# CIS 505: Software Systems
# Lecture Note on Logical Clocks


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## Clocks

1. physical clocks
   - Protocols to control drift exist, but physical clock timestamps cannot assign an ordering to “nearly concurrent” events.
2. logical clocks
   - Simple timestamps guaranteed to respect causality: “*A*’s current time is later than the timestamp of any event *A* knows about, no matter where it happened or who told *A* about it.”
3. vector clocks
   - Order(N) timestamps that say exactly what *A* knows about events on *B*, even if *A* heard it from *C*.
4. matrix clocks
   - Order($N^2$) timestamps that say what *A* knows about what *B* knows about events on *C*.
   - *Acknowledgement vectors*: an O(N) approximation to matrix clocks.

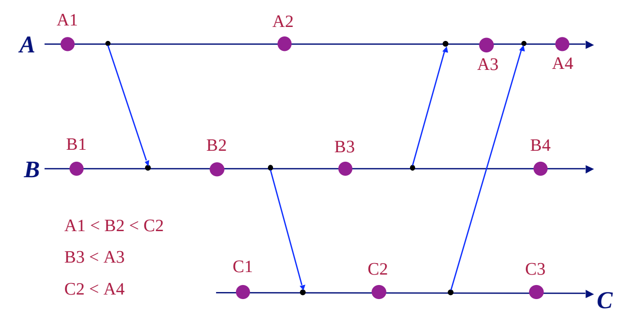


## Event Ordering

- When there is no common memory or clock, it is sometimes impossible to say which of two events occurred first.
- The *happened-before* relation is a partial ordering of events in distributed systems such that
  1. If *A* and *B* are events in the same process, and *A* was executed before *B*, then $A \Rightarrow B$.
  2. If *A* is the event of sending a message by one process and *B* is the event of receiving that by another process, then $A \Rightarrow B$.
  3. If $A \Rightarrow B$ and $B \Rightarrow C$, then $A \Rightarrow C$.
- If two events *A* and *B* are not related by the $\Rightarrow$ relation, then they are executed concurrently (no causal relationship)



## Causality Example: Event Ordering



# Causality and Logical Time

- Constraint: The update ordering must respect *potential causality*.
  - o Communication patterns establish a ***happened-before*** order on events, which tells us when ordering *might* matter.
  - o Event $e_1$ ***happened-before*** $e_2$ iff $e_1$ could possibly have affected the generation of $e_2$: we say that $e_1 < e_2$.
    - $e_1 < e_2$ iff $e_1$ was "known" when $e_2$ occurred.
    - Events $e_1$ and $e_2$ are *potentially causally related.*



# Logical Clocks [Lamport]

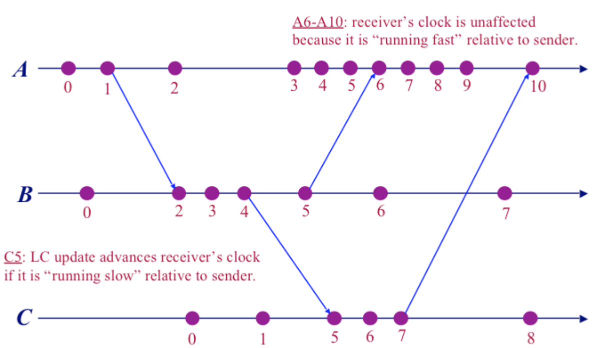
- Solution: timestamp updates with *logical clocks* Timestamping updates with the originating node's logical clock *LC* induces a partial order that respects potential causality.

  ***Clock condition***: $e_1 < e_2$ implies that $LC(e_1) < LC(e_2)$

  1. Each site maintains a monotonically increasing clock value ***LC***.
  2. Globally visible events (e.g., updates) are timestamped with the current ***LC*** value at the generating site.
     Increment local ***LC*** on each new event: ***LC = LC + 1***
  3. Piggyback current clock value on all messages.
     Receiver resets local LC: **if** $LC_s > LC_r$ **then** $LC_r = LC_s + 1$
- Use processor ids to break ties to create a total ordering.

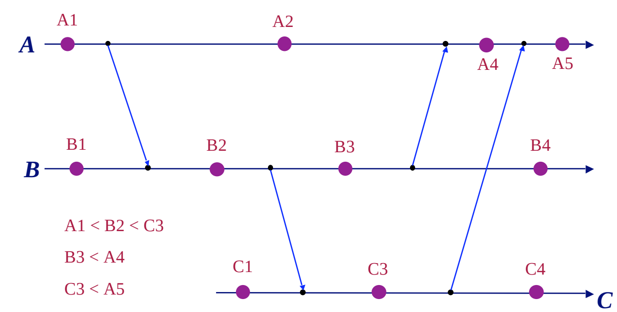


# Logical Clocks: Example






# Causality and Updates: Example



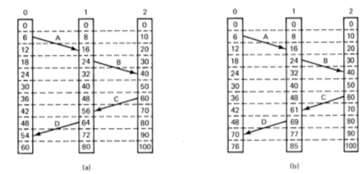
## Update Ordering

- Problem: how to ensure that all sites recognize a fixed order on updates, even if updates are delivered out of order?
- Solution: Assign timestamps to updates at their accepting site, and order them by source timestamp at the receiver.
  - Assign nodes unique IDs: break ties with the origin node ID.
  - Problem: What (if different) ordering exists between updates accepted by different sites?
    - Comparing physical timestamps is arbitrary: physical clocks drift.
    - Even a protocol to maintain loosely synchronized physical clocks cannot assign a meaningful ordering to events that occurred at "almost exactly the same time".



