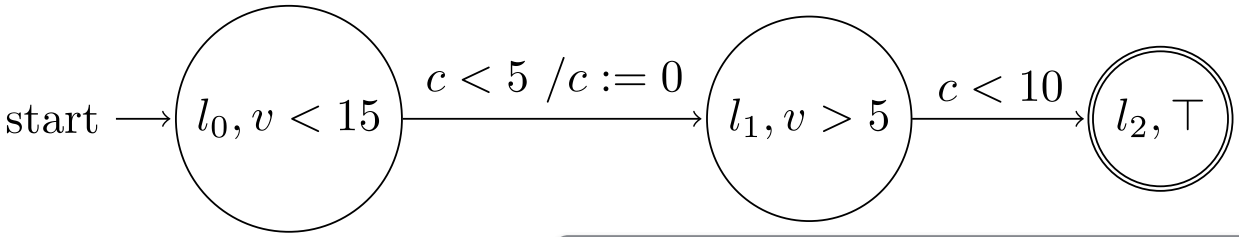


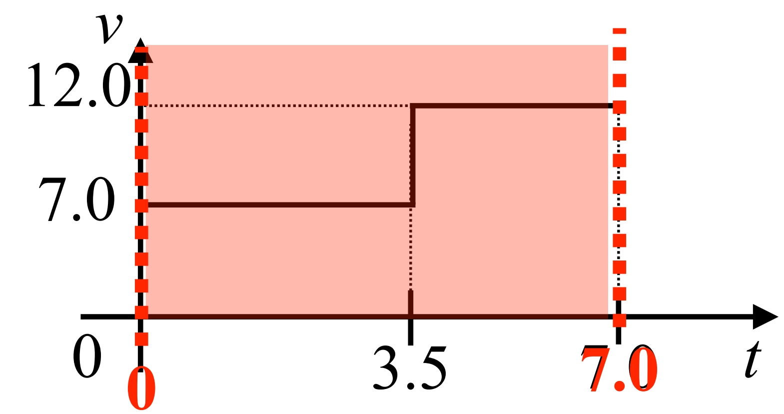
- T: absolute time
- Accepted ⇔ transit to acc. loc. at $T = |\sigma|$ (= 7.0)

