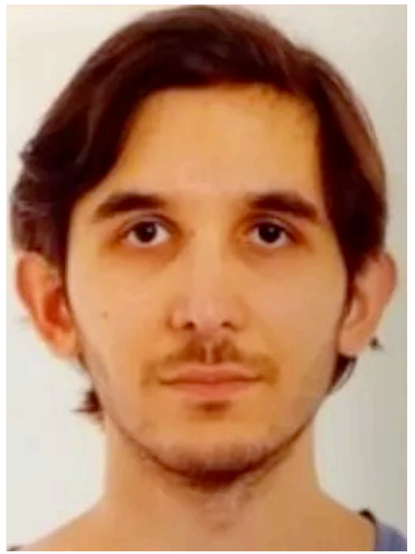
Timestamping through a Data-Structure Lens

Umang Mathur

Joint Work with Awesome Collaborators






A Tree Clock Data Structure for Causal Orderings in Concurrent Executions

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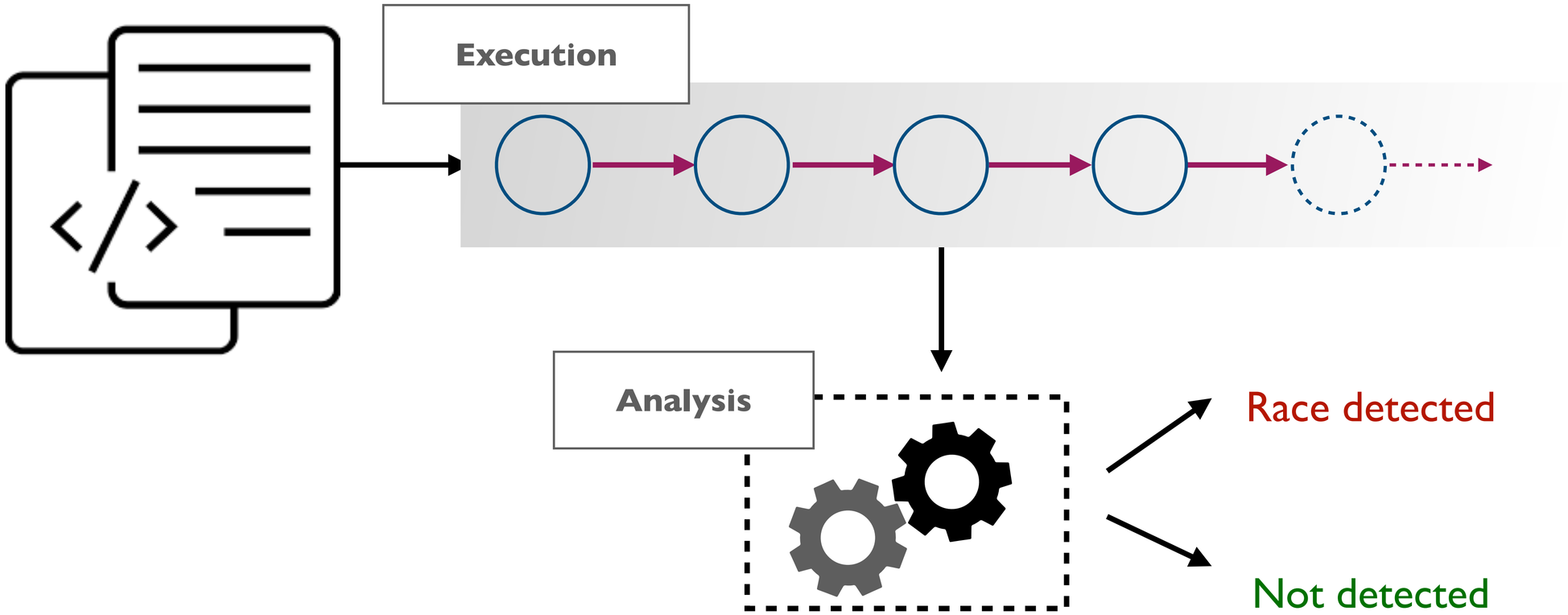
What do I do?



Dynamic Analysis for Detecting Concurrency Bugs

Causality in Concurrent Computations

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Are two given events causally related?

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> **Causality—determining which event happens before what others—is vital in distributed computations.**

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Distributed Storage (Dynamo)

Debugging and Visualization

Program Analysis for Bugs Detection

Happens-Before for Capturing Causality

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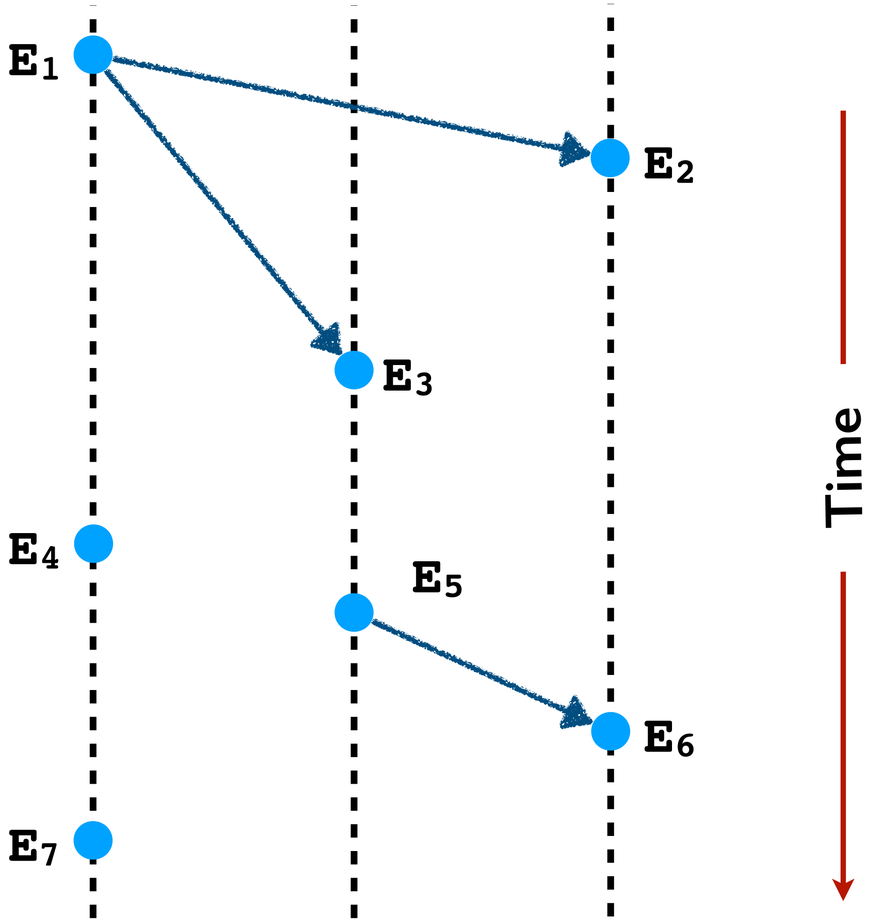
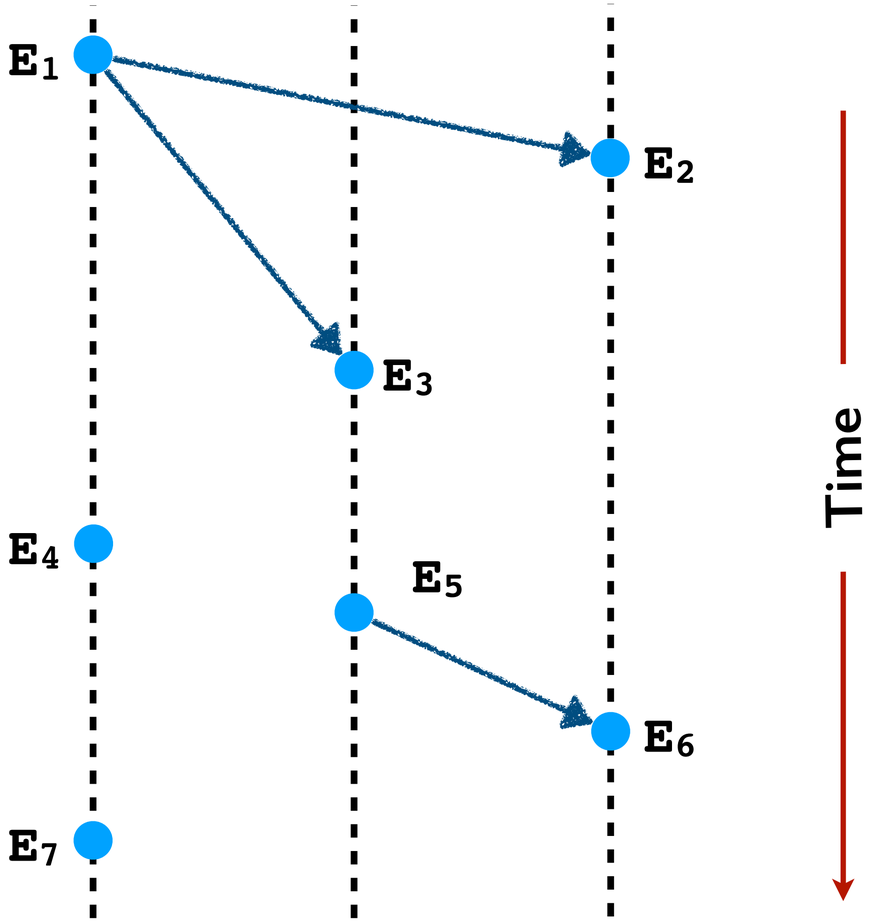
Are two given events causally related?



Happens-Before for Capturing Causality

Are two given events causally related?

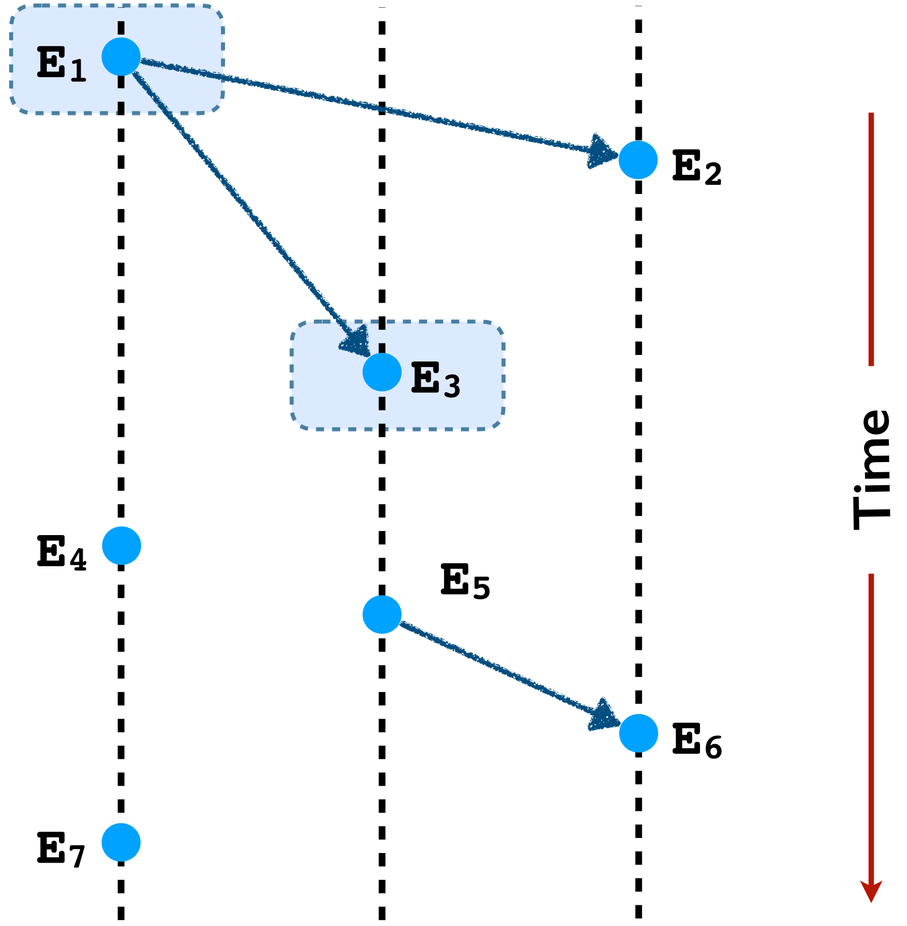
- Happens-before ($<_{HB}$) *partial order* on events
- $E_i <_{HB} E_j$ ("E_i happens before E_j") if
  - E_i and E_j are in the same process
  - E_j receives the message that E_i sends
  - transitively ($E_i <_{HB} E_k$ and $E_k <_{HB} E_j$)



Happens-Before for Capturing Causality

Are two given events causally related?

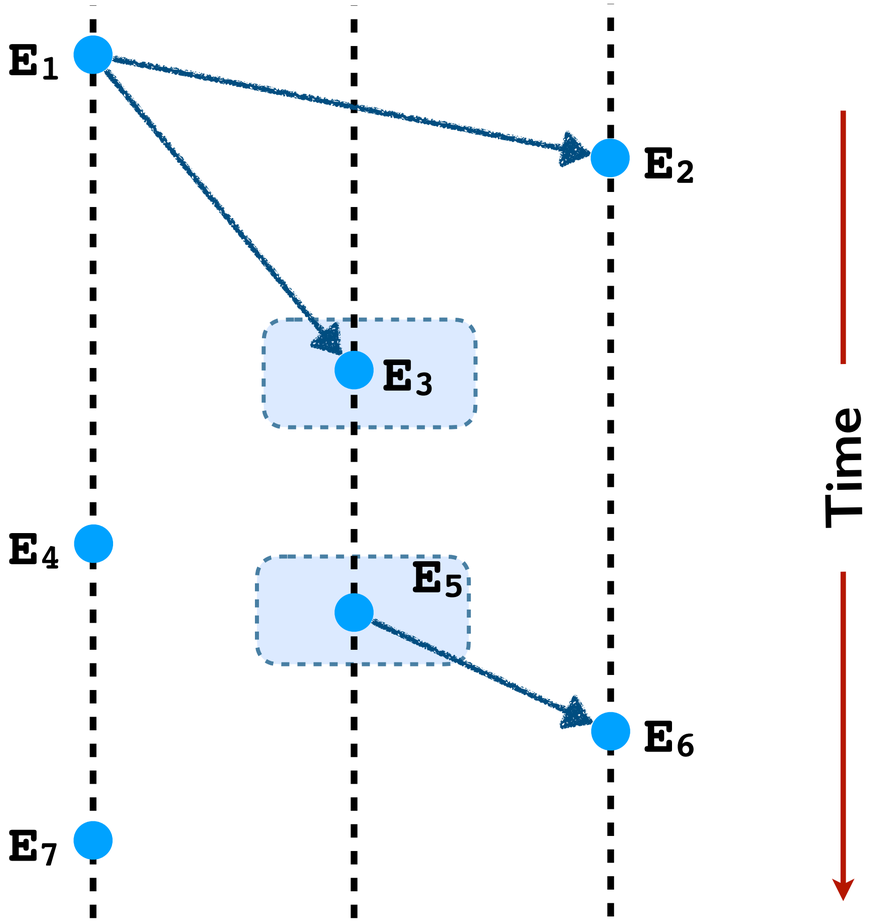
- $E_1 <_{HB} E_3$ (send-receive)



Happens-Before for Capturing Causality

Are two given events causally related?

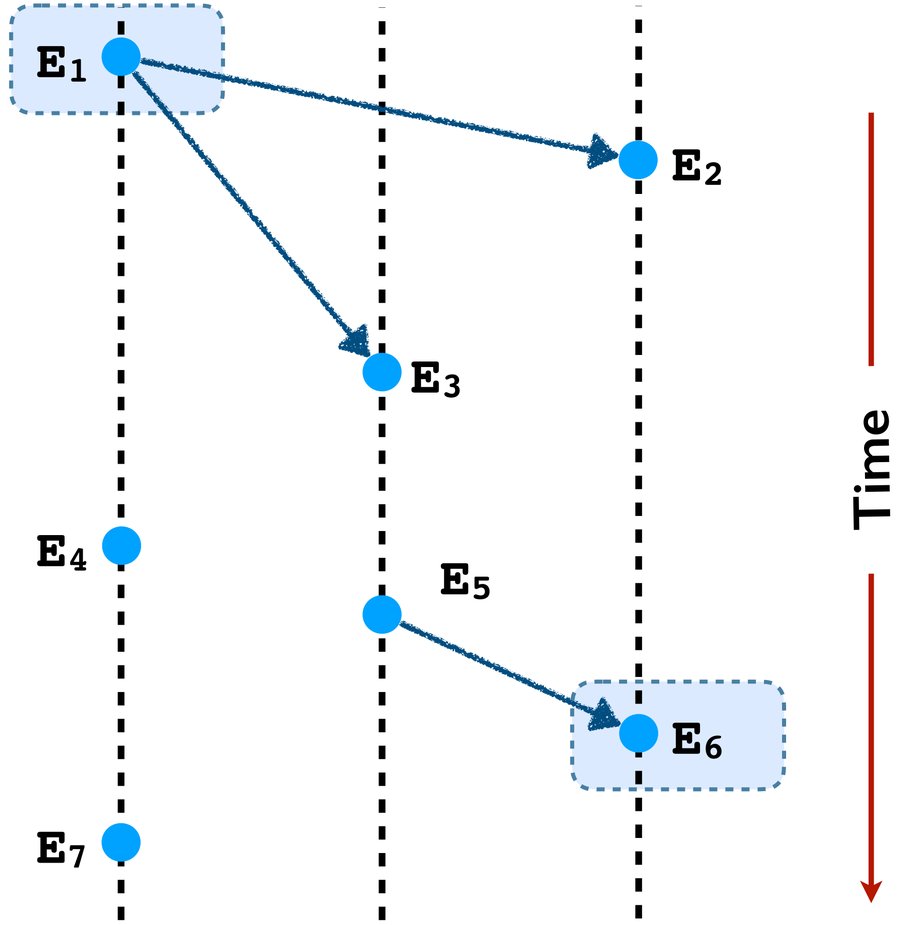
- $E_1 <_{HB} E_3$ (send-receive)
- $E_3 <_{HB} E_5$ (same process)



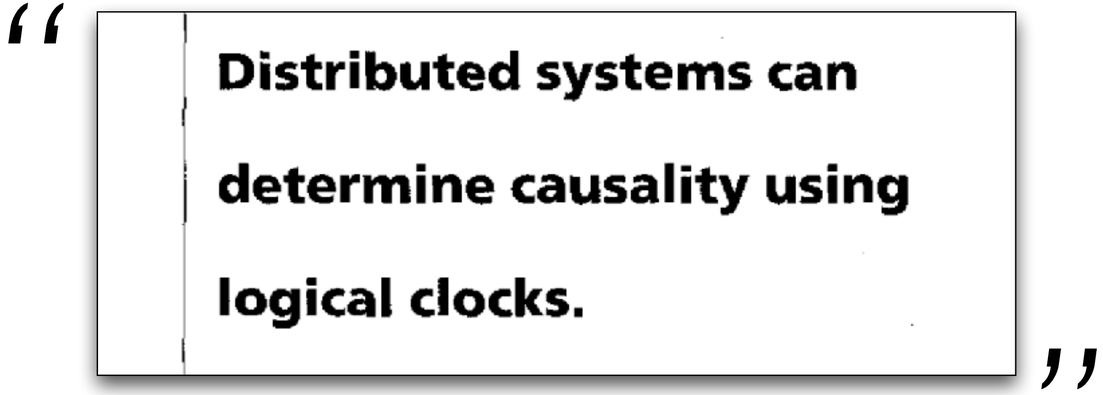
Happens-Before for Capturing Causality

Are two given events causally related?

- $E_1 <_{HB} E_3$ (send-receive)
- $E_3 <_{HB} E_5$ (same process)
- $E_1 <_{HB} E_6$ (transitivity)



Logical Timestamps



Logical Timestamps

Timestamp of event E

V_E : Processes → $\mathbb{N}$

- $V_E(p)$ = Number of events of process p that E *"knows"* about

"

> **Distributed systems can determine causality using logical clocks.**

"

Logical Timestamps

Timestamp of event E

V_E : Processes → $\mathbb{N}$

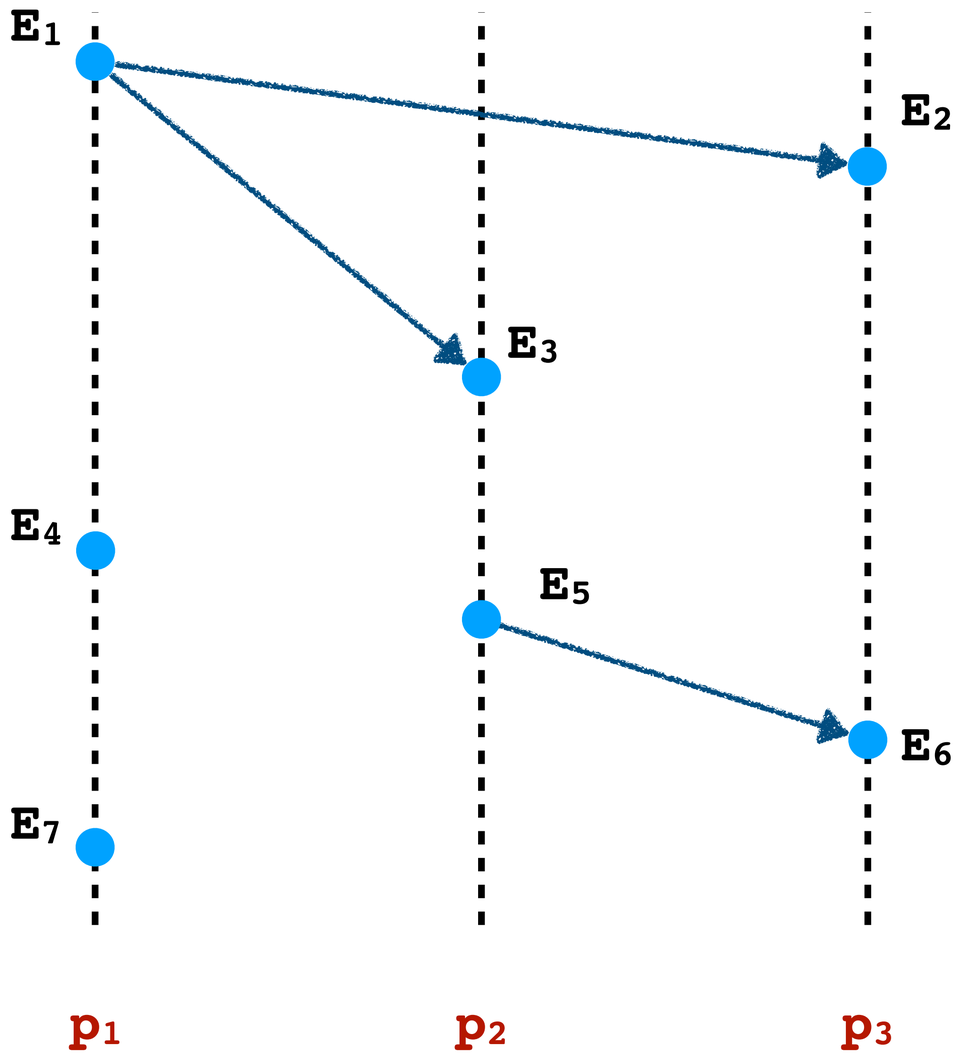
- $V_E(p)$ = Number of events of process p that E *"knows"* about

For all p,
$V_{E1}(p) \leq V_{E2}(p)$

$E1 \leq_{HB} E2$ iff $V_{E1} \sqsubseteq V_{E2}$

Computing Timestamps

- For every process p, maintain V_p



Computing Timestamps

- For every process p, maintain V_p
- Initially:
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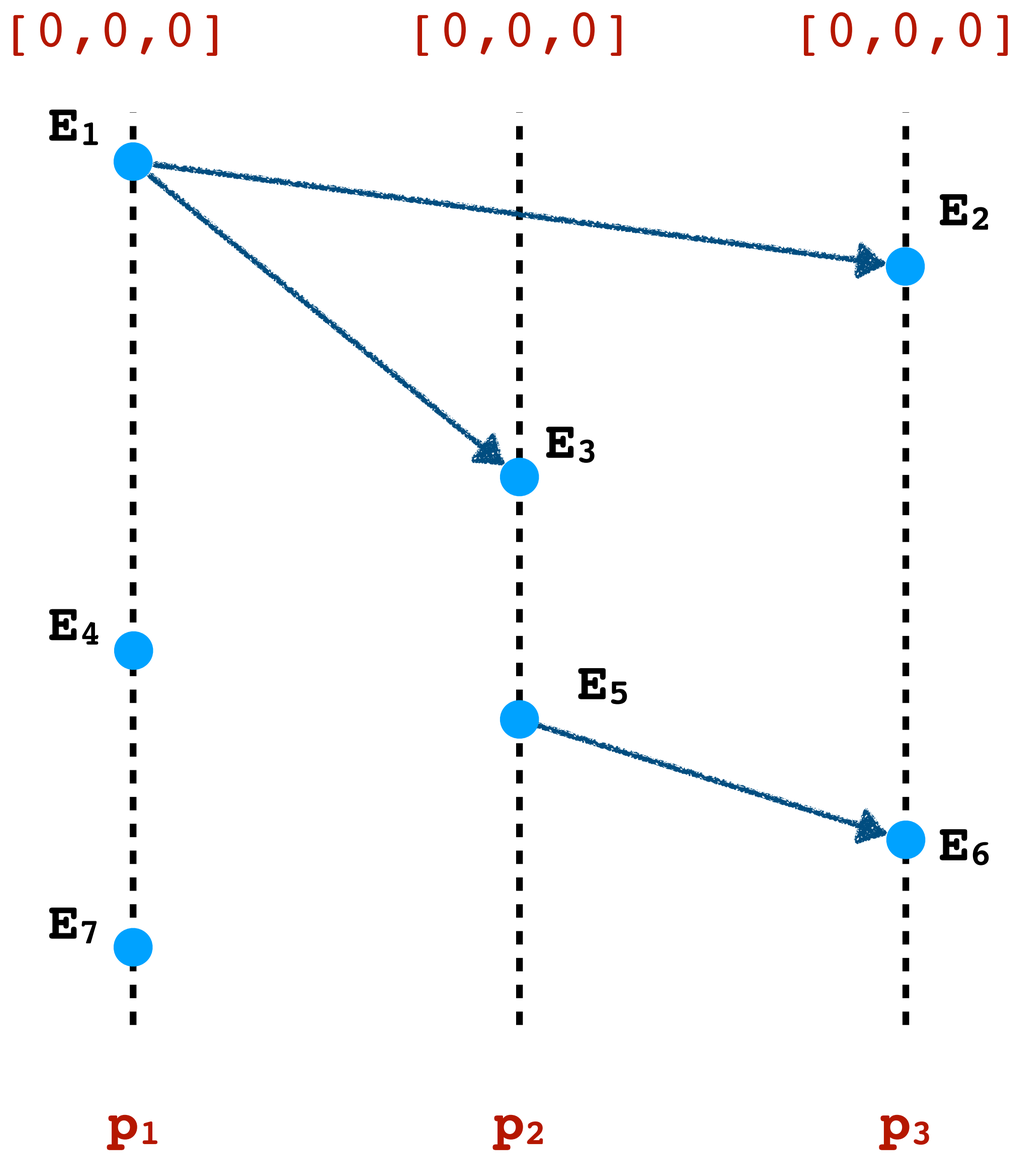

Computing Timestamps

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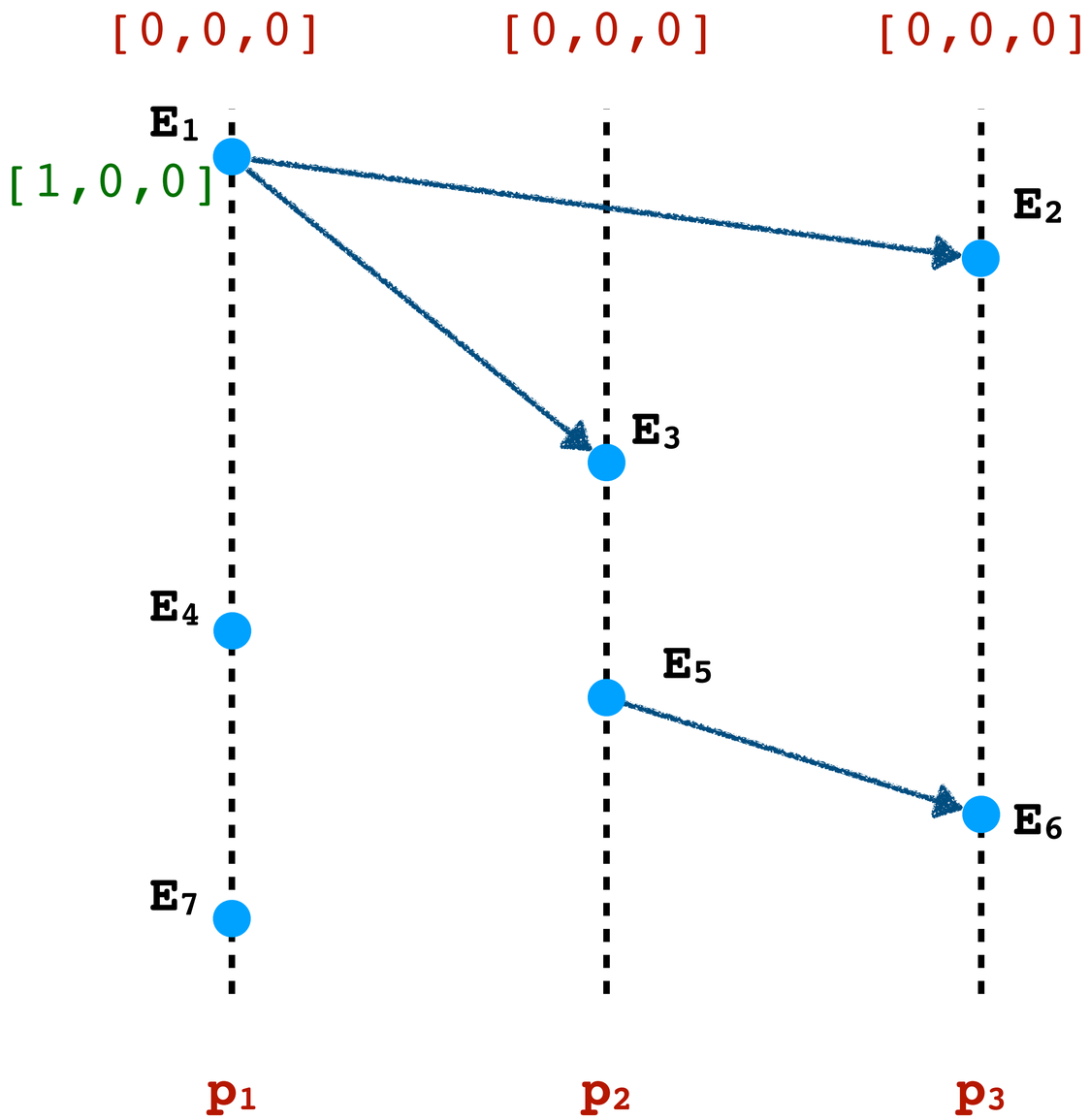

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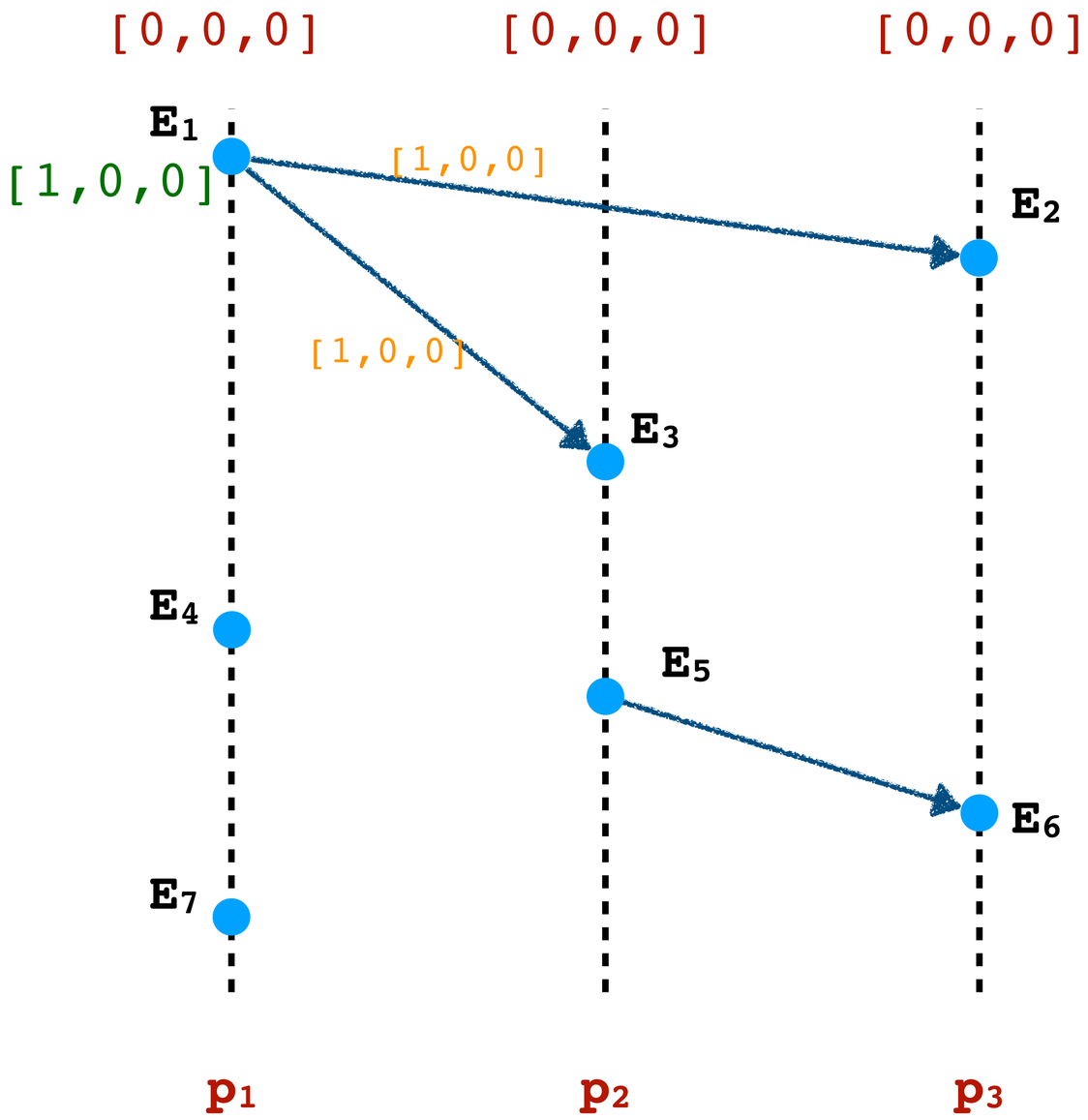

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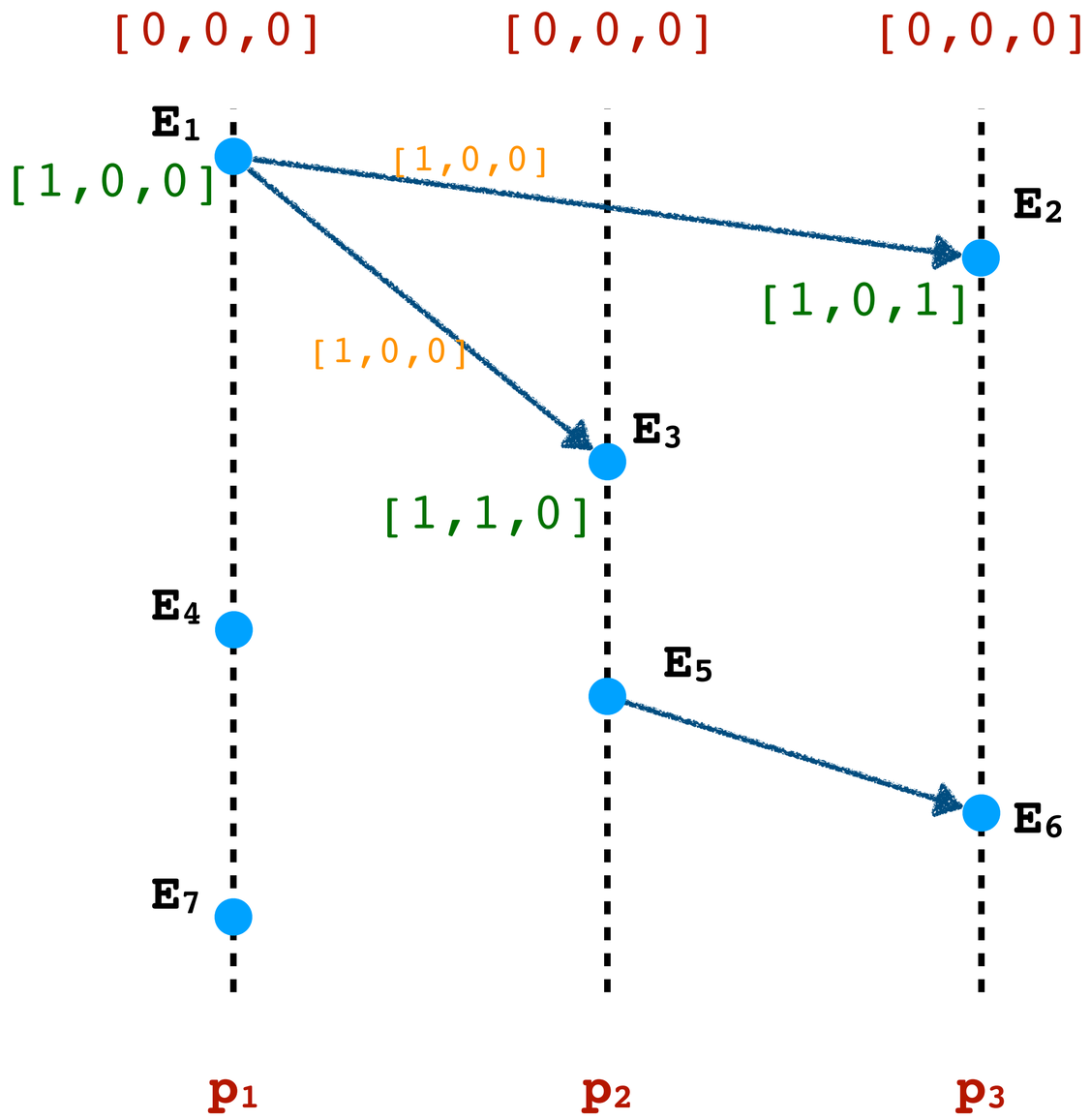
- At a receive (of message m) event in p:
  - *merge* the timestamp of m
  - $V_p \leftarrow V_p \sqcup V_m$

Point-wise maximum or "Join"



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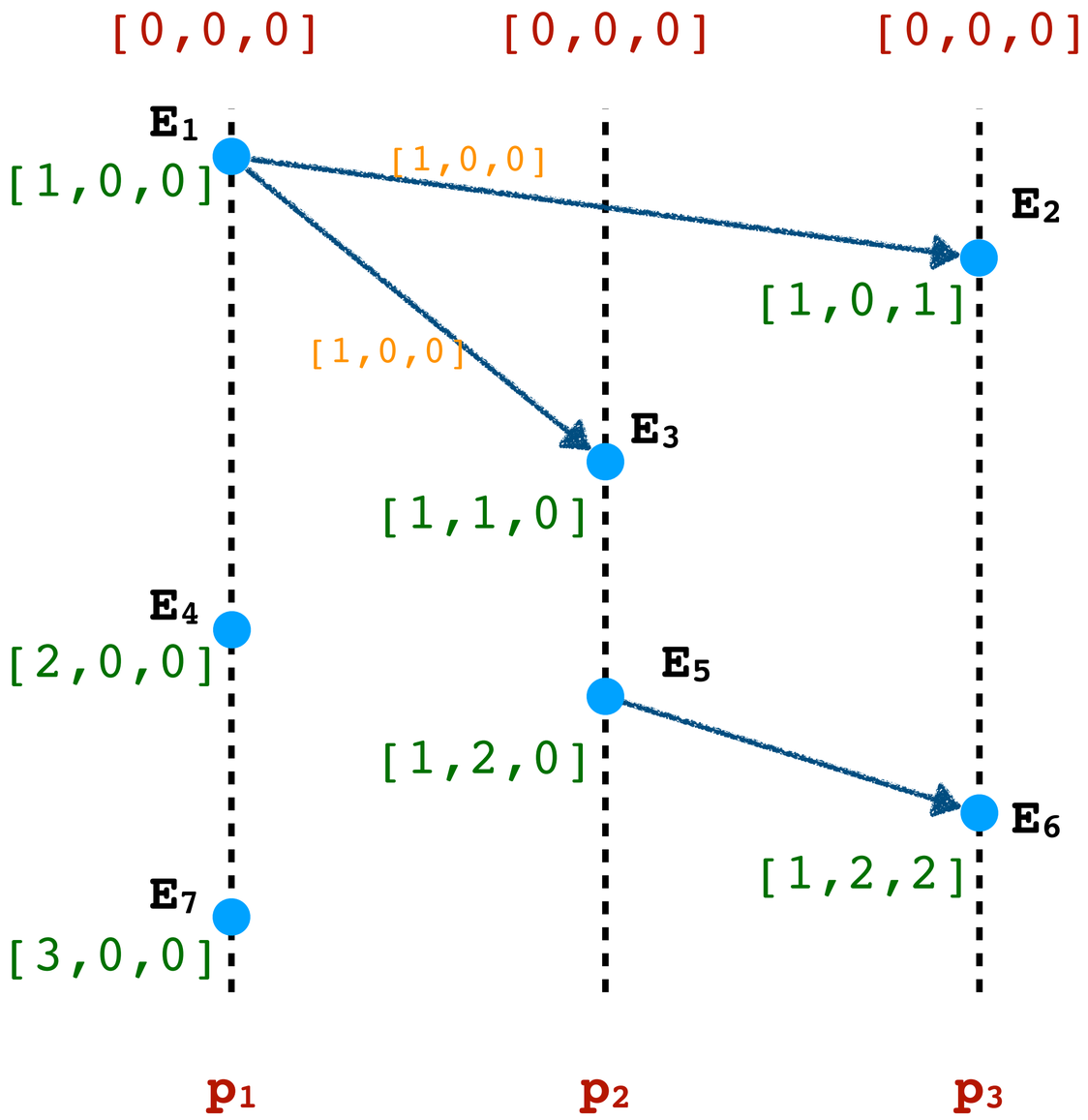

