Early Detection of Business Rule Violations

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PhD Committee

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Events Streams Must Satisfy Business Rules

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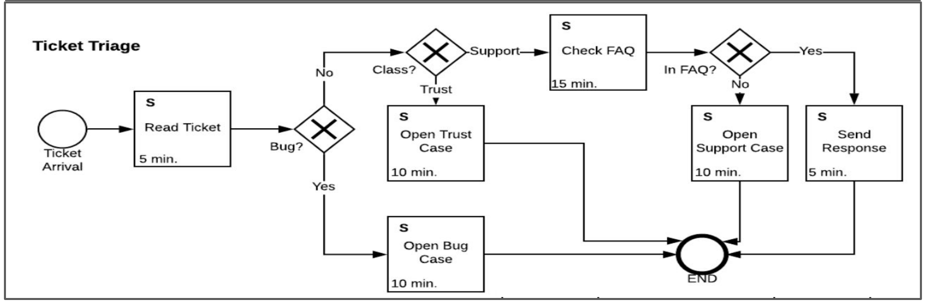
Business Workflows



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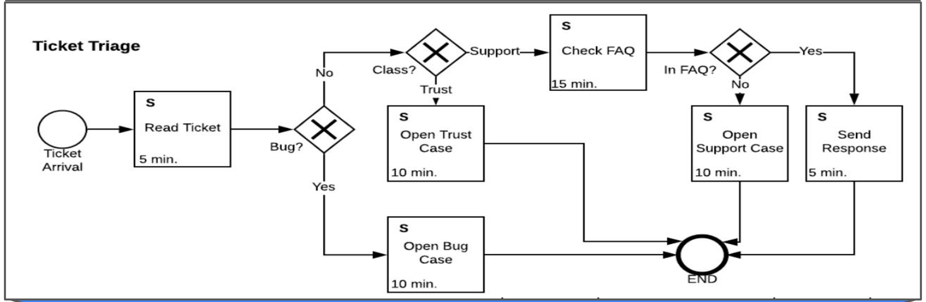

Event Streams

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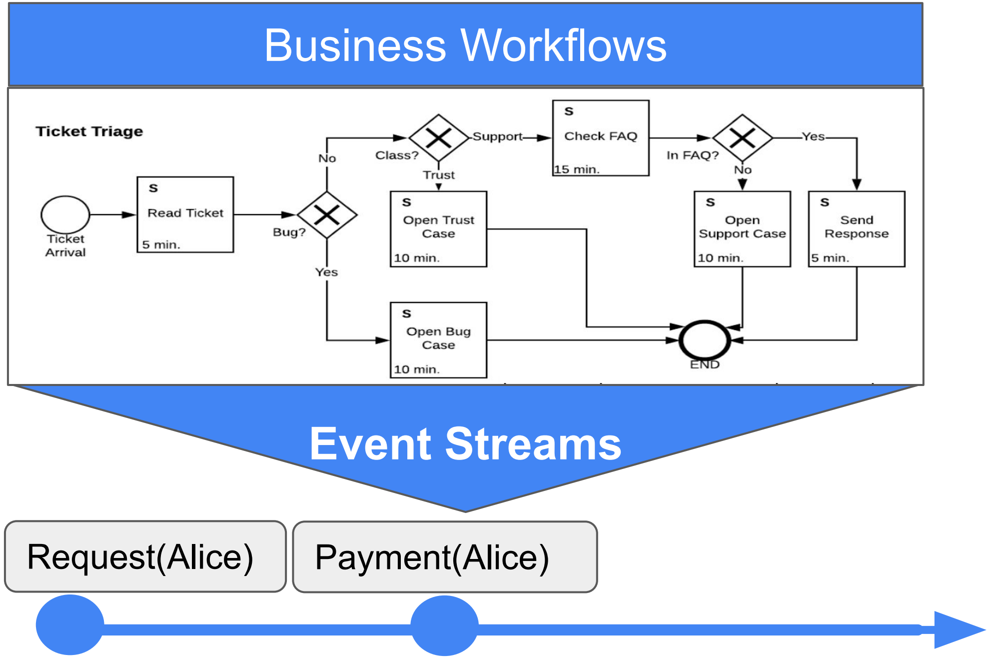

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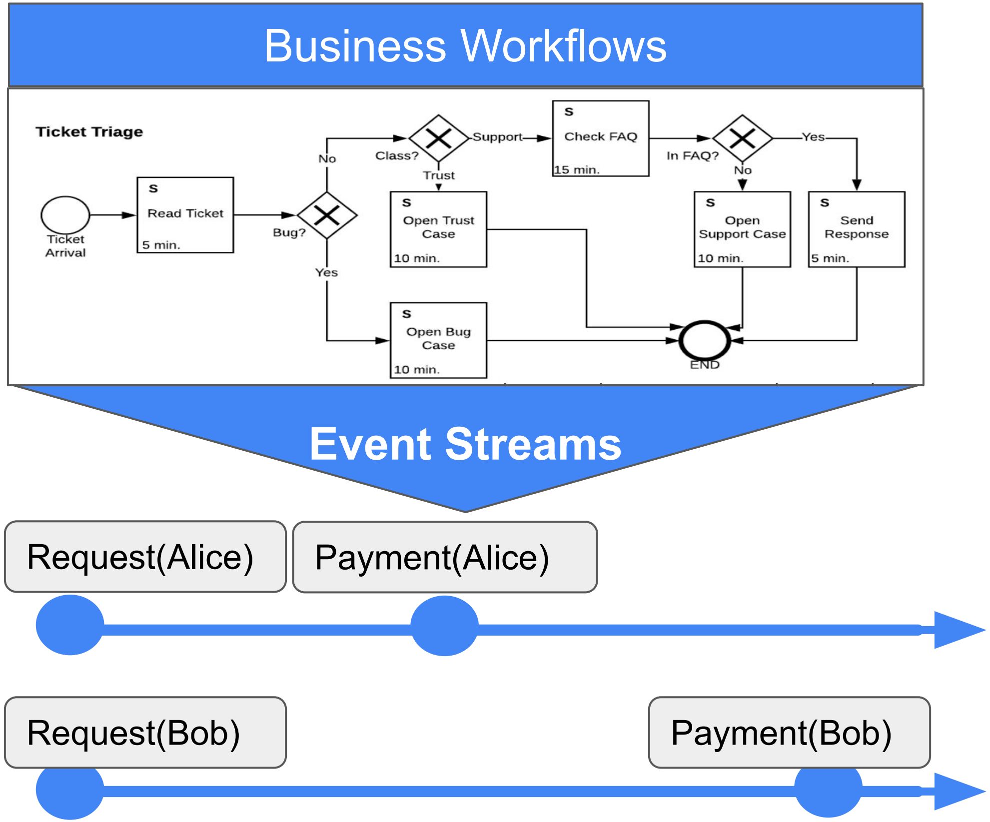

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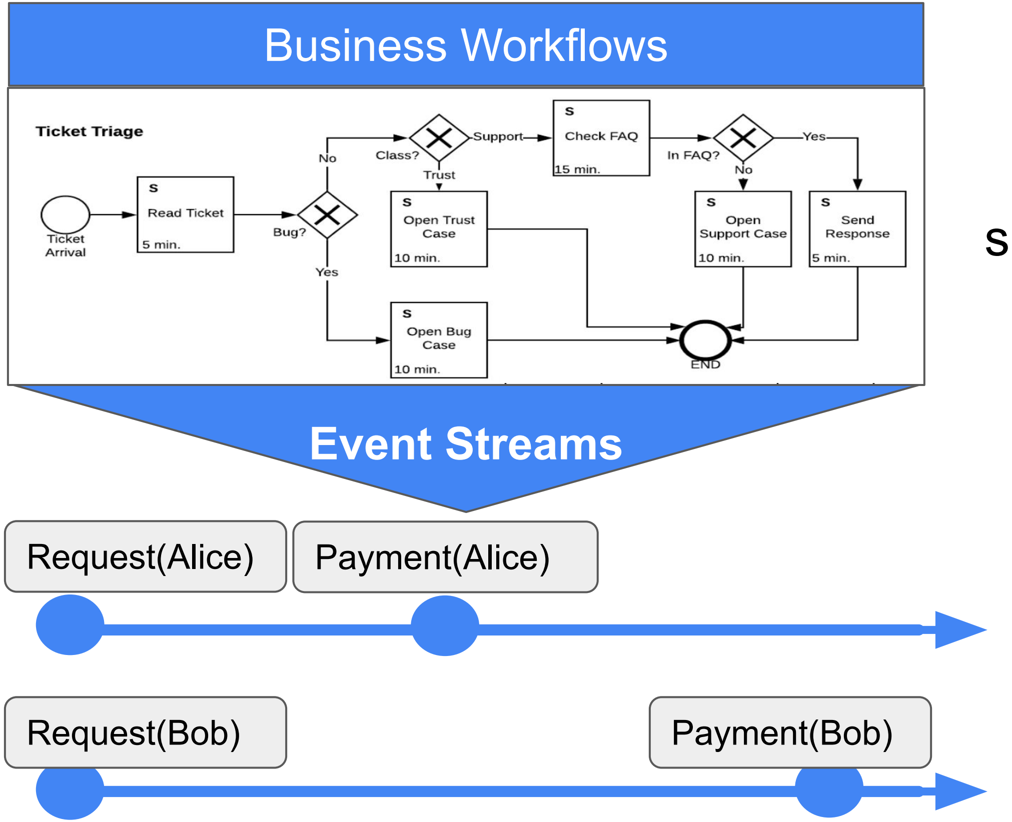
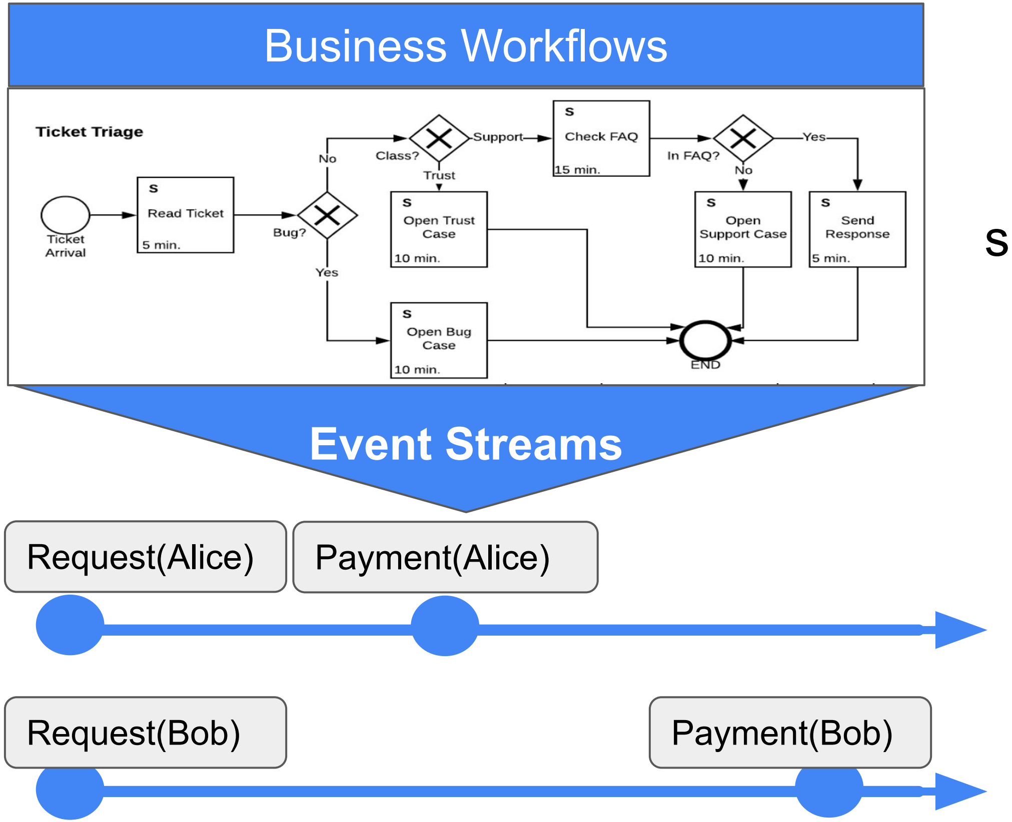


