Logical Time and Clocks

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Recall cloud "layers"

- Highest level consists of applications
- These are composed from services that run on data harvested by applications using tools Map-Reduce
- The overall system is managed by a collection of core infrastructure services, such as locking and node status tracking
- How can we "reason" about the behavior of such components?
  - The scale and complexity makes it seem hard to say more than "Here's a service. This is what it does"

But we can do more

- We can describe distributed systems in more rigorous ways that let us say stronger things about them
- The trick is to start at the bottom, not the top
- This week: we'll focus on concepts of *time* as they arise in distributed systems

What time is it?

- In distributed system we need practical ways to deal with time
  - E.g. we may need to agree that update A occurred before update B
  - Or offer a "lease" on a resource that expires at time 10:10.0150
  - Or *guarantee* that a time critical event will reach all interested parties within 100ms

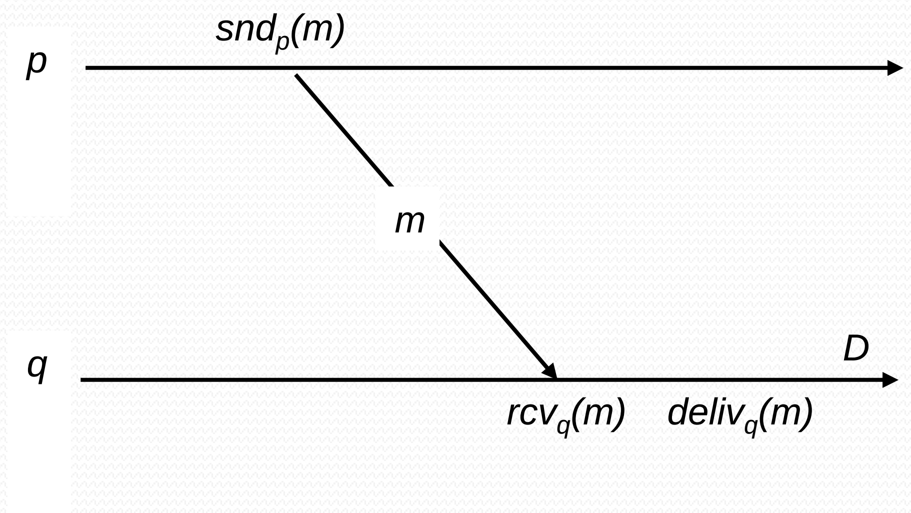
But what does time “mean”?

- Time on a global clock?
  - E.g. with GPS receiver
- … or on a machine’s local clock
  - But was it set accurately?
  - And could it drift, e.g. run fast or slow?
  - What about faults, like stuck bits?
- … or could try to agree on time

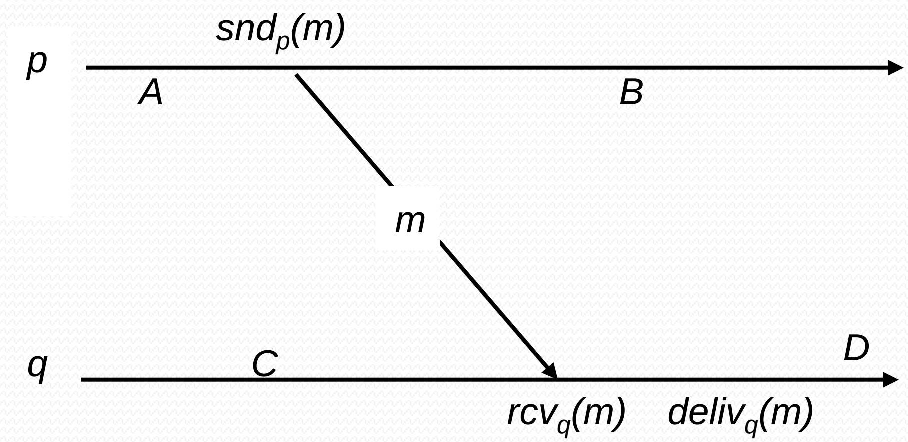
Lamport's approach

- Leslie Lamport suggested that we should reduce time to its basics
  - Time lets a system ask "Which came first: event A or event B?"
  - In effect: time is a means of labeling events so that…
    - If A happened before B, TIME(A) < TIME(B)
    - If TIME(A) < TIME(B), A happened before B

Drawing time-line pictures:

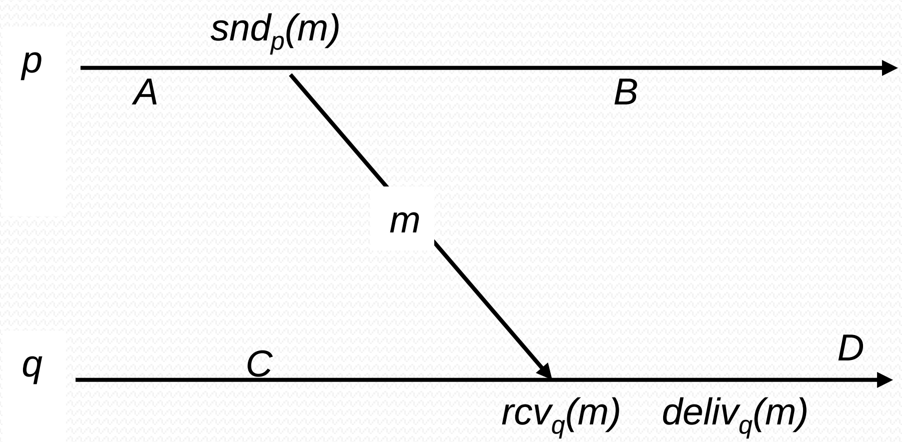


Drawing time-line pictures:



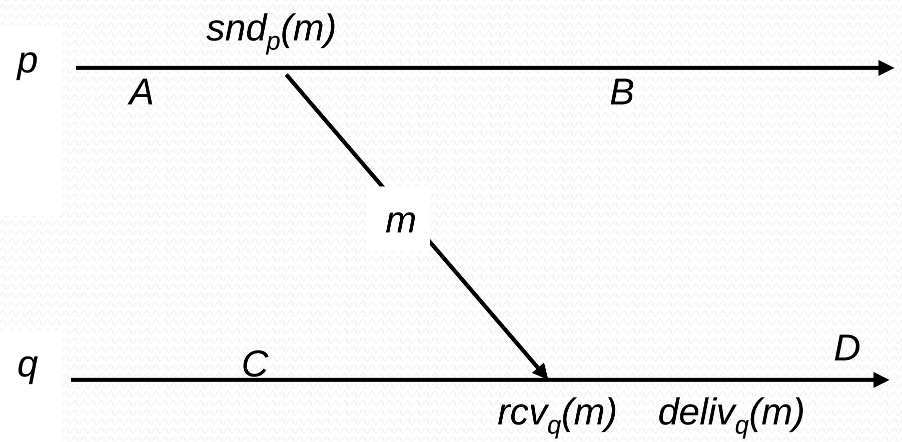
- A, B, C and D are “events”.
  - Could be anything meaningful to the application
  - So are snd(m) and rcv(m) and deliv(m)
- What ordering claims are meaningful?

Drawing time-line pictures:



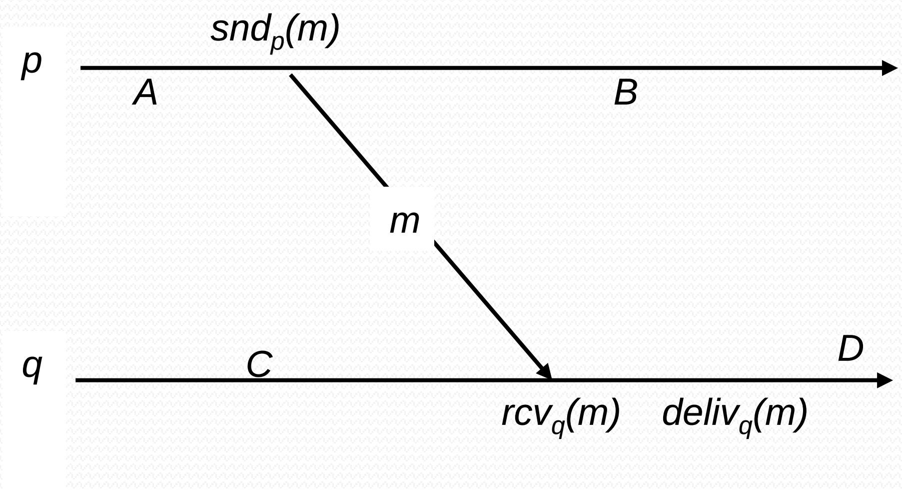
- A happens before B, and C before D
  - "Local ordering" at a single process
  - Write $A \xrightarrow{p} B$ and $C \xrightarrow{q} D$

Drawing time-line pictures:



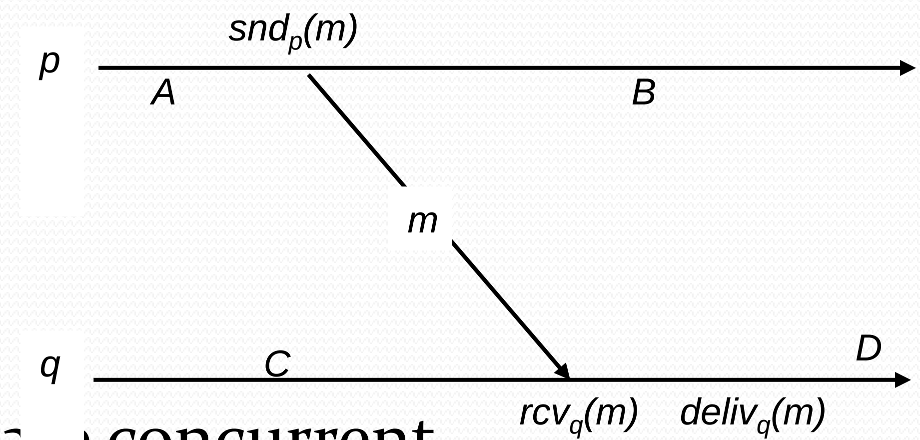
- $snd_p(m)$ also happens before $rcv_q(m)$
  - "Distributed ordering" introduced by a message
  - Write $snd_p(m) \xrightarrow{M} rcv_q(m)$

Drawing time-line pictures:



- A happens before D
  - Transitivity: A happens before $snd_p(m)$, which happens before $rcv_q(m)$, which happens before D

Drawing time-line pictures:



- B and D are concurrent
  - Looks like B happens first, but D has no way to know. No information flowed…

Happens before "relation"

- We'll say that "A happens before B", written $A \rightarrow B$, if
  1. $A \rightarrow^{P} B$ according to the local ordering, or
  2. A is a *snd* and B is a *rcv* and $A \rightarrow^{M} B$*, or*
  3. A and B are related under the transitive closure of rules (1) and (2)
- So far, this is just a mathematical notation, not a "systems tool"