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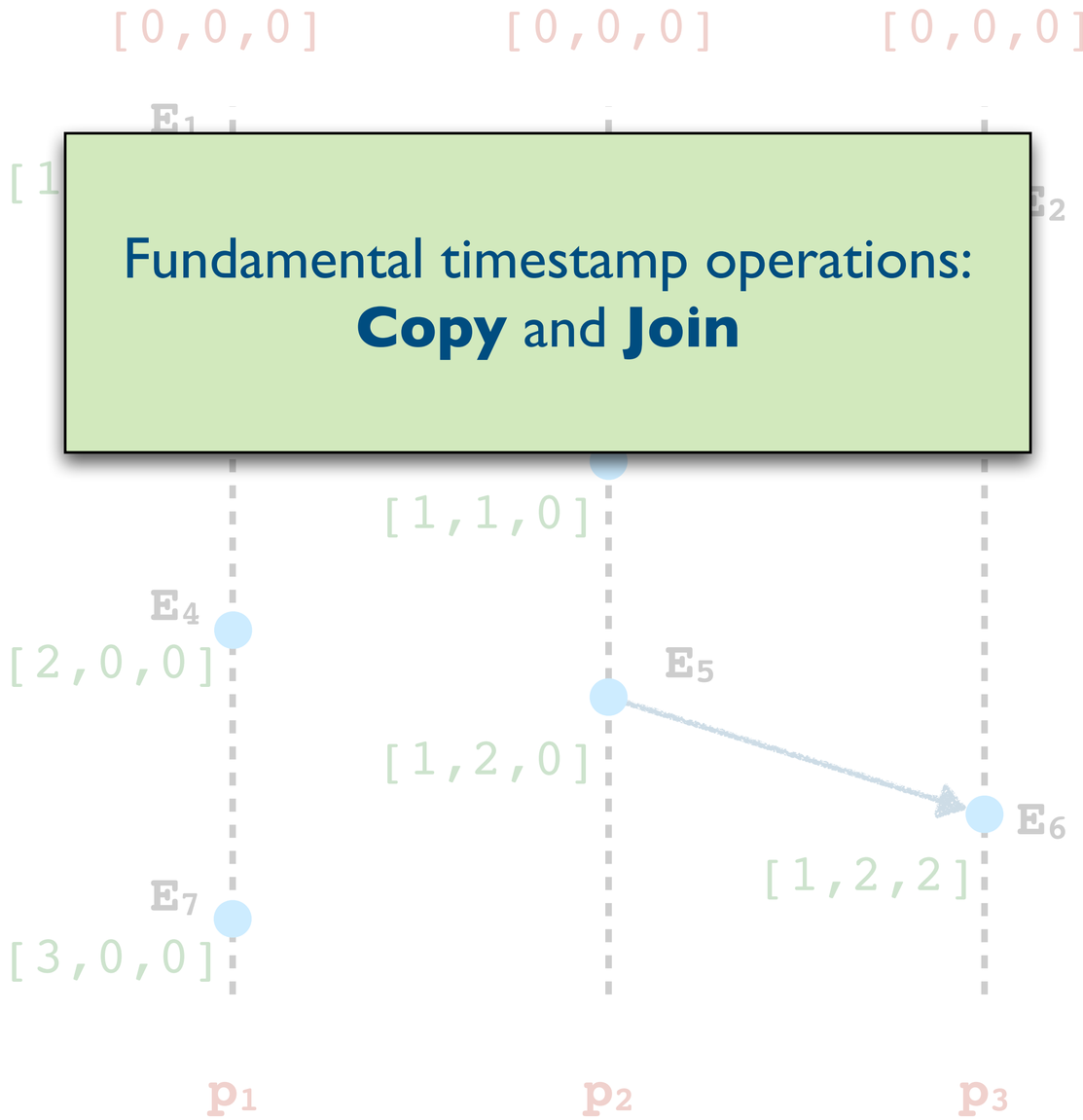
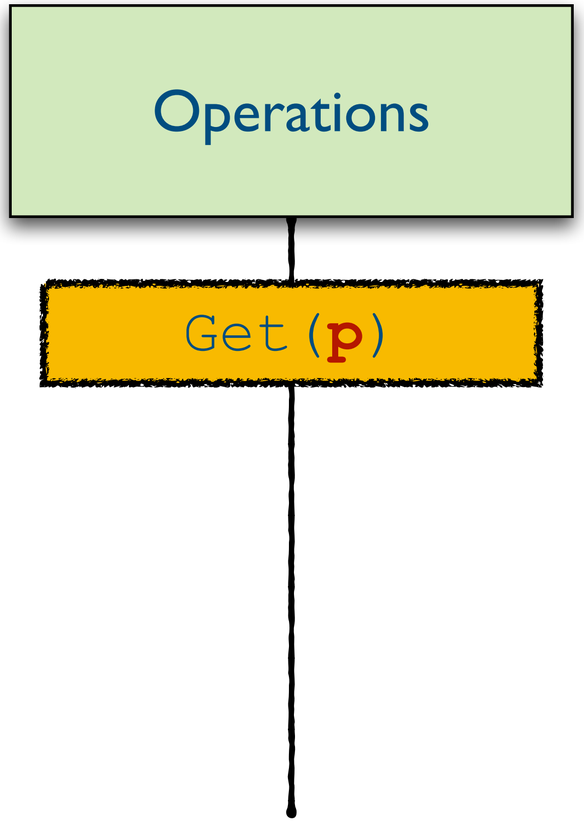
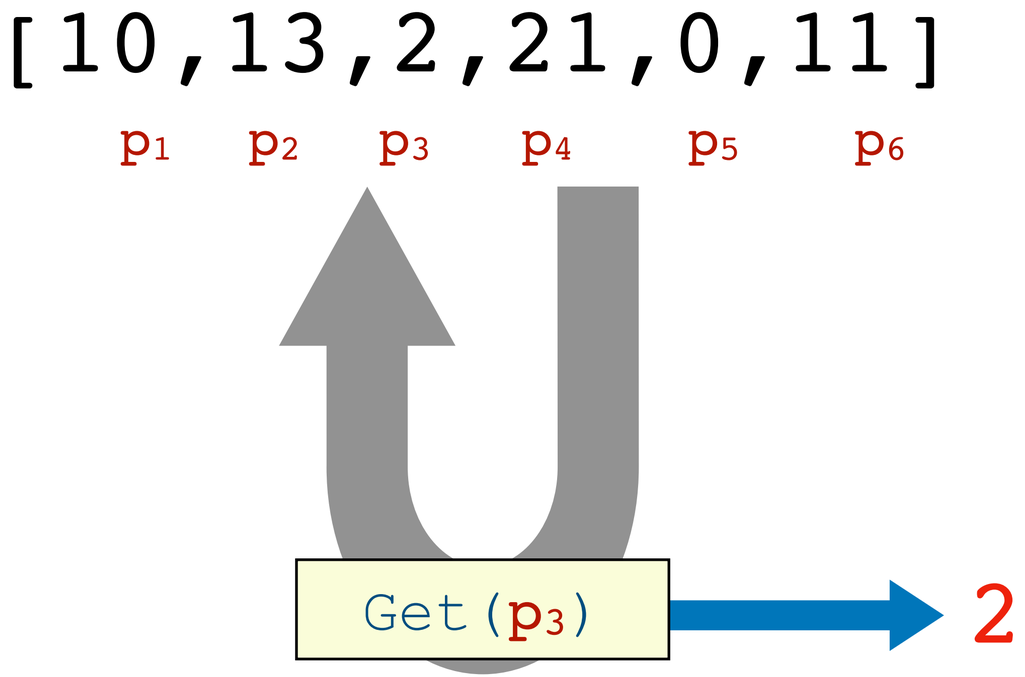


Fundamental timestamp operations:
Copy and **Join**

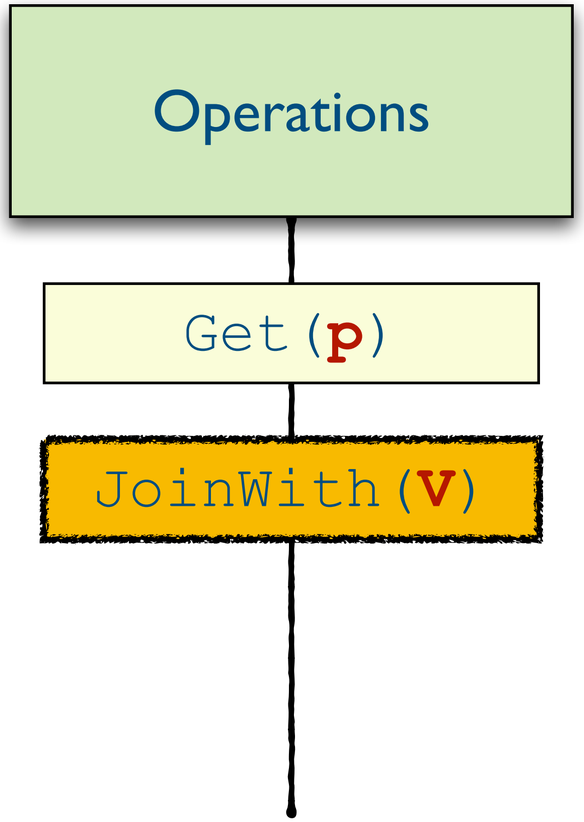
Data Structure for Timestamping

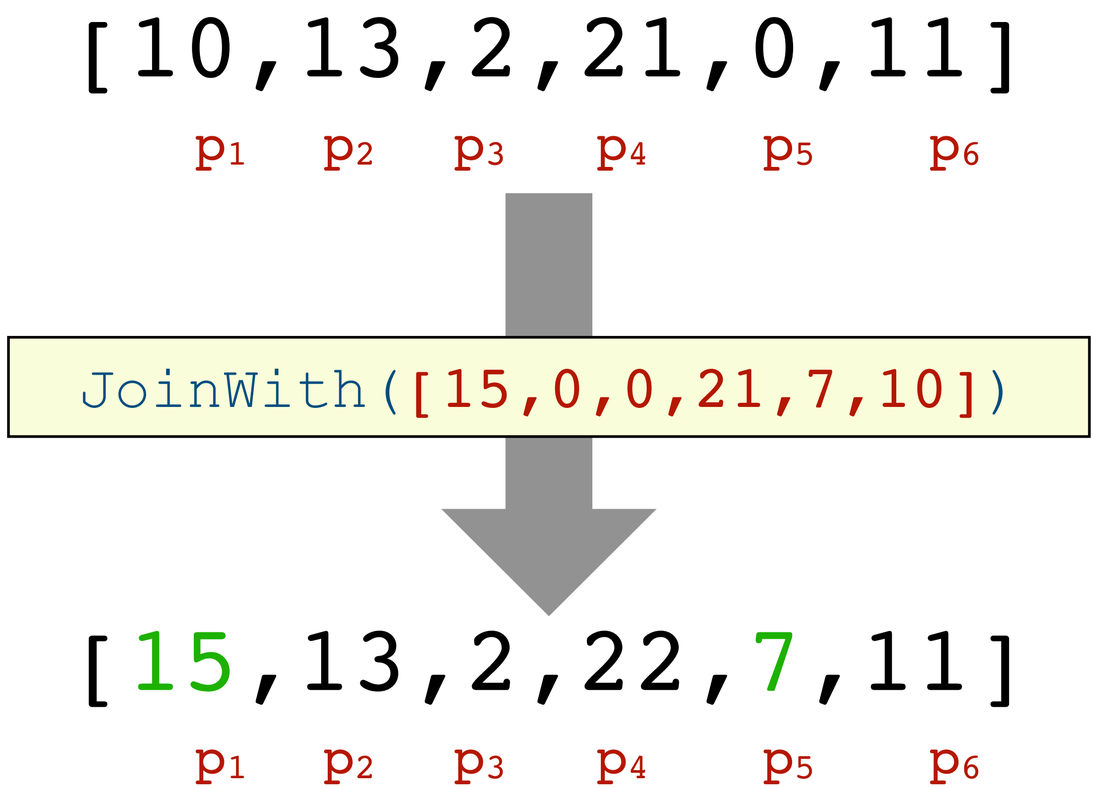
Data Structure for Timestamping





Data Structure for Timestamping





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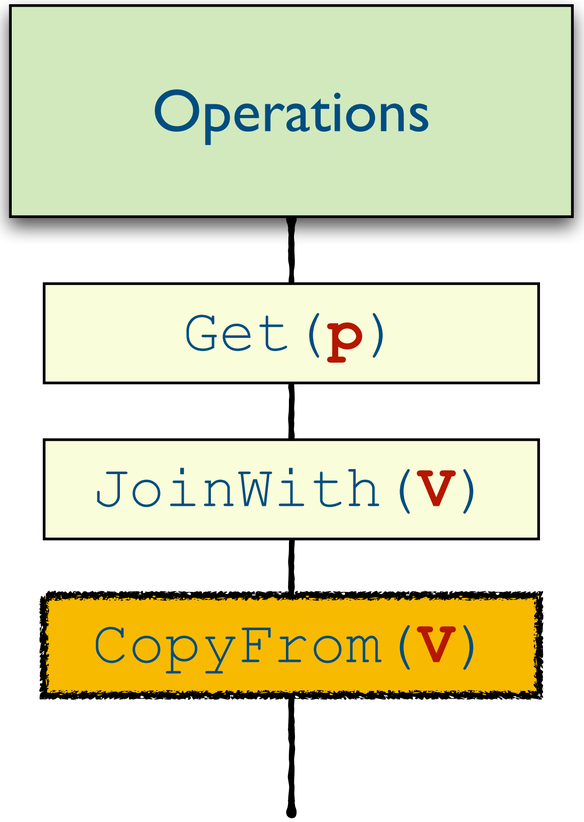

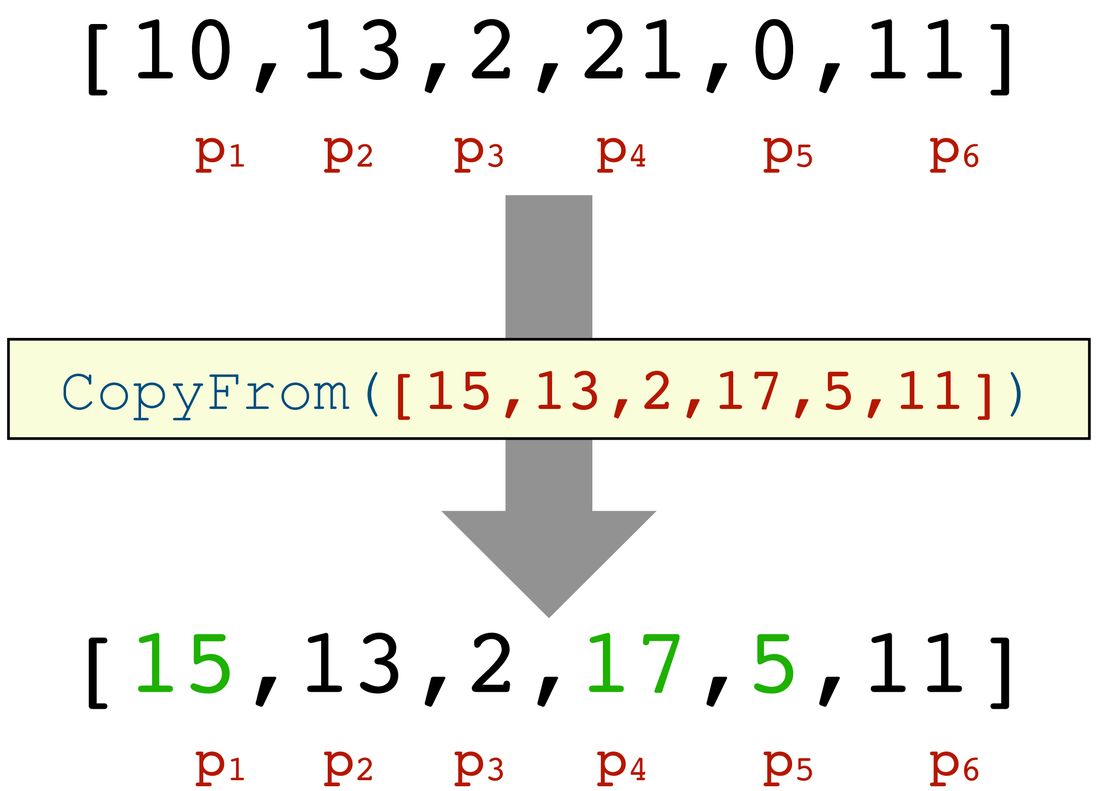

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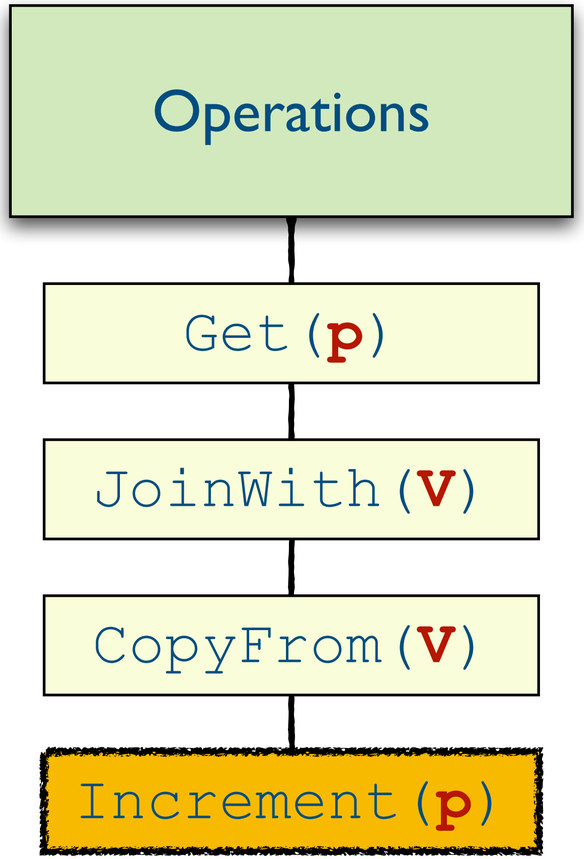

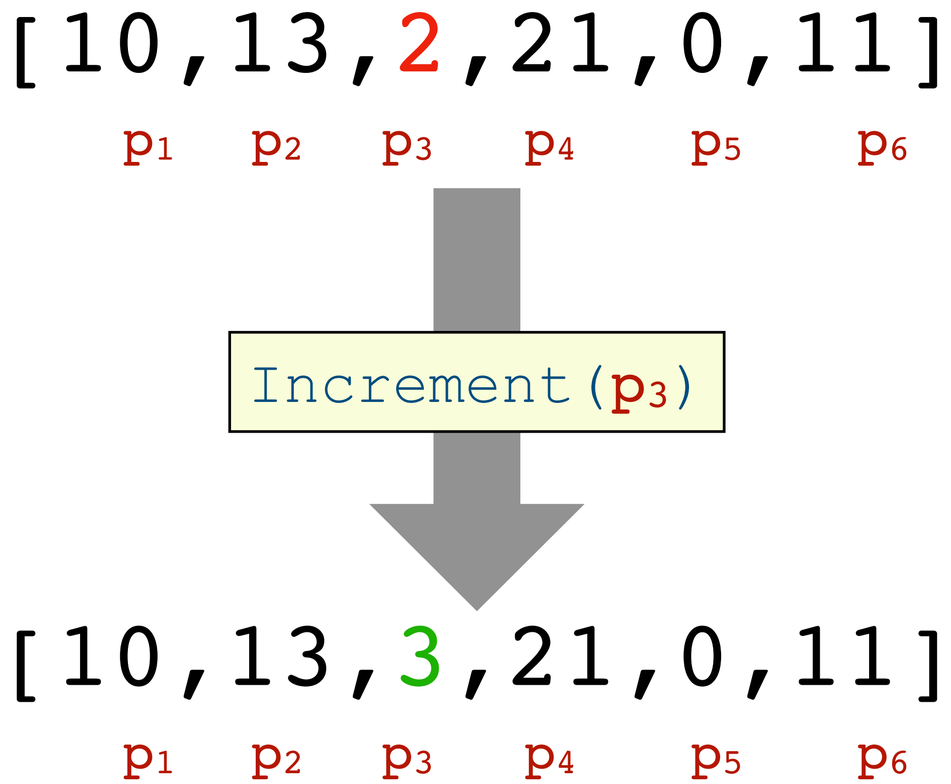

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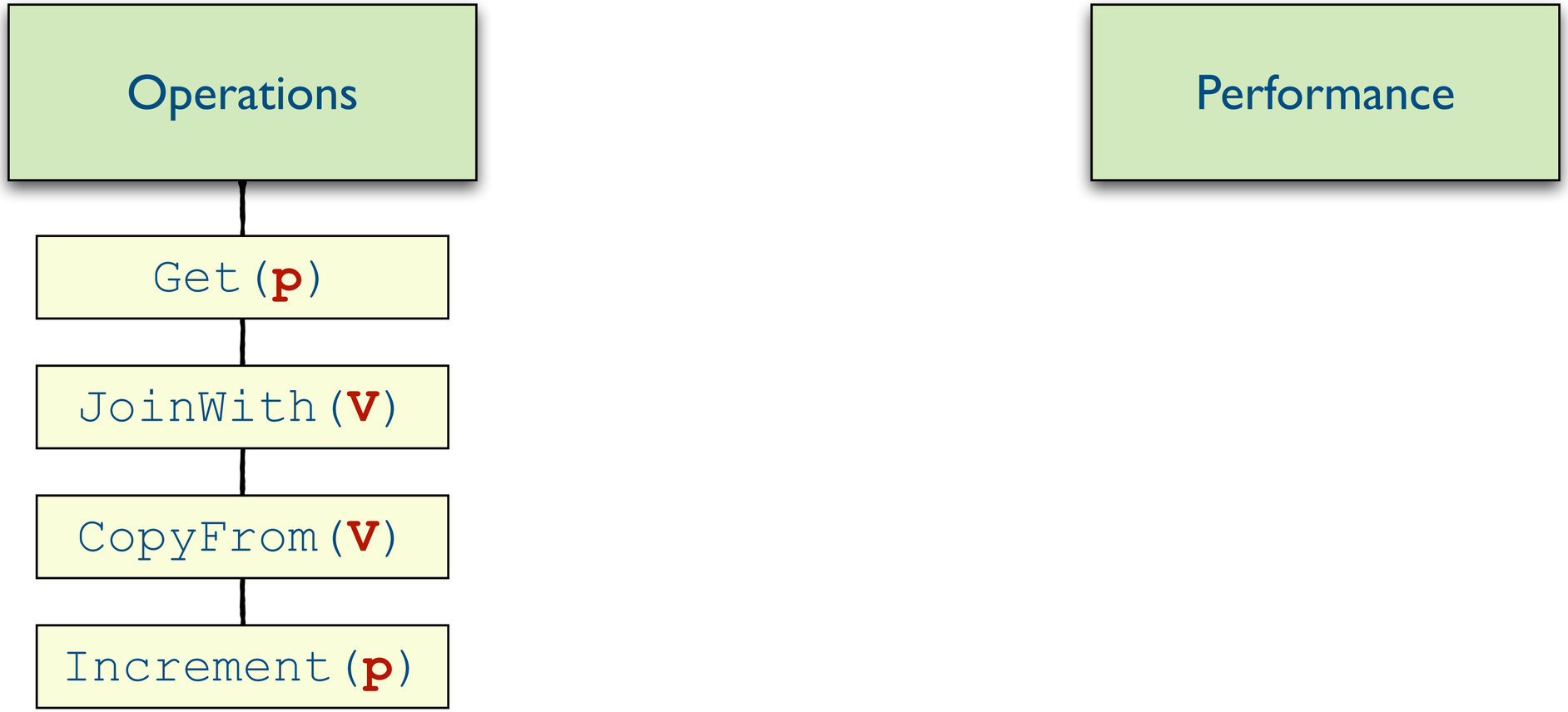

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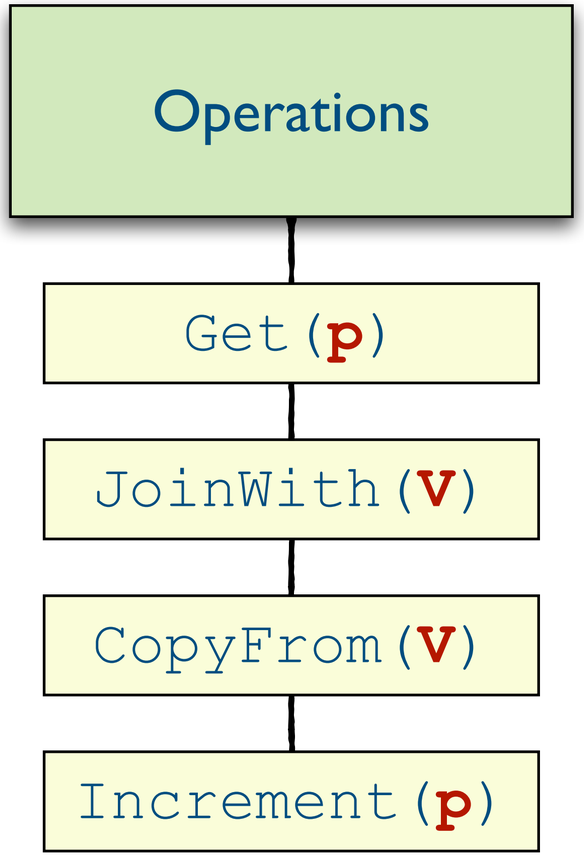

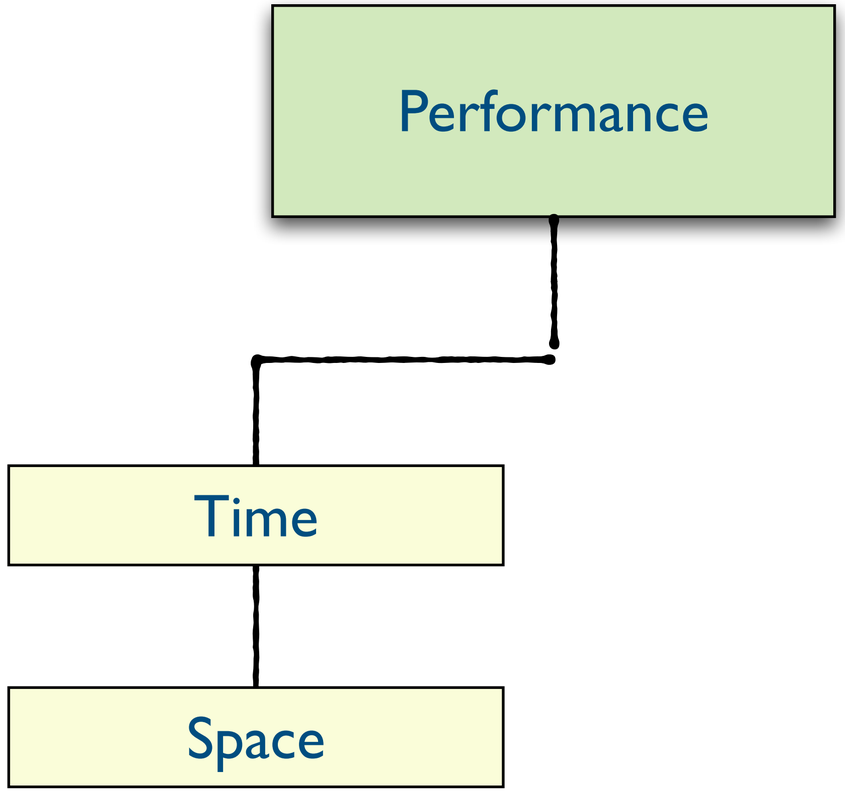

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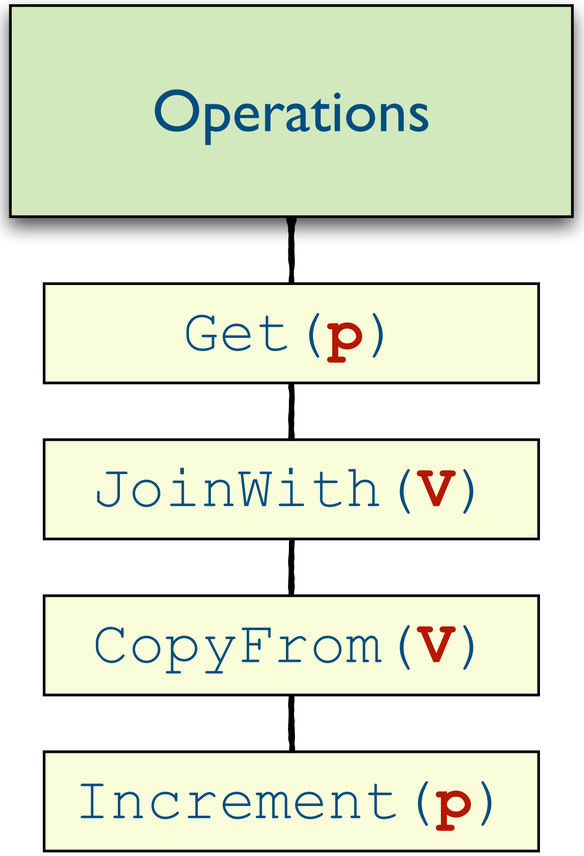
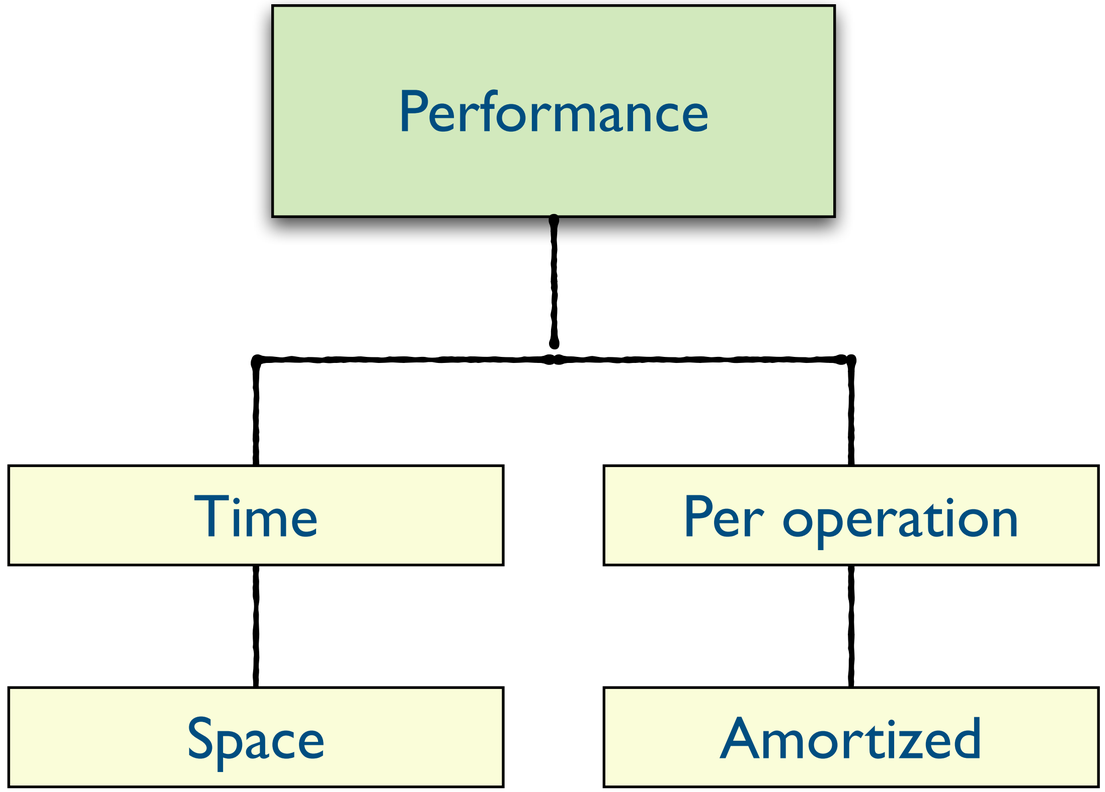
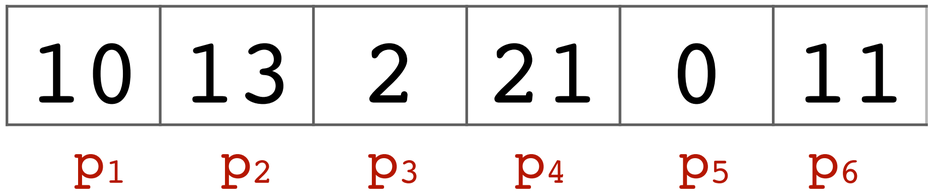




Vector Clock

Vector Clock

Flat array/map, indexed by process ids



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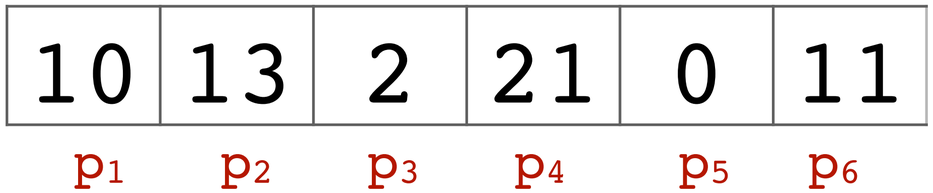

V1.JoinWith(**V2**)

```
for each process p:
    if V1.Get(p) < V2.Get(p):
        V1.p := V2.Get(p)
```

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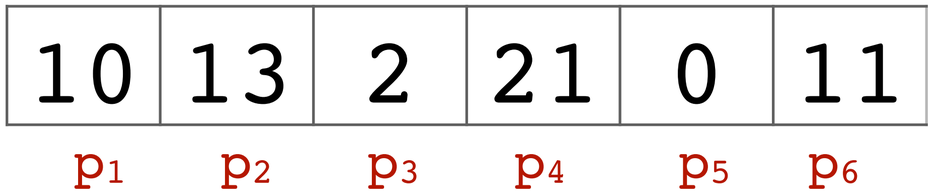

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for each process p:
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V1.CopyFrom(**V2**)

```
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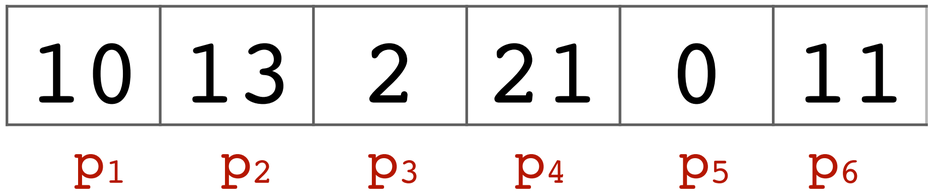
```

Vector Clock

Flat array/map, indexed by process ids



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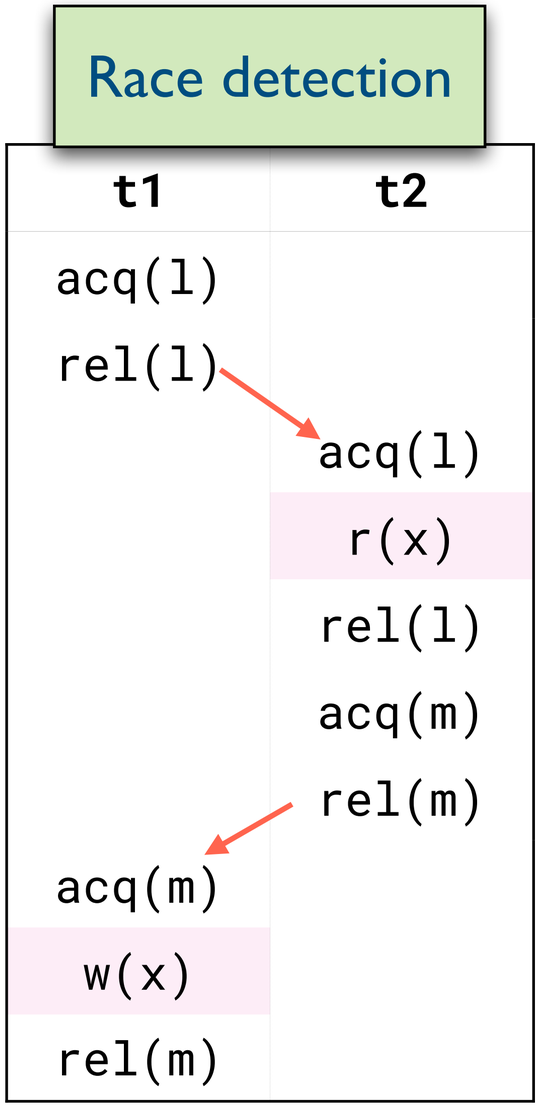
```

Both **Join** and **Copy** take Θ(|Processes|) time for Vector Clocks

Vector Clock Overhead

Vector Clock Overhead



Vector Clock Overhead

- For every thread `t`, maintain vector clock V_t
- For every lock `lk`, maintain vector clock V_{lk}

```
procedure acq(t, lk)
    Vt.JoinWith(Vlk)

