Race Detection

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cs380p

Outline

Agenda

- Race Detection

Acknowledgements:

- *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

Race Detection

Locks: a litany of problems

Race Detection

Locks: a litany of problems

- Deadlock

Race Detection

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- Deadlock
- Priority inversion

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Solution: don’t use locks

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

Race Detection

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- Priority inversion
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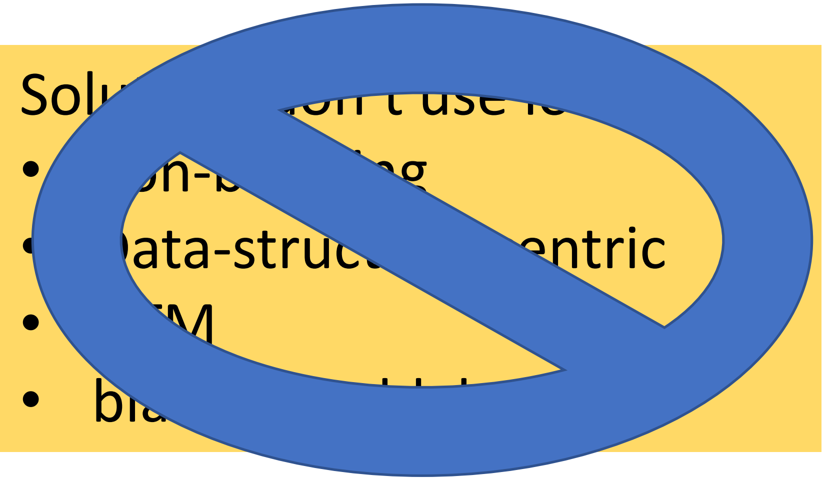

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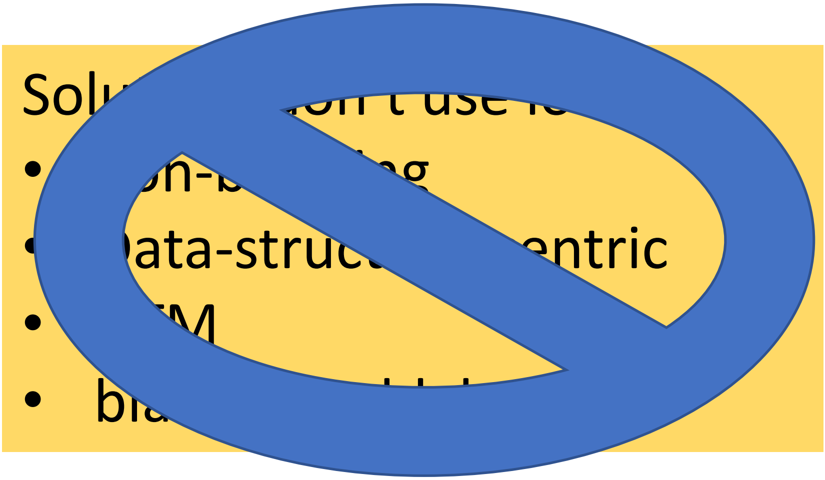

Use locks!

- But automate bug-finding!

Races

```
Lock(lock);
Read-Write(X);
Unlock(lock);
```

```

Read-Write(X);

```

Races

```
Lock(lock);
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- Is there a race here?

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- Informally: accesses with missing/incorrect synchronization
- Formally:
  - >1 threads access same item
  - No intervening synchronization
  - At least one access is a write

Races

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1 Lock(lock);            1
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How to detect races:

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

Races

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

 read-write(X);

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```

Is there a race here?

How can a race detector tell?

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- Benign due to fork/join

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Unsynchronized access can be

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

Is there a race here?
How can a race detector tell?

Detecting Races

How to detect races:

```
forall(X) {
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    declare_race()
}
```

- Static
  - Run a tool that analyses just code
  - Maybe code is annotated to help
  - Conservative: may 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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Lock(lock);
Read-Write(X);
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```

```

Read-Write(X);

```

Static Data Race Detection

Static Data Race Detection

- Type-based analysis
  - Language type system augmented
    - express common synchronization relationships:
    - correct typing→no data races
  - Difficult to do *(although…cf. Rust)*
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What if these *never* run concurrently? (False Positive)

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Unlock(lock);
```

```

Read-Write(X);

```

Lockset Algorithm

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

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

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  - Track locks held by thread t
  - On access to var v, check if t holds the proper locks
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Narrow down set of locks maybe protecting v

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.

Lockset Algorithm Example

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

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

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

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{lockA}	
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$C(v) \cap locks\_held(t)$

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`lock(lockA);`	{lockA}	
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`unlock(lockA);`	{}	
`lock(lockB);`		
`v++;`		
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lock(lockB);	{lockB}	
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v++;		{} ACK! race
unlock(lockB);	{}	

Lockset Algorithm Example

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	{}	{lockA, lockB}
lock(lockA);	{lockA}	
v++;		{lockA}
unlock(lockA);	{}	
lock(lockB);	{lockB}	
		{} ACK! race
kB);	{}	

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);

}
```

Improving over lockset

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Lockset detects a race

There is no race: why not?

Improving over lockset

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

thread B

```
1 thread-proc() {
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 when *“happens-before”* cannot be known

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- *Happens-before* relation
  - Within single thread
  - Between threads

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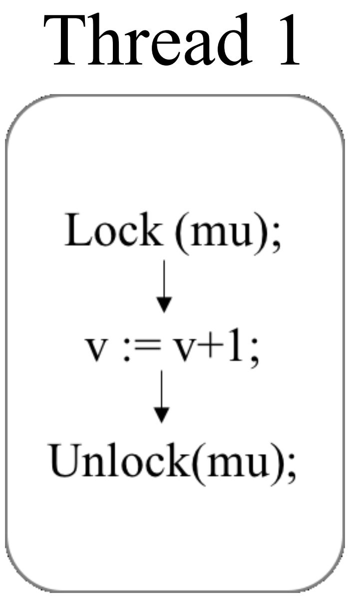

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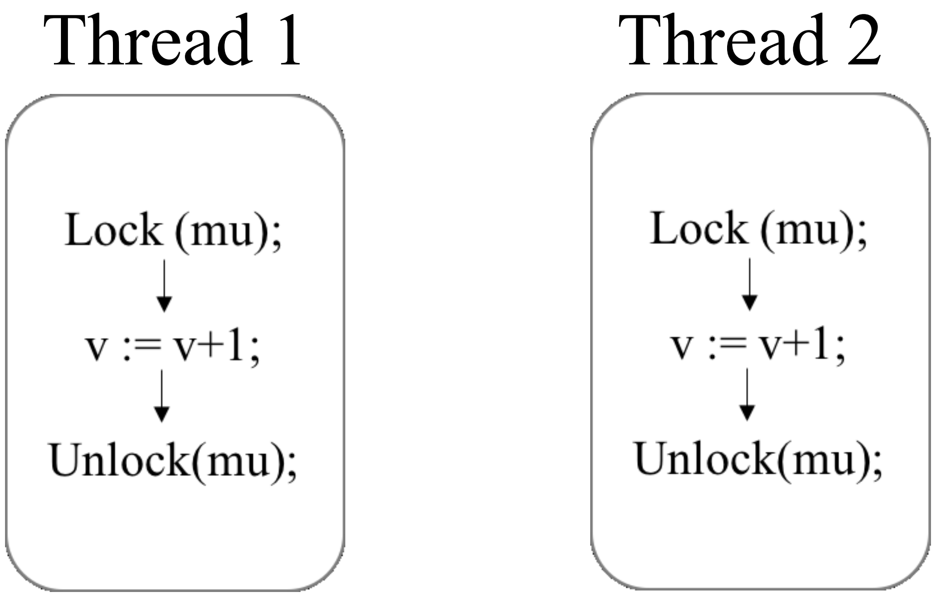

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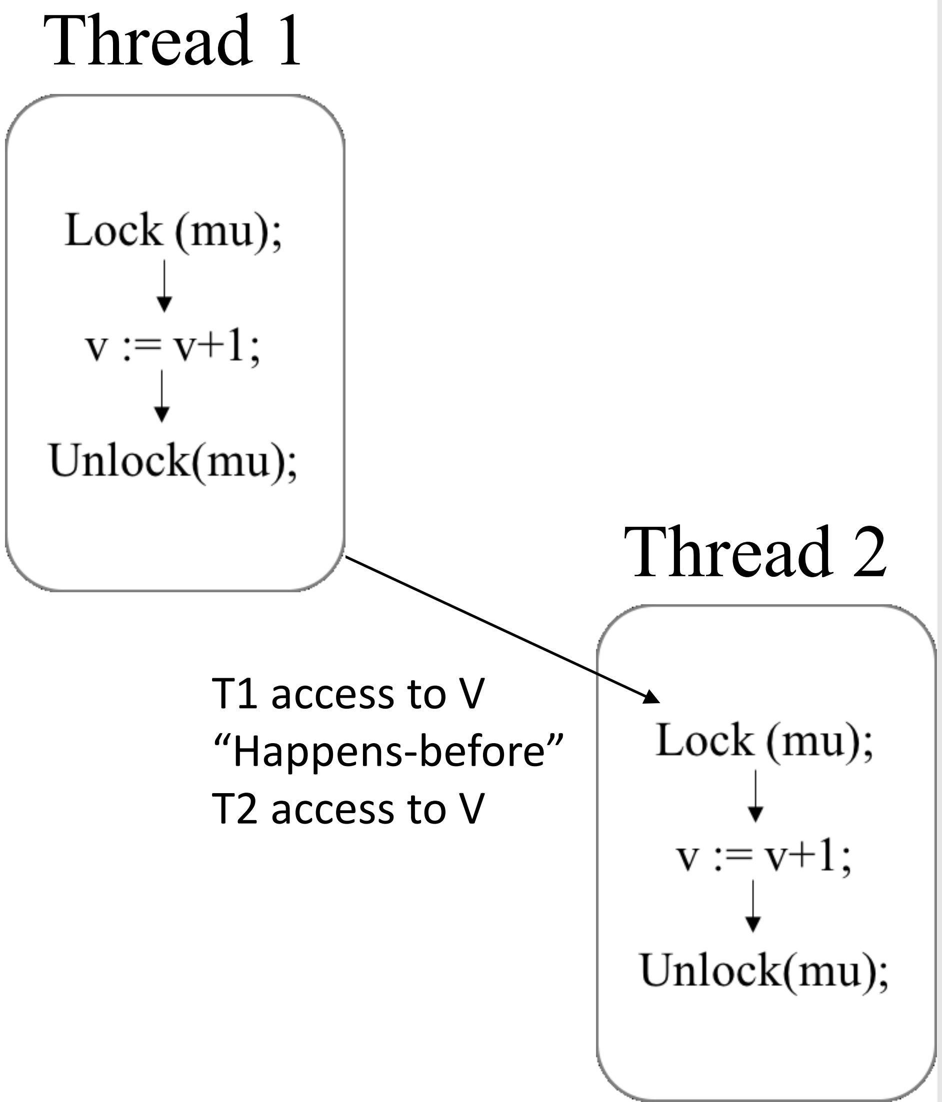

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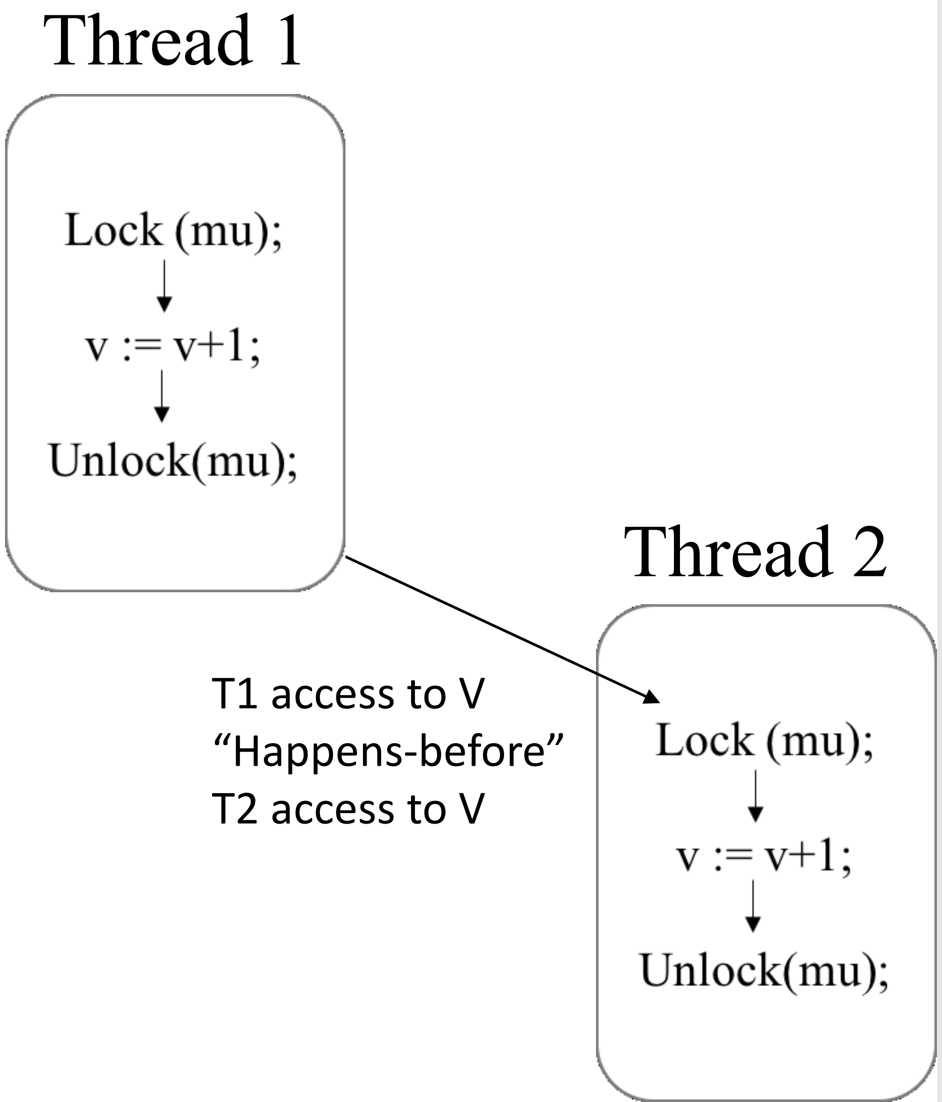

Happens-before

- *Happens-before* relation
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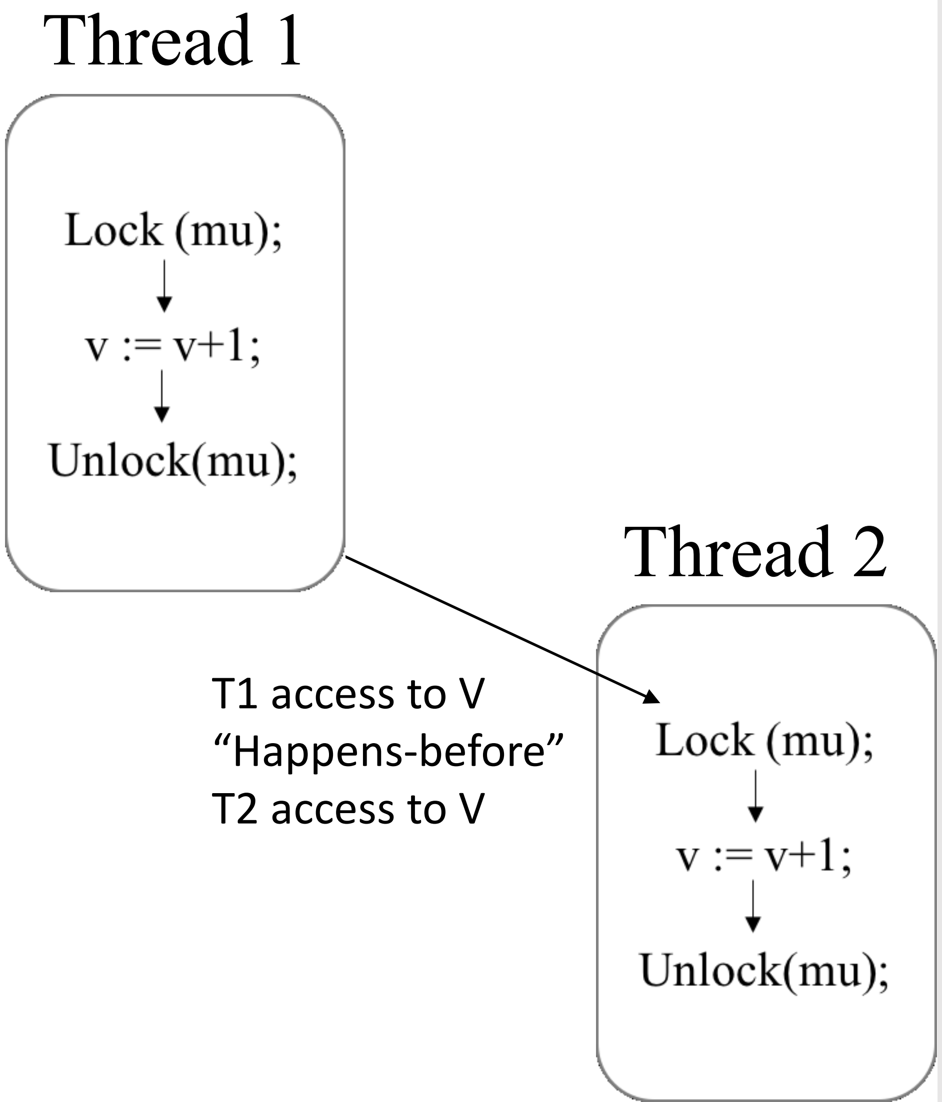
- Accessing vars not ordered by *happens-before* → race
- Captures locks + dynamism
- How to track *happens-before?*
  - Sync objects → ordering
  - fork/join/etc → ordering
  - *But how to order events across different threads/CPUs?*



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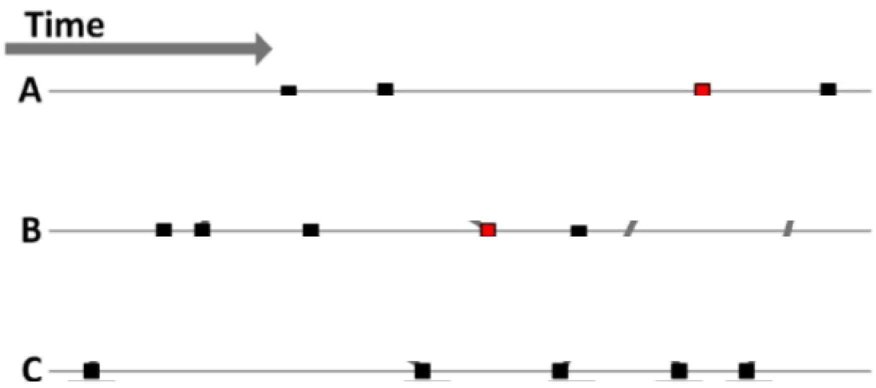

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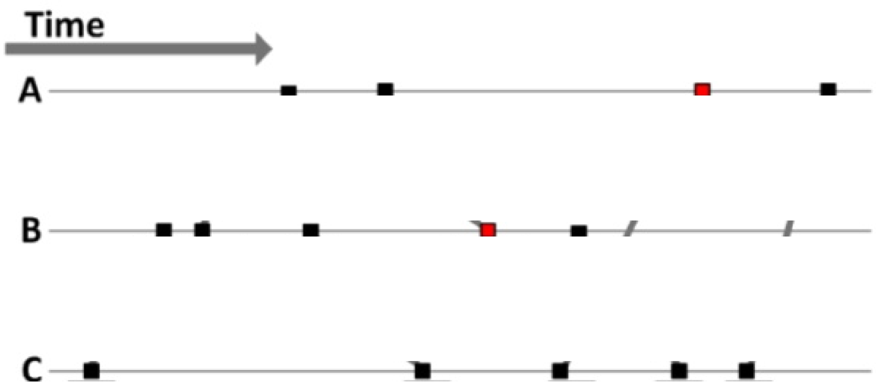

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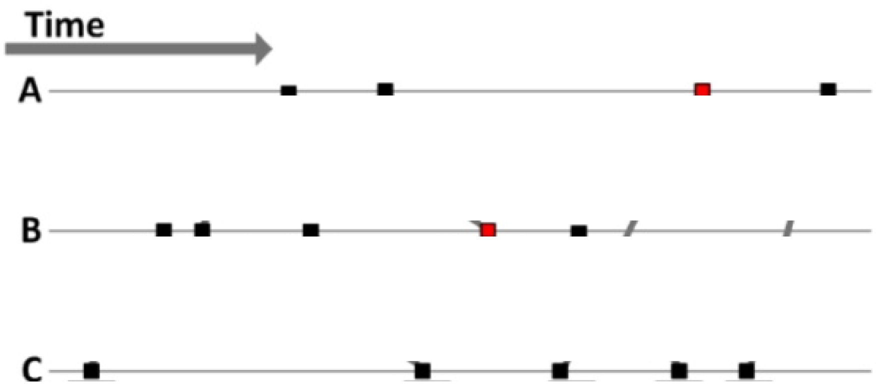

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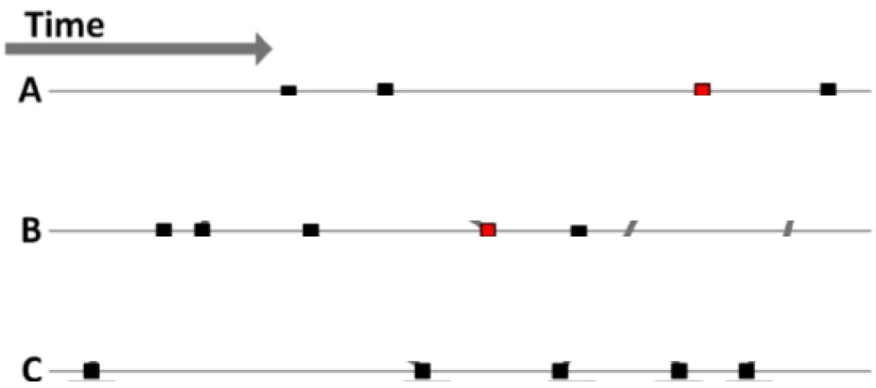

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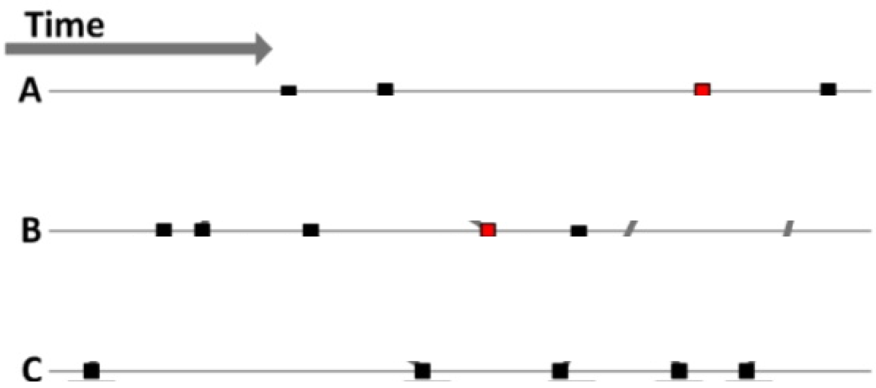

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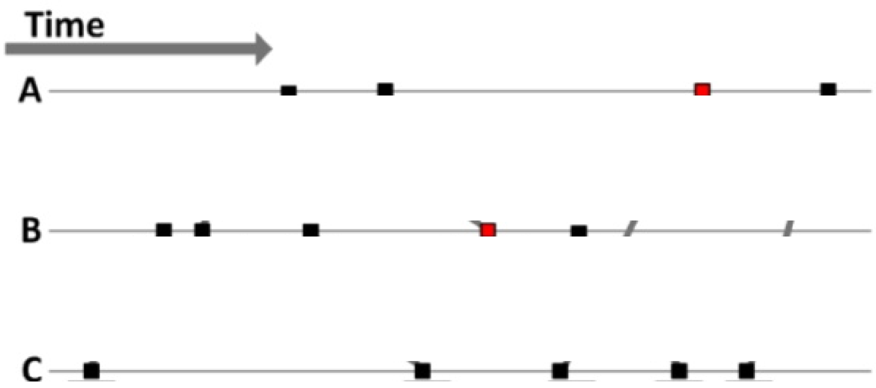

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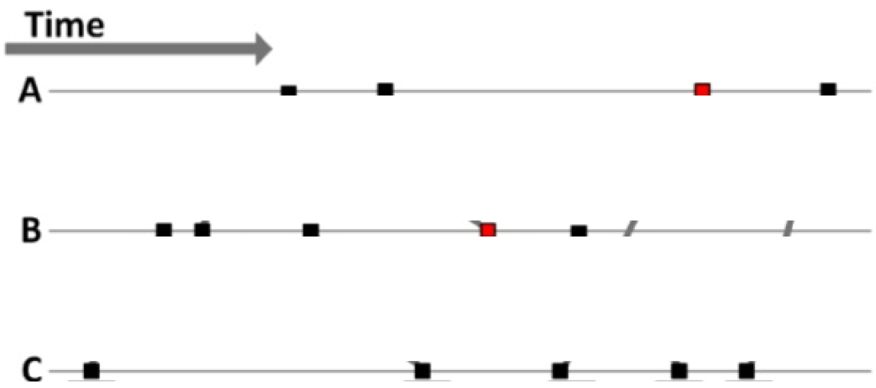

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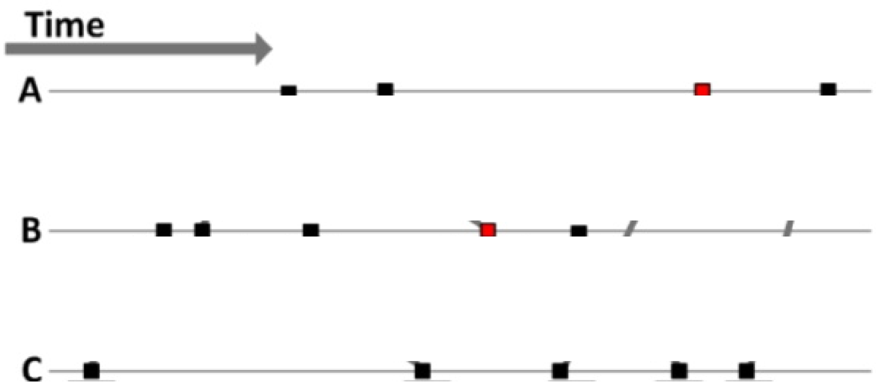

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- **Vector**
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- Matrix
  - TS(A) is N^2: pairwise knowledge

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- Each system records each event, timestamp
- Suppose events occur in *this* real order:

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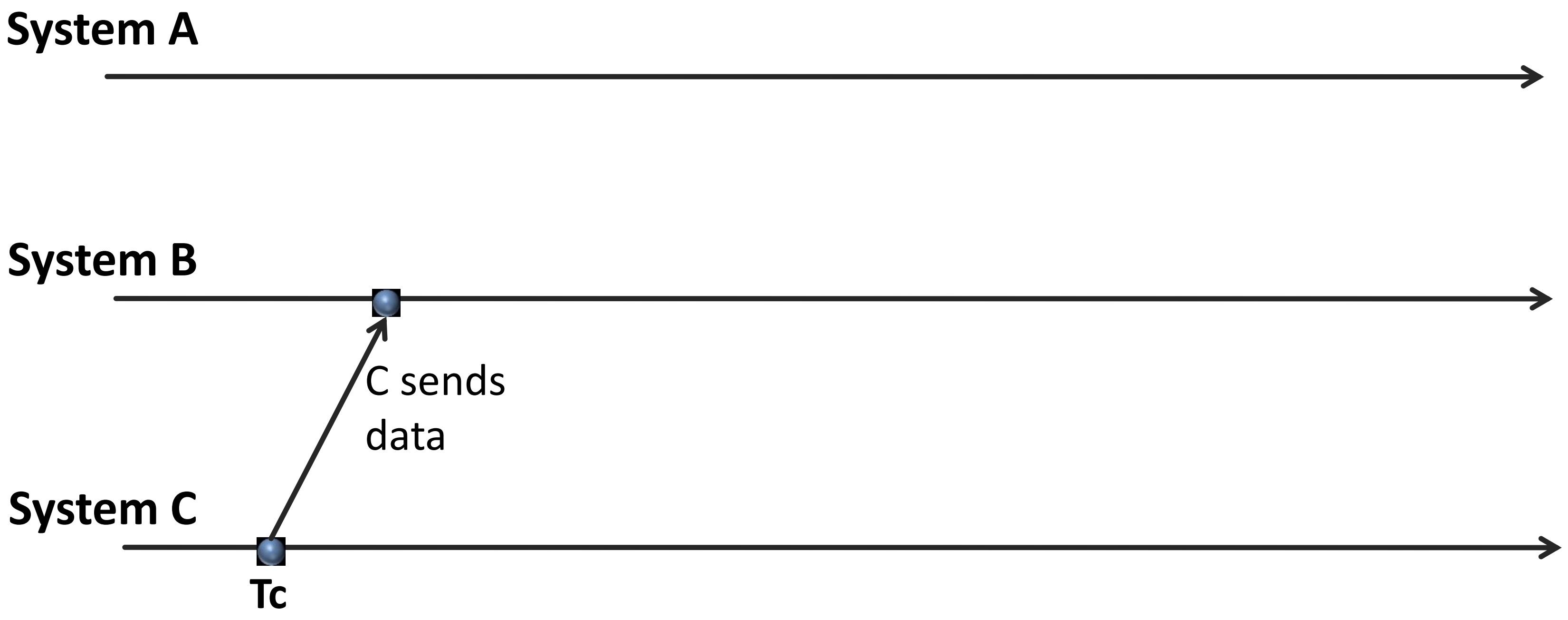

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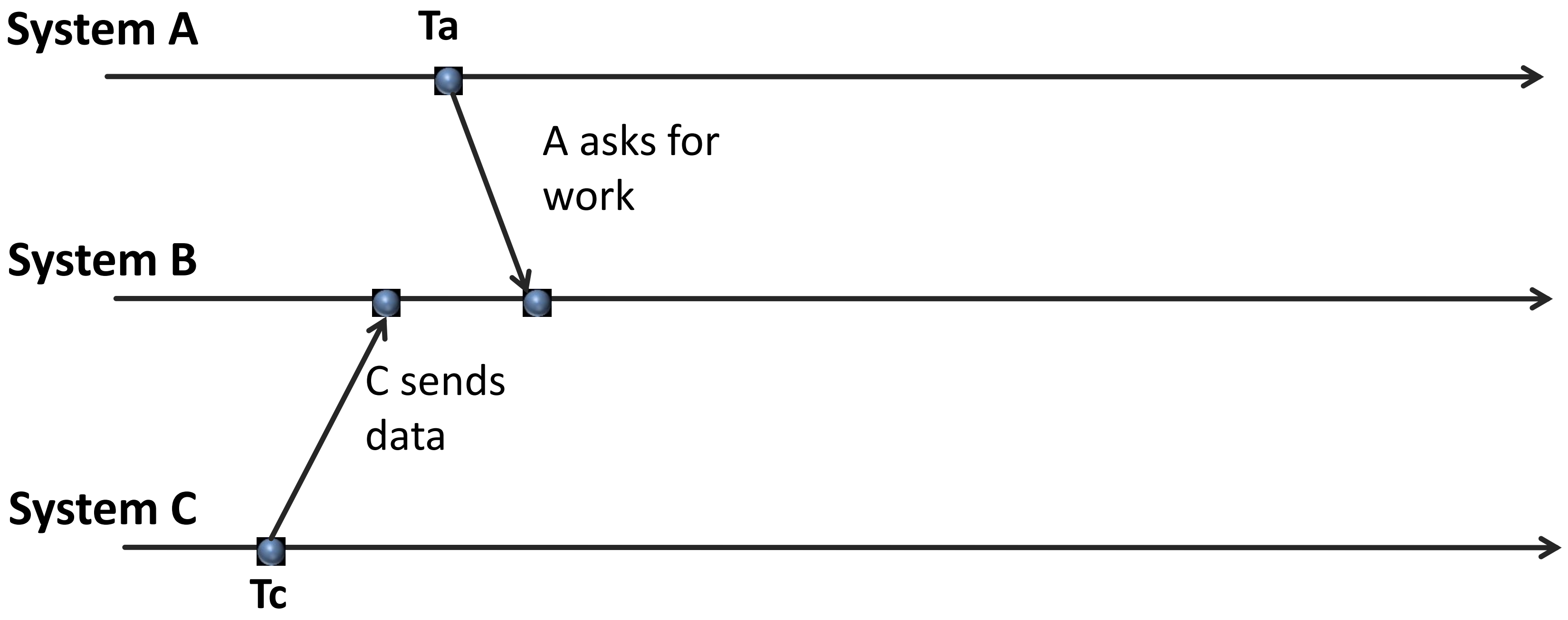

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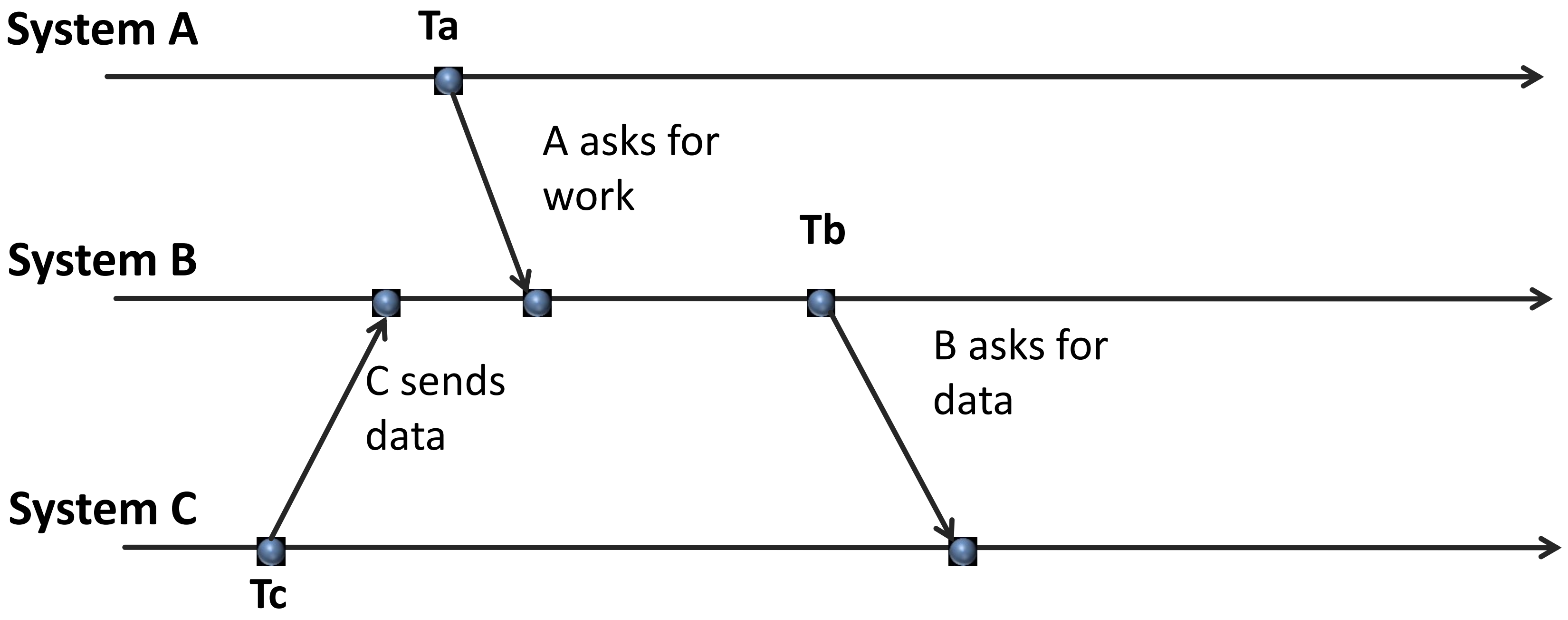