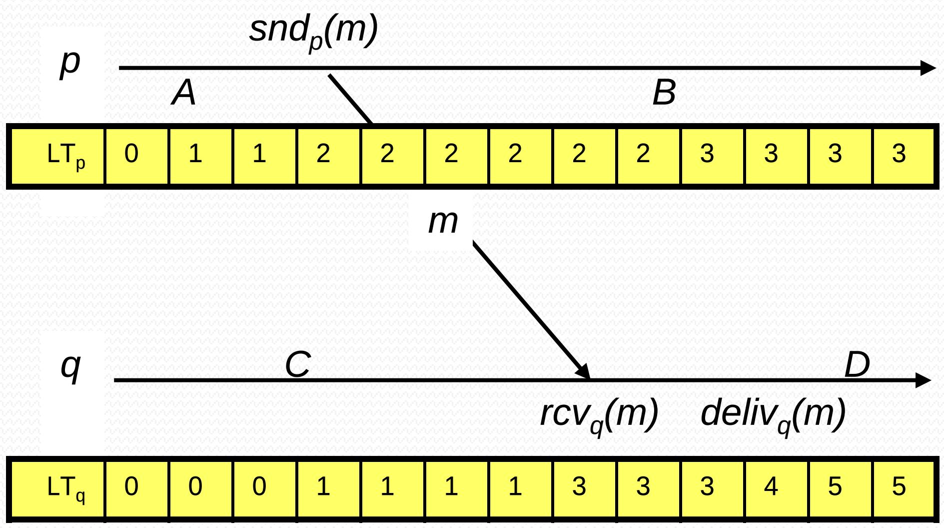
Logical clocks

- A simple tool that can capture parts of the happens before relation
- First version: uses just a single integer
  - Designed for big (64-bit or more) counters
  - Each process *p* maintains LT_p, a local counter
  - A message *m* will carry LT_m

Rules for managing logical clocks

- When an event happens at a process *p* it increments LT_p.
  - Any event that matters to *p*
  - Normally, also *snd* and *rcv* events (since we want receive to occur “after” the matching send)
- When p sends *m*, set
  - $LT_m = LT_p$
- When q receives *m*, set
  - $LT_q = \max(LT_q, LT_m)+1$

Time-line with LT annotations



- LT(A) = 1, LT(snd_p(m)) = 2, LT(m) = 2
- LT(rcv_q(m))=max(1,2)+1=3, etc…

Logical clocks

- If A happens before B, $A \rightarrow B$, then $LT(A) < LT(B)$
- But converse might not be true:
  - If $LT(A) < LT(B)$ can't be sure that $A \rightarrow B$
  - This is because processes that don't communicate still assign timestamps and hence events will "seem" to have an order

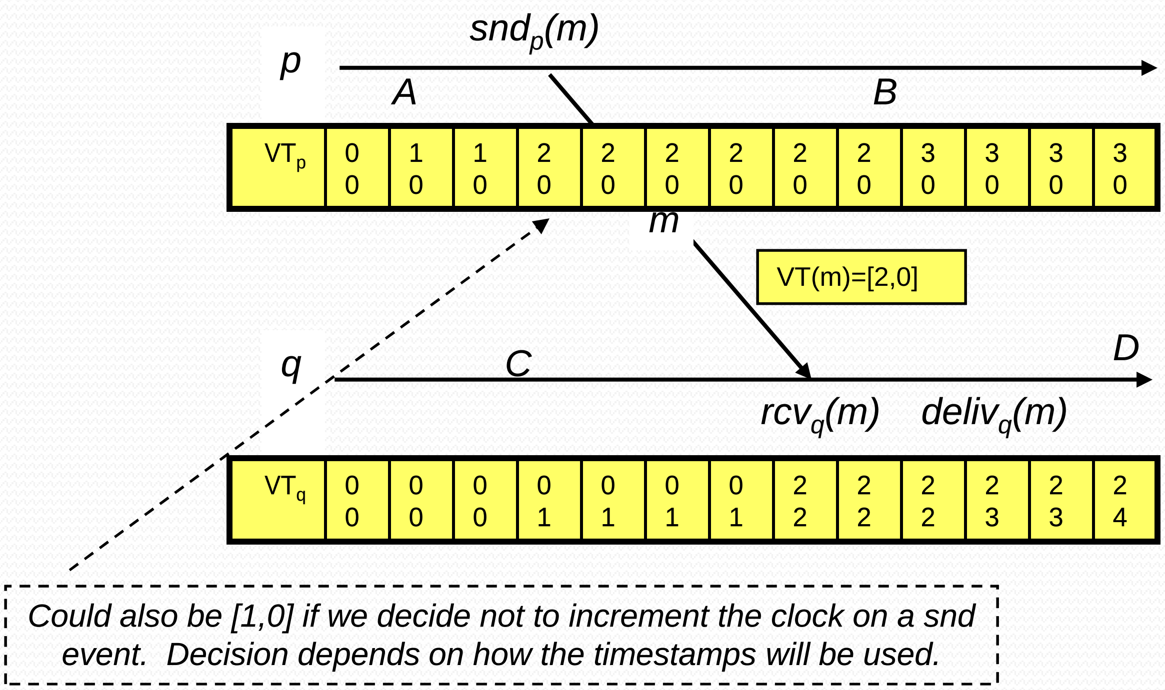
Can we do better?

- One option is to use *vector* clocks
- Here we treat timestamps as a list
  - One counter for each process
- Rules for managing vector times differ from what did with logical clocks

Vector clocks

- Clock is a vector: e.g. VT(A)=[1, 0]
  - We'll just assign p index 0 and q index 1
  - Vector clocks require either agreement on the numbering, or that the actual process id's be included with the vector
- Rules for managing vector clock
  - When event happens at p, increment $VT_p[index_p]$
    - Normally, also increment for snd and rcv events
  - When sending a message, set $VT(m)=VT_p$
  - When receiving, set $VT_q=max(VT_q, VT(m))$

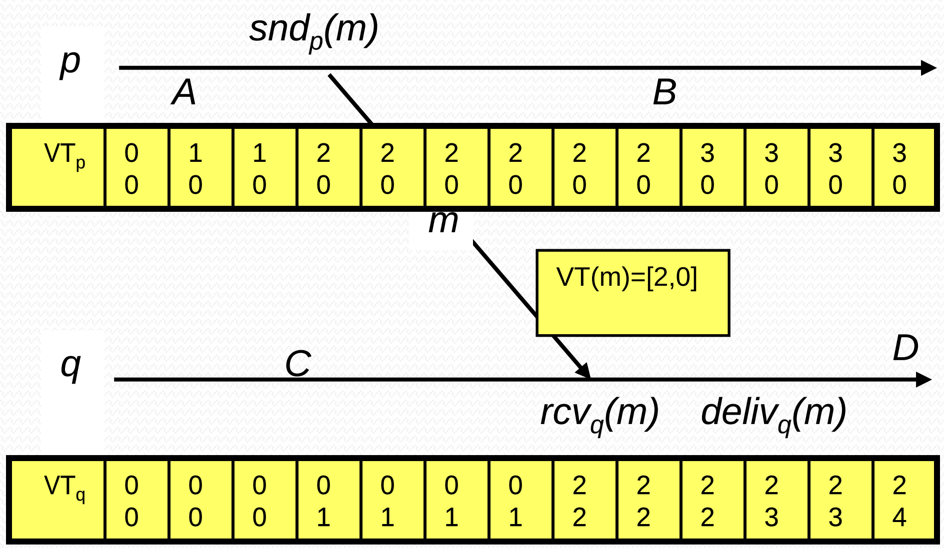
Time-line with VT annotations



Rules for comparison of VTs

- We'll say that $VT_A \leq VT_B$ if
  - $\forall_I$, $VT_A[i] \leq VT_B[i]$
- And we'll say that $VT_A < VT_B$ if
  - $VT_A \leq VT_B$ but $VT_A \neq VT_B$
  - That is, for some i, $VT_A[i] < VT_B[i]$
- Examples?
  - [2,4] ≤ [2,4]
  - [1,3] < [7,3]
  - [1,3] is "incomparable" to [3,1]

Time-line with VT annotations



- VT(A)=[1,0]. VT(D)=[2,4]. So VT(A)<VT(D)
- VT(B)=[3,0]. So VT(B) and VT(D) are incomparable

Vector time and happens before

- If $A \rightarrow B$, then $VT(A) < VT(B)$
  - Write a chain of events from A to B
  - Step by step the vector clocks get larger
- If $VT(A) < VT(B)$ then $A \rightarrow B$
  - Two cases: if A and B both happen at same process p, trivial
  - If A happens at p and B at q, can trace the path back by which q “learned” $VT_A[p]$
- Otherwise A and B happened concurrently

Temporal snapshots

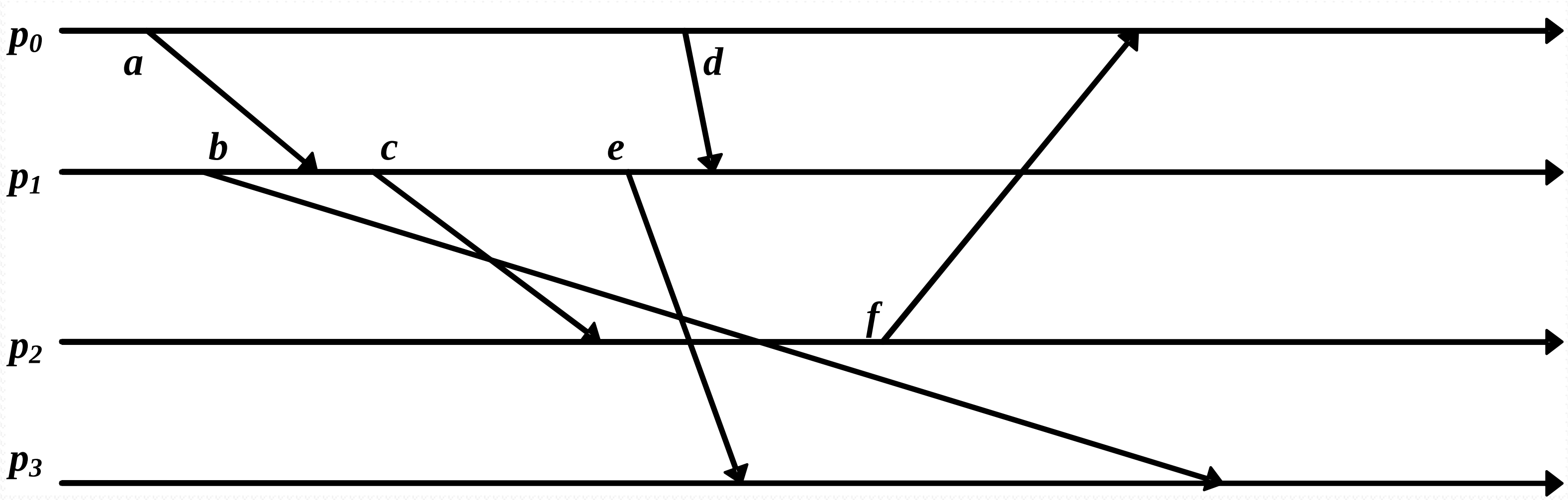
- Suppose that we want to take a photograph of a system while it executes: our goal is to capture the state of each node and each channel at some instant in time
- We can see now that the notion of an "instant in time" is tricky
  - For example, if each node writes down its state at logical time 10000, would this be a "snapshot" that corresponds to anything an external user would perceive as "time"?
  - …. Clearly not. My logical clock could advance much faster than yours

Temporal distortions

- Things can be complicated because we can’t predict
  - Message delays (they vary constantly)
  - Execution speeds (often a process shares a machine with many other tasks)
  - Timing of external events
- Lamport looked at this question too