procedure rel(t, lk)
    Vlk.CopyFrom(Vt)
```

Race detection

t1	t2
acq(l)	
rel(l)	
	acq(l)
	r(x)
	rel(l)
	acq(m)
	rel(m)
acq(m)	
w(x)	
rel(m)	

Vector Clock Overhead

Total overhead = Θ(|Processes| * Number of Events)

- Typically, ~10 billion events and ~100 processes
- Immense slowdown when detecting data races

Can we do better?

How can we do better?

Sub-linear time in **join** and **copy**?

How can we do better?

Sub-linear time in **join** and **copy**?

Skip looking at some entries

We *may* be able to do better!

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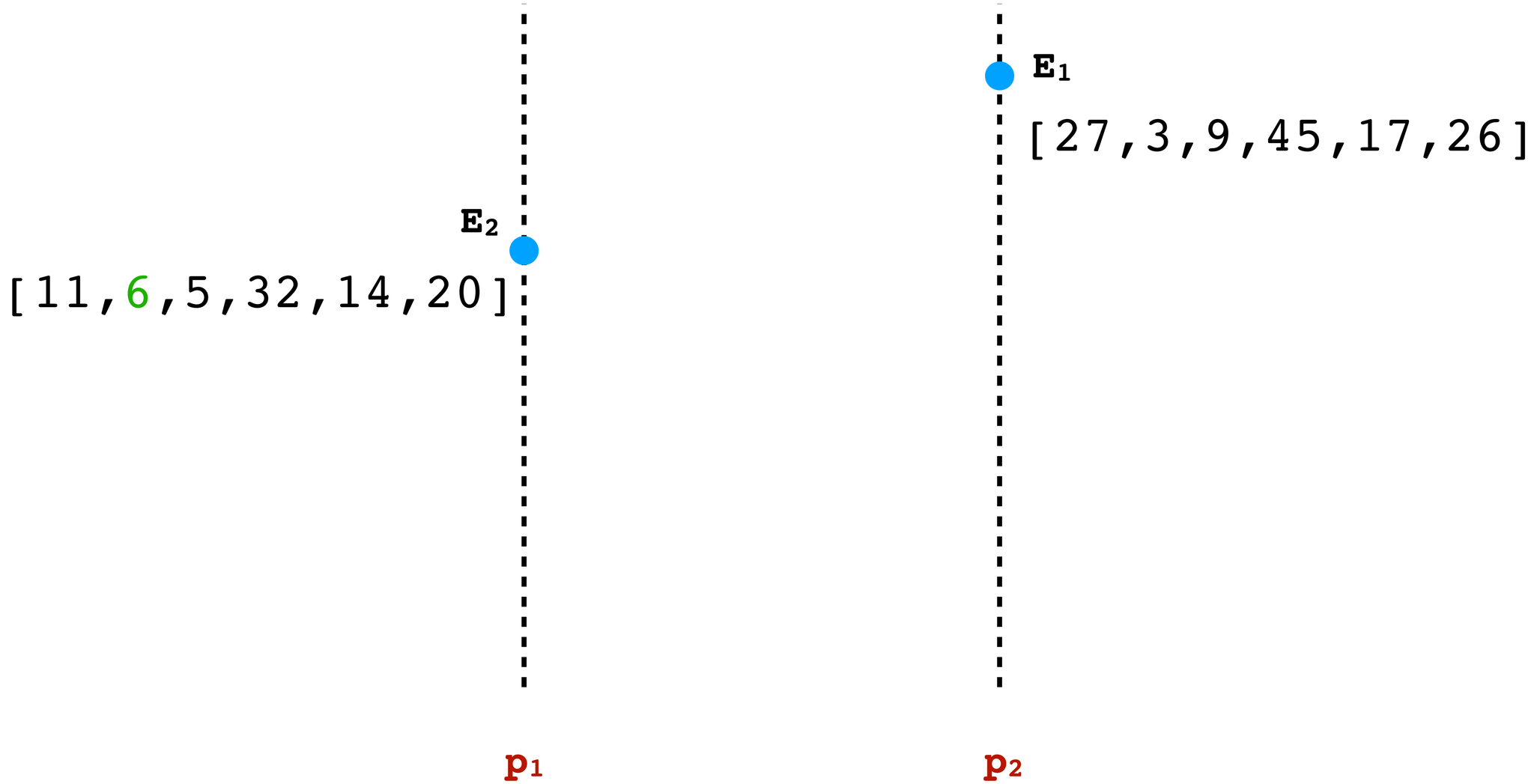

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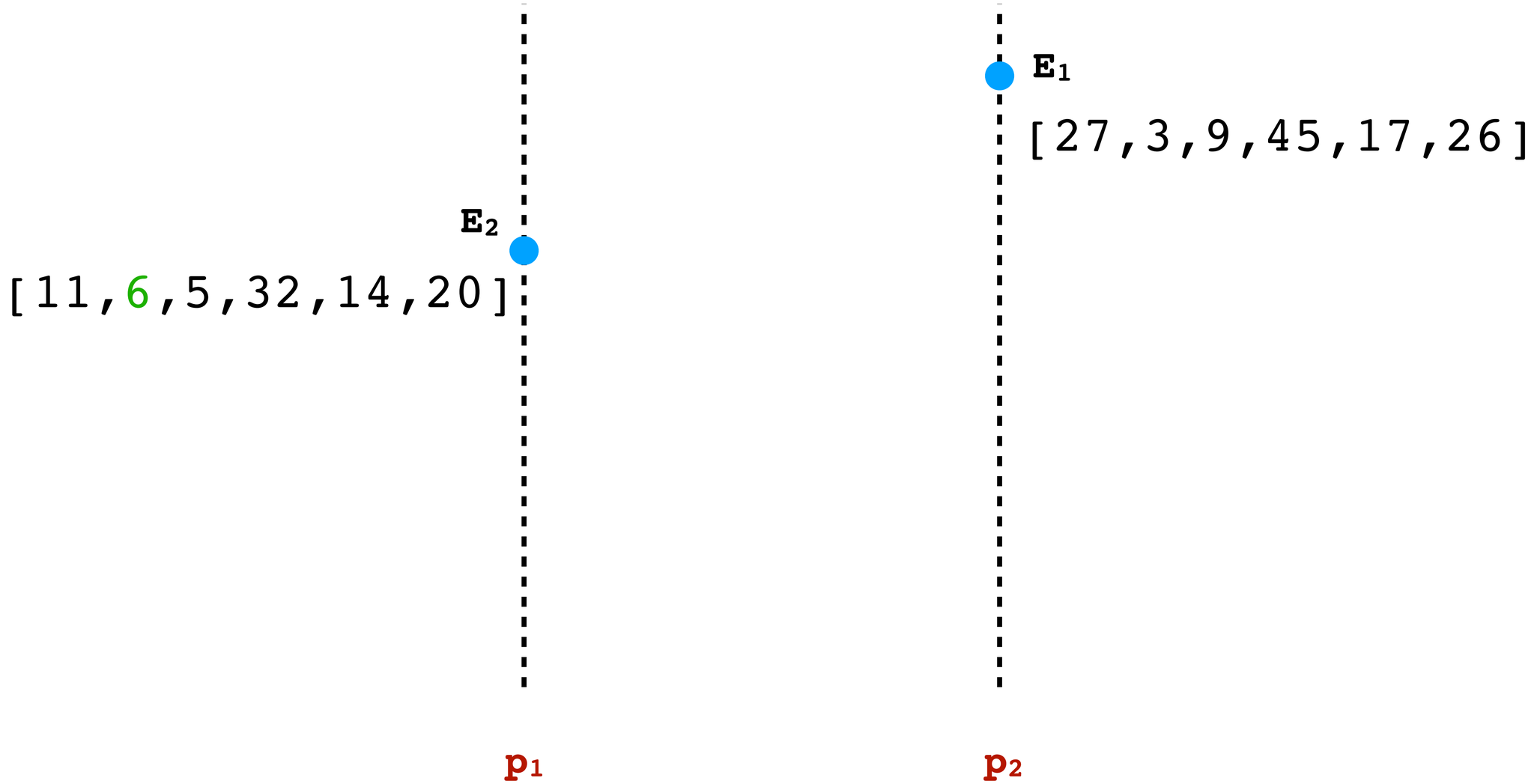

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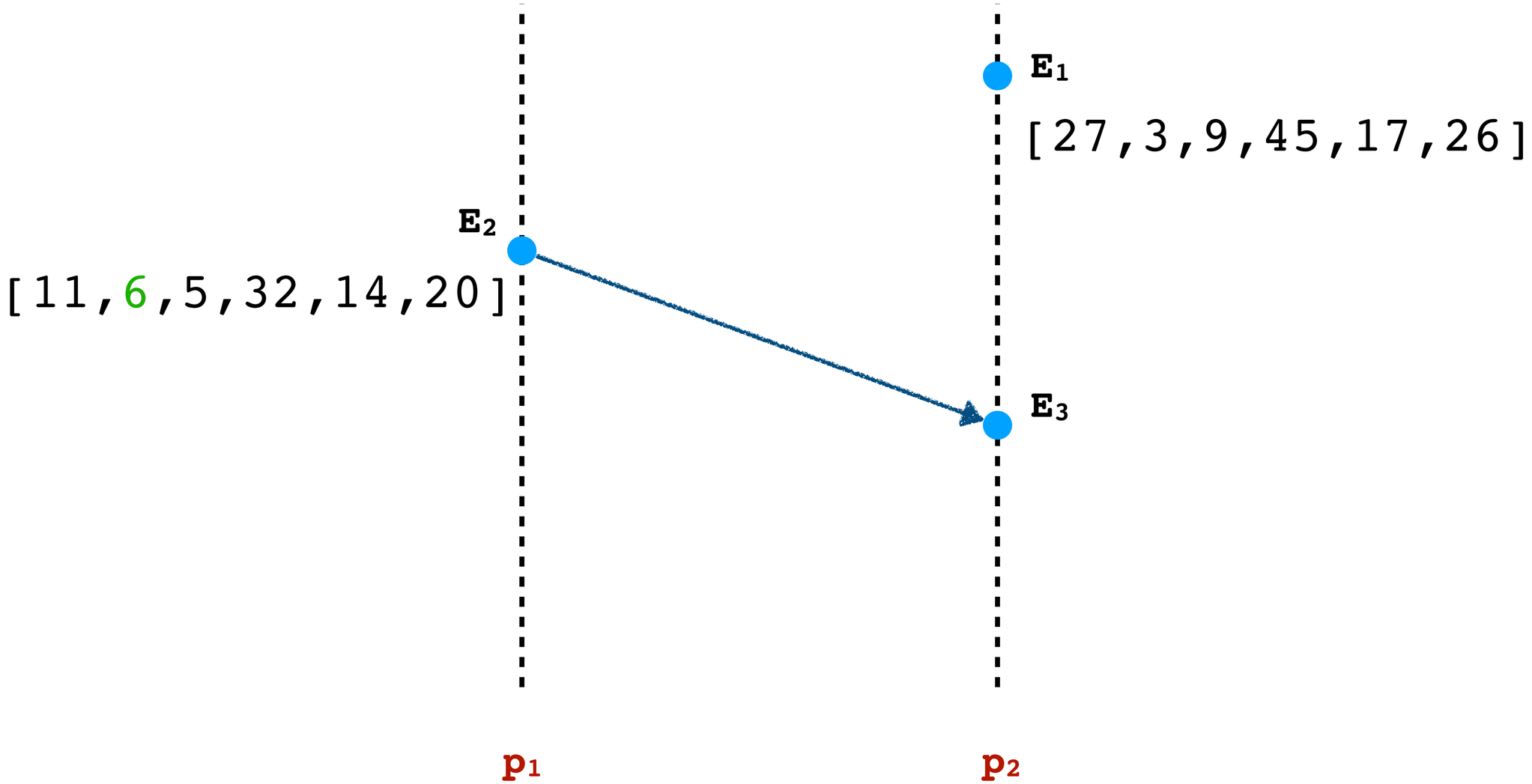

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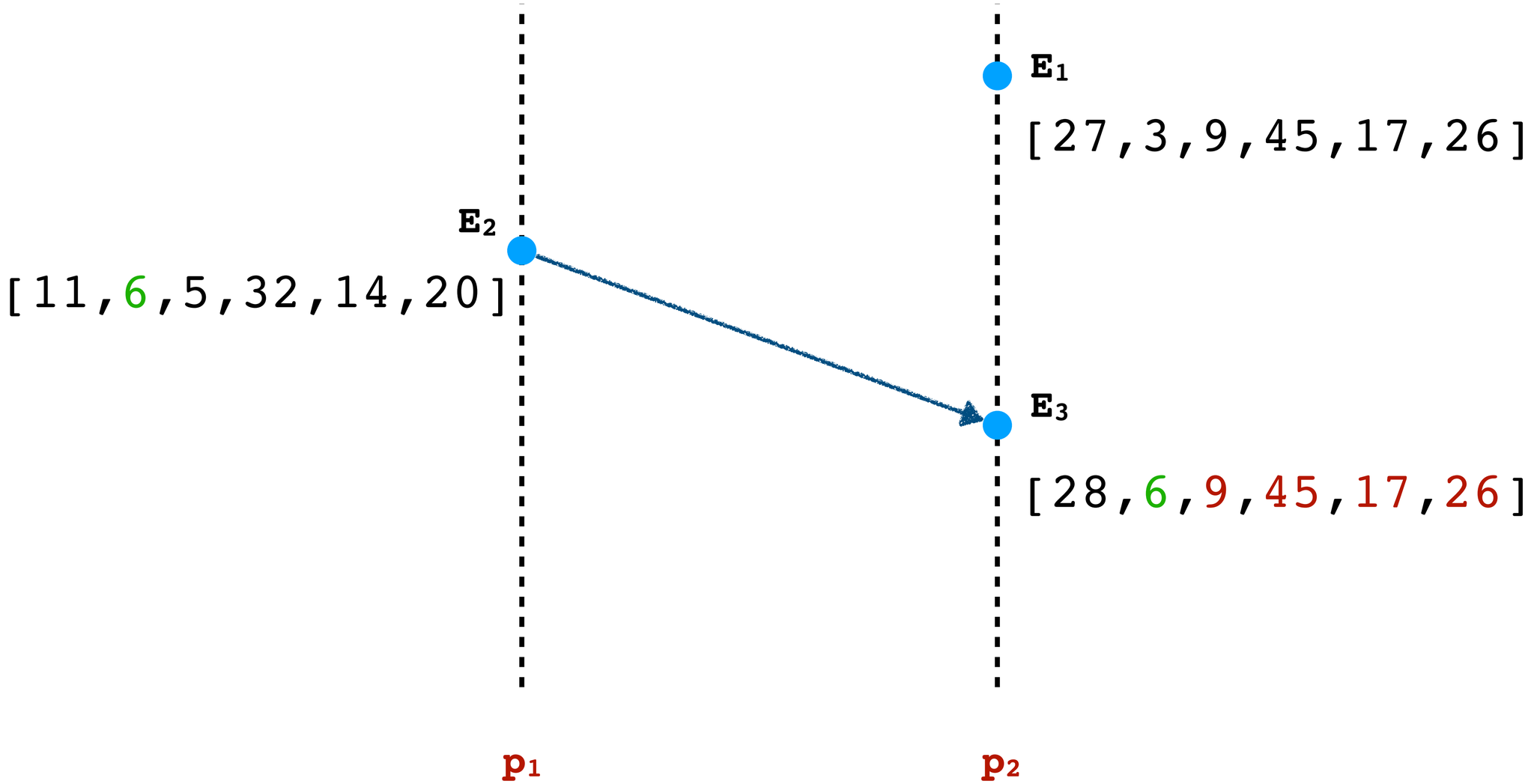

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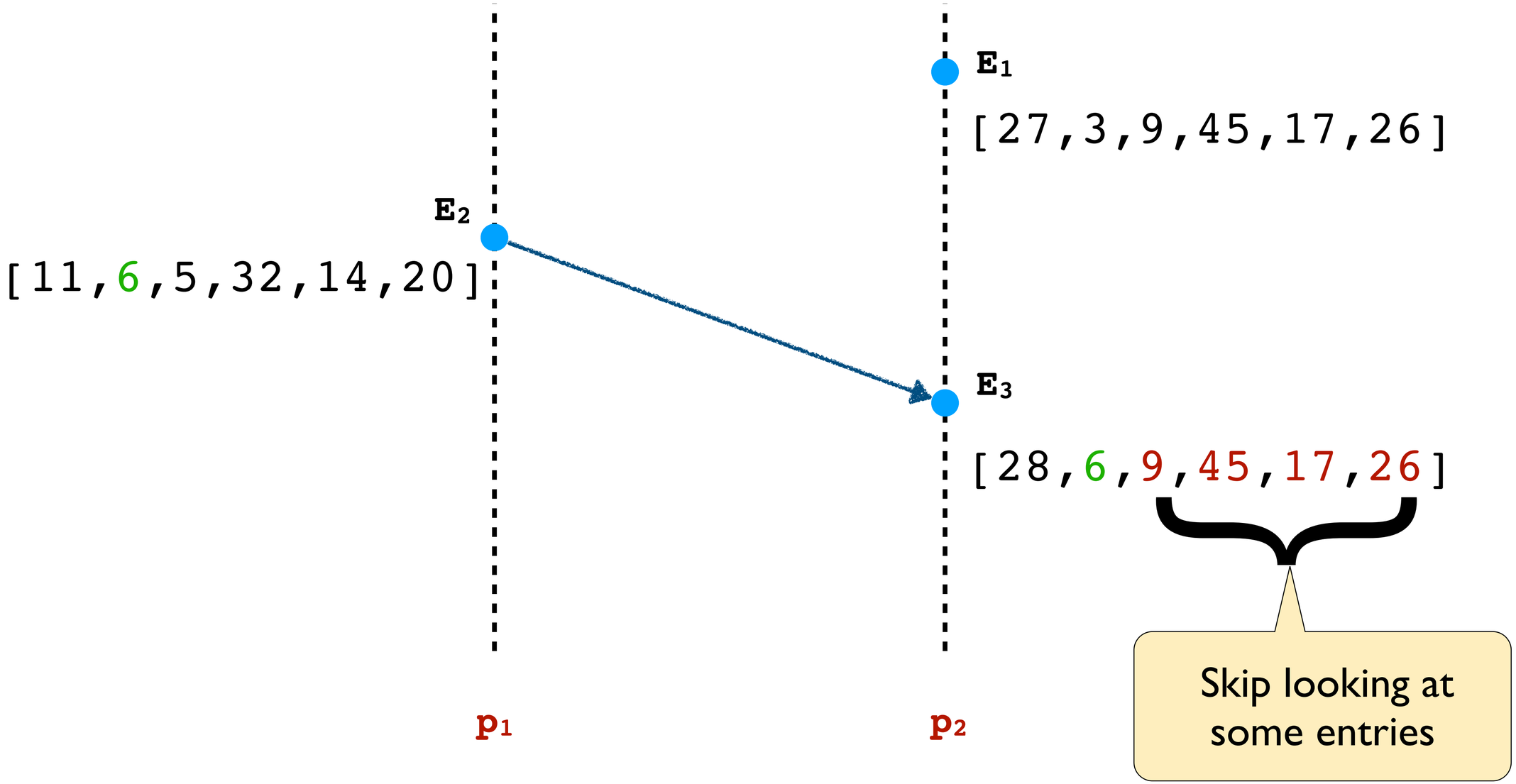
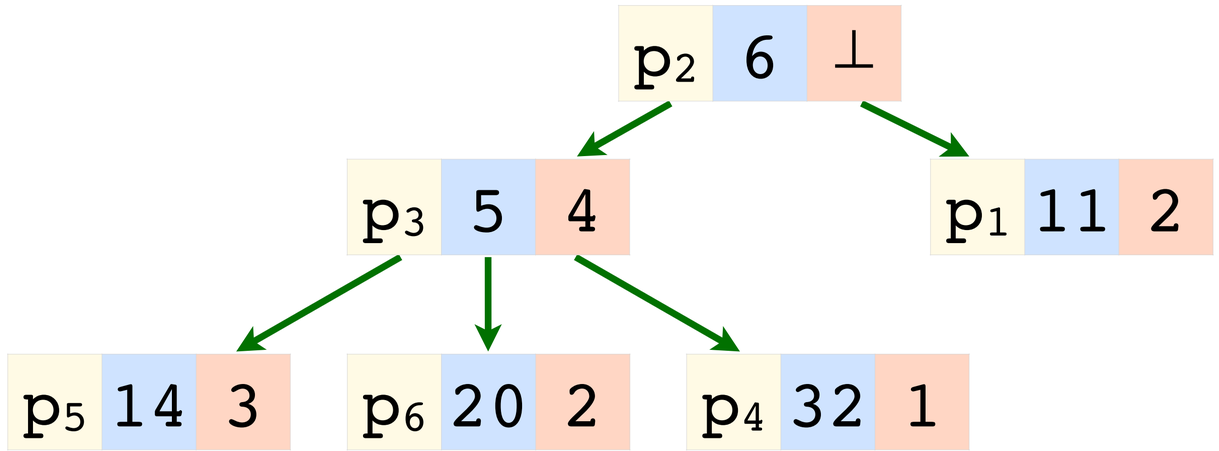


Tree Clocks

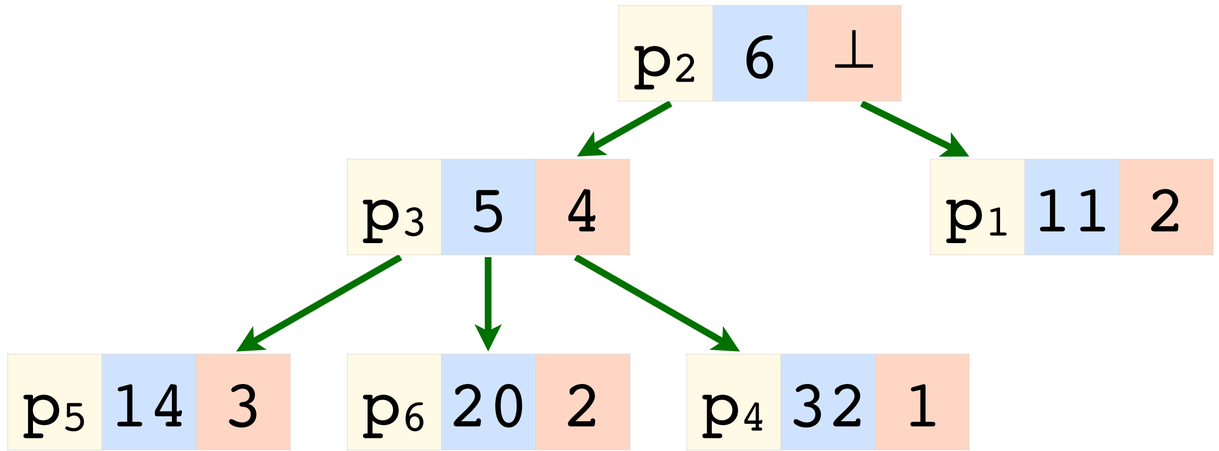
Tree Clocks

- Store **provenance information** hierarchically



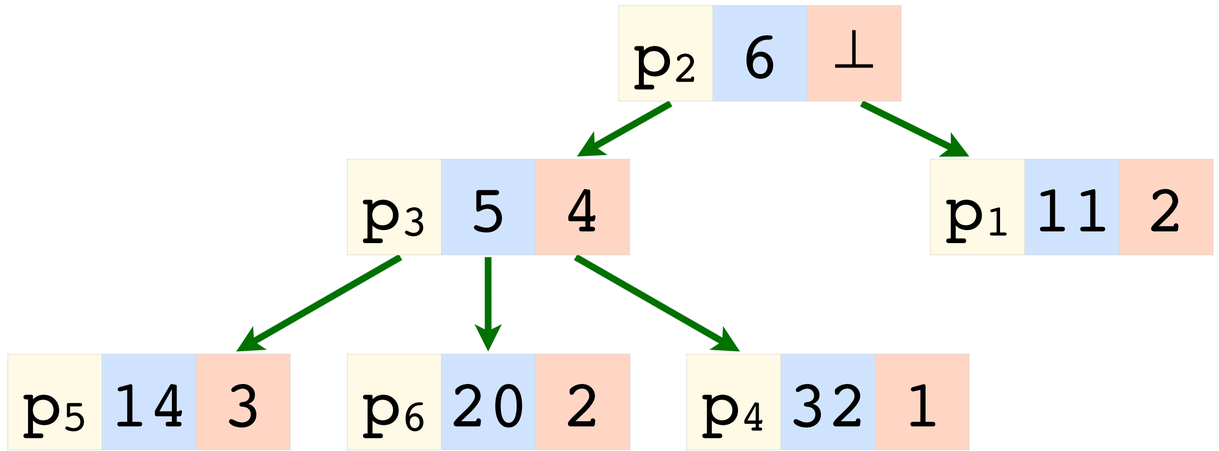
Tree Clocks

- Store **provenance information** hierarchically
  - Nodes store local times + extra metadata



Tree Clocks

- Store **provenance information** hierarchically
  - Nodes store local times + extra metadata
  - Hierarchical structure: how and when information was obtained



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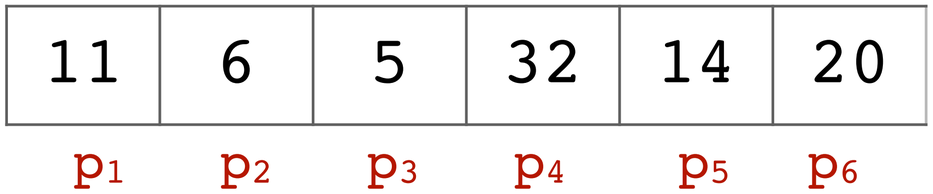
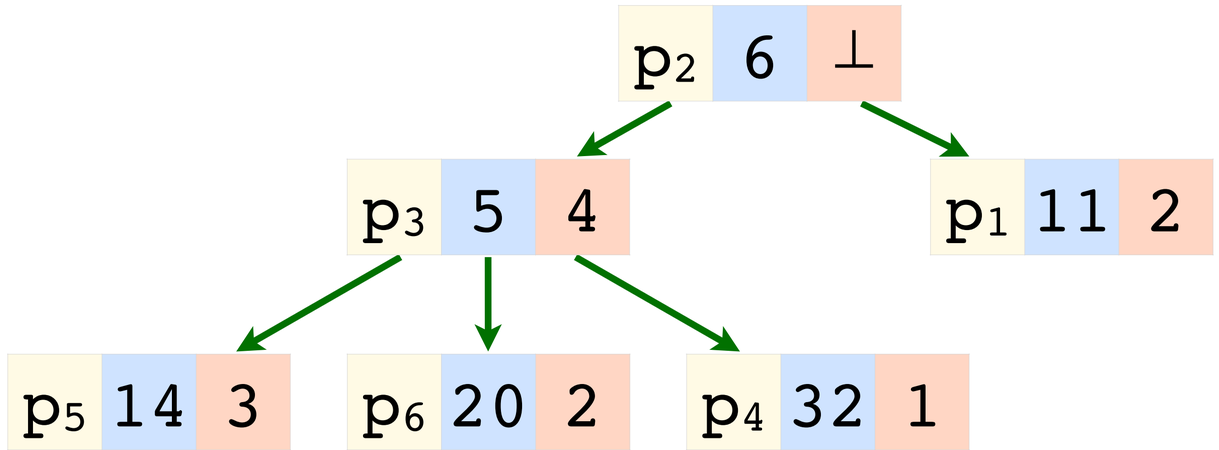
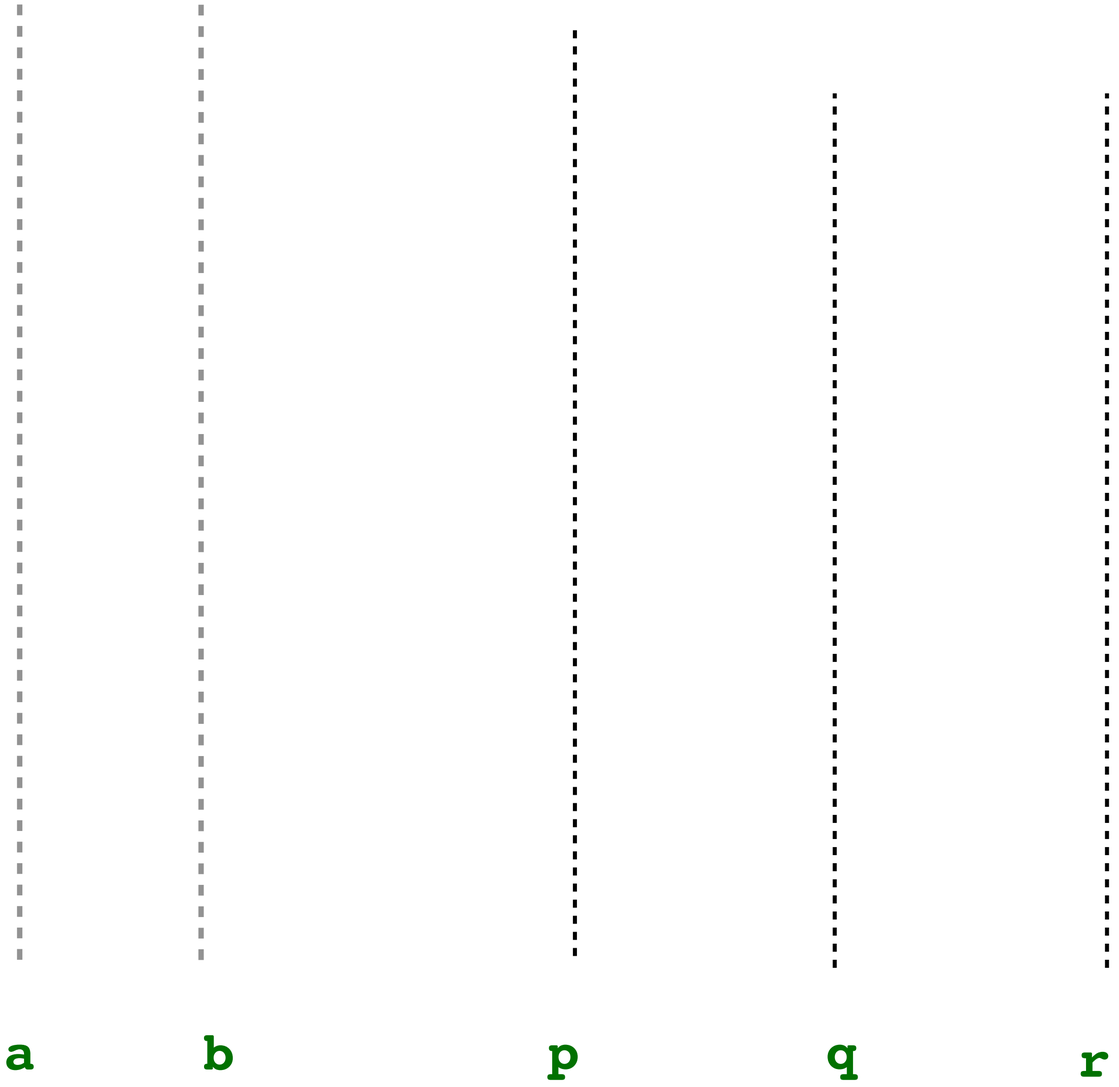


Vector Clock

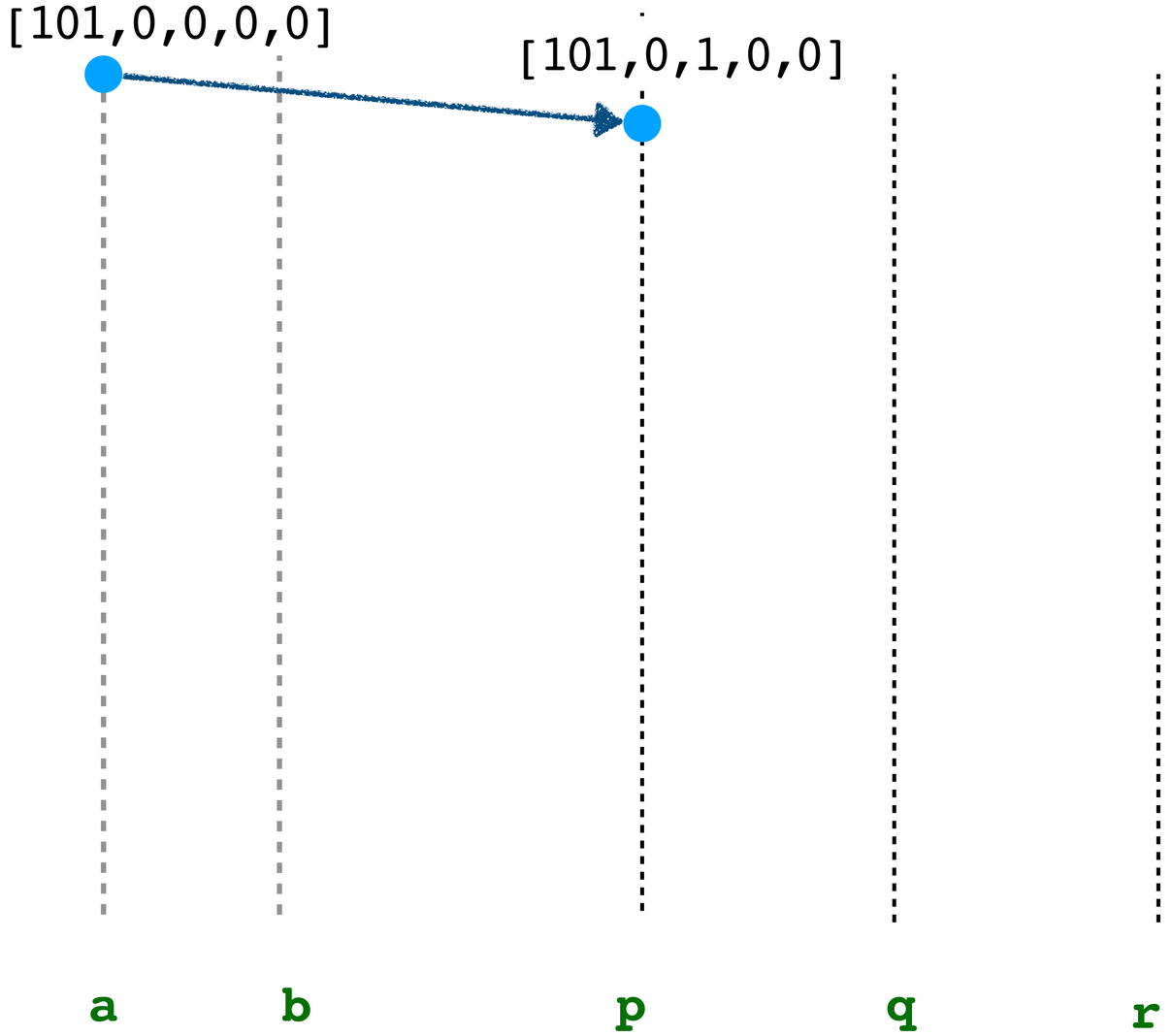


Tree Clock

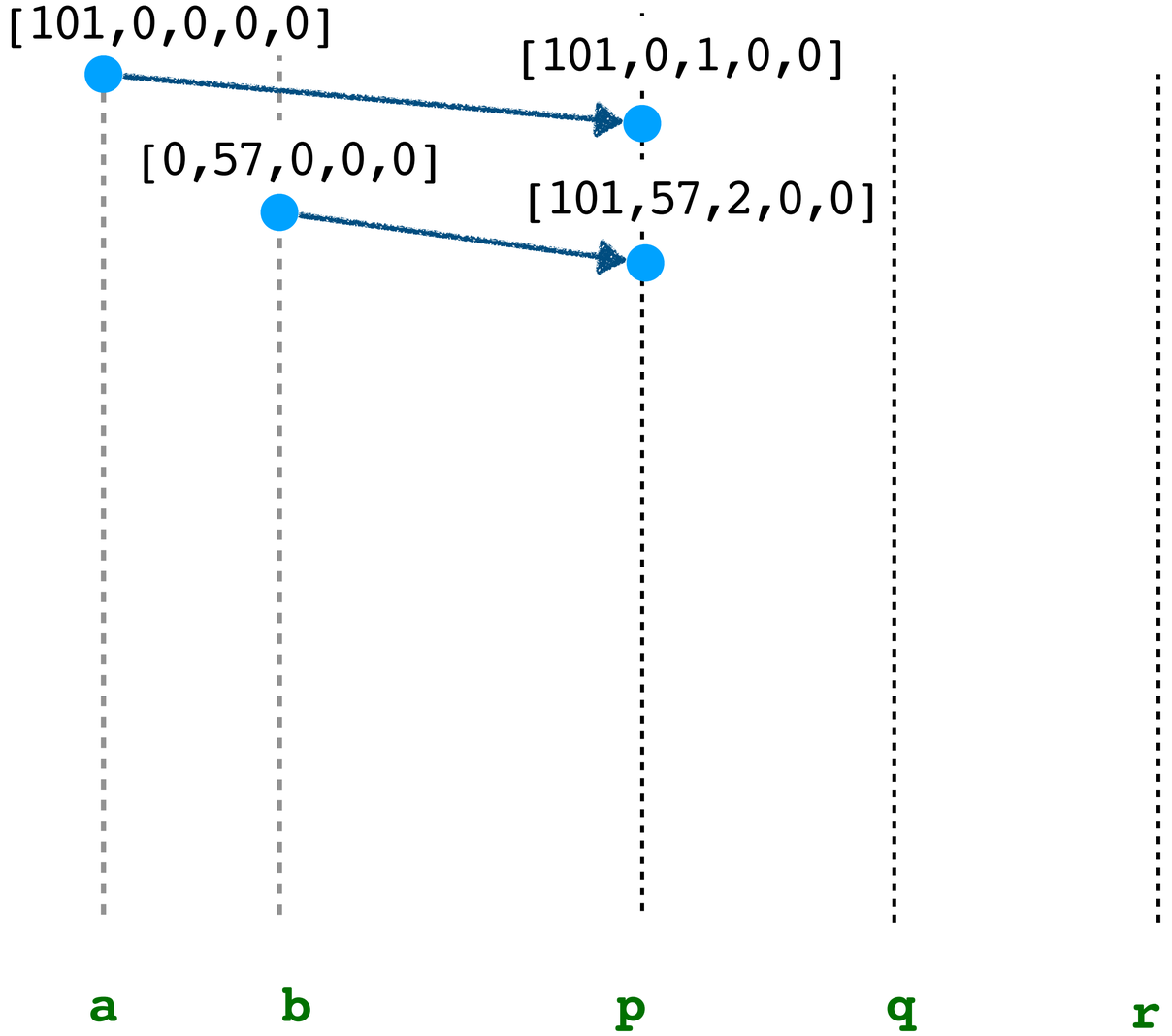
Provenance using **Transitivity**



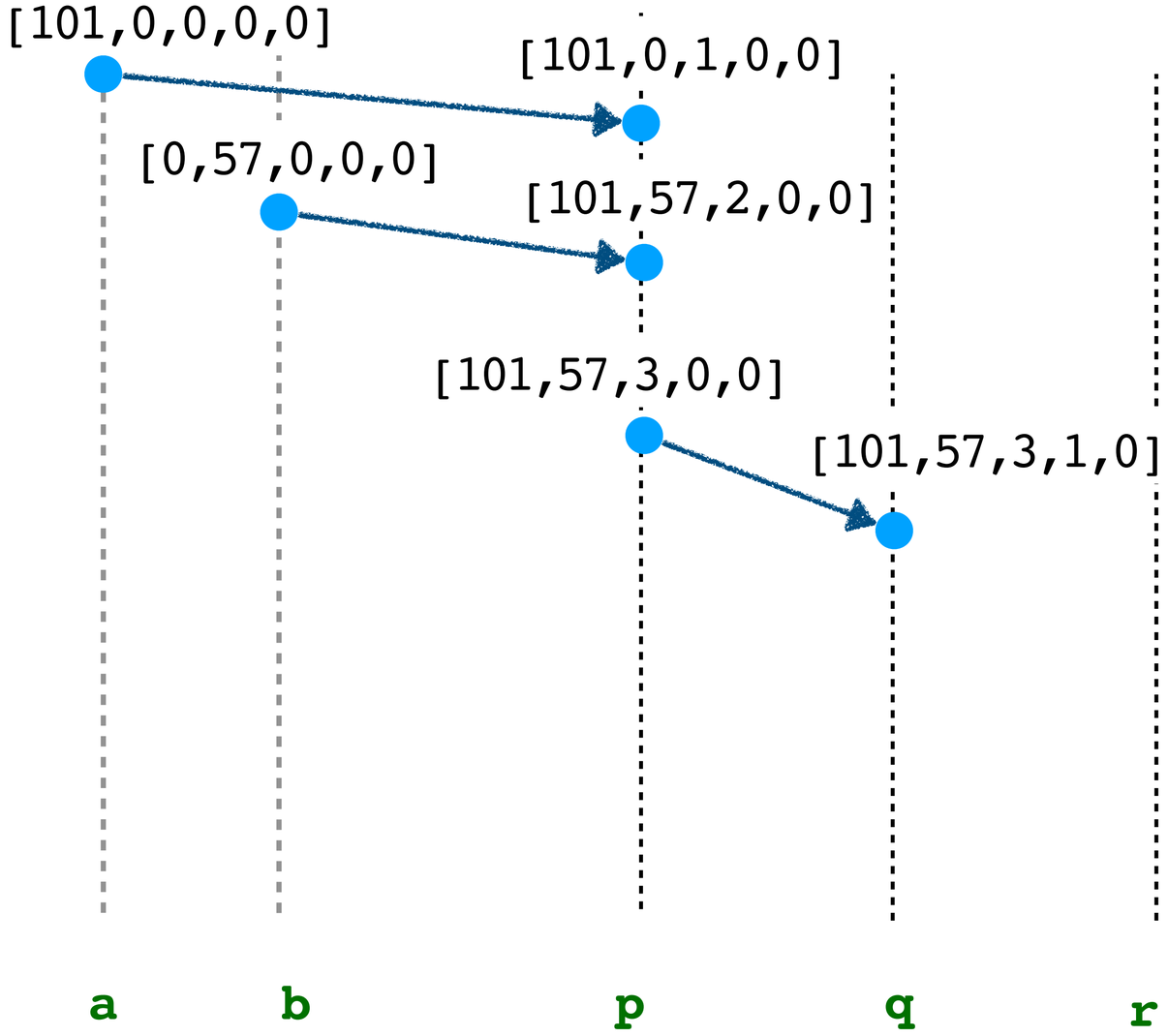
Provenance using **Transitivity**



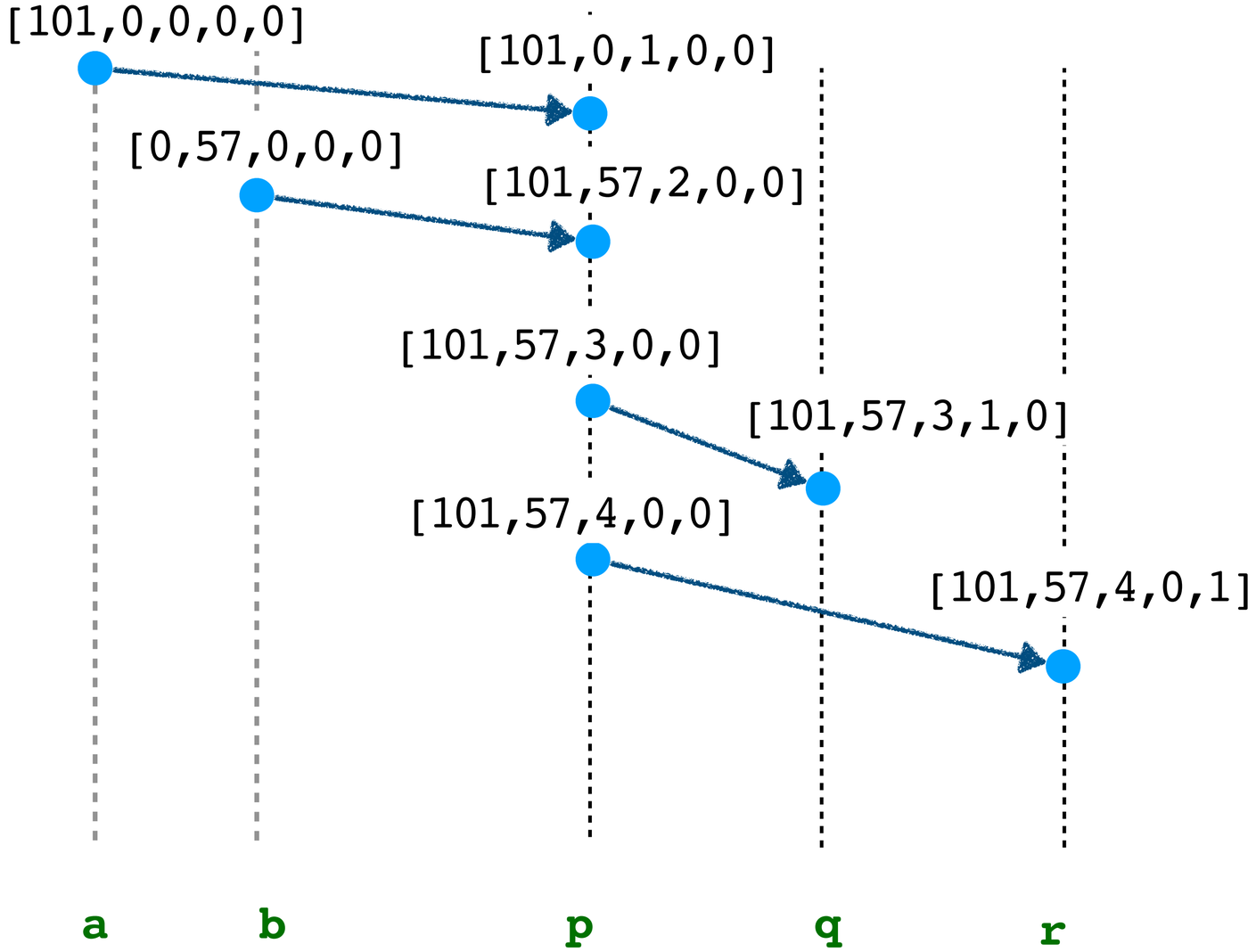
Provenance using **Transitivity**



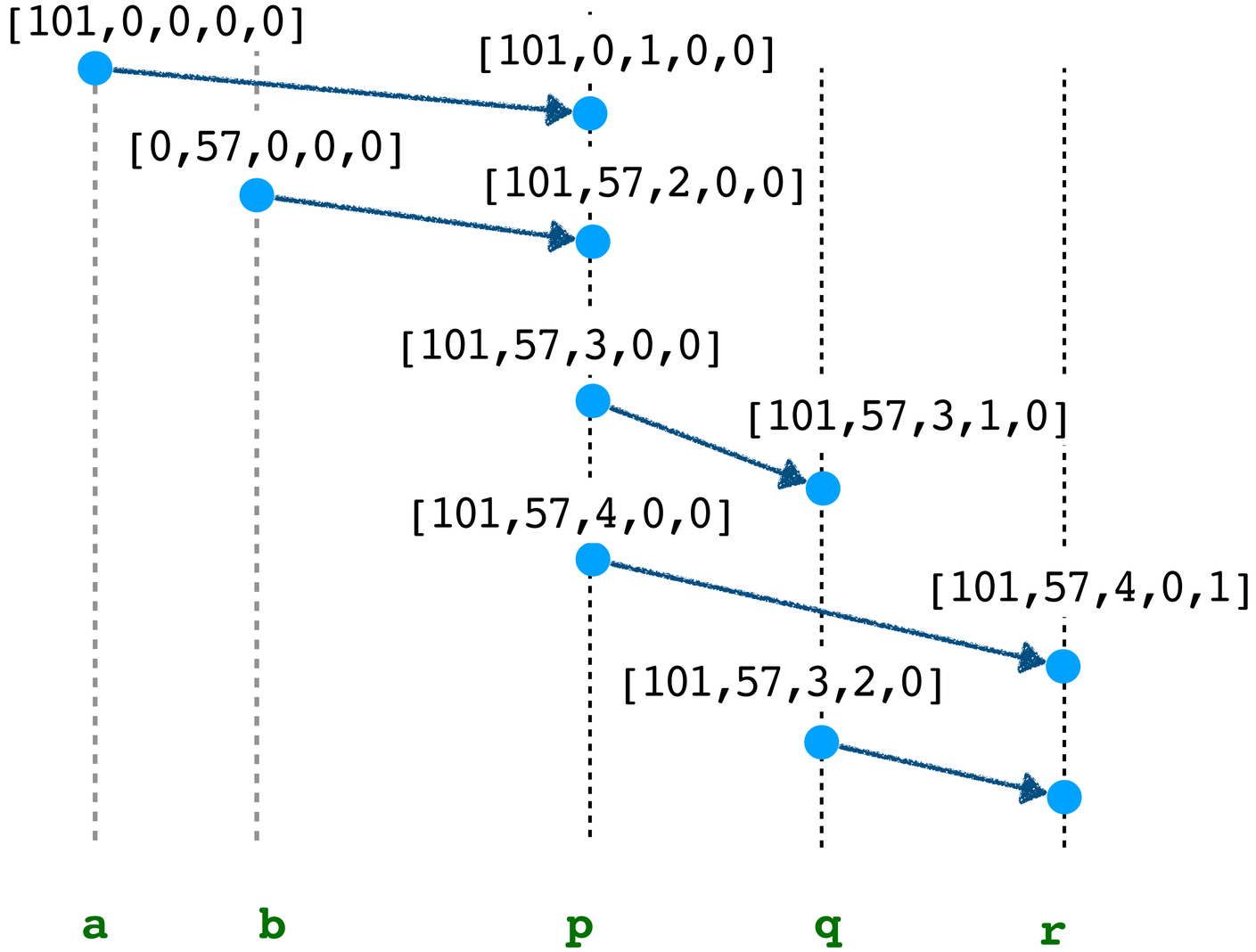
Provenance using **Transitivity**



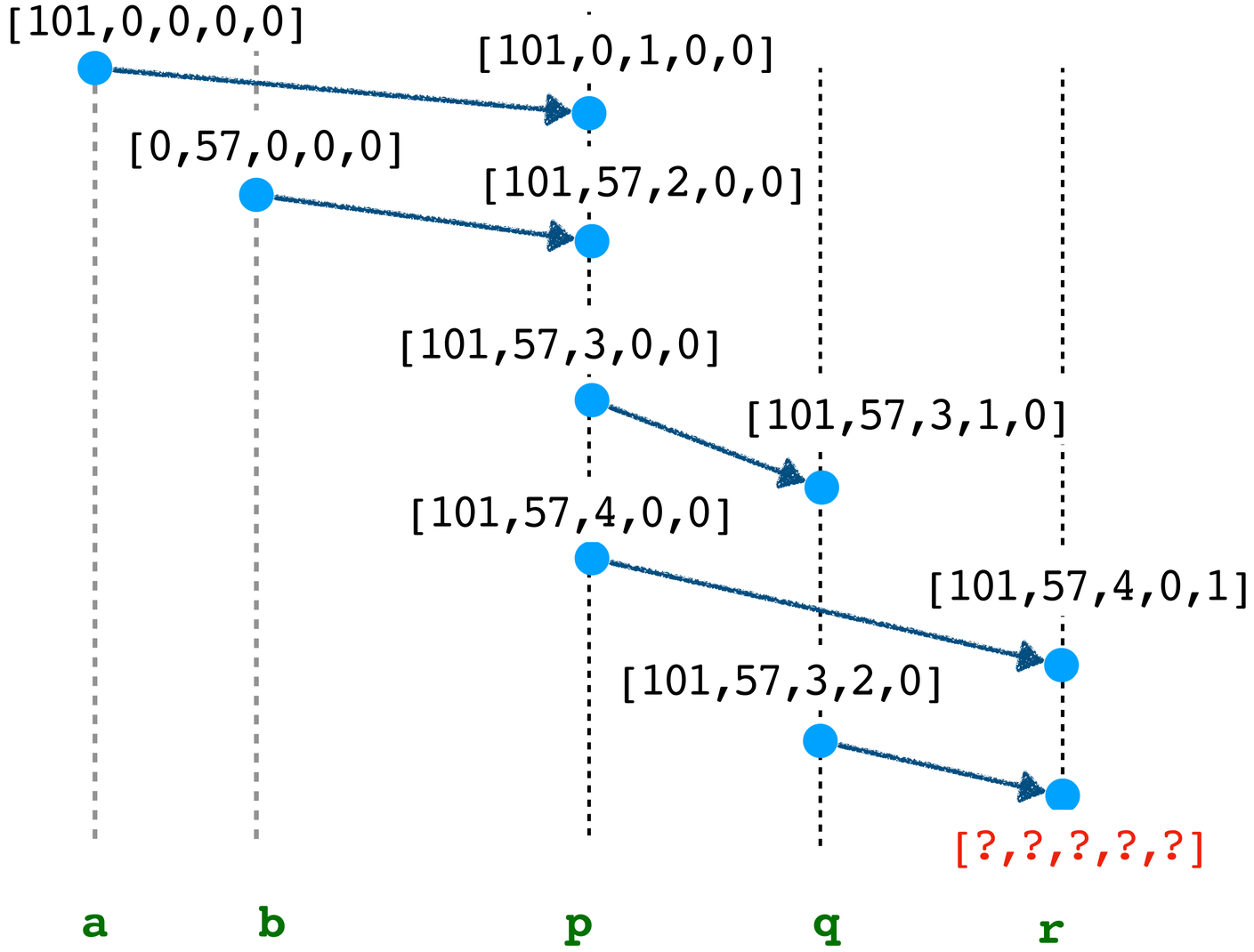
Provenance using **Transitivity**



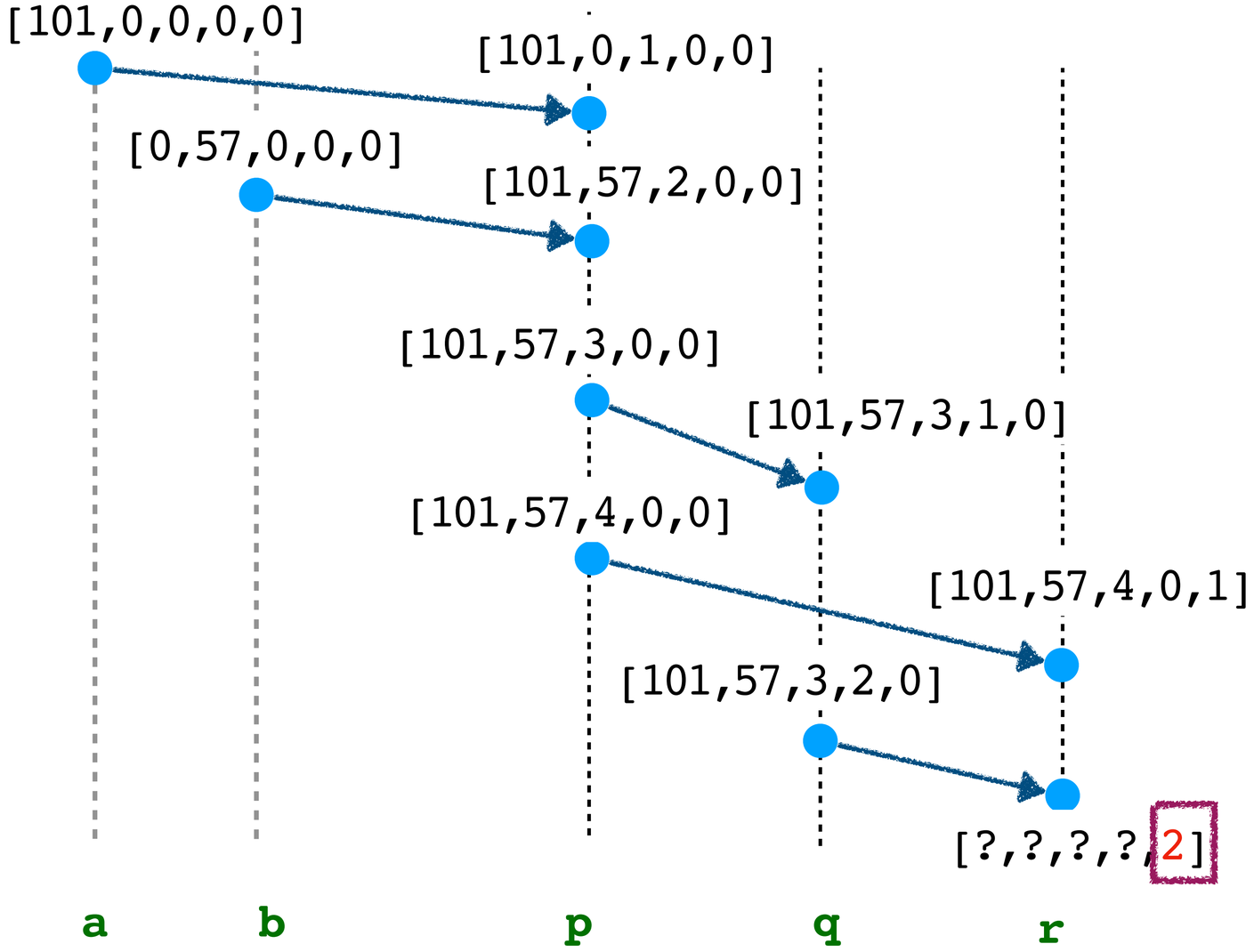
Provenance using **Transitivity**



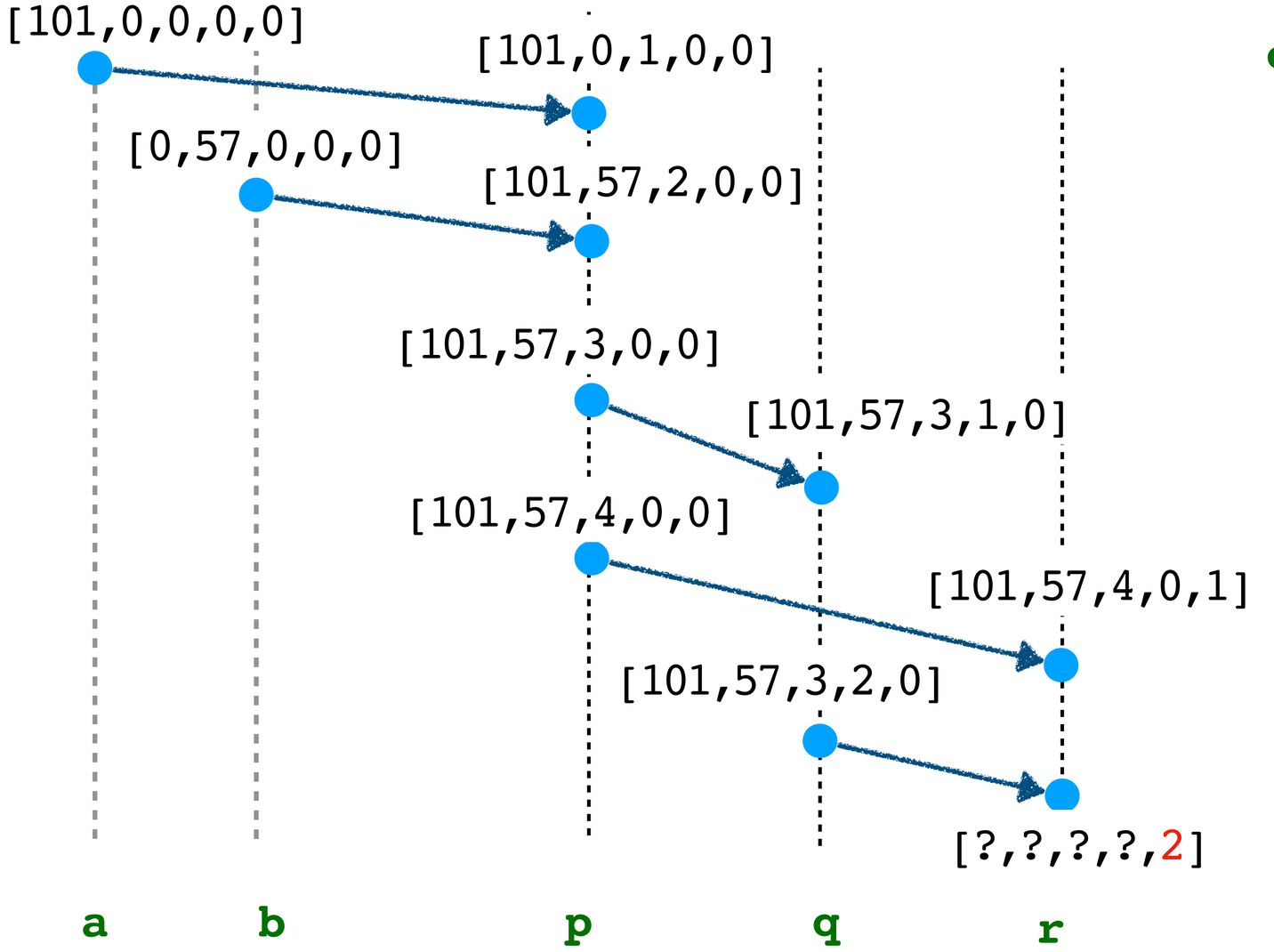
Provenance using **Transitivity**



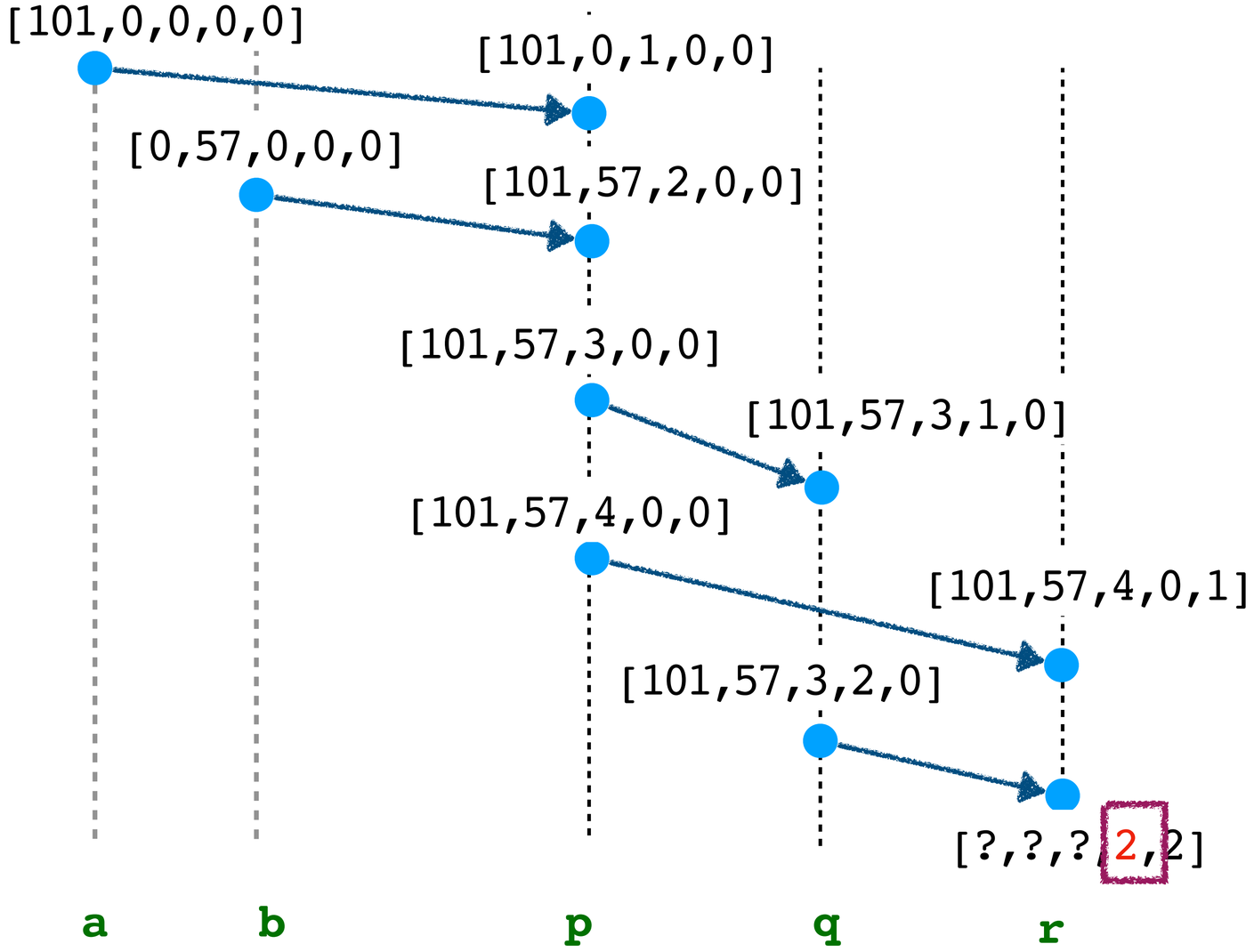
Provenance using **Transitivity**

