CS 60002: Distributed Systems

T4:
More on Clocks!

Department of Computer Science
and Engineering

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What We Have Learnt So Far ...

- Common and Distributed Knowledge
- Global States
- Logical Clocks
- Distributed Checkpoint
- Consistency and Consistent Cuts

Message Delivery - FIFO

- For a process k
  - Send (k, M) ⇒ Process k sends a message M
  - Receive (k, M) ⇒ Process k receives a message M

- Consider process j sends messages M and M' to process k, and Send (k, M) → Send (k, M')

- **FIFO delivery** ensures, Receive (k, M) → Receive (k, M')

Message Delivery - FIFO

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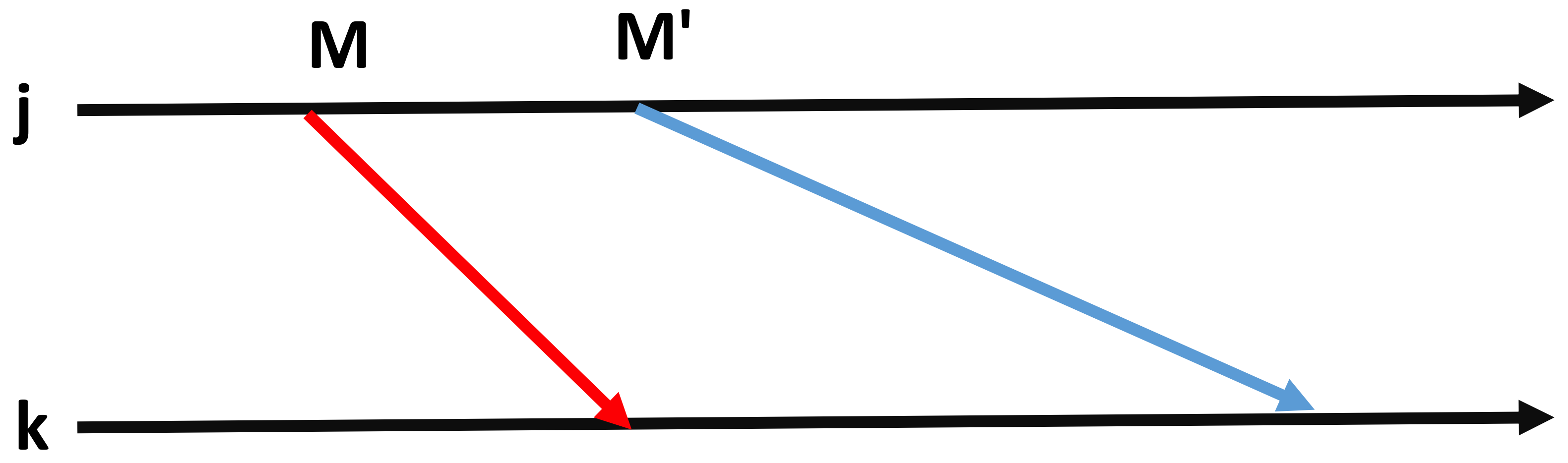
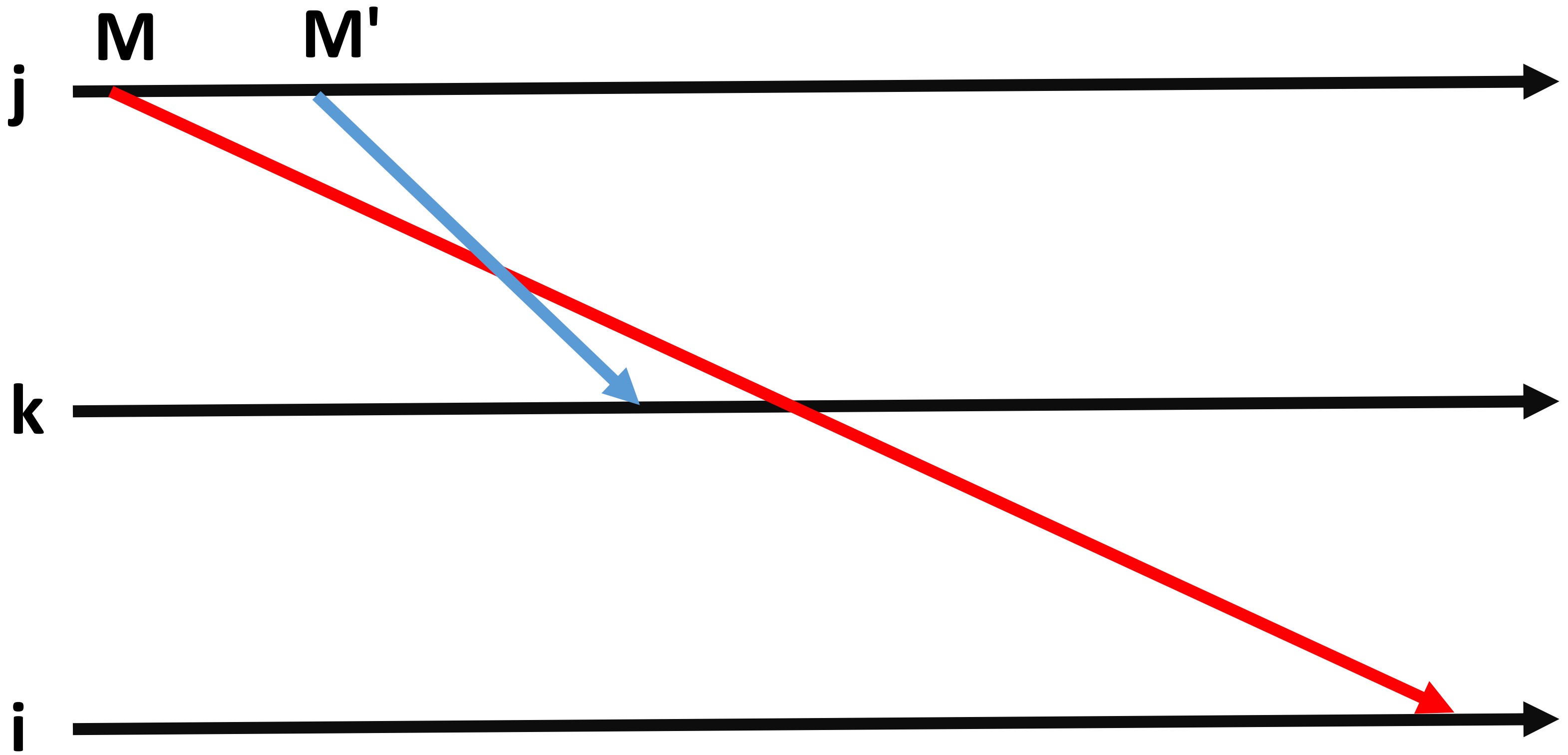


Message Delivery - FIFO

- **Can you characterize FIFO across three processes?**



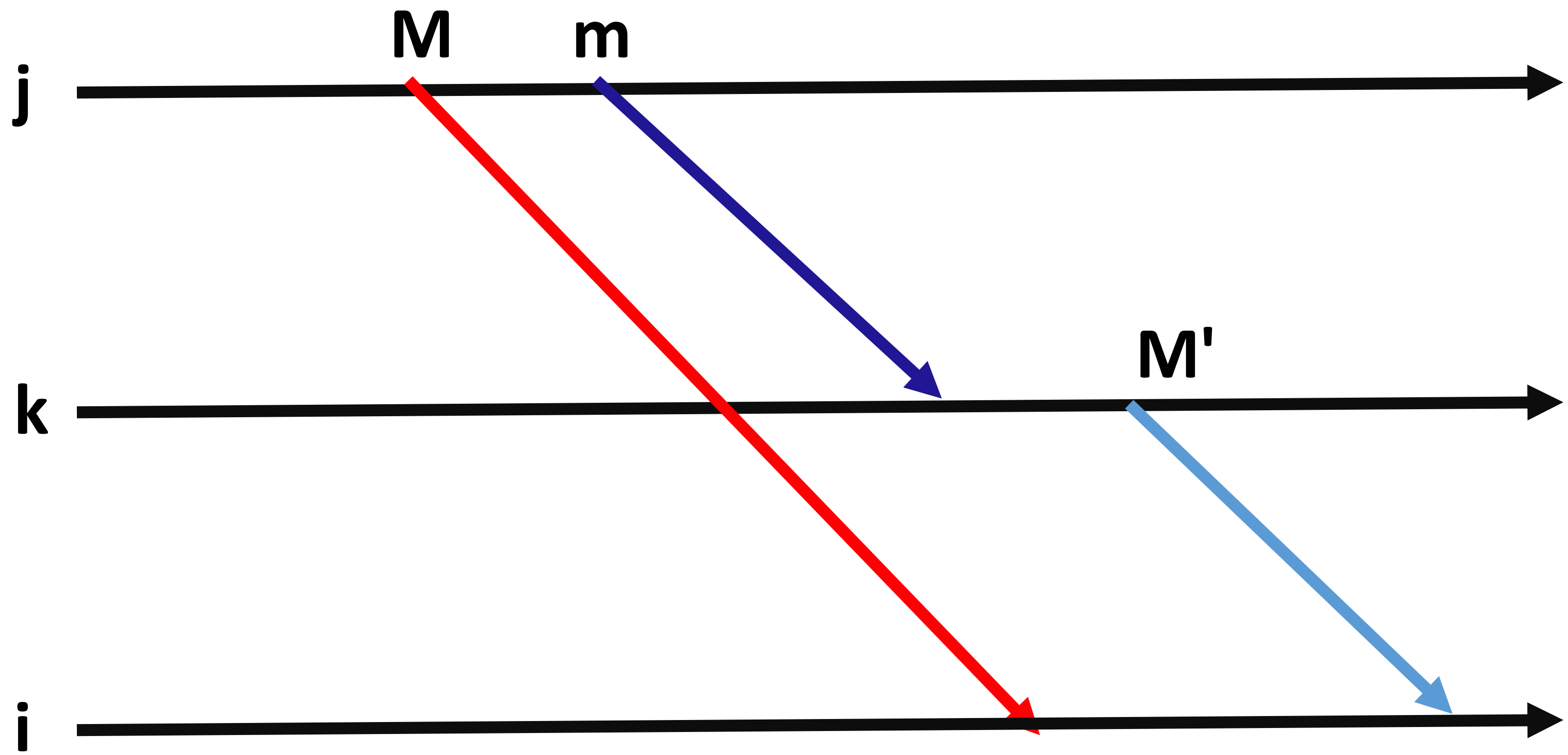
Message Delivery - Causal

- For a process k
  - Send (k, M) ⇒ Process k sends a message M
  - Receive (k, M) ⇒ Process k receives a message M

- Consider process i sends message M and process j sends message M' to process k, and
  Send (i, M) → Send (j, M')

- **Causal delivery** ensures, Receive (k, M) → Receive (k, M')
  - The messages are causally related, even if they are sent by different processes

Causal Delivery



Causal Delivery

- Does FIFO between each pair of processes ensure Causal?

