Logical Clocks and Distributed Snapshots

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1. Time in Distributed Systems
2. Sample Scenario
3. Lamport Logical Clock
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5. Global Snapshot – Count Money

Philosophical Questions

- Does time exists? Is it linear? No loops?
- What is causality? Vs correlation ...
- What is the meaning of happened-before? Or concurrent?

Time in distributed computing

- No global clock
- Each node has its own clock, unreliable (not totally reliable)
  - Never totally synchronised
  - Drifts, more or less

- Can we avoid these unreliable physical clocks?
- Yes, using logical clocks, that are independent of the physical time

Happens-before = potential causation

- Event a happens-before event b, $\boxed{a \prec b}$, $\boxed{a \to b}$, iff

  1. a and b occur in the same node, and a happened before b, according to the local clock
  2. a is a send event and b is the corresponding receive event (same message, two nodes)

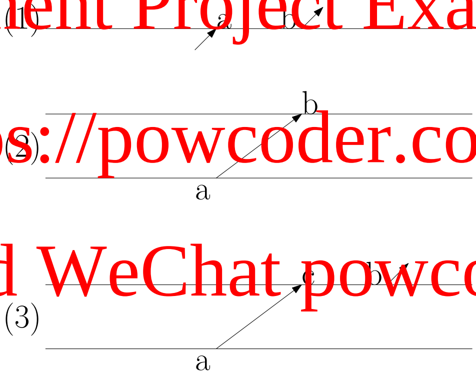
     - here we assume that messages are sent and received one by one, but broadcasts/multicasts can be included

  3. There is an event c, s.t. $a \prec c \prec b$: transitive closure

- This happens-before ($a \prec b$) determines a partial order (creates a dag)

- For us here, happens-before $\equiv$ potential causality

Happens-before = potential causation



Logical time and logical clocks

- Logical time is a mapping C from events to elements of a partially ordered set, s.t. $\boxed{a \prec b \Rightarrow C(a) < C(b)}$
  - Counterfactual: $\boxed{C(a) \not< C(b) \Rightarrow a \not\prec b}$
- If $\boxed{a \not\prec \not\succ b}$, then a and b are called concurrent, $\boxed{a \parallel b}$

Logical time and logical clocks

- Logical clock is a device (algorithm) that makes these mappings in a distributed network

- Must have feature: should be determined by nodes themselves
- Must have feature: unique, i.e. one-to-one (injective)

- Good feature: same times, if "essentially" same execution
- Ideal / exact match feature: $\boxed{a \prec b \Leftrightarrow C(a) < C(b)}$ – NOT all clocks!
  - Factual: $\boxed{C(a) < C(b) \Rightarrow a \prec b}$

- If the clock maps to a totally ordered set, then it is not "ideal"

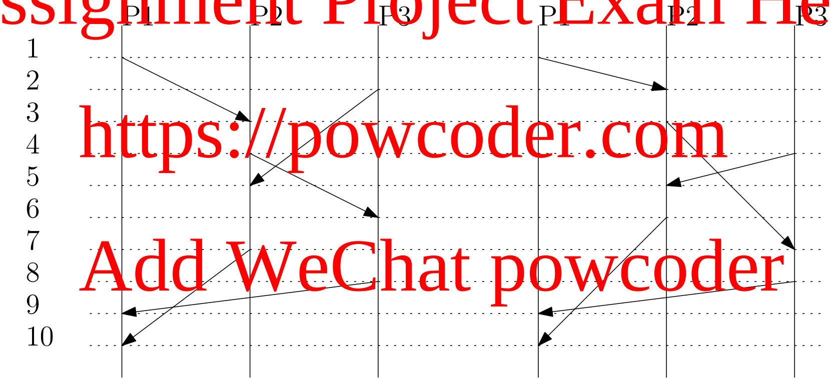
Logical time in A#1?

- According to this definition, what is the logical time in A#1?
  - Message.time?
  - First four components: (.time, .code, .from, .to)?
  - What if we drop one of these?