subject to **Business Rules**

Events Streams Must Satisfy Business Rules

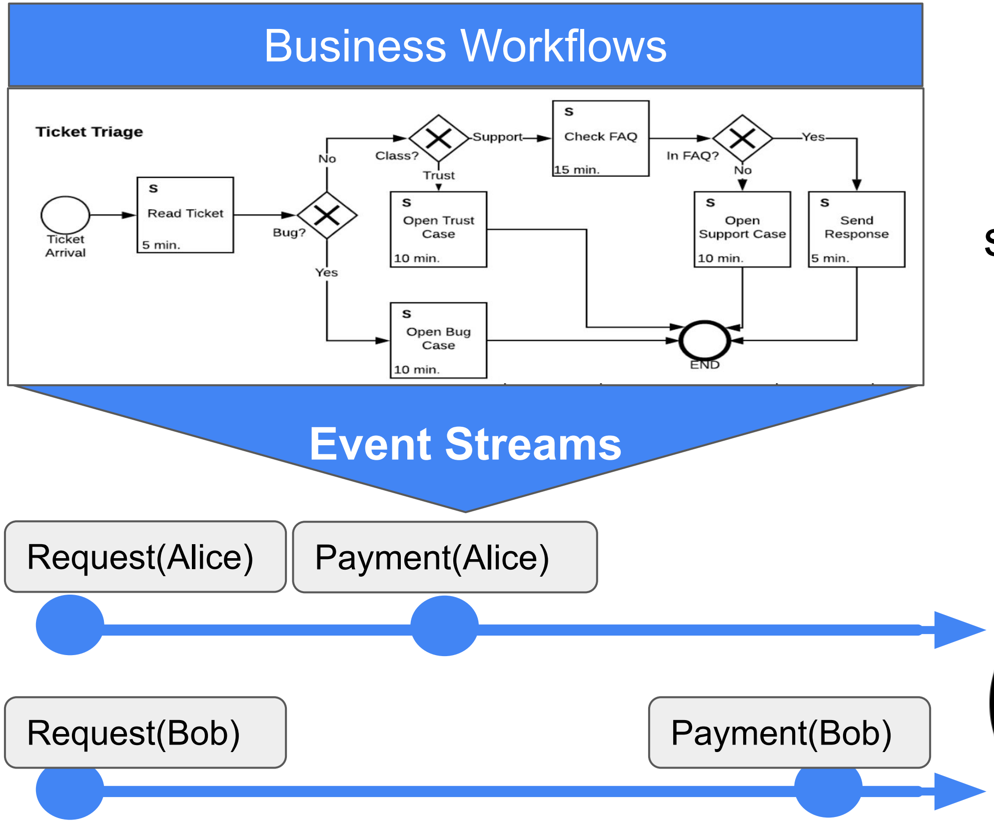


subject to

Business Rules

- Organizational goals
- Resource limits
- Safety regulations
- ...

Events Streams Must Satisfy Business Rules



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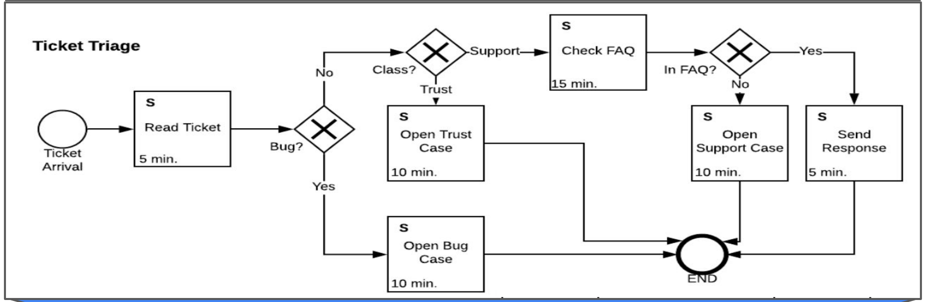

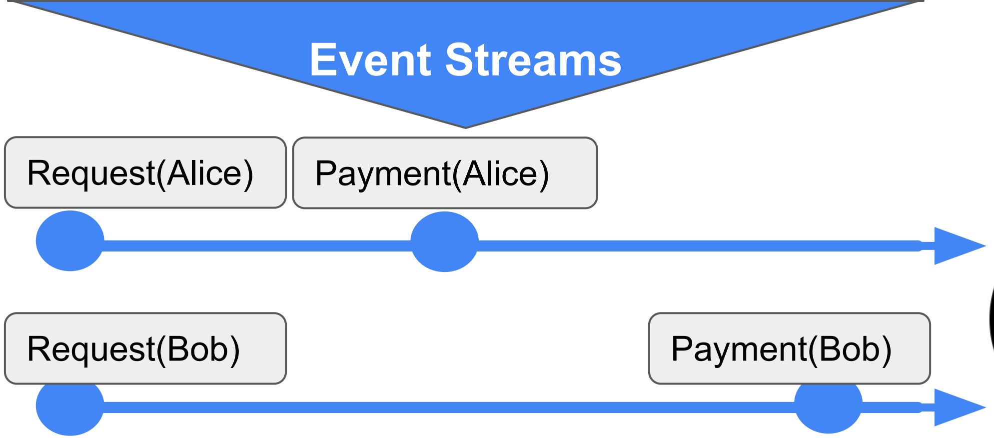

subject to

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- Organizational goals
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- ...

SATISFIES RULES

VIOLATION, e.g., Late Payment

Rule Specification Language

Rule Specification Language

Request(user u)@x, Approval(user u)@y, x+1 ≤ y

→

Payment(user v)@z, Receipt(user v)@w, z ≤ y+10, z ≤ w ≤ z+2

Rule Specification Language

$$\overbrace{\text{Request(user u)@x}}^{\textit{event}}\text{, Approval(user u)@y, x+1} \le \text{y}$$

→

Payment(user v)@z, Receipt(user v)@w, z ≤ y+10, z ≤ w ≤ z+2

Rule Specification Language

$\overbrace{\text{Request(user u)@x}}^{\textit{event}}$, Approval(user u)@y, $\overbrace{x+1 \le y}^{\textit{quantitative time gap}}$

→

Payment(user v)@z, Receipt(user v)@w, $z \le y+10$, $z \le w \le z+2$

Rule Specification Language

$$\overbrace{\text{Request(user u)@x}}^{\textit{event}}, \text{ Approval(user u)@y}, \ \overbrace{x+1 \le y}^{\textit{quantitative time gap}}$$

$$\rightarrow$$

$$\text{Payment(user v)@z, Receipt(user v)@w}, \ z \le y+10, \ z \le w \le z+2$$

data variable *time variable*

Rule Specification Language

$\overbrace{\text{Request(user u)@x}}^{\textit{event}}$, Approval(user u)@y, $\overbrace{x+1 \le y}^{\textit{quantitative time gap}}$ *body*

$\rightarrow$

Payment(user v)@z, Receipt(user v)@w, $z \le y+10$, $z \le w \le z+2$ *head*

data variable *time variable*

Rule Specification Language

$\overbrace{\text{Request(user u)@x}}^{\textit{event}}$, Approval(user u)@y, $\overbrace{x+1 \leq y}^{\textit{quantitative time gap}}$ *body*

$\rightarrow$

Payment(user v)@z, Receipt(user v)@w, z ≤ y+10, z ≤ w ≤ z+2 *head*

data variable *time variable*

Request(Alice)@1

Rule Specification Language

$$\overbrace{\text{Request(user u)@x}}^{\textit{event}}\text{, Approval(user u)@y, }\overbrace{x+1 \le y}^{\textit{quantitative time gap}} \qquad \textit{body}$$

$$\rightarrow$$

$$\text{Payment(user v)@z, Receipt(user v)@w, } z \le y+10,\ z \le w \le z+2 \qquad \textit{head}$$

data variable *time variable*

Request(Alice)@1

Request(Alice)@1 — Approval(Alice)@2 — Payment(Bob)@11 — Receipt(Bob)@12

Detecting Rule Violations at the Earliest Possible Time

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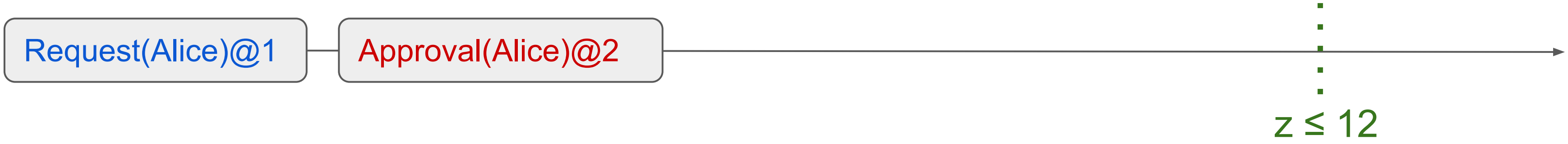