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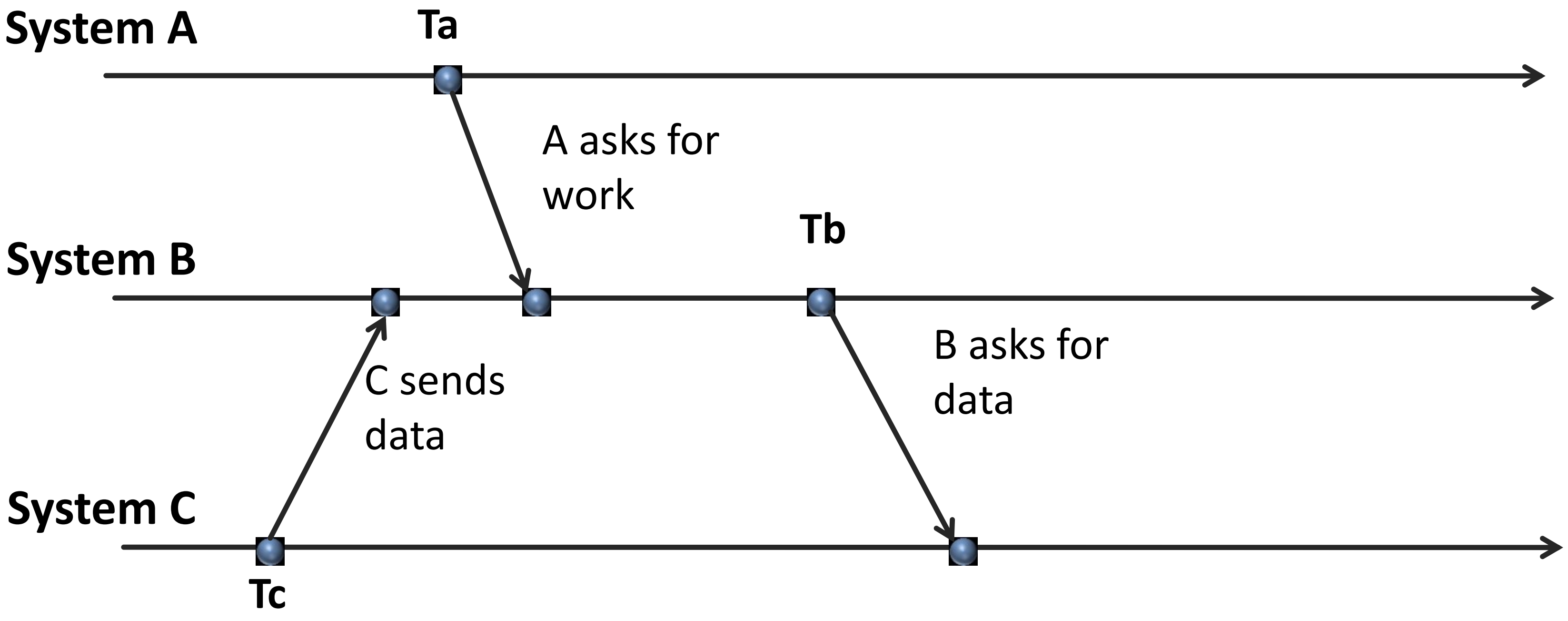

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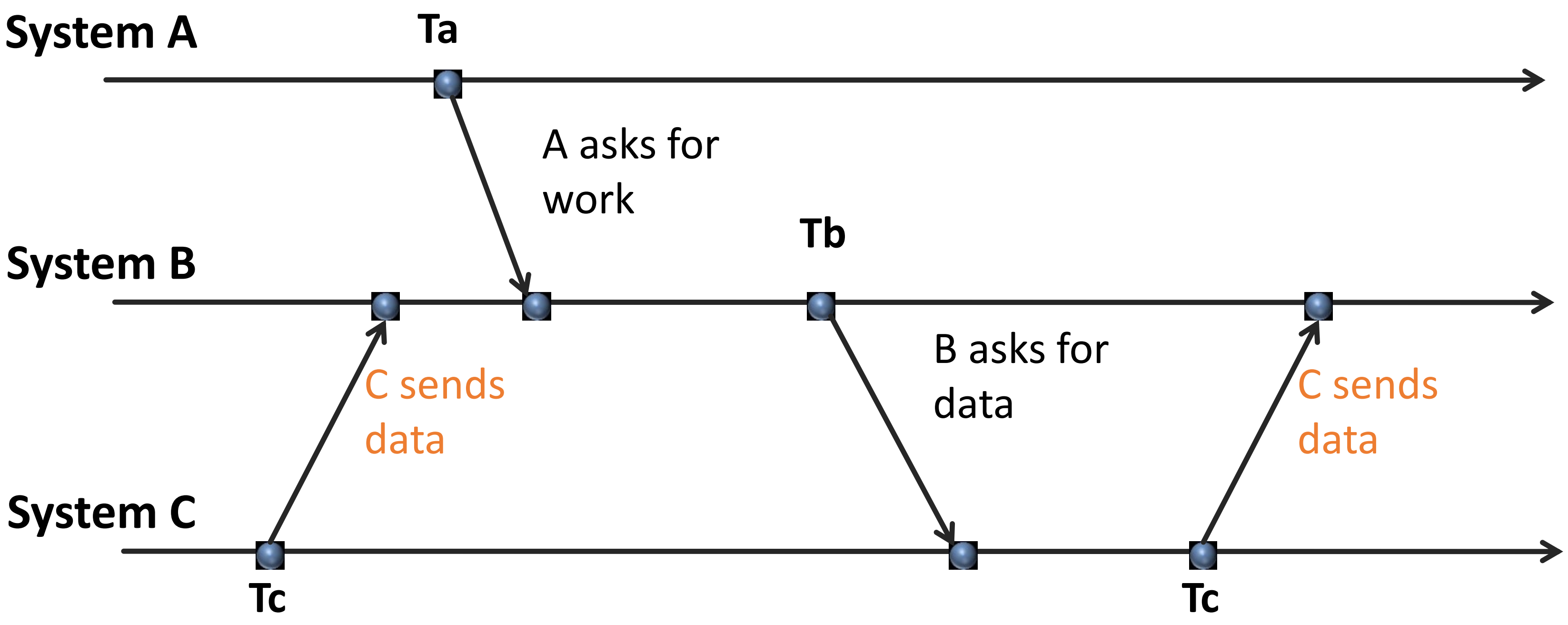
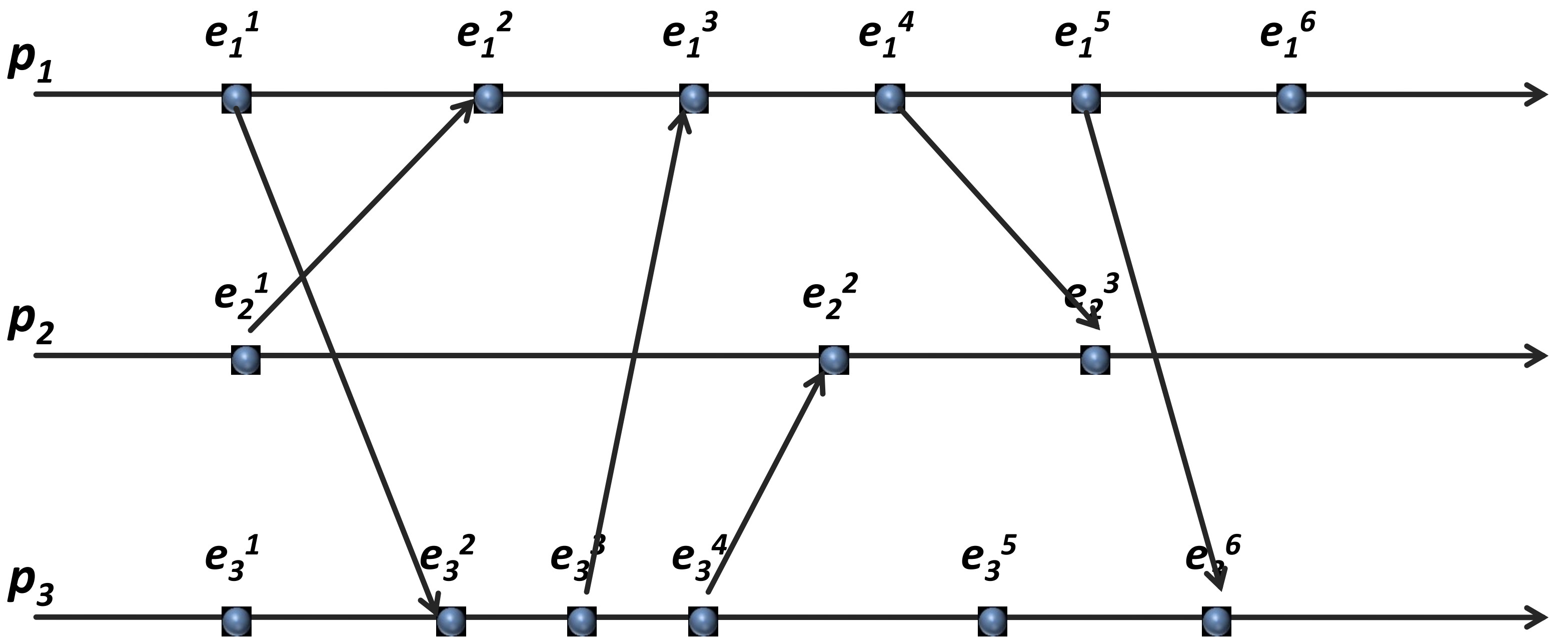


Rules for Ordering of Events

- local events precede one another → precede one another globally:
  - If $e_i^k, e_i^m \in h_i$ and $k < m$, then $e_i^k \rightarrow e_i^m$
- Send of message always precedes receipt :
  - 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



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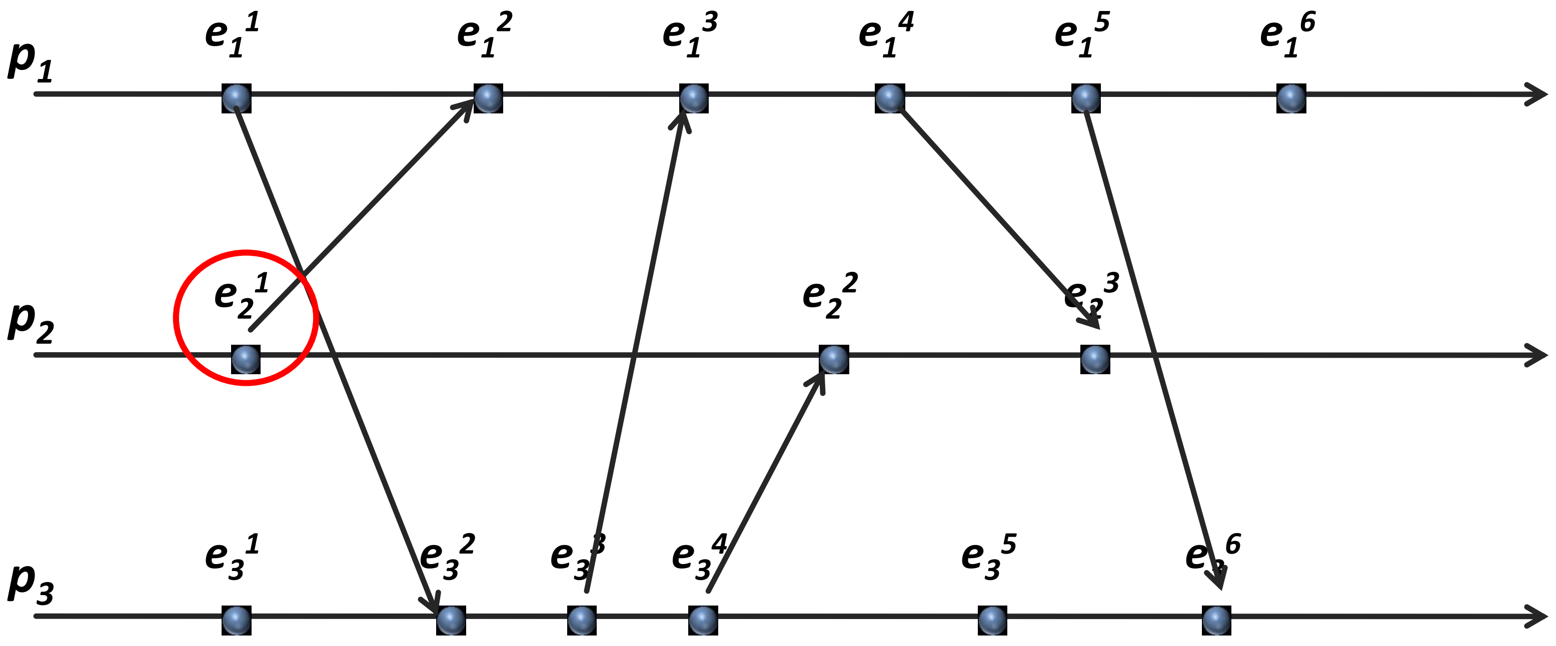

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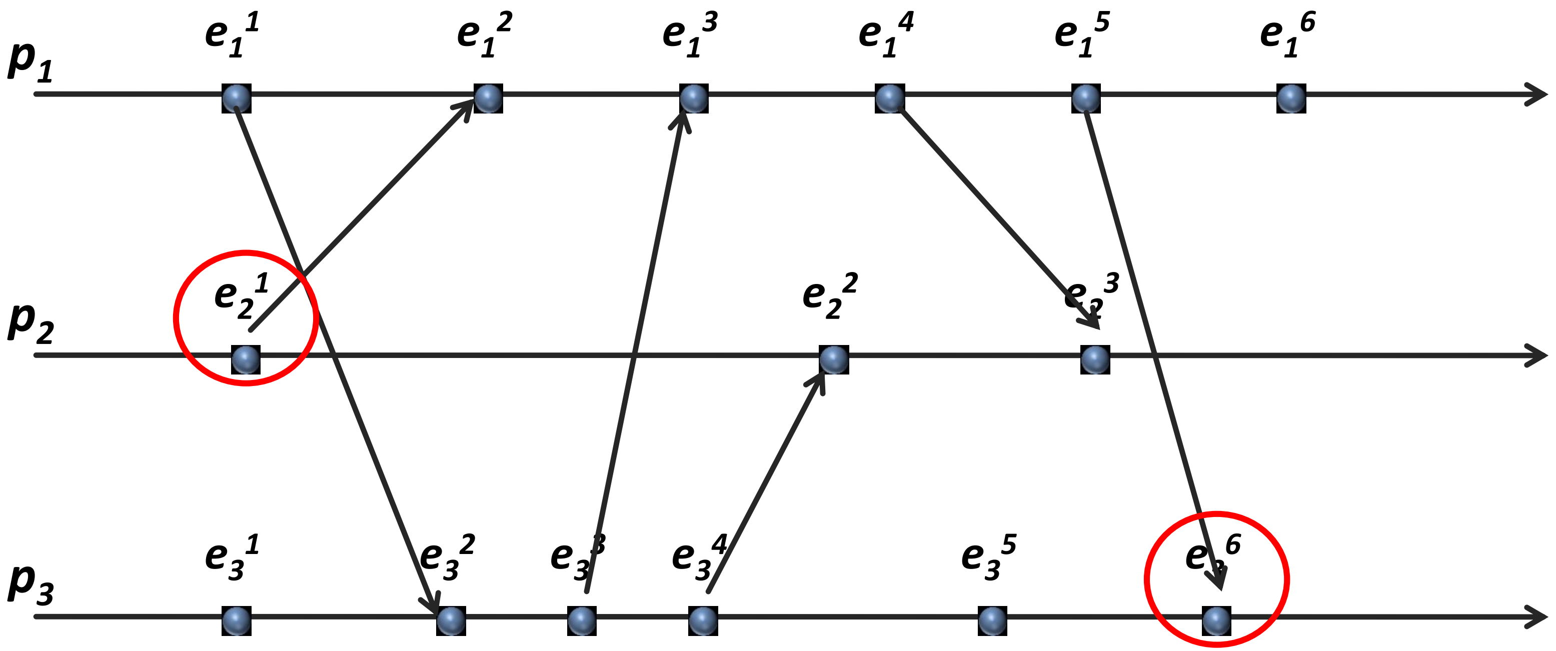

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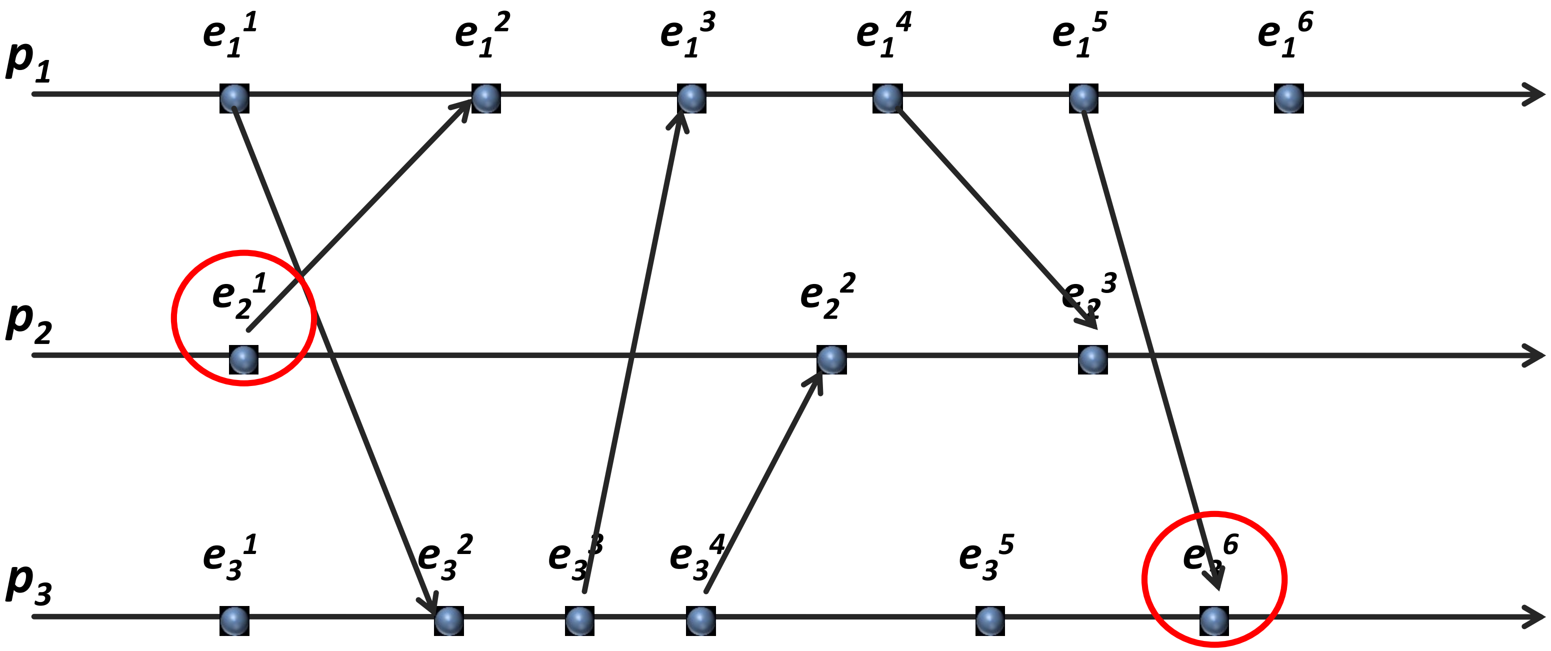

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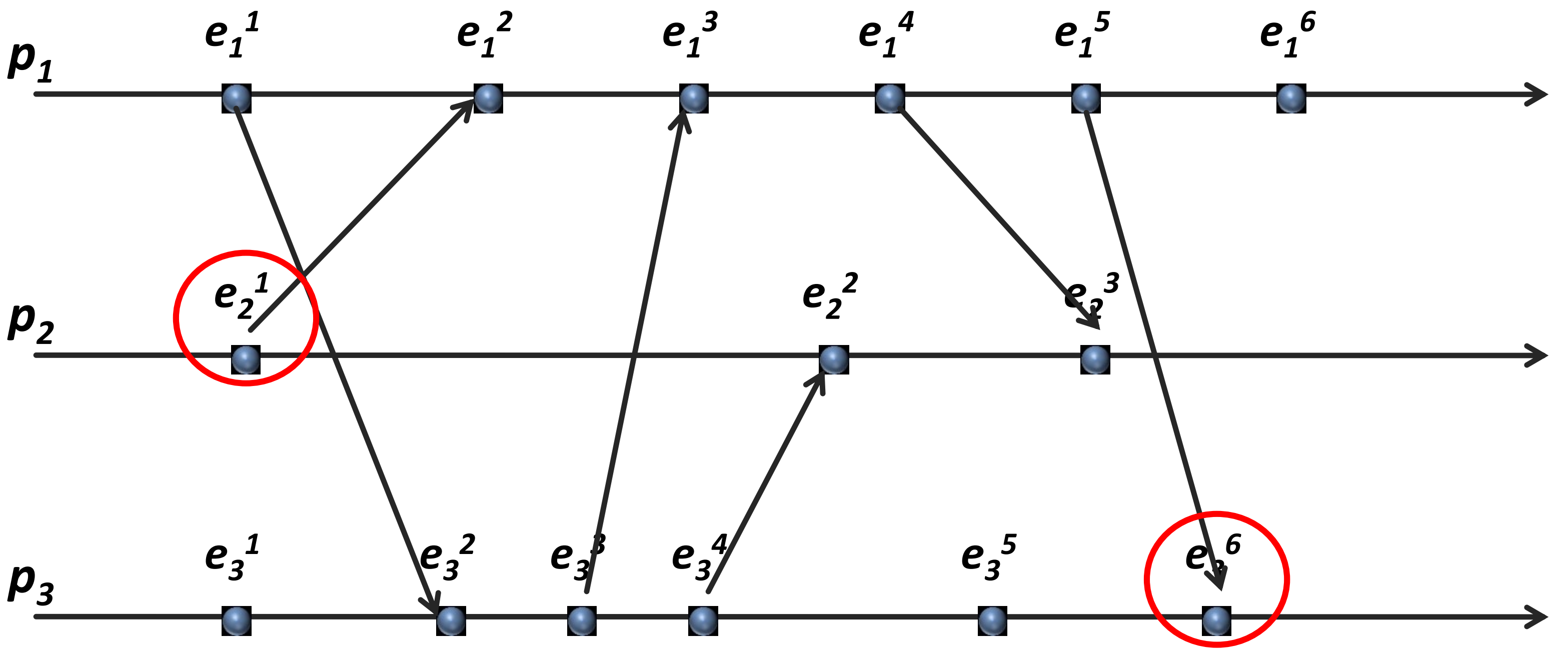

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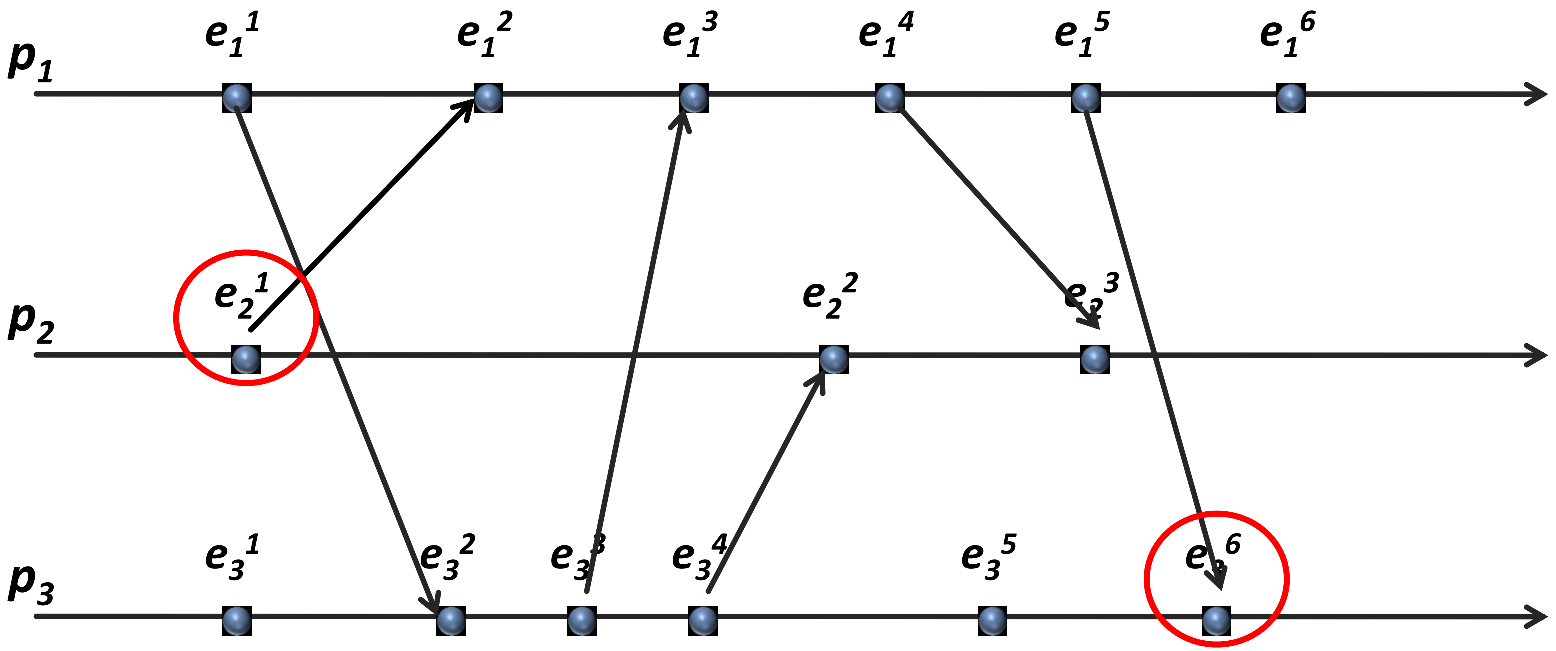

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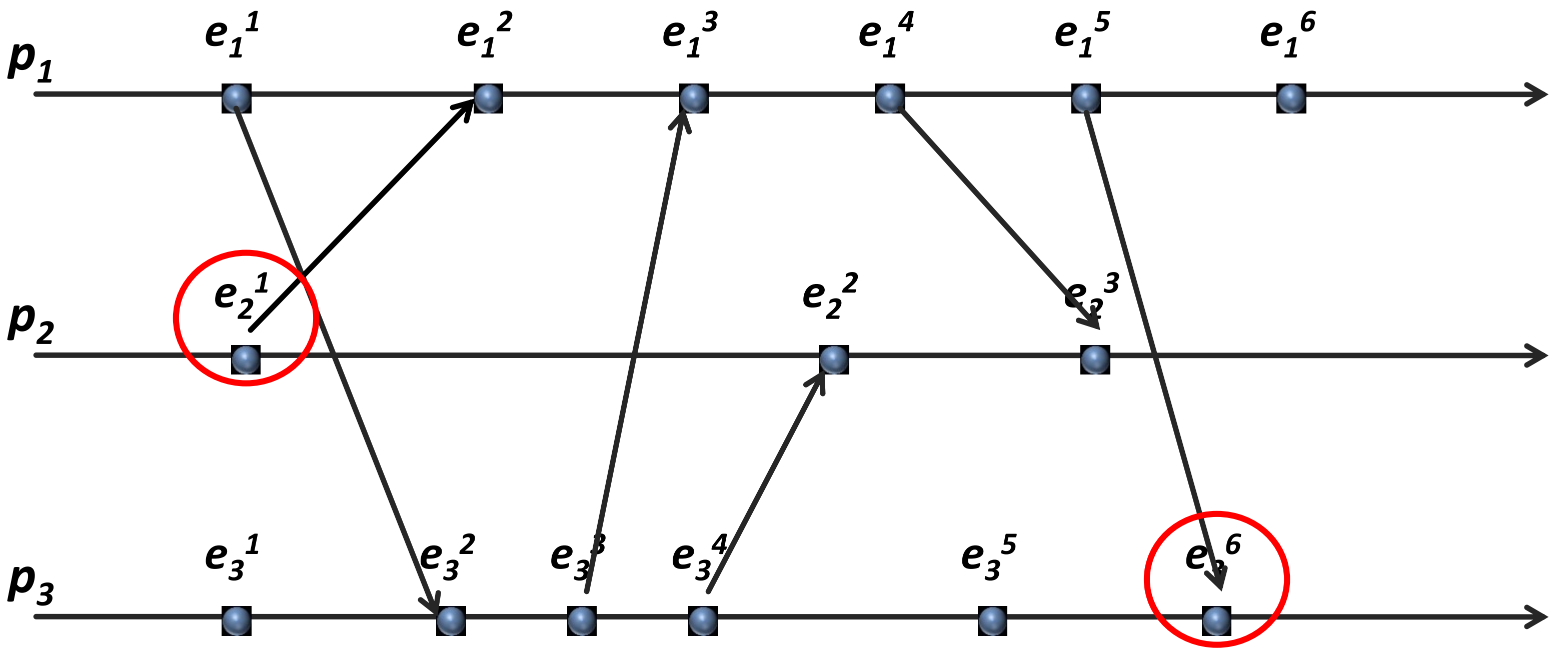

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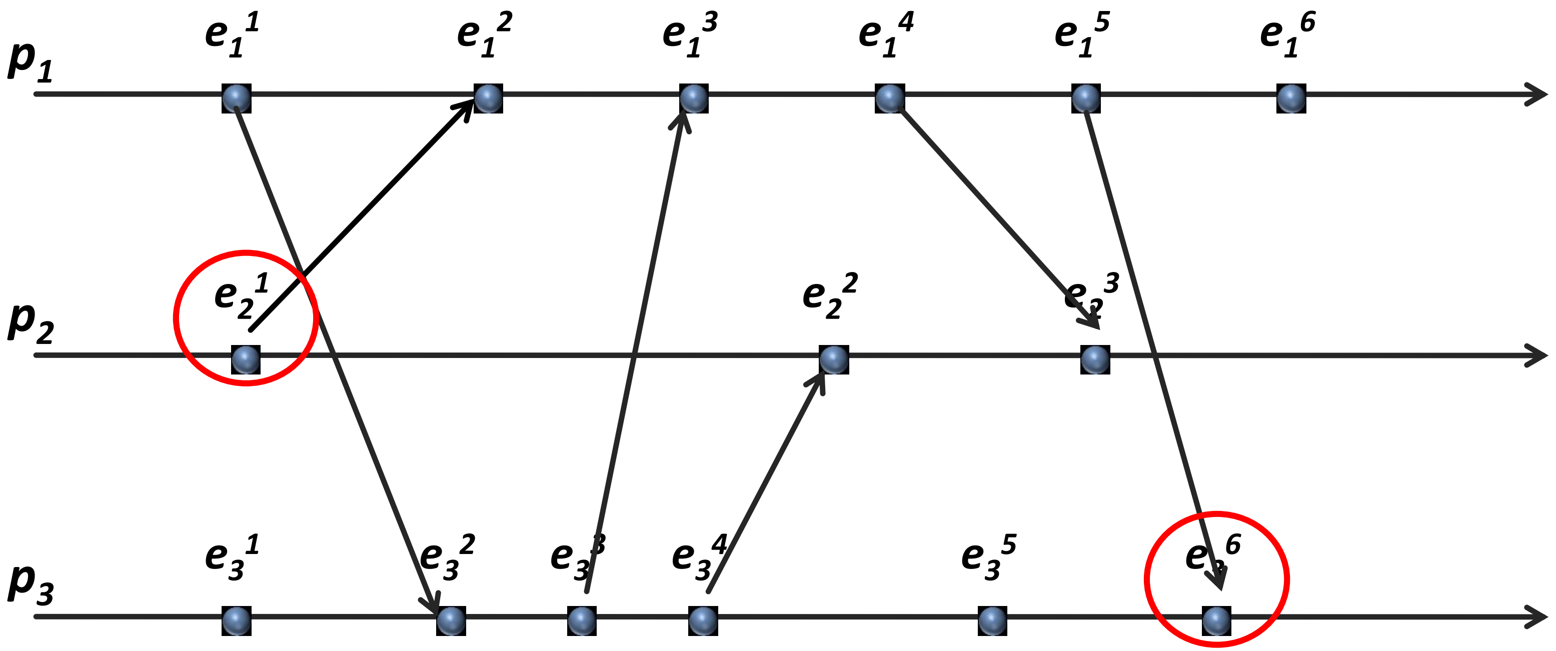

