Race Detection

cs378h

Pro Forma

- Questions?
- Administrivia:
  - Course/Instructor Survey : https://utdirect.utexas.edu/ctl/ecis/
  - Next class: review – send questions!
  - Thoughts on exam
  - Thoughts on project presentation day
- Agenda
  - Linearizability clarification
  - Race Detection
- Acknowledgements:
  - https://ecksit.wordpress.com/2015/09/07/difference-between-sequential-consistency-serializability-and-linearizability/
  - https://www.cl.cam.ac.uk/teaching/1718/R204/slides-tharris-2-lock-free.pptx
  - http://concurrencyfreaks.blogspot.com/2013/05/lock-free-and-wait-free-definition-and.html
  - http://swtv.kaist.ac.kr/courses/cs492b-spring-16/lec6-data-race-bug.pptx
  - https://www.cs.cmu.edu/~clegoues/docs/static-analysis.pptx
  - http://www.cs.sfu.ca/~fedorova/Teaching/CMPT401/Summer2008/Lectures/Lecture8-GlobalClocks.pptx

Change-a-thon 2021 Outreach

In partnering with ACM for Change, we're excited to announce our second Spring event on May 8th, Change-a-thon 2021!! Change-a-thon aims to promote innovative ideas, implementations, and conversations centered around positive change. We hope to address cultural issues in the tech space (projects to improve mental health within the tech environment, ethical computer science idea proposals, equity solutions, technical solutions to climate change, etc) and use technology to affect change in the social issues we face.

Change-a-thon aims to create a safe space for people both inside and outside the tech community to converse and collaborate to make lasting change and a better environment for everyone. If you think you can make change for the better, SIGN UP NOW!

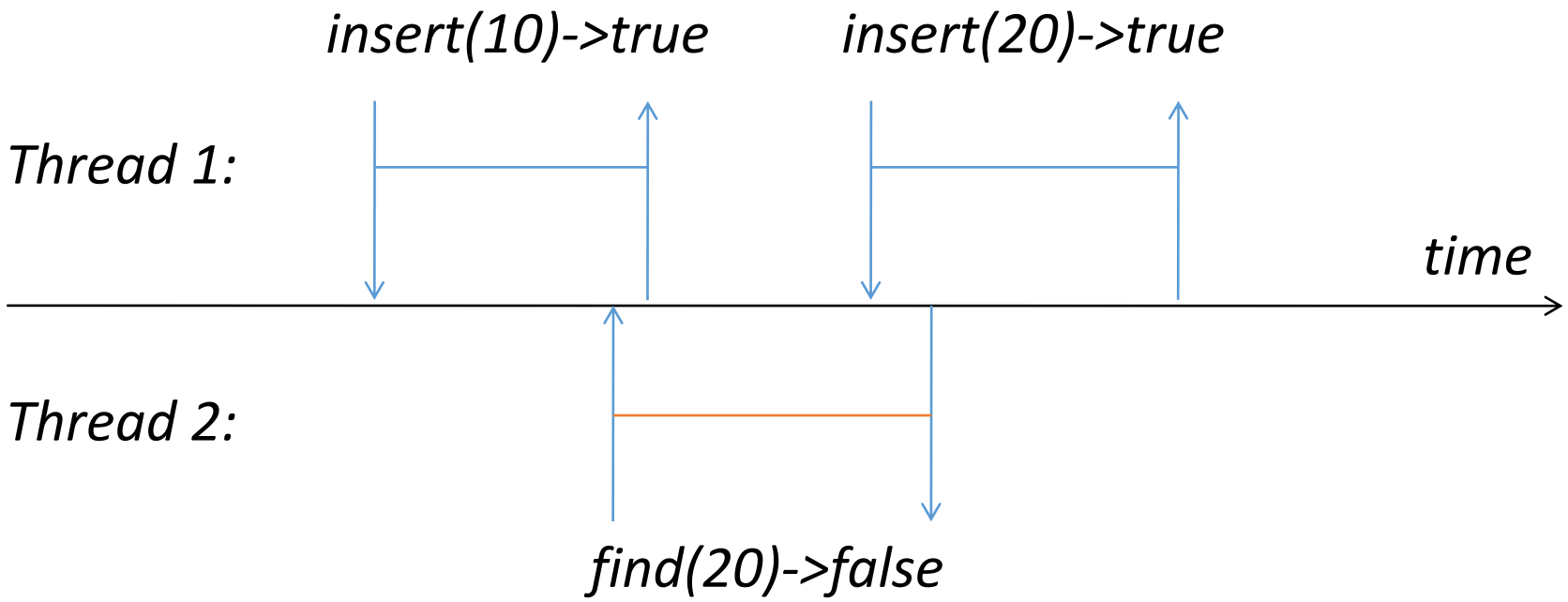
- REGISTER HERE: https://rb.gy/bevxae
- LEARN MORE: https://freetailhackers.com/changeathon/
- MENTOR SIGNUP: https://rb.gy/zut7yc

Race Detection Faux Quiz

- Are linearizable objects composable? Why/why not? Is serializable code composable?
- What is a data race? What kinds of conditions make them difficult to detect automatically?
- What is a consistent cut in a distributed causality interaction graph?
- List some tradeoffs between static and dynamic race detection
- What are some pros and cons of happens-before analysis for race detection? Same for lockset analysis?
- Why might one use a vector clock instead of a logical clock?
- What are some advantages and disadvantages of combined lock-set and happens-before analysis?

Review: Concurrent history

Allow *overlapping* invocations



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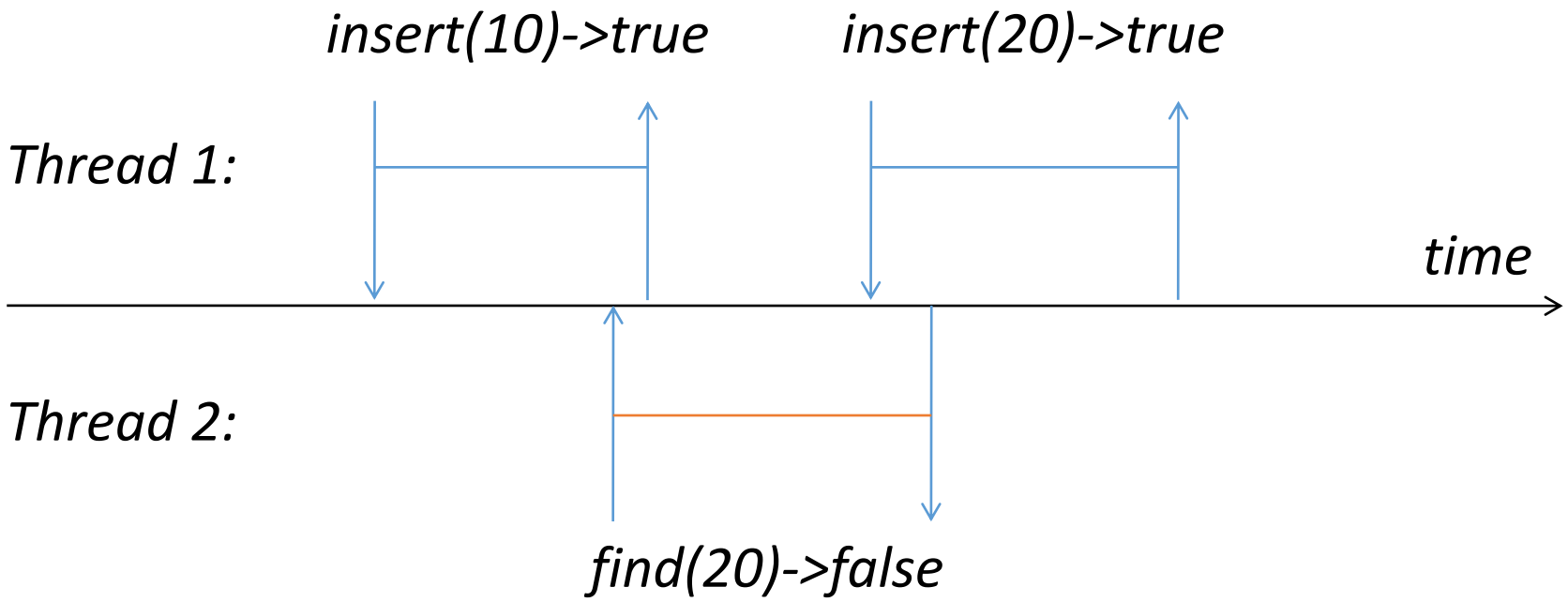

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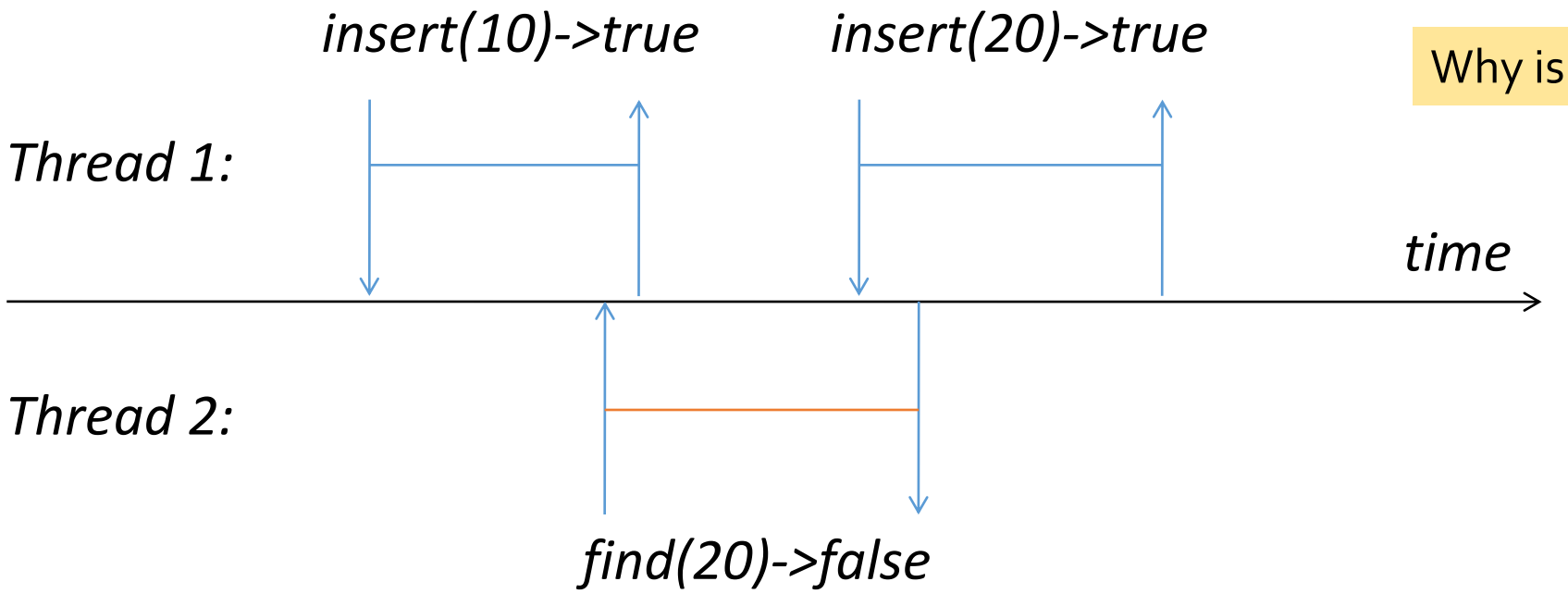

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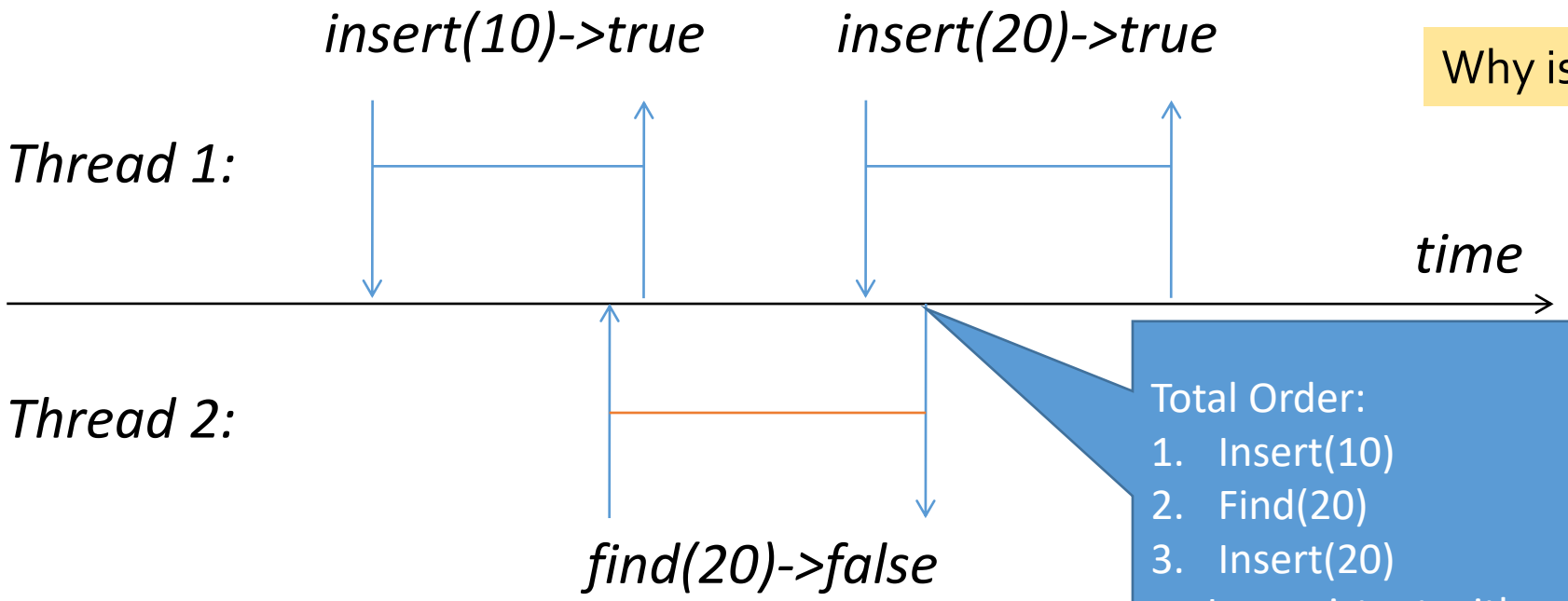


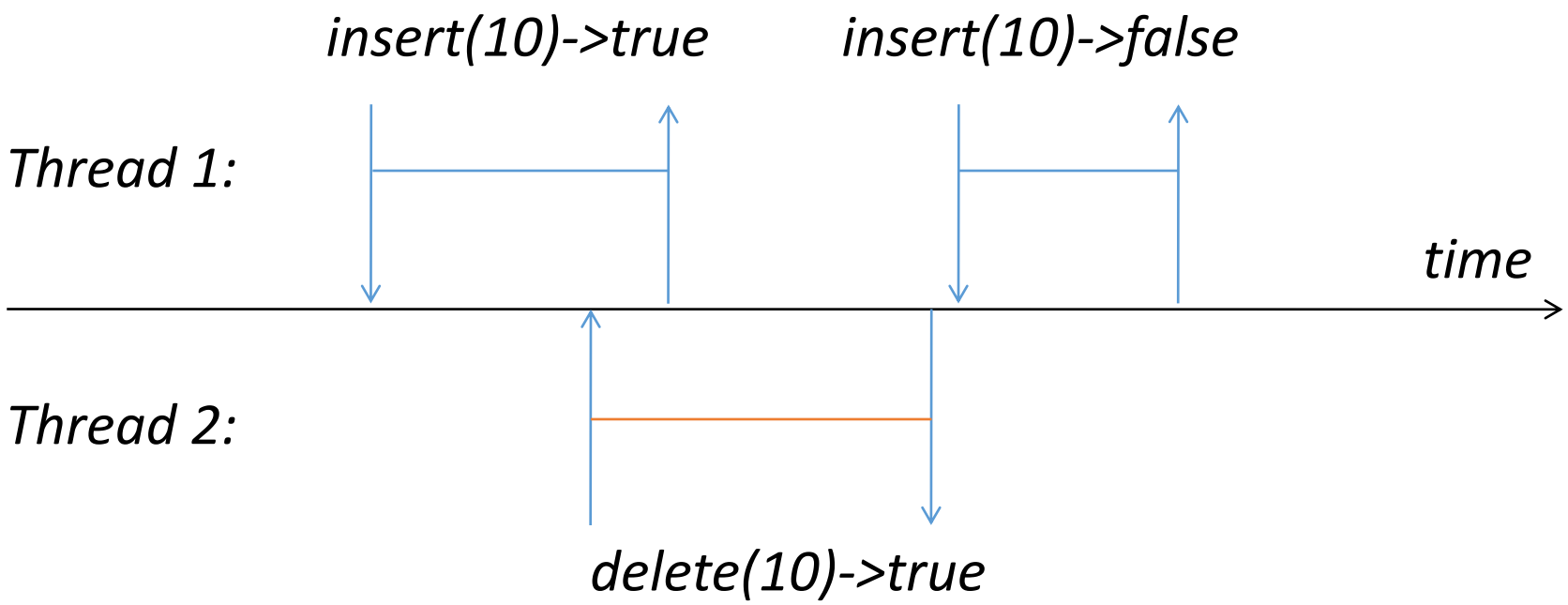
Why is this one OK?

Total Order:

1. Insert(10)
2. Find(20)
3. Insert(20)

- Is consistent with real-time order
- 2, 3 overlap, but return order OK

Review: not linearizable



Assumptions:

- The set is initially empty
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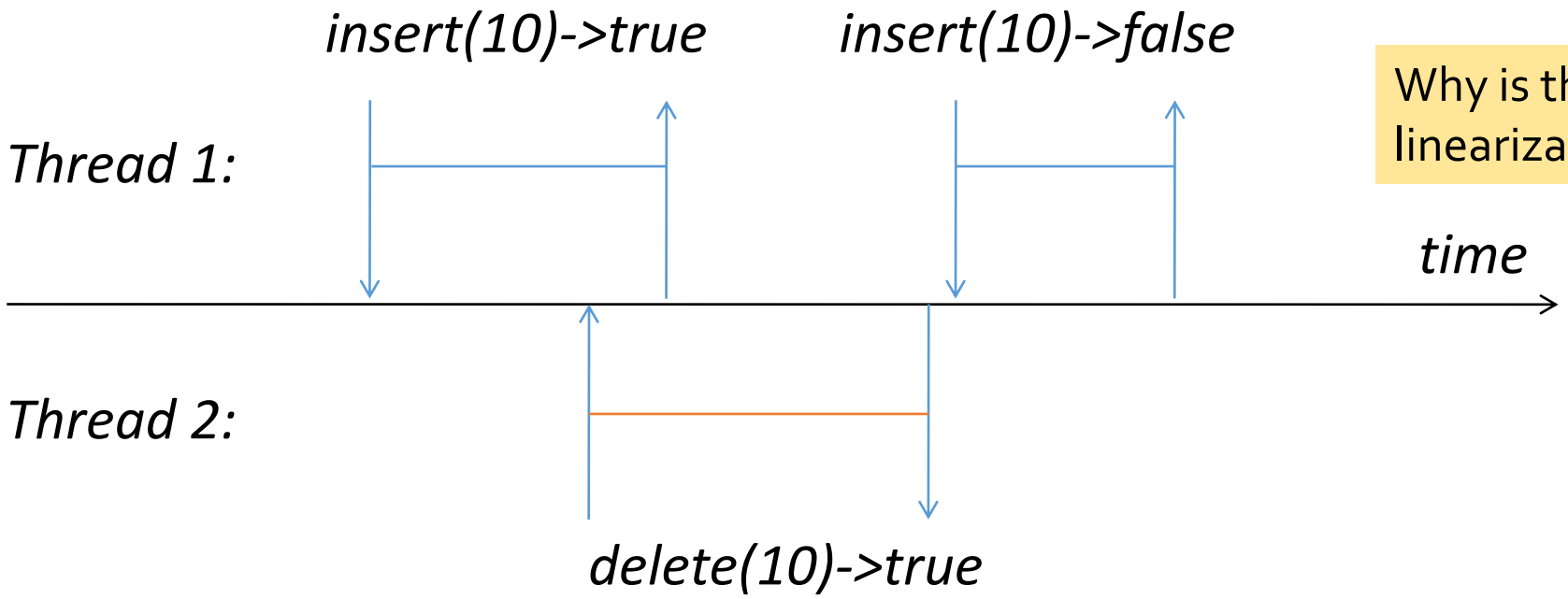

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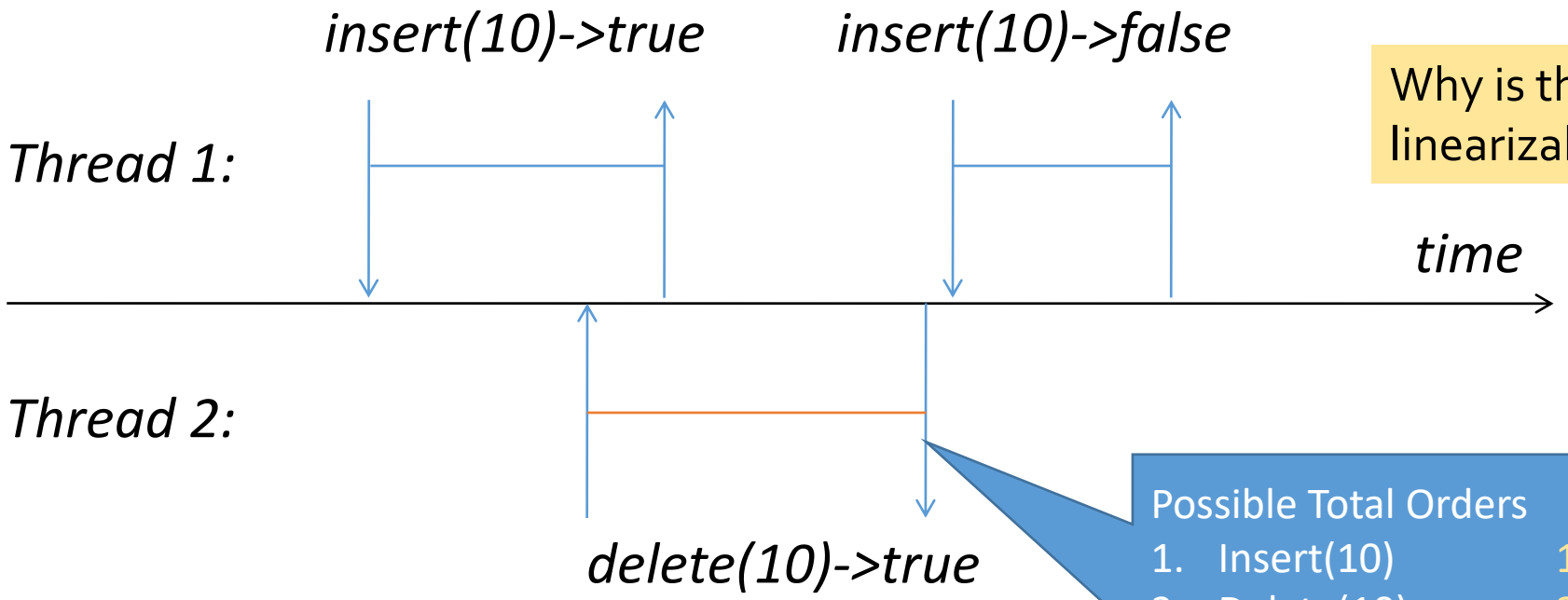

Why is this one NOT linearizable?

Possible Total Orders

1. Insert(10)	1. Delete(10)
2. Delete(10)	2. Insert(10)
3. Insert(10)	3. Insert(10)

- Both consistent with real-time order
- Neither is consistent w return values
- 1, 2 overlap, but 3 doesn't

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  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.

Composability

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Painting with a very broad brush
Composition with linearizability is really about composed schedules

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- These are related but differ in subtle ways
- Non-composability of serializability is really about composing schedules

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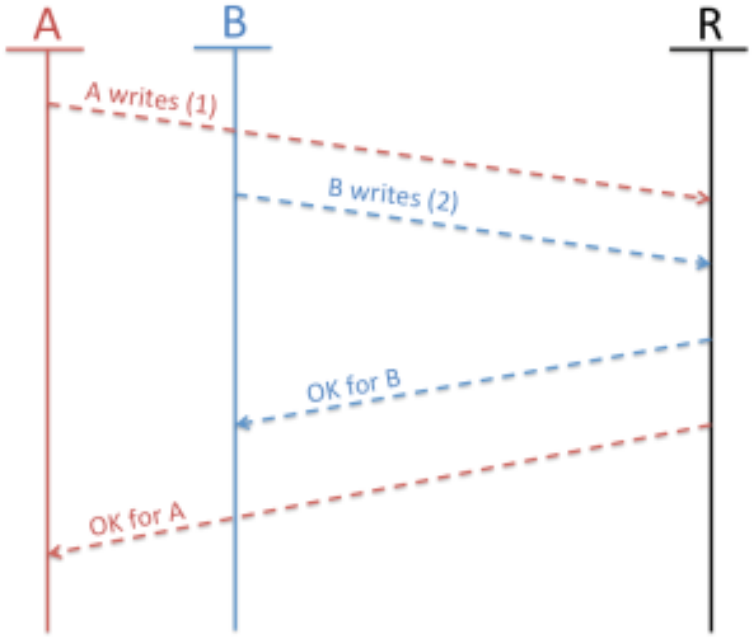

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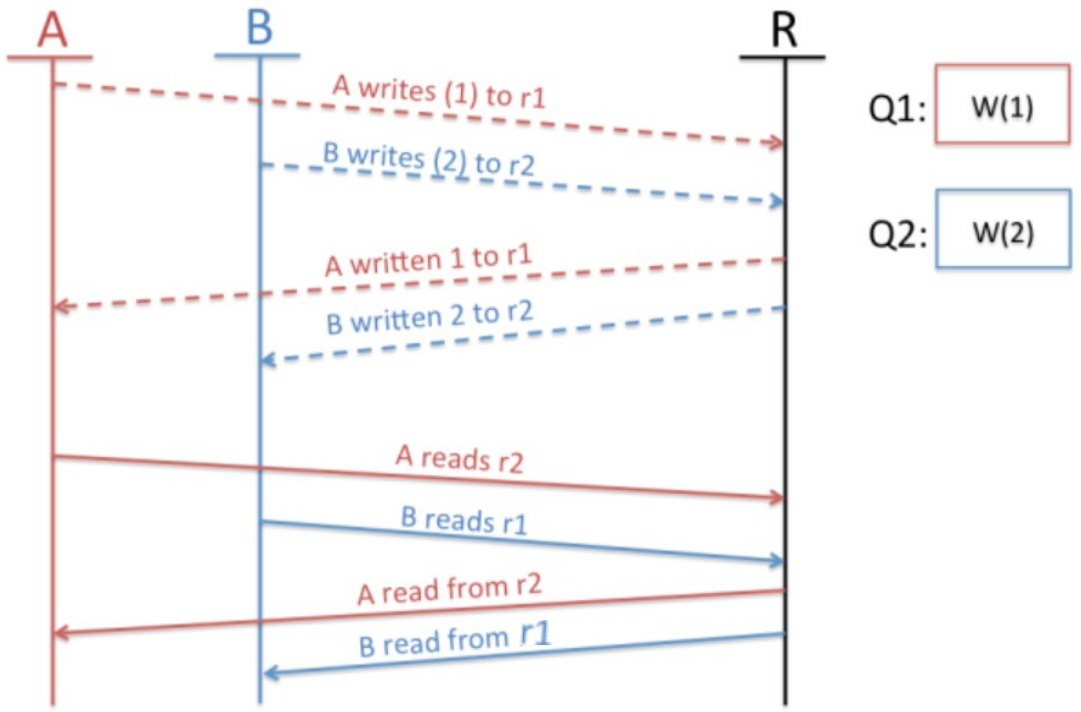

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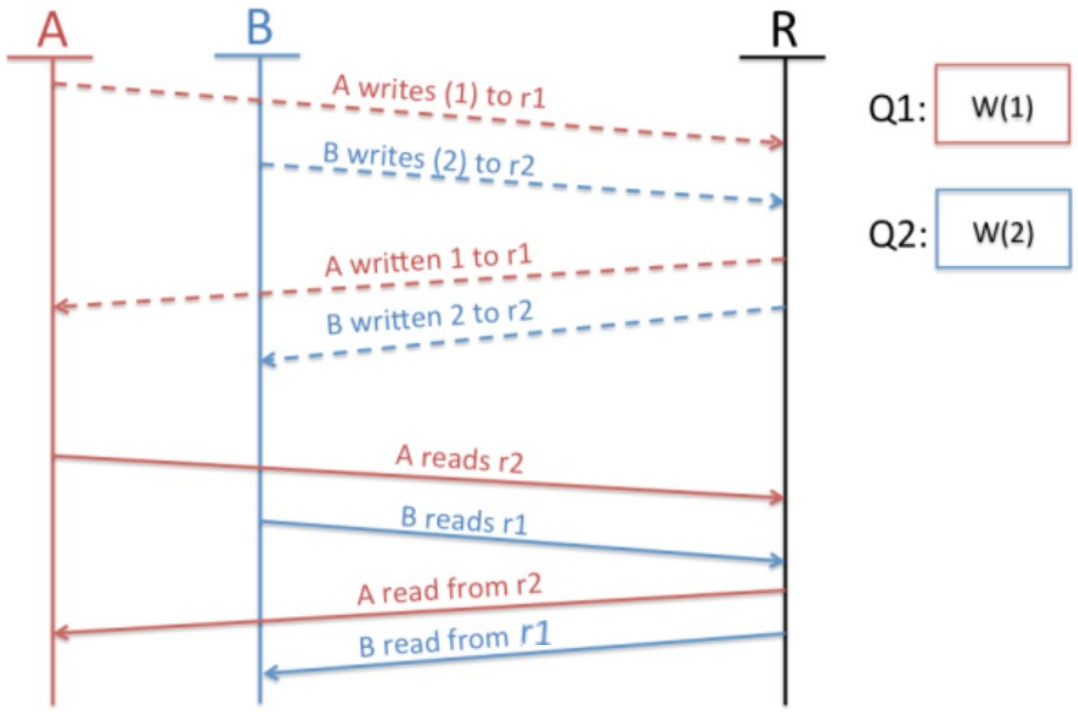
- Serializability:
  - Execution equivalent to *some serial order*
  - All see same order



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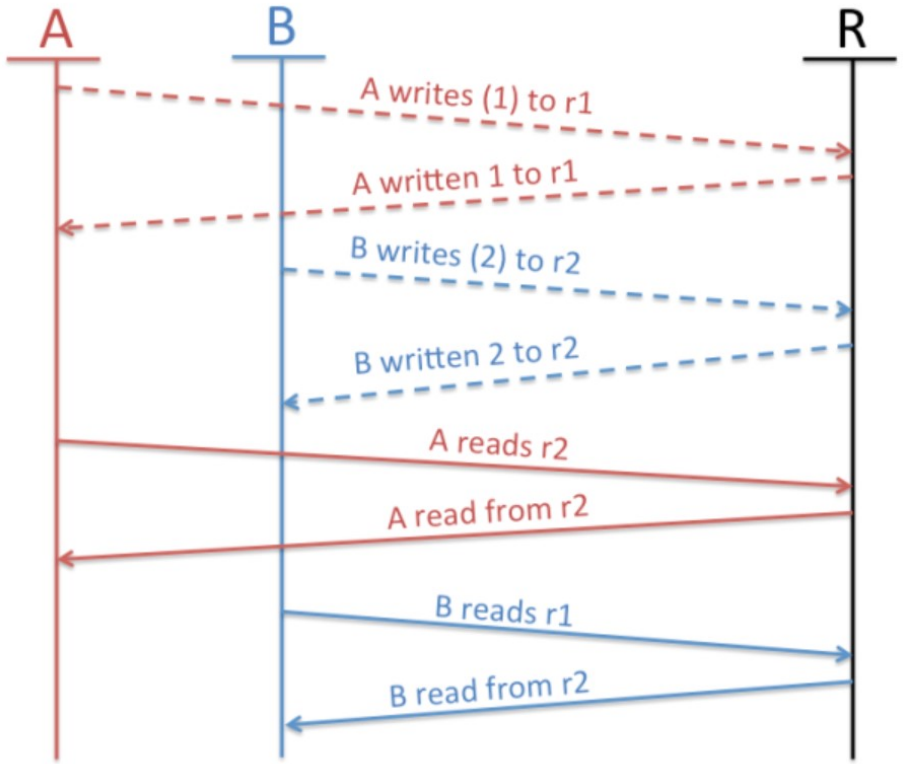

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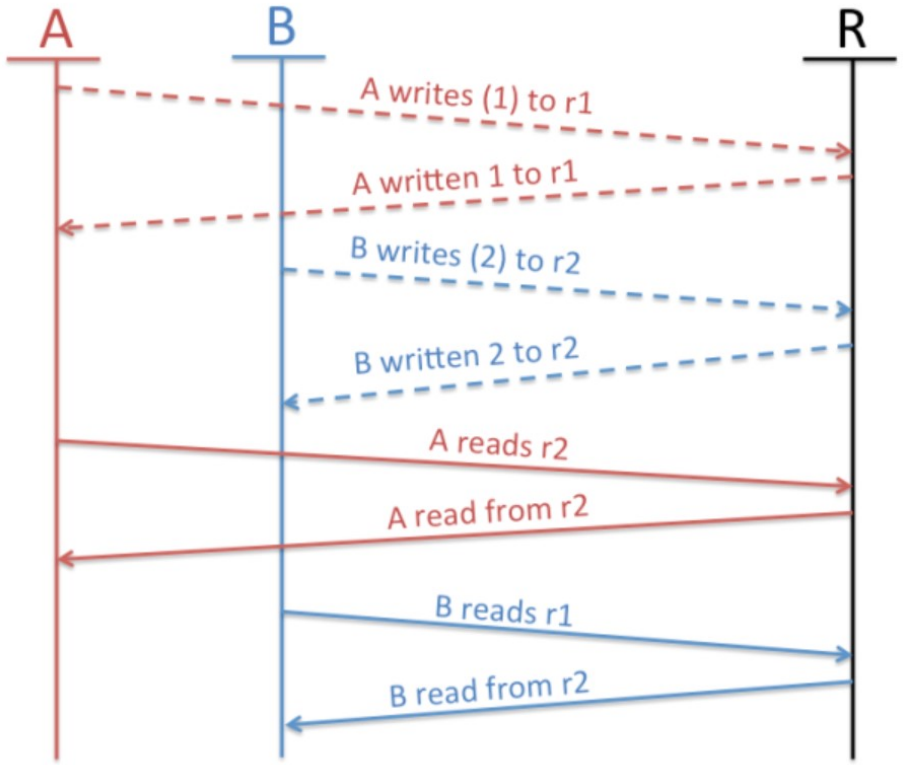

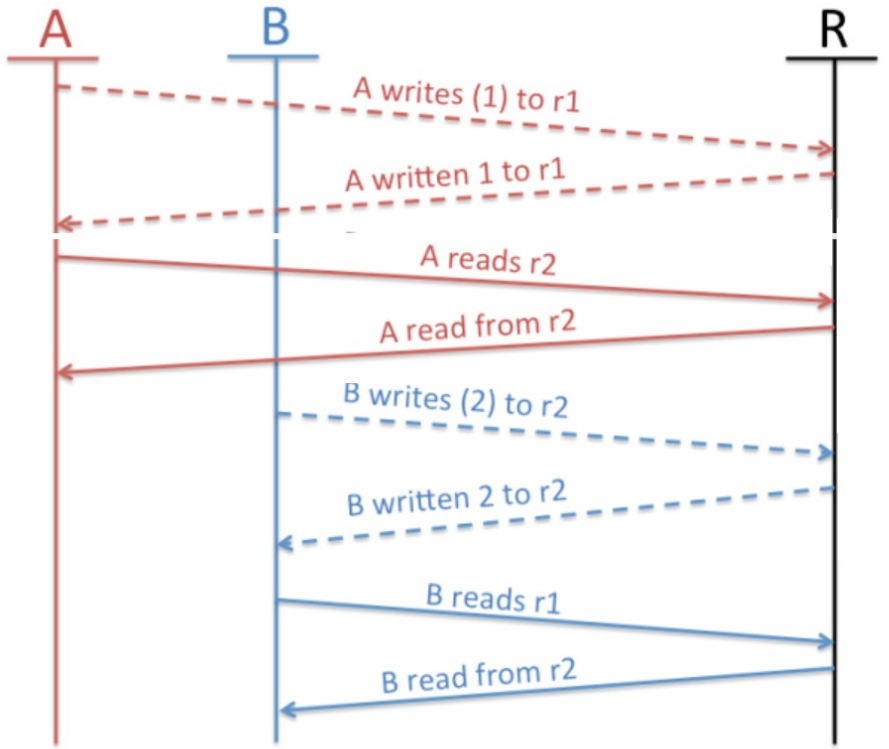

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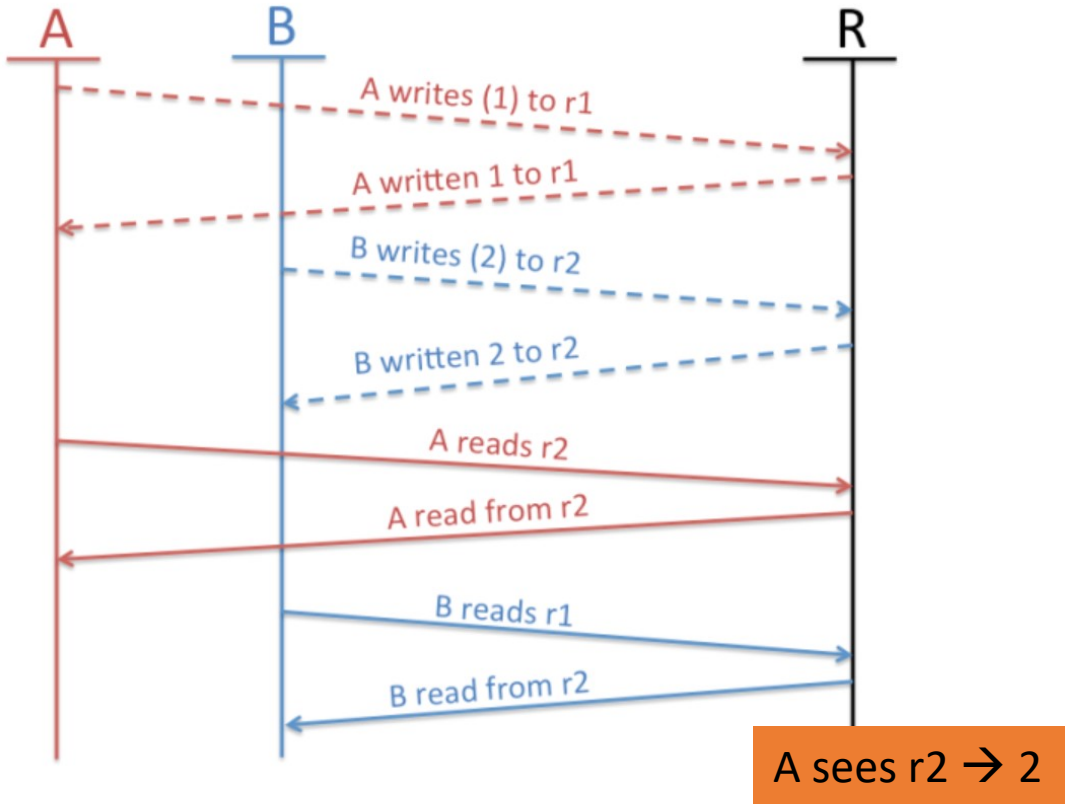

