Moore-Machine Filtering for Timed and Untimed Pattern Matching

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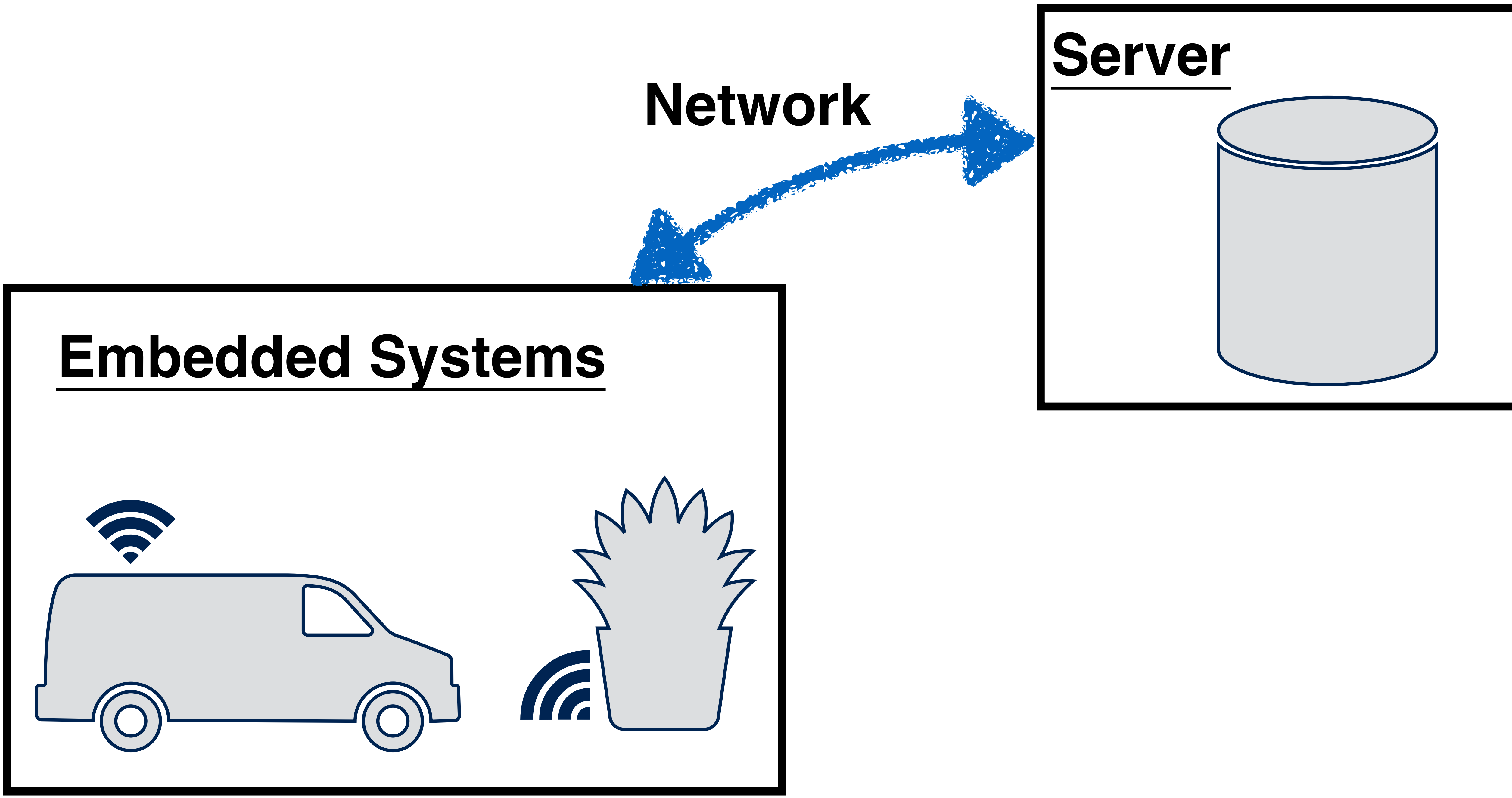
IoT / Embedded Systems Connected via Network



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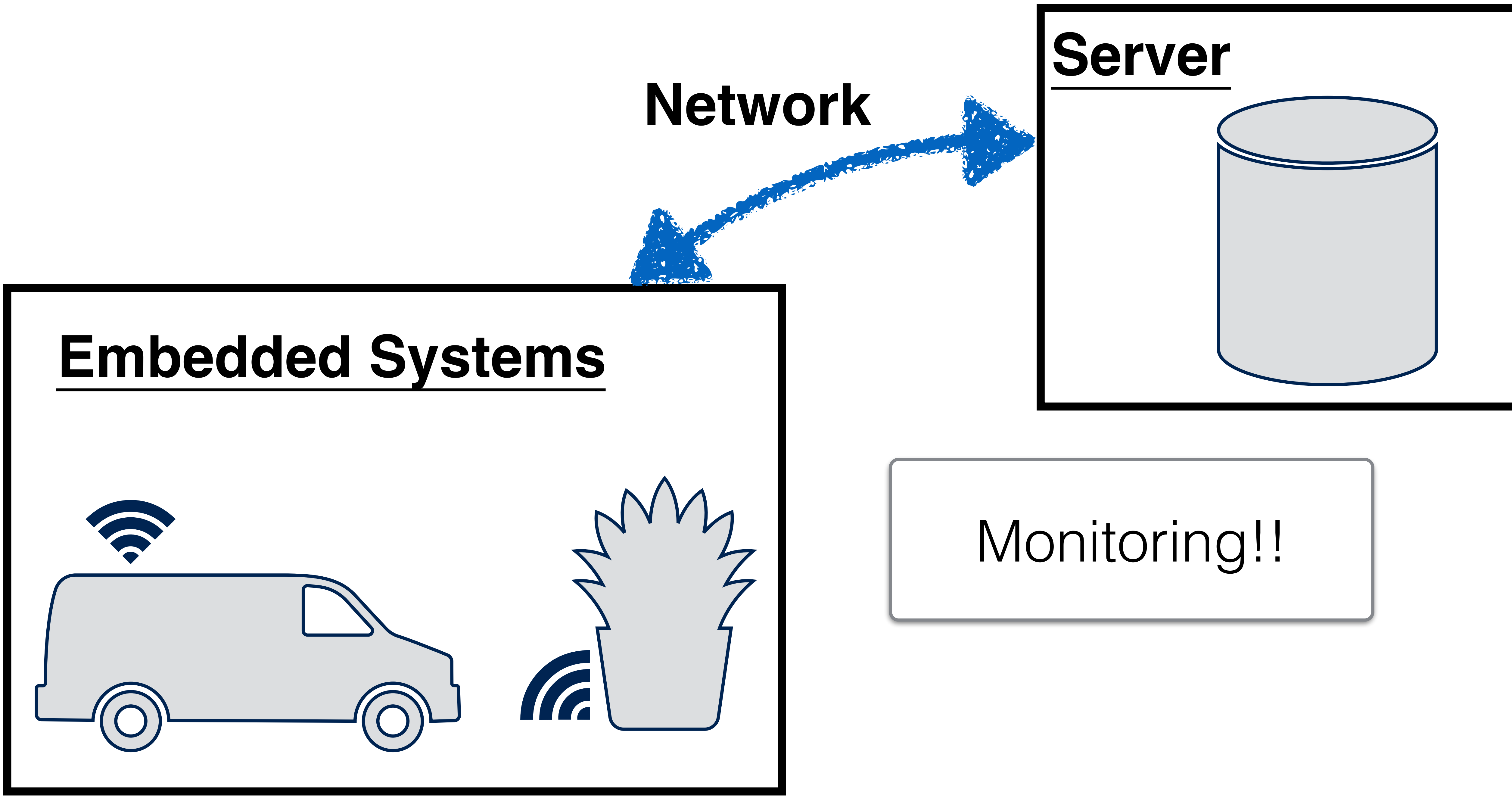


Monitoring!!

Timed Pattern Matching

[Ulus et al., FORMATS'14]

Input

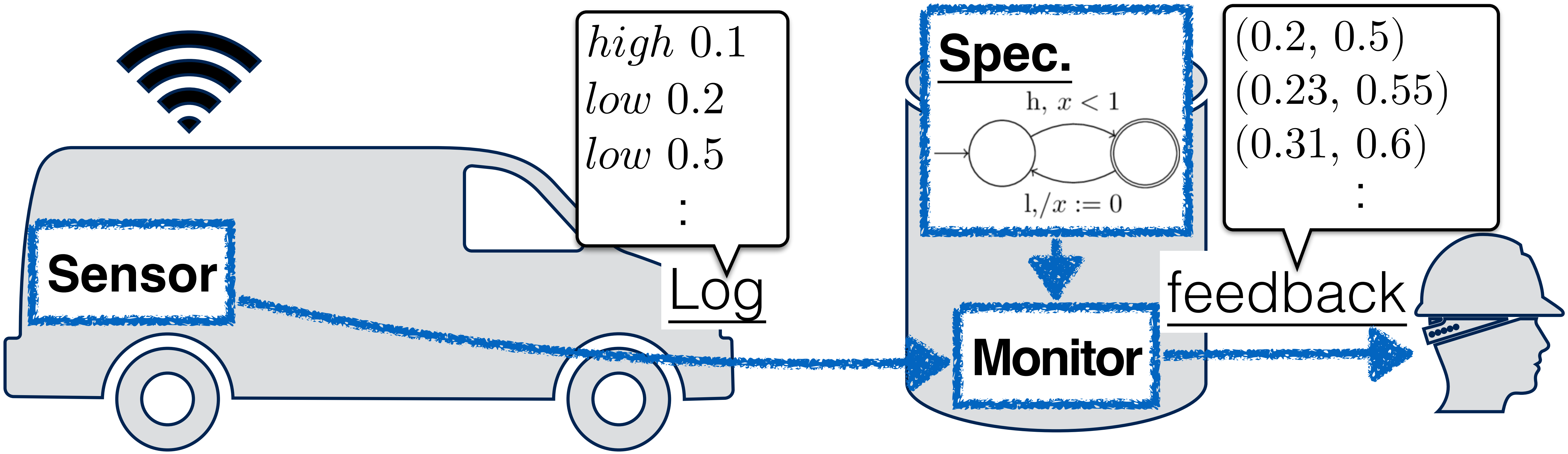
- **Time-series data** (***Logs*** of a car/ a robot)
  e.g., The gear of a car: ***high*** at 0.1s, ***low*** at 0.2s, …
- **Real-time spec.** (***Spec.*** useful for debugging)
  e.g., Frequent gear change of a car

Output

- The intervals where the ***spec.*** is satisfied in the ***log***
  e.g., Frequent gear change in 0.2s-0.7s

M. Waga (NII)

Remote Monitoring



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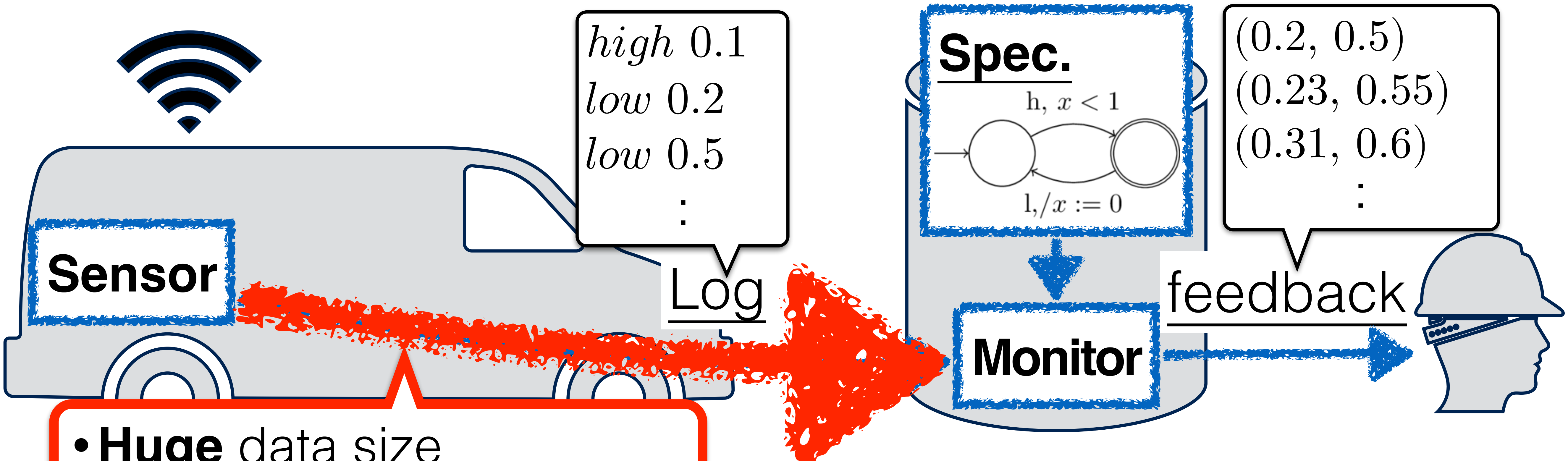
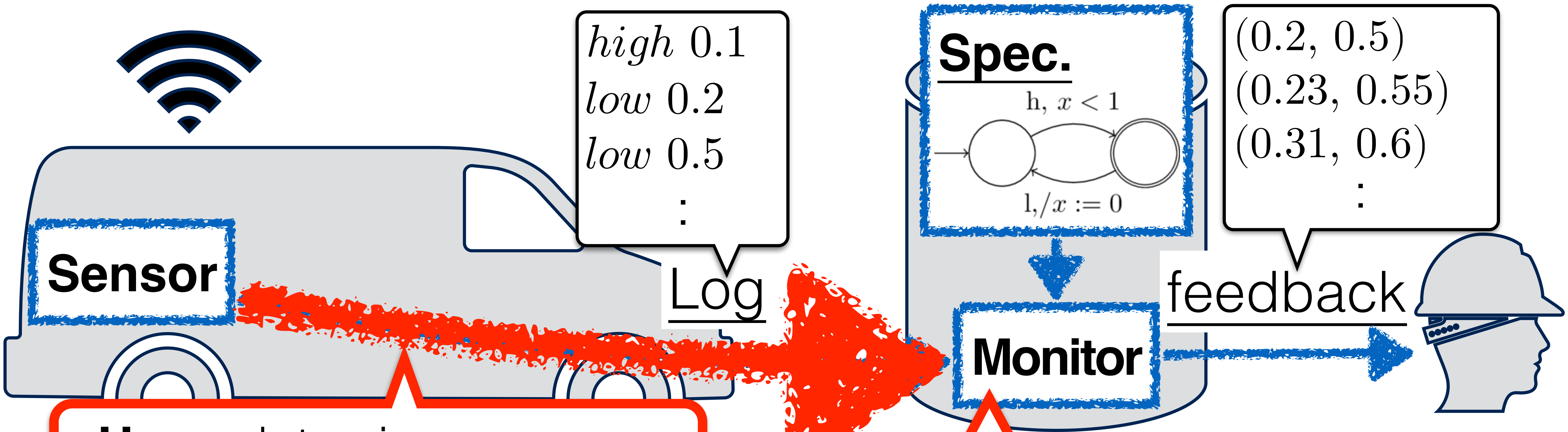
Remote Monitoring



- **Huge** data size
- **Limited** network capacity

⇒ Reduce the size!!