- Is this "ideal"? Is this total?
- Is this determined by the nodes? Or by Arcs ☹
- Briefly: total logical time, but Arcs is NOT a true logical clock

Sample Scenario – Total orders

Two compatible totals orders for essentially the same execution



A good logical clock should generate same logical timestamps

Lamport Logical Clock – Part I

- Each processing node has its own logical clock, initialised by

  $\boxed{\text{clock} = 0}$

- Before each internal or send event, the clock is incremented

  $\boxed{\text{clock} \mathrel{+}= 1}$

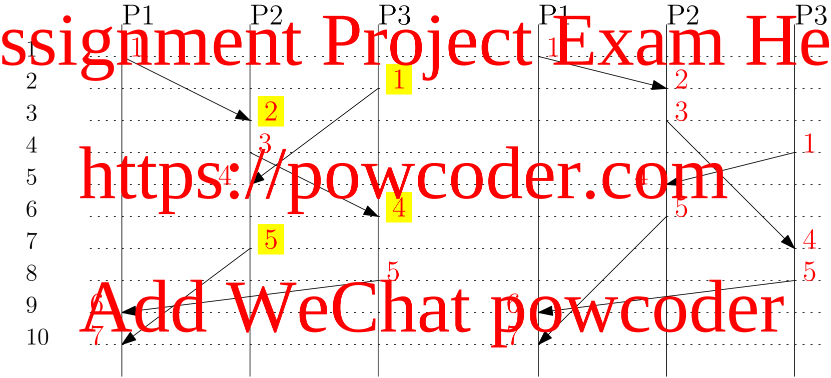
- Each sent messages carries the sender's clock

- After receiving a message, the receiving node updates its clock

  $\boxed{\text{clock} = \max\,(\text{clock, received-clock}) + 1}$

Lamport Logical Clock – Part I

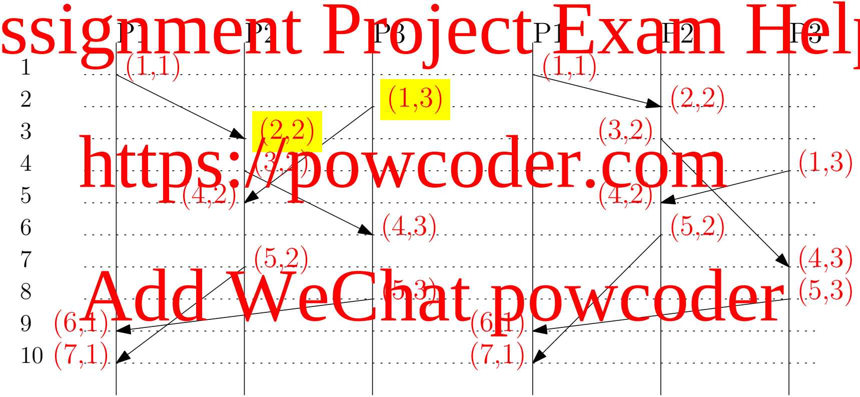
Same logical timestamps for essentially the same execution



- NOT "ideal order": $P3 : \boxed{4} < P2 : \boxed{5}$, but $P3 : \boxed{4} \not\rightarrow P2 : \boxed{5}$
- Total order, b/c timestamps have simple numerical values
- More: timestamps are NOT unique!

Lamport Logical Clock – Part II

Ensure uniqueness by adding process IDs – lexicographic order



- Unique, but otherwise same problems, NOT “ideal”
- NOT “ideal order”: $P3$: (1,3) $<$ $P2$: (2,2), but $P3$: (1,3) $\not<$ $P2$: (2,2) – in fact, these are concurrent

Lamport Logical Clock – Exercise (WanFok)

- Consider the following sequences of events at processes p_1, p_2, p_3:

$p_1 : a \ s_1 \ r_3 \ b$

$p_2 : c \ r_2 \ s_3$

$p_3 : r_1 \ d \ s_2 \ e$

- where s_i and r_i are corresponding send and receive events, for $i = 1, 2, 3$.
- Provide all events with Lamport's clock values.