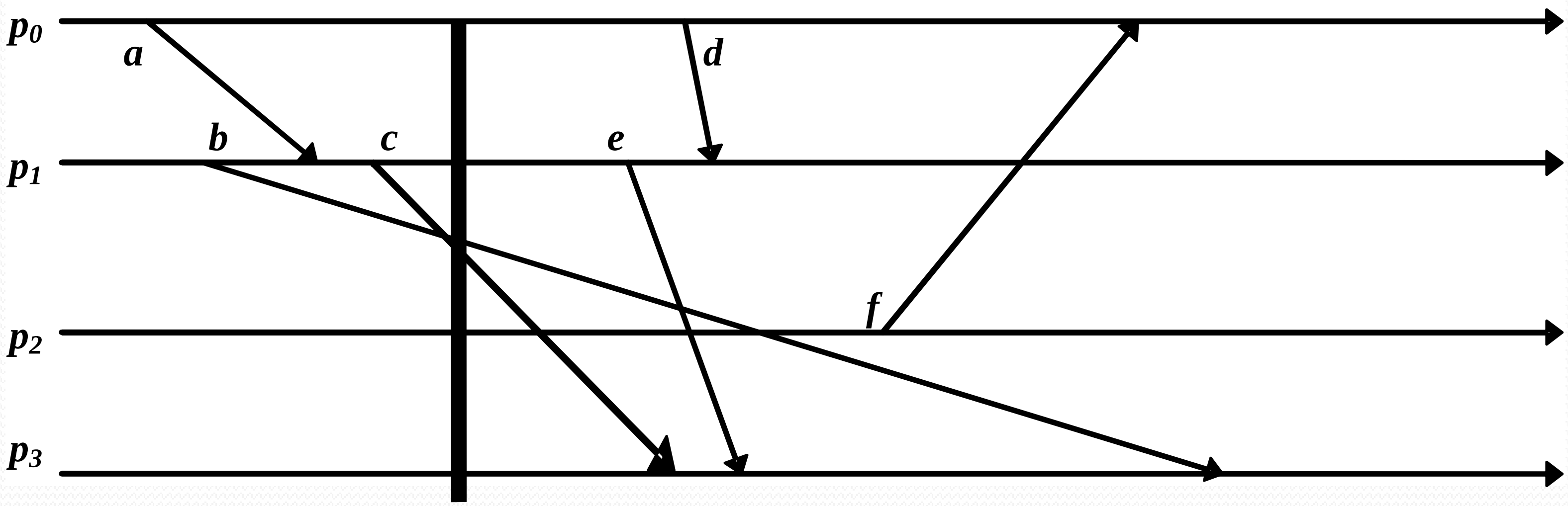
Temporal distortions

- What does "now" mean?



Temporal distortions

- What does “now” mean?



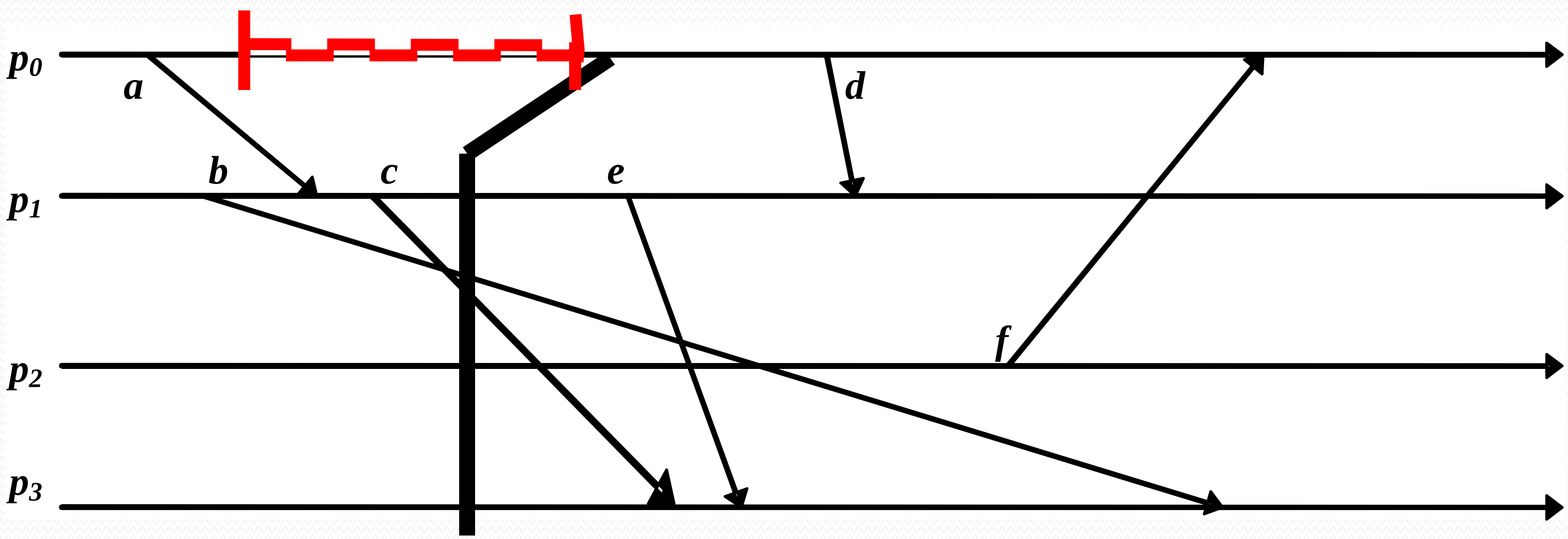
Consider…

- The picture we drew represents reality, but
  - With the same inputs, perhaps scheduling or contention on the machines could slow some down, or speed some up
  - Messages may be lost and need to be retransmitted, or might hit congested links
  - Or perhaps those problems occurred in the run in the picture but have gone away now

- In fact a given system might yield MANY pictures of this sort, depending on "luck"…

Temporal distortions

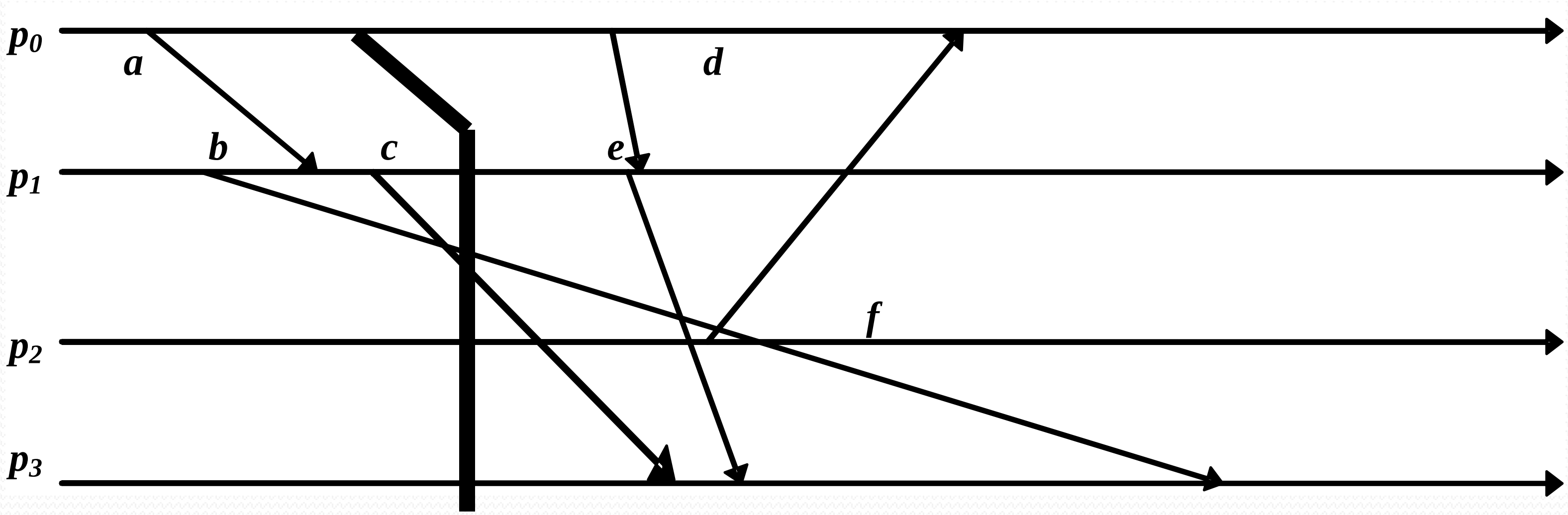
- Timelines can “stretch”…



- … caused by scheduling effects, message delays, message loss…

Temporal distortions

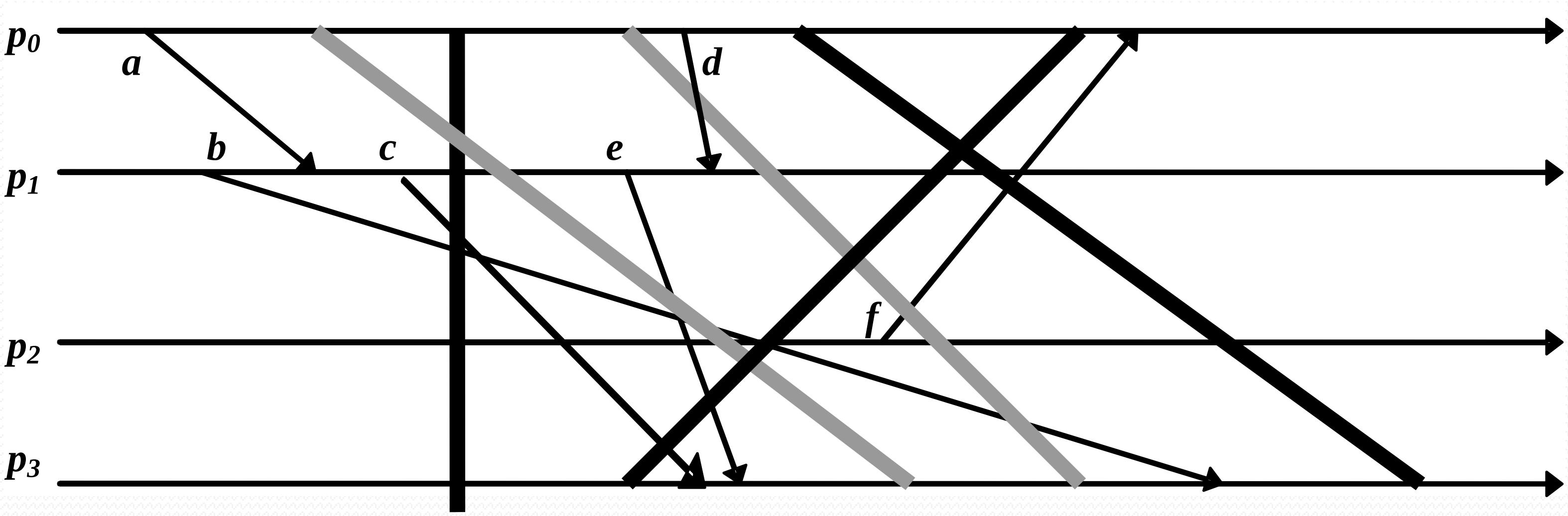
- Timelines can “shrink”



- E.g. something lets a machine speed up

Temporal distortions

- *Cuts* represent instants of time.



