Race Detection

cs378h

Pro Forma

- Questions?
- Administrivia:
  - Course/Instructor Survey : https://utdirect.utexas.edu/ctl/ecis/
  - 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

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?

Race Detection

Race Detection

Locks: a litany of problems

Race Detection

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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

- Deadlock
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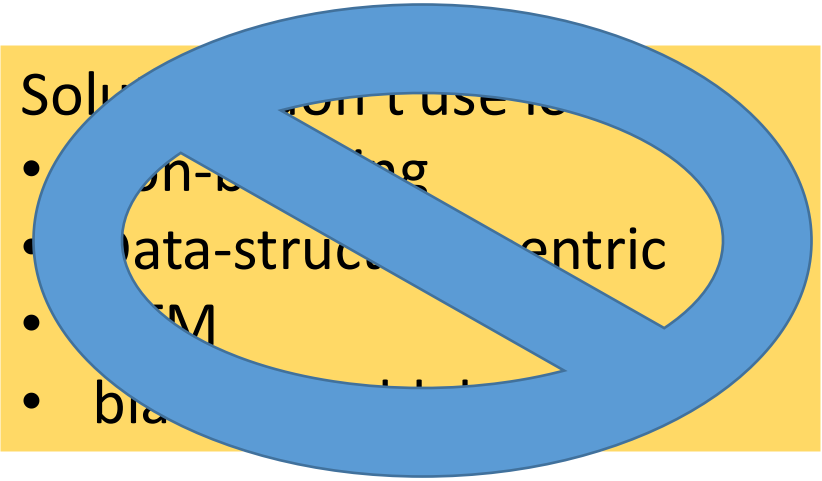

Race Detection

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Solu… on't use lo…
- …on-b… …ng
- …ata-struc… …entric
- …M
- bla…

Use locks!
- But automate bug-finding!

Races

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Lock(lock);
Read-Write(X);              Read-Write(X);
Unlock(lock);
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- Is there a race here?

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- Formally:
  - >1 threads access same item
  - No intervening synchronization
  - At least one access is a write

Races

Thread 1	Thread 2
`Lock(lock);`	
`Read-Write(X);`	`Read-Write(X);`
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How to detect races:

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forall(X) {
  if(not_synchronized(X))
    declare_race()
}
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Races

```
read-write(X);
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do_stuff();
do_more_stuff();
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```
thread-proc() {

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How can a race detector tell?

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- Benign due to fork/join
- Benign due to view serializability
- Benign due to application-level constraints
- E.g. approximate stats counters

Detecting Races

- Static
  - Run a tool that analyses just code
  - Maybe code is annotated to help
  - Conservative: detect races that never occur
- Dynamic
  - Instrument code
  - Check synchronization invariants on accesses
  - More precise
  - Difficult to make fast
  - ***Lockset vs happens-before***

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```

Read-Write(X);

```

Static Data Race Detection

- Type-based analysis
  - Language type system augmented
    - express common synchronization relationships”: correct typing→no data races
  - Difficult to do
  - Restricts the type of synchronization primitives
- Language features
  - e.g., use of monitors
  - Only works for static data – not dynamic data
- Model Checking
- Path analysis
  - Doesn’t scale well
  - Too many false positives

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What if these *never* run concurrently? (False Positive)

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Lockset Algorithm

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

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  - On each access, use locks held by thread to narrow that assumption

Lockset Algorithm

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  - Every shared mutable variable is protected by some locks
- Core idea
  - Track locks held by thread t

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.

Narrow down set of locks maybe protecting v

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

Lockset Algorithm Example

thread t

```
lock(lockA);
v++;
unlock(lockA);

lock(lockB);
v++;
unlock(lockB);
```

locks_held(t)	C(v)
{}	{lockA, lockB}

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ACK! race

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ACK! race

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

Improving over lockset

thread A

```
read-write(X);
fork(thread-proc);
do_stuff();
do_more_stuff();
join(thread-proc);
read-Write(X);
```

thread B

```
thread-proc() {
 read-write(X);
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Lockset detects a race

There is no race: why not?

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```
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2
3   read-write(X);
4
5 }
```

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”?
  - Sync objects are ordering events
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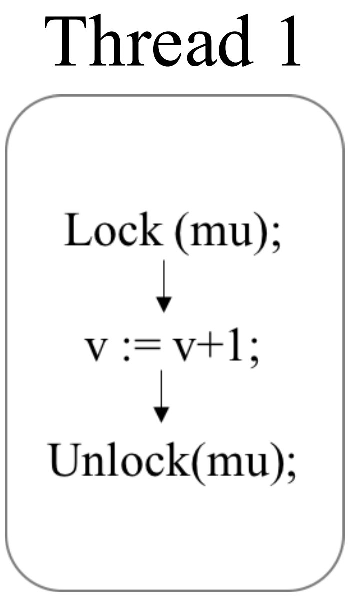

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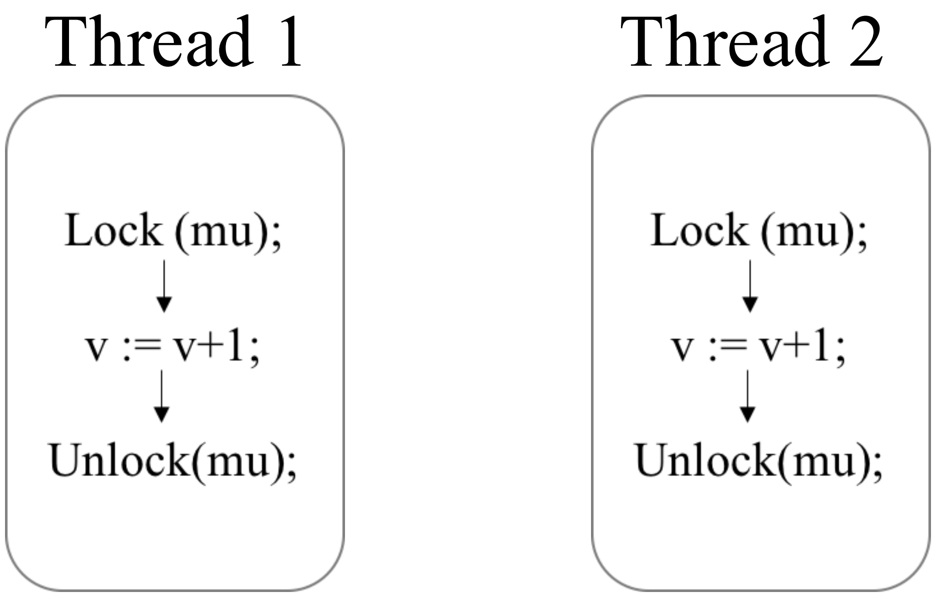

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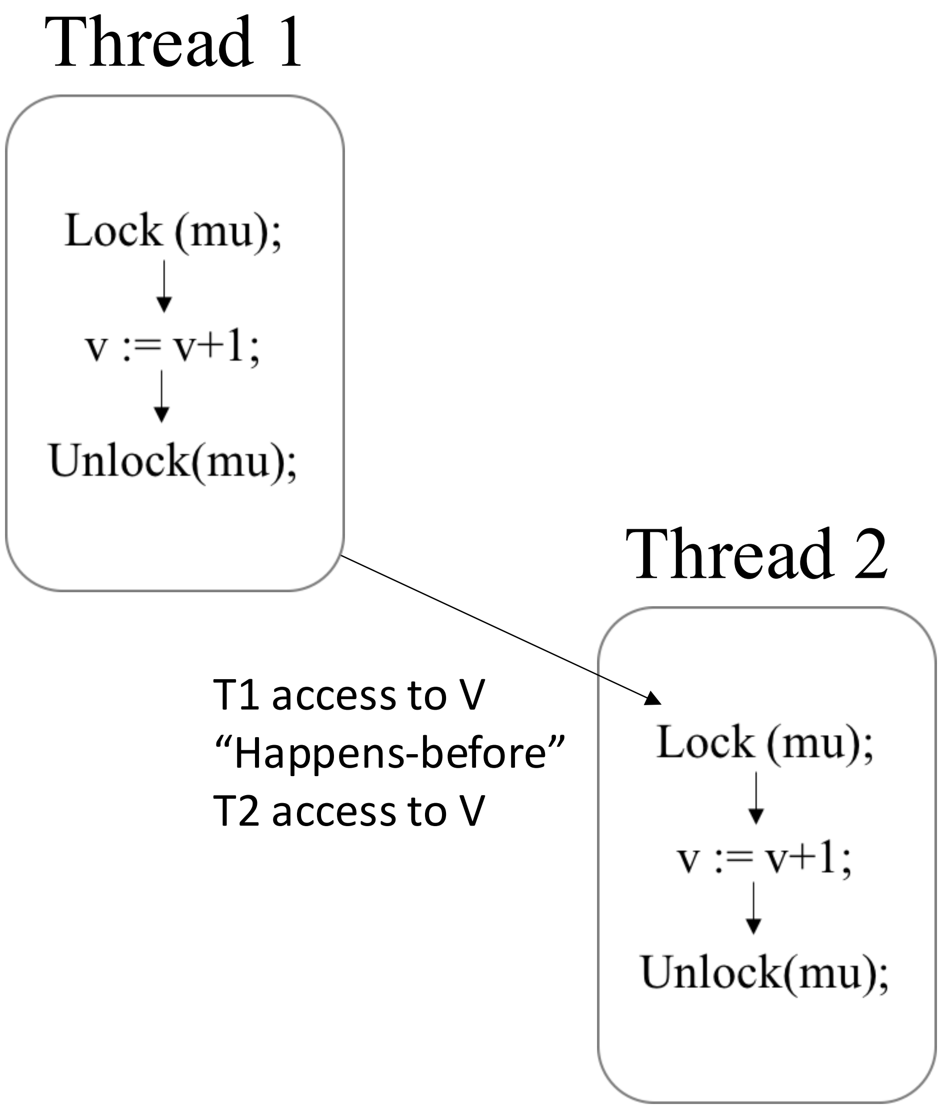

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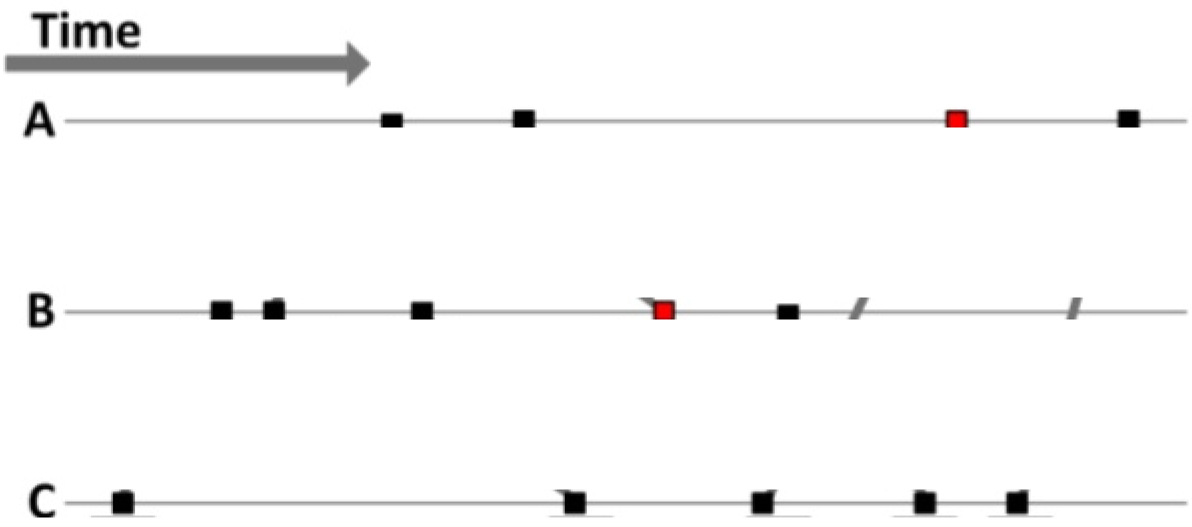

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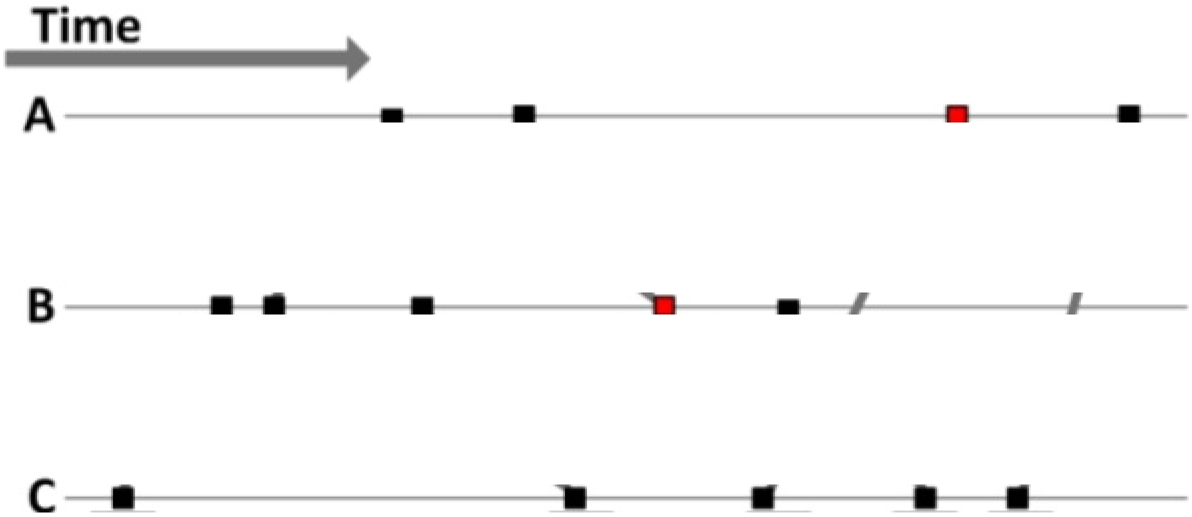

A, B, C have local orders

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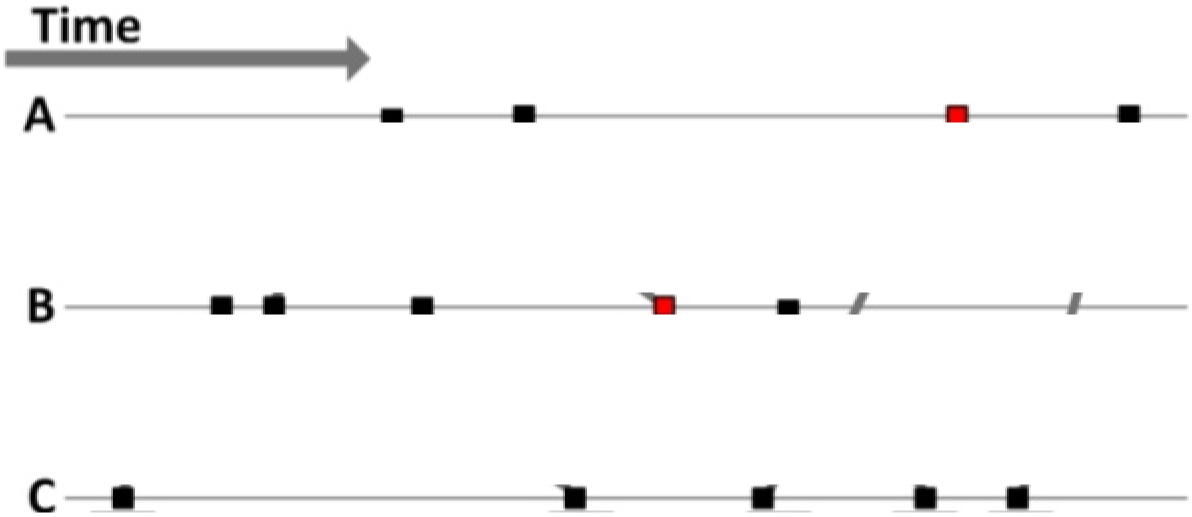

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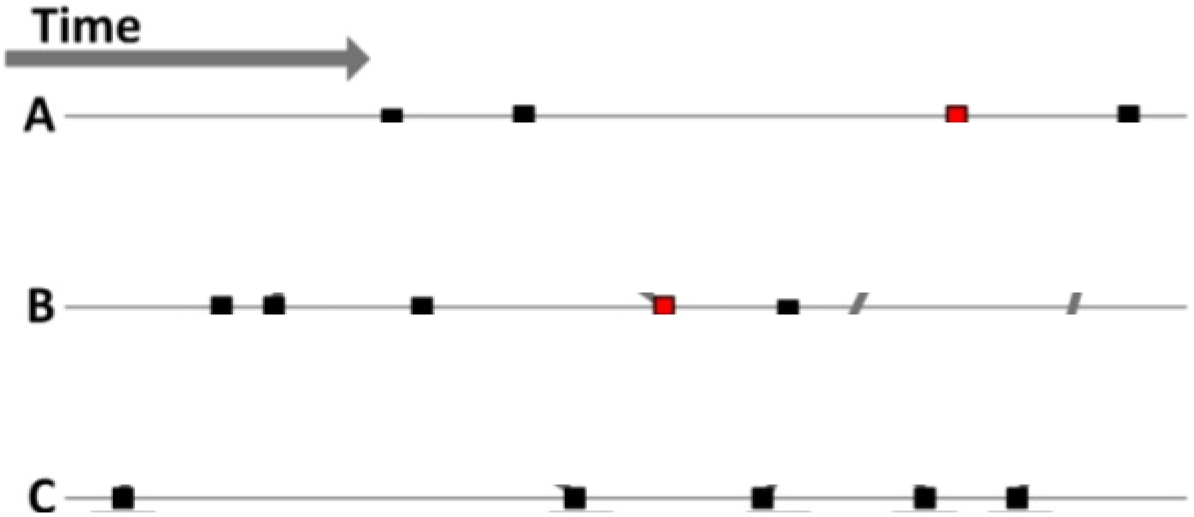

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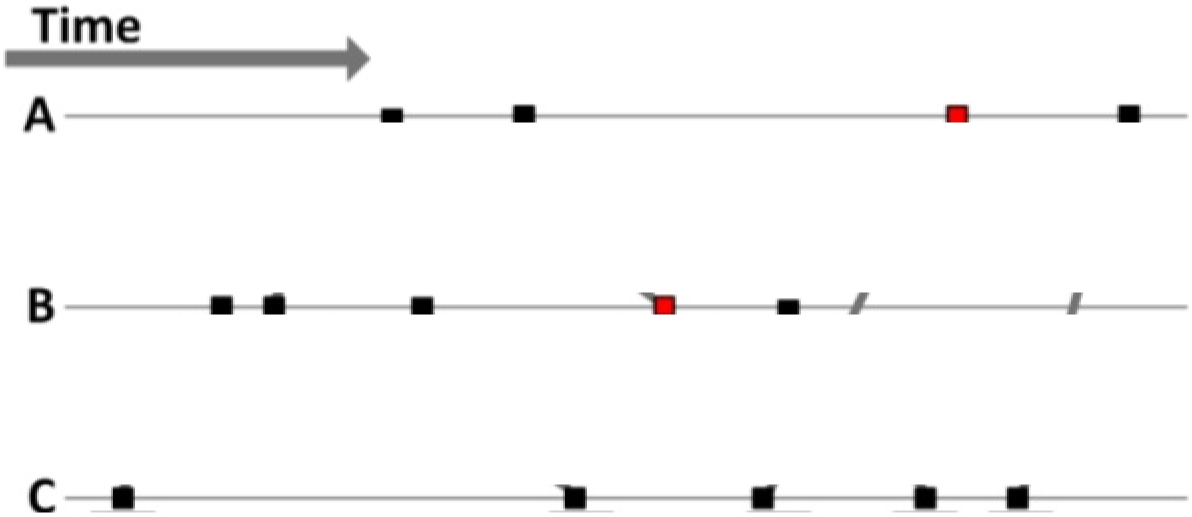

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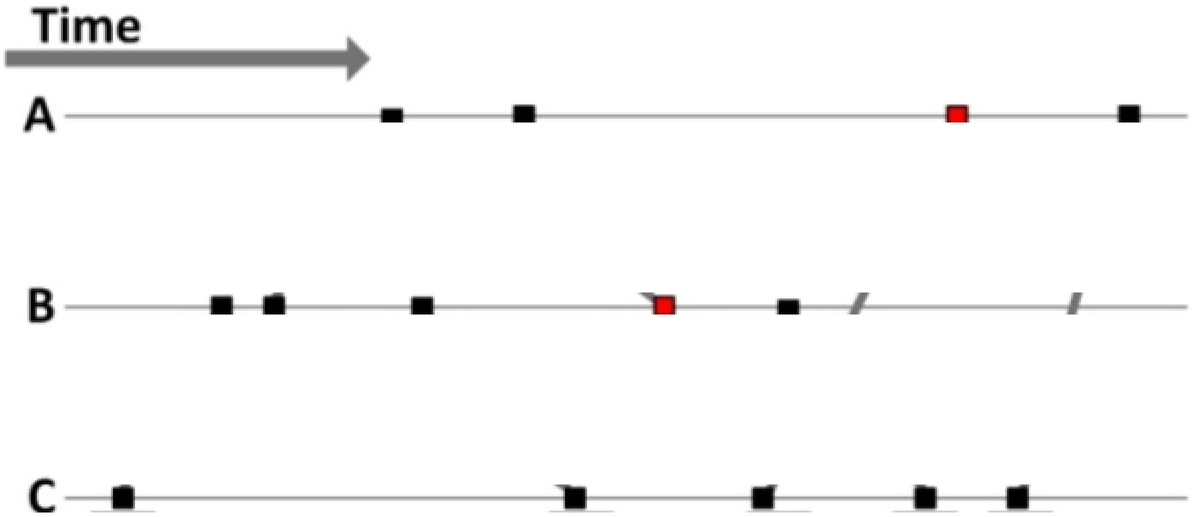

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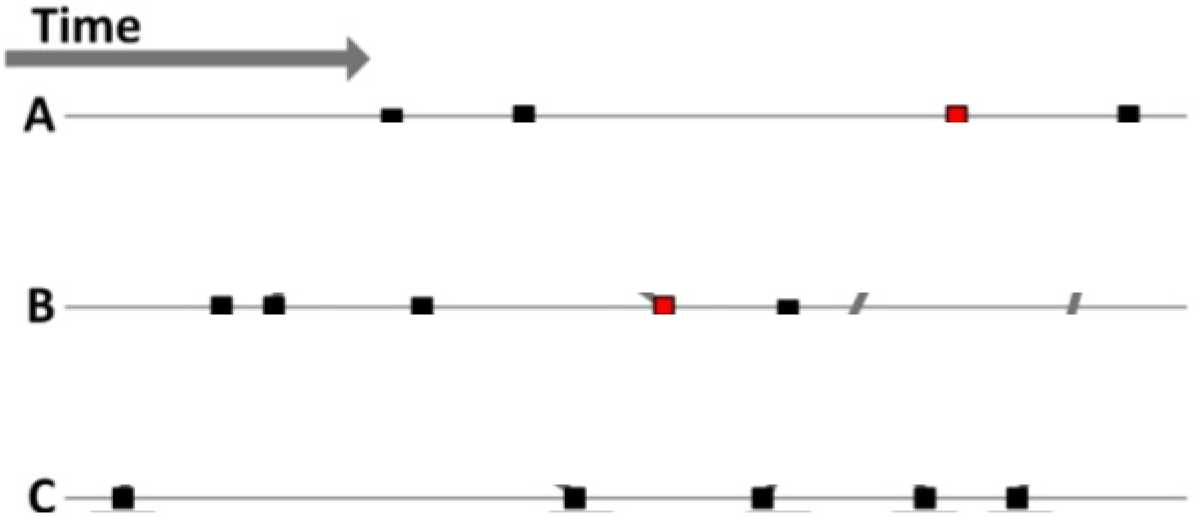

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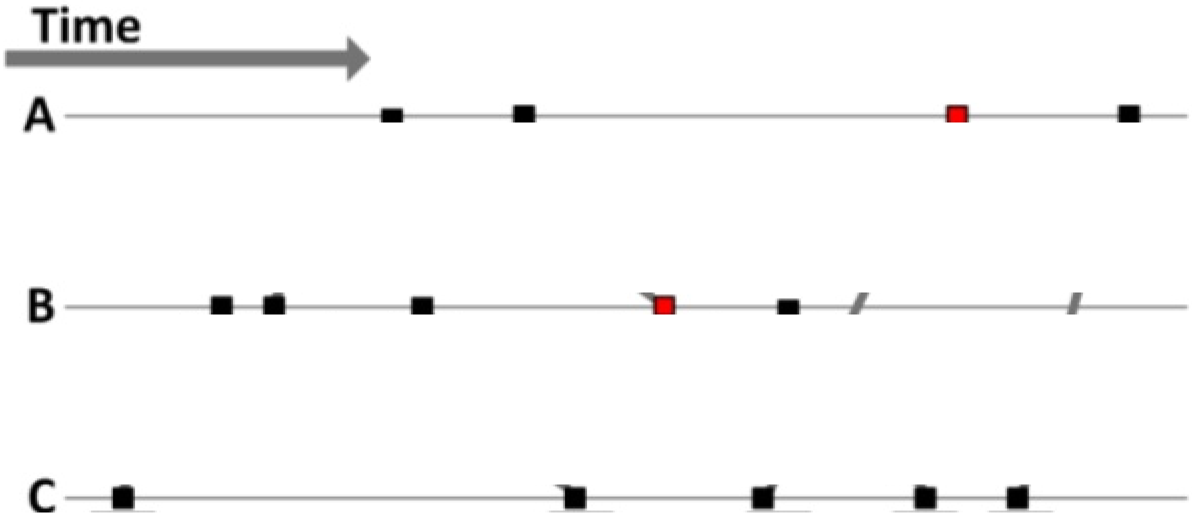

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- Matrix
  - TS(A) is N^2 showing pairwise knowledge

A Naïve Approach

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- Suppose events in the this system happened in this real order:

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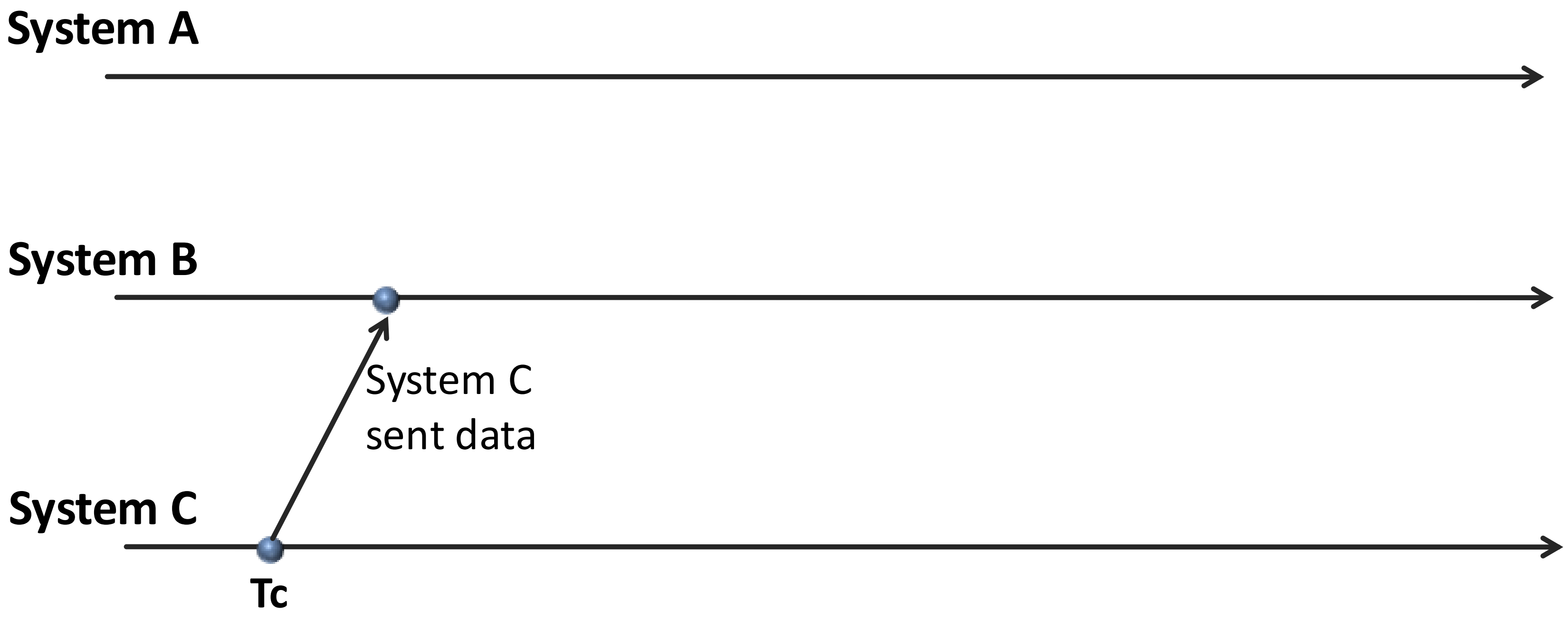

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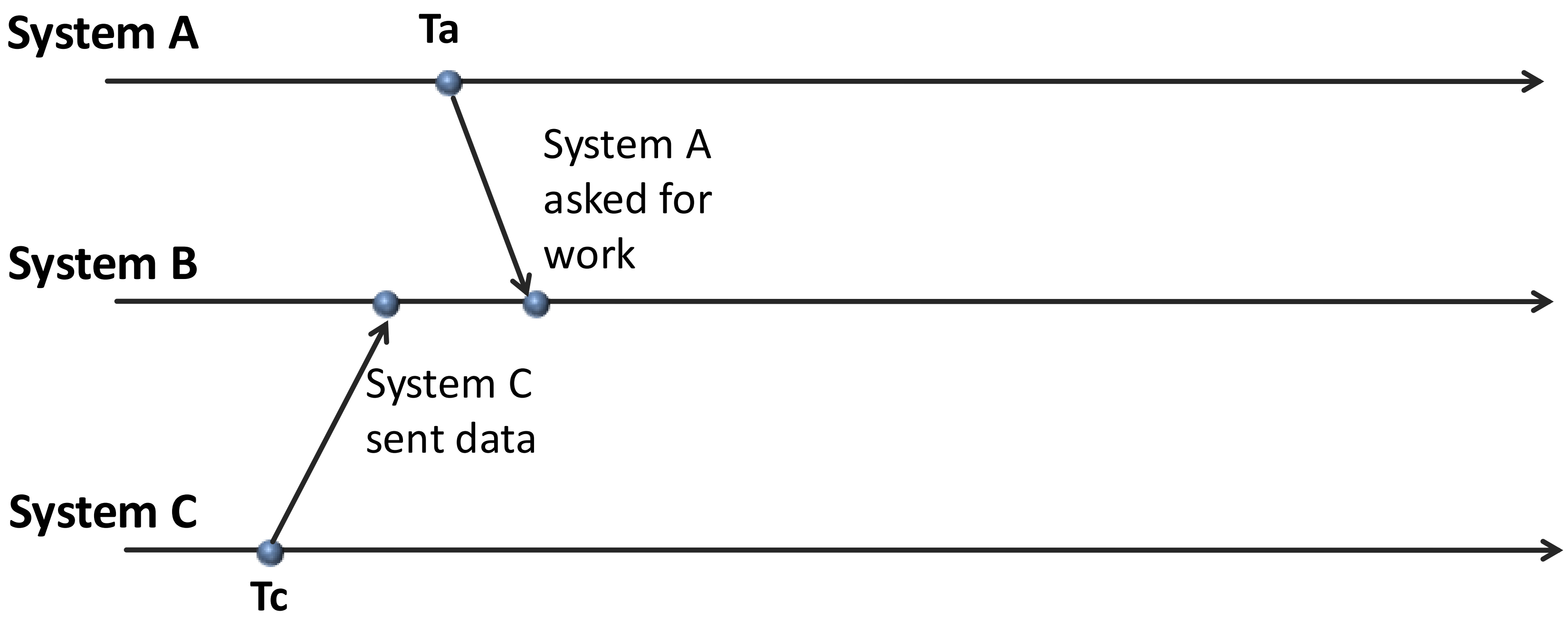