This is OK for monitoring



Zone construction with weight

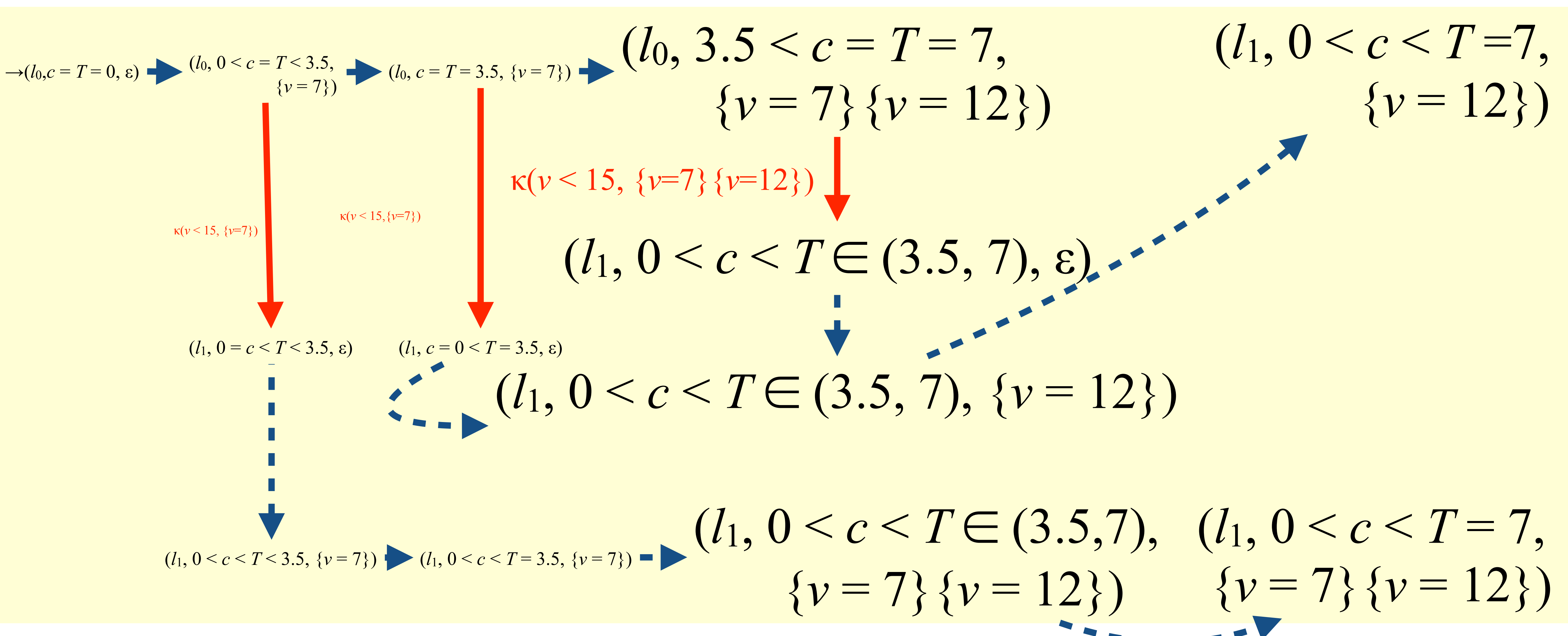




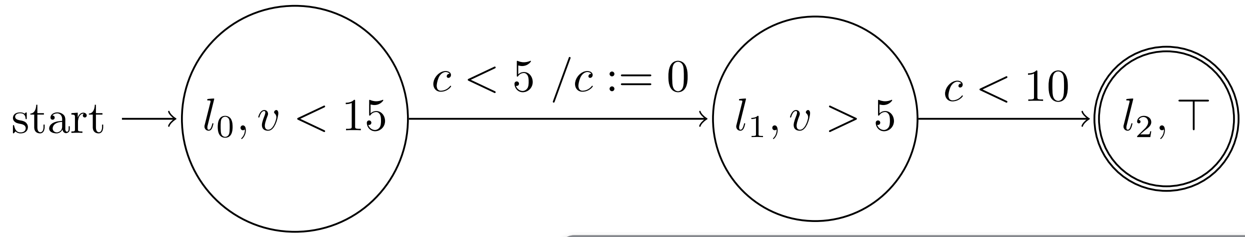
- T: absolute time

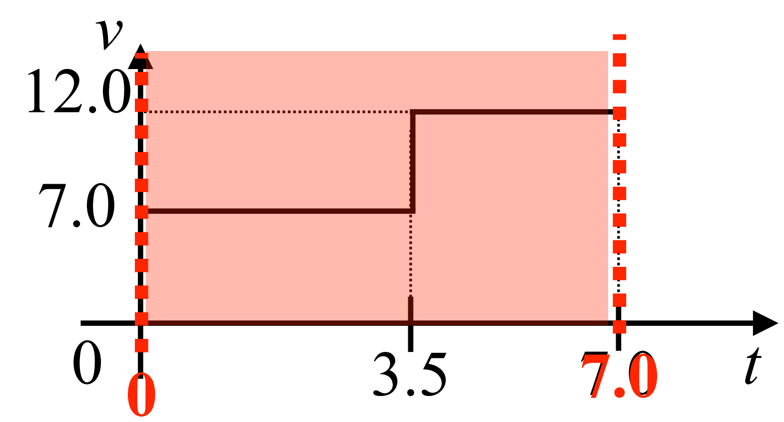
  This is OK for monitoring

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



Zone construction with weight

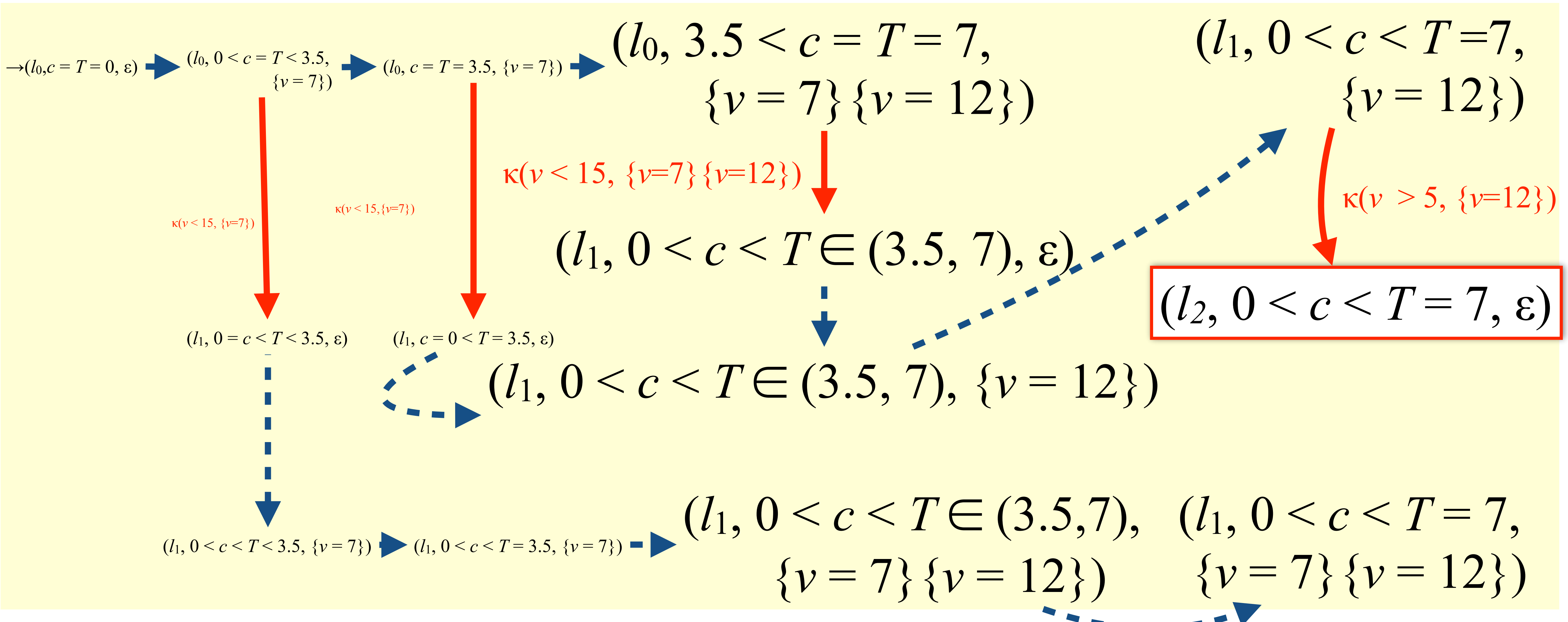




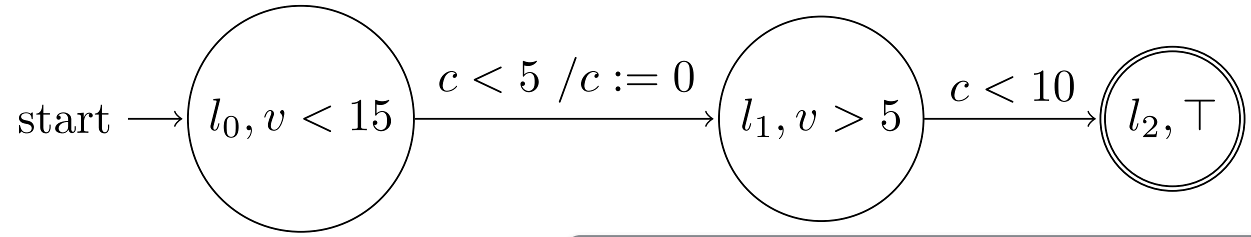
- T: absolute time

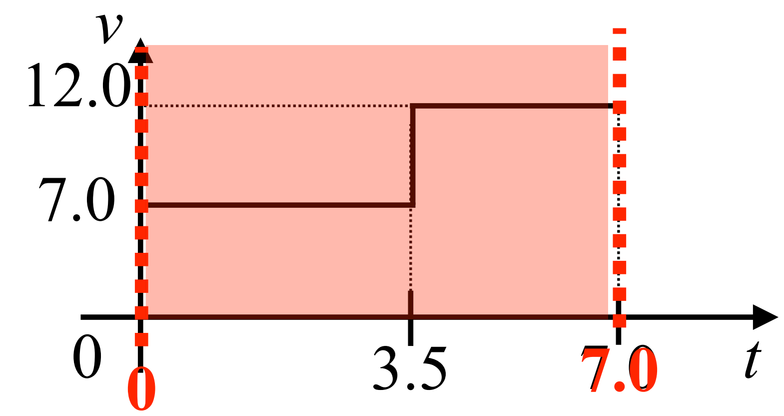
This is OK for monitoring

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



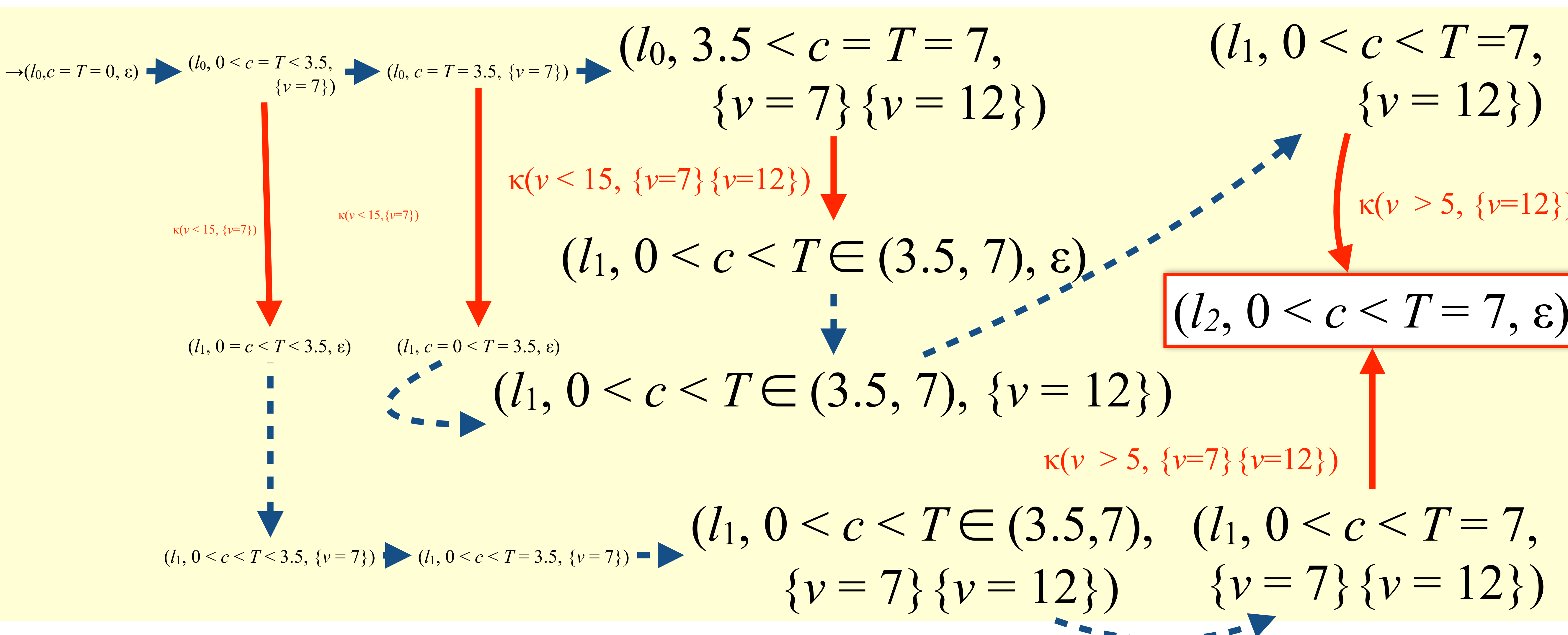
