CS514: Intermediate Course in Computer Systems

Lecture 11: Oct. 6, 8, 2003

Time and ordering

Time and Ordering

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- We tend to casually use temporal concepts
- Example: "membership changes dynamically"
  - Implies a notion of time: *first* membership was X, *later* membership was Y
  - Challenge: relating local notion of time in a single process to a global notion of time
- Will discuss this issue before developing multicast delivery ordering options in more detail

Time in Distributed Systems

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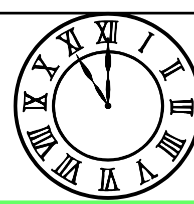
- Three notions of time:
  - Time seen by external observer. A global clock of perfect accuracy
  - Time seen on clocks of individual processes. Each has its own clock, and clocks may drift out of sync
  - Logical notion of time: event *a* occurs before event *b* and this is detectable because information about *a* may have reached *b*

External Time



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- The "gold standard" against which many protocols are defined
  - *Not implementable*: no system can avoid uncertain details that limit temporal precision!
  - Use of external time is also risky: many protocols that seek to provide properties defined by external observers are *extremely* costly and, sometimes, are unable to cope with failures

Time seen on internal clocks

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- Most workstations have reasonable clocks
- Clock synchronization is the big problem (will visit topic later in course): clocks can drift apart and resynchronization, in software, is inaccurate
  - Unpredictable speeds a feature of all computing systems, hence can't predict how long events will take (e.g. how long it will take to send a message and be sure it was delivered to the destination)

Logical notion of time

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- Has no clock in the sense of "real-time"
- Focus is on definition of the "happens before" relationship: *"a happens before b" if:*
  - both occur at same place and *a* finished before *b* started, or
  - *a* is the send of message *m, b* is the delivery of *m*, or
  - *a* and *b* are linked by a chain of such events

Logical time as a time-space picture

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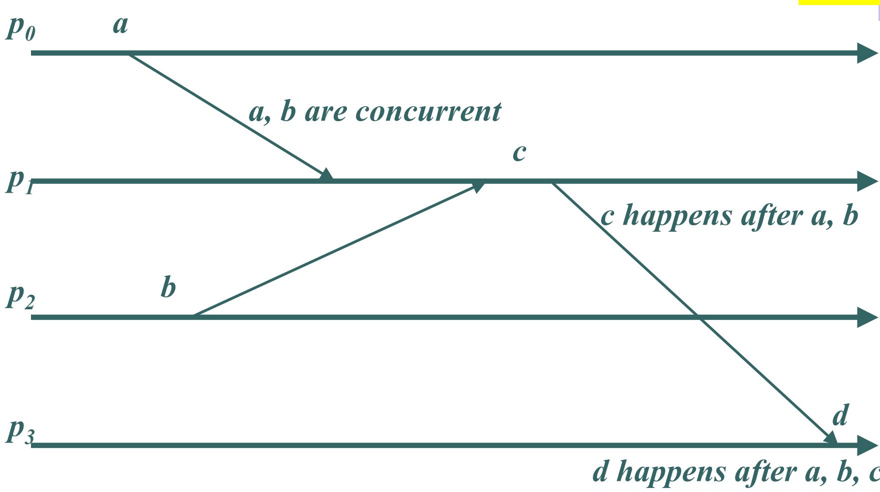

Notation

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- Use “arrow” to represent happens-before relation
- For previous slide:
  - $a \rightarrow c$, $b \rightarrow c$, $c \rightarrow d$
  - *hence*, $a \rightarrow d$, $b \rightarrow d$
  - *a, b are concurrent*
- Also called the “potential causality” relation

Logical clocks

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- Proposed by Lamport to represent causal order
- Write: LT(e) to denote logical timestamp of an event e, LT(m) for a timestamp on a message, LT(p) for the timestamp associated with process p
- Algorithm ensures that if $a \rightarrow b$, then $LT(a) < LT(b)$

Algorithm

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- Each process maintains a counter, *LT(p)*
- For each event other than message delivery: set *LT(p) = LT(p)+1*
- When sending message m, *LT(m) = LT(p)*
- When process q receives message m, set *LT(q) = max(LT(m), LT(q))+1*

Illustration of logical timestamps

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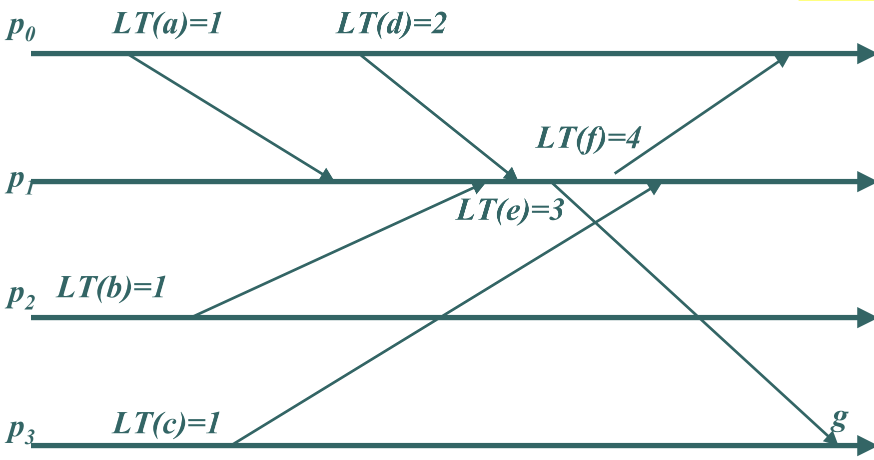

Concurrent events

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- If a, b are concurrent, LT(a) and LT(b) may have arbitrary values!
- Thus, logical time lets us determine that *a* potentially happened before *b*, but not that *a* definitely did so!
- Example: processes p and q never communicate. Both will have events 1, 2, ... but even if LT(e)<LT(e') e may not have happened before e'

Example . . .