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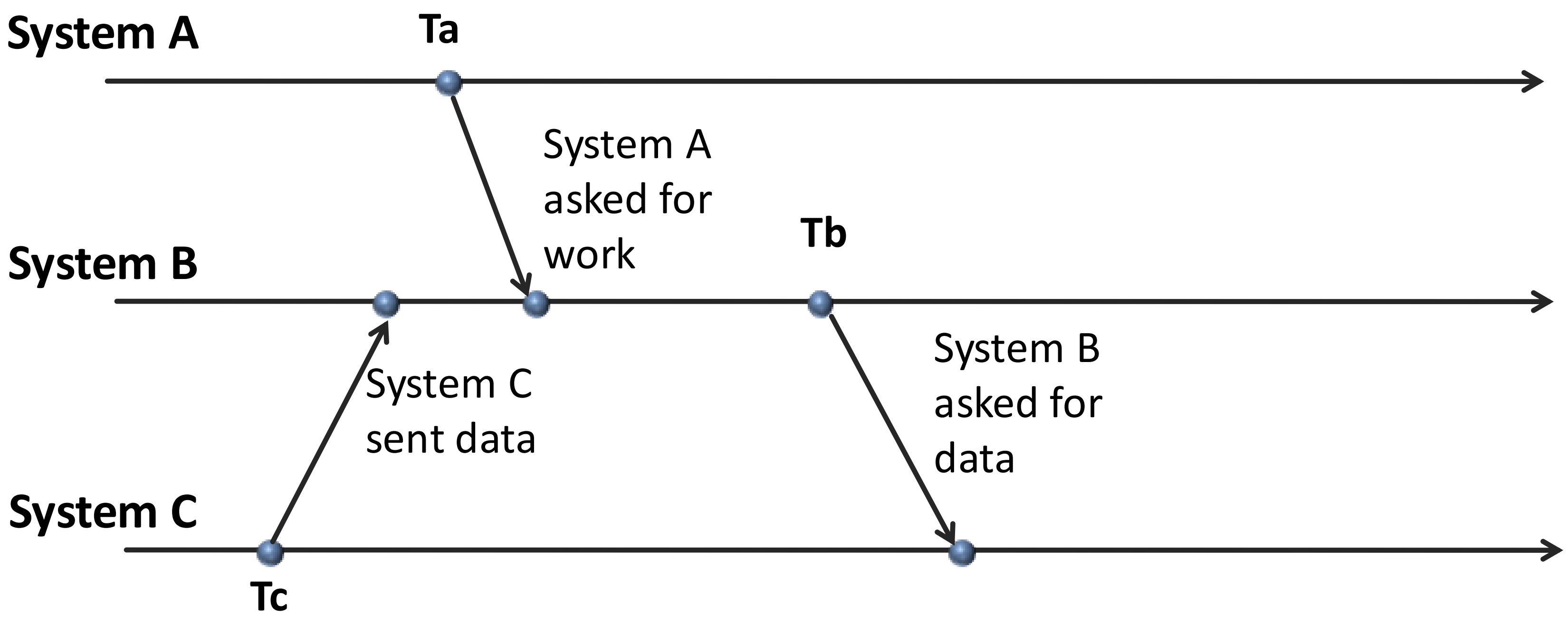

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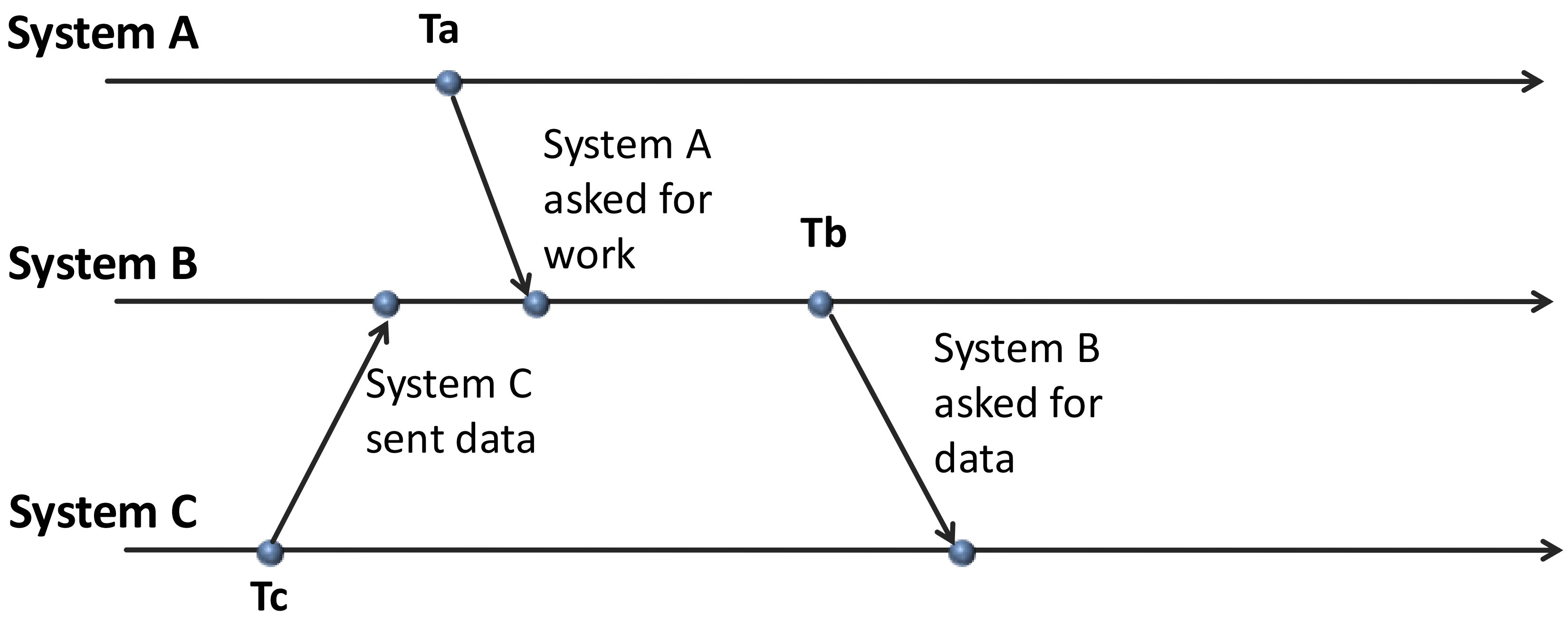

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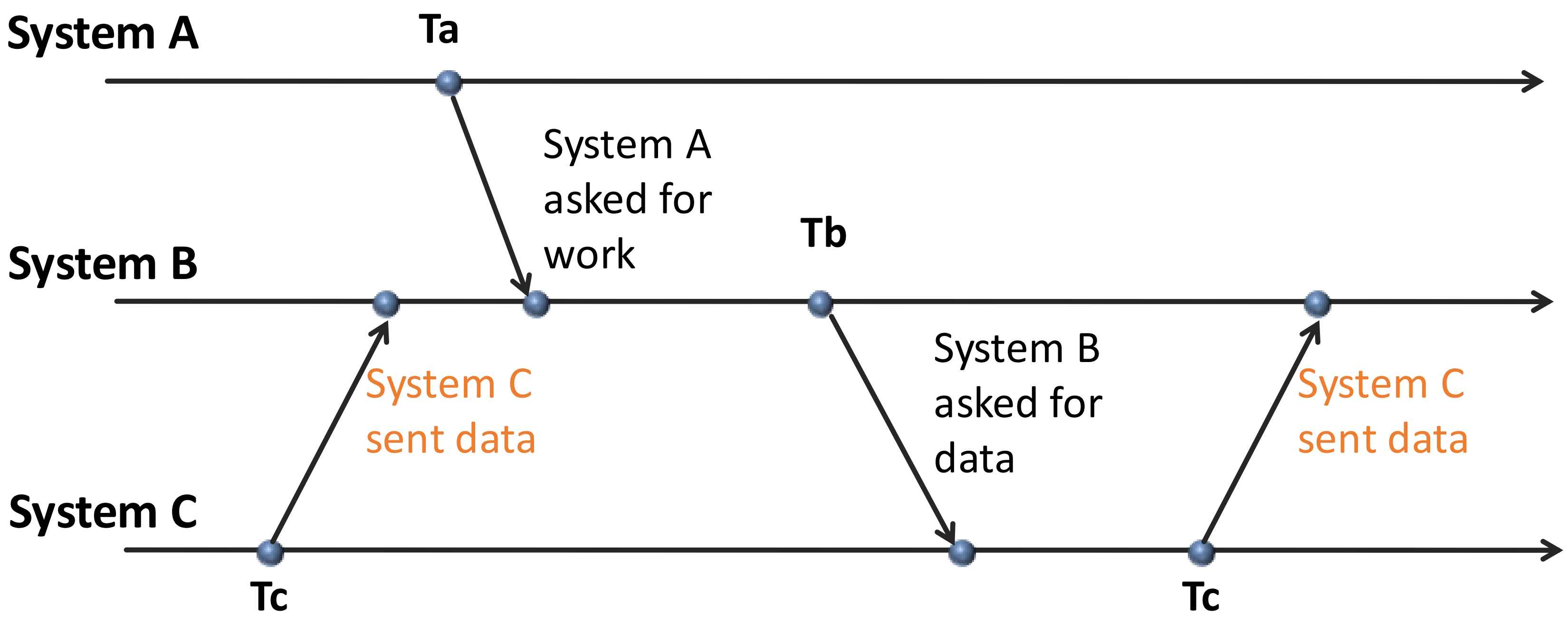
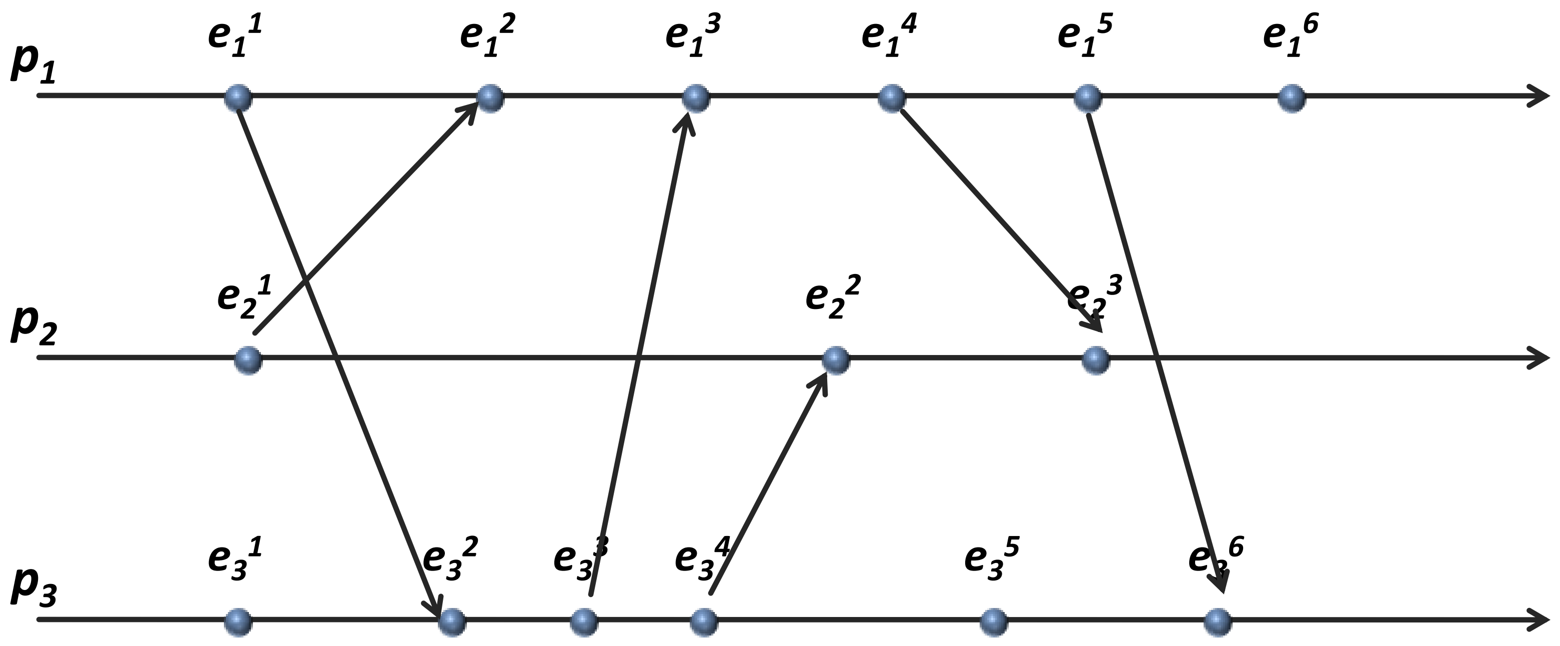


Rules for Ordering of Events

- 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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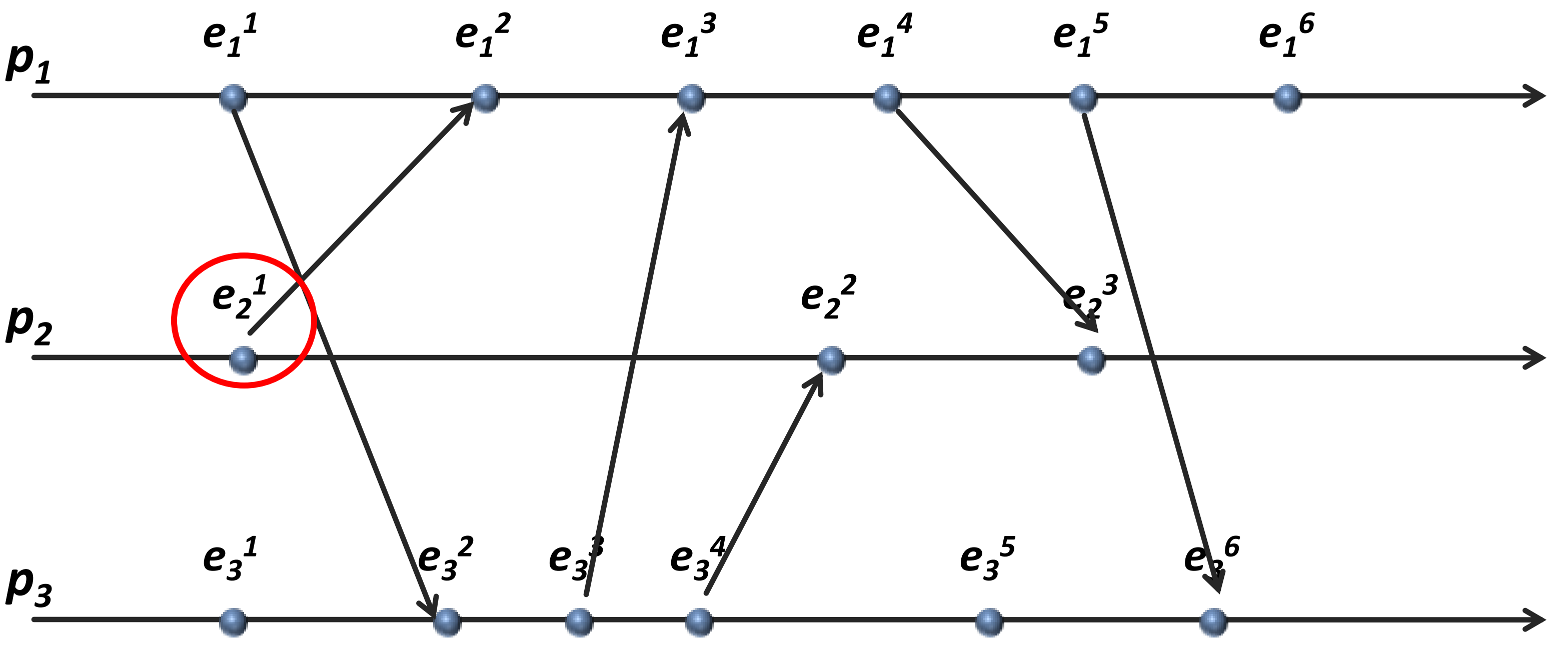

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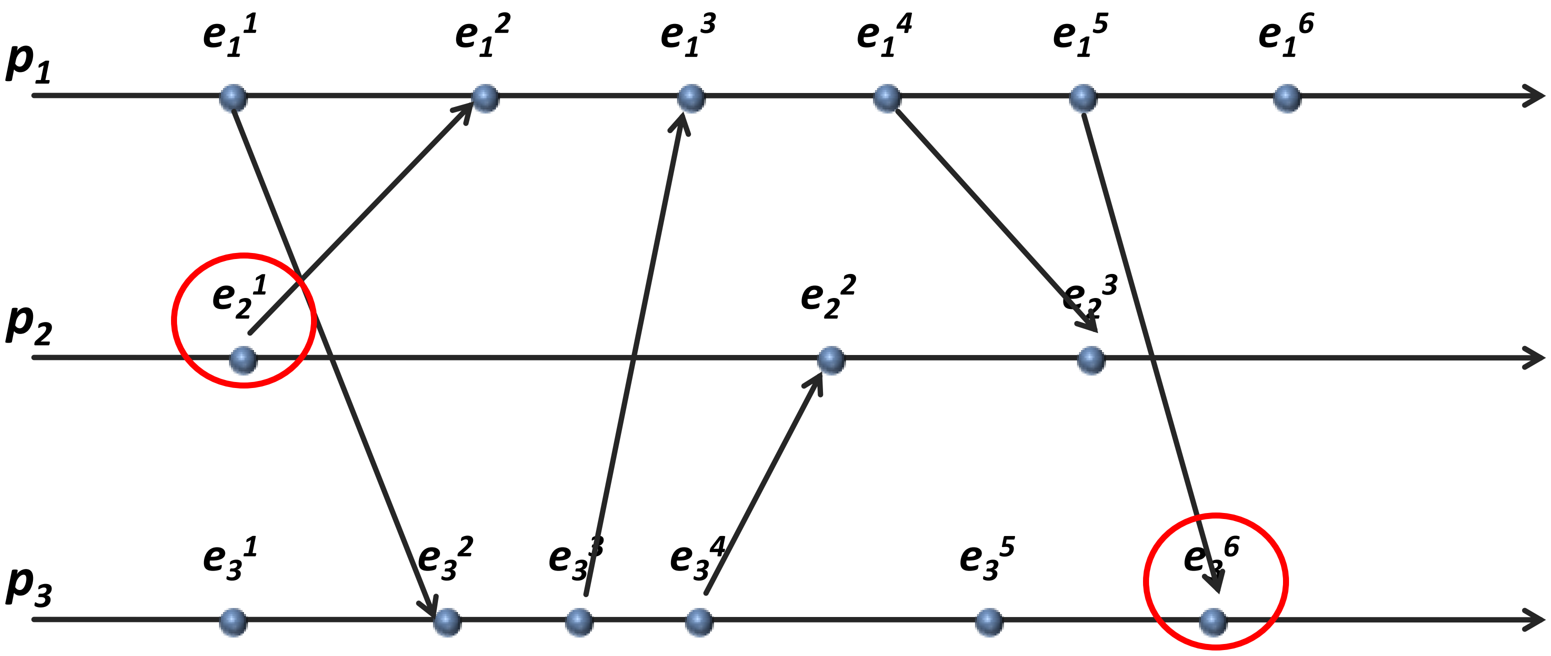

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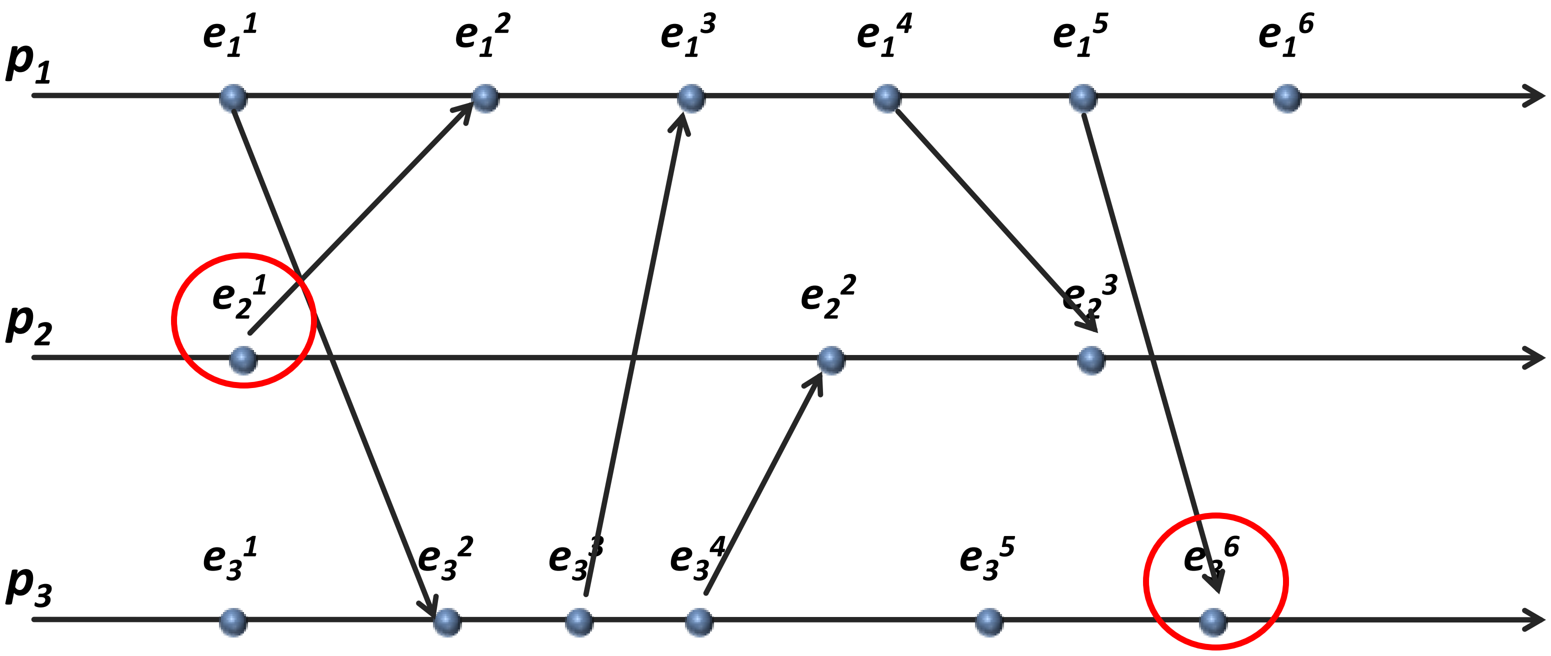

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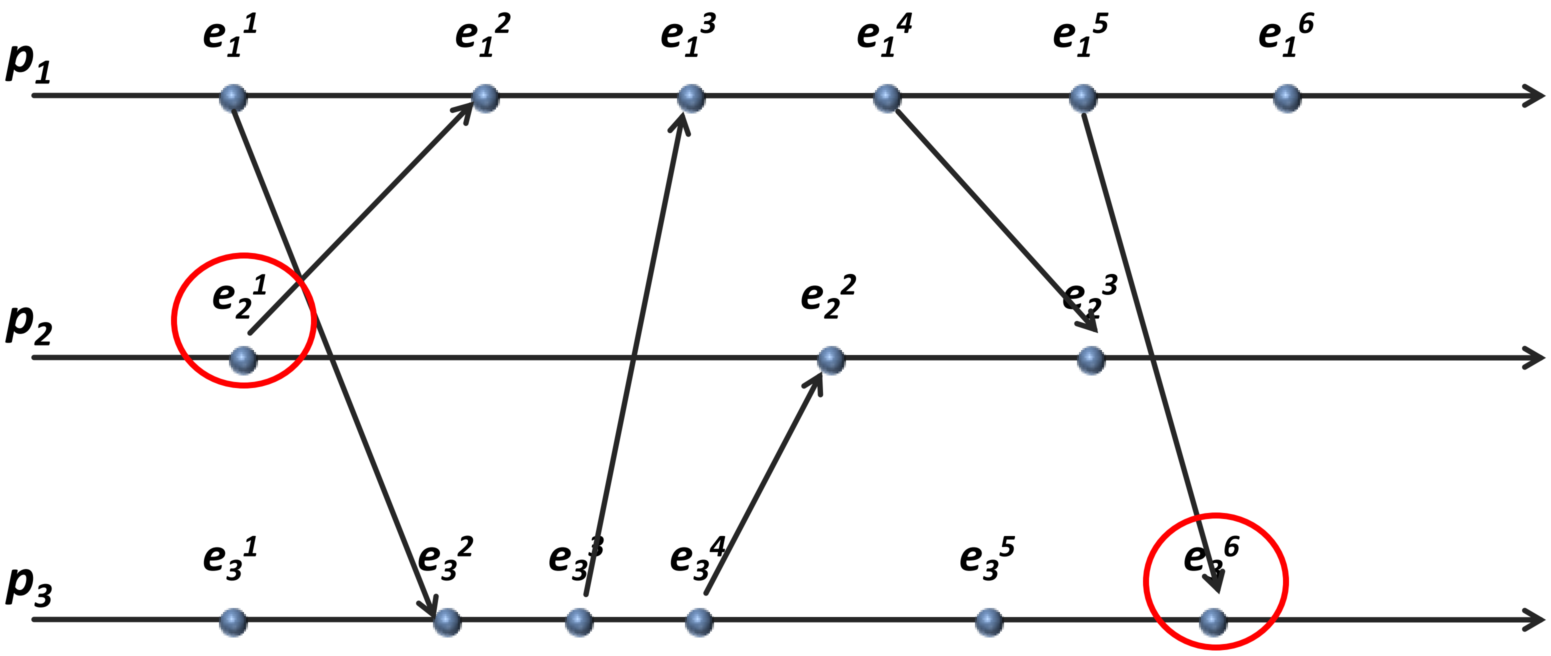

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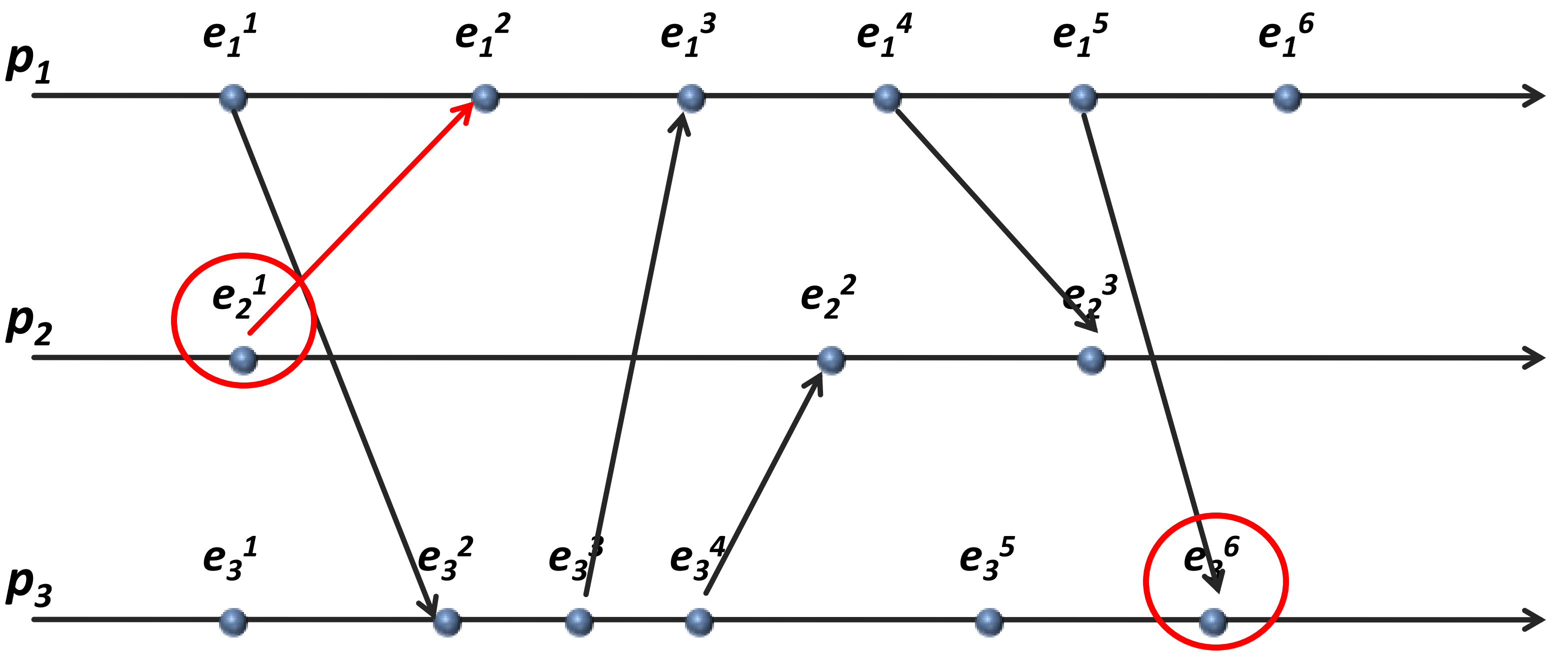

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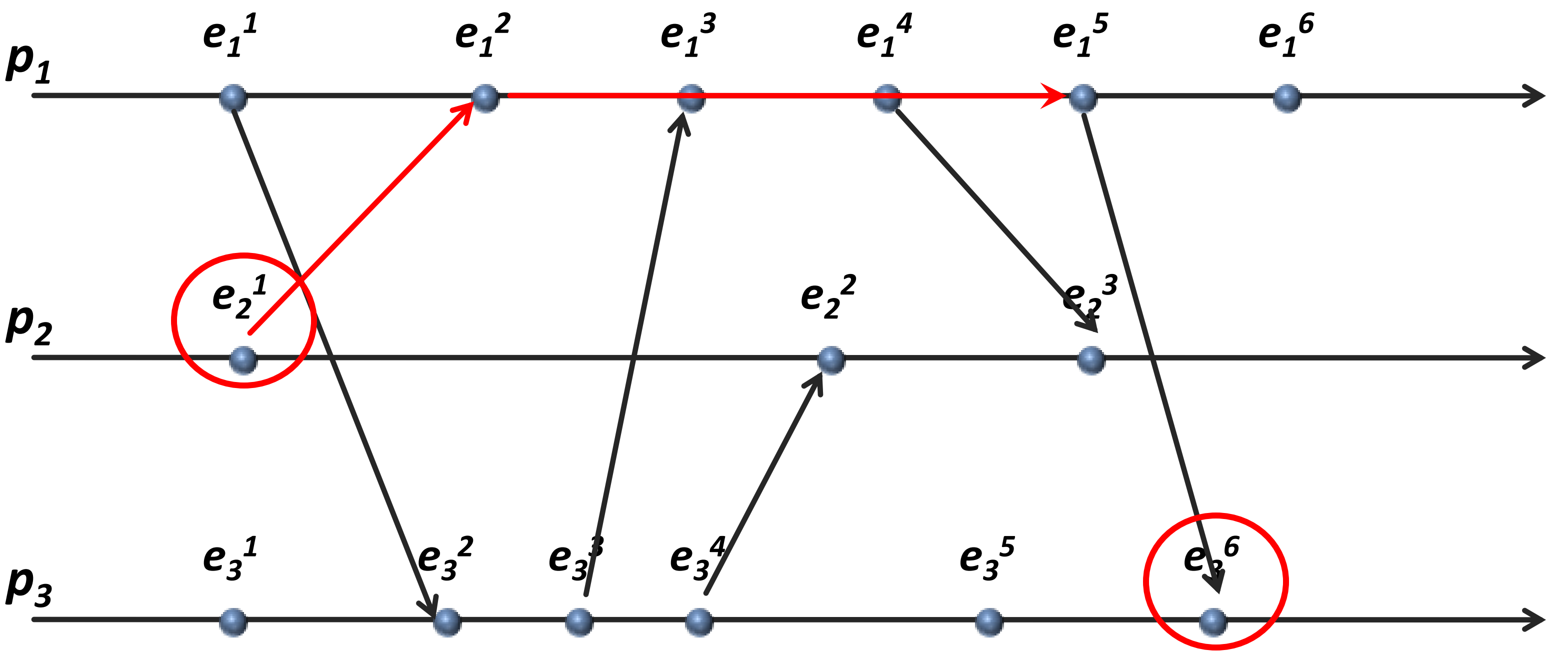

