# Online Parametric Timed Pattern Matching with Automata-Based Skipping

**Masaki Waga**[1,2,3] and Étienne André[4,5,1]

National Institute of Informatics[1], SOKENDAI[2],
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LIPN, Université Paris 13, CNRS[4], JFLI, UMI CNRS[5]

7 May 2019, NFM 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 and by the ANR national research program PACS (ANR-14-CE28-0002).

Parameterized Specification

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
- We do not need system model (black box is OK)
- Usually scalable



M. Waga (NII)

# (Non-Parametric) Timed Pattern Matching

[Ulus+, FORMATS'14, Waga+, FORMATS'16]

**Input**

- **Time-series data**
  - System ***log***
    - e.g., change of engine rotation ($\omega$) / velocity ($v$) of a car
      $v$↑ at 0.1s, $\omega$↓ at 0.2s, …
- **Real-time spec.**
  - ***Spec.*** useful for debugging
    - e.g., unexpected behavior of a car
      $\omega$ gets high and remains ⇒ $v$ gets high > 2 s. later

**Output**

- The intervals where the ***spec.*** is satisfied in the ***log***
  - e.g., The above behavior occurs in 0.8s-3.4s

# Parametric Timed Pattern Matching

[André, Hasuo, & Waga, ICECCS'18]

**Input**

- **Time-series data**
  - System ***log***
    - e.g., change of engine rotation ($\omega$) / velocity ($v$) of a car
      $v\uparrow$ at 0.1s, $\omega\downarrow$ at 0.2s, …
- ***Parametric*** **Real-time spec.**
  - ***Spec.*** useful for debugging (with **parameters**)
    - e.g., unexpected behavior of a car (with **parameters**)
      $\omega$ gets high and remains ⇒ $v$ gets high $p$ s. later

**Output**

- The intervals **+ param. valuation**, s.t. the ***spec.*** is satisfied in the ***log***
  - e.g., The above behavior occurs in 0.8s-3.4s, $p = 2.5$

# Parametric Timed Pattern Matching

[André, Hasuo, & Waga, ICECCS'18]

**Input**

- **Time-series data**
  - System ***log***
    - e.g., change of engine rotation ($\omega$) / velocity ($v$) of a car
      $v\uparrow$ at 0.1s, $\omega\downarrow$ at 0.2s, …
- ***Parametric*** **Real-time spec.**
  - ***Spec.*** useful for debugging (with **parameters**)
    - e.g., unexpected behavior of a car (with **parameters**)
      $\omega$ gets high and remains ⇒ $v$ gets high $p$ s. later

$p > 2$ : satisfied (unexpected beh.)
$p \leq 2$ : violated (expected beh.)

**Output**

- The intervals **+ param. valuation**, s.t. the ***spec.*** is satisfied in the ***log***
  - e.g., The above behavior occurs in 0.8s-3.4s, $p = 2.5$

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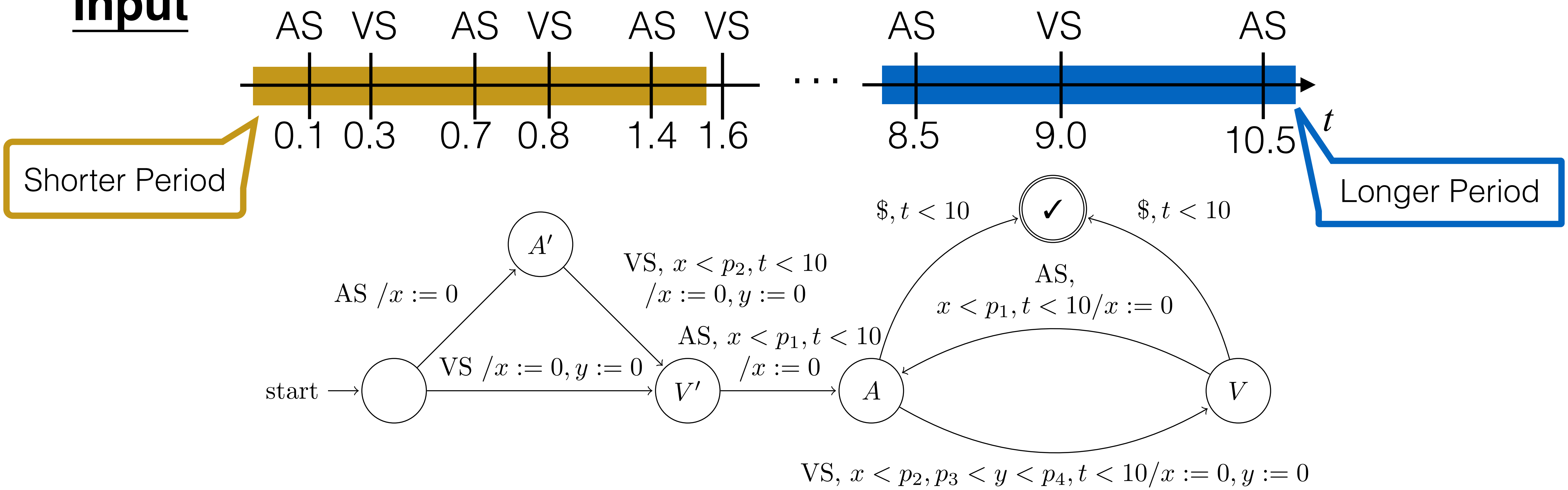
# PTPM for Periods Detection

**Imaginary Example**: Electrocardiography (Atrial/Ventricular Spikes)

**Input**




**Output**

$$\mathrm{Match}(w, \mathcal{A}) = \boxed{\{(t,t',v) \mid t \in [0,0.1),\ t' \in (1.4,\ 1.6],\ \underline{v(p_1) > \mathbf{0.6}},\ v(p_2) > \mathbf{0.2},\ \ldots\}}$$

$$\cup \ldots \cup \boxed{\{(t,t',v) \mid t \in [1.6,\ 8.5),\ t' \in (10.5,\infty),\ \underline{v(p_1) > \mathbf{1.5}}, v(p_2) > \mathbf{0.5}\}}$$

# Contribution

- Give a specialized alg. for parametric timed pattern matching
  - [André, Hasuo, & Waga, ICECCS'18] IMITATOR-based

    Model Checker for PTA
- Optimized the algorithm with **skipping** from string matching (FJS)
- Implementation + experiment
  - we have 3 new Alg. + IMITATOR-based:
    naive, parametric/non-parametric skipping
  - Our algorithms are much faster than IMITATOR-based algorithm

# Outline

- Motivation + Introduction
- Technical Part
  - The parametric timed pattern matching problem
  - Naive algorithm for Parametric TPM [Alg. 1]
  - Skipping optimization for Parametric TPM
    - Parametric Skipping Algorithm [Alg. 2]
    - Non-Parametric Skipping Algorithm [Alg. 3]
- Experiment

# Parametric Timed Pattern Matching

[André, Hasuo, & Waga, ICECCS'18]

## Input

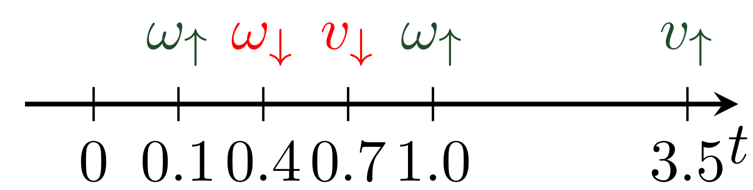
- Timed word $w \in (\Sigma \times \mathbb{R}_{>0})^*$
  - System ***log***
- PTA $\mathcal{A}$
  - Parameterized ***spec.***

## Output

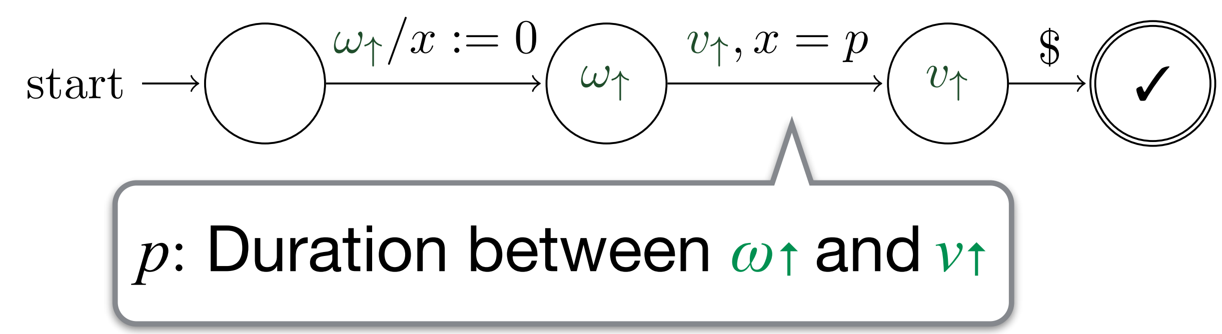
- $\mathrm{Match}(w, \mathcal{A}) = \{(t,t',v) \mid w|_{(t,t')} \in \mathcal{L}(v(\mathcal{A}))\}$
  - Interval $(t,t')$ + param. val. $v$ s.t. spec. is satisfied