Zone construction with weight





This is OK for monitoring

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



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!!

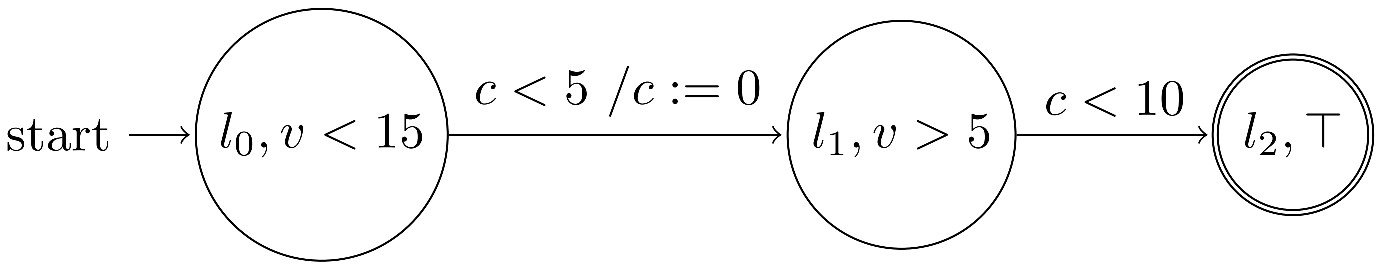
	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

Local Conclusion: Zone Construction with Weight

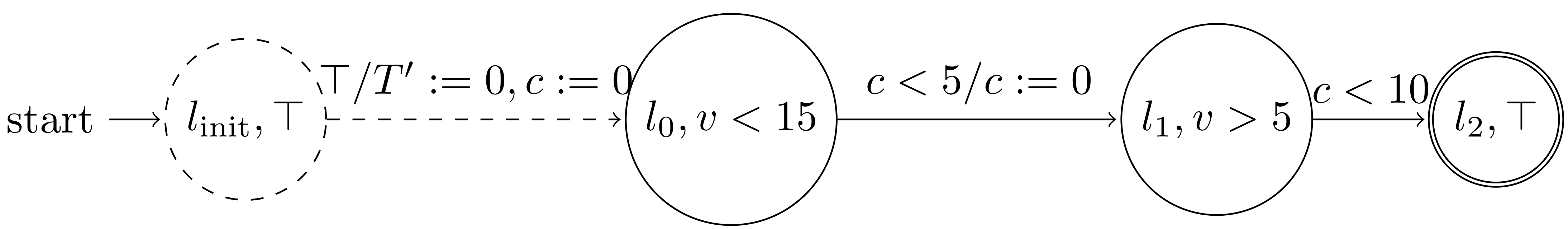
- The construction is basically same as the usual zone construction
- Weights are same as weighted TTS
- The state space is **finite** thanks to **zones** and **finite horizon** of the input signal