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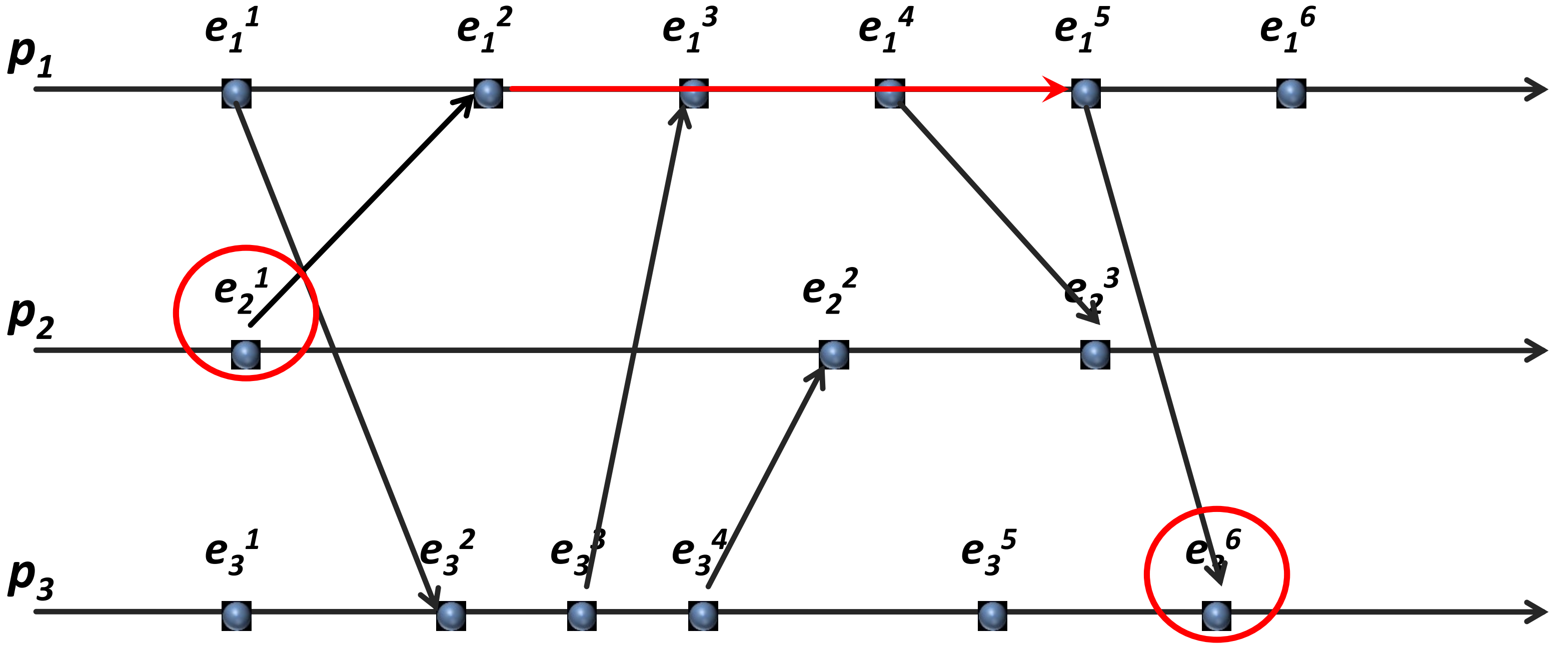

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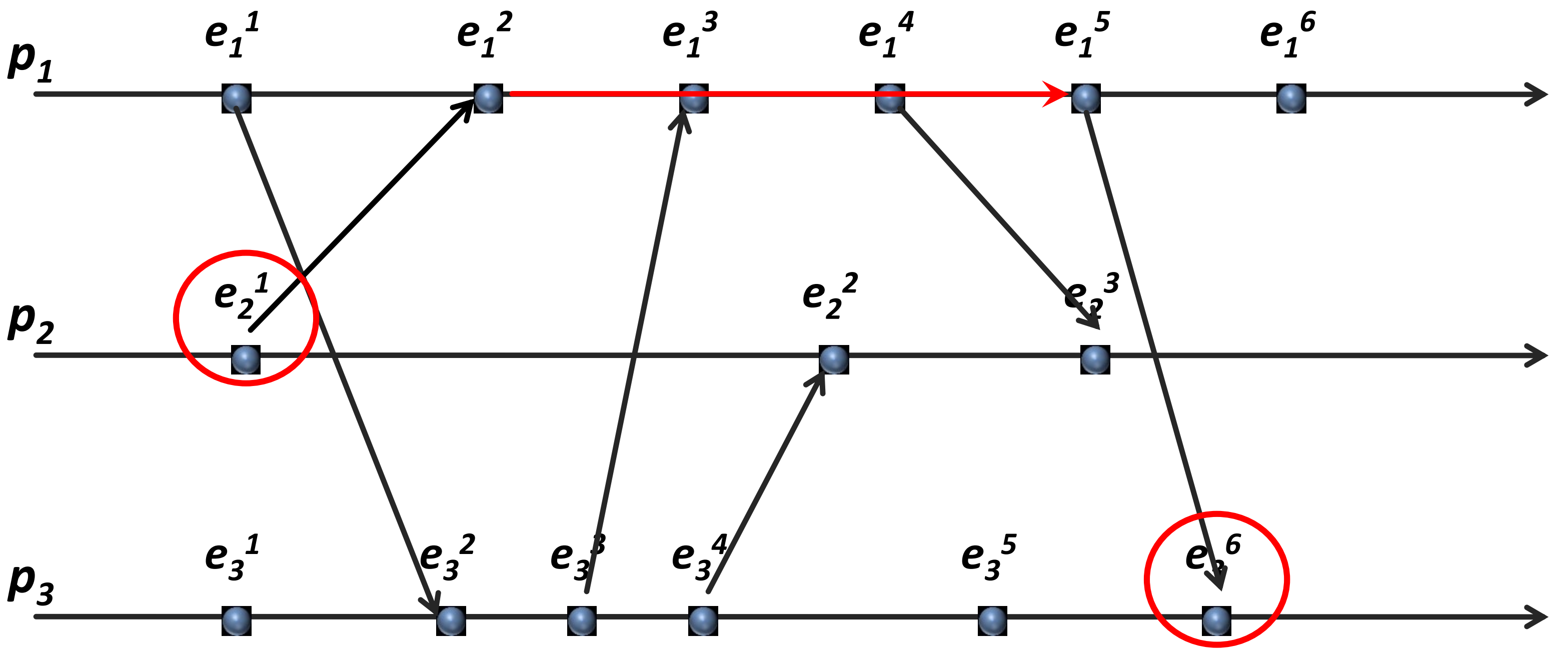

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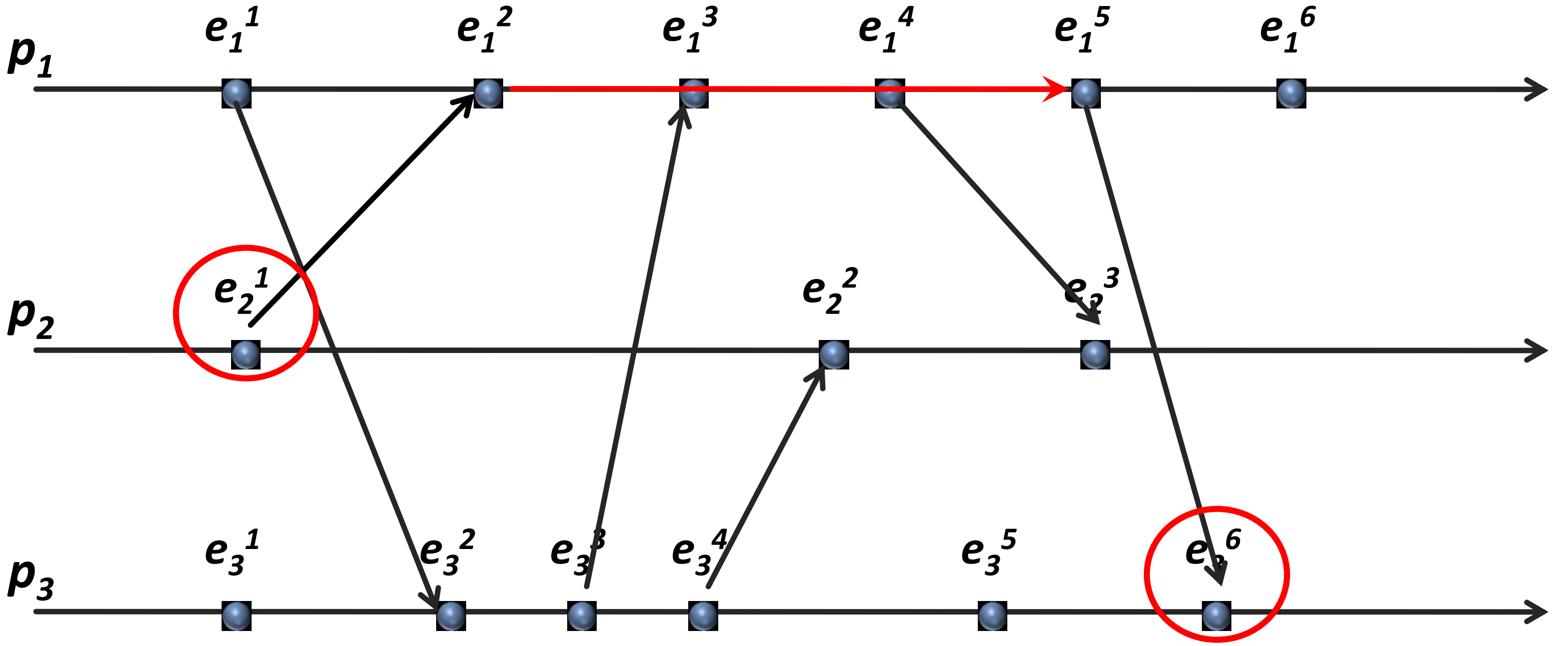

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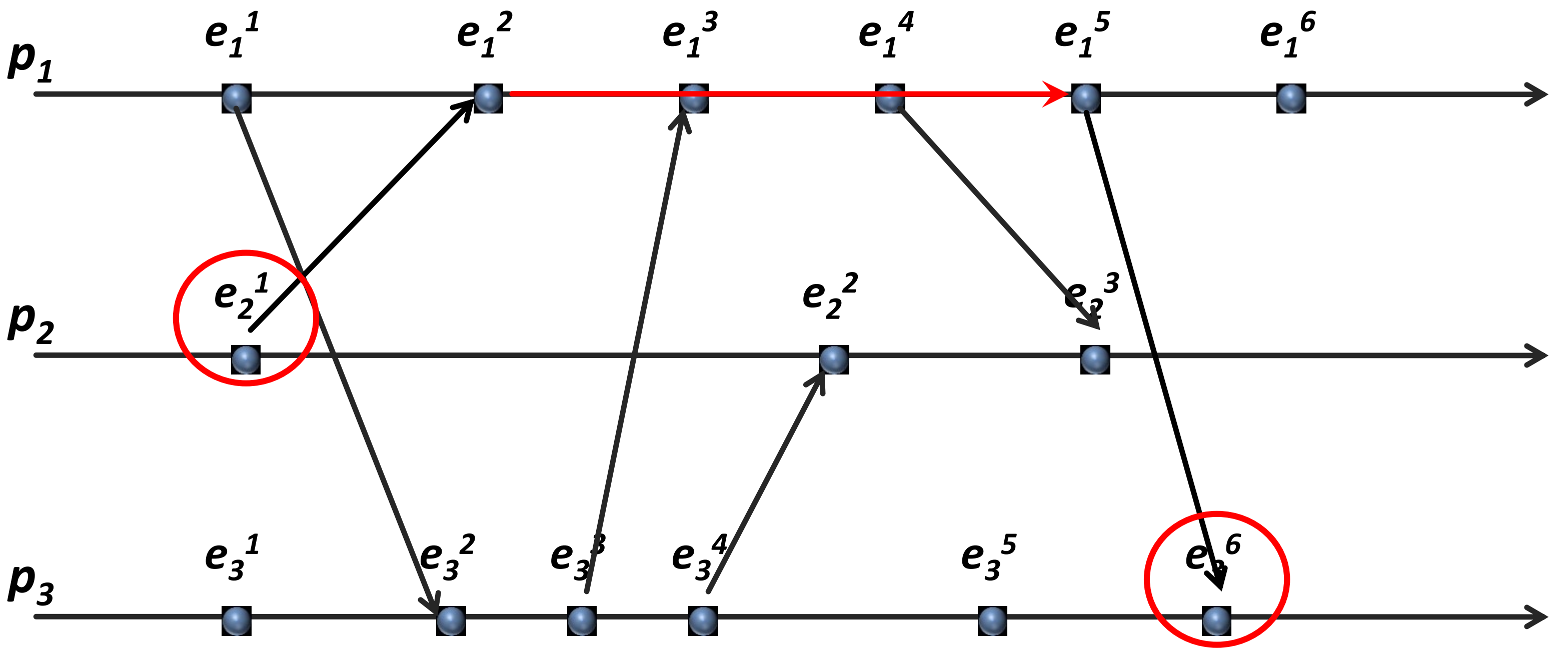

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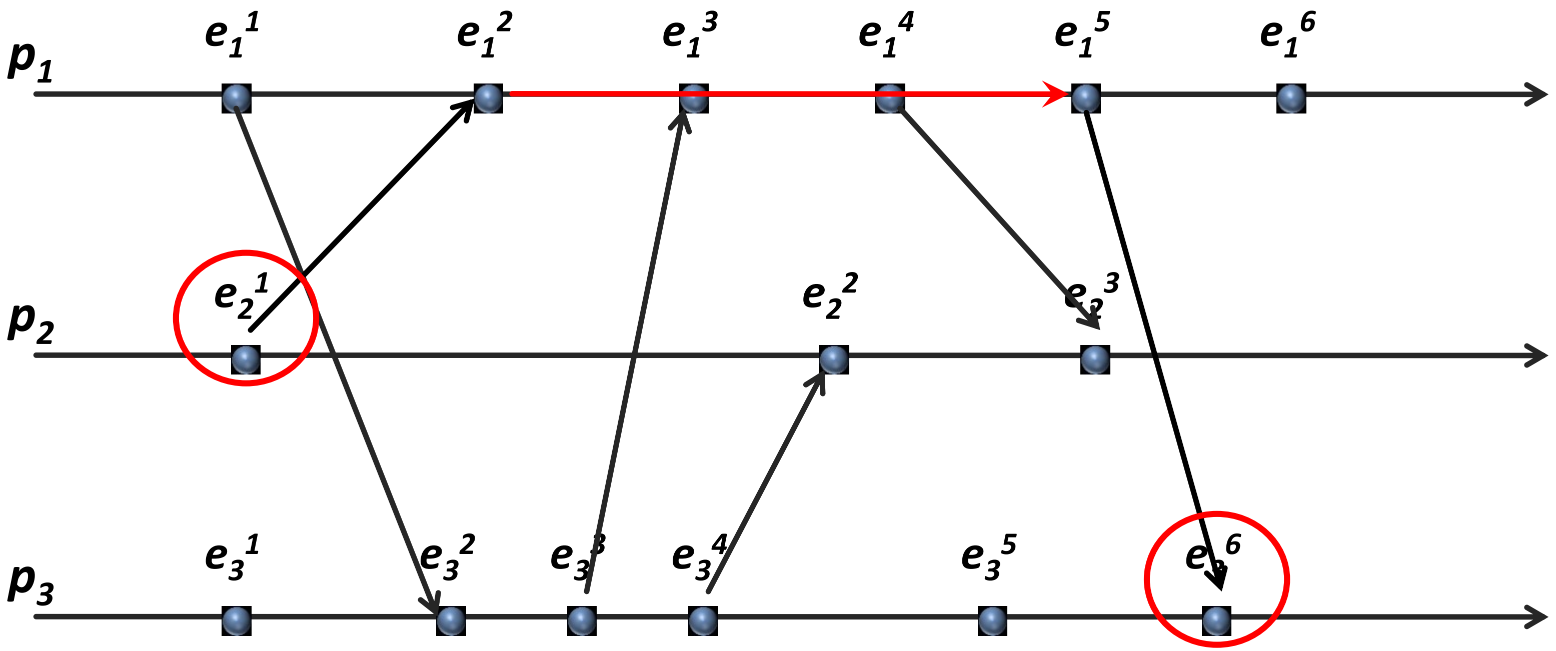

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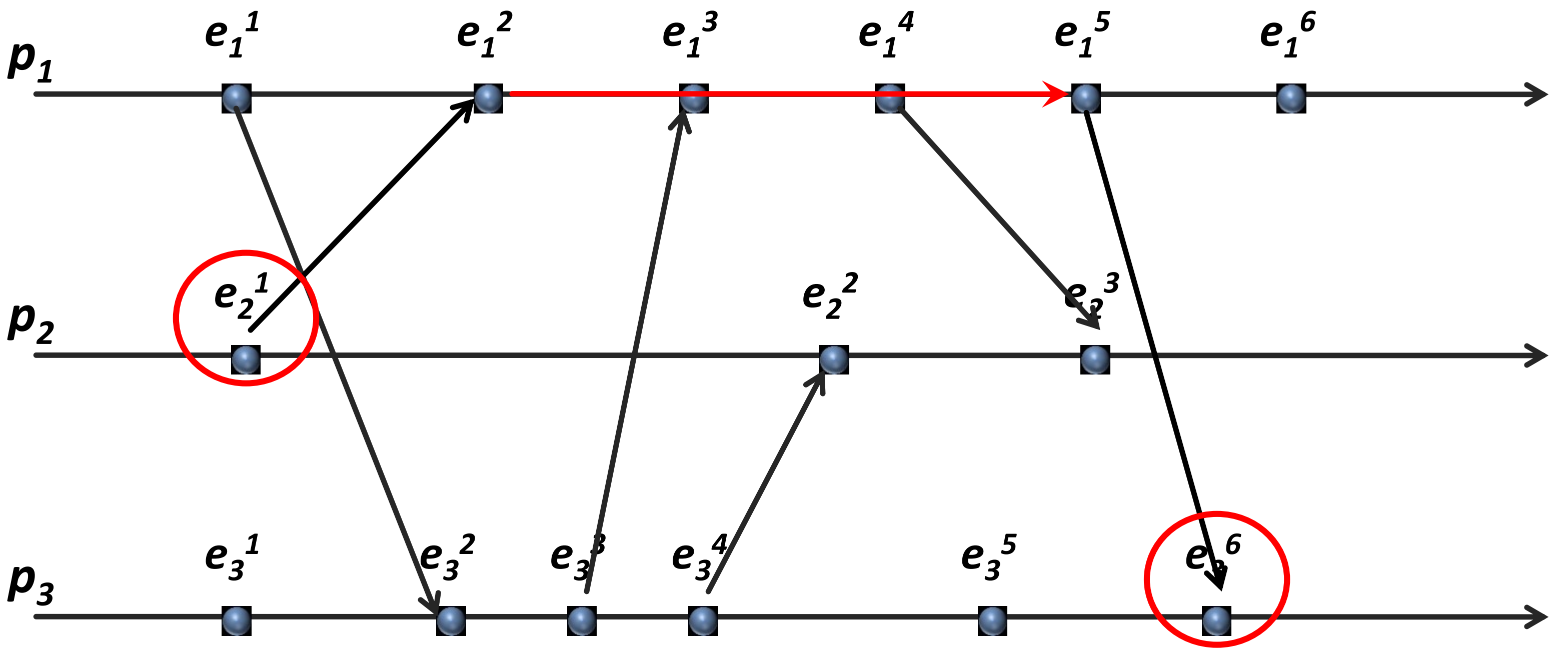

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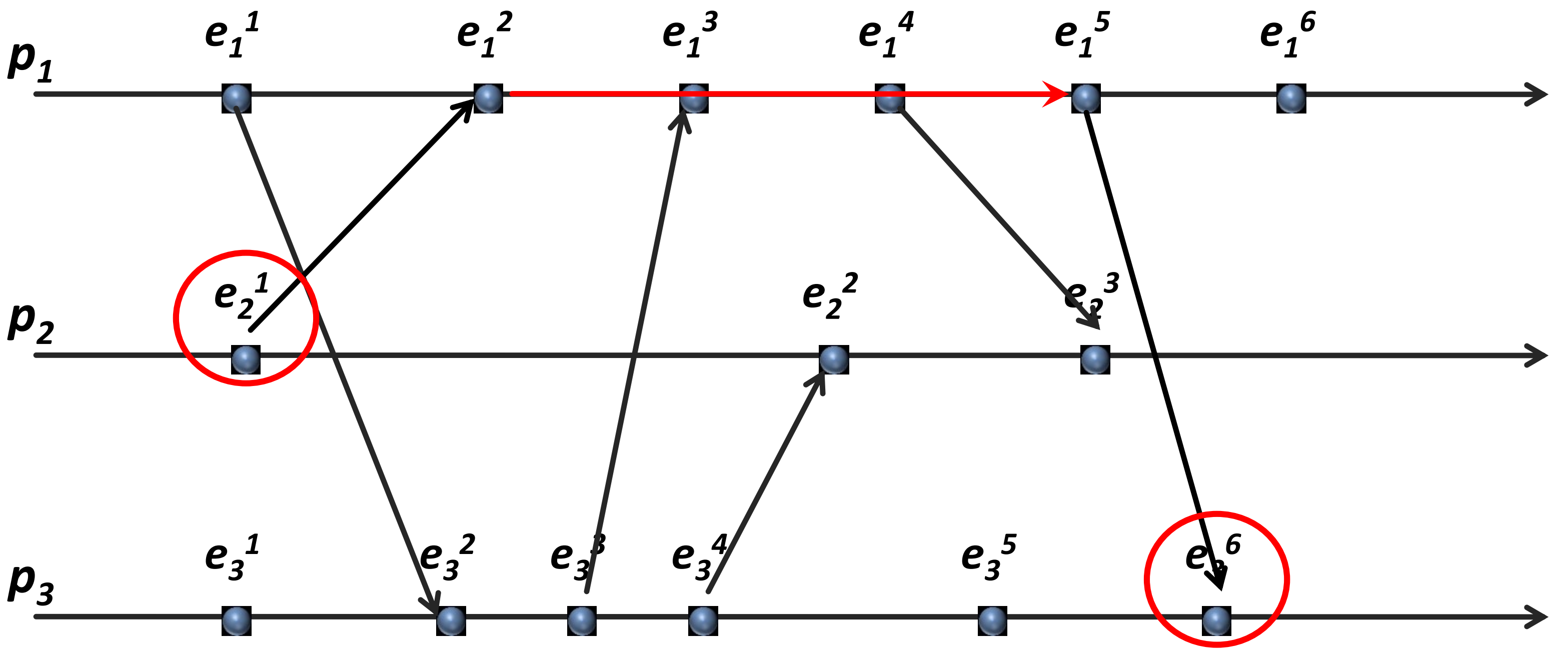

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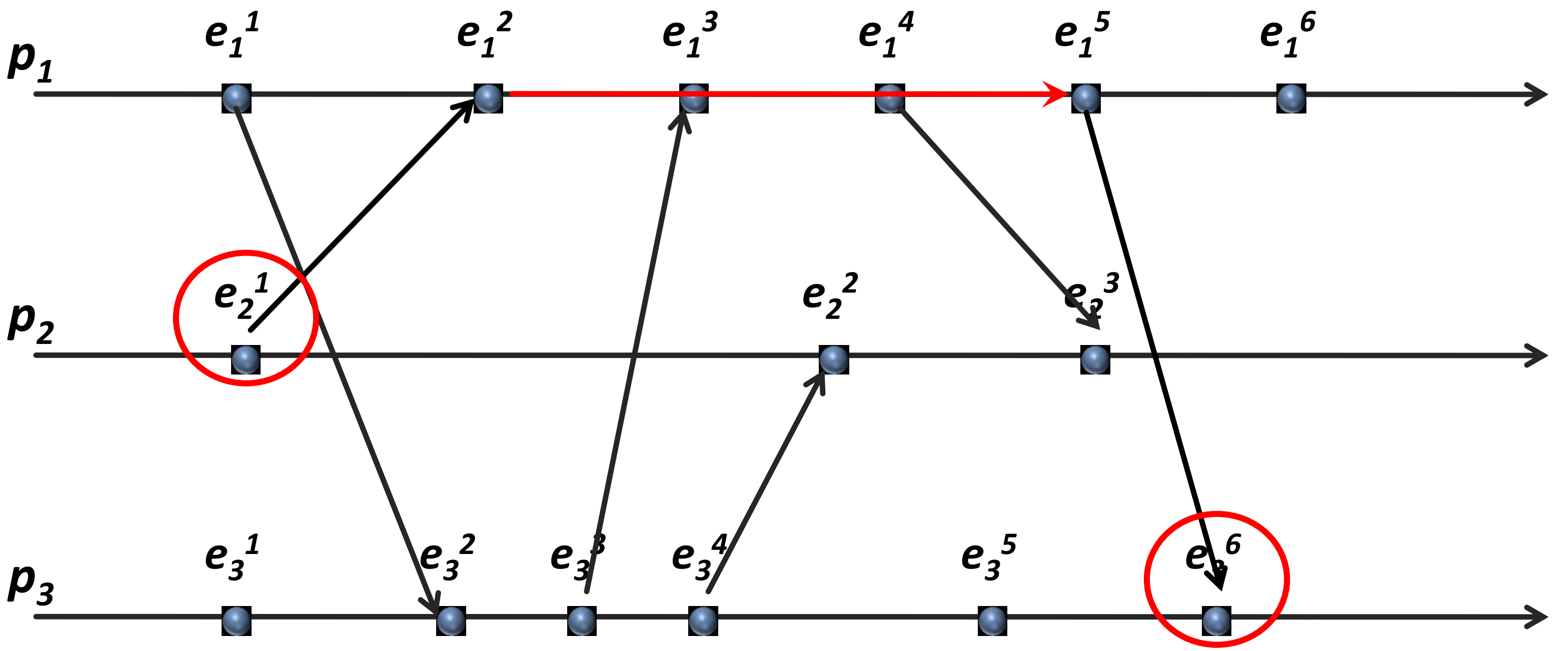

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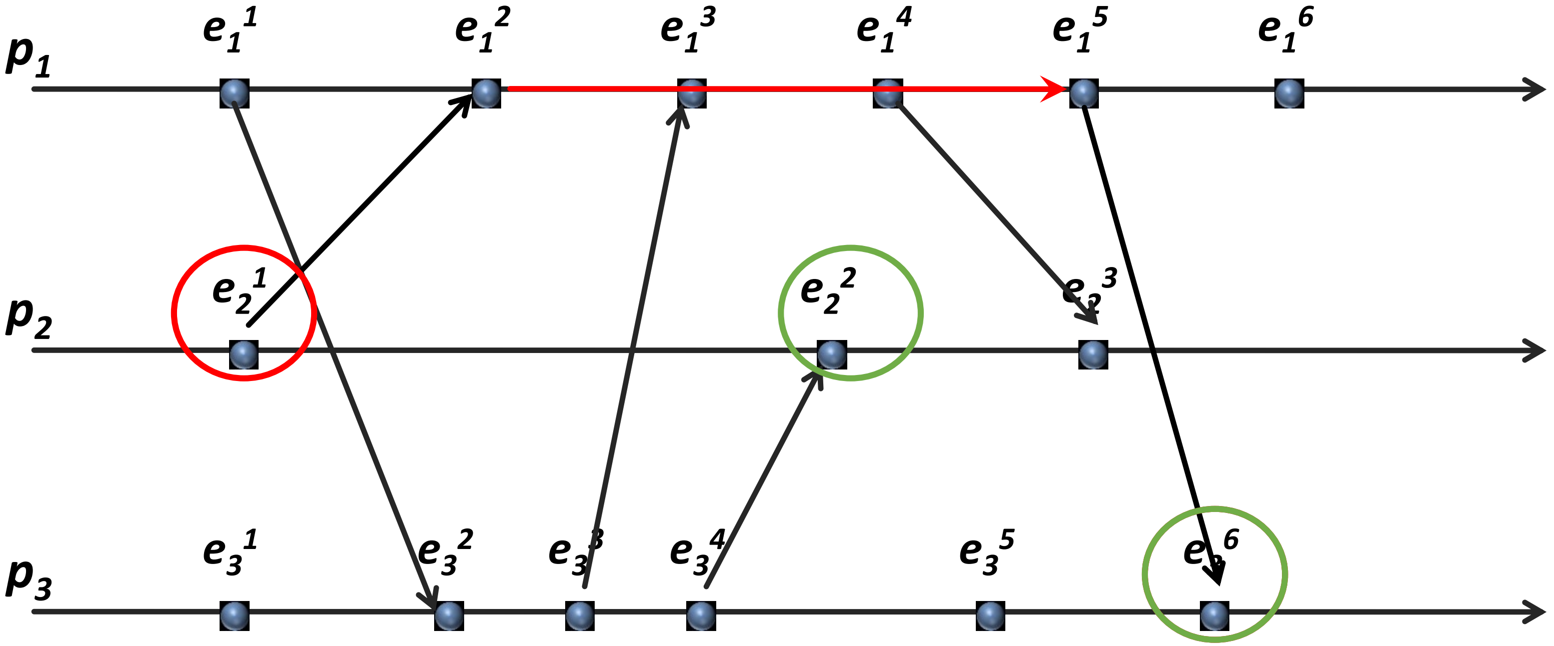

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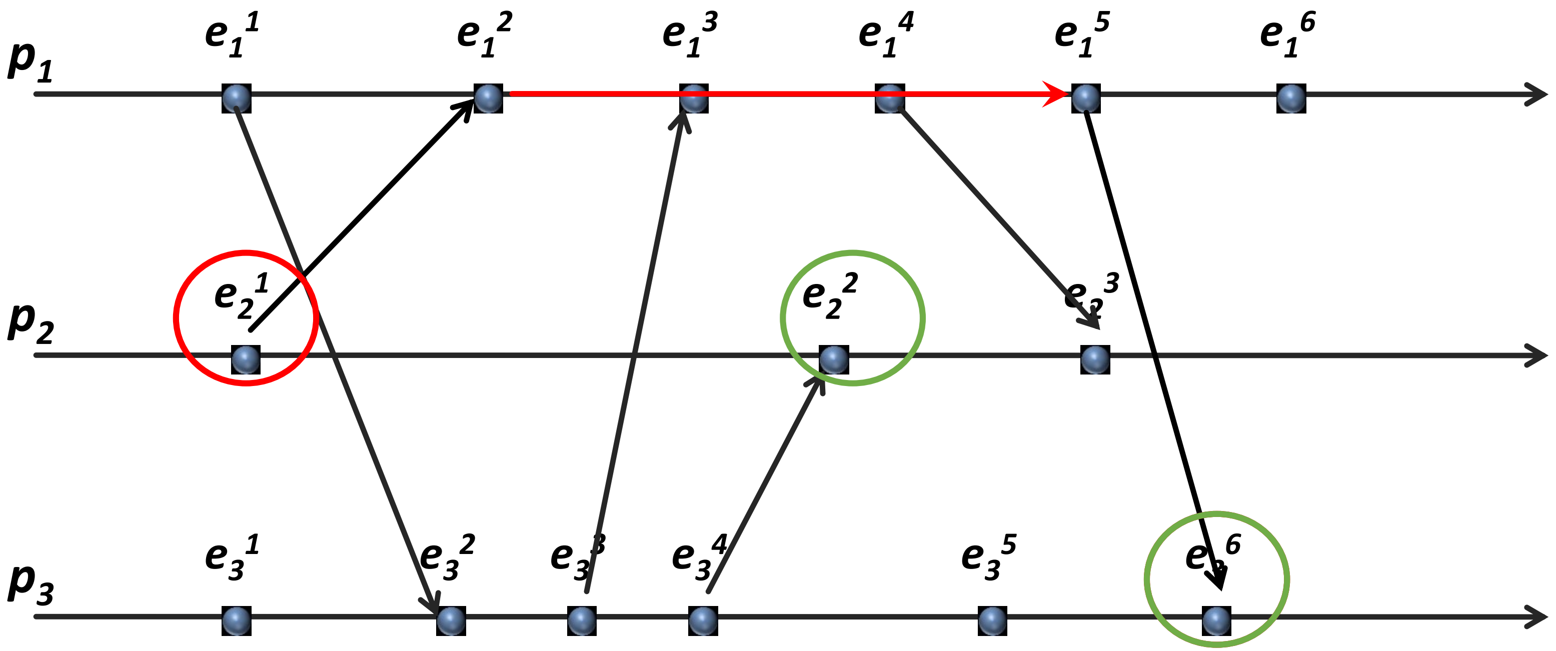

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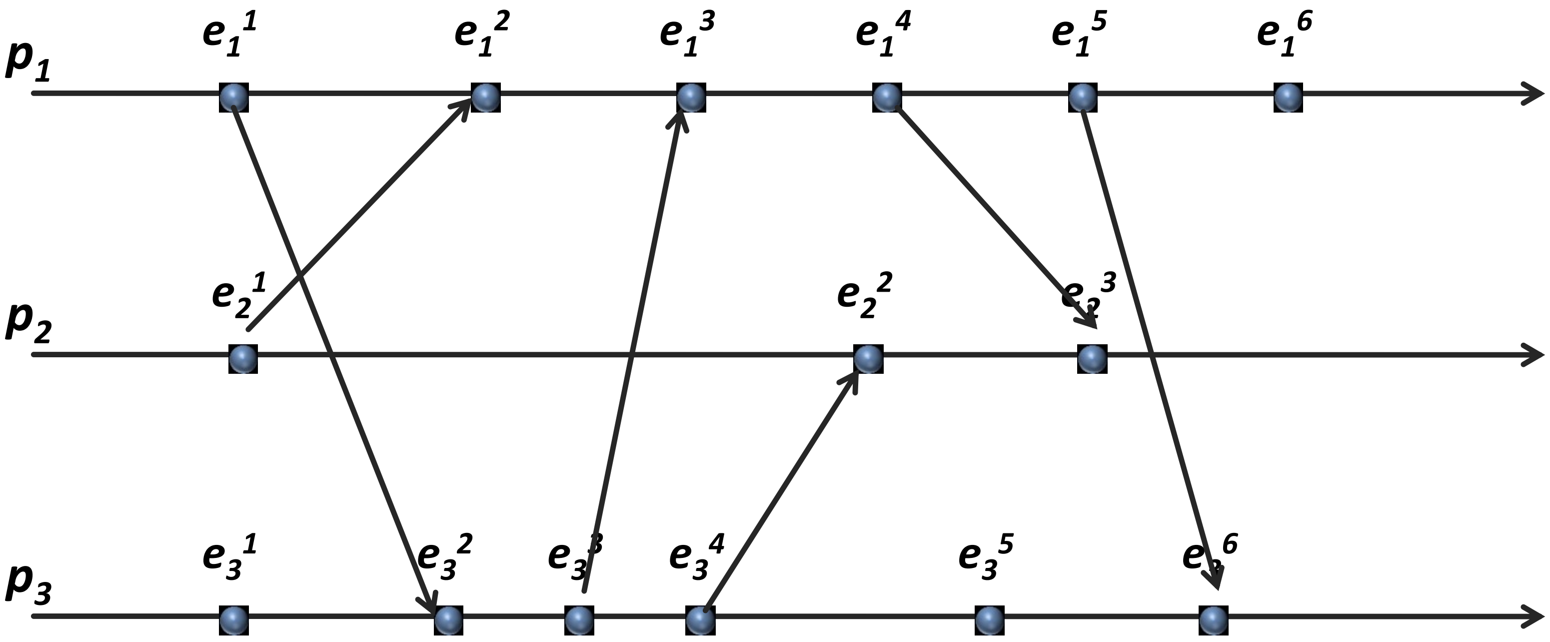
Cuts of an Asynchronous Computation