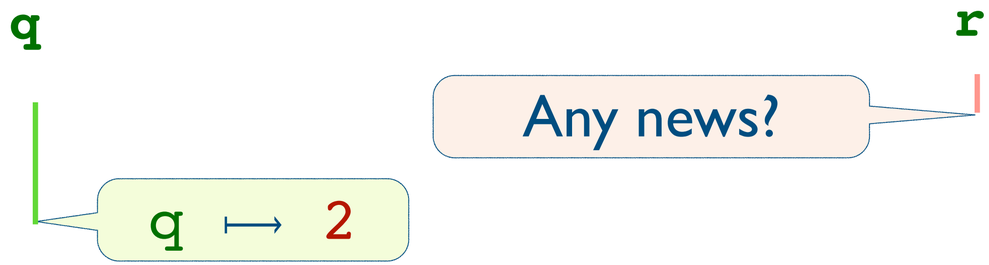


Provenance using **Transitivity**

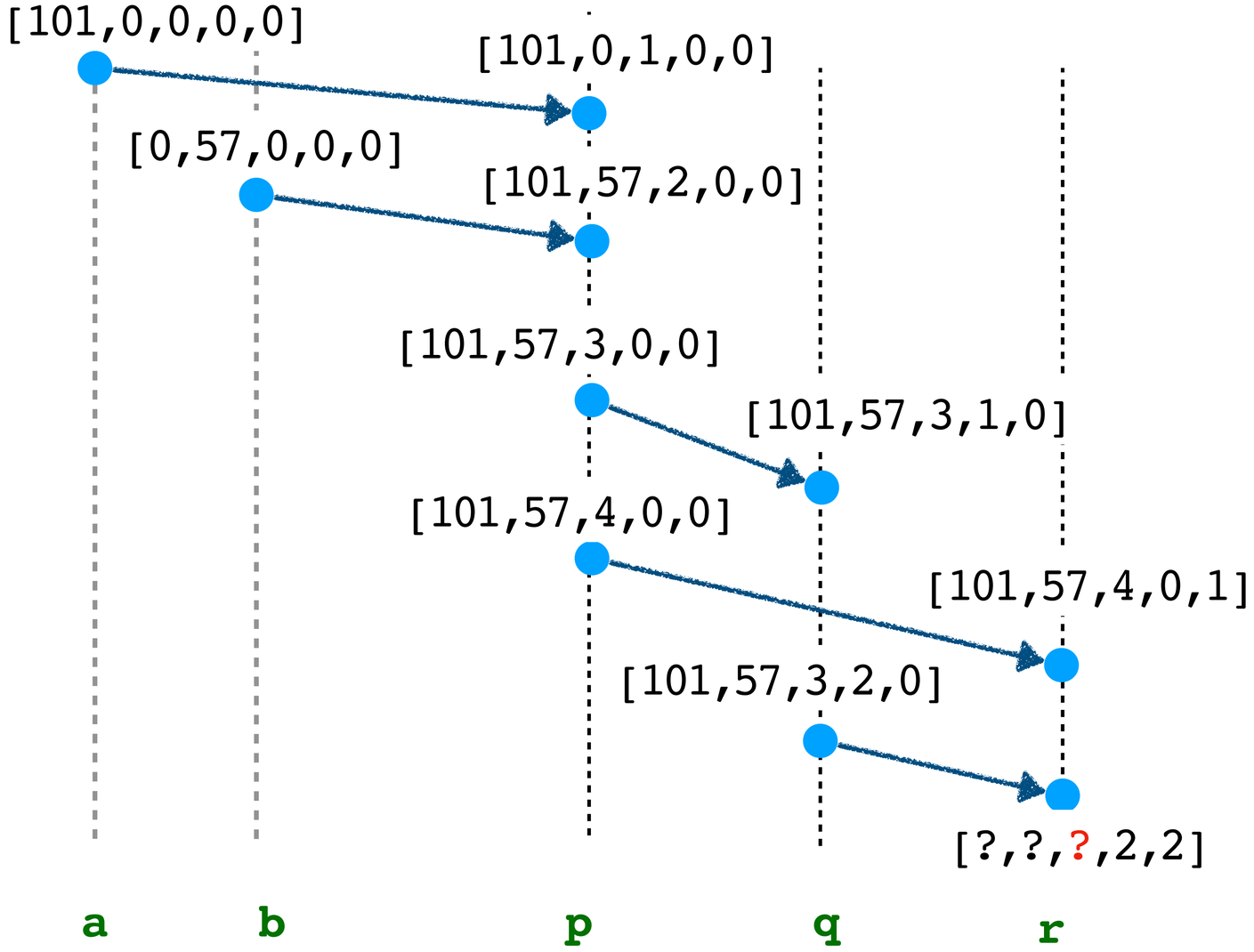


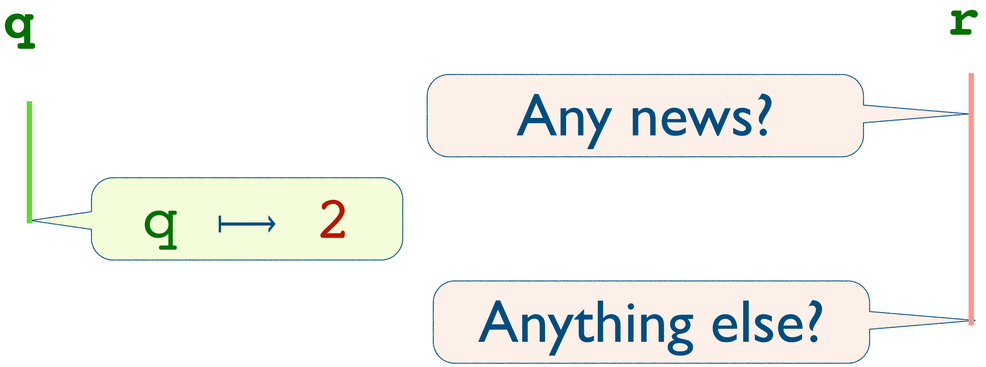
Provenance using **Transitivity**



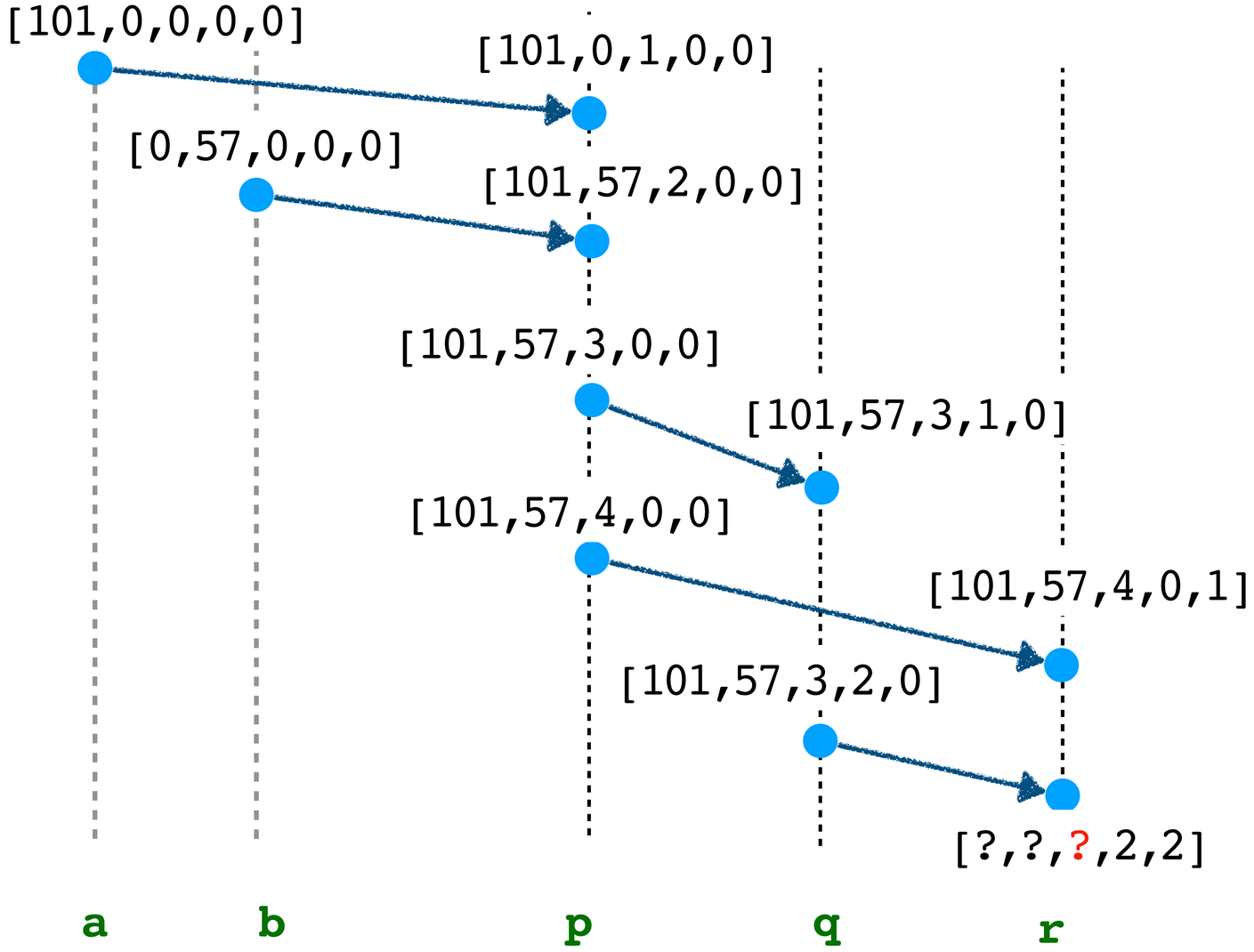


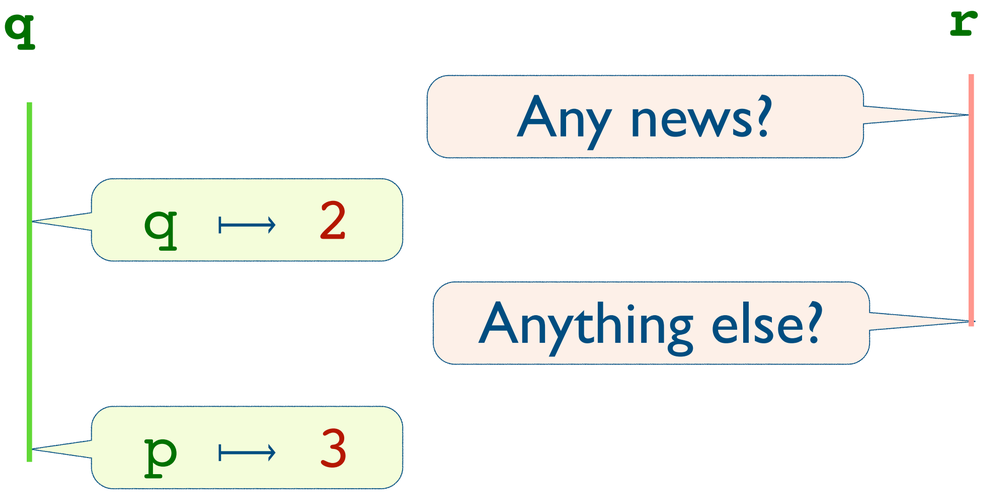
Provenance using **Transitivity**



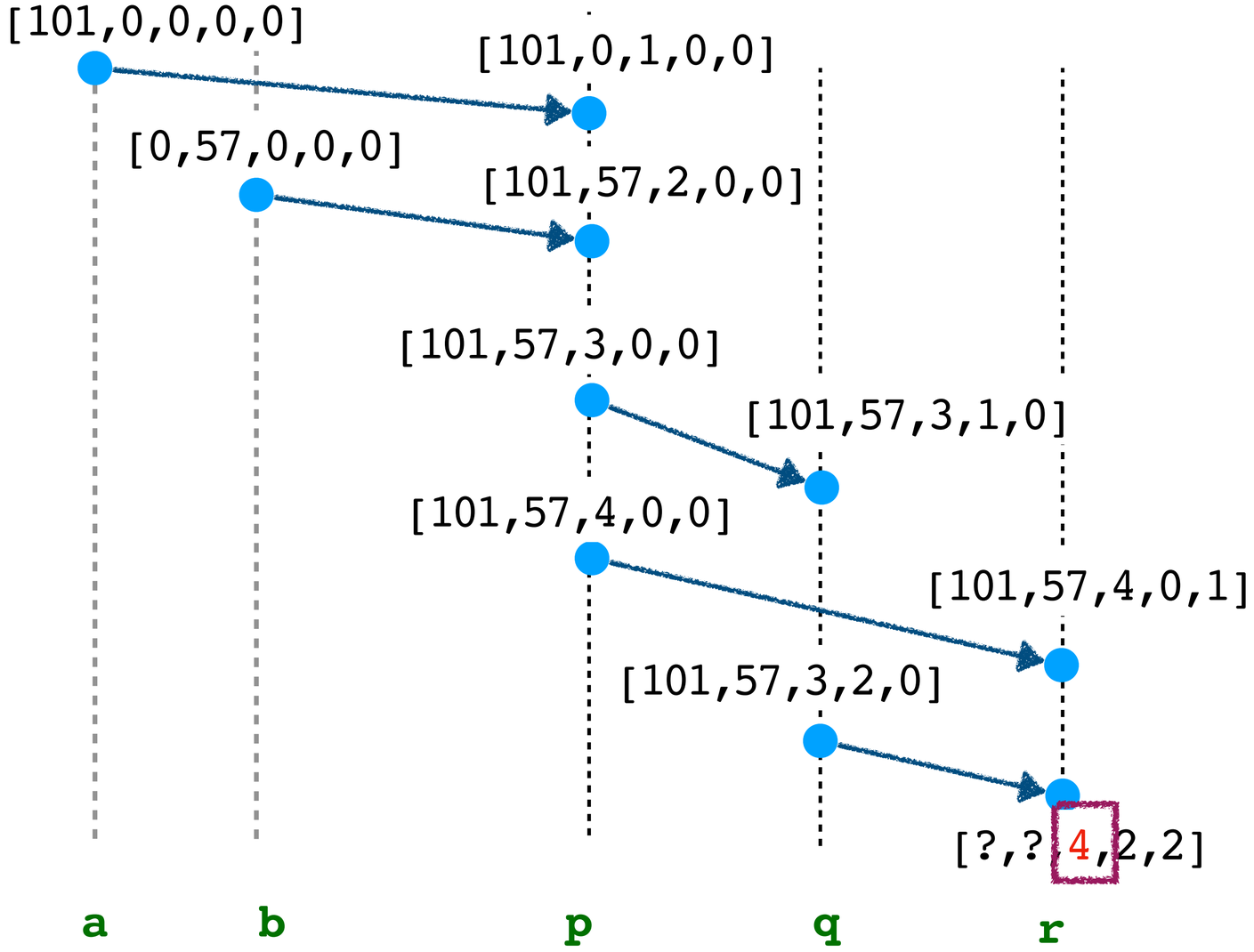


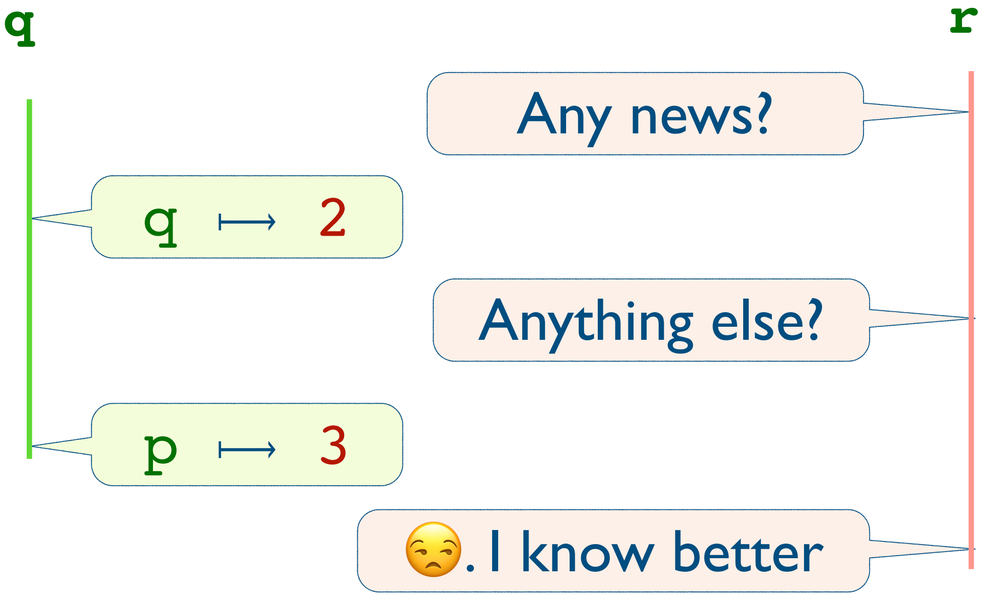
Provenance using **Transitivity**



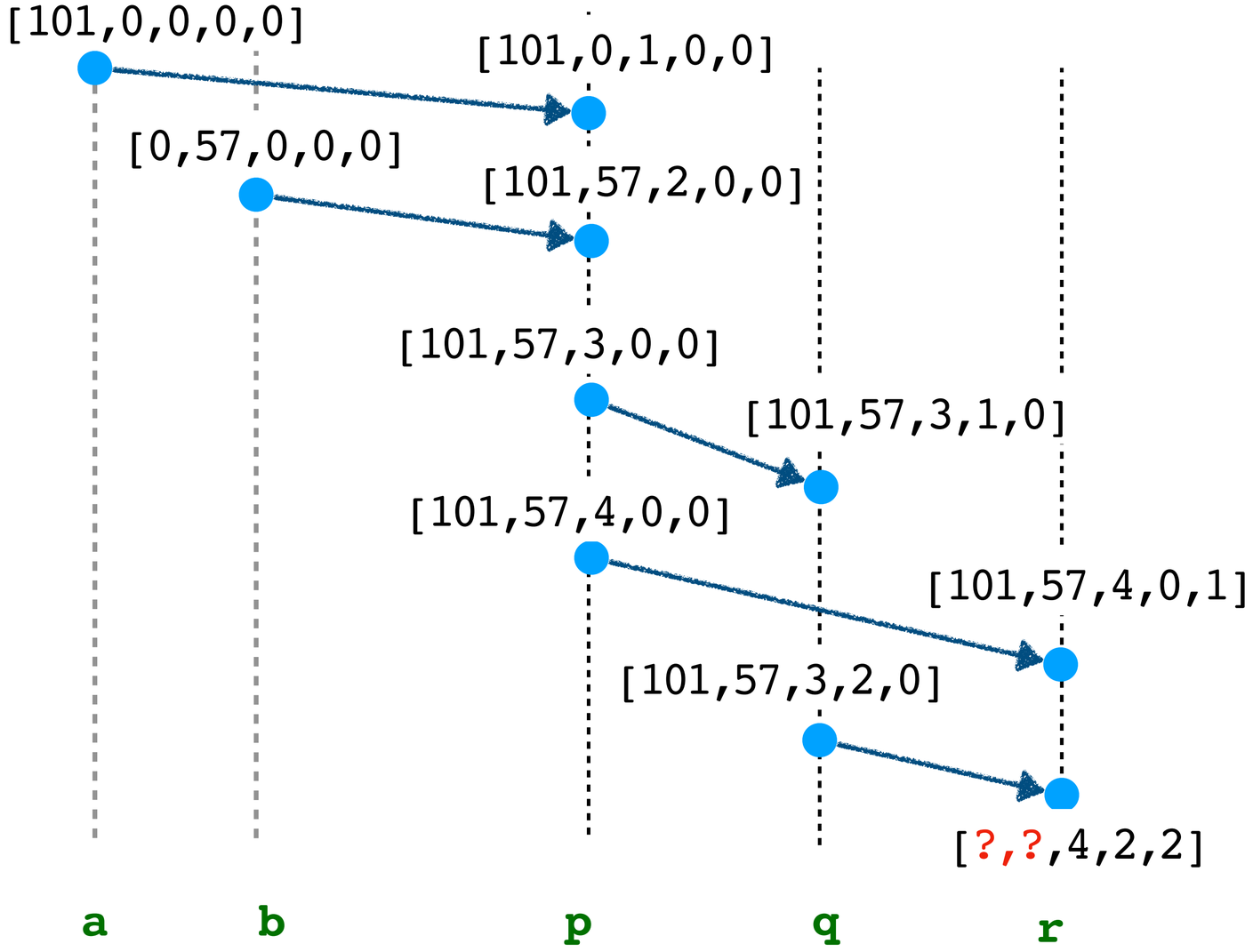


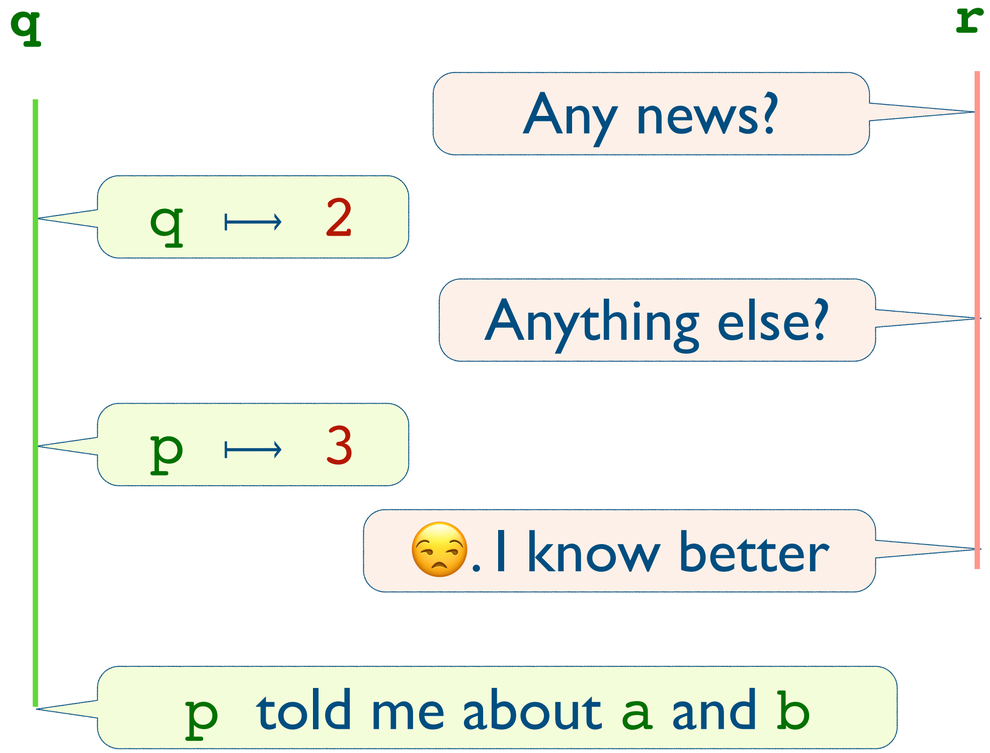
Provenance using **Transitivity**



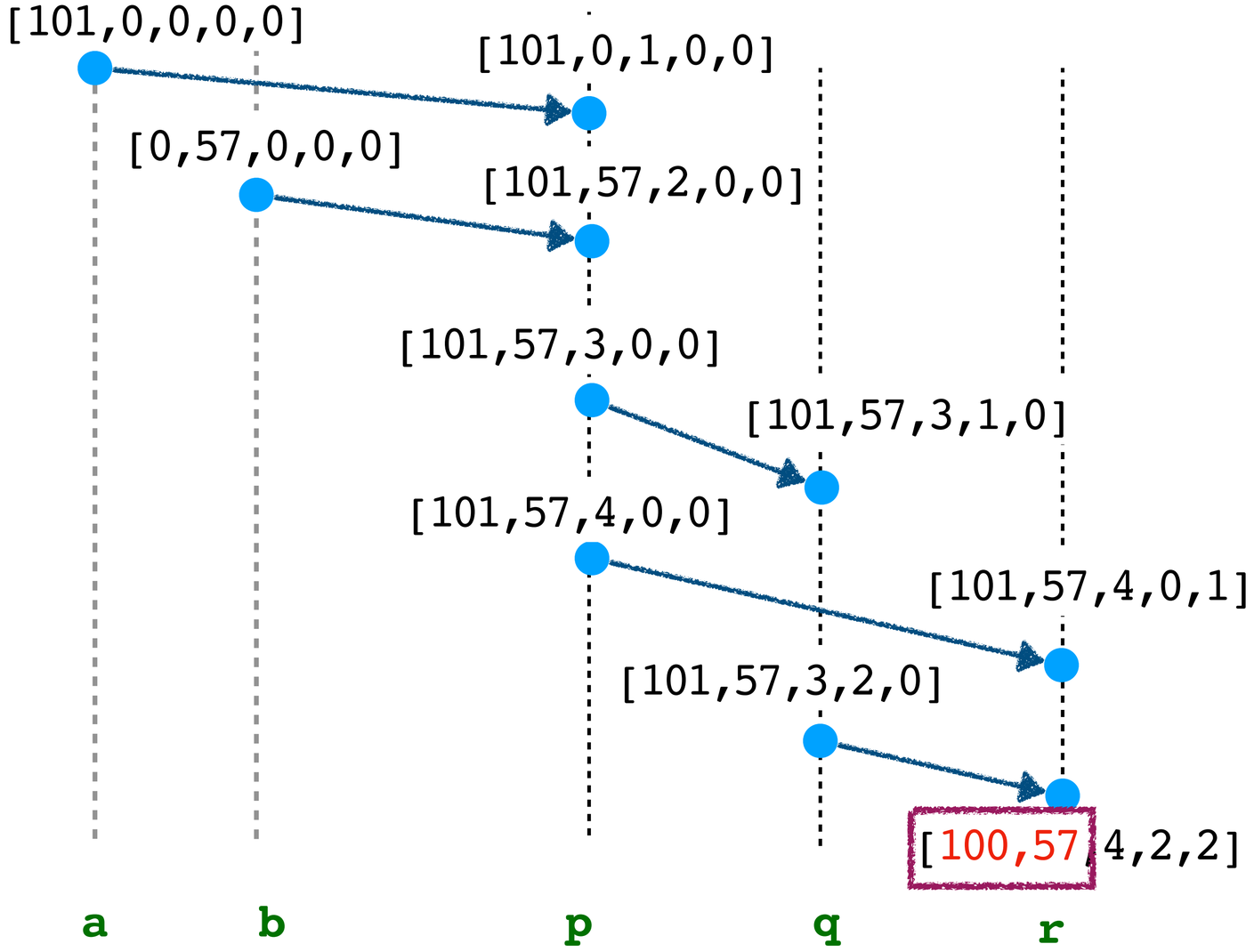


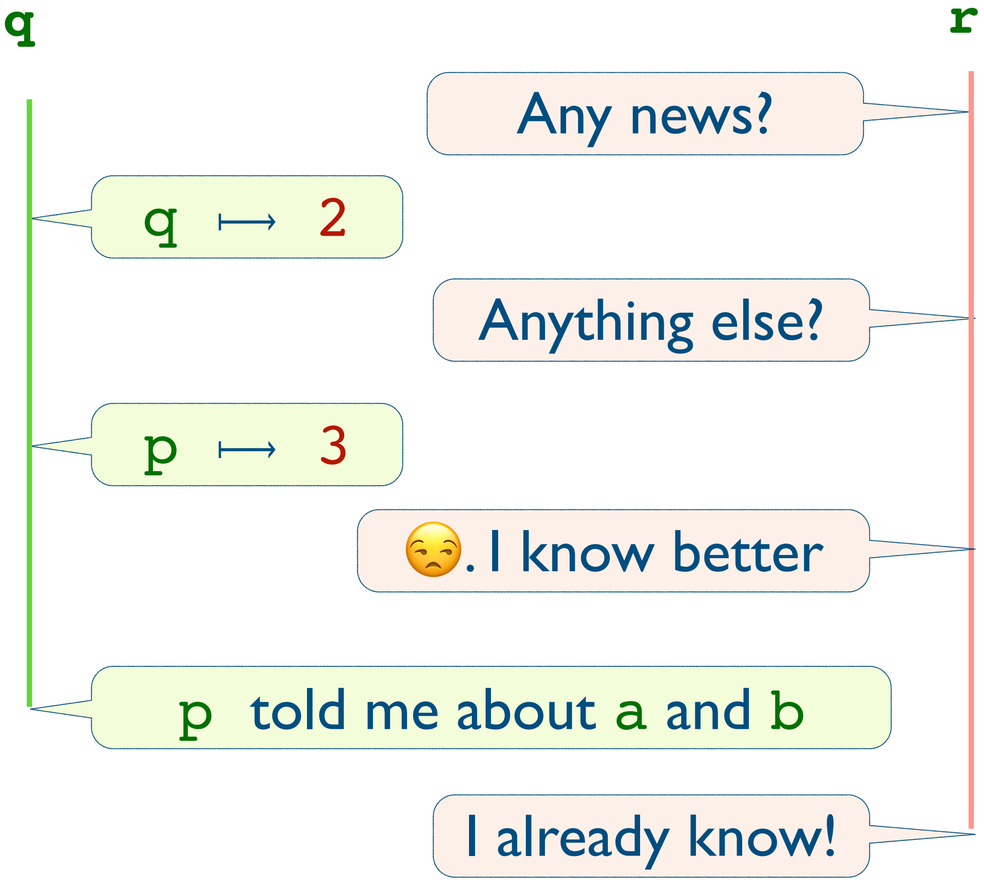
Provenance using **Transitivity**



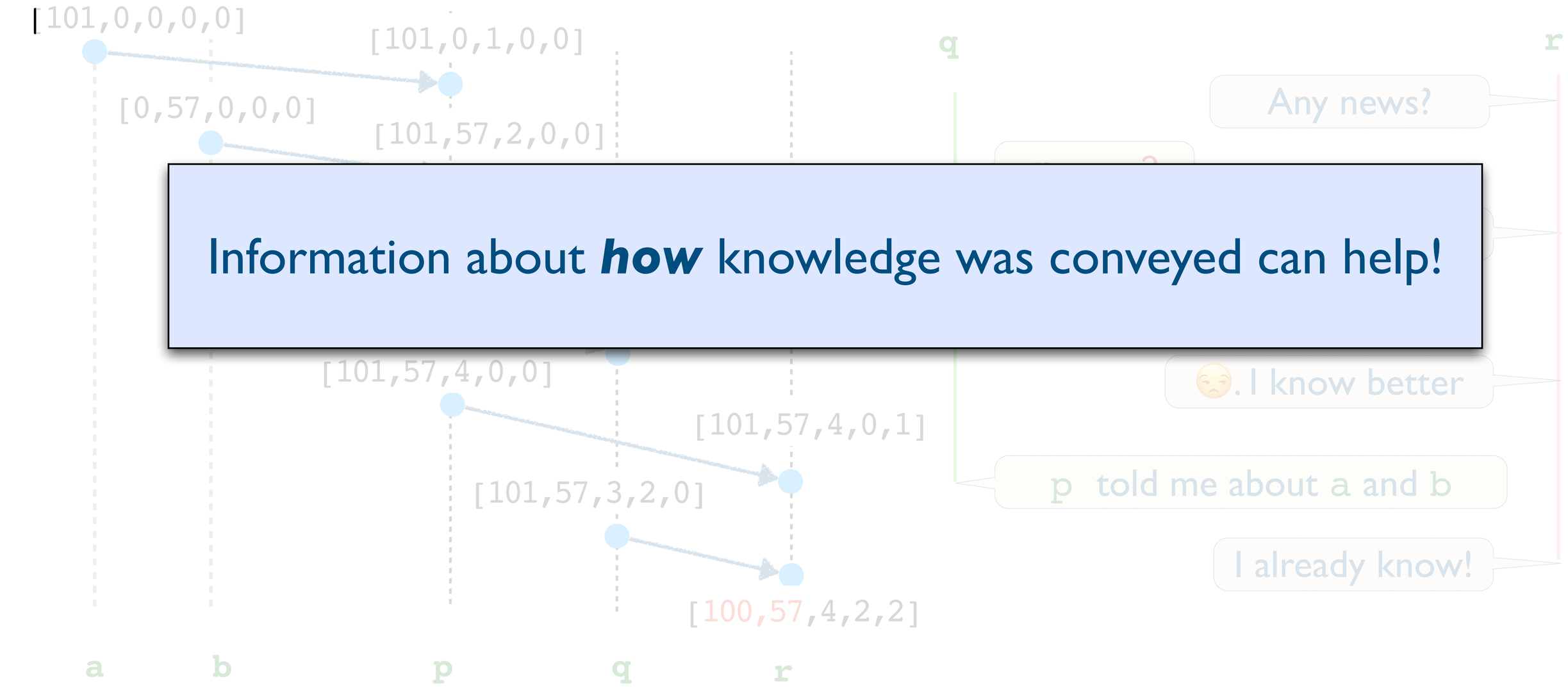


Provenance using **Transitivity**



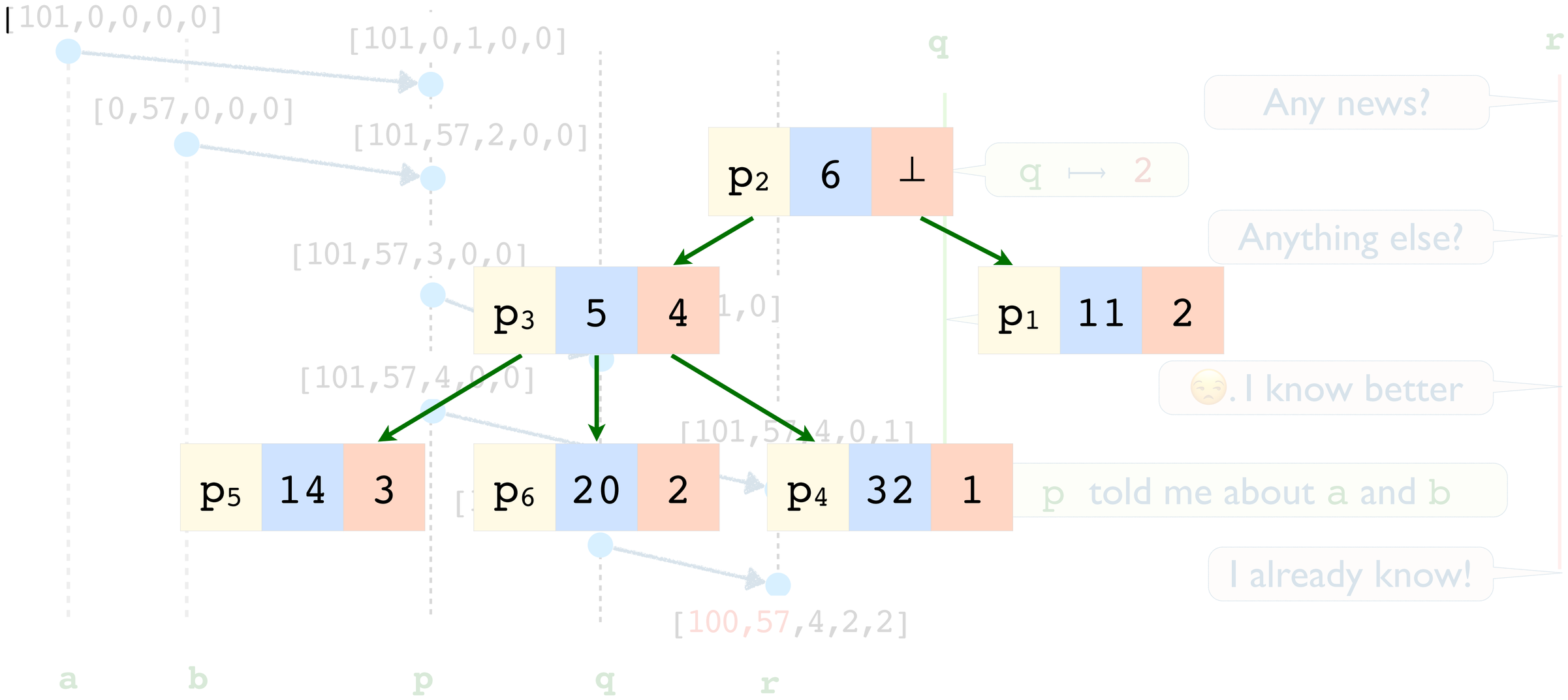


Provenance using **Transitivity**

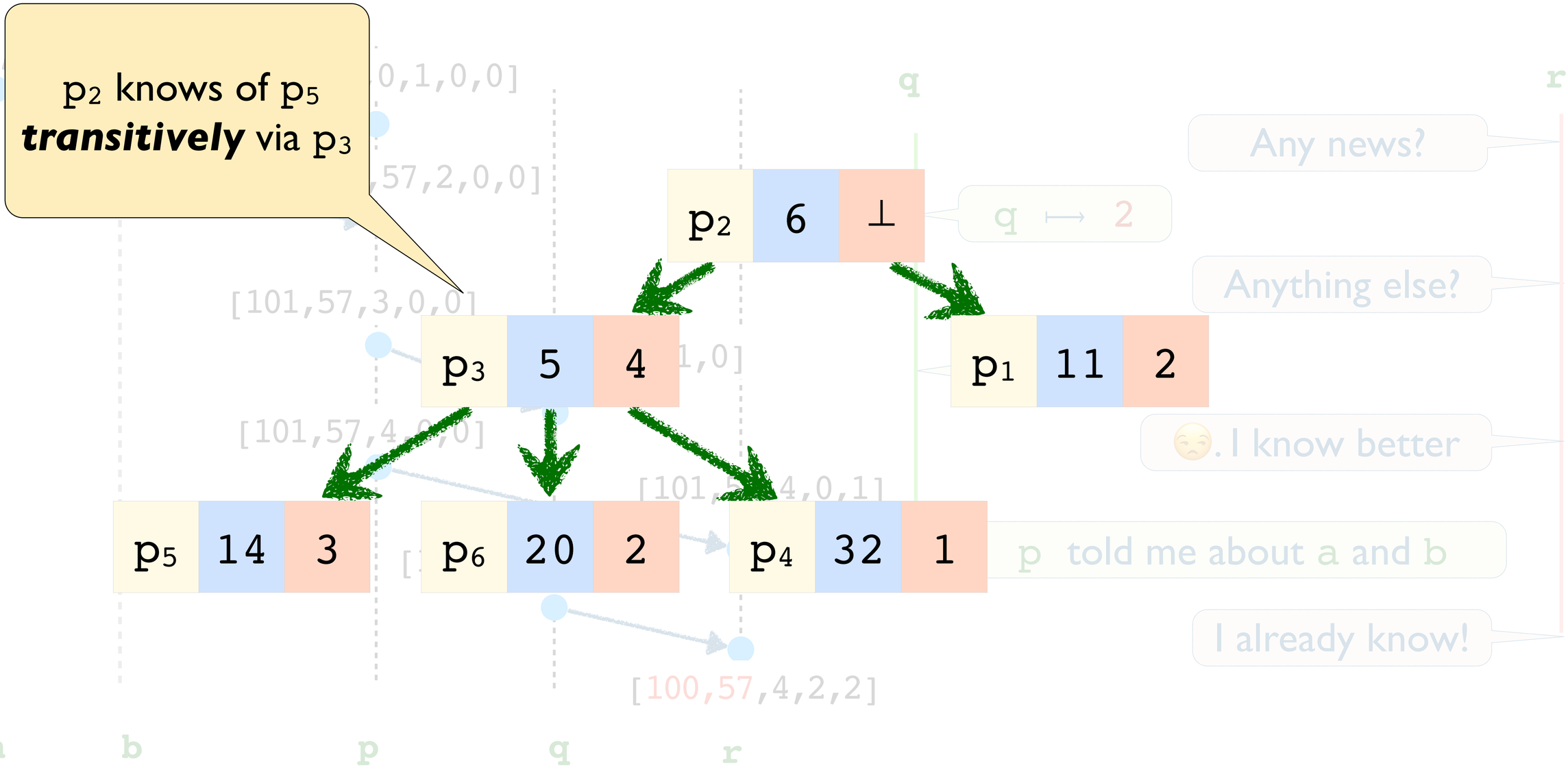


Information about ***how*** knowledge was conveyed can help!

Provenance using **Transitivity**

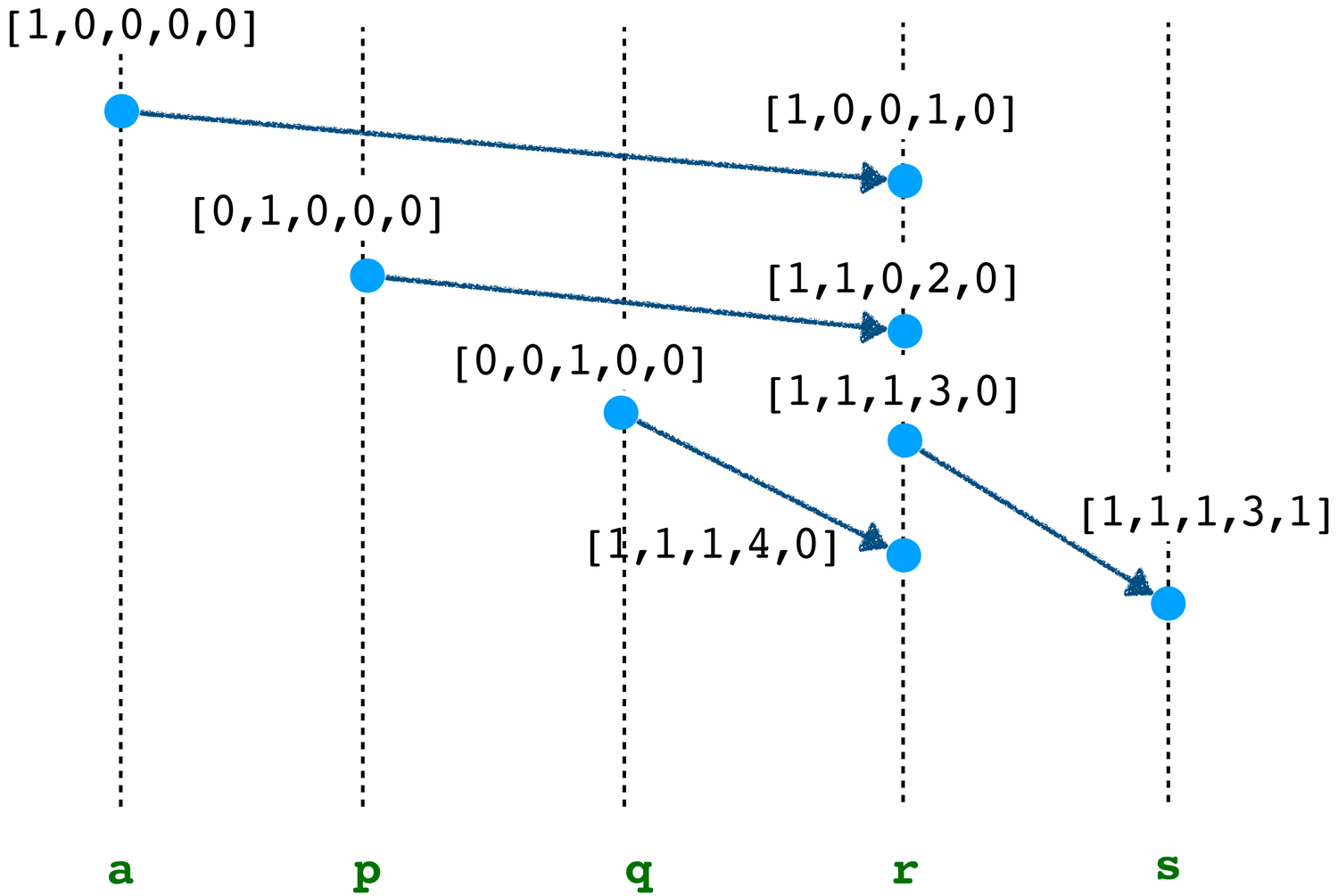


Provenance using **Transitivity**

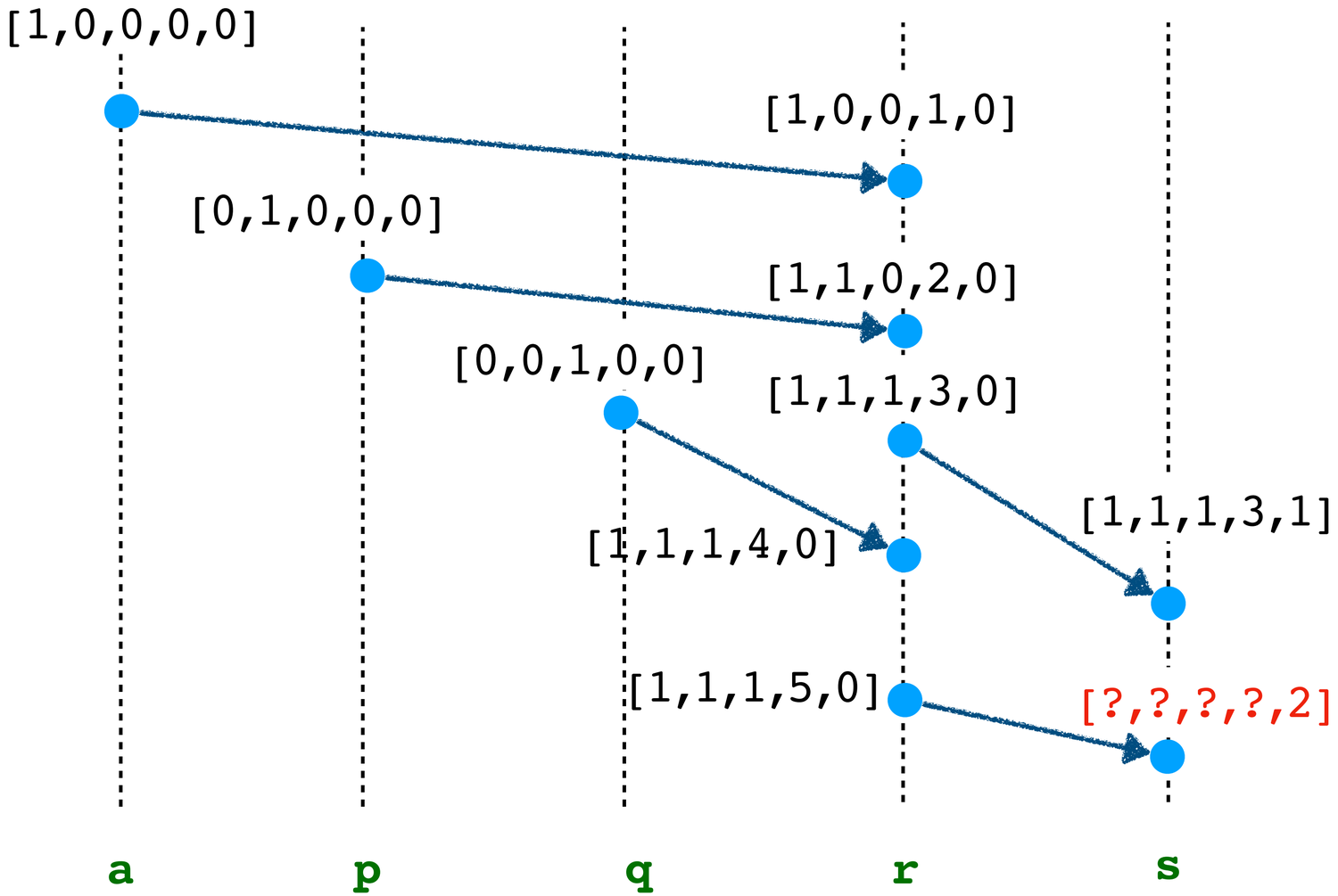


Provenance using **Time of Arrival**

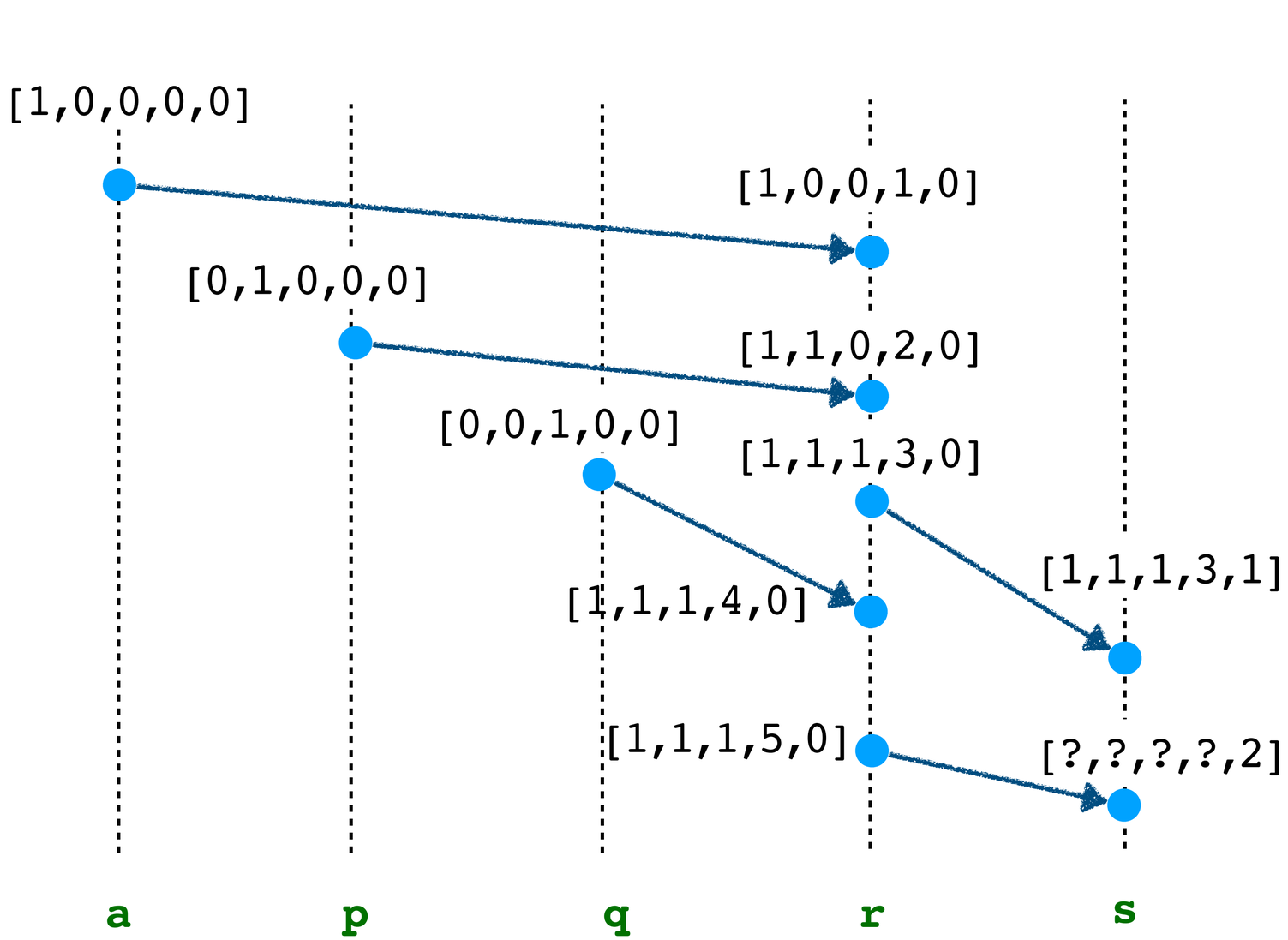
Provenance using **Time of Arrival**



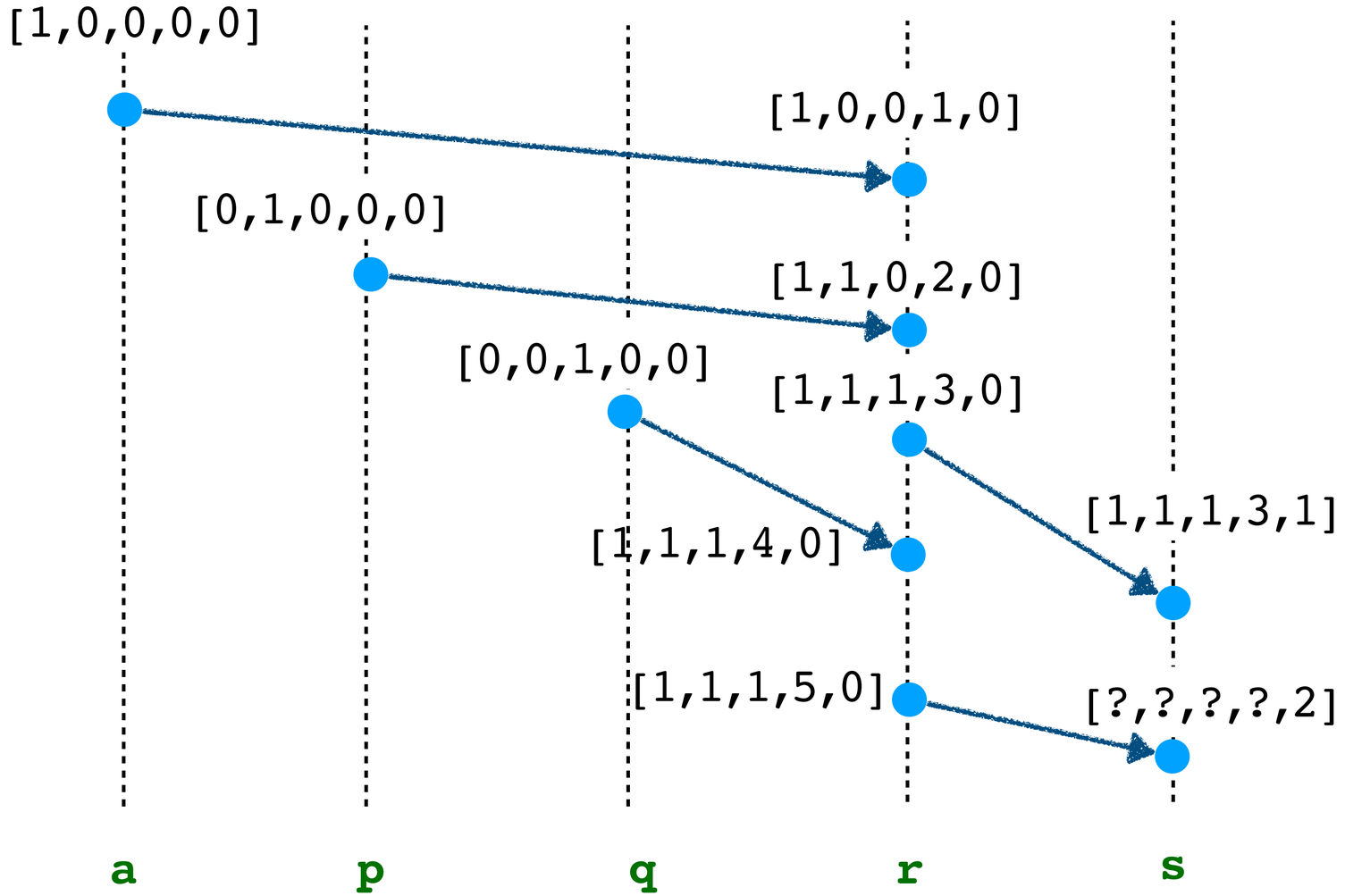
Provenance using **Time of Arrival**



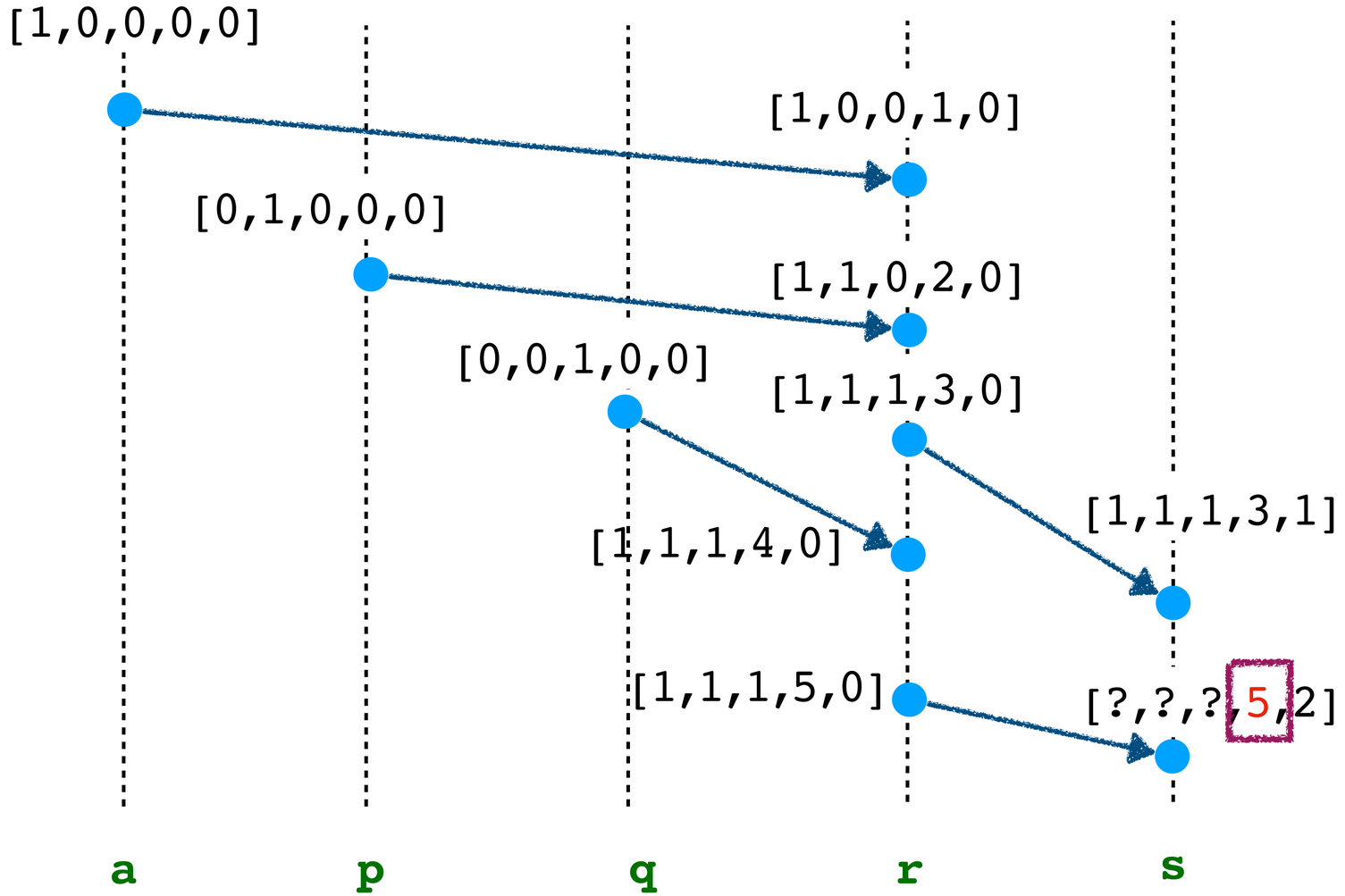
Provenance using **Time of Arrival**



Provenance using **Time of Arrival**



Provenance using **Time of Arrival**



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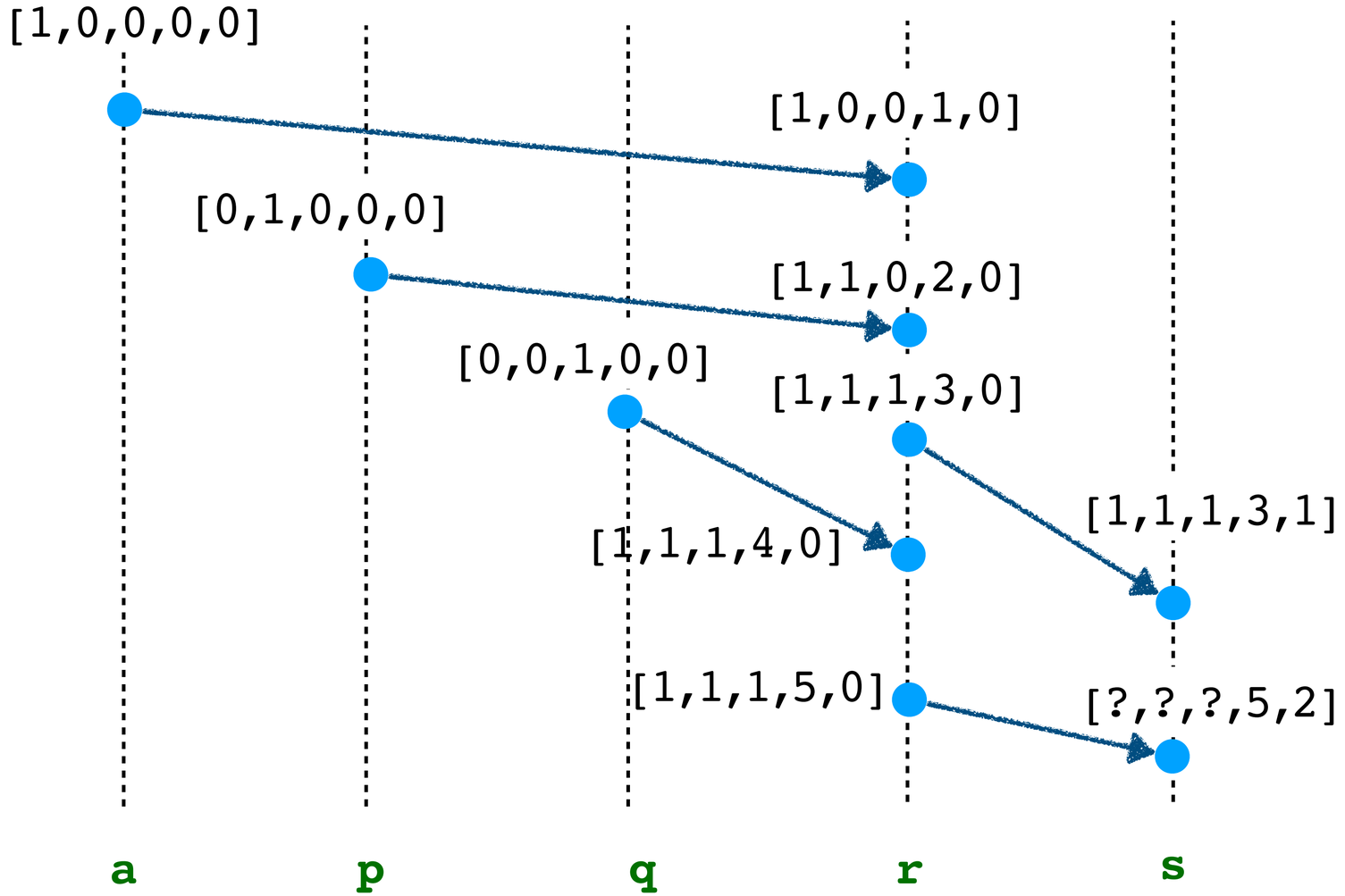
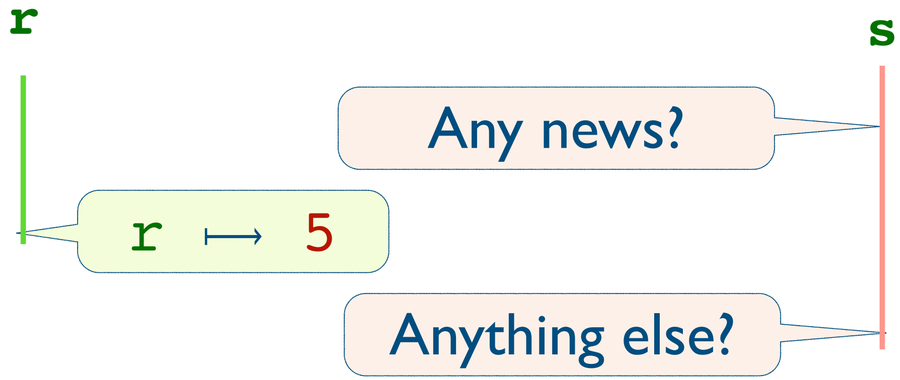
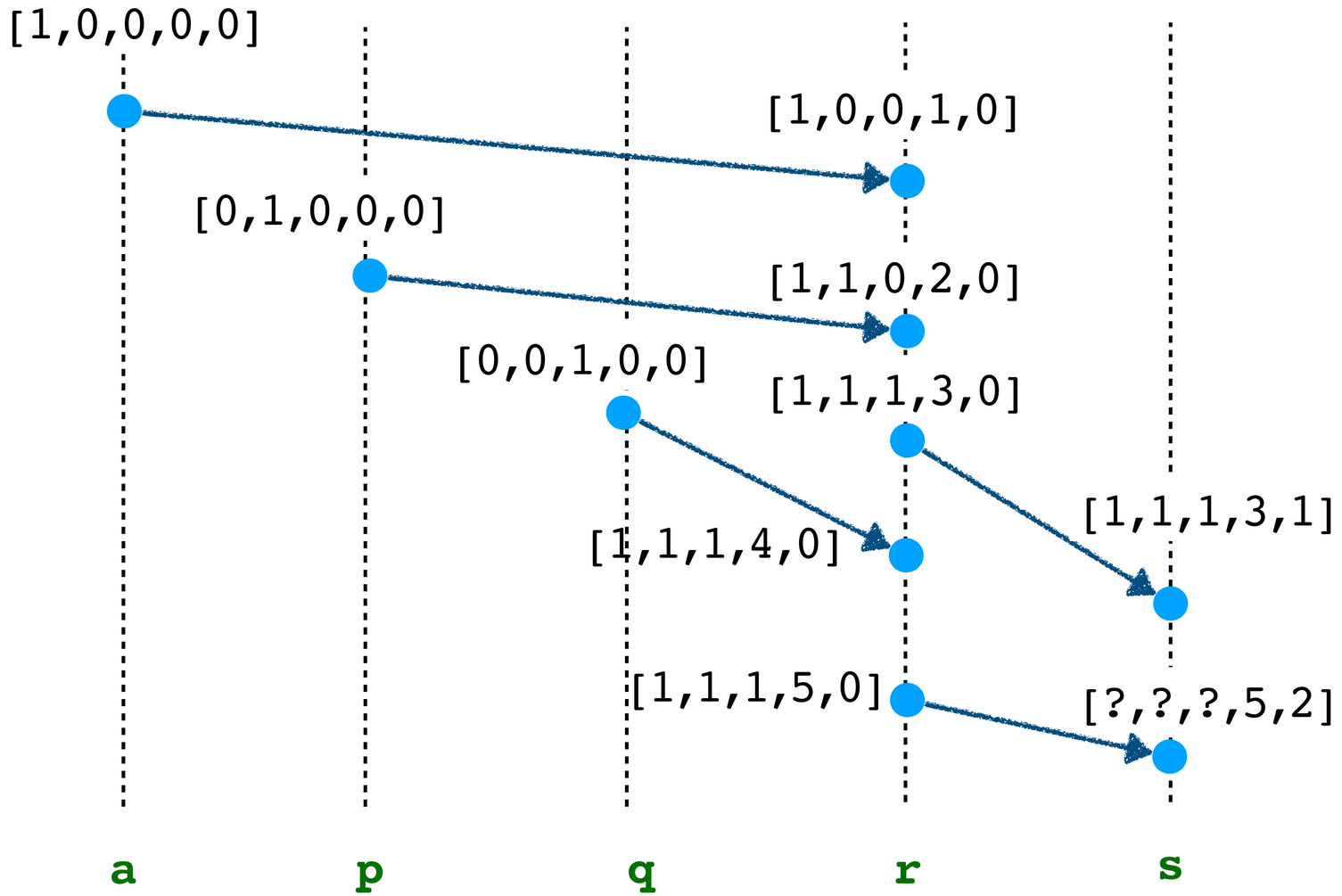
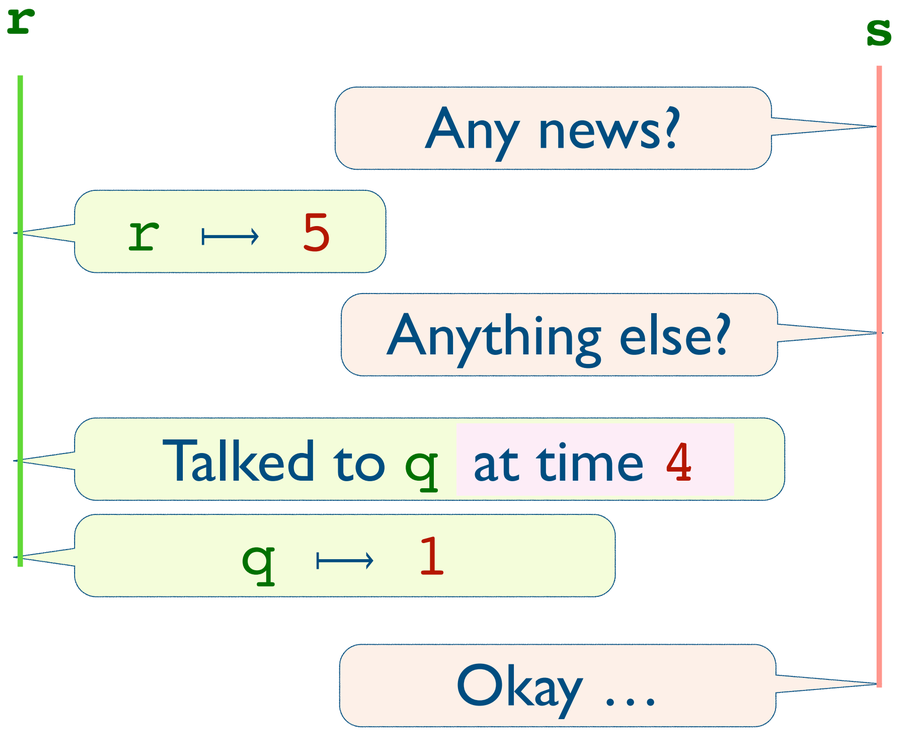




Provenance using **Time of Arrival**





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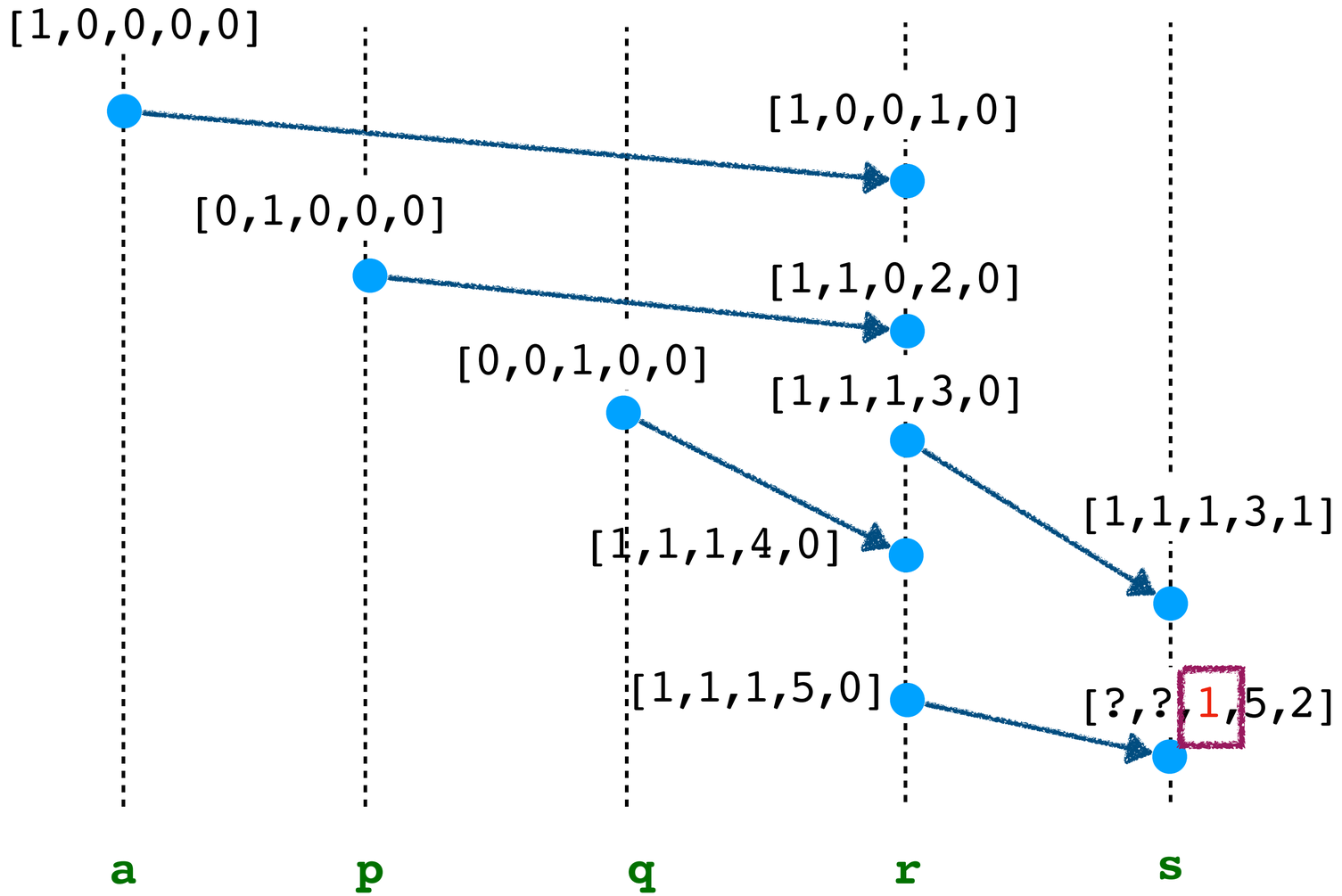
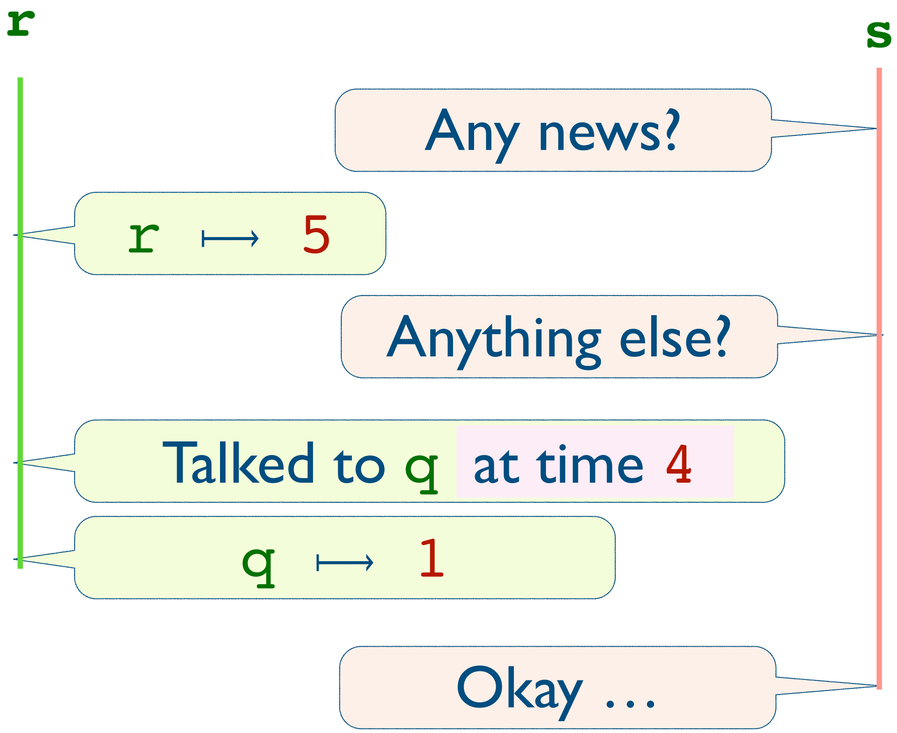
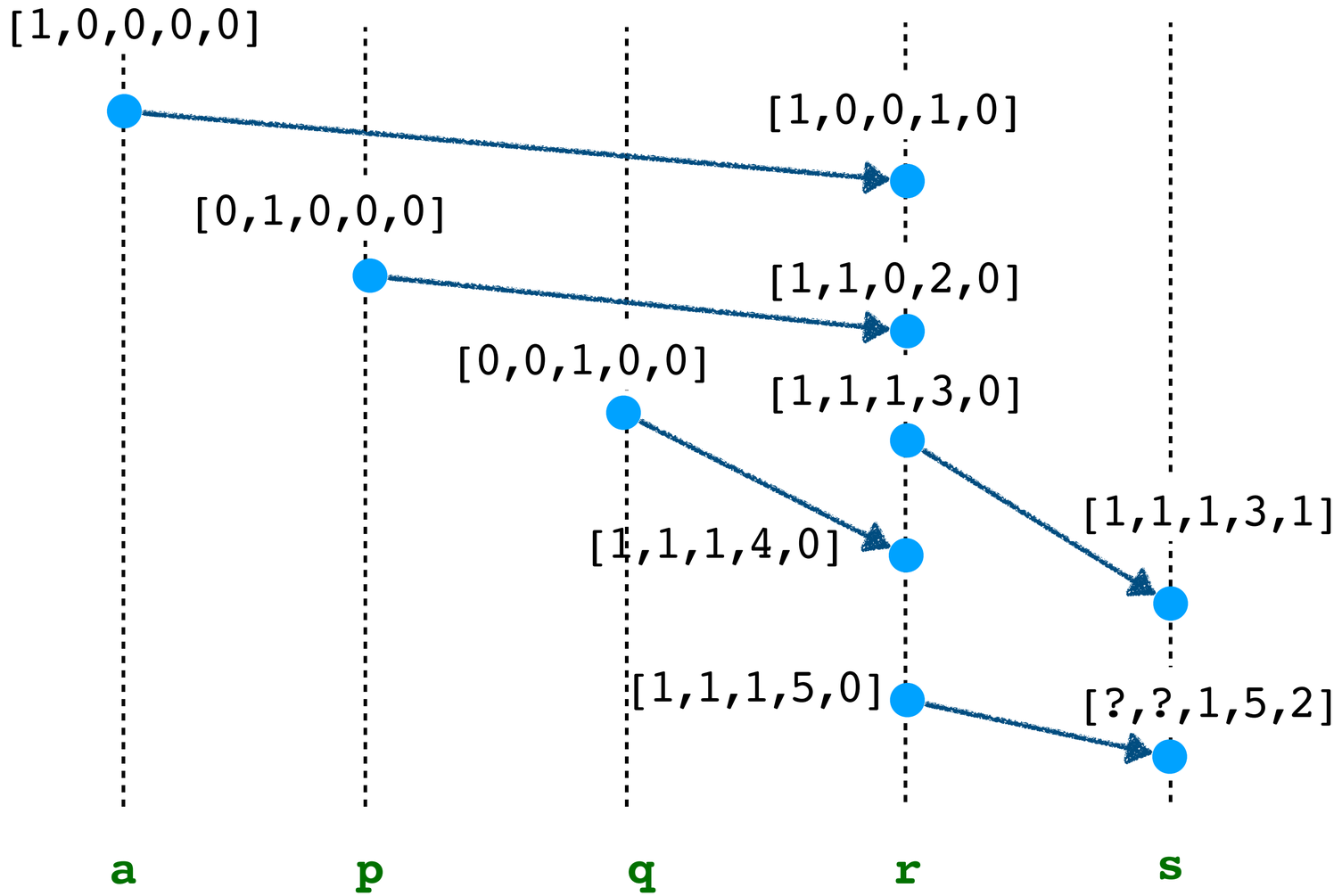
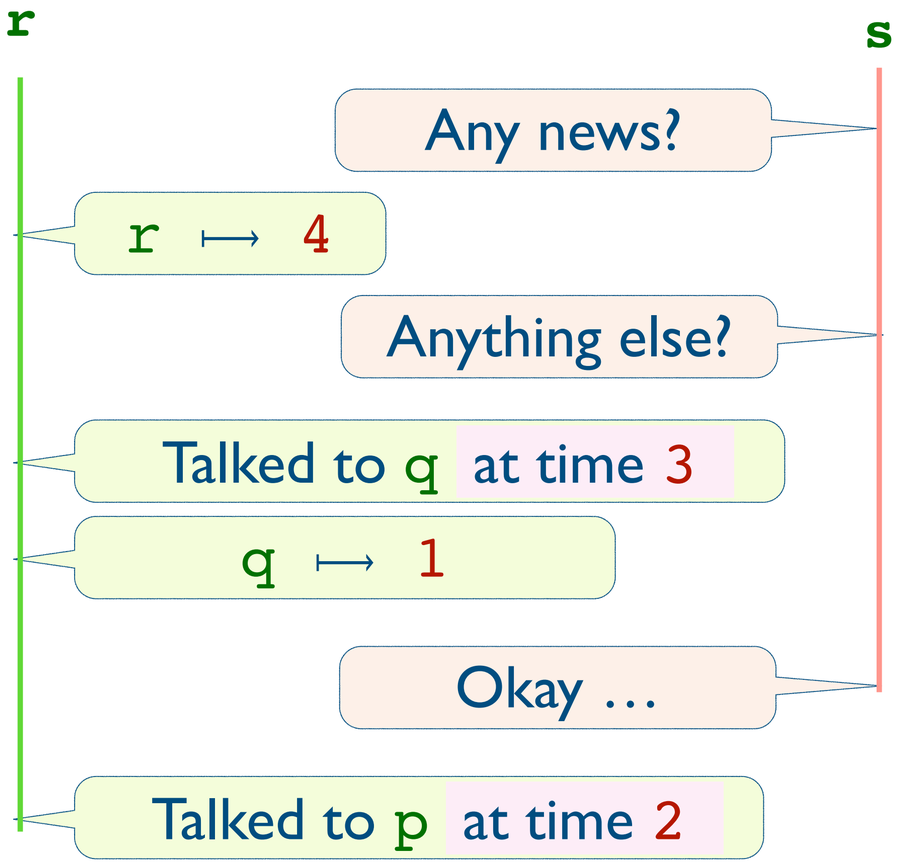


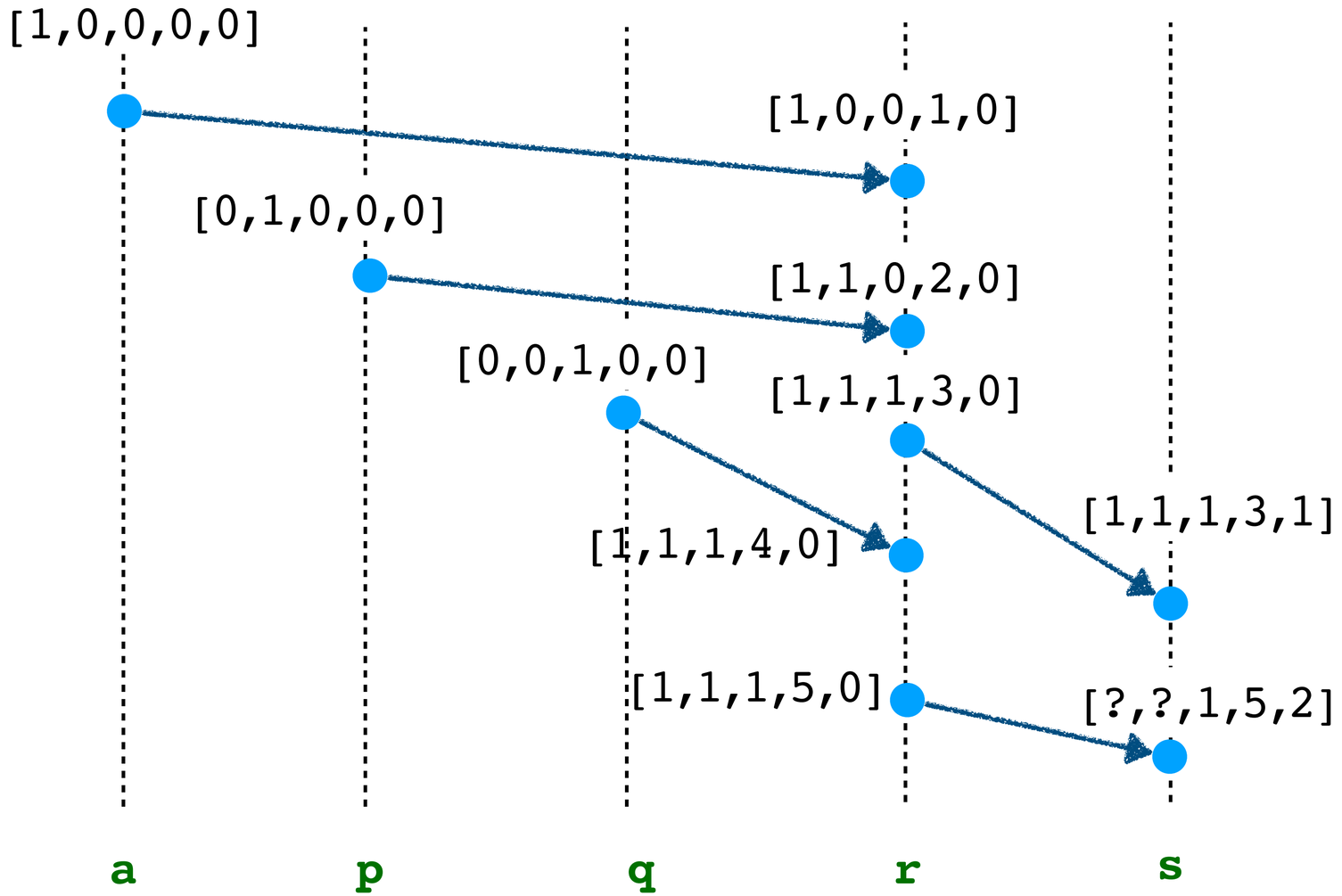


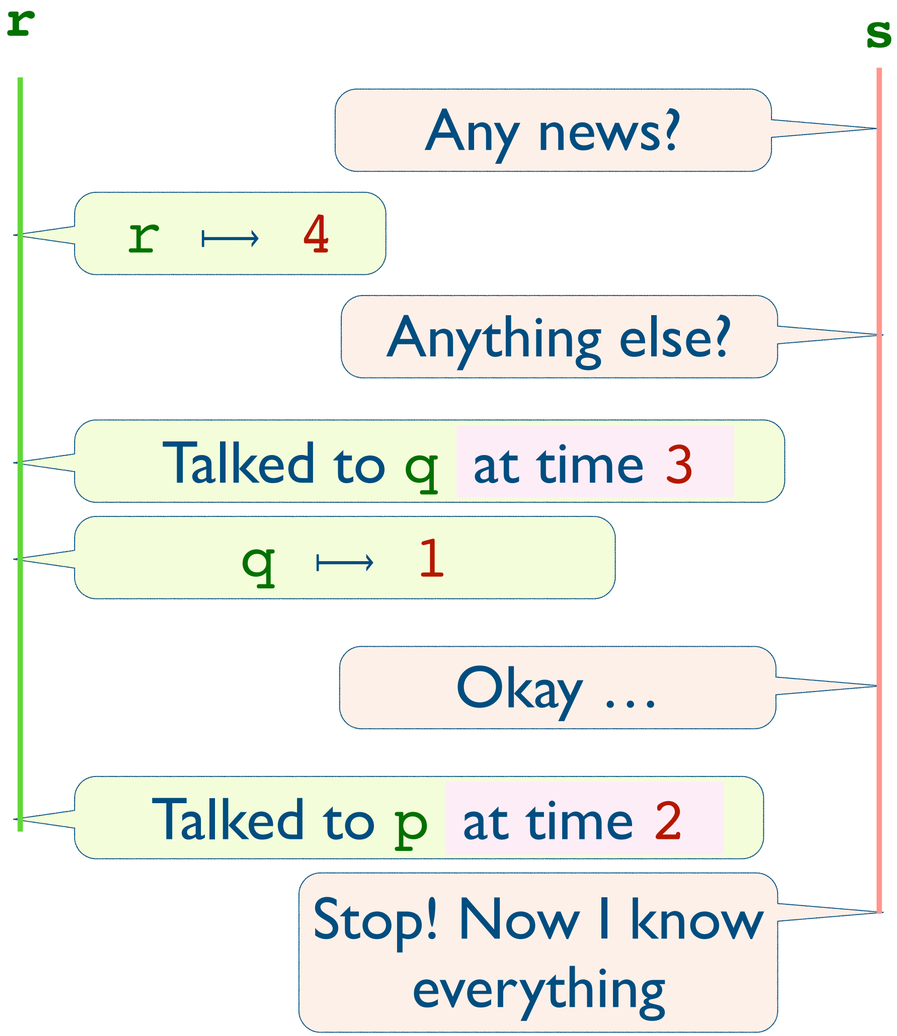
Provenance using **Time of Arrival**



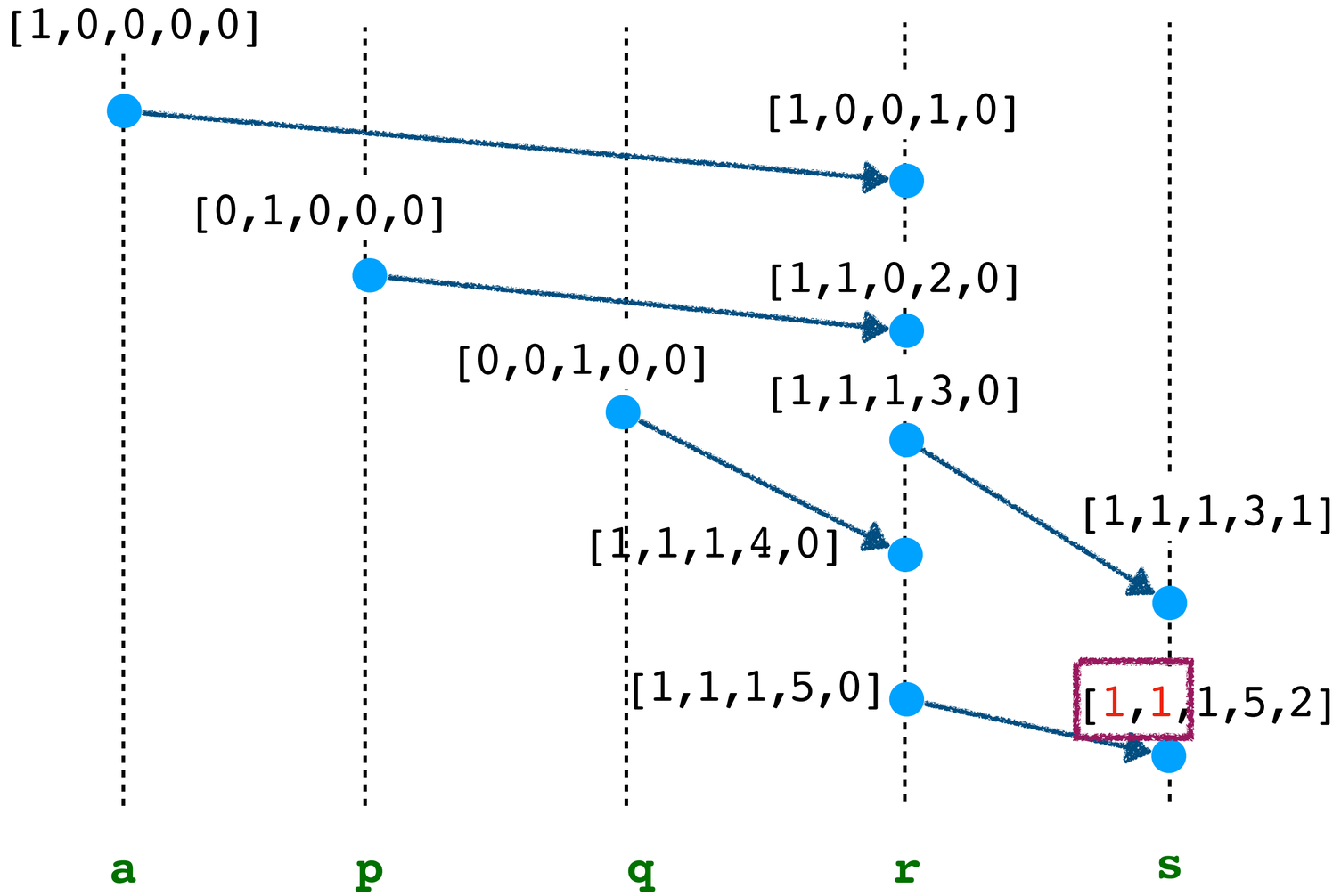


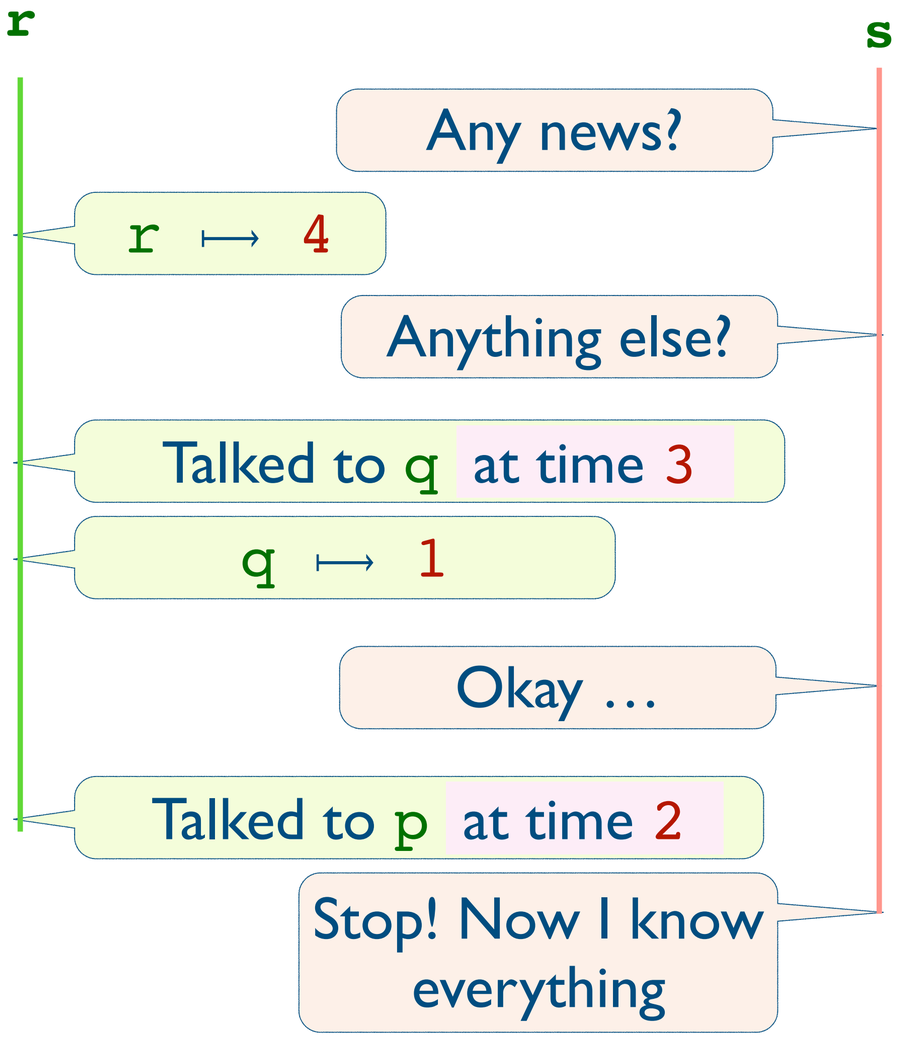
Provenance using **Time of Arrival**



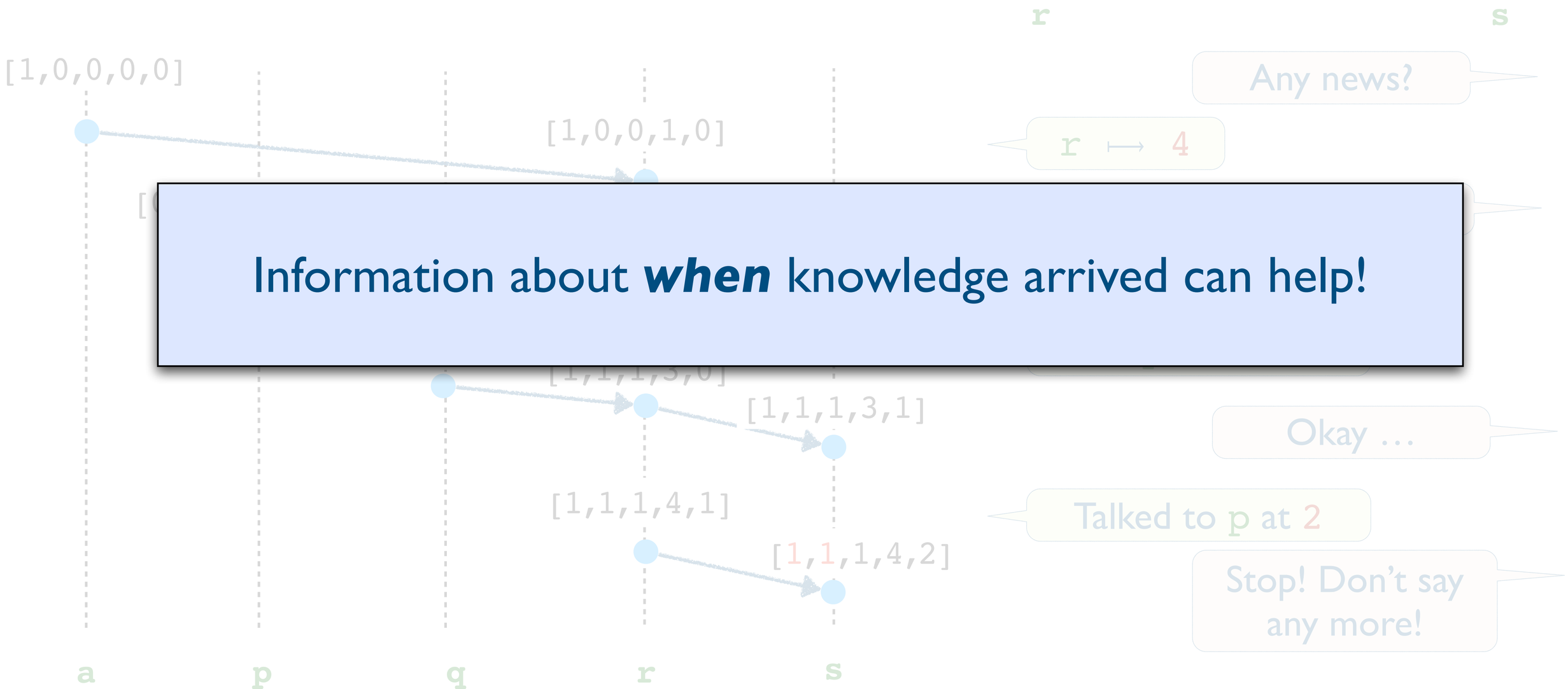


Provenance using **Time of Arrival**

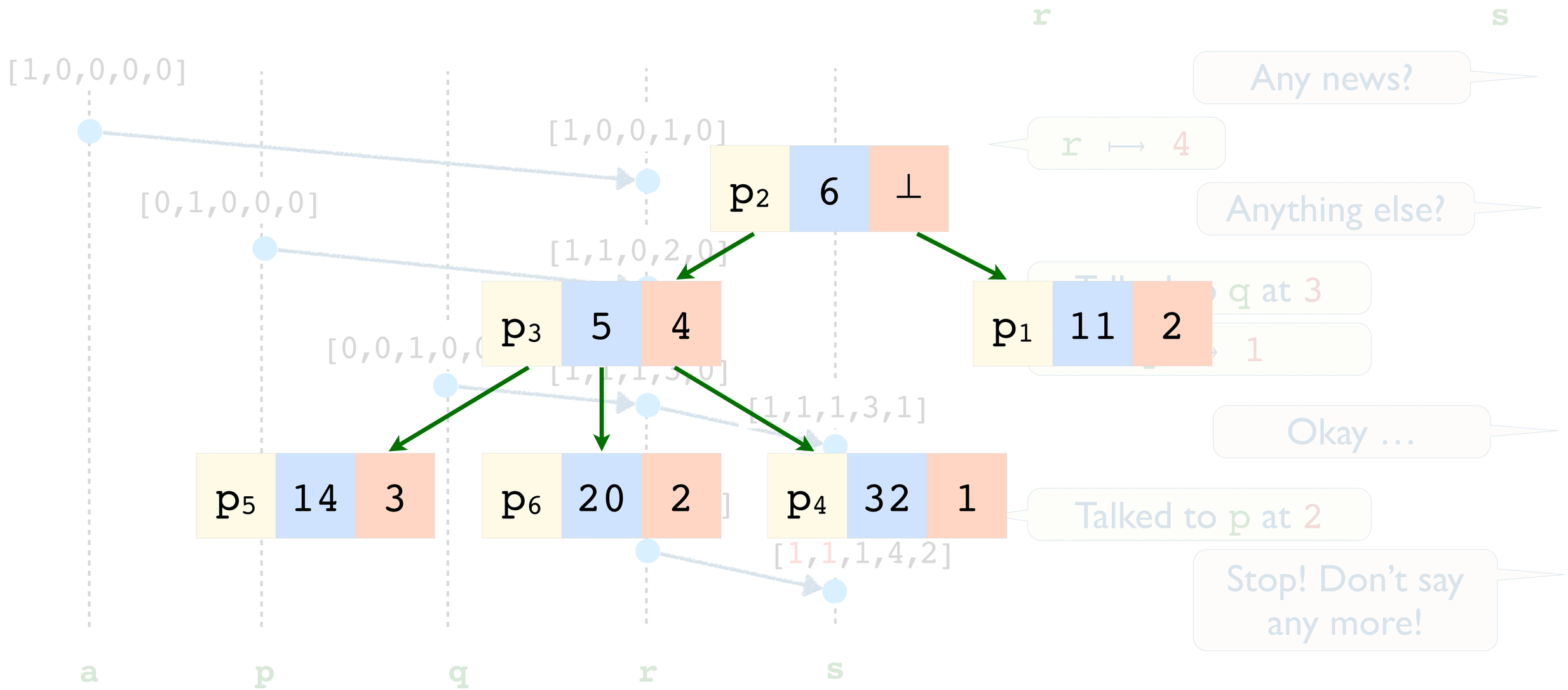




Provenance using **Time of Arrival**