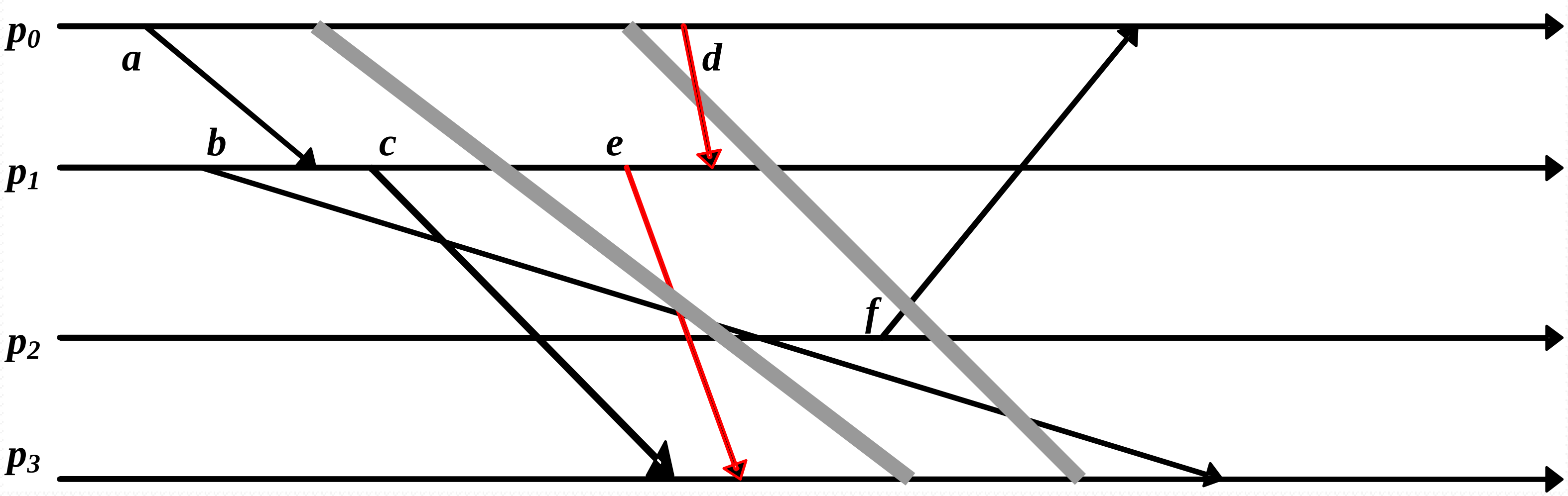
- But not every “cut” makes sense
  - Black cuts could occur but not gray ones.

Consistent cuts and snapshots

- Idea is to identify system states that "might" have occurred in real-life
  - Need to avoid capturing states in which a message is received but nobody is shown as having sent it
  - This the problem with the gray cuts

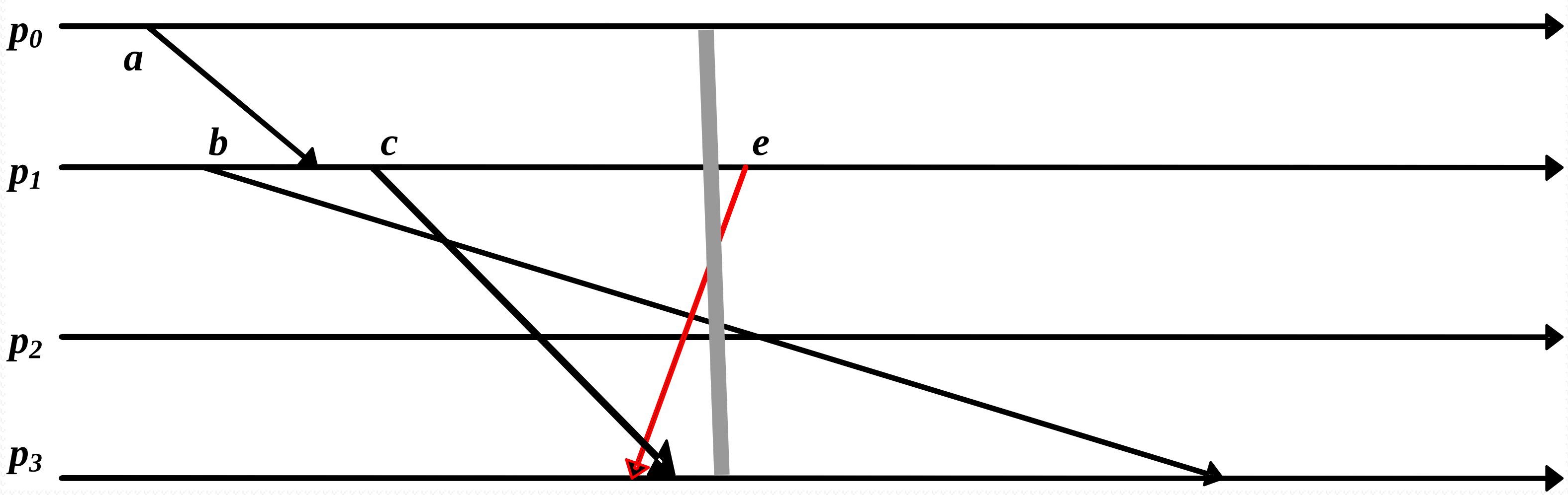
Temporal distortions

- Red messages cross gray cuts “backwards”



Temporal distortions

- Red messages cross gray cuts “backwards”



- In a nutshell: the cut includes a message that “was never sent”

Who cares?

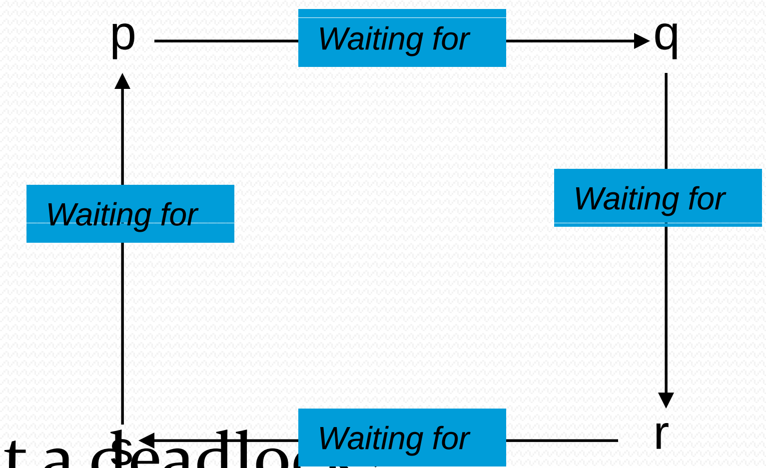
- In our auditing example, we might think some of the bank’s money is missing
- Or suppose that we want to do distributed deadlock detection
  - System lets processes “wait” for actions by other processes
  - A process can only do one thing at a time
  - A deadlock occurs if there is a circular wait

Deadlock detection "algorithm"

- p worries: perhaps we have a deadlock
- p is waiting for q, so sends "what's your state?"
- q, on receipt, is waiting for r, so sends the same question… and r for s…. And s is waiting on p.

Suppose we detect this state

- We see a cycle…

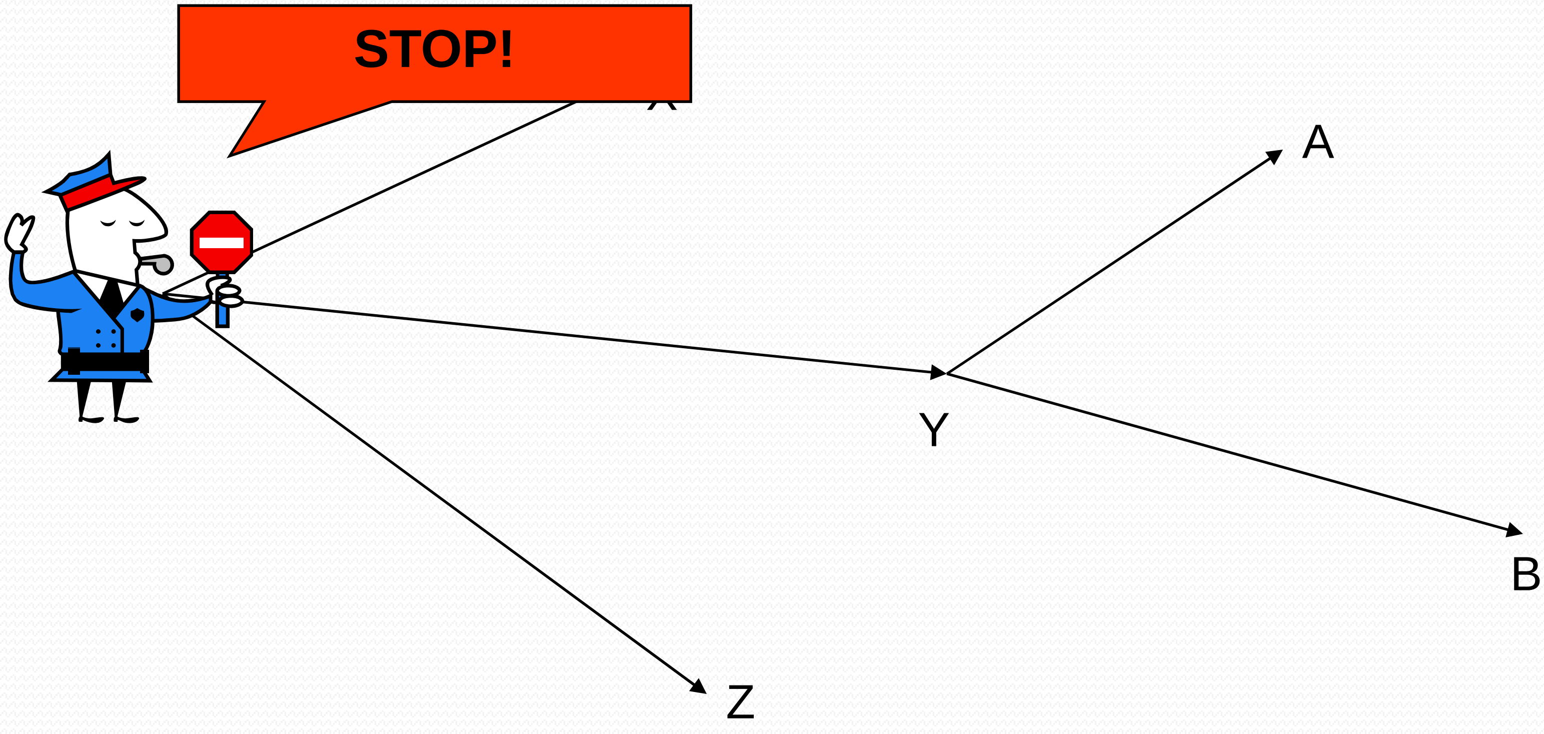


- … but is it a deadlock?

Phantom deadlocks!

- Suppose system has a *very high rate* of locking.
- Then perhaps a lock release message “passed” a query message
  - i.e. we see “q waiting for r” and “r waiting for s” but in fact, by the time we checked r, q was no longer waiting!
- In effect: we checked for deadlock on a gray cut – an inconsistent cut.