## *Example*

$w =$




$\mathcal{A} =$




$$\mathrm{Match}(w, \mathcal{A}) = \{(t,t',v) \mid 0.7 \leq t < 1.0,\ 3.5 < t',\ v(p) = 2.5\}$$

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- Experiment

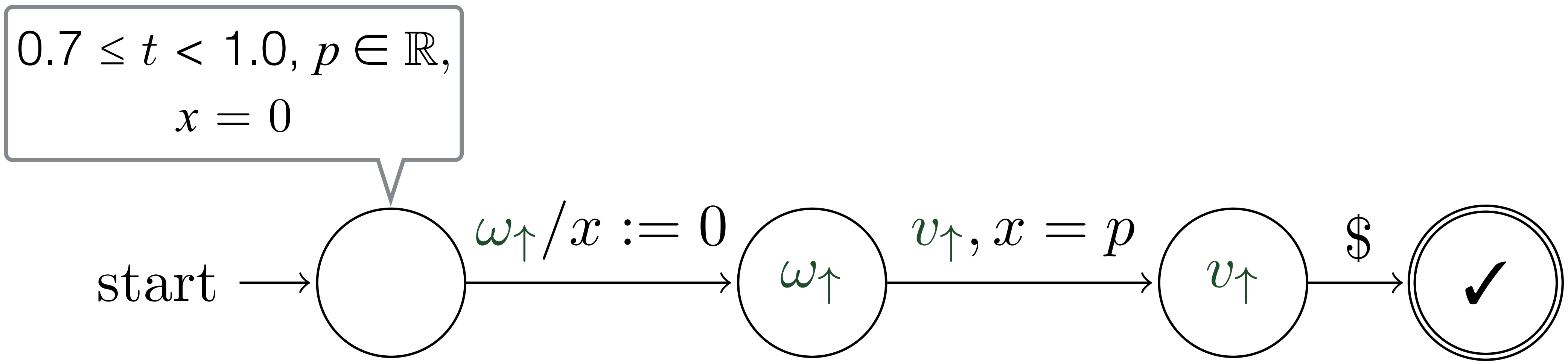
# Idea of our (naive) online algorithm

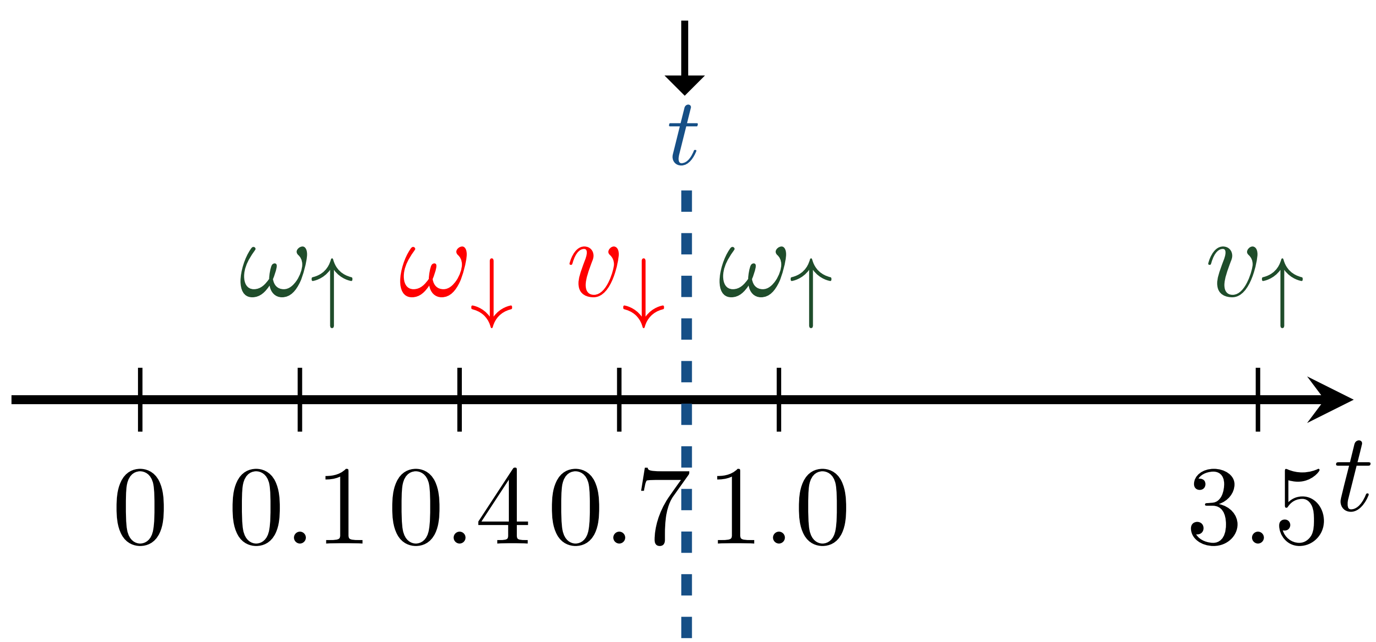
follow the transitions of PTA

+

abstraction of clock/param. val.
by convex polyhedra

# Our online (naive) algorithm



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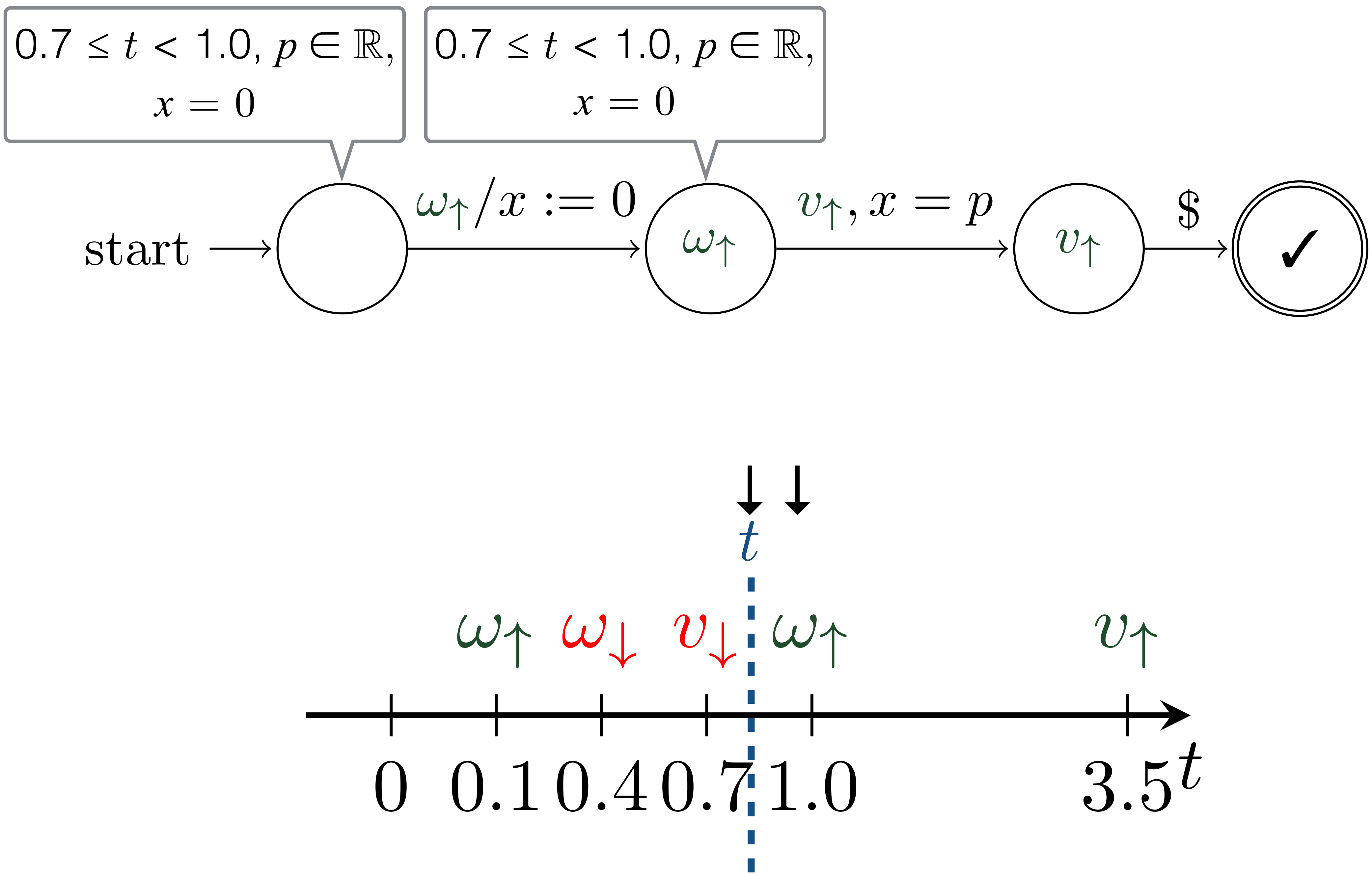
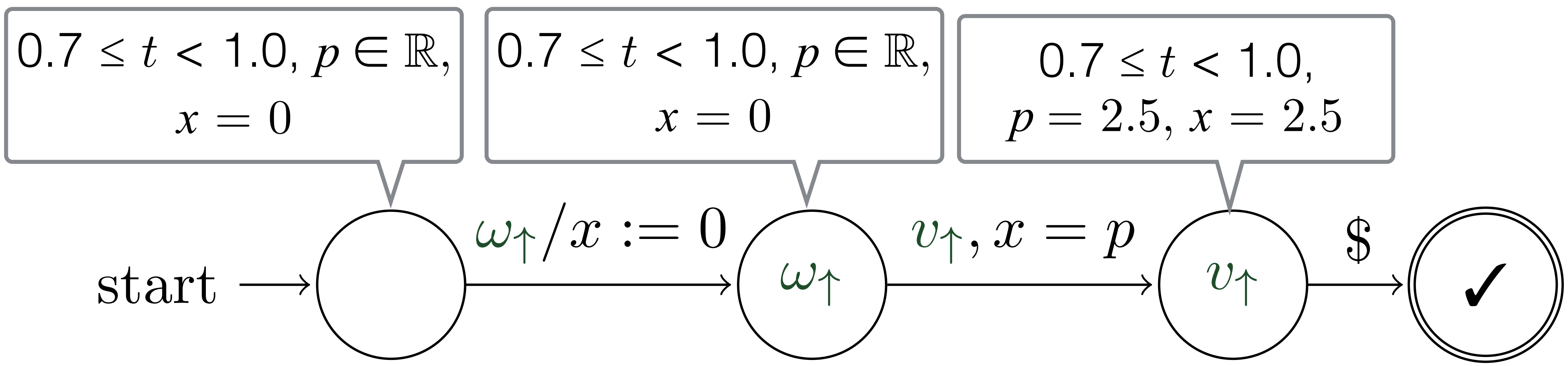
# Our online (naive) algorithm