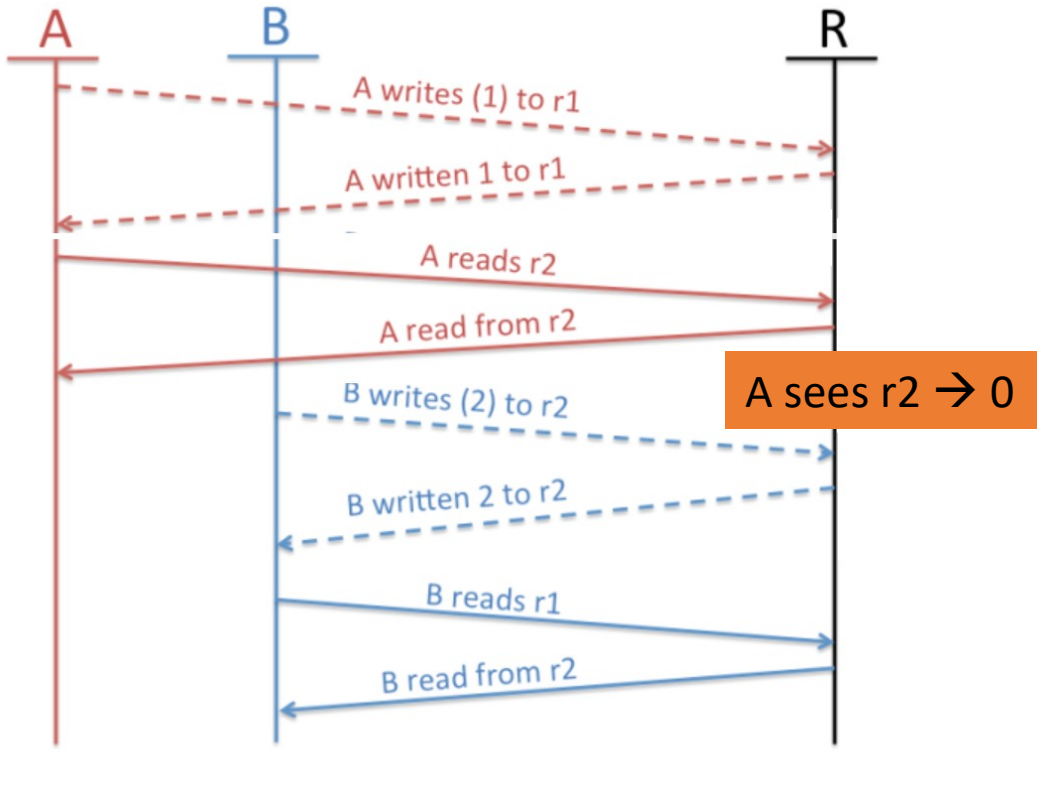

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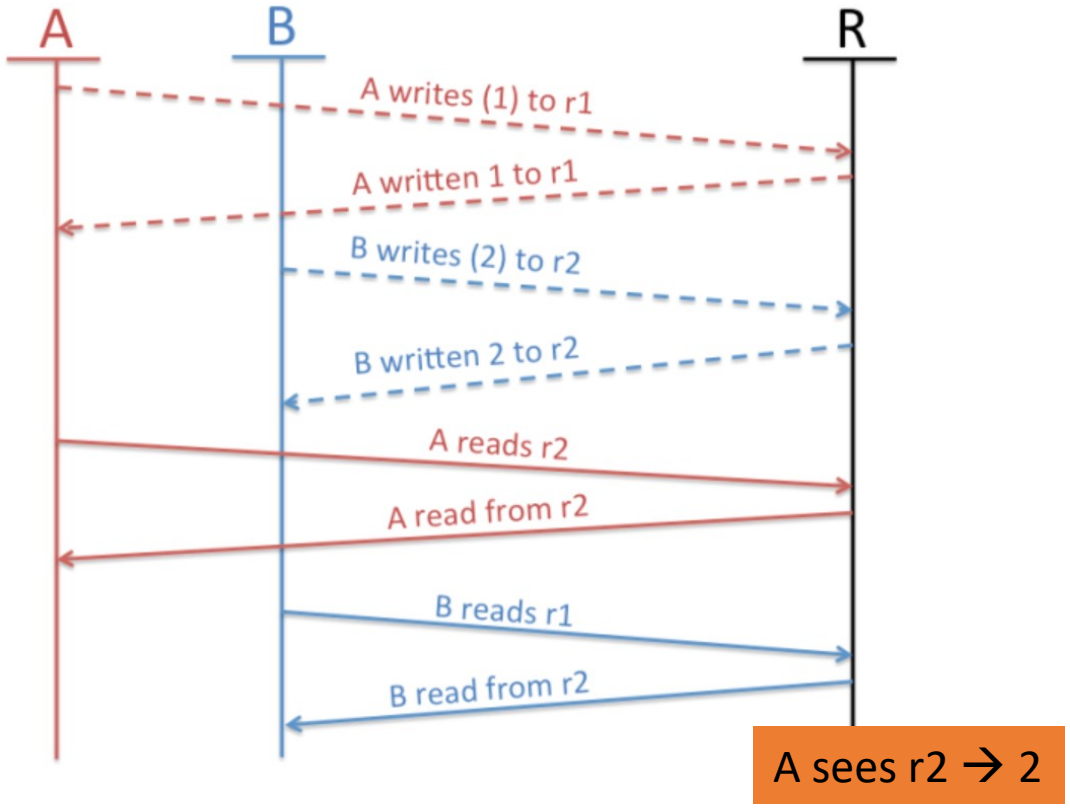

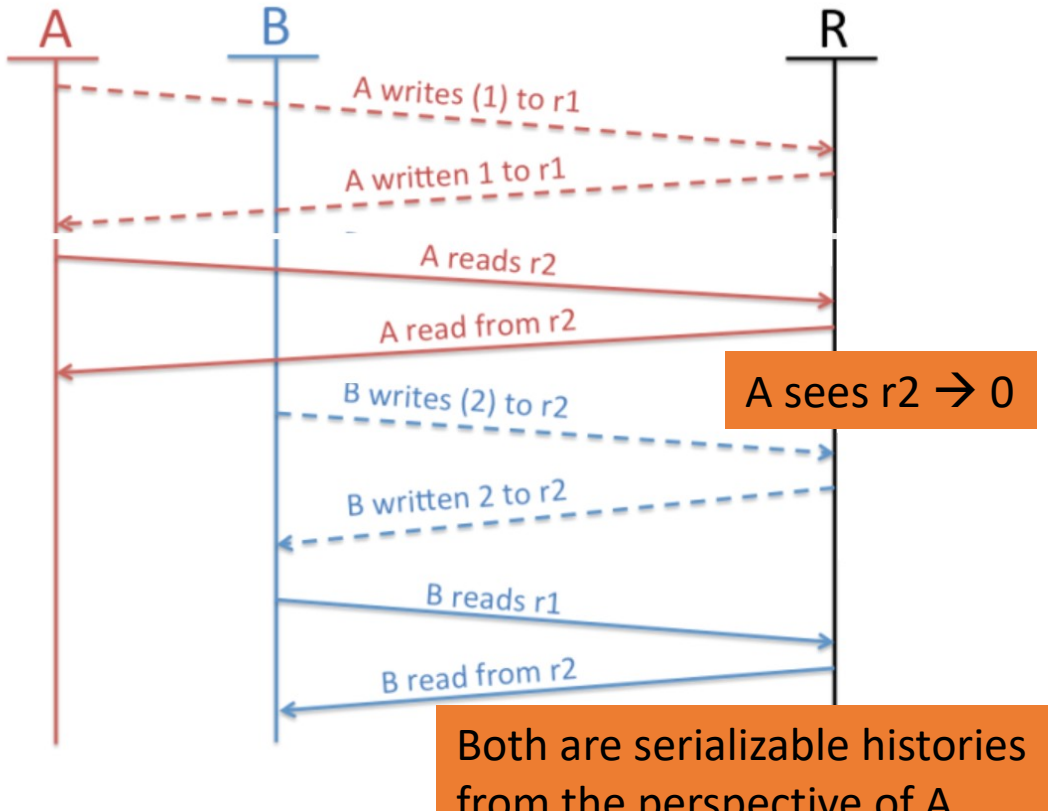

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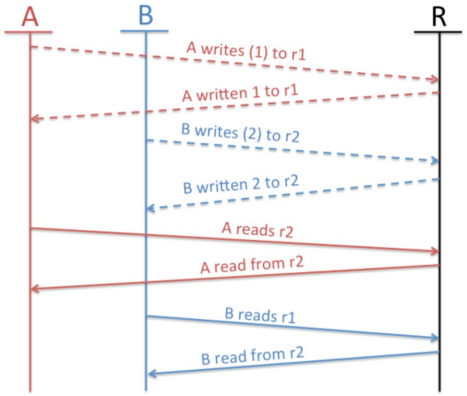

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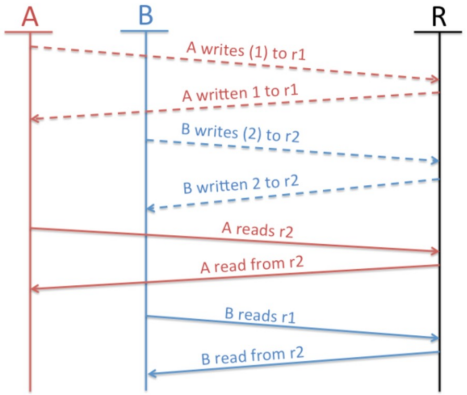

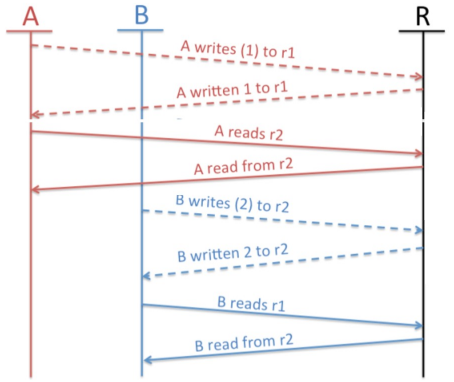

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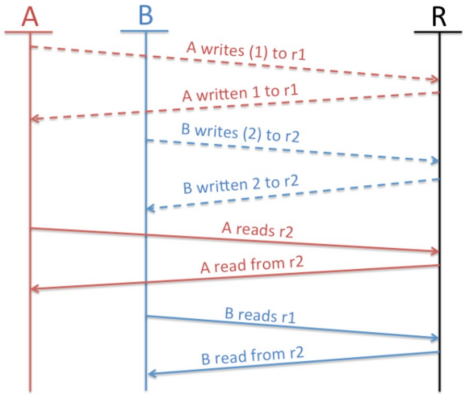

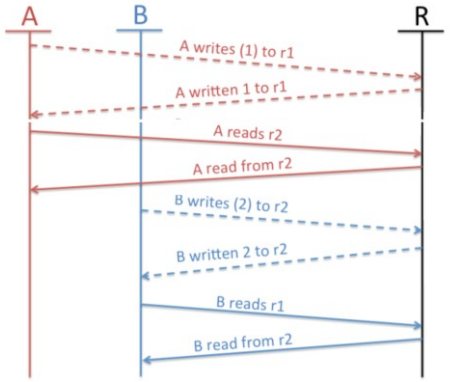

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H1a	A writes r1=1, reads r2 → 0
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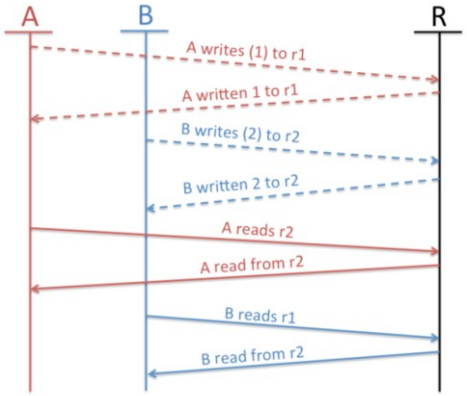

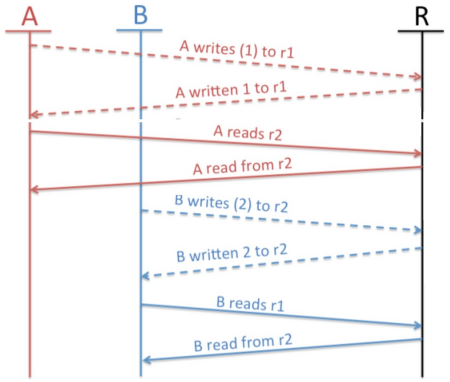

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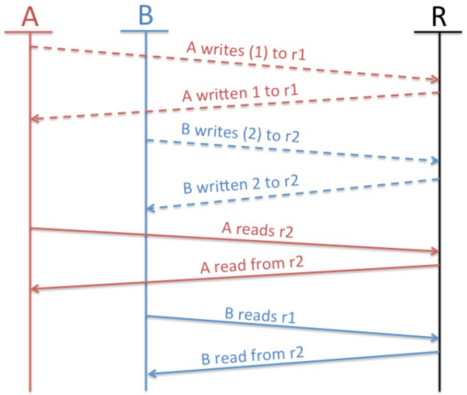

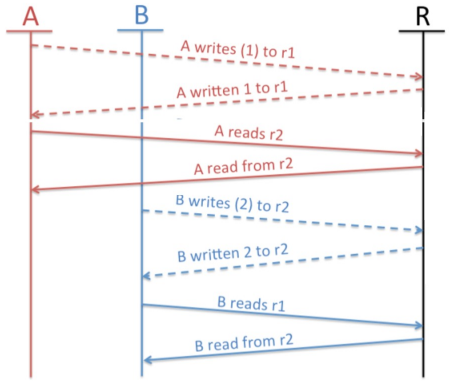

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From the perspective threads A, B, all sub-histories are serializable

- They respect program order for each of A, B
- And are equivalent to *some* serial execution
- If we “compose” these histories, some composed histories not serializable

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History	Effect
H1ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 0
H2ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 1
H3ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 0
H4ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 1

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- Composition of serializable histories → non-serializable histories

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- Ex. H1ab is not serializable

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Histories for multiple concurrent registers

- Compose sub-histories to form all possible histories
- Composition of serializable histories → non-serializable histories
- Ex. H1ab is not serializable

Sub-History	Outcome
H1a	A writes r1=1, reads r2 → 0
H2a	A writes r1=1, reads r2 → 2
H1b	B writes r2=2, reads r1 → 0
H2b	B writes r2=2, reads r1 → 1

History	Effect
H1ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 0
H2ab	A writes r1=1, B writes r2=2 reads r2 → 0, B reads r1 → 1
H3ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 0
H4ab	A writes r1=1, B writes r2=2 reads r2 → 2, B reads r1 → 1

4 serializable sub-histories composed
To form 4 complete histories,
Only H4ab is actually serializable

Linearizability Properties

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  -

Linearizability Properties

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- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - A system composed of linearizable objects remains linearizable
  - Does this mean you get txn or lock-like composition for free?
    - In general no
    - Serializability is a property of transactions, or groups of updates
    - Linearizability is a property of concurrent objects
    - The two are often conflated (e.g. because txns update only a single object)

Race Detection

Race Detection

Locks: a litany of problems

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- Deadlock

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Solution: don’t use locks

- non-blocking
- Data-structure-centric
- HTM
- blah, blah, blah..

Race Detection

Locks: a litany of problems

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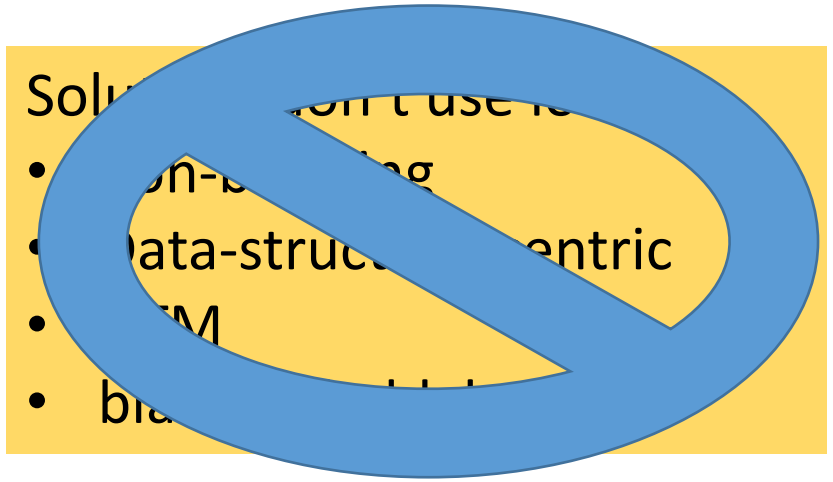

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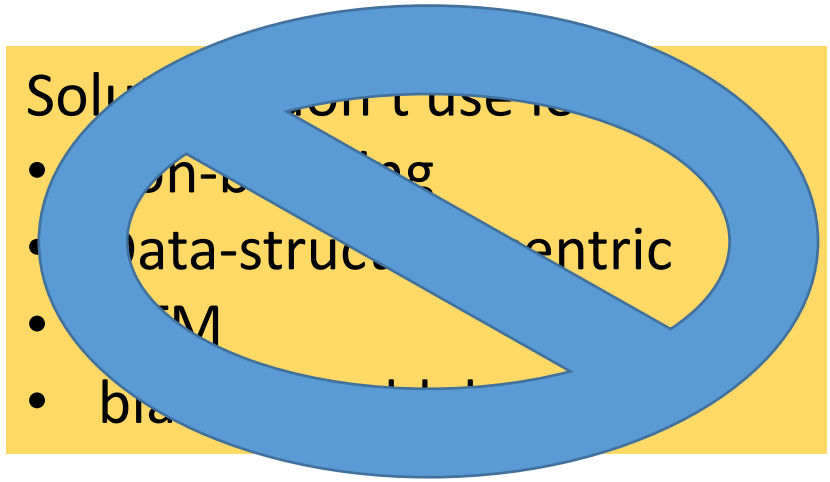

Use locks!

- But automate bug-finding!

Lockset Algorithm

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- Locking discipline
  - Every shared mutable variable is protected by some locks

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Lockset Algorithm

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Let $locks\_held(t)$ be the set of locks held by thread t.
For each v, initialize $C(v)$ to the set of all locks.
On each access to v by thread t,
set $C(v) := C(v) \cap locks\_held(t)$;
if $C(v) = \{\ \}$, then issue a warning.

- Assume every lock protects every variable
  - On each access, use locks held by thread to narrow that assumption

Narrow down set of locks maybe protecting v

Lockset Algorithm Example

thread t	locks_held(t)	C(v)
	{}	{lockA, lockB}
lock(lockA);		
v++;		
unlock(lockA);		
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`v++;`	`{}`	`{}` ACK! race
`unlock(lockB);`		

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ACK! race

Pretty clever! Why isn't this a complete solution?

Improving over lockset

thread A

```
1 read-write(X);
2 fork(thread-proc);
3 do_stuff();
4 do_more_stuff();
5 join(thread-proc);
6 read-Write(X);
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thread B

```
1 thread-proc() {
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There is no race: why not?

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Lockset detects a race

There is no race: why not?

- A-1 happens before B-3
- B-3 happens before A-6
- Insight: races occur when “happens-before” cannot be known

Happens-before

- *Happens-before* relation
  - Within single thread
  - Between threads
- Accessing variables not ordered by “happens-before” is a race
- Captures locks and dynamism
- How to track “happens-before”?
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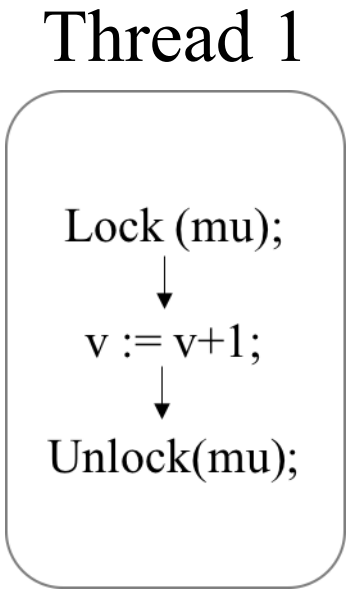

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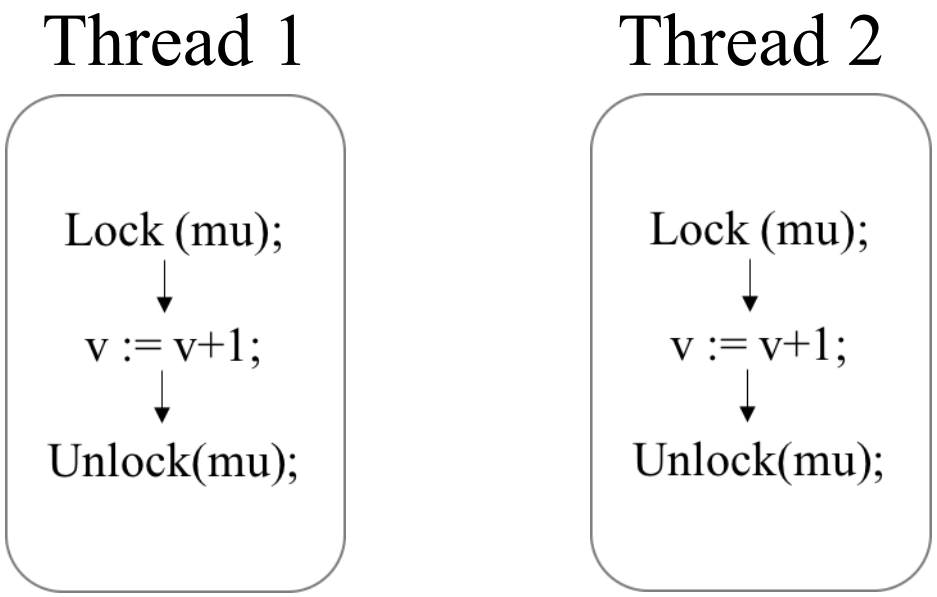

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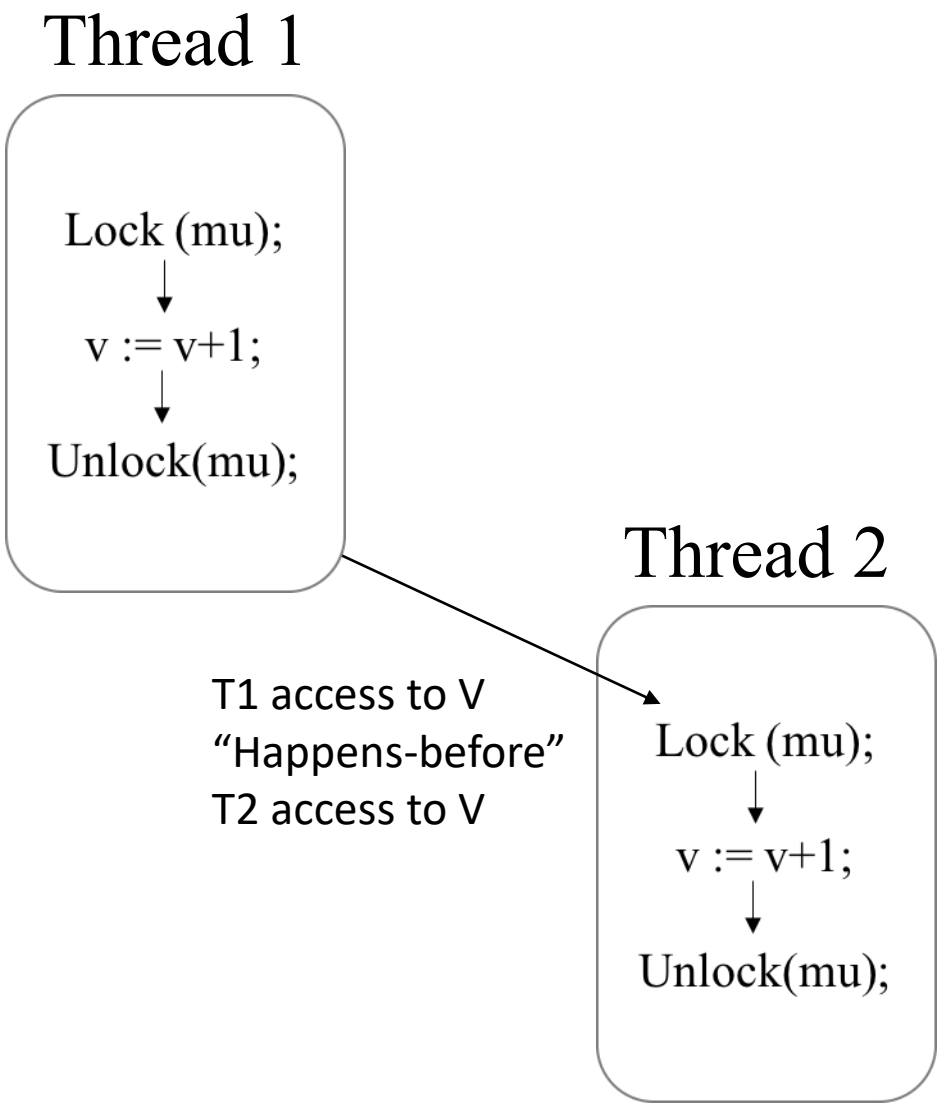
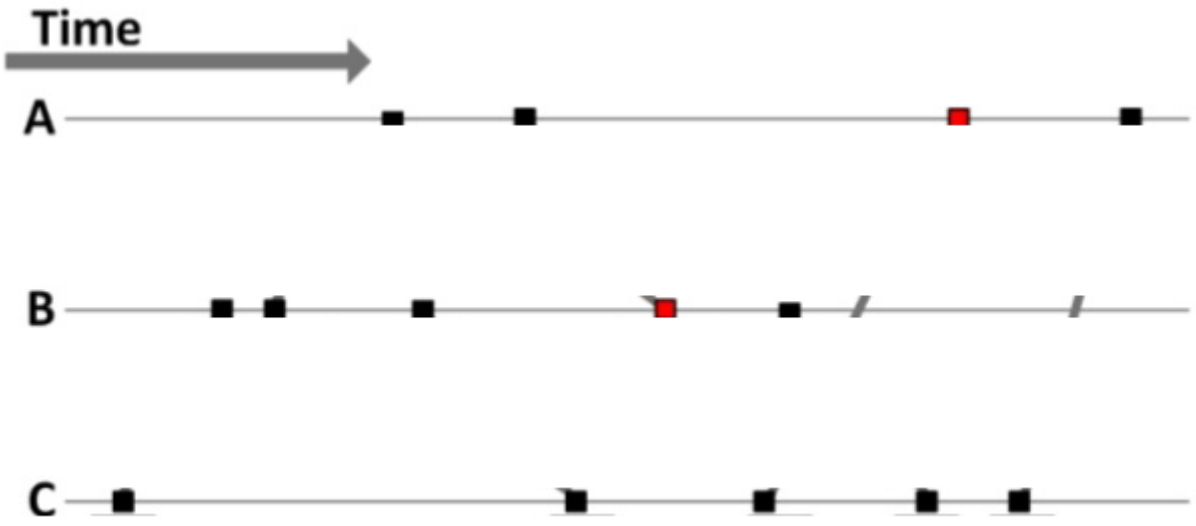


Ordering and Causality



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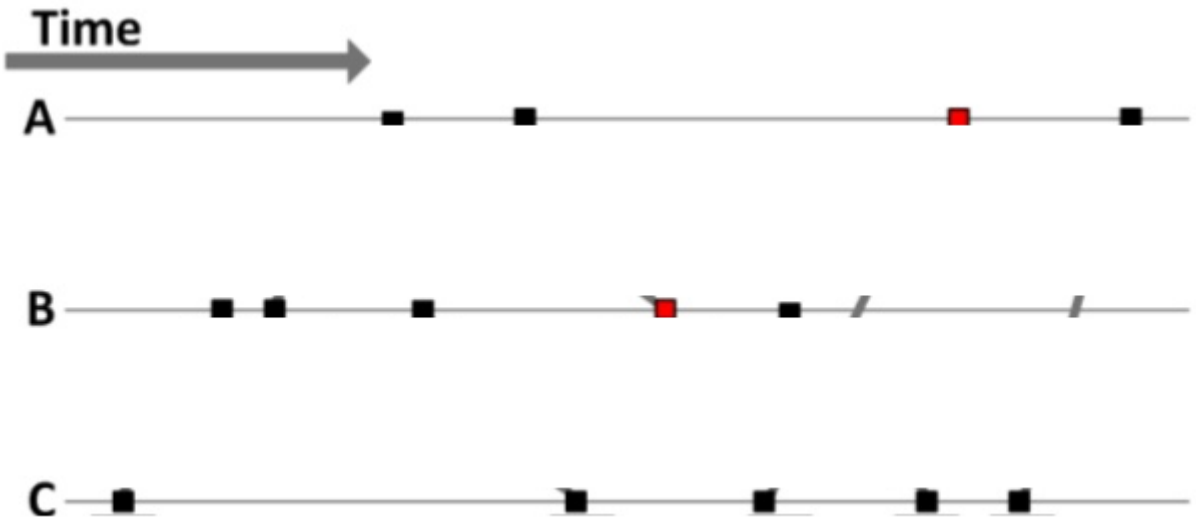

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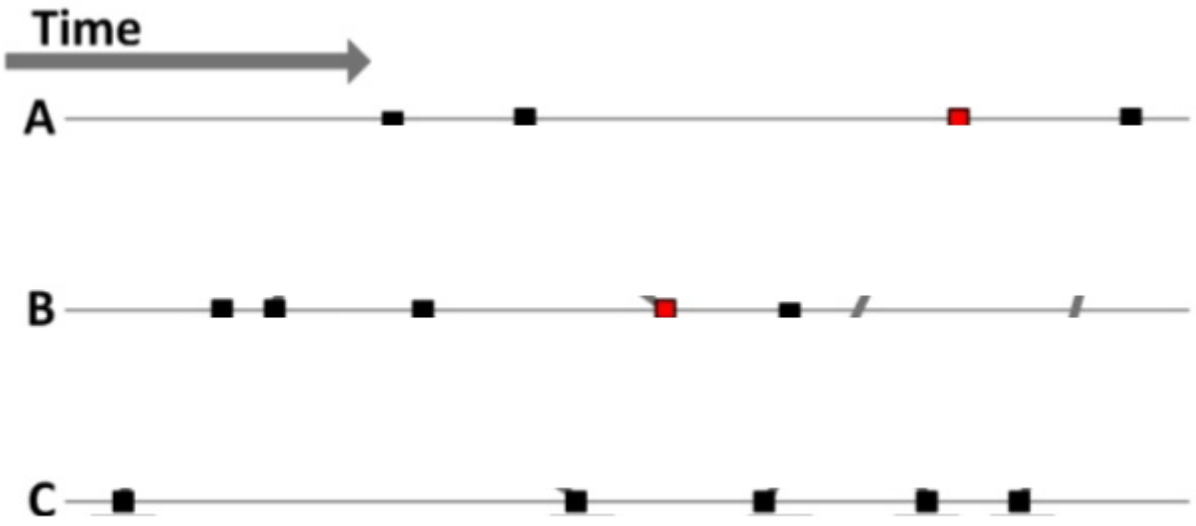

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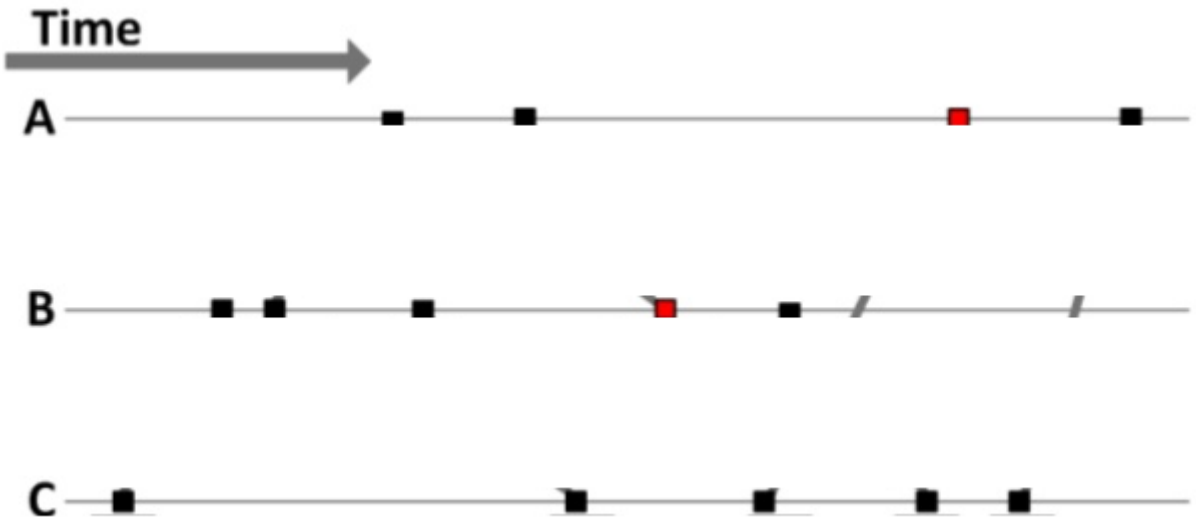

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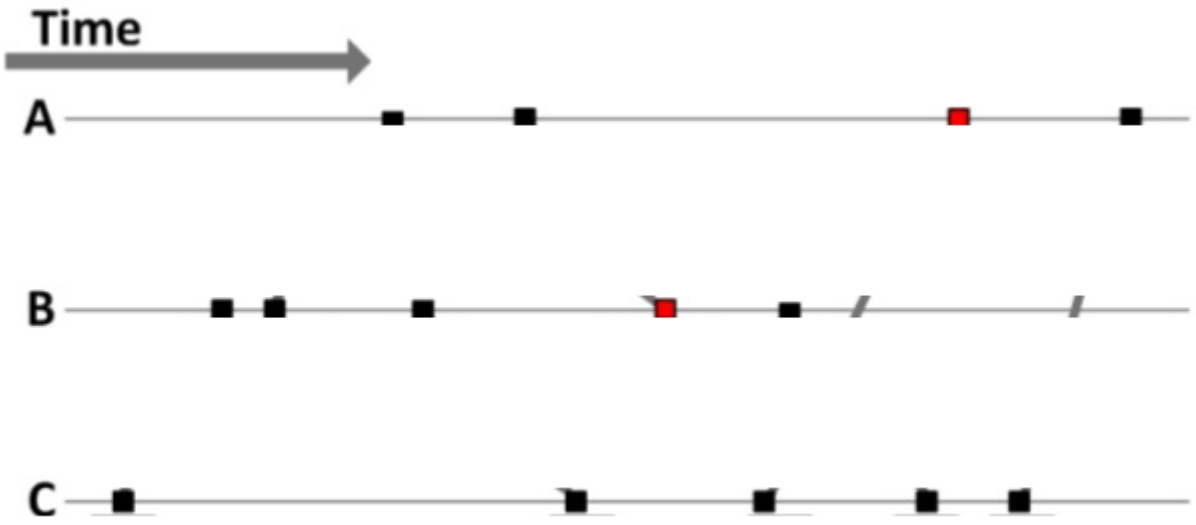

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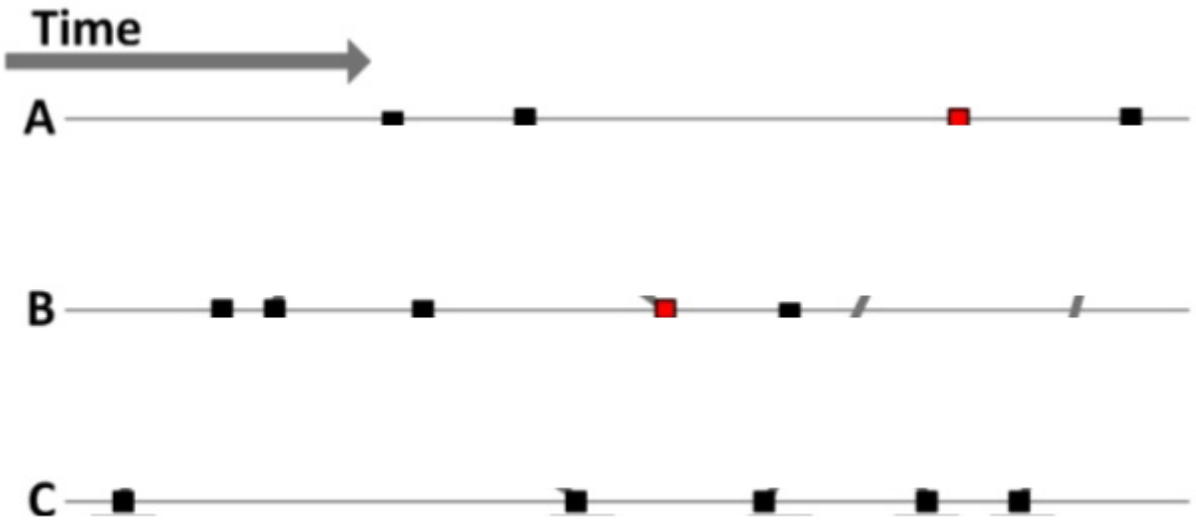

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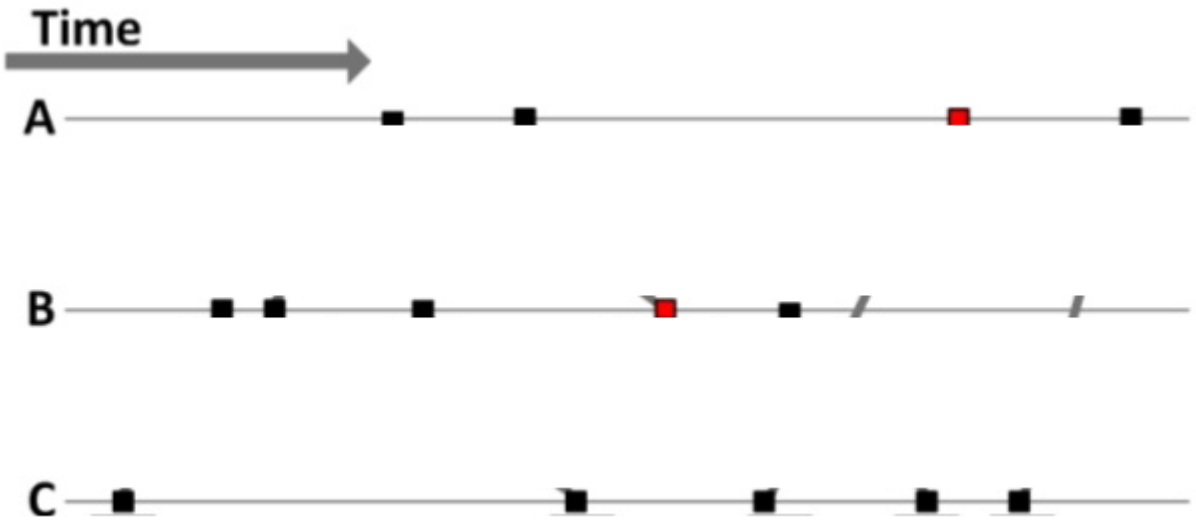