One solution is to "freeze" the system



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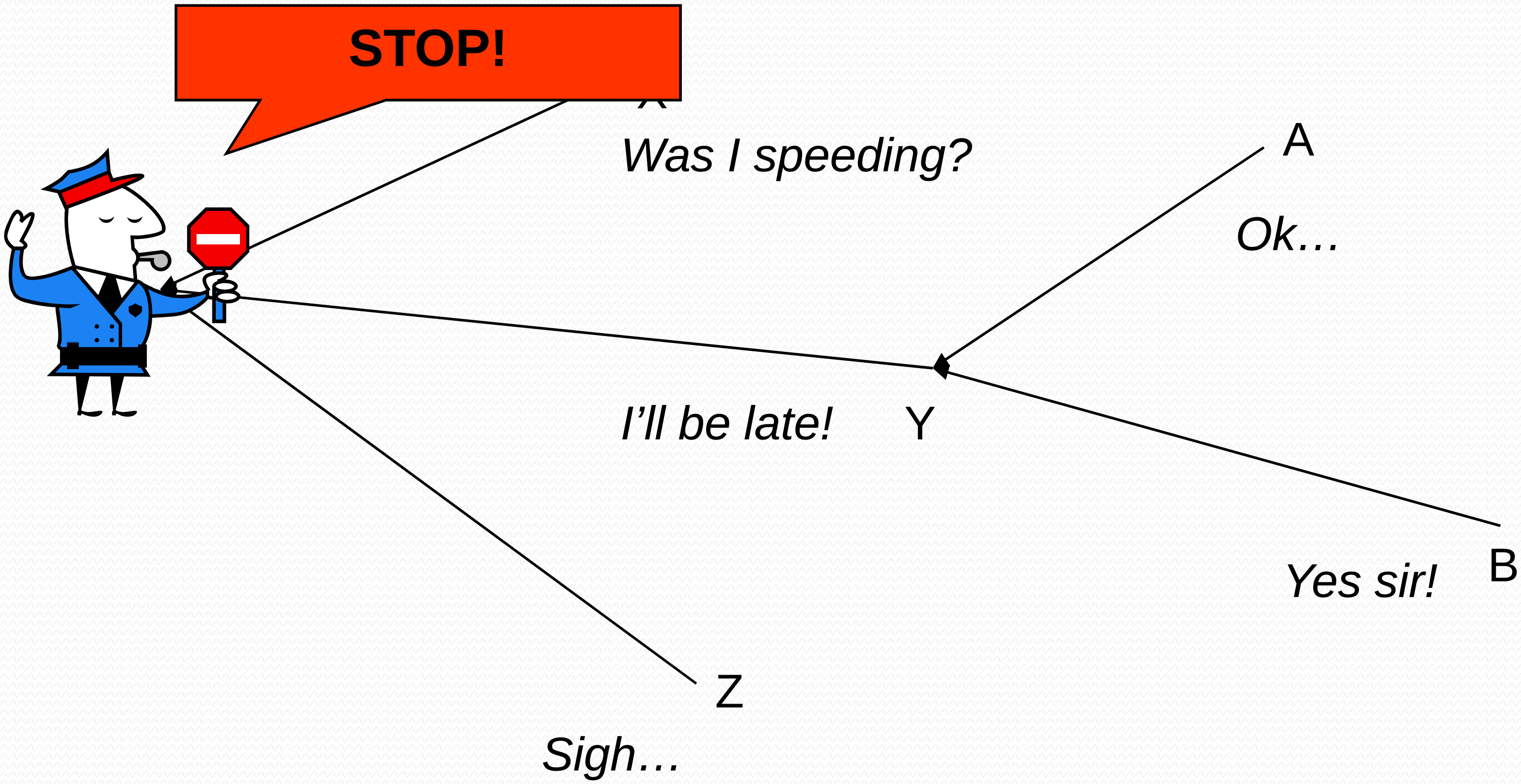

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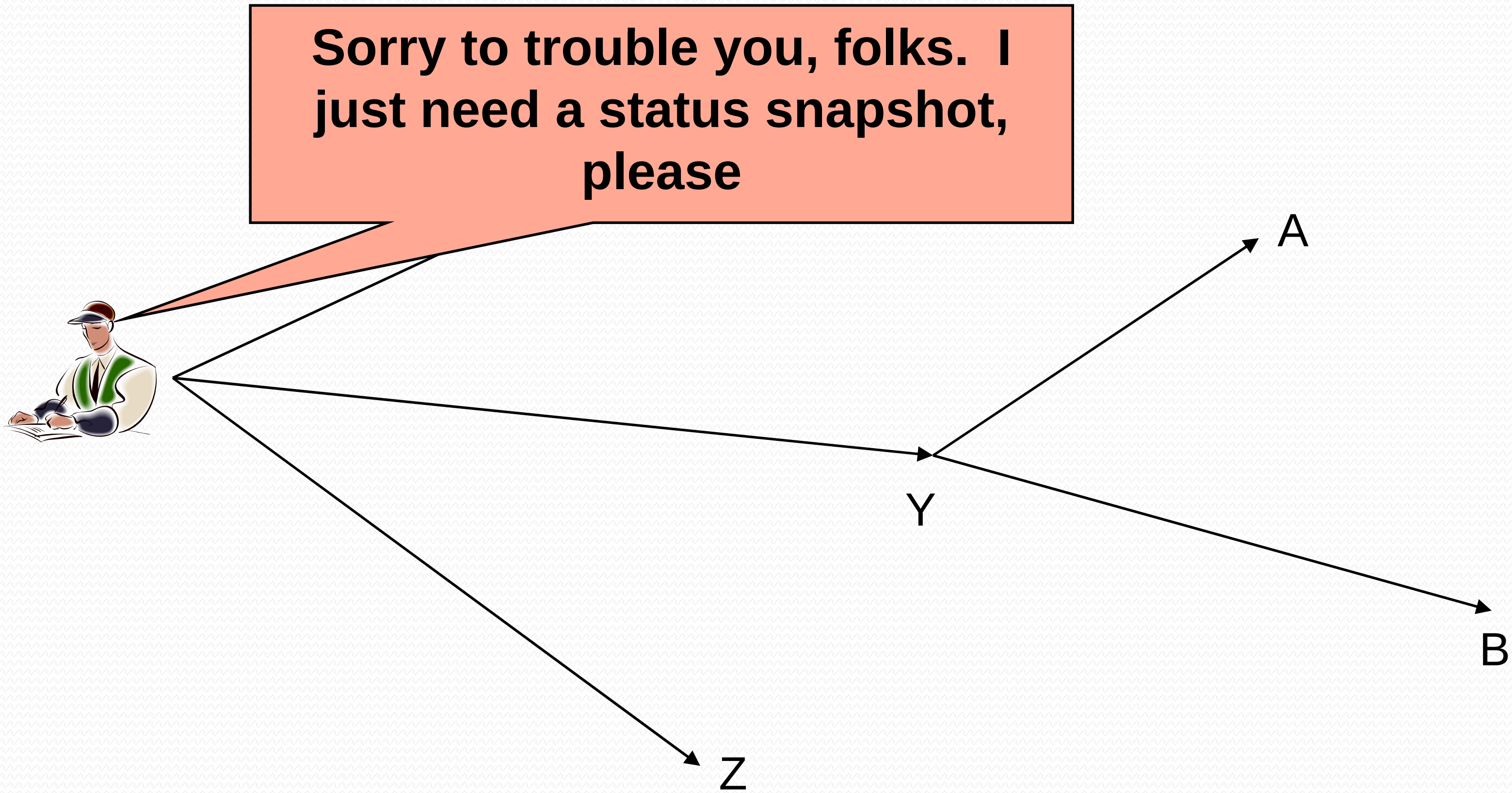

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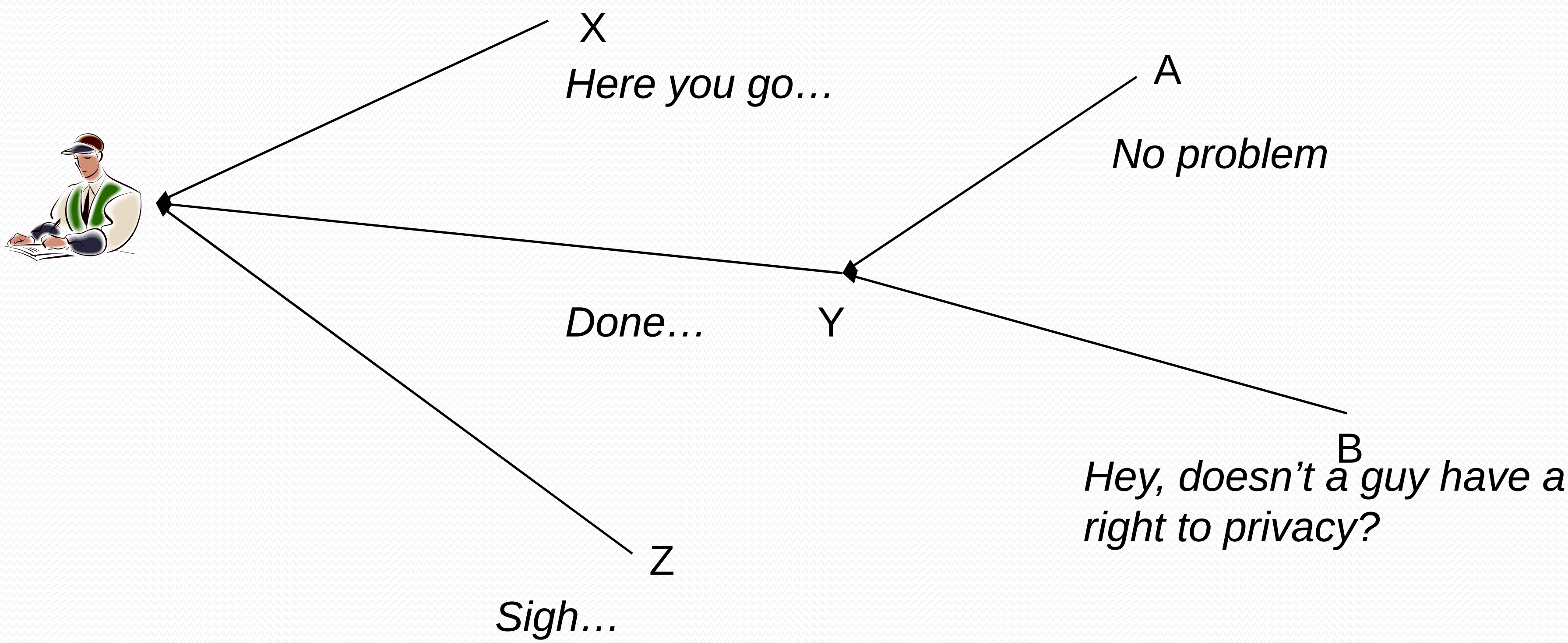