- 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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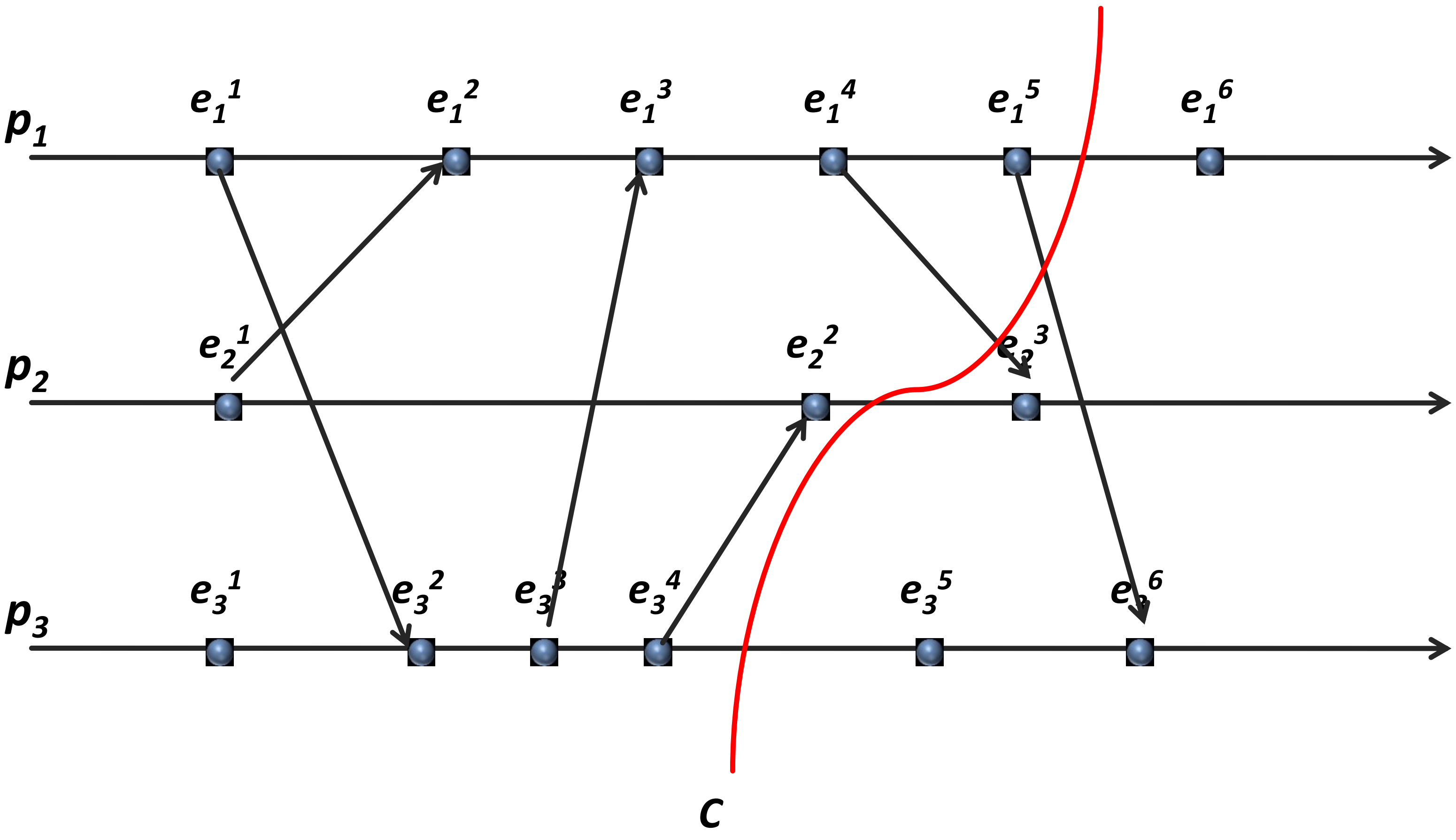

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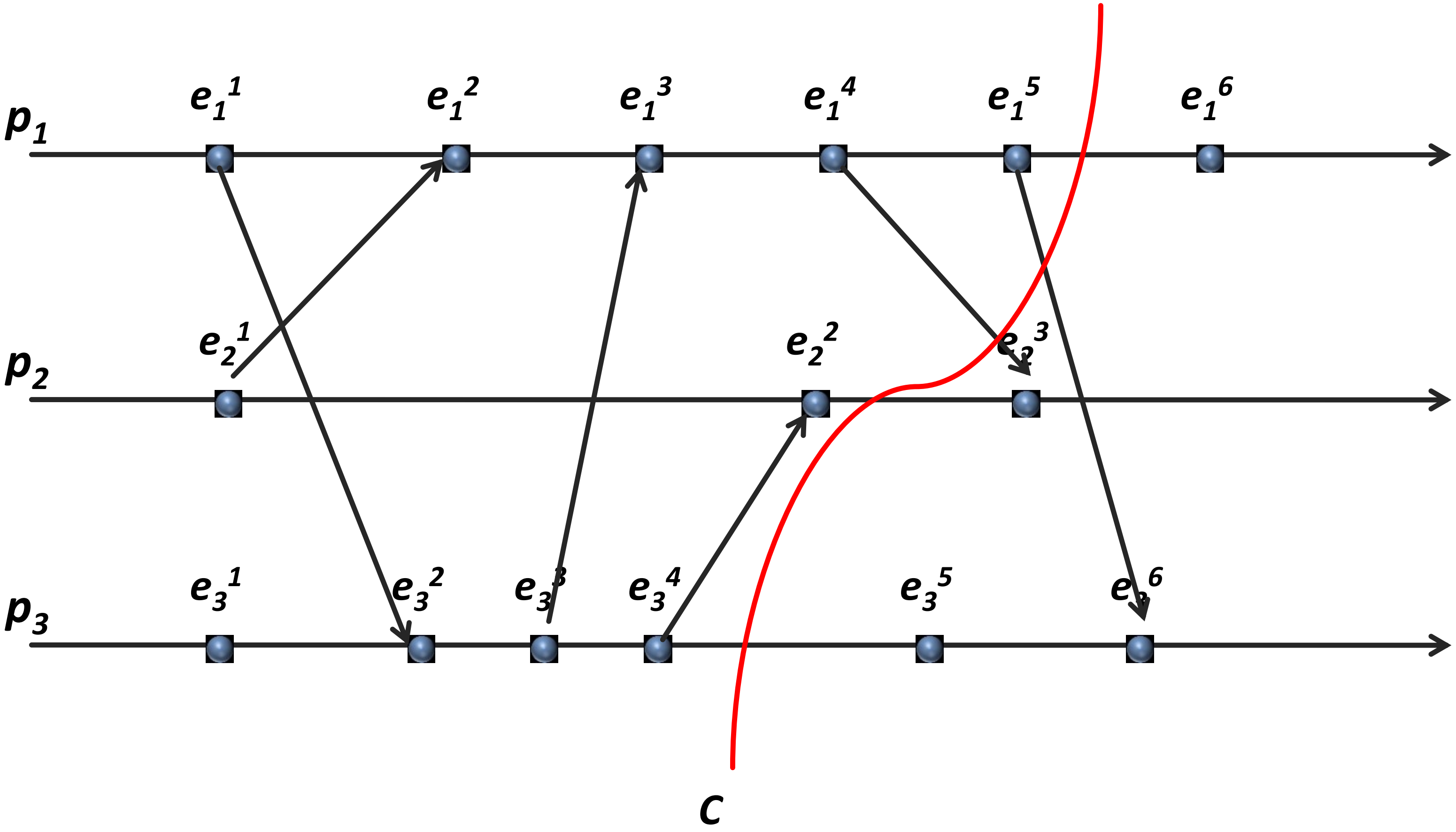

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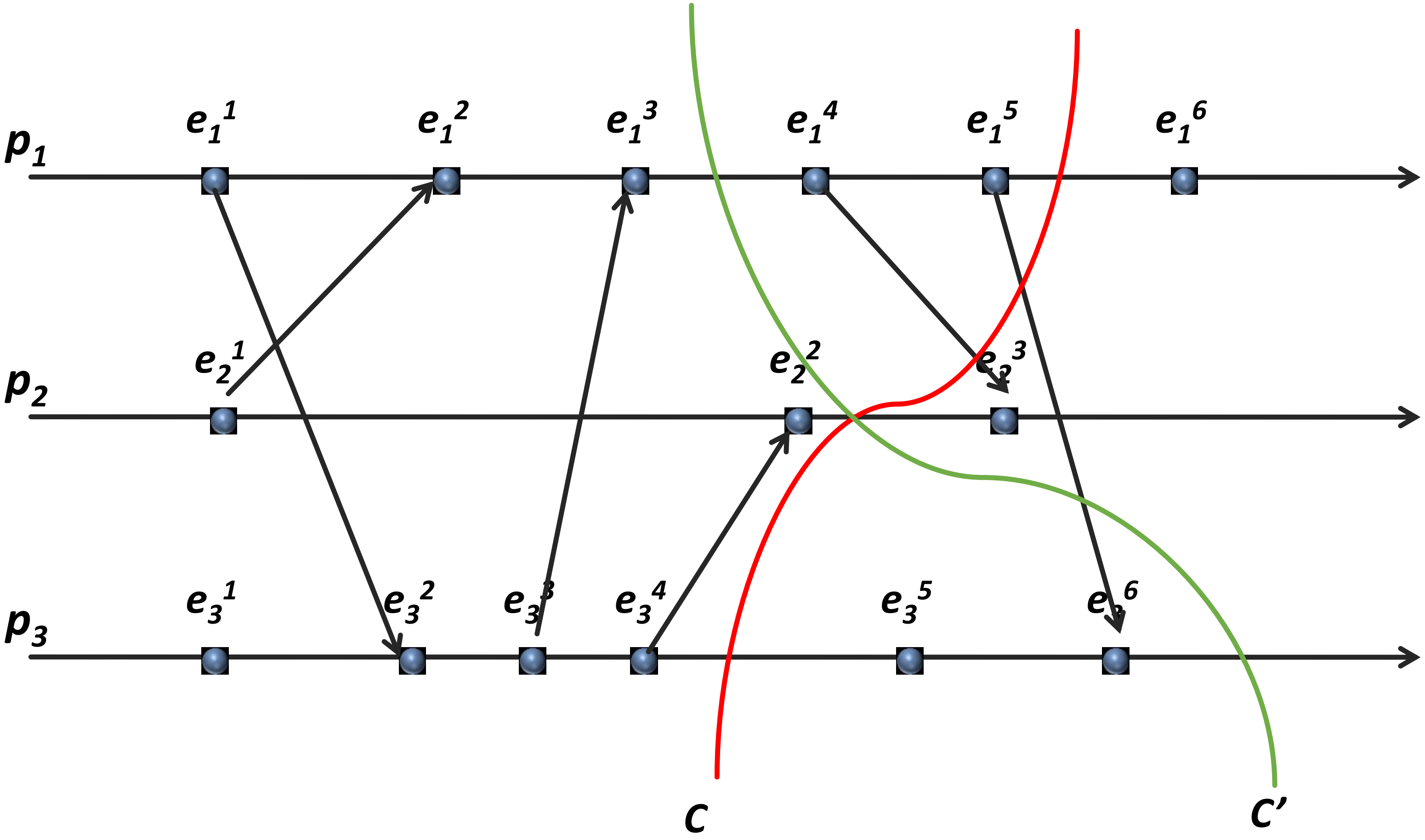
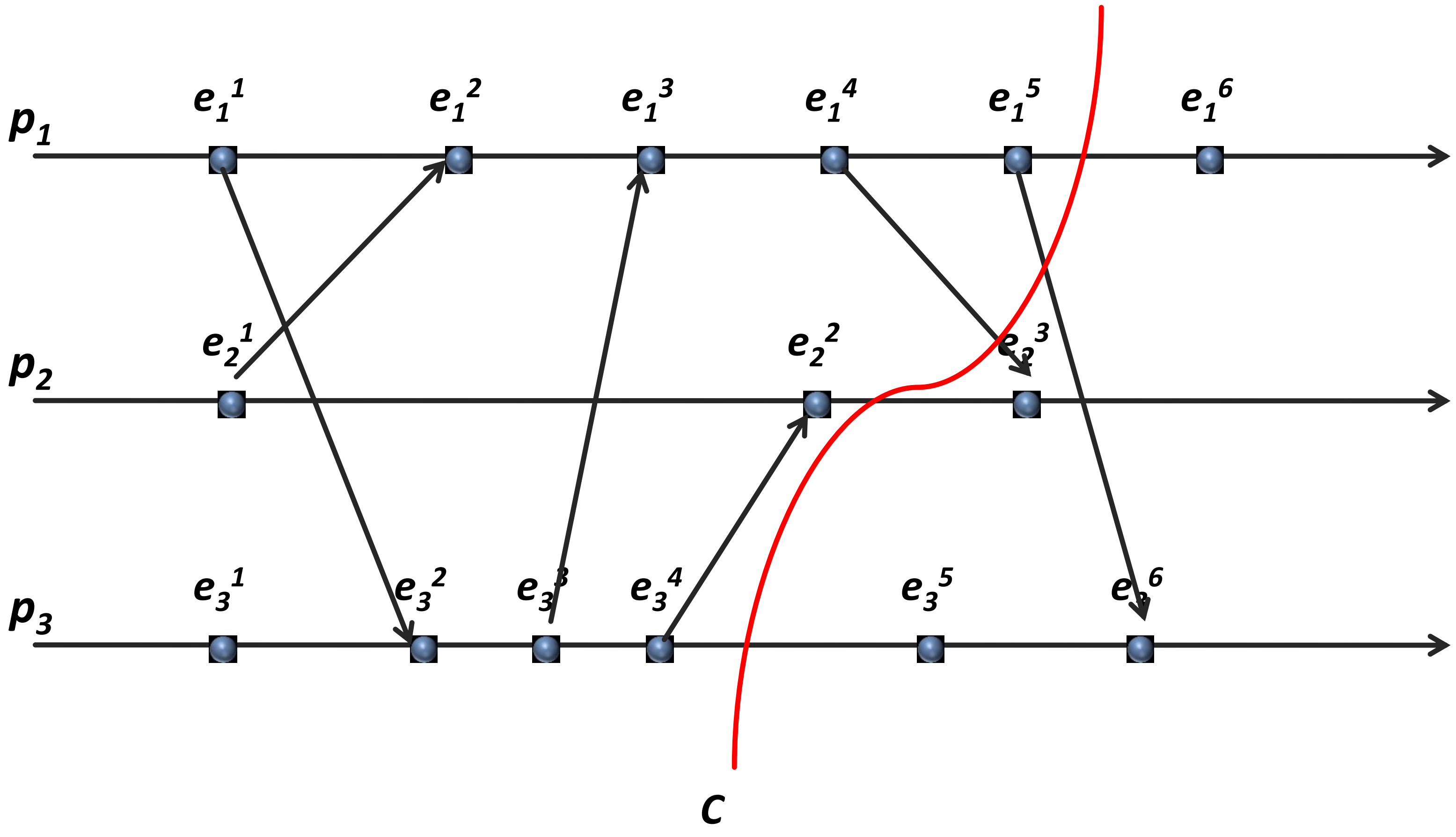


Consistent vs. Inconsistent Cuts

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

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

Are These Cuts Consistent?



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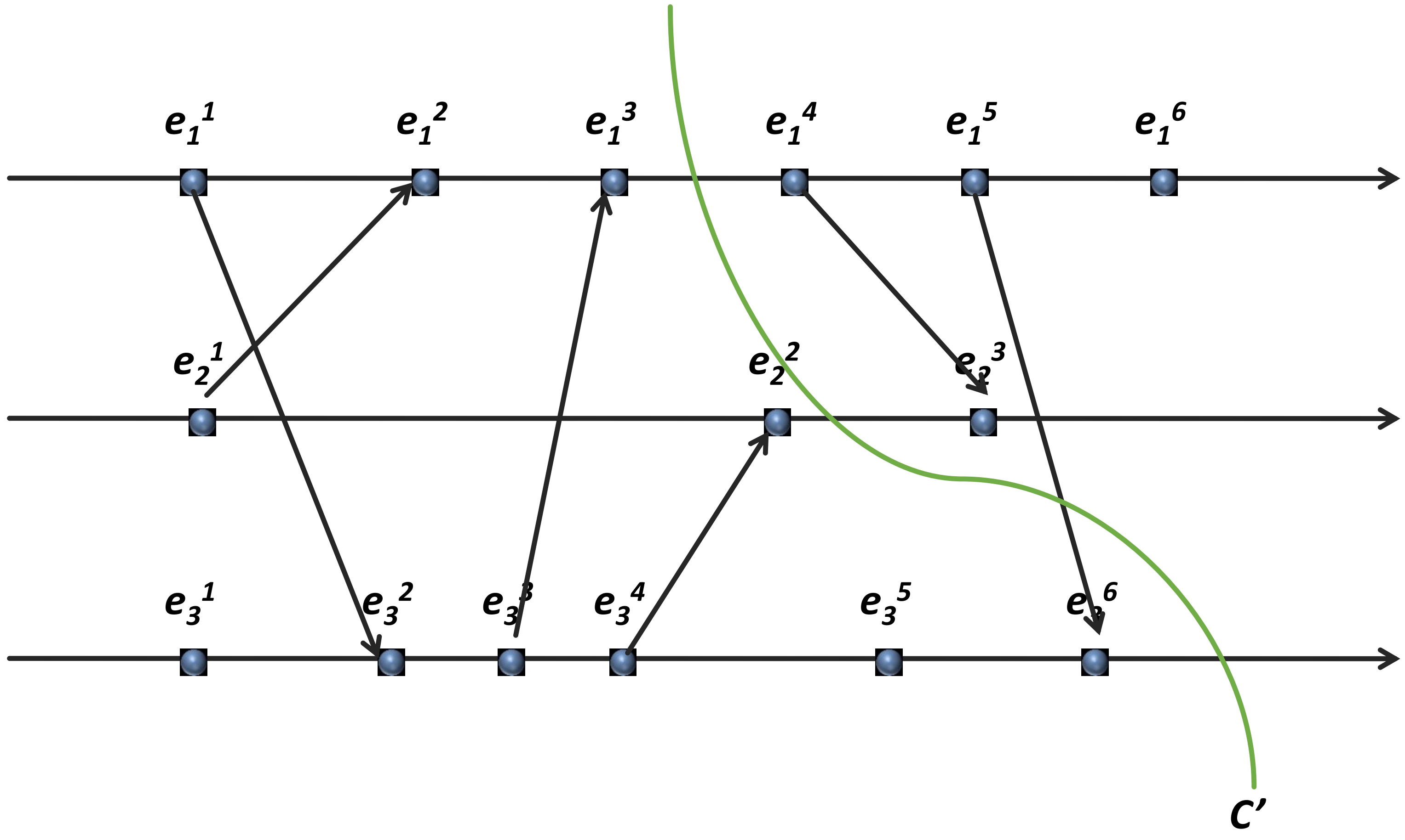

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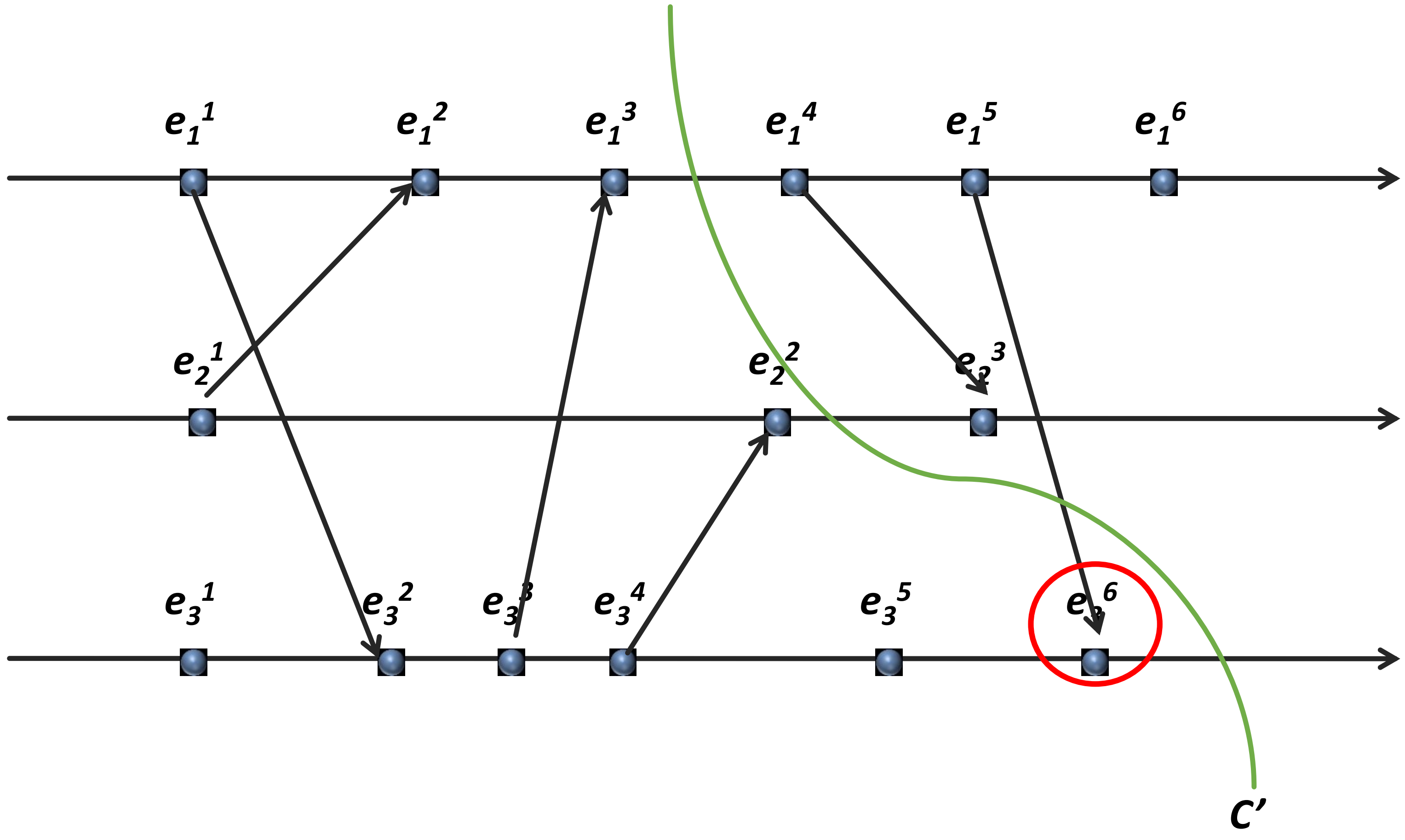

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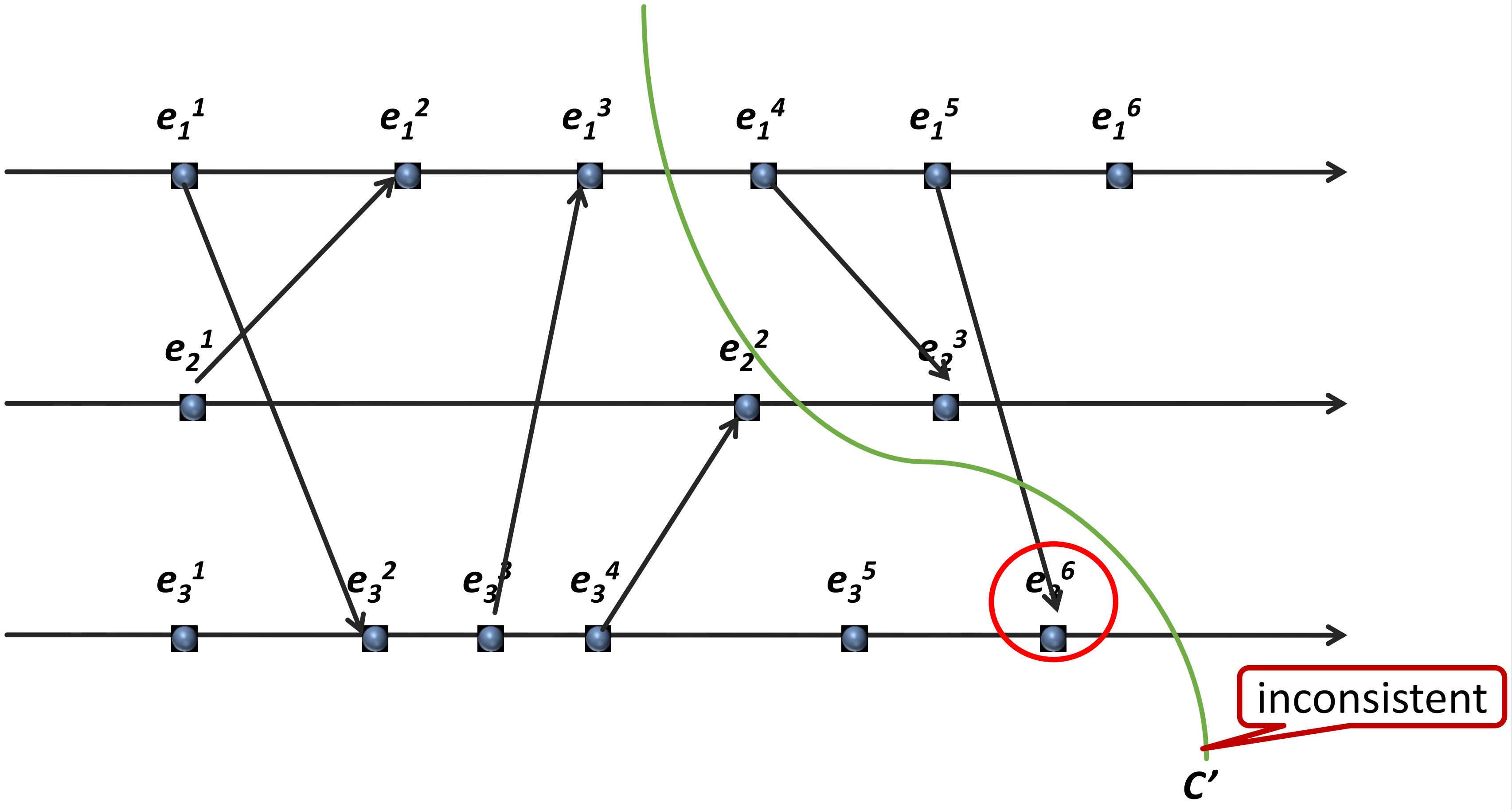

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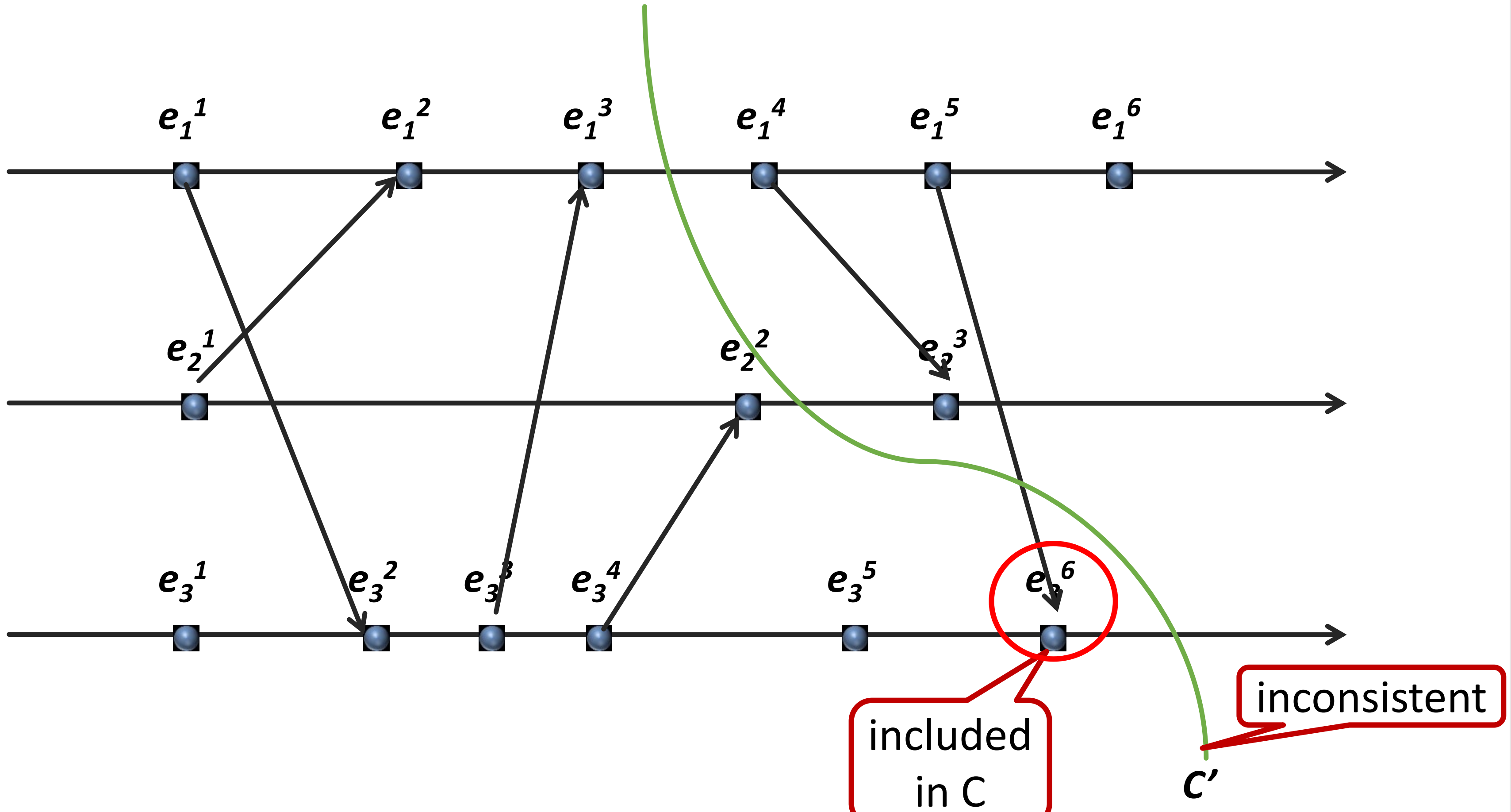

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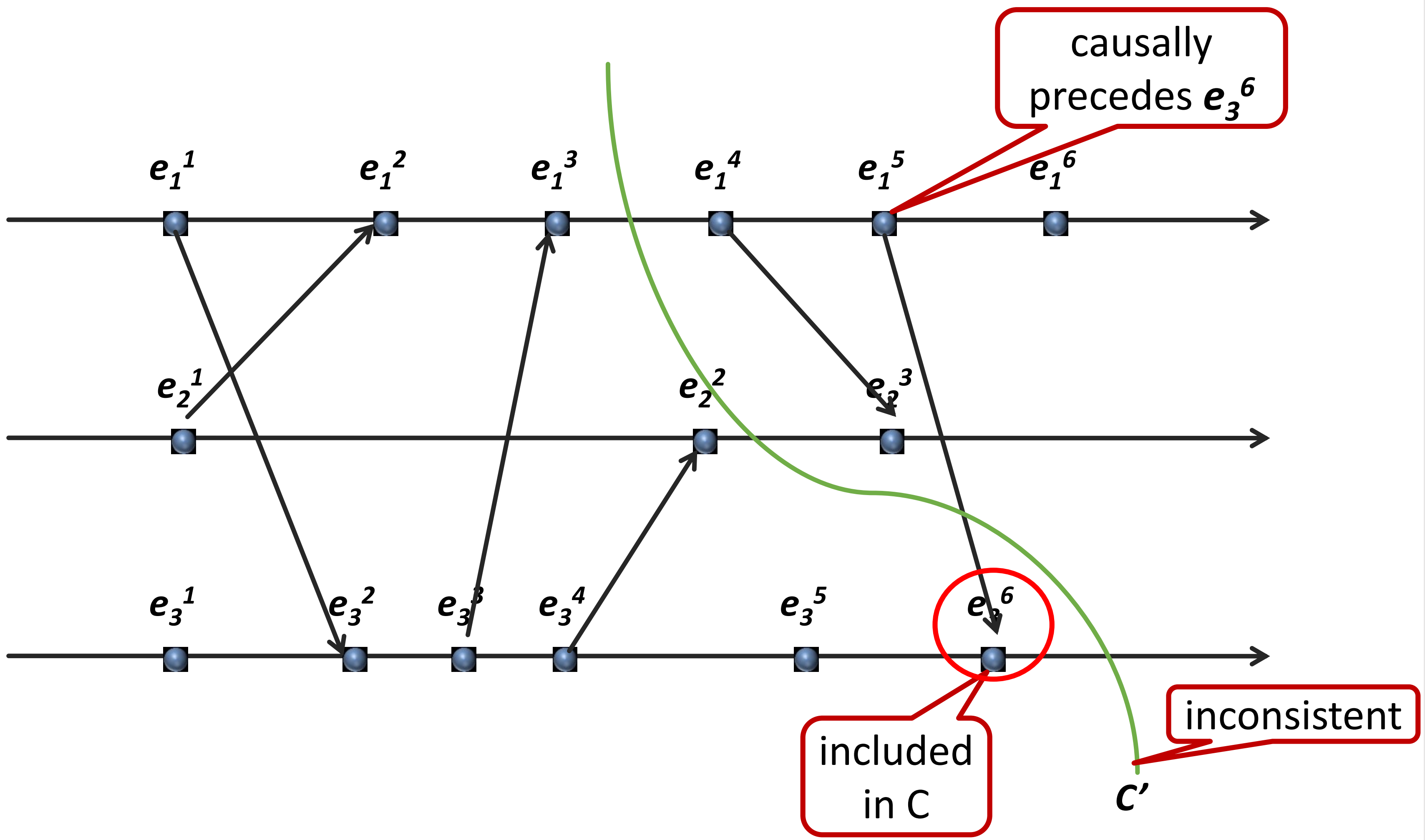