Remote Monitoring



- **Huge** data size
- **Limited** network capacity
  ⇒ Reduce the size!!

- Timed Pattern Matching
- **Assumption**: **Too Heavy** for embedded systems

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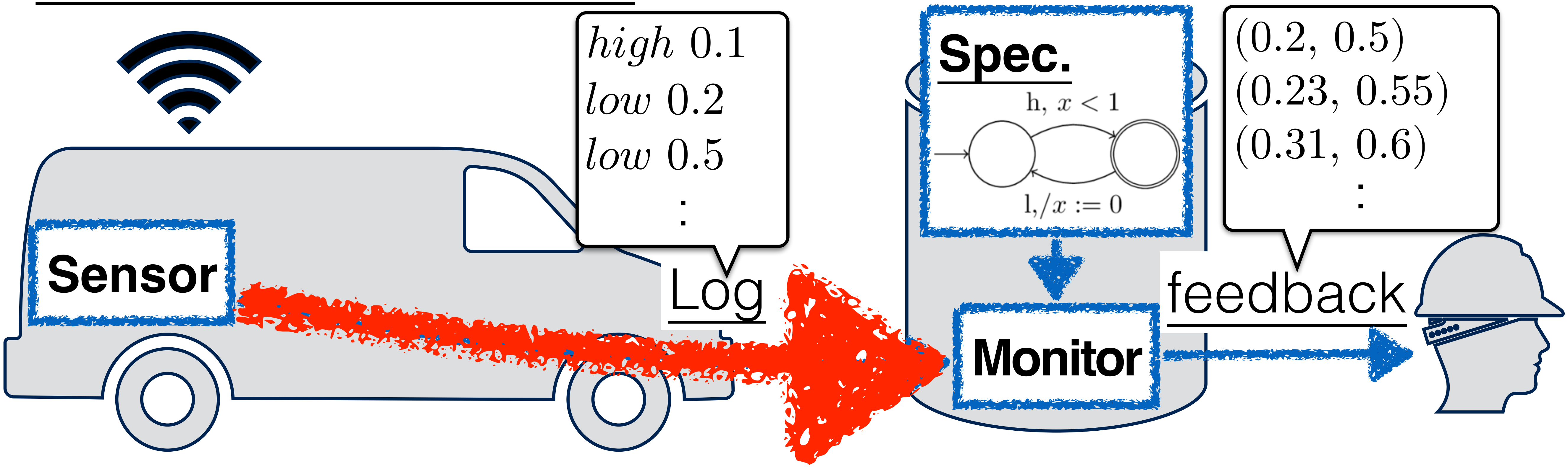
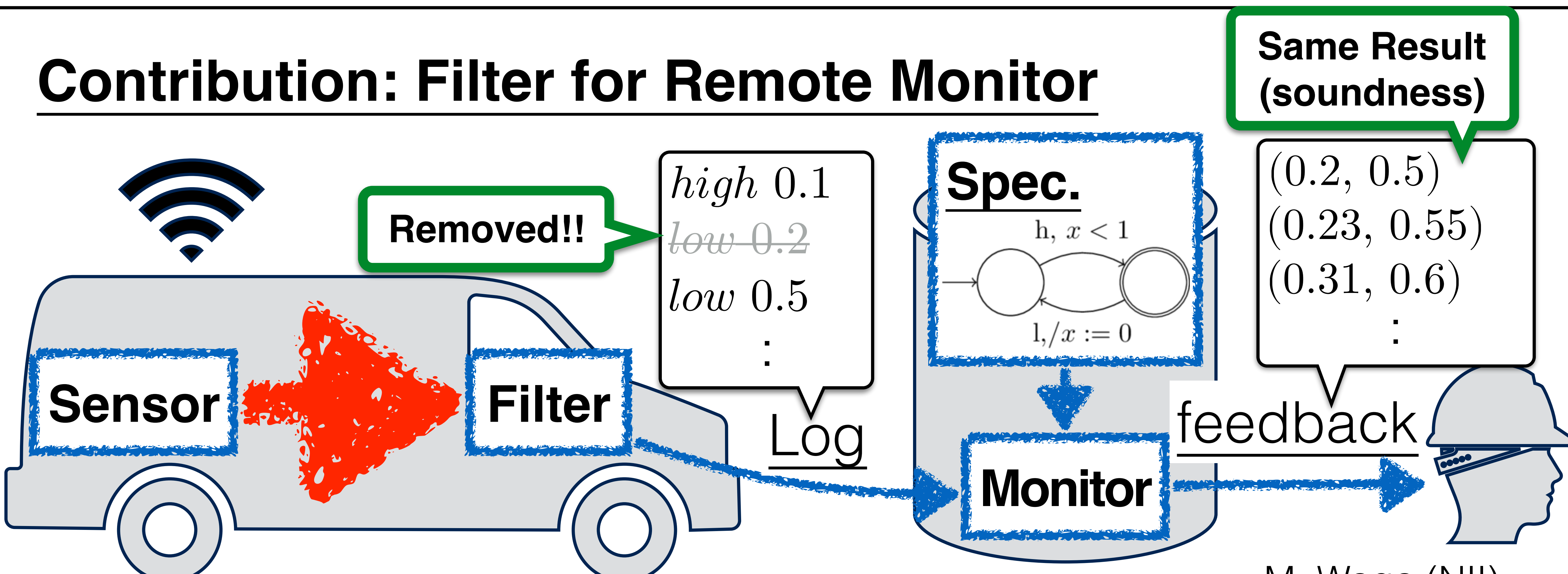
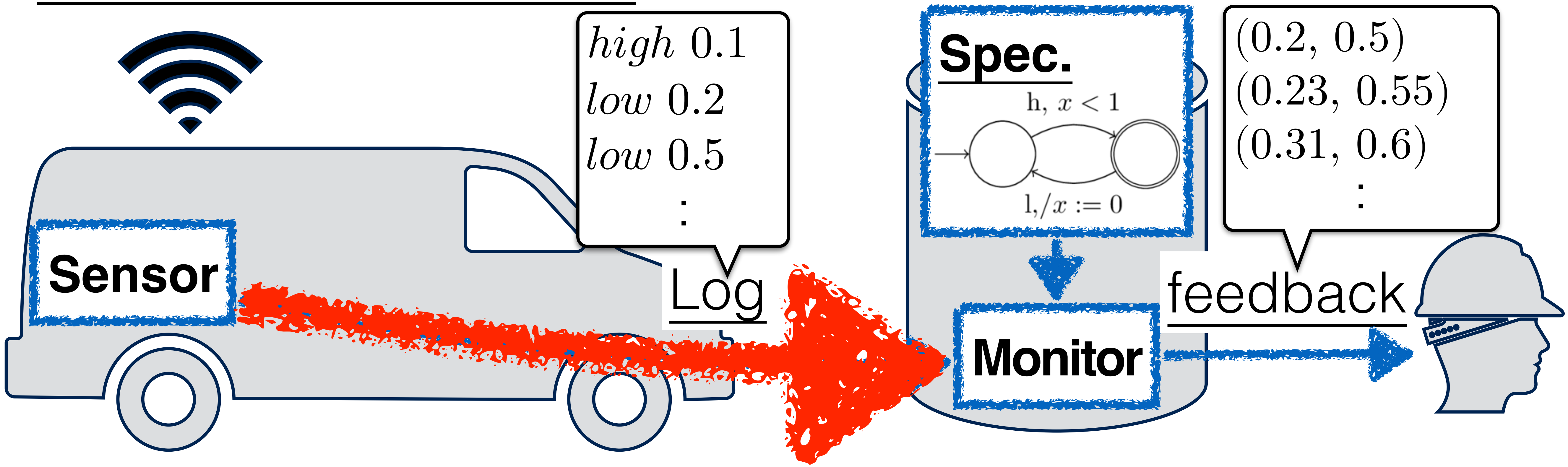
Naive Remote Monitor



Contribution: Filter for Remote Monitor



Naive Remote Monitor



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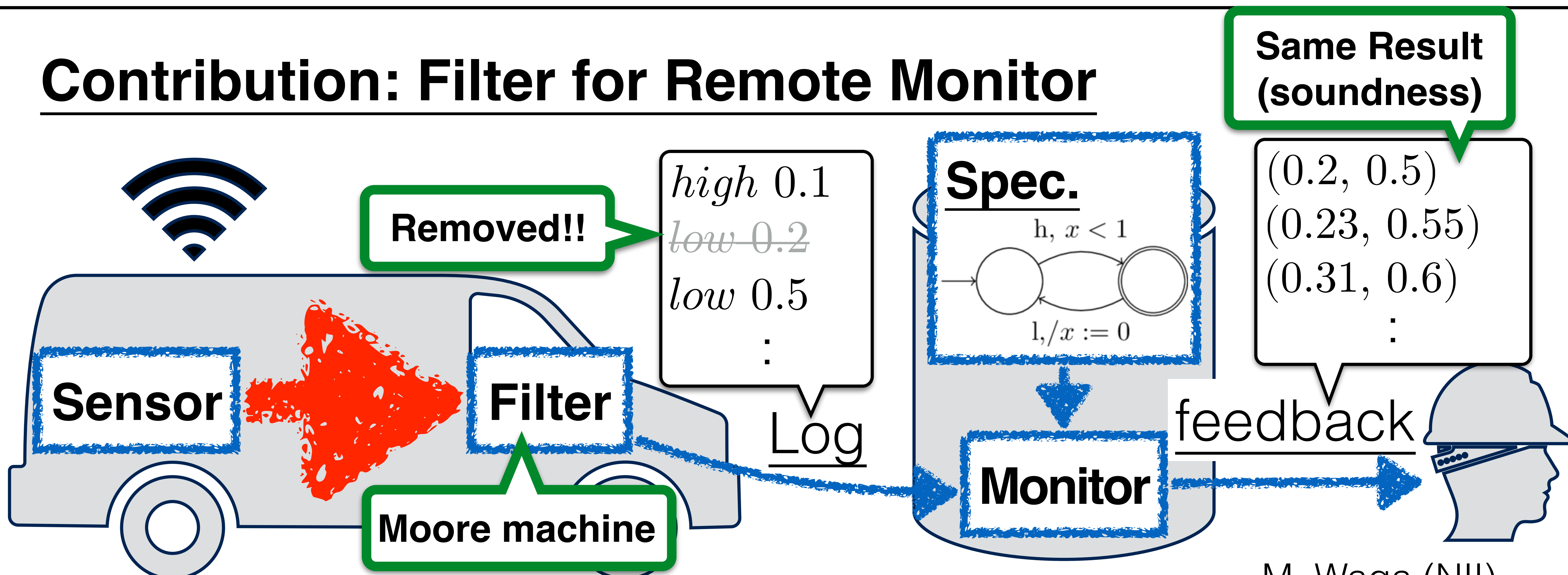
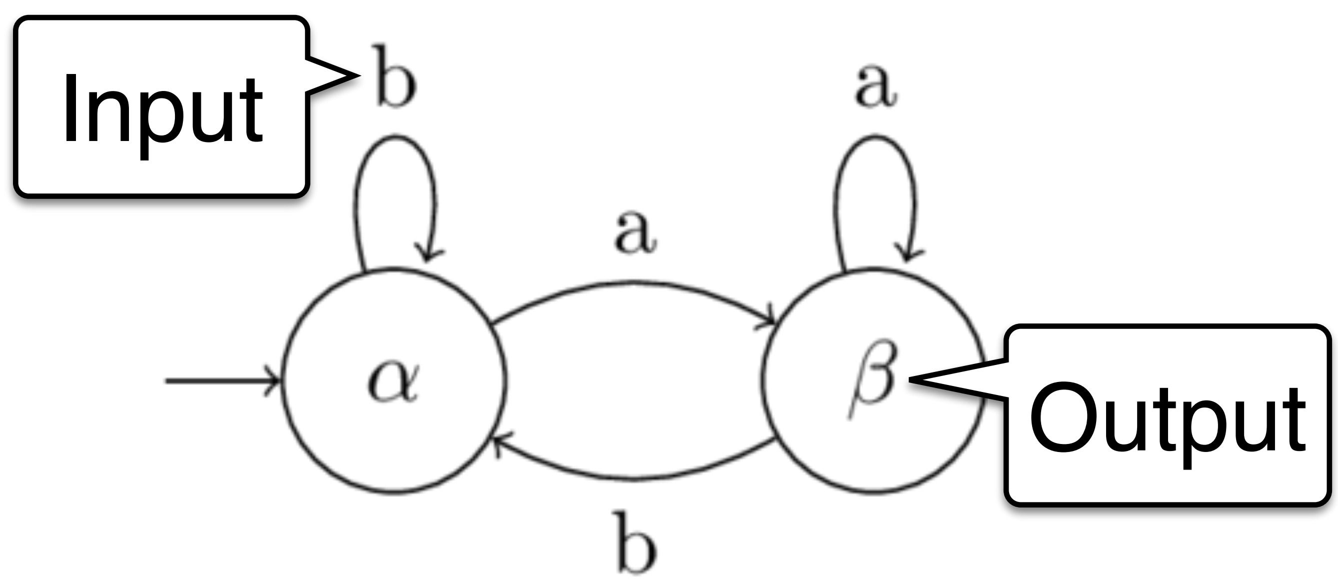