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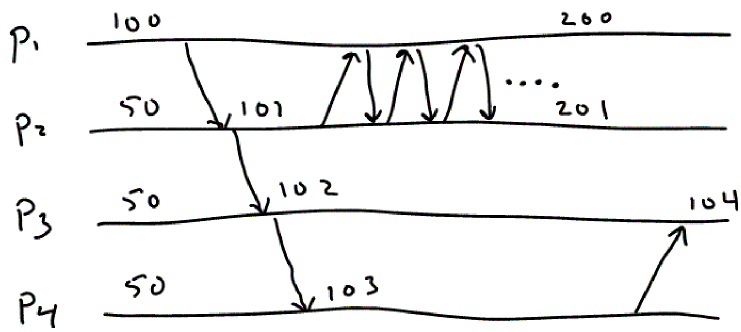
- Logical timestamps fall "out of sync" with lack of message "cross pollination"



Example . . .

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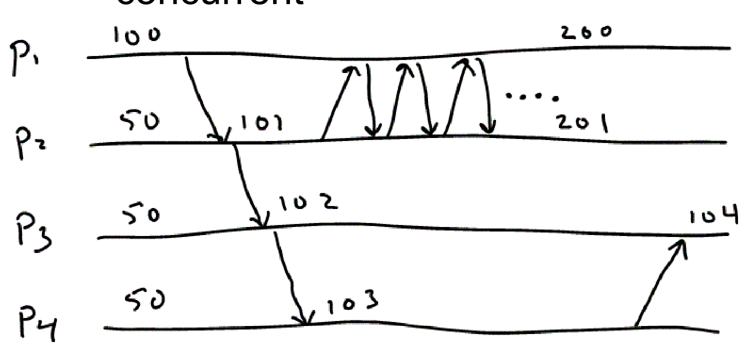
- We can't compare Lamport LTs out-of-context and know if they are causal or concurrent



Vector timestamps

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- Extend logical timestamps into a list of counters, one per process in the system
- Again, each process keeps its own copy
- Event e occurs at process p:
  p increments VT(p)[p]
  (p'th entry in its own vector clock)
- q receives a message from p:
  q sets VT(q)=max(VT(q),VT(p))
  (element-by-element)

Illustration of vector timestamps

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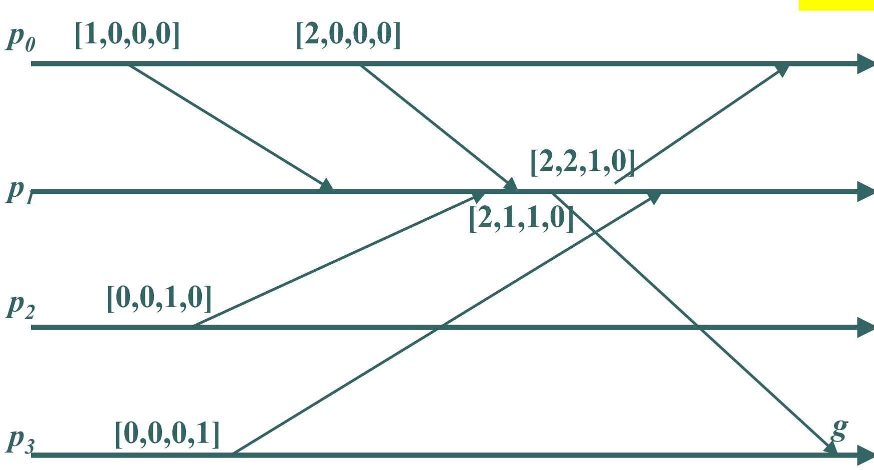

Vector timestamps accurately represent the happens-before relationship!

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- Define VT(e)<VT(e’) if,
  - for all i, VT(e)[i]≤VT(e’)[i], and
  - for some j, VT(e)[j]<VT(e’)[j]
- Example: if VT(e)=[2,1,1,0] and VT(e’)=[2,3,1,0] then VT(e)<VT(e’)
- Notice that not all VT’s are “comparable” under this rule: consider [4,0,0,0] and [0,0,0,4]

Vector timestamps accurately represent the happens-before relationship!

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- Now can show that VT(e)<VT(e’) if and only if e $\rightarrow$ e’:
  - If e $\rightarrow$ e’, there exists a chain $e_0 \rightarrow e_1 \dots \rightarrow e_n$ on which vector timestamps increase “hop by hop”
  - If VT(e)<VT(e’) suffices to look at VT(e’)[proc(e)], where proc(e) is the place that e occurred. By definition, we know that VT(e’)[proc(e)] is at least as large as VT(e)[proc(e)], and by construction, this implies a chain of events from e to e’

Examples of VT's and happens-before

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- Example: suppose that VT(e)=[2,1,0,1] and VT(e')=[2,3,0,1], so VT(e)<VT(e')
- How did e' "learn" about the 3 and the 1?
  - Either these events occurred at the same place as e', or
  - Some chain of send/receive events carried the values!
- If VT's are not comparable, the corresponding events are concurrent!

Same example . . .