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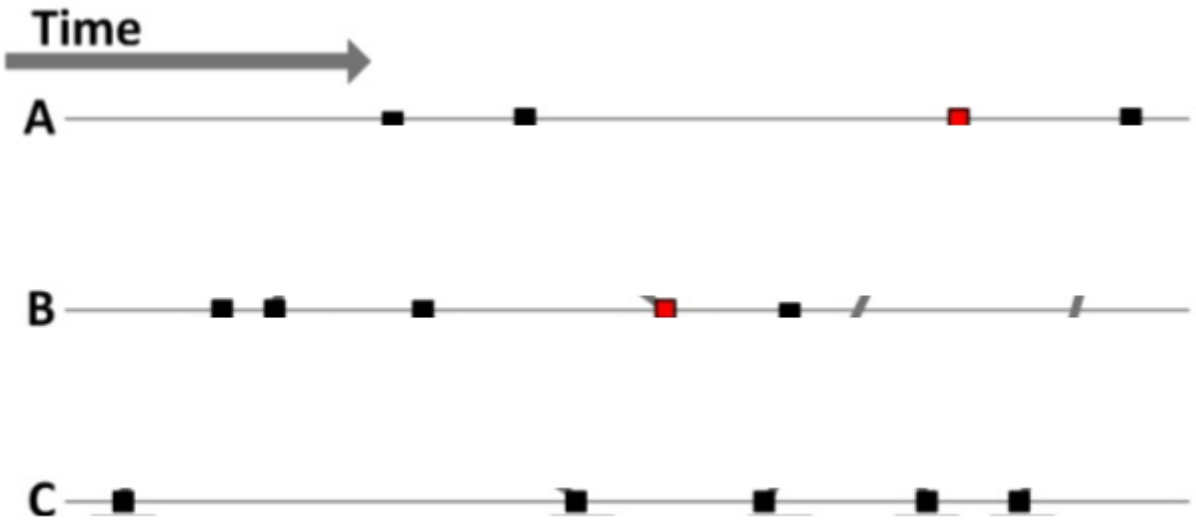

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- Matrix
  - TS(A) is N^2 showing pairwise knowledge

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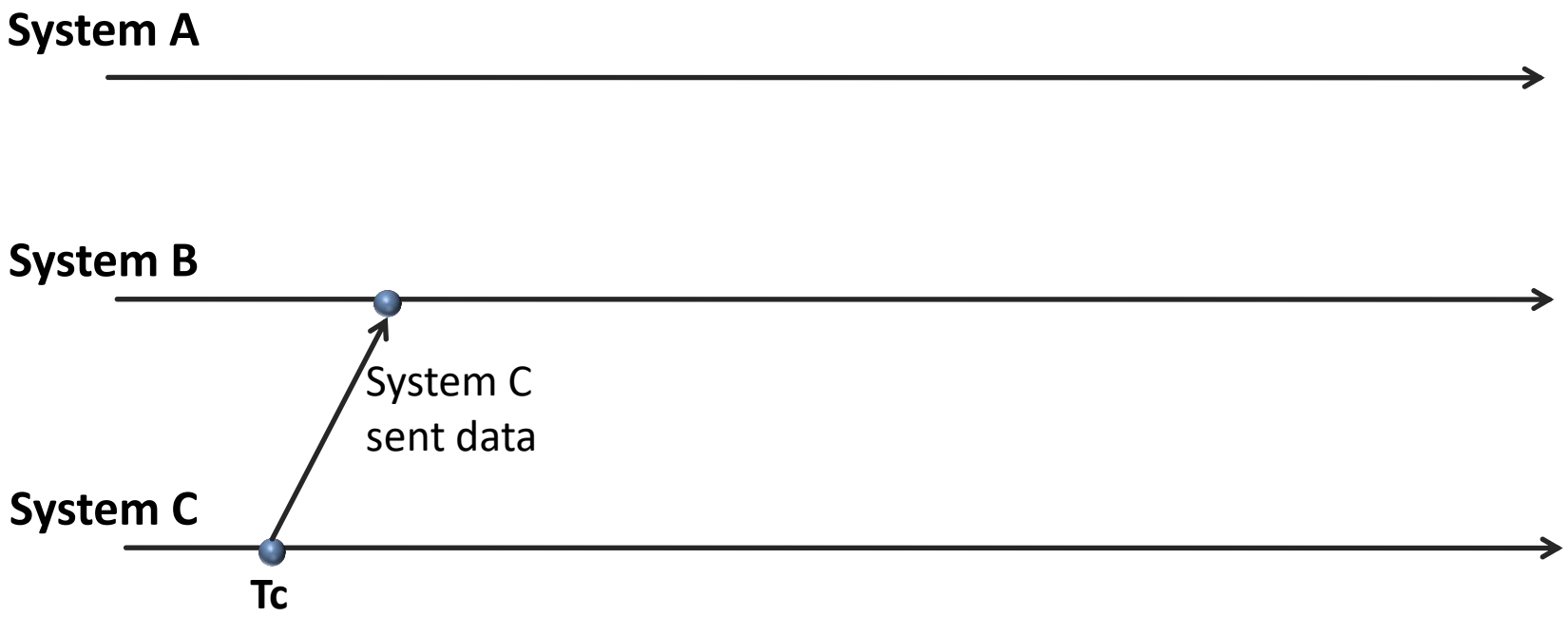

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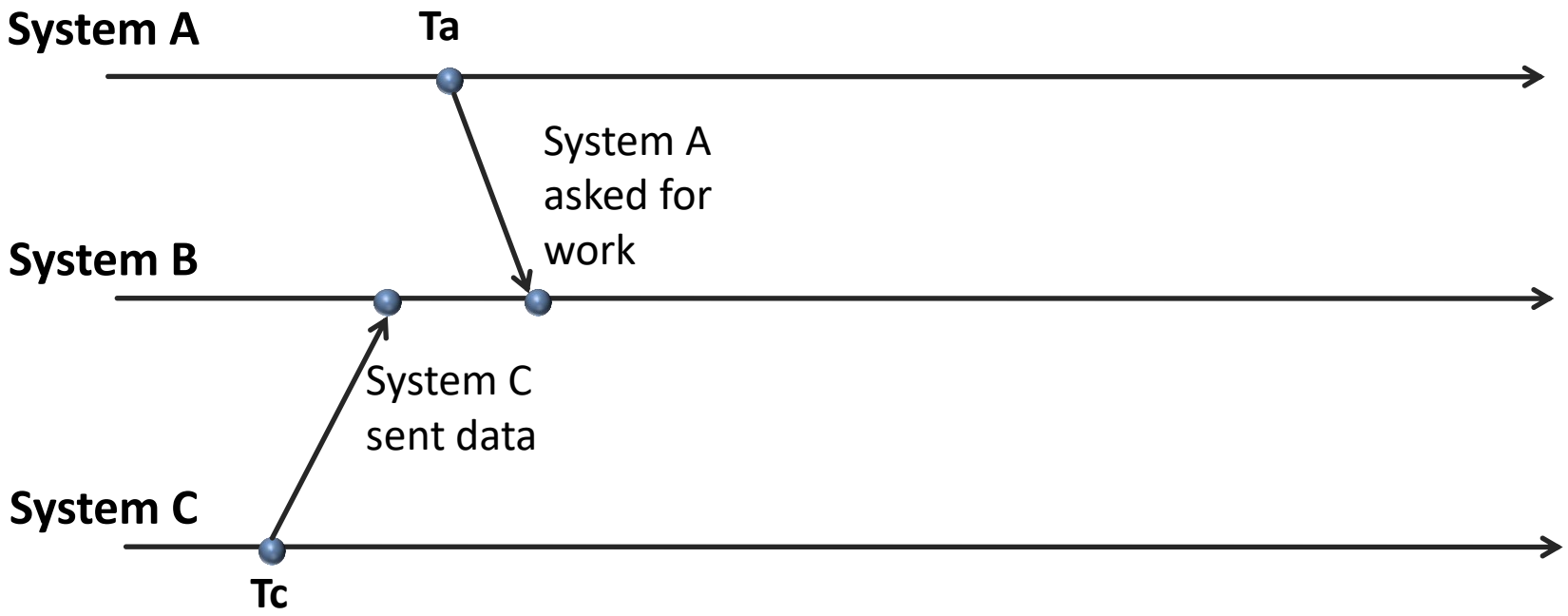

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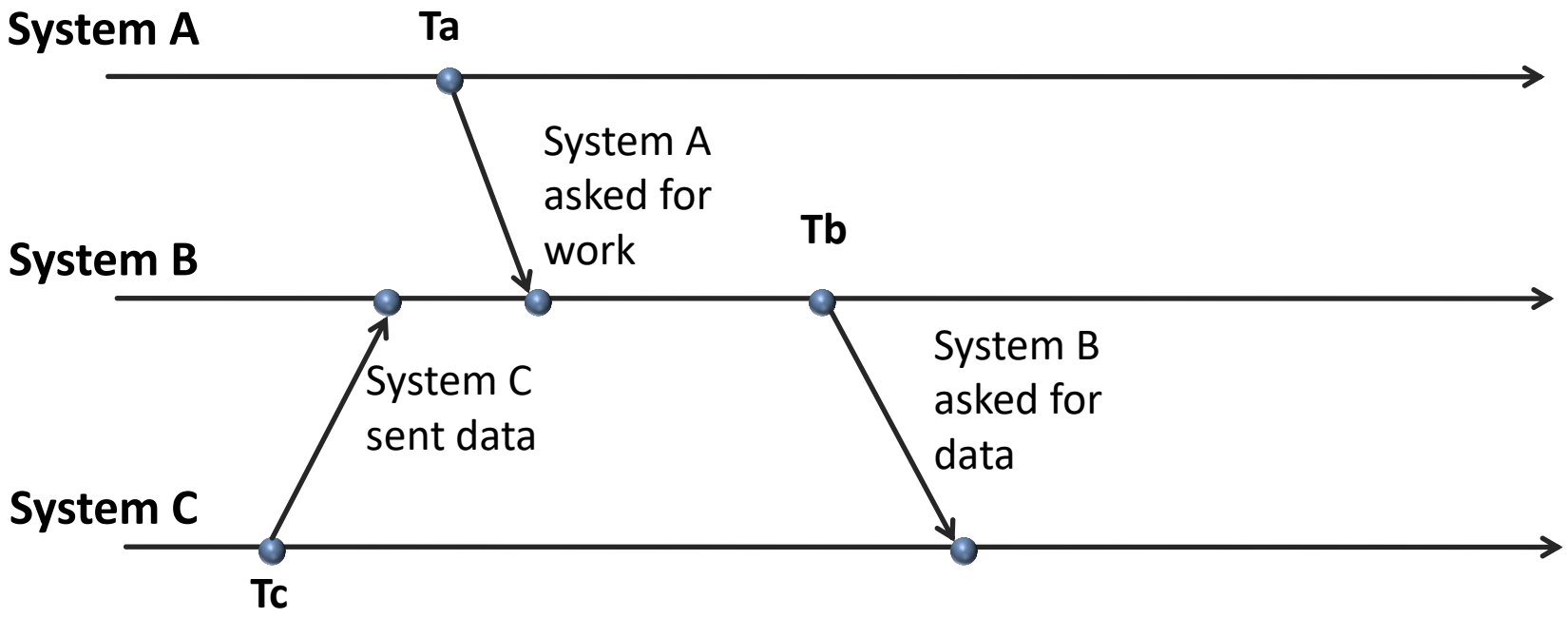

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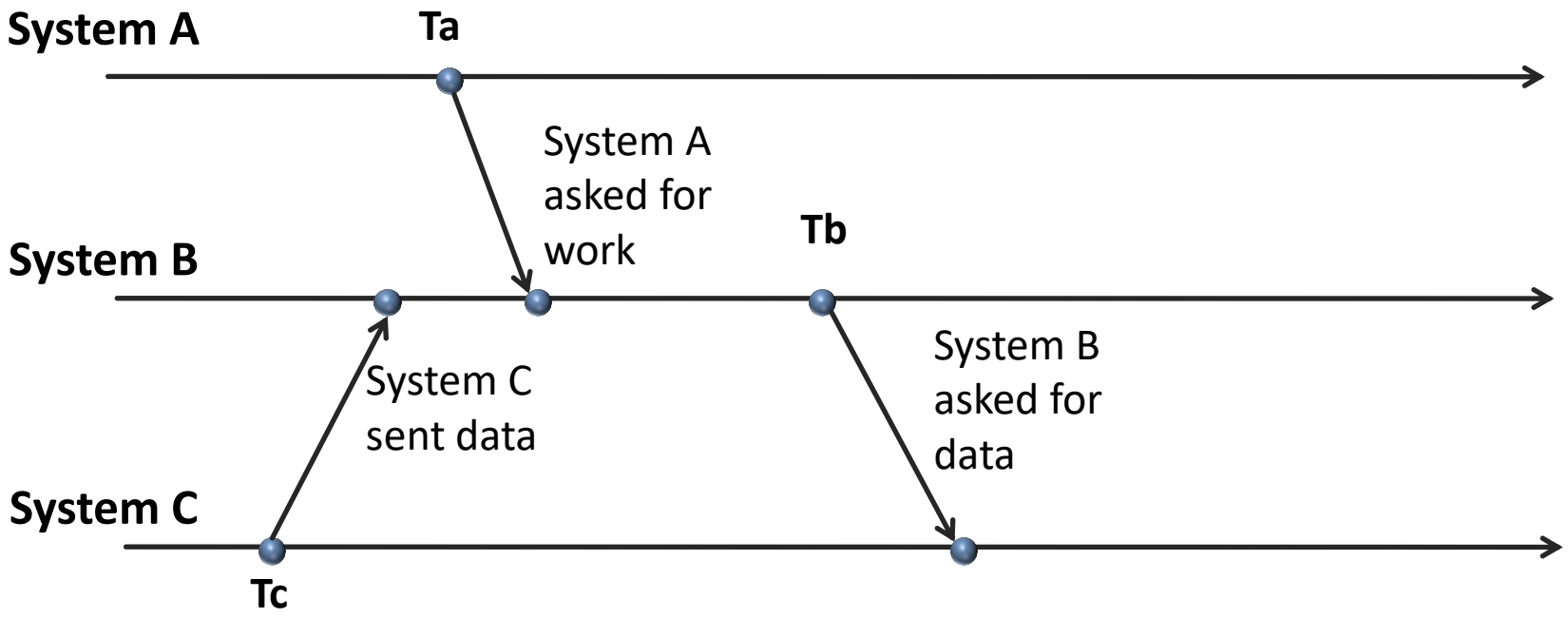

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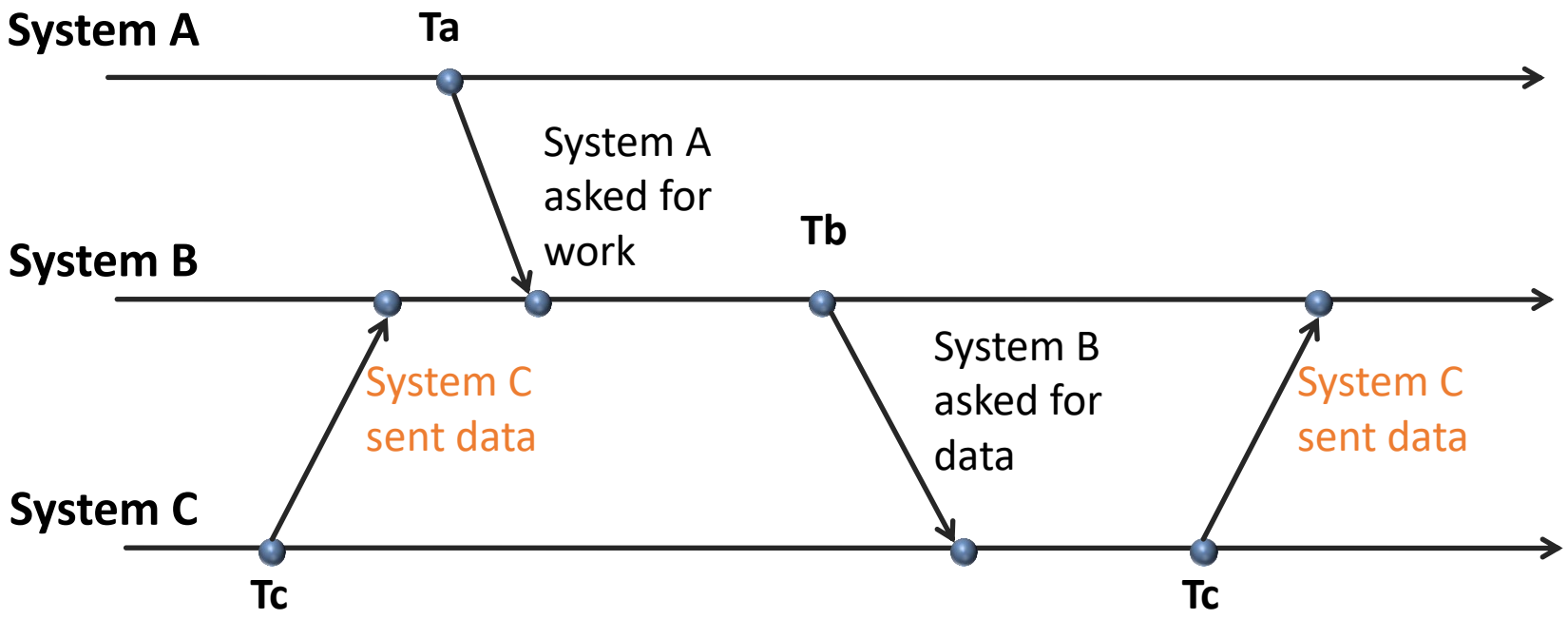
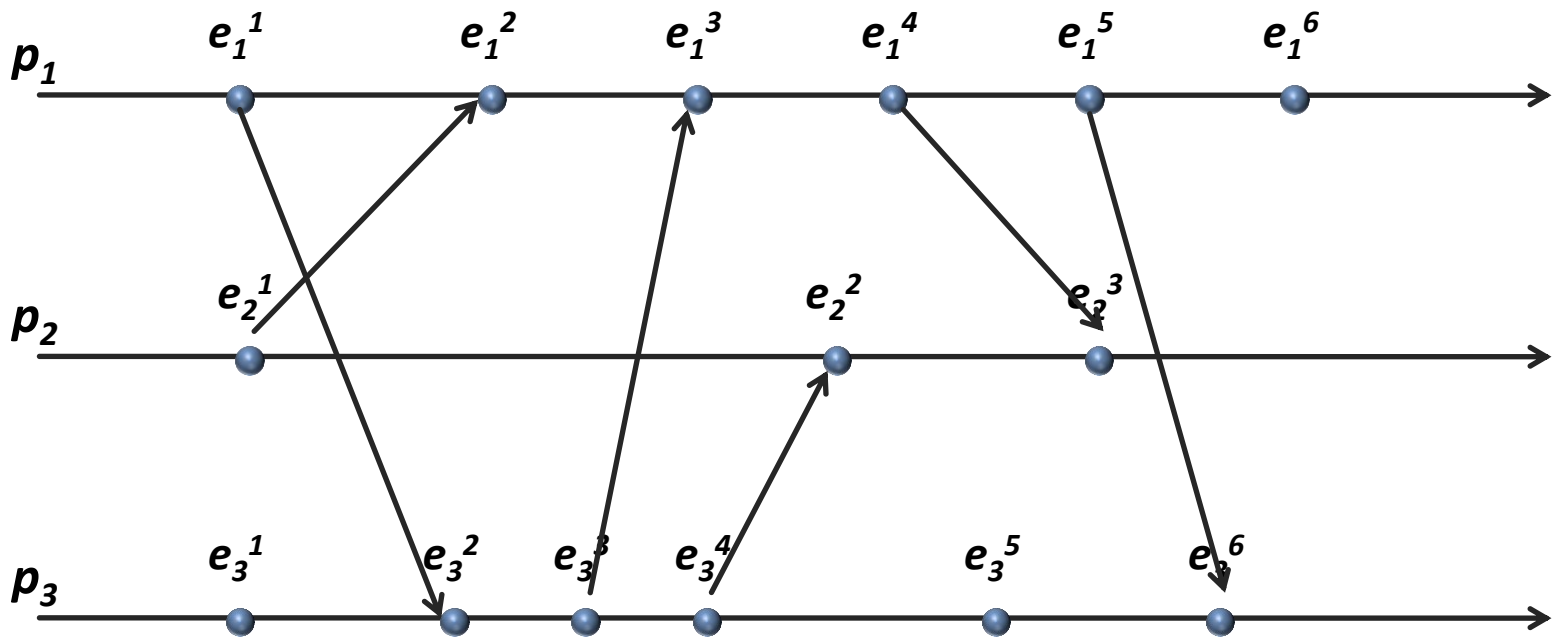


Rules for Ordering of Events

- local events precede one another → precede one another globally:
  - If $e_i^k, e_i^m \in h_i$ and $k < m$, then $e_i^k \rightarrow e_i^m$
- Sending a message always precedes receipt of that message:
  - If $e_i = send(m)$ and $e_j = receive(m)$, then $e_i \rightarrow e_j$
- Event ordering is transitive:
  - If $e \rightarrow e'$ and $e' \rightarrow e''$, then $e \rightarrow e''$

Space-time Diagram for Distributed Computation



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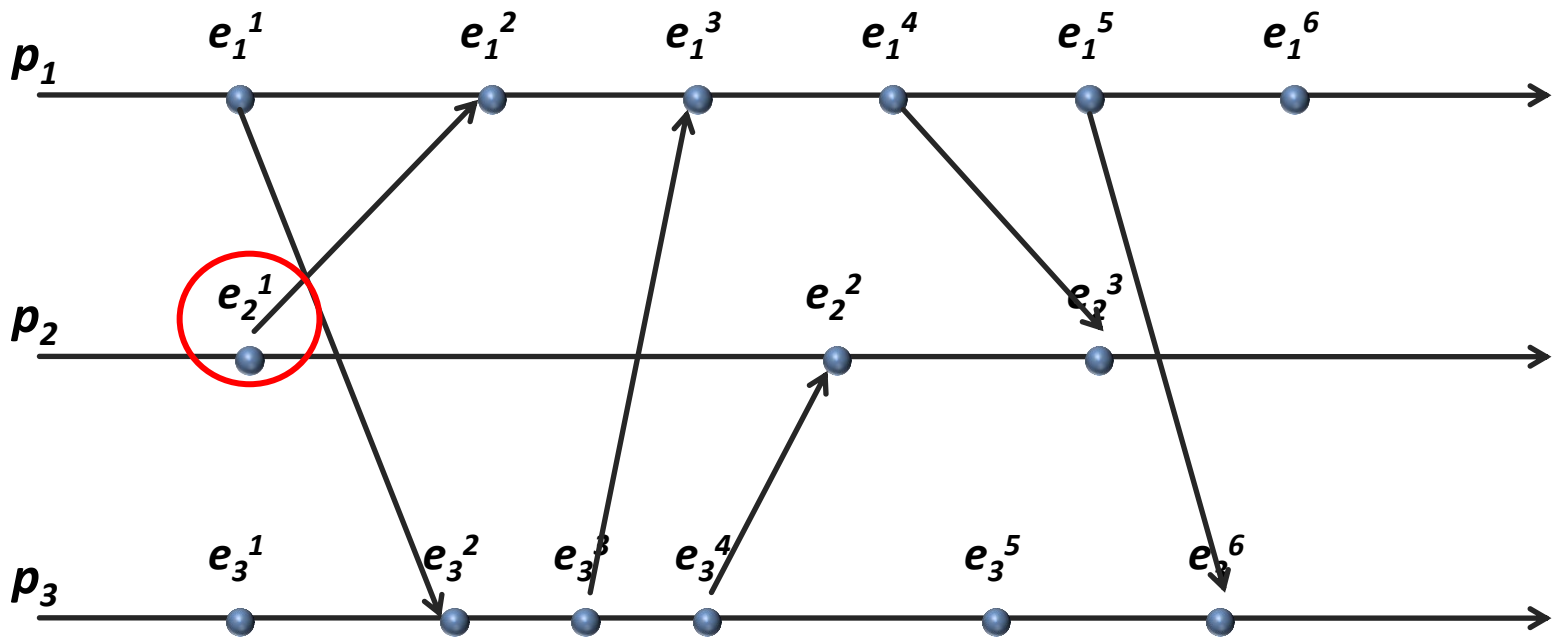

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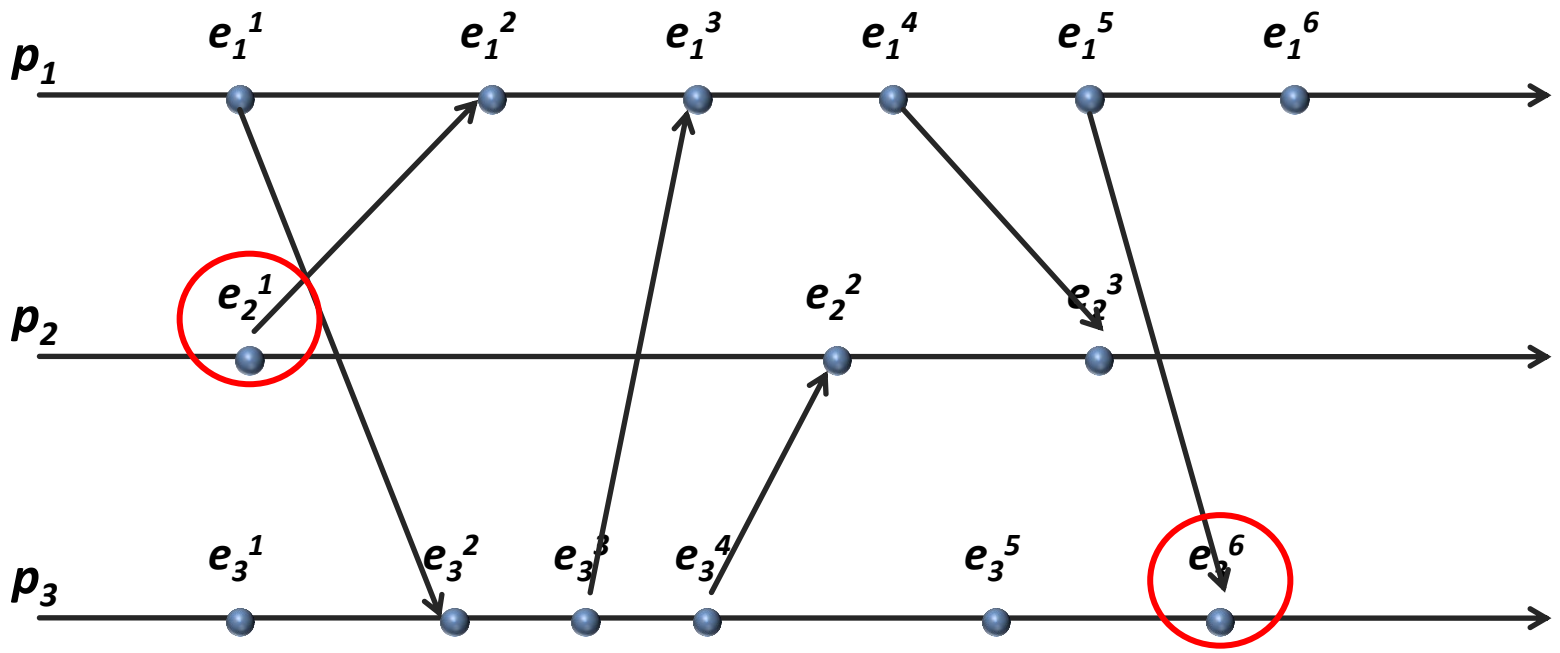

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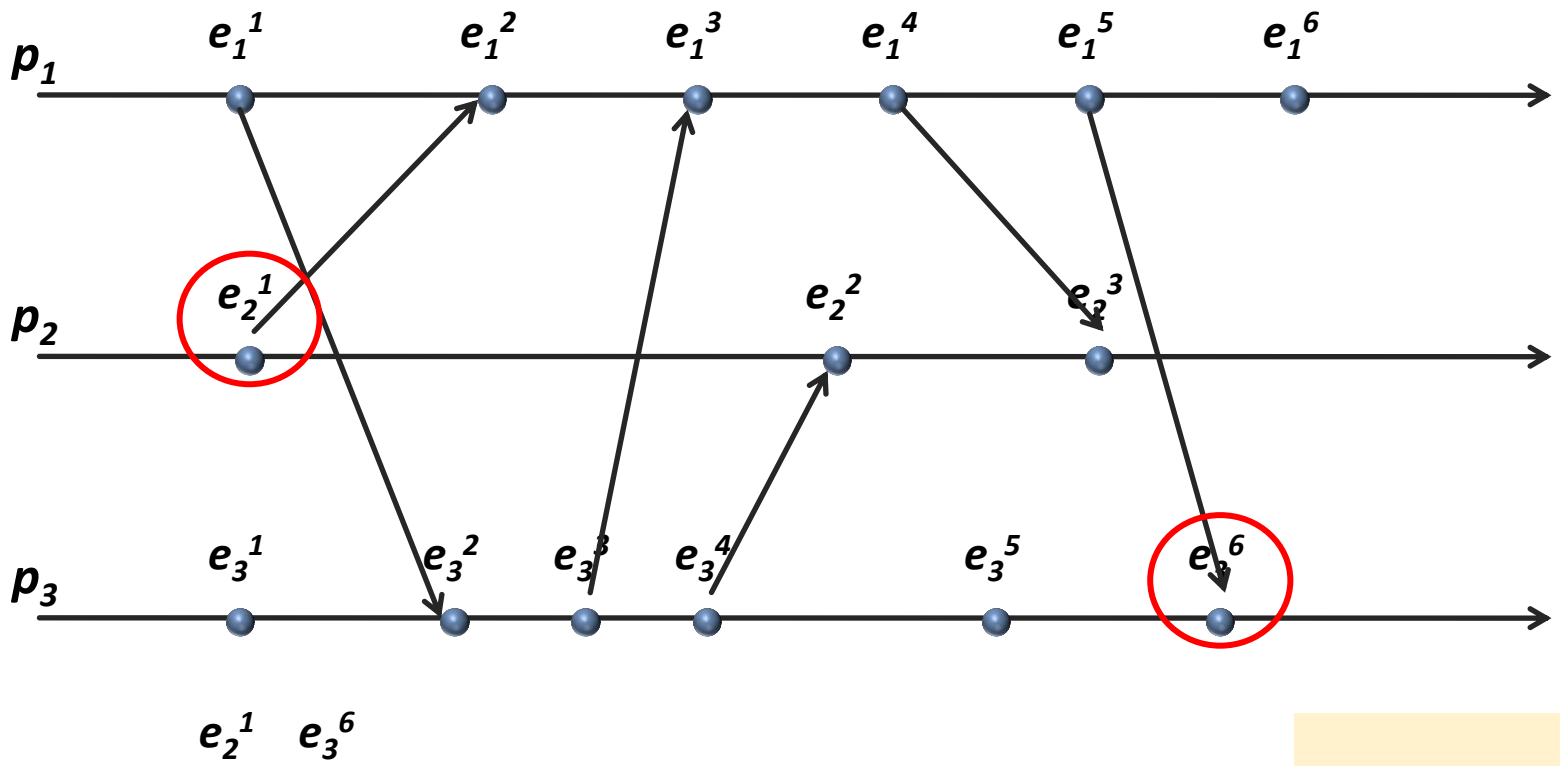

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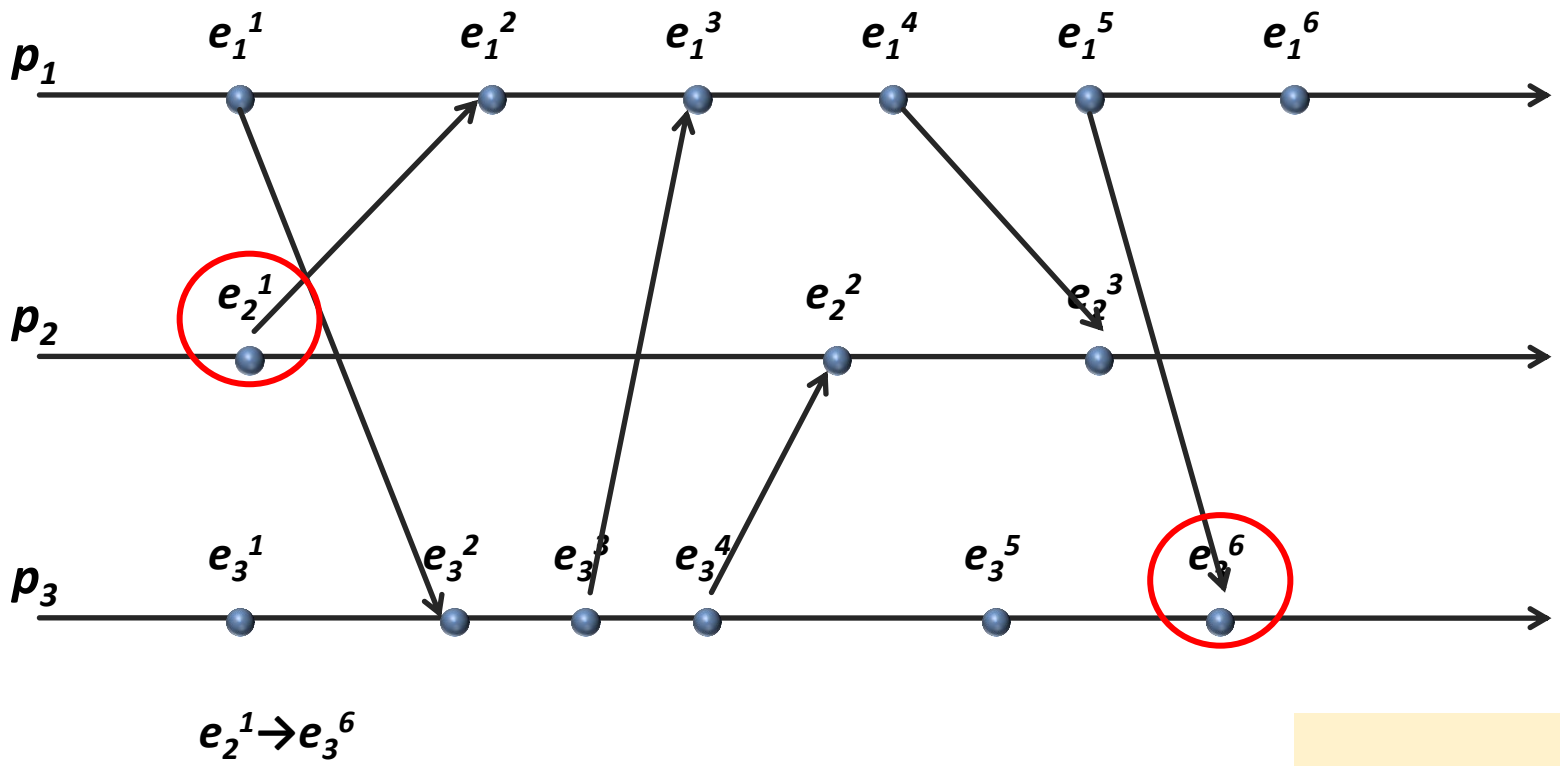

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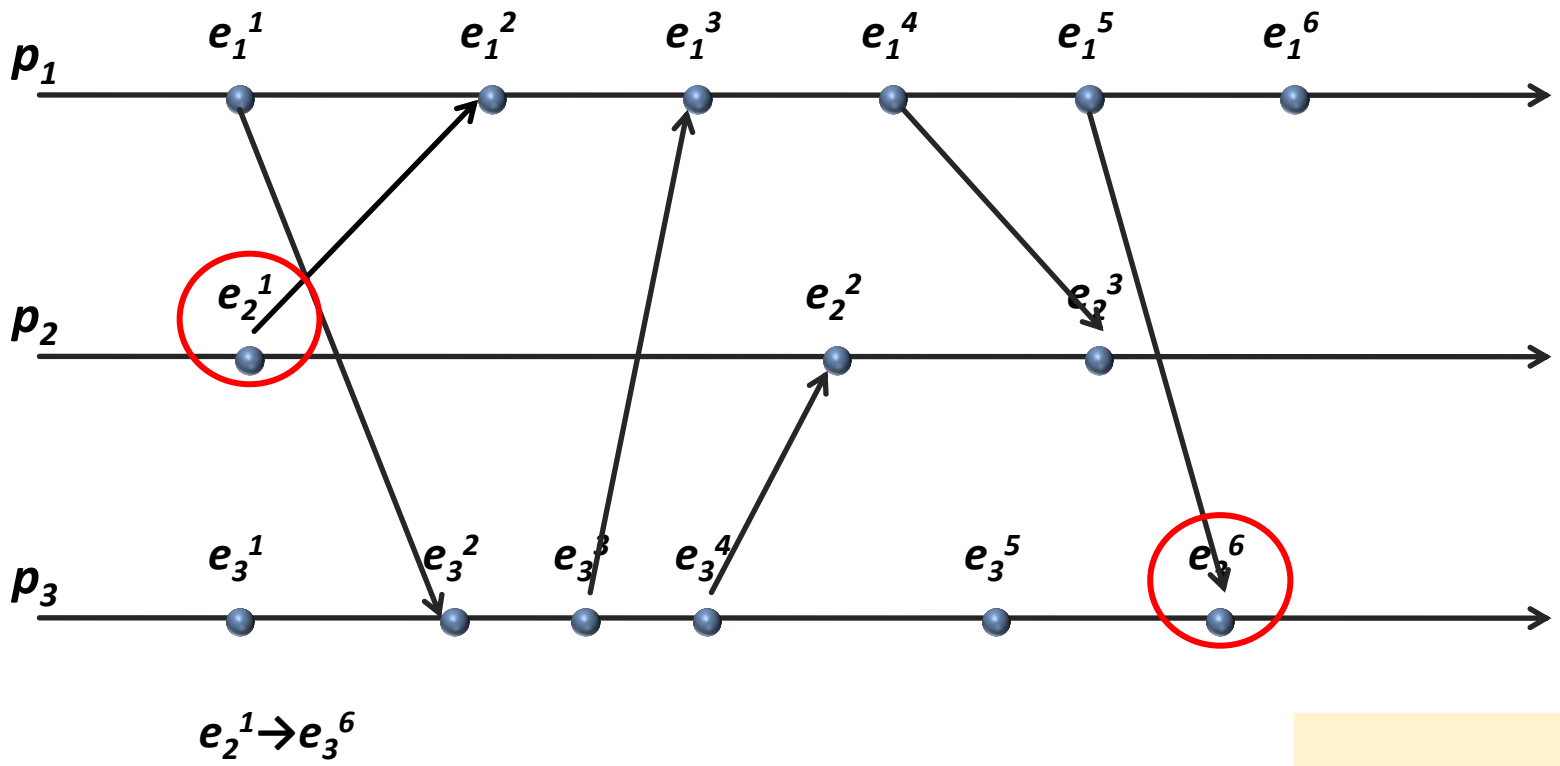
Space-time Diagram for Distributed Computation