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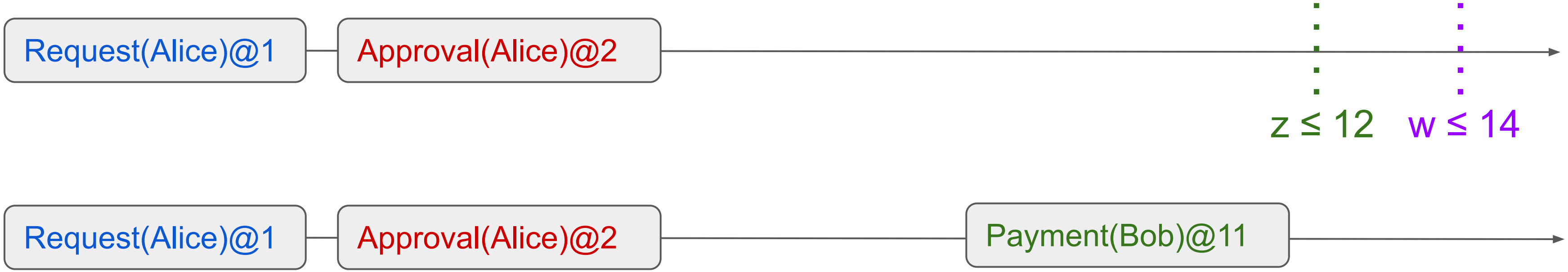

Detecting Rule Violations at the Earliest Possible Time

$\text{Request(user u)@}x$, $\text{Approval(user u)@}y$, $x+1 \leq y$

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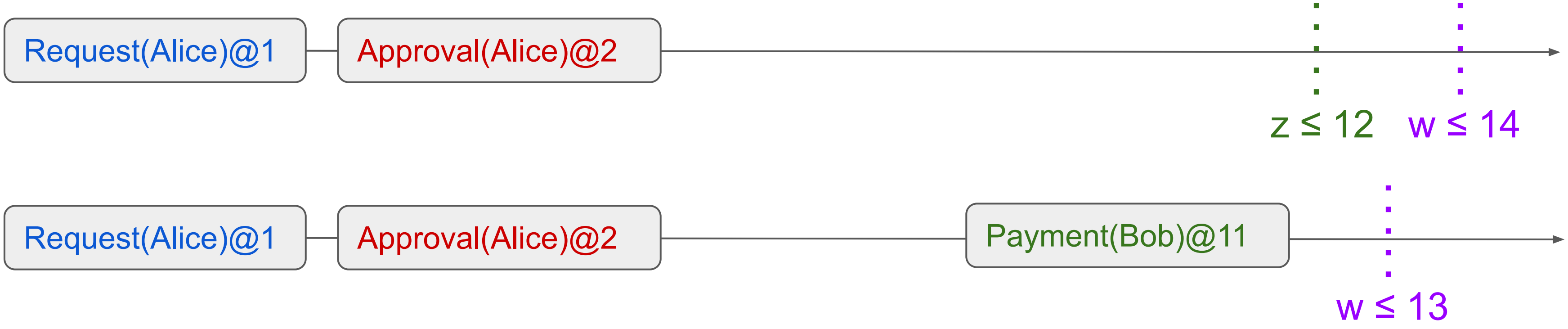

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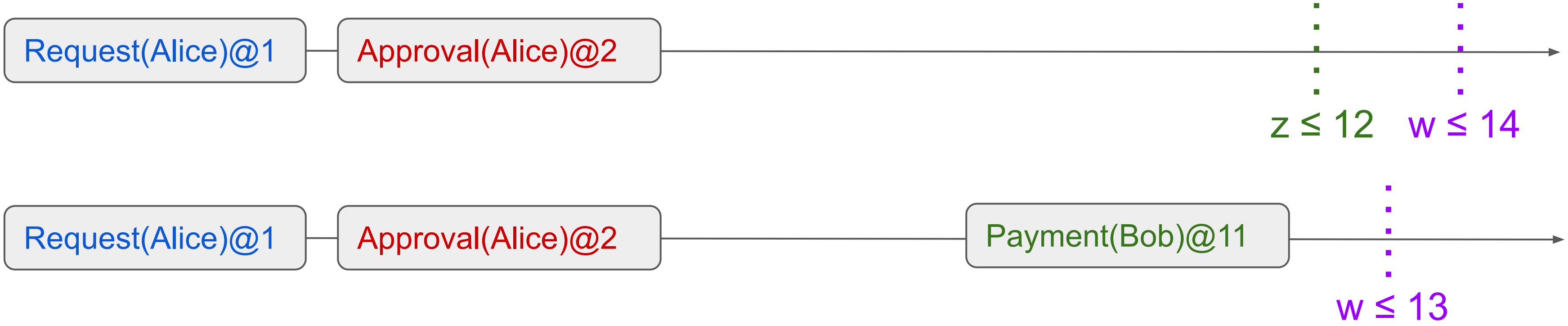

An event stream *e* is a ***violation*** of a rule (set of rules) *R* if no extension of *e* satisfies (each rule in) *R*.

Detecting Rule Violations at the Earliest Possible Time

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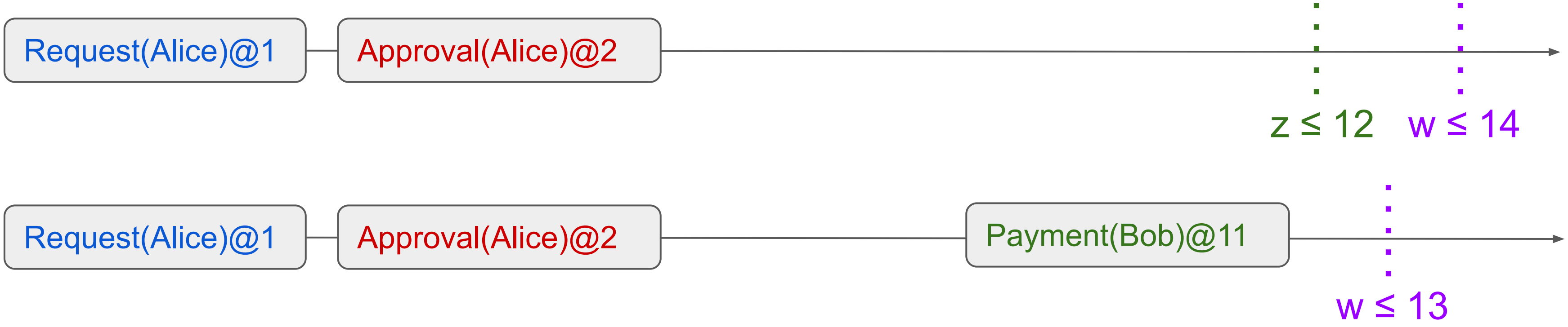

An event stream *e* is a ***violation*** of a rule (set of rules) *R* if no extension of *e* satisfies (each rule in) *R*.

Can we detect violations at the earliest possible time?

Outline

Rules

1. without Data (Mackey & Su, Info. Sys., 2023), Comparison with Other Work

with Data

2. Individual Rules (Mackey et al., TIME 2022)

Sets of Rules

Acyclic Sets

Chase Process

(Mackey & Su, Info. & Comp., in revision, 2023)

3. with Aggregation Functions on Time Windows

4. Unrestricted Sets (Early Detection is Impossible)

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- For each singly-linked, acyclic, dataless rule r, an equivalent LTL formula whose size is *single-exponential* in |r|.

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(Mackey & Su, Info. Sys., 2023) provides translations...

- For each singly-linked, acyclic, dataless rule r, an equivalent LTL formula whose size is *single-exponential* in |r|.
- For each singly-linked, dataless rule r, an equivalent LTL formula whose size is *double-exponential* in |r|.

Outline

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Interactions in Sets of Rules Creates Earlier Violations

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$$\begin{cases} \text{A:} \quad \mathrm{Request}(u)@x \rightarrow \mathrm{Payment}(u)@y,\ x \le y \\ \text{B:} \quad \mathrm{Request}(u)@x,\ \mathrm{Payment}(u)@y,\ x+5 \le y \rightarrow \mathrm{Approval}(v)@z,\ z < x \end{cases}$$

Interactions in Sets of Rules Creates Earlier Violations

A: Request(u)@x → Payment(u)@y, x ≤ y

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Interactions in Sets of Rules Creates Earlier Violations

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Request(Alice)@10

Payment(Alice)@y, 10 ≤ y

Interactions in Sets of Rules Creates Earlier Violations

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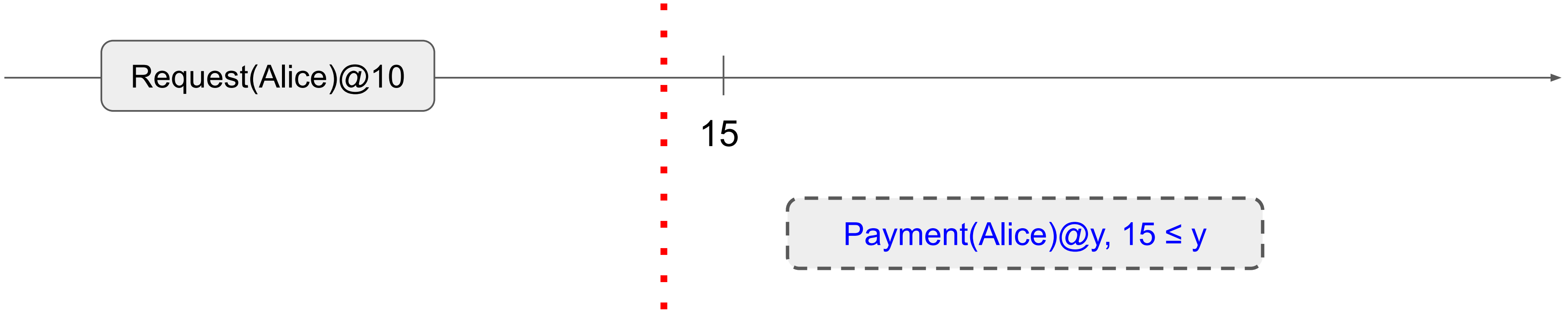

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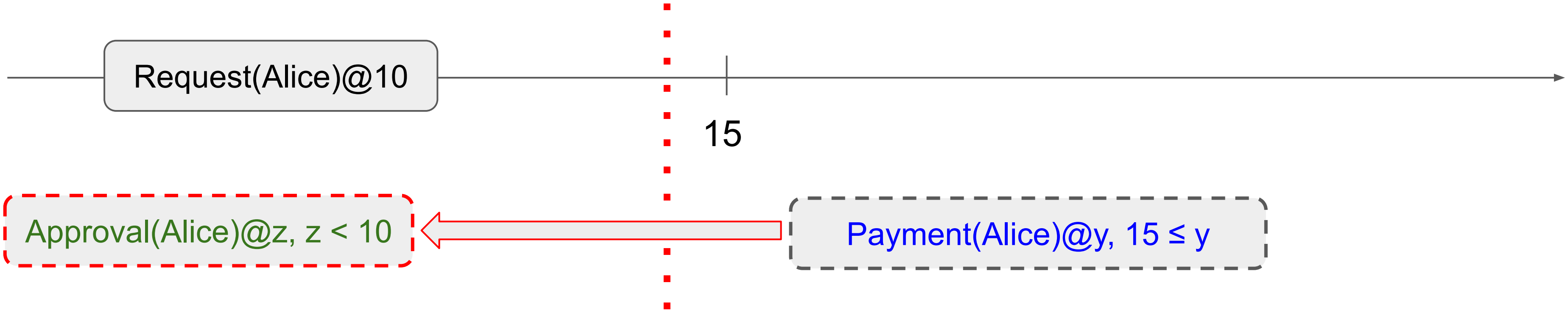