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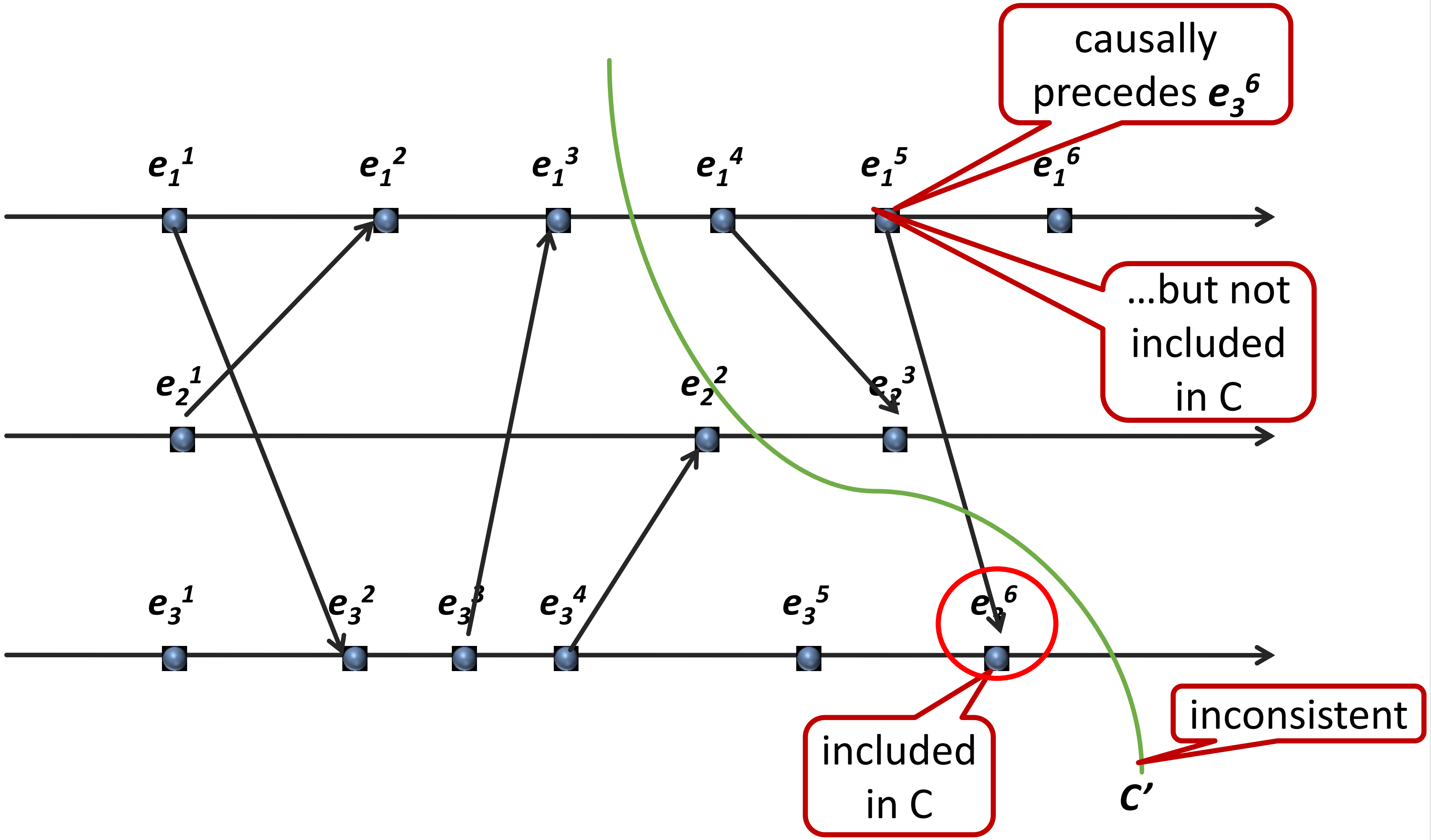

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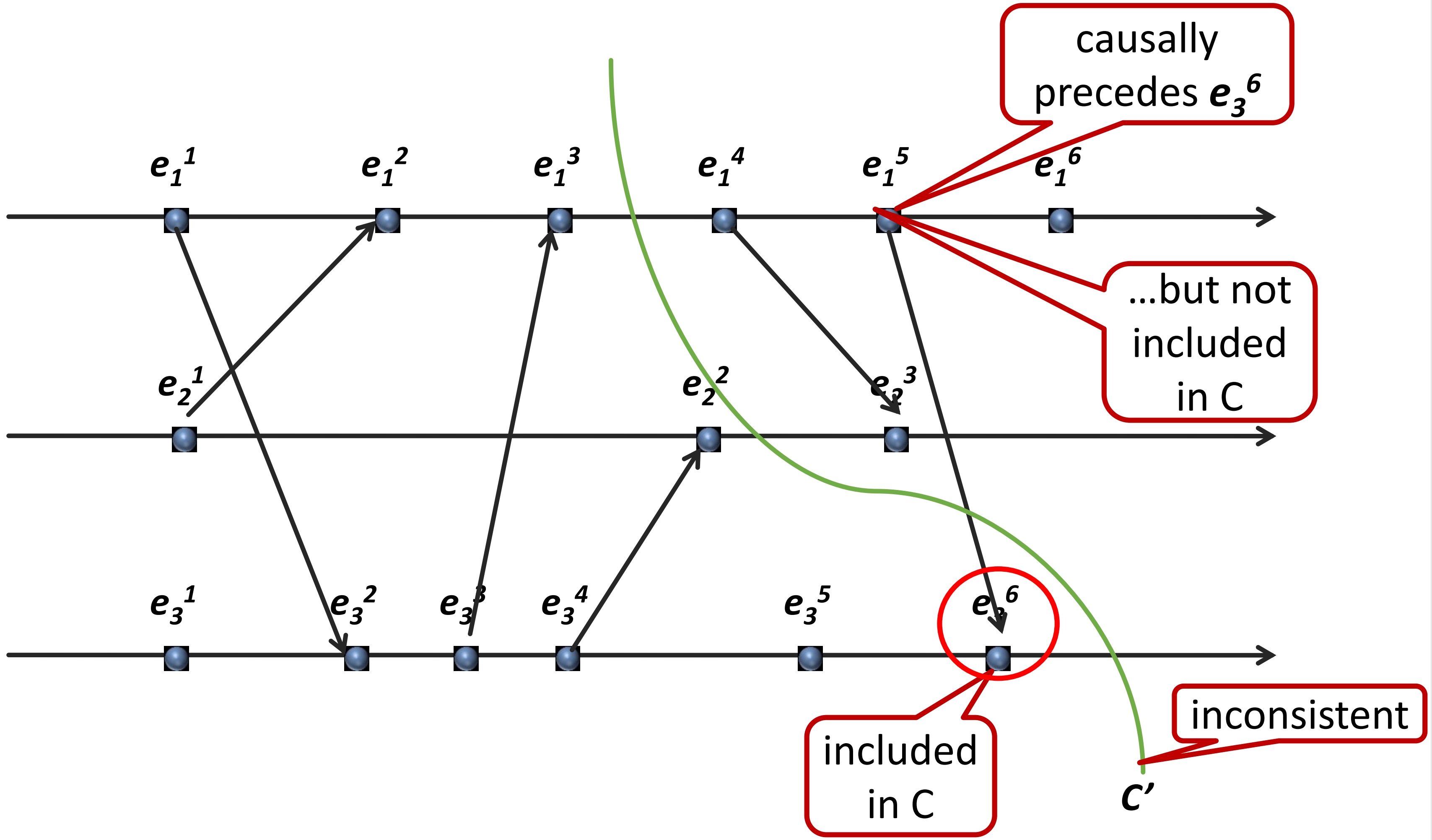
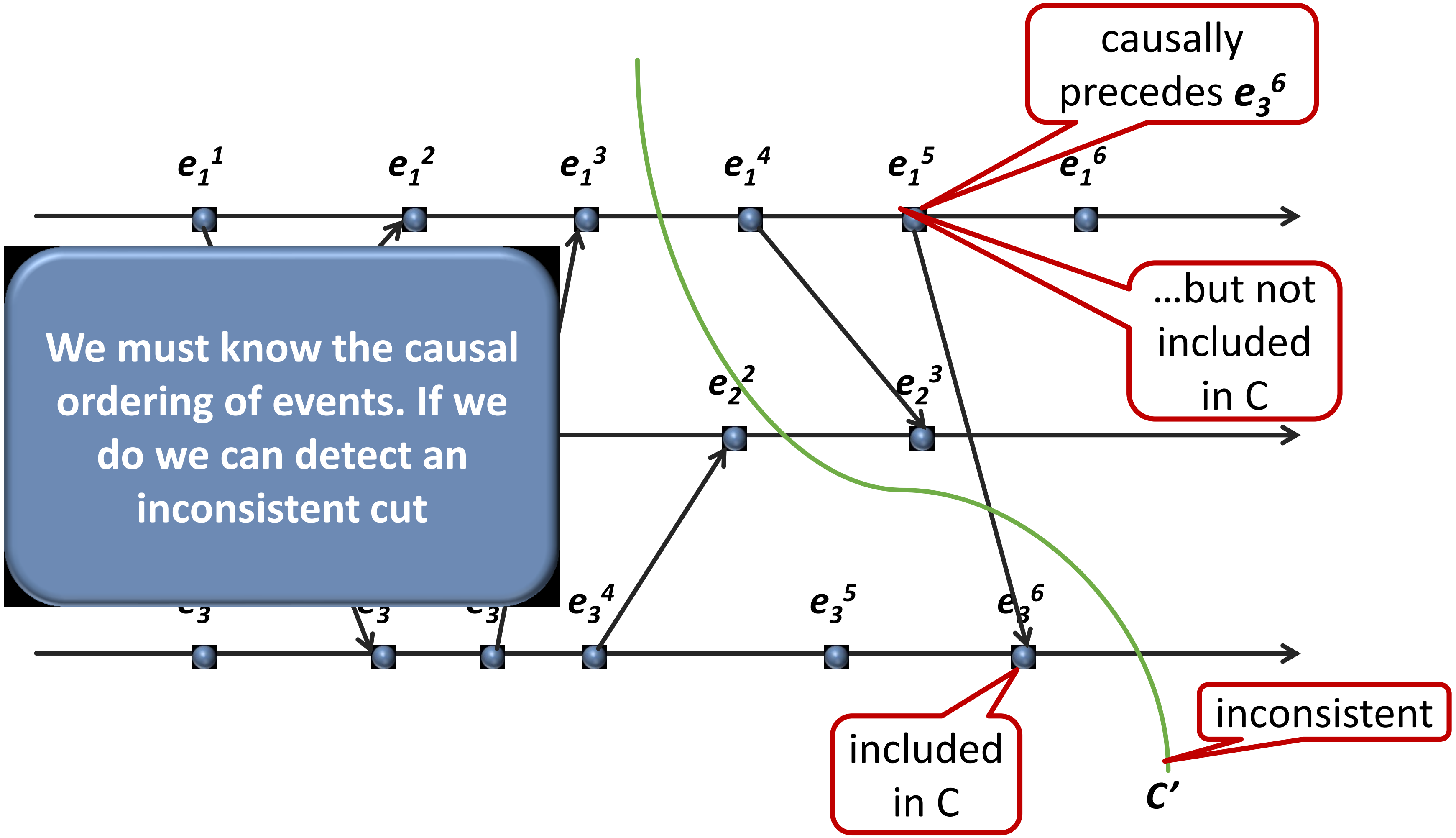


A consistent cut corresponds to a consistent global state

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



Logical Clocks

- Each process maintains a local value of a logical clock ***LC***
- LC for process *p* counts **how many events 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 only a single process:

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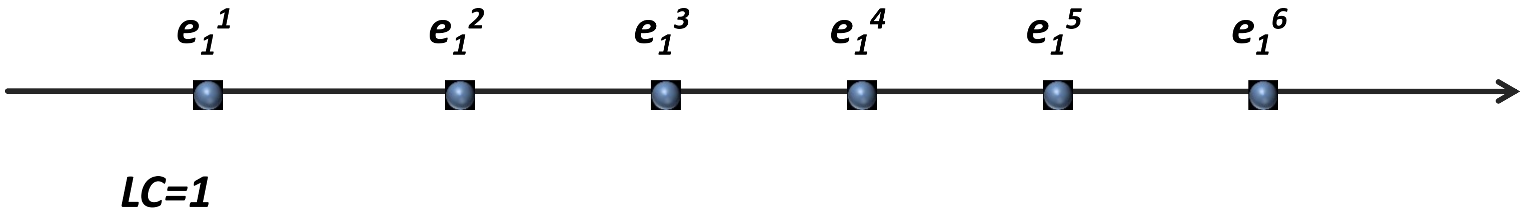

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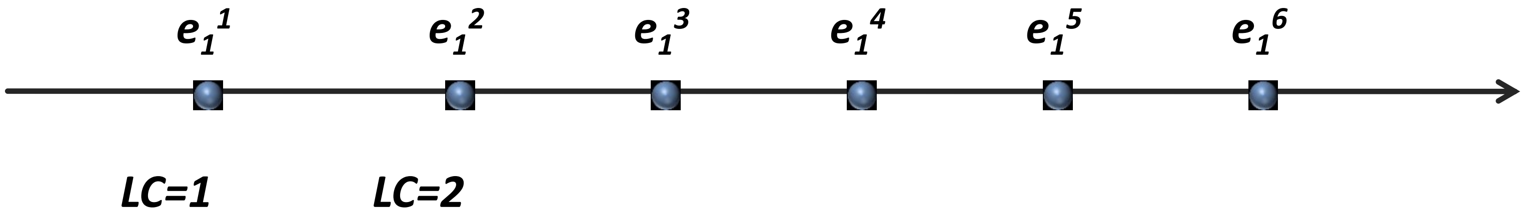

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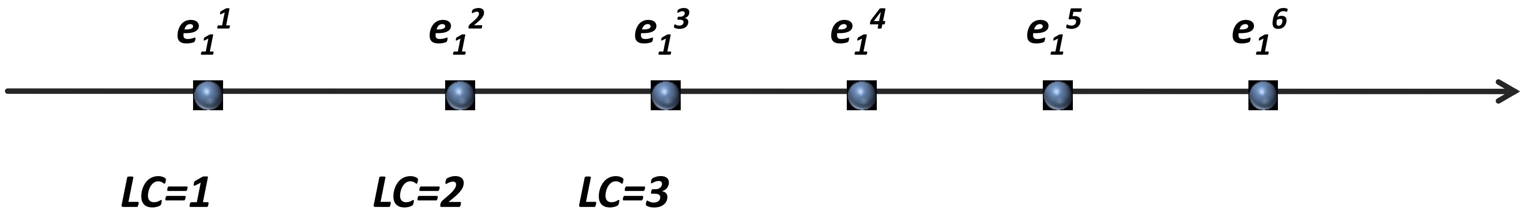

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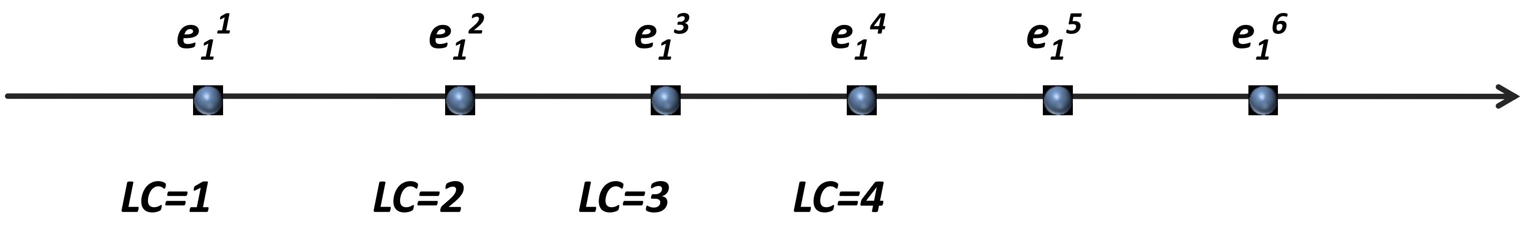

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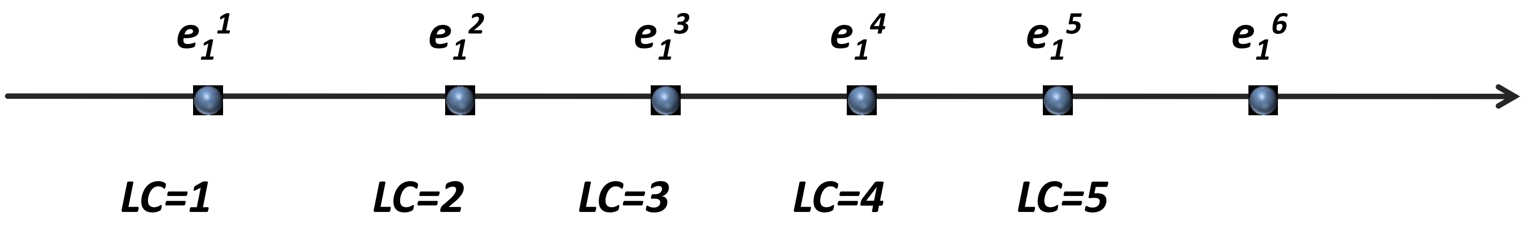

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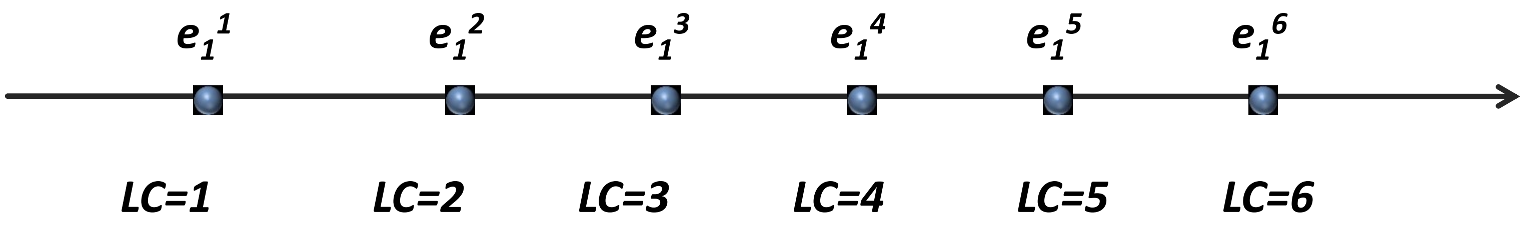

Logical Clocks (cont.)

With >1 process (thread) logical clocks updated:

- Each message m sent contains a timestamp TS(m)
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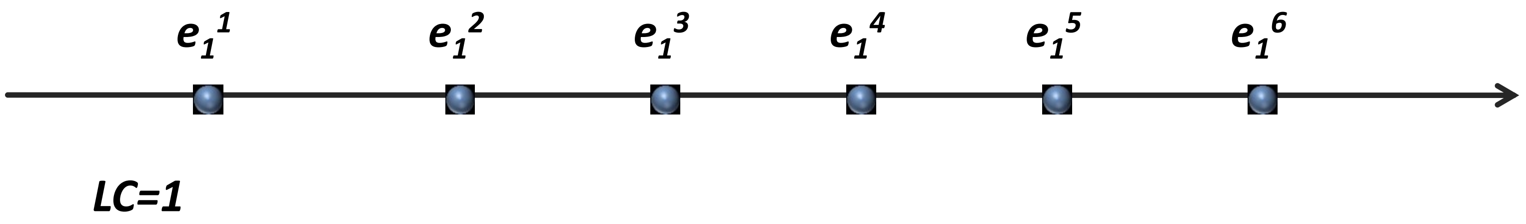

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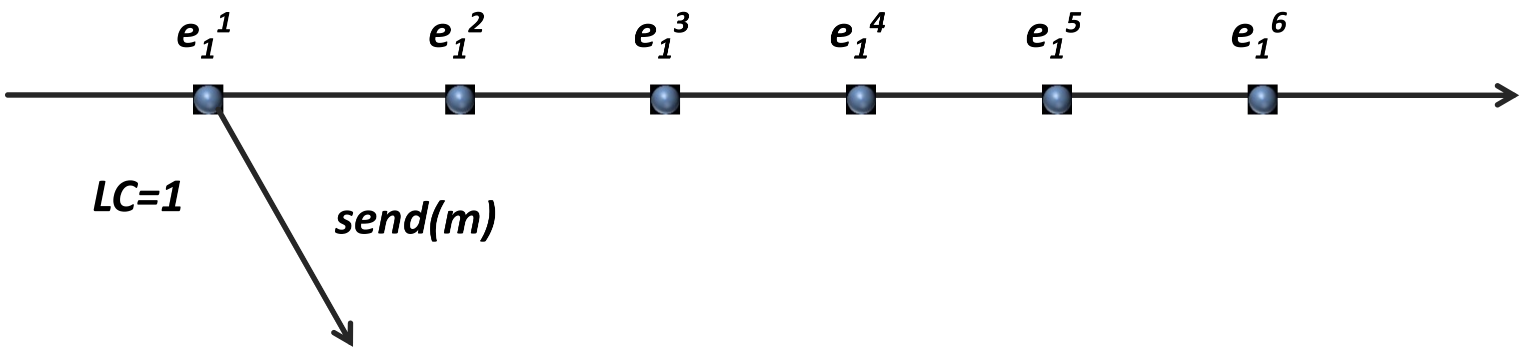

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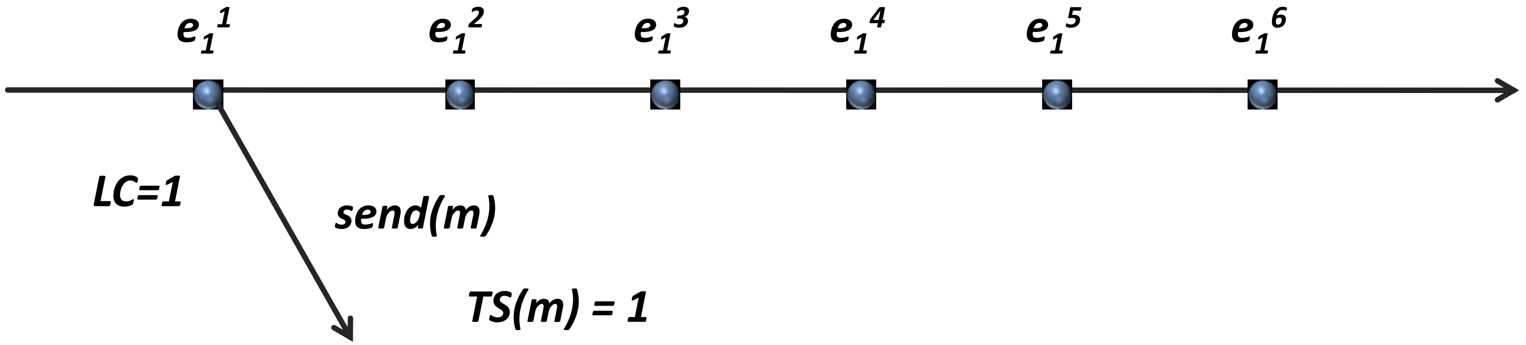

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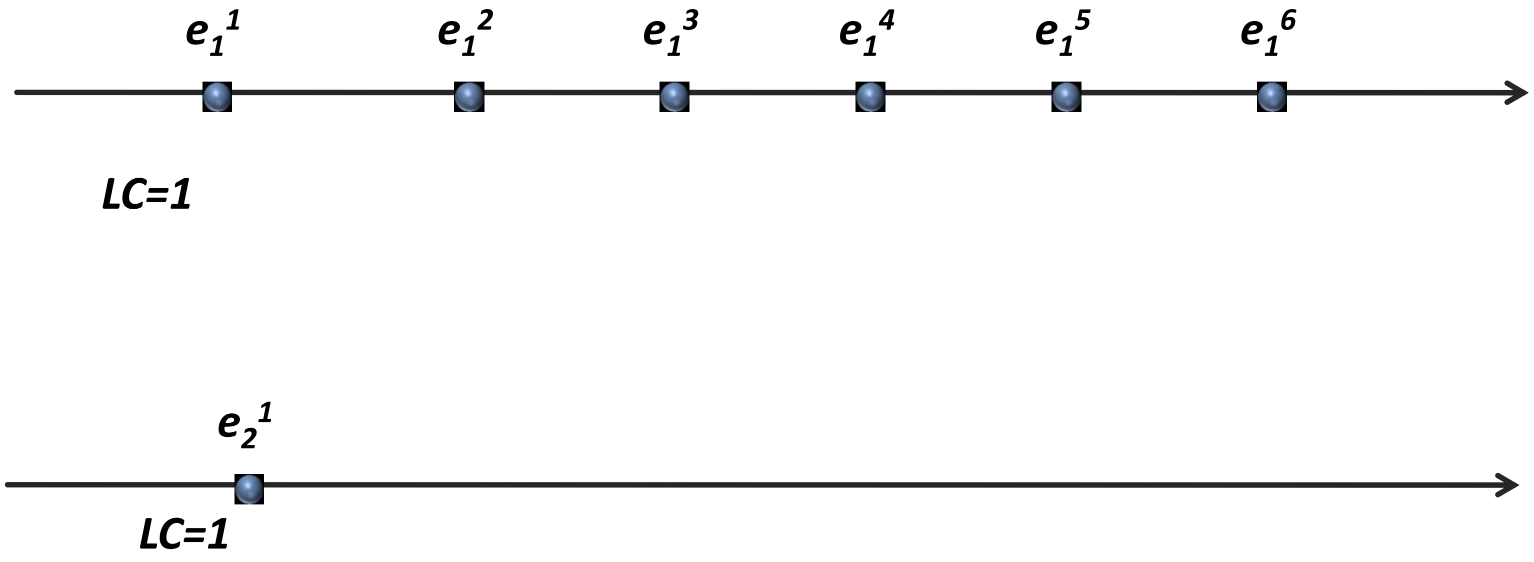

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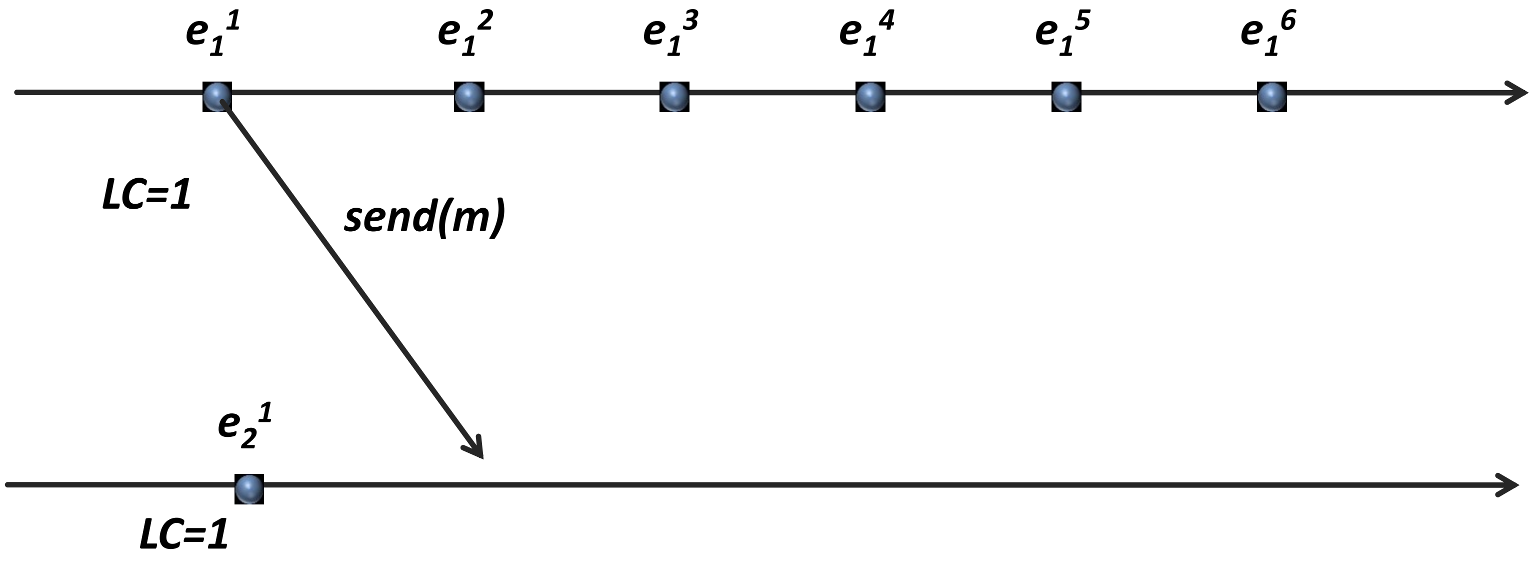

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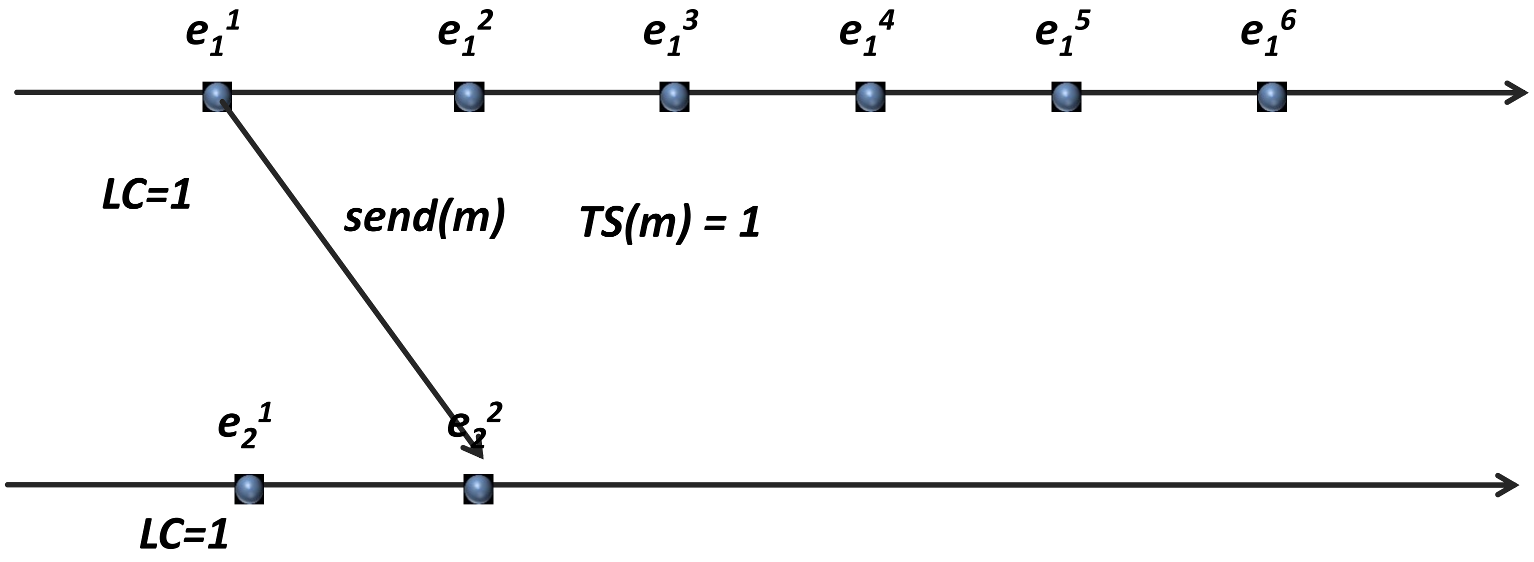

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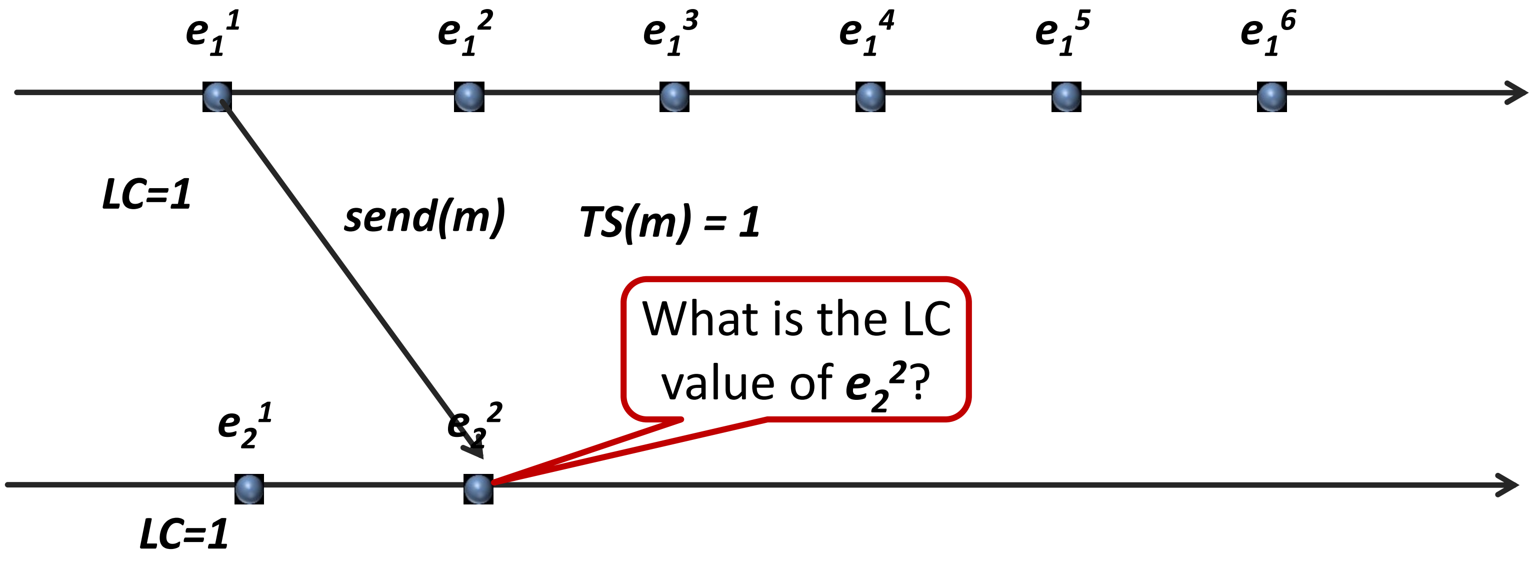