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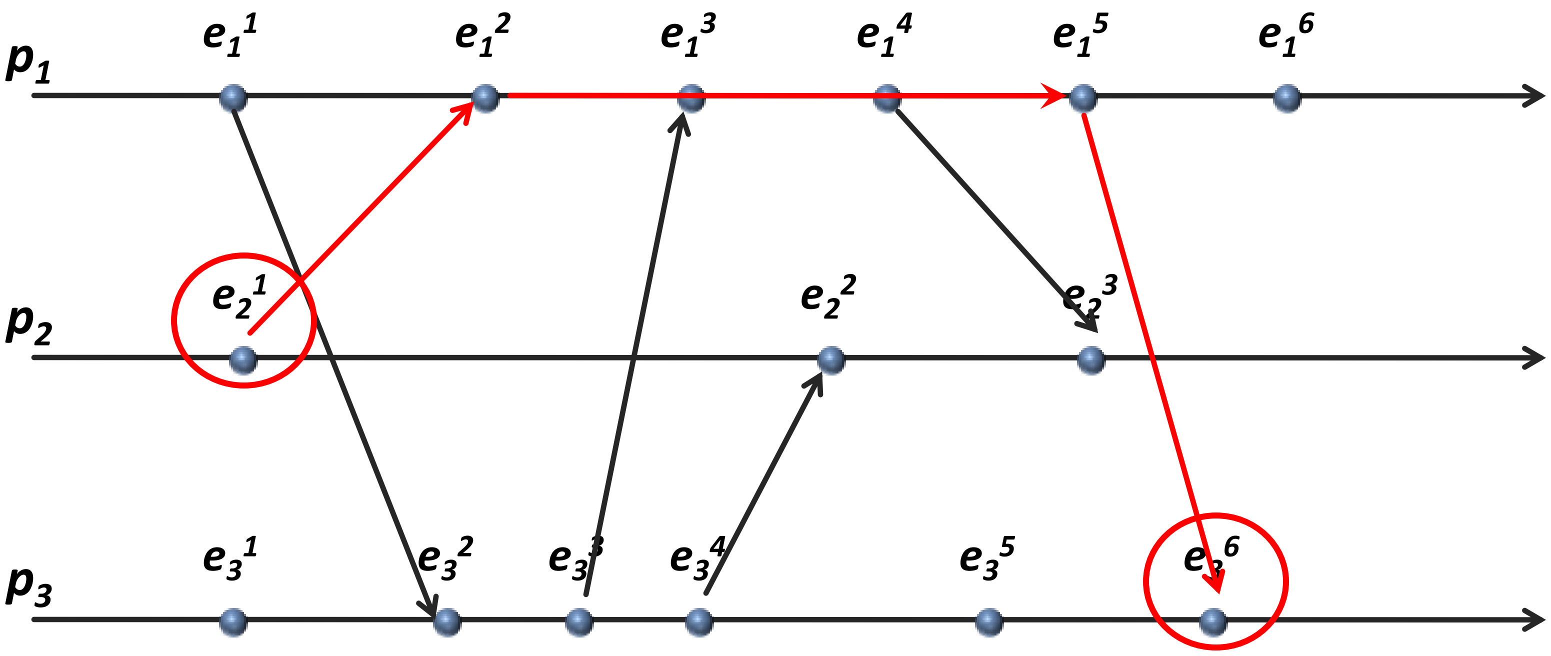

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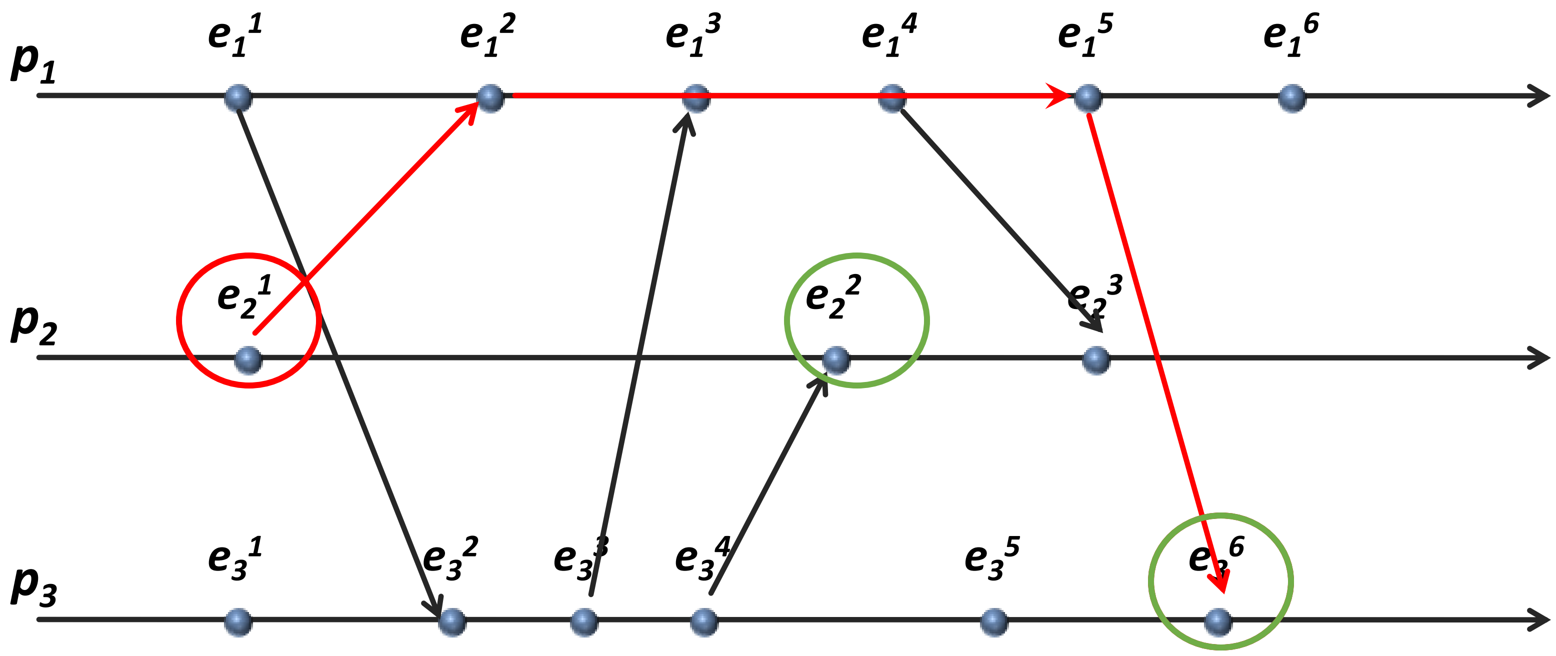

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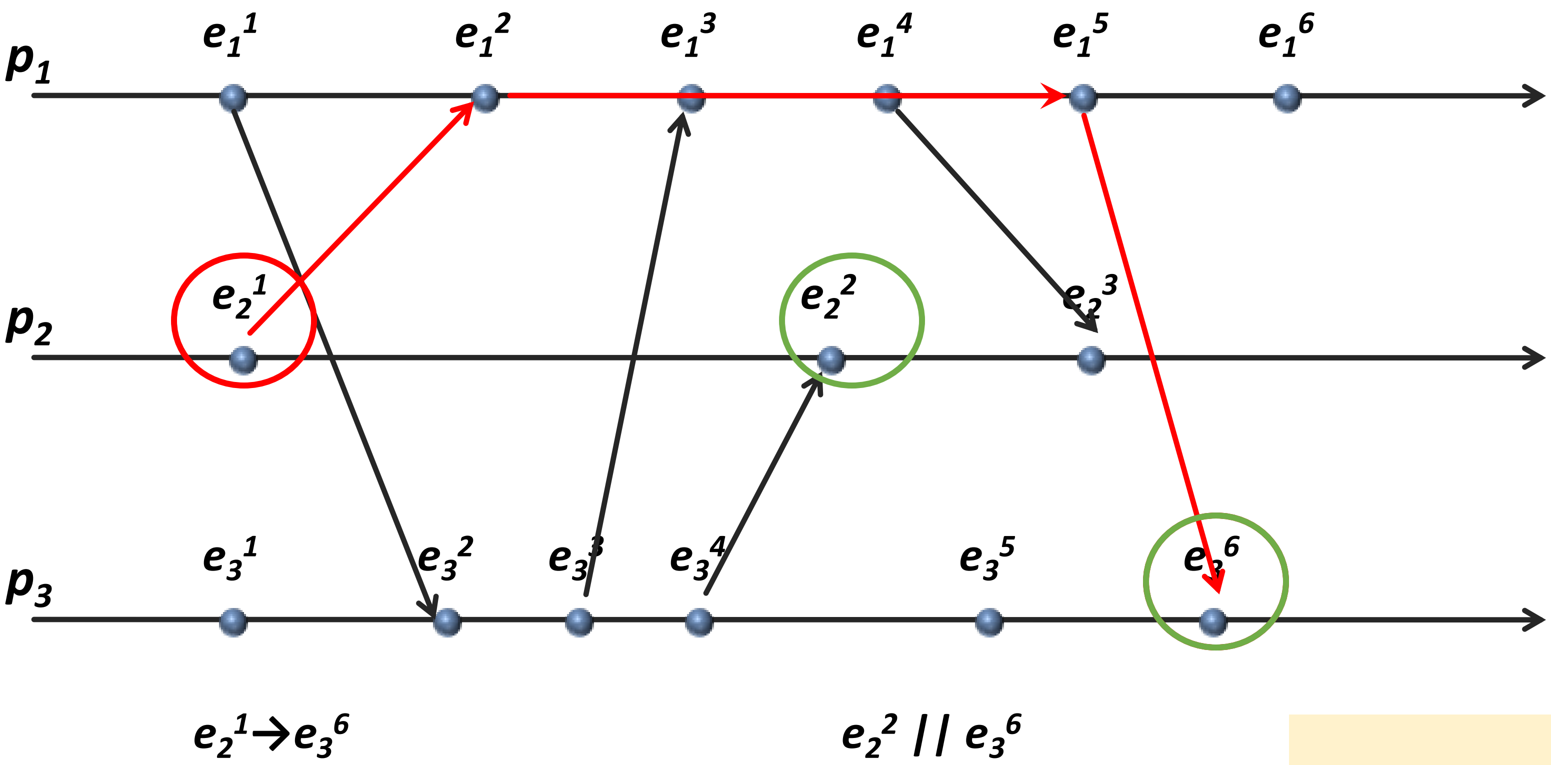

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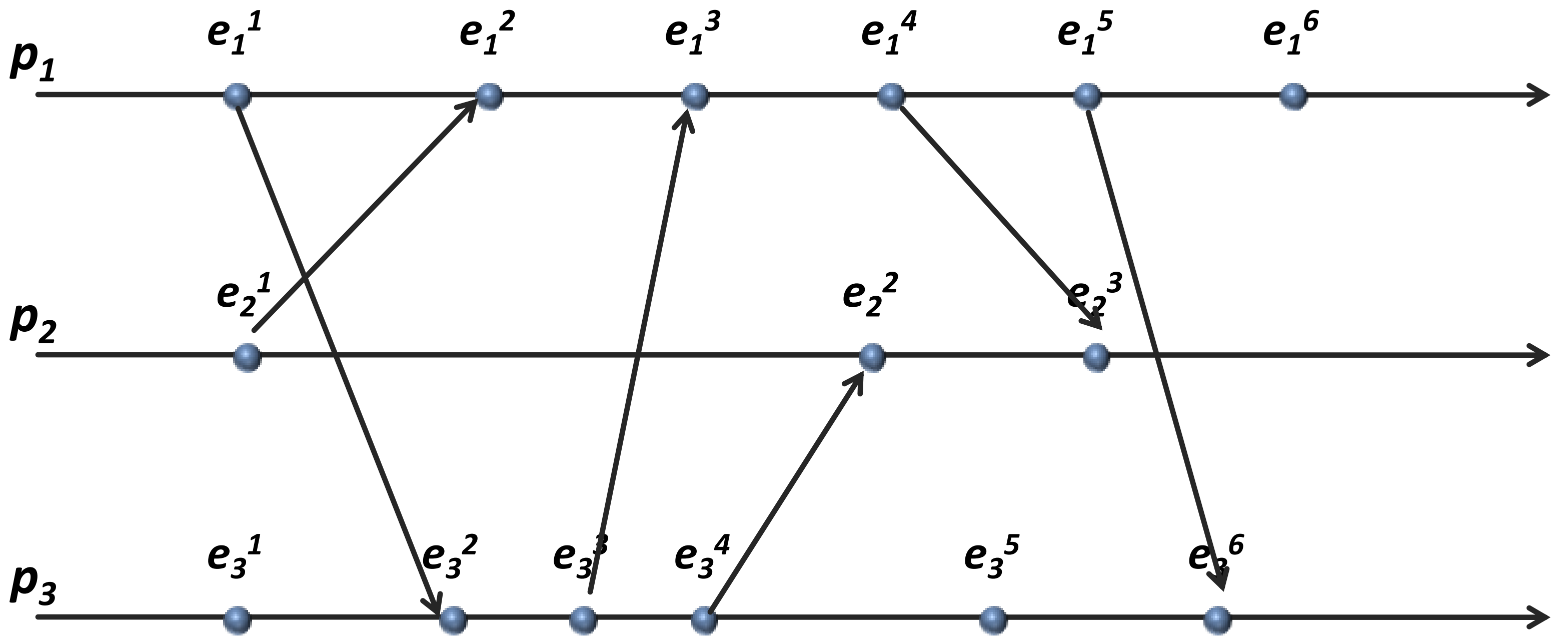
Cuts of a Distributed Computation

- 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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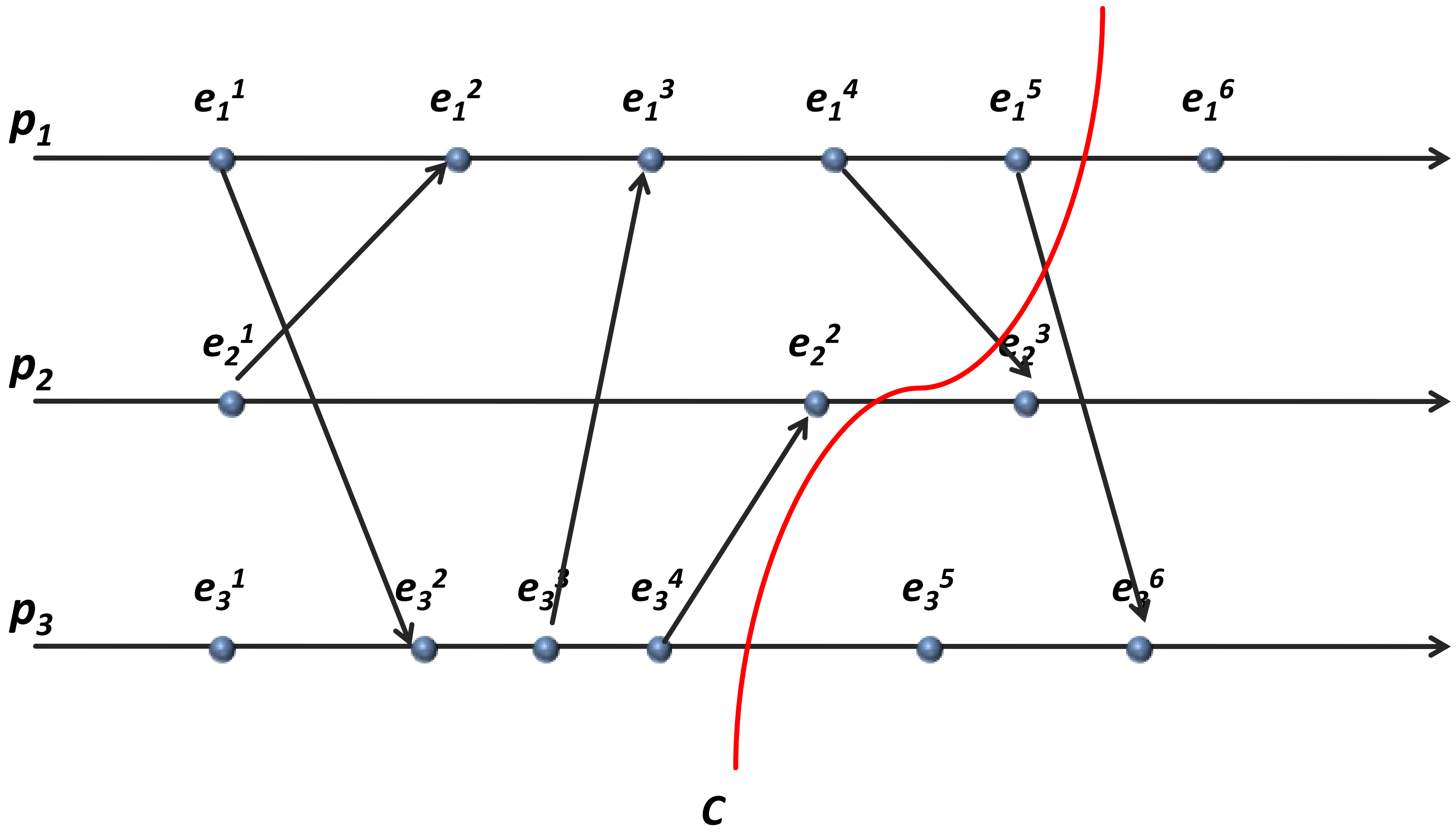

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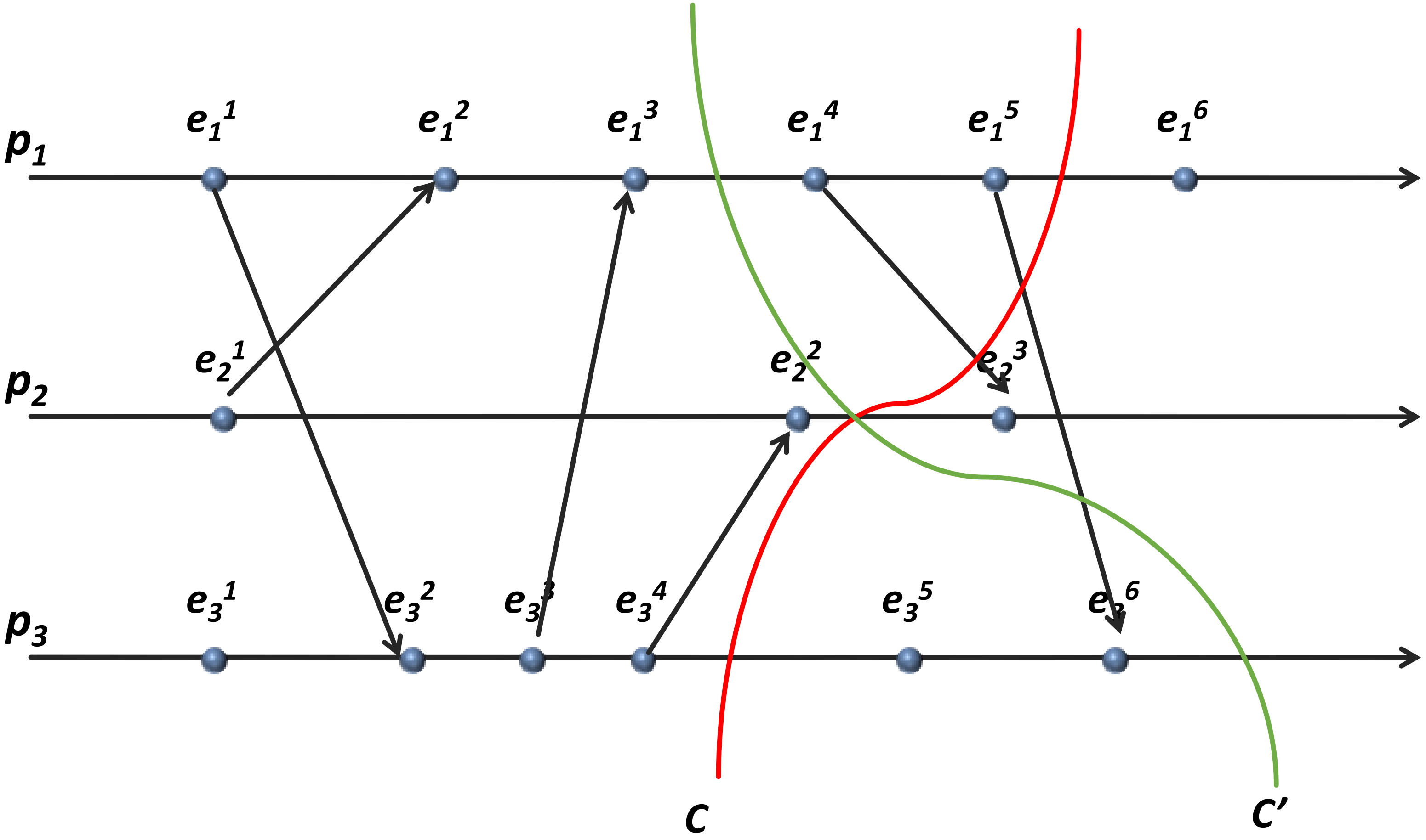
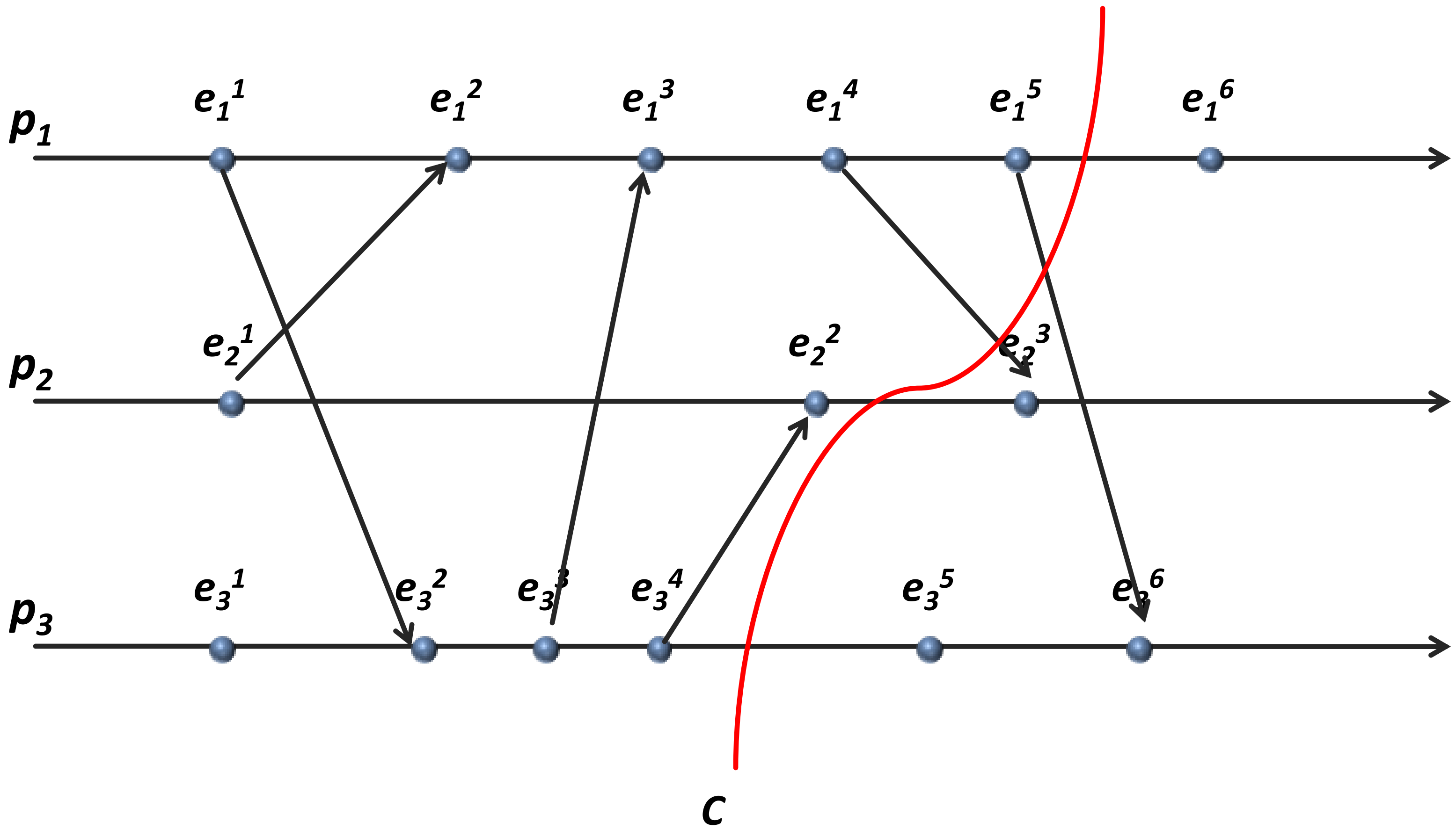


Consistent vs. Inconsistent Cuts

- 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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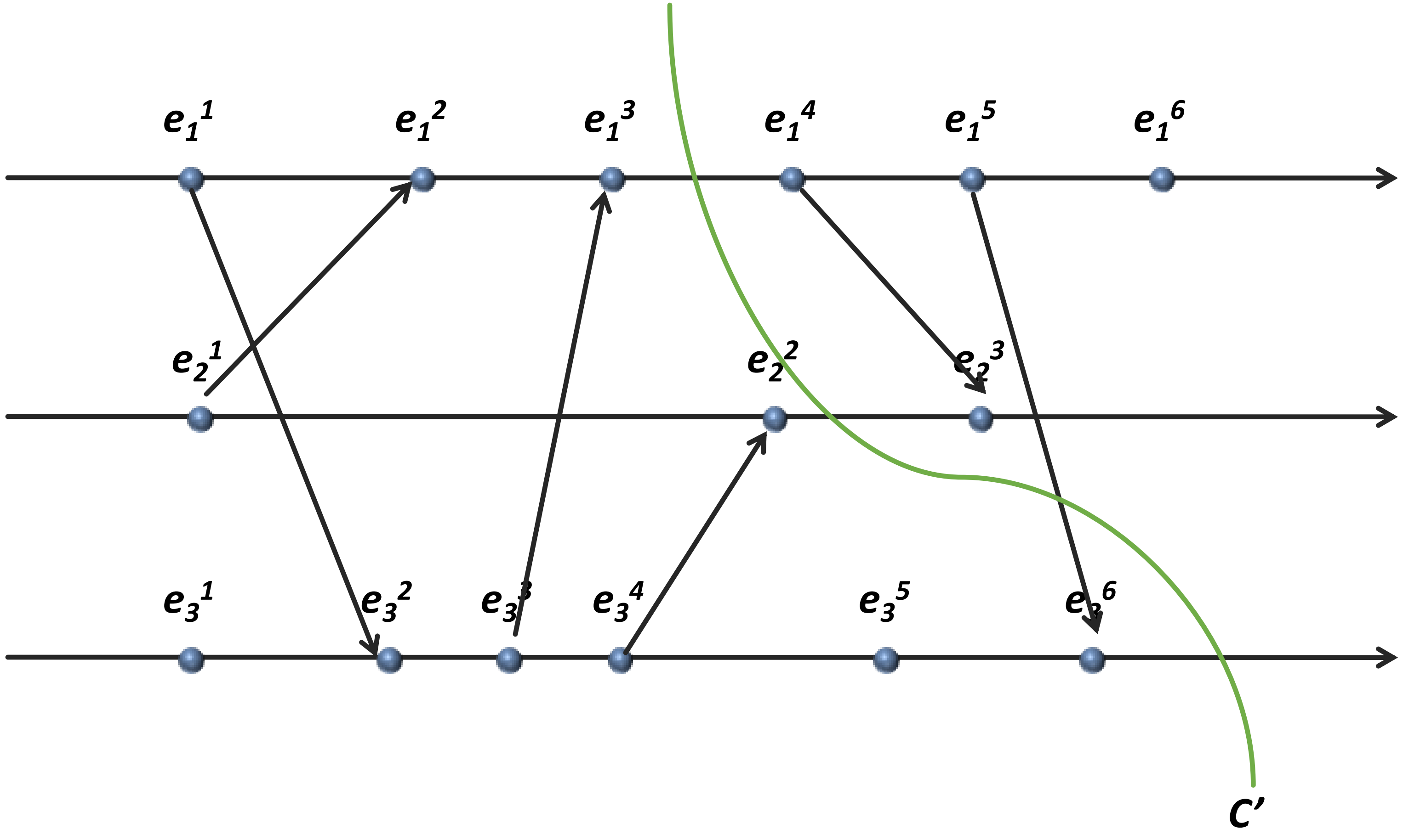

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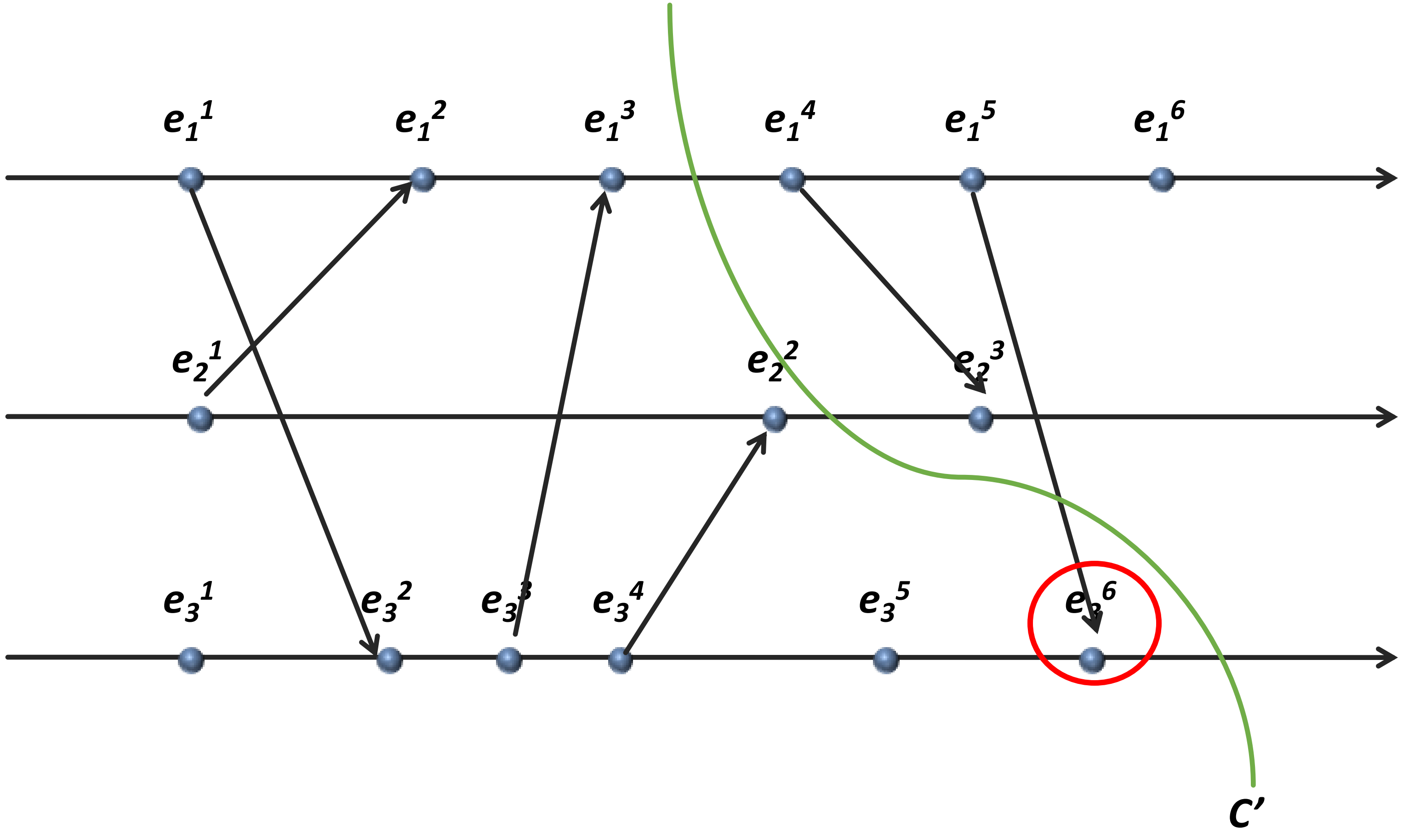