Moore Machine

DFA + state-dependent output



- Efficient (linear time)
- Hardware implementable

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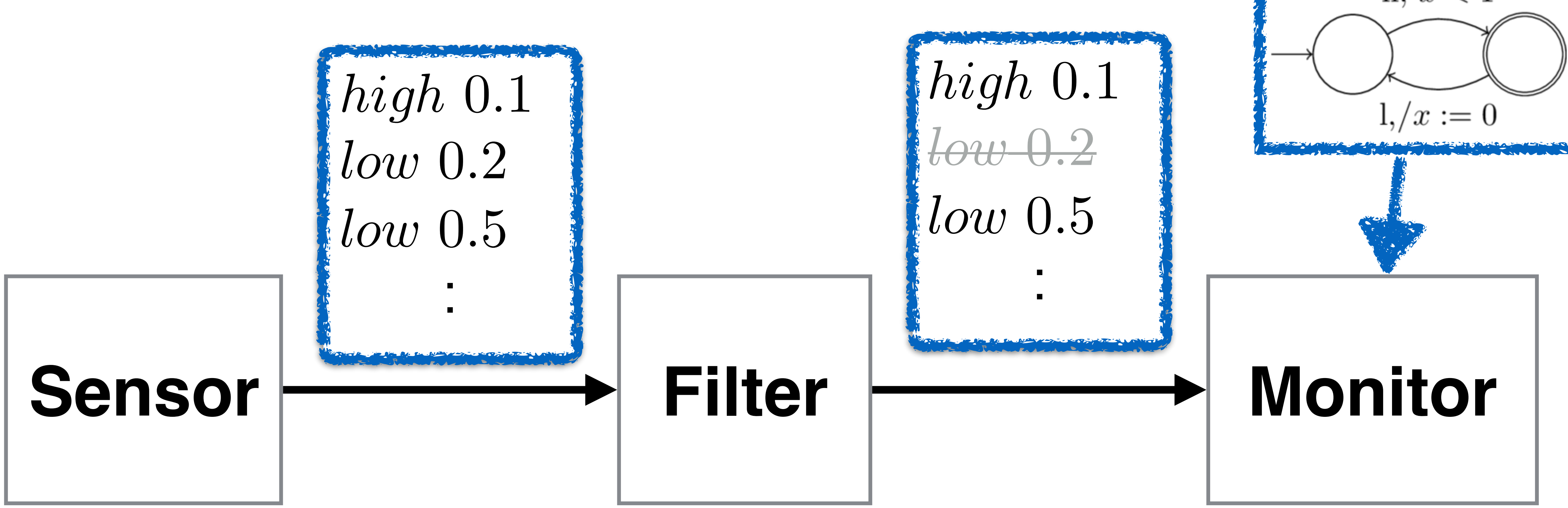
Contribution



- Moore machine filter from NFA / TA
- Soundness (the result is the same)
- Implementation & experiment
  - Data size ≈ 1/100 — 1/2

Related Works

Timed Pattern Matching

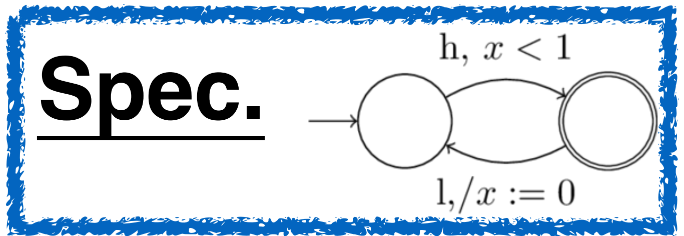
- Offline Algorithm
  - [Ulus+, FORMATS'14]
- Online Algorithm
  - [Ulus+, TACAS'16]
- Optimization (skipping)
  - [**Waga**+, FORMATS'16]
  - [**Waga**+, FORMATS'17]

Filtering for Pattern Matching

- Multiple string
  - [Salmela+, JEA'06]
  - [Kandhan+, PVLDB'10]
- regular expression
  - (different problem)
  - [Liu+, ACNS'12]

:

This Work



Outline

Sensor → Filter → Monitor

Theoretical preparation

- Moore Machine Filter for **Untimed** Pattern Matching
  - Spec.: NFA $\mathcal{A}$
  - Log: word ($w \in \Sigma^*$)

Main Problem

- Moore Machine Filter for **Timed** Pattern Matching
  - Spec.: TA $\mathcal{A}$
  - Log: timed word ($w \in (\Sigma \times \mathbb{R}_{>0})^*$)
- Experiments (**timed**)

(Untimed) Pattern Matching

Input

Log

- Word $w \in \Sigma^*$
- NFA $\mathcal{A}$

Spec.

Output

indices

$$\mathrm{Match}(w,\,\mathcal{A}) = \{(i,j) \mid w(i,j) \in L(\mathcal{A})\}$$

Example

$w = \mathrm{dbadcdc}$

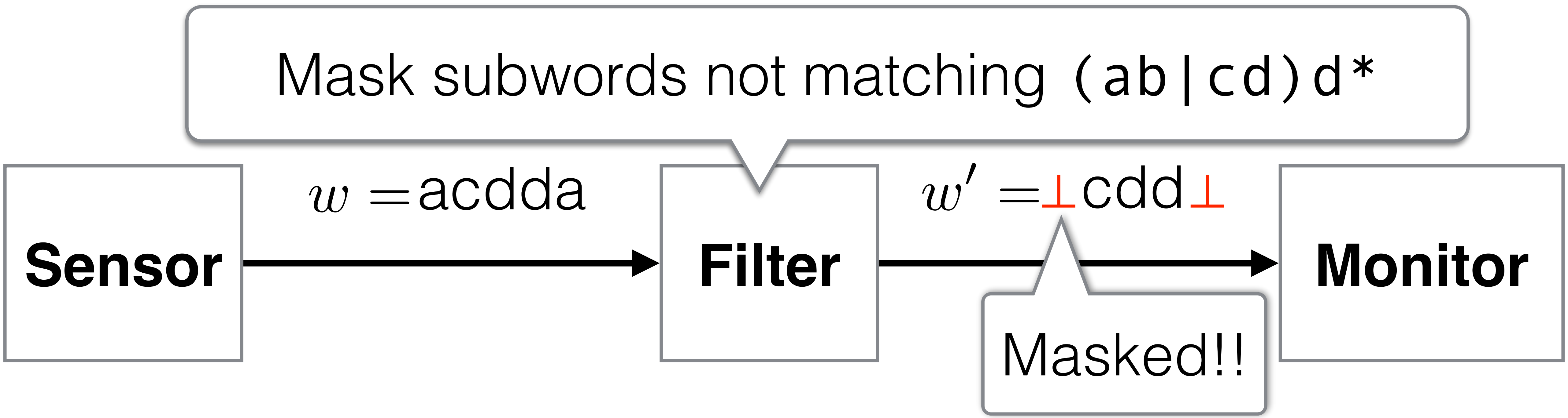
$L(\mathcal{A}) = $ dc*{ba|dc}

$\mathrm{Match}(w,\,\mathcal{A}) = \{(1,3),\,(4,7)\}$

$w(1,3) = \mathrm{dba} \in L(\mathcal{A})$

$w(4,7) = \mathrm{dcdc} \in L(\mathcal{A})$

Idea: Filtering by Masking

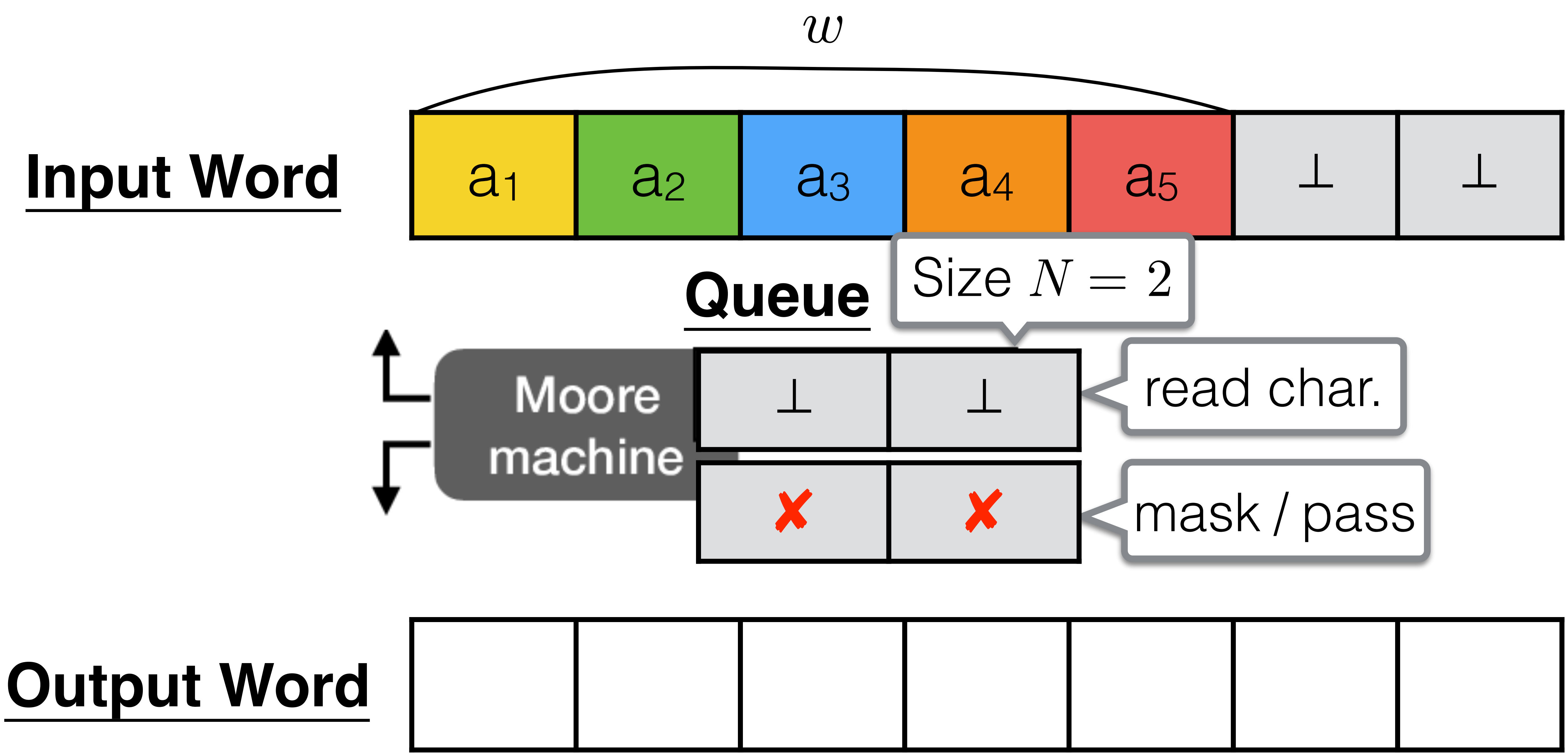


Goal

Construct a sound and efficient filter
⇒ by a Moore machine

DFA + state-dependent output

Overview of Filtering



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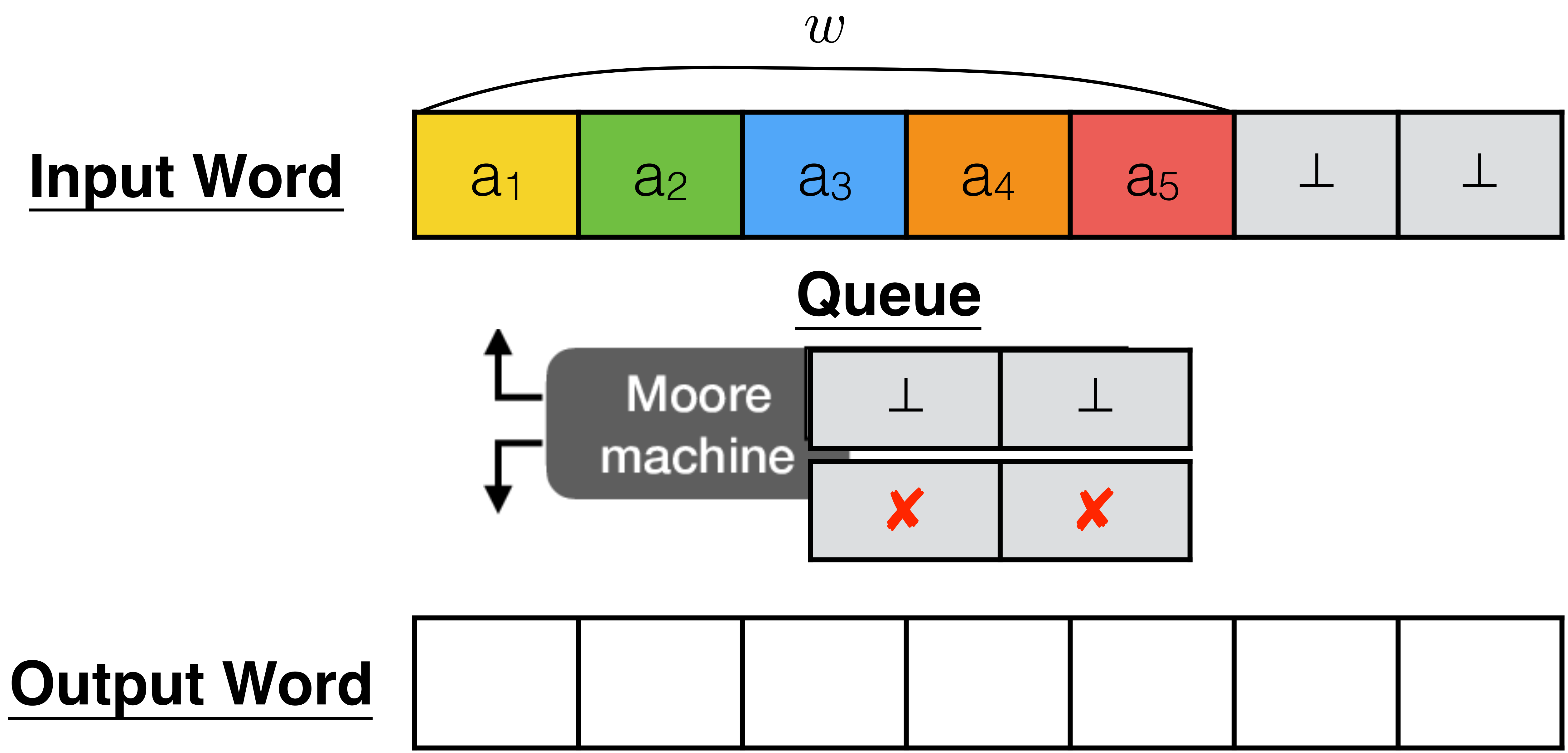