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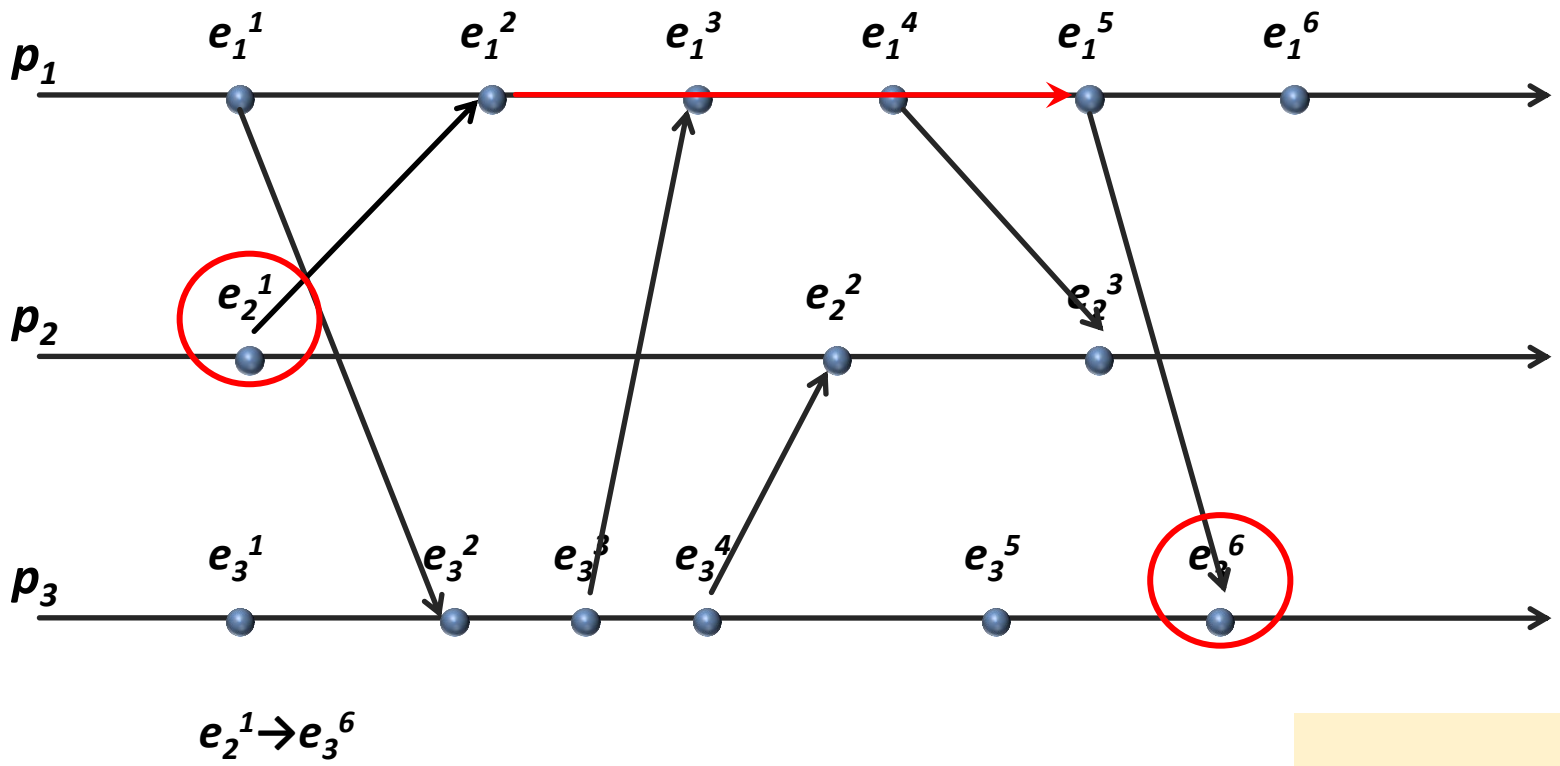

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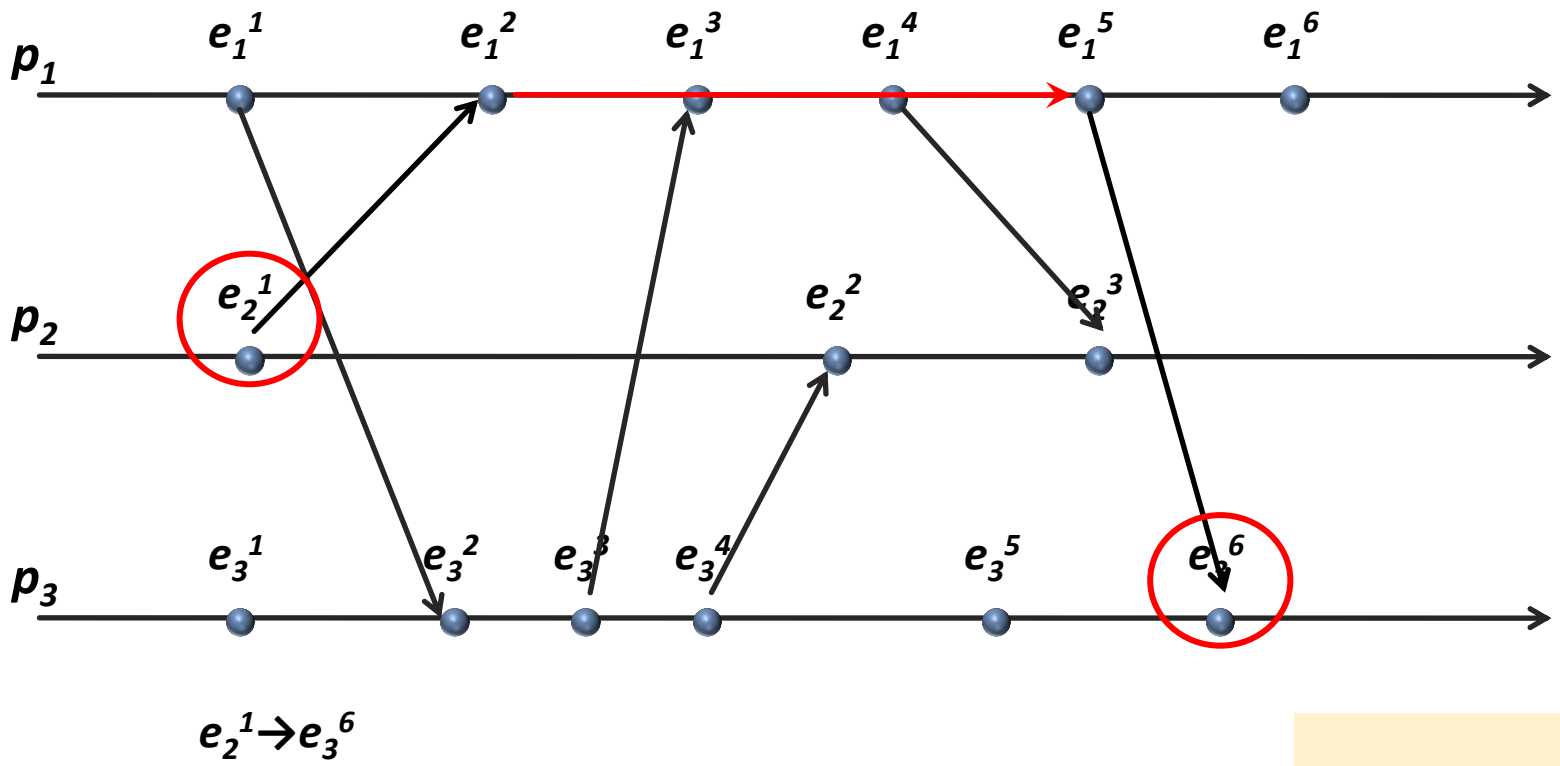

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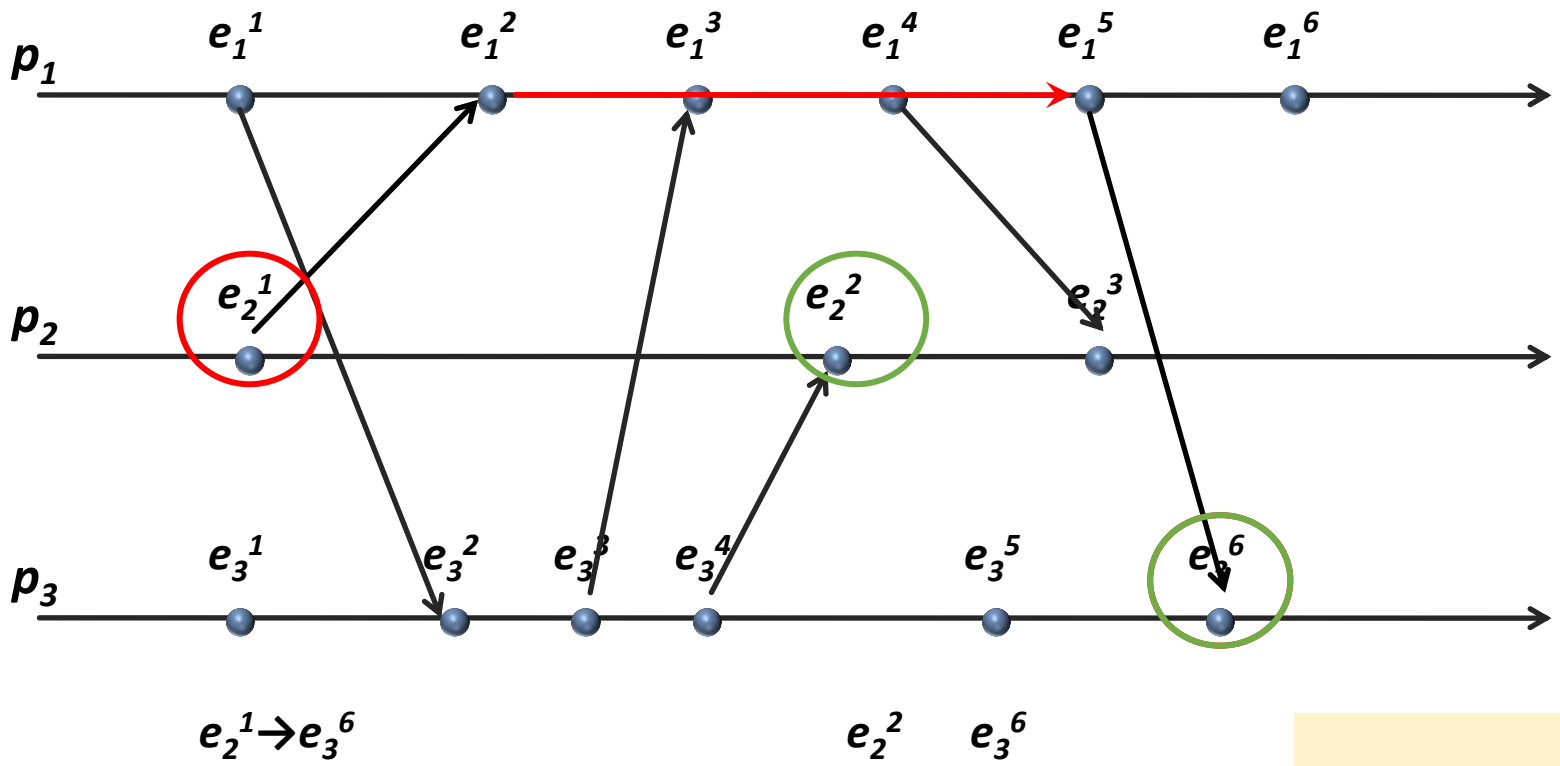

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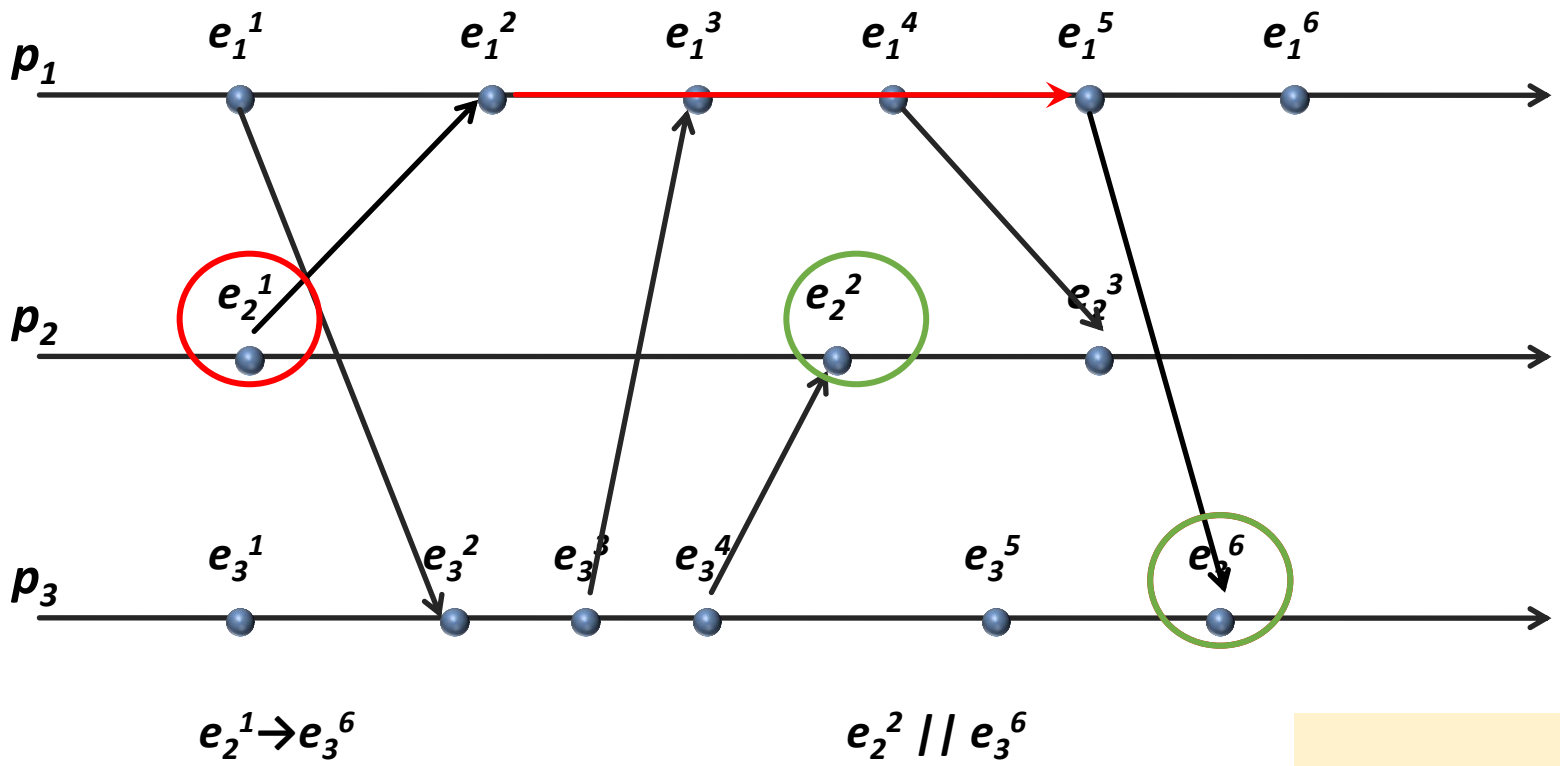

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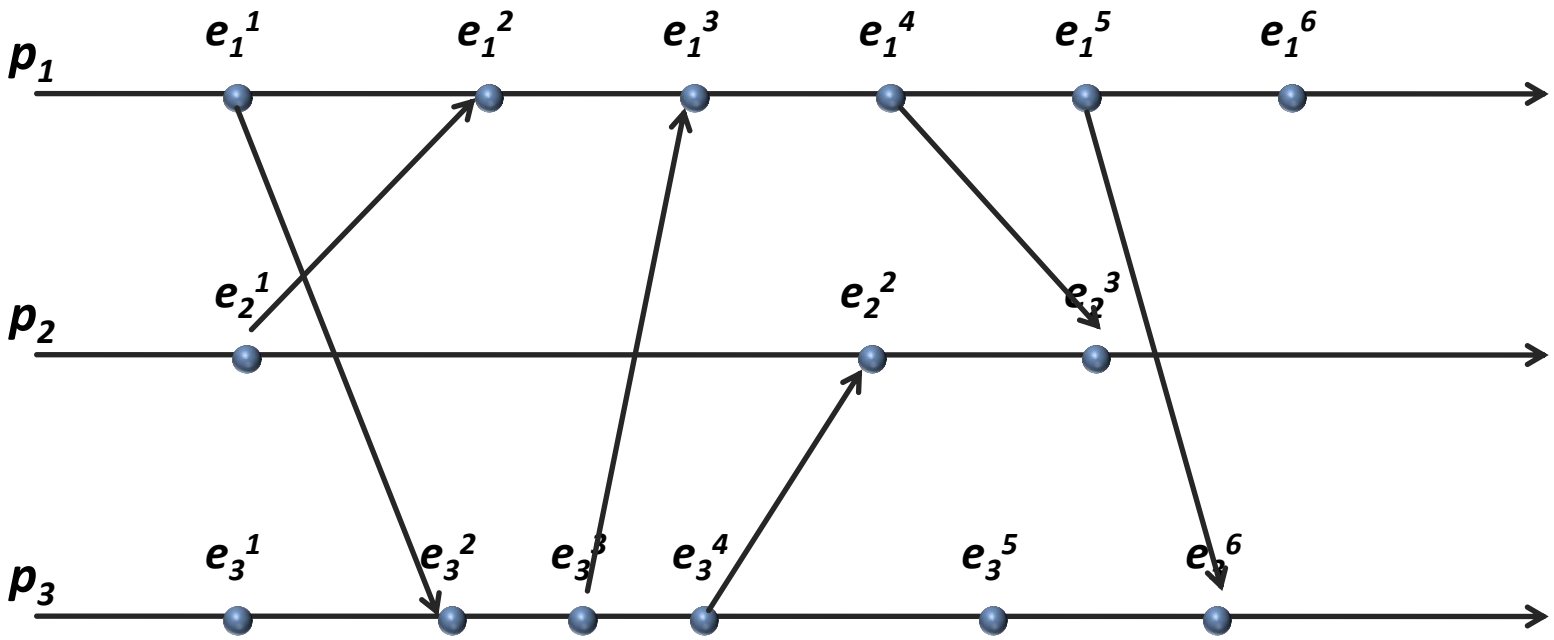
Cuts of a Distributed Computation

- Suppose there is an ***external monitor*** process
- External monitor constructs a global state:
  - Asks processes to send it local history
- Global state constructed from these local histories is:

a ***cut of a distributed computation***

Example Cuts



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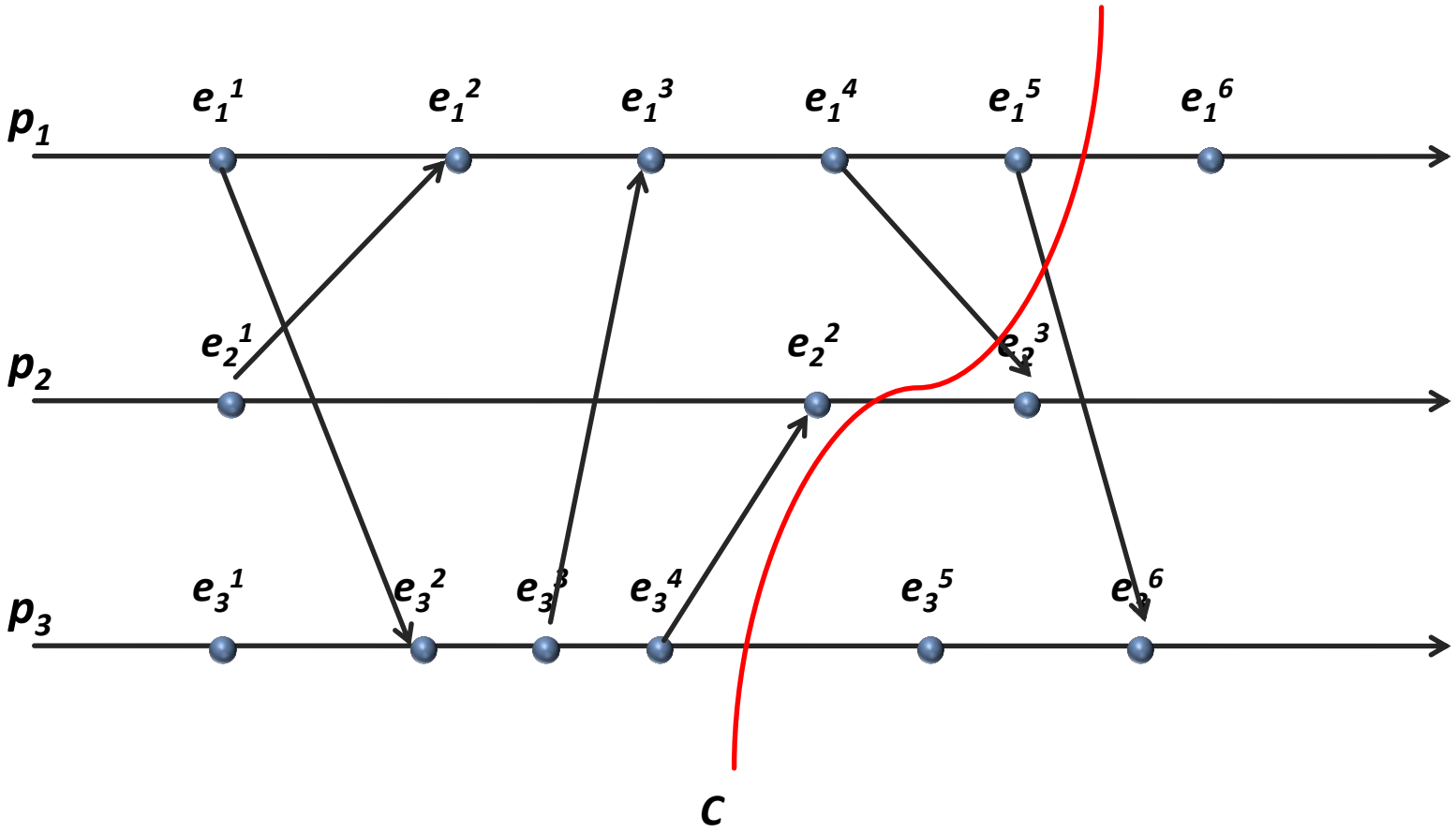

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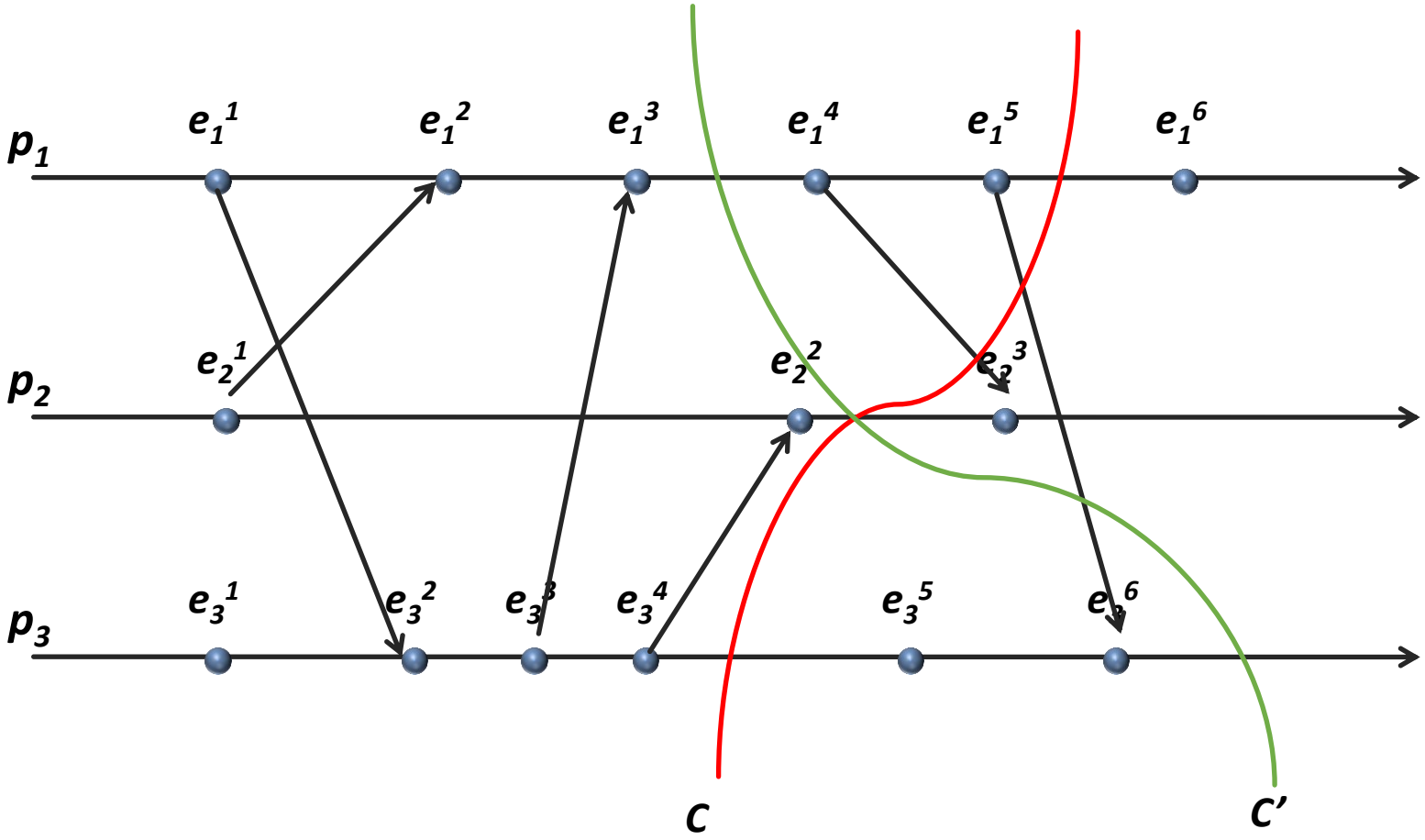
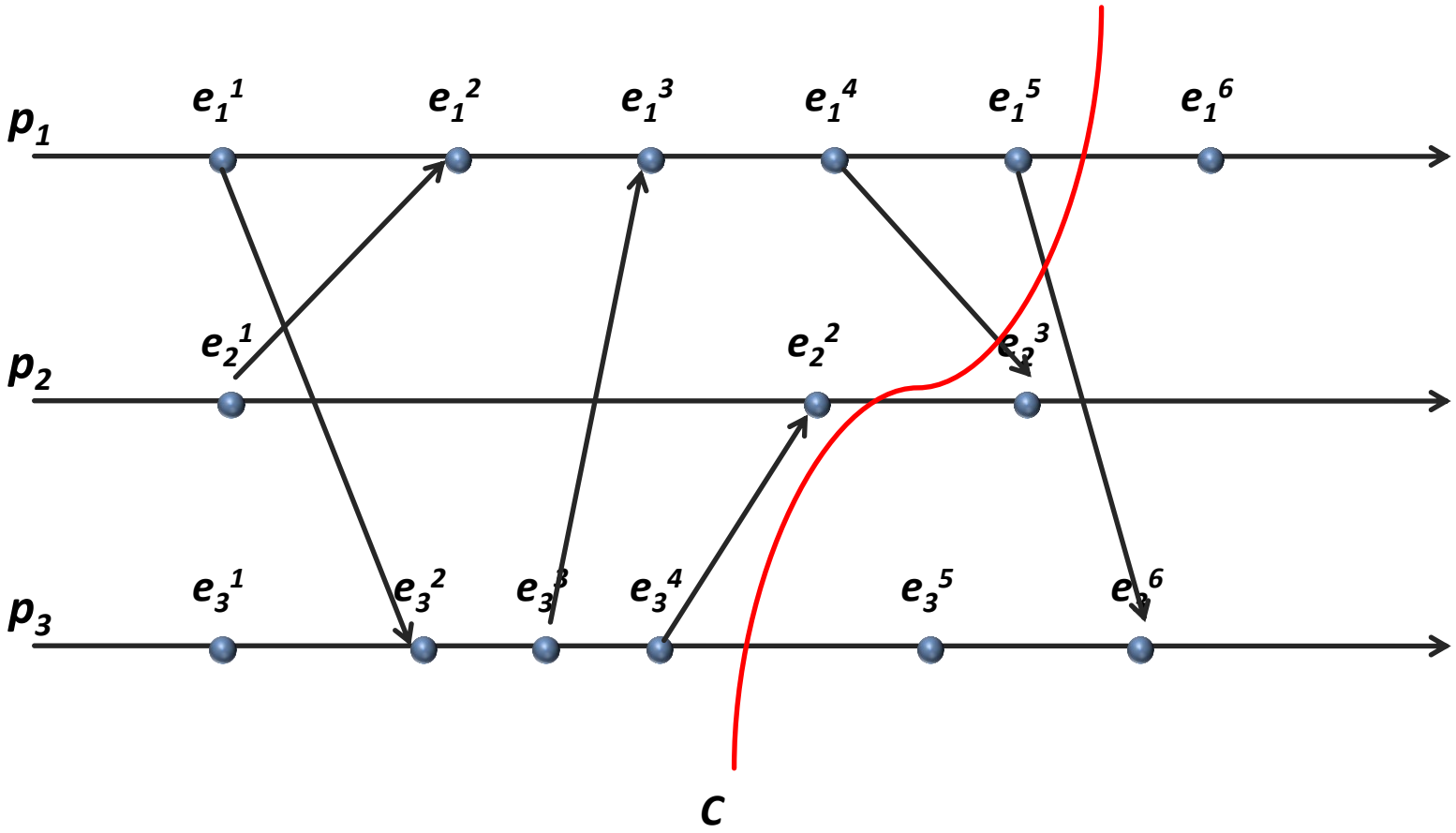


Consistent vs. Inconsistent Cuts

- A cut is consistent if
  - for any event *e* included in the cut
  - any event *e'* that causally precedes *e* is also included in that cut
- For cut *C:*

$$(e \in C) \wedge (e' \rightarrow e) \Rightarrow e' \in C$$

Are These Cuts Consistent?



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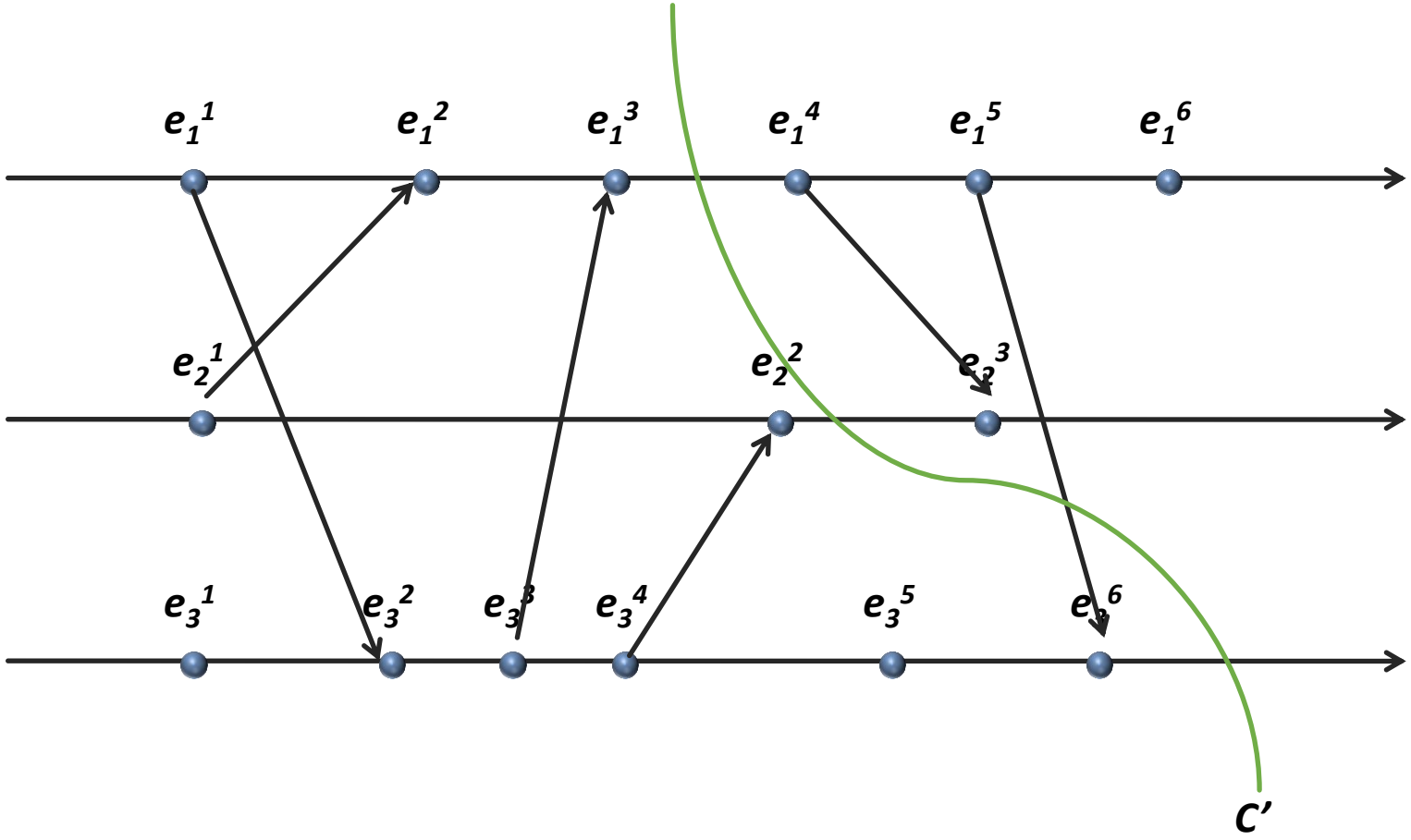

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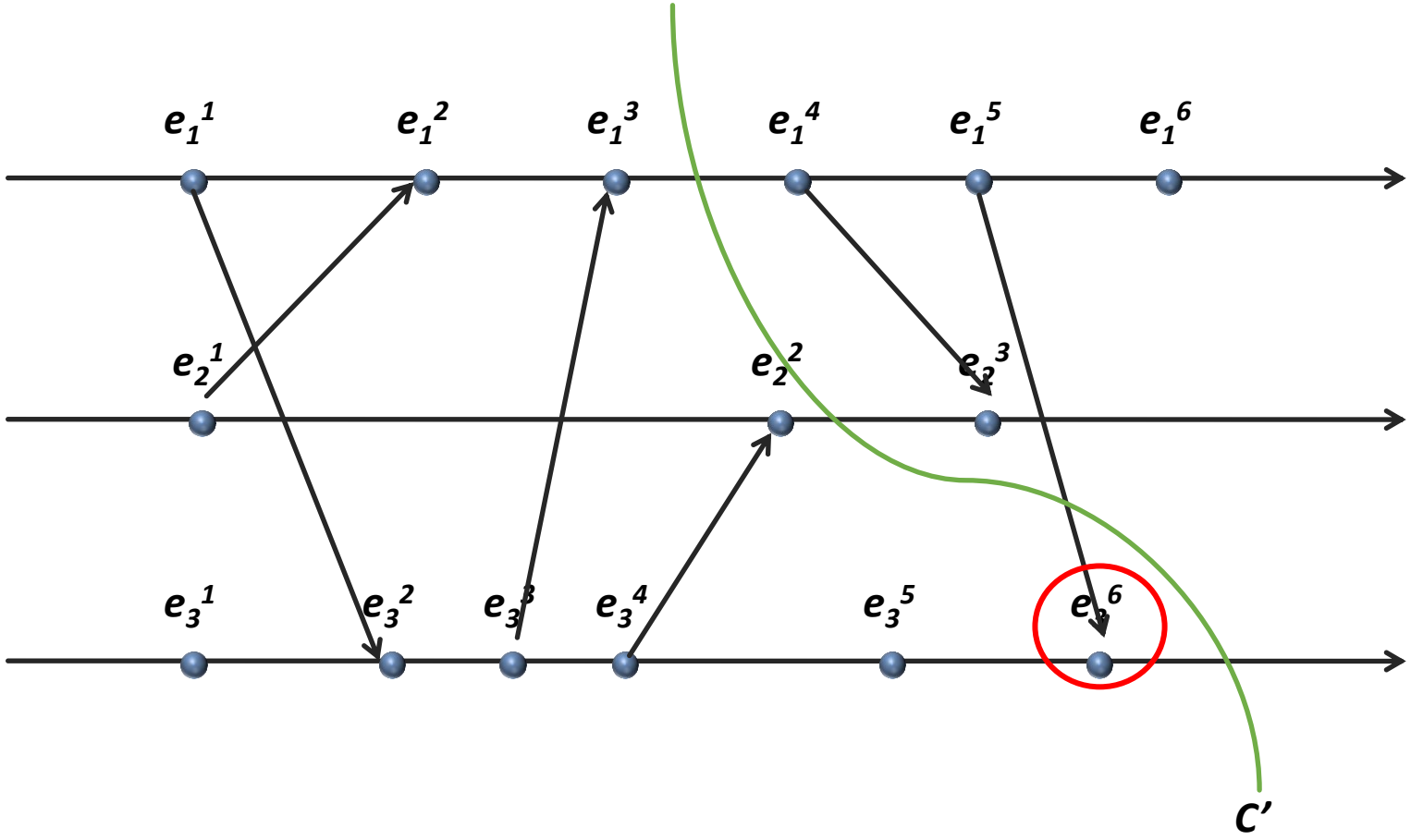

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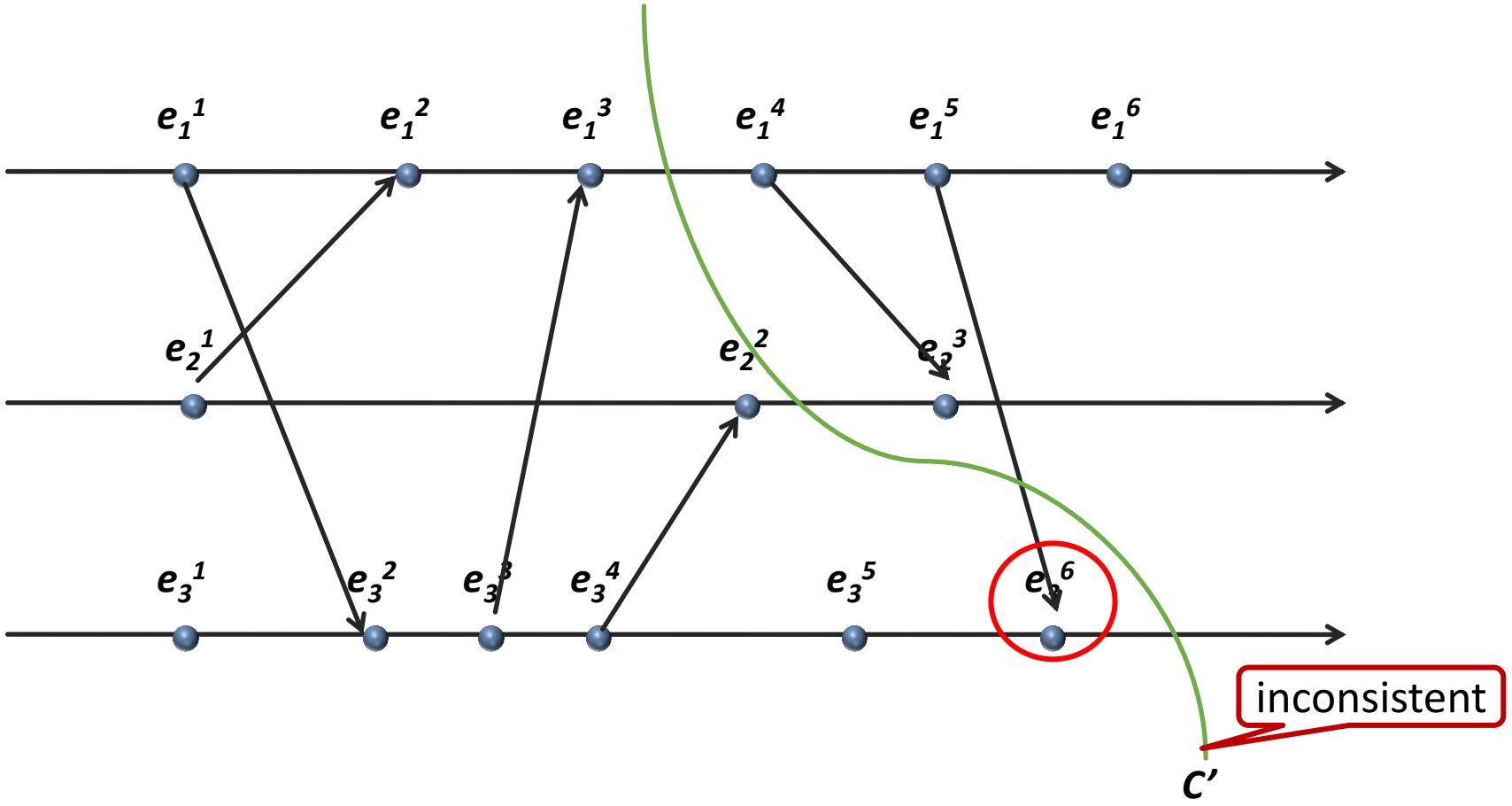