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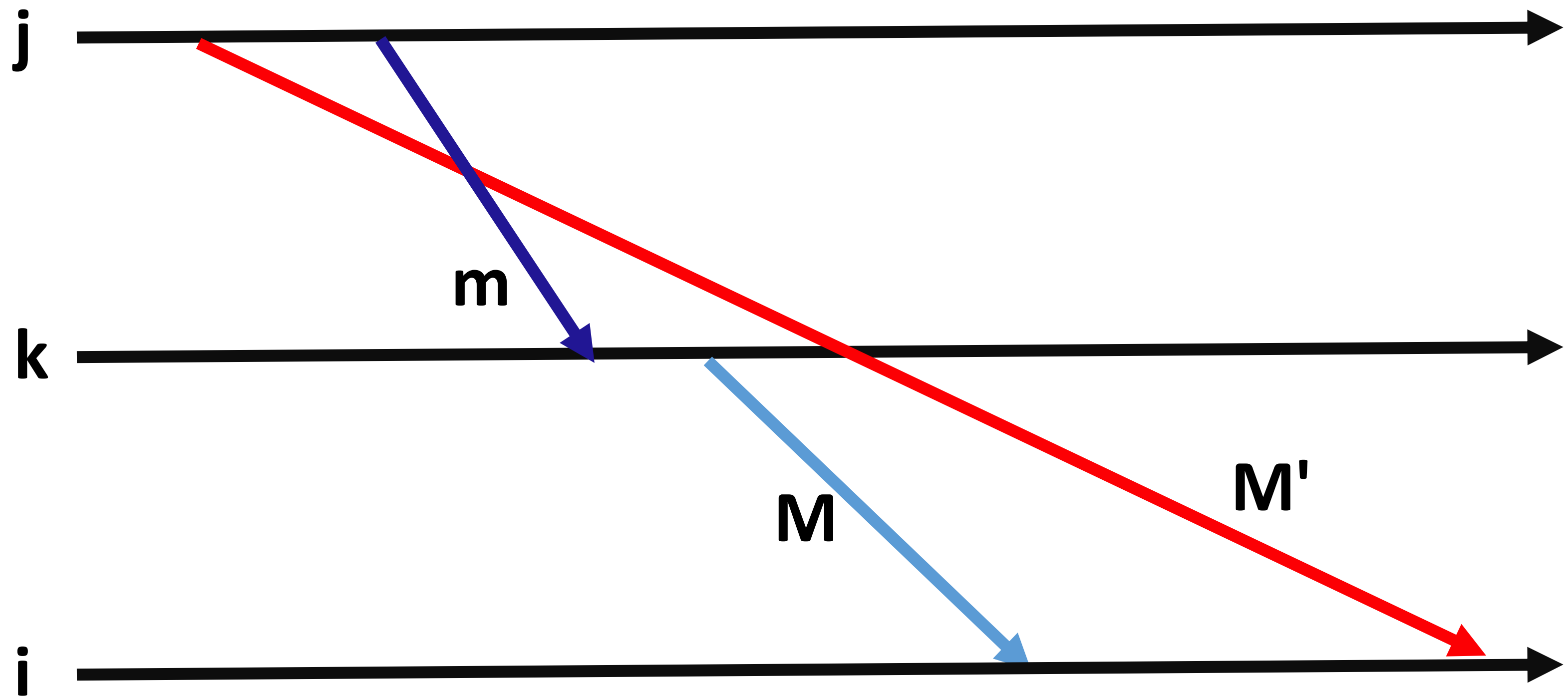
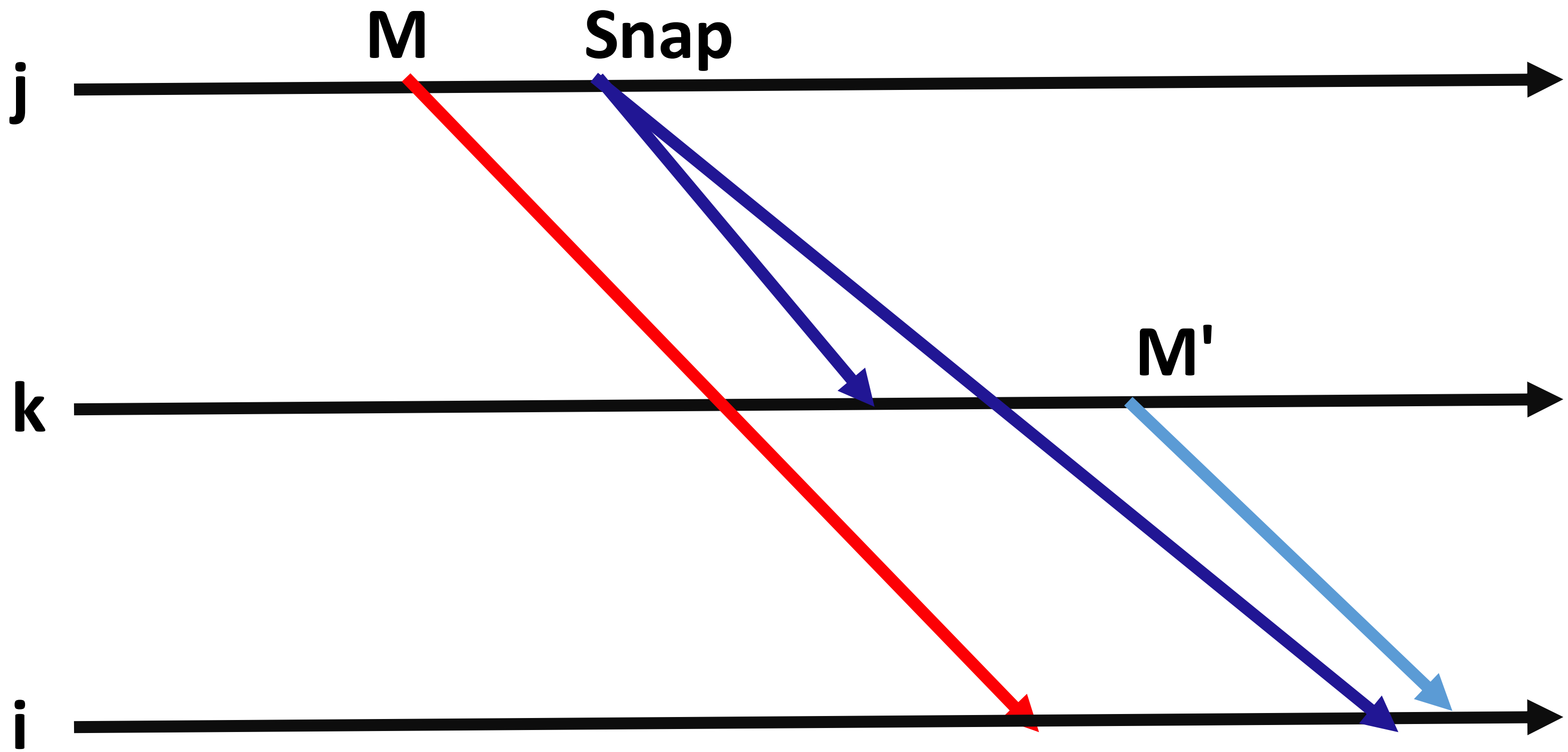


FIFO between (j, k), (k, i), (j, i) but not Causal

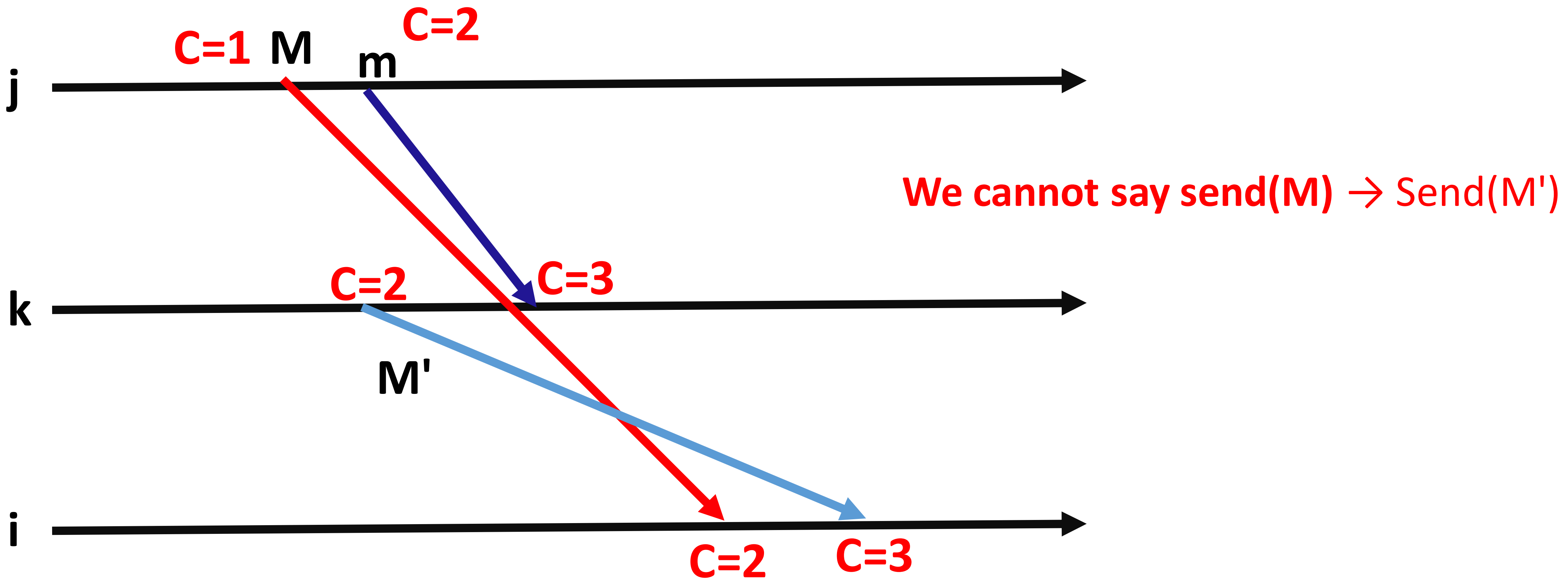
Causal Delivery and Consistency

- If a process uses a delivery rule satisfying causal delivery, then all of its observations will be consistent.
  - The process always receives messages in the causal order in which they have been sent → not possible that the receipt of the message is logged but the sent has not been logged



How Do We Ensure Causal Delivery

- Lamport's clock does not tell anything about the ordering of the events based on their clock – **is its major limitation**



Stable Messages

- Let a message M be received at a process p with timestamp TS(M). Let logical clock be used to generate the timestamp.

- Message M is called to be stable, if process p receives no other message M' after the receipt of M such that TS(M') < TS(M)

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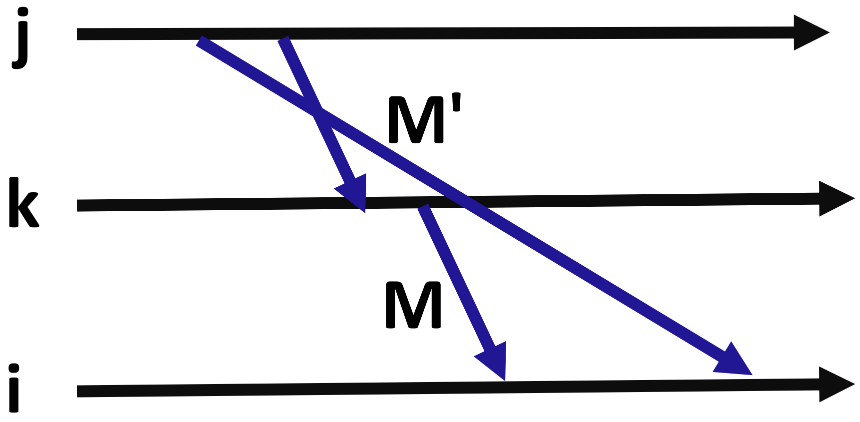

Not Stable

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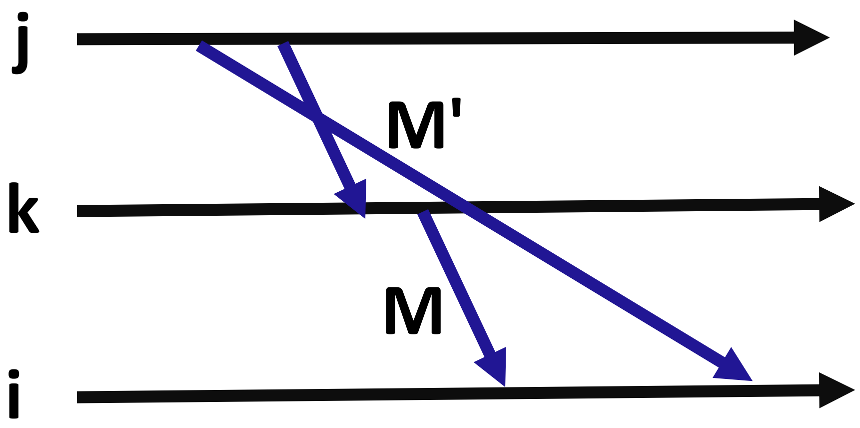

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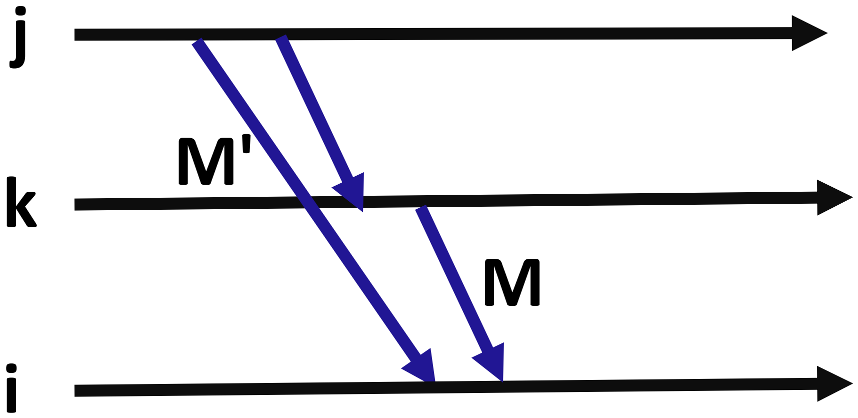