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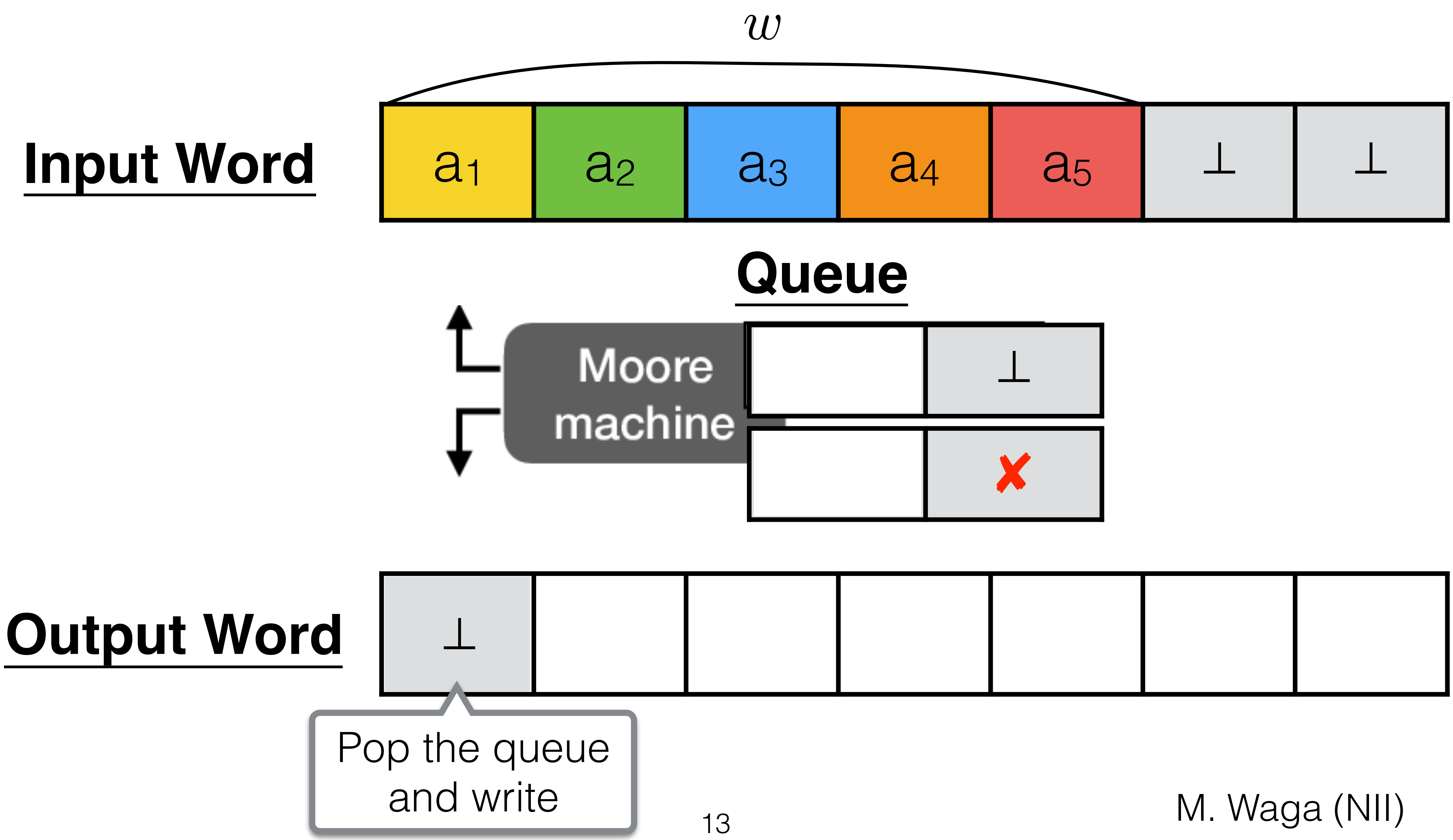
Overview of Filtering



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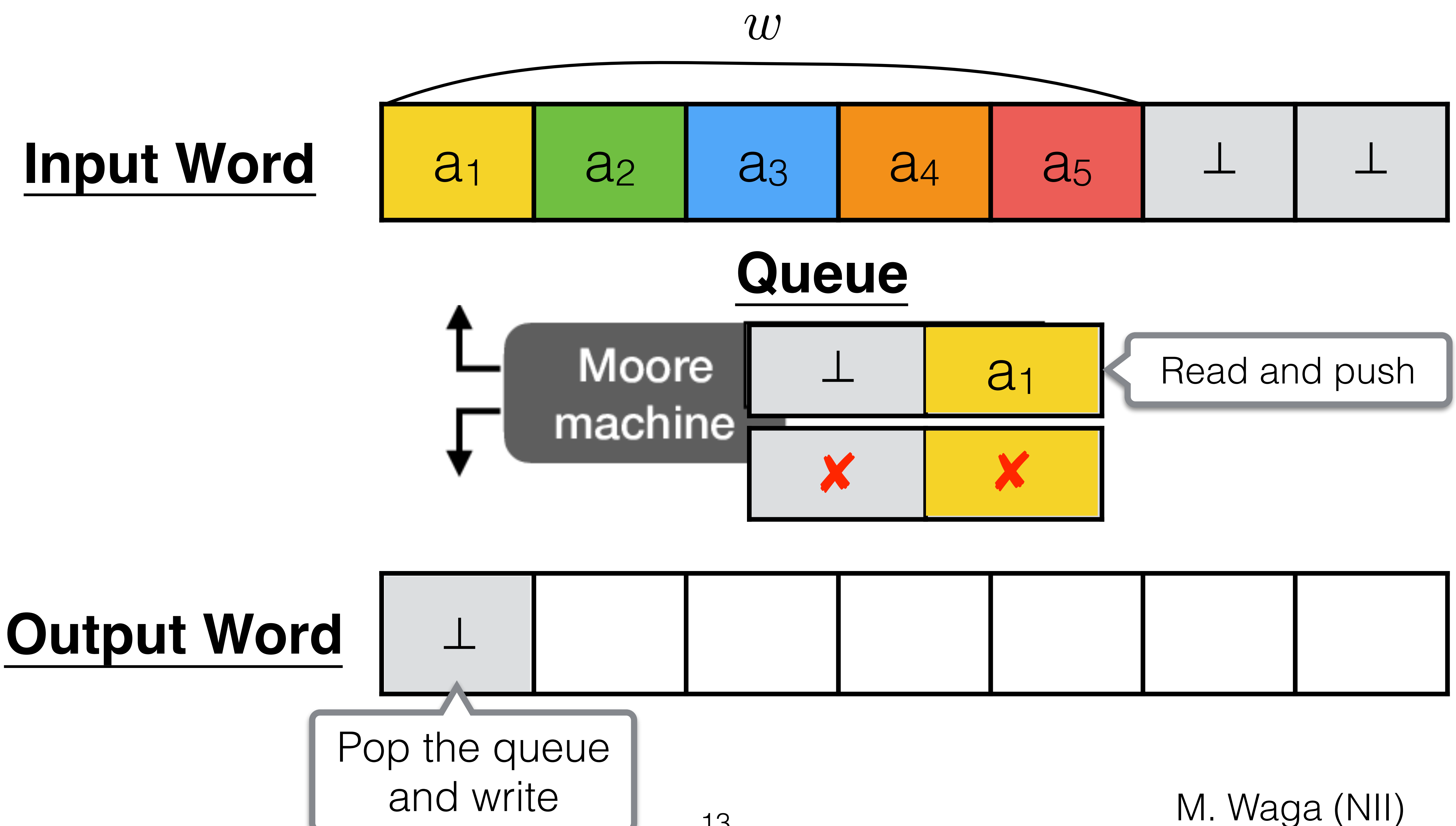

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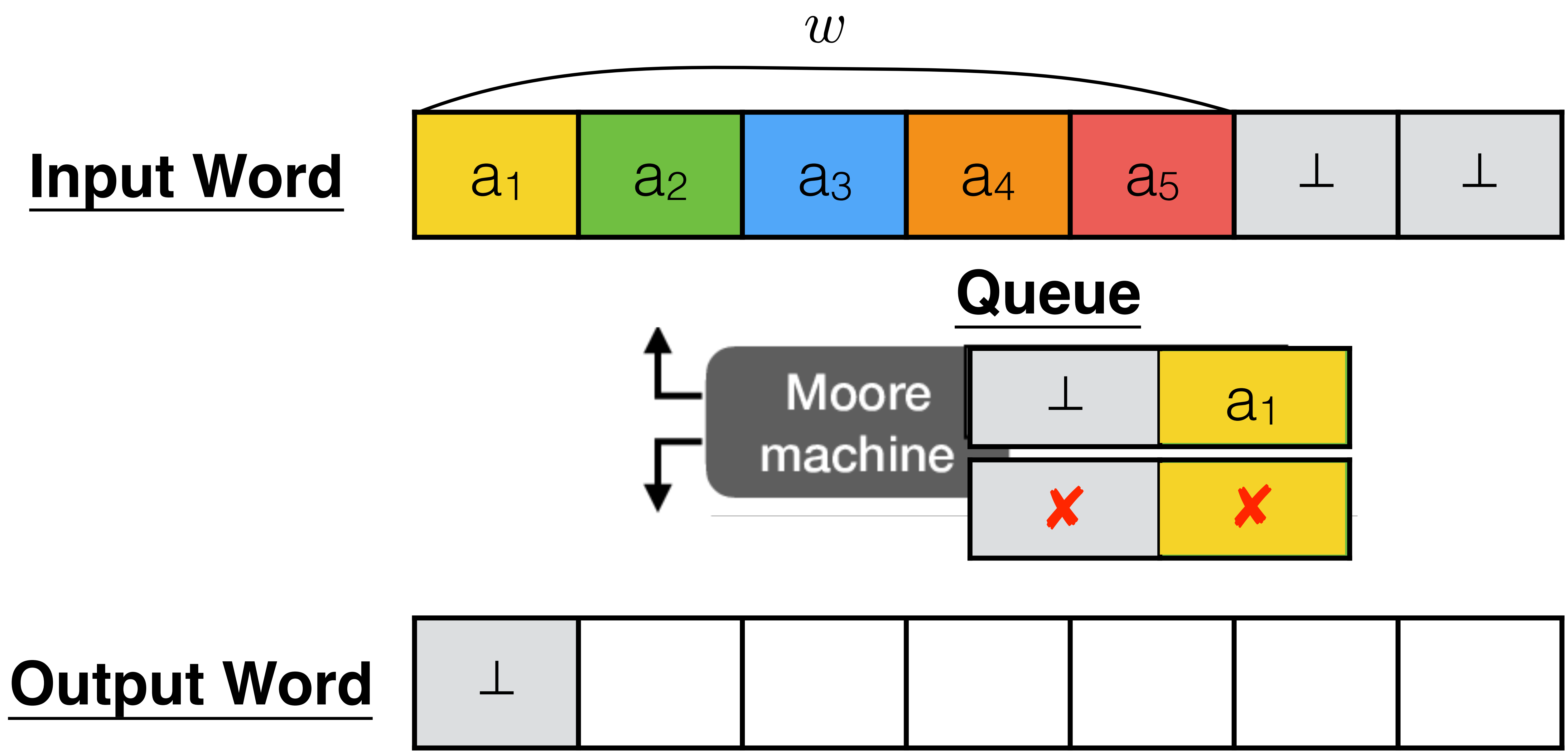

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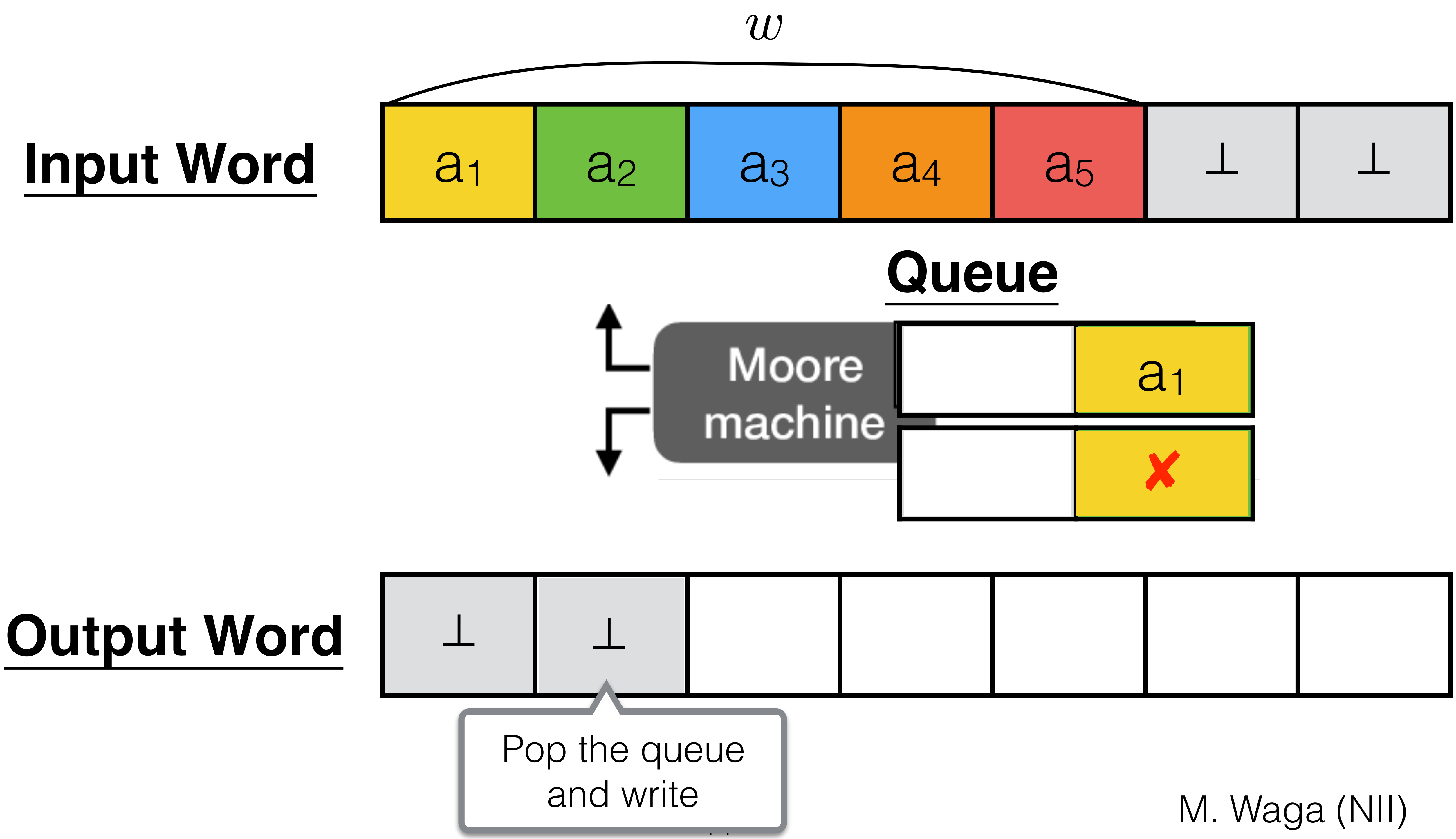