Provenance using **Time of Arrival**



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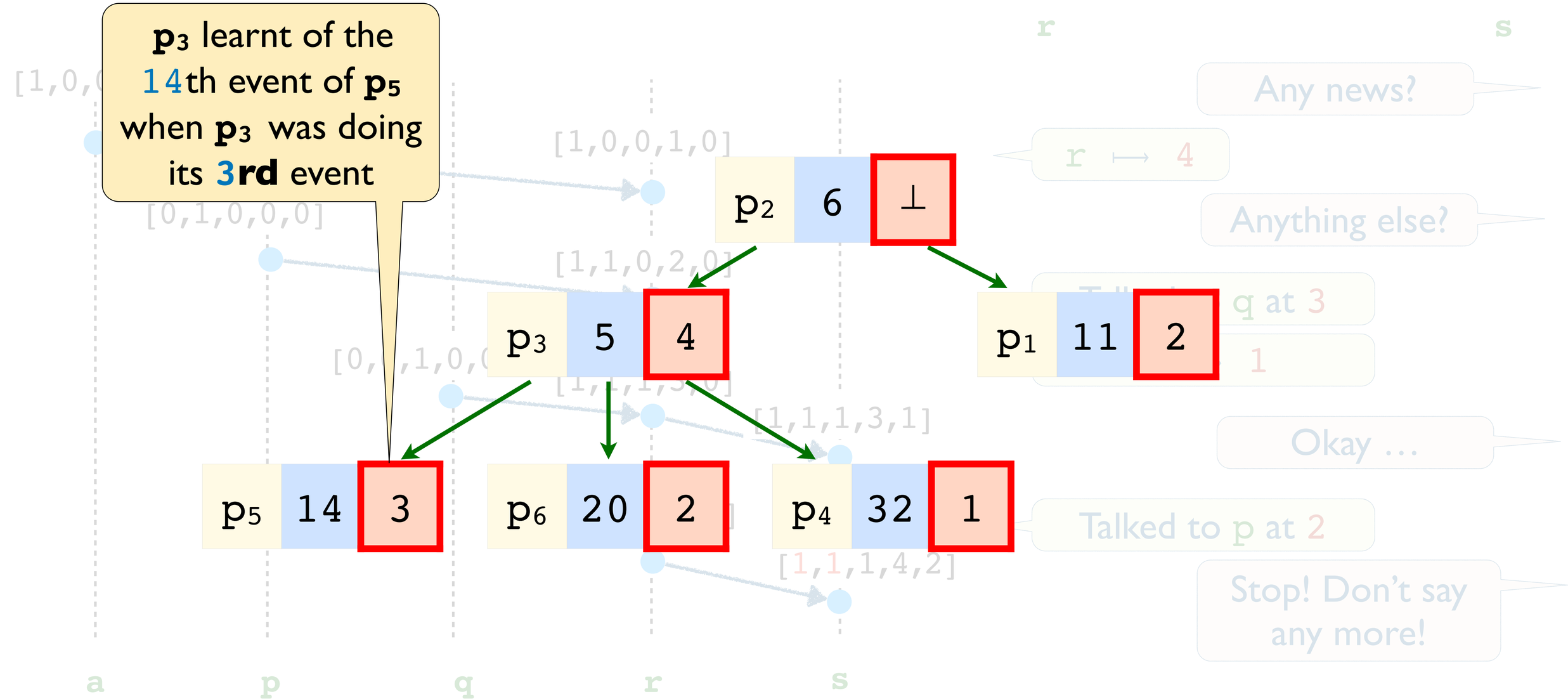


Provenance

How
knowledge arrived

+

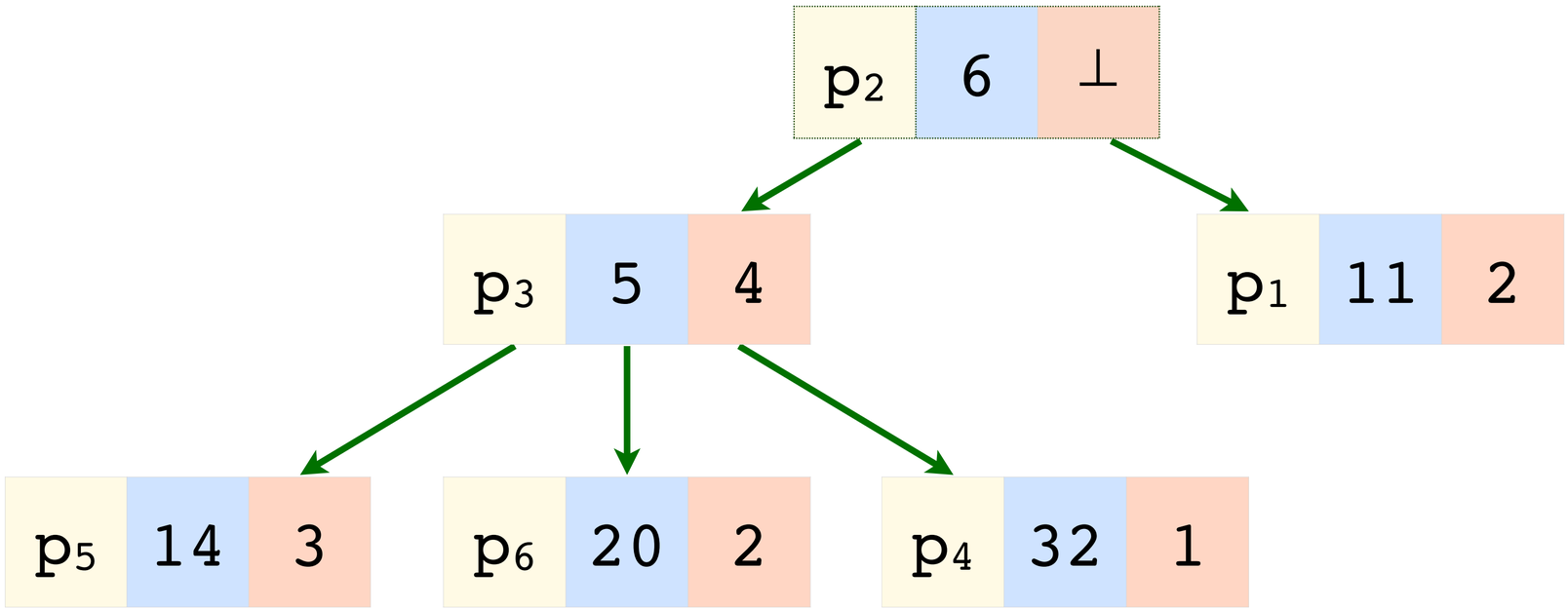
When
knowledge arrived

=

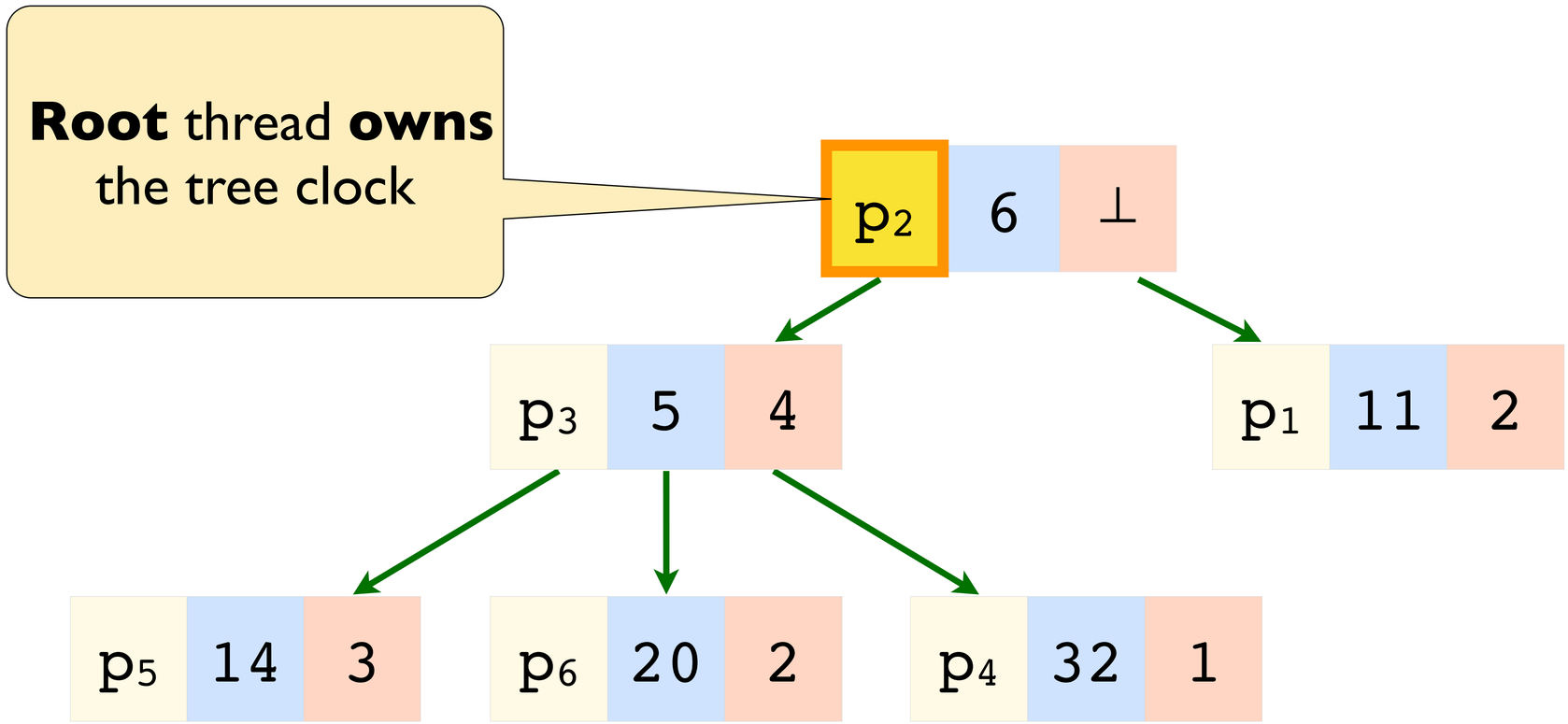
Sub-linear time

Tree Clock

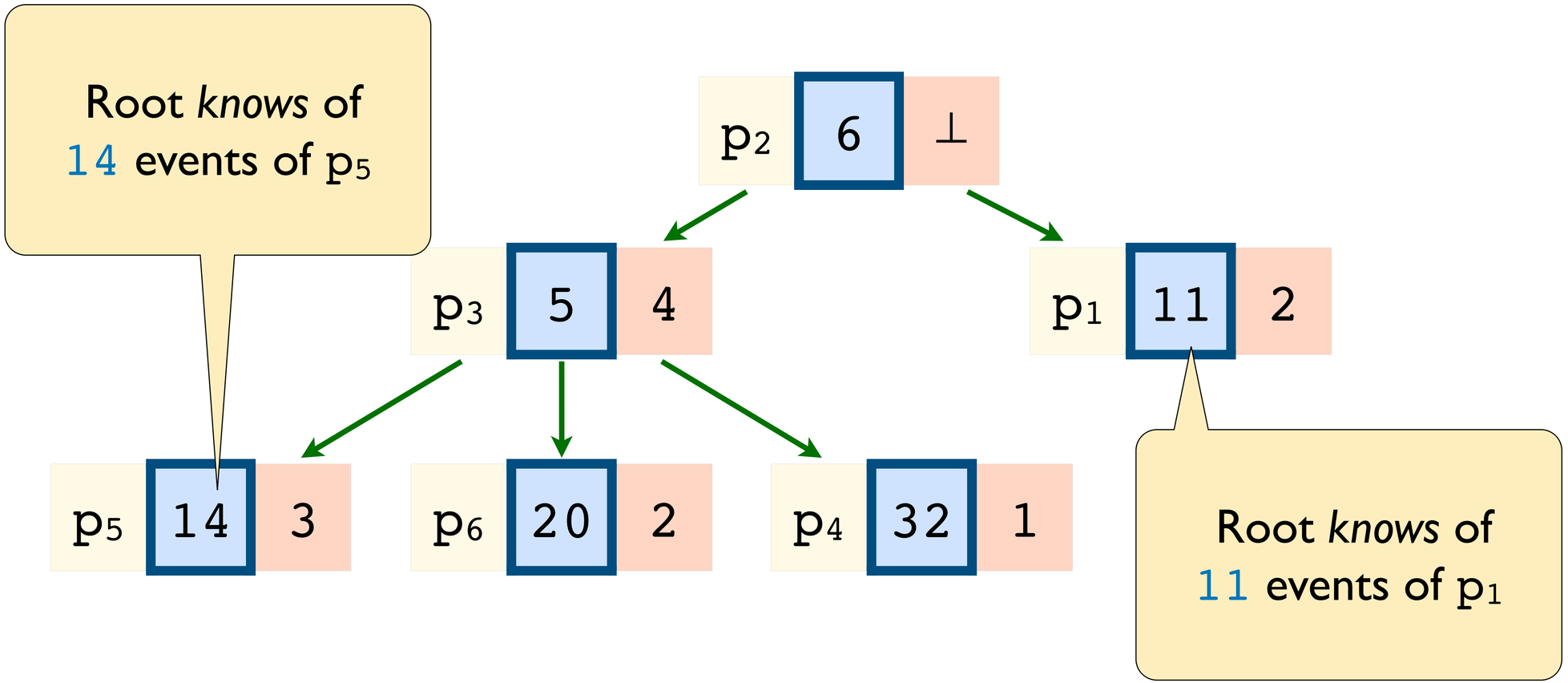
Tree Clock



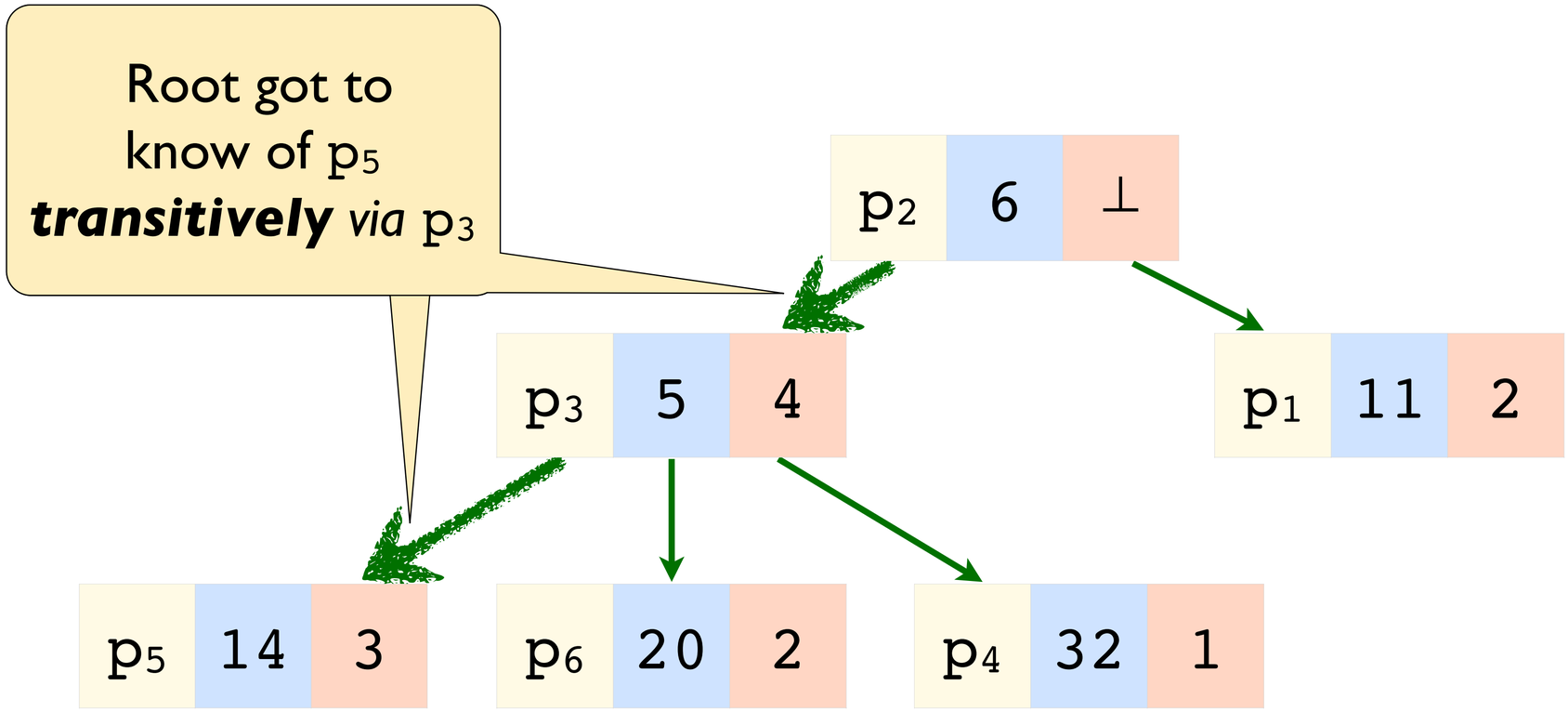
Tree Clock


Root thread **owns** the tree clock
p_2 6 $\perp$
p_3 5 4
p_1 11 2
p_5 14 3
p_6 20 2
p_4 32 1

Tree Clock

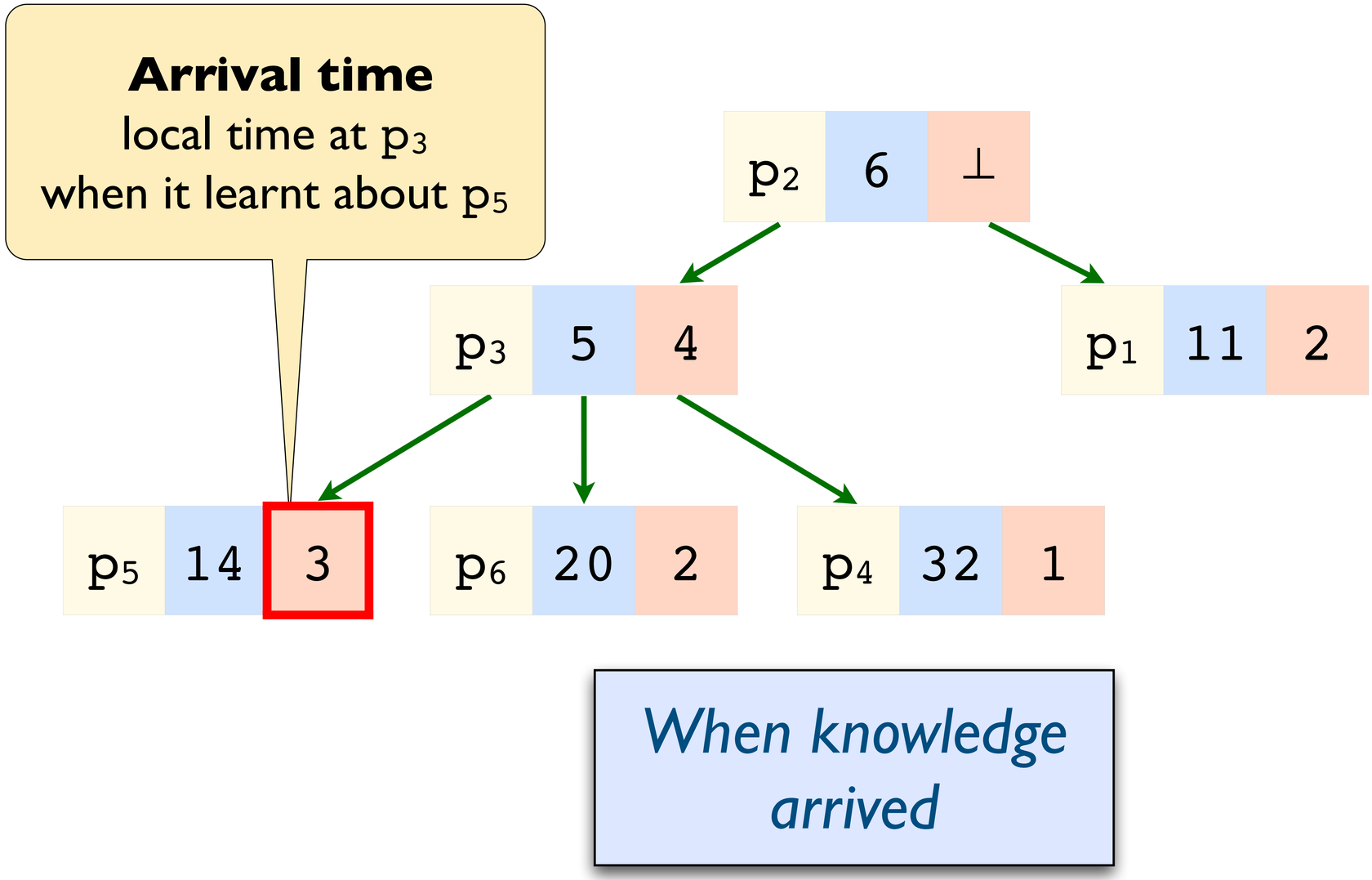

Root *knows* of
14 events of p_5
p_2 6 ⊥
p_3 5 4
p_1 11 2
p_5 14 3
p_6 20 2
p_4 32 1
Root *knows* of
11 events of p_1

Tree Clock

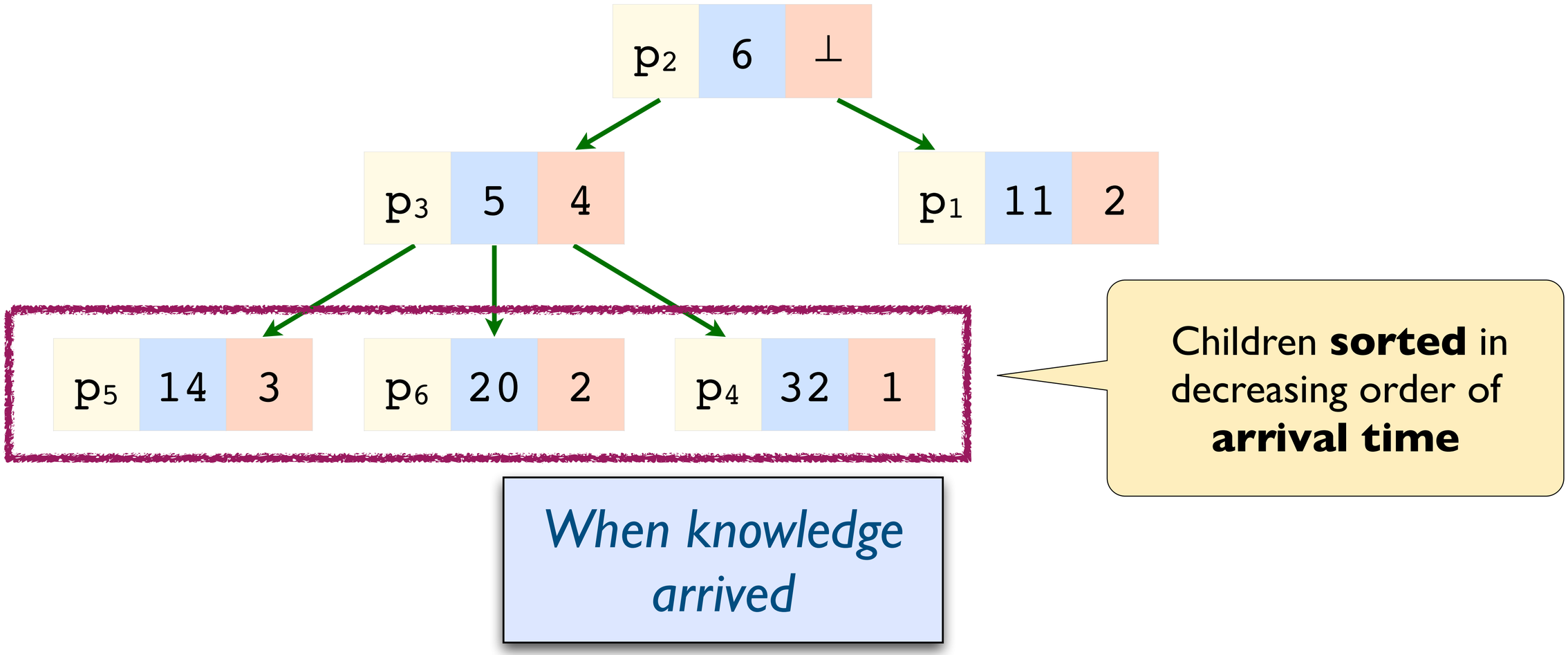


How knowledge arrived

Tree Clock

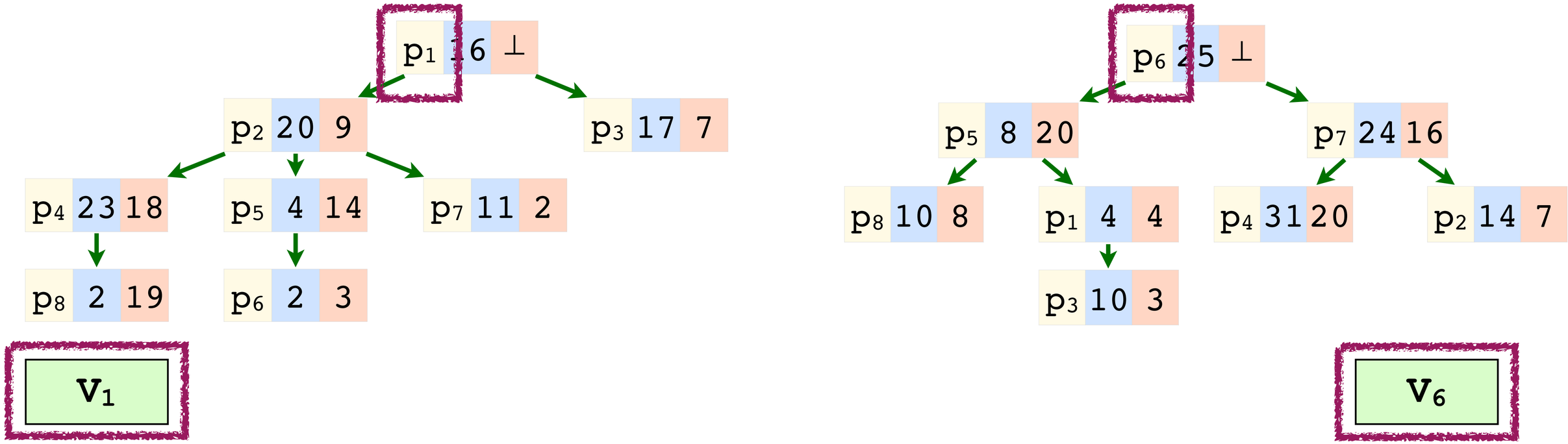

Arrival time
local time at p_3
when it learnt about p_5
p_2 6 ⊥
p_3 5 4
p_1 11 2
p_5 14 3
p_6 20 2
p_4 32 1
When knowledge arrived

Tree Clock

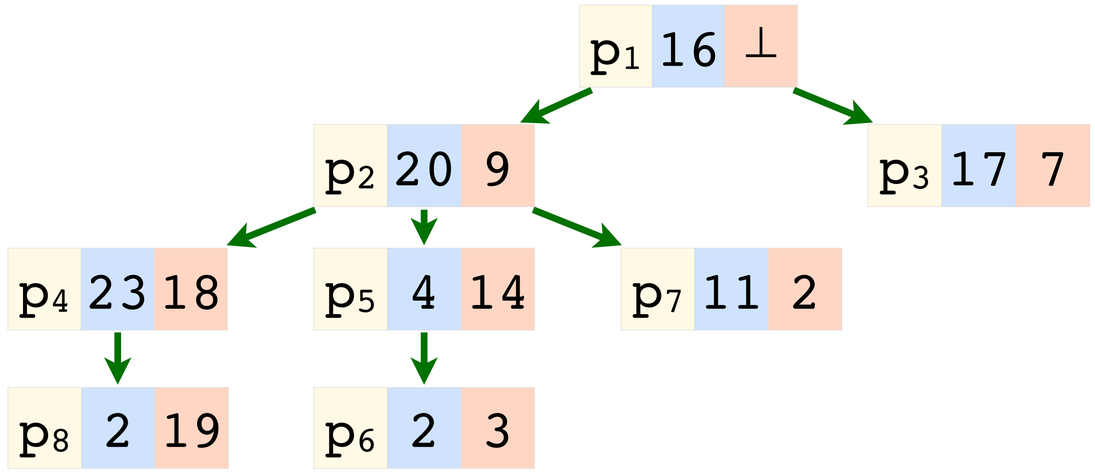

p2 6 ⊥
p3 5 4
p1 11 2
p5 14 3
p6 20 2
p4 32 1
Children **sorted** in decreasing order of **arrival time**
When knowledge arrived

Tree Clock Join

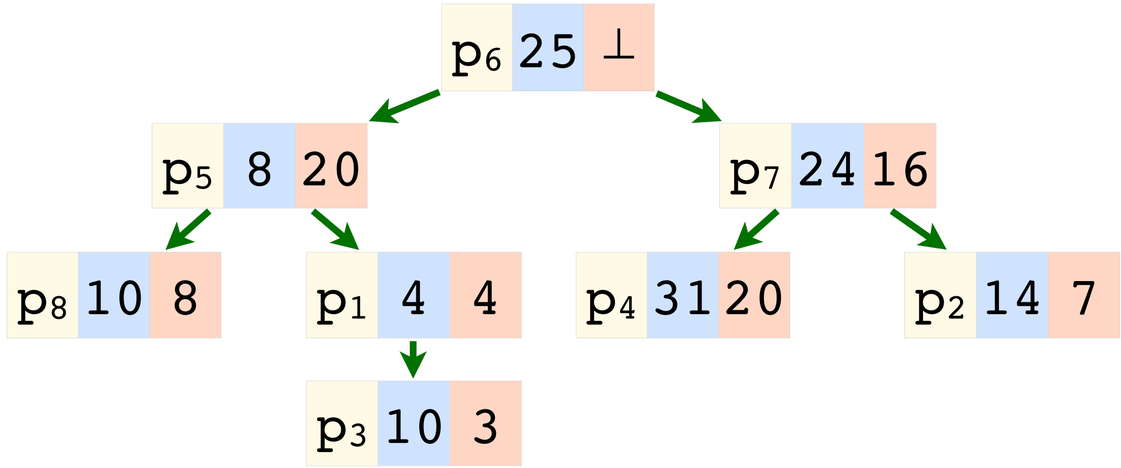
Tree Clock Join



Tree Clock Join



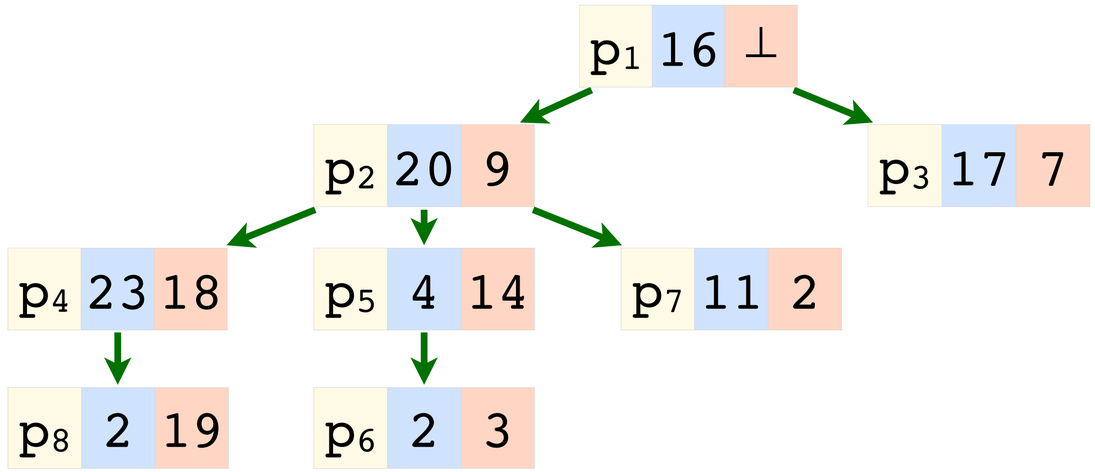
$\mathbf{V_1}$

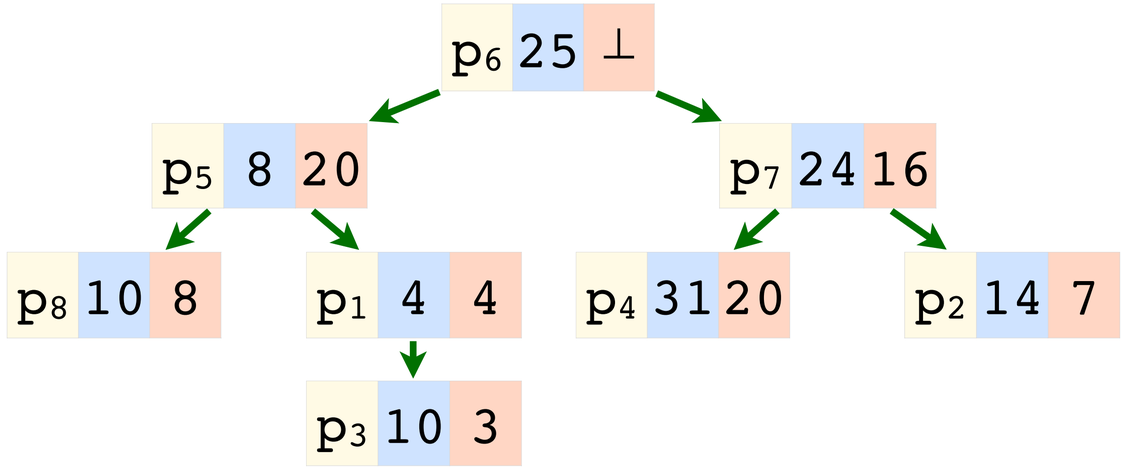


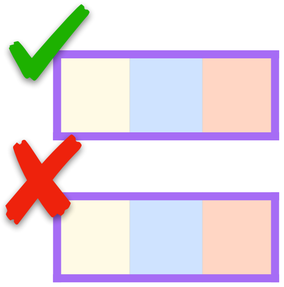
$\mathbf{V_6}$

$\mathbf{V_6}$.JoinWith($\mathbf{V_1}$)

Tree Clock Join



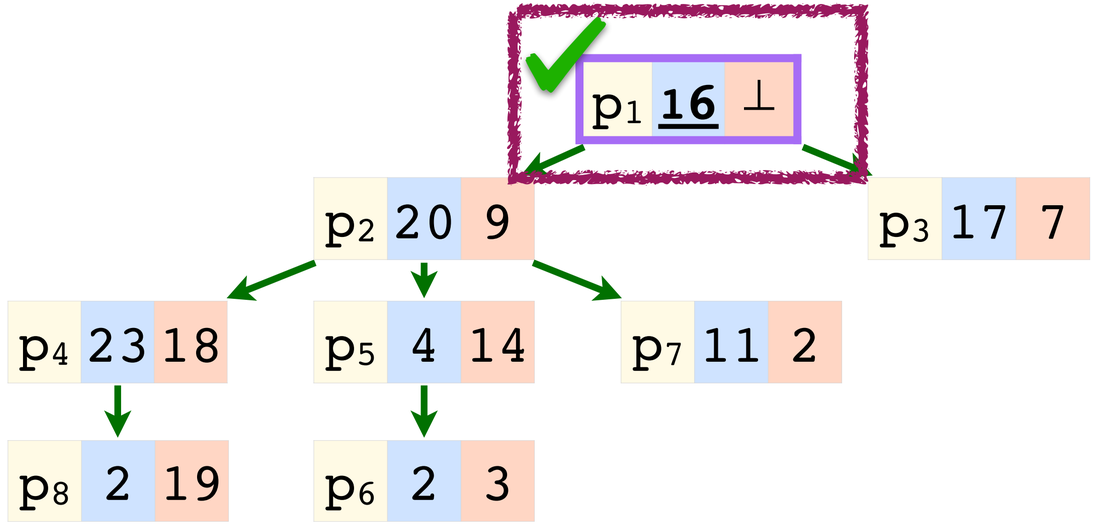


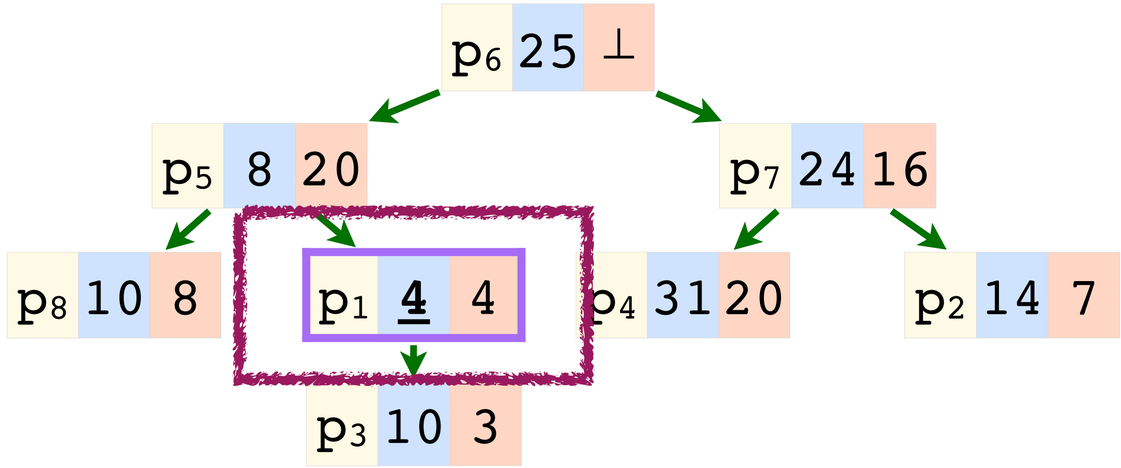


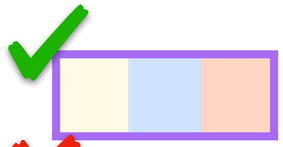
Traversed and Updated

Only Traversed

Tree Clock Join







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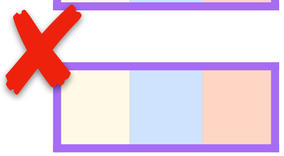

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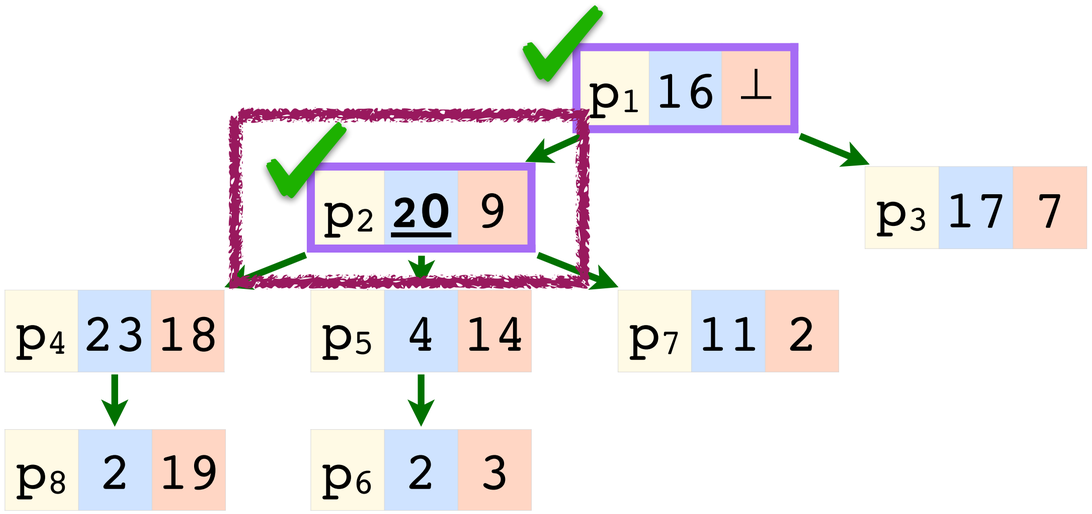

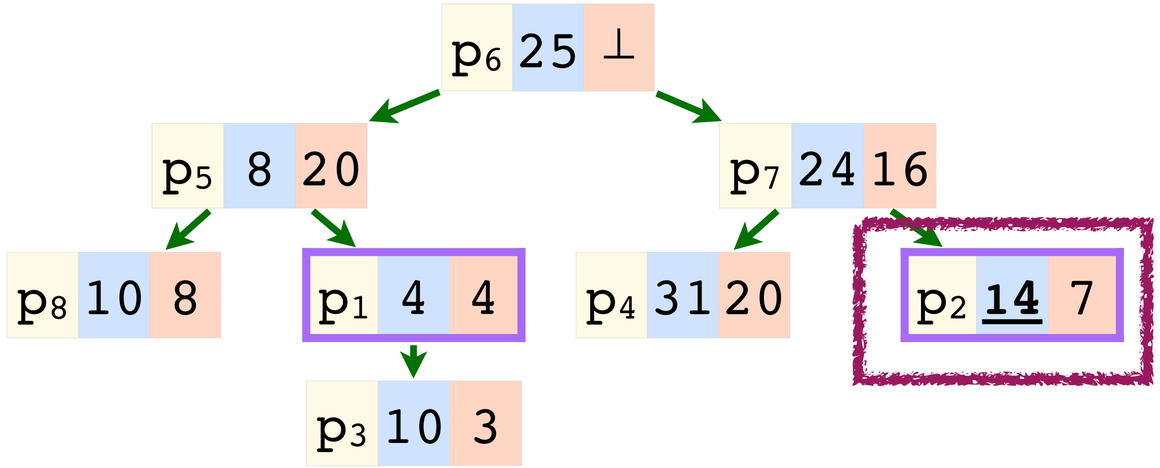

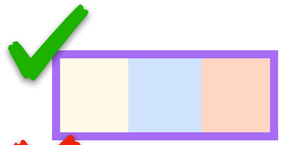

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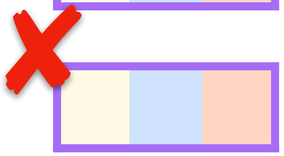

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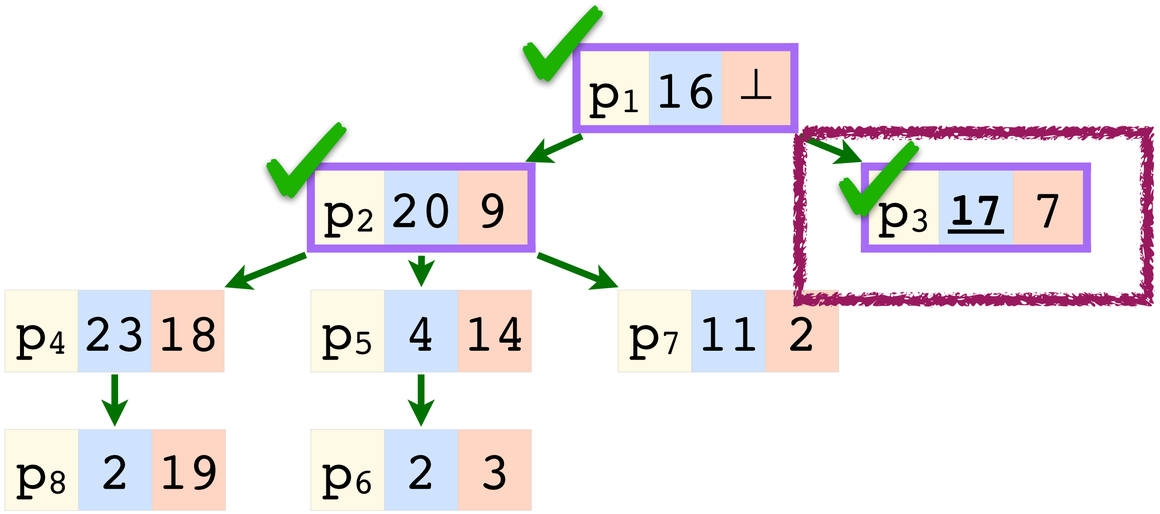

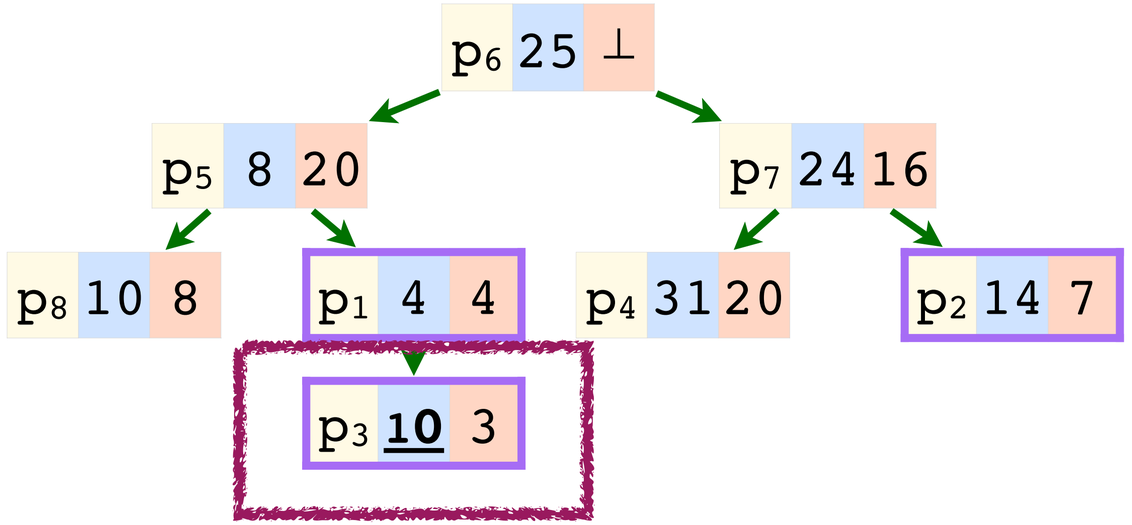

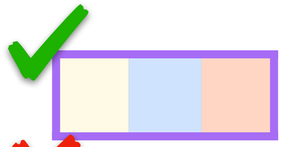

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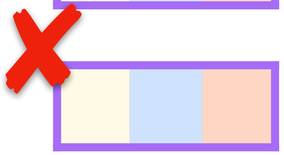

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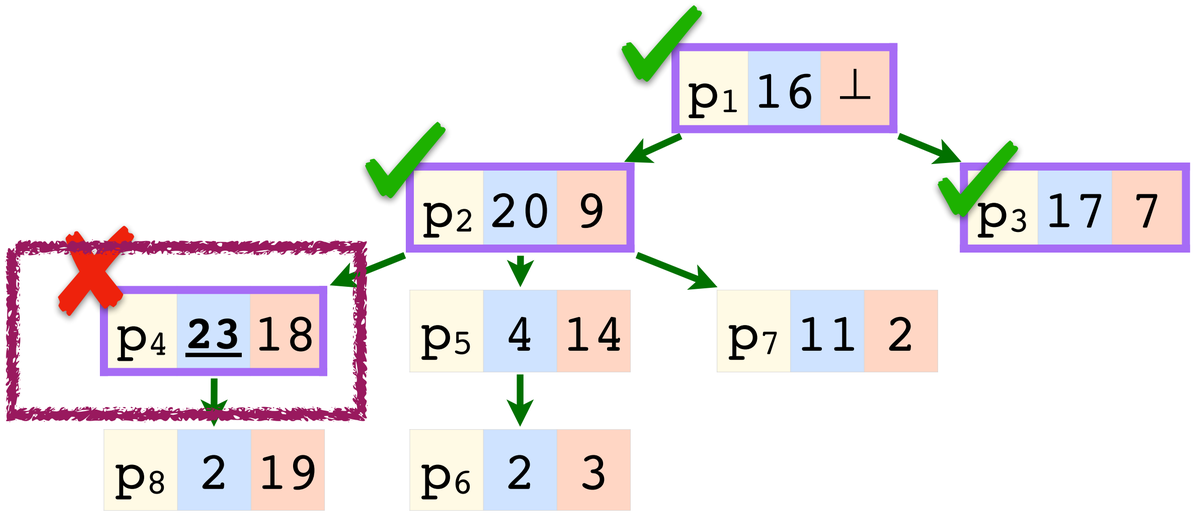