- Answer:

$p_1 \ : \ 1 \ \ 2 \ \ 8 \ \ 9$

$p_2 \ : \ 1 \ \ 6 \ \ 7$

$p_3 \ : \ 3 \ \ 4 \ \ 5 \ \ 6$

Vector Logical Clock – Exact Match

- Each process keeps a vector (tuple) containing all known local logical times, e.g.

$$V(P_2) = (v_1, v_2, v_3)$$

- These tuples are ordered on each component, i.e. NOT lexicographically, e.g.

$$(v_1, v_2, v_3) \leq (v'_1, v'_2, v'_3) \Leftrightarrow v_1 \leq v'_1, v_2 \leq v'_2, v_3 \leq v'_3,$$

- The local logical time is incremented before each local or send event, e.g.

$$V(P_2) : (v_1, v_2, v_3) \Rightarrow (v_1, v_2 + 1, v_3)$$

- ...

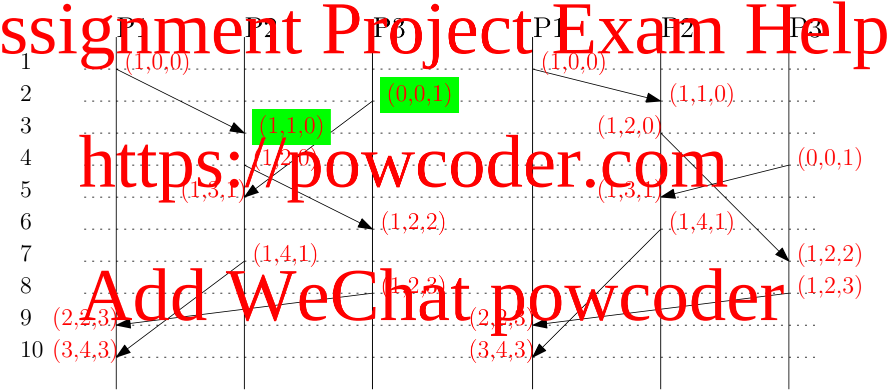
Vector Logical Clock

- ...
- For send events, these tuples are sent along with the message

- For receive events, the new vector is the maximum of local and received tuple, with an incremented local logical time, e.g.

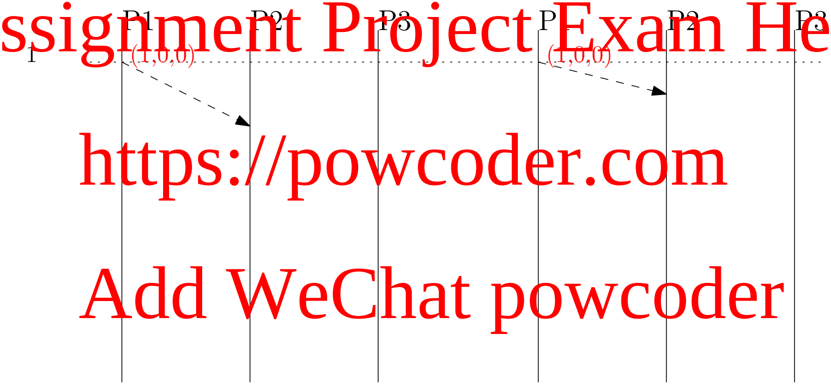
```
$V(P_2) : (v_1, v_2, v_3), (r_1, r_2, r_3)$
        $\Rightarrow (\max(v_1, r_1), \max(v_2, r_2) + 1, \max(v_3, r_3))$
```

Vector Logical Clock – Complete example

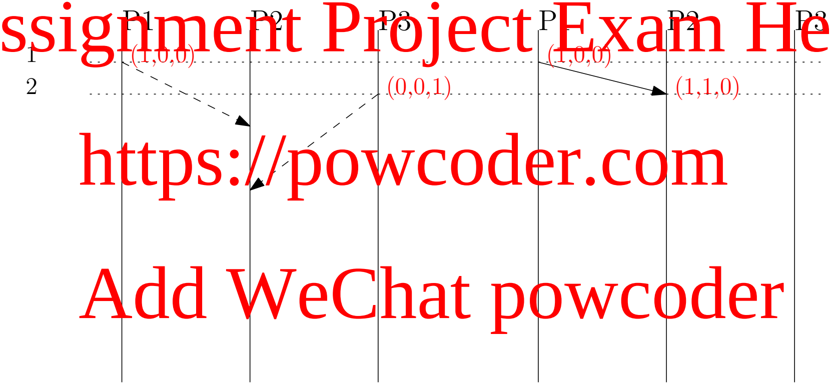


$(1, 1, 0)$ and $(0, 0, 1)$ denote concurrent events and are incomparable!