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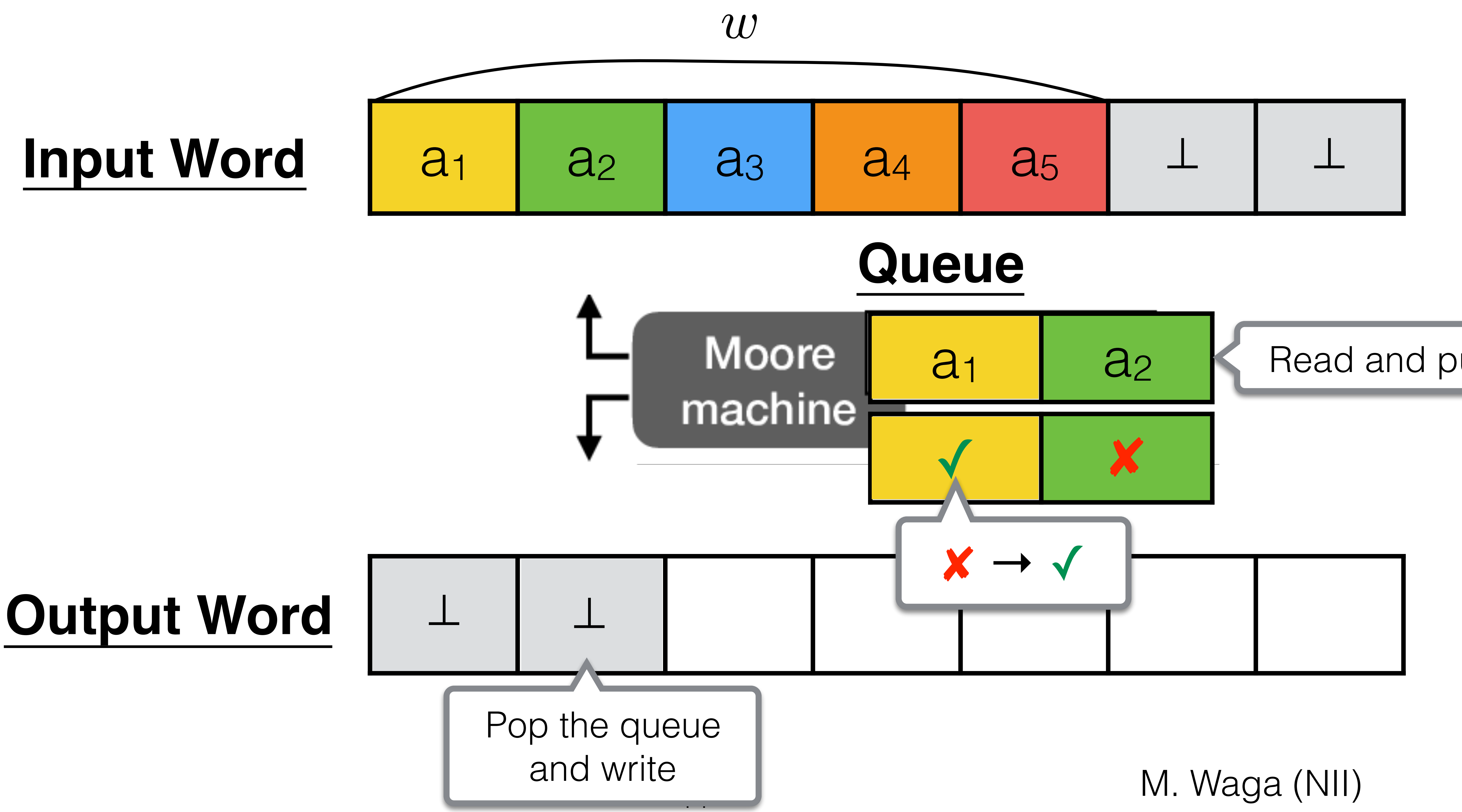

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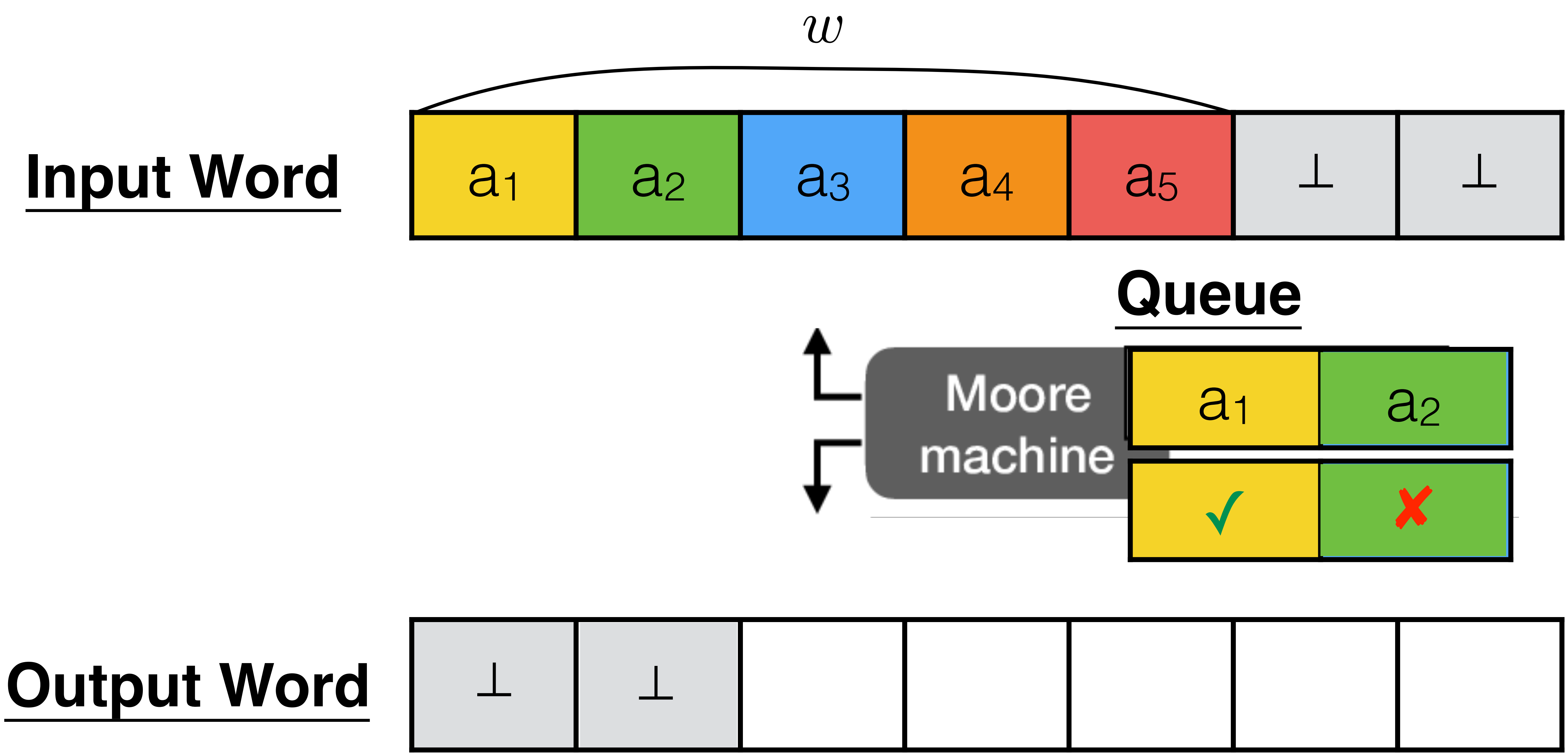

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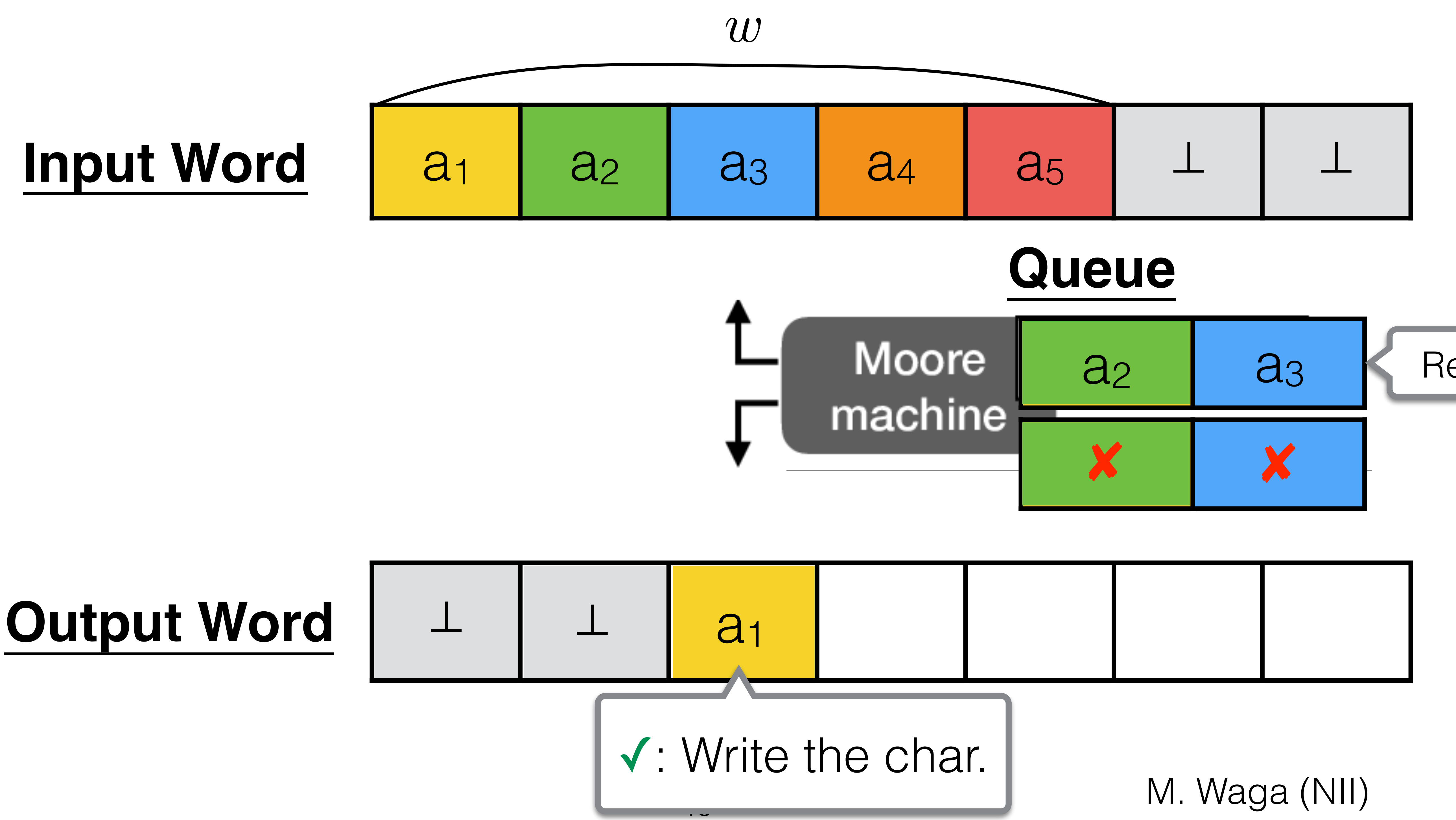

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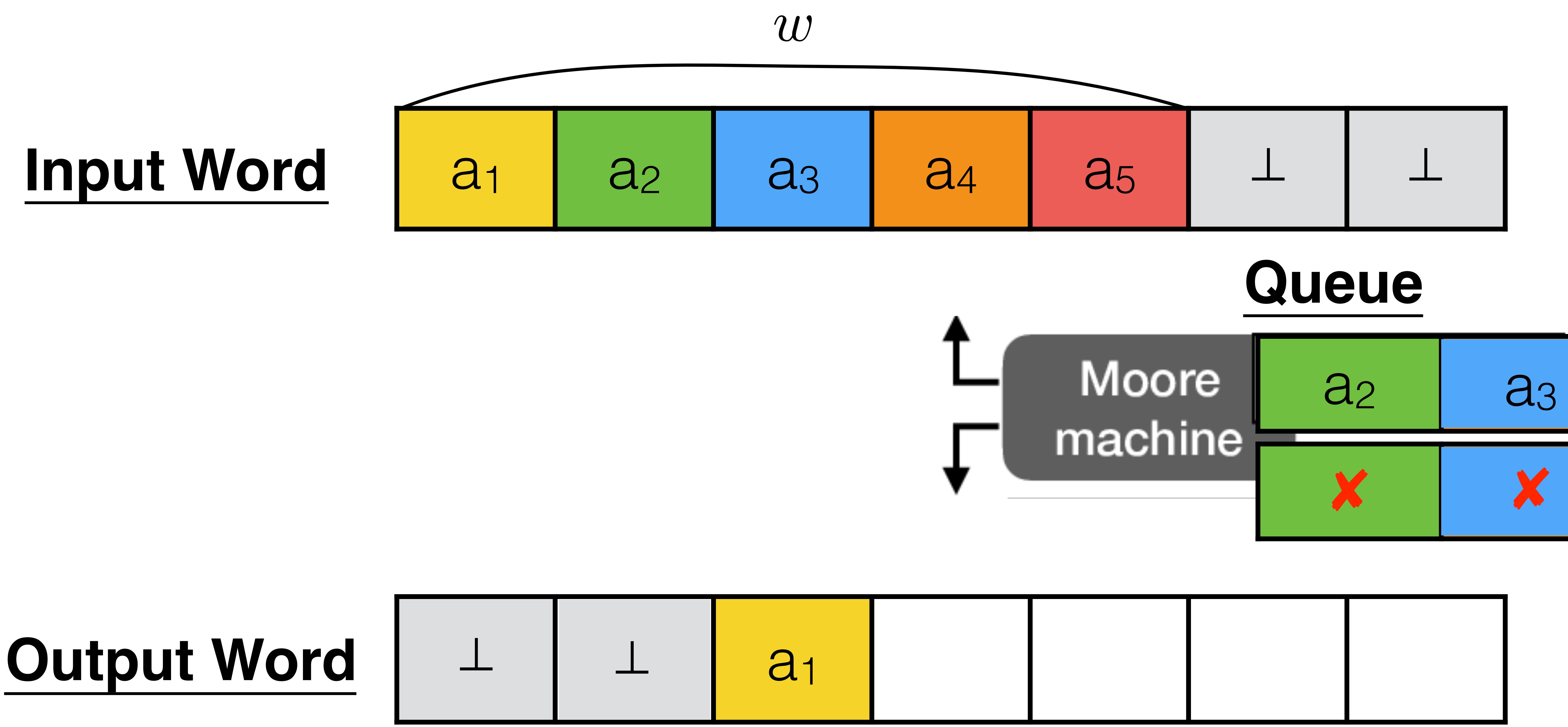