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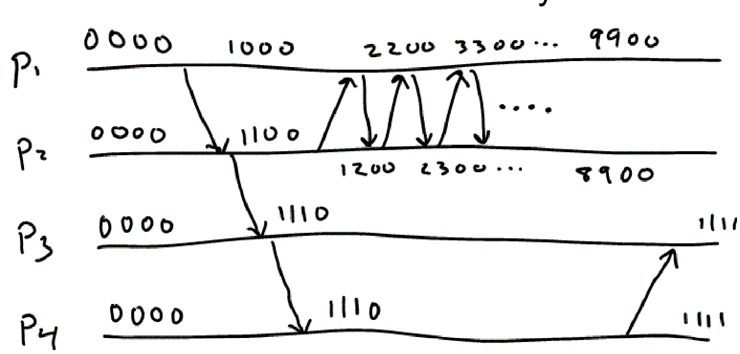
- 1000 is causal to 1111 and 8900
- 1111 is not causal to 8900
- Now we can determine causality and concurrency!



Notice that vector timestamps require a static notion of system membership

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- For vector to make sense, must agree on the number of entries
- But vector timestamps are useful within process groups because the groups synchronize on “views”
- Vector timestamp really looks like:
  - View-ID, [p1, p2, p3, . . . pN]

Vector Compression Tricks

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- Size of the vector is the main overhead
- Subsequent timestamps in a “burst” of multicasts can be omitted
  - Receiver understands that the vector entry of the sender can be incremented
- Reset timestamp values with each view
- Sort vector so that “receive-only” processes are last
  - Truncate vector by eliminating trailing zeros
- Send the difference between current and last vector

What about "real-time" clocks?

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- Accuracy of clock synchronization is ultimately limited by uncertainty in communication latencies
- These latencies are "large" compared with speed of modern processors (typical latency may be 35us to 500us, time for thousands of instructions)
- Limits use of real-time clocks to "coarse-grained" applications

What about GPS-based synchronization?

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- Inexpensive GPS clocks accurate to ±1microsecond are available (<$500)
  - 2 microseconds is 1/15000th of a typical cross-country latency
  - But about the same latency as a small packet over a short gigabit link
- So increasingly can't be used to indicate message order in some environments
  - Also, GPS clock may fail . . .

Interpretations of temporal terms

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- Understand now that "a happens before b" means that information can flow from a to b
- Understand that "a is concurrent with b" means that there is no information flow between a and b
- What about the notion of an "instant in time", over a set of processes?

Chandy and Lamport: Consistent cuts

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- Draw a line across a set of processes
- Line cuts each execution
- Consistent cut has property that the set of included events is closed under happens-before relation:
  - If the cut "includes" event b, and event a happens before b, then the cut also includes event a
  - In practice, this means that every "delivered" message was sent within the cut

Illustration of consistent cuts

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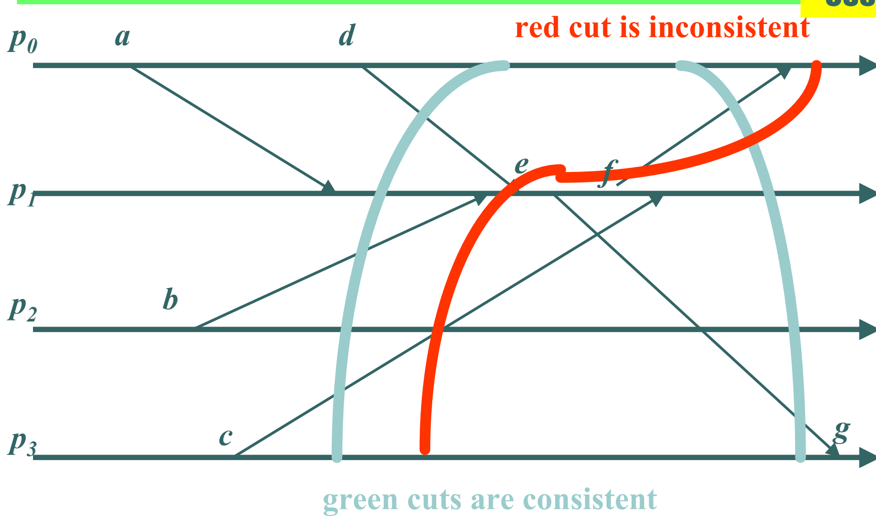

Intuition into consistent cuts

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- A consistent cut is a state that *could* have arisen during execution, depending on how processes were scheduled
- An inconsistent cut could not have arisen during execution
- One way to see this: think of process timelines as rubber bands. Scheduler stretches or compresses time but can't deliver message before it was sent

Illustration of consistent cuts

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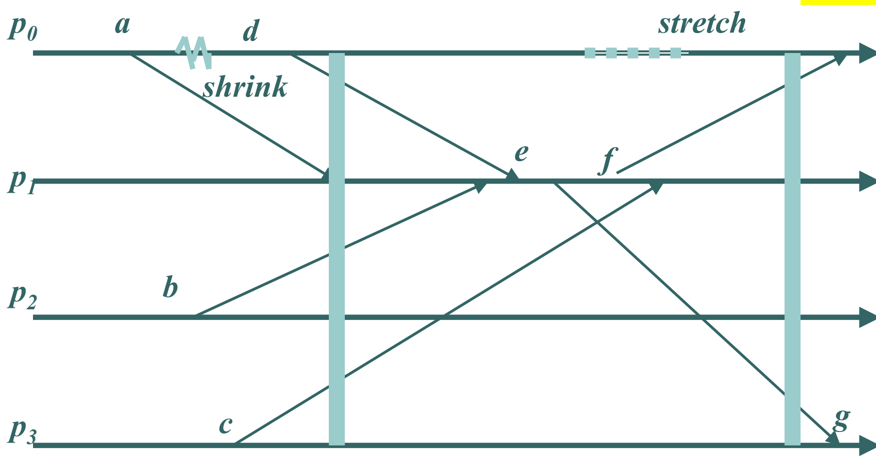