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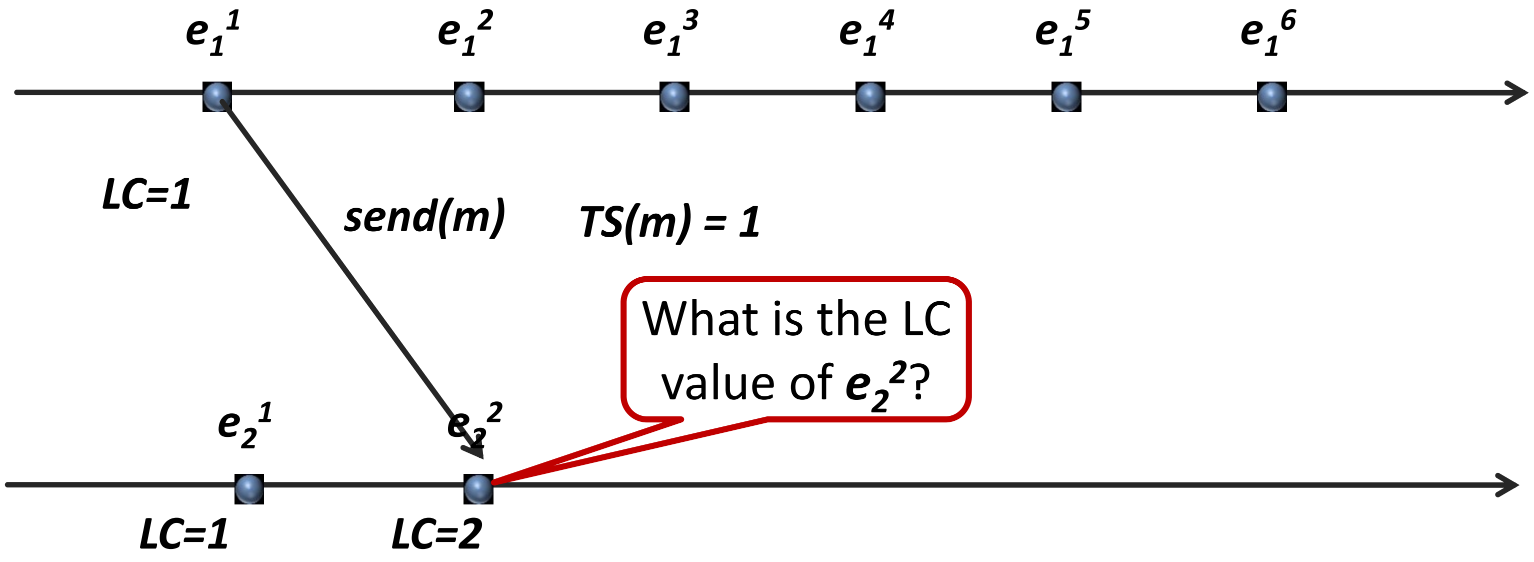
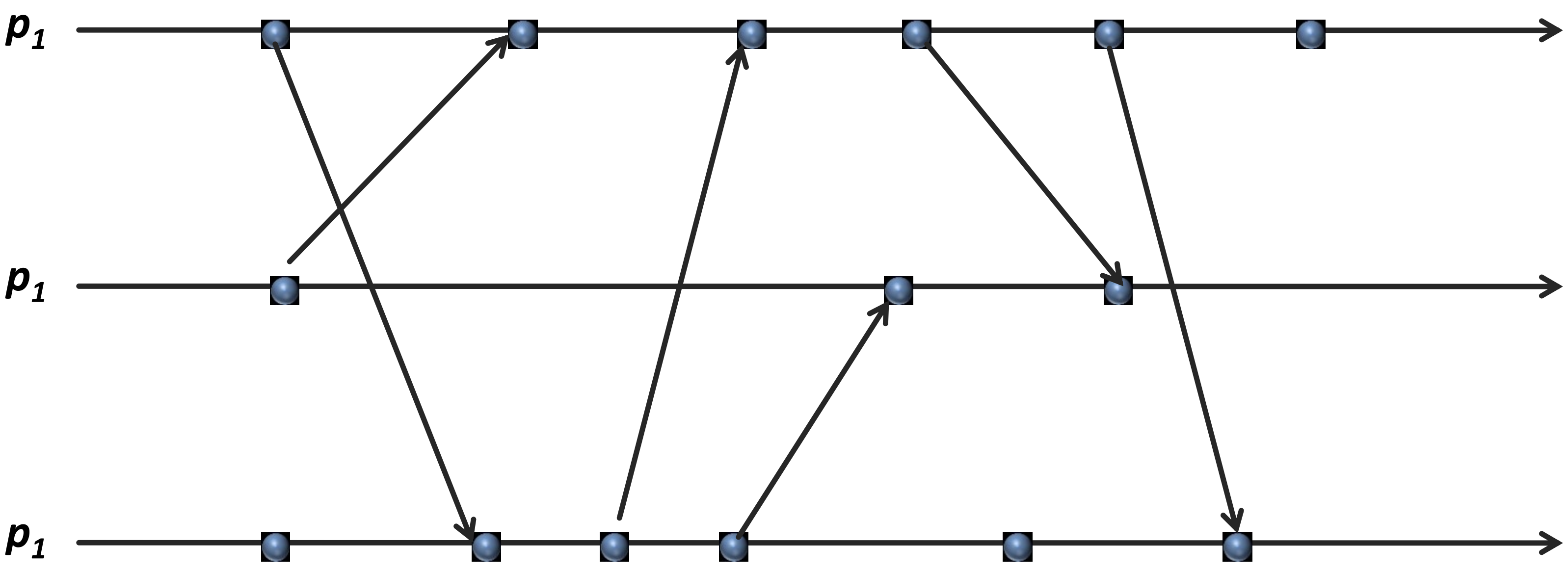


Illustration of a Logical Clock



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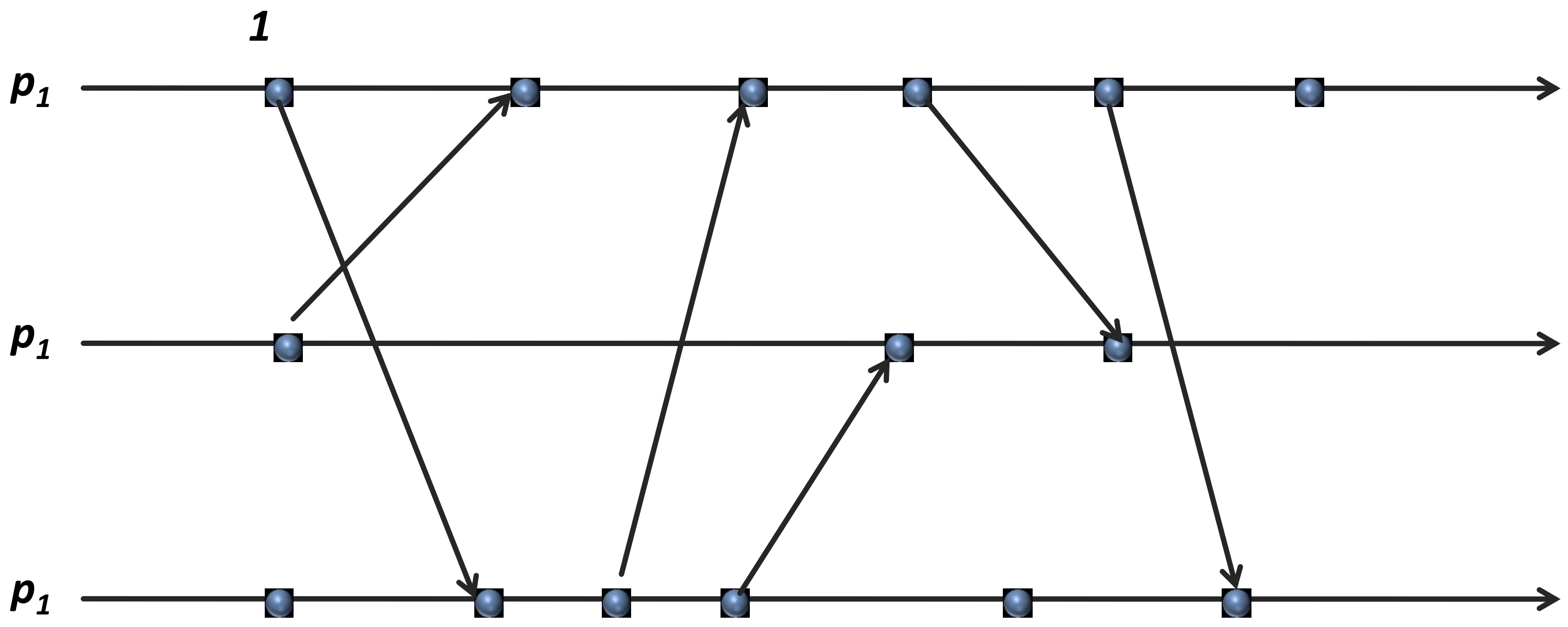

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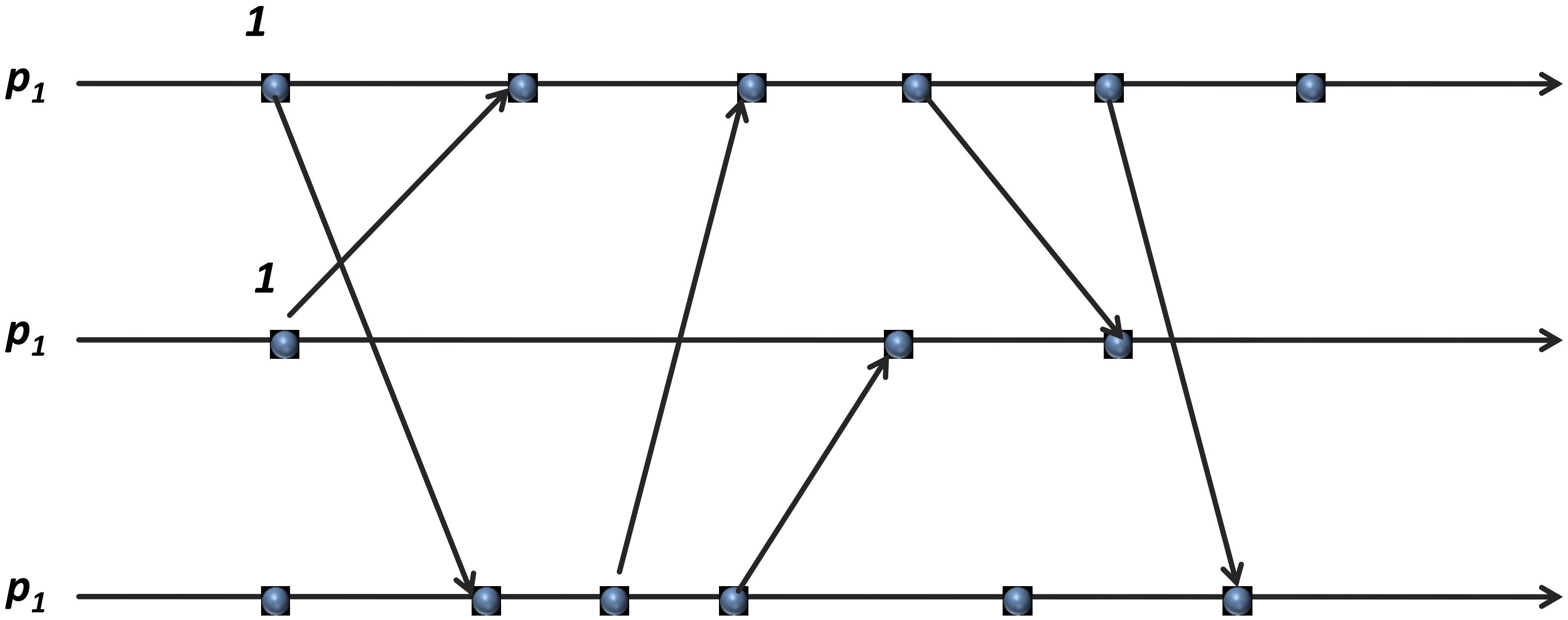

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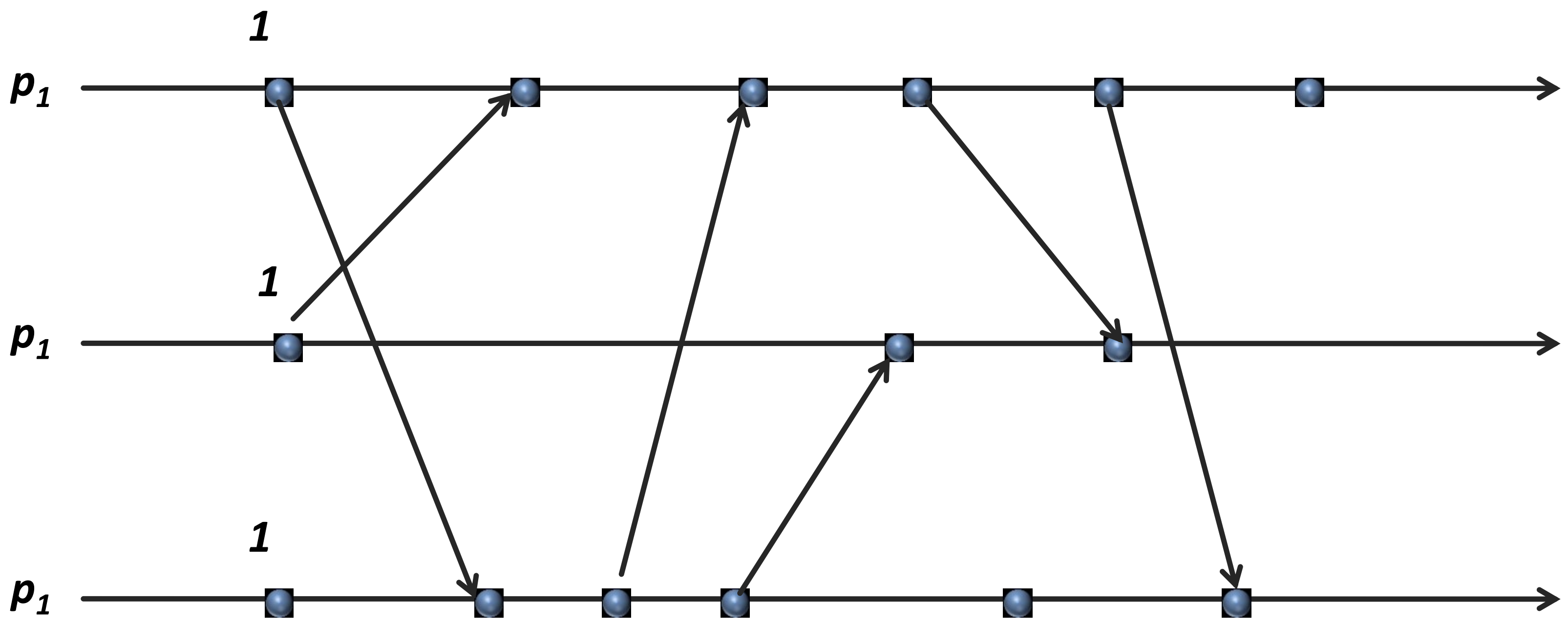

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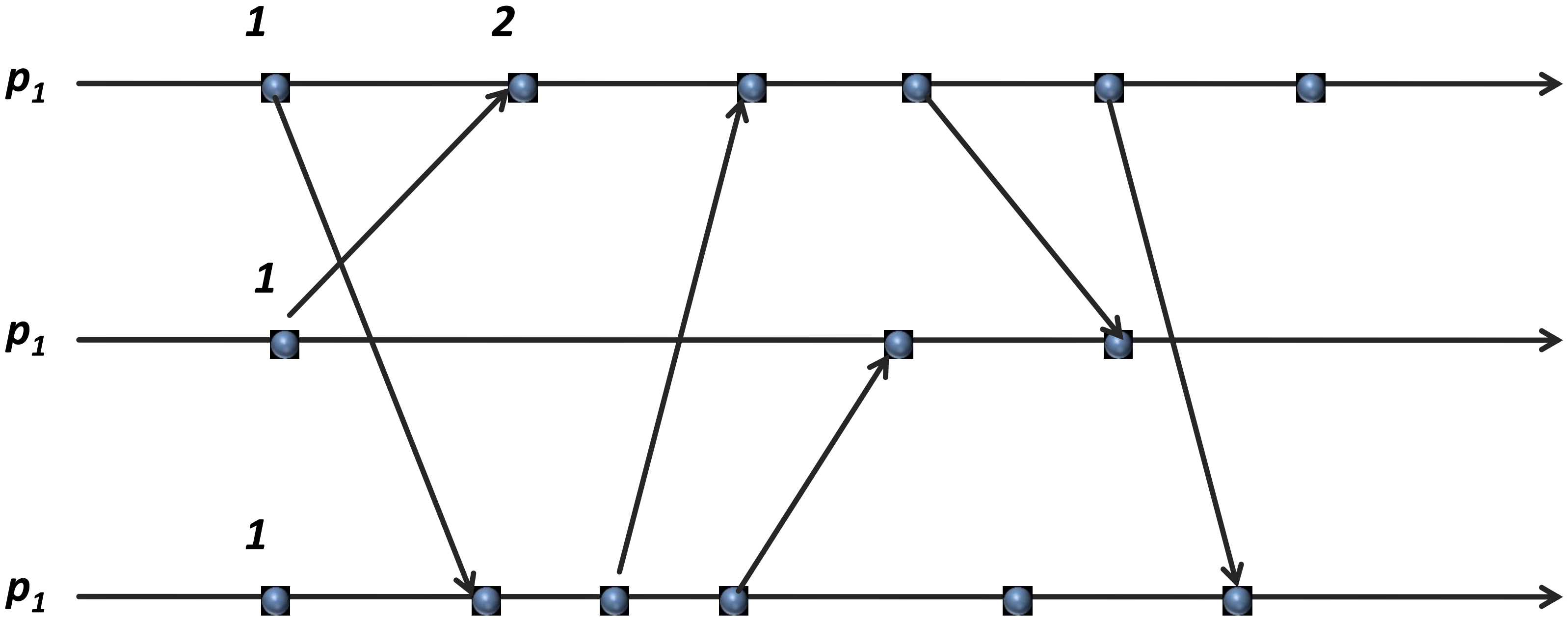

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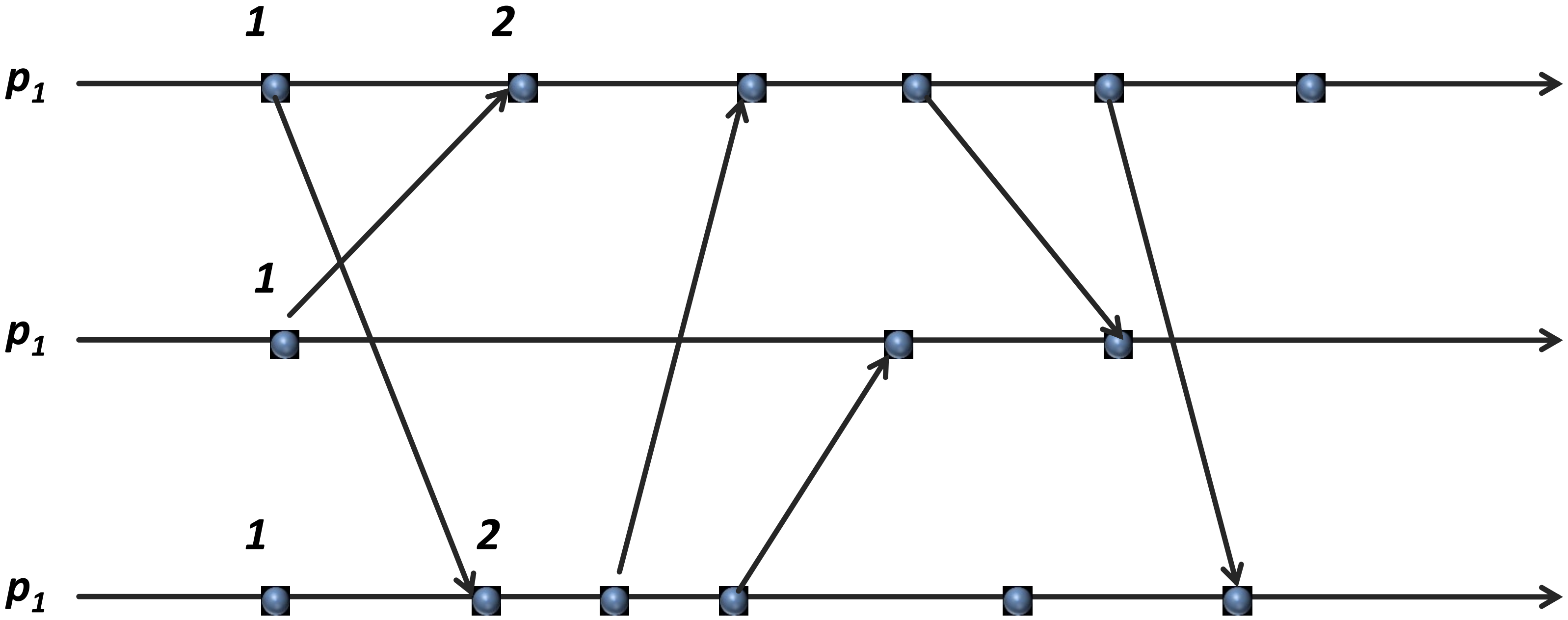

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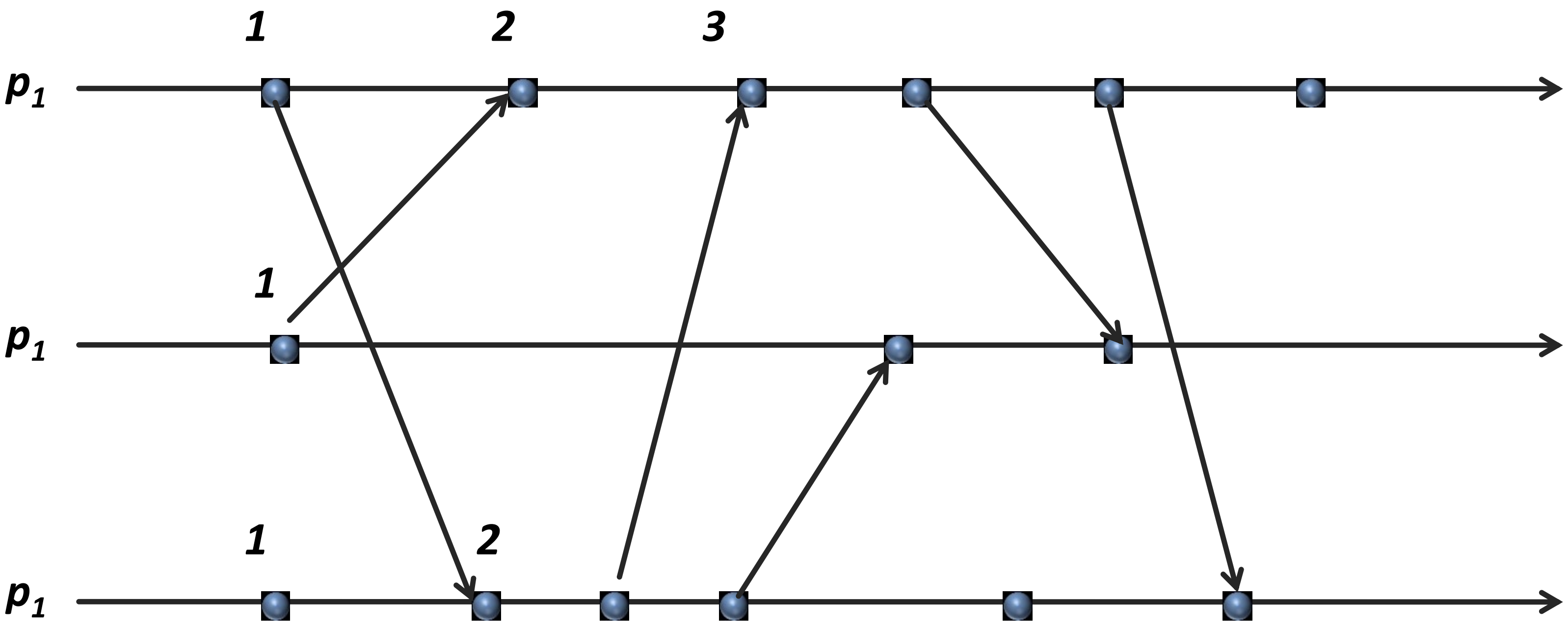

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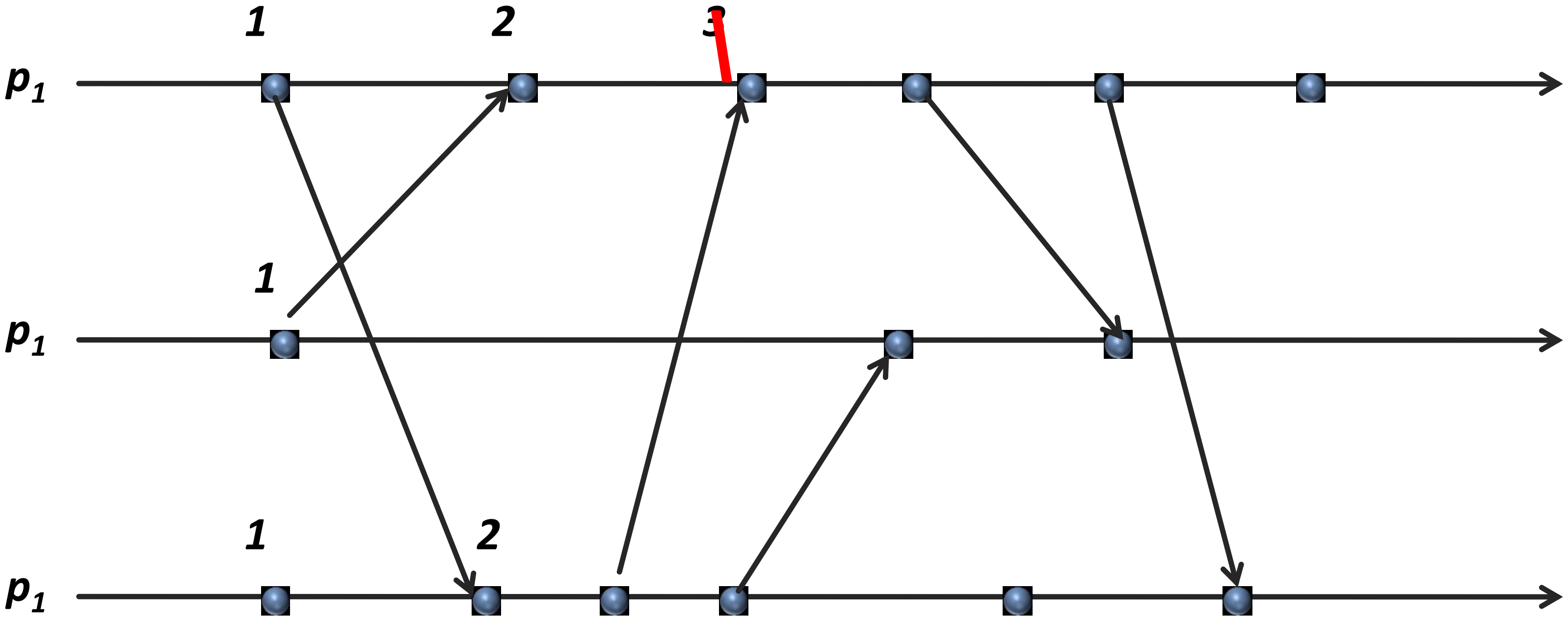

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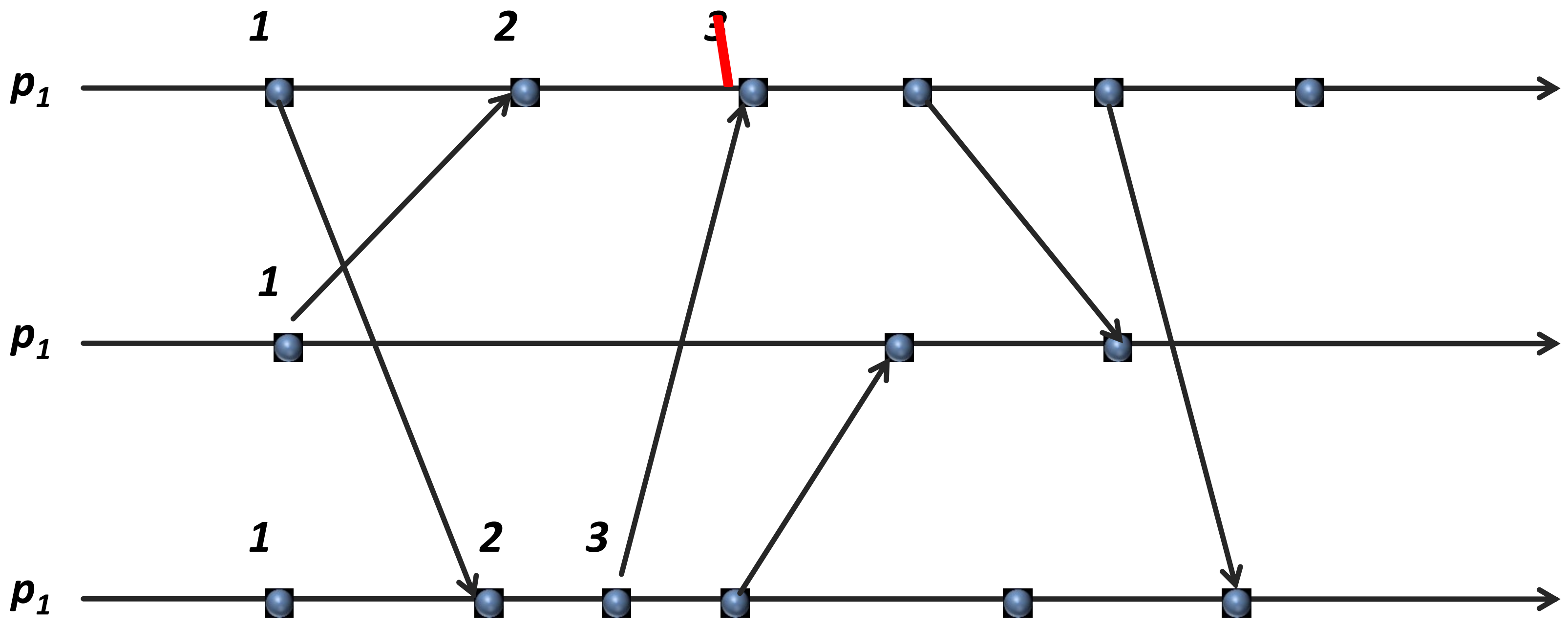

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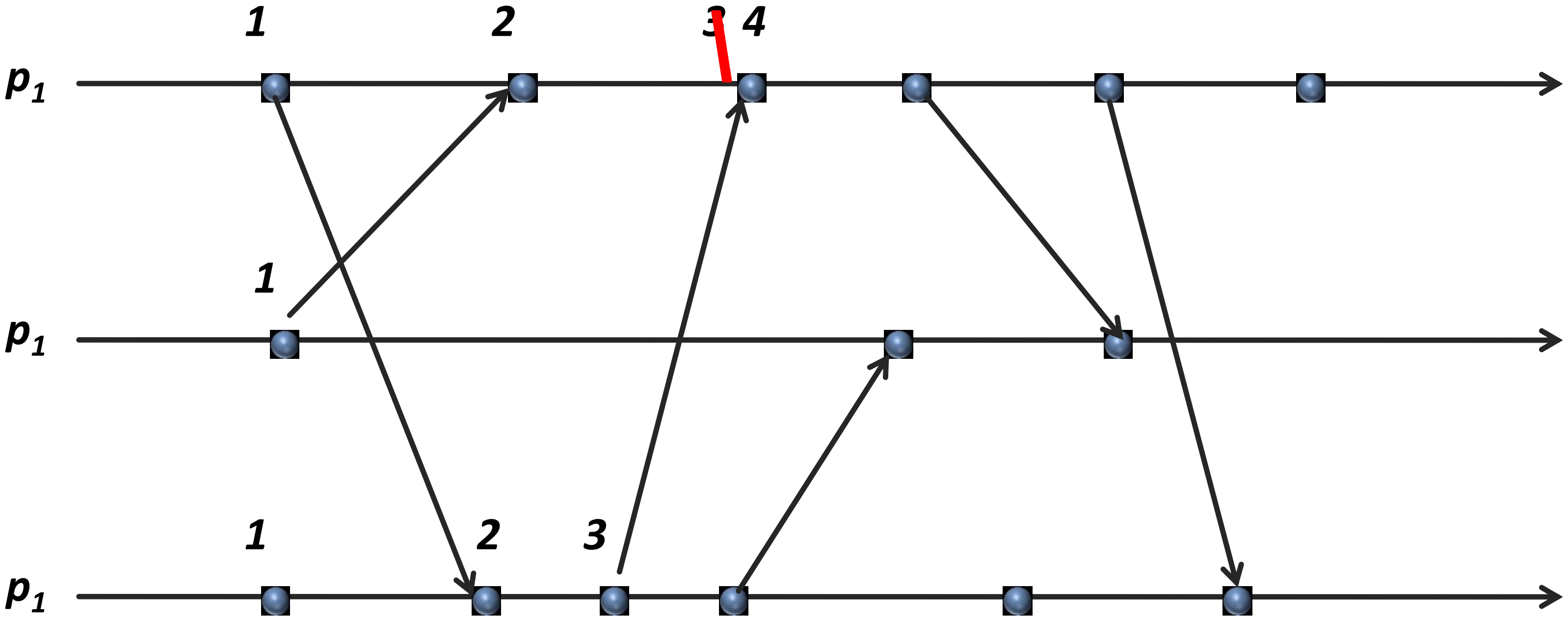

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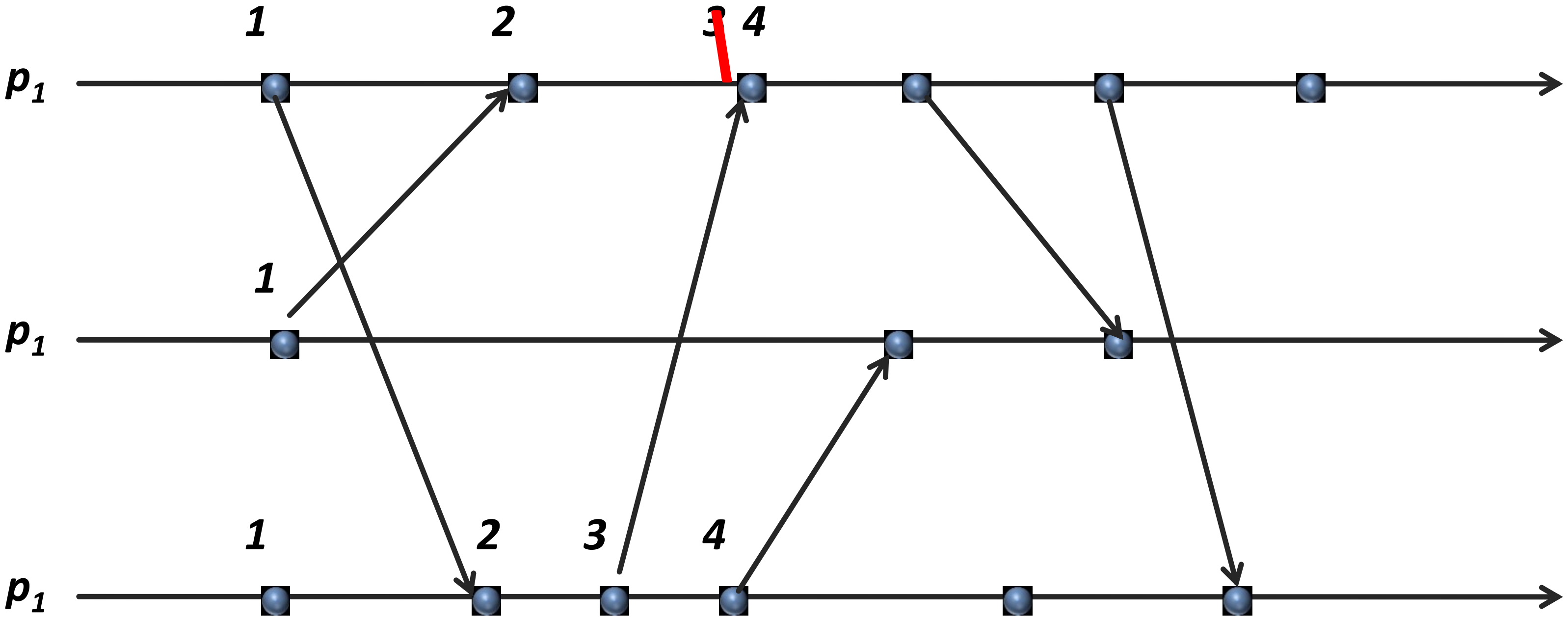