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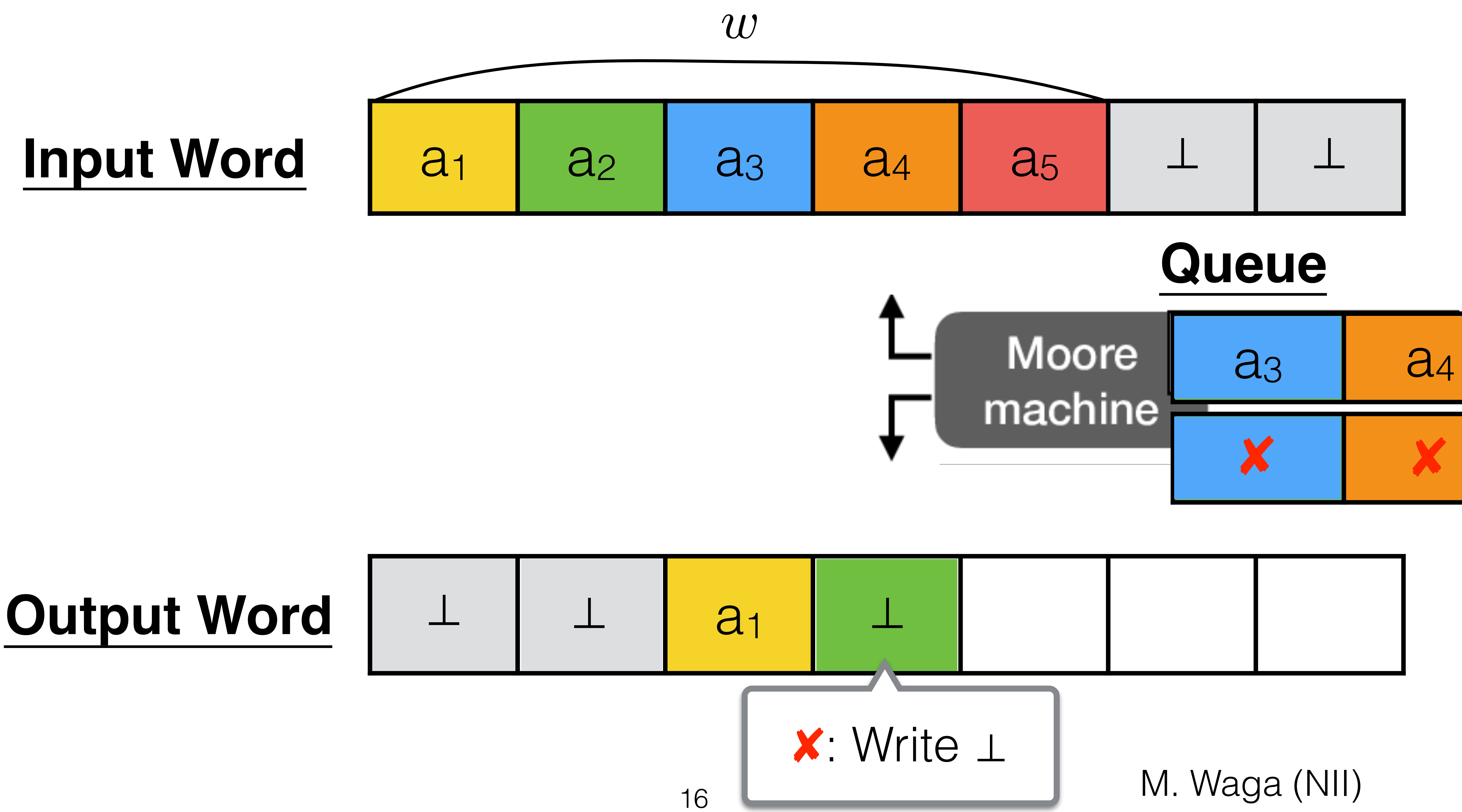

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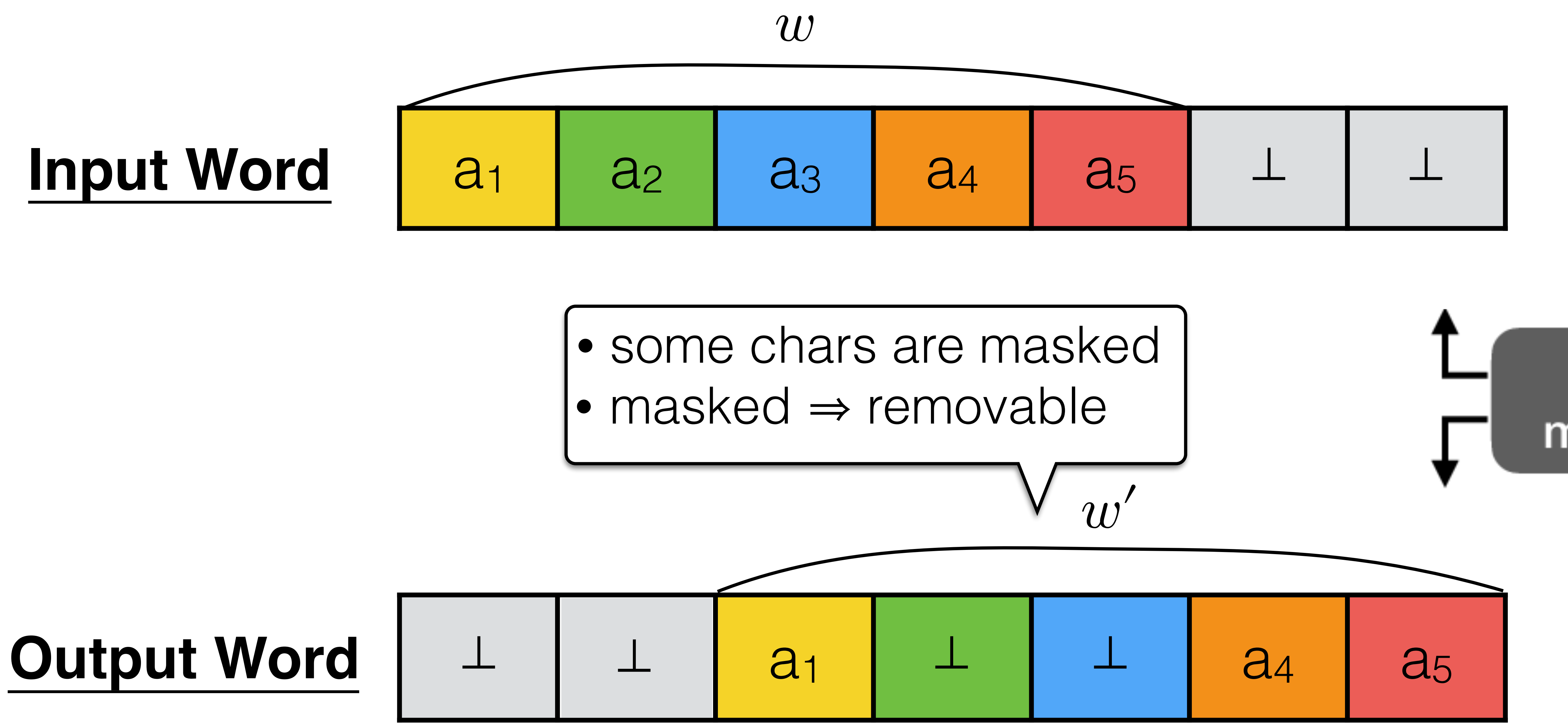
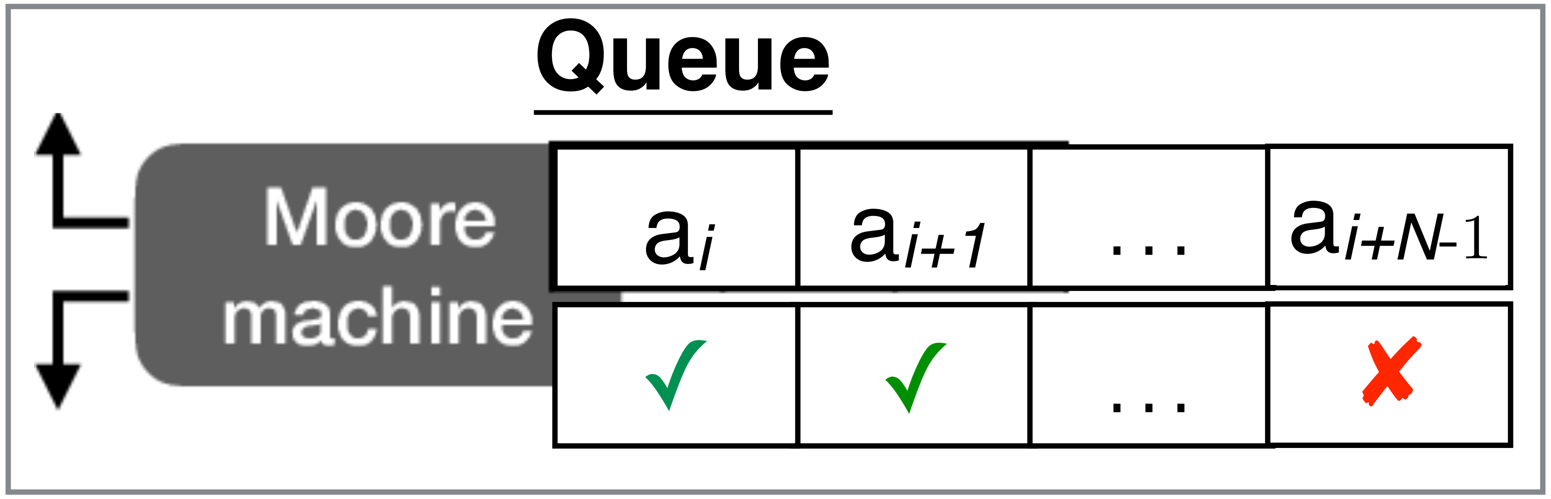


Untimed Filter Construction

1. add a **counter** to each state
   ← Count: distance from the init. state mod N
2. **powerset** construction
   ← Moore machine (deterministic)
3. add **queue**

Idea of Mask / Unmask



- Surely Unused ⇒ **Mask** (✘)
- Surely Used ⇒ **Pass** (✓)
- Not Sure ⇒ **Pass** (✓)

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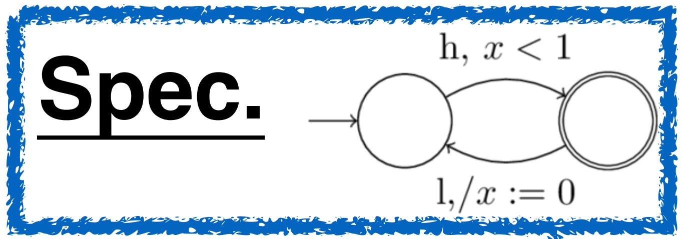
Properties of Untimed Moore Machine Filter

Log: $w = a_1 a_2 \dots a_n$ Pattern: $\mathcal{A}$ Queue size: N

Thm. (soundness)
Our filter Moore machine $\mathcal{M}$ does not change the result of the untimed pattern matching problem.

Thm. (finite completeness)
Our filter Moore machine $\mathcal{M}$ masks any unused char. if we have $\max\{|w| \mid w \in \mathrm{L}(\mathcal{A})\} \leq N < \infty$.

Thm. (monotonicity)
The Moore machine filter with N-length queue does not mask more events than the filter with with mN-length queue.



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  - Spec.: TA $\mathcal{A}$
  - Log: timed word ($w \in (\Sigma \times \mathbb{R}_{>0})^*$)
- Experiments (**timed**)

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Timed Pattern Matching

[Ulus et al., FORMATS'14]

Input

Log

- Timed Word $w \in (\Sigma \times \mathbb{R}_{>0})^*$
- TA $\mathcal{A}$

Spec.

Output

$\mathrm{Match}(w, \mathcal{A}) =$

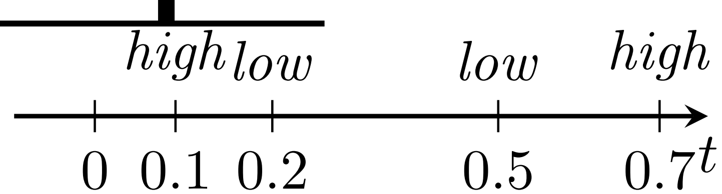
$\{(t,t') \mid w|_{(t,t')} \in L(\mathcal{A})\}$

Intervals where spec. is satisfied

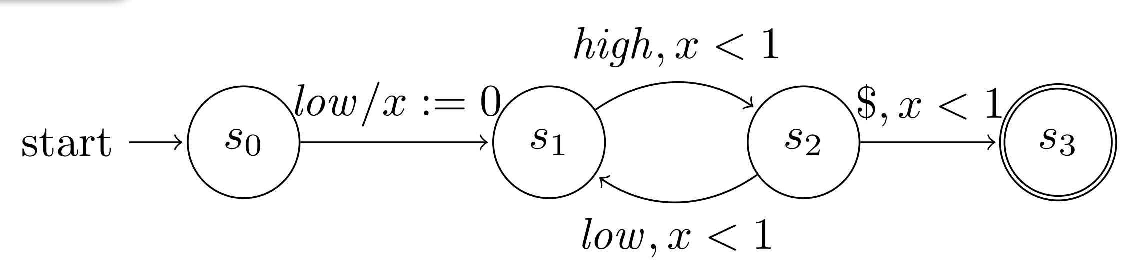
Find frequent gear change

Example

$w =$



$\mathcal{A} =$



$\mathrm{Match}(w, \mathcal{A}) = \{(t,t') \mid 0.2 \leq t < 0.5,\ 0.7 < t'\}$

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Timed Filter Construction

1. add a **counter** to each state
   ← Count: distance from the init. state mod N
2. **powerset** construction
   ← impossible for timed automata
   (state space will be infinite)
   ⇒ Overapproximation!!
3. add **queue**

One-Clock Determinization

[Krichen & Tripakis, FMSD'09]

Thm.

For any TA $\mathcal{A}$, there exists a DRTA $\mathcal{A}^{\mathrm{rt}}$ s.t. $\mathrm{L}(\mathcal{A}) \subseteq \mathrm{L}(\mathcal{A}^{\mathrm{rt}})$

DRTA : (deterministic real-time autom.)

- Restricted form of TA
- Guard: the duration at the source state
- Transition function $\Delta : Q \times (\Sigma \times \mathbb{R}_{\geq 0}) \to Q$

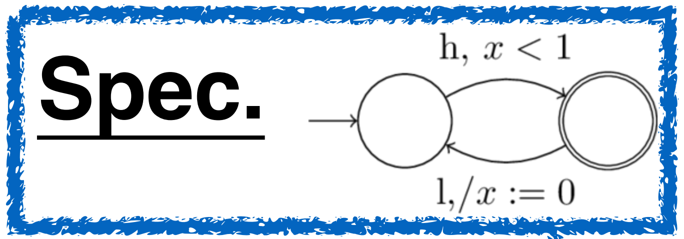
Timed Filter Construction

1. add a **counter** to each state
   ← Count: distance from the init. state mod N
2. **One-clock determinization**
   ← DRTA: similar to DFA
3. add **queue**

Properties of Timed Moore Machine Filter

Thm. (soundness)
Our filter Moore machine $\mathcal{M}$ does not change the result of the timed pattern matching problem.