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



Outline

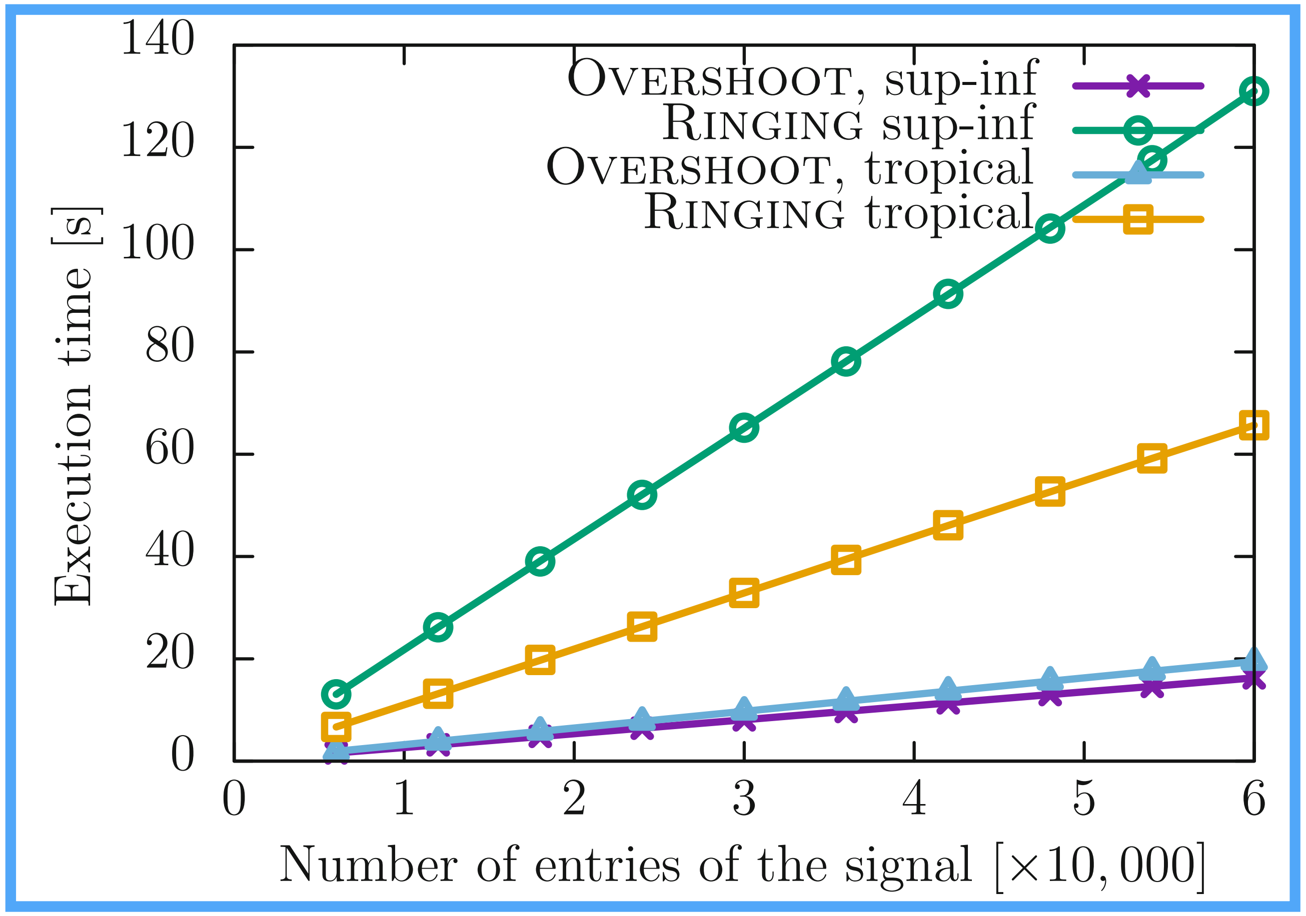
- Motivation + Introduction
- Technical Part
  - Timed symbolic weighted automata (TSWA)
    - TSWA: TA with signal constraints + weight function
  - Quantitative monitoring/timed pattern matching algorithm
    - Idea: zone construction with weight
- Experiments

Environment of Experiments

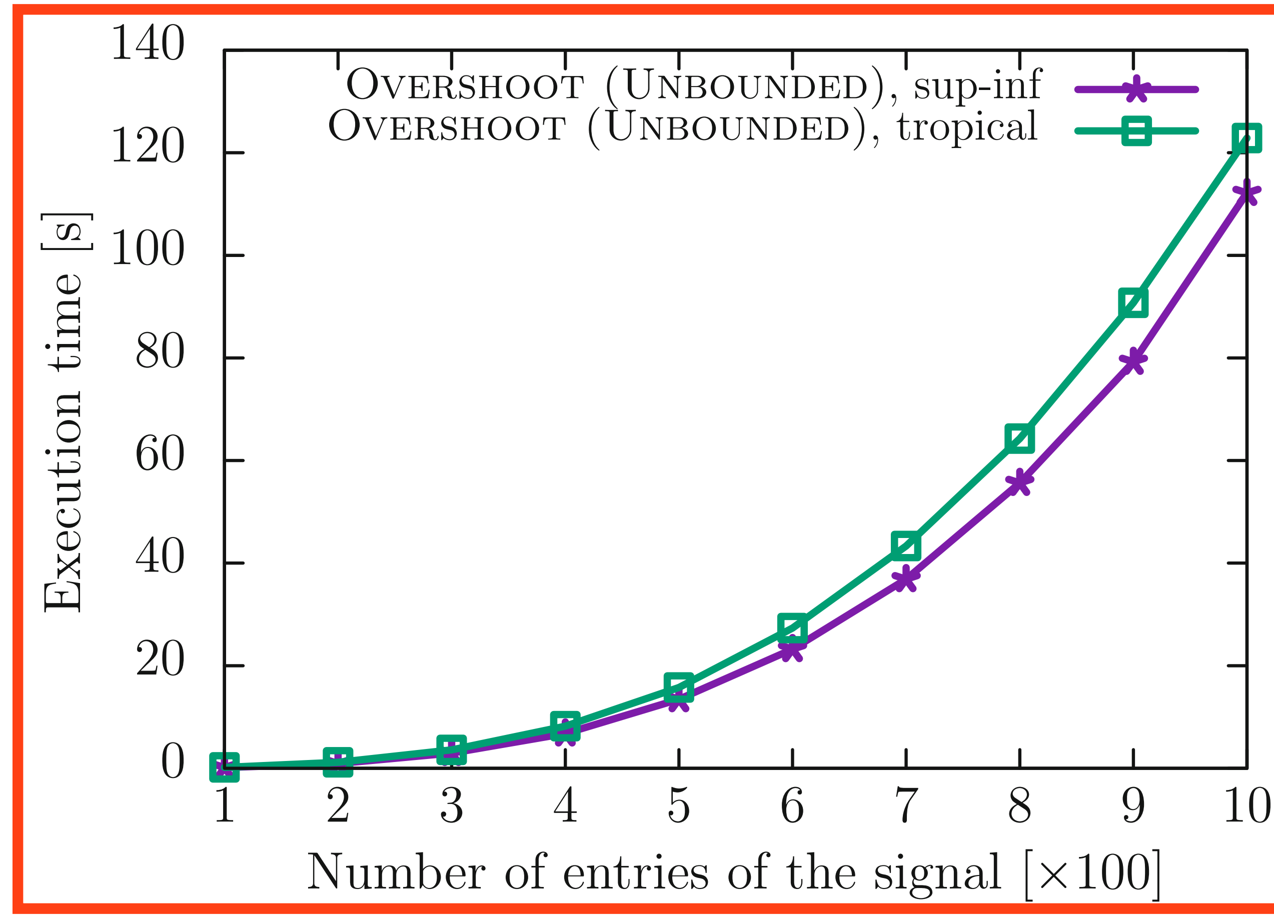
- **Semirings**: sup-inf ($\mathbb{R} \cup \{\pm \infty\}$, sup, inf) and tropical ($\mathbb{R} \cup \{+ \infty\}$, inf, +)
- Used 3 original benchmarks (automotive):
  - Inspired by ST-Lib [Kapinski+, SAE Technical Paper'16]
- **Overshoot**: $|v_{\mathrm{ref}} - v|$ gets large after v_{ref} changed
  - 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