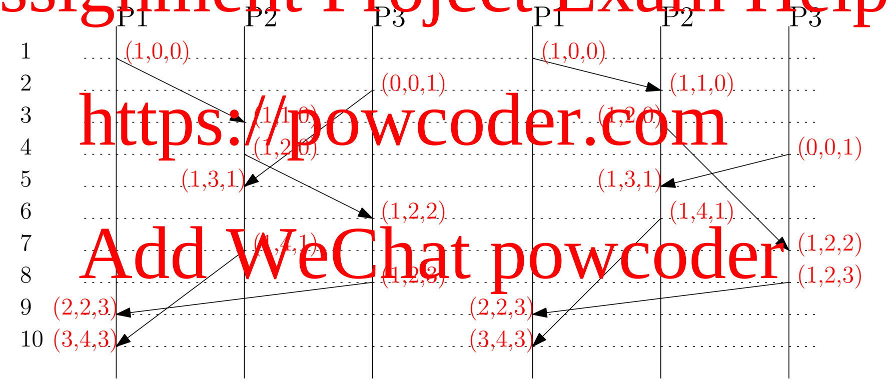
Vector Logical Clock – Steps



Vector Logical Clock – Steps

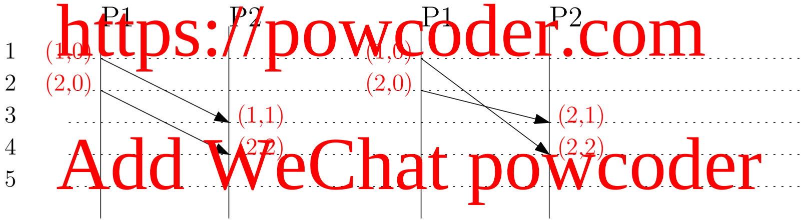


Vector Logical Clock – Steps



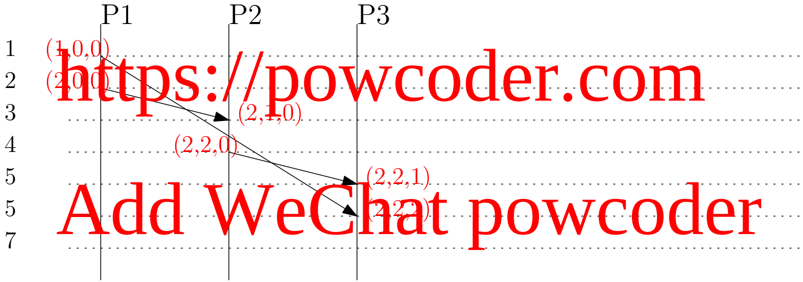
Vector Logical Clock – FIFO example / counter-example