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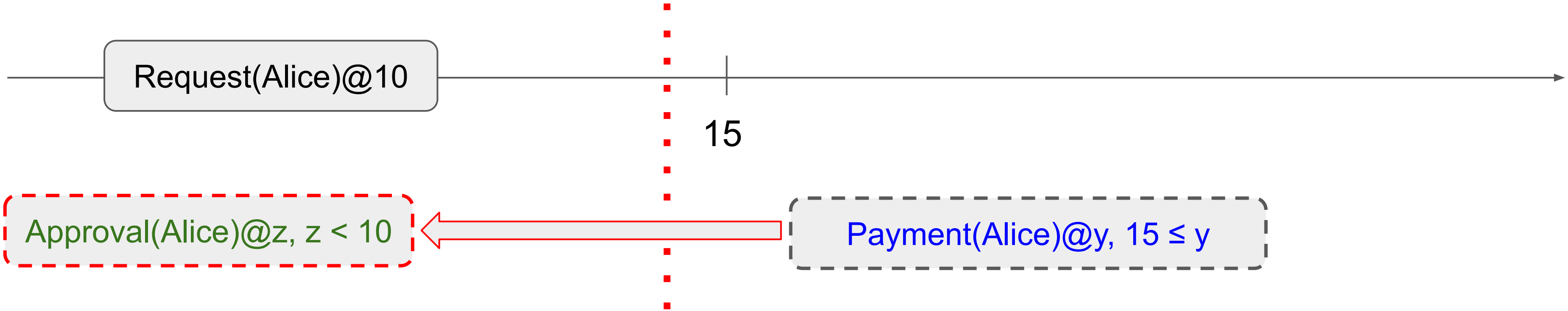

- No violation of A at *t* =15
- No violation of B at *t* =15

Interactions in Sets of Rules Creates Earlier Violations

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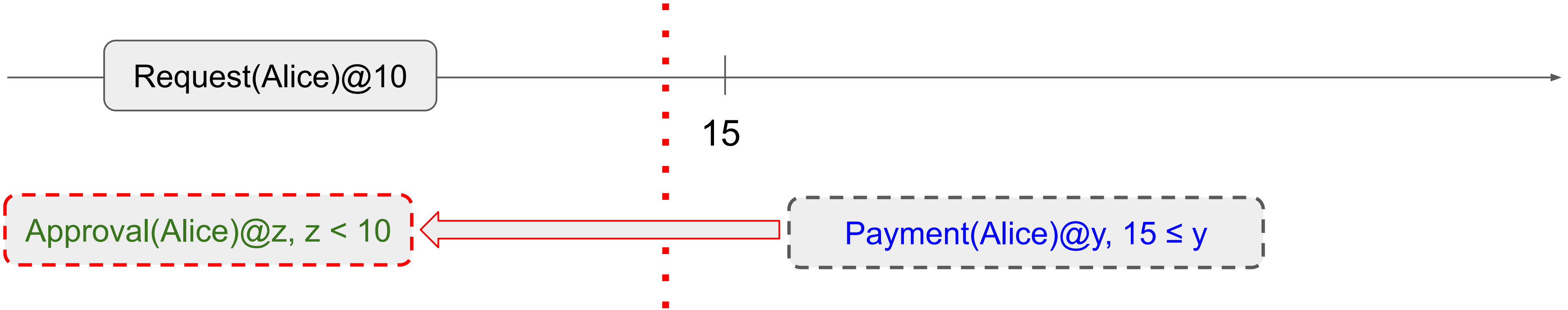

- No violation of A at *t* =15
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  ... but { A, B } is violated after *t* =15

Chase Creates Expected Events

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Request(Alice)@10

Chase Creates Expected Events

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Request(Alice)@10

Chasing A with
(u=Alice, x=10)

Chase Creates Expected Events

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Request(Alice)@10

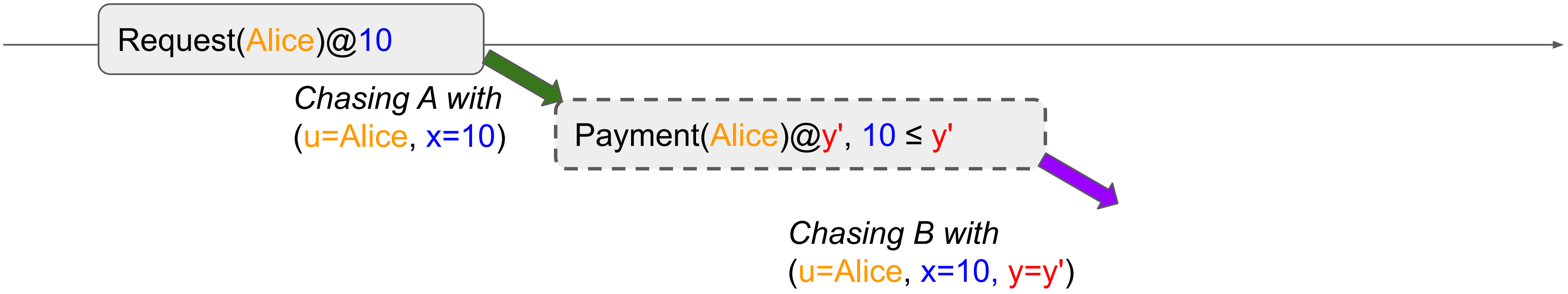
Chasing A with
(u=Alice, x=10)

Payment(Alice)@y', 10 ≤ y'

Chase Creates Expected Events

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x



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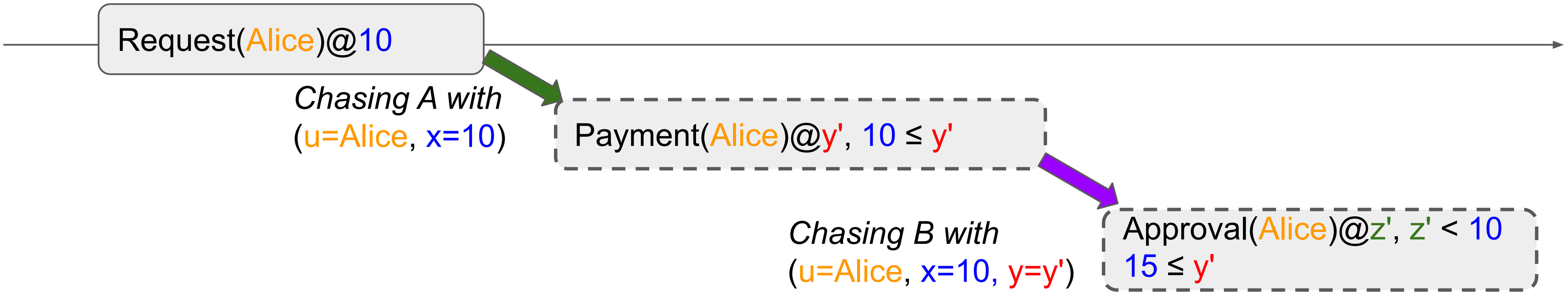

Acyclic Set of Rules Guarantees Chase Termination

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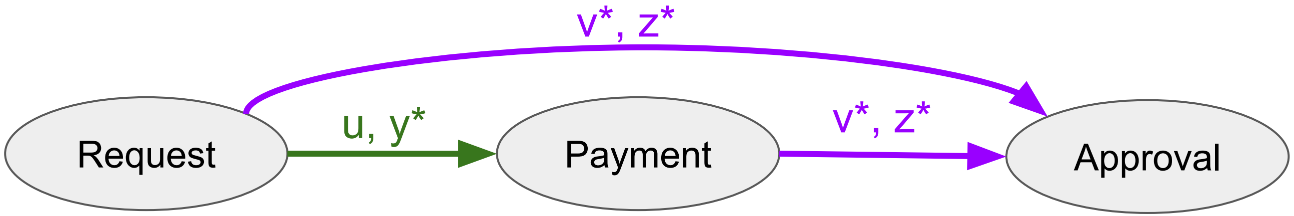

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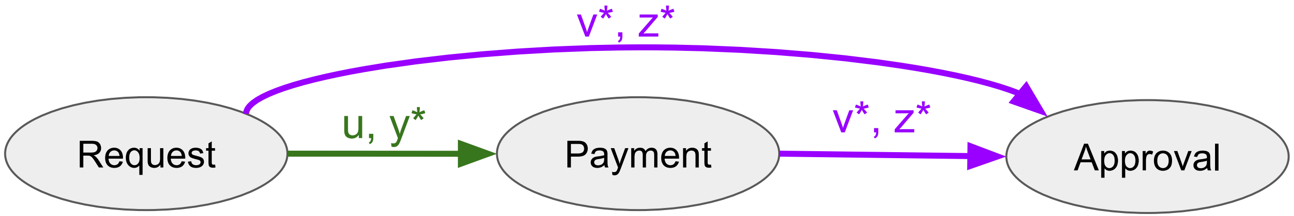

Chasing acyclic rules always terminates (Kolatis et al., PODS 2006)

Individual Rules: Match Assignments Before Deadlines

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Individual Rules: Match Assignments Before Deadlines

Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Body assignments				
id	u	x	y	gaps

Individual Rules: Match Assignments Before Deadlines

$Request(u)@x,\ Payment(u)@y,\ x+5 \leq y \quad \rightarrow \quad Approval(v)@z,\ z < x$

Body assignments				
id	u	x	y	gaps

Head assignments				
id	v	z	gaps	deadline

Individual Rules: Match Assignments Before Deadlines

Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Body assignments				
id	u	x	y	gaps

Head assignments				
id	v	z	gaps	deadline

Extensions			
body	head	gaps	deadline

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Extensions			
body	head	gaps	deadline

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Body assignments				
id	u	x	y	gaps

Head assignments				
id	v	z	gaps	deadline

Extensions			
body	head	gaps	deadline

Approval(Bob)@9

Individual Rules: Match Assignments Before Deadlines

$\text{Request}(u)@x,\ \text{Payment}(u)@y,\ x+5 \le y \ \rightarrow\ \text{Approval}(v)@z,\ z < x$

Body assignments				
id	u	x	y	gaps

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 →

Individual Rules: Match Assignments Before Deadlines

Request(u)@x, Payment(u)@y, $x+5 \leq y$ $\rightarrow$ Approval(v)@z, $z < x$

Body assignments				
id	u	x	y	gaps

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 → Request(Alice)@10 →

Individual Rules: Match Assignments Before Deadlines

$\text{Request}(u)@x,\ \text{Payment}(u)@y,\ x+5 \leq y \ \rightarrow\ \text{Approval}(v)@z,\ z < x$