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.

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

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

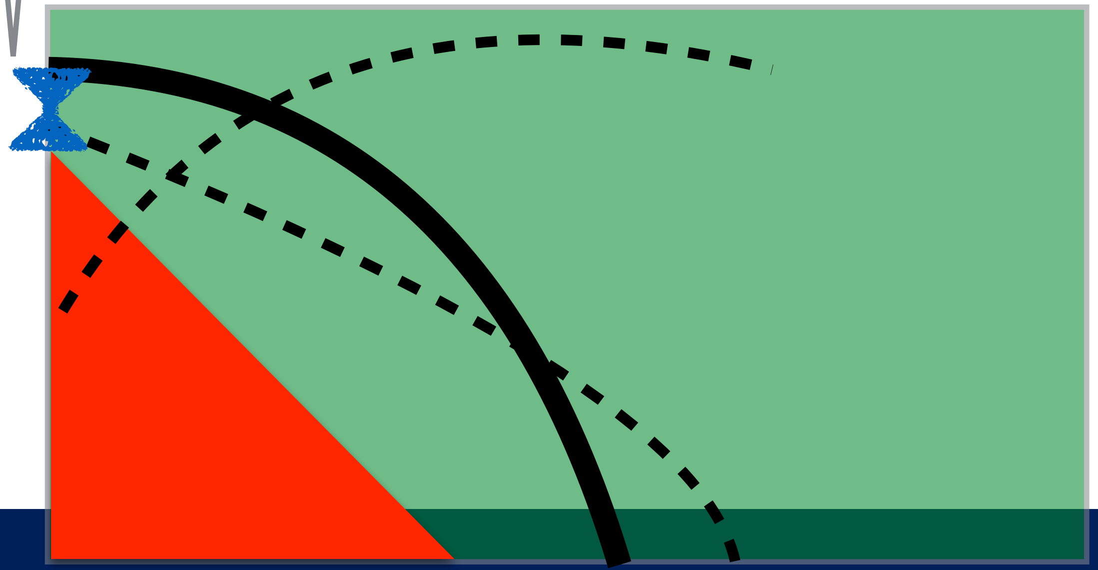
$$\kappa_r(\bigwedge_{i=1}^{n} (x_i \bowtie_i d_i), (a)) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(x_i \bowtie_i d_i, (a)) \text{ where } \bowtie_i \in \{>, \geq, \leq, <\}$$

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

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

Robustness

Semiring: sup-inf semiring



Example: "Robust" Semantics

Weight Function: minimum distance from the threshold

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

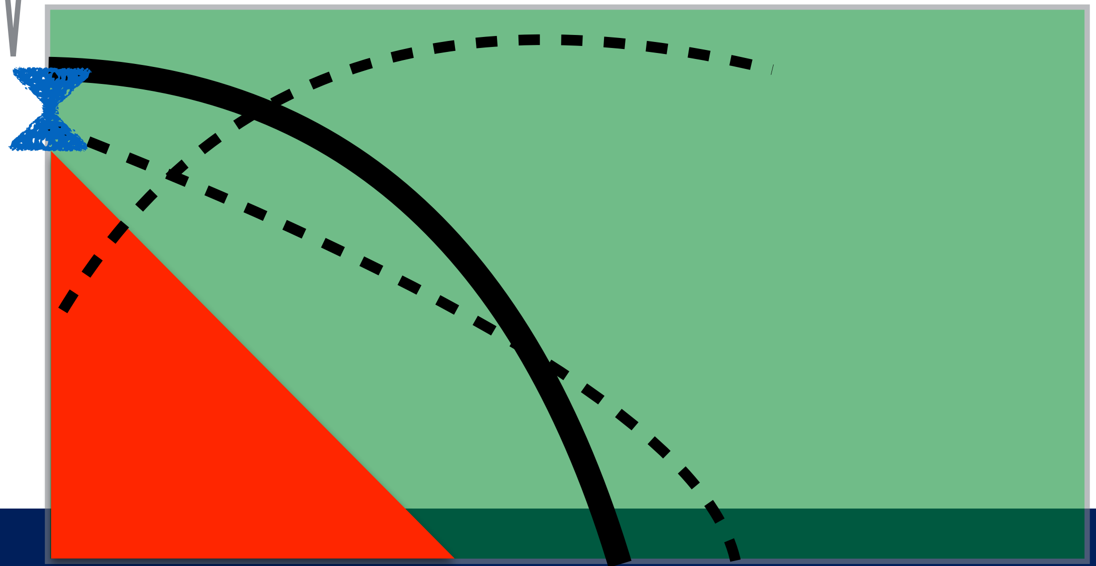
$$\kappa_r(\bigwedge_{i=1}^{n}(x_i \bowtie_i d_i),(a)) = \inf_{i \in \{1,2,\dots,n\}} \kappa_r(x_i \bowtie_i d_i,(a)) \text{ where } \bowtie_i \in \{>,\geq,\leq,<\}$$