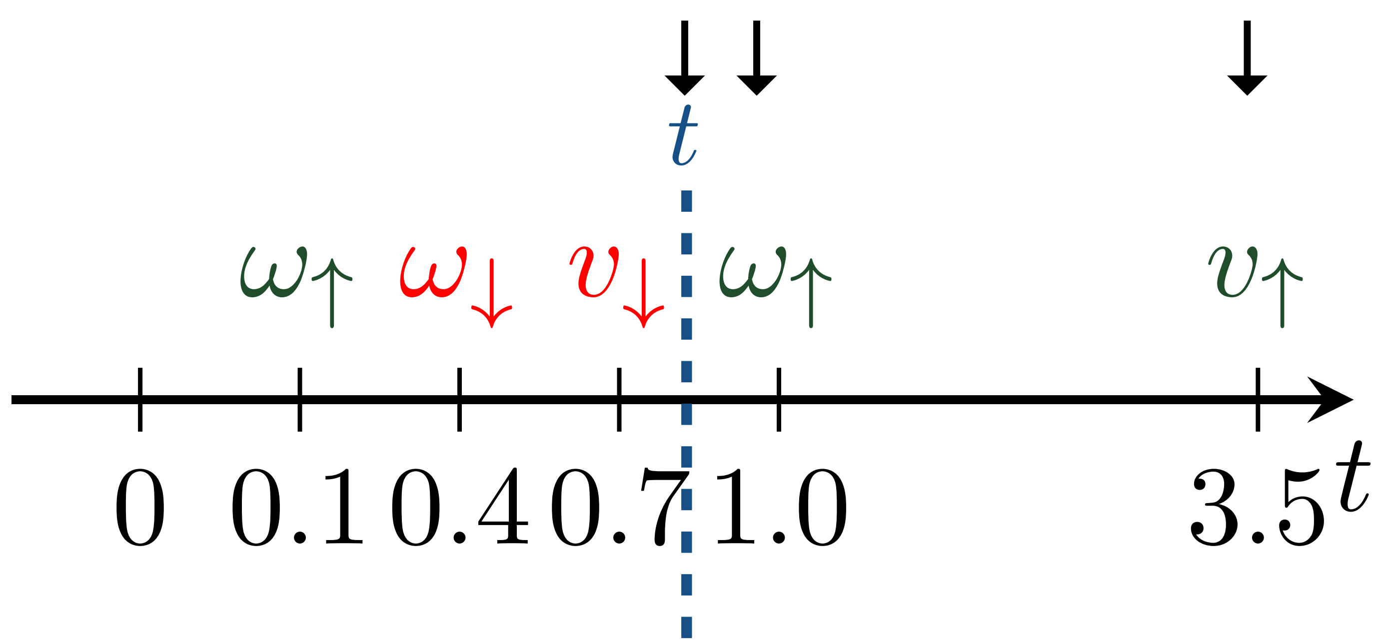





M. Waga (NII)

# Our online (naive) algorithm



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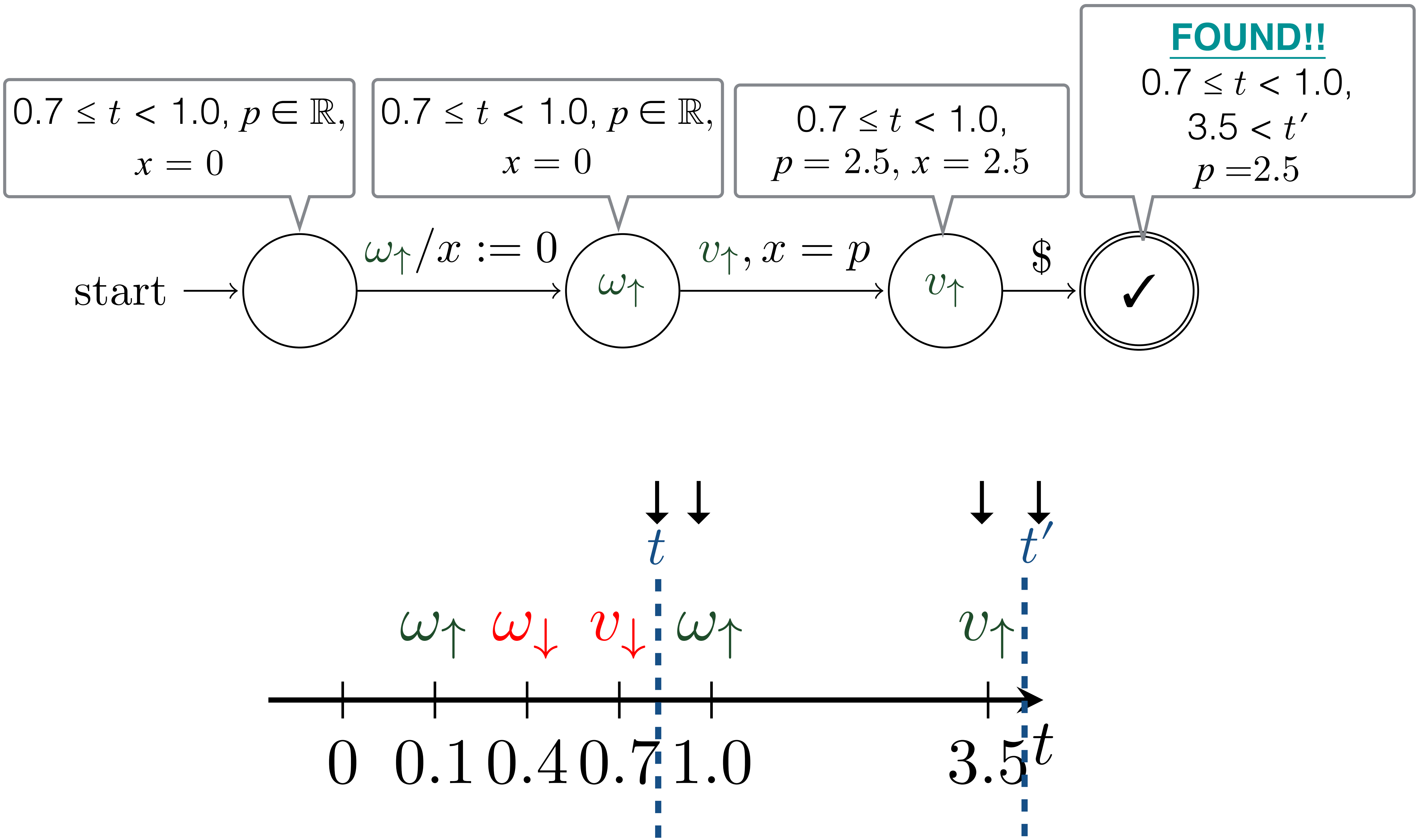
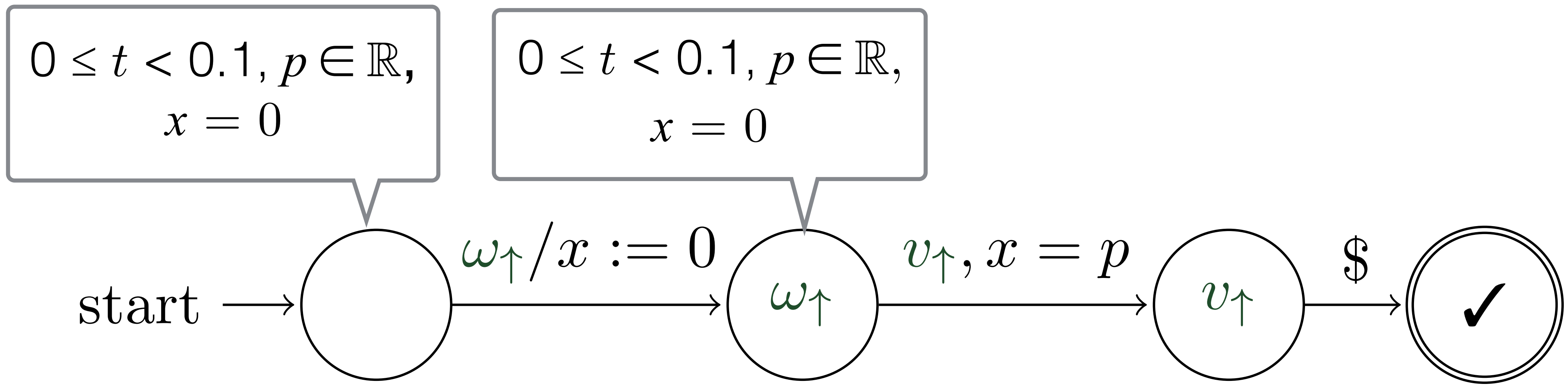
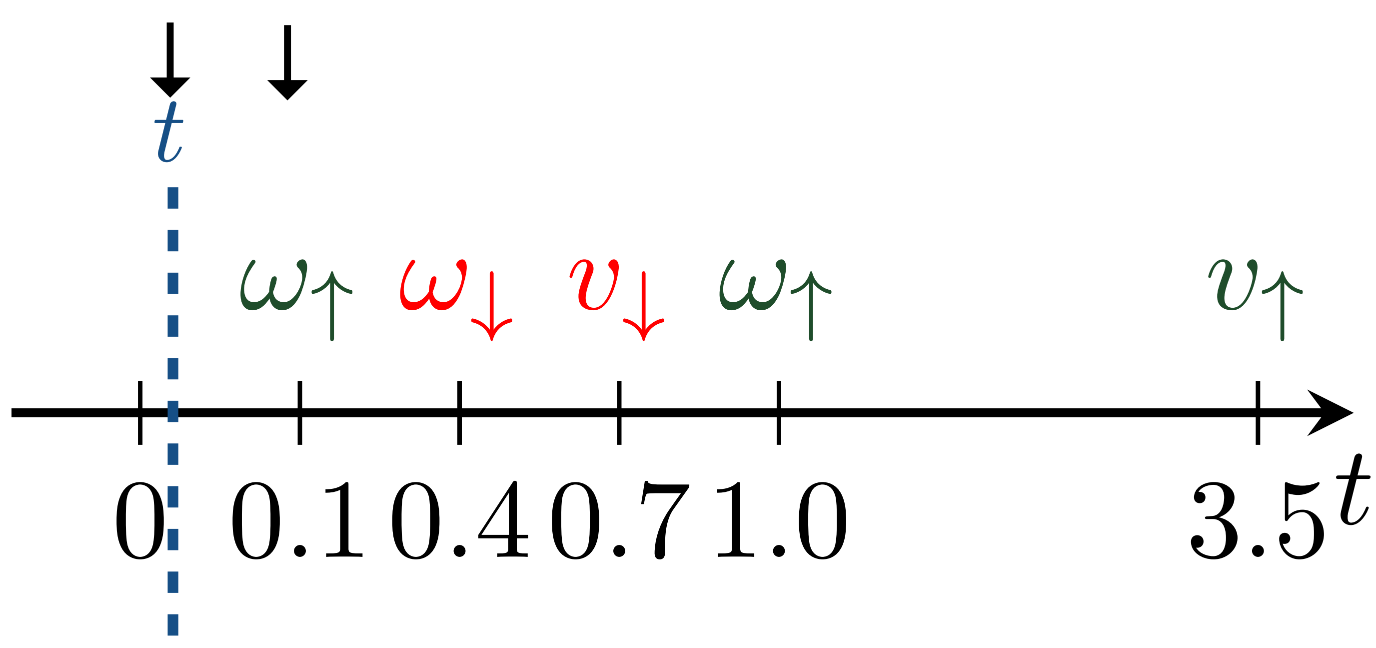
# Our online (naive) algorithm