Body assignments				
id	u	x	y	gaps
α_1	Alice	10	-	$10 \leq y$

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 → Request(Alice)@10 →

Individual Rules: Match Assignments Before Deadlines

$$\text{Request}(u)@x,\ \text{Payment}(u)@y,\ x+5 \leq y \ \rightarrow\ \text{Approval}(v)@z,\ z < x$$

Body assignments				
id	u	x	y	gaps
α_1	Alice	10	-	$10 \leq y$

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 — Request(Alice)@10 — Payment(Alice)@16 →

Individual Rules: Match Assignments Before Deadlines

Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

Body assignments				
id	u	x	y	gaps
α_1	Alice	10	-	10 ≤ y
α_2	Alice	-	16	x ≤ 16

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	9 < x	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 → Request(Alice)@10 → Payment(Alice)@16 →

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$$\text{Request}(u)@x,\ \text{Payment}(u)@y,\ x+5 \leq y \ \rightarrow\ \text{Approval}(v)@z,\ z < x$$

Body assignments				
id	u	x	y	gaps
α_1	Alice	10	-	$10 \leq y$
α_2	Alice	-	16	$x \leq 16$
α_3	Alice	10	16	$10 \leq 16$

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline

Approval(Bob)@9 → Request(Alice)@10 → Payment(Alice)@16 →

Individual Rules: Match Assignments Before Deadlines

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Body assignments				
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α_1	Alice	10	-	$10 \leq y$
α_2	Alice	-	16	$x \leq 16$
α_3	Alice	10	16	$10 \leq 16$

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10

Approval(Bob)@9 → Request(Alice)@10 → Payment(Alice)@16 →

Individual Rules: Match Assignments Before Deadlines

$\text{Request}(u)@x,\ \text{Payment}(u)@y,\ x+5 \leq y \ \rightarrow\ \text{Approval}(v)@z,\ z < x$

Body assignments				
id	u	x	y	gaps
α_1	Alice	10	-	$10 \leq y$
α_2	Alice	-	16	$x \leq 16$
α_3	Alice	10	16	$10 \leq 16$

Head assignments				
id	v	z	gaps	deadline
β_2	Bob	9	$9 < x$	-

Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10
α_3	β_2	-	-

Approval(Bob)@9 → Request(Alice)@10 → Payment(Alice)@16 →

Expected Events Allow Violation Detection

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, $x \leq y$

B: Request(u)@x, Payment(u)@y, $x+5 \leq y$ → Approval(v)@z, $z < x$

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, $x \leq y$

B: Request(u)@x, Payment(u)@y, $x+5 \leq y$ → Approval(v)@z, $z < x$

B: Body assignments				
id	u	x	y	gaps

B: Head assignments				
id	v	z	gaps	deadline

B: Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, $x \leq y$

B: Request(u)@x, Payment(u)@y, $x+5 \leq y$ → Approval(v)@z, $z < x$

B: Body assignments					
id	u	x	y	gaps	Chased

B: Head assignments				
id	v	z	gaps	deadline

B: Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

B: Body assignments					
id	u	x	y	gaps	Chased

B: Head assignments				
id	v	z	gaps	deadline

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	10 ≤ y	-
α_2	Alice	-	y'	x ≤ y'	-
α_3	Alice	10	y'	10 ≤ y'	-

B: Head assignments				
id	v	z	gaps	deadline

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	10 ≤ y	-
α_2	Alice	-	y'	x ≤ y'	-
α_3	Alice	10	y'	10 ≤ y'	*Yes*

B: Head assignments				
id	v	z	gaps	deadline

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10

Approval(Alice)@z', z' < 10
15 ≤ y'

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, $x \leq y$

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B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	$10 \leq y$	-
α_2	Alice	-	y'	$x \leq y'$	-
α_3	Alice	10	y'	$10 \leq y'$	Yes

B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10

Approval(Alice)@z', $z' < 10$
$15 \leq y'$

Request(Alice)@10

Payment(Alice)@y', $10 \leq y'$

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, $x \leq y$

B: Request(u)@x, Payment(u)@y, $x+5 \leq y$ → Approval(v)@z, $z < x$

B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	$10 \leq y$	-
α_2	Alice	-	y'	$x \leq y'$	-
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B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10
α_3	β_2	$z' < 10$ $15 \leq y'$	10

Approval(Alice)@z', $z' < 10$
$15 \leq y'$

Request(Alice)@10

Payment(Alice)@y', $10 \leq y'$

Expected Events Allow Violation Detection

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α_1	Alice	10	-	$10 \leq y$	-
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α_3	Alice	10	y'	$10 \leq y'$	Yes

B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	$z < 10$	10
α_3	β_2	$z' < 10$ $15 \leq y'$	10

Approval(Alice)@z', $z' < 10$
$15 \leq y'$

Request(Alice)@10

Payment(Alice)@y', $10 \leq y'$

No violation at time *t* iff (when α_3 exists at *t*, it can match with β_2)

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	10 ≤ y	-
α_2	Alice	-	y'	x ≤ y'	-
α_3	Alice	10	y'	10 ≤ y'	*Yes*

B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10
α_3	β_2	z' < 10 15 ≤ y'	10

Approval(Alice)@z', z' < 10
15 ≤ y'

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

No violation at time *t* iff (when α_3 exists at *t*, it can match with β_2)

No violation at time *t* iff SAT((15 ≤ y' → z' < 10)

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A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

B: Body assignments					
id	u	x	y	gaps	Chased
α_1	Alice	10	-	10 ≤ y	-
α_2	Alice	-	y'	x ≤ y'	-
α_3	Alice	10	y'	10 ≤ y'	*Yes*

B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10
α_3	β_2	z' < 10 15 ≤ y'	10

Approval(Alice)@z', z' < 10
15 ≤ y'

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

No violation at time *t* iff (when α_3 exists at *t*, it can match with β_2)

No violation at time *t* iff SAT((15 ≤ y' → z' < 10) ∧ (*t* < y') ∧ (*t* < z'))

Expected Events Allow Violation Detection

A: Request(u)@x → Payment(u)@y, x ≤ y

B: Request(u)@x, Payment(u)@y, x+5 ≤ y → Approval(v)@z, z < x

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id	u	x	y	gaps	Chased
α_1	Alice	10	-	10 ≤ y	-
α_2	Alice	-	y'	x ≤ y'	-
α_3	Alice	10	y'	10 ≤ y'	*Yes*

B: Head assignments				
id	v	z	gaps	deadline
β_2	Bob	z'	-	-

B: Extensions			
body	head	gaps	deadline
α_3	-	z < 10	10
α_3	β_2	z' < 10 15 ≤ y'	10

Approval(Alice)@z', z' < 10
15 ≤ y'

Request(Alice)@10

Payment(Alice)@y', 10 ≤ y'

No violation at time *t* iff (when α_3 exists at *t*, it can match with β_2)

No violation at time *t* iff SAT((15 ≤ y' → z' < 10) ∧ (*t* < y') ∧ (*t* < z'))

SAT while *t* < 15

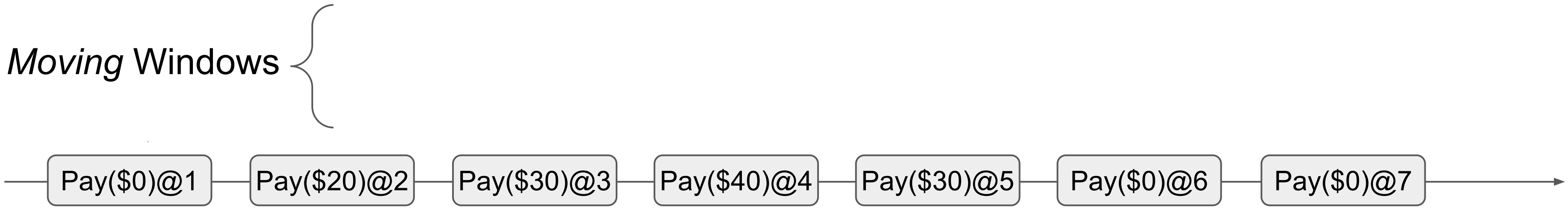
Outline

Rules

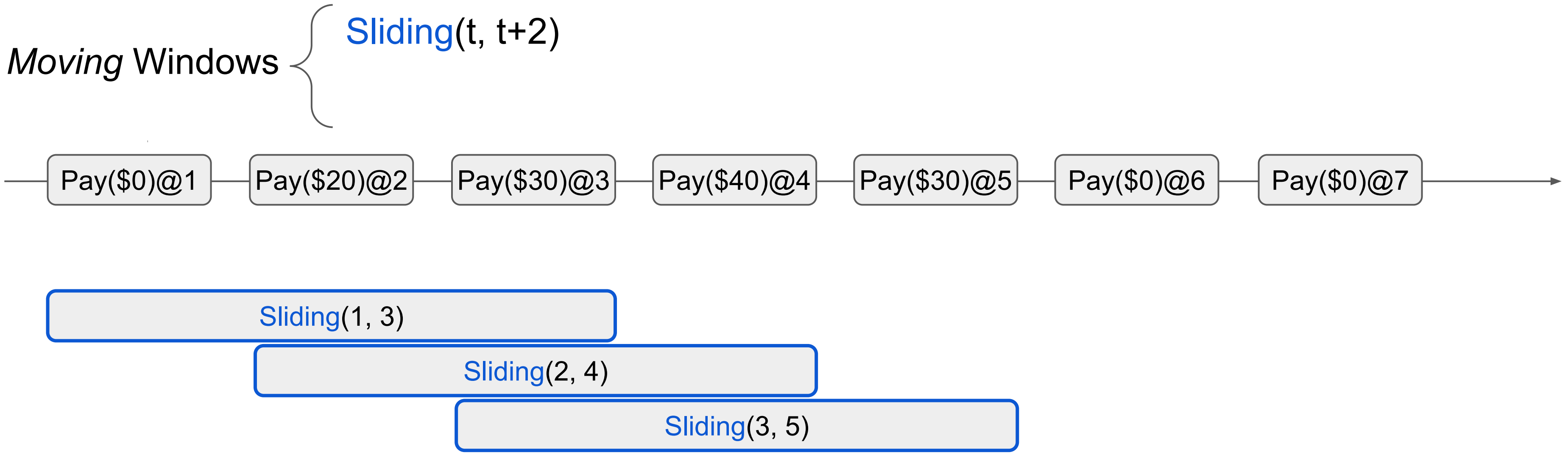
- **1.** without Data (Mackey & Su, Info. Sys., 2023), Comparison with Other Work
- with Data
  - **2.** Individual Rules (Mackey et al., TIME 2022)
  - Sets of Rules
    - Acyclic Sets
      - Chase Process (Mackey & Su, Info. & Comp., in revision, 2023)
      - **3. with Aggregation Functions on Time Windows**
    - **4.** Unrestricted Sets (Early Detection is Impossible)