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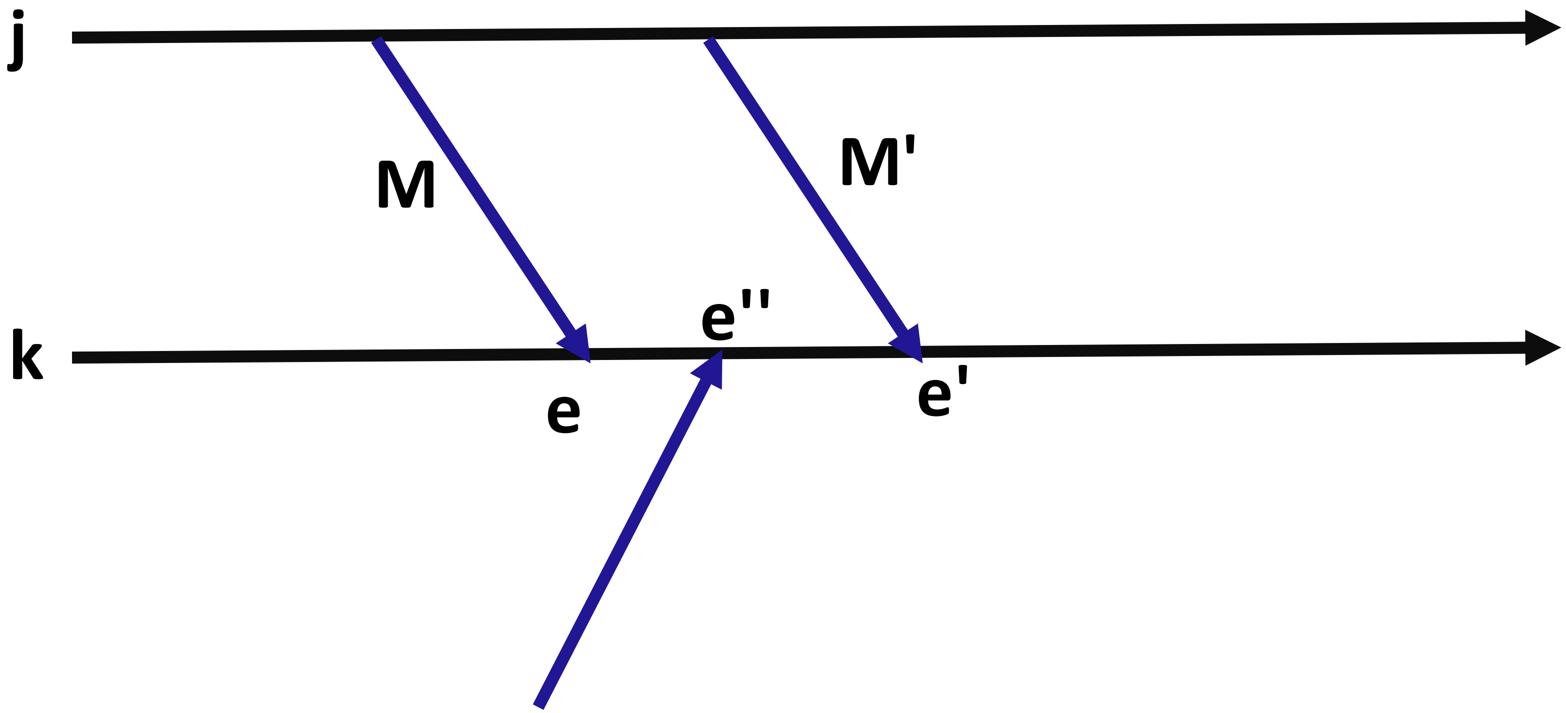
- **Causal delivery ensures that the message is stable.**

Gap Detection – Ensuring Causal Delivery

- Given two events e and e' along with their logical clock values LC(e) and LC(e') where LC(e) < LC(e'), determine whether some other event e'' exists such that LC(e) < LC(e'') < LC(e')



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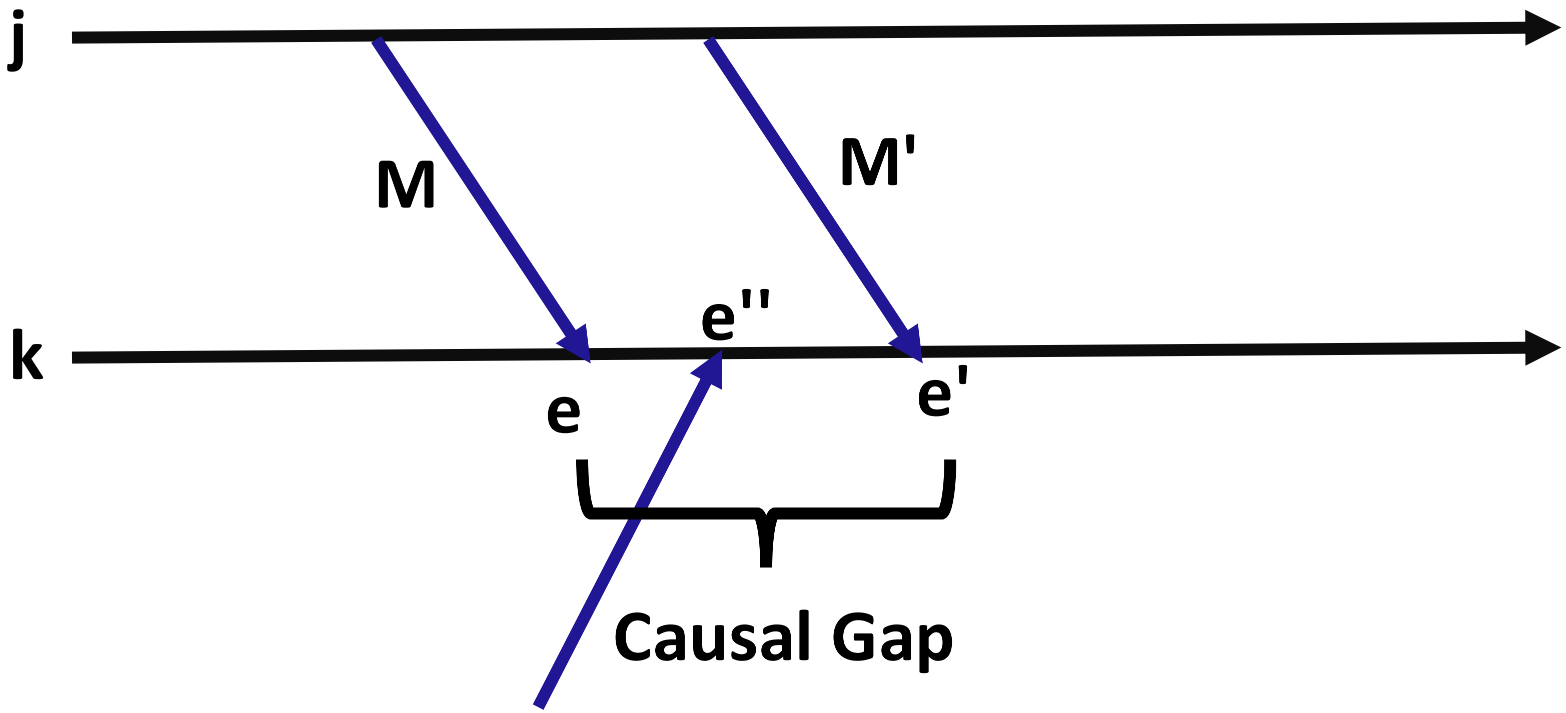

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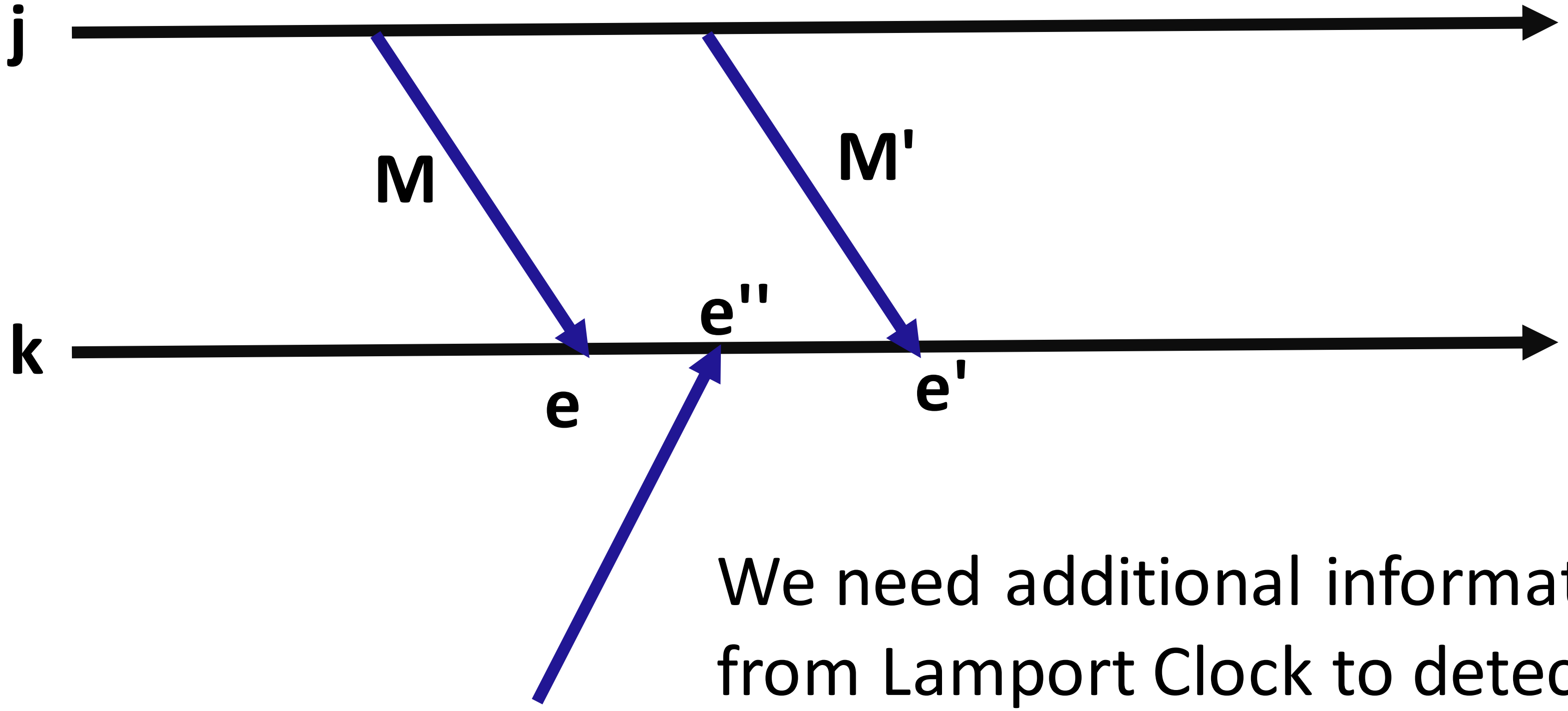
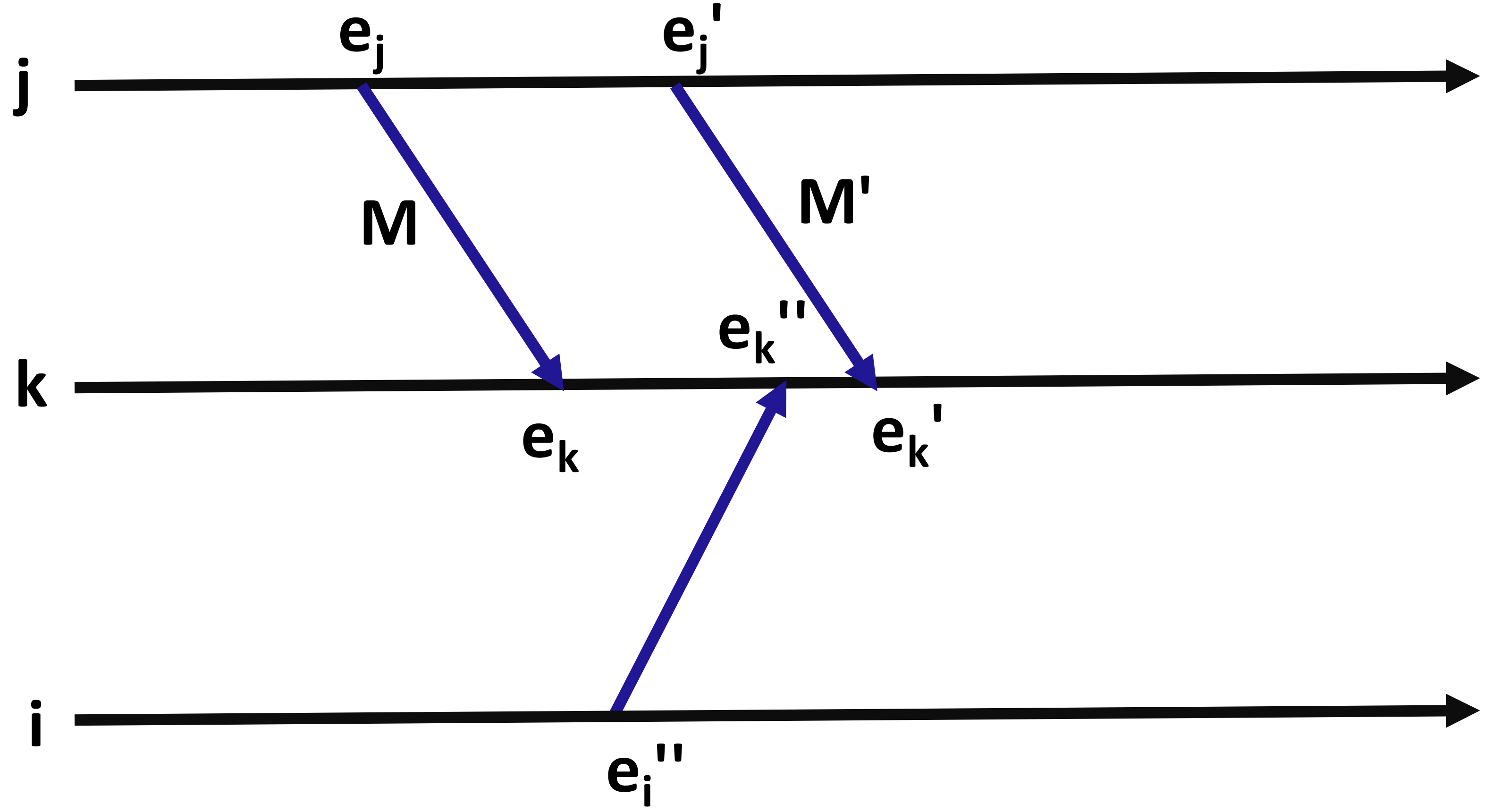