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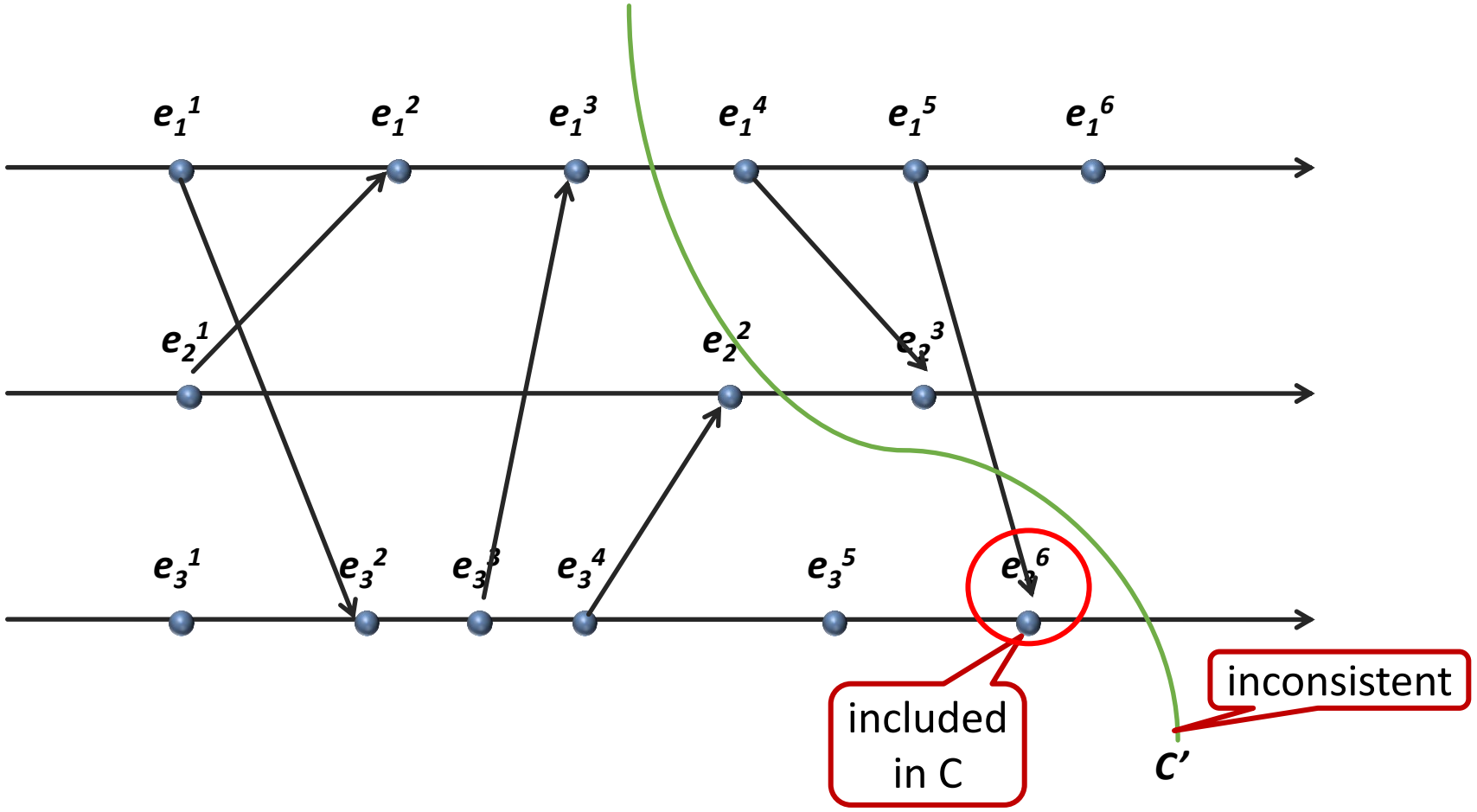

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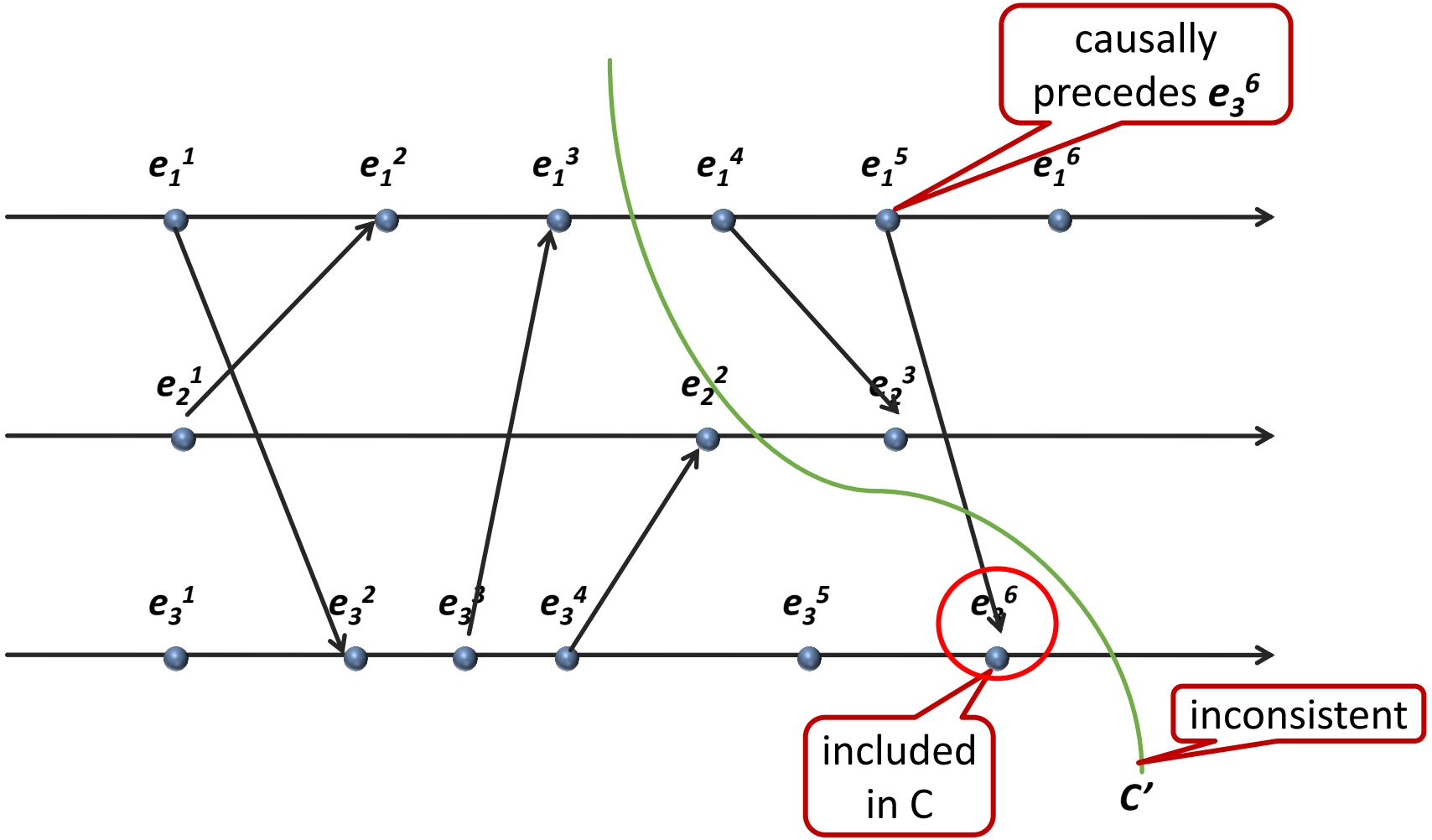

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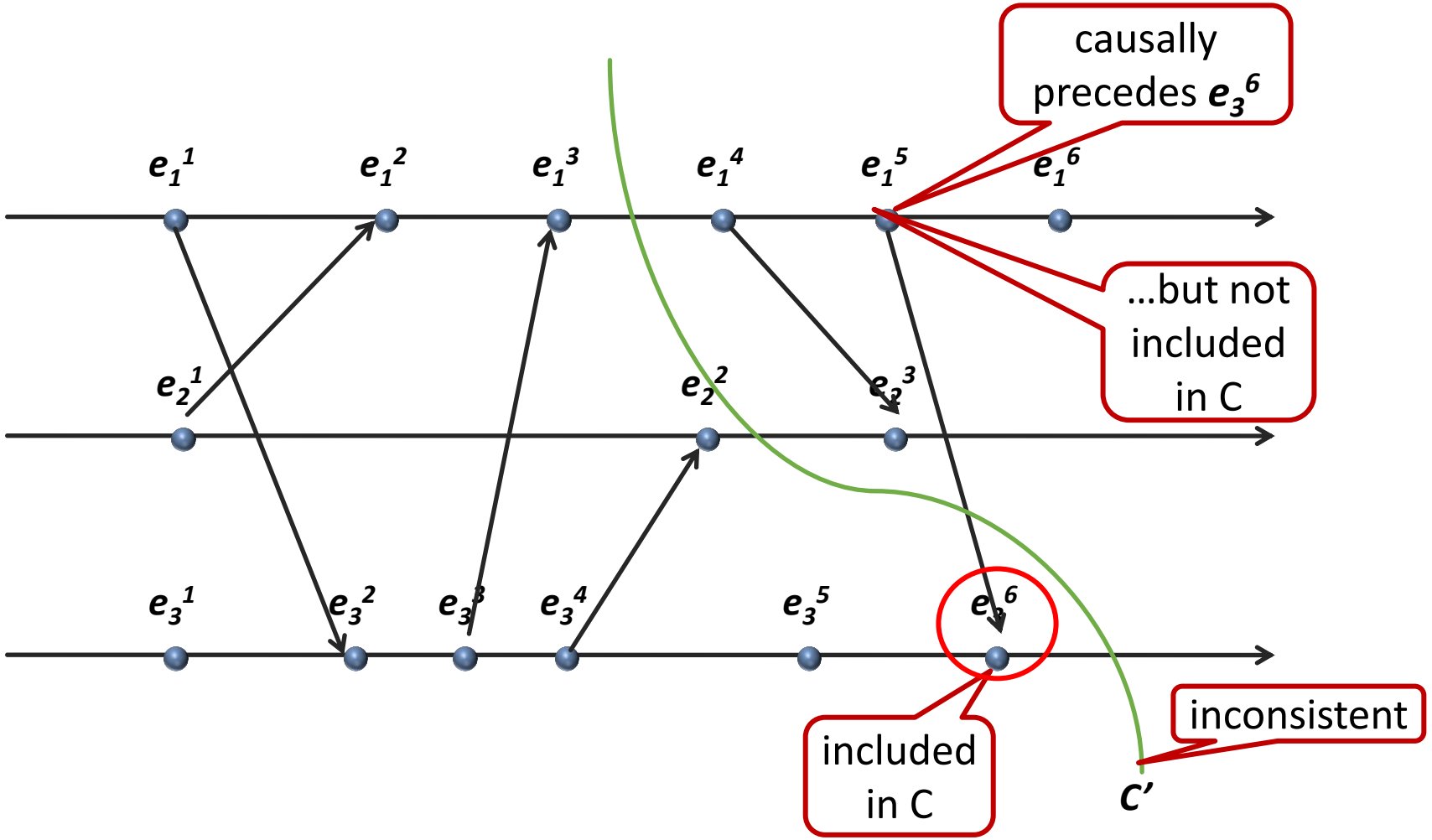

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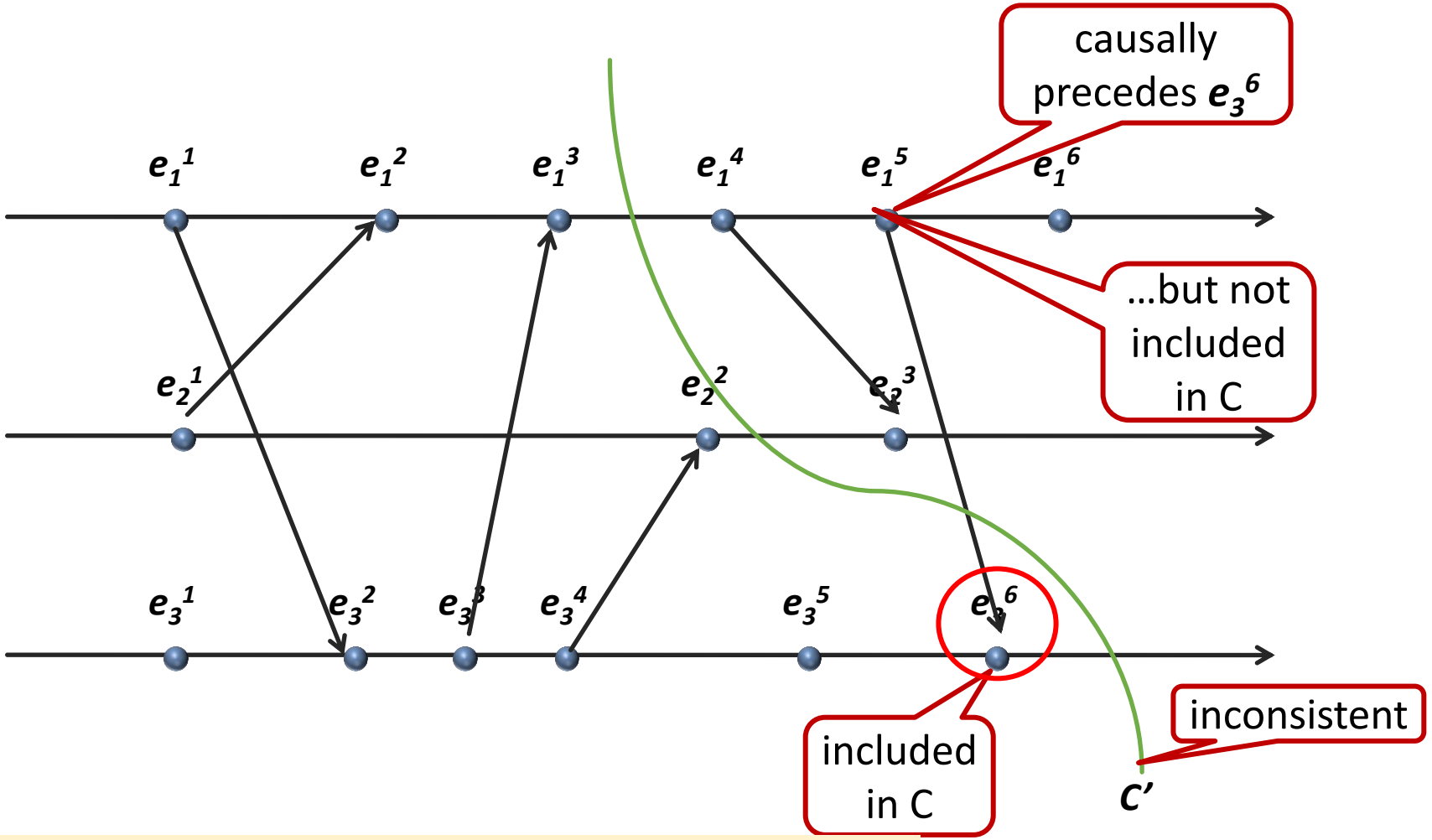
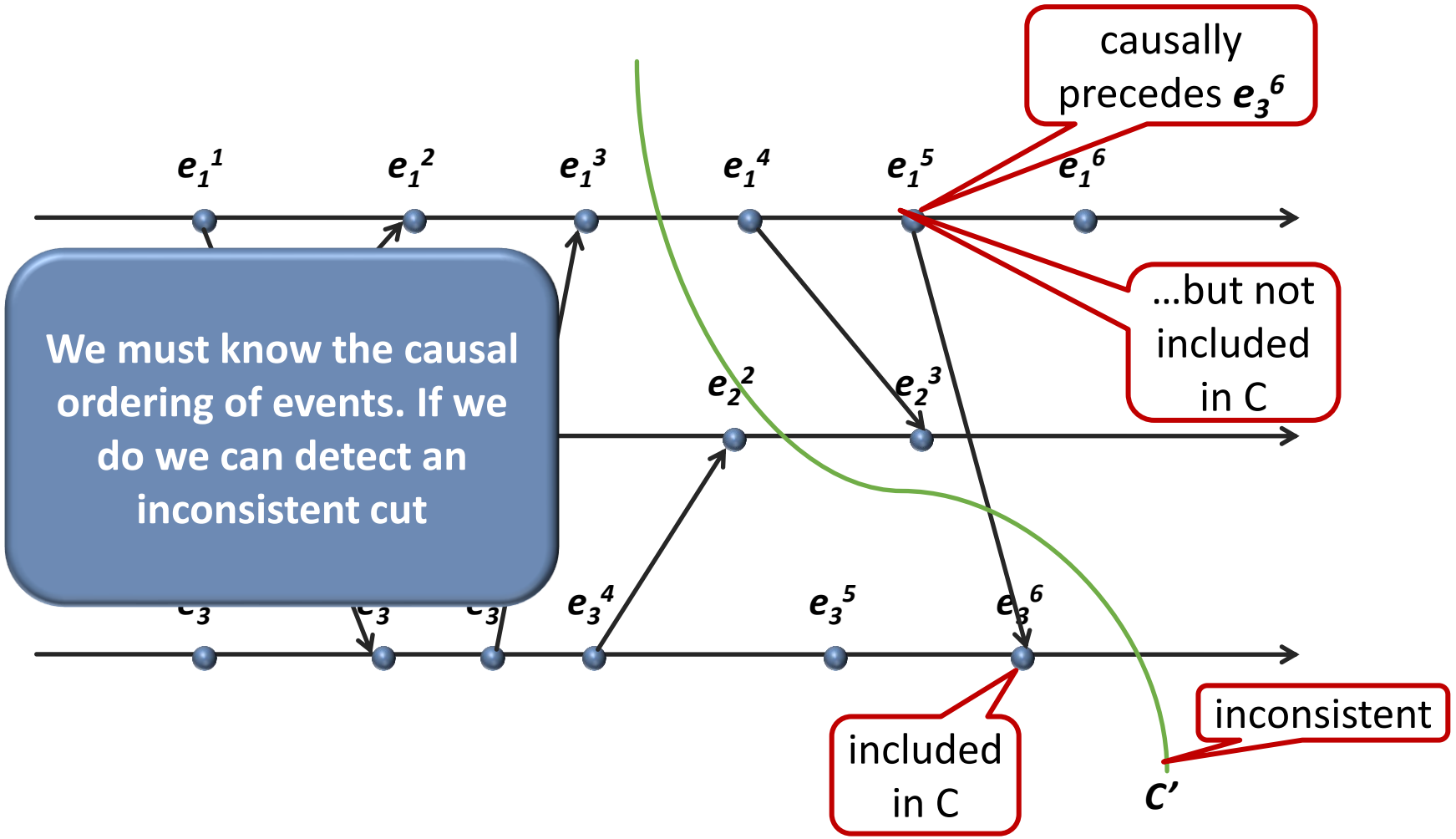


A consistent cut corresponds to a consistent global state

What Do We Need to Know to Construct a Consistent Cut?



Logical Clocks

- Each process maintains a local value of a logical clock ***LC***
- Logical clock of process *p* counts **how many events in a distributed computation causally preceded the current event at *p*** (including the current event).
- $LC(e_i)$ – the logical clock value at process p_i at event e_i
- Suppose we had a distributed system with only a single process

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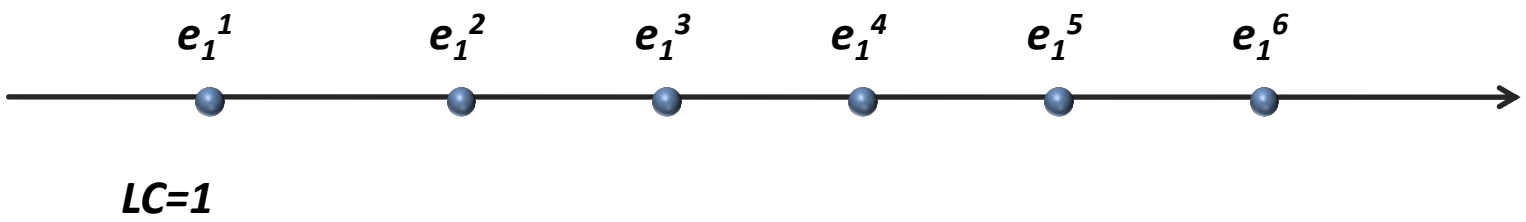

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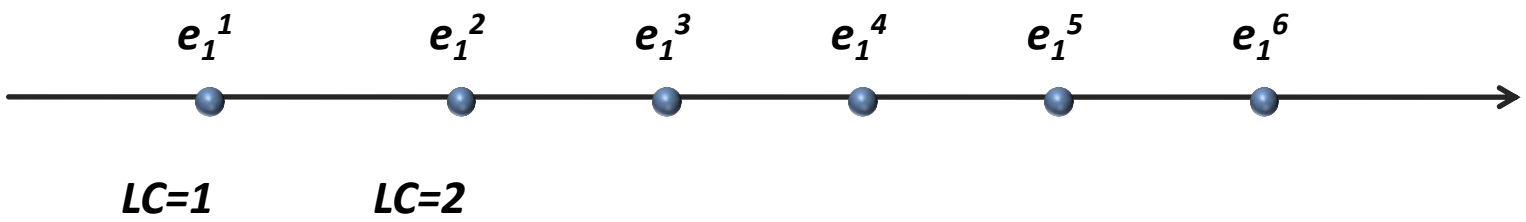

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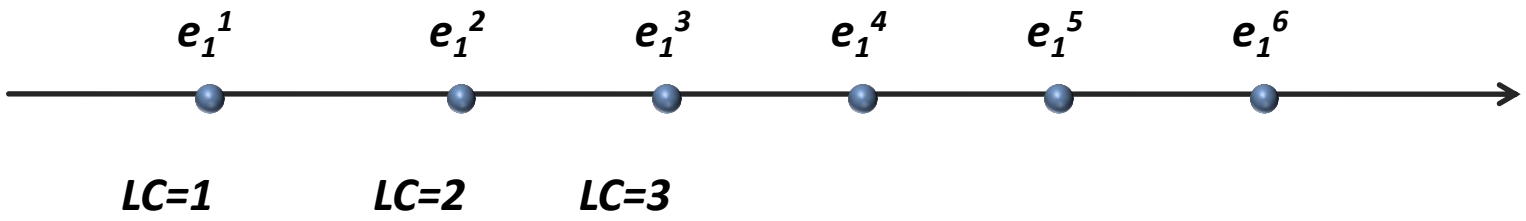

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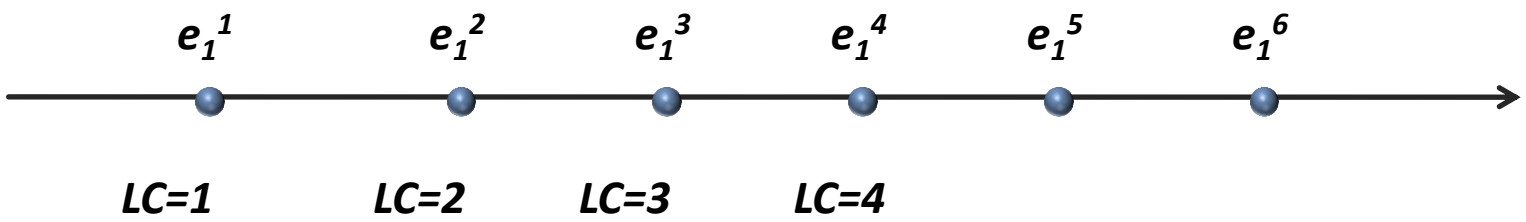

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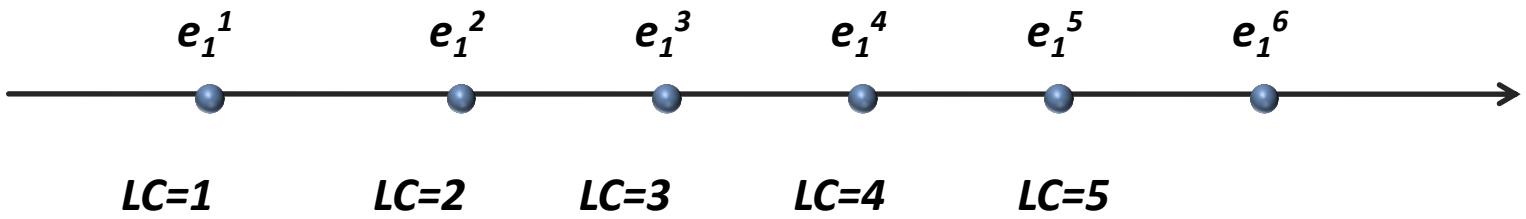

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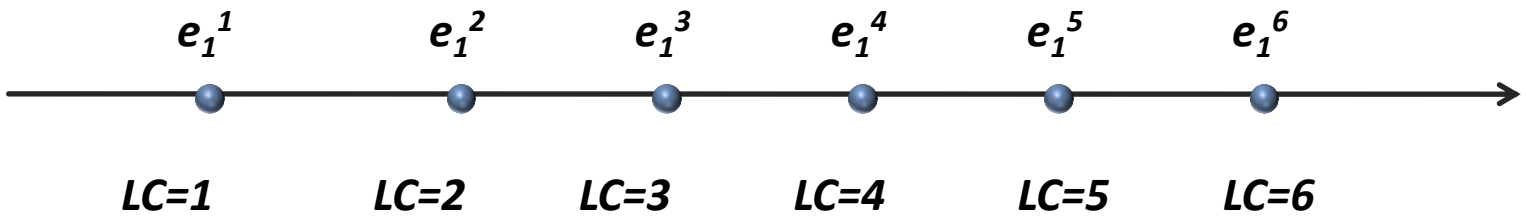

Logical Clocks (cont.)

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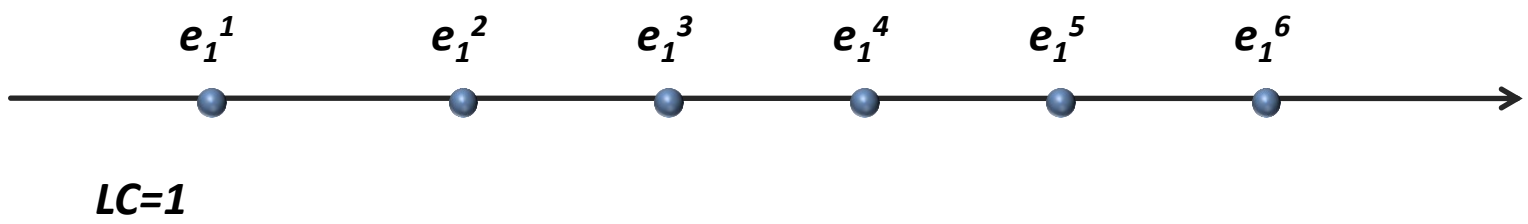

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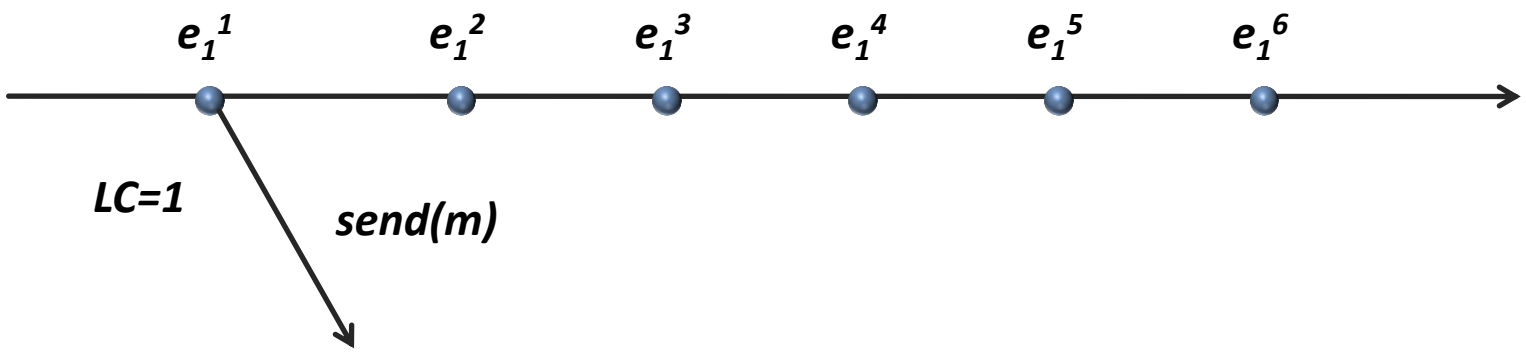

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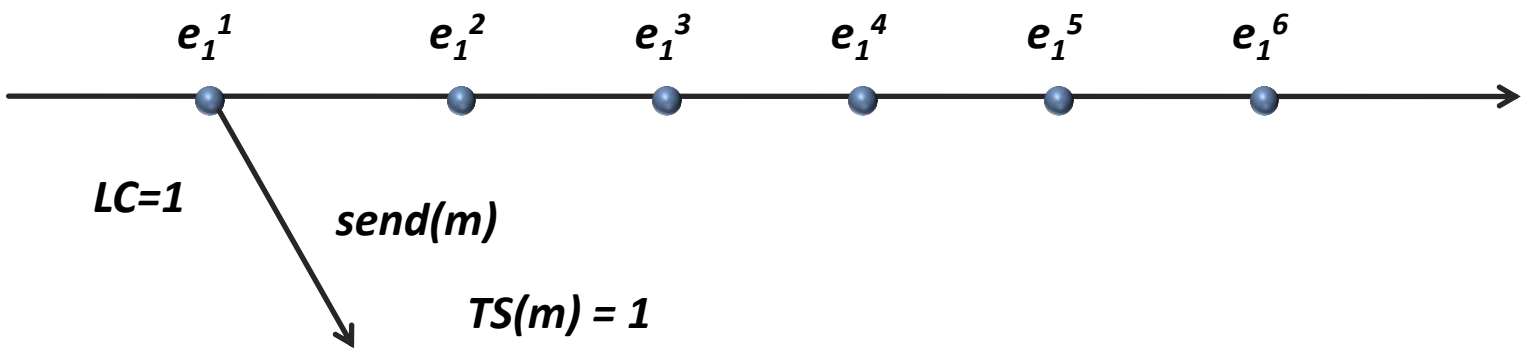

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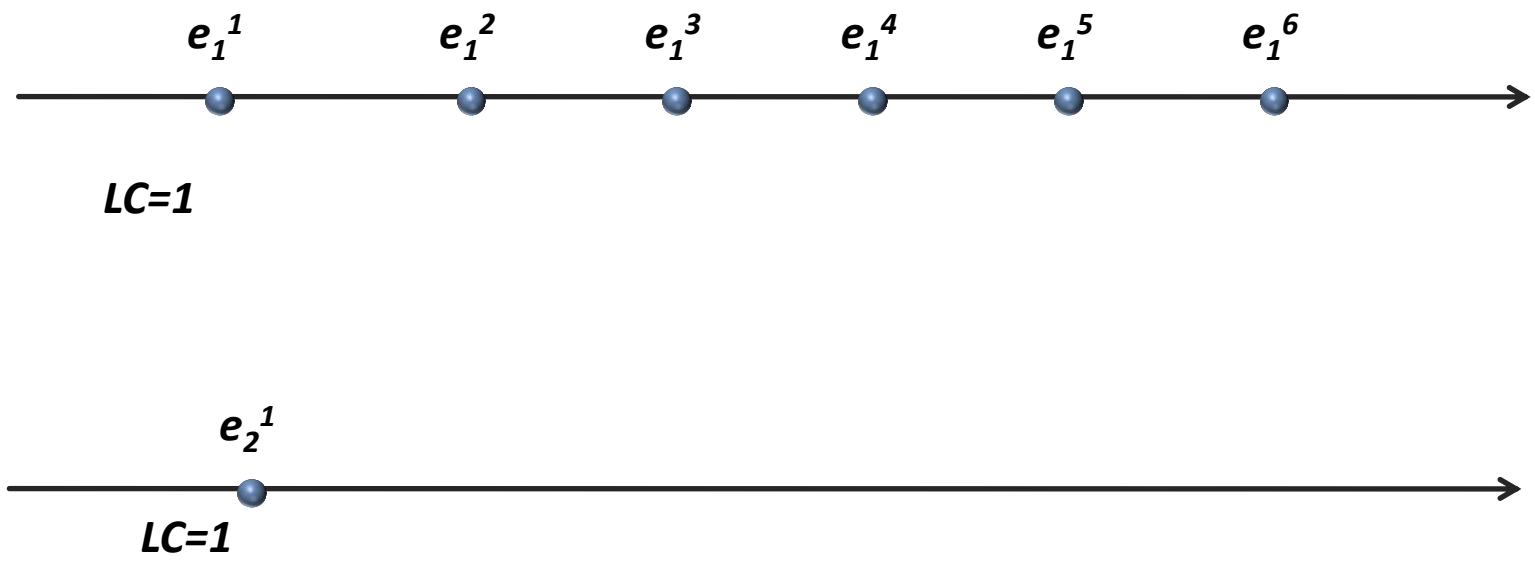

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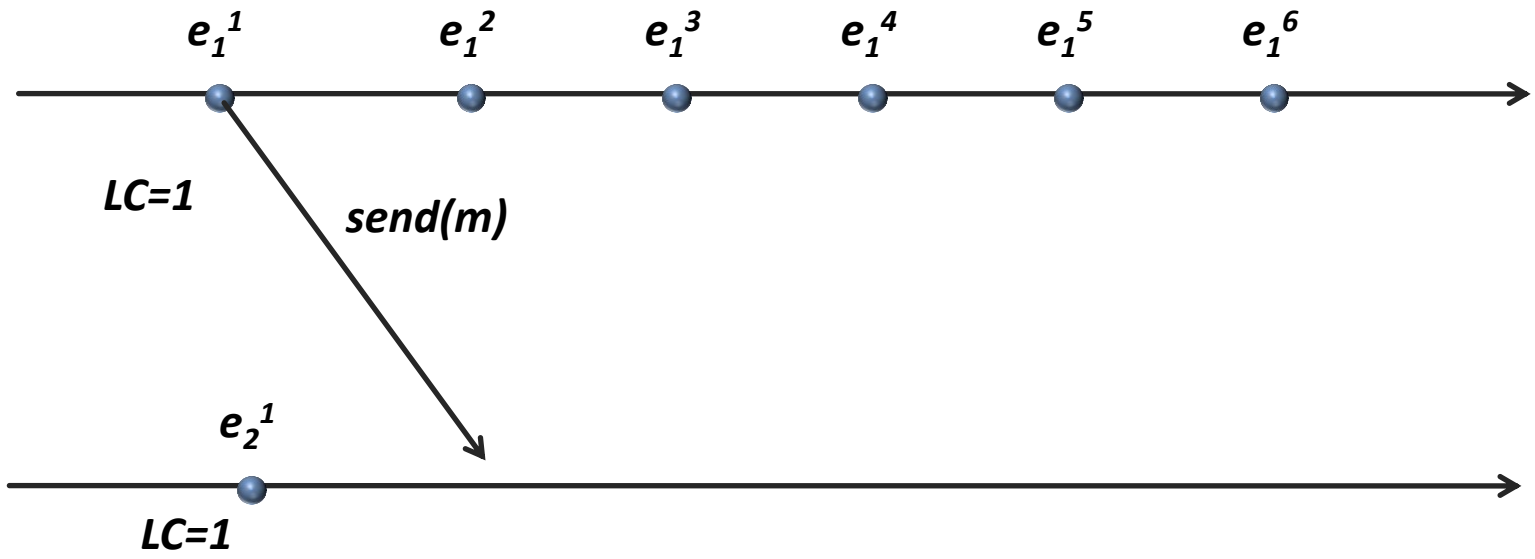

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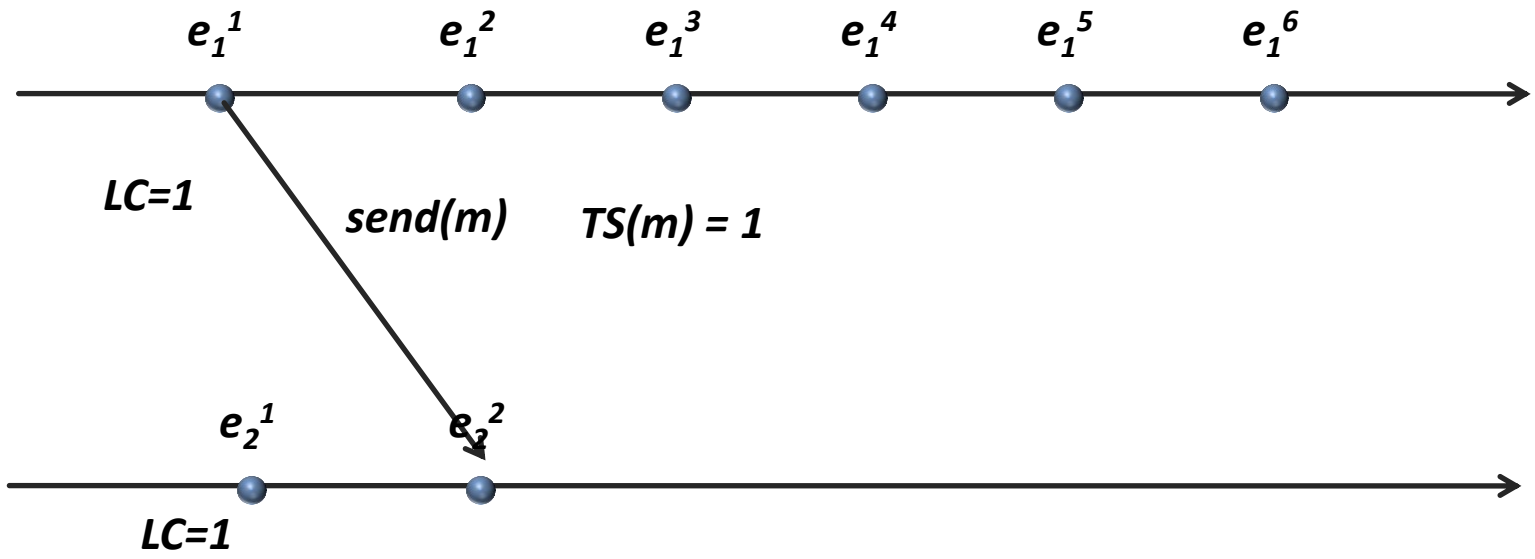

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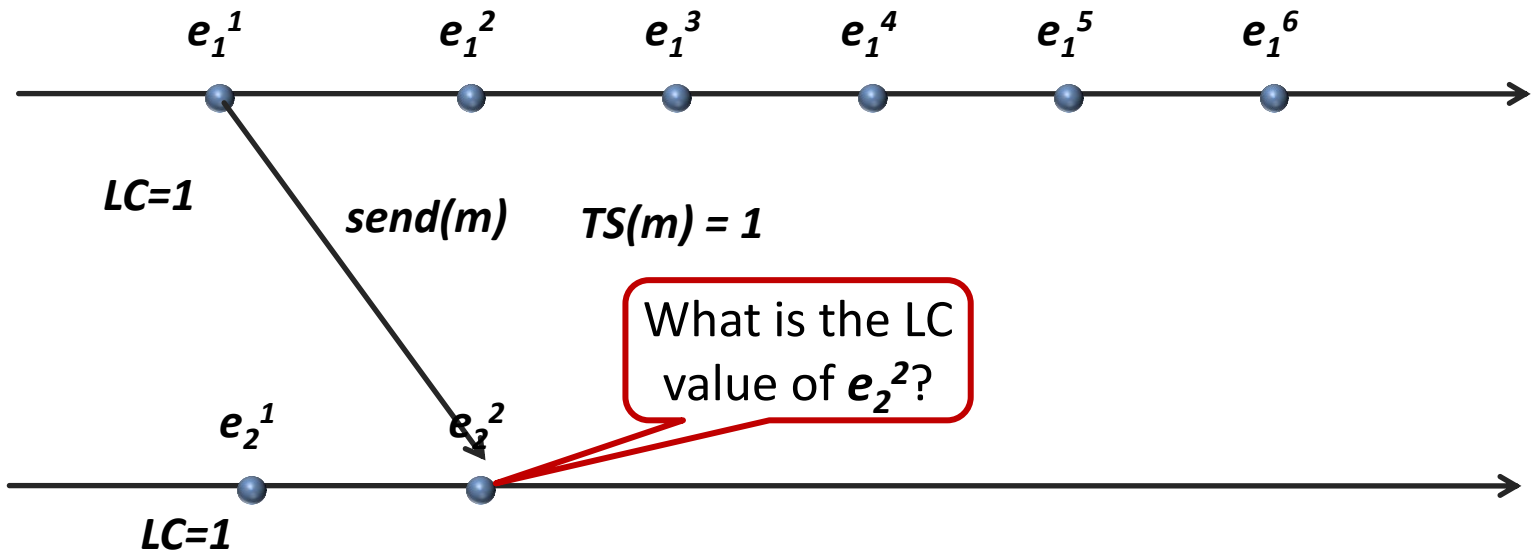