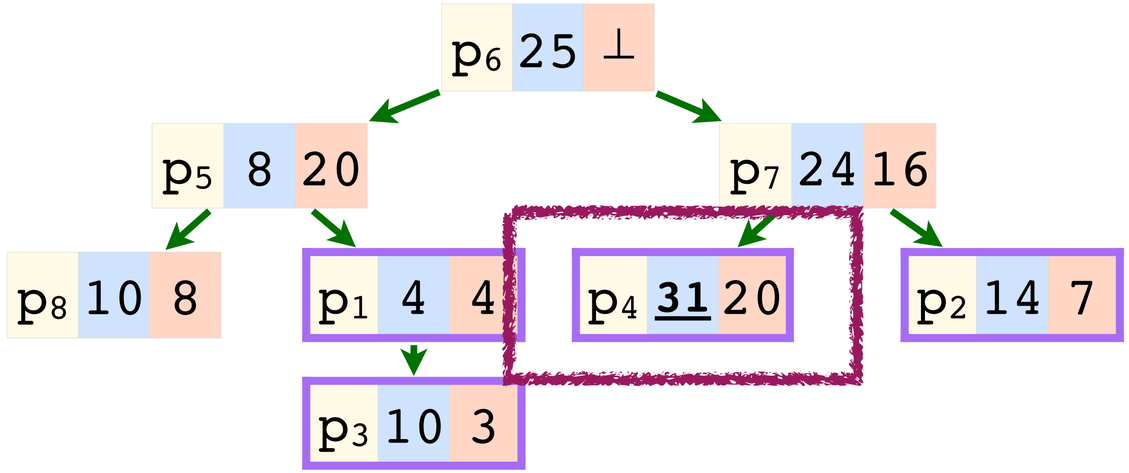

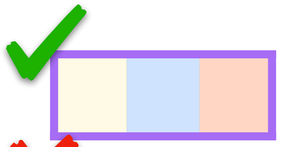

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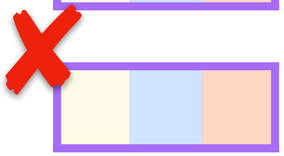

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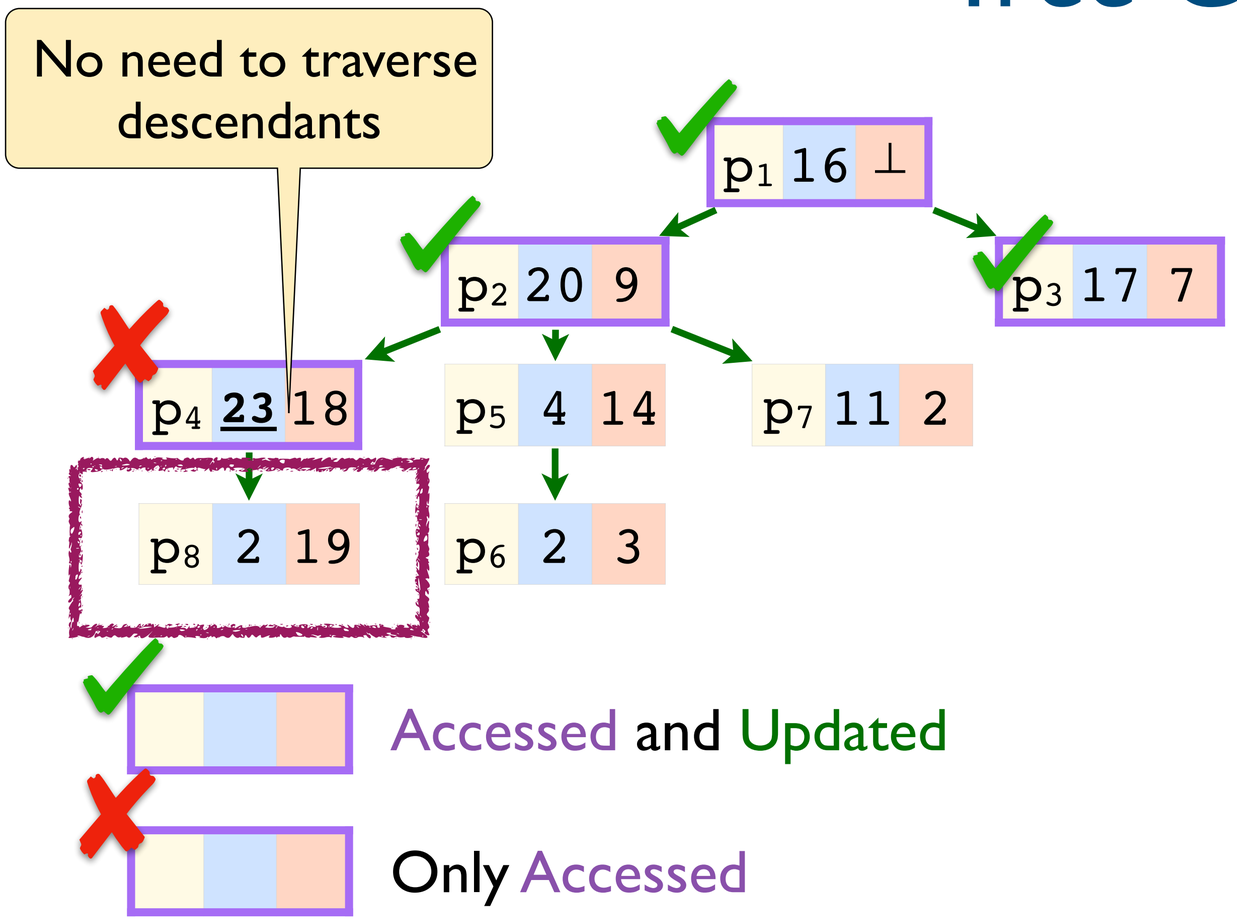

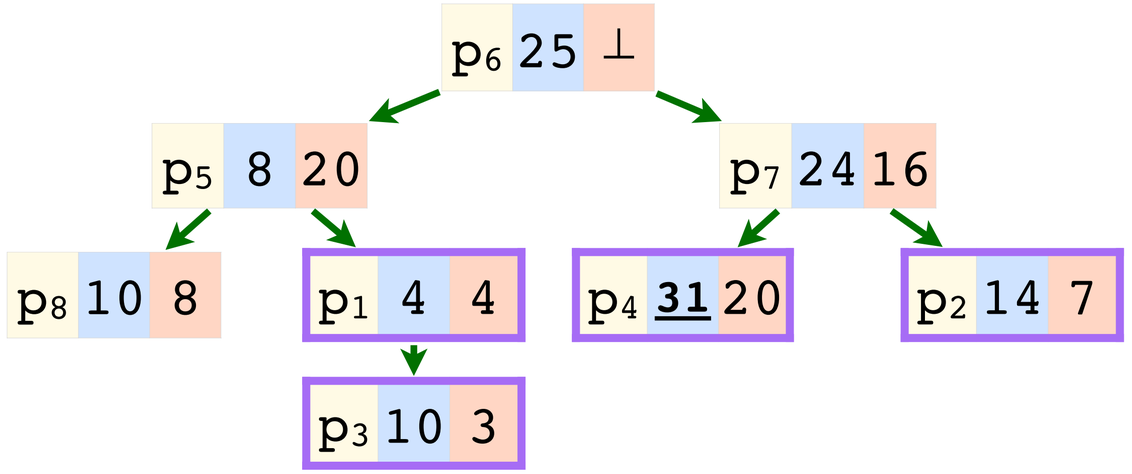

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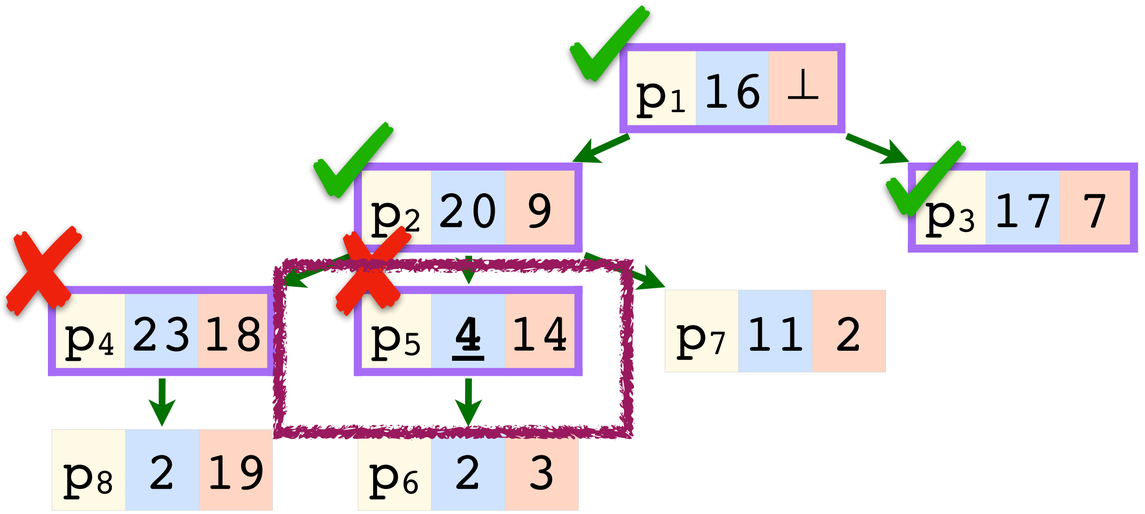

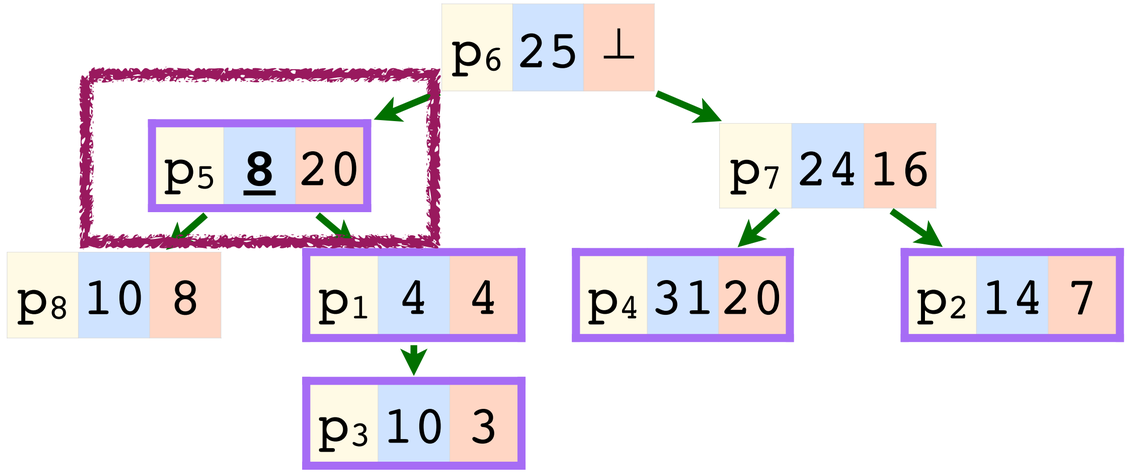

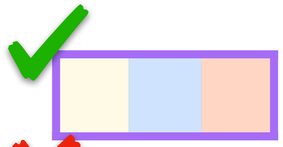

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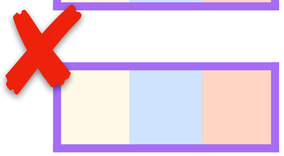

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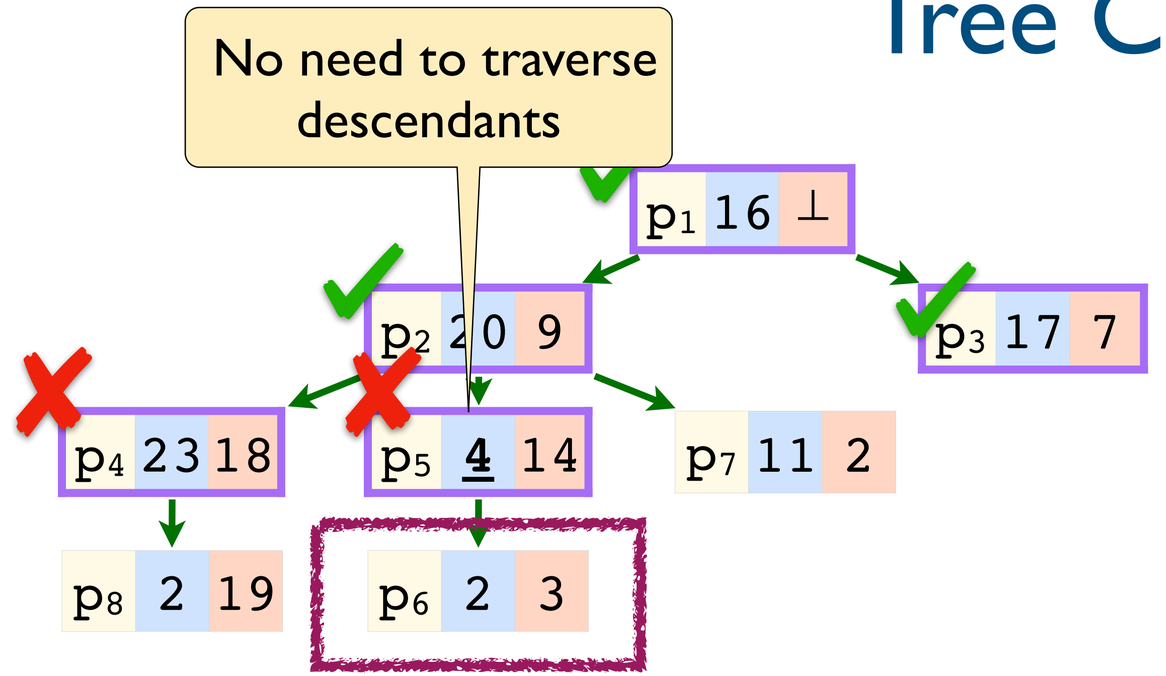

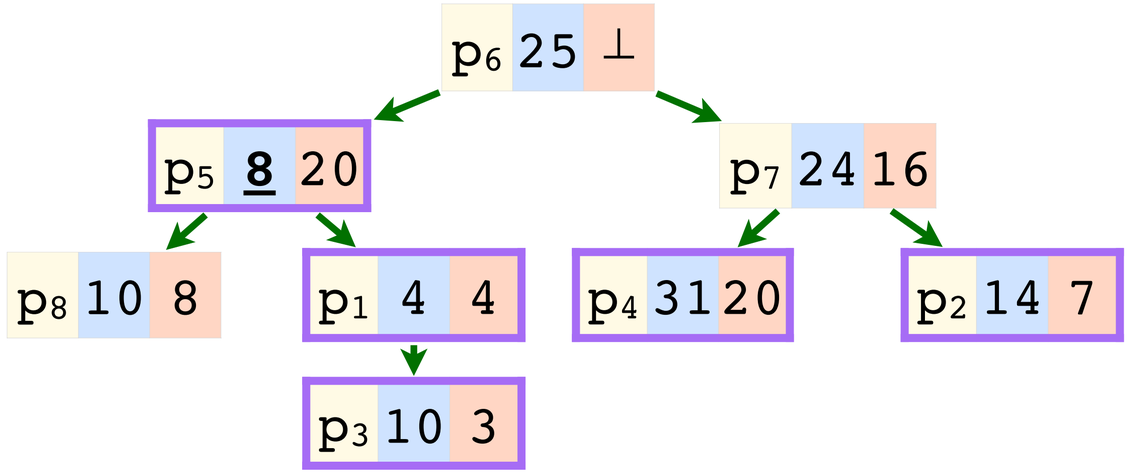

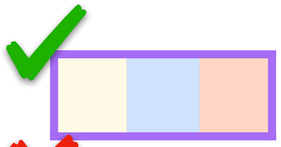

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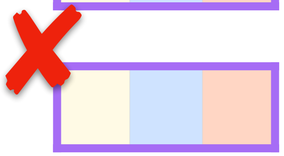

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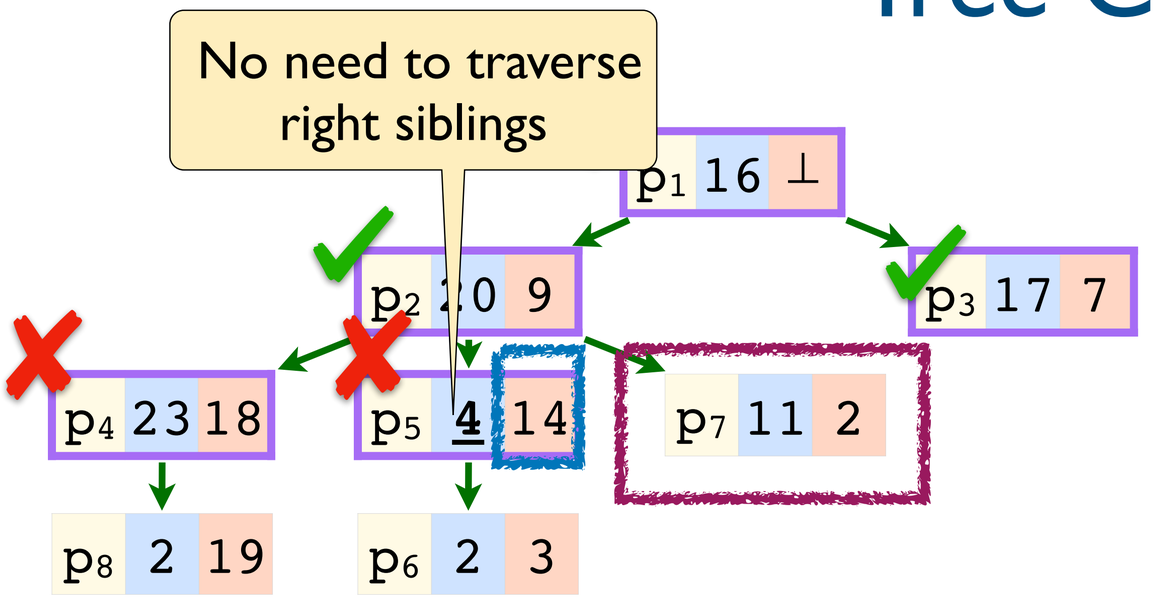

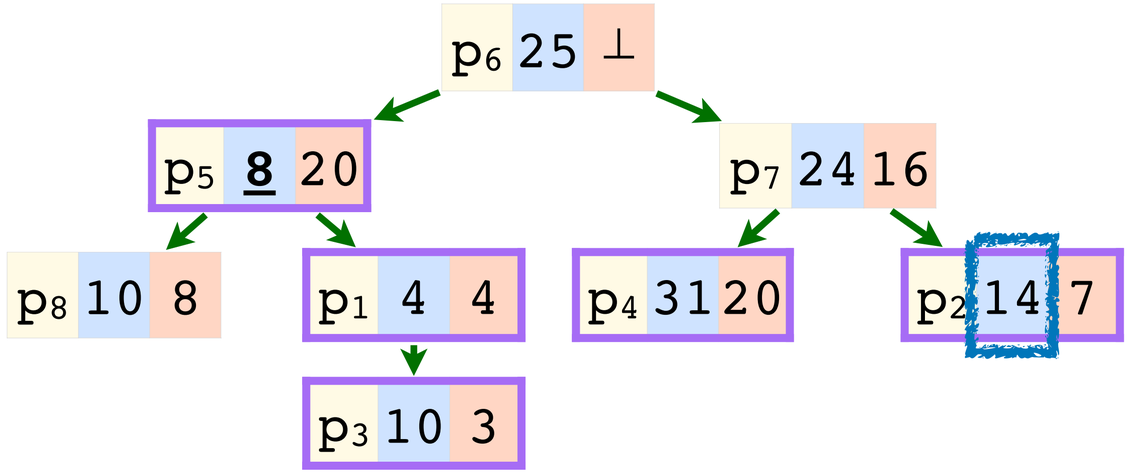

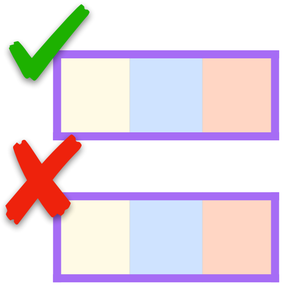

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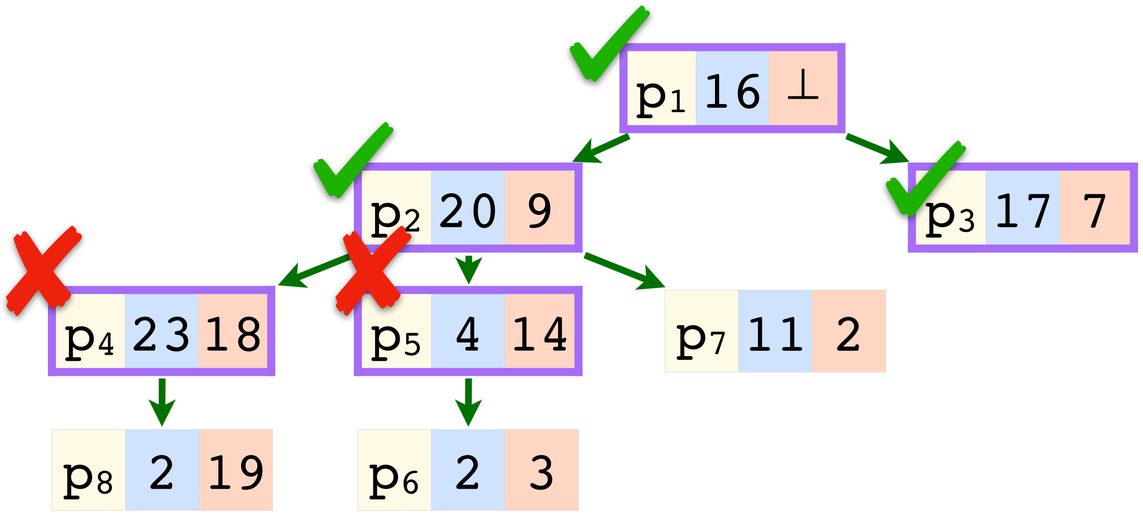

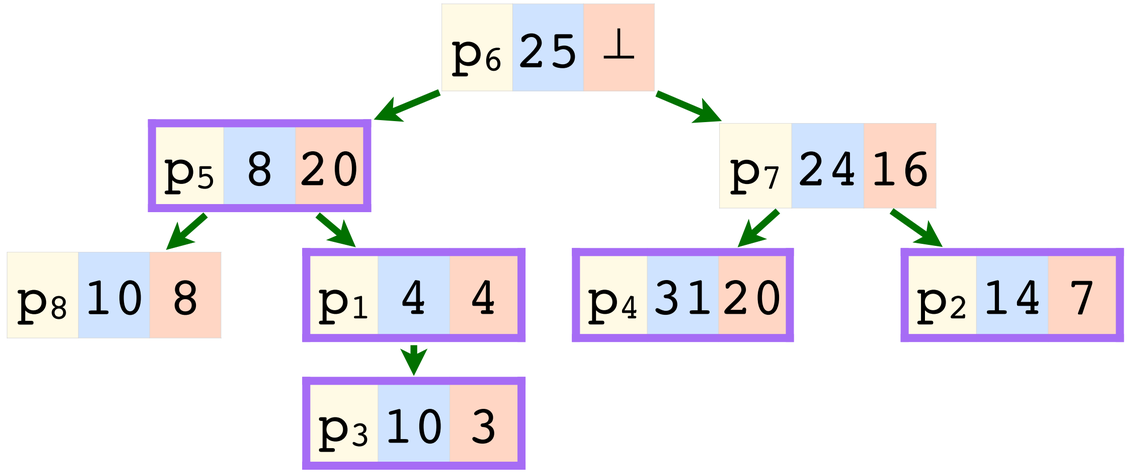

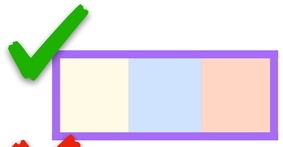

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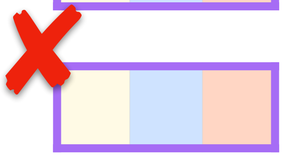

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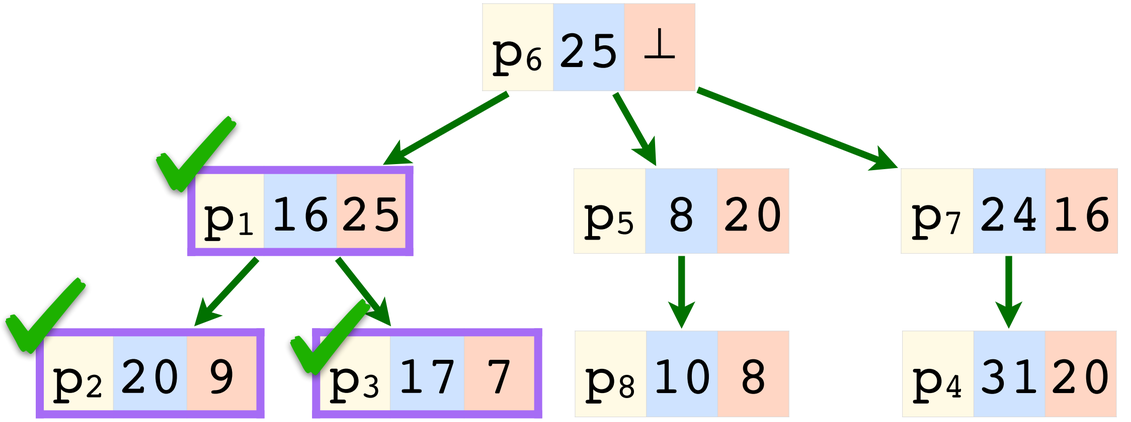

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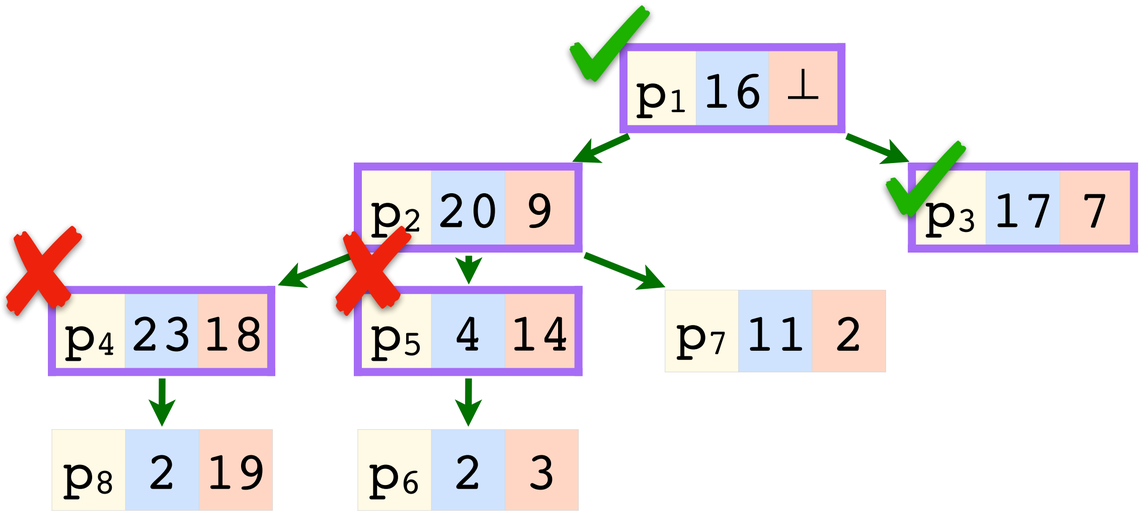

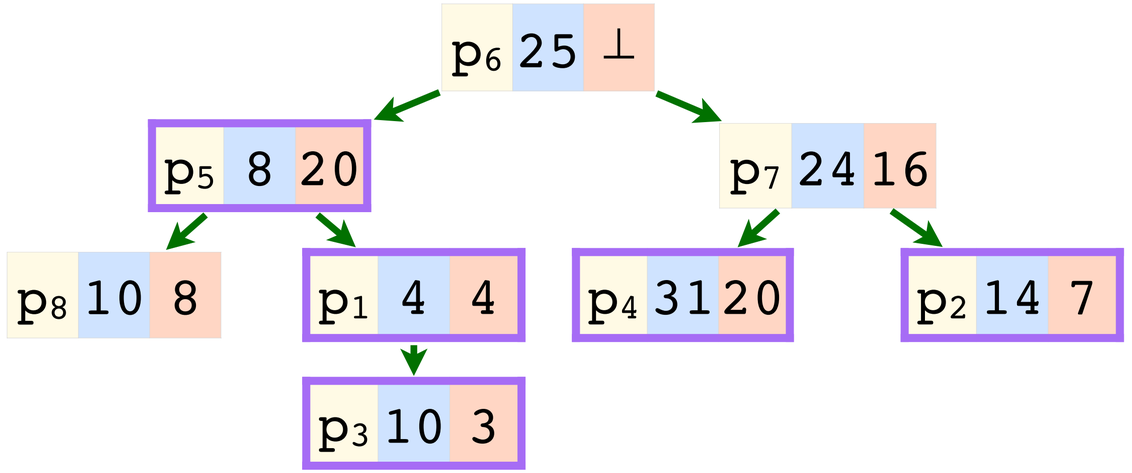

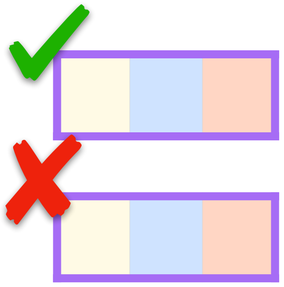

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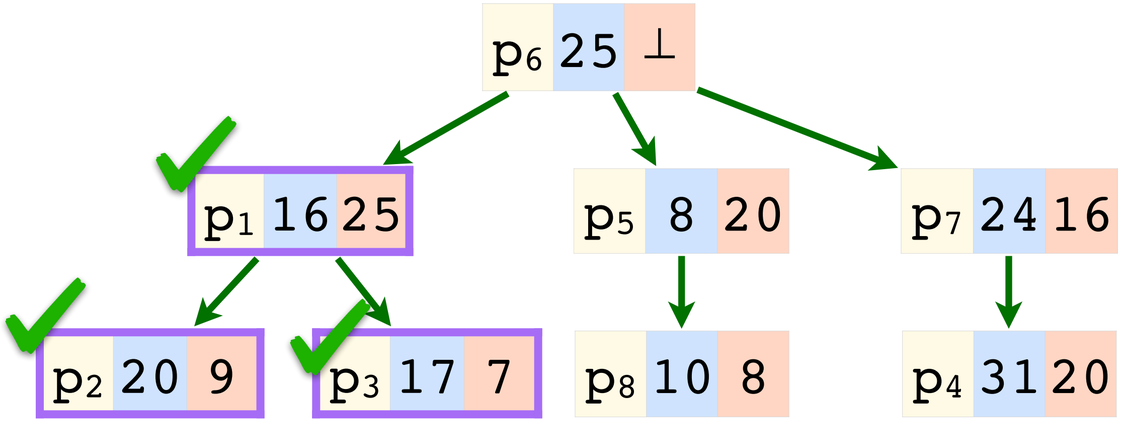
16	20	17	23	4	2	11	2
p1	p2	p3	p4	p5	p6	p7	p8



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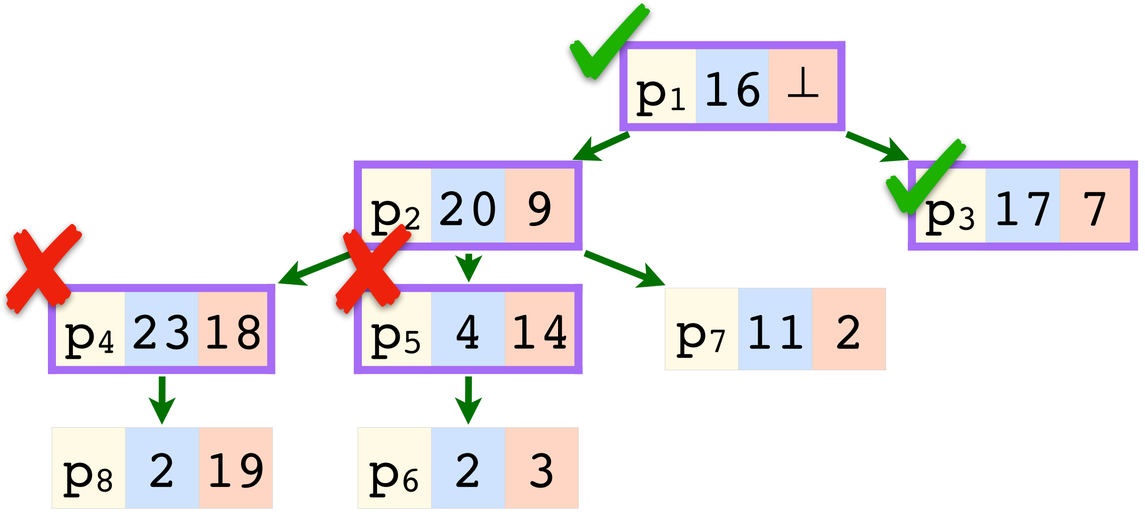

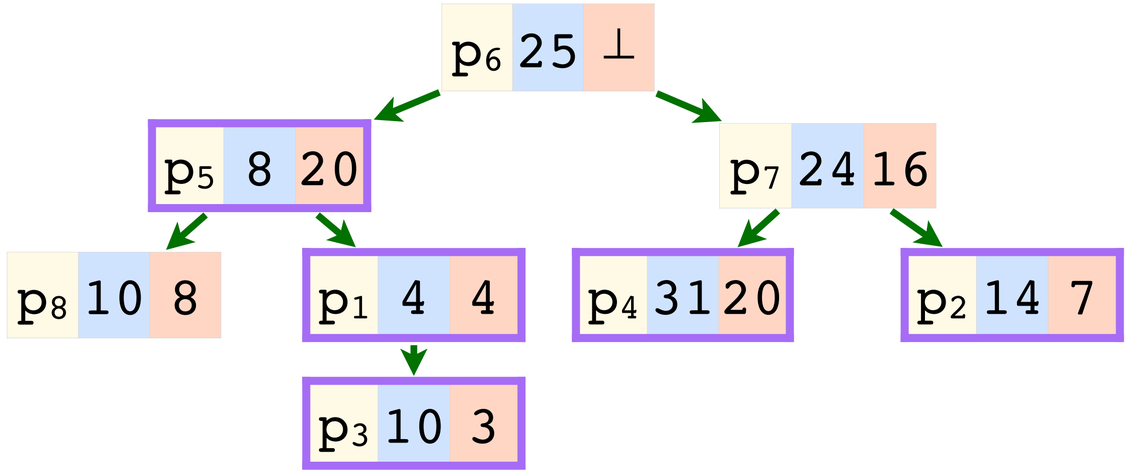

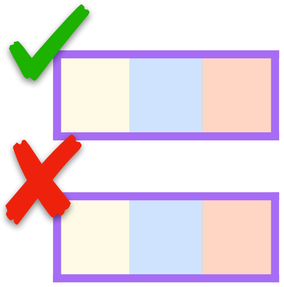

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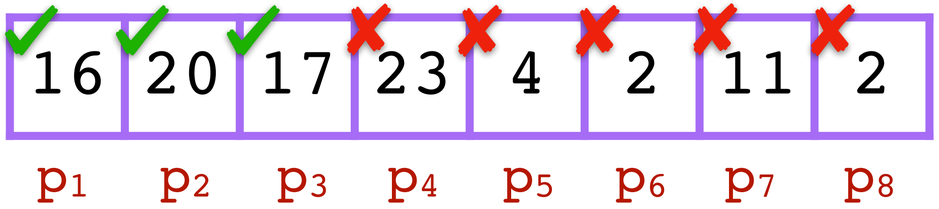

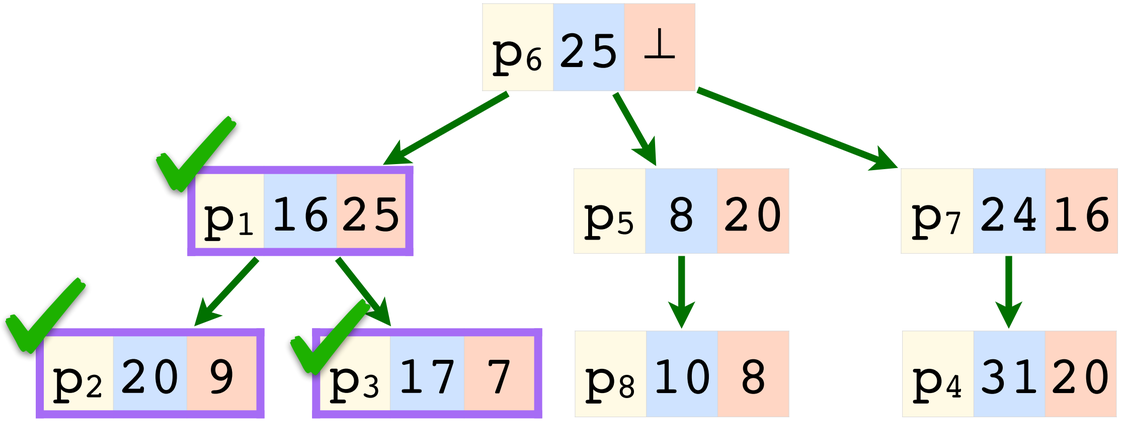

Tree Clock Copy?

Tree Clock Copy?

In general, tree clock copy will take O(|proceses|) time

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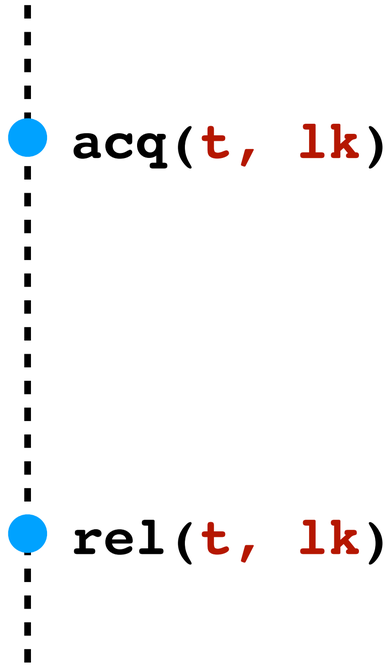
In general, tree clock copy will take O(|proceses|) time

Race detection