green cuts are consistent

There may be many consistent cuts through any point in the execution

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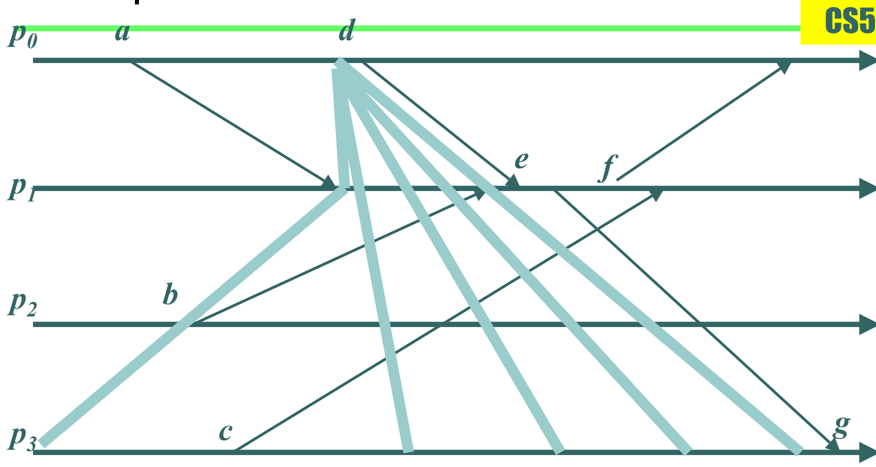

possible cuts define a range of potentially instantaneous system states

Illustration of consistent cuts

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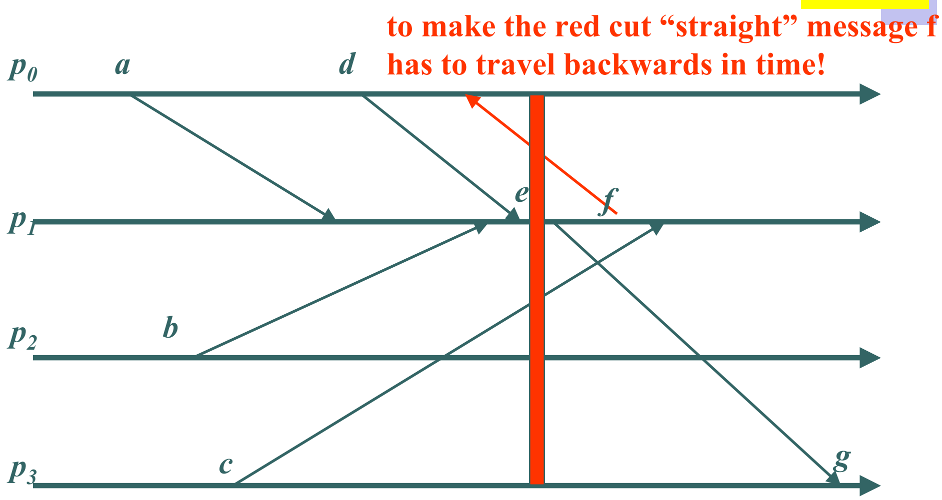

Moving from model to practice

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- Now we have basic elements of a model
  - It lets us talk about executions, gives meaning to temporal terms like “now”, “when”, “before”, “after”, “at the same time”, “concurrently”
- Move on to solve problems using this model and timestamps

Ordering properties: FIFO

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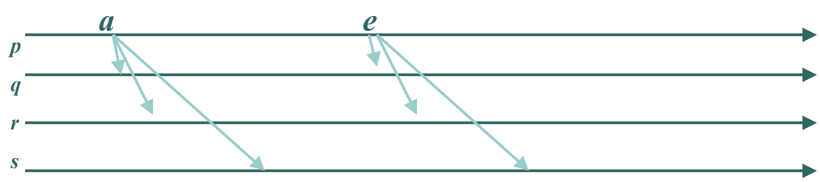
- *Fifo* or *sender ordered* multicast: ***fbcast***

  Messages are delivered in the order they were sent (by any single sender)



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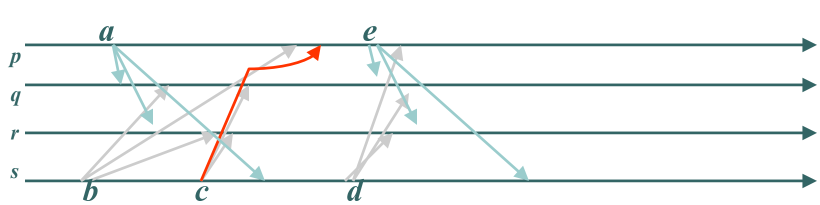

delivery of c to p is delayed until after b is delivered

Implementing FIFO order

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- Basic reliable multicast algorithm has this property
  - Without failures all we need is to run it on FIFO channels (like TCP, except "wired" to our GMS
- Multithreaded applications: must carefully use locking or order can be lost as soon as delivery occurs!