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

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

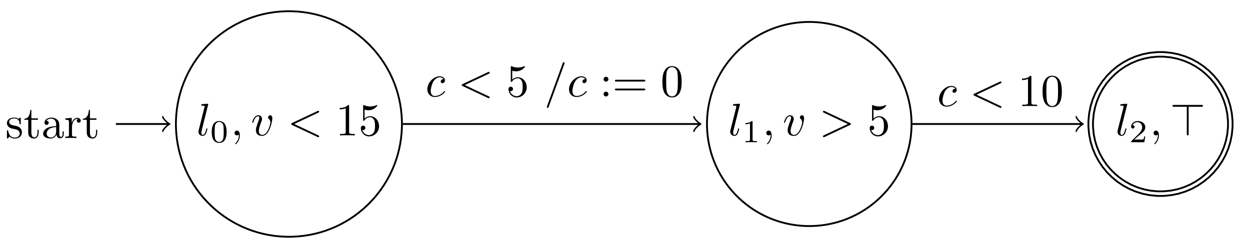
Robustness

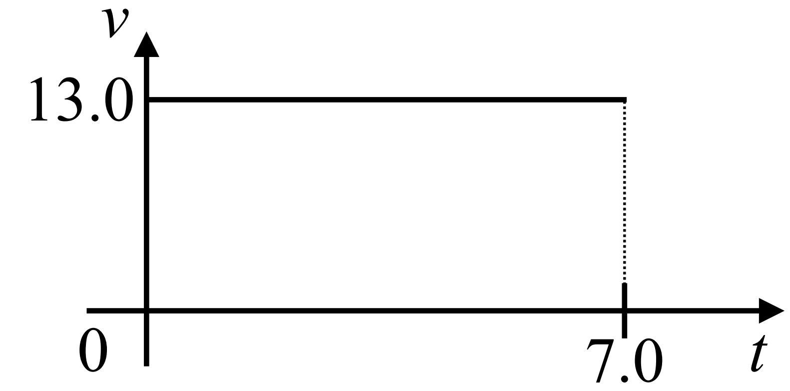
Semiring: sup-inf semiring



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

Comparison of the semiring





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

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

Sup-inf semiring

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

Tropical semiring

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

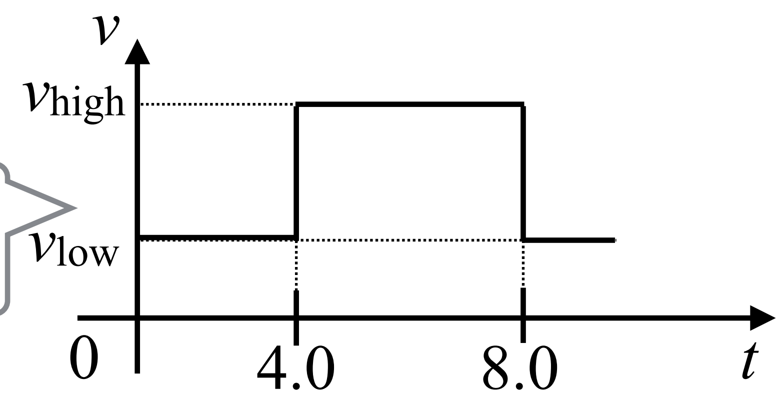
	Boolean	sup-inf	tropical
S	{True/False}	$\mathbb{R} \cup \{\pm\infty\}$	$\mathbb{R} \cup \{+\infty\}$
$\oplus$	$\vee$	sup	inf
$\otimes$	$\wedge$	inf	$+$

(Qualitative) timed pattern matching

Input [Ulus+, FORMATS'14]

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

discretized!!



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

Output

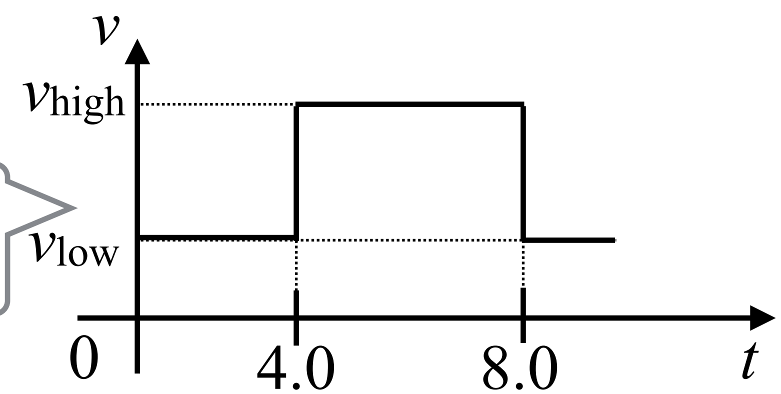
- **All** the subsignals σ([t,t′)) of the ***log*** satisfies the ***spec.***
  - e.g., σ([4.0,8.0)), σ([6.0,8.0)), σ([6.0,7.5)), …

M. Waga (NII)

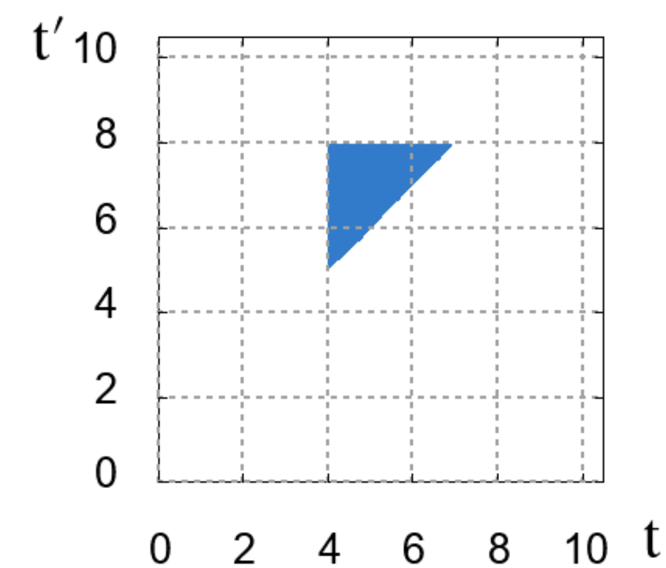
(Qualitative) timed pattern matching

Input [Ulus+, FORMATS'14]

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



- **Real-time spec.** $\mathscr{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high f