We need additional information apart from Lamport Clock to detect gaps

Ex. FIFO delivery of two consecutive messages between a pair of processes

The Causal Dilemma with Lamport's Clock



- With Lamport's clock, we really do not know whether $\mathbf{e_i''} \rightarrow e_j'$
  - Whether to log e_k'' or not, depends upon this causal relationship.

Requirement for Causal Delivery

- Given events e and e' that are causally related and their clock values, does there exist some other events e'' such that $e \rightarrow e'' \rightarrow e'$?
  - e'' falls in the causal gap between e and e'

- Lamport clock ensures, $e \rightarrow e' \Rightarrow LC(e) < LC(e')$

- We need a true clock (TC), $e \rightarrow e' \Leftrightarrow TC(e) < TC(e')$

- Method for generating true clocks:
  - Causal history (a brute force approach)
  - Vector clocks

Vector Clocks

- Discovered independently by many researchers in many different contexts !

- Each process p_i maintains a local vector VC of natural numbers where $VC(e_i)$ denotes the vector clock value of p_i when it executes event e_i

- Each process initializes VC to contain all zeros; all messages contain a timestamp TS(m)

Reinhard Schwarz and Friedemann Mattern. **Detecting causal relationships in distributed computations: In search of the Holy Grail**. Technical Report SFB124-15/92, Department of Computer Science, University of Kaiserslautern, Kaiserslautern, Germany, December 1992

Vector Clocks – Update Rules

- $VC(e_i)[i] := VC[i] + 1$ if e_i is an internal or a send event
    - Internal of send events simply increment the local component of the vector clock

- $VC(e_i) := \max\{VC, TS(m)\}$ if $e_i = receive(m)$
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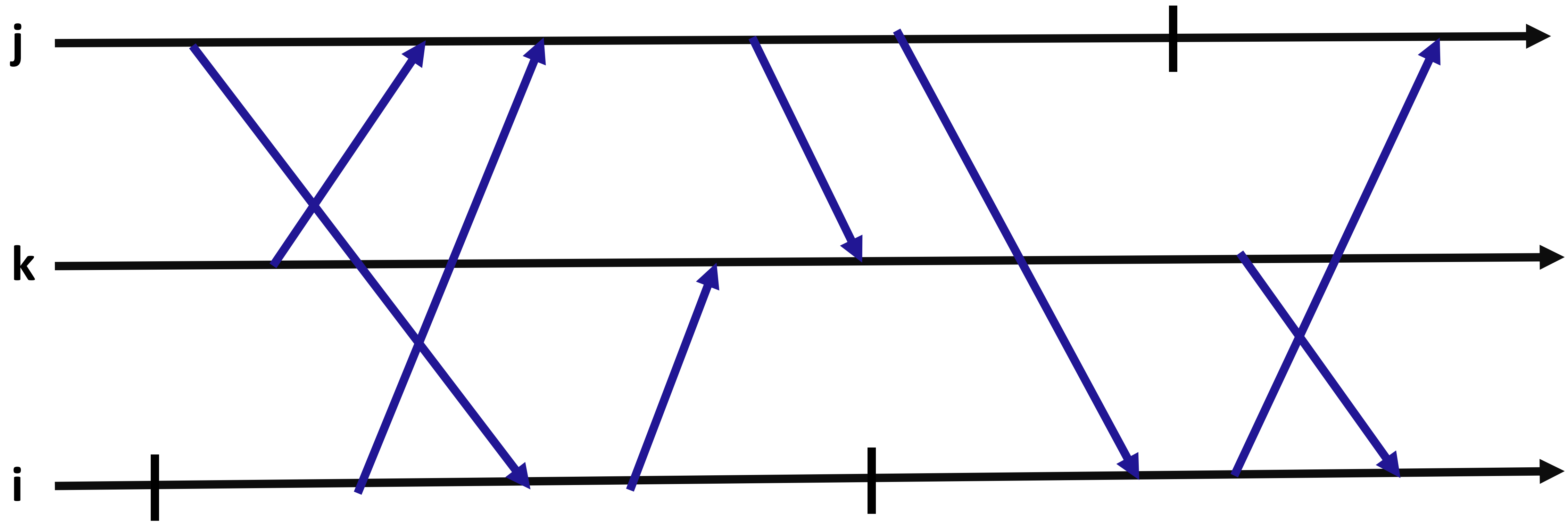
    - For a receive event, update the vector clock with the greater of local clock and the received timestamp, and then increment it

Vector Clock -- Visualization



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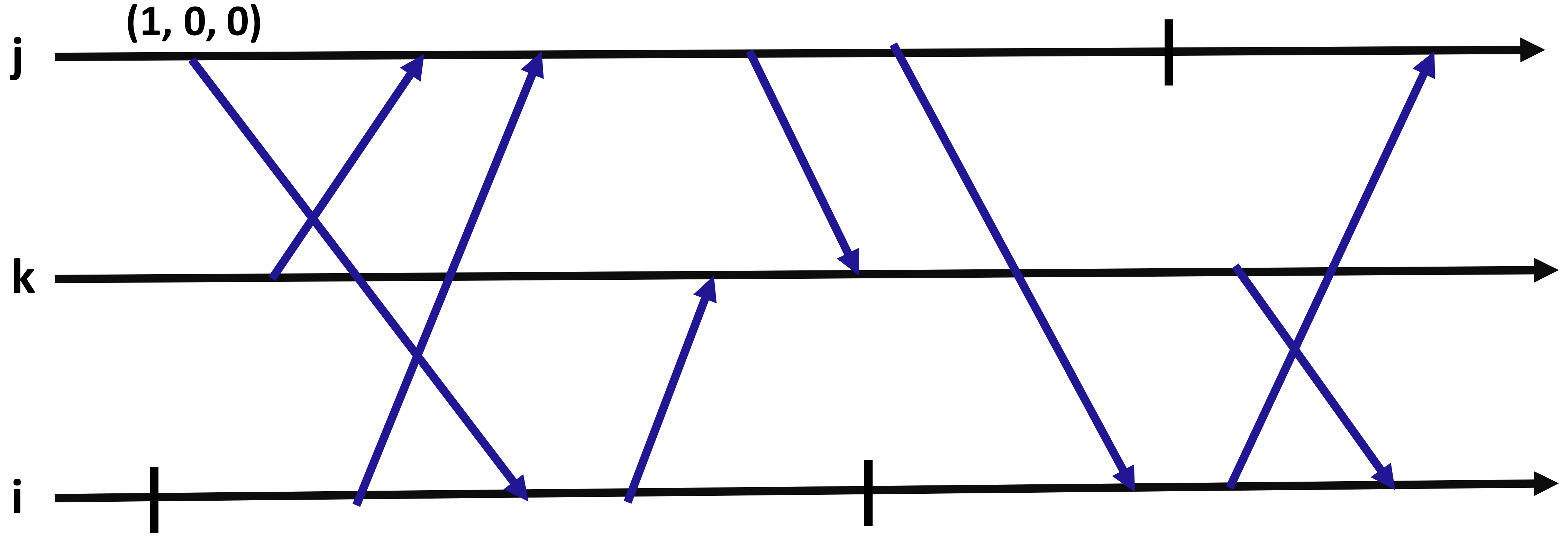

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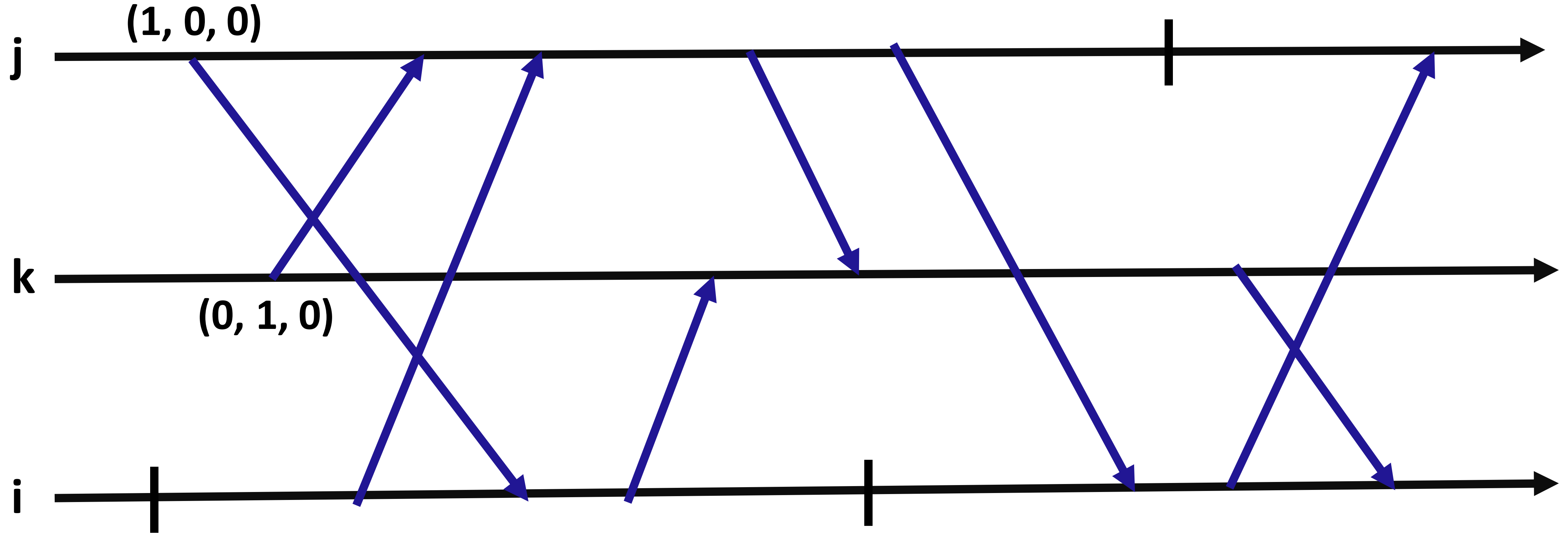