## Example: Lamport's Algorithm

- Three processes, each with its own clock. The clocks run at different rates.
- Lamport's Algorithm corrects the clock.



- Note: $ts(A) < ts(B)$ does not imply A happened before B.
- What if we use this to synchronize physical clocks?



## Motivation for Vector Clocks

- *Logical* clocks induce an order consistent with causality, but
  - the converse of the *clock condition* does not hold: it may be that $LC(e_1) < LC(e_2)$ even if $e_1$ and $e_2$ are concurrent.
    - If *A* could know anything *B* knows, then it must be $LC_A > LC_B$.
    - But if $LC_A > LC_B$ then this doesn't make it so; i.e., "false positives".
    - Concurrent updates may be ordered unnecessarily.
- We need a clock mechanism that is necessary and sufficient in capturing causality.

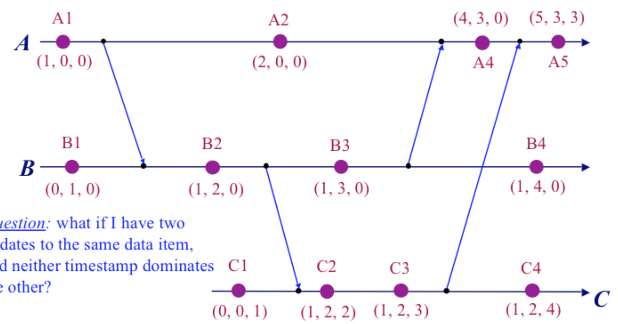


## Vector Clocks

- *Vector clocks* (AKA *vector timestamps* or *version vectors*) are a more detailed representation of what a site might know.

1. In a system with ***N*** nodes, each site keeps a vector timestamp *TS[N]* as well as a logical clock *LC*.
   - $TS_j[i]$ at site *i* is the most recent value of site *j*'s logical clock that site *i* "heard about".
   - $TS_i[i] = LC_i$: each site *i* keeps its own *LC* in *TS[i]*.
2. When site *i* generates a new event, it increments its logical clock.
   - $TS_i[i] = TS_i[i] + 1$
3. A site *r* observing an event (e.g., receiving a message) from site *s* sets its $TS_r$ to the pairwise maximum of $TS_s$ and $TS_r$.
   - For each site *i*, $TS_r[i] = \mathbf{max}\,(TS_r[i], TS_s[i])$

## Vector Clocks: Example




*Question*: what if I have two updates to the same data item, and neither timestamp dominates the other?



## Vector Clocks and Causality

- Vector clocks induce an order that *exactly* reflects causality.
  - o Tag each event *e* with current *TS* vector at originating site.
    - vector timestamp *TS(e)*
  - o $e_1$ ***happened-before*** $e_2$ *if and only if* $TS(e_2)$ **dominates** $TS(e_1)$
    - $e_1 < e_2$ iff $TS(e_1)[i] <= TS(e_2)[i]$ for each site *i*
    - "Every event or update visible when $e_1$ occurred was also visible when $e_2$ occurred."
    - *Proof?*
  - o Vector timestamps allow us to ask if two events are concurrent, or if one ***happened-before*** the other.
    - If $e_1 < e_2$ then $LC(e_1) < LC(e_2)$ **and** $TS(e_2)$ dominates $TS(e_1)$.
    - "If $TS(e_2)$ does **not** dominate $TS(e_1)$ then it is not true that $e_1 < e_2$."



## The Need for Propagating Acknowledgments

- Vector clocks tell us what *B* knows about *C*, but they do not reflect what *A* knows about what *B* knows about *C*.
  - Nodes need this information to determine when it is safe to discard/stabilize updates.
  - o *A* can always tell if *B* has seen an update *u* by asking *B* for its vector clock and looking at it.
    - If *u* originated at site *i*, then *B* knows about *u* if and only if $TS_B$ *covers* its accept stamp $LC_u$: $TS_B[i] >= LC_u$.
  - o *A* can only know that *every* site has seen *u* by looking at the vector clocks for *every* site.
    - Even if *B* recently received updates from *C*, *A* cannot tell (from looking at *B*'s vector clock) if *B* got *u* from *C* or if *B* was already aware of *u* when *C* contacted it.



## Solution: Matrix Clocks

- *Matrix clocks* extend vector clocks to capture "what *A* knows about what *B* knows about *C*".
  - o Each site *i* maintains a matrix $MC_i(N,N)$.
    - Row *j* of *i*'s matrix clock $MC_i$ is the most recent value of *j*'s vector clock $TS_j$ that *i* has heard about.
    - $MC_i[i, i] = LC_i$ and $MC_i[i, *] = TS_i$
    - $MC_i[j,k]$ = what *i* knows about what *j* knows about what happened at *k*.
  - o If *A* sends a message to *B*, then $MC_B$ is set to the pairwise maximum of $MC_A$ and $MC_B$.
    - If *A* knows that *B* knows *u*, then after *A* talks to *C*, *C* knows that *B* knows *u* too.