Vector logical clocks can also detect simple FIFO violations, but not Lamport

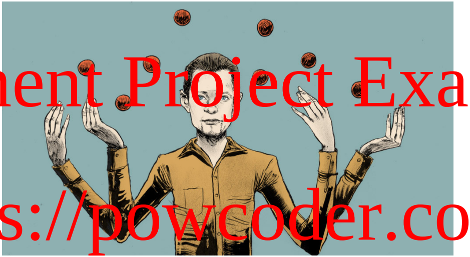


Vector Logical Clock – Causal ordering counter-example

Causal ordering ≈ FIFO++ ☺

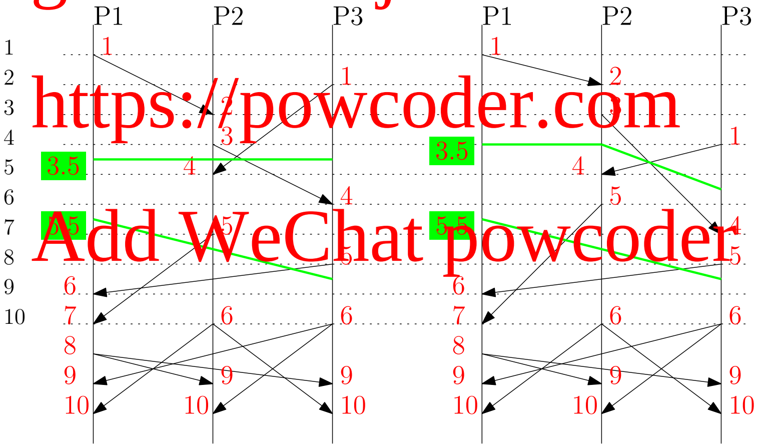


How many objects are in these systems?



Count Money Example – How much money in each node?

- Just after logical time 3 (3.5) or 5 (5.5)?
- Assume: initial deposits 100$ each, arrow transfers 10$ each.



Count Money – Algorithm

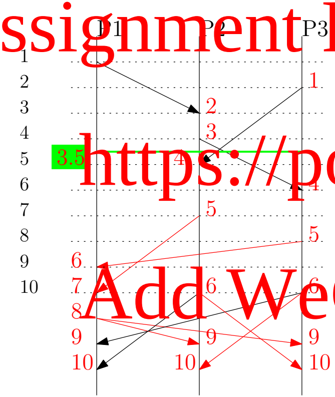
- Given Lamport time t, at each node “bank account”, sum

- The amount already there at time t
- Plus the money already sent to you, but still in transit
  - I.e., for each channel

  - Keep adding all incoming money until you get the first message sent after time t – aka marker message
  - Don’t bother about money you send out after time t

- Assumption #1: on each channel, the message flow is potentially infinite (it never stops, both ways)
- Assumption #2: FIFO flows ?
- Can we work around the FIFO restriction?

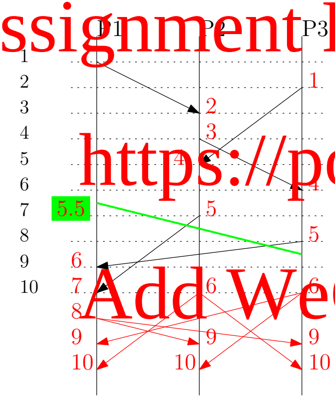
Count Money Example – Amounts at Lamport times 3.5



- ? = bad, ✓ = good accounting
- @ local Lamport time to sum-up

	P1	P2	P3	T
0	100	100	100	300
3.5 ?	90	100	90	280 ?
3.5 ✓	90 @7	110 @10	100 @10	300 ✓

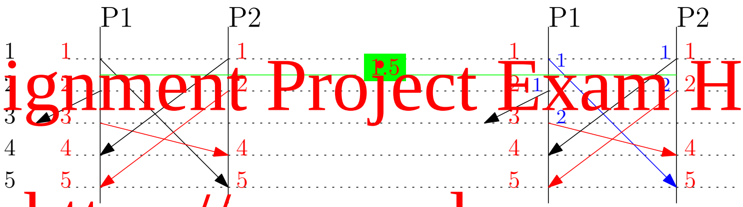
Count Money Example – Amounts at Lamport times 5.5



- ? = bad, ✓ = good accounting
- @ local Lamport time to sum-up

	P1	P2	P3	T
0	100	100	100	300
5.5 ?	90	100	90	280 ?
5.5 ✓	110 @10	100 @10	90 @10	300 ✓

Count Money Example – FIFO Discussion



- FIFO fix: Add sequence numbers, for each channel! (TCP?)
- FIFO problems!
- Ensure that you sum all messages sent before the "markers"!

	P1	P2
0	100	100
1.5 ?	90	90
1.5 ???	100 @5	90 @4

	P1	P2
0	100	100
1.5 ?	90	90
1.5 ???	100 @5	90 @4
1.5 ✓	100 @5	100 @5