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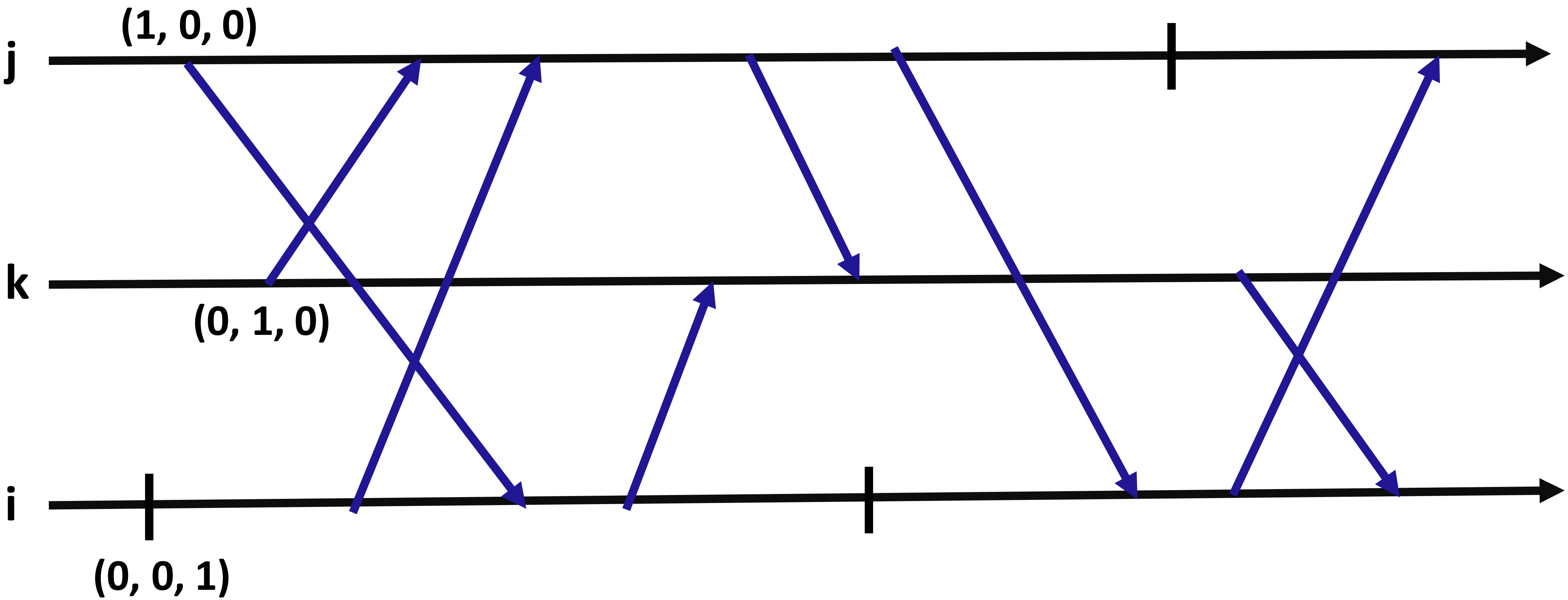

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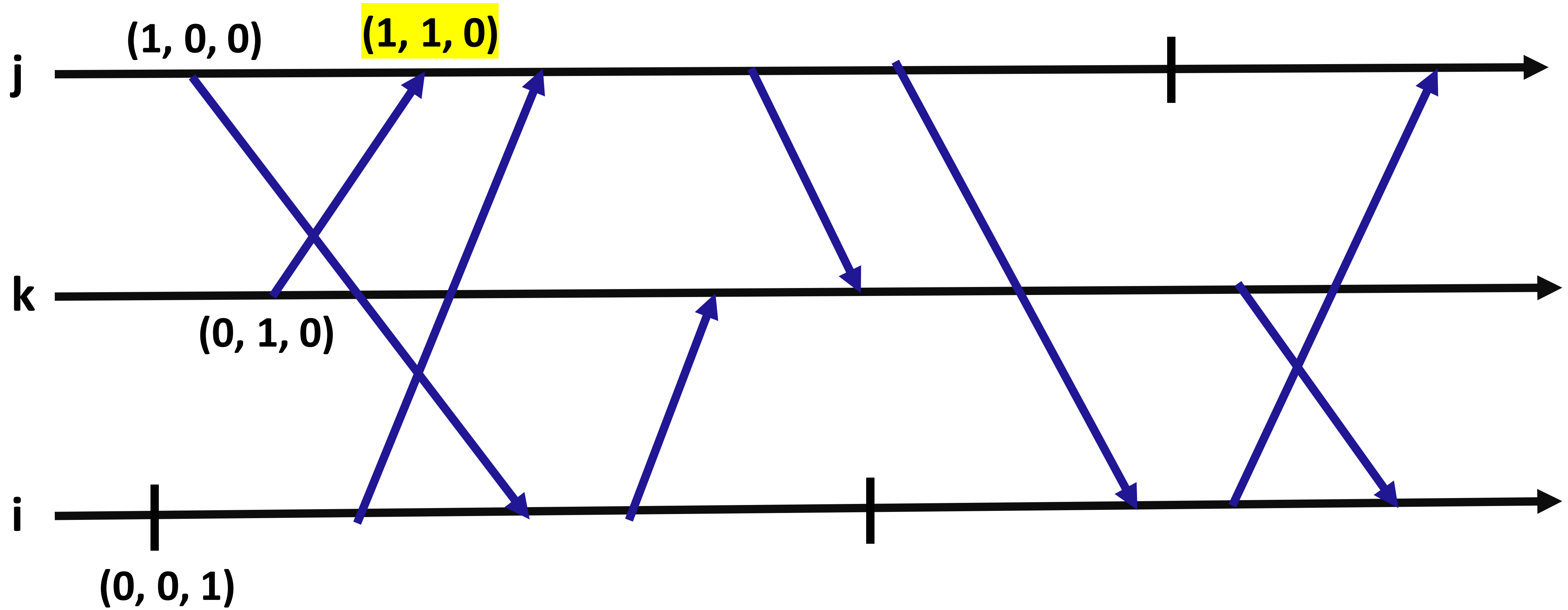

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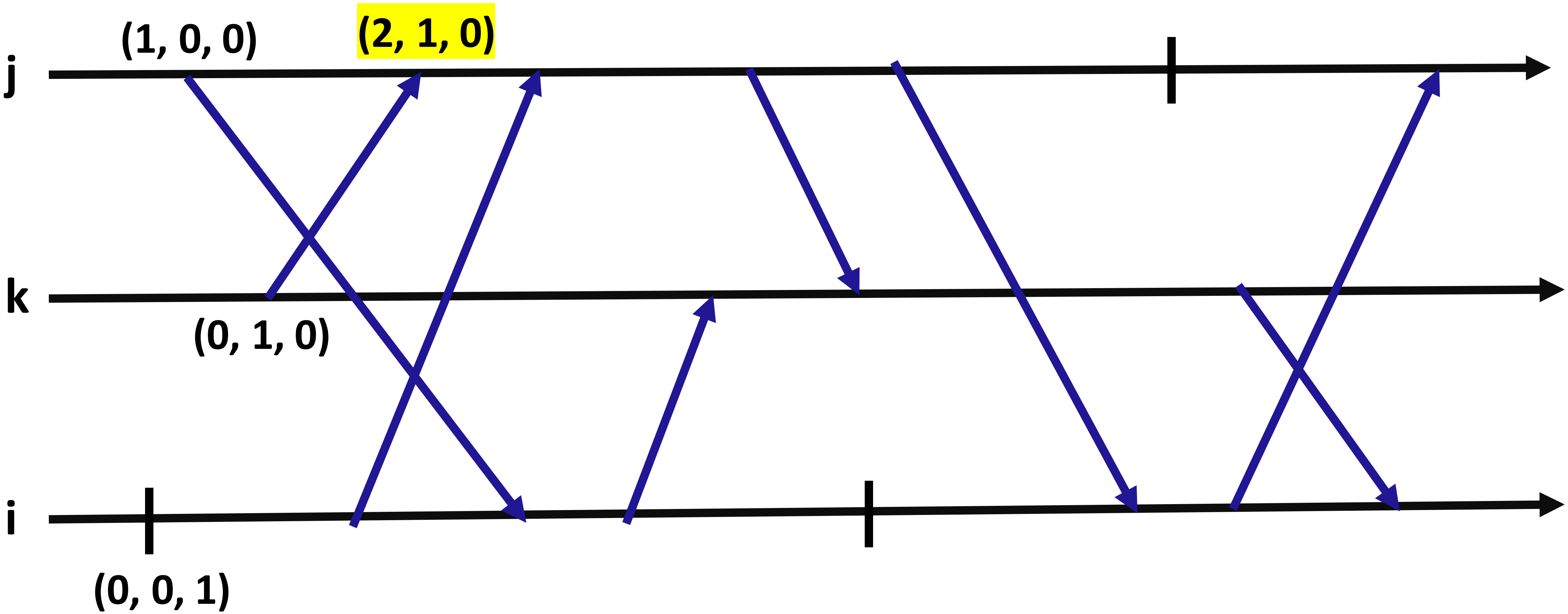

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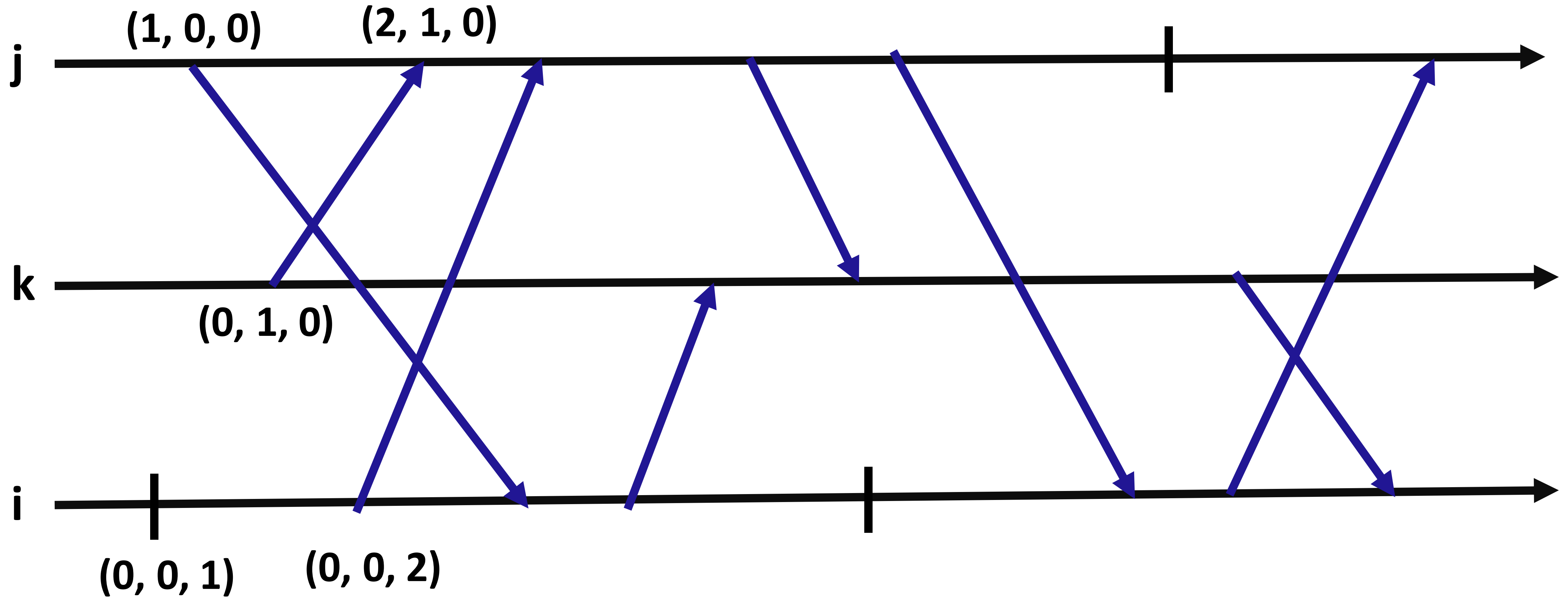