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)), …

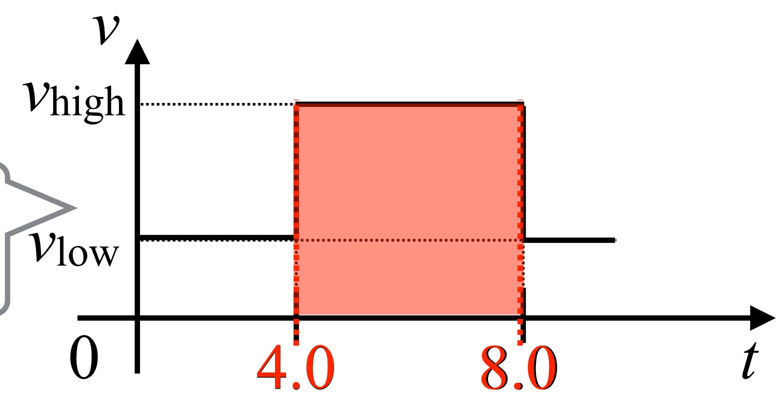
M. Waga (NII)

(Qualitative) timed pattern matching

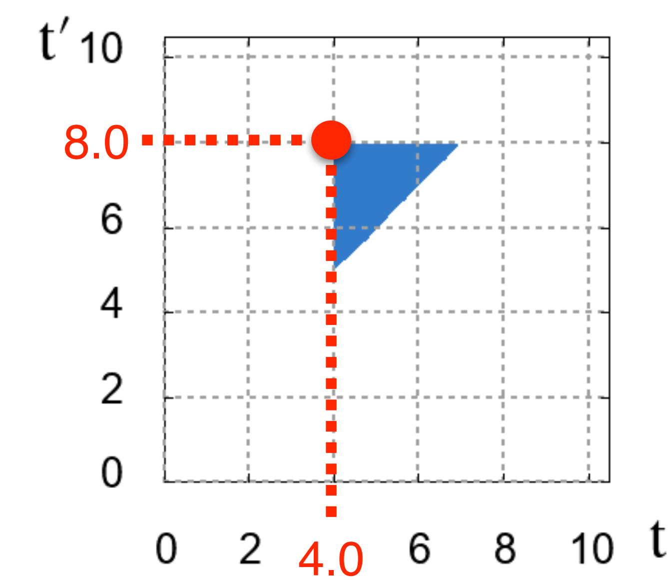
Input [Ulus+, FORMATS'14]

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

discretized!!



- **Real-time spec. $\mathscr{W}$**
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high f



Output

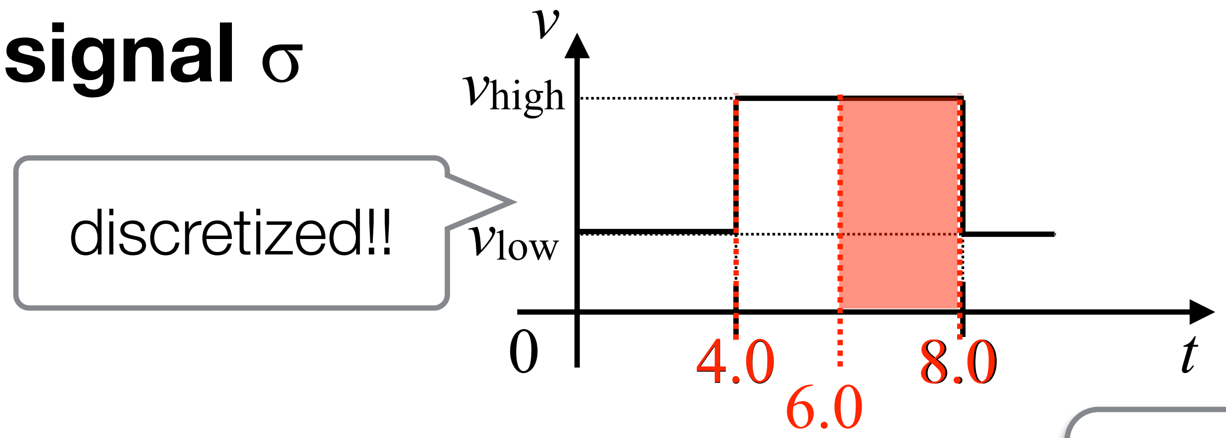
- **All** the subsignals σ([t,t′)) of the ***log*** satisfies the ***spec.***
  - e.g., σ([4.0,8.0)), σ([6.0,8.0)), σ([6.0,7.5)), …

(Qualitative) timed pattern matching

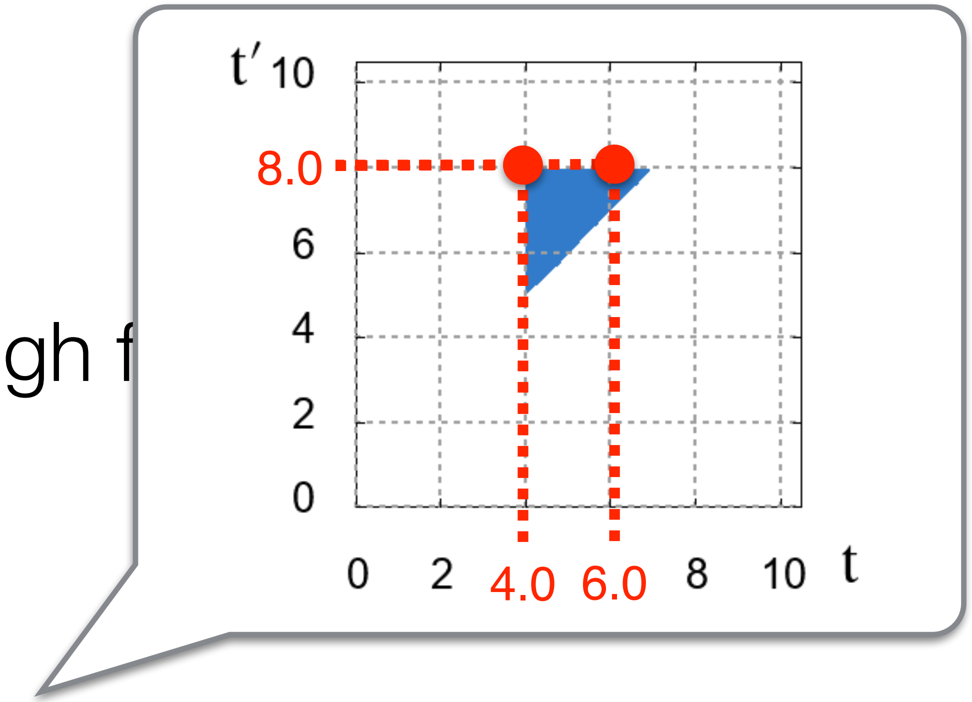
Input

[Ulus+, FORMATS’14]

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



- **Real-time spec. $\mathscr{W}$**
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high f