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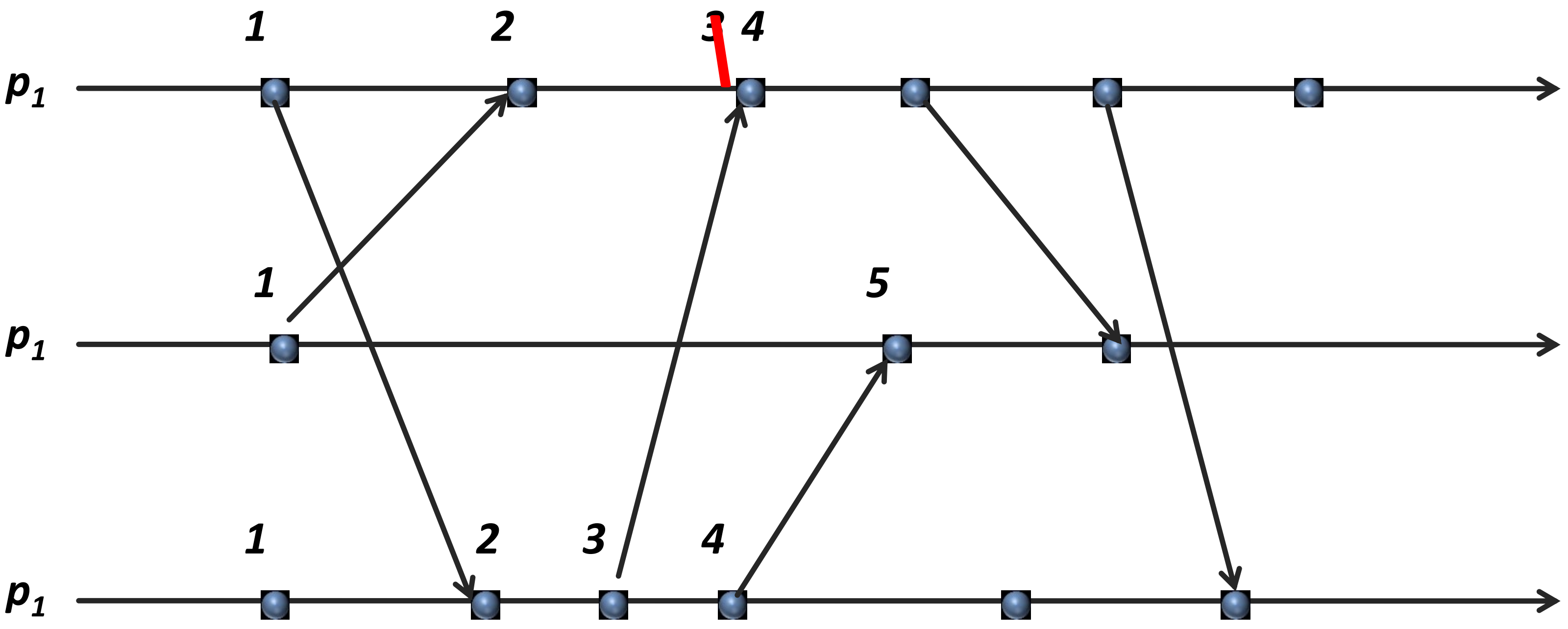

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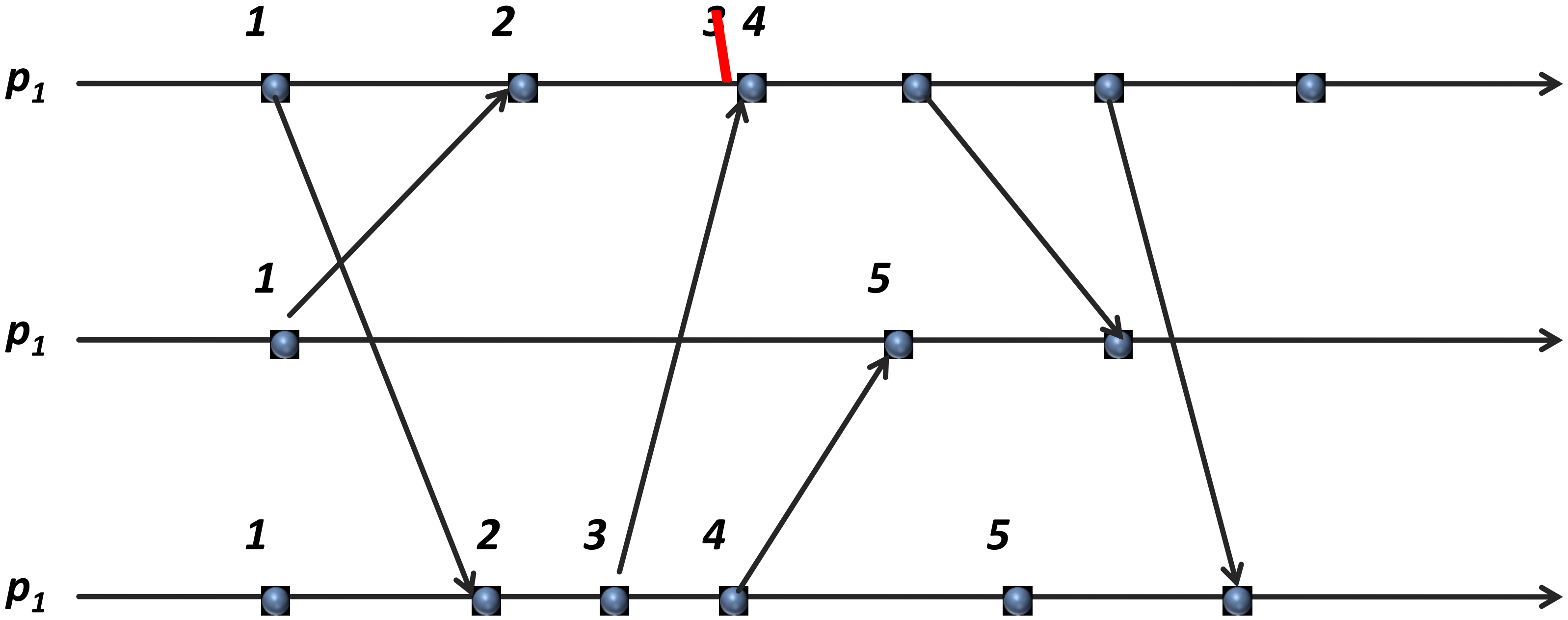

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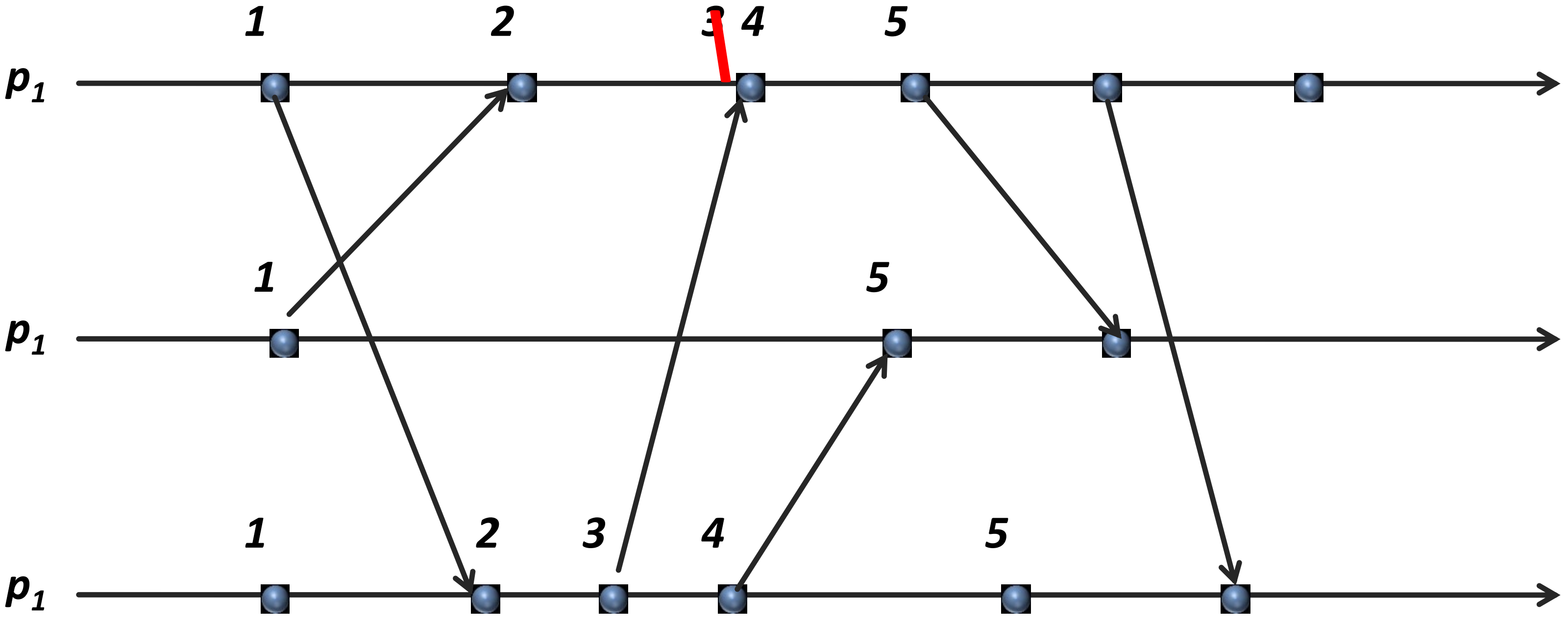

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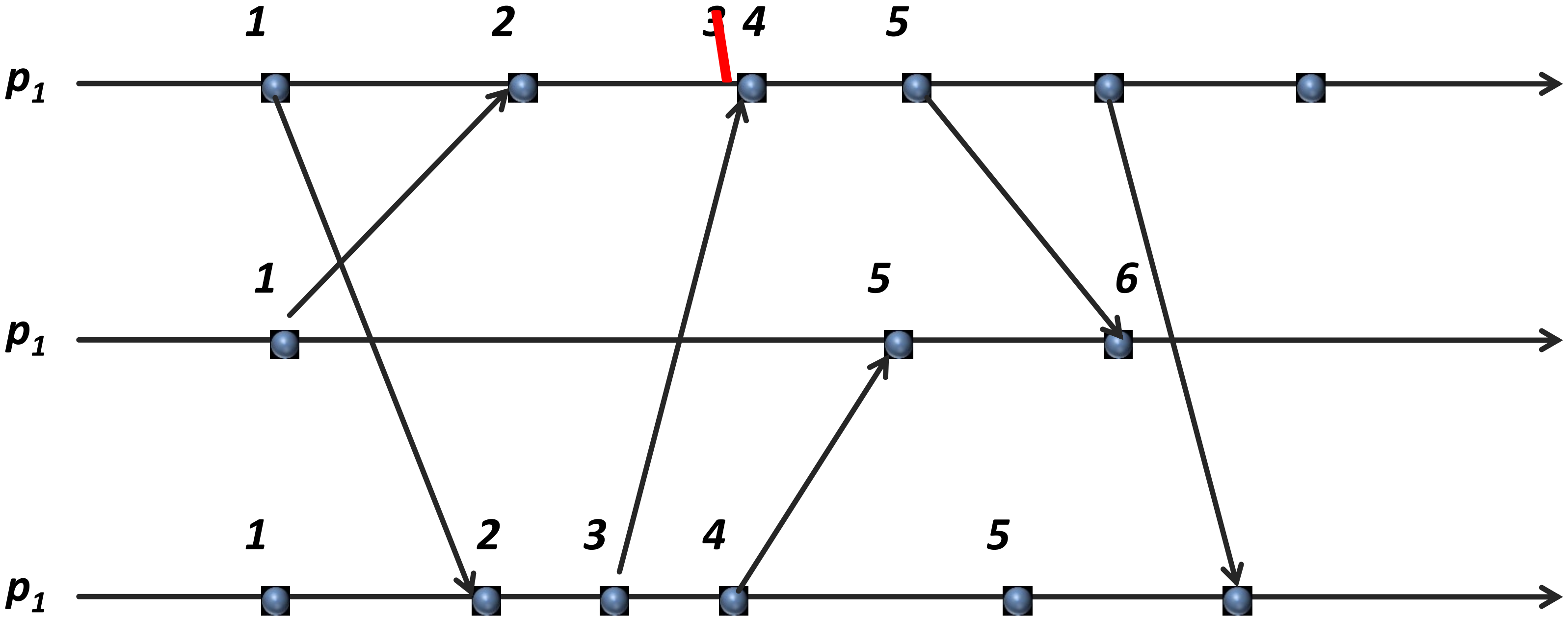

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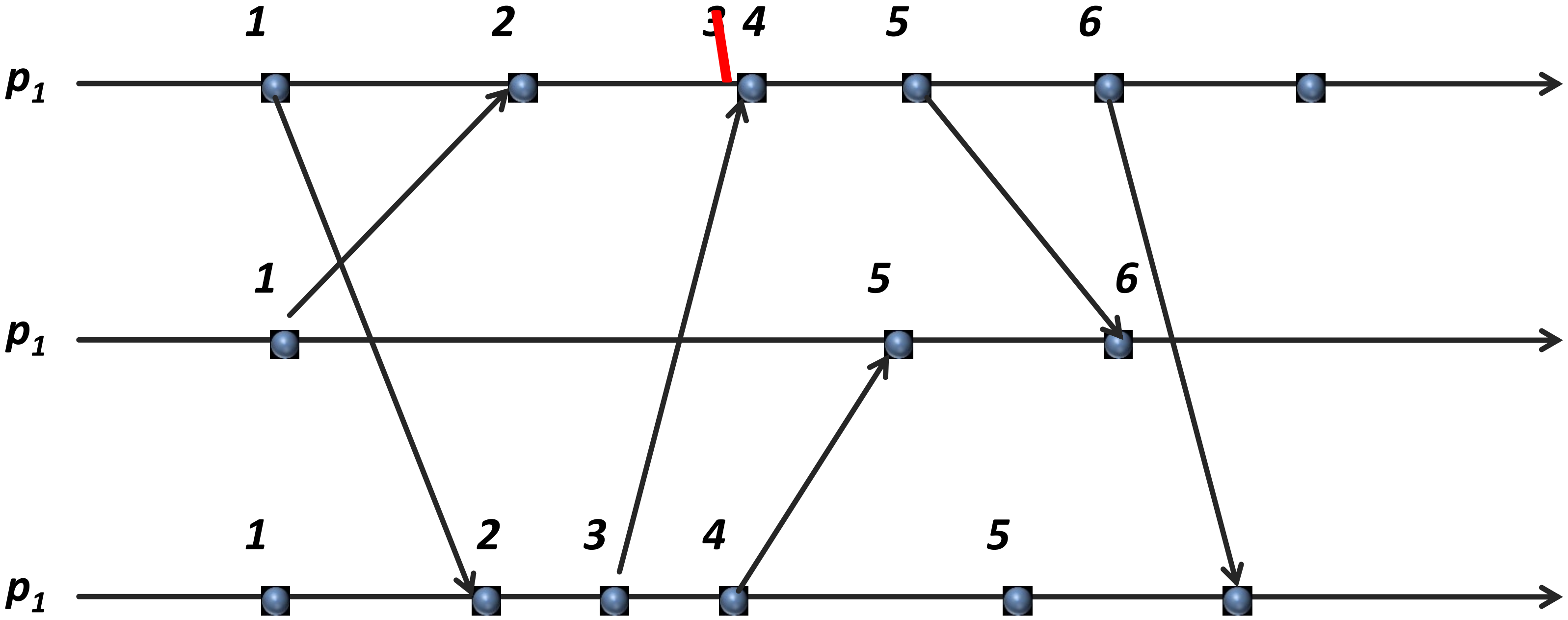

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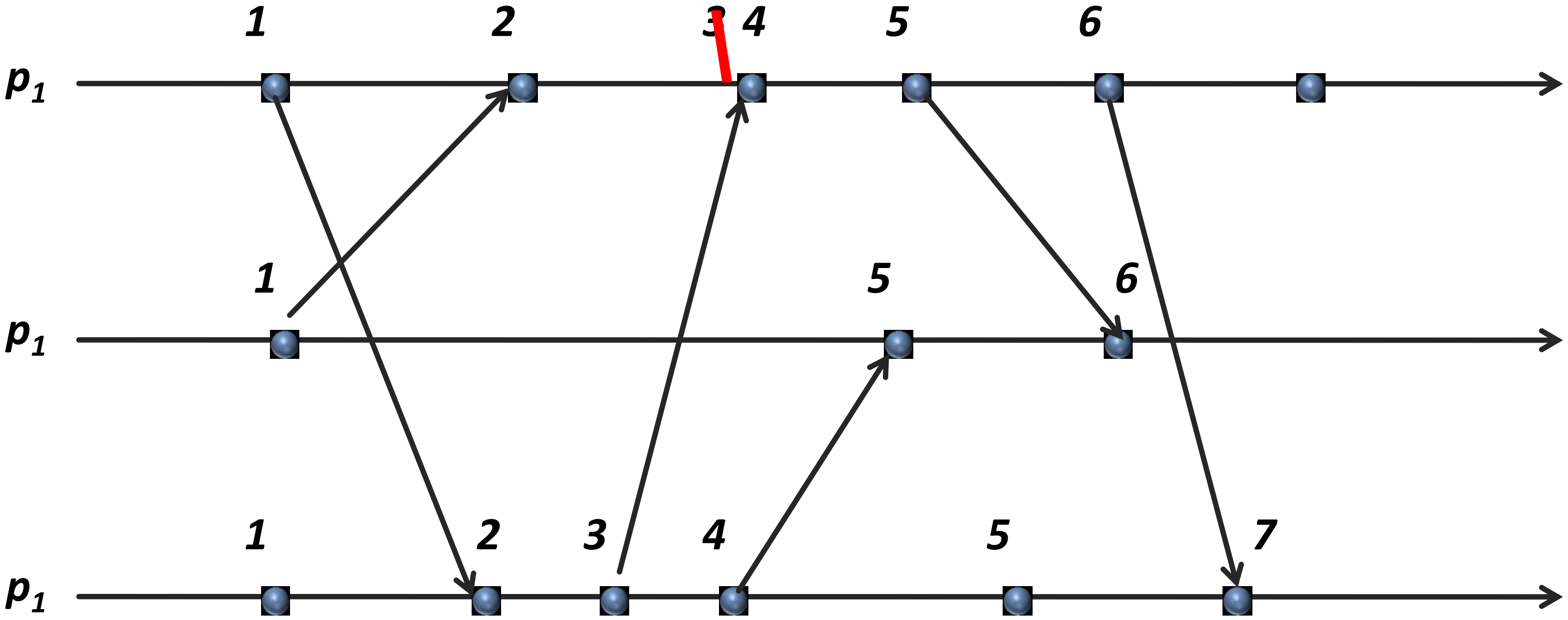

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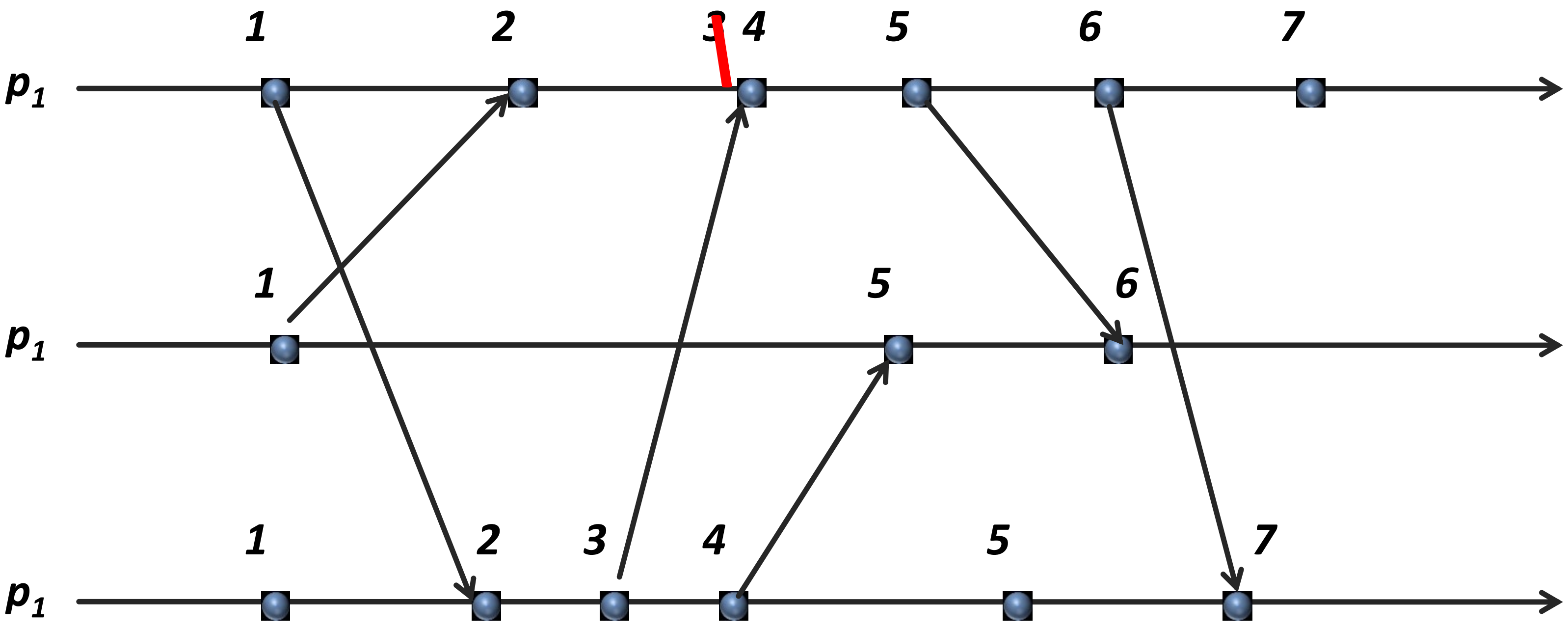

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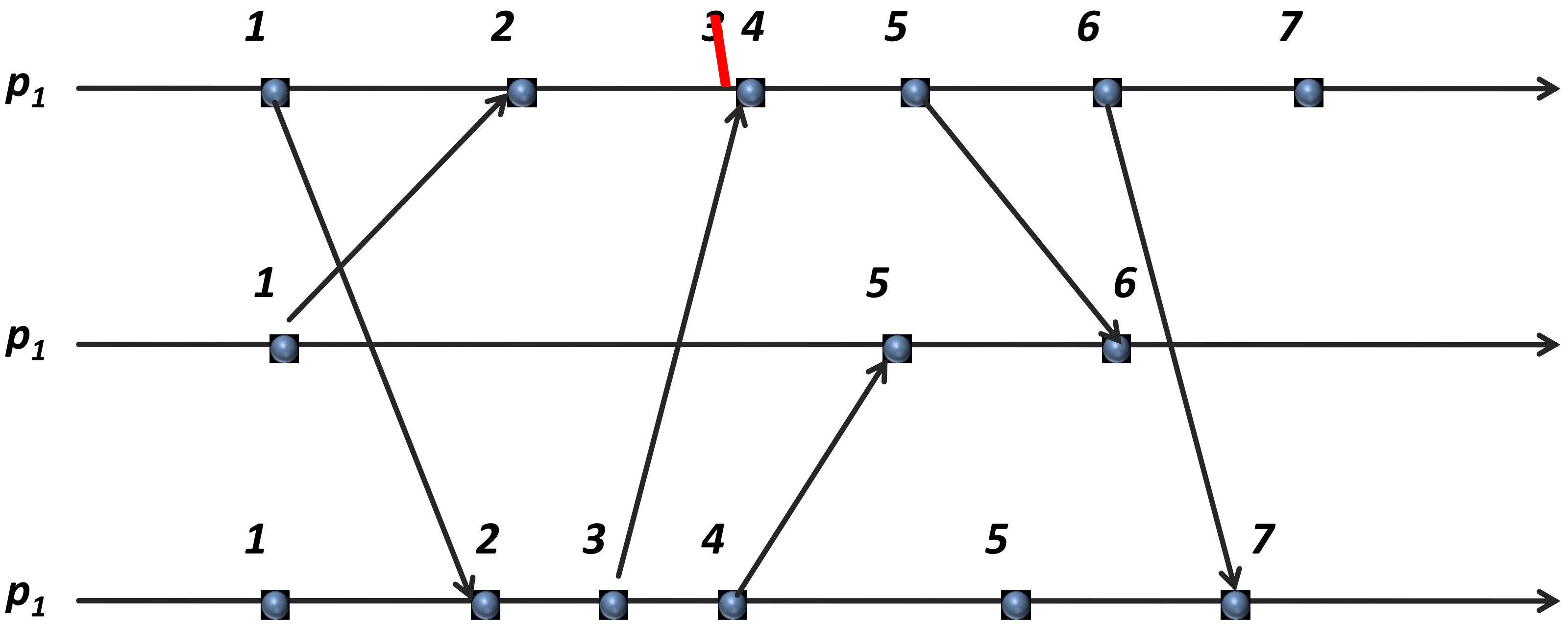

Awesome, right?
Any drawbacks?

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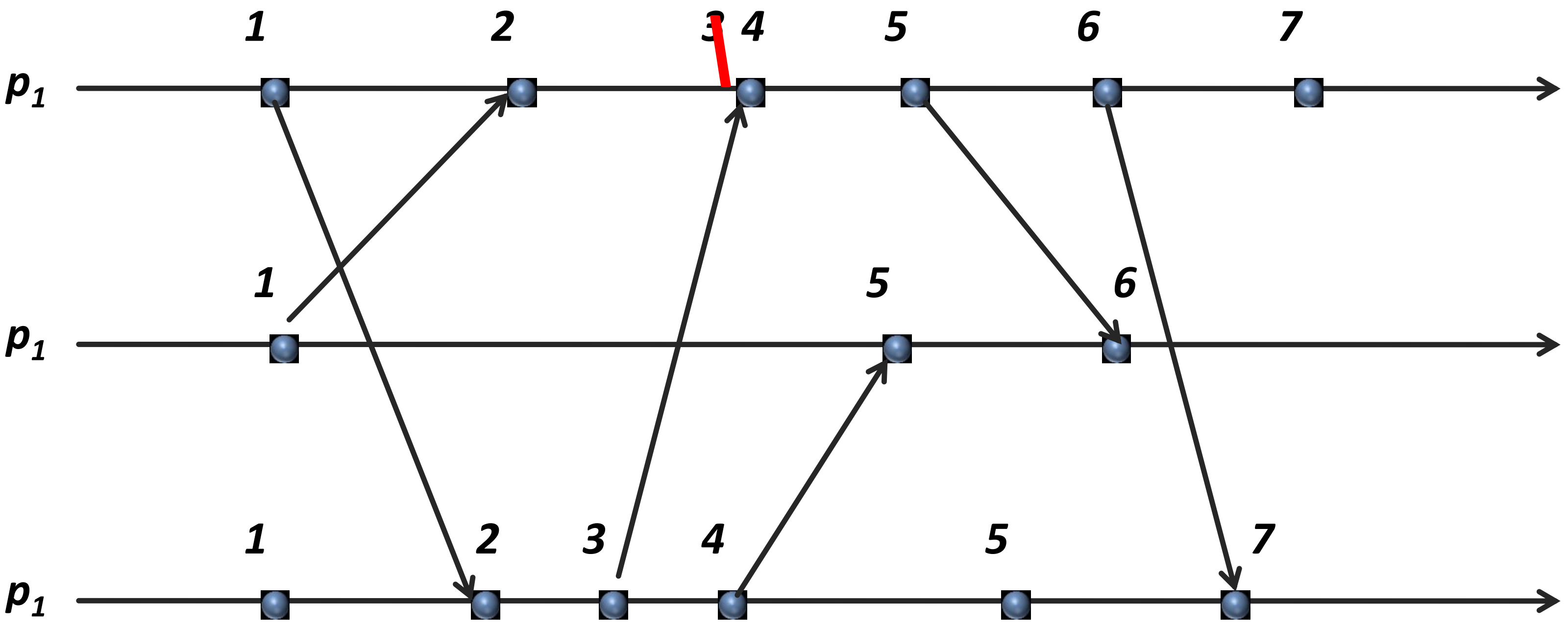

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Total vs Partial Order

Vector Clock

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Replace Logical scalar with Vector!