Time Windows over Event Streams

Time Windows over Event Streams

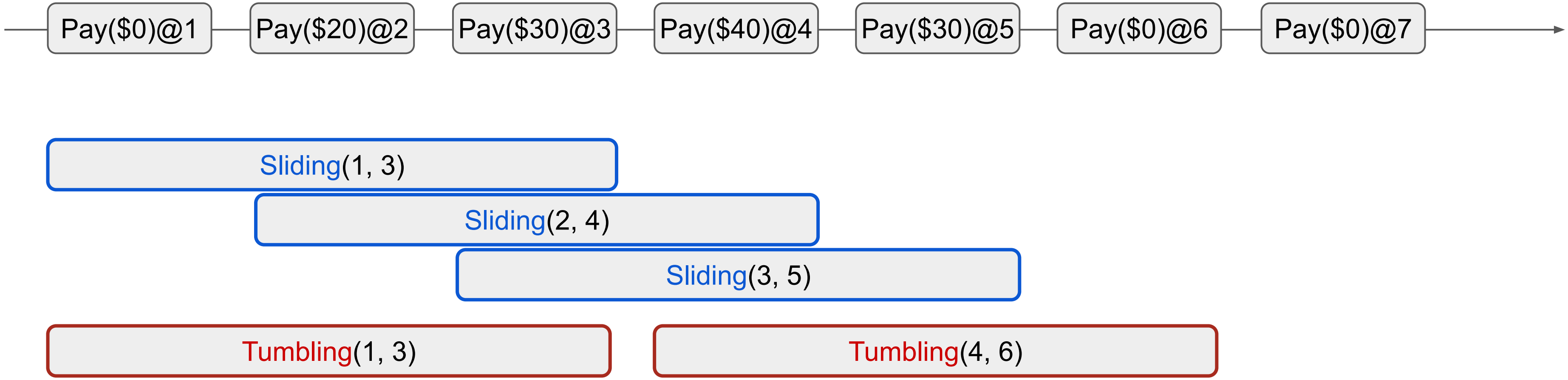


Time Windows over Event Streams



Time Windows over Event Streams

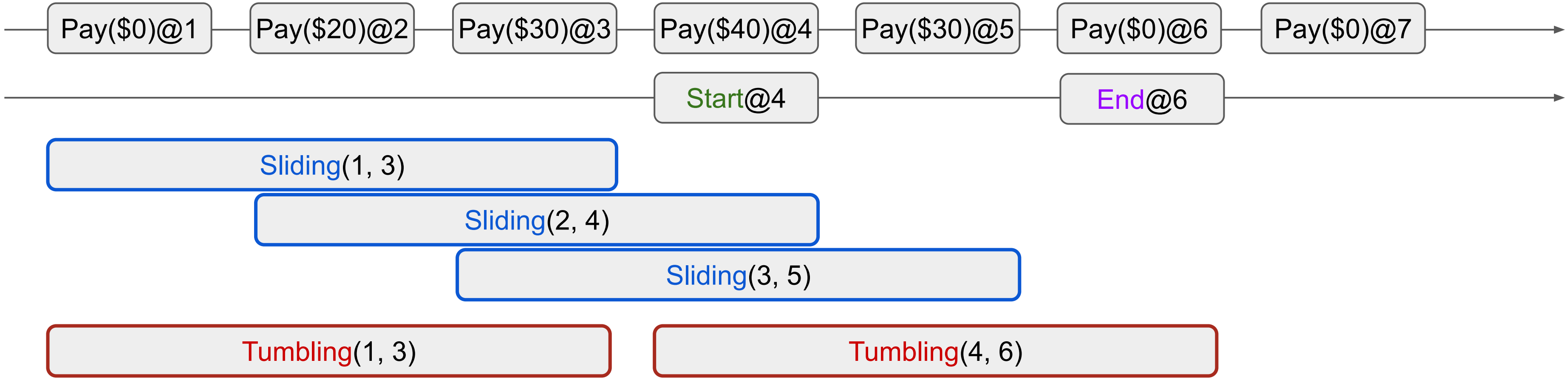
Moving Windows
- Sliding(t, t+2)
- Tumbling(t, t+2)



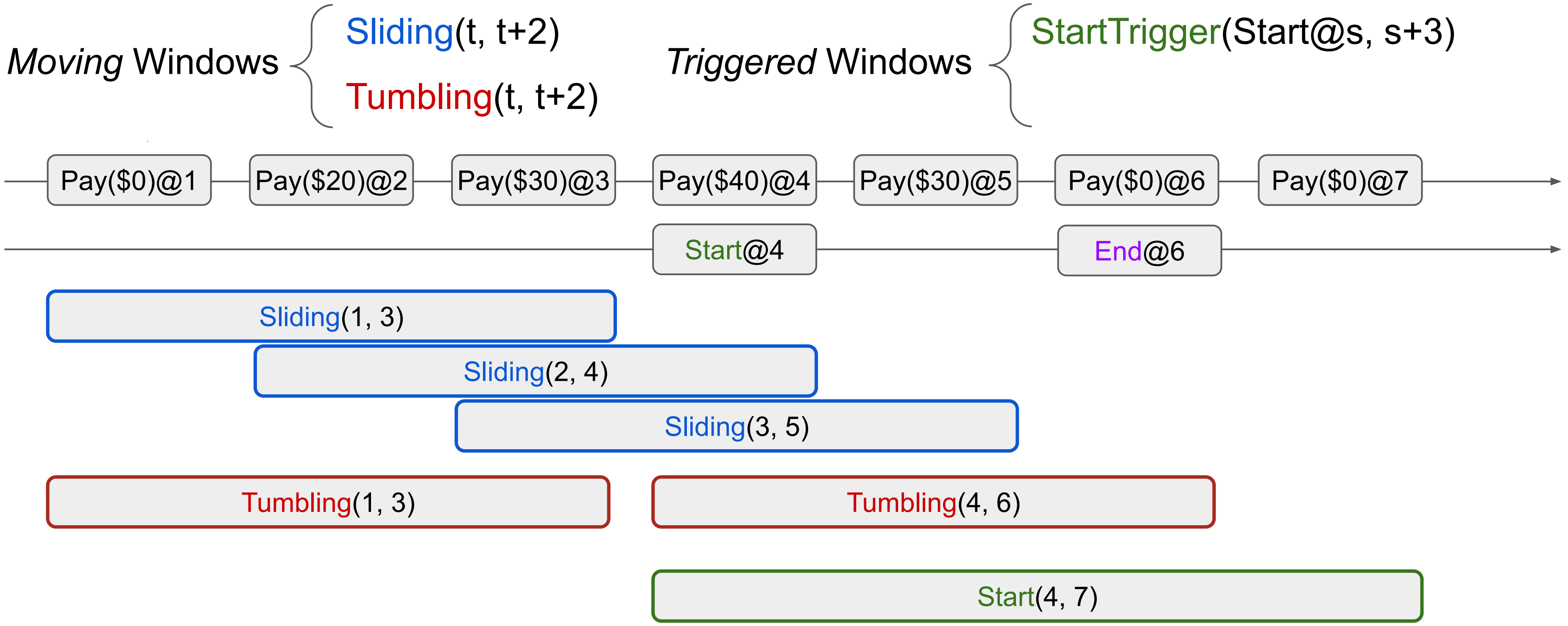
Time Windows over Event Streams

Moving Windows
Sliding(t, t+2)
Tumbling(t, t+2)

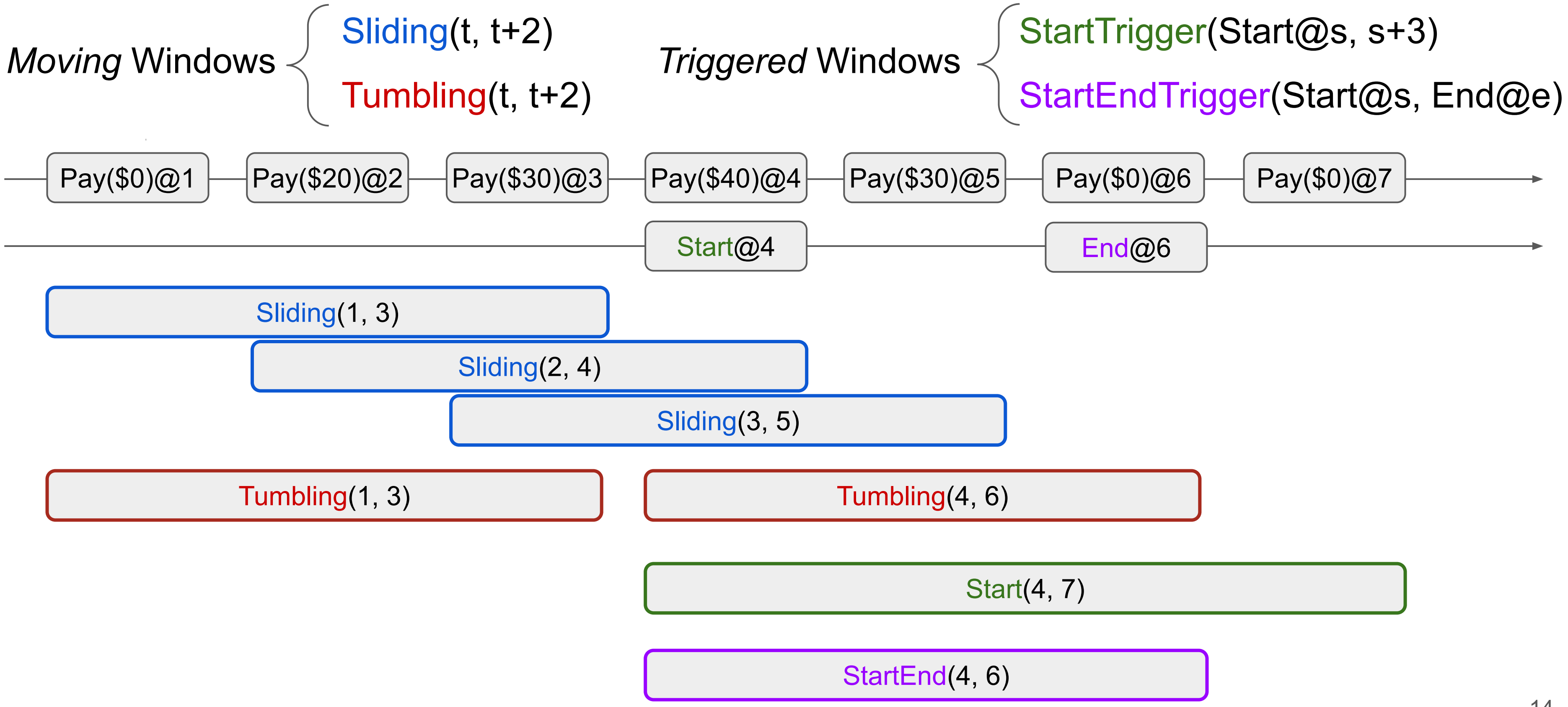
Triggered Windows



Time Windows over Event Streams



Time Windows over Event Streams



Aggregation Functions

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Aggregation functions: *sum*, *max*, *min*, *count, countu*