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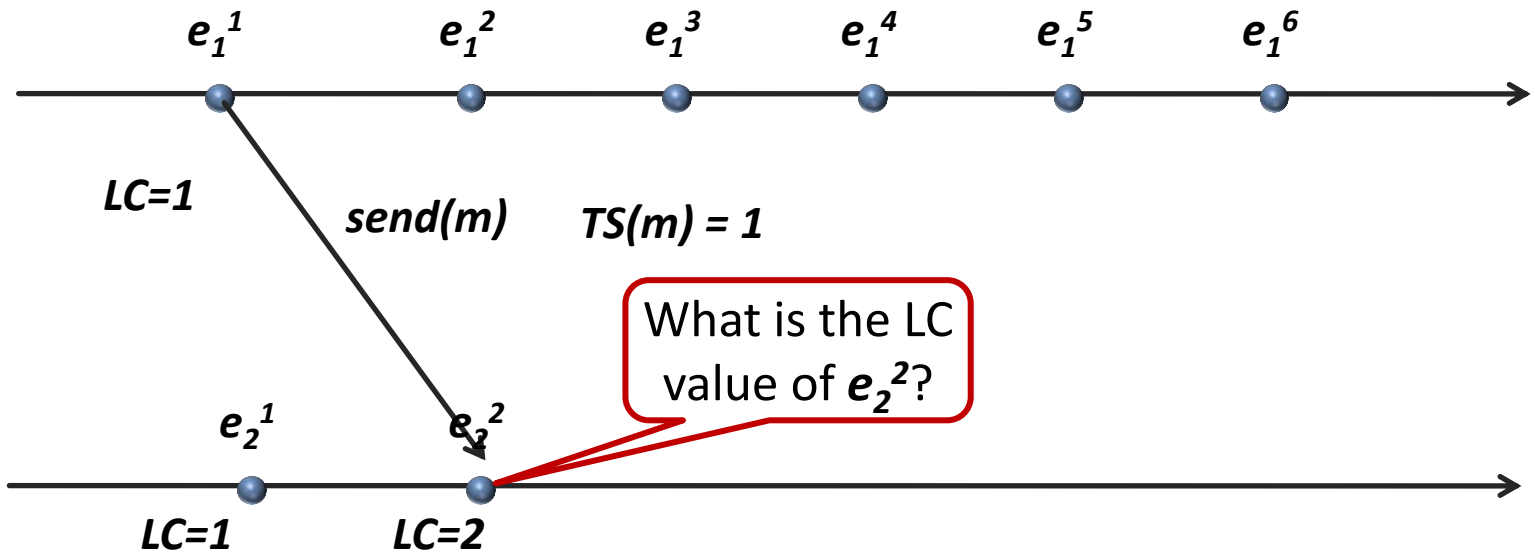

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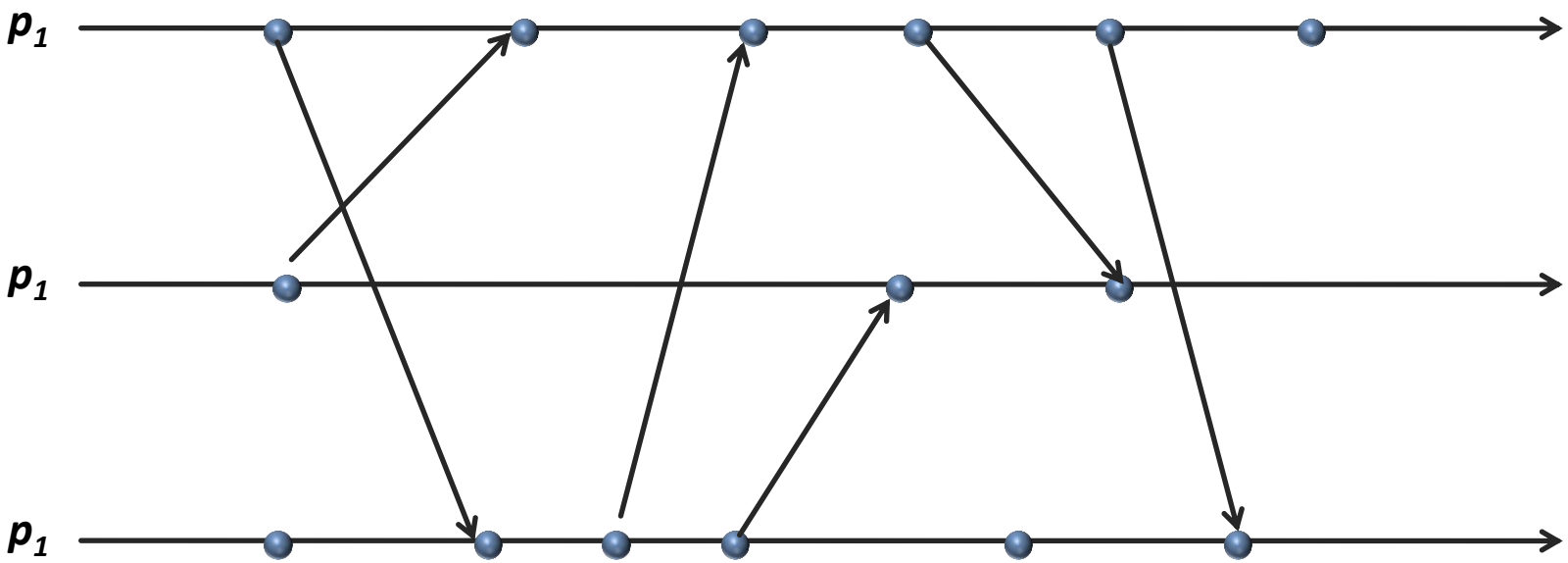

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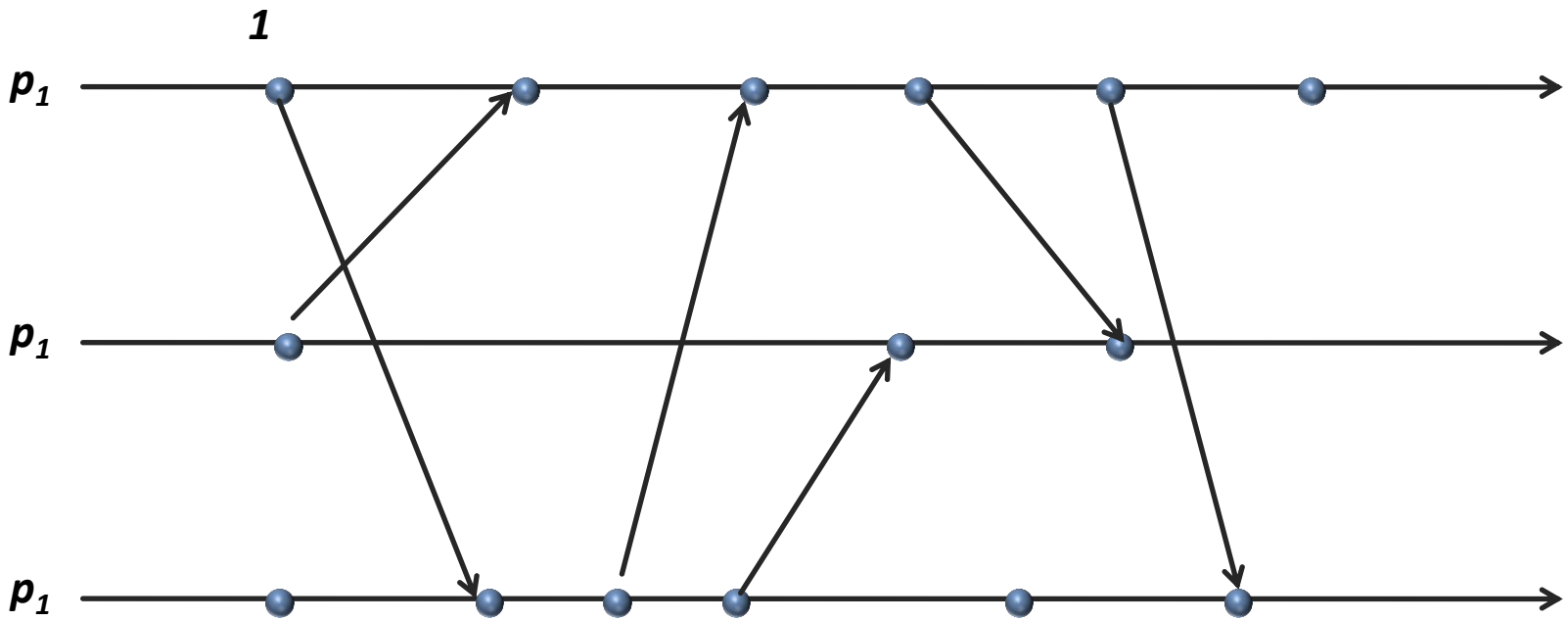

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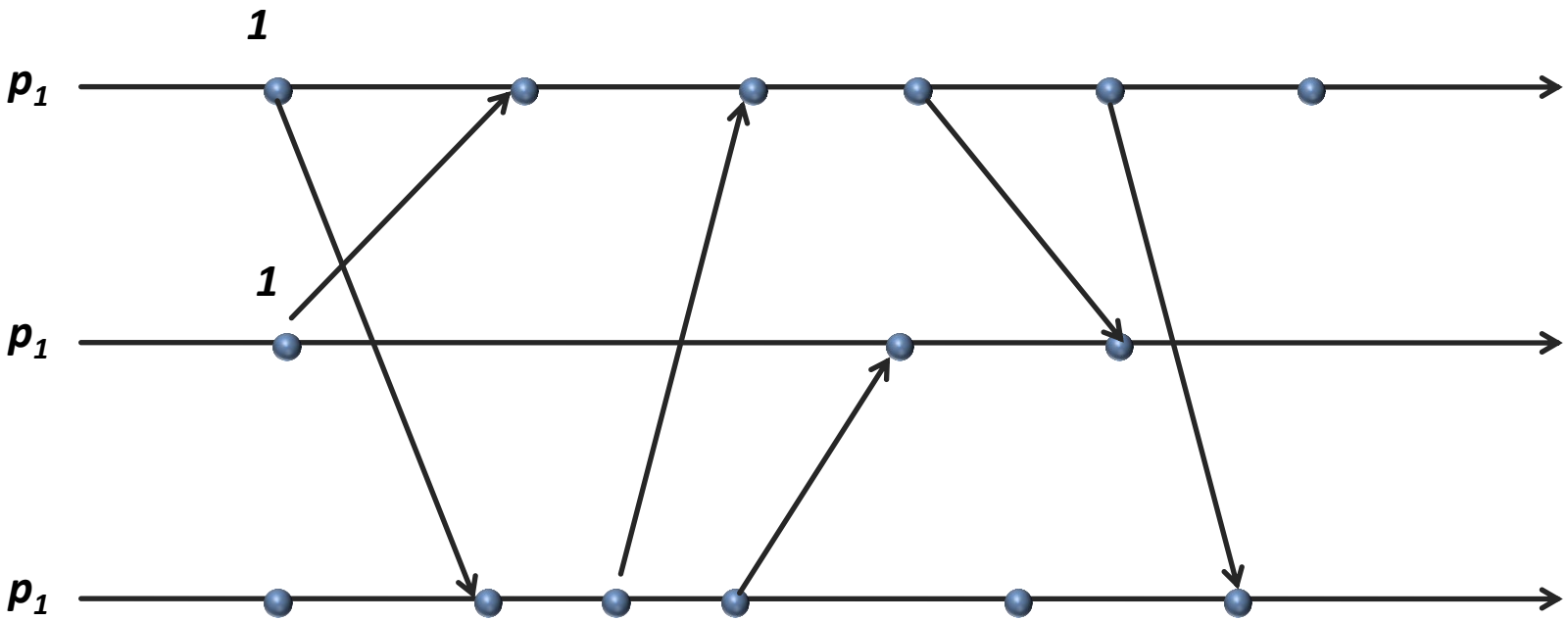

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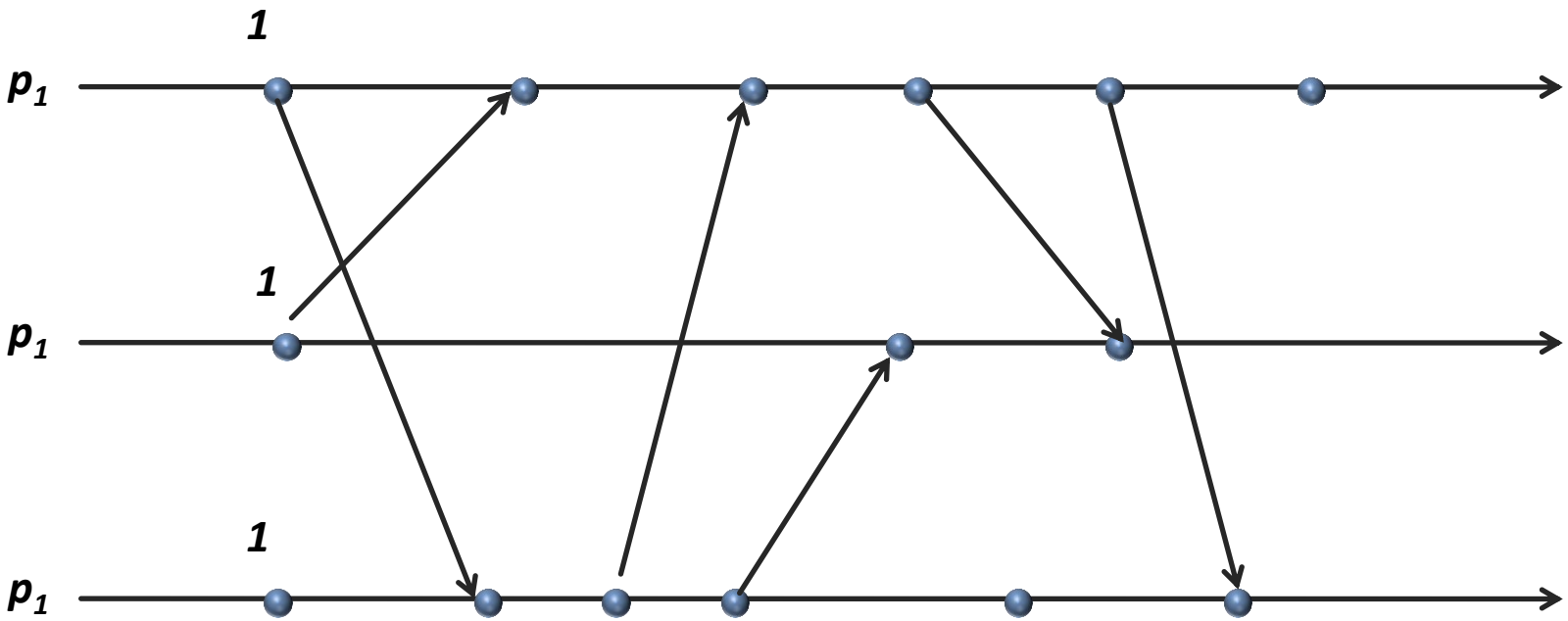

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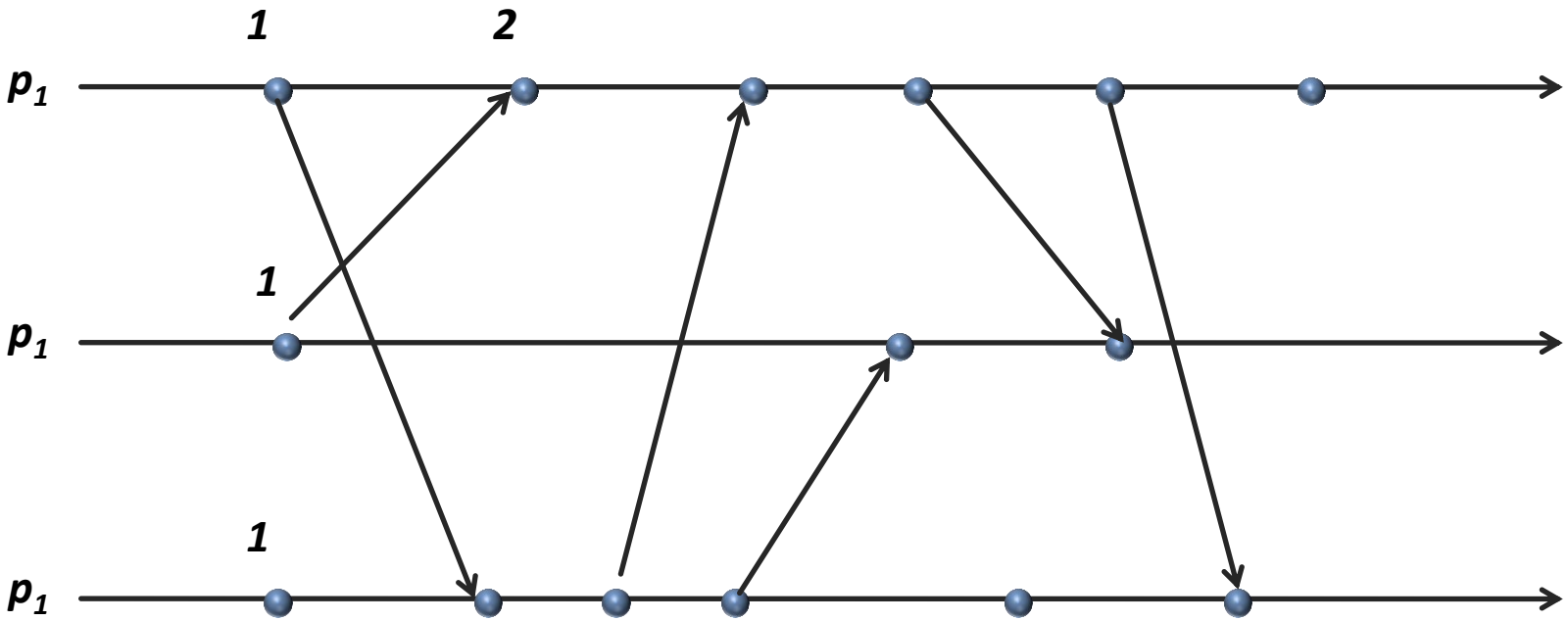

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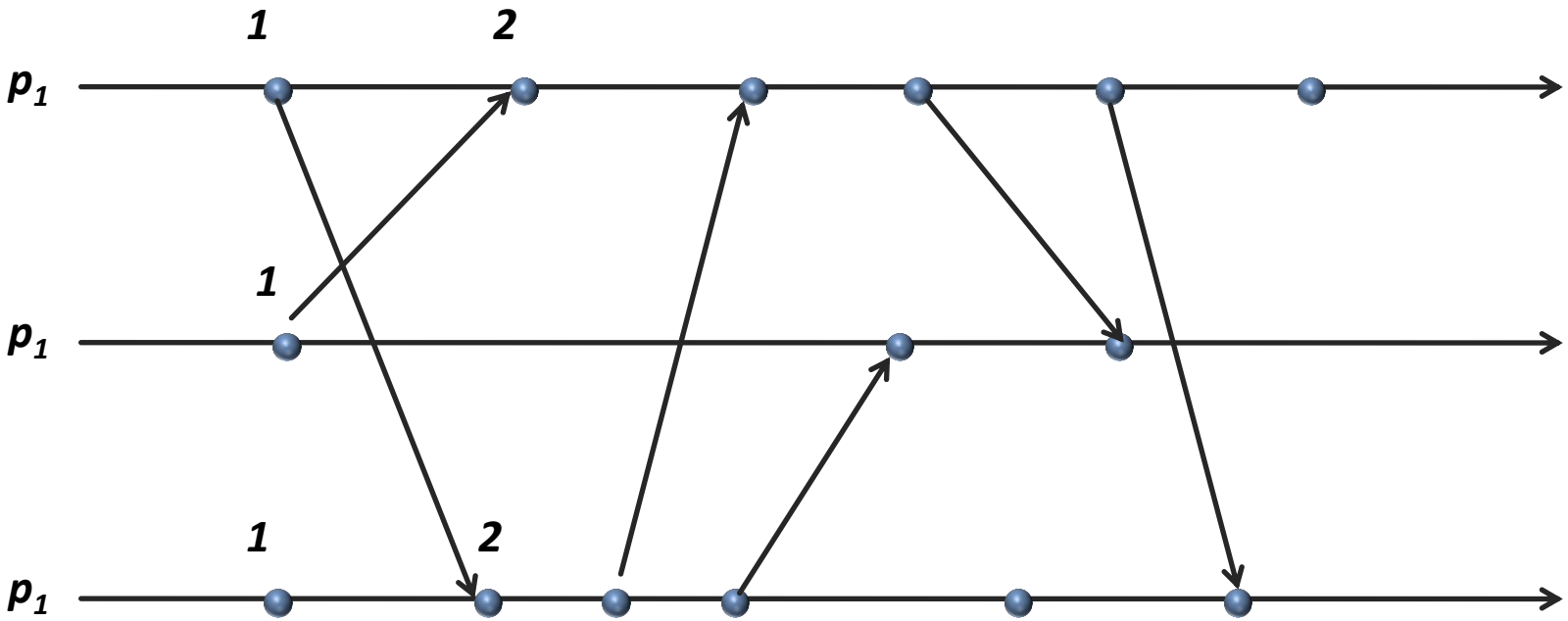

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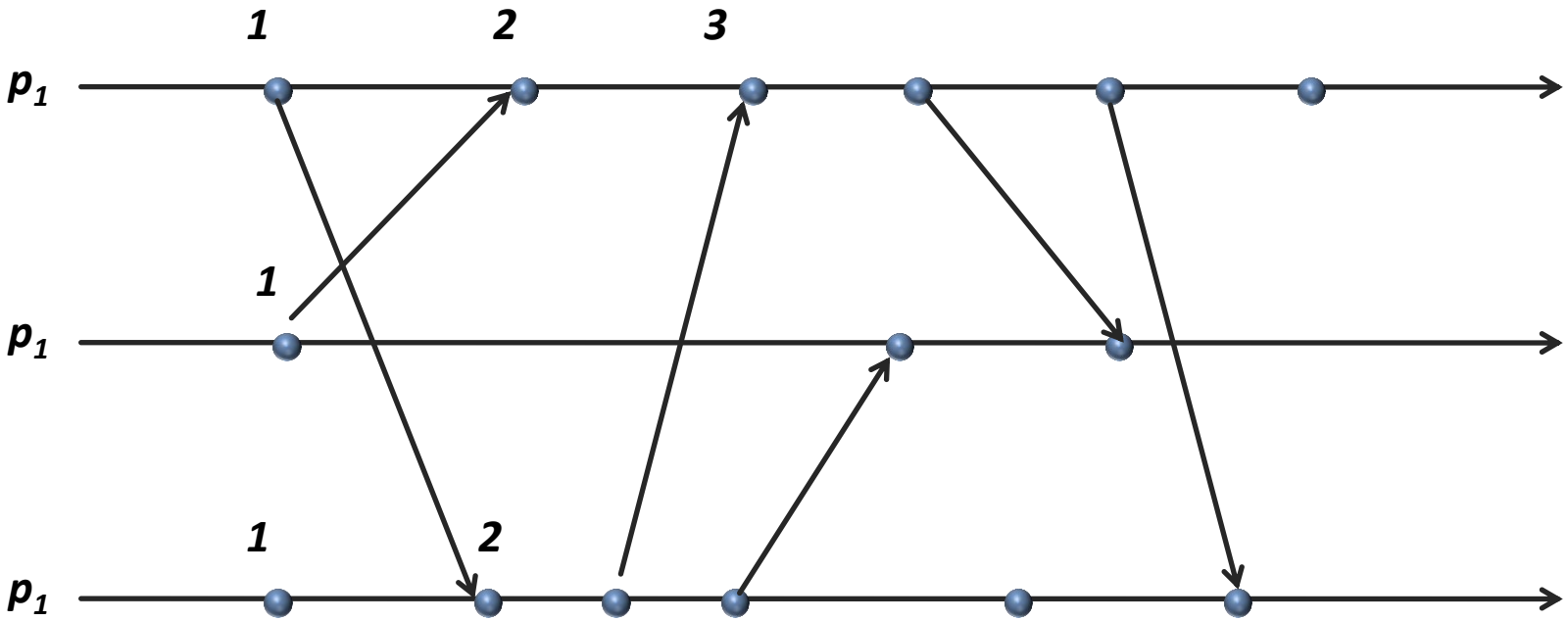

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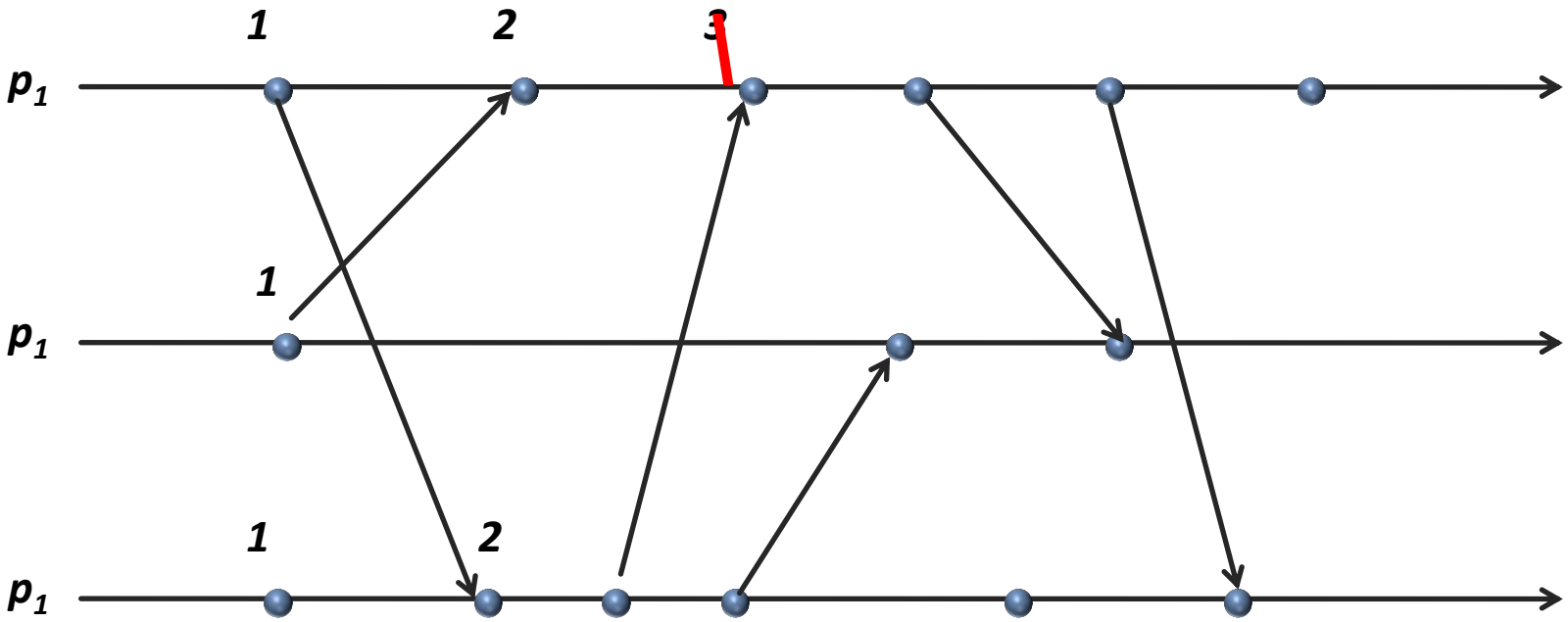

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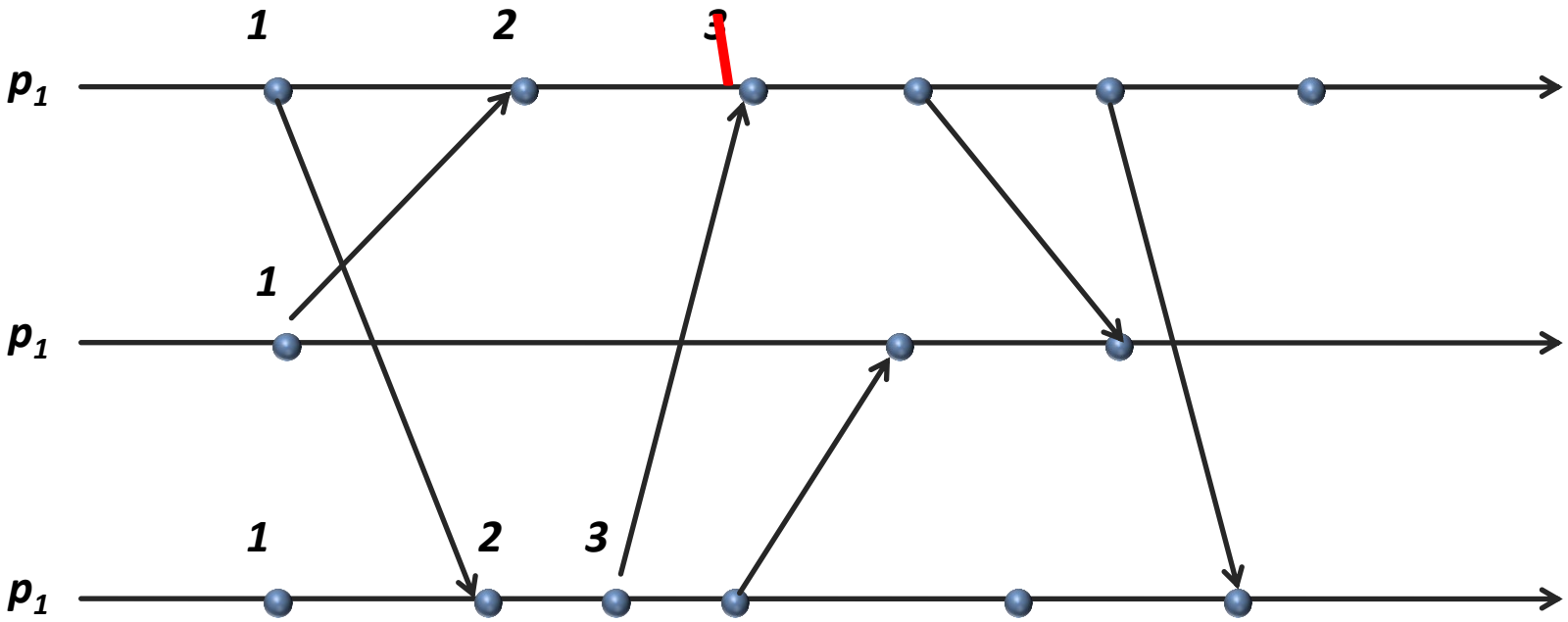

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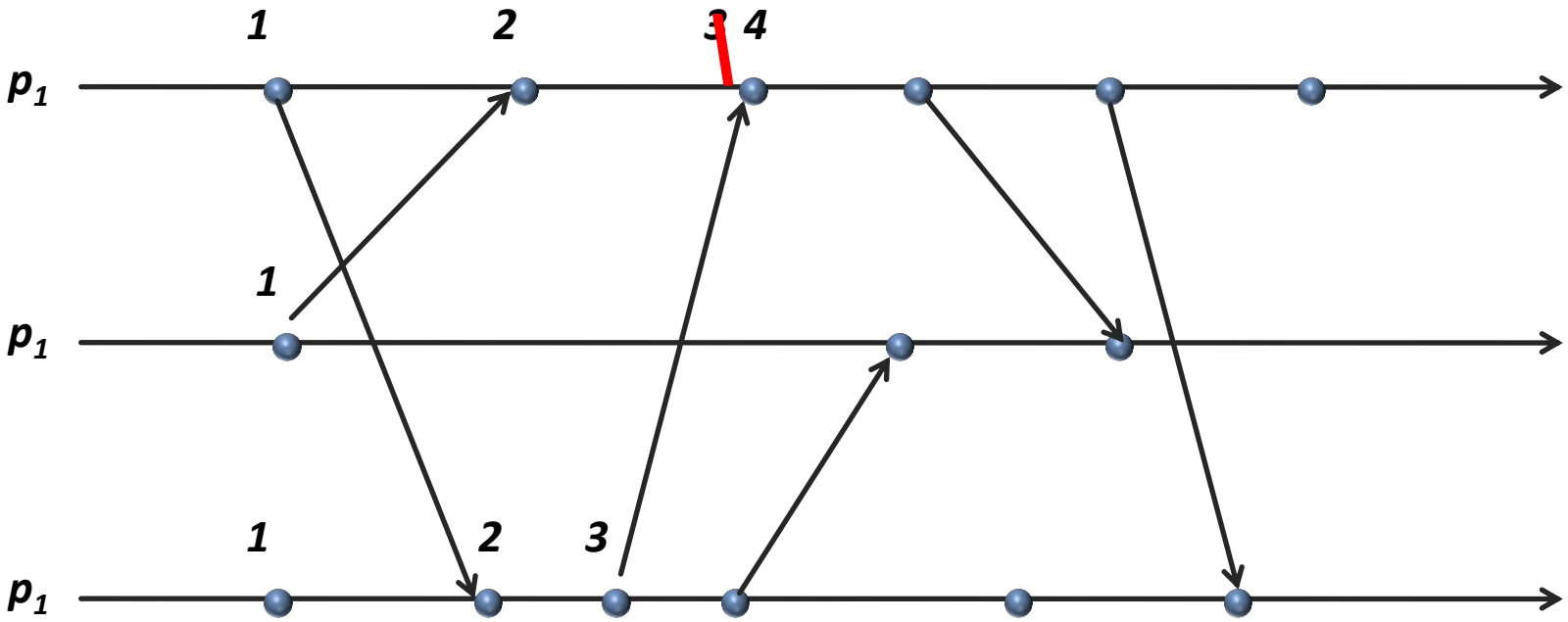

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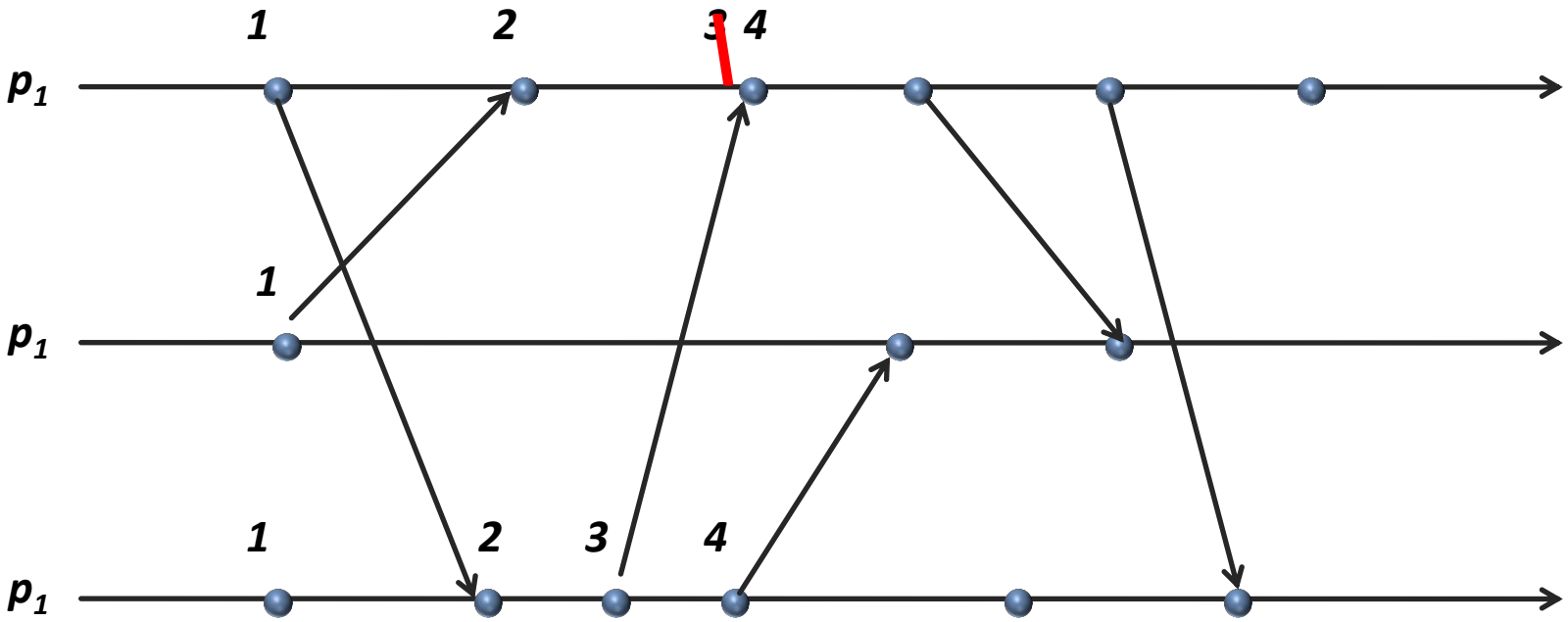

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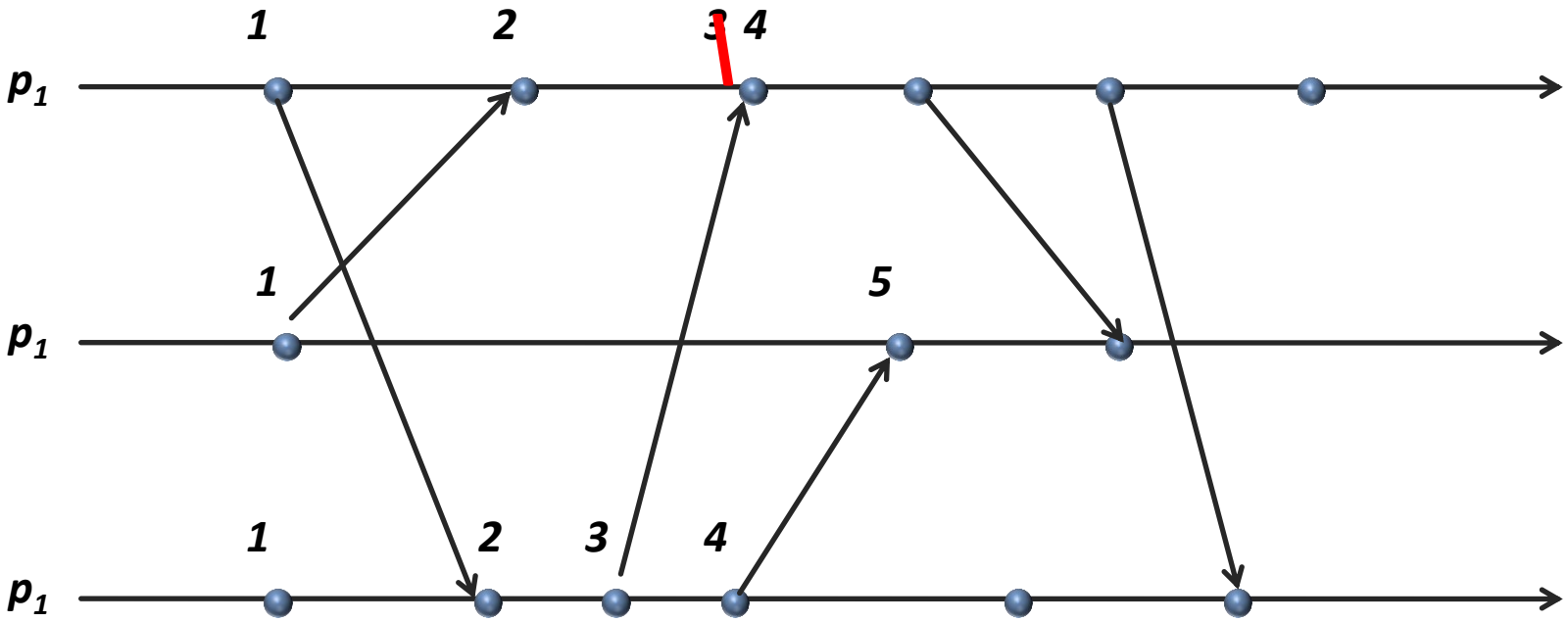