Completeness does not hold ⇒ experimental results



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  - Log: timed word ($w \in (\Sigma \times \mathbb{R}_{>0})^*$)
- Experiments (**timed**)

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Research Questions

Sensor → Filter → Monitor

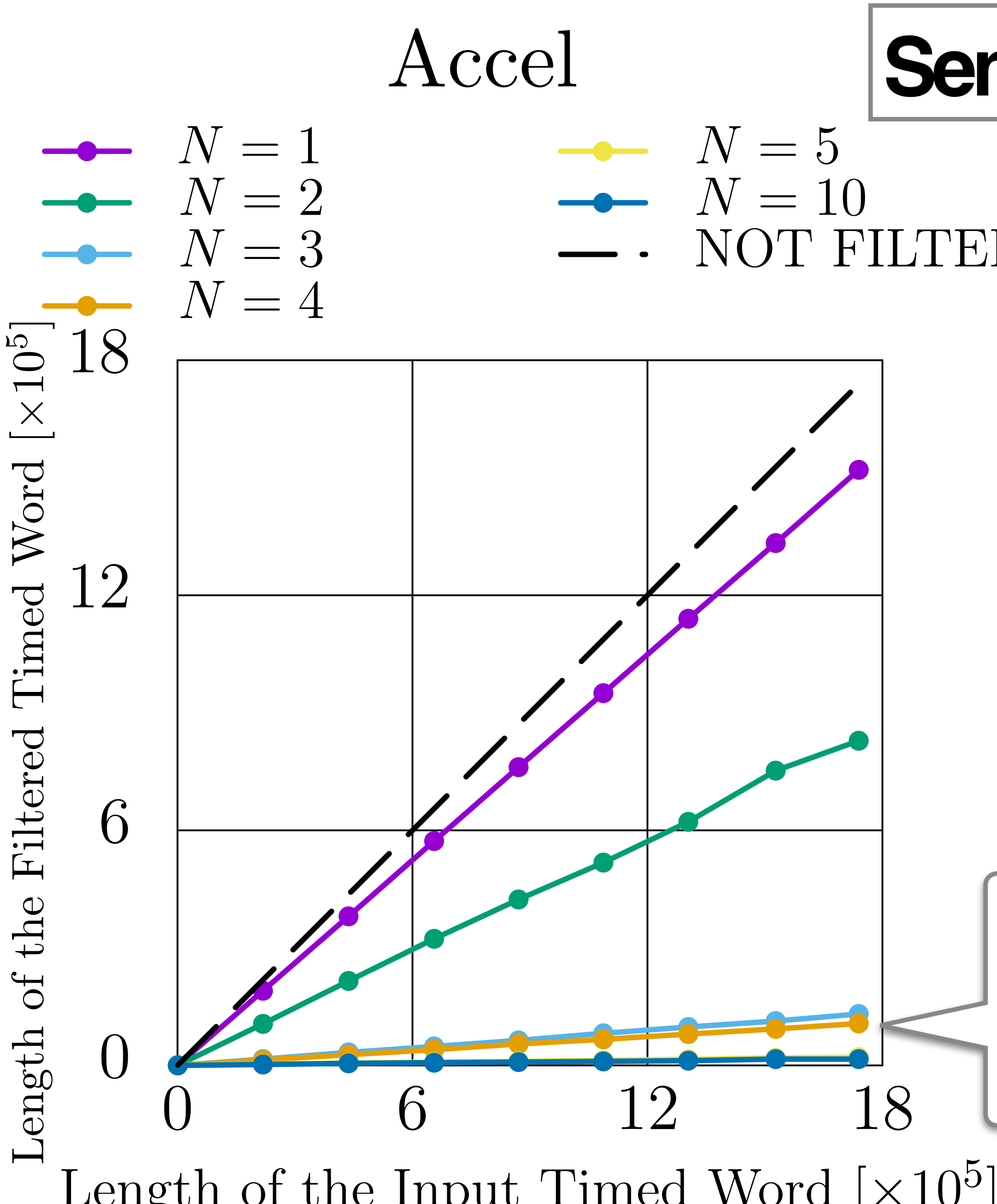
- RQ1: Does our filter Moore machine mask many events?
  - Theoretically, only soundness
  - Queue size vs. filtering rate
- RQ2: Is our filter Moore machine online capable?
  - Linear time? Constant memory usage?

Environment of Experiment

- MacBook Pro Early 2013
  - Intel Core i5 2.6 GHz and DDR3 1600MHz 8 GB
- Mac OS 10.13.4
- clang-900.0.39.2 with optimization flag -O3
- Used 3 benchmarks (Accel, Gear, Torque)

Automotive

RQ1: Filtering Rate



N: size of queue

N=10 looks enough (length: 1/100)

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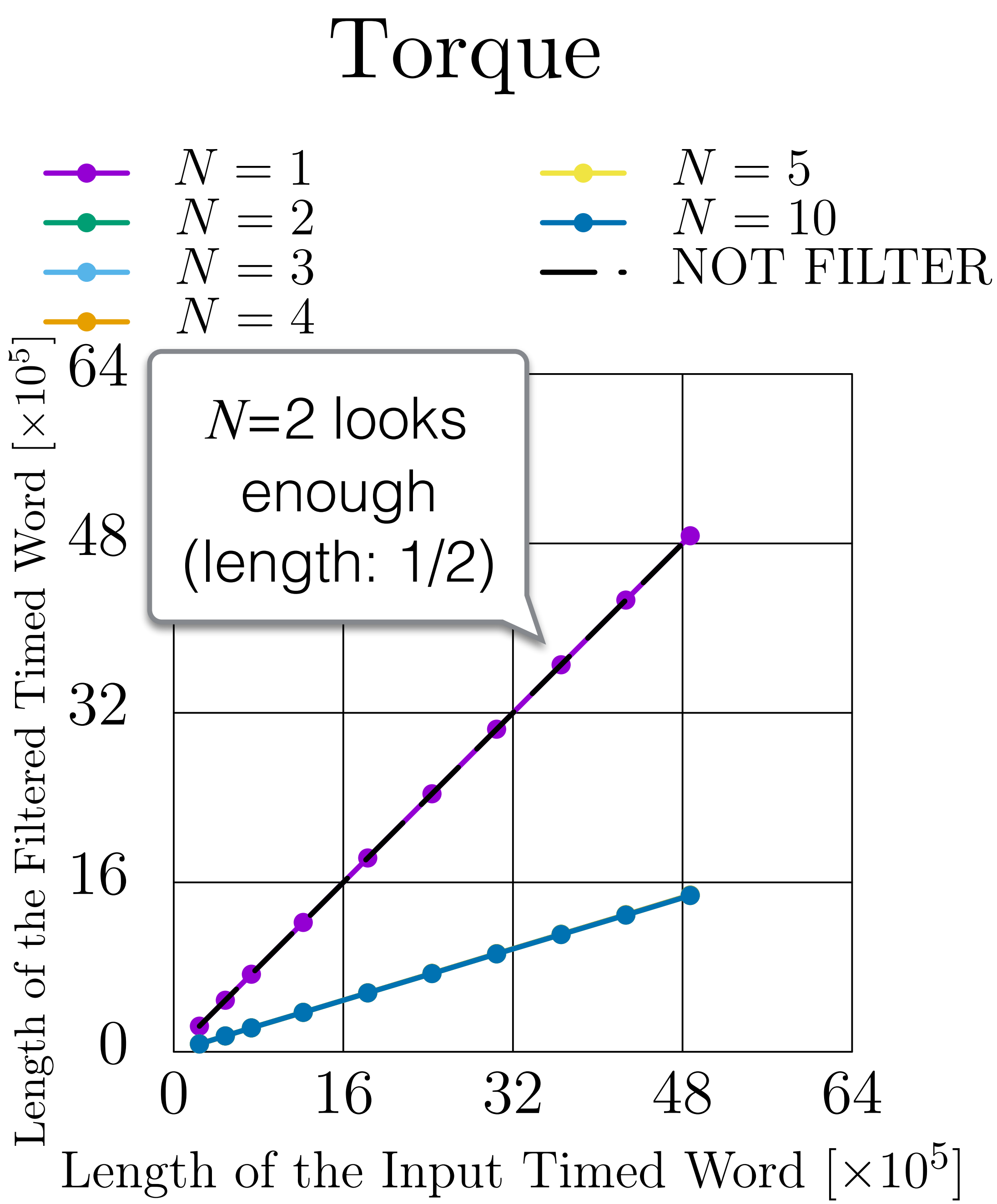
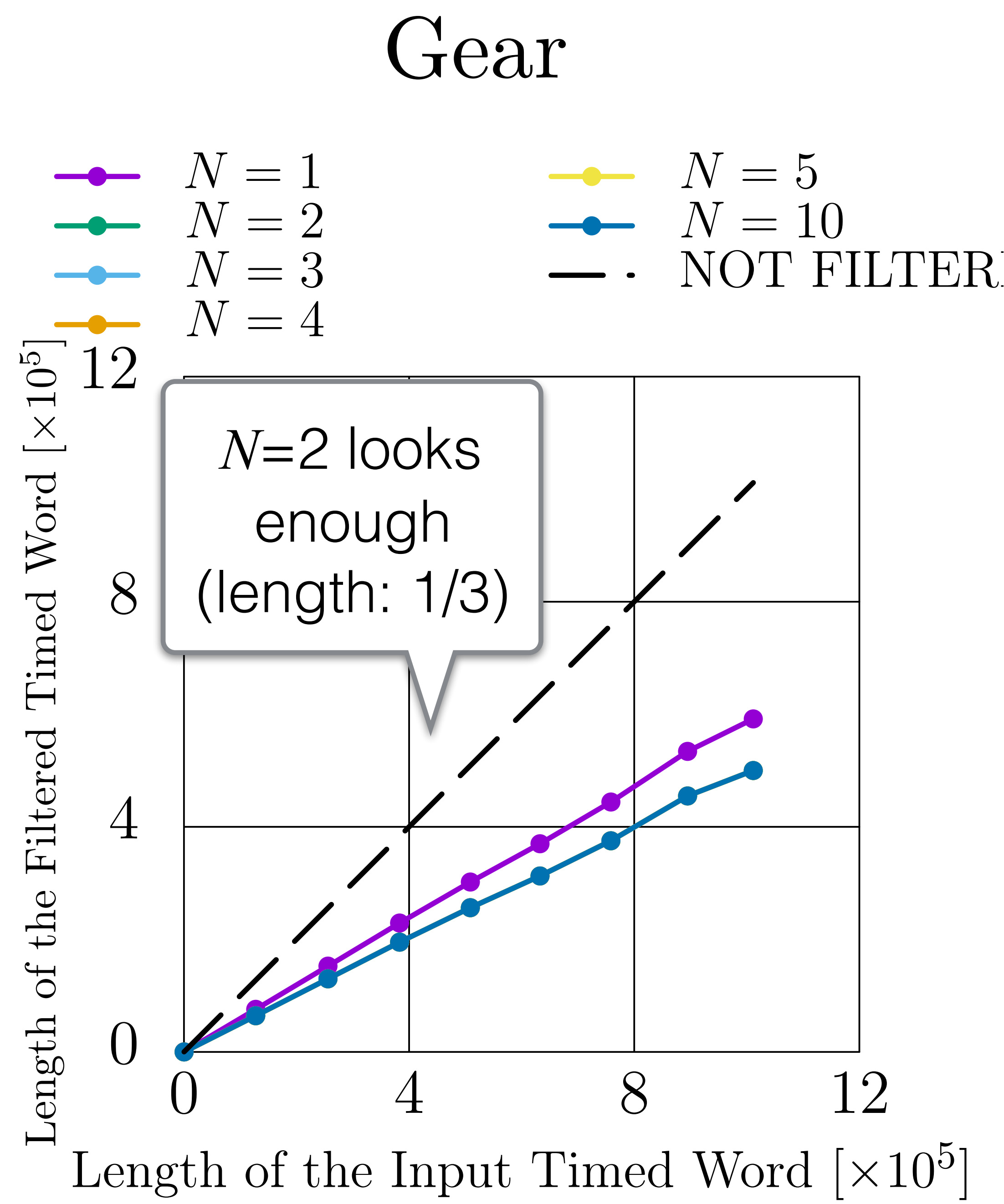
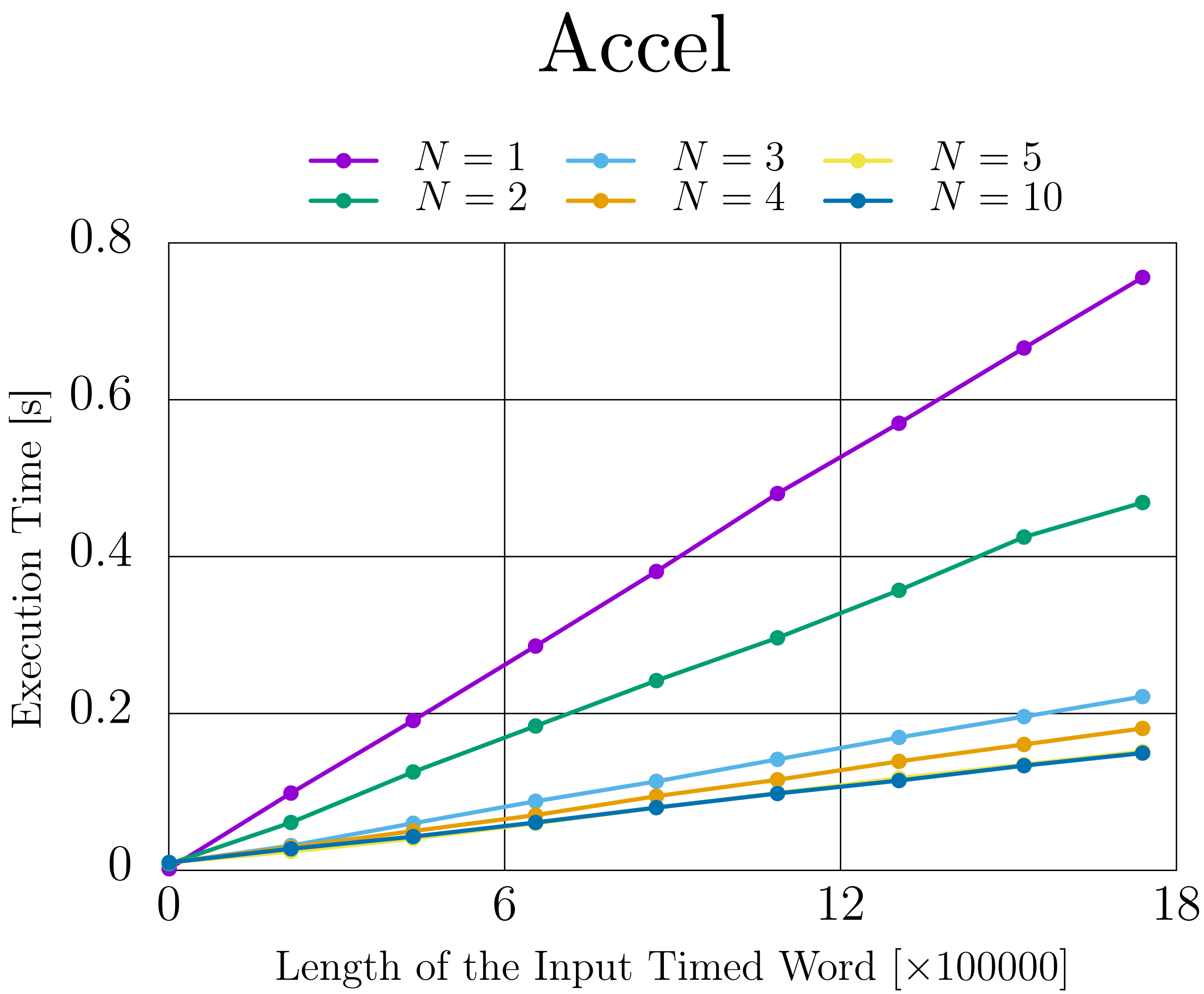
RQ1: Filtering Rate (Cont'd)