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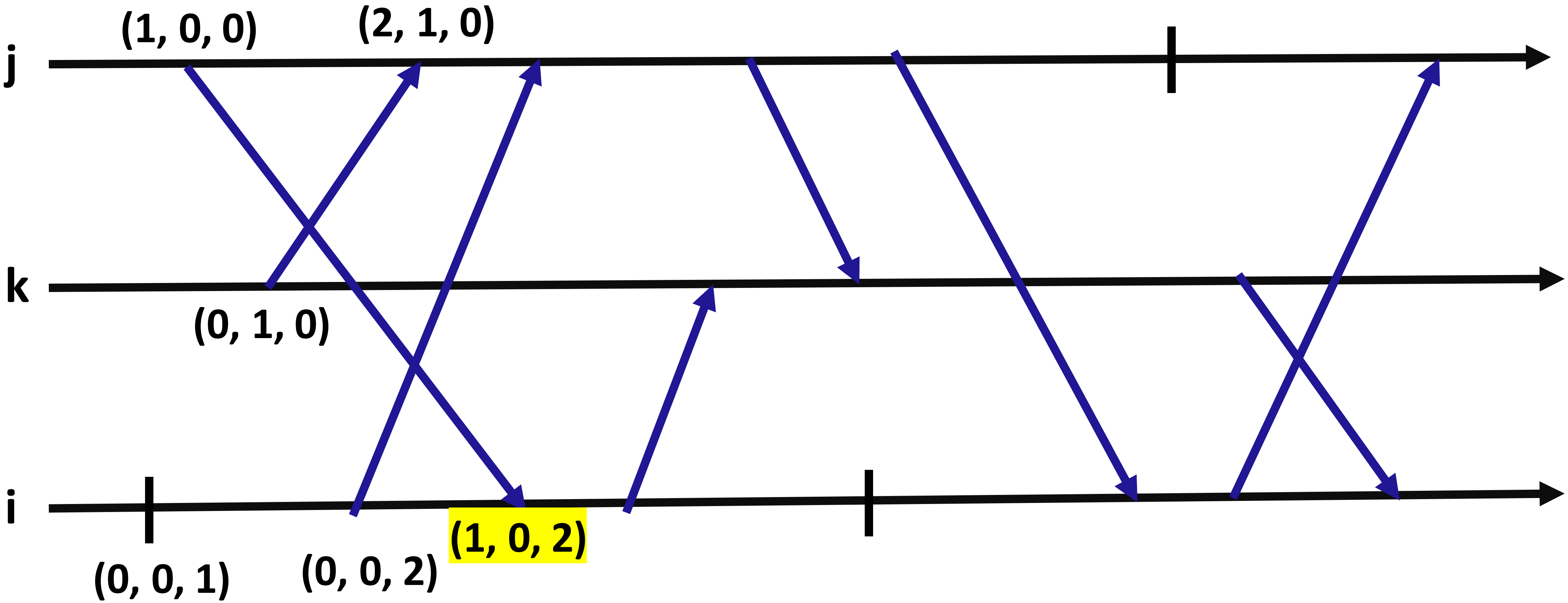

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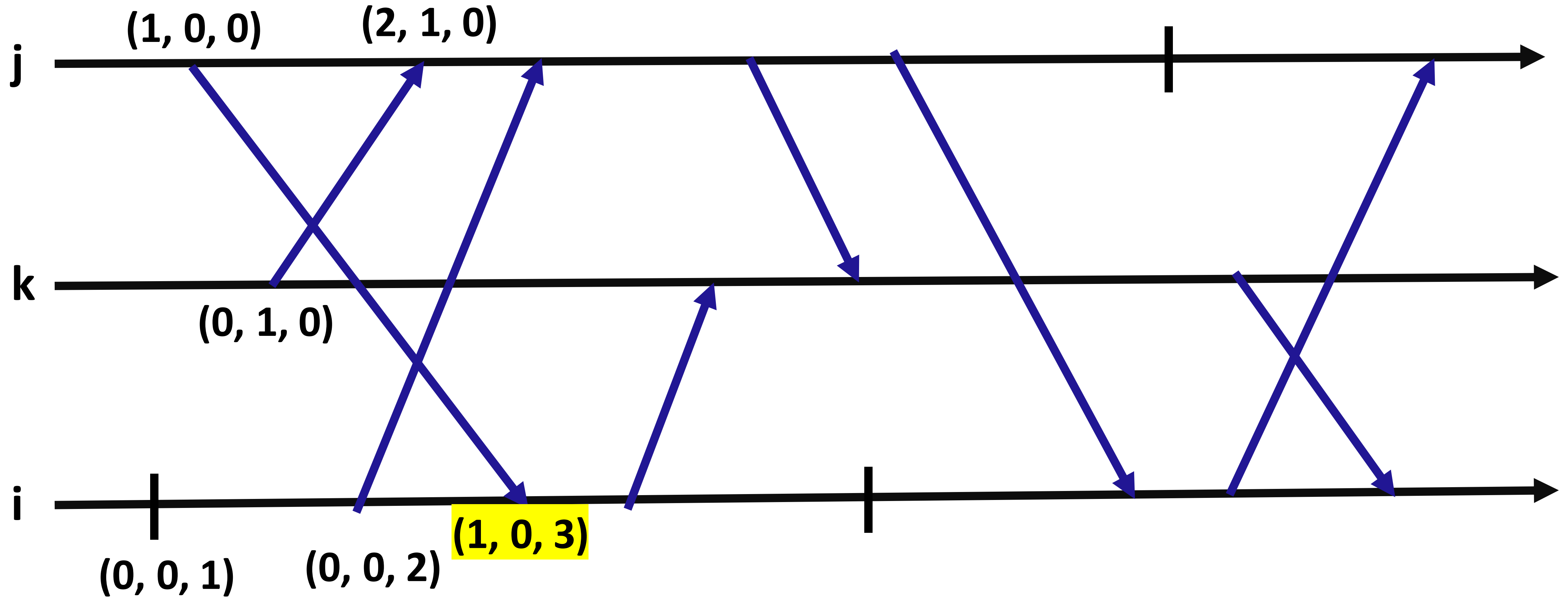

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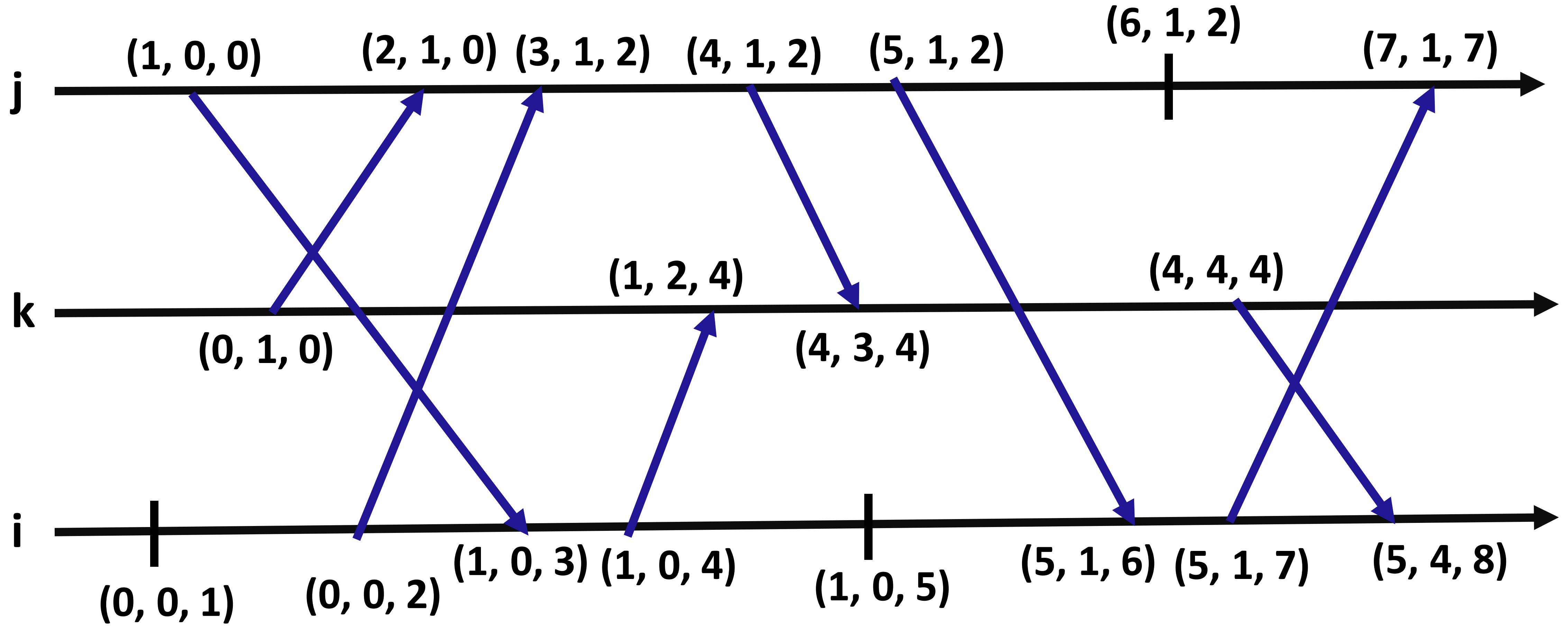

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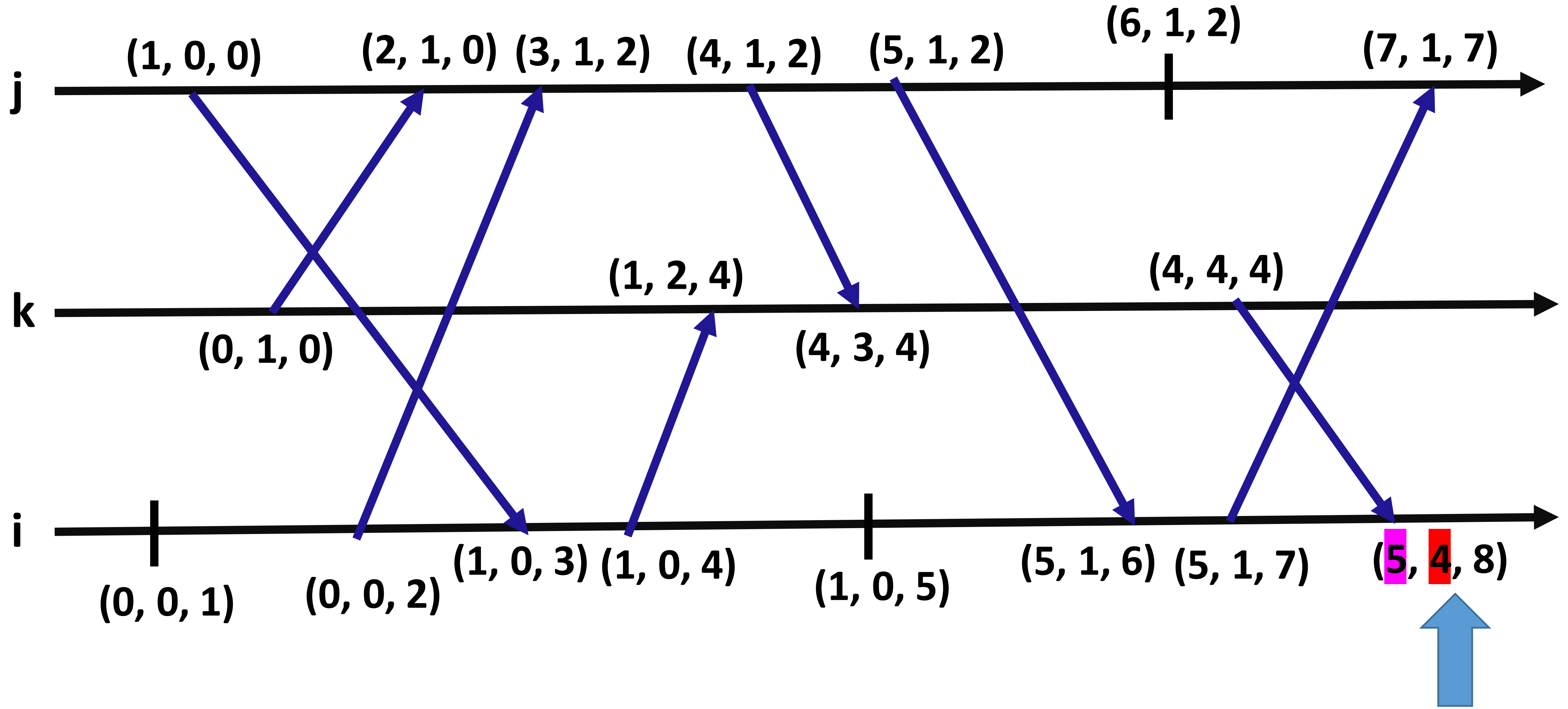
- **For all $j \neq i$,**
  $VC(e_i)[j]$ = number of events of p_j that causally preceeds event e_i of p_i

Vector Clock and Causality



There are 5 events from process P_j and 4 events from process P_k that causally preceeds this event