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SlidingSum(*s* = *sum*(a), t)@t+2

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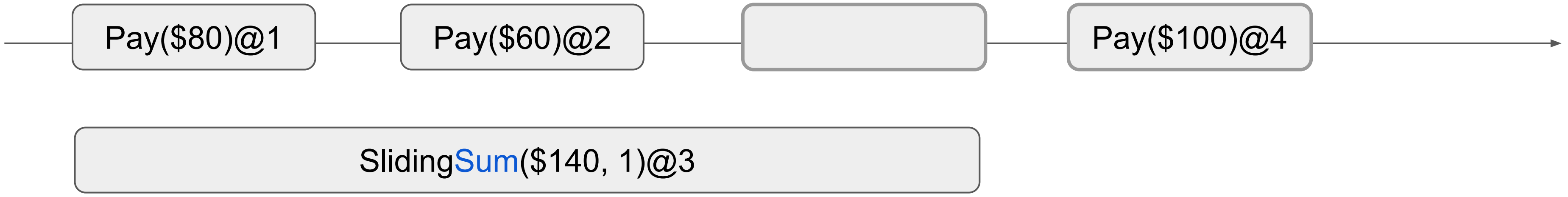
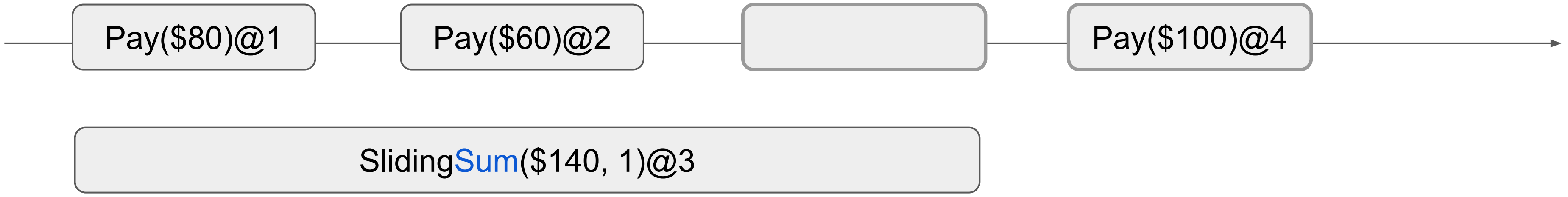


Aggregation Functions

Aggregation functions: *sum*, *max*, *min*, *count, countu*

SlidingSum(*s* = *sum*(a), t)@t+2

SlidingMax(*m* = *max*(a), t)@t+2



Aggregation Functions

Aggregation functions: *sum*, *max*, *min*, *count, countu*

SlidingSum(*s* = *sum*(a), t)@t+2

SlidingMax(*m* = *max*(a), t)@t+2

Pay($80)@1 Pay($60)@2 Pay($100)@4

SlidingSum($140, 1)@3

SlidingMax($80, 1)@3

Chasing Windows with Presburger Arithmetic

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For each (open) window and aggregation function (*sum*, *max*, *min*, *count, countu*), there is an equivalent Presburger arithmetic constraint.

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SlidingSum(*s* = sum(a), t)@t+2

Chasing Windows with Presburger Arithmetic

For each (open) window and aggregation function (*sum*, *max*, *min*, *count, countu*), there is an equivalent Presburger arithmetic constraint.

SlidingSum(s = sum(a), t)@t+2

Pay($80)@1 — Pay($60)@2 — Pay(a)@3 →

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

Chasing Windows with Presburger Arithmetic

For each (open) window and aggregation function (*sum*, *max*, *min*, *count, countu*), there is an equivalent Presburger arithmetic constraint.

SlidingSum(s = sum(a), t)@t+2

SlidingMax(m = max(a), t)@t+2

Pay($80)@1 — Pay($60)@2 — Pay(a)@3 →

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

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SlidingSum(s = sum(a), t)@t+2

SlidingMax(m = max(a), t)@t+2

Pay($80)@1 — Pay($60)@2 — Pay(a)@3

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

SlidingMax(m', 1)@3, $((m' = 80) \lor (m' = 60) \lor (m' = a)) \land ((80 \leq m') \land (60 \leq m') \land (a \leq m'))$

Detecting Violations

Detecting Violations

$$\begin{cases} \text{SlidingSum}(\ s = sum(\text{a}),\ \text{t})@\text{t+2} \rightarrow s \leq 200 \\ \text{SlidingMax}(\ m = max(\text{a}),\ \text{t})@\text{t+2} \rightarrow m \geq 100 \end{cases}$$

Detecting Violations

$$\begin{cases} \text{SlidingSum}(\ s = sum(\text{a}),\ \text{t})@\text{t}+2 \ \rightarrow s \leq 200 \\ \text{SlidingMax}(\ m = max(\text{a}),\ \text{t})@\text{t}+2 \rightarrow m \geq 100 \end{cases}$$

Pay($80)@1 — Pay($60)@2 — Pay(*a*)@3

Detecting Violations

$$\begin{cases} \text{SlidingSum}(\ s = sum(\text{a}),\ \text{t})@\text{t+2} \ \rightarrow s \le 200 \\ \text{SlidingMax}(\ m = max(\text{a}),\ \text{t})@\text{t+2} \rightarrow m \ge 100 \end{cases}$$

Pay(\$80)@1 — Pay(\$60)@2 — Pay(a)@3

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

SlidingMax(m', 1)@3, $((m' = 80) \lor (m' = 60) \lor (m' = a))$
$\land$
$((80 \le m') \land (60 \le m') \land (a \le m'))$

Detecting Violations

Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

$$\begin{cases} \text{SlidingSum}(\ s = sum(\text{a}),\ \text{t})@\text{t}+2 \ \rightarrow s \le 200 \\ \text{SlidingMax}(\ m = max(\text{a}),\ \text{t})@\text{t}+2 \rightarrow m \ge 100 \end{cases}$$

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$\land$
$((80 \le m') \land (60 \le m') \land (a \le m'))$

Detecting Violations

Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

SlidingSum($s = sum(a)$, t)@t+2 $\rightarrow s \leq 200$

SlidingMax($m = max(a)$, t)@t+2 $\rightarrow m \geq 100$

SlidingSum Head assignments			
id	t	s	gaps
α_1	1	s'	$s' = 80 + 60 + a$ $s' \leq 200$

Pay($80)@1 — Pay($60)@2 — Pay(a)@3

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

SlidingMax(m', 1)@3, $((m' = 80) \vee (m' = 60) \vee (m' = a))$
$\wedge$
$((80 \leq m') \wedge (60 \leq m') \wedge (a \leq m'))$

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Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

$$\begin{cases} \text{SlidingSum}(\ s = sum(\text{a}),\ \text{t})@\text{t+2} \ \rightarrow s \leq 200 \\ \text{SlidingMax}(\ m = max(\text{a}),\ \text{t})@\text{t+2} \rightarrow m \geq 100 \end{cases}$$

Pay($80)@1 — Pay($60)@2 — Pay(a)@3

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

SlidingMax(m', 1)@3, $((m' = 80) \lor (m' = 60) \lor (m' = a)) \land ((80 \leq m') \land (60 \leq m') \land (a \leq m'))$

SlidingSum Head assignments			
id	t	s	gaps
α_1	1	s'	$s' = 80 + 60 + a$ $s' \leq 200$

SlidingSum Head assignments			
id	t	m	gaps
β_1	1	m'	$((m' = 80) \lor (m' = 60) \lor (m' = a))$ $\land ((80 \leq m') \land (60 \leq m') \land (a \leq m'))$, $m \geq 100$

Detecting Violations

Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

$$\begin{cases} \text{SlidingSum}(\, s = sum(\text{a}),\ \text{t})@\text{t+2} \ \rightarrow s \leq 200 \\ \text{SlidingMax}(\, m = max(\text{a}),\ \text{t})@\text{t+2} \rightarrow m \geq 100 \end{cases}$$

Pay($80)@1 — Pay($60)@2 — Pay(a)@3

SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

SlidingMax(m', 1)@3, $((m' = 80) \lor (m' = 60) \lor (m' = a))$
$\land$
$((80 \leq m') \land (60 \leq m') \land (a \leq m'))$

SlidingSum Head assignments			
id	t	s	gaps
α_1	1	s'	$s' = 80 + 60 + a$ $s' \leq 200$

$a \leq 60$

SlidingSum Head assignments			
id	t	m	gaps
β_1	1	m'	$((m' = 80) \lor (m' = 60) \lor (m' = a))$ $\land ((80 \leq m') \land (60 \leq m') \land (a \leq m'))$, $m \geq 100$

Detecting Violations

Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

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SlidingSum(s', 1)@3, $s' = 80 + 60 + a$

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SlidingSum Head assignments			
id	t	s	gaps
α_1	1	s'	$s' = 80 + 60 + a$ $s' \leq 200$

$a \leq 60$

SlidingSum Head assignments			
id	t	m	gaps
β_1	1	m'	$((m' = 80) \lor (m' = 60) \lor (m' = a))$ $\land ((80 \leq m') \land$ [illegible] $m')), m \geq 100$

$a \geq 100$

Detecting Violations

Theorem. The earliest violation for an acyclic set of rules with aggregation can be computed.

$$\left\{\begin{array}{l} \mathrm{SlidingSum}(\ s = sum(\mathrm{a}),\ \mathrm{t})@\mathrm{t}{+}2 \ \rightarrow s \le 200 \\ \mathrm{SlidingMax}(\ m = max(\mathrm{a}),\ \mathrm{t})@\mathrm{t}{+}2 \rightarrow m \ge 100 \end{array}\right.$$

$\mathrm{Pay}(\$80)@1$ — $\mathrm{Pay}(\$60)@2$ — $\mathrm{Pay}(a)@3$

$\mathrm{SlidingSum}(s', 1)@3,\ s' = 80 + 60 + a$

$\mathrm{SlidingMax}(m', 1)@3,\ ((m' = 80) \vee (m' = 60) \vee (m' = a)) \wedge ((80 \le m') \wedge (60 \le m') \wedge (a \le m'))$

SlidingSum Head assignments

id	t	s	gaps
α_1	1	s'	$s' = 80 + 60 + a$ $s' \le 200$

$a \le 60$

SlidingSum Head assignments

id	t	m	gaps
β_1	1	m'	$((m' = 80) \vee (m' = 60) \vee (m' = a))$ $\wedge ((80 \le m') \wedge$ [illegible] $m')), m \ge 100$

$a \ge 100$

No violation at $t = 2$ iff
SAT((true $\rightarrow \alpha_1$) $\wedge$ (true $\rightarrow \beta_1$))

Outline

- Rules
  - **1.** without Data (Mackey & Su, Info. Sys., 2023), Comparison with Other Work
  - with Data
    - **2.** Individual Rules (Mackey et al., TIME 2022)
    - Sets of Rules
      - Acyclic Sets
        - Chase Process

          (Mackey & Su, Info. & Comp., in revision, 2023)
        - **3.** with Aggregation Functions on Time Windows
      - **4.** **Unrestricted Sets (Early Detection is Impossible)**

Early Violation Detection is Impossible for an Arbitrary Set of Rules

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Theorem. Early violation detection for a set of rules is impossible.