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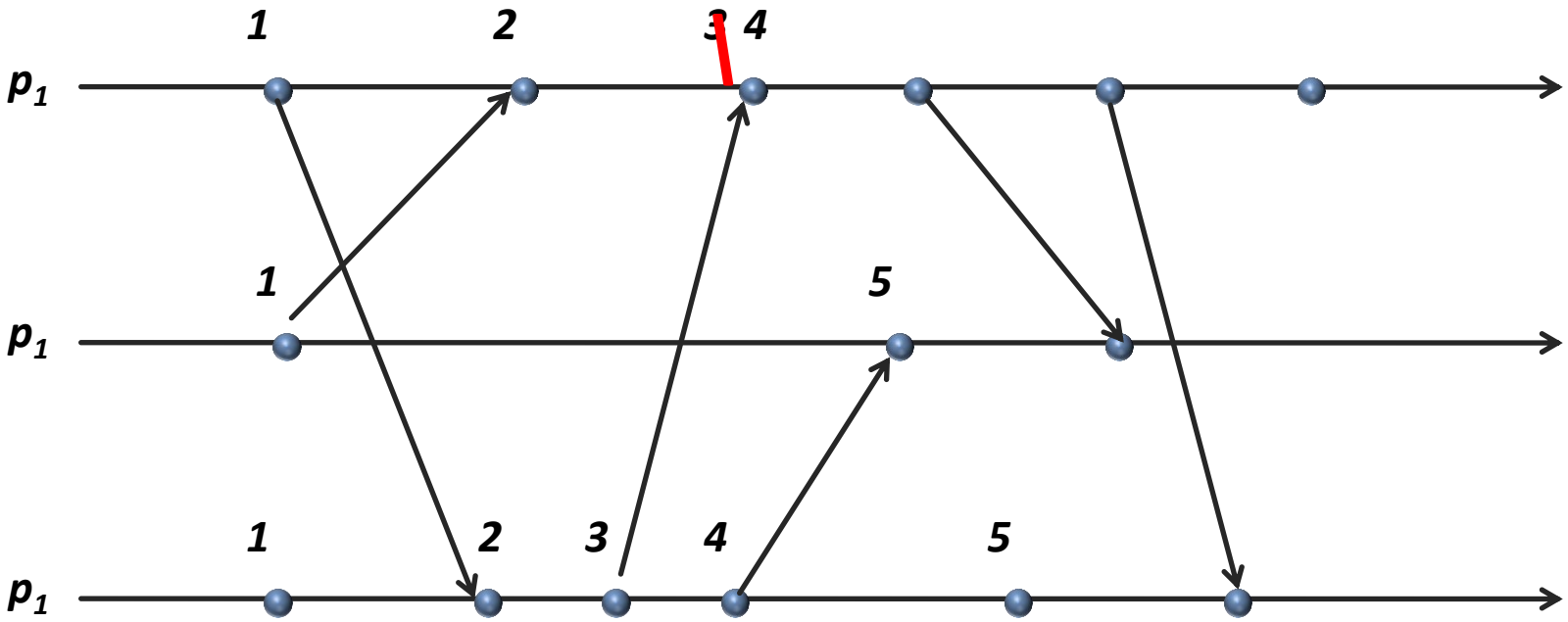

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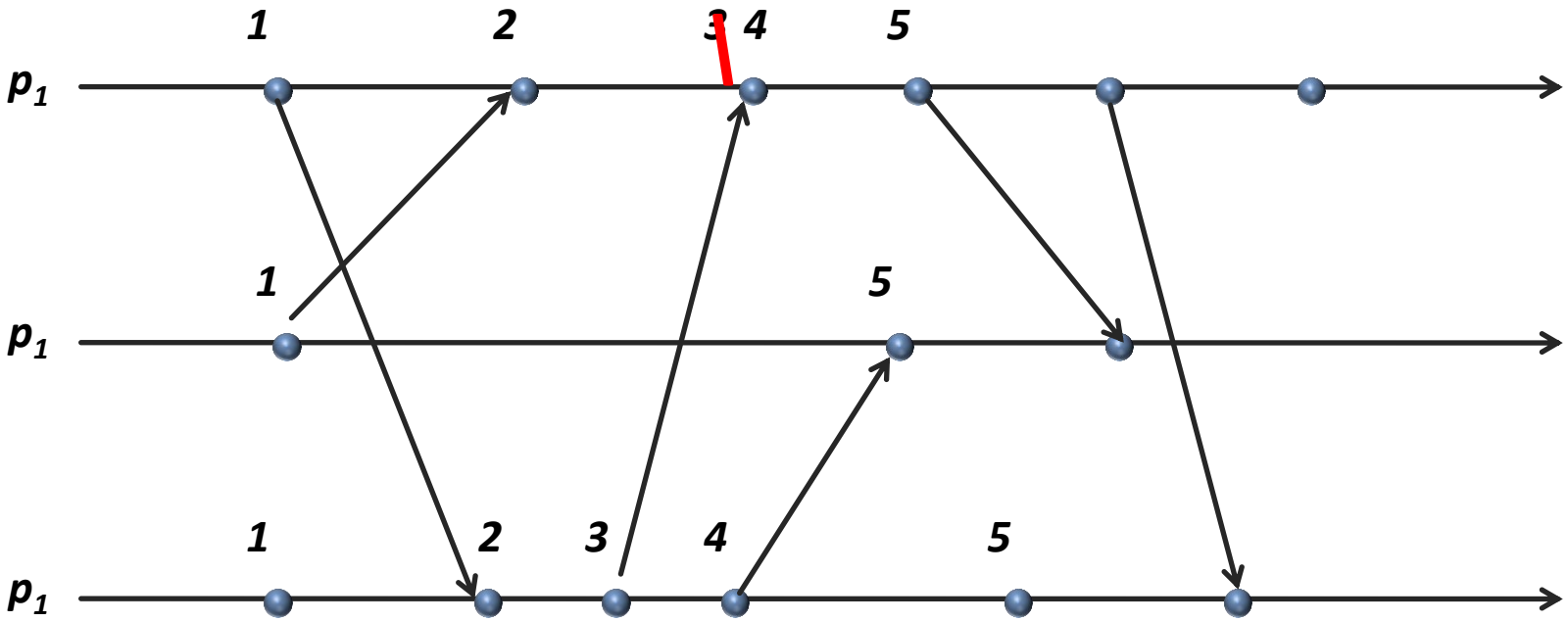

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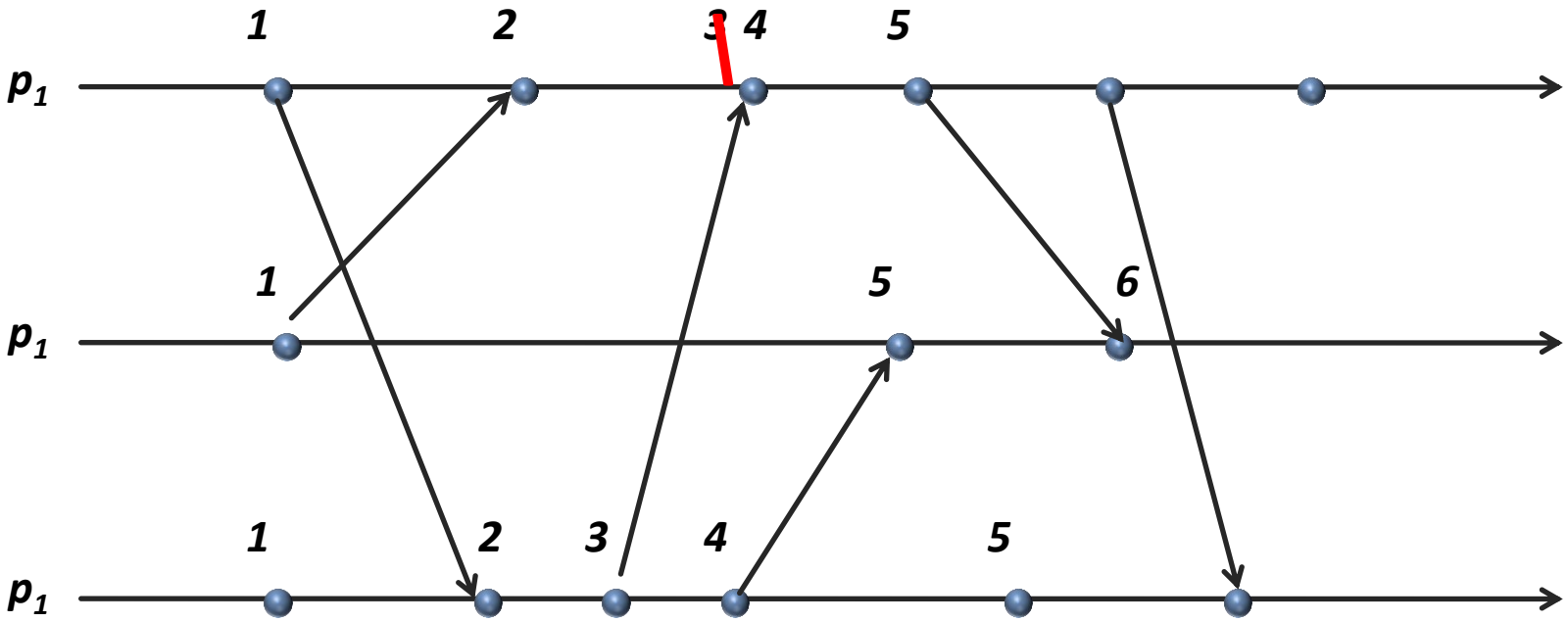

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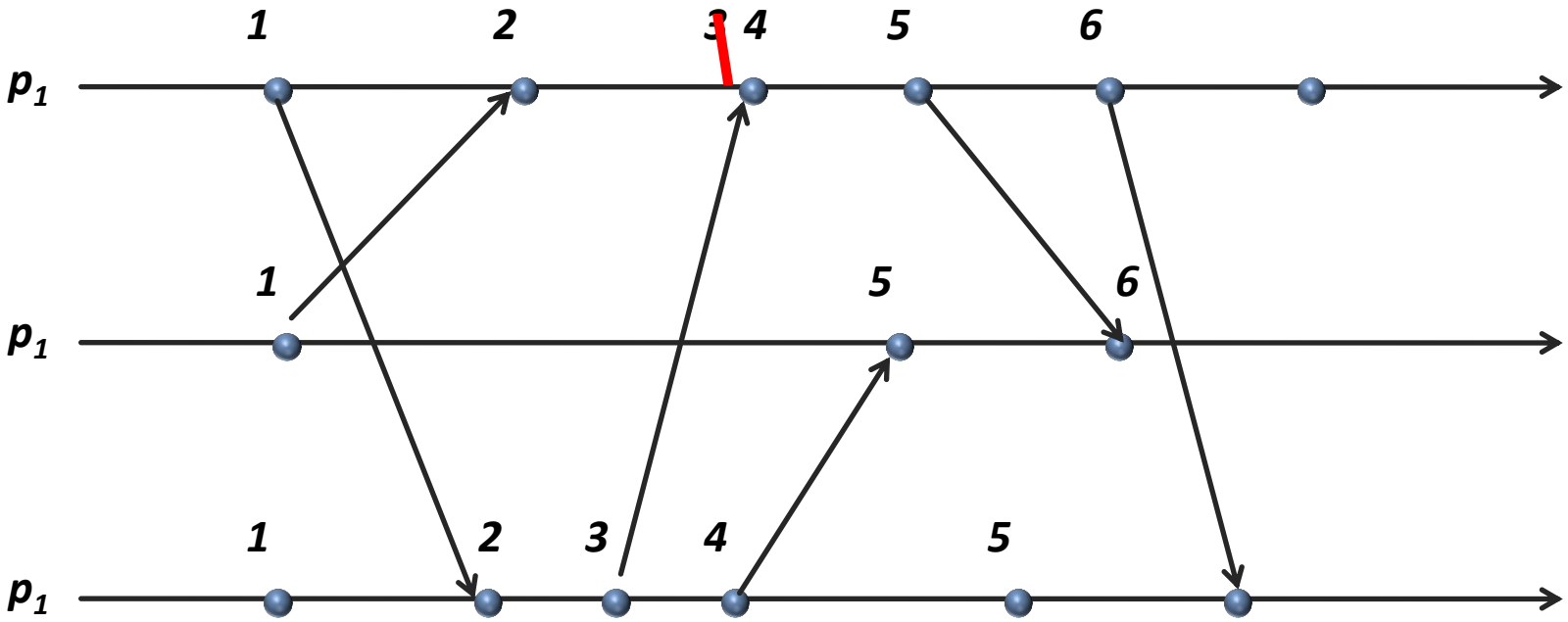

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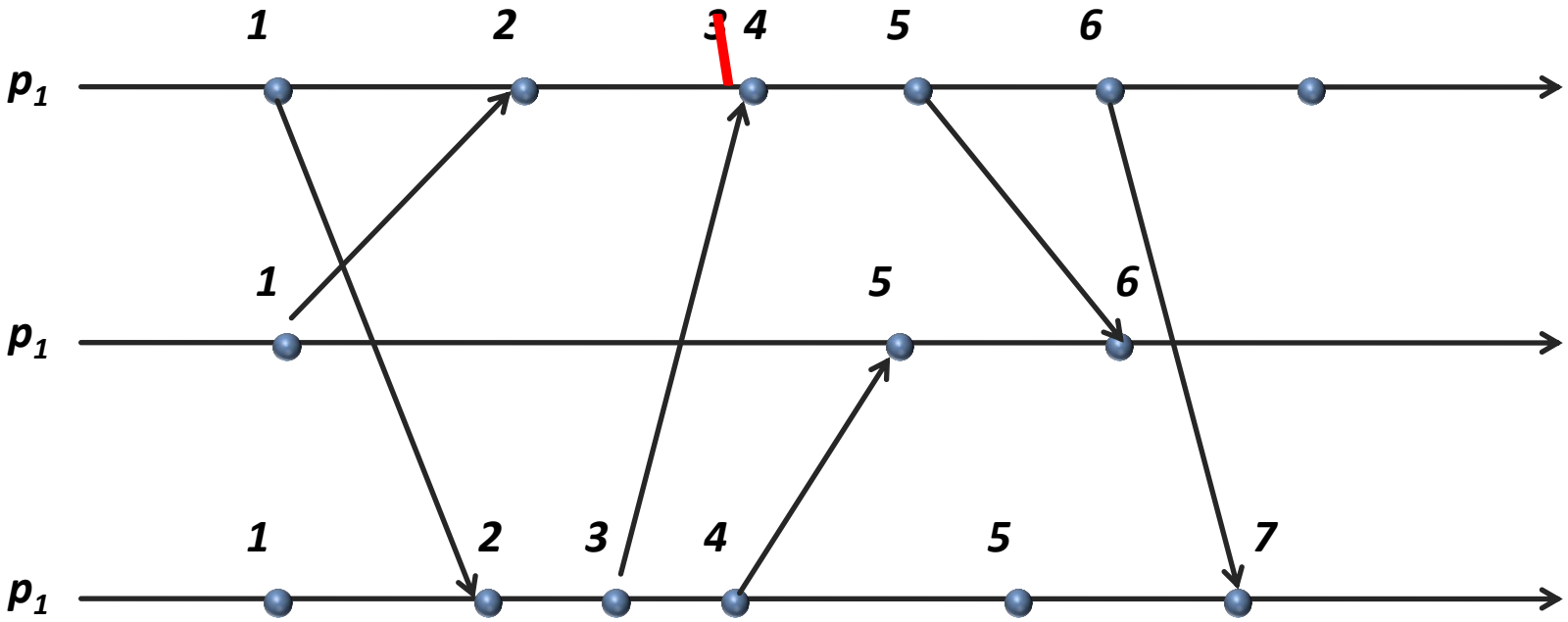

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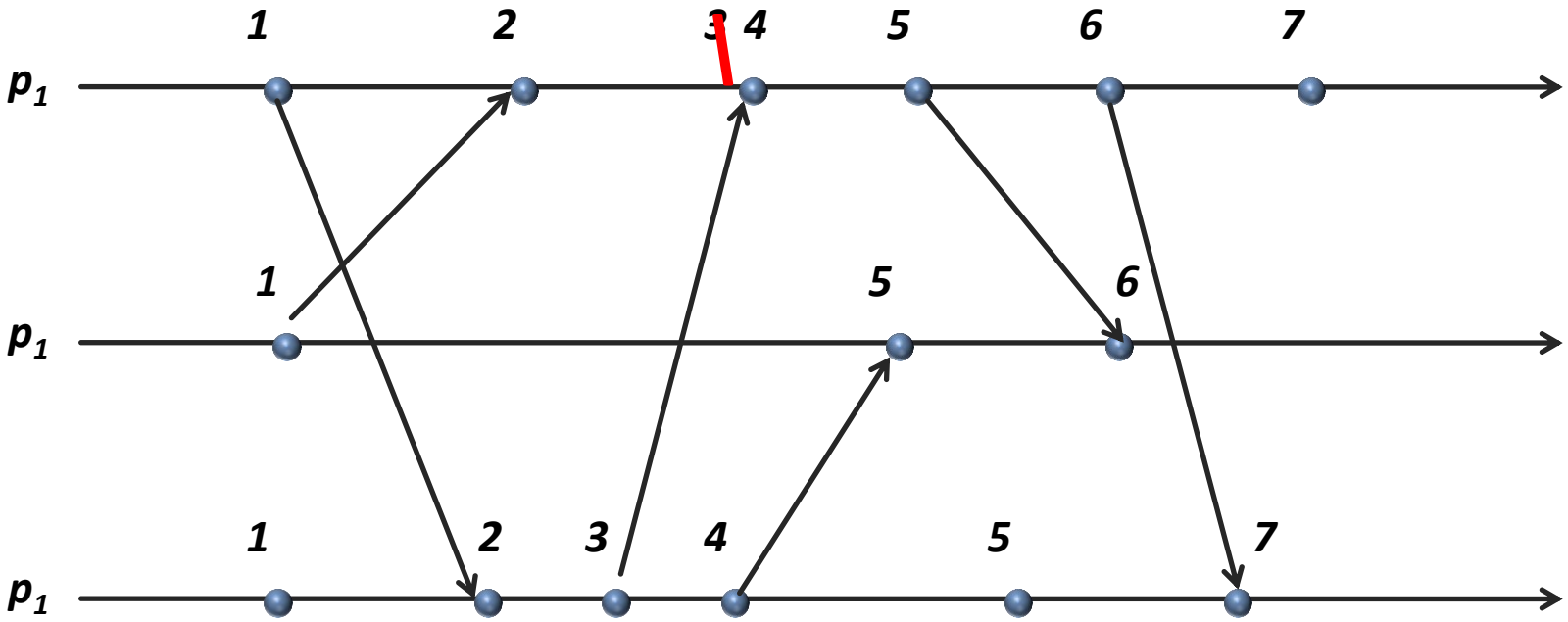

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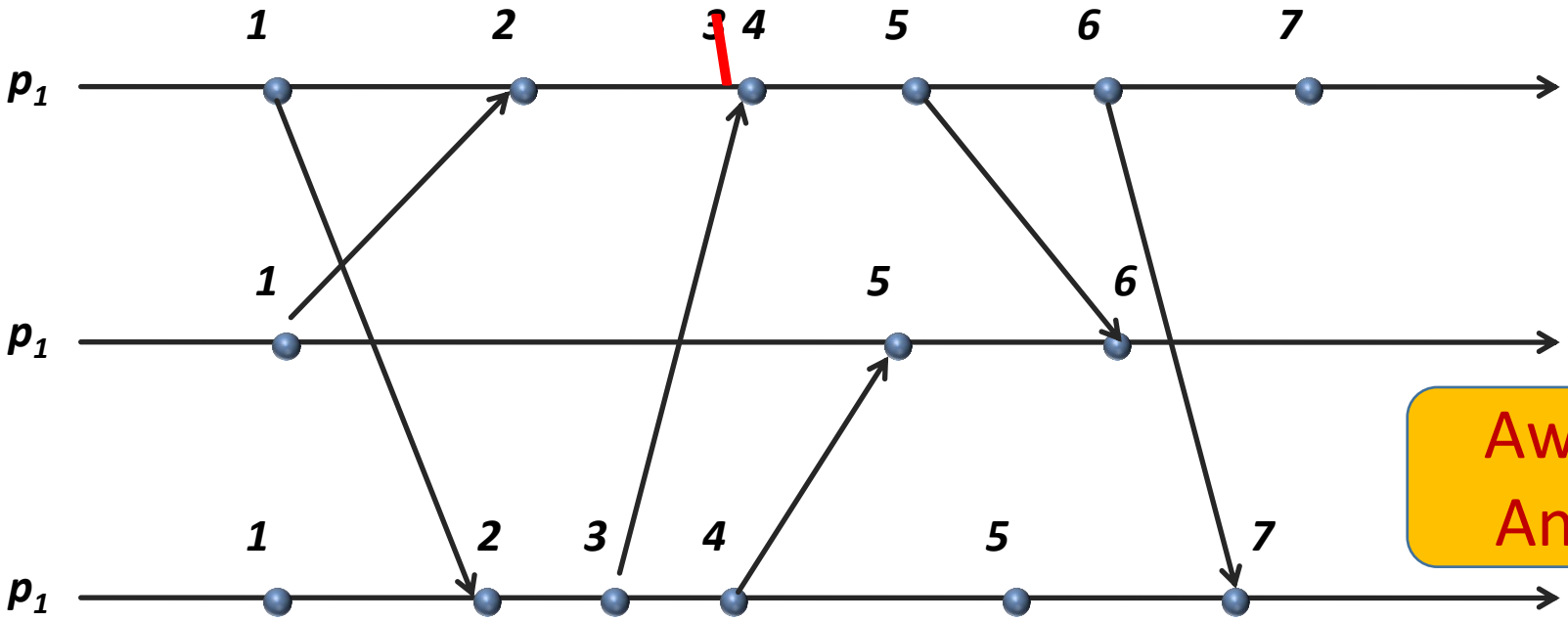

Awesome, right?
Any drawbacks?

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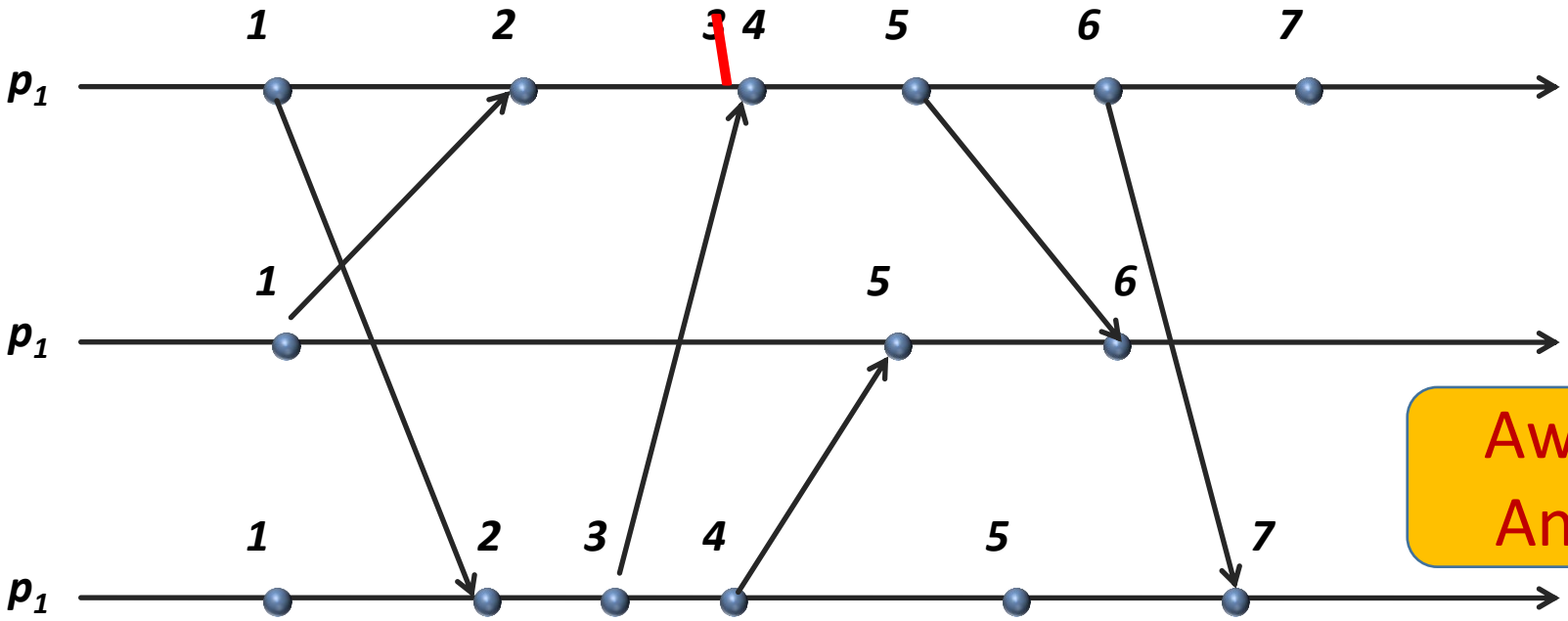

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e_x < e_y → TS(e_x) < TS(e_y), but
TS(e_x) < TS(e_y) doesn't guarantee e_x < e_y

Vector Clock

Vector Clock

Replace Single Logical value with Vector!

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$V_i[i]$: #events occurred at i

$V_i[j]$: #events i knows occurred at j

Update

- On local-event: increment $V_i[I]$
- On send-message: increment, piggyback entire local vector V
- On recv-message: $V_j[k]$ = max($V_j[k], V_i[k]$)
  - $V_j[i] = V_j[i]+1$ *(increment local clock)*
  - Receiver learns about number of events sender knows occurred elsewhere

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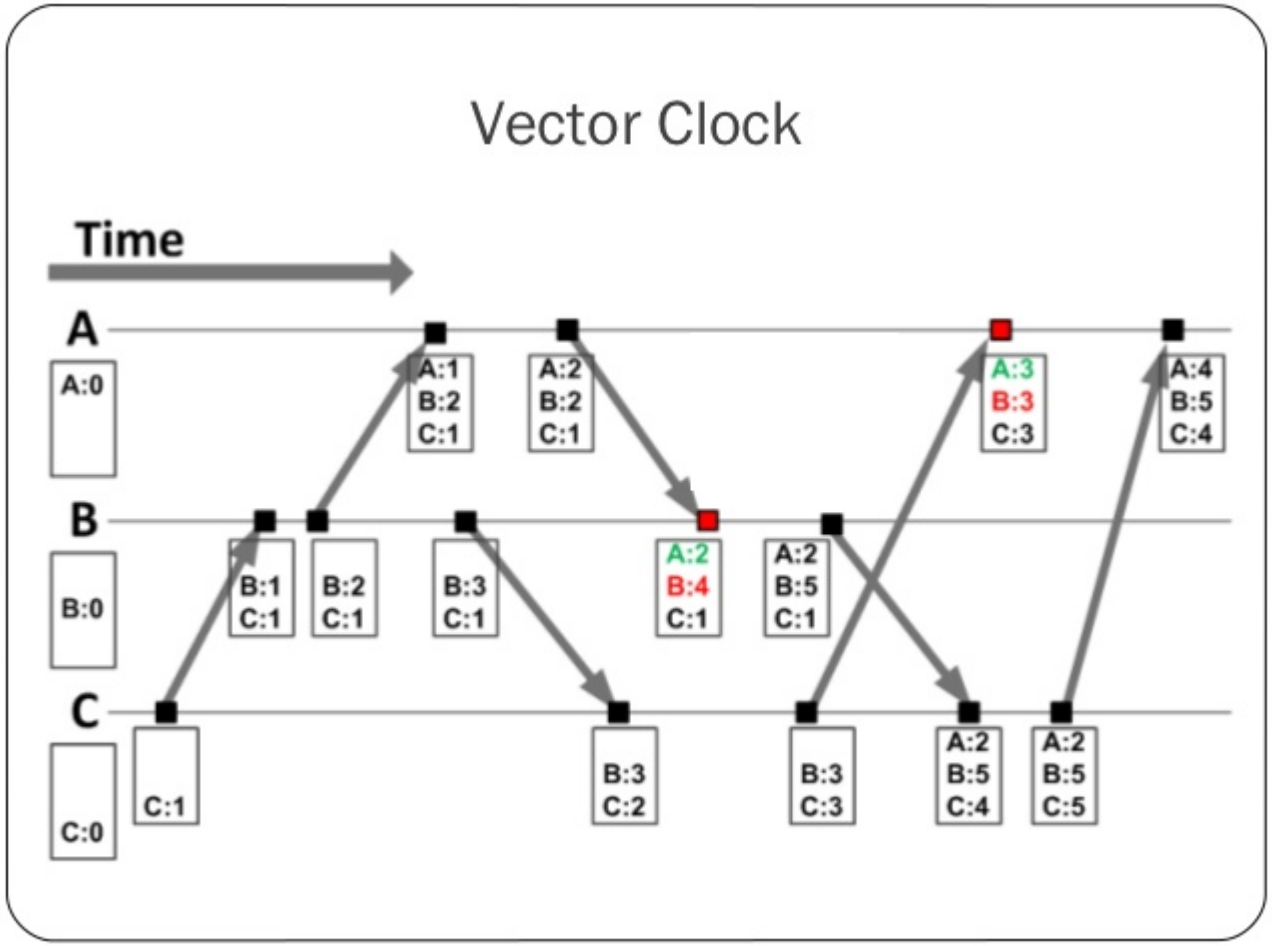

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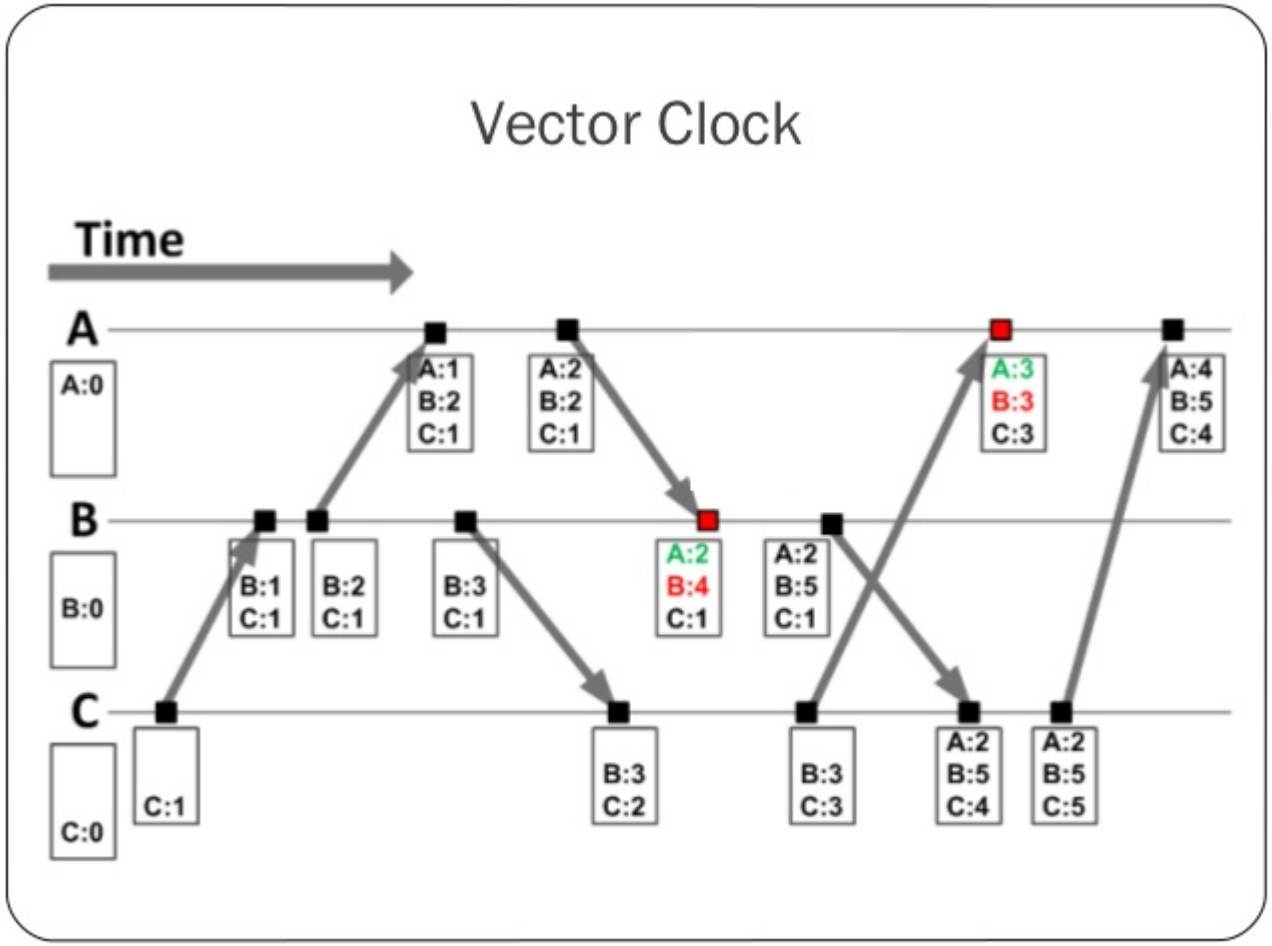

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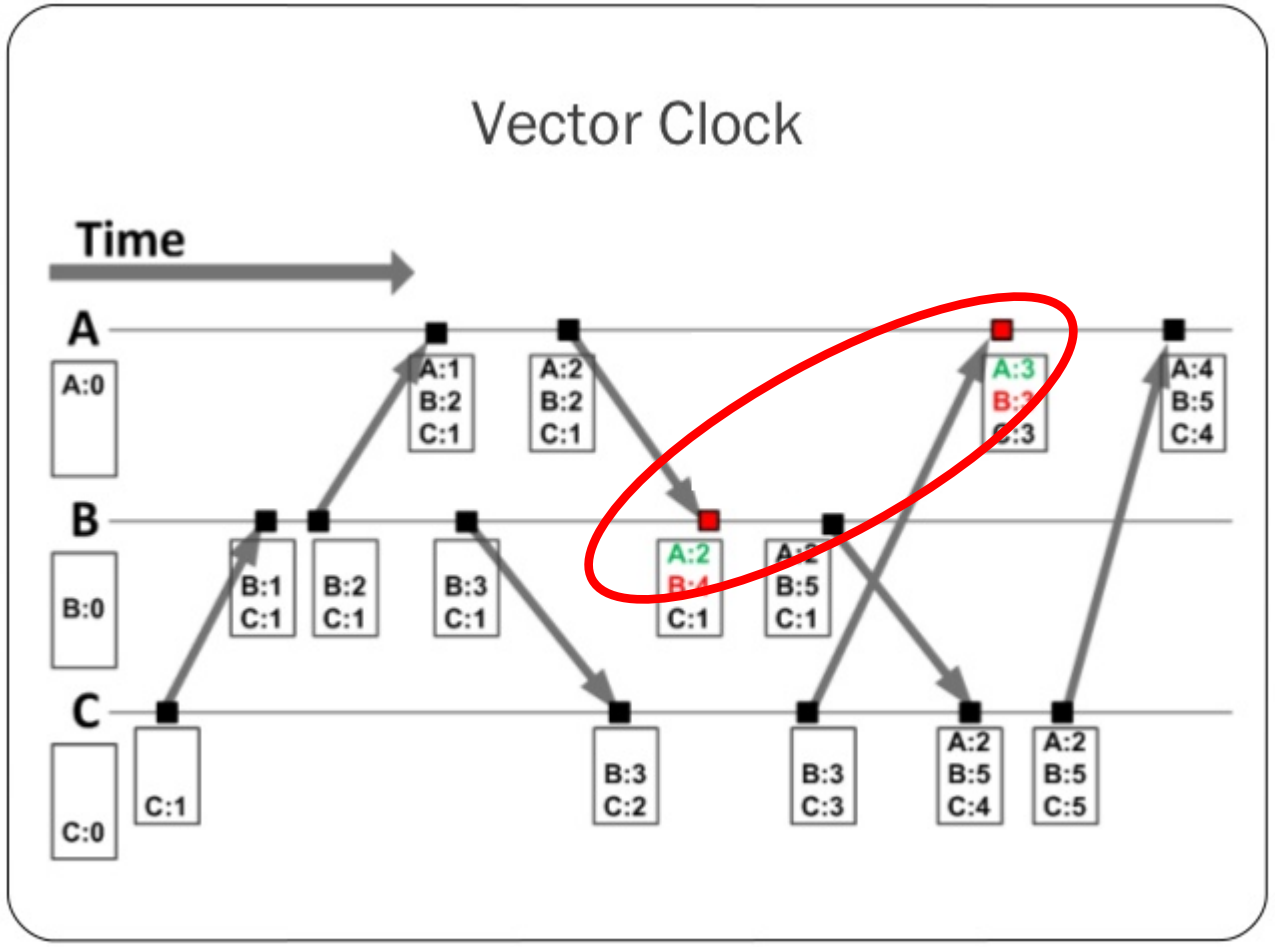