Strong (True) Clock Condition

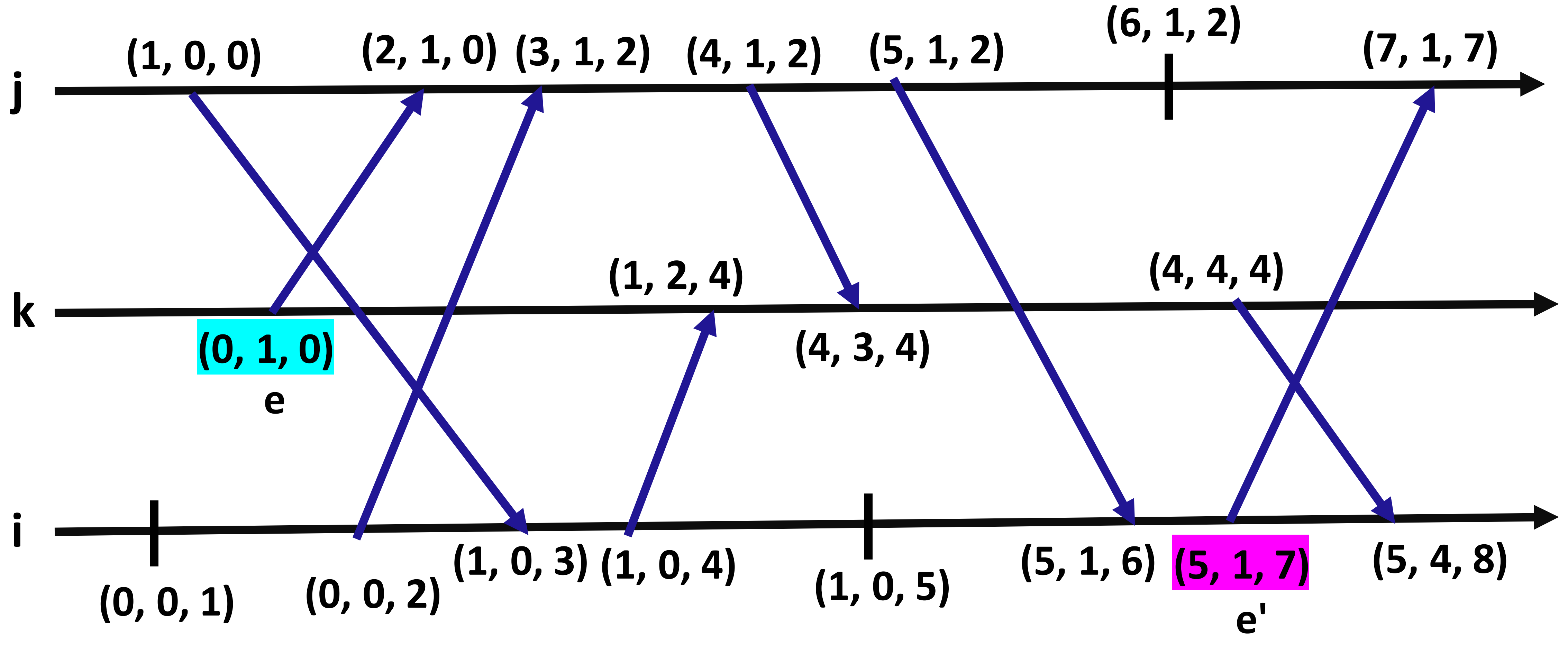
- Given two n-dimensional vector V and V'

$$V < V' \Rightarrow (V \neq V') \wedge (\forall k: 1 \leq k \leq n: V[k] \leq V'[k])$$

- Vector clock supports strong (true) clock condition:

$$e \rightarrow e' \Leftrightarrow VC(e) < VC(e')$$

Strong (True) Clock Condition



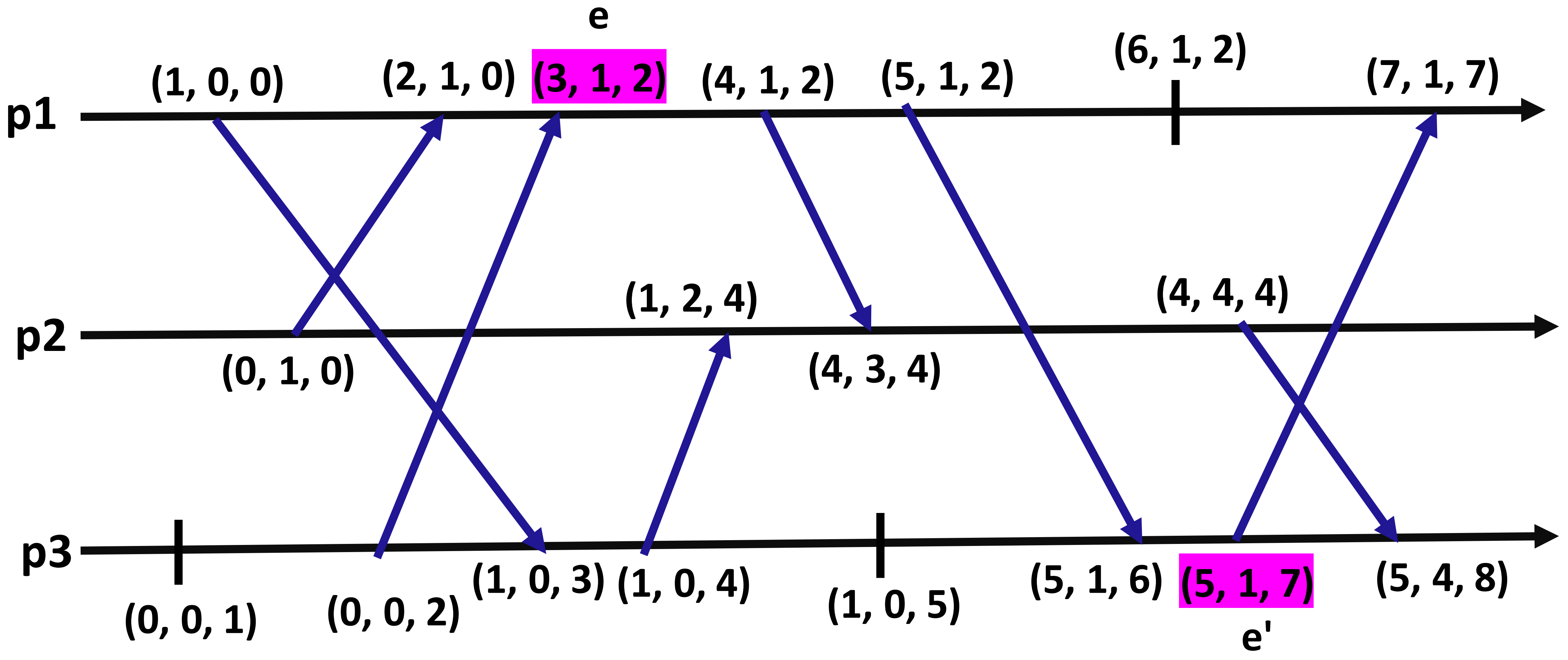
$e \rightarrow e'$

Properties of Vector Clocks

- **Simplified Strong Clock Condition:** Given event e_i of process p_i and event e_j of process p_j, where $i \neq j$,

$$e_i \rightarrow e_j \Leftrightarrow VC(e_i)[i] \leq VC(e_j)[i]$$

Properties of Vector Clock



e → e'

Properties of Vector Clocks

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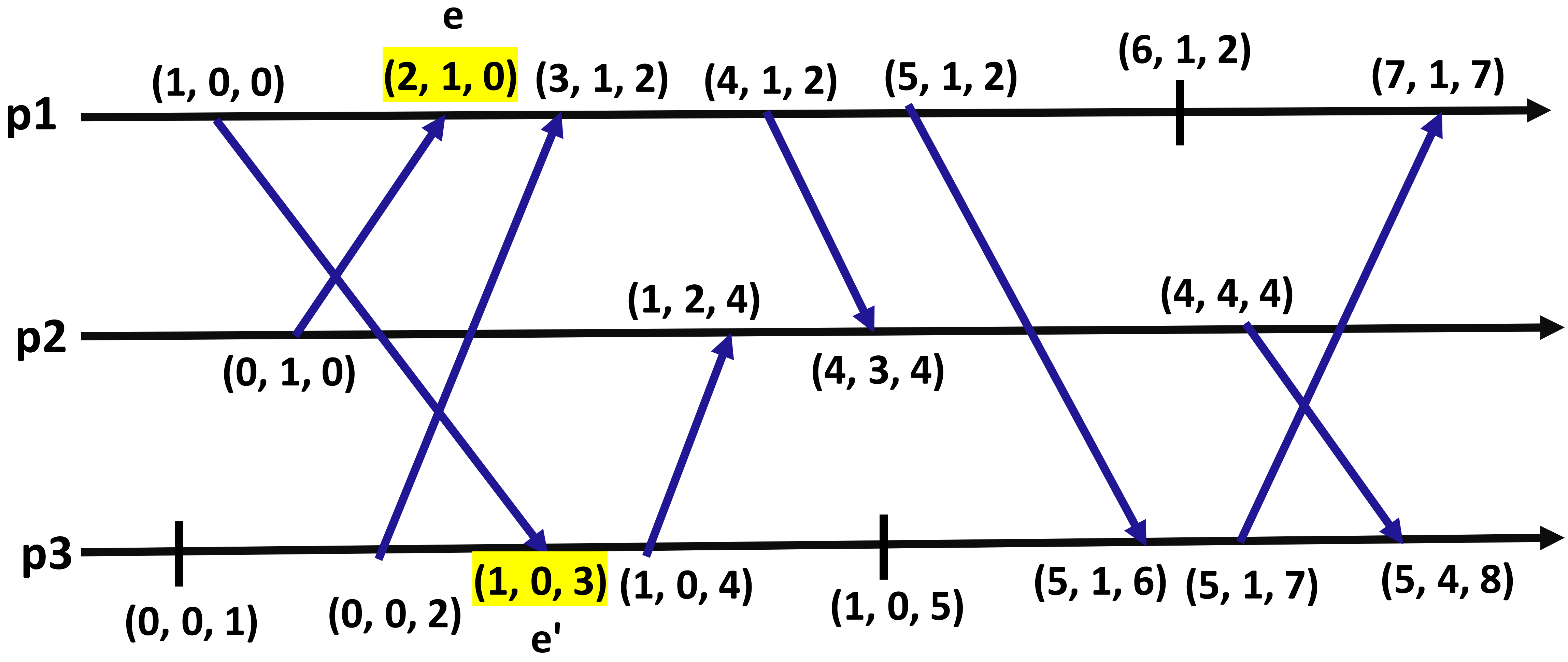
$$e_i \rightarrow e_j \Leftrightarrow VC(e_i)[i] \leq VC(e_j)[i]$$

- **Concurrent events:** Given event ei of process pi and event ej of process pj, where $i \neq j$,

$$e_i \mid\mid e_j \Leftrightarrow (VC(e_i)[i] > VC(e_j)[i]) \text{ AND } (VC(e_j)[j] > VC(e_i)[j])$$

Properties of Vector Clock



e || e'