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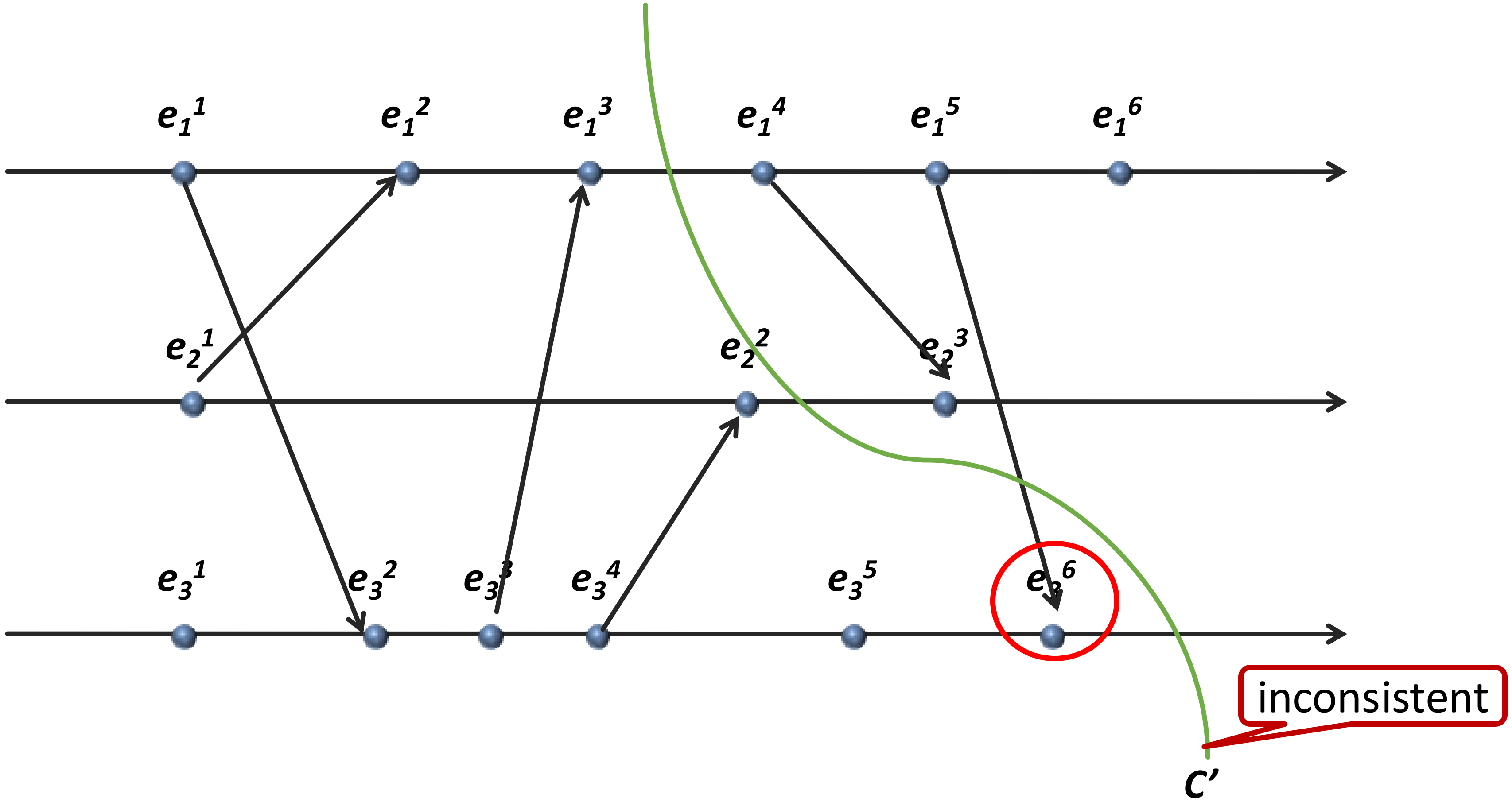

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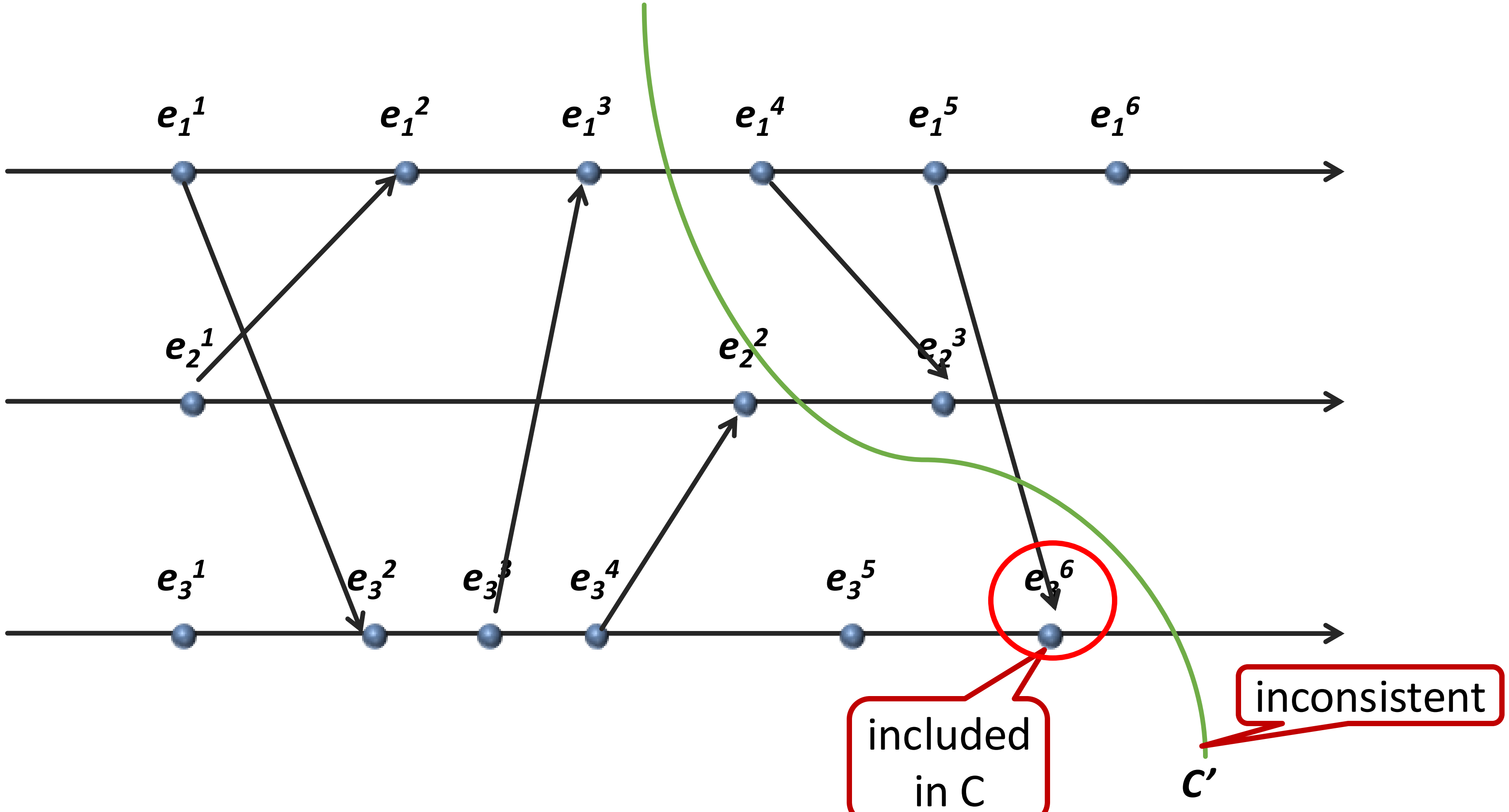

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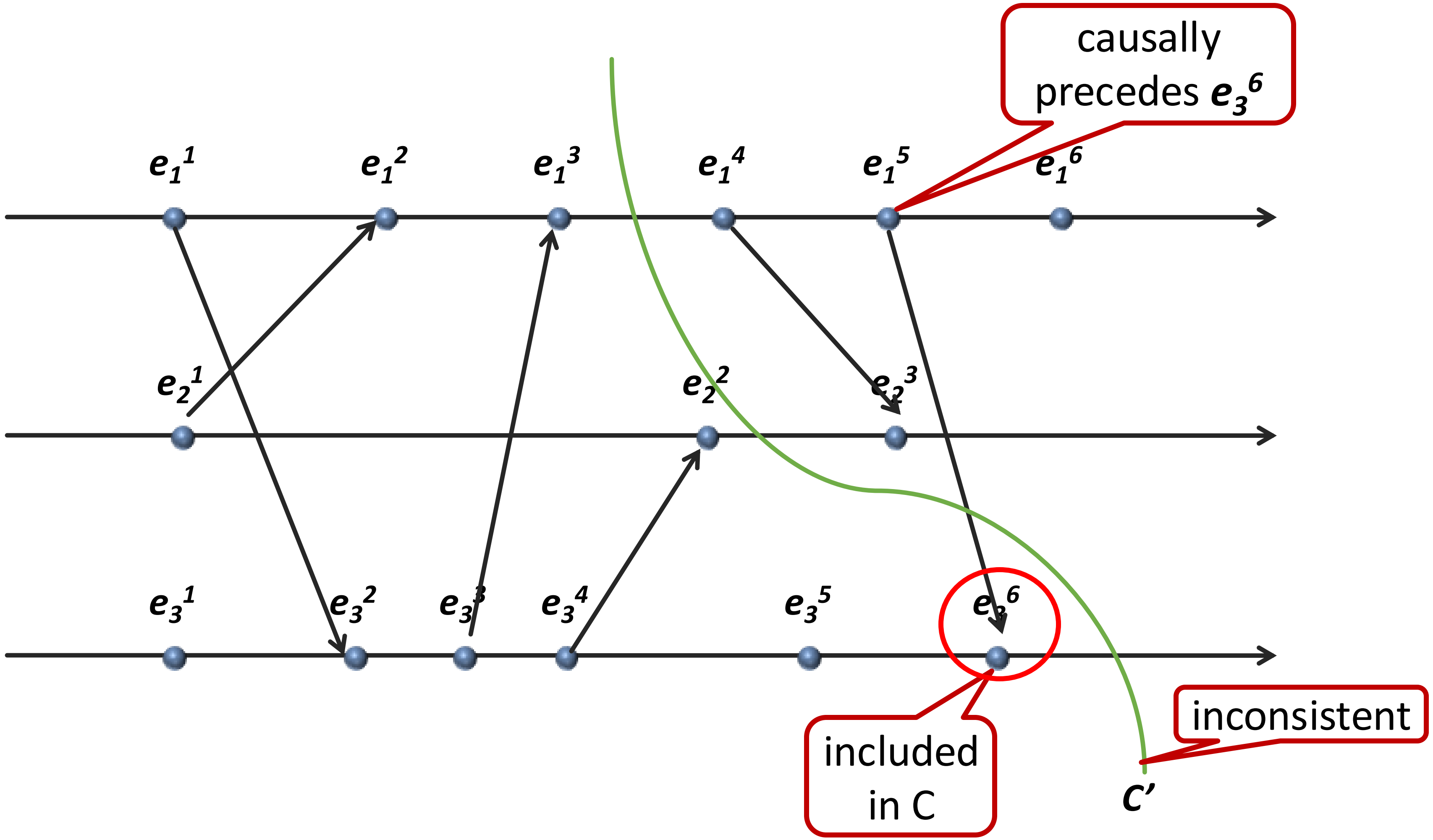

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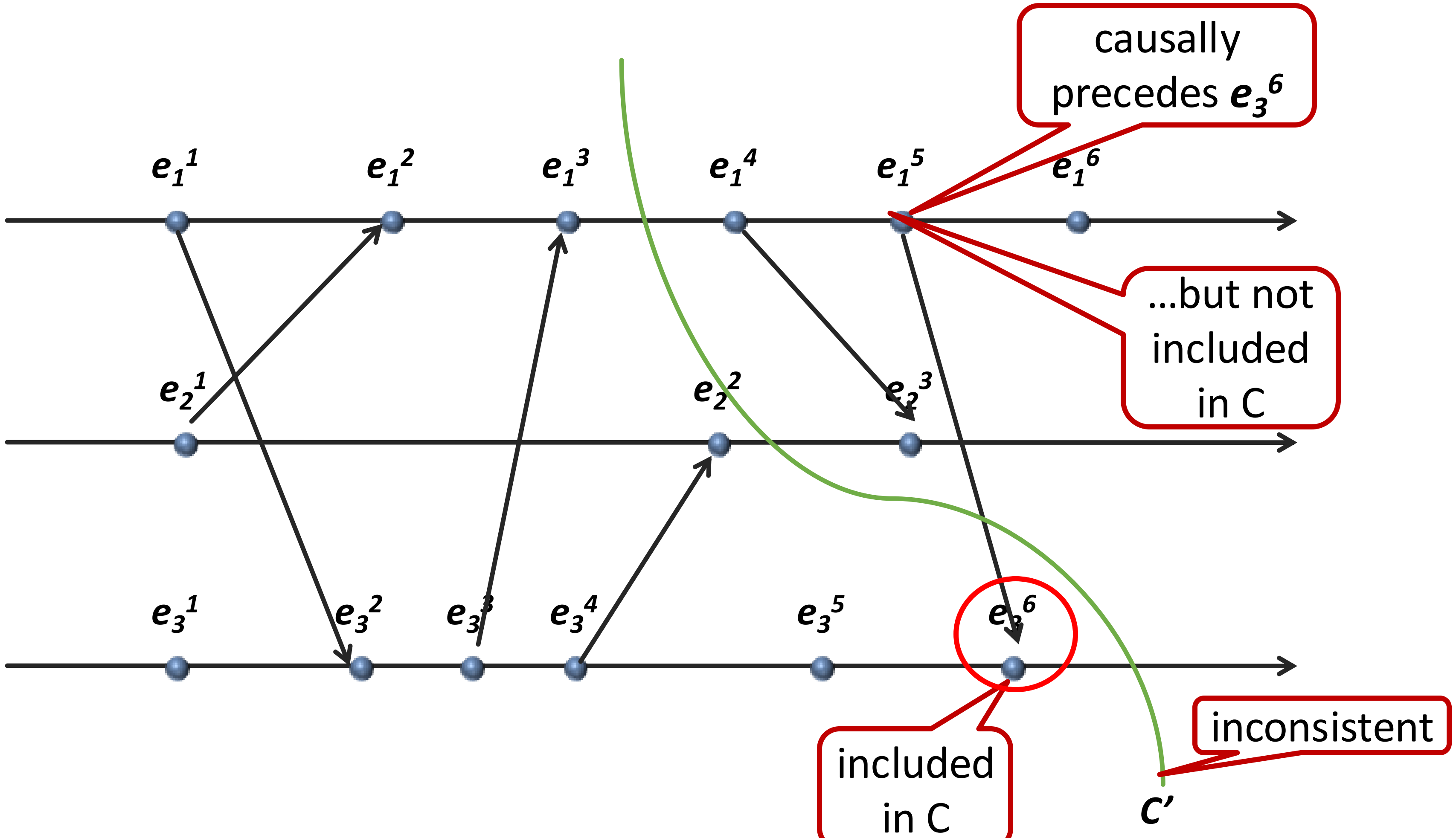

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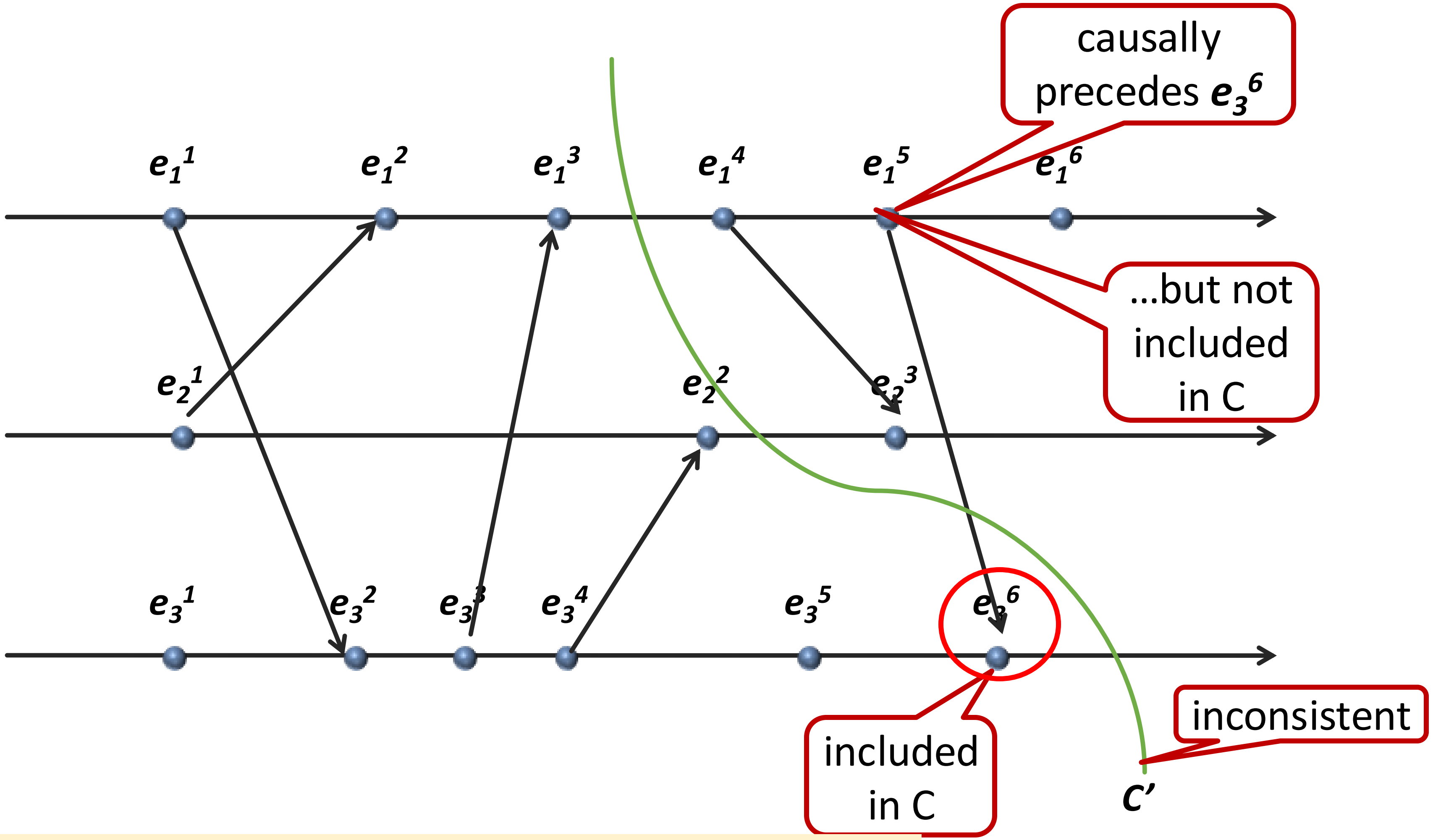
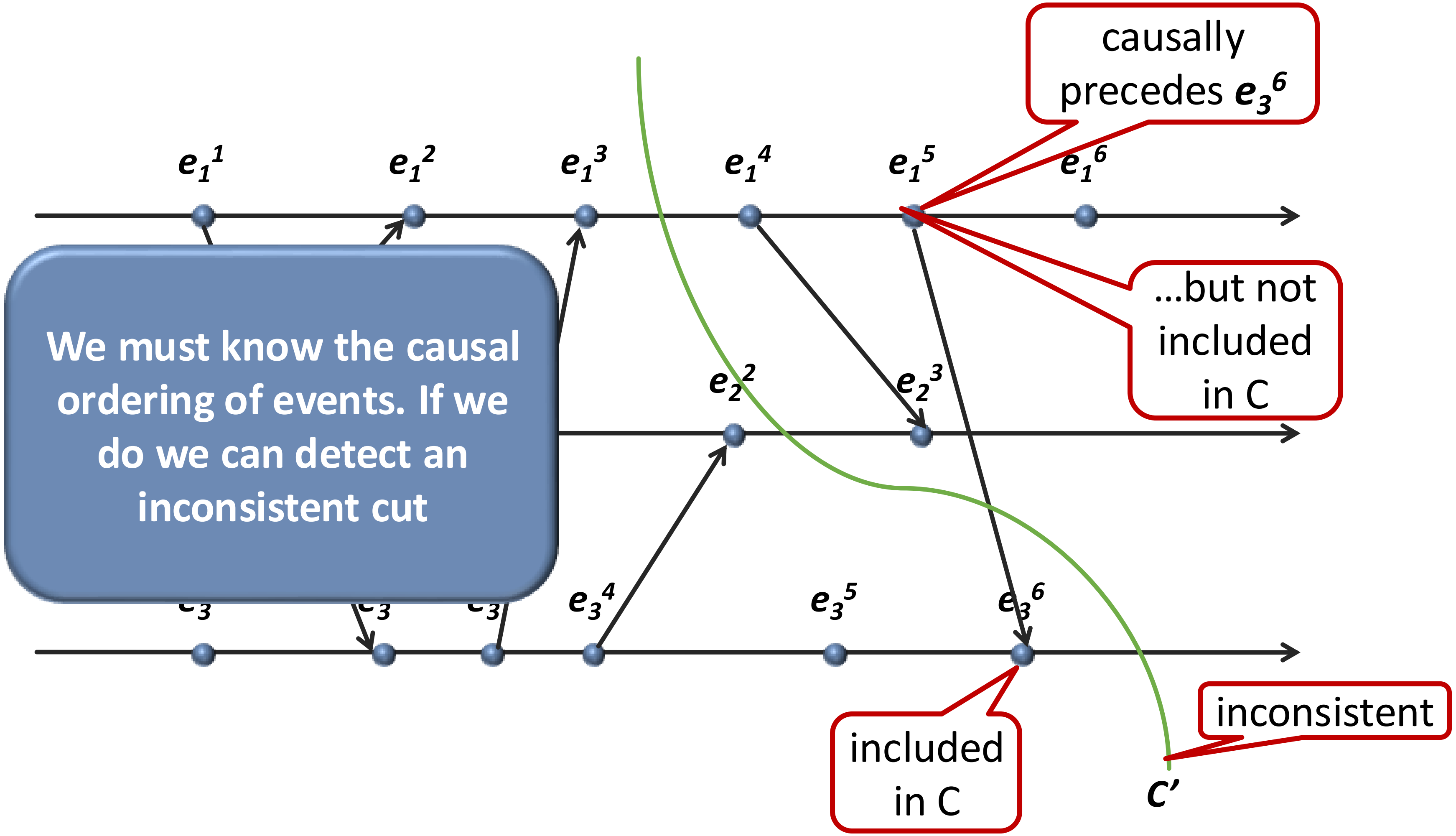


A consistent cut corresponds to a consistent global state

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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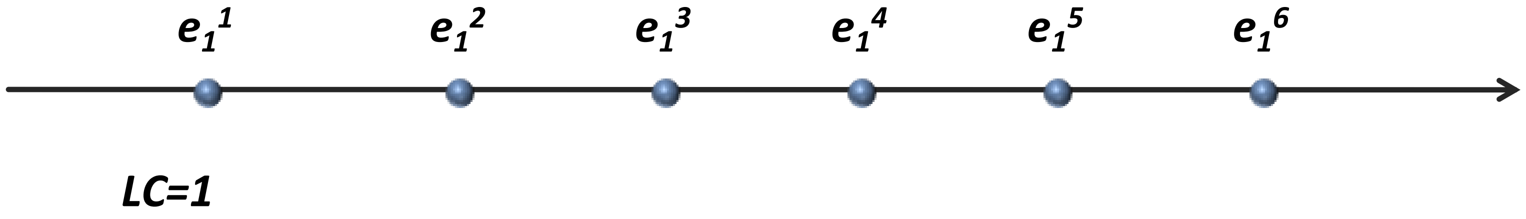

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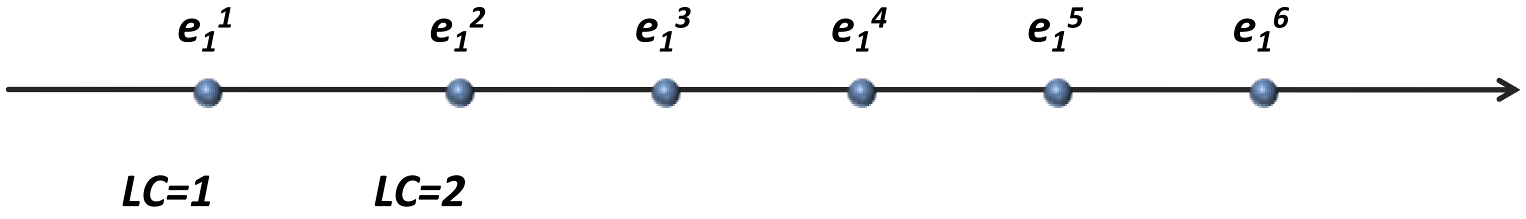

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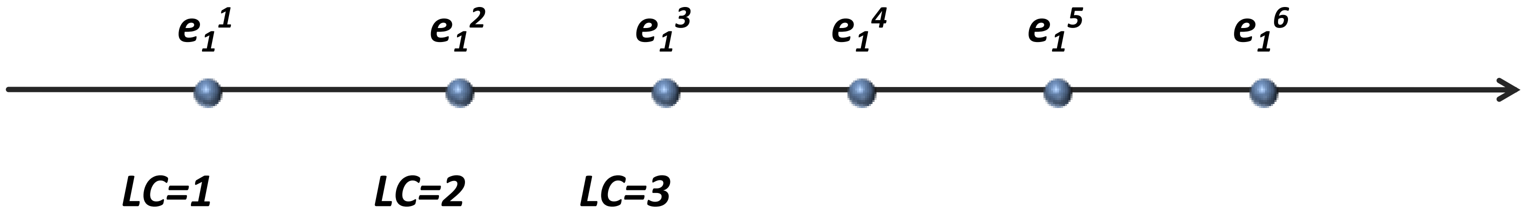

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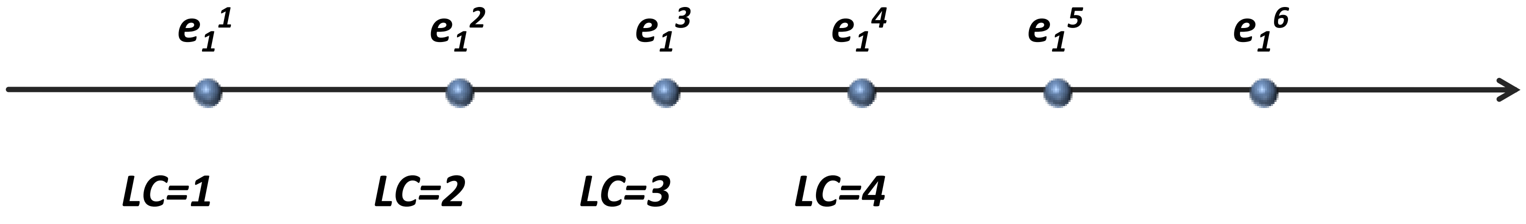

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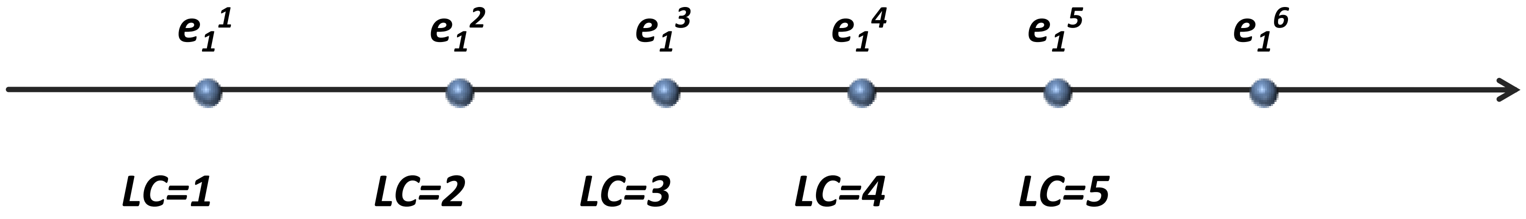

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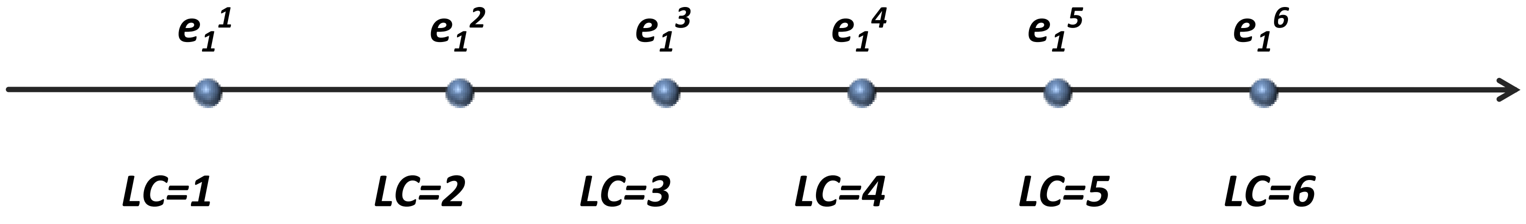

Logical Clocks (cont.)