```
procedure acq(t, lk)
    Vt.JoinWith(Vlk)

procedure rel(t, lk)
    Vlk.CopyFrom(Vt)
```



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Race detection

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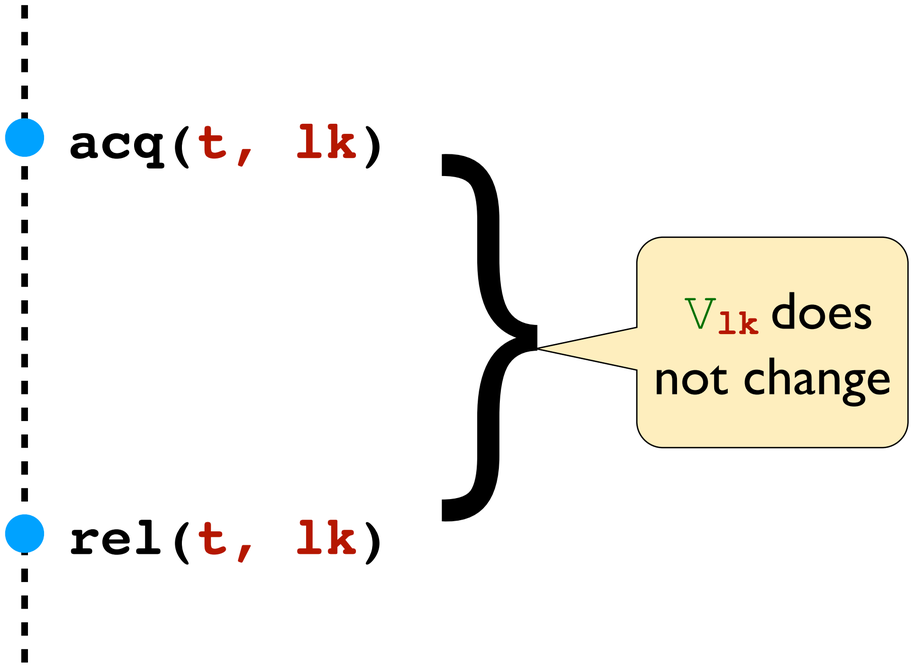


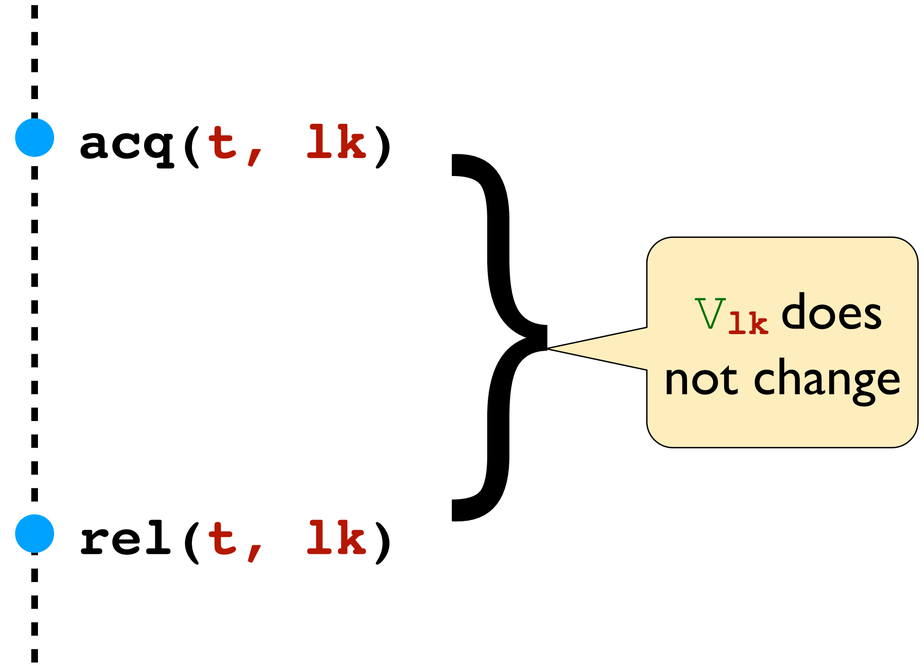
Tree Clock Copy?

In general, tree clock copy will take O(|proceses|) time

Race detection