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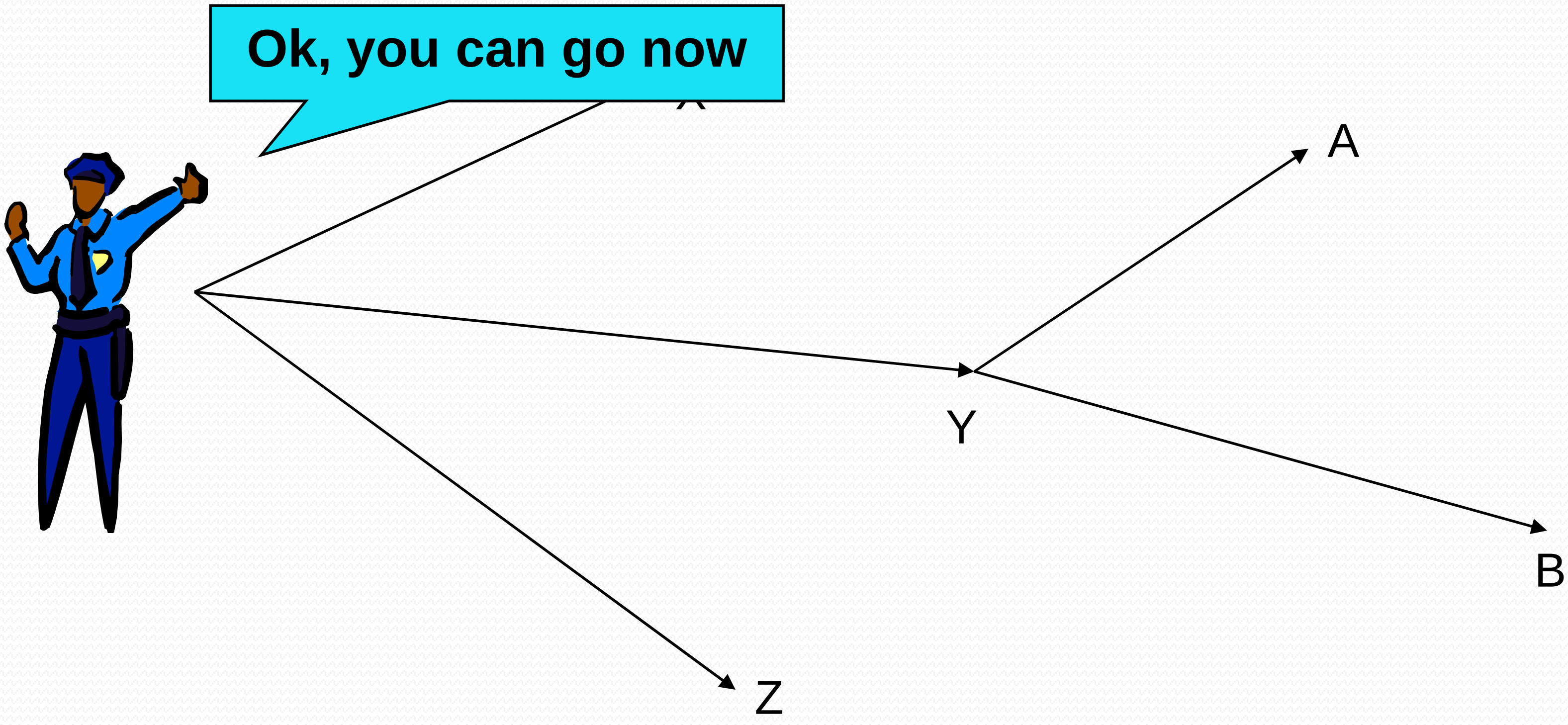


Why does it work?

- When we check bank accounts, or check for deadlock, the system is idle
- So if “P is waiting for Q” and “Q is waiting for R” we really mean “simultaneously”
- But to get this guarantee we did something very costly because no new work is being done!

Consistent cuts and snapshots

- Goal is to draw a line across the system state such that
  - Every message "received" by a process is shown as having been sent by some other process
  - Some pending messages might still be in communication channels
- And we want to do this *while running*

Turn idea into an algorithm

- To start a new snapshot, p_i …
  - Builds a message: "P_i is initiating snapshot k".
    - The tuple (p_i, k) uniquely identifies the snapshot
  - Writes down its own state
  - Starts recording incoming messages on all channels

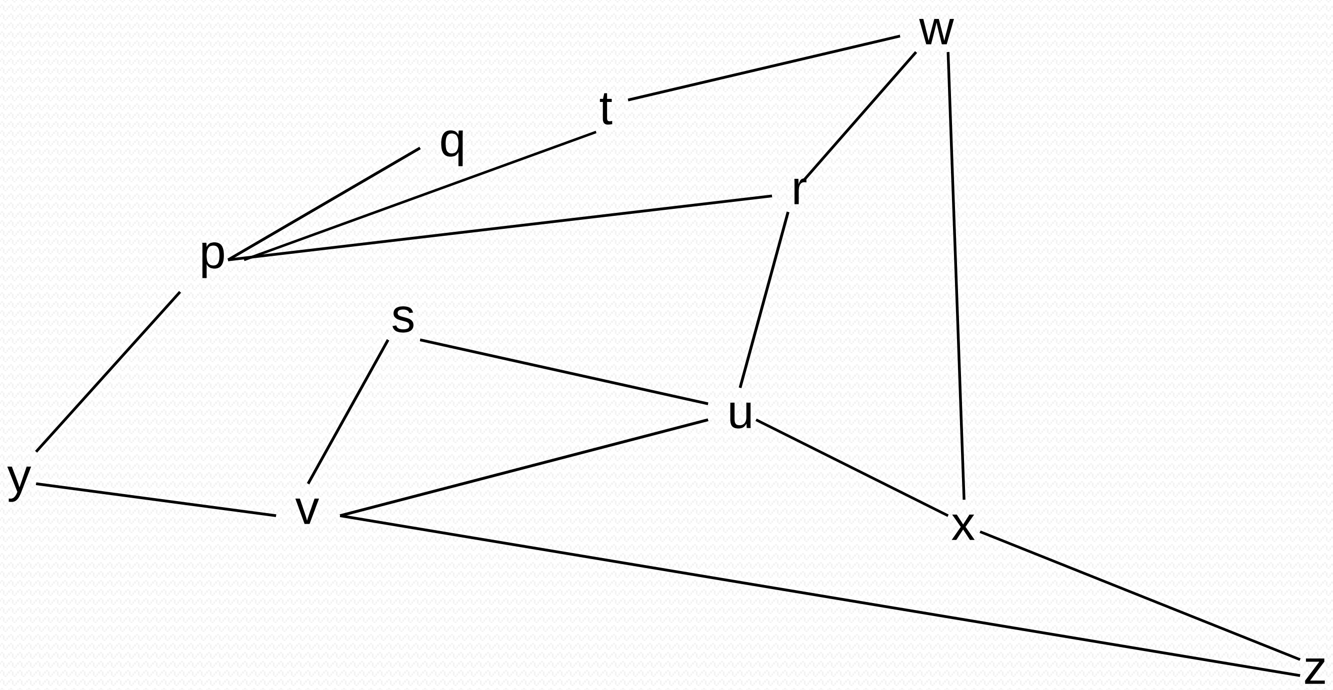
Turn idea into an algorithm

- Now p_i tells its neighbors to start a snapshot
- In general, on first learning about snapshot (p_i, k), p_x
  - Writes down its state: p_x's contribution to the snapshot
  - Starts "tape recorders" for all communication channels
  - Forwards the message on all outgoing channels
  - Stops "tape recorder" for a channel when a snapshot message for (p_i, k) is received on it
- Snapshot consists of all the local state contributions and all the tape-recordings for the channels

Chandy/Lamport

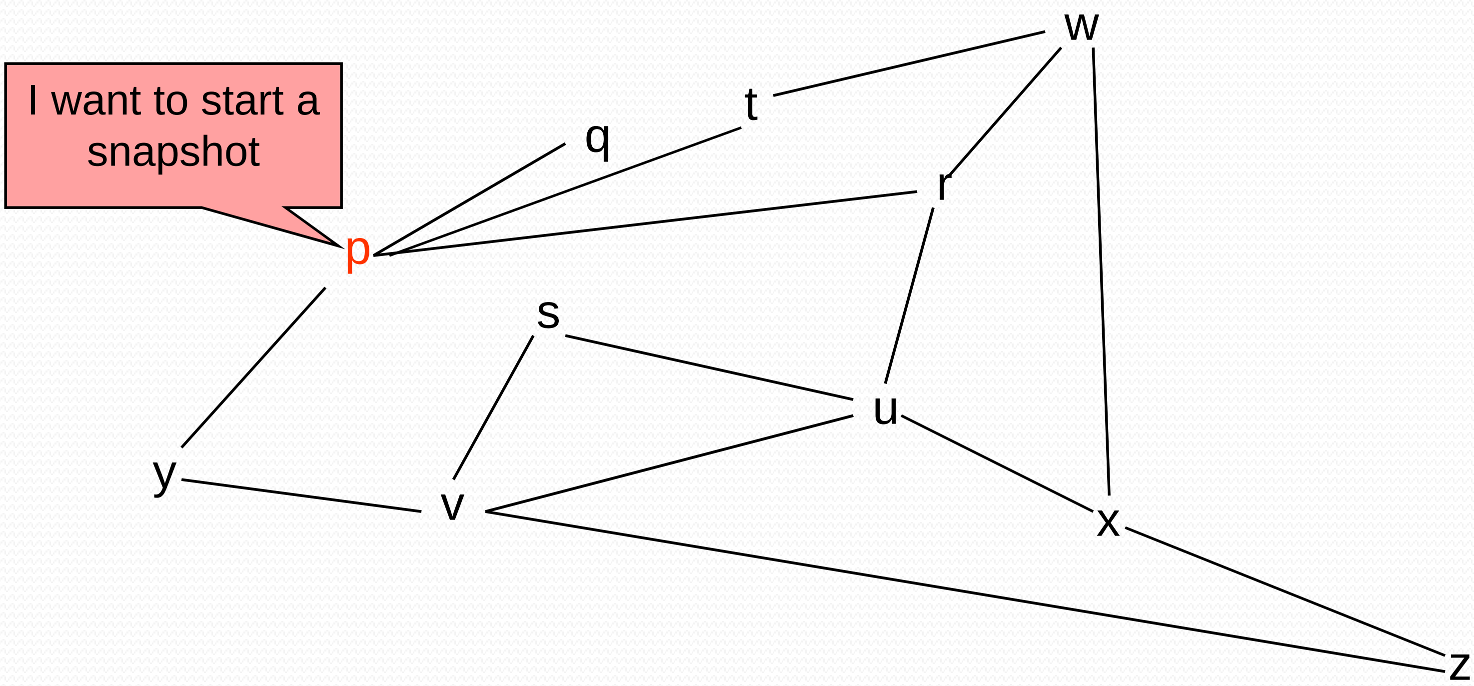
- Outgoing wave of requests… incoming wave of snapshots and channel state
- Snapshot ends up accumulating at the initiator, p_i
- Algorithm doesn’t tolerate process failures or message failures.