# Our online (naive) algorithm



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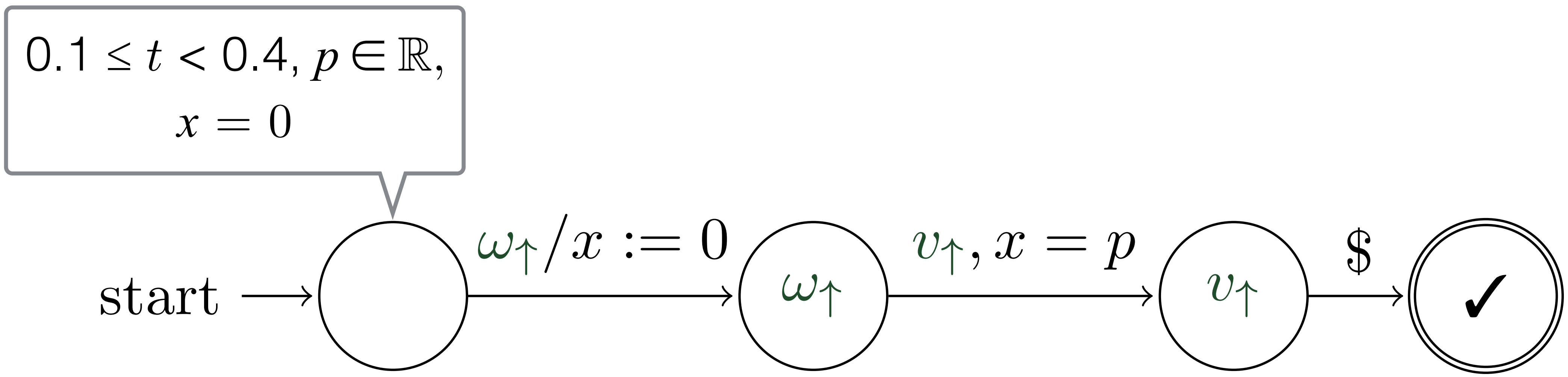
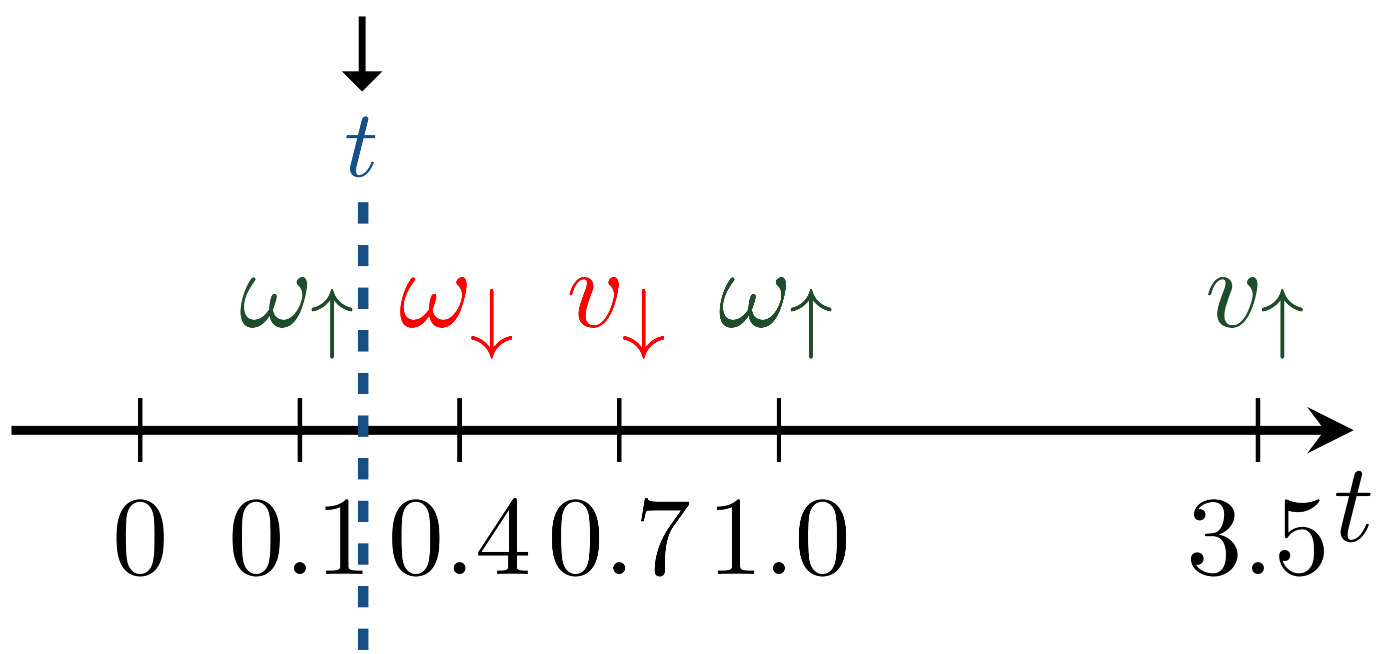
# Our online (naive) algorithm