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Proof Idea: We introduce *finite satisfiability* for a set of rules,

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- Finite Satisfiability: given a set of rules R, is there a finite event stream that satisfies R?

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Proof Idea: We introduce *finite satisfiability* for a set of rules,

- Finite Satisfiability: given a set of rules R, is there a finite event stream that satisfies R?

which reduces to early violation detection,

Early Violation Detection is Impossible for an Arbitrary Set of Rules

Theorem. Early violation detection for a set of rules is impossible.

Proof Idea: We introduce *finite satisfiability* for a set of rules,

- Finite Satisfiability: given a set of rules R, is there a finite event stream that satisfies R?

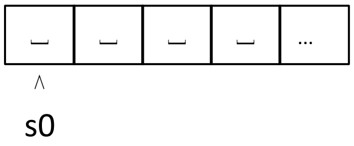
which reduces to early violation detection,

and we show finite satisfiability is undecidable by a reduction from the empty-tape Turing machine halting problem.

Encoding configurations of TM with **Config** events

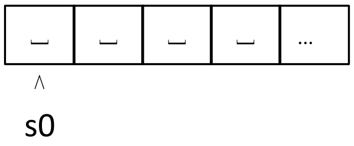
Encoding configurations of TM with **Config** events

configurations



Encoding configurations of TM with **Config** events

configurations



Config(0, #, -)

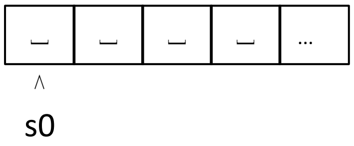
Config(1, ␣, s0)

Config(2, #, -)

Encoding configurations of TM with **Config** events

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-

configurations



Config(0, #, -)

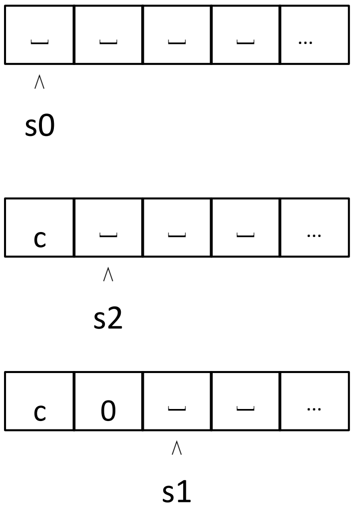
Config(1, ␣, s0)

Config(2, #, -)

Encoding configurations of TM with **Config** events

Config		
index	tape	state
0	#	-
1	⎵	s0
2	#	-

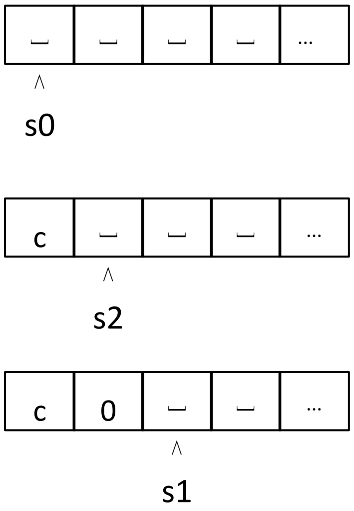
configurations



Encoding configurations of TM with **Config** events

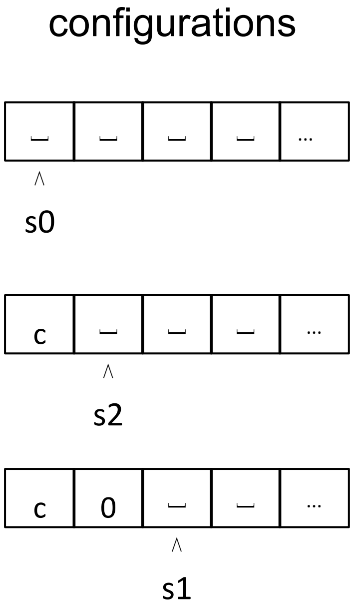
Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
4	␣	s2
5	#	-

configurations



Encoding configurations of TM with **Config** events

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
4	␣	s2
5	#	-
6	c	-
7	0	-
8	␣	s1
9	#	-



Encoding initial empty-tape configuration

Config		
index	tape	state

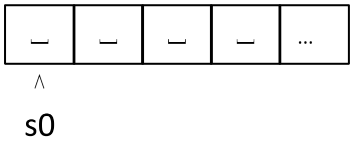
␣	␣	␣	␣	…

^

s0

Encoding initial empty-tape configuration

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-



Encoding initial empty-tape configuration

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-

␣	␣	␣	␣	…

^

s0

If M starts in s0, then R_M has:

true

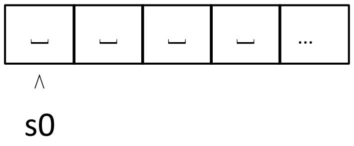
→

Config(0, #, -), Config(1, ␣, s0), Config(2, #, -)

Encoding initial empty-tape configuration

Next	
index	next
0	2
1	3
2	5

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-



If M starts in s0, then R_M has:

true

→

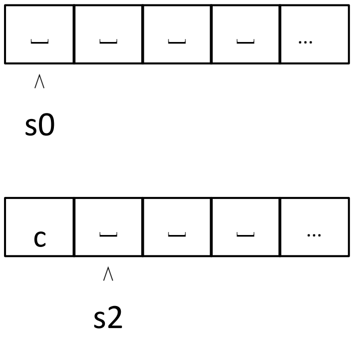
Config(0, #, -), Config(1, ␣, s0), Config(2, #, -)

Next(0, 2), Next(1, 3), Next(2, 5),

Encoding transitions of TM with **Config**, **Next**, and rules

Next	
index	next
0	2
1	3
2	5

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-

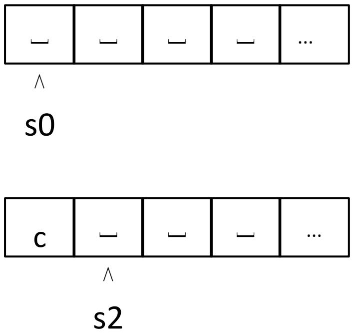


If M has δ(s0, ␣) = (c, s2, R), then R_M has:

Encoding transitions of TM with **Config**, **Next**, and rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
4	␣	s2
5	#	-



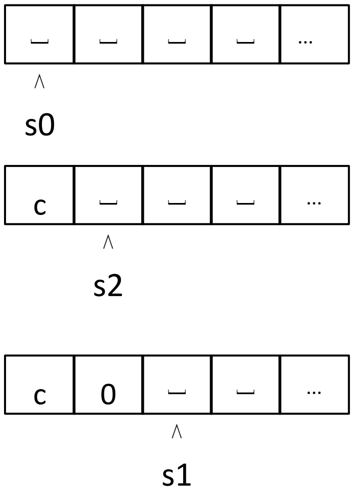
If M has $\boldsymbol{\delta}$(s0, ␣) = (c, s2, R), then R_M has:

Next(x-1, y-1), Config(x-1, #, -), Config(x, ␣, s0),
Config(x+1, #, -)
→
Next(x+2, y+3), Config(y-1, #, -), Config(y, c, -),
Config(y+1, ␣, s2), Config(x+2, #, -)

Encoding transitions of TM with **Config**, **Next**, and rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	13

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
4	␣	s2
5	#	-
6	c	-
7	0	-
8	␣	s1
9	#	-



If M has δ(s2, ␣) = (0, s1, R), then R_M has:

Next(x-1, y-1), Config(x-1, #, -), Config(x, ␣, s2), Config(x+1, #, -)

→

Next(x+2, y+3), Config(y-1, #, -), Config(y, 0, -), Config(y+1, ␣, s1), Config(x+2, #, -)

Detect non-valid computations with **Error** rules

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Error
x

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Error
x
0

Don't allow malformed configurations:

Config(x, a, s), Config(x, b, s'), a ≠ b

→

Error(0)

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Error
x
0

Don't allow malformed configurations:

Config(x, a, s), Config(x, b, s'), a ≠ b

→

Error(0)

Propagate Errors infinitely:

Error(x)

→

Error(x+1)

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Error
x
0
1
2
3
...

Don't allow malformed configurations:

Config(x, a, s), Config(x, b, s'), a ≠ b

→

Error(0)

Propagate Errors infinitely:

Error(x)

→

Error(x+1)

Detect non-valid computations with **Error** rules

Next	
index	next
0	2
1	3
2	5
3	6
4	7
5	9
6	10
7	11
8	12
9	14

Config		
index	tape	state
0	#	-
1	␣	s0
2	#	-
3	c	-
3	␣	s2
4	␣	-
5	#	-
6	c	-
7	0	-
8	␣	s1

Error
x
0
1
2
3
...

Don't allow malformed configurations:

Config(x, a, s), Config(x, b, s'), a ≠ b

→

Error(0)

Propagate Errors infinitely:

Error(x)

→

Error(x+1)

For a Turing machine M, the set R_M is finitely satisfiable *iff* M halts on empty tape.

Outline

Rules

1. without Data (Mackey & Su, Info. Sys., 2023), Comparison with Other Work

with Data

2. Individual Rules (Mackey et al., TIME 2022)

Sets of Rules

Acyclic Sets

Chase Process

(Mackey & Su, Info. & Comp., in revision, 2023)

3. with Aggregation Functions on Time Windows

4. Unrestricted Sets (Early Detection is Impossible)

Thesis Organization

- Rules
  - Chapter 3. without Data (Mackey & Su, Info. Sys., 2023), Comparison with Other Work
  - with Data
    - Chapter 4. Individual Rules (Mackey et al., TIME 2022)
    - Sets of Rules
      - Acyclic Sets
        - Chase Process (Mackey & Su, Info. & Comp., in revision, 2023)
        - Chapter 5. with Aggregation Functions on Time Windows
      - Chapter 6. Unrestricted Sets (Early Detection is Impossible)

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Future Directions

- Can violations of more complex time constraints be detected early?
- Do richer sets of rules have (efficient) algorithms, e.g., negation, disjunction?

Thank you! Questions?