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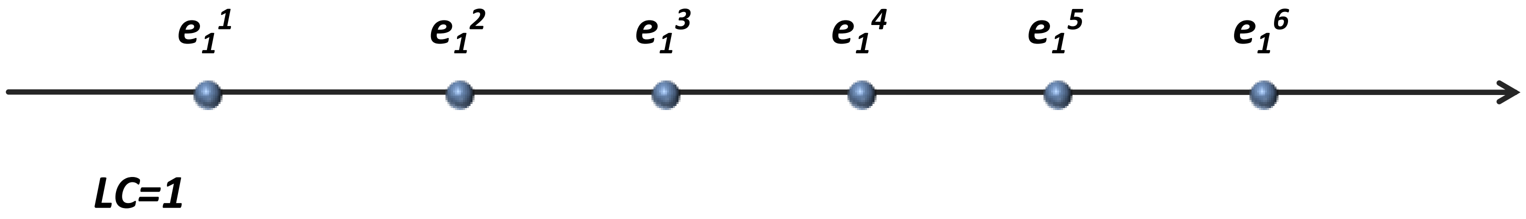

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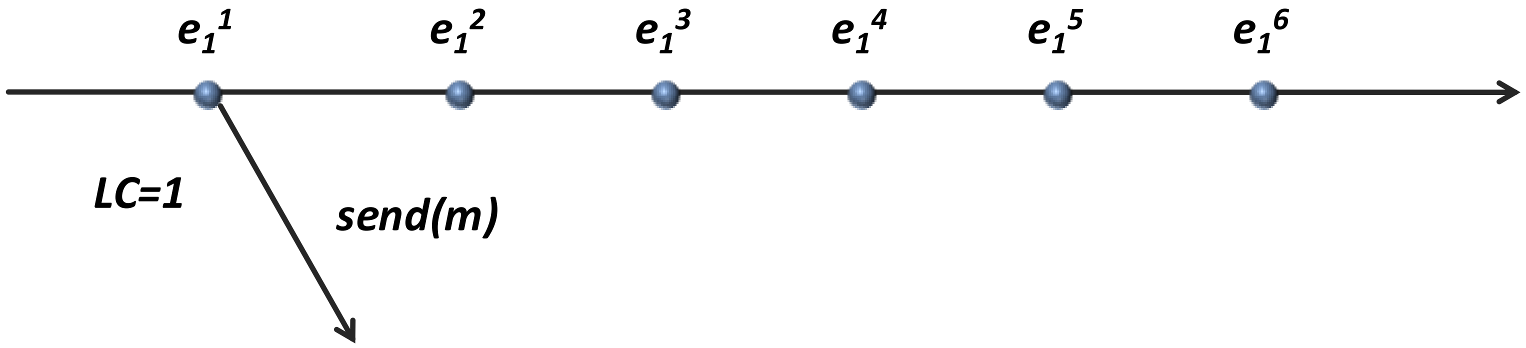

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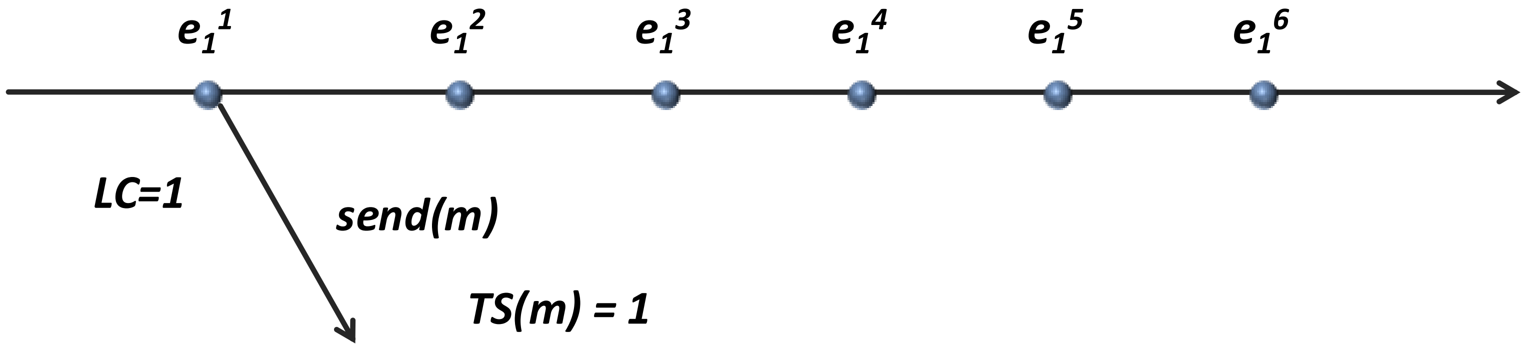

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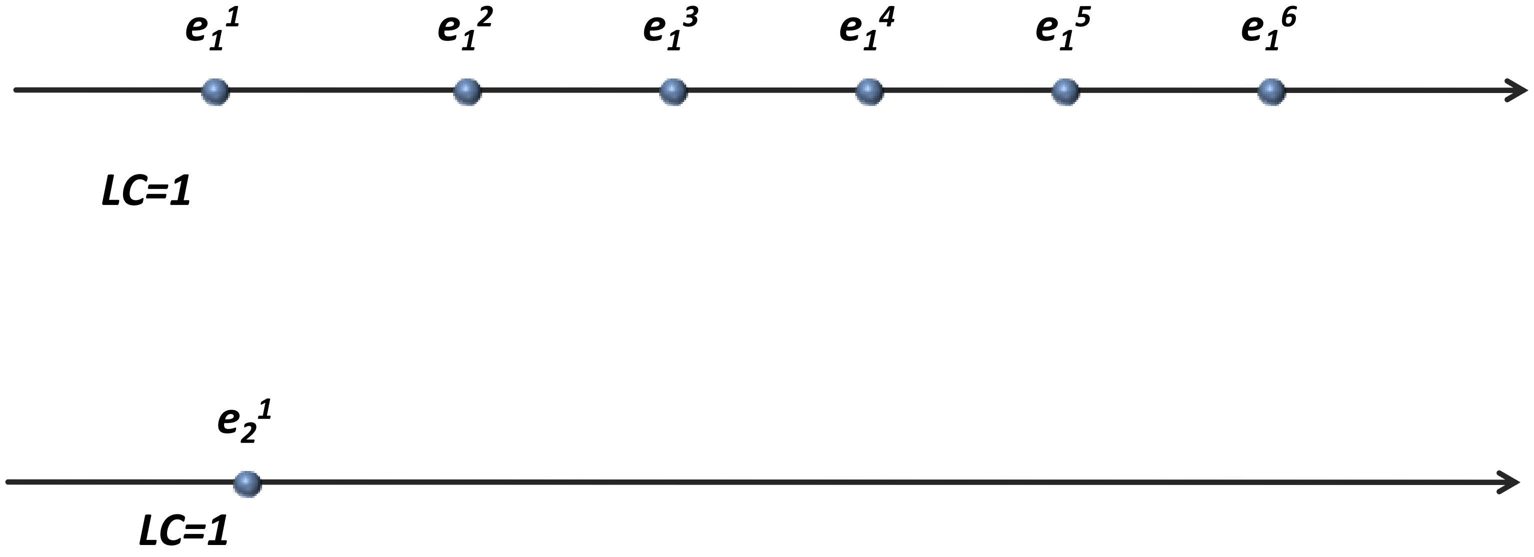

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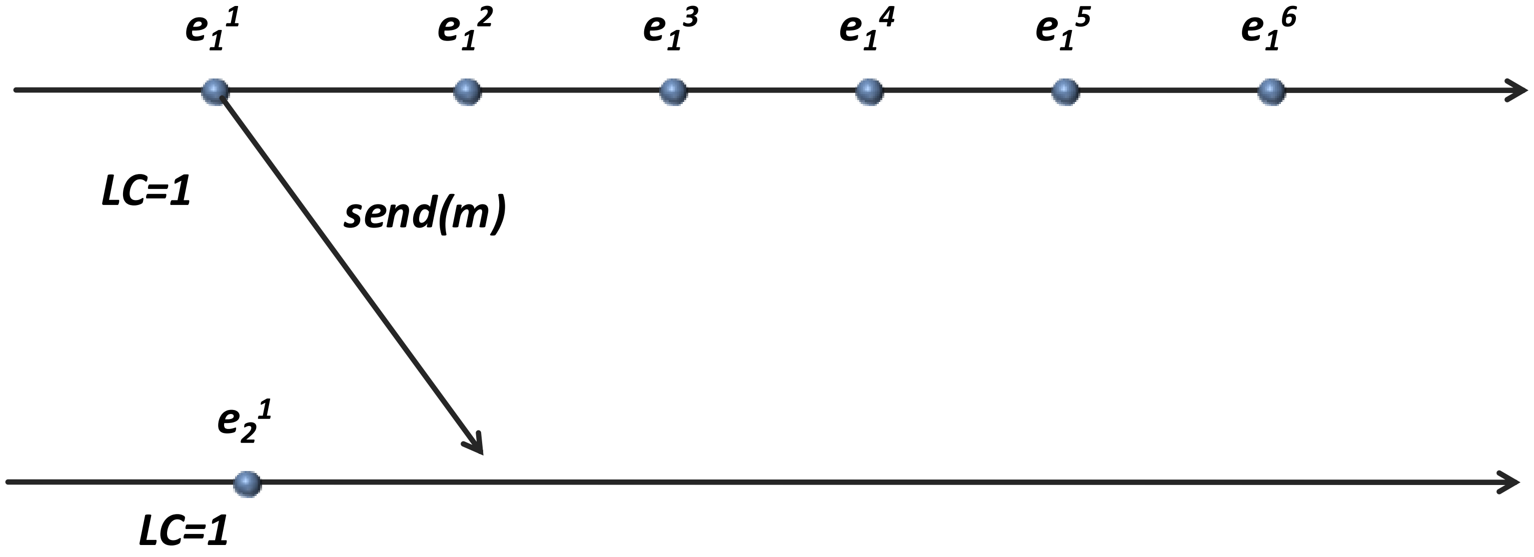

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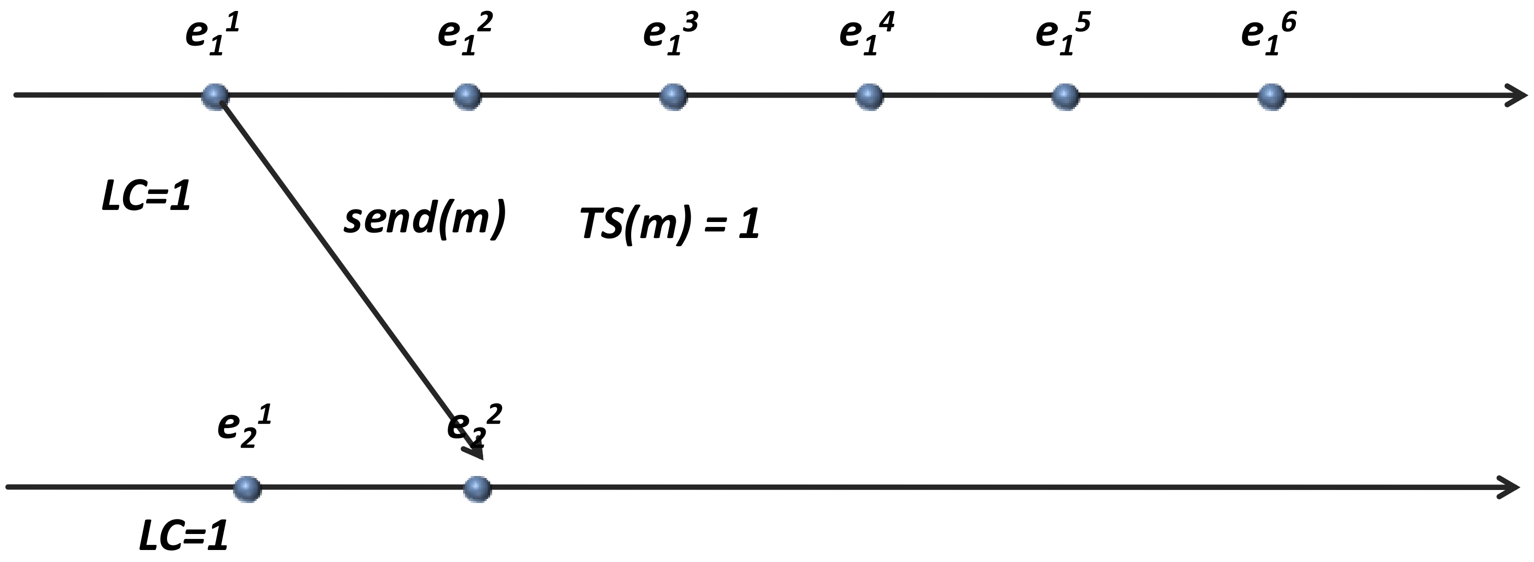

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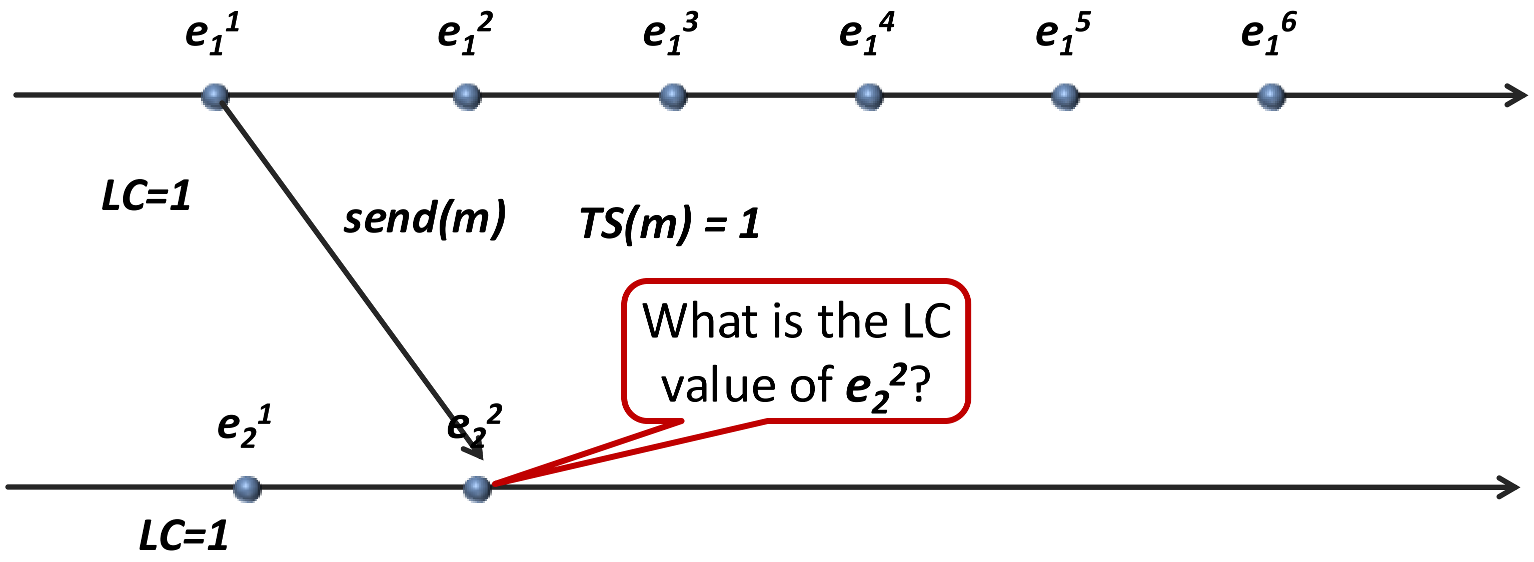

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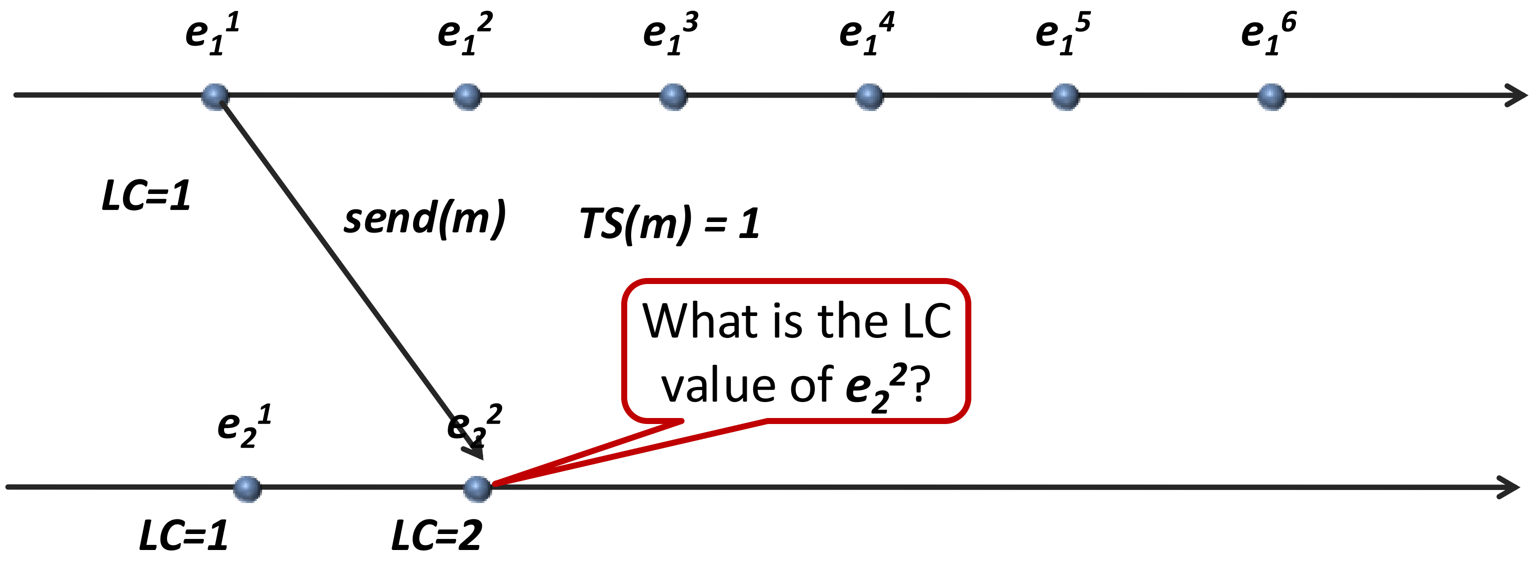

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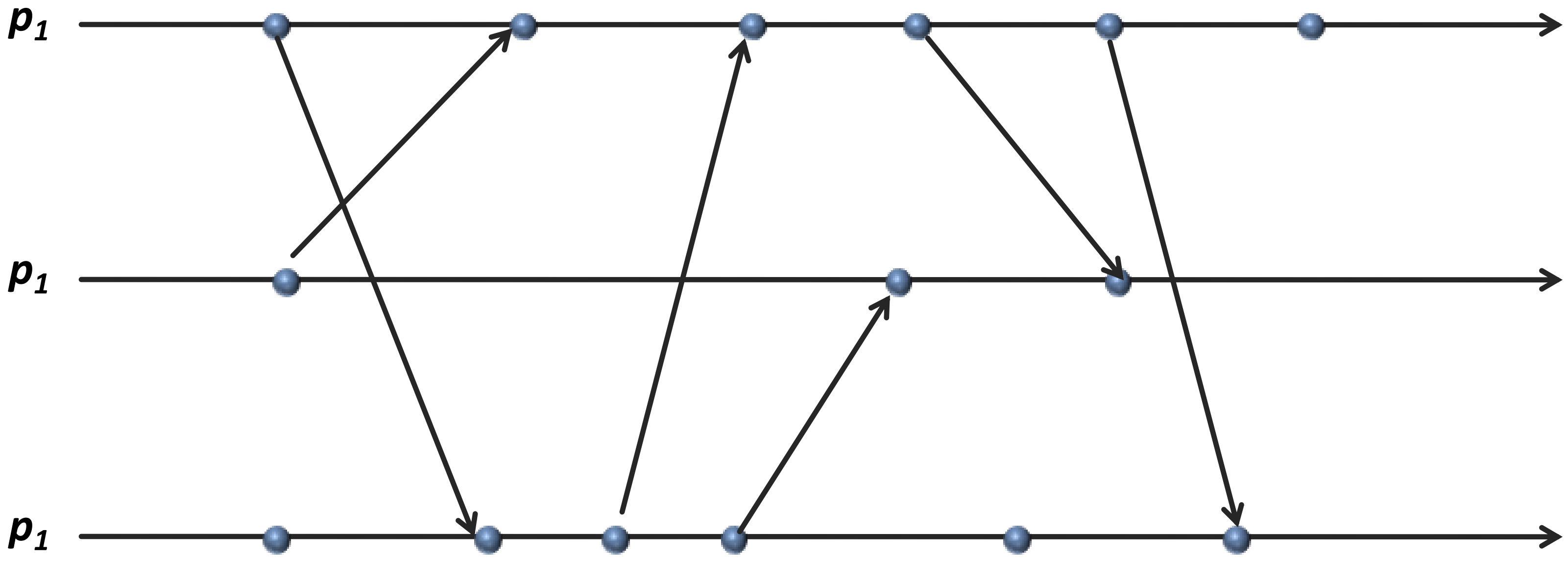

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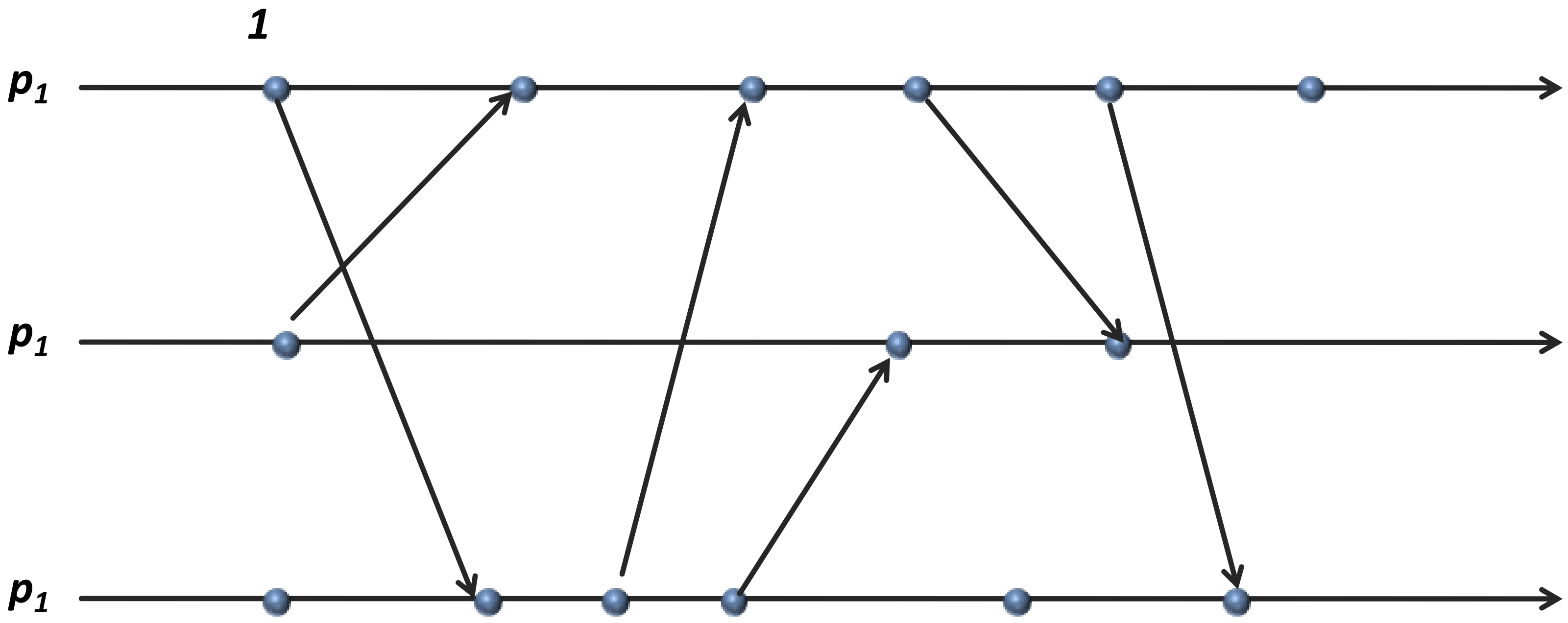

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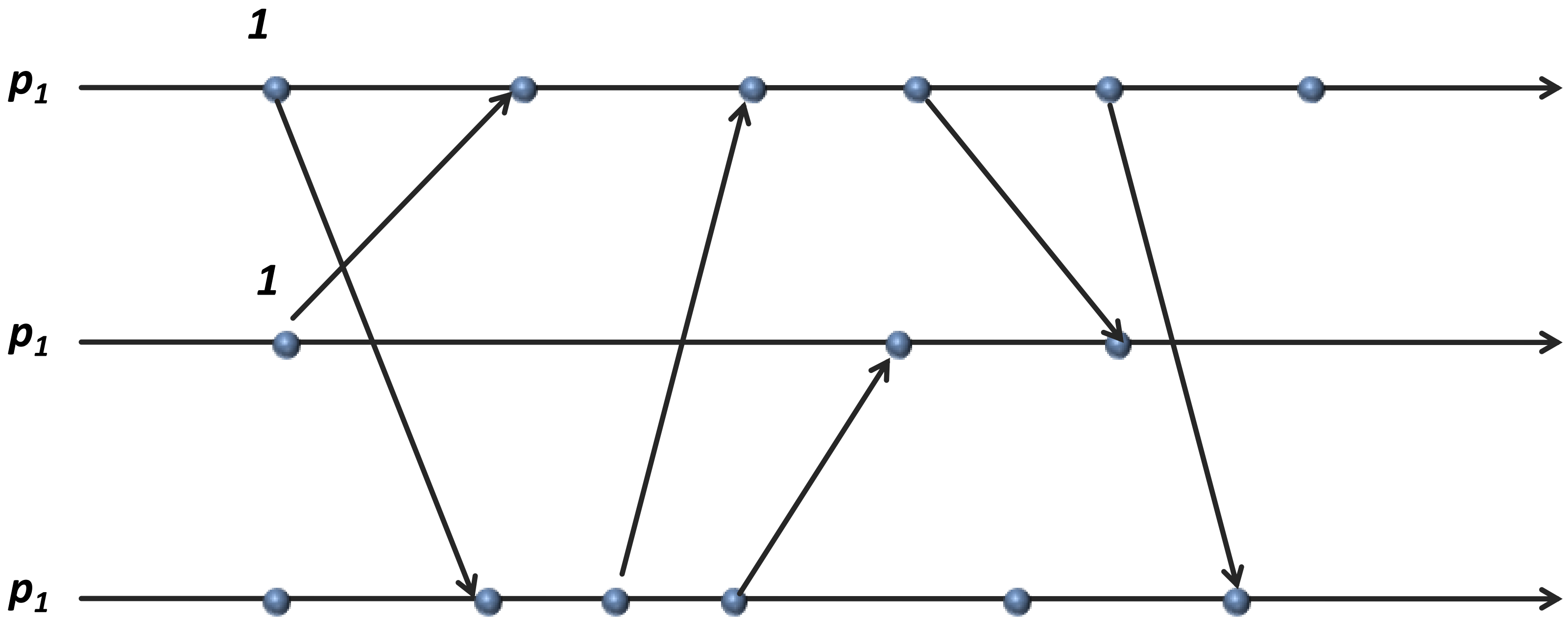

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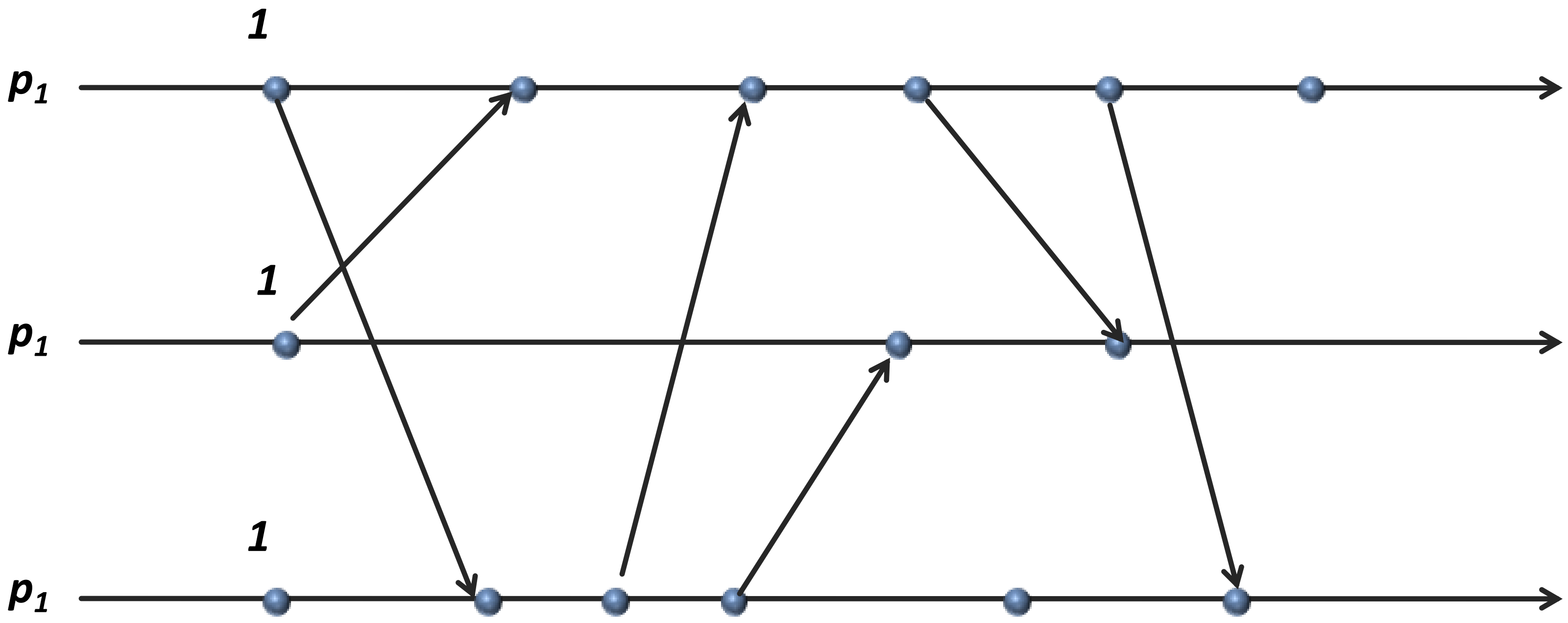

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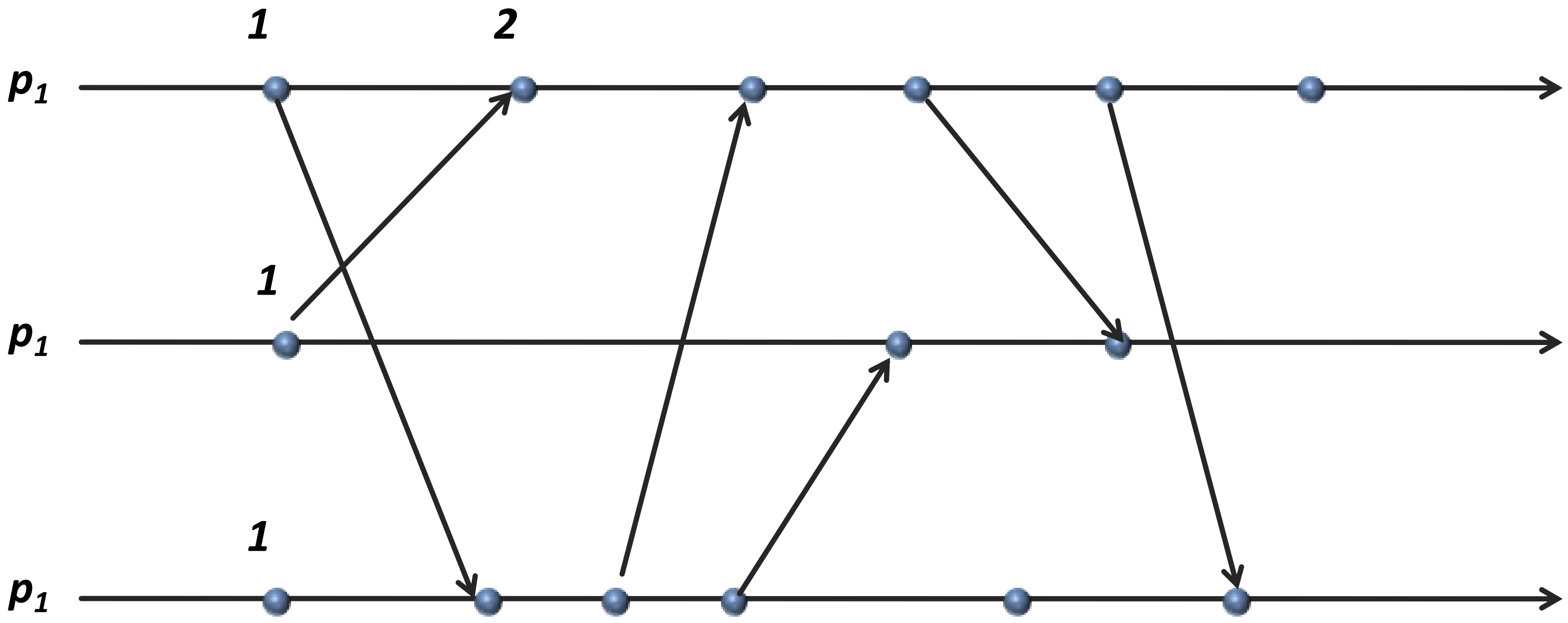