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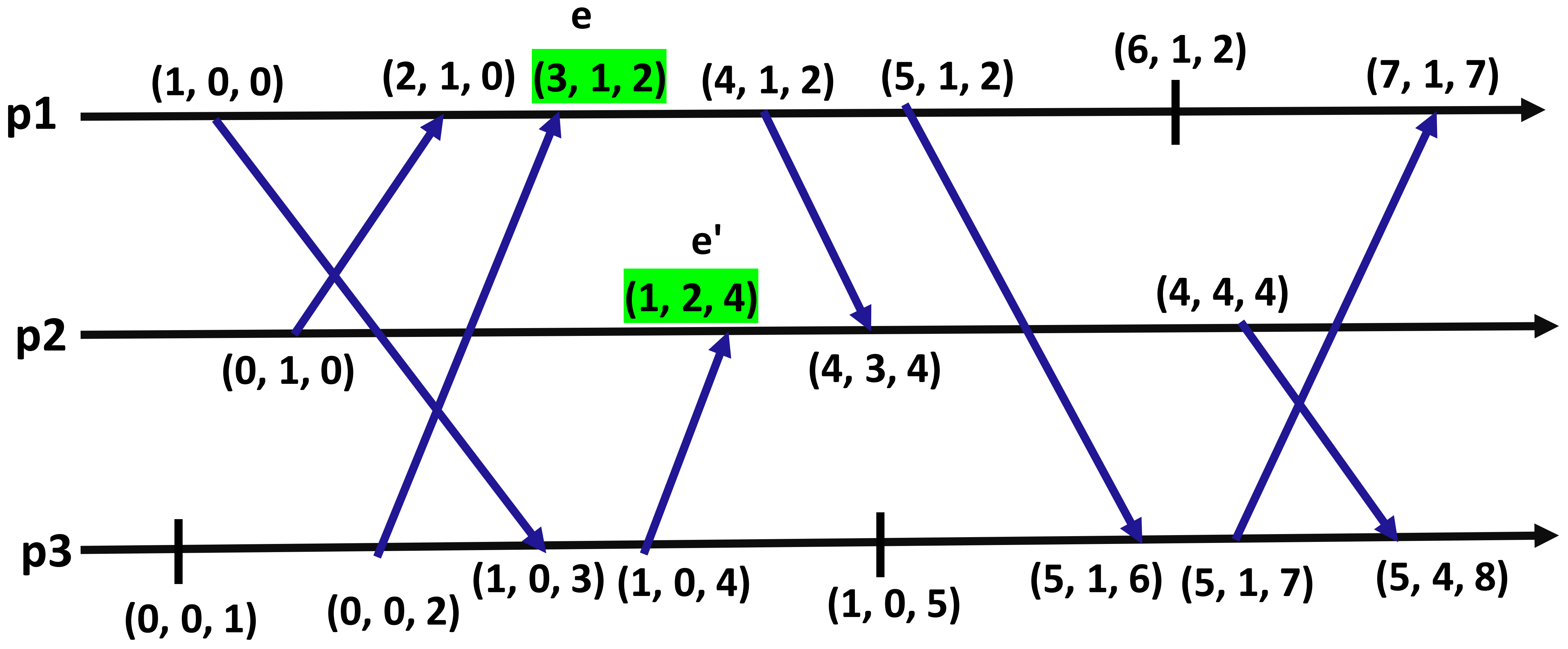
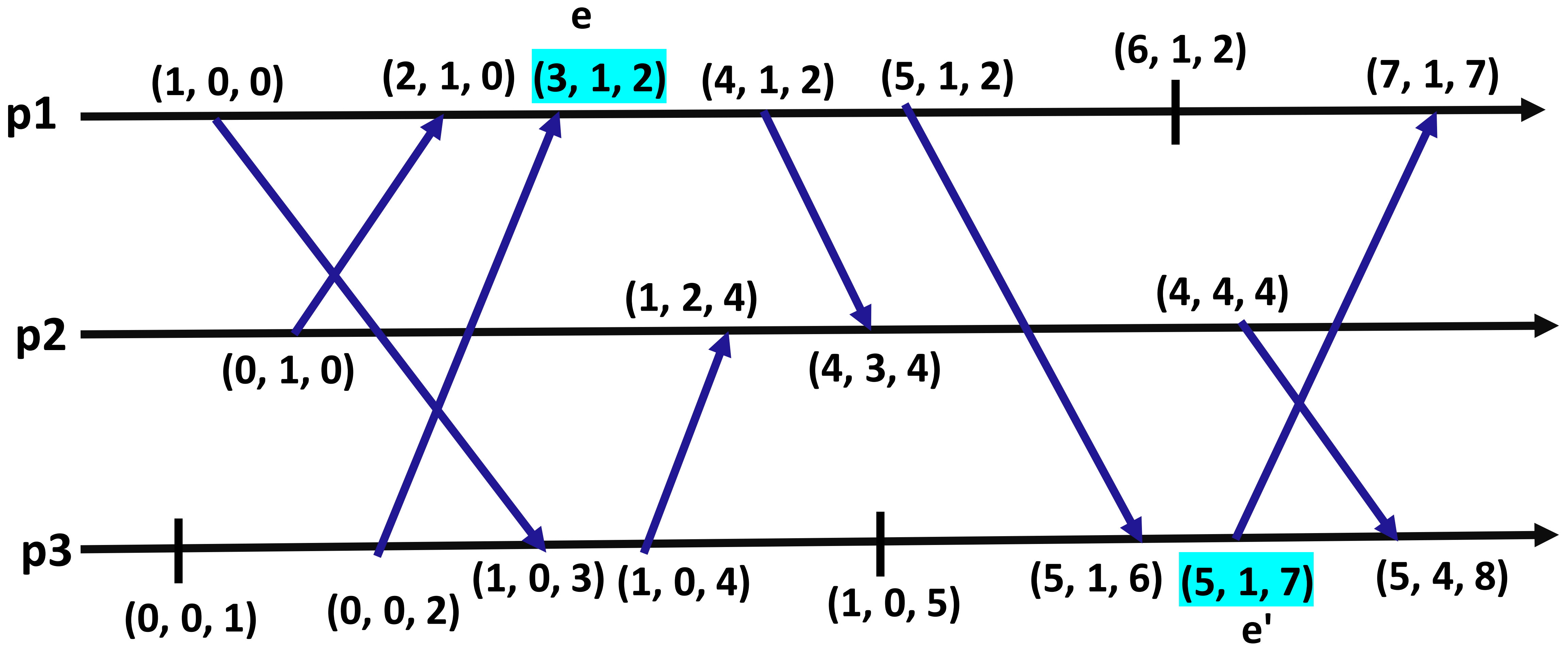


What is the relationship between e and e'?

Properties of Vector Clock



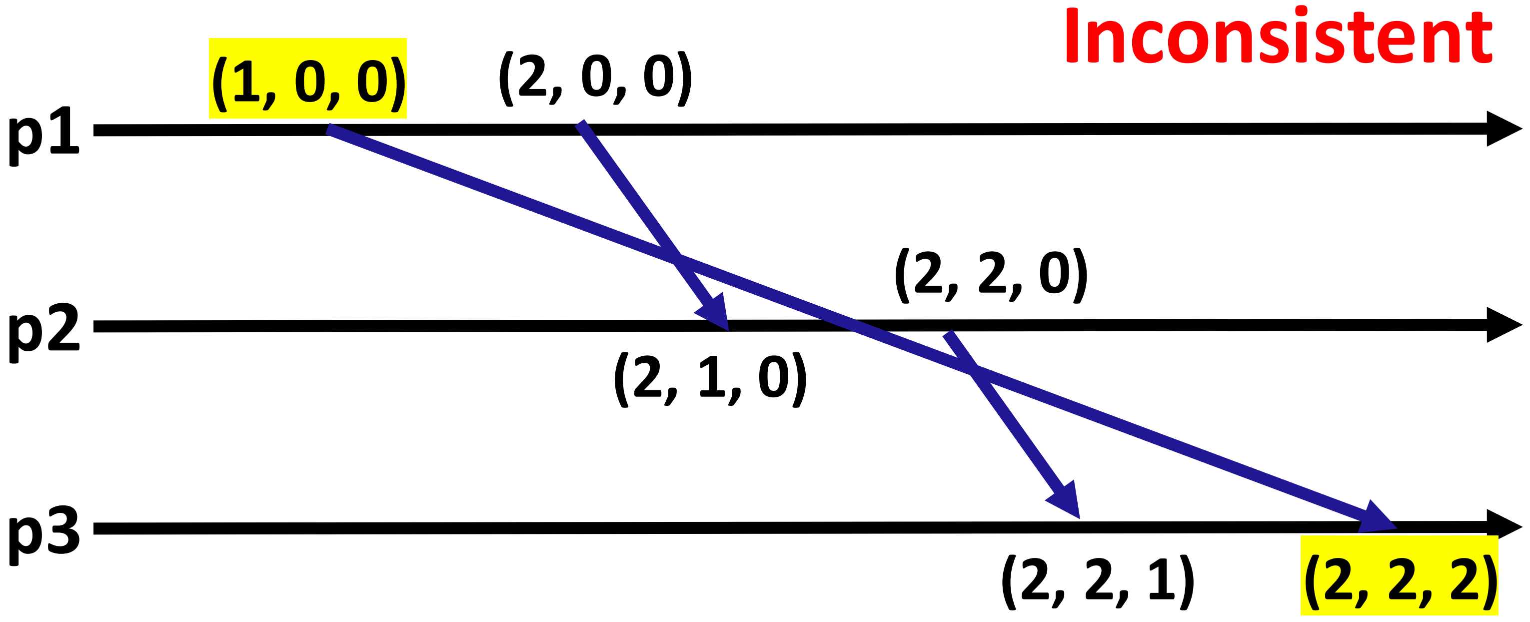
What is the relationship between e and e'?

Pairwise Inconsistent Events

- Event e_i or process p_i is **pairwise inconsistent** with event e_j of process p_j, where $i \neq j$ if and only if

$$(VC(e_i)[i] < VC(e_j)[i]) \text{ OR } (VC(e_j)[j] < VC(e_i)[j])$$

Pairwise :=
{send(M), Receive(M)}



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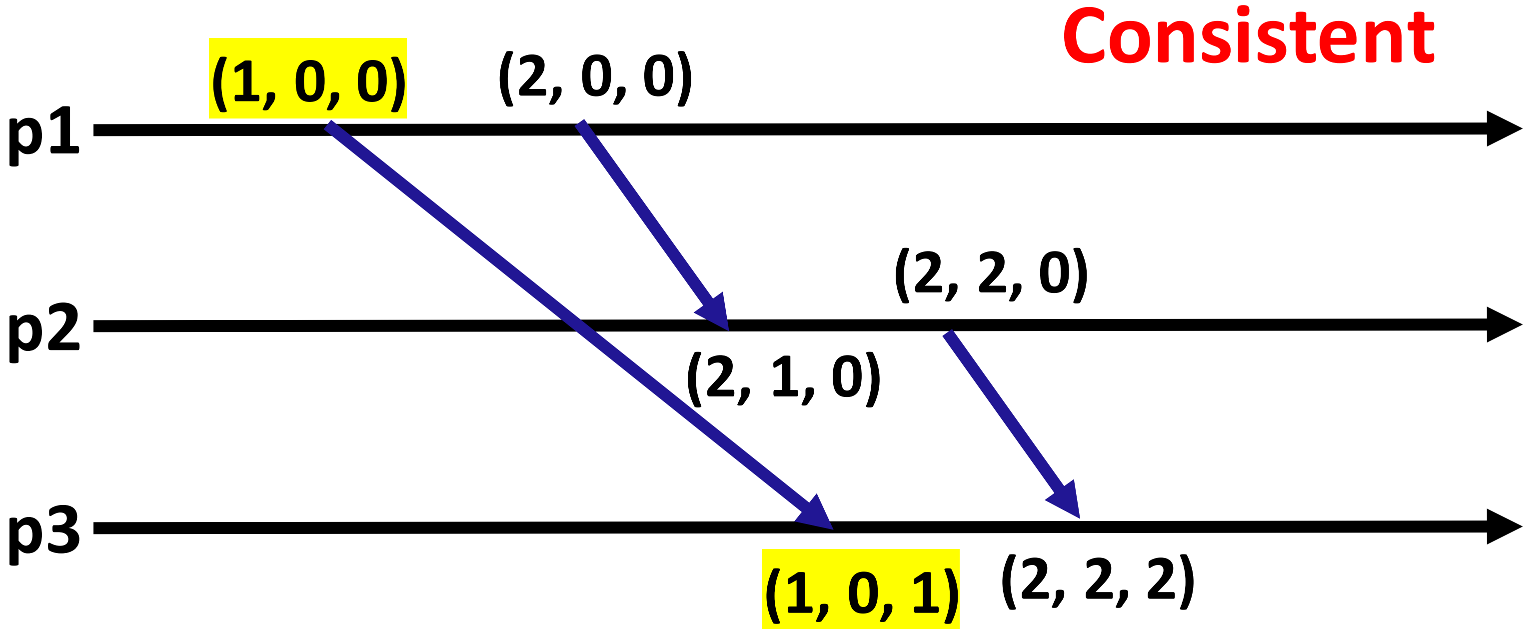

Causal Delivery using Vector Clock

- Each application process contains a middleware that delivers the message to the application based on the causal rule.

- Each message contains a timestamp, i.e., vector clock of the corresponding Send event.

- The middleware delivers the message M, if
  - No other message from the sender causally preceeds M
  - Let M' be the last delivered message. There is no other message M'' from a third process, such that Send (M') → Send(M'') → Send (M)

Further Reads

- Kshemkalyani, Ajay D., Michel Raynal, and Mukesh Singhal. "**An introduction to snapshot algorithms in distributed computing**." *Distributed systems engineering* 2.4 (1995): 224.
  - Summarizes snapshot algorithms under FIFO, non-FIFO, and causal channels

Happy Learning