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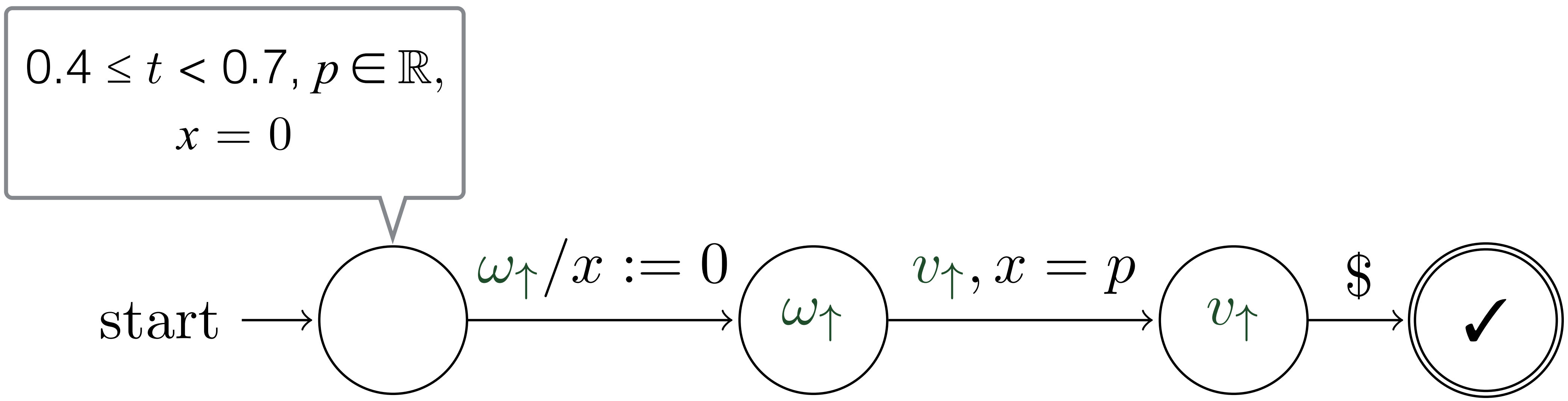
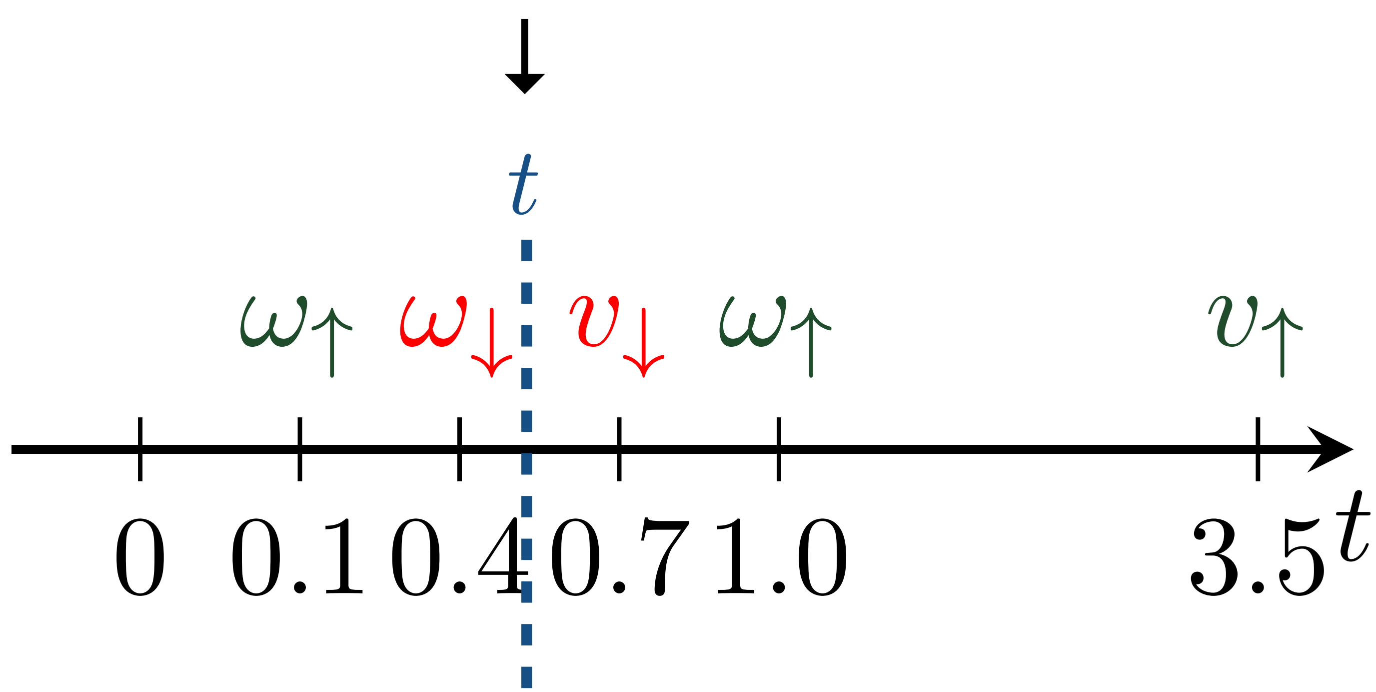
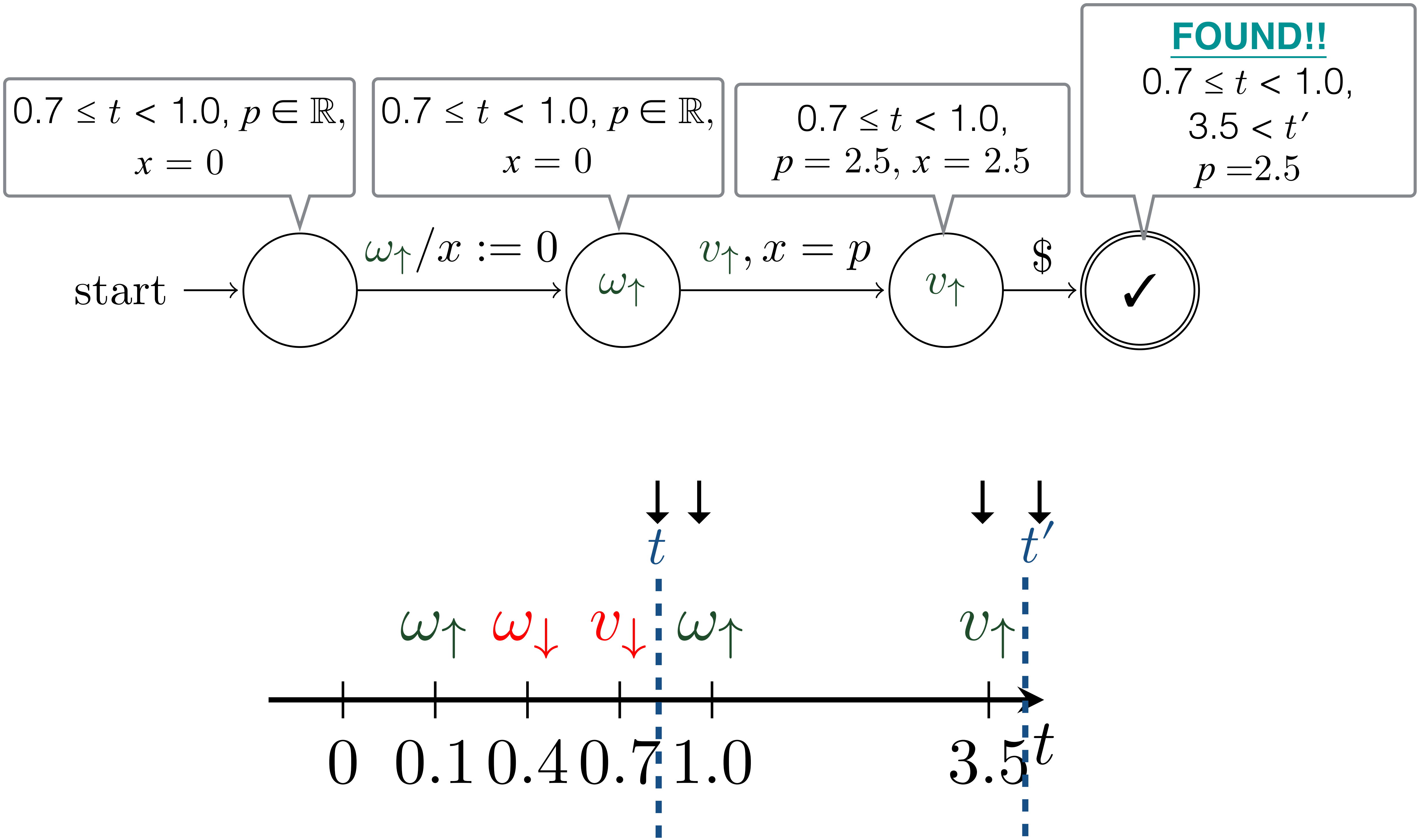
# Our online (naive) algorithm