Implementing FIFO order: Sender sequence numbers

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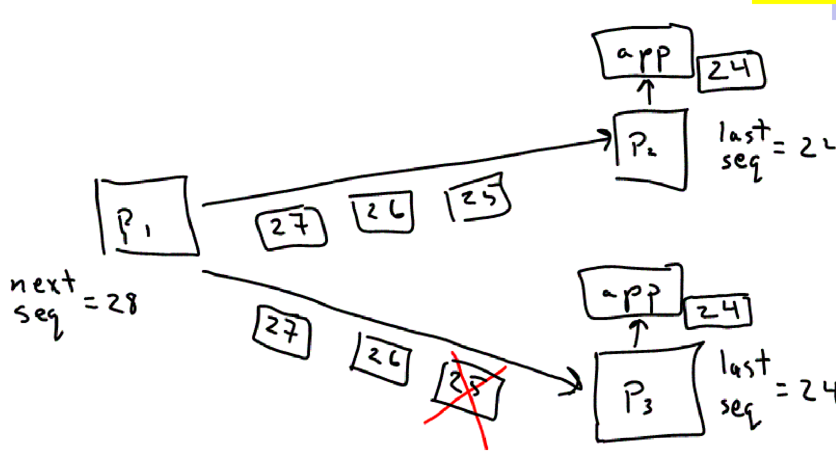

Immediate in-sequence message delivery

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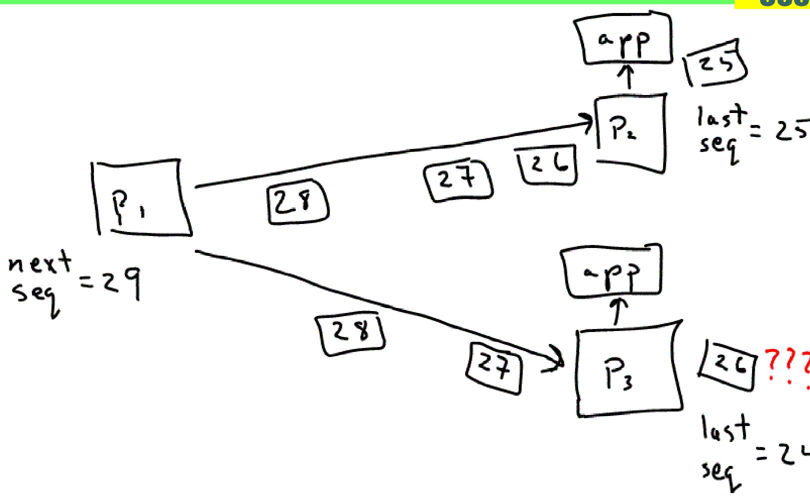

Careful with thread locking

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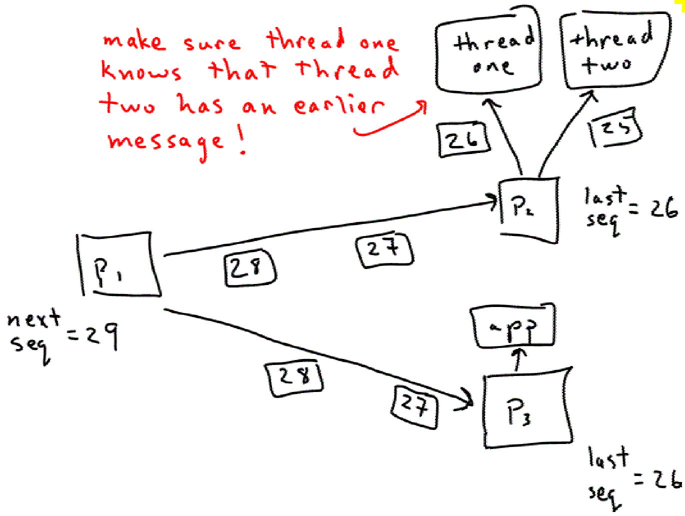

Sender crash

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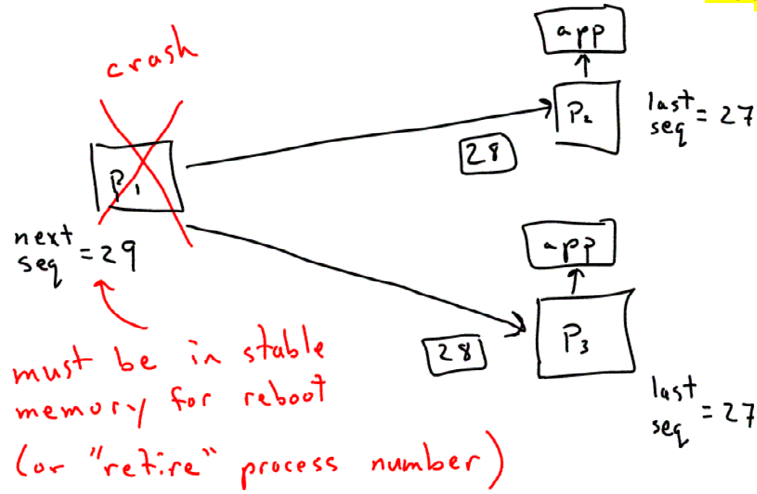

Receiver crash

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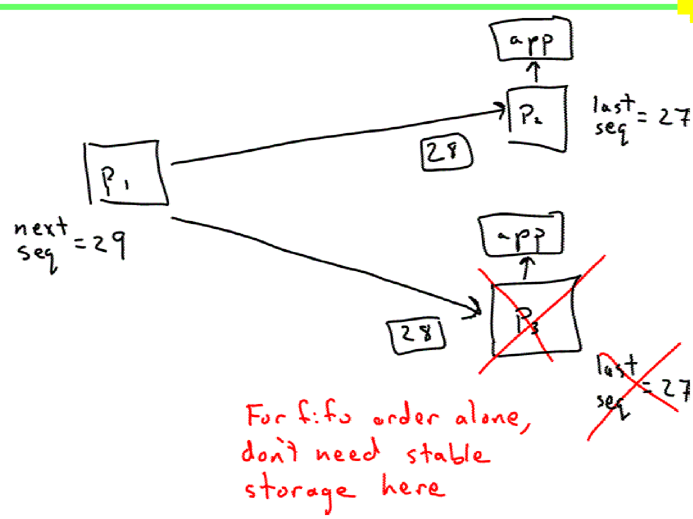