```
procedure acq(t, lk)
    Vt.JoinWith(Vlk)

procedure rel(t, lk)
    Vlk.MonotoneCopyFrom(Vt)
```



Copy is monotone ⇒ **same semantics as join!**

Data Structure Optimality

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Optimality of data-structure

Data structure D is **optimal**

if

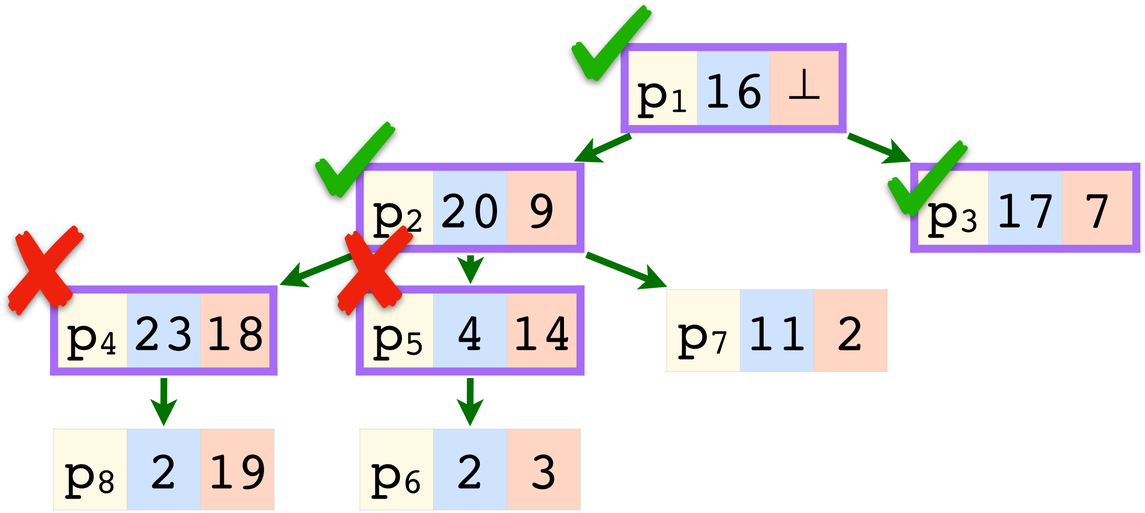
no other data structure can offer asymptotically better performance

Tree Clock Optimality for Race Detection

Optimality of Tree-Clocks

Tree Clocks offer **optimal** performance when computing Happens-Before partial order for the purpose of data race detection

Tree Clock Optimality for Race Detection



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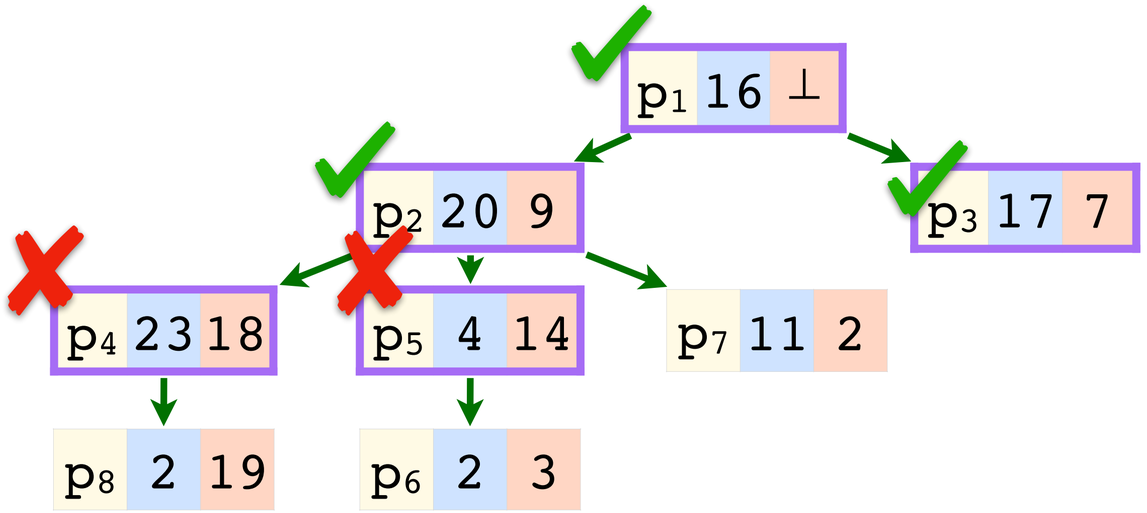
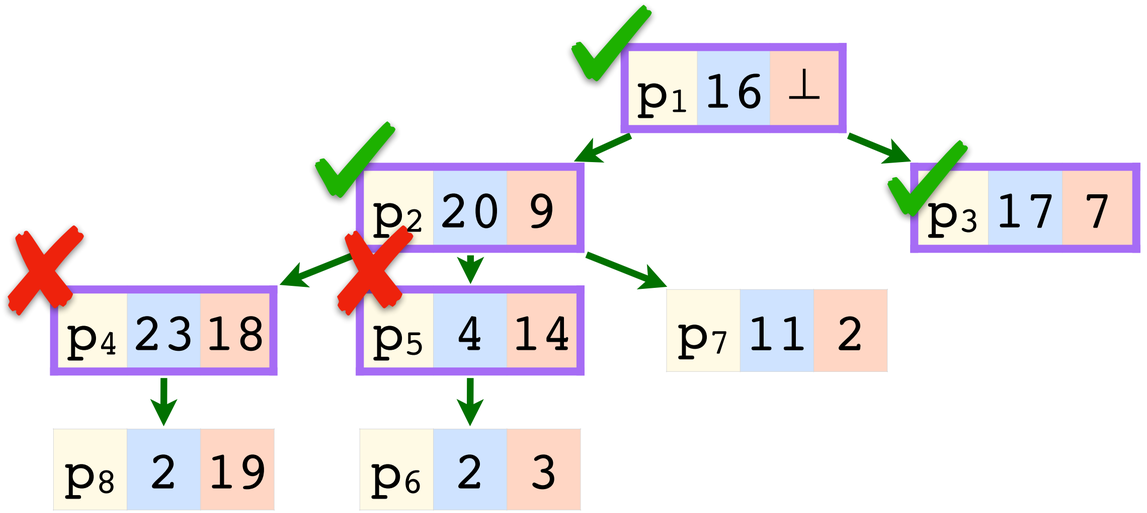


Minimum Timestamp Work
MinWork(σ)

Smallest number of data structure accesses when analysing σ

Tree Clock Optimality for Race Detection



Minimum Timestamp Work
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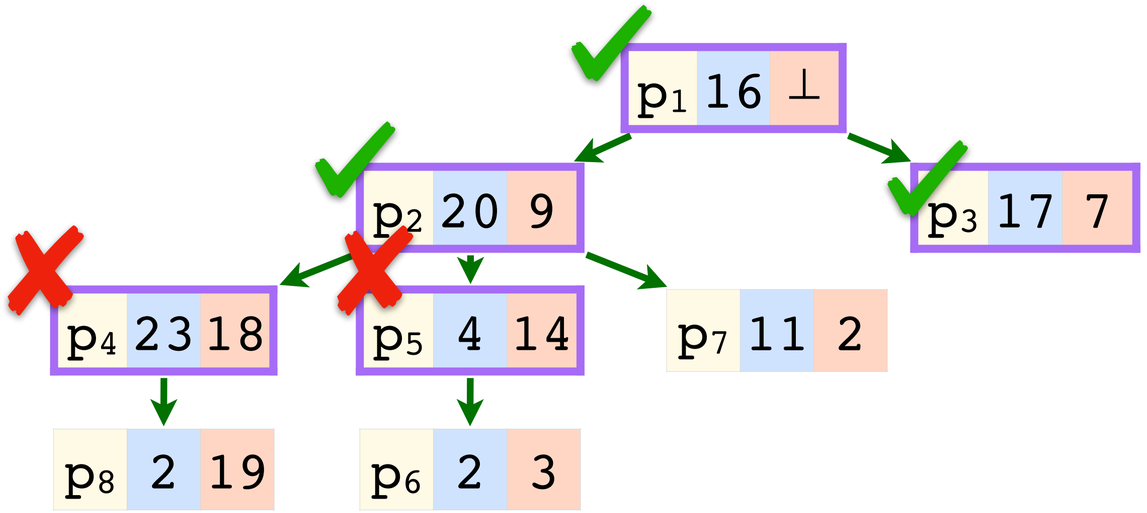
Smallest number of data structure accesses when analysing σ

TreeClock Work
TCWork(σ)

Number of tree clock nodes traversed when analysing σ

Tree Clock Optimality for Race Detection



Minimum Timestamp Work
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Smallest number of data structure accesses when analysing σ

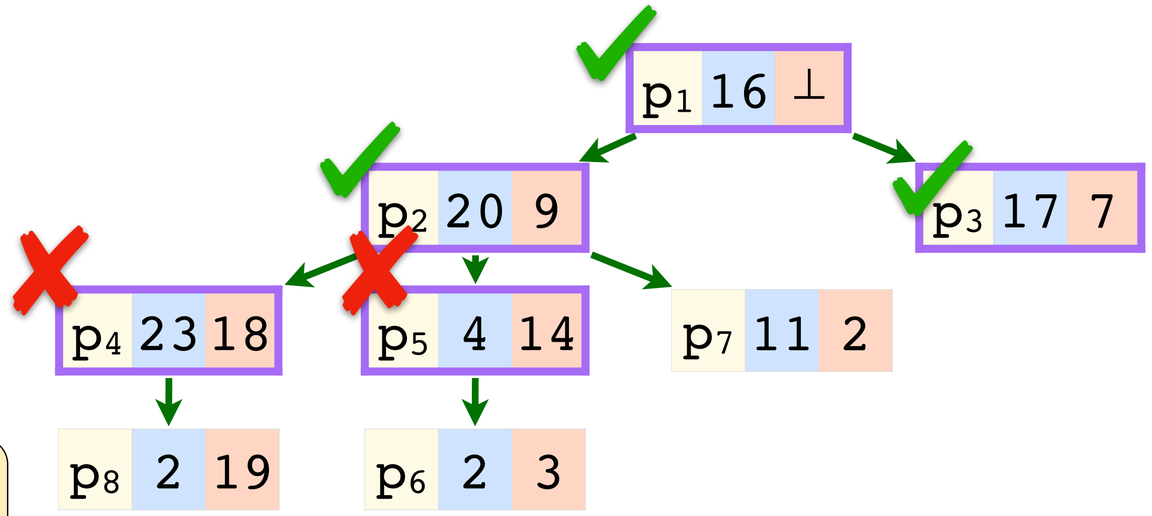
TreeClock Work
TCWork(σ)

Number of tree clock nodes traversed when analysing σ

VectorClock Work
VCWork(σ)

Number of vector clock entires accessed when analysing σ

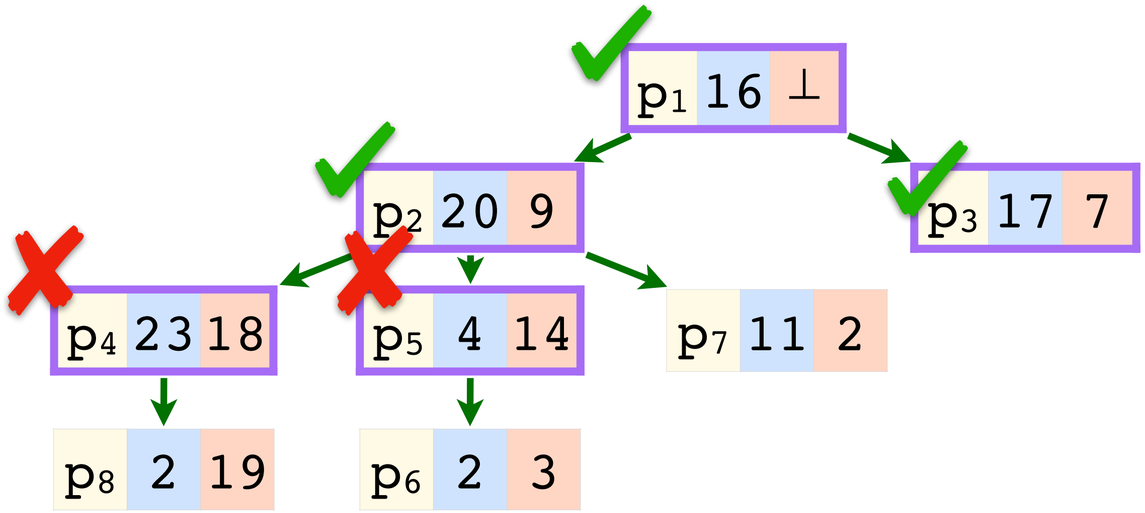
Tree Clock Optimality for Race Detection



k processes

VCWork(σ) ≃ k * MinWork(σ)

Tree Clock Optimality for Race Detection



VCWork(σ) ≃ k * MinWork(σ)

Optimality of Tree-Clocks

TCWork(σ) ≤ 3 * TimeWork(σ)

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github.com/umangm/rapid

- 153 benchmarks
- Trace sizes - 51 to 2.1B

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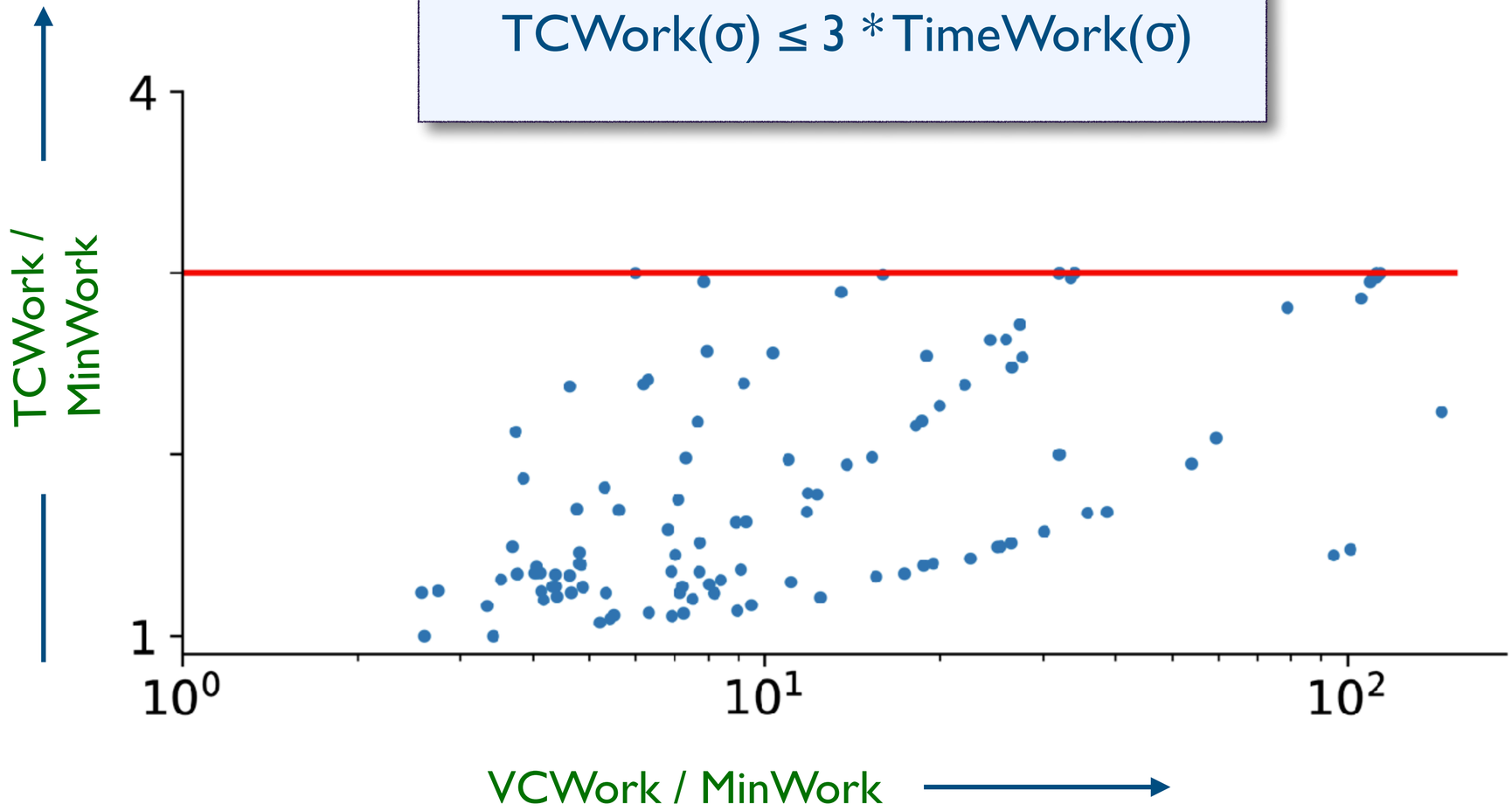
- 153 benchmarks
- Trace sizes - 51 to 2.1B

Task	HB	SHB	Maz
Partial Order	2.97x	2.66x	2.02x
Partial Order + Race Detection	1.11x	1.80x	1.49x

Does it work?

Optimality of Tree-Clocks

$\text{TCWork}(\sigma) \leq 3 * \text{TimeWork}(\sigma)$



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To Summarize

- **Timestamping via a data structure lens**
  - Abstract operations stay same
  - Implementation details differ, and matter!
- **Tree clocks**
  - Store how and when knowledge was discovered
  - Optimal data structure for data race detection
  - Impressive speedups
- **What's next?**
  - Tree clocks in other domains
  - Design/discovery of new data structures

Thank You!