# Our online (naive) algorithm



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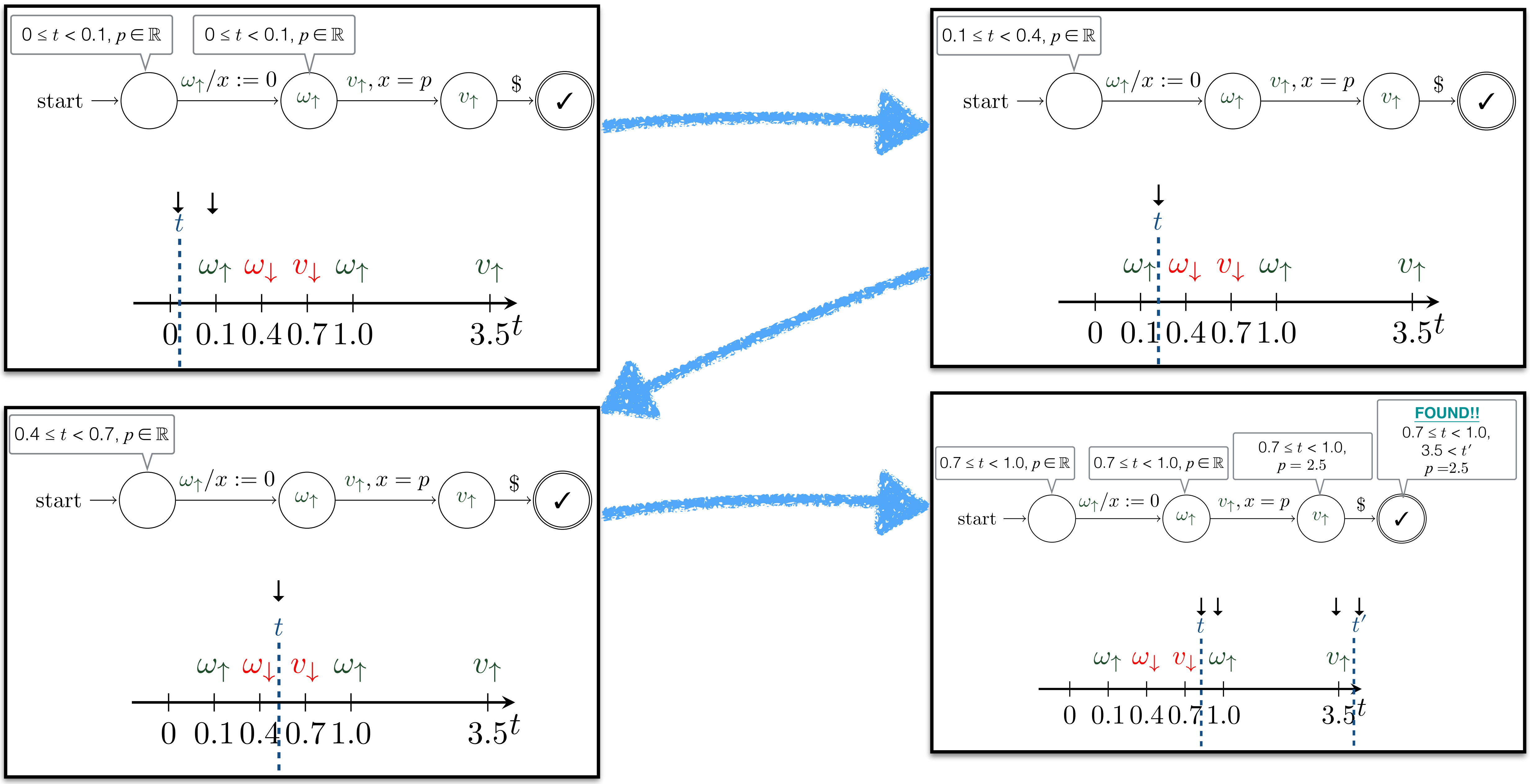
# Motivation: Skip Unnecessary Trials




Can we skip some of them? ⇒ (Usually) Yes!! by skipping from string matching



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# Idea of Skipping from String Matching

- For each length $n \in \mathbb{N}$, check if

$$\boxed{\text{Over-approx. of the read timed word}} \cap \boxed{n\text{-shift + accepted timed words}} = \emptyset$$

  before the matching trials.
- Empty ⇒ no need to try $n$-shift
- Over-approx. using location $l \in L$ (finite)
  - In PTA, we also use param. val. $v$: $\mathbb{P} \to \mathbb{R}$
  - Infinite but represented by convex polyhedra

# Skipping from Non-Parametric to Parametric

## Skipping for TA [Waga+, FORMATS'17]

For each $l \in L$, $n \in \mathbb{N}$, if $\boxed{\mathcal{L}(\mathcal{A}_l) \cdot \mathcal{T}(\Sigma)} \cap \boxed{\mathcal{T}^n(\Sigma) \cdot \mathcal{L}(\mathcal{A})} = \emptyset$

Over-approx. of the read timed word

n-shift + accepted timed words

## (Parametric) Skipping for PTA [Contribution, Alg. 2]

For each $l \in L$, $v\colon \mathbb{P} \to \mathbb{R}$ $n \in \mathbb{N}$, if there is $v'\colon \mathbb{P} \to \mathbb{R}$ s.t.

$$\boxed{\mathcal{L}(v(\mathcal{A}_l)) \cdot \mathcal{T}(\Sigma)} \cap \boxed{\mathcal{T}^n(\Sigma) \cdot \mathcal{L}(v'(\mathcal{A}))} = \emptyset$$

Over-approx. of the read timed word for the **given** param. val. $v$

n-shift + accepted timed words for some param. val. $v'$

# Skipping from Non-Parametric to Parametric

**Skipping for TA** [Waga+, FORMATS'17]

For each $l \in L$, $n \in \mathbb{N}$, if $\boxed{\mathcal{L}(\mathcal{A}_l) \cdot \mathcal{T}(\Sigma)} \cap \boxed{\mathcal{T}^n(\Sigma) \cdot \mathcal{L}(\mathcal{A})} = \emptyset$

Over-approx. of the read timed word

n-shift + accepted timed words

---

**(Parametric) Skipping for PTA** [Contribution, Alg. 2]

For each $l \in L$, $v\colon \mathbb{P} \to \mathbb{R}$ $n \in \mathbb{N}$, if there is $v'\colon \mathbb{P} \to \mathbb{R}$ s.t.