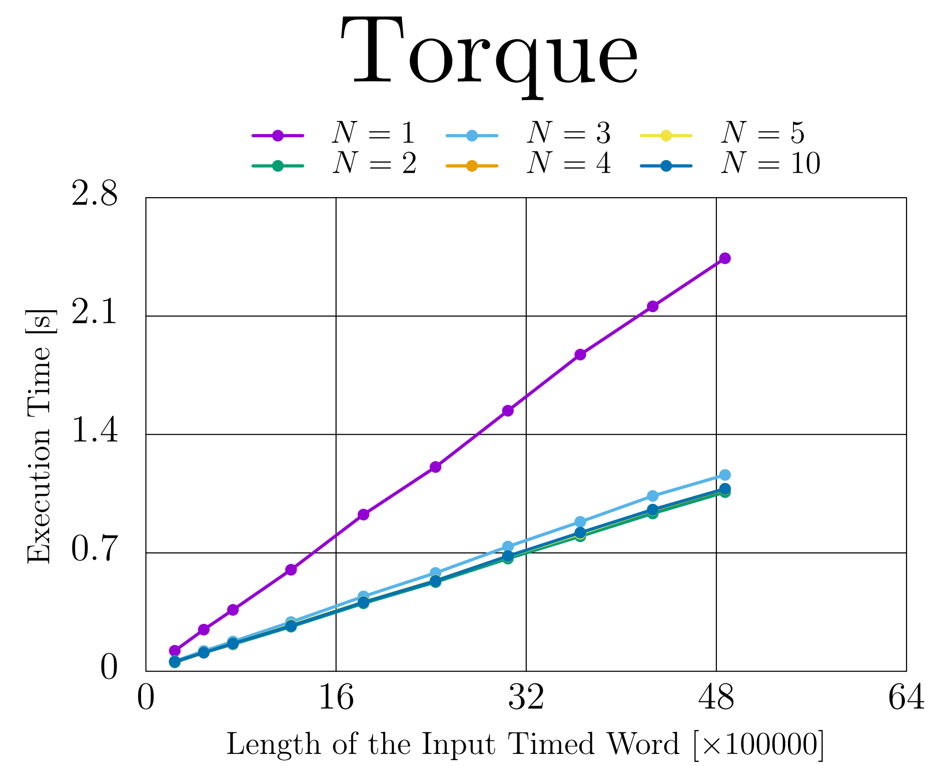
Sensor → Filter → Monitor

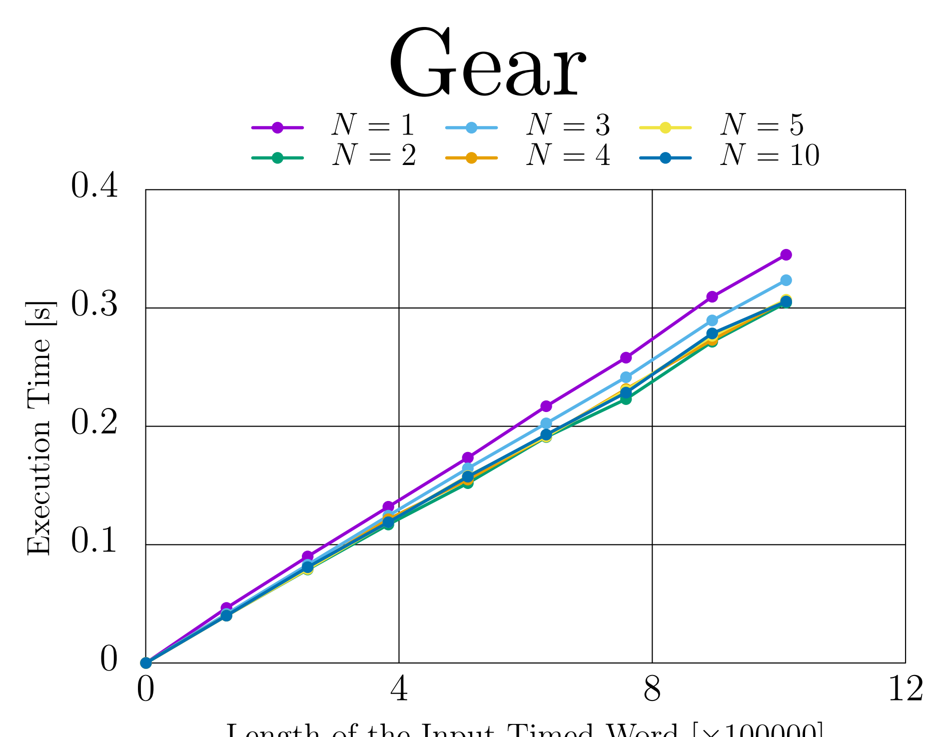




RQ2: Execution Time

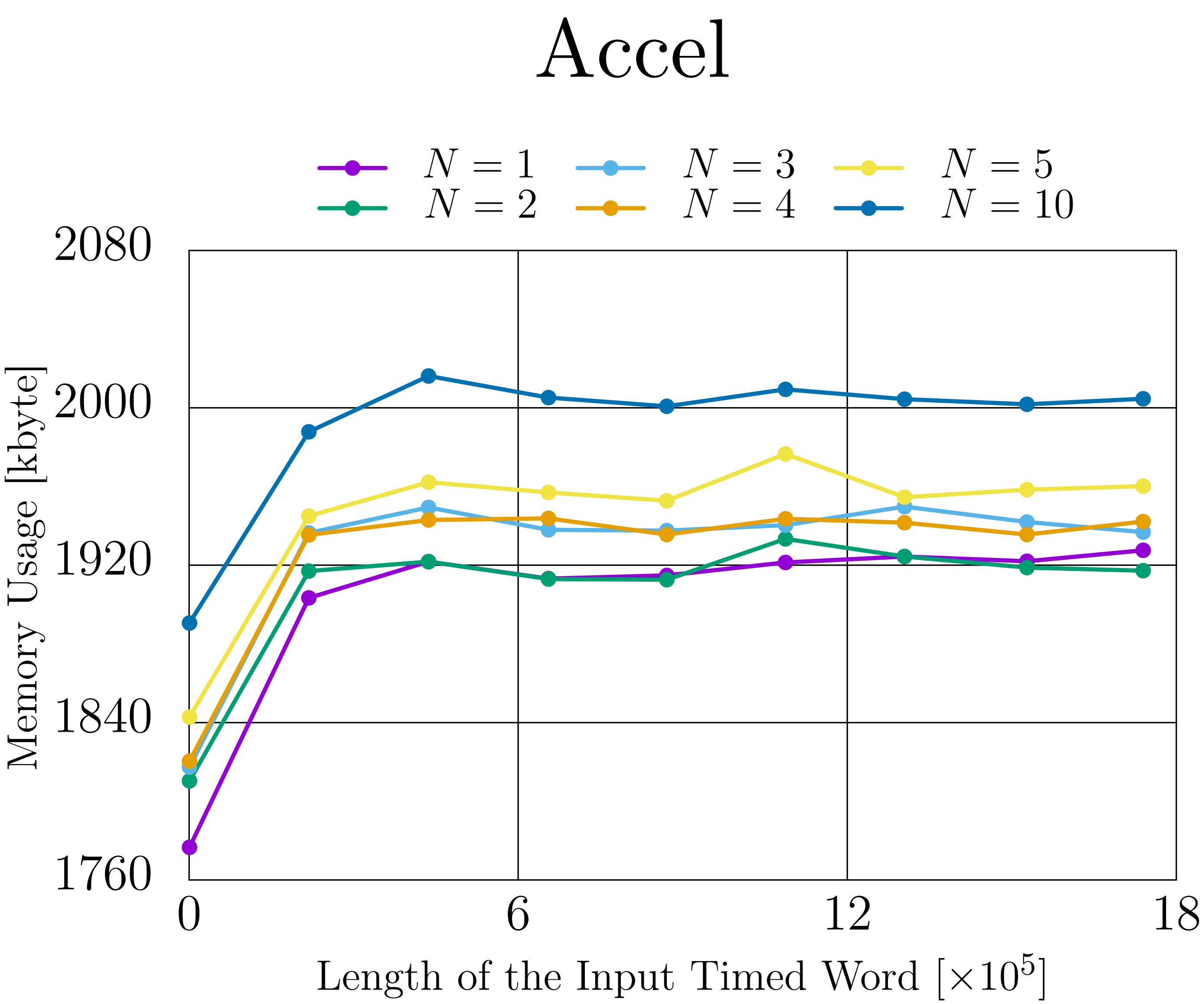


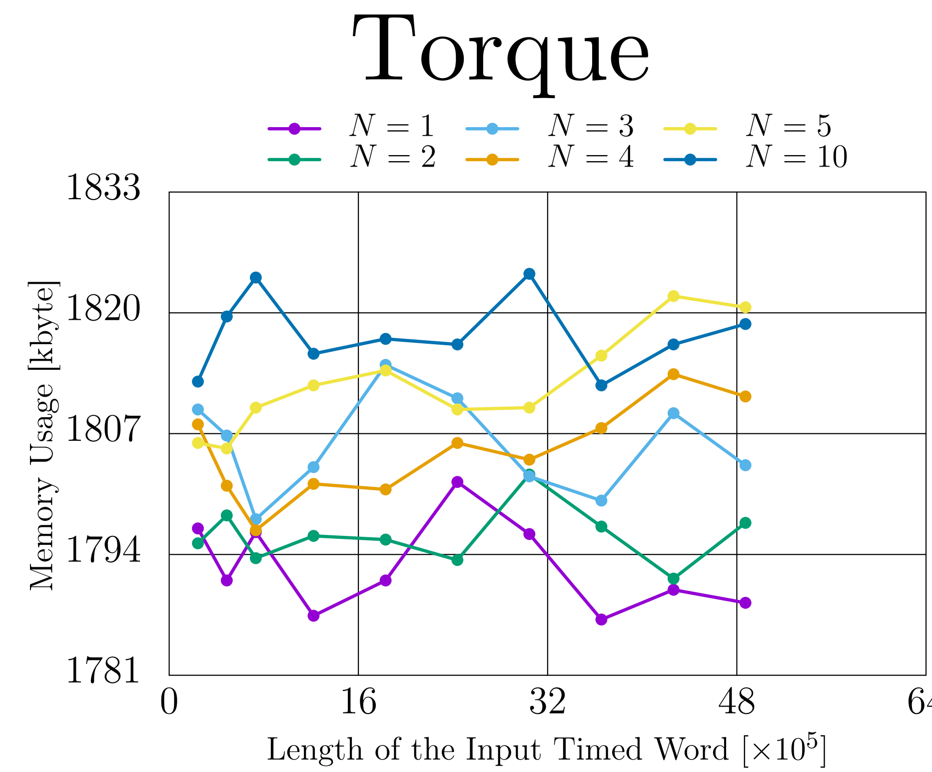


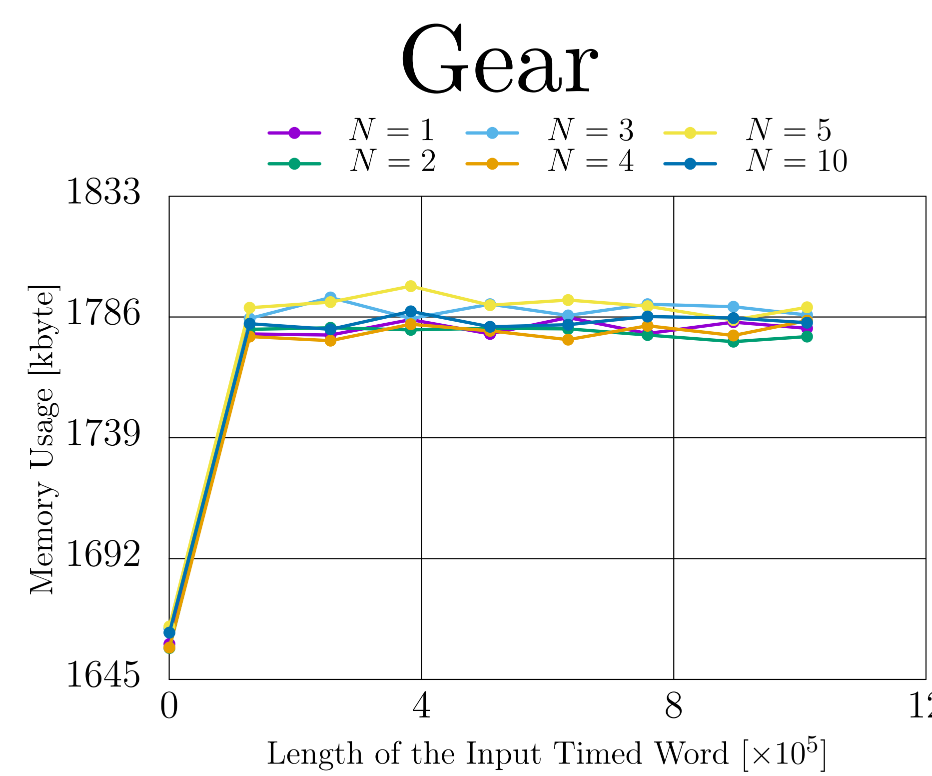


Linear Execution Time

RQ2: Memory Usage







Constant Memory Usage

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Conclusion

Sensor → Filter → Monitor

- We proposed Moore machine filter for untimed/timed pattern matching
- Reduces the data size to send
- online capable
- (omitted in this talk) it also accelerates timed pattern matching.

Future Works

- Case study in an embedded system
- Extension to distributed systems
  - Many sensor node vs one central server
- Hardware Implementation (e.g., FPGA, ASIC)