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)), …

M. Waga (NII)

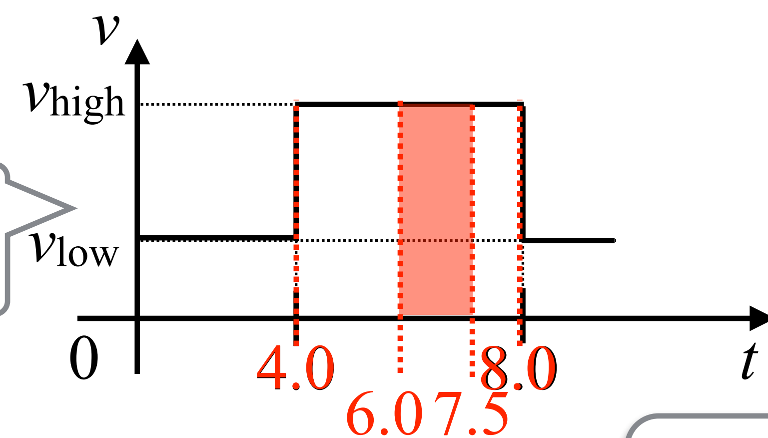
(Qualitative) timed pattern matching

Input

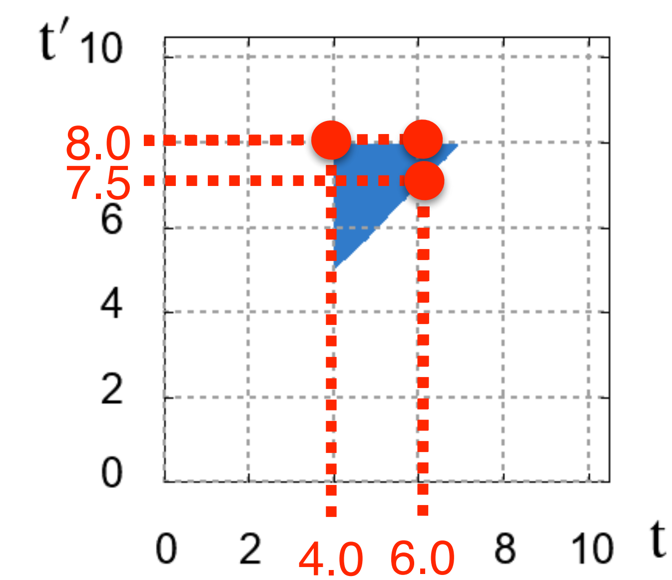
[Ulus+, FORMATS’14]

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

discretized!!



- **Real-time spec.** $\mathscr{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high f



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)), …

M. Waga (NII)

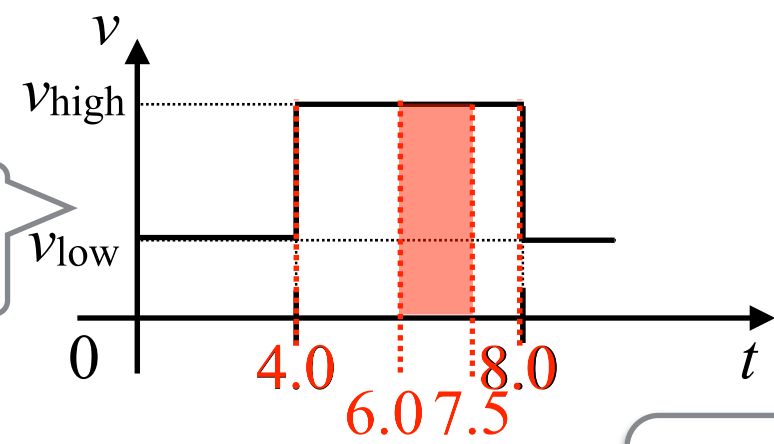
(Qualitative) timed pattern matching

Input

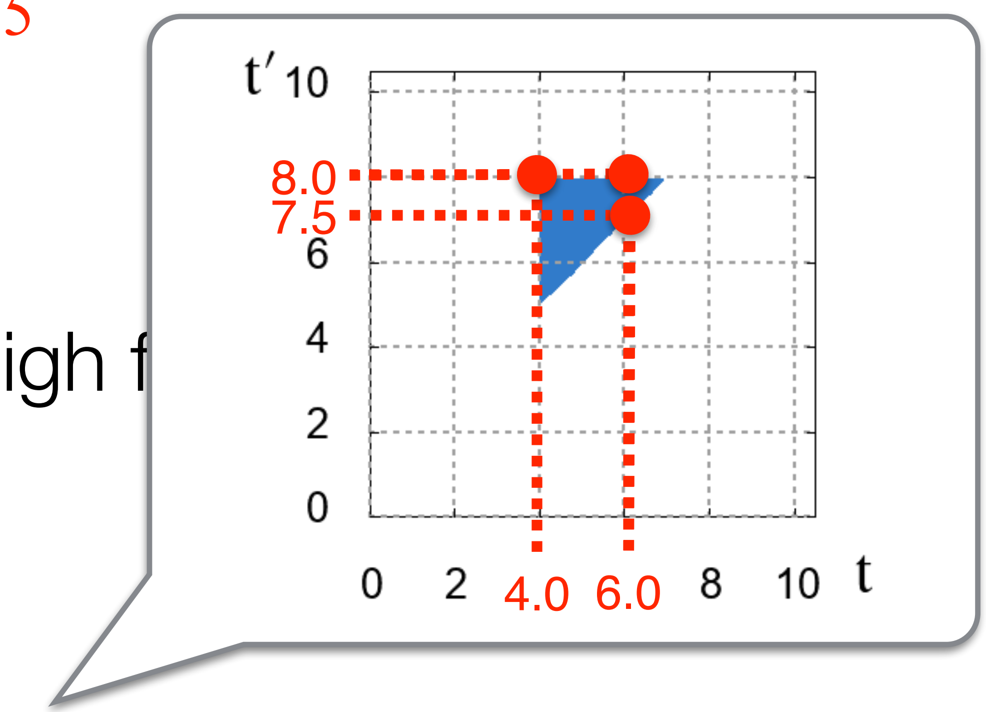
[Ulus+, FORMATS'14]

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

discretized!!



- **Real-time spec.** $\mathscr{W}$
  - ***Spec.*** to be monitored
    - e.g., The velocity should not keep high f



Output

- **All** the subsignals $\sigma([t,t'))$ of the ***log*** satisfies the ***spec.***
  - e.g., $\sigma([4.0,8.0))$, $\sigma([6.0,8.0))$, $\sigma([6.0,7.5))$, …

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