Chandy/Lamport



A network

Chandy/Lamport



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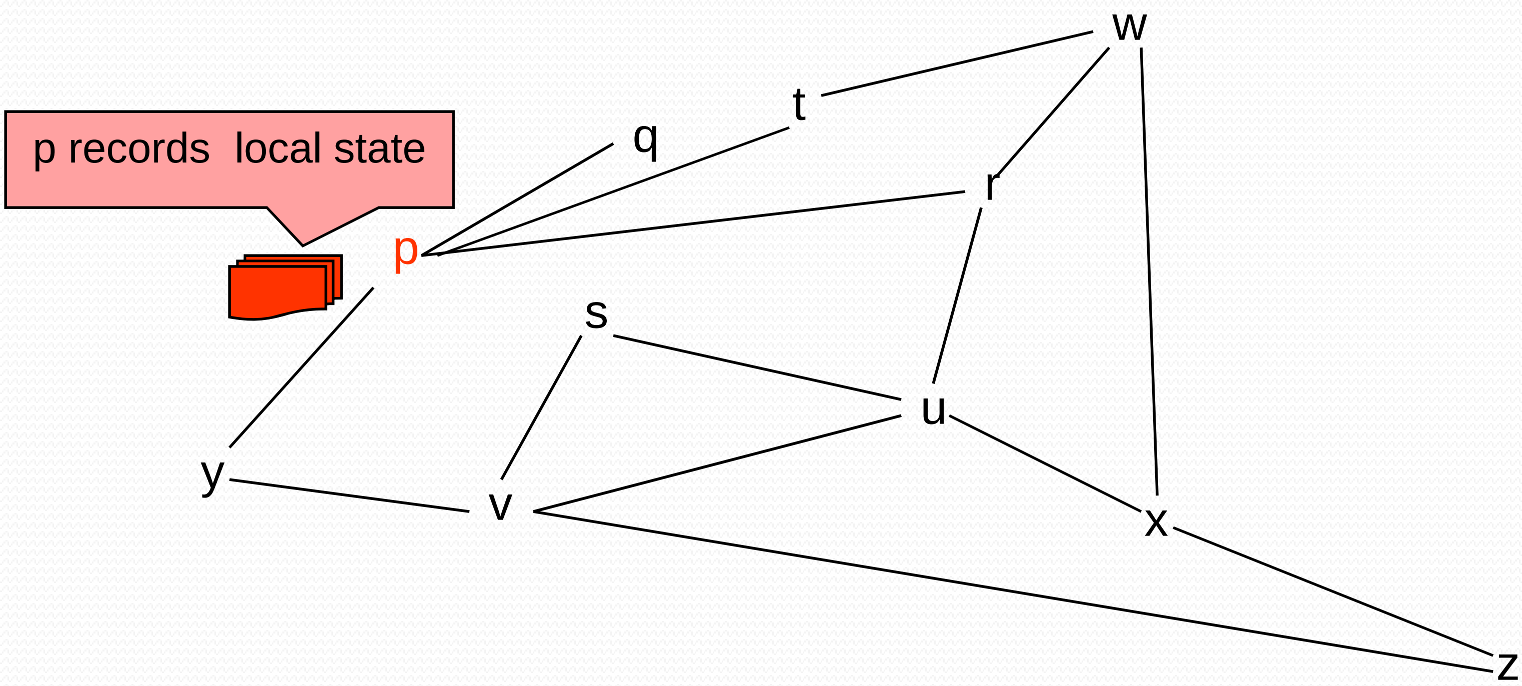

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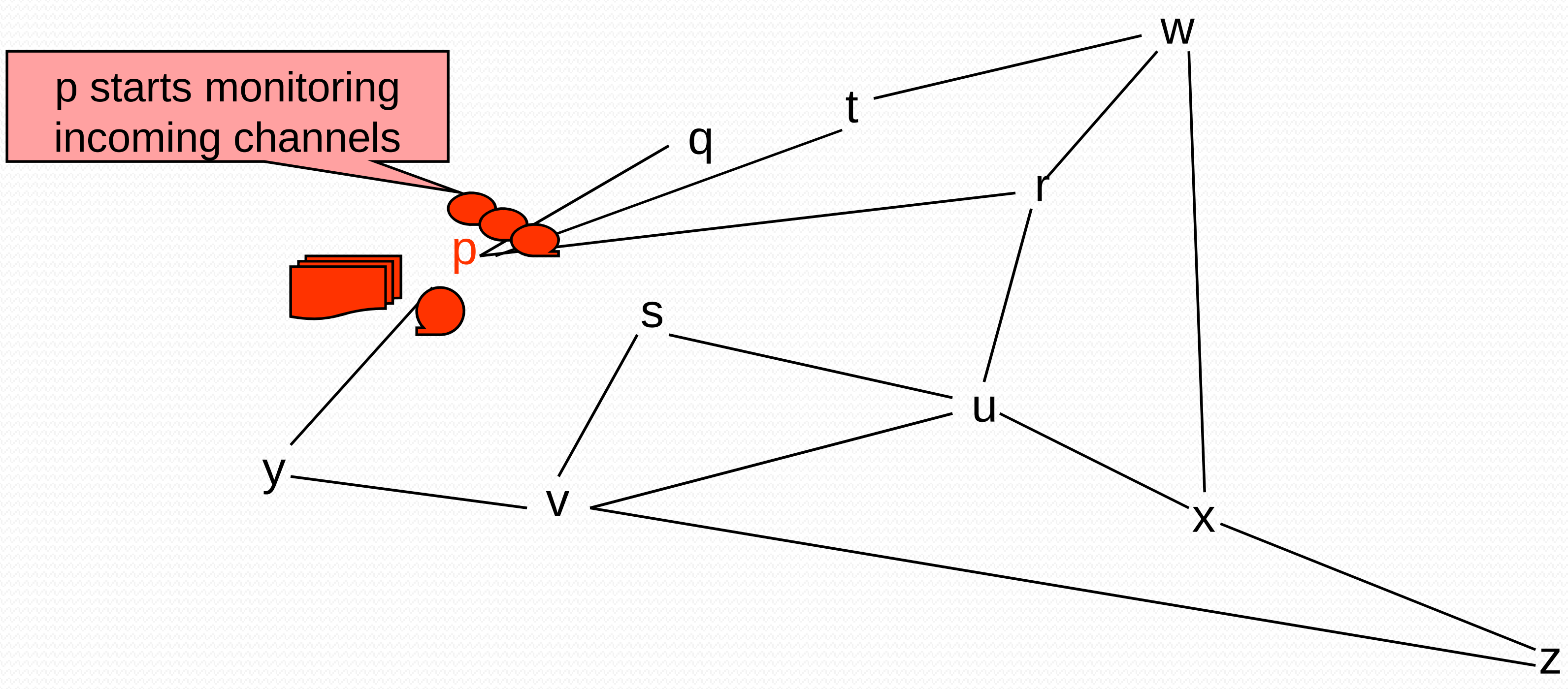

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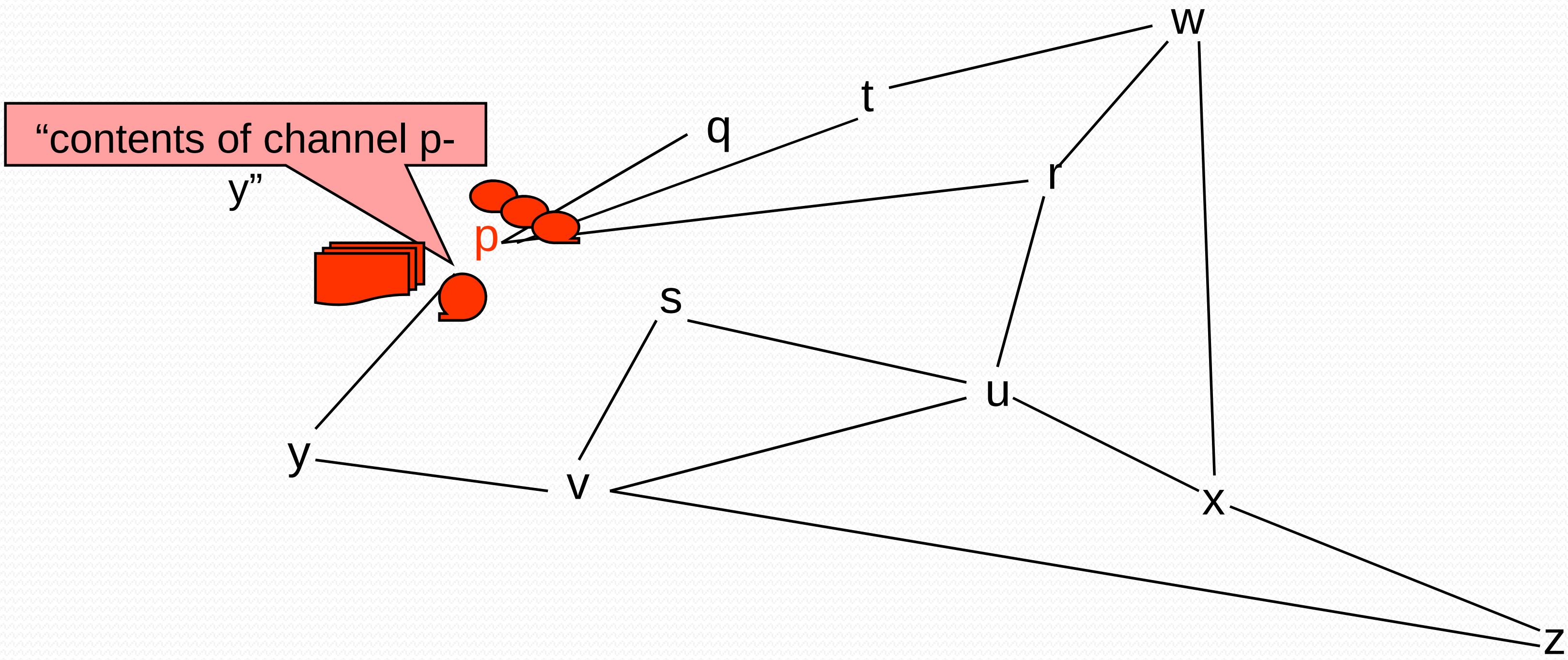

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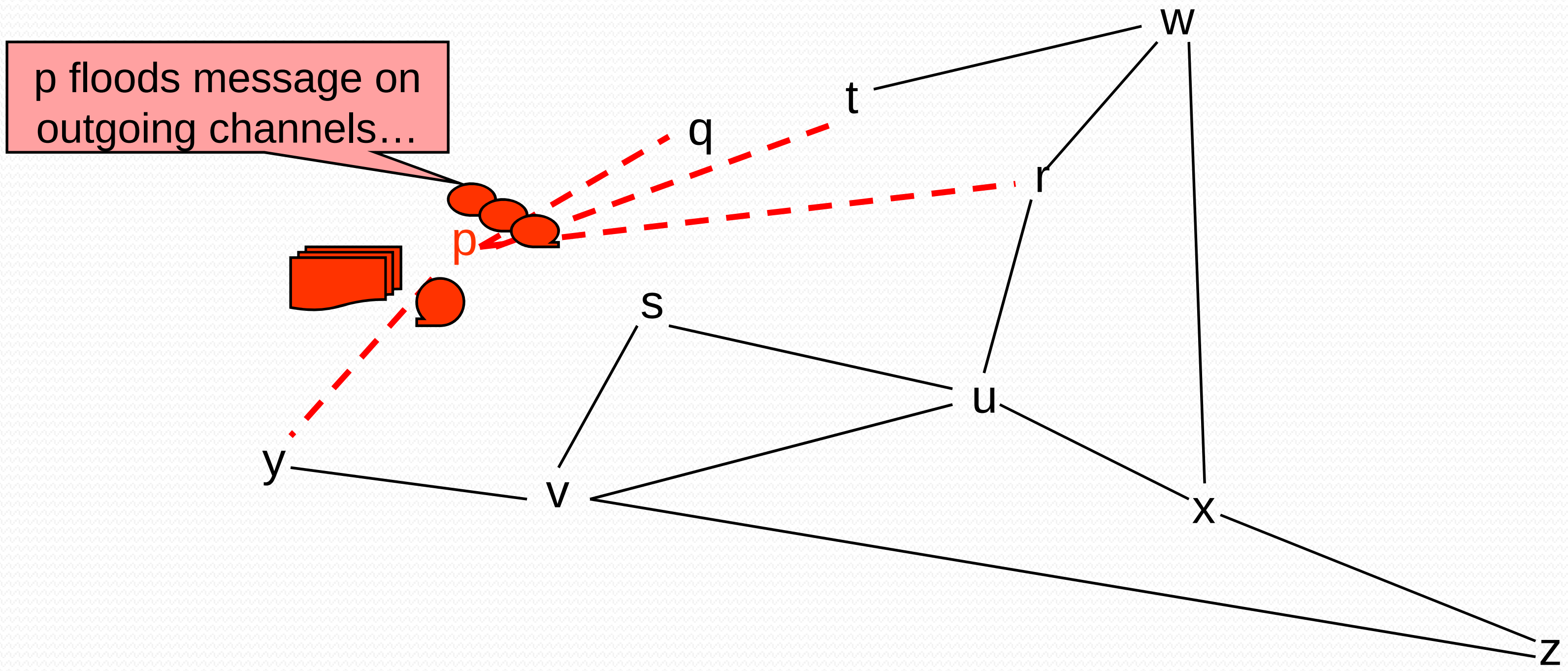