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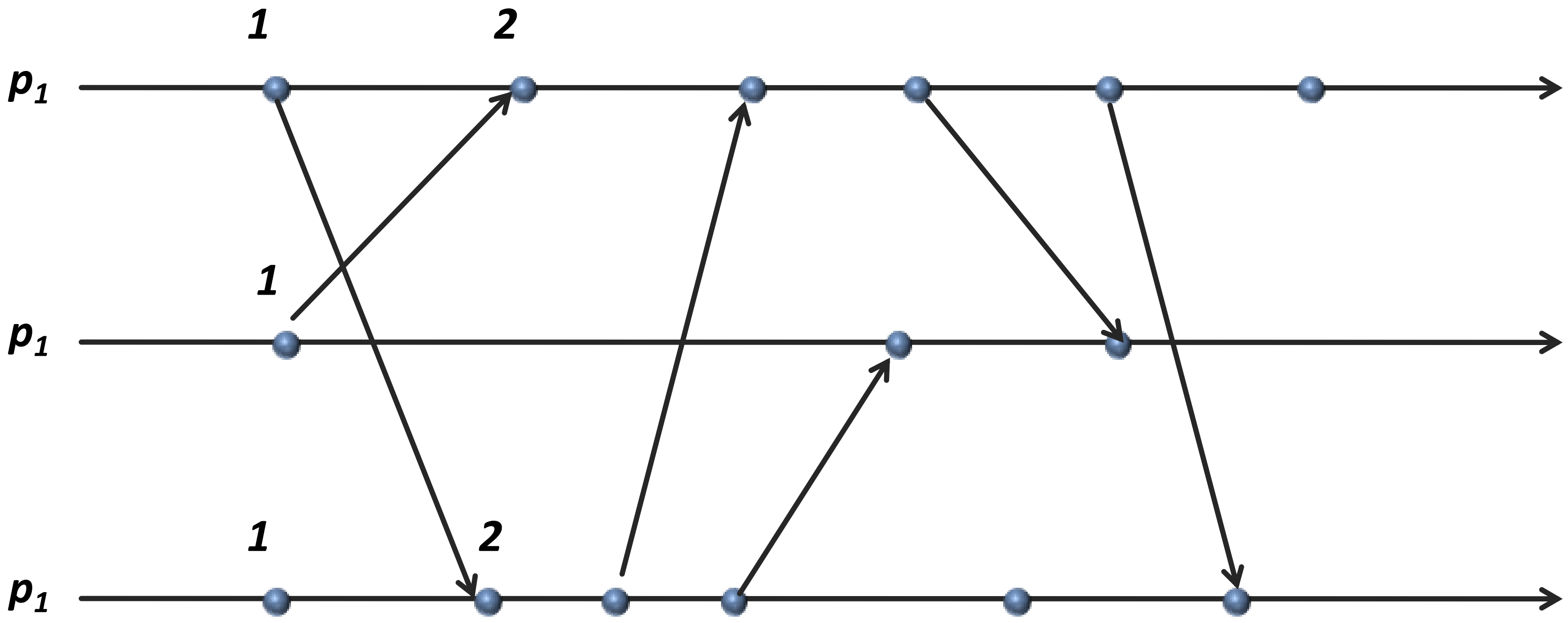

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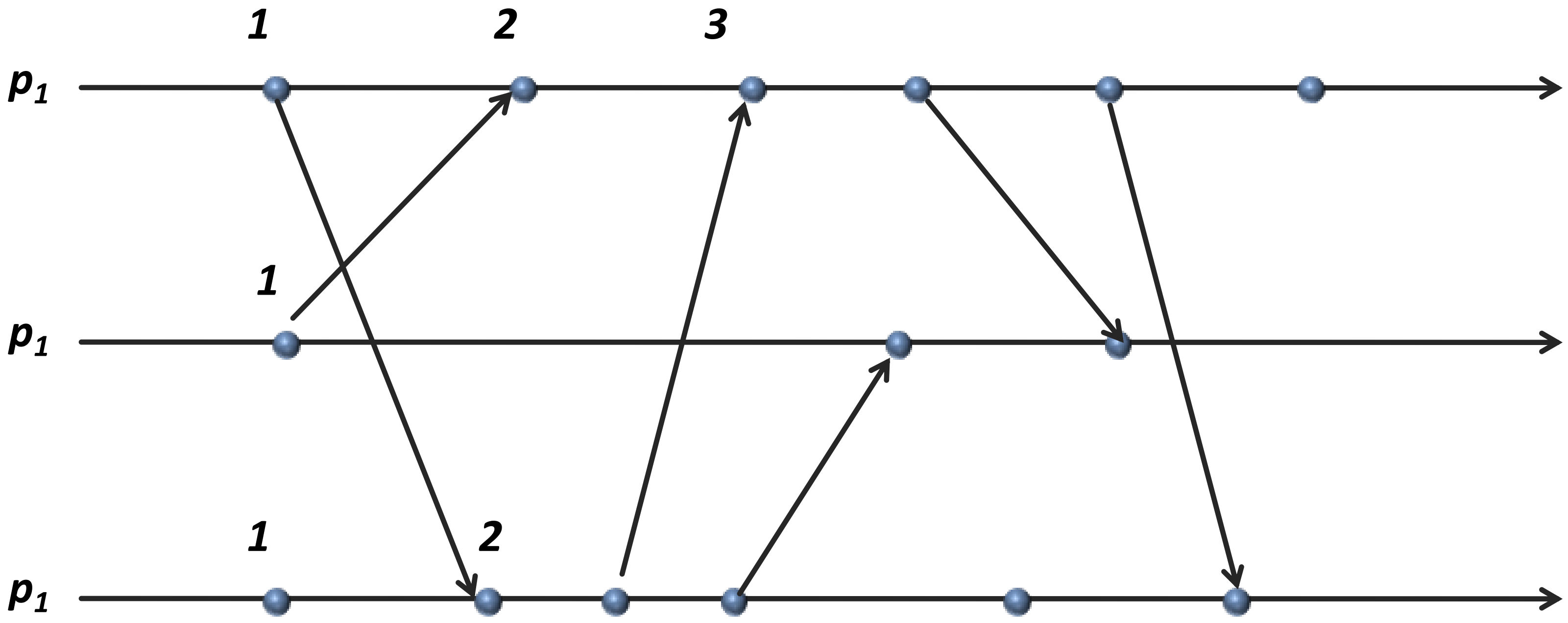

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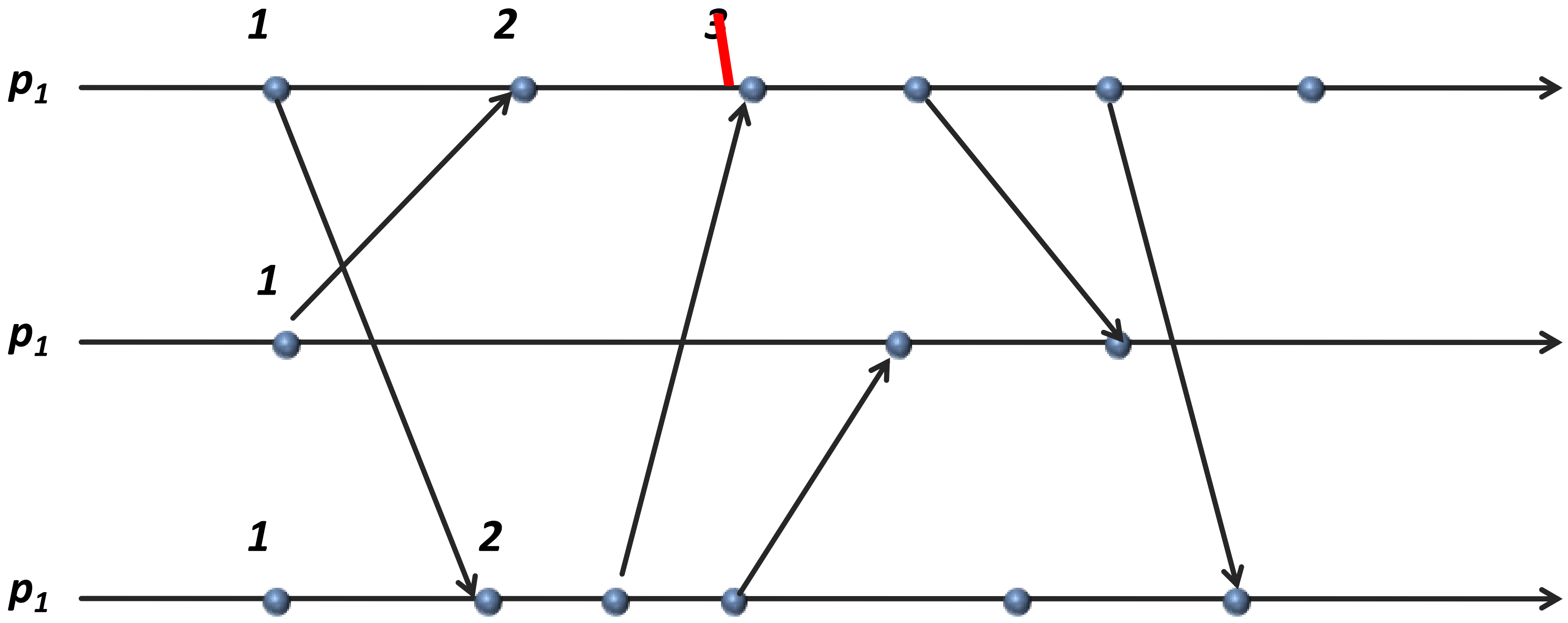

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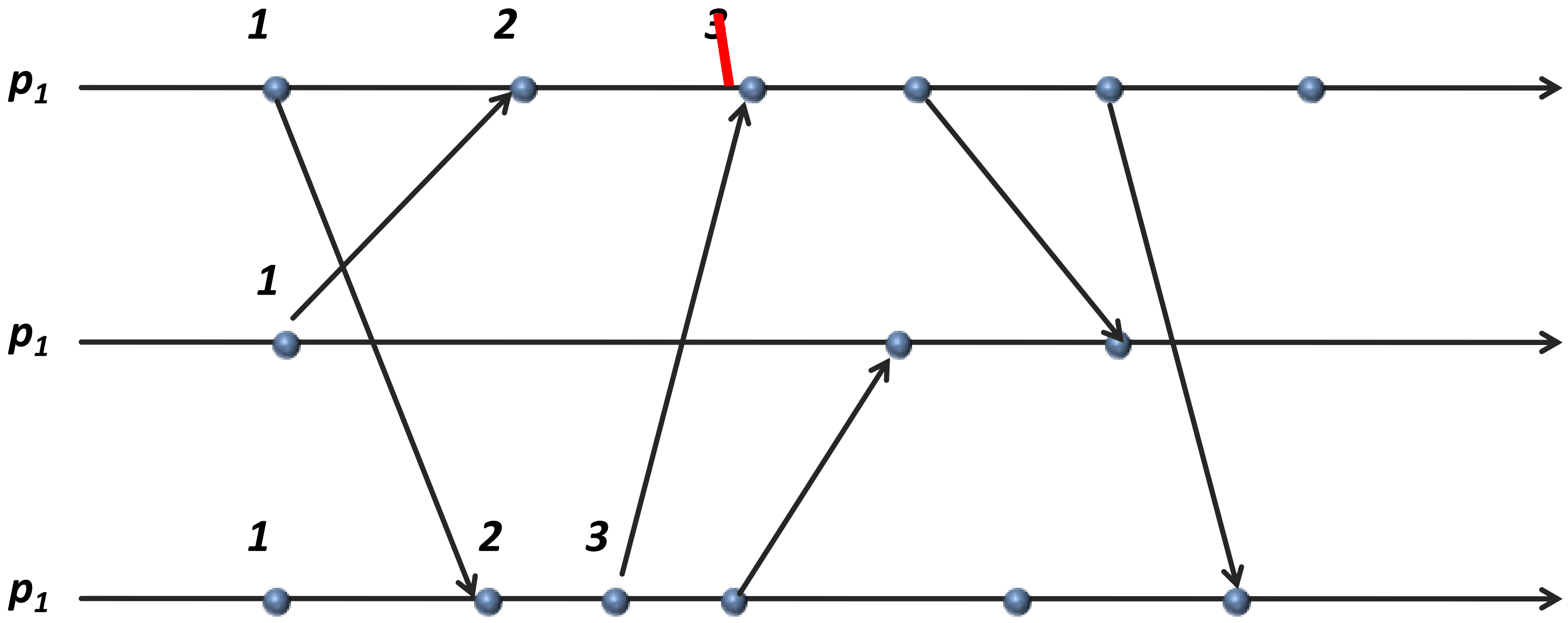

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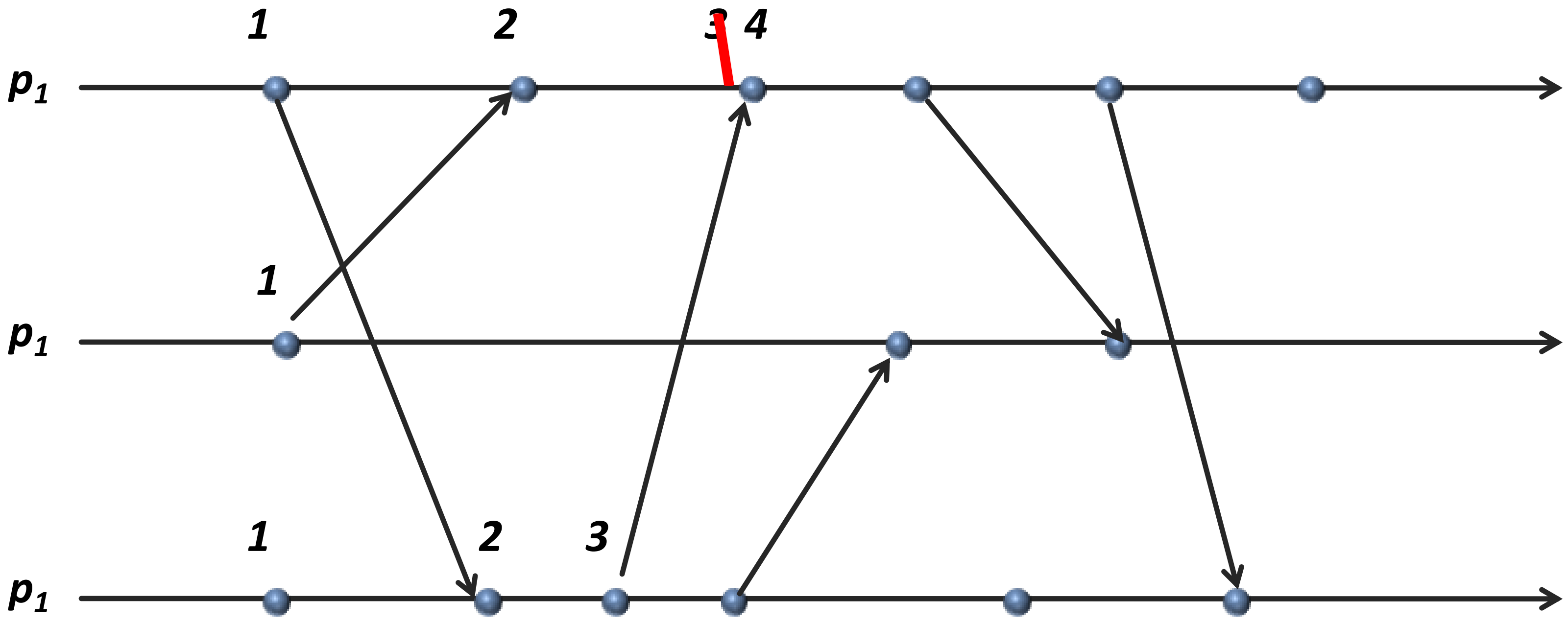

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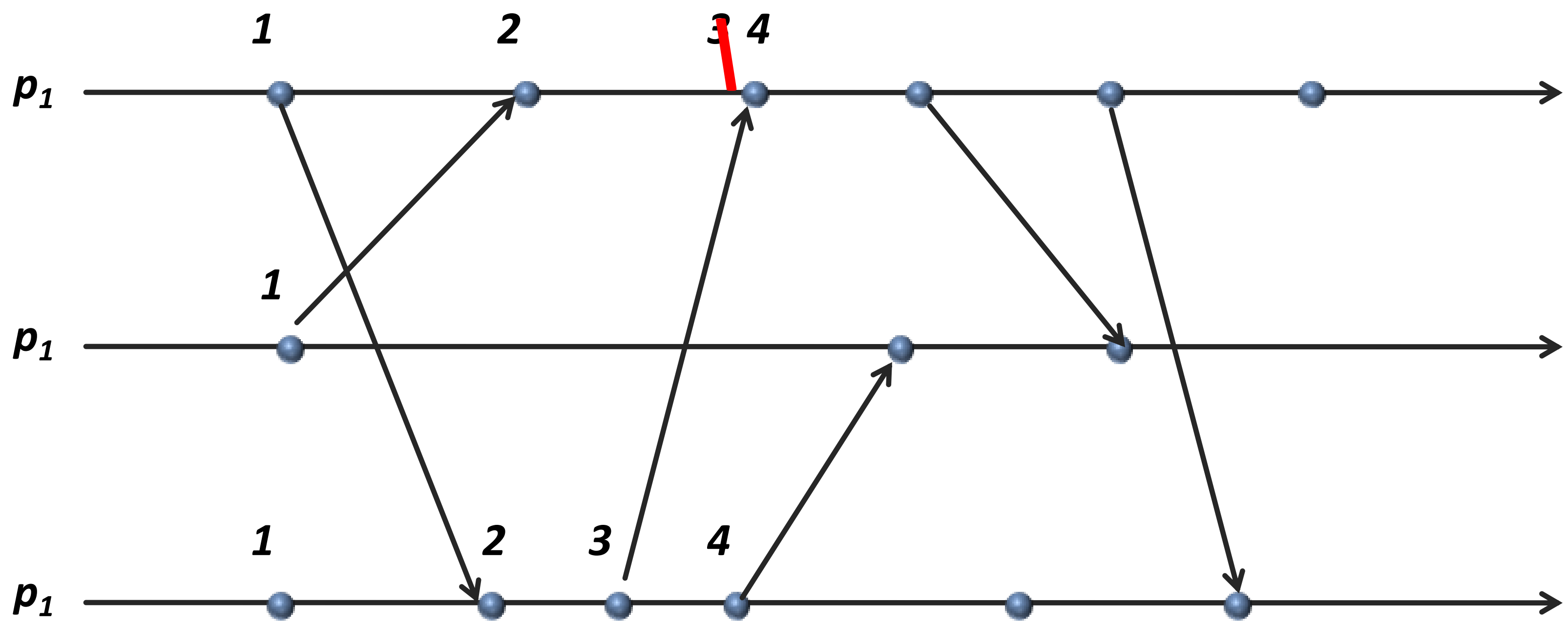

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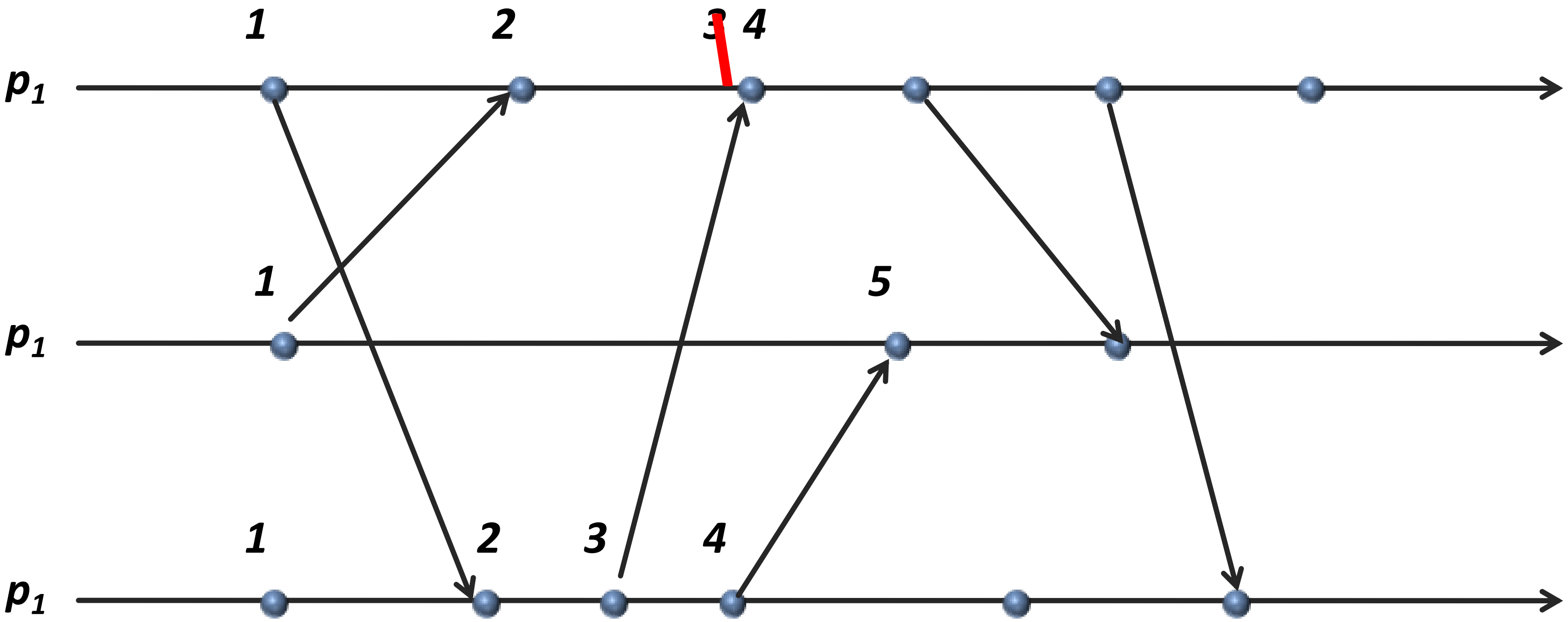

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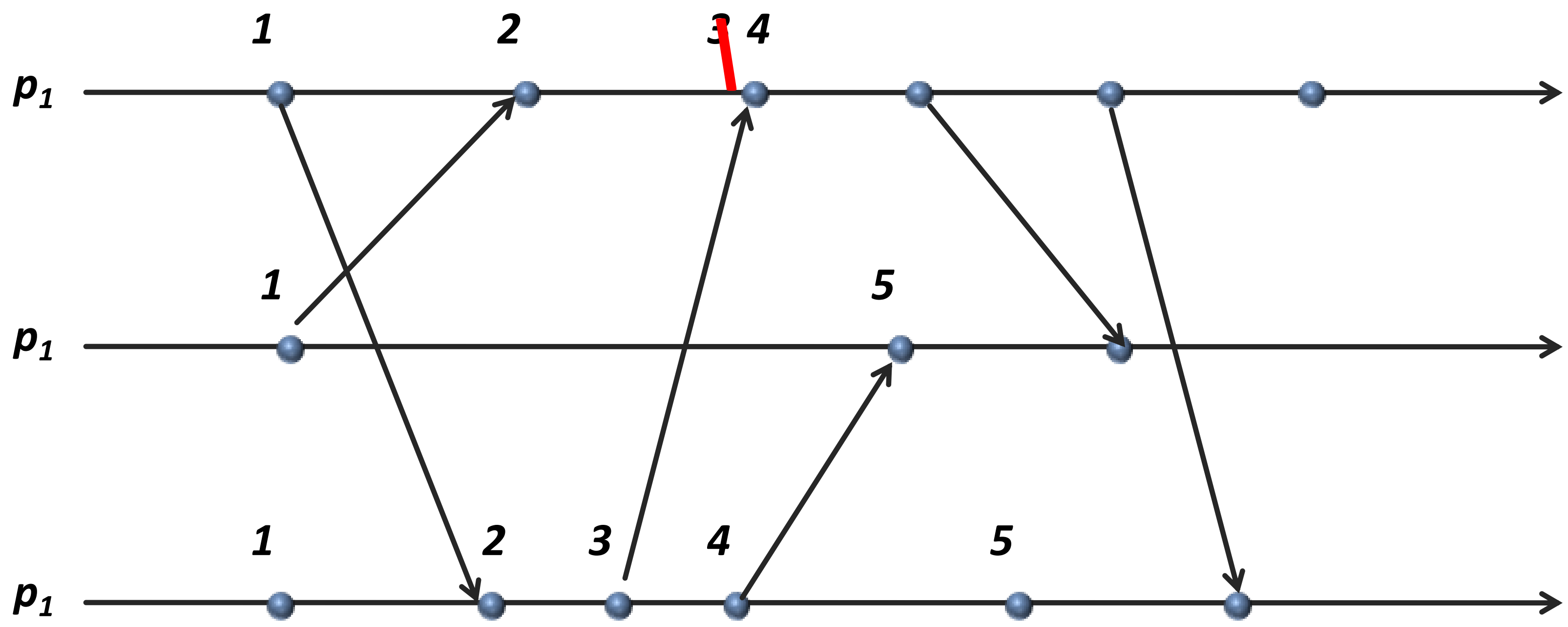

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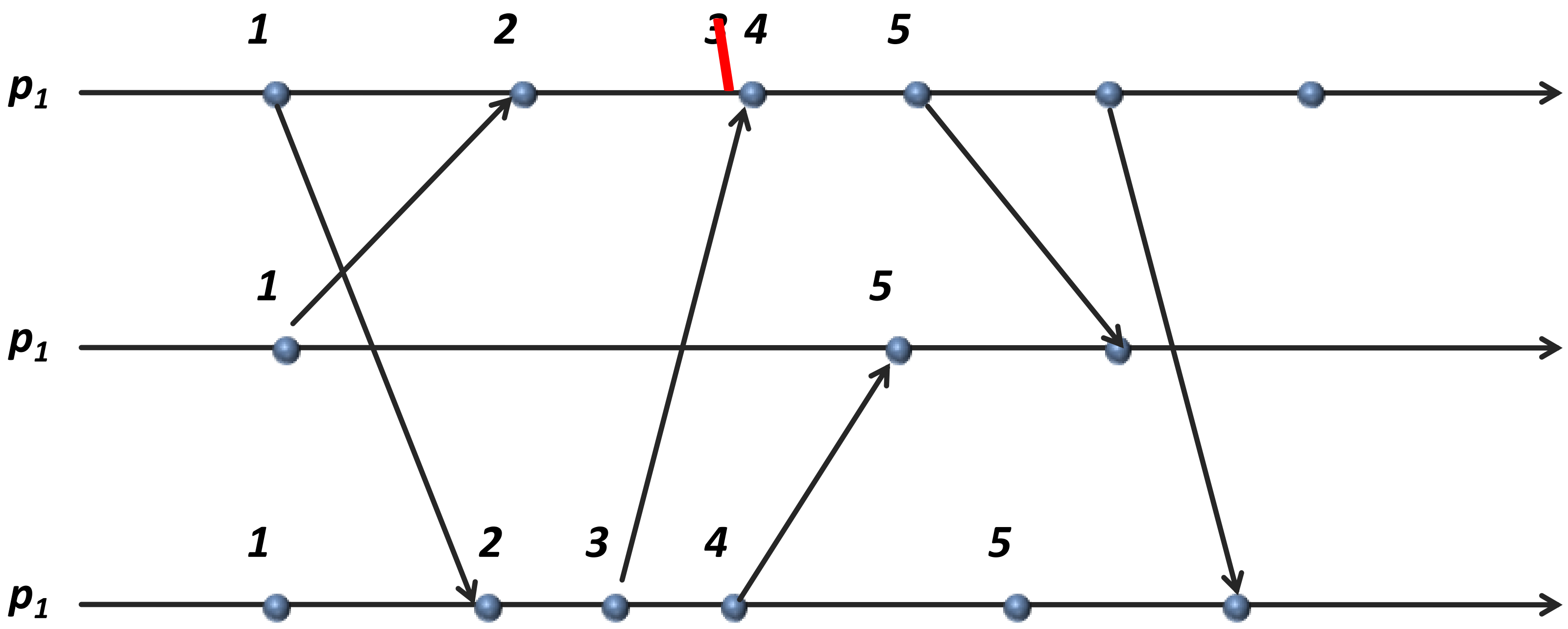

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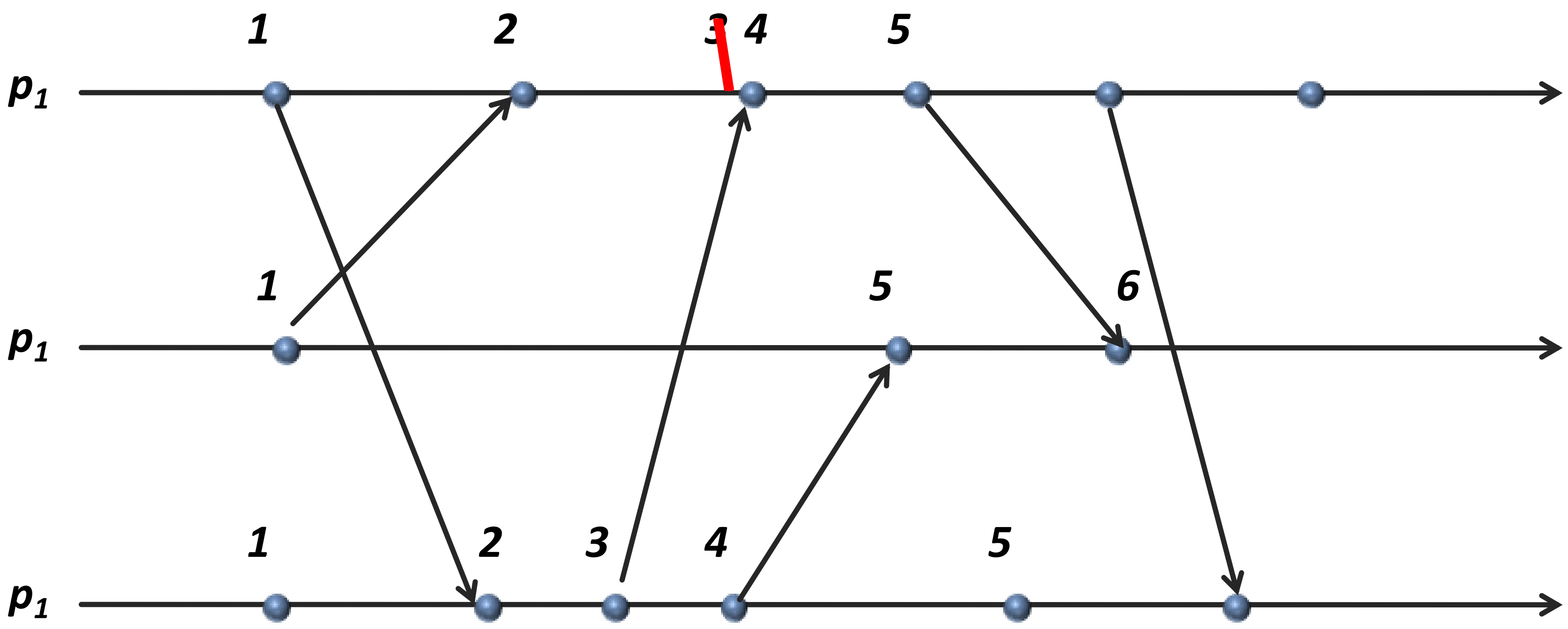