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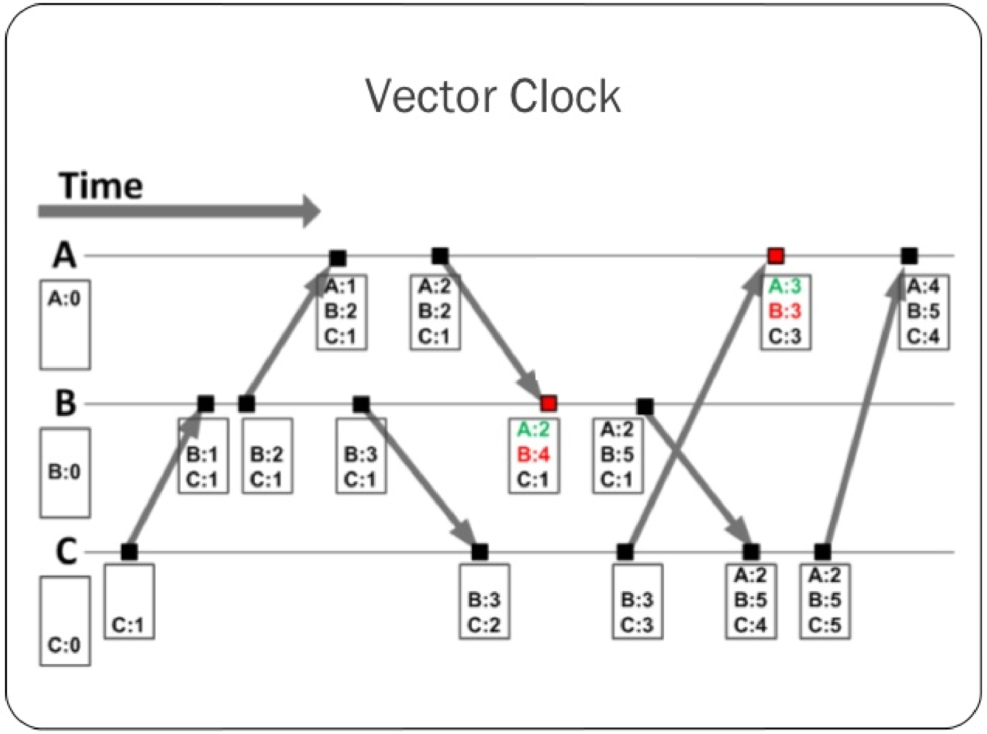
$V_i[i]$: #events occurred at i

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

Update

- On local-event: increment $V_i[I]$
- On send: 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

Vector Clock



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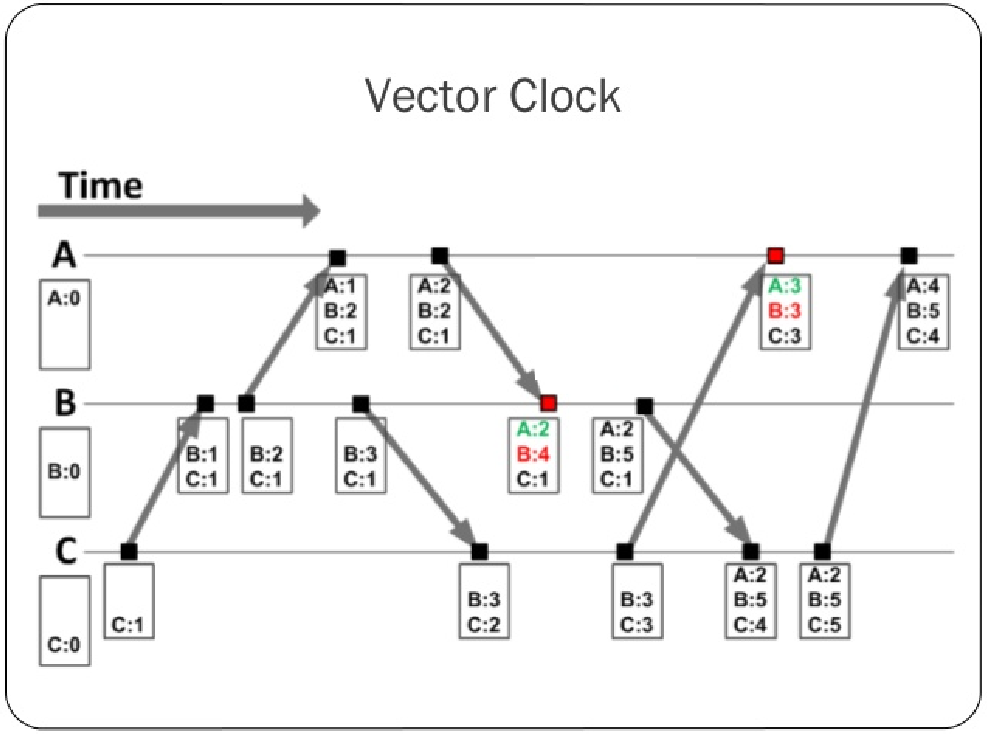

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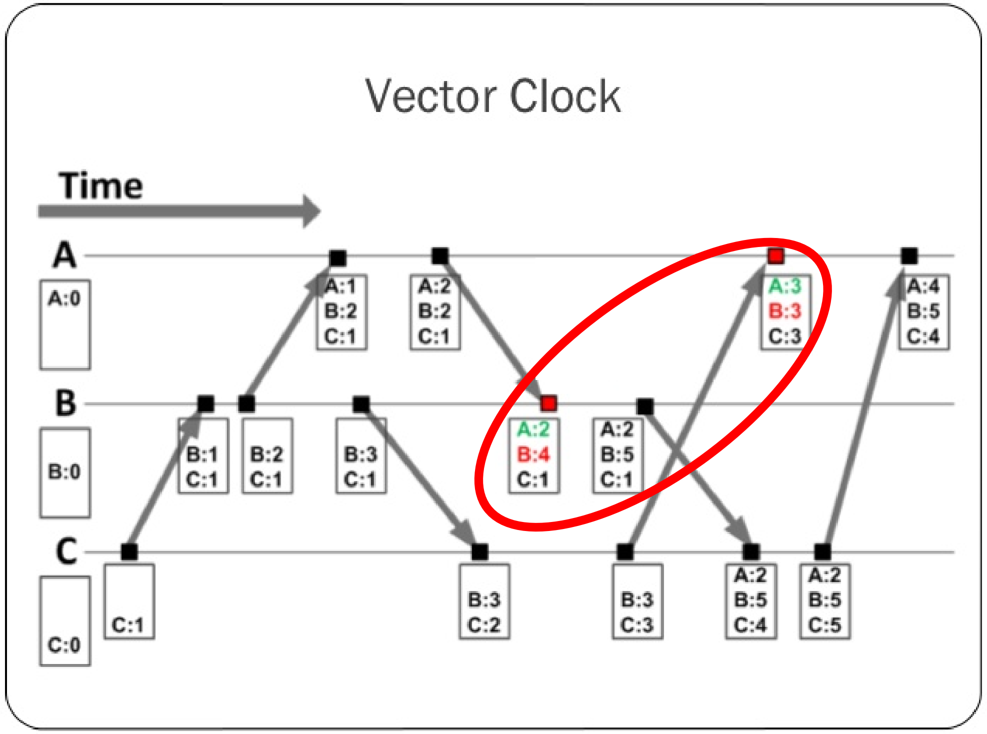

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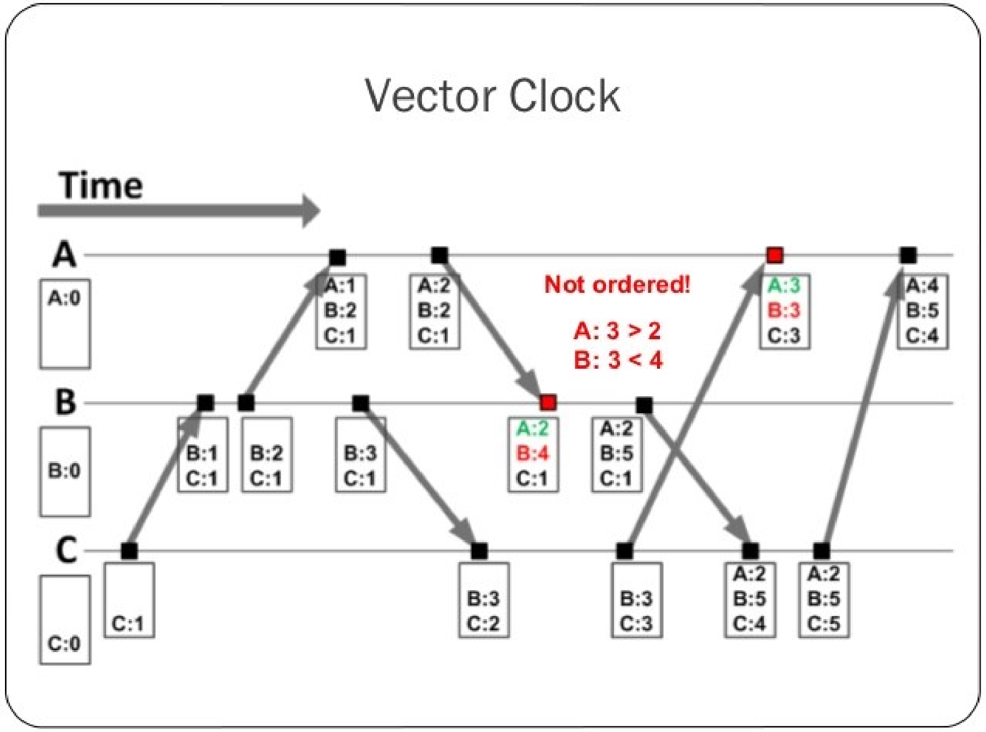

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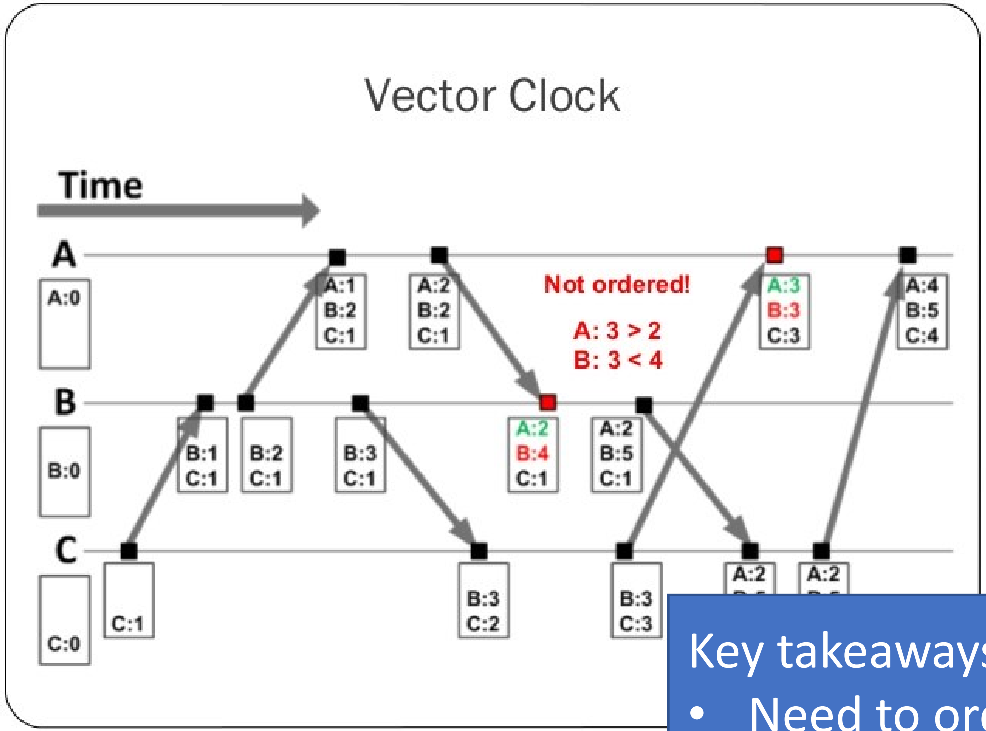

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Key takeaways:

- 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
- *Good primitive for tracking happens-before*

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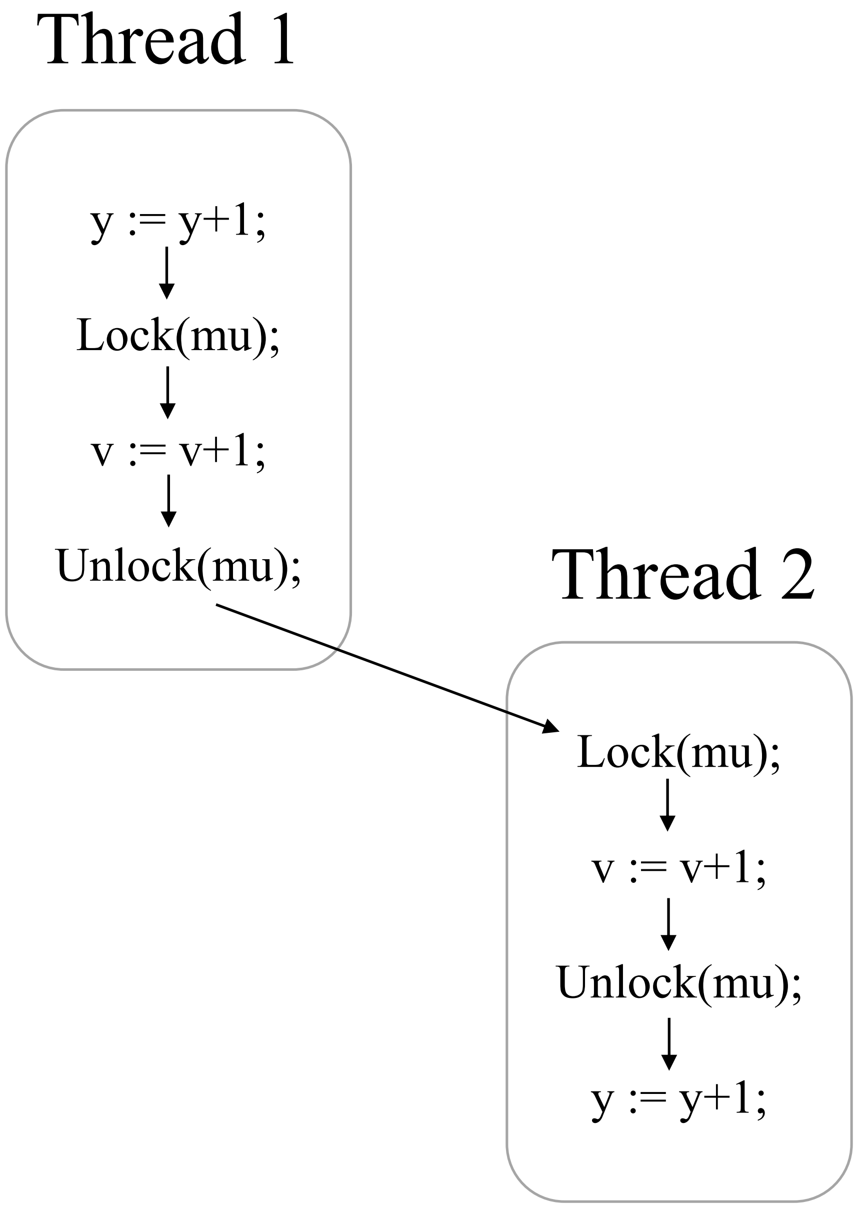

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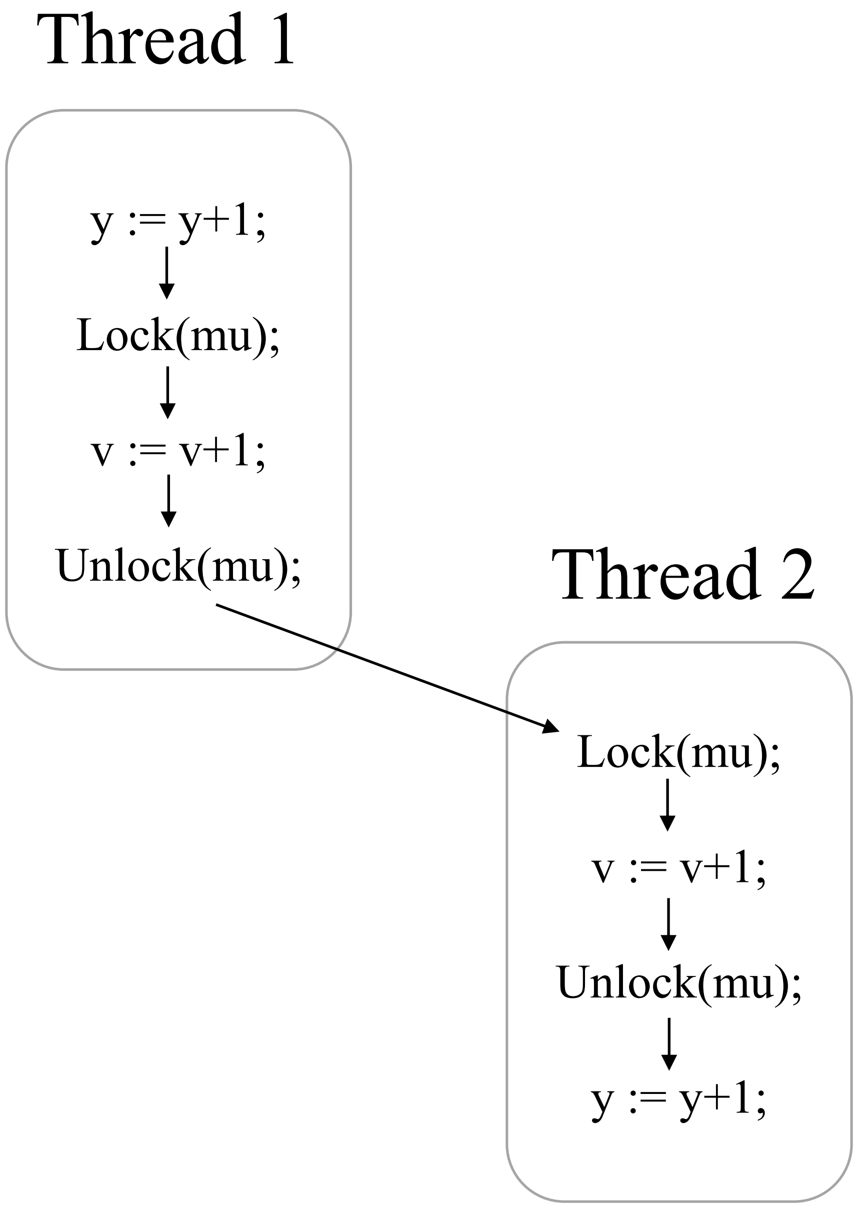

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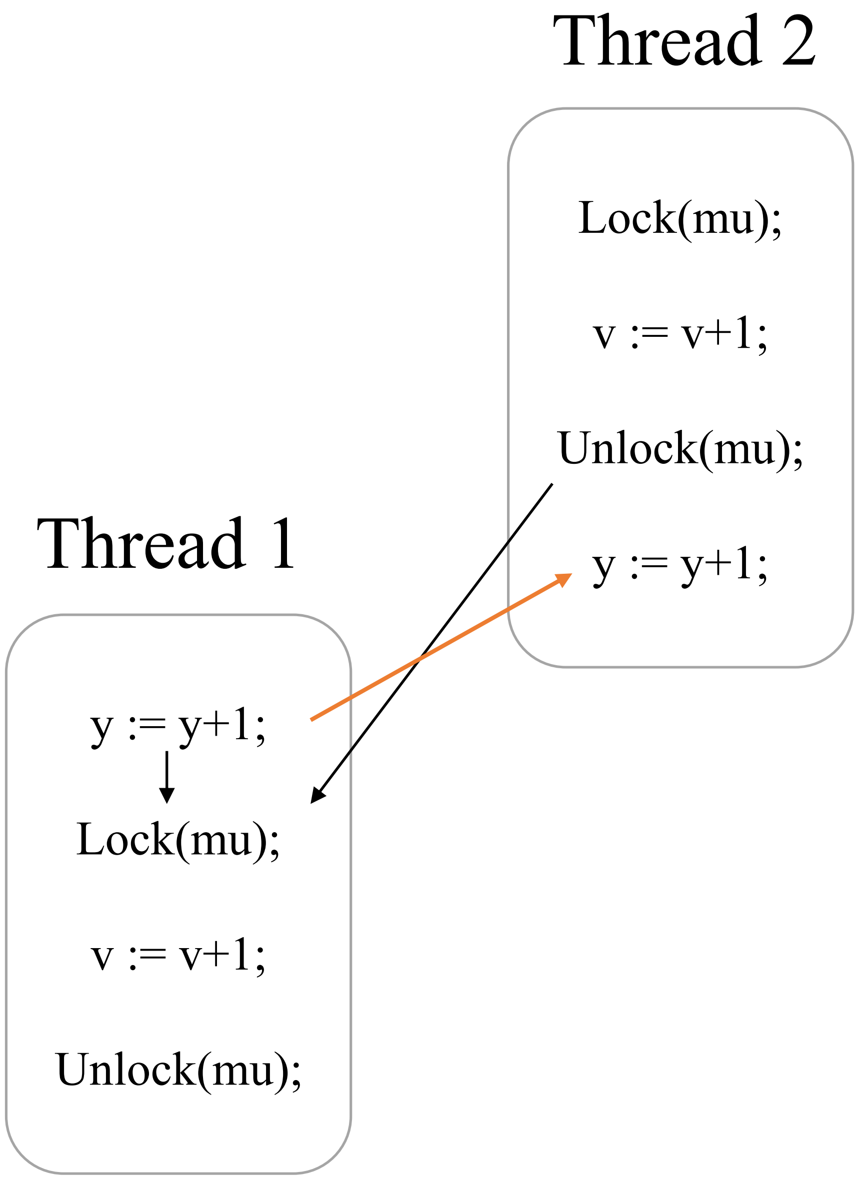


Better Dynamic Race Detection

- 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

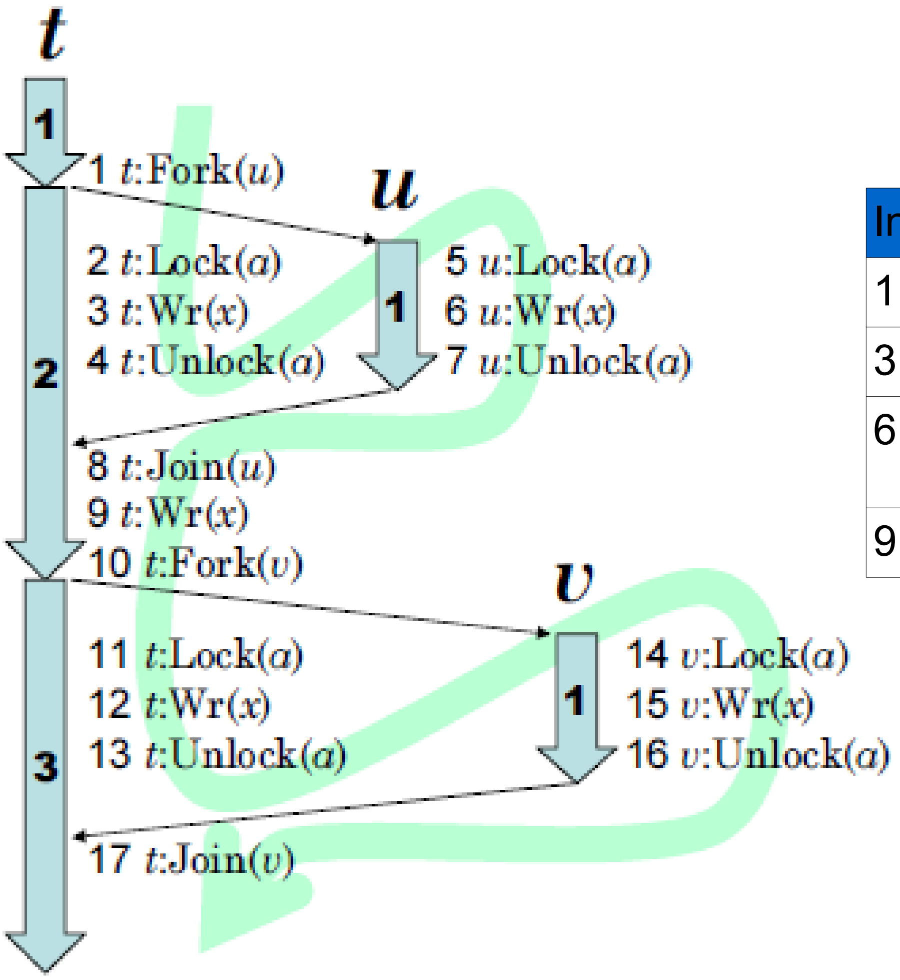
RaceTrack = Lockset + Happens-before

Summary

Race detection

- Static vs Dynamic
- Lock set vs. Happens-Before
- Lots of really interesting related work
- Lots of increasingly practical tools

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) \\
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RaceTrack Algorithm

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

$$
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$$

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

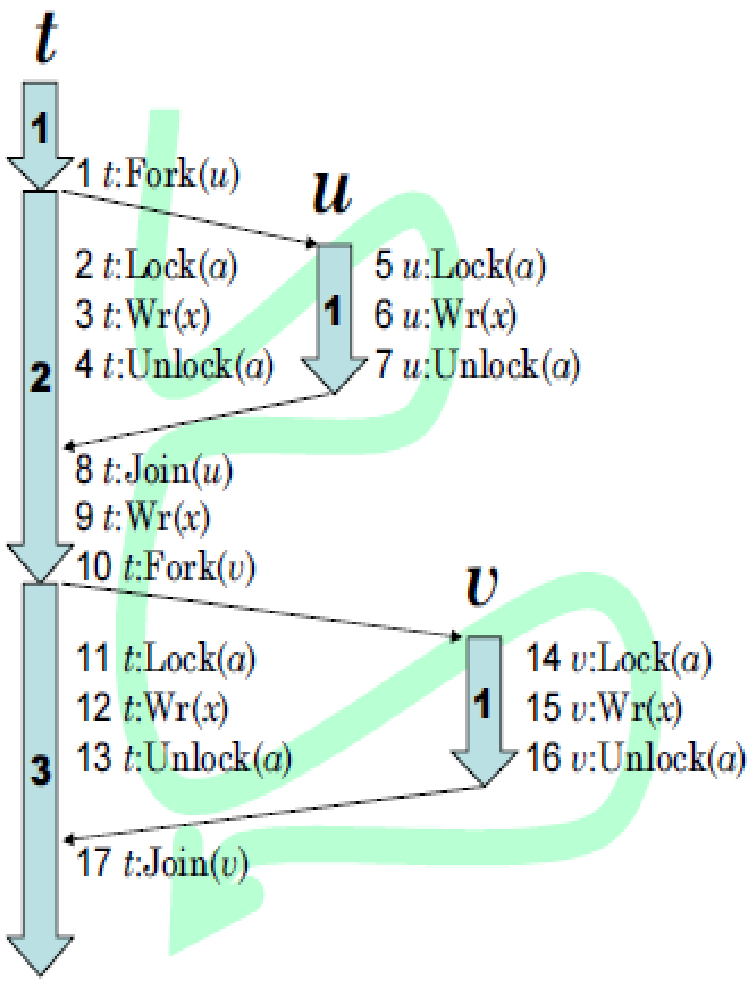
At t:Unlock(l):
$\quad L_t \leftarrow L_t - \{l\}$

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):
$\quad B_t \leftarrow Merge(B_t, B_u)$

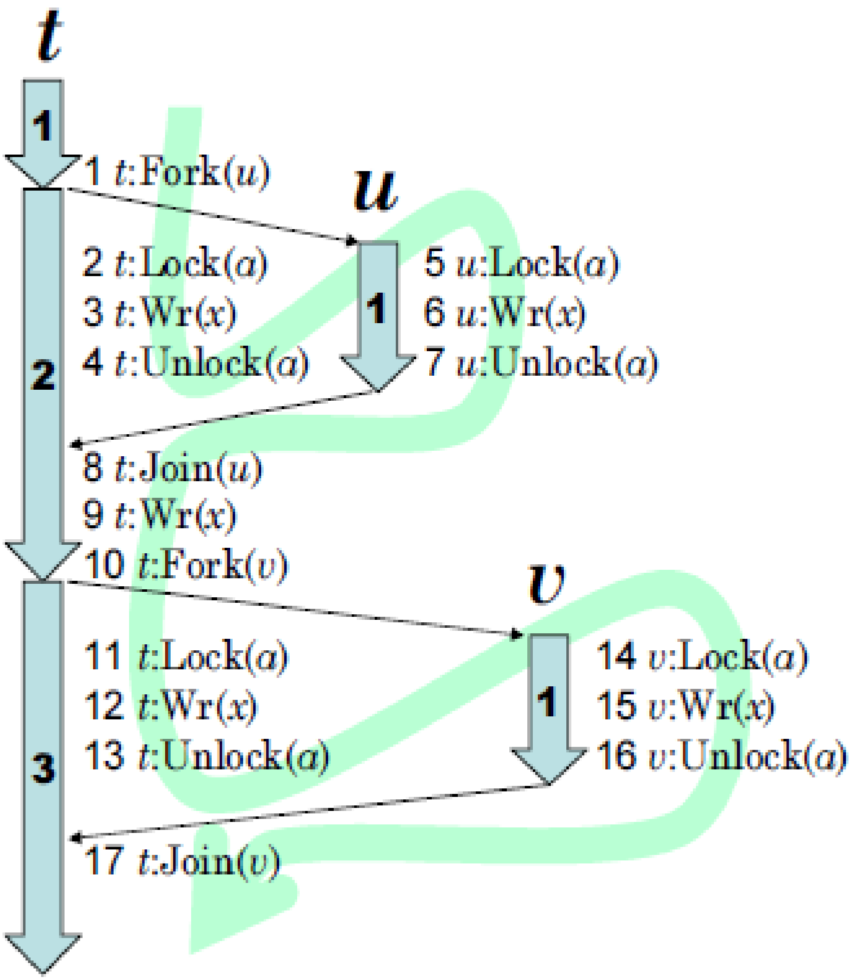
At t:Rd(x) or t:Wr(x):
$\quad S_x \leftarrow Merge(Remove(S_x, B_t), \{\langle t, B_t(t)\rangle\})$
$\quad$ if $|S_x| > 1$
$\quad\quad$ then $C_x \leftarrow C_x \cap L_t$
$\quad\quad$ else $C_x \leftarrow L_t$
$\quad$ if $|S_x| > 1 \wedge C_x = \{\}$ then report race

Avoiding Lockset's false positive (1)



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)



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					{ }	

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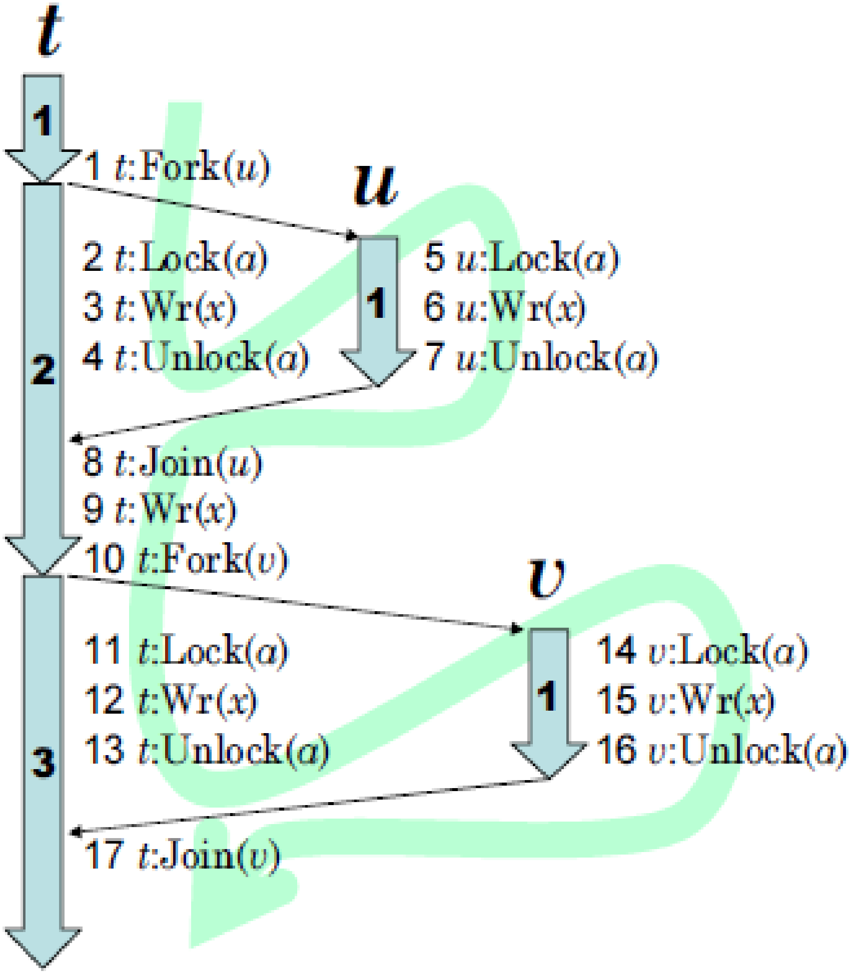
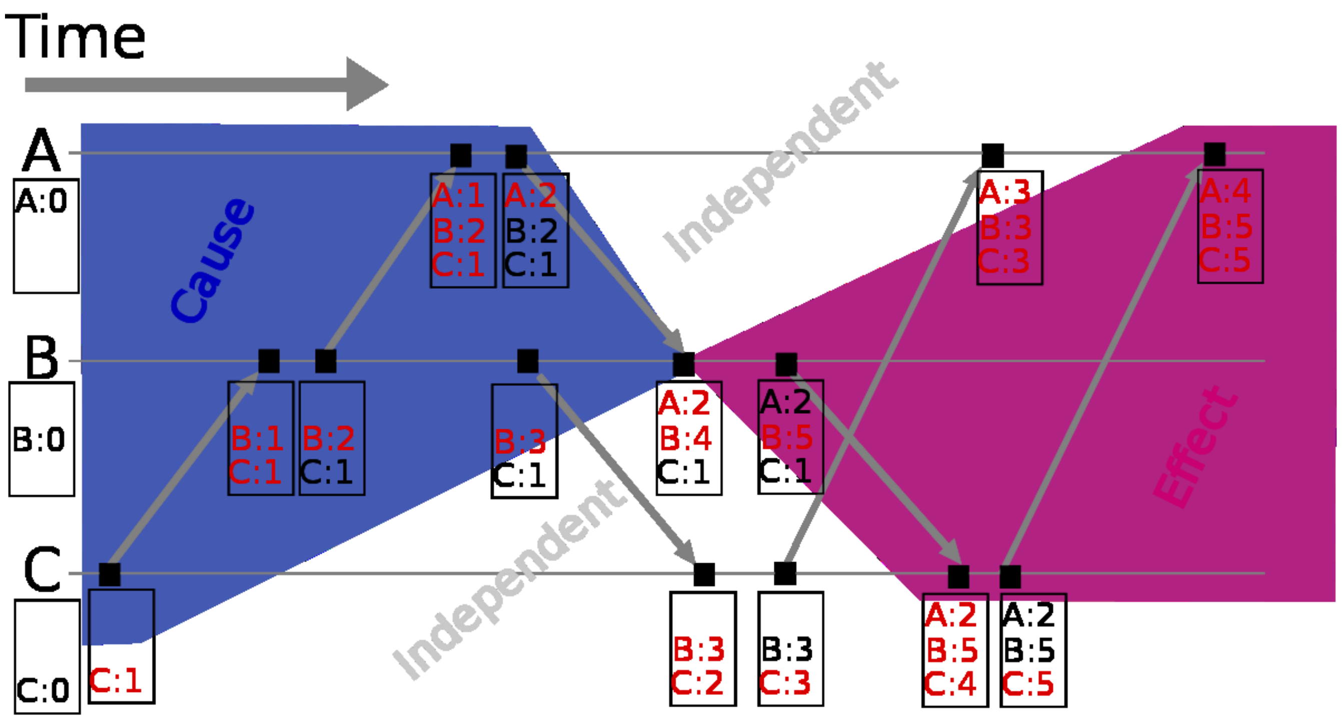


Inst	C_x	S_x	L_t	B_t	L_v	B_v
8	{a}	$\{t_2,u_1\}$	{ }	$\{t_2,u_1\}$	-	-
9	{ }	$\{t_2\}$				
10				$\{t_3,u_1\}$	{ }	$\{t_2,v_1\}$
11			{a}			
12	{a}	$\{t_3\}$				
13			{ }			
14					{a}	
15		$\{t_3,v_1\}$				
16					{ }	

Only one thread!

Are we done?

Vector Clock Example



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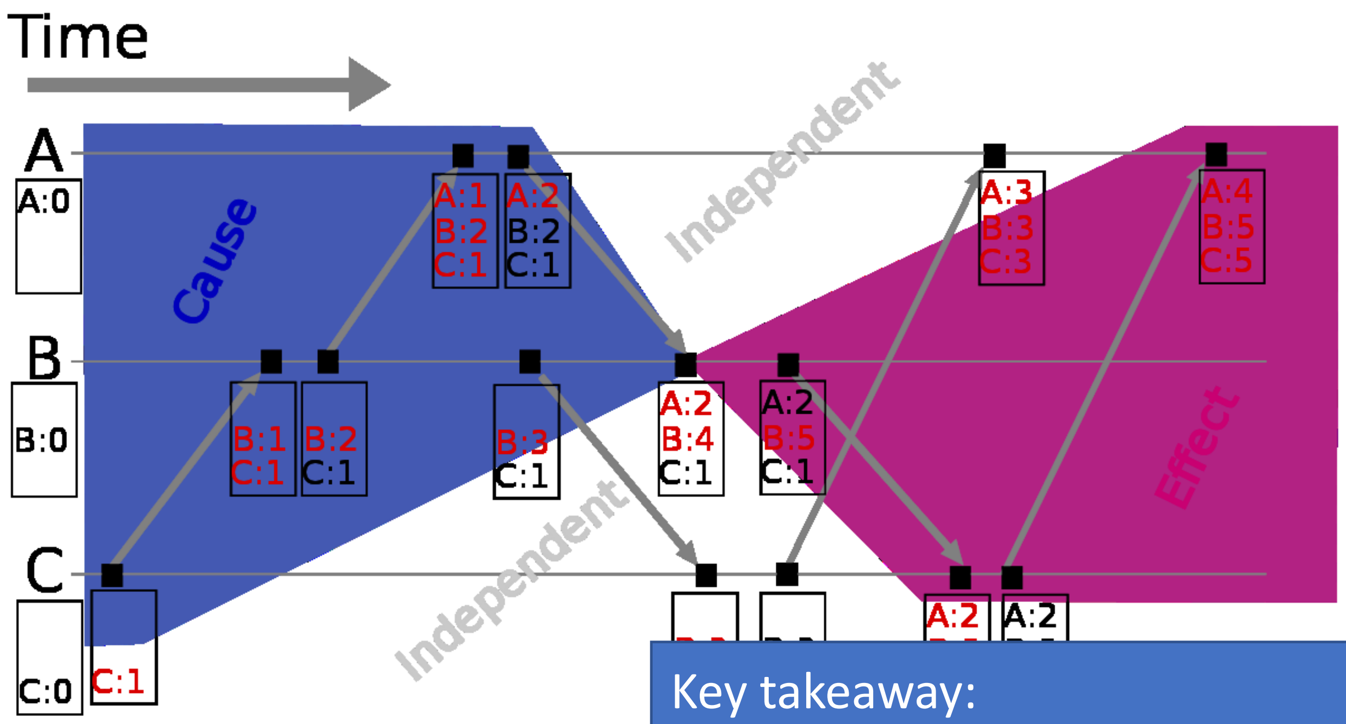

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