Runtime Overhead!!

$$\boxed{\mathcal{L}(v(\mathcal{A}_l)) \cdot \mathcal{T}(\Sigma)} \cap \boxed{\mathcal{T}^n(\Sigma) \cdot \mathcal{L}(v'(\mathcal{A}))} = \emptyset$$

Over-approx. of the read timed word for the **given** param. val. $v$

n-shift + accepted timed words for some param. val. $v'$

# Skipping with Less Overhead

## (Parametric) Skipping for PTA [Contribution, Alg. 2]

For each $l \in L$, $v$: $\mathbb{P} \to \mathbb{R}$ $n \in \mathbb{N}$, if there is $v'$: $\mathbb{P} \to \mathbb{R}$ s.t.

**More** overhead
**better** approx.

$$\mathcal{L}(v(\mathcal{A}_l)) \cdot \mathcal{T}(\Sigma) \cap \mathcal{T}^n(\Sigma) \cdot \mathcal{L}(v'(\mathcal{A})) = \emptyset$$

Over-approx. of the read timed word for the **given** param. val. $v$

n-shift + accepted timed words for some param. val. $v'$

**Trade off!!**

## (Non-Parametric) Skipping for PTA [Contribution, Alg. 3]

For each $l \in L$, $n \in \mathbb{N}$, if there is $v$, $v'$: $\mathbb{P} \to \mathbb{R}$ s.t.

**Less** overhead
**worse** approx.

$$\mathcal{L}(v(\mathcal{A}_l)) \cdot \mathcal{T}(\Sigma) \cap \mathcal{T}^n(\Sigma) \cdot \mathcal{L}(v'(\mathcal{A})) = \emptyset$$

Over-approx. of the read timed word for **some** param. val. $v$

n-shift + accepted timed words for some param. val. $v'$

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# RQ: Which is the fastest algorithm?

Contribution

**Algorithms**

- Naive
- Parametric Skip
- Non-Parametric Skip
- IMITATOR-based

[André, Hasuo, & Waga, ICECCS'18]

- Probably, IMITATOR-based is not very fast
  - it solves more general problem (model checking)
- Param. Skip vs. Non-Param. Skip
  - Better over-approx. vs. Less Overhead

# Environment of Experiment

- Amazon EC2 c4.large instance
  - 2.9 GHz Intel Xeon E5-2666 v3, 2 vCPUs, 3.75 GiB RAM
- Ubuntu 18.04 LTS (64 bit)
- GCC 7.3.0 with optimization flag -O3
- Used 4 benchmarks
  - **Automotive**: Accel, Gear
  - **Toy**: Blowup, OnlyTiming

Performance for extreme inputs

# Comparison with IMITATOR

Table 2: Execution time for Gear [s]

| $\lvert w \rvert$ | No Skip | Non-Param. Skip | Param. Skip | IMITATOR |
|---|---|---|---|---|
| 1467 | 0.04 | 0.05 | 0.05 | 1.781 |
| 2837 | 0.0725 | 0.0805 | 0.09 | 3.319 |
| 4595 | 0.124 | 0.13 | 0.1405 | 5.512 |
| 5839 | 0.1585 | 0.156 | 0.17 | 7.132 |
| [illegible] | 0.201 | 0.193 | 0.2115 | 8.909 |
| [illegible] | 0.241 | 0.2315 | 0.2505 | 10.768 |
| [illegible] | 0.2815 | 0.269 | 0.2875 | 12.778 |
| [illegible] | 0.322 | 0.301 | 0.325 | 14.724 |
| 13183 | [illegible] | 0.3245 | 0.353 | 16.453 |
| 14657 | 0.392 | 0.361 | 0.395 | 18.319 |

60x faster

Table 3: Execution time for Accel [s]

| $\lvert w \rvert$ | No Skip | Non-Param. Skip | Param. Skip | IMITATOR |
|---|---|---|---|---|
| 2559 | 0.03 | 0.0515 | 0.06 | 2.332 |
| 4894 | 0.0605 | 0.0605 | 0.0705 | 4.663 |
| 7799 | 0.1005 | 0.071 | 0.08 | 7.532 |
| 10045 | 0.13 | 0.08 | 0.09 | 9.731 |
| 12531 | 0.161 | 0.09 | 0.1 | 12.503 |
| 15375 | 0.1985 | 0.1005 | 0.113 | 15.583 |
| 17688 | 0.2265 | 0.1095 | 0.1215 | 17.754 |
| 20299 | 0.261 | 0.115 | 0.1325 | [illegible] |
| 22691 | 0.288 | 0.121 | [illegible] | 23.044 |
| 25137 | 0.3205 | 0.1315 | 0.159 | 25.815 |

200x faster

Table 4: Execution time for Blowup [s]

| $\lvert w \rvert$ | No Skip | Non-Param. Skip | Param. Skip | IMITATOR |
|---|---|---|---|---|
| 2000 | 66.75 | 68.0125 | 67.9735 | OutOfMemory |
| 4000 | 267.795 | 271.642 | 269.084 | OutOfMemory |
| 6000 | 601.335 | 611.782 | 607.58 | OutOfMemory |
| 8000 | 1081.42 | 1081.25 | 1079 | OutOfMemory |
| 10000 | 1678.15 | 1688.22 | 1694.53 | OutOfMemory |

out of memory!!

Table 5: Execution time for OnlyTiming [s]

| $\lvert w \rvert$ | No Skip | Non-Param. Skip | Param. Skip | IMITATOR |
|---|---|---|---|---|
| 1000 | 0.0995 | 0.1305 | 0.11 | 1.690 |
| 2000 | 0.191 | 0.23 | 0.191 | 3.518 |
| 3000 | 0.2905 | 0.3265 | 0.273 | 5.499 |
| 4000 | 0.3905 | 0.426 | 0.3525 | 7.396 |
| 5000 | 0.488 | 0.5225 | 0.4325 | 9.123 |
| 6000 | 0.588 | 0.6235 | 0.517 | 11.005 |