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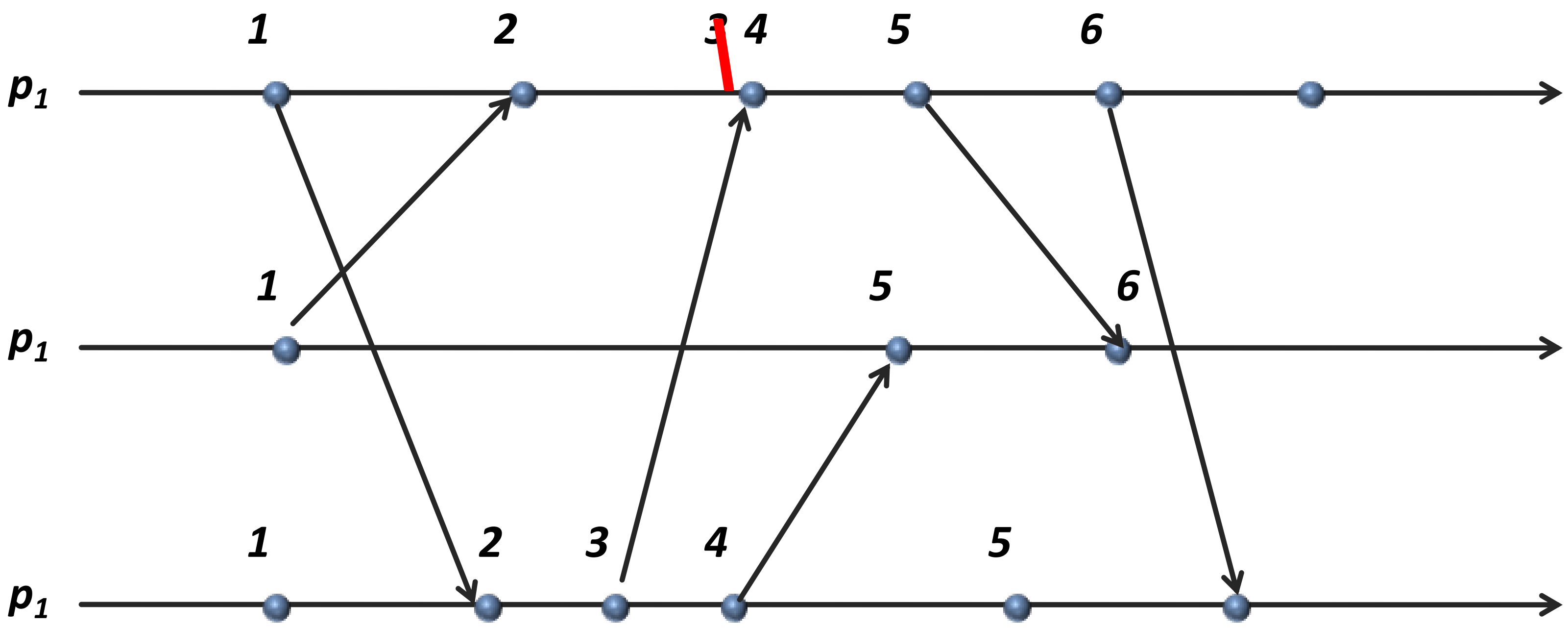

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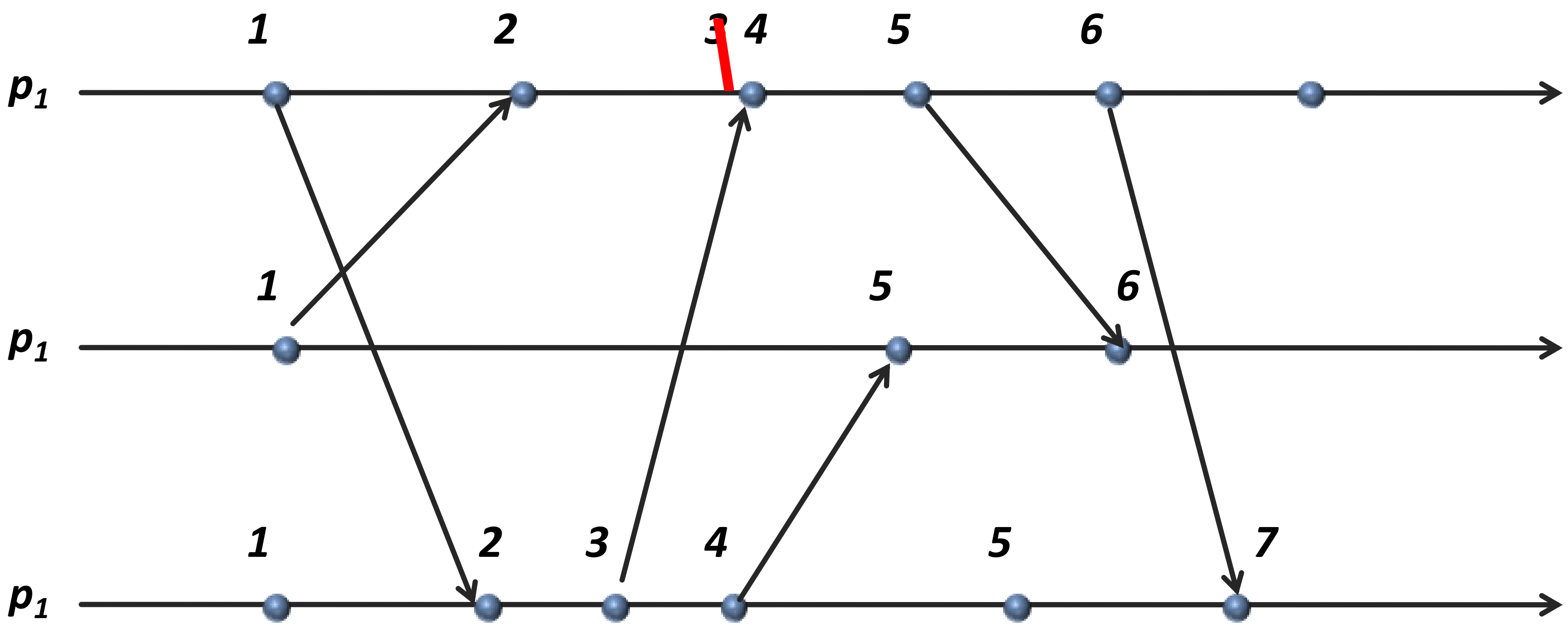

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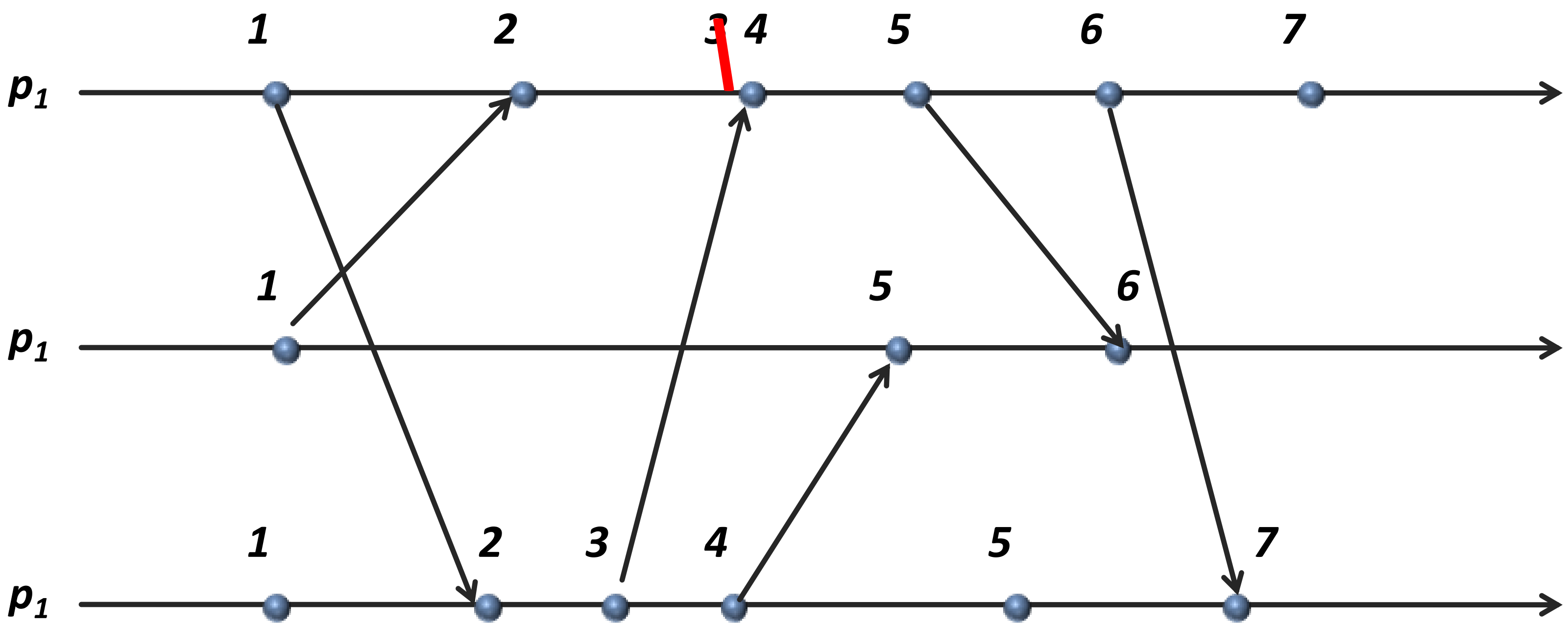

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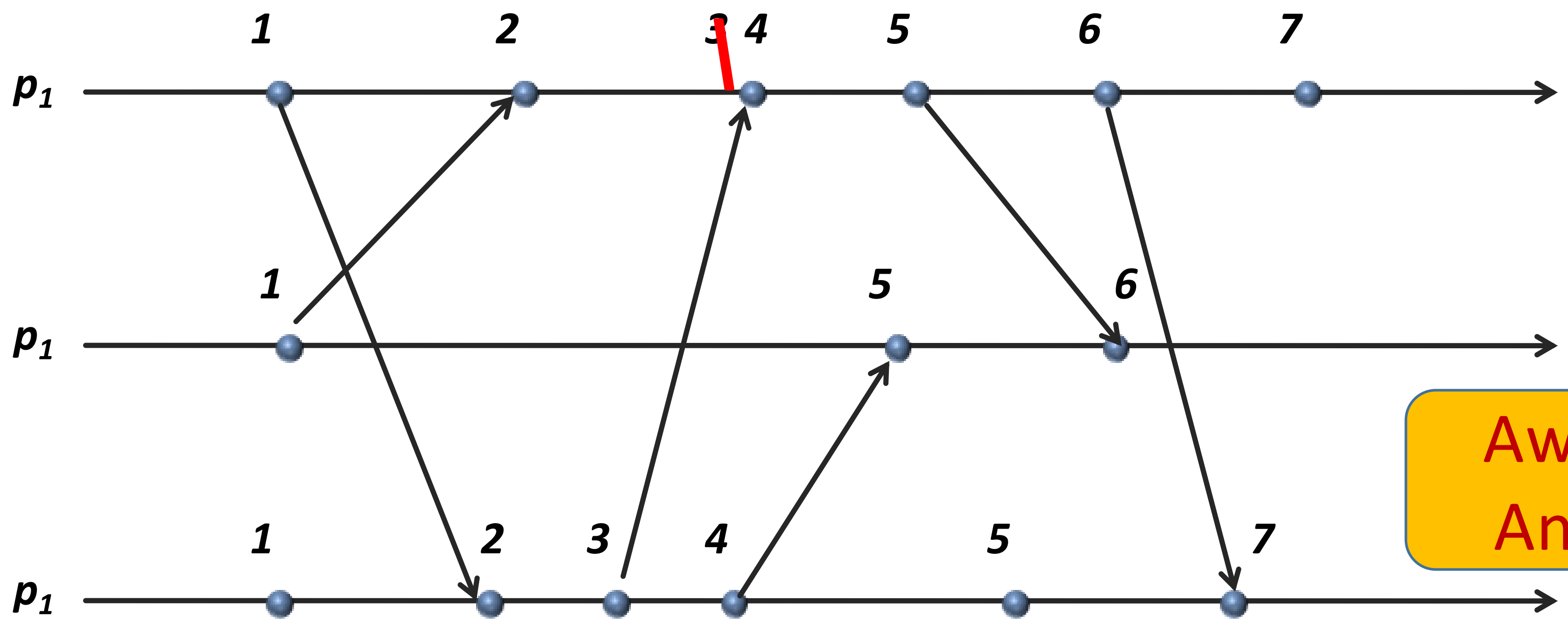

Awesome, right?
Any drawbacks?

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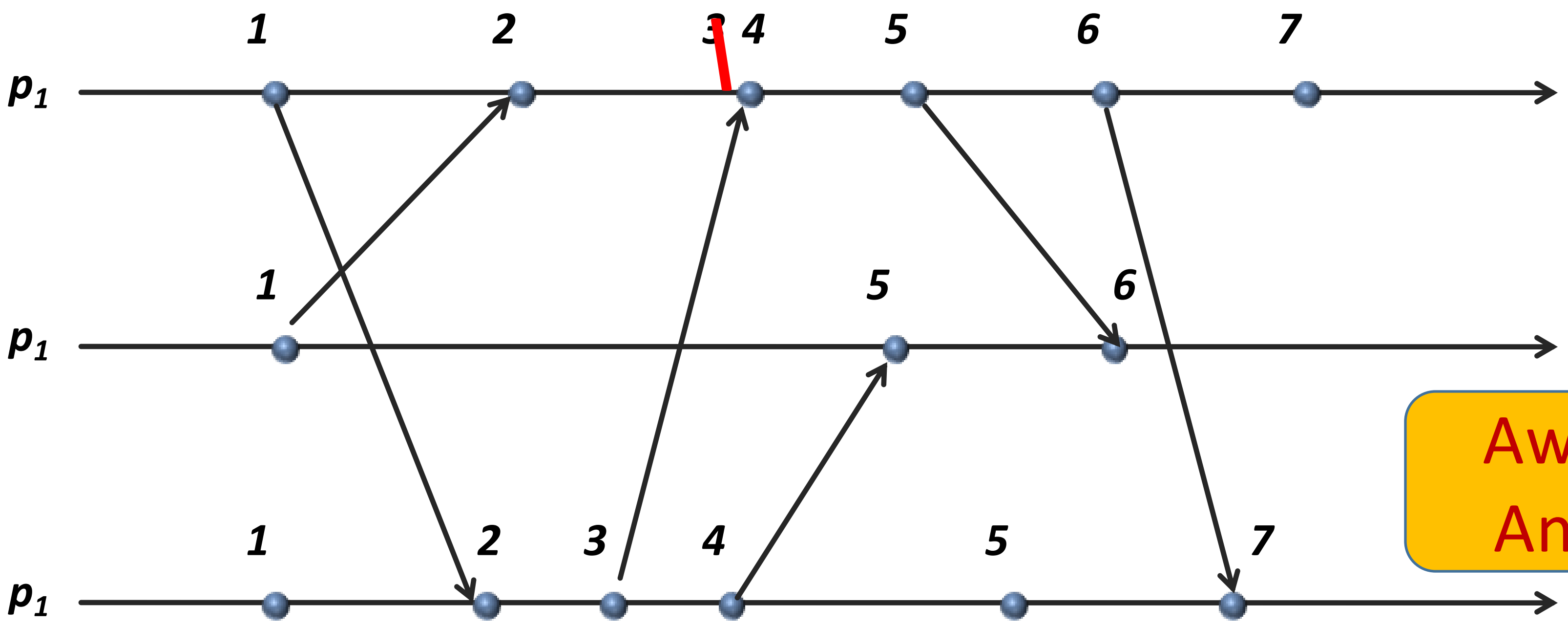

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e_x < e_y → TS(e_x) < TS(e_y), but
TS(e_x) < TS(e_y) doesn't guarantee e_x < e_y

Vector Clock

Vector Clock

Replace Single Logical value with Vector!

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

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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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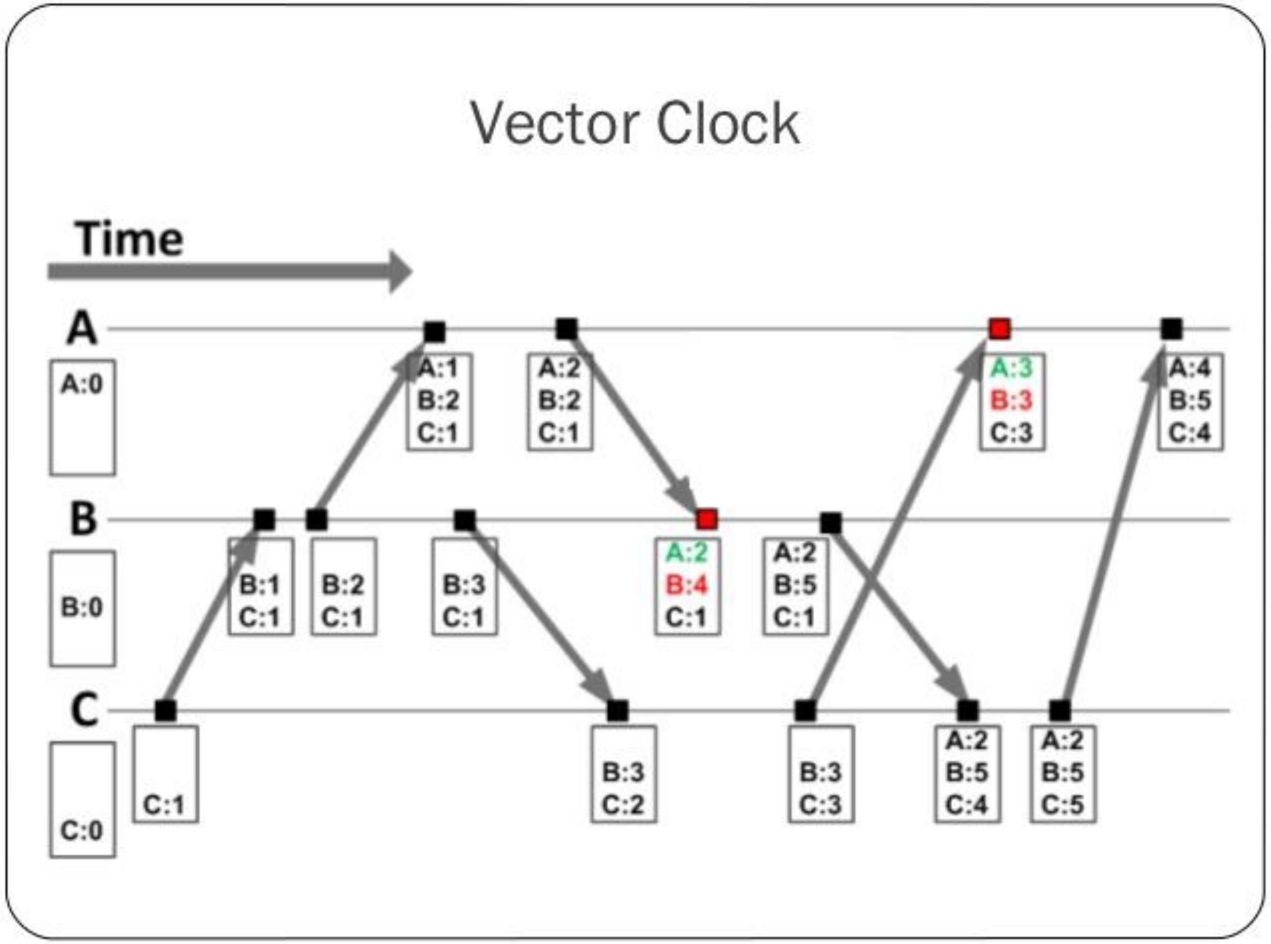

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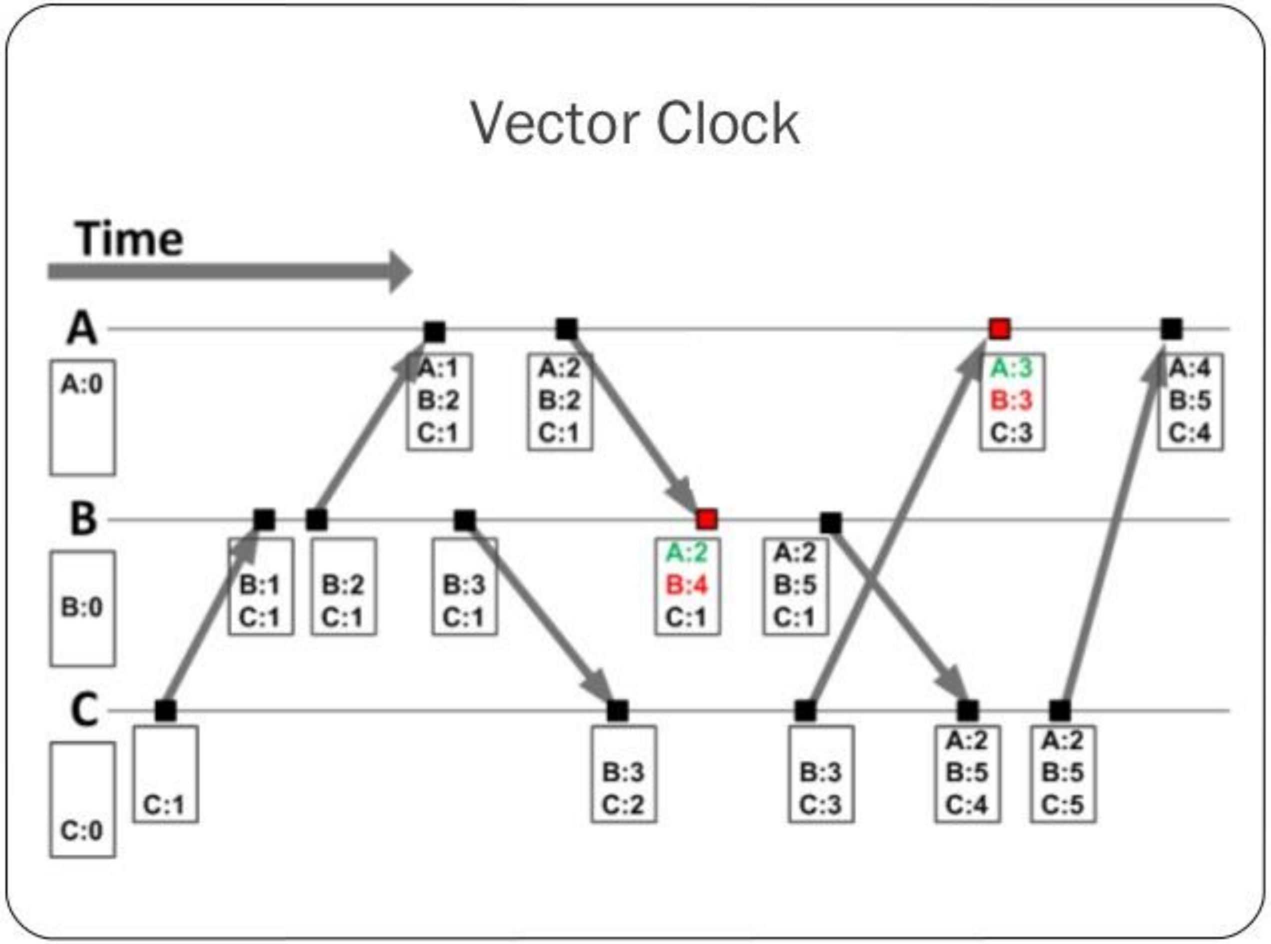

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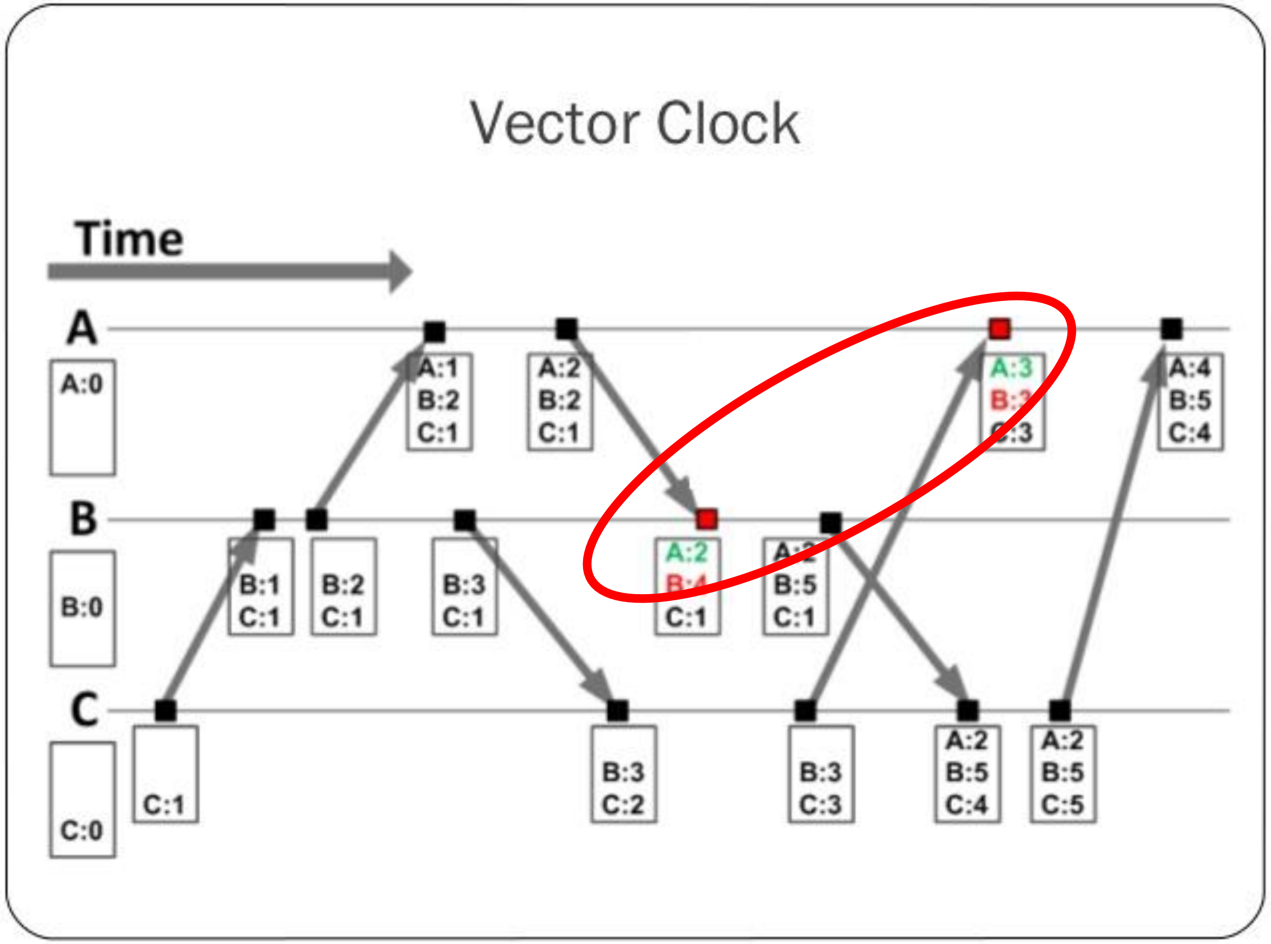

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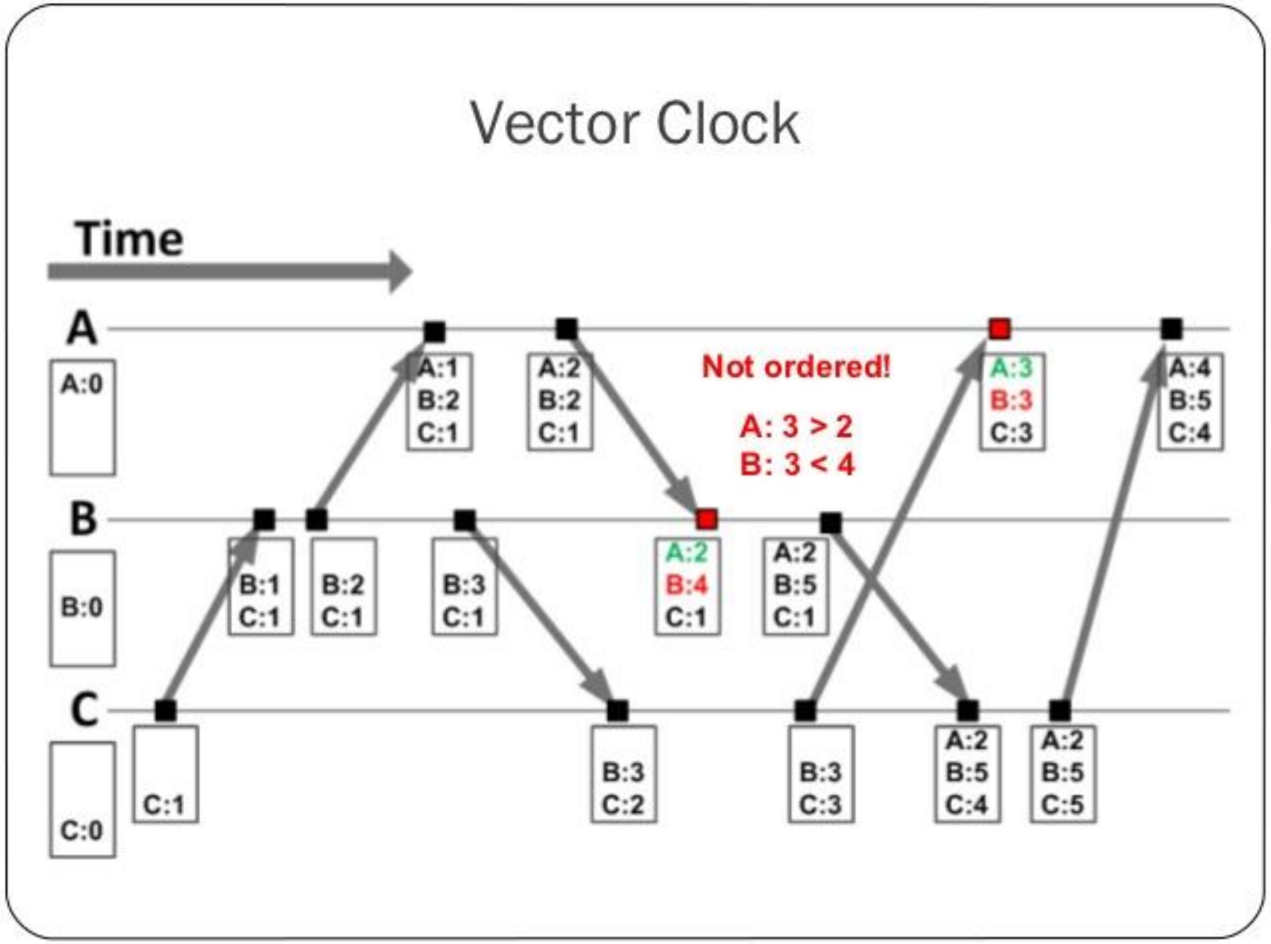

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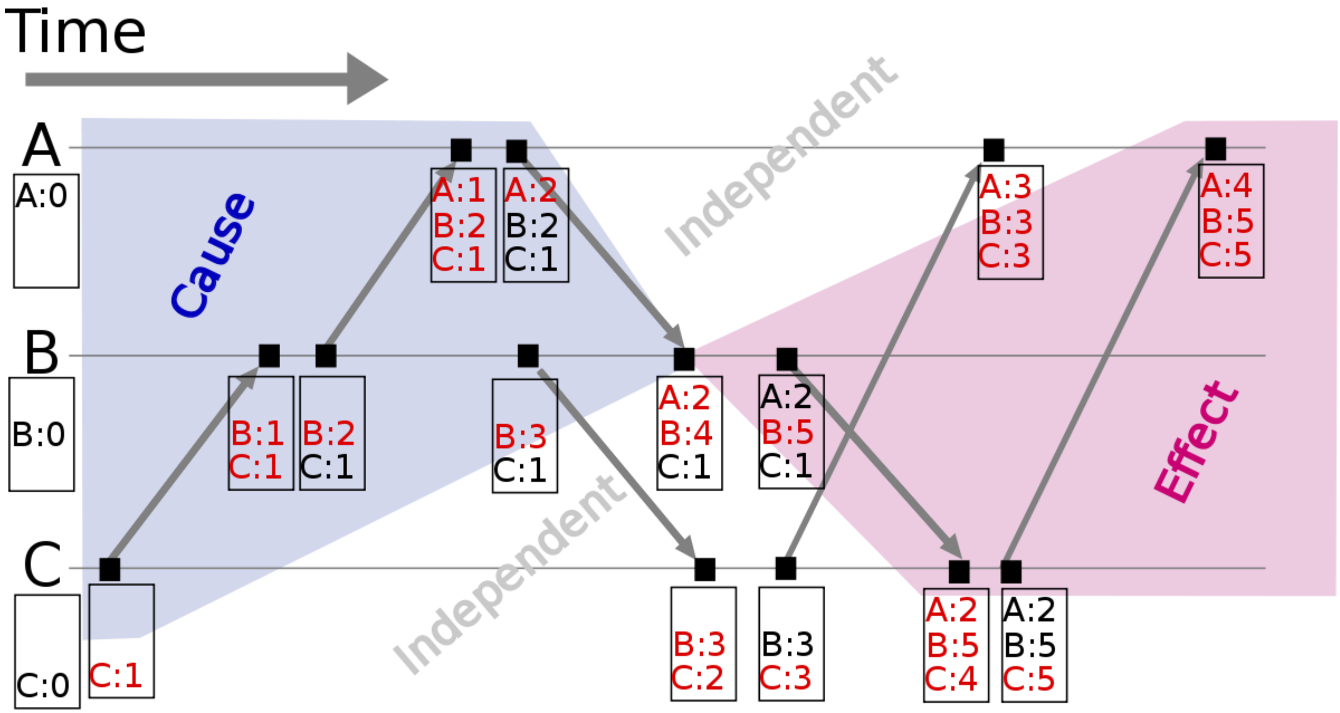