Ordering properties: Causal

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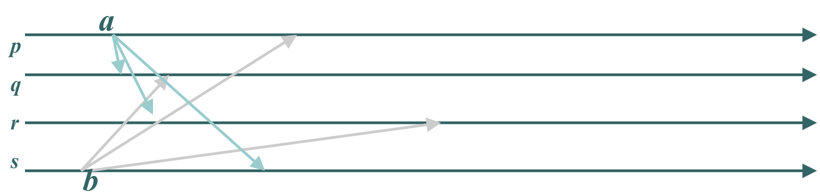
- *Causal* or *happens-before* ordering: ***cbcast***

  If send(a) → send(b) then deliver(a) occurs before deliver(b) at common destinations



Ordering properties: Causal

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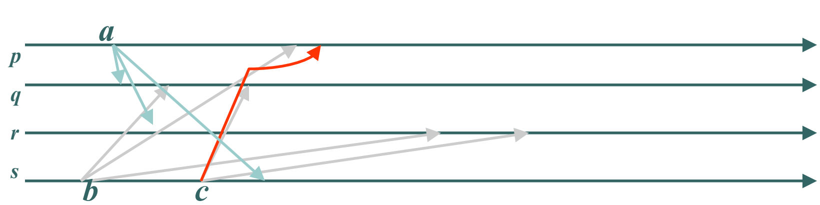

delivery of c to p is delayed until after b is delivered

Ordering properties: Causal

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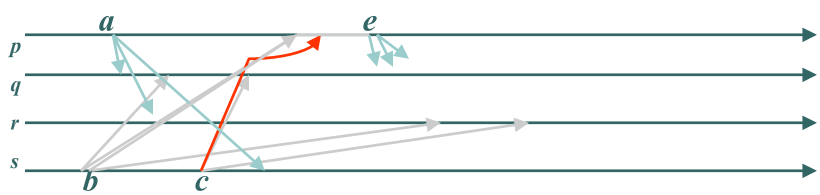

delivery of c to p is delayed until after b is delivered

e is sent (causally) after b

Ordering properties: Causal

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- *Causal* or *happens-before* ordering: ***cbcast***

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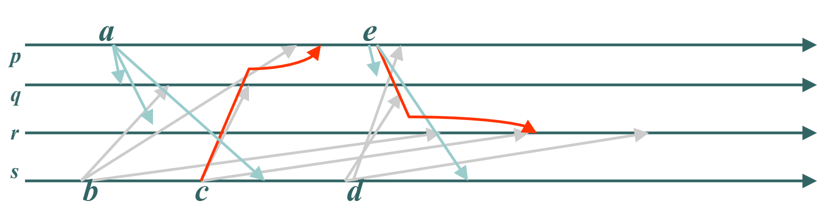

delivery of c to p is delayed until after b is delivered

delivery of e to r is delayed until after b&c are delivered

Implementing causal order

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- Start with a FIFO multicast
- Frank Schmuck showed that we can always strengthen this into a causal multicast by adding vector time (no additional messages needed)
  - If group membership were static this is easily done, small overhead
  - With dynamic membership, at least abstractly, we need to identify each VT index with the corresponding process, which seems to double the size

Insights about c/fbcast

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- These two primitives are *asynchronous*:
  - Sender doesn't get blocked and can deliver a copy to itself without "stopping" to learn a safe delivery order
  - If used this way, the multicast can seem to sit in the output buffers a long time, leading to surprising behavior
  - But this also gives the system a chance to concatenate multiple small messages into one larger one

Concatenation

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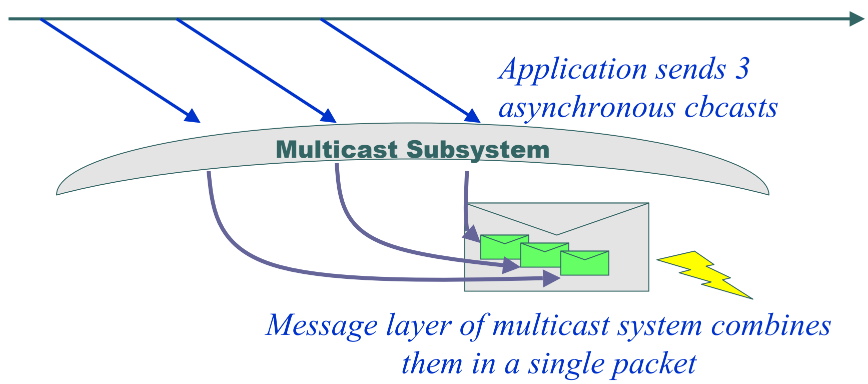

State Machine Concept

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- Sometimes, we want a replicated object or service that advances through a series of "state machine transitions"
  - Every process stays exactly in sync
  - Used for Byzantine failure modes
- Clearly will need all copies to make the same transitions
- Leads to a need for totally ordered multicast

Ordering properties: Total

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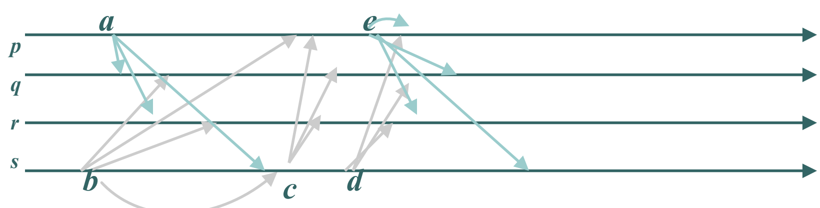
- *Total* or *locally total* multicast: ***abcast***