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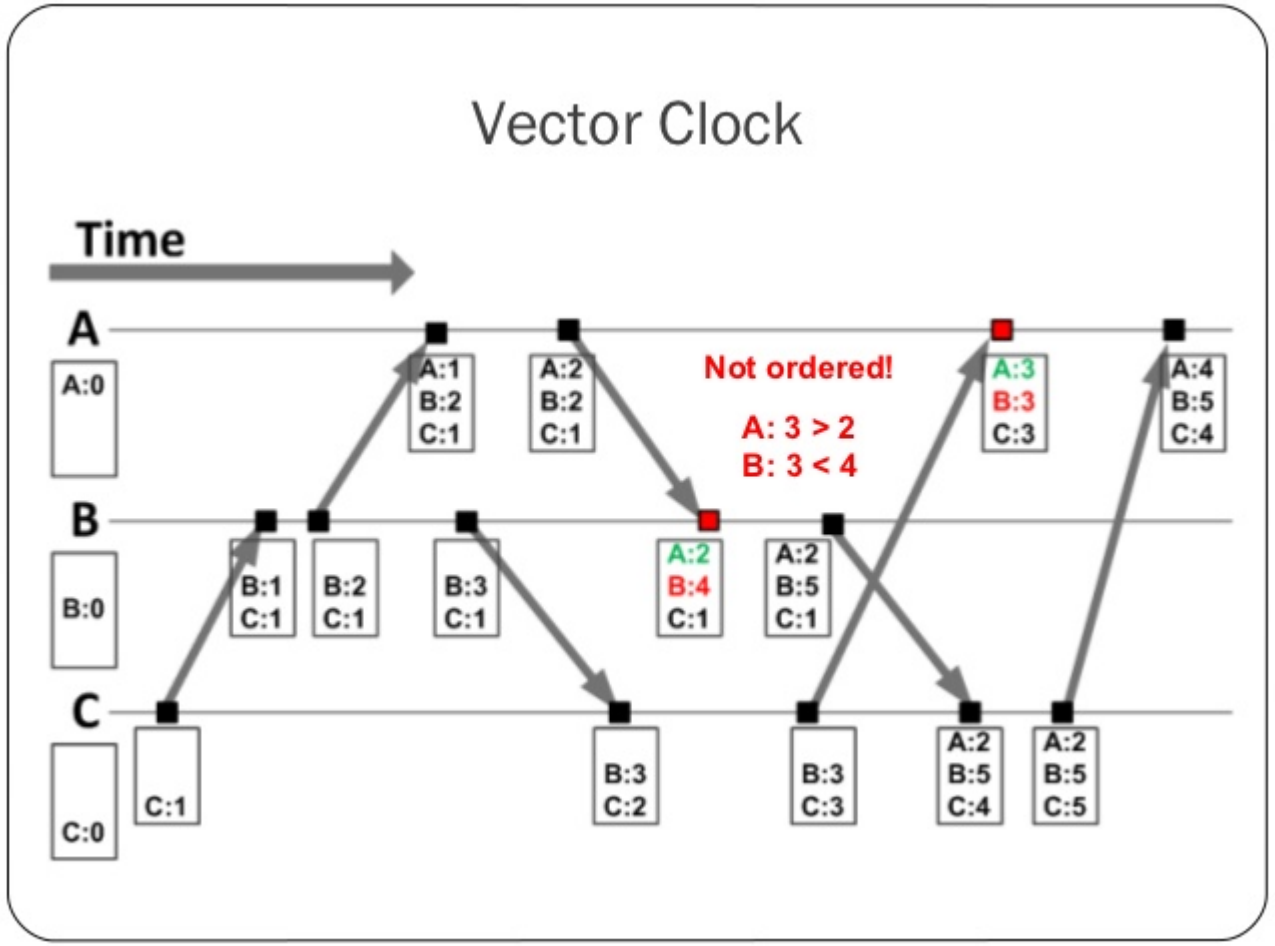

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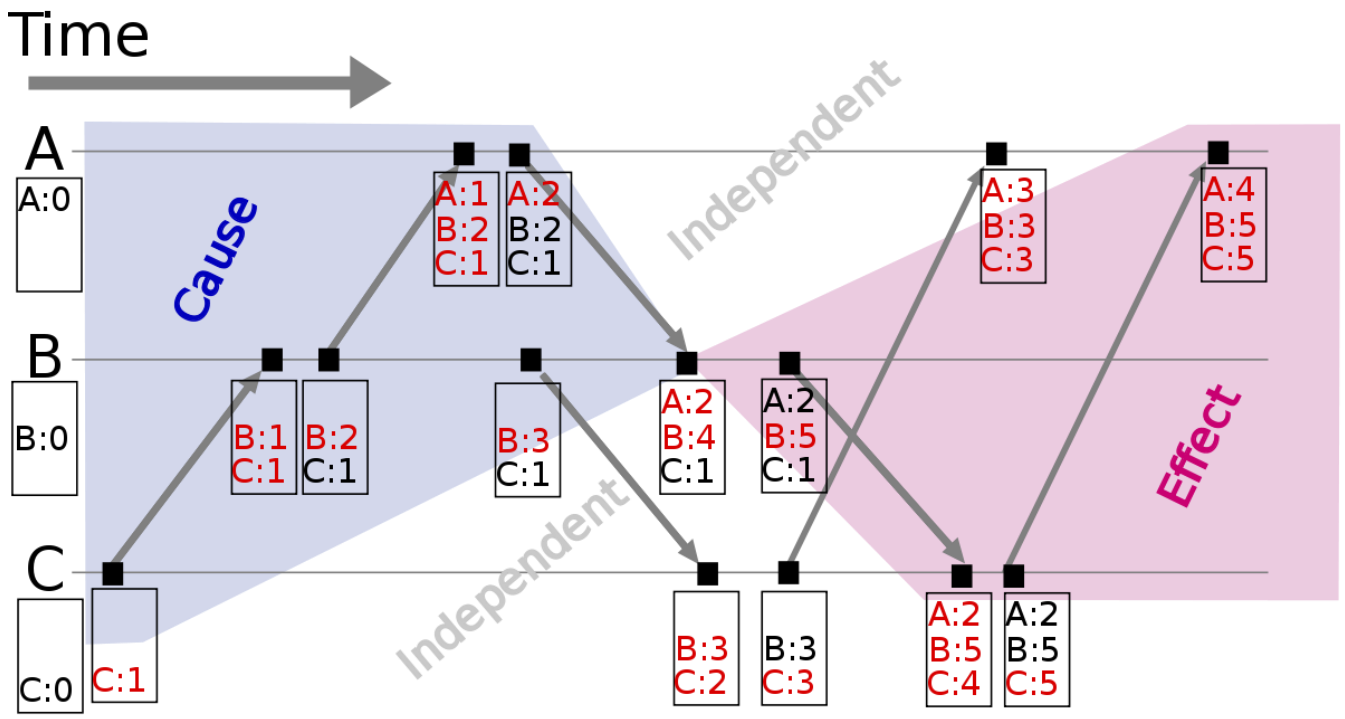
Vector Clock Example



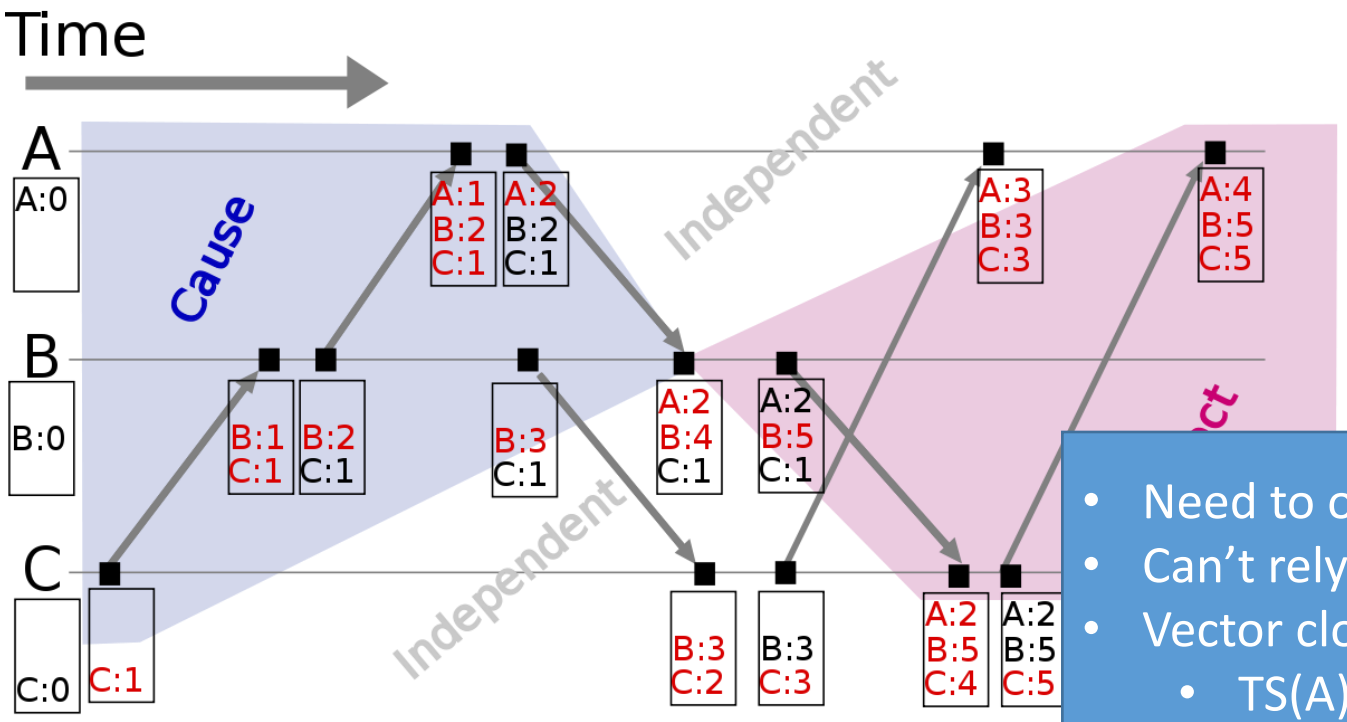
Each process *i* maintains a vector V_i

- $V_i[i]$: number of events that have occurred at i
- $V_i[j]$: number of events I knows have occurred at process j

Update

- Local event: increment $V_i[I]$
- Send a message :piggyback entire vector V
- Receipt of a message: $V_j[k] = \max(V_j[k], V_i[k])$
  - Receiver is told about how many events the sender knows occurred at another process *k*
  - Also $V_j[i] = V_j[i]+1$

Vector Clock Example



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- $V_i[i]$: number of events that have occurred at i
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Update

- Local event: increment $V_i[I]$

- Need to order operations
- Can't rely on real-time
- Vector clock: timestamping algorithm s.t.
  - TS(A) < TS(B) → A happens before B
  - Independent ops remain unordered

See any drawbacks?

Happens-before

- *Happens-before* relation
  - Within single thread
  - Between threads
- Accessing variables not ordered by “happens-before” is a race
- Captures locks and dynamism
- How to track “happens-before”?
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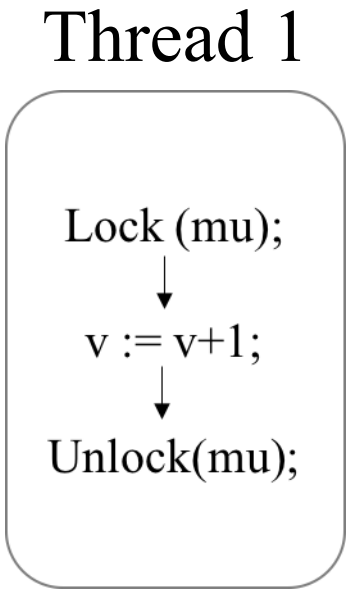

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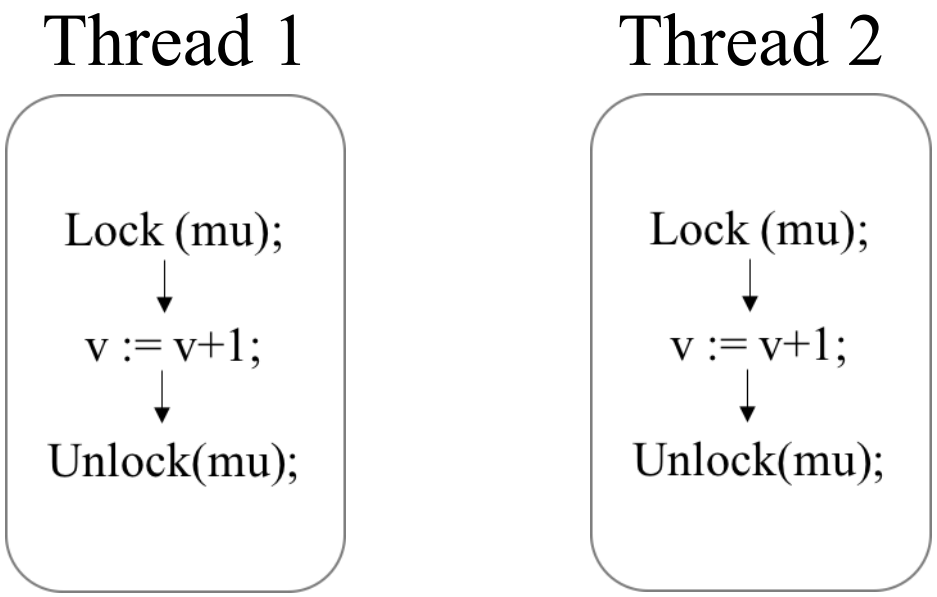

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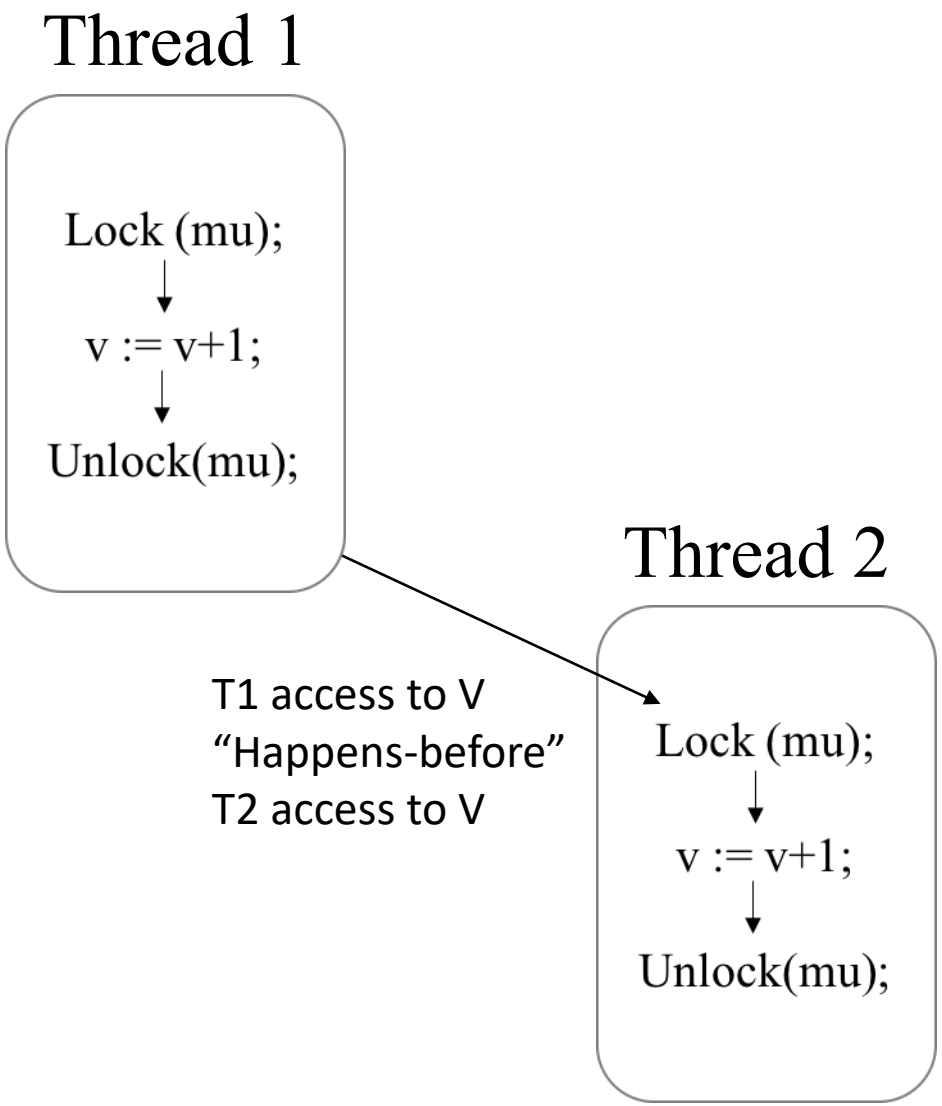

Flaws of *Happens-before*

- Difficult to implement
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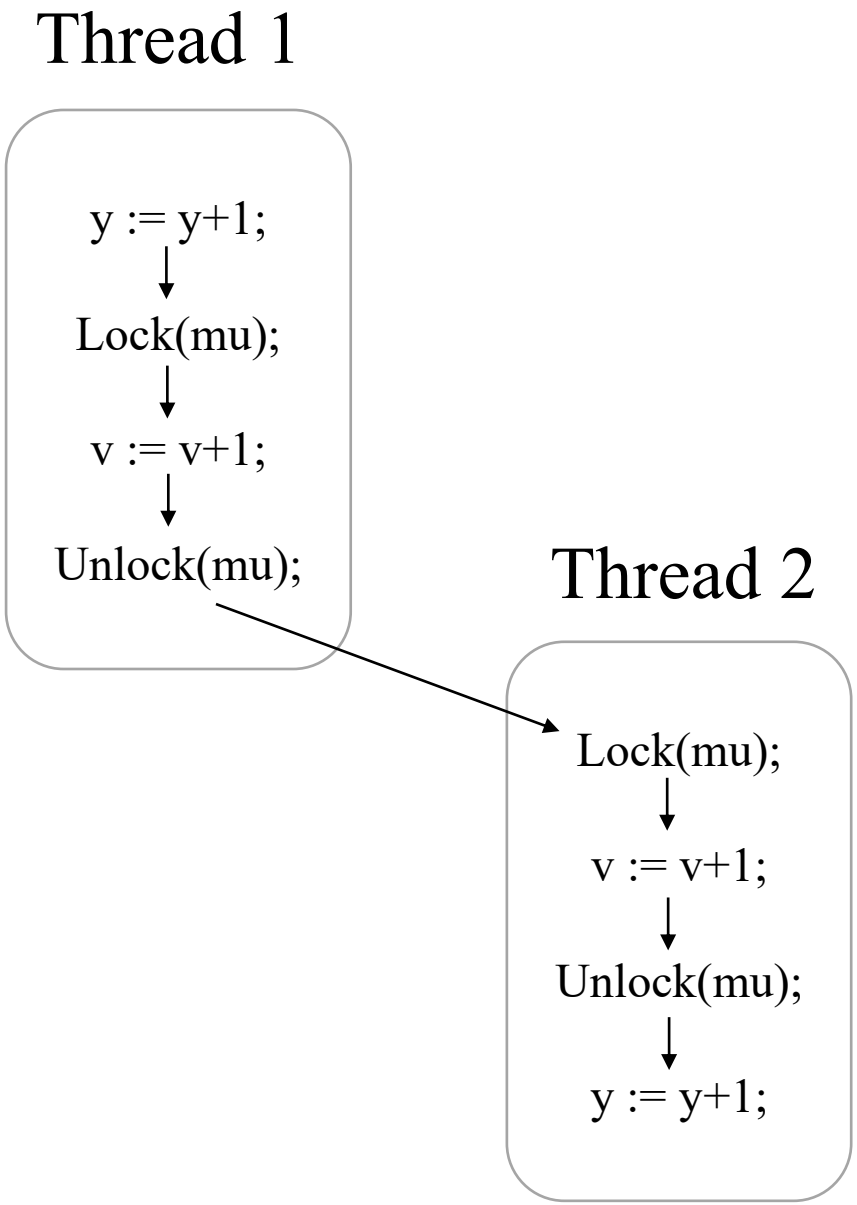

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  - T1-acc(v) happens before T2-acc(v)
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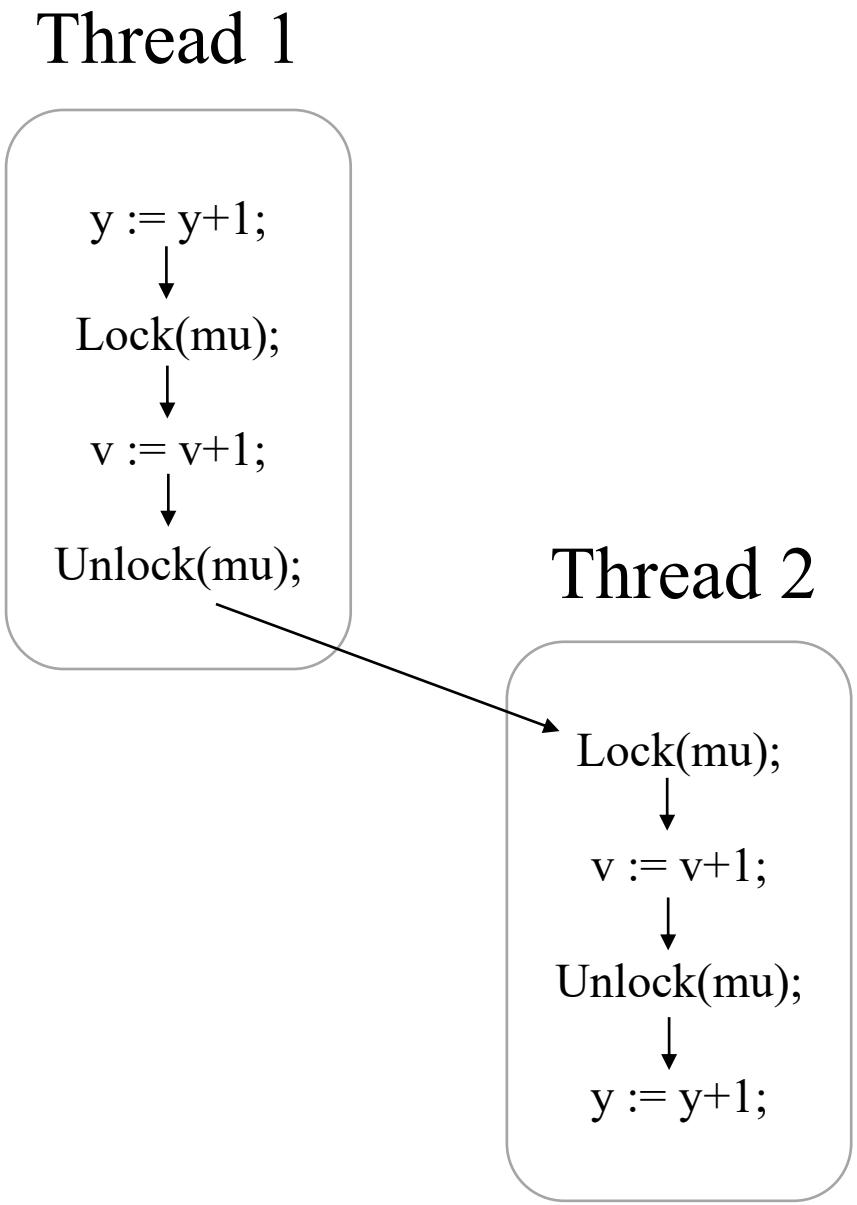
  - Conclusion: no race on Y!
  - Finding doesn't generalize



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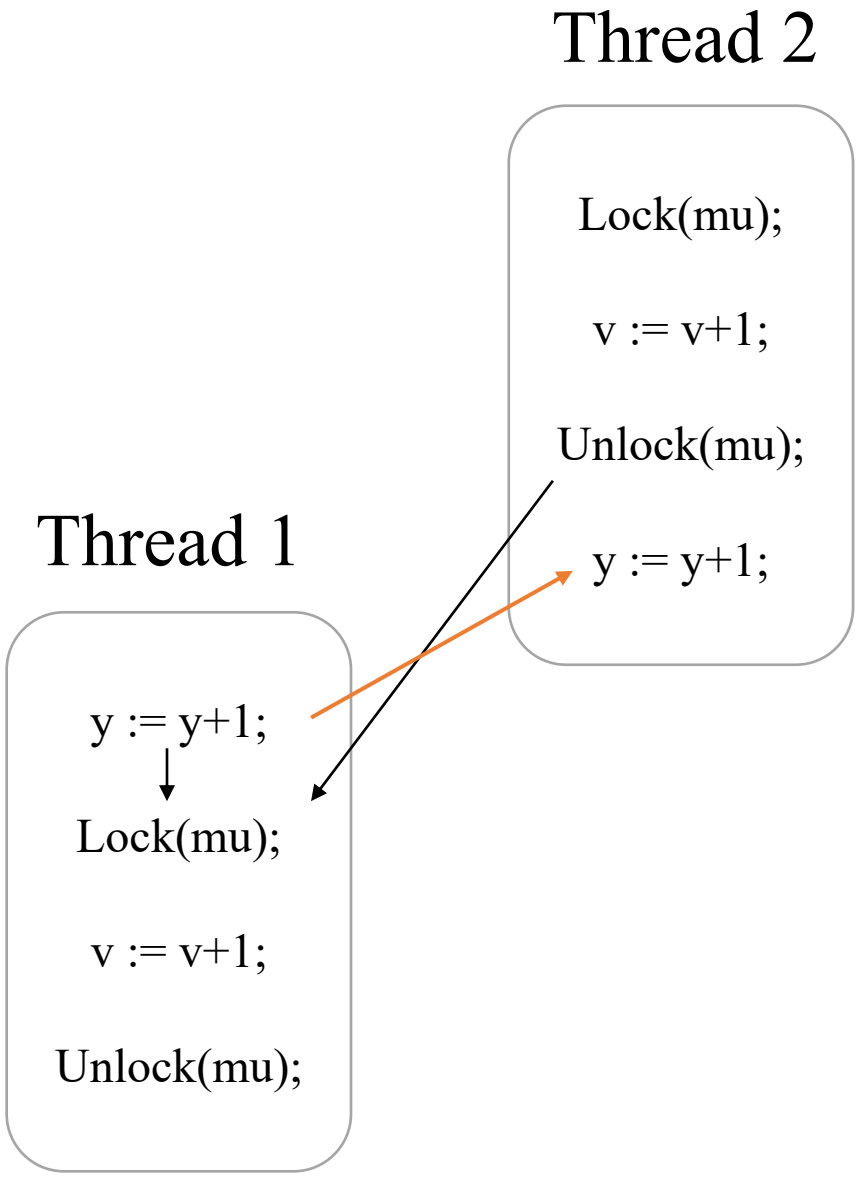
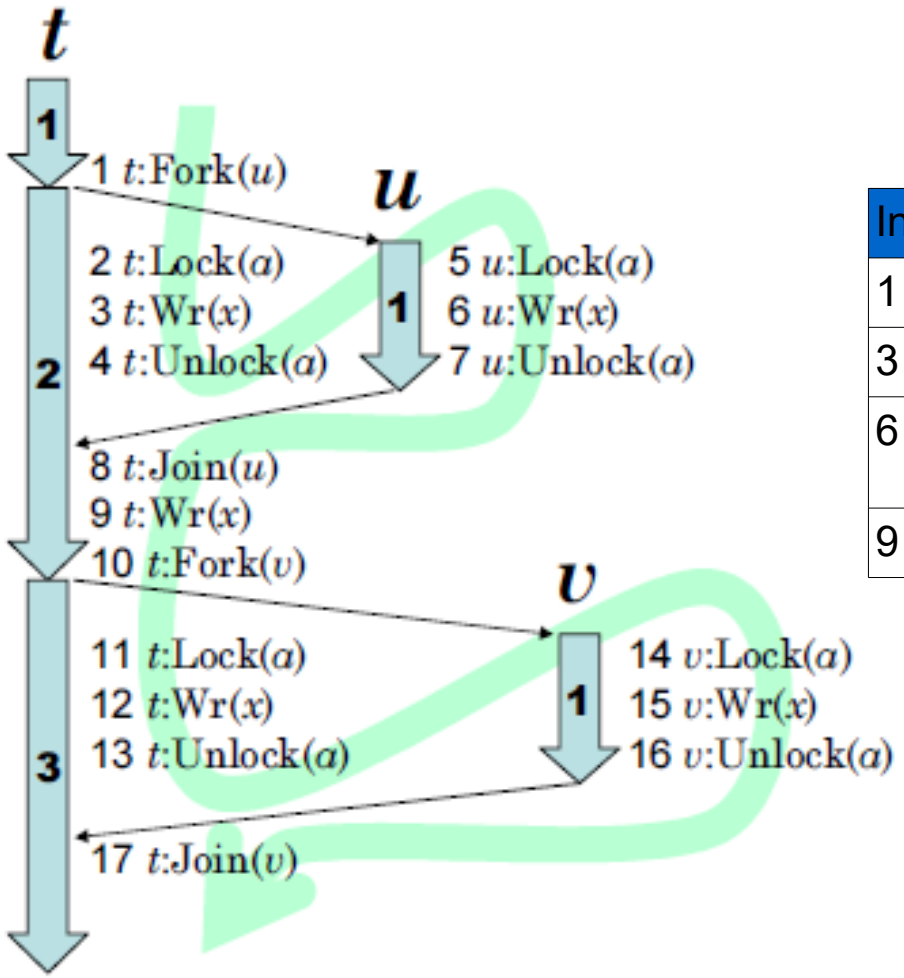


Dynamic Race Detection Summary

- Lockset: verify locking discipline for shared memory
  - ✓ Detect race regardless of thread scheduling
  - ✘ False positives because other synchronization primitives (fork/join, signal/wait) not supported
- Happens-before: track partial order of program events
  - ✓ Supports general synchronization primitives
  - ✘ Higher overhead compared to lockset
  - ✘ False negatives due to sensitivity to thread scheduling

RaceTrack = Lockset + Happens-before

False positive using Lockset



Tracking accesses to X

Inst	State	Lockset
1	Virgin	{ }
3	Exclusive:**t**	{ }
6	Shared Modified	{**a**}
9	Report race	{ }

RaceTrack Notations

Notation	Meaning
L_t	Lockset of thread **t**
C_x	Lockset of memory **x**
B_u	Vector clock of thread **u**
S_x	Threadset of memory **x**
$\mathbf{t_i}$	Thread **t** at clock time **i**

$$
\begin{aligned}
|V| &\triangleq |\{t \in T : V(t) > 0\}| \\
Inc(V,t) &\triangleq u \mapsto \text{if } u = t \text{ then } V(u) + 1 \text{ else } V(u) \\
Merge(V,W) &\triangleq u \mapsto max(V(u), W(u)) \\
Remove(V,W) &\triangleq u \mapsto \text{if } V(u) \leq W(u) \text{ then } 0 \text{ else } V(u)
\end{aligned}
$$

RaceTrack Algorithm

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B_t	Vector clock of thread **t**
S_x	Threadset of memory **x**
$\mathbf{t_1}$	Thread **t** at clock time 1

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\end{aligned}
$$

At t:Lock(l):
$L_t \leftarrow L_t \cup \{l\}$

At t:Unlock(l):
$L_t \leftarrow L_t - \{l\}$

At t:Fork(u):
$L_u \leftarrow \{\}$
$B_u \leftarrow Merge(\{\langle u, 1\rangle\}, B_t)$
$B_t \leftarrow Inc(B_t, t)$

At t:Join(u):
$B_t \leftarrow Merge(B_t, B_u)$

At t:Rd(x) or t:Wr(x):
$S_x \leftarrow Merge(Remove(S_x, B_t), \{\langle t, B_t(t)\rangle\})$
if $|S_x| > 1$
then $C_x \leftarrow C_x \cap L_t$
else $C_x \leftarrow L_t$
if $|S_x| > 1 \wedge C_x = \{\}$ then report race

Avoiding Lockset's false positive (1)

Notation	Meaning
L_t	Lockset of thread **t**
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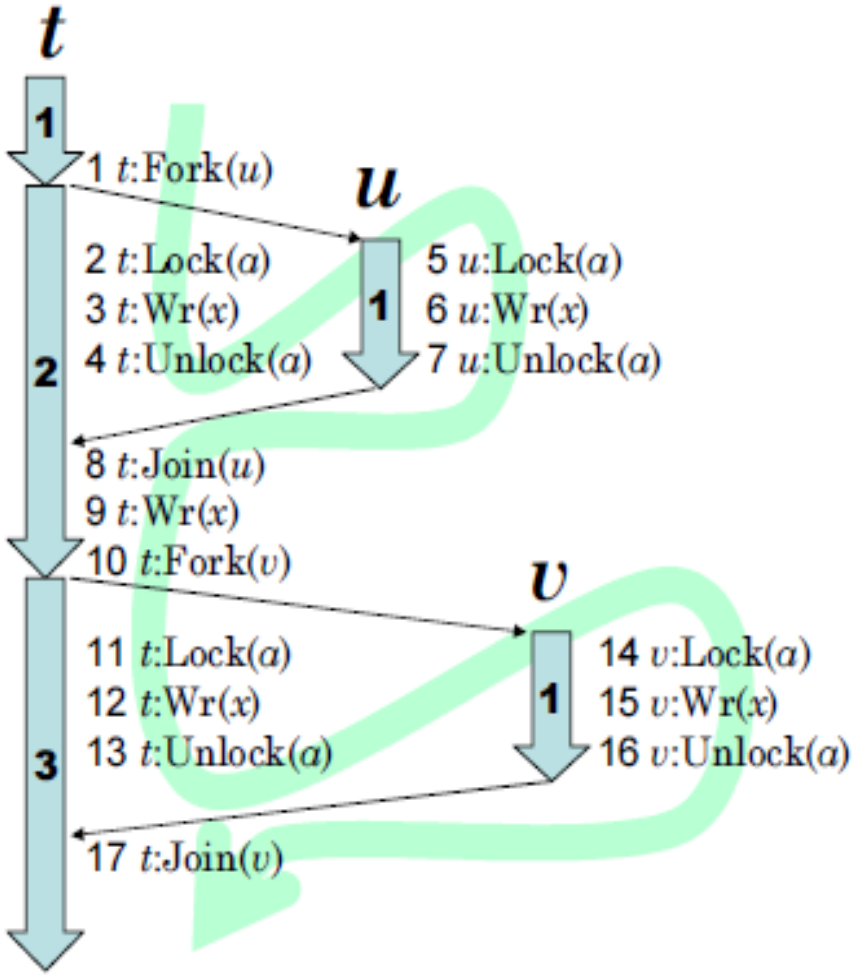
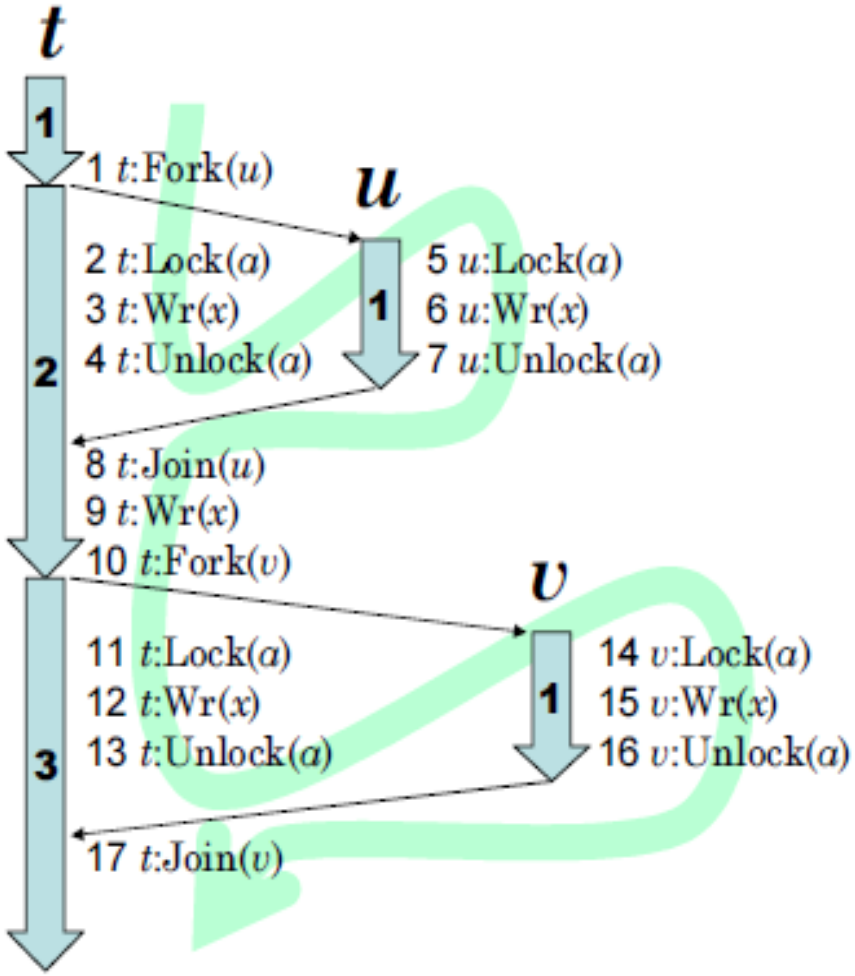


Inst	C_x	S_x	L_t	B_t	L_u	B_u
0	All	{ }	{ }	$\{t_1\}$	-	-
1				$\{t_2\}$	{ }	$\{ t_1,u_1 \}$
2			{a}			
3	{a}	$\{t_2\}$				
4			{ }			
5					{a}	
6		$\{t_2,u_1\}$				
7 8				$\{t_2,u_1\}$	{ } -	-

Avoiding Lockset's false positive (2)

Notation	Meaning
L_t	Lockset of thread **t**
C_x	Lockset of memory **x**
B_t	Vector clock of thread **t**
S_x	Threadset of memory **x**
t_1	Thread **t** at clock time 1



Inst	C_x	S_x	L_t	B_t	L_v	B_v
8	{a}	$\{t_2,u_1\}$	{ }	$\{t_2,u_1\}$	-	-
9	{ }	$\{t_2\}$				
10				$\{t_3,u_1\}$	{ }	$\{t_2,v_1\}$
11			{a}			
12	{a}	$\{t_3\}$				
13			{ }			
14					{a}	
15 16		$\{t_3,v_1\}$			 { }	

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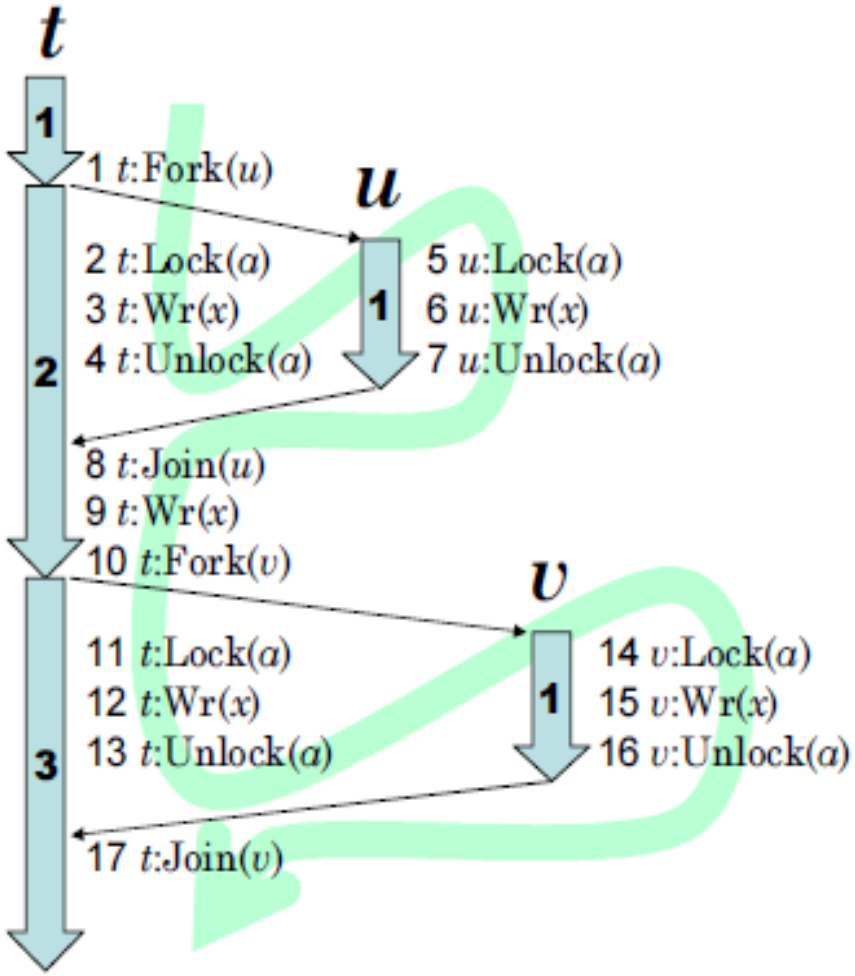

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11			{a}			
12	{a}	$\{t_3\}$				
13			{ }			
14					{a}	
15		$\{t_3,v_1\}$				
16					{ }	

Only one thread!
Are we done?