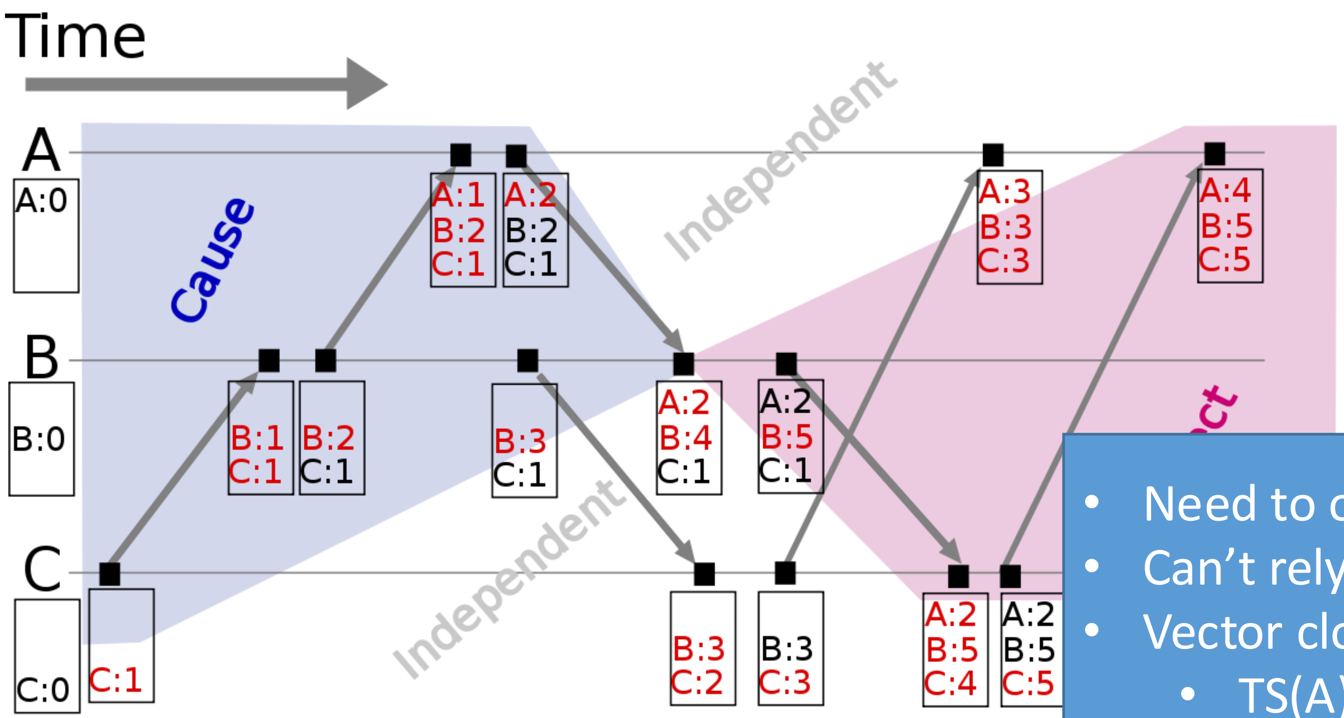
Each process *i* maintains a vector V_i

- $V_i[i]$: 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 $V_i[I]$

…or V

…$V_i[k]$)

…s the

…cess *k*

- 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
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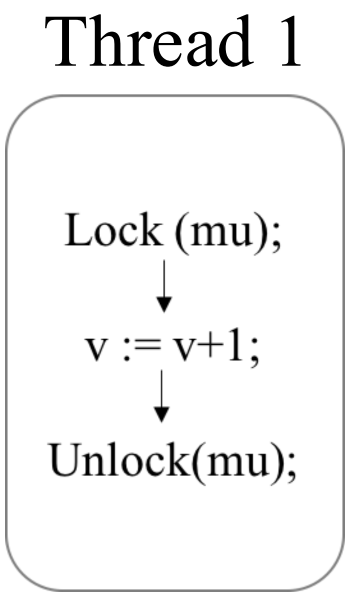

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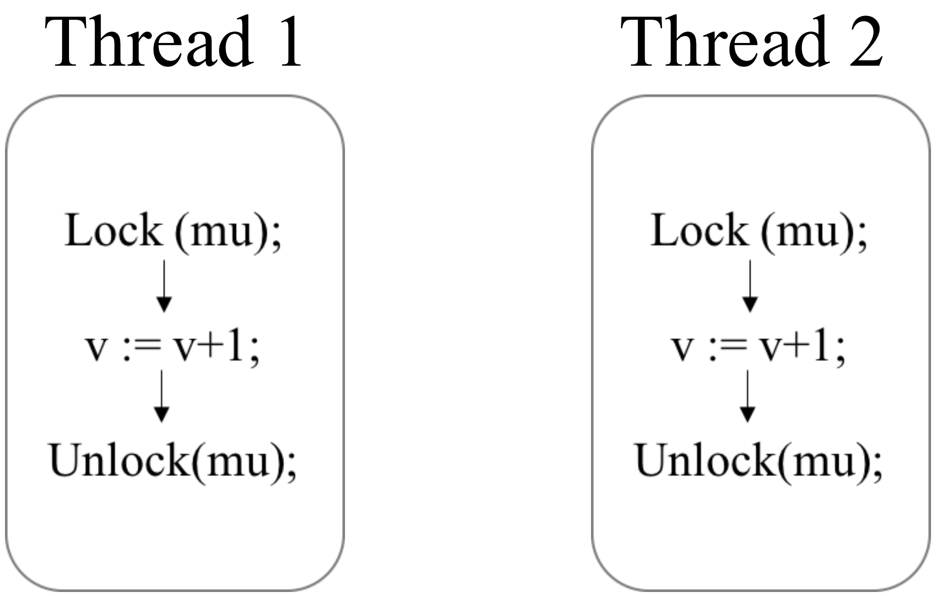

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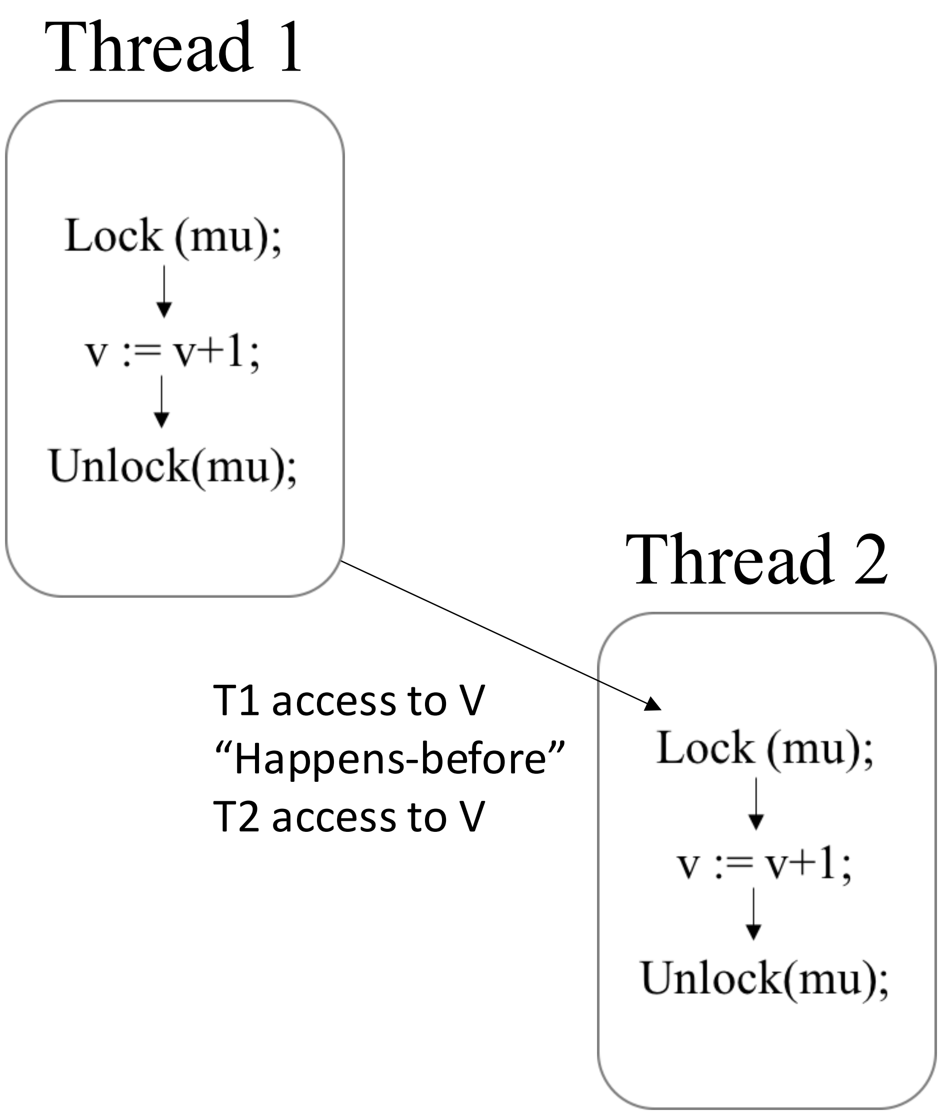

Flaws of *Happens-before*

- Difficult to implement
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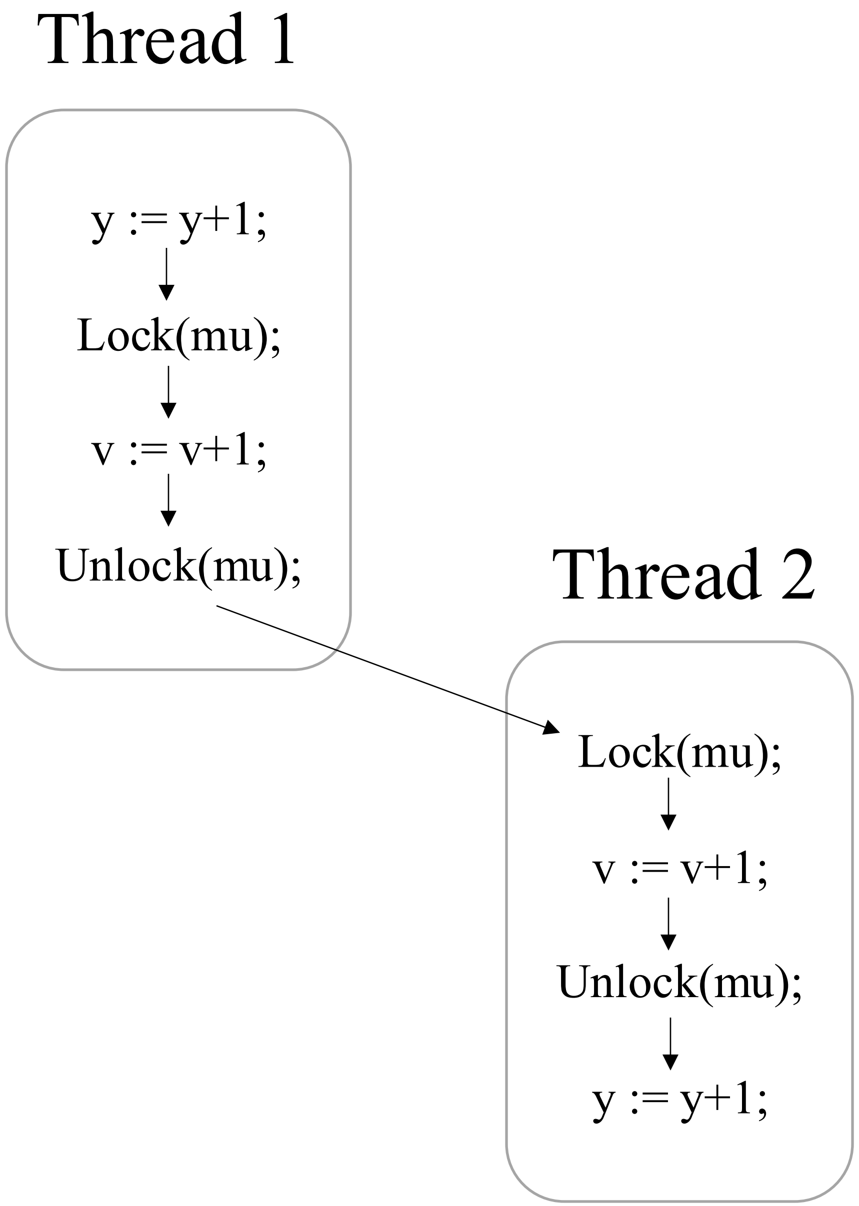

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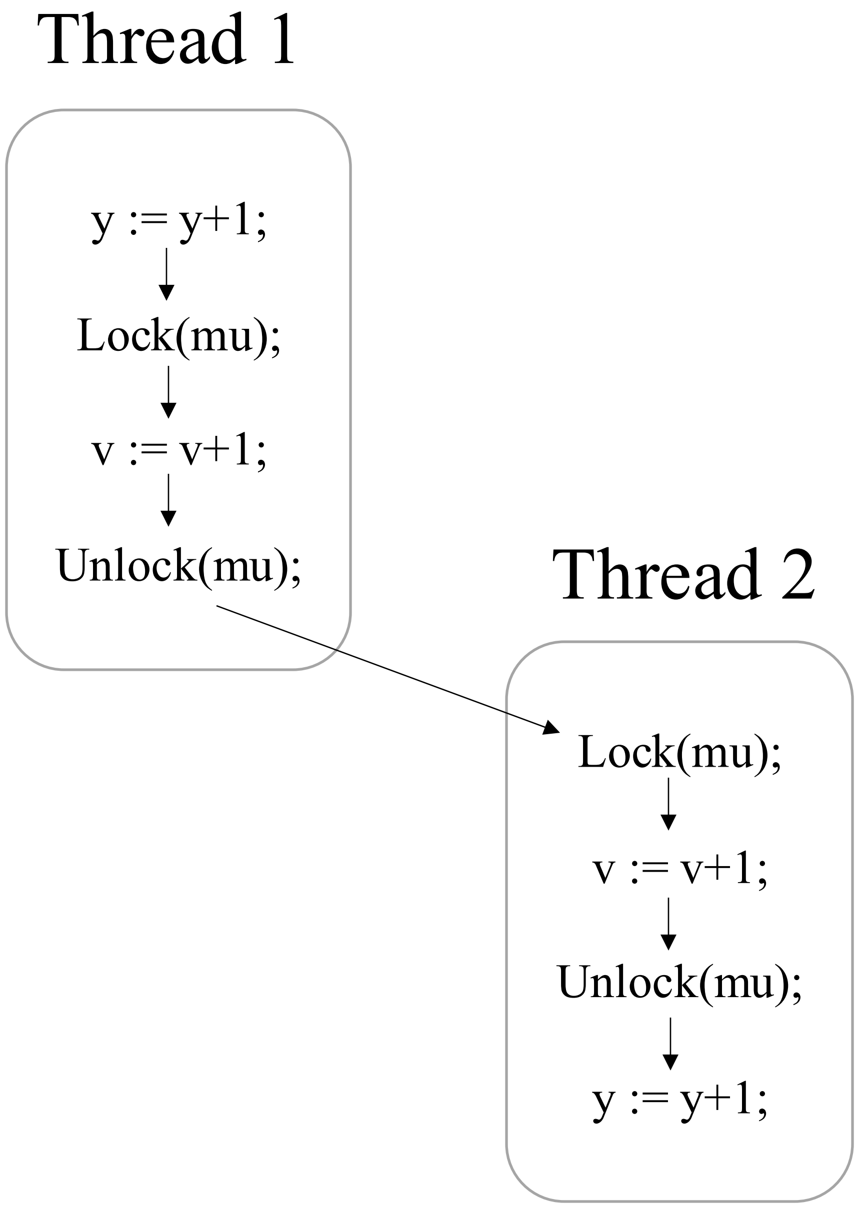
  - Conclusion: no race on Y!
  - Finding doesn't generalize



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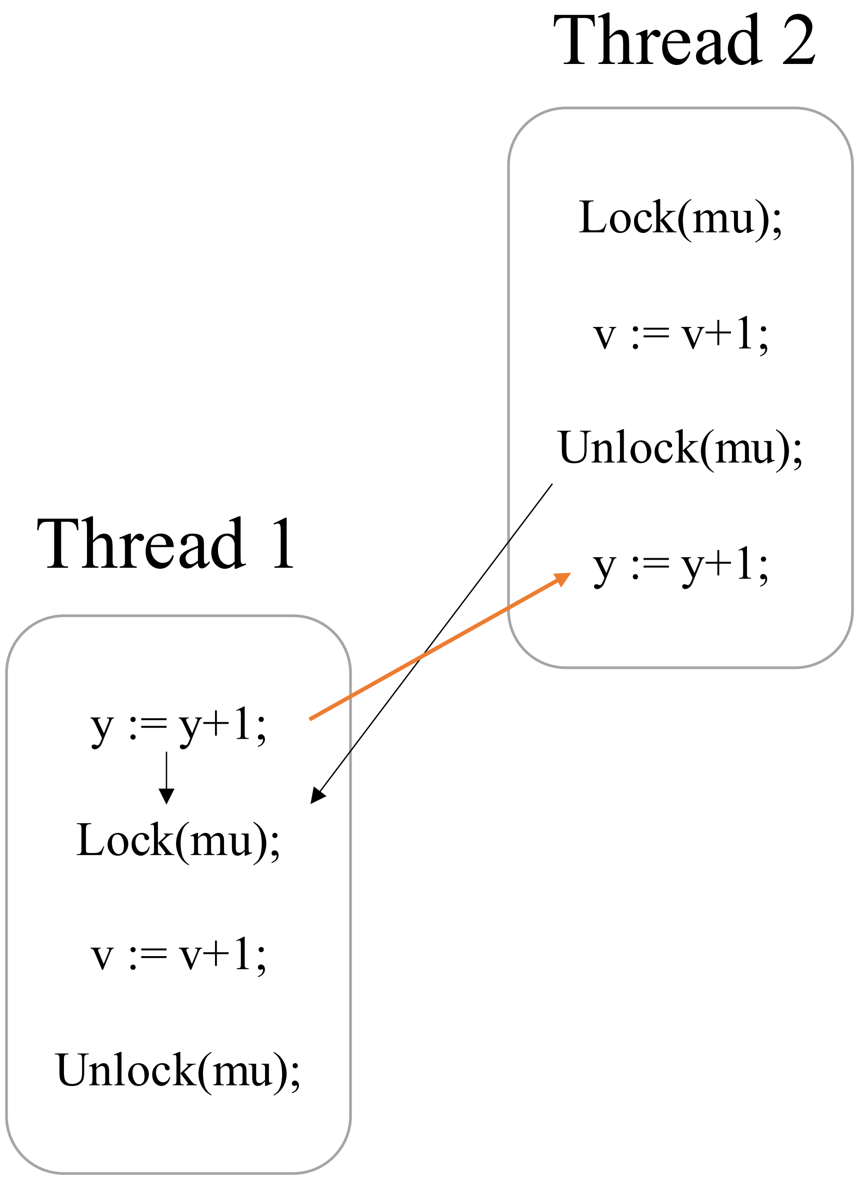
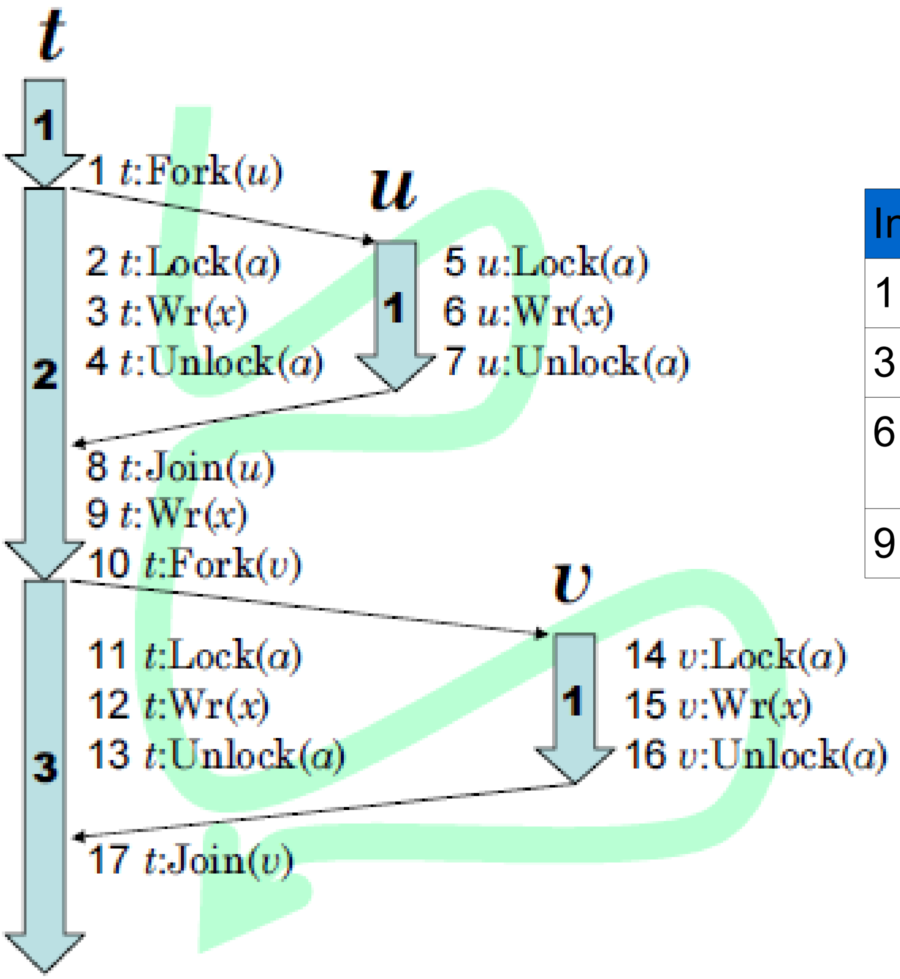


Dynamic Race Detection Summary

- 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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L_t	Lockset of thread **t**
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$\mathbf{t_1}$	Thread **t** at clock time 1

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\end{aligned}$$

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

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

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

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

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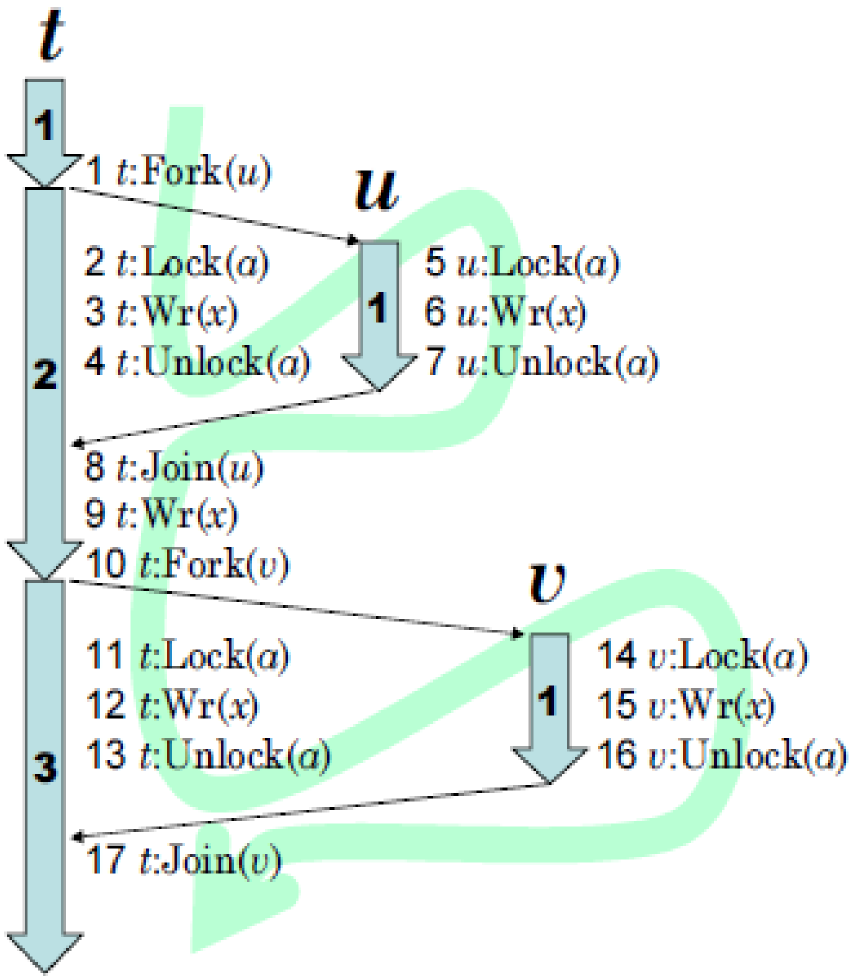
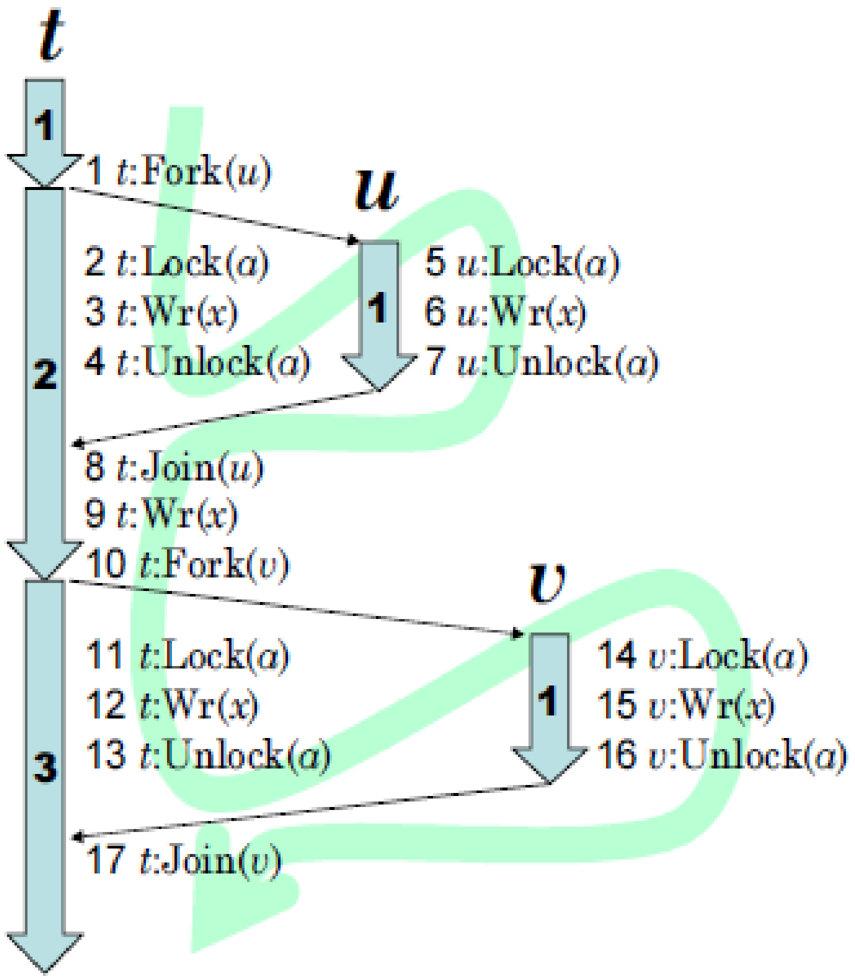


Inst	C_x	S_x	L_t	B_t	L_u	B_u
0	All	{ }	{ }	$\{t_1\}$	-	-
1				$\{t_2\}$	{ }	$\{t_1, u_1\}$
2			{a}			
3	{a}	$\{t_2\}$				
4			{ }			
5					{a}	
6		$\{t_2, u_1\}$				
7					{ }	
8				$\{t_2, u_1\}$	-	-

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**
$\mathbf{t_1}$	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		$\{t_3,v_1\}$				
16					{ }	

Notation	Meaning
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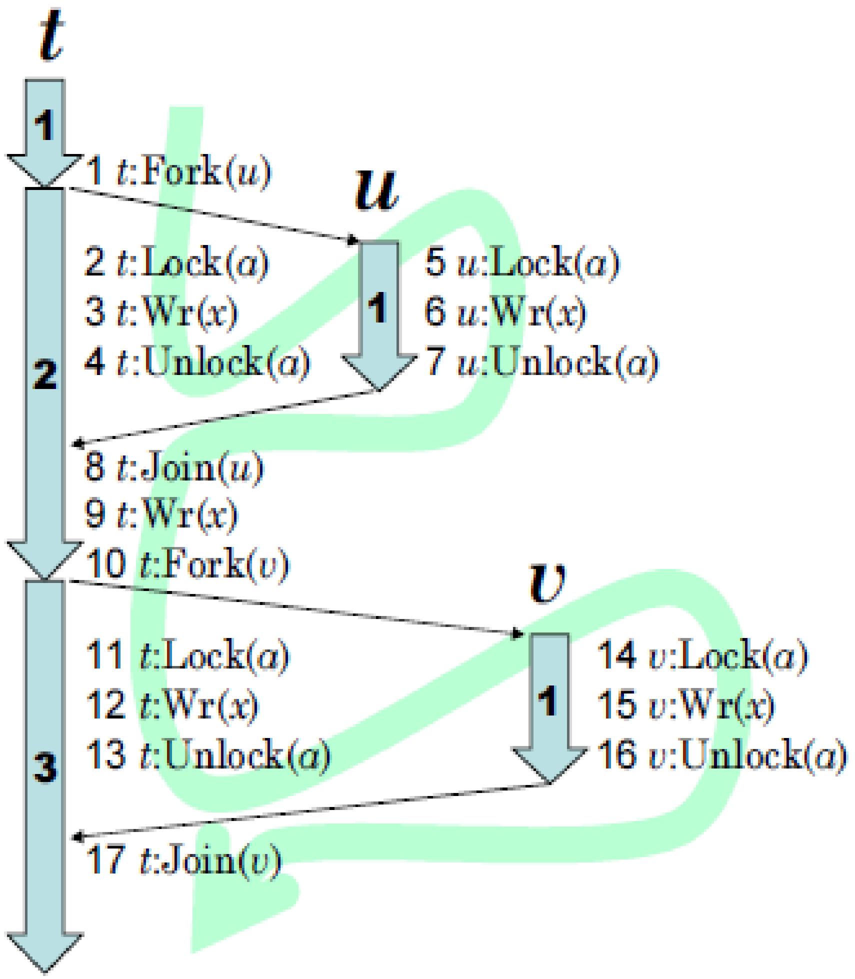

Inst	C_x	S_x	L_t	B_t	L_v	B_v
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13			{ }			
14					{a}	
15		$\{t_3,v_1\}$				
16					{ }	

Only one thread!

Are we done?