  Messages are delivered in same order to all recipients (including the sender)



all deliver a, b, c, d, then e

Basic Idea

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- With causal ordering, causal messages are received by all group members in the same order
- But the order of concurrent messages is not defined
- Total ordering arbitrarily defines an “agreed” ordering of concurrent messages
  - E.g. LT+process_id

Two basic approaches

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- Token ring
  - A token containing the global sequence number is passed around
  - Spread, Totem, Transis
- Sequencer
  - A single node sequences all messages
    - ISIS
- Either way, the trick is to only give one node control at a time

Sequencer

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- All multicast messages passed through a sequencer
- Sequencer assigns a total sequence number, informs all nodes
- Either:
  - The sender multicasts the message
    - Followed by sequence multicast from sequencer
  - The sequencer multicasts the message

Sequencer

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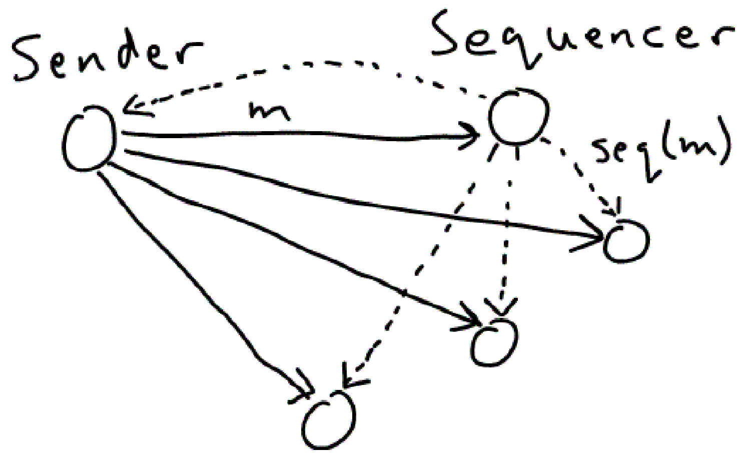

Token ring approach

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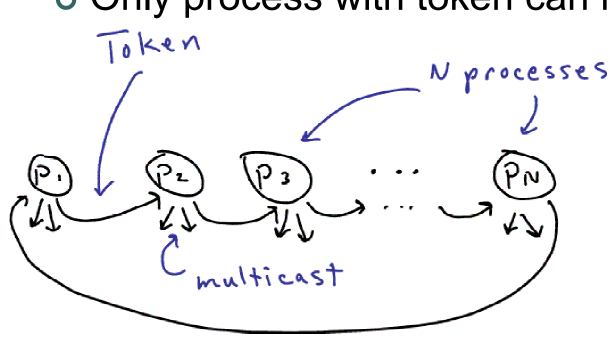
- Token with total sequence number passed around processes
- Only process with token can multicast



Token has other uses

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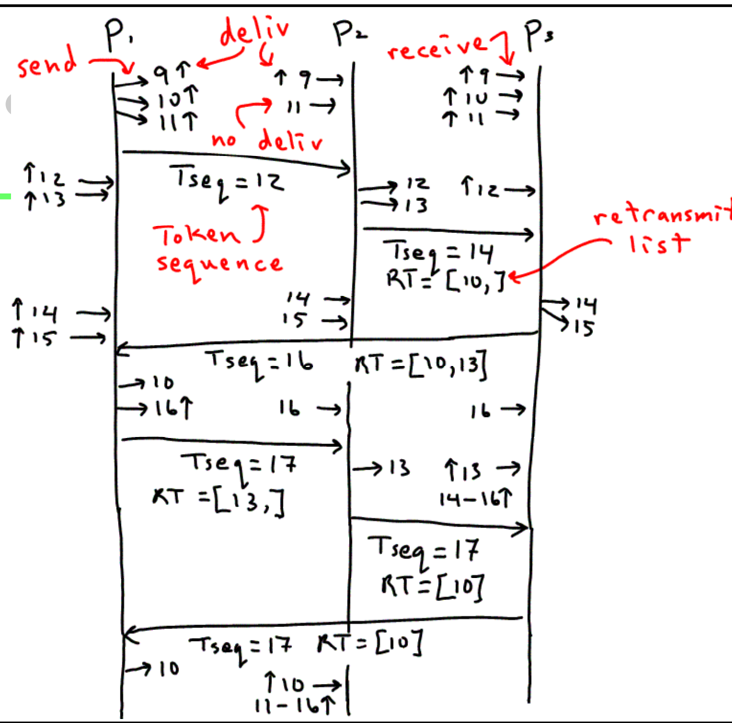
- Used for message reliability
  - Token has a “retransmit list”
- Used for “Safe” message delivery
  - Message not delivered until all processes have received it
  - Ken calls “dynamically uniform”
  - Big performance penalty!
- Used for flow control
  - Token says how many messages have been sent