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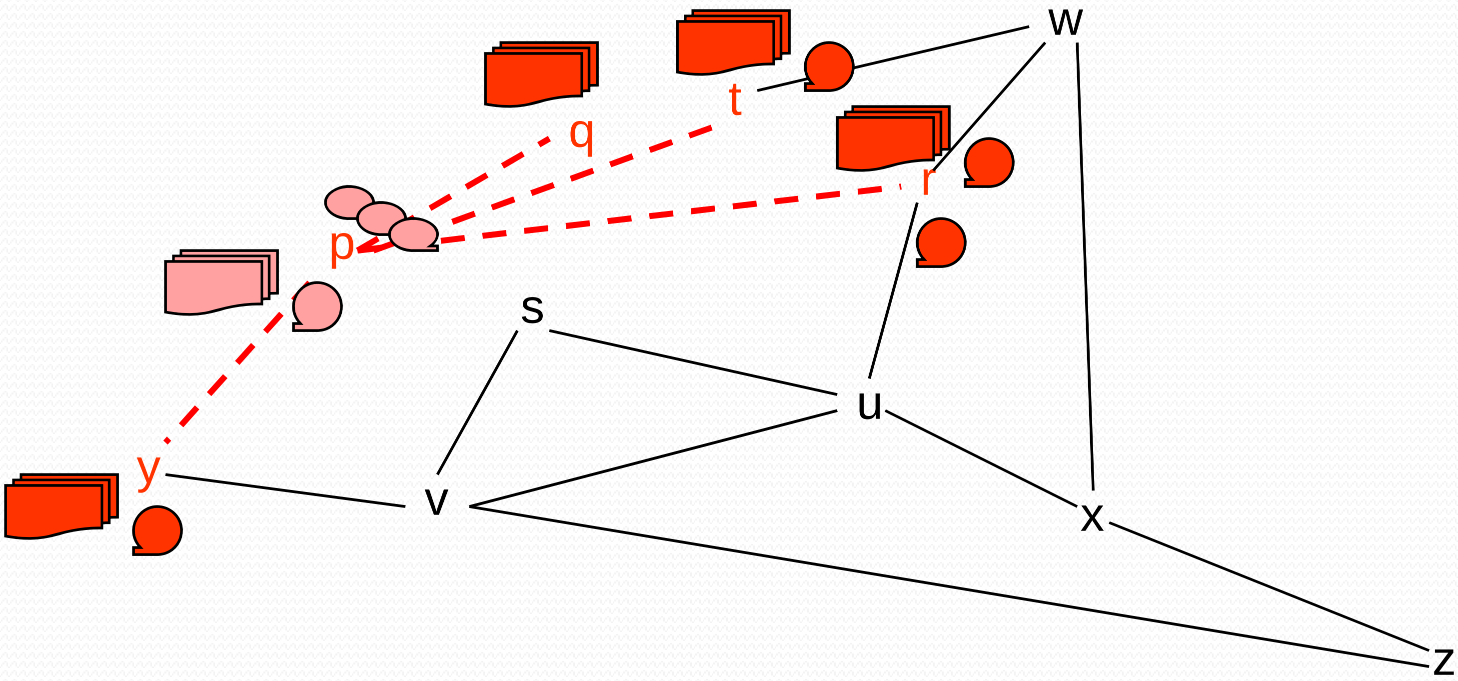

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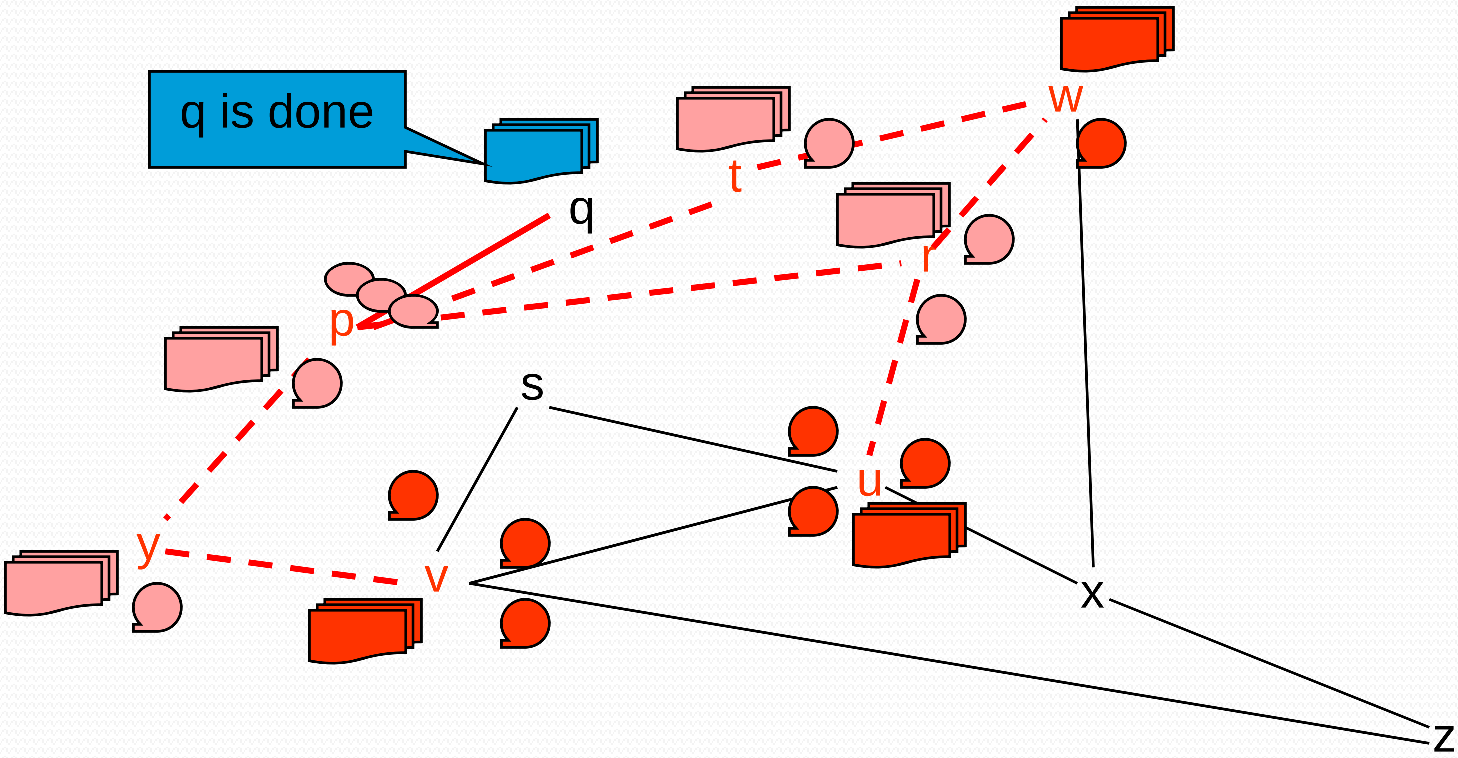

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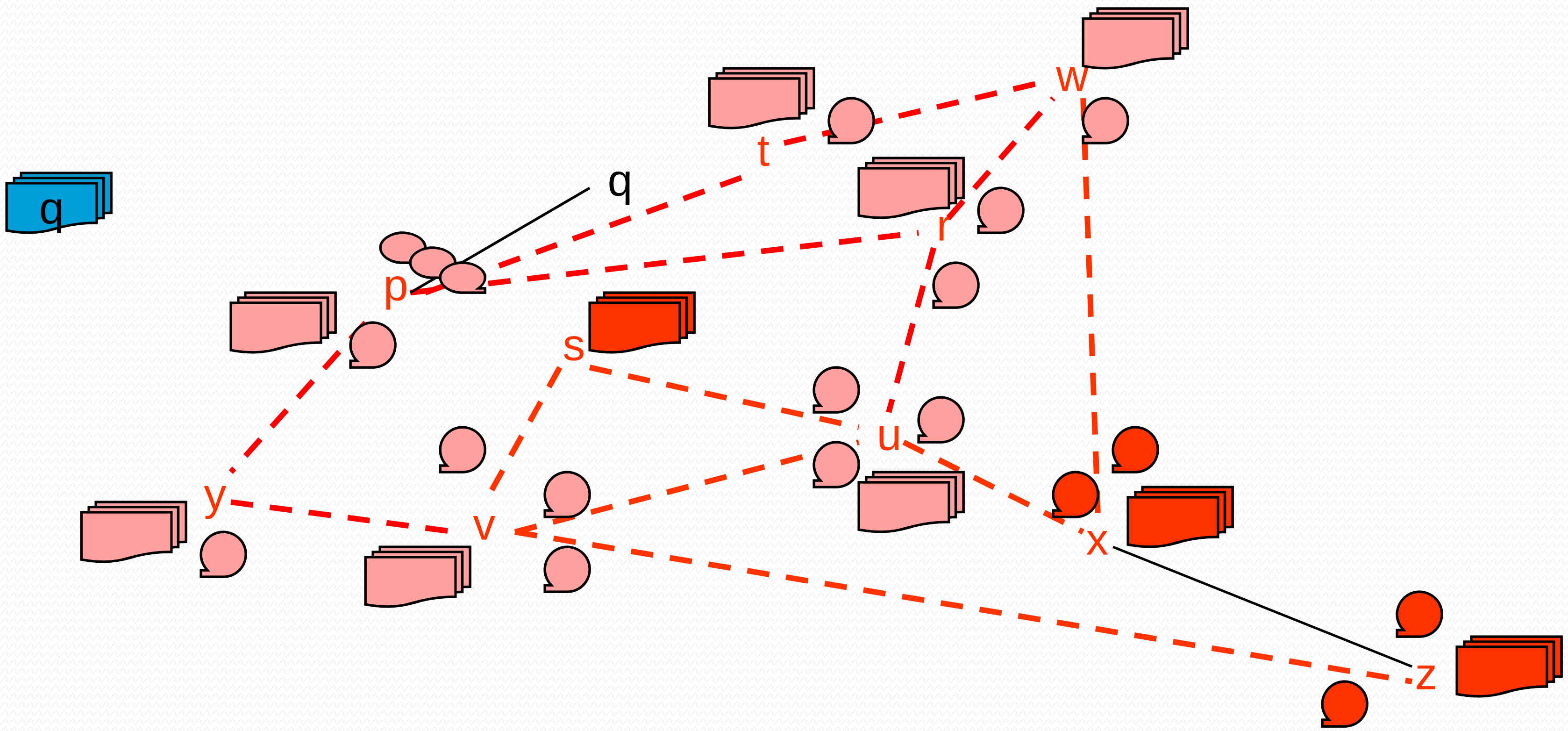

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