20x faster



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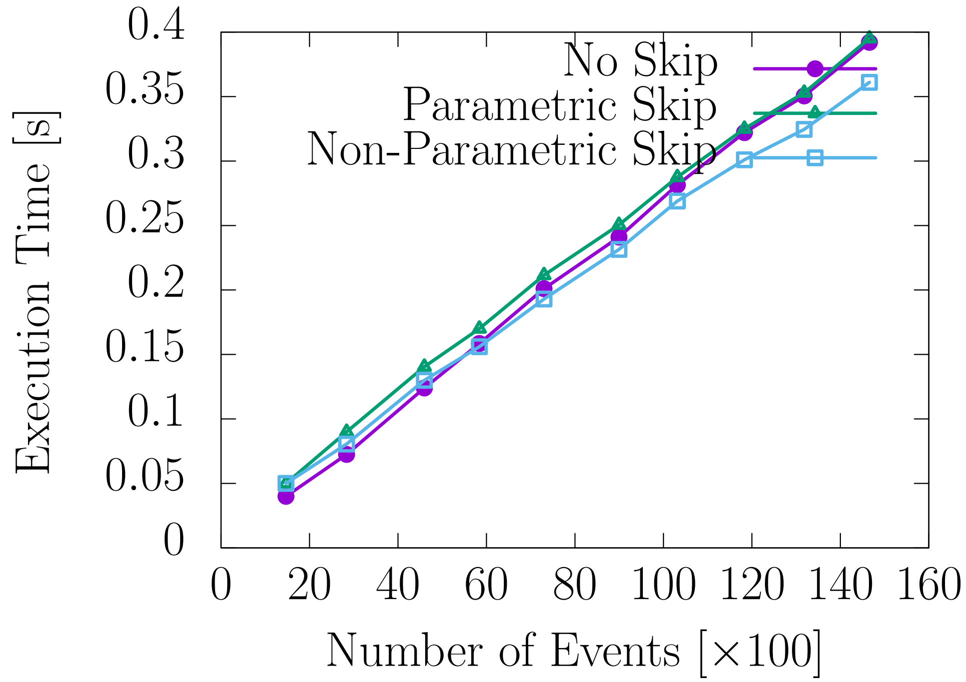
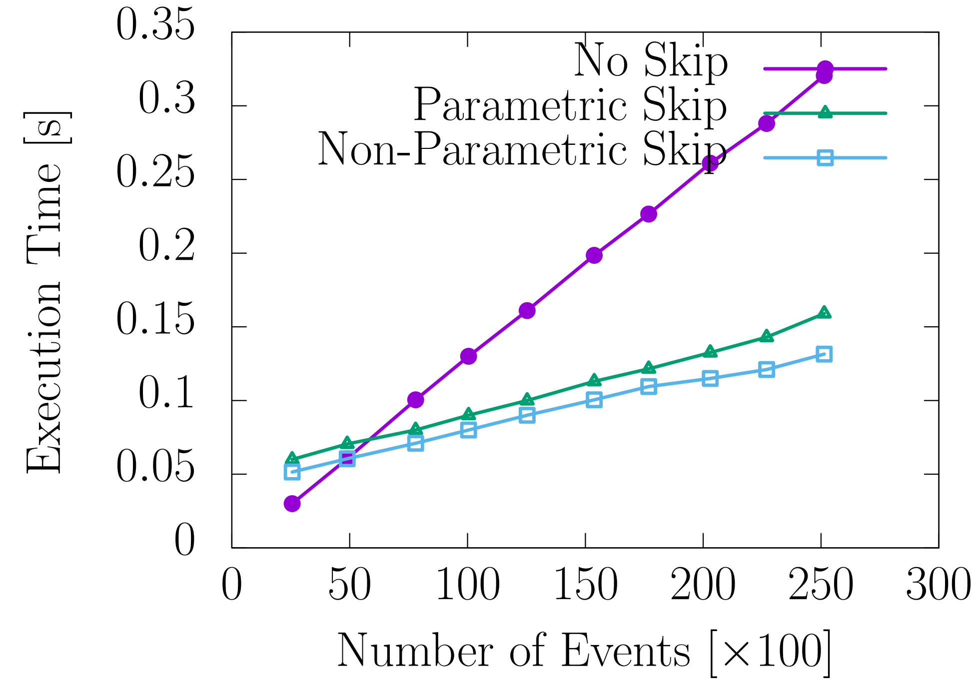
# Comparison among ours (Accel & Gear)

Accel




Gear




- No Skip has the steepest slope ⇒ worst scalability
- Parametric Skip is slower than Non-Parametric Skip due to the overhead

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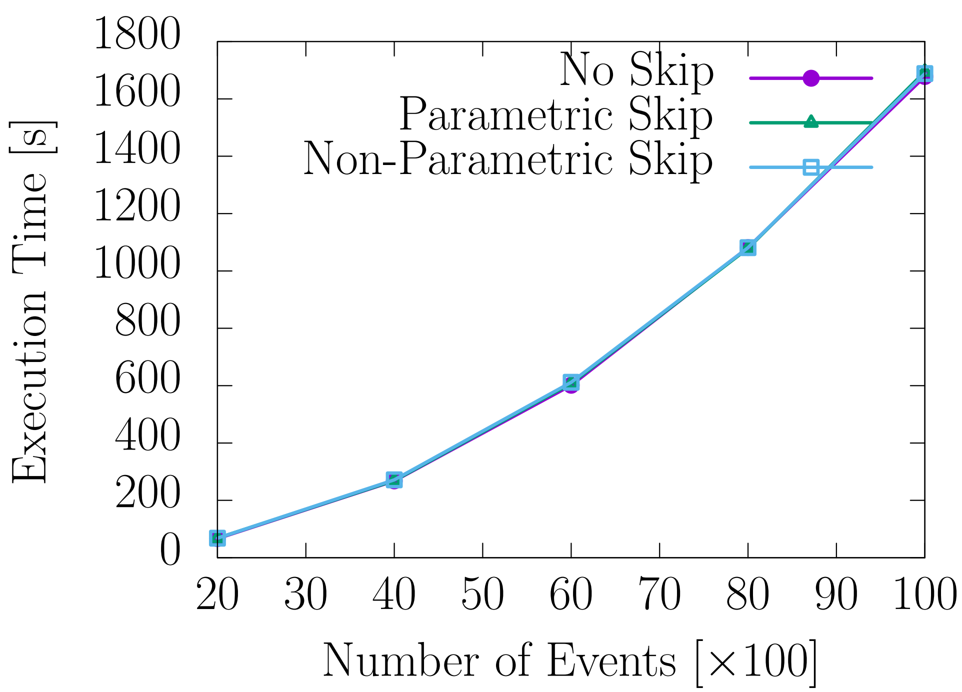
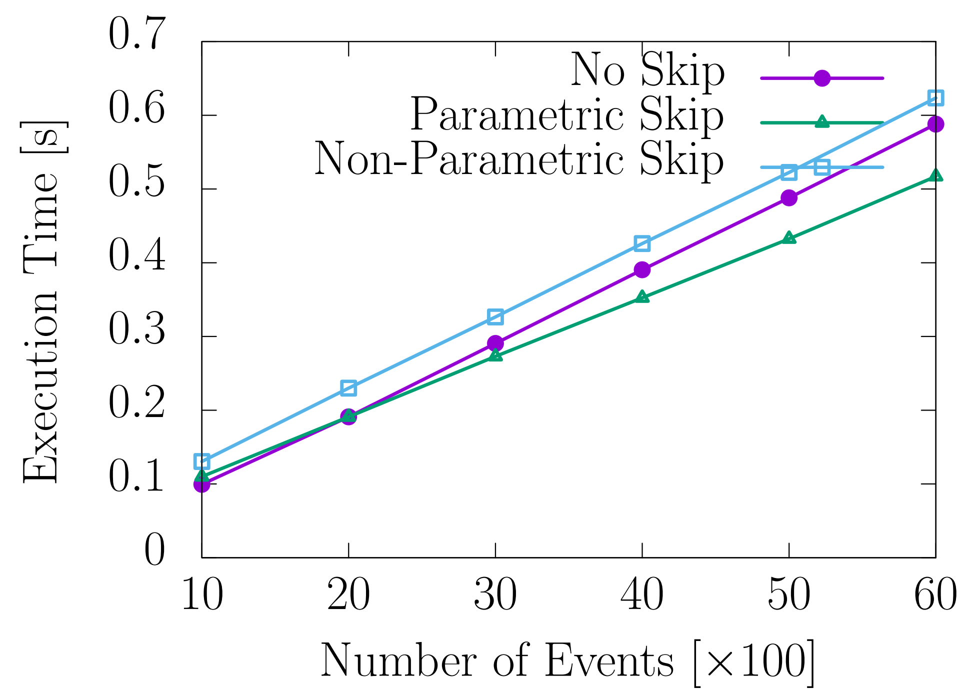
# Comparison among ours (Blowup & OnlyTiming)

Blowup




OnlyTiming




- <u>Blowup</u>: Skipping does not help much
  - Exponential blowup vs. constant speed up by skipping
- <u>OnlyTiming</u>: No Skip has the steepest slope ⇒ worst scalability

  Parametric Skip is the fastest due to the better over-approx.

# Conclusion

- Give a specialized alg. for param. timed pattern matching
- Optimized the algorithm by **skipping** from string matching
- Our algorithms are much faster than the state-of-the-art (IMITATOR-based algorithm)
- Param. vs. Non-Param. Skipping depends on the Autom.

# Future Works

- Hybrid of Parametric/Non-Parametric Skipping
  - Maybe the best trade-off
- More expressive logic (e.g., FOL)
- Case study
  - not only automotive domain but also medical CPS or IoT (security)

# Appendix

# Why Autom? not TL or RE?

## Cons.

- Difficult to write (and read?) for the end user

## Pros.

- More straightforward online monitoring algorithm
- Optimization technique from untimed to timed

  e.g., **Skipping** in this talk
- TRE → TA, MITL → TA are possible

  Easy 😃

  Not easy…😟
  - TA as common platform
  - In our industrial collaboration, we use TRE → TA