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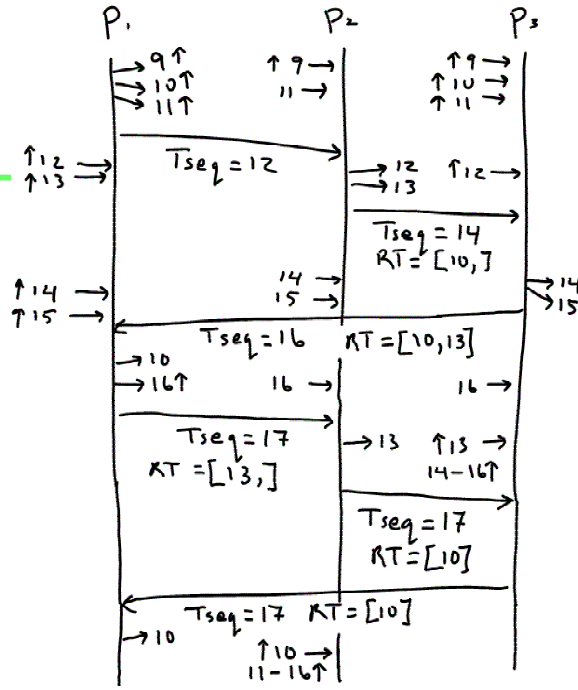
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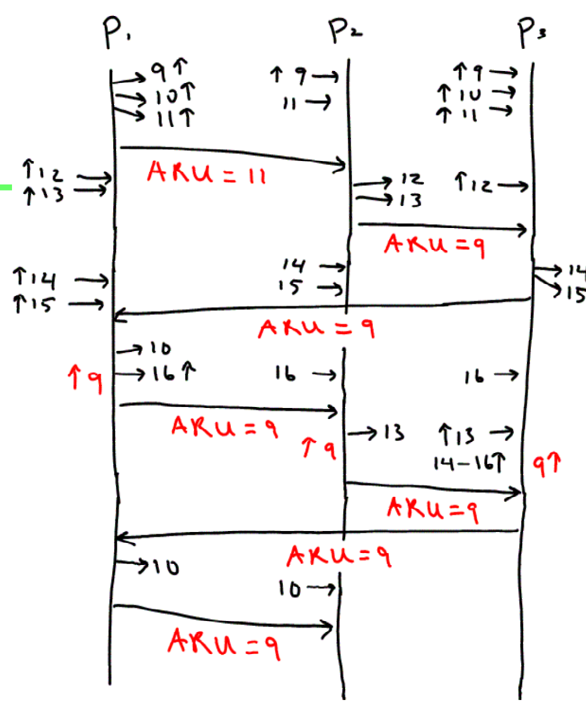
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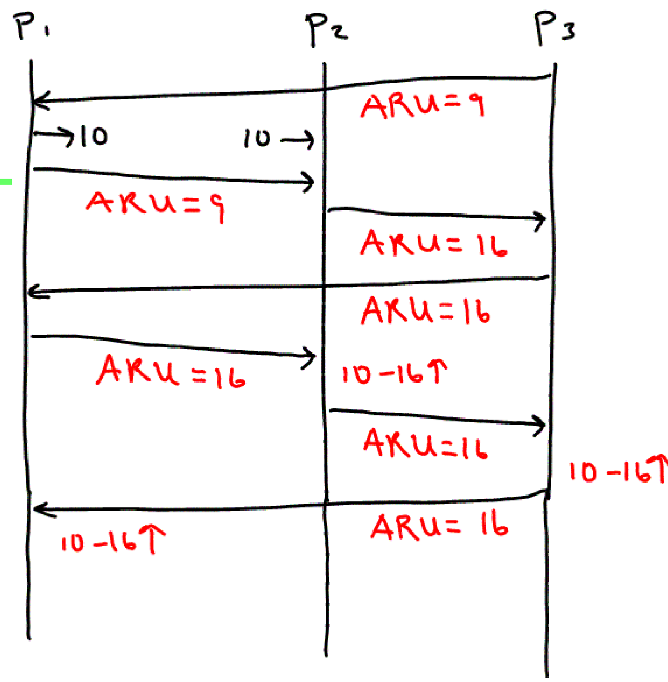

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Wide area total ordering (Totem)

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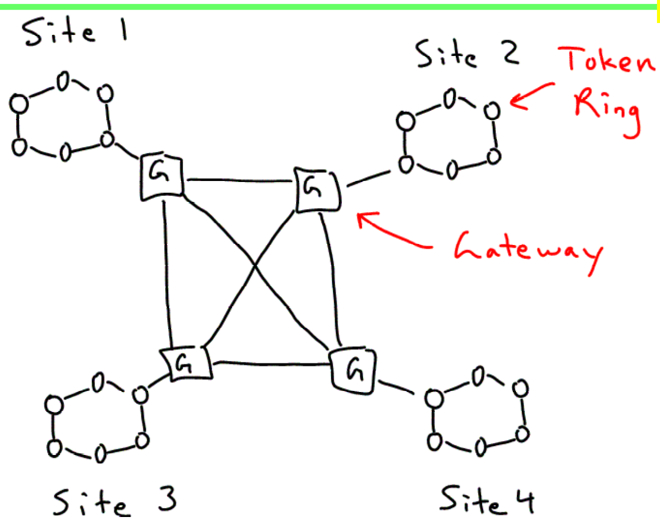

Wide area total ordering (Totem)

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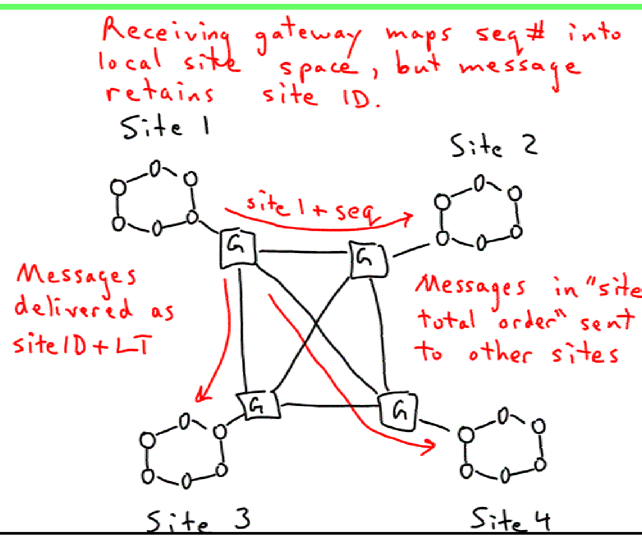

Wide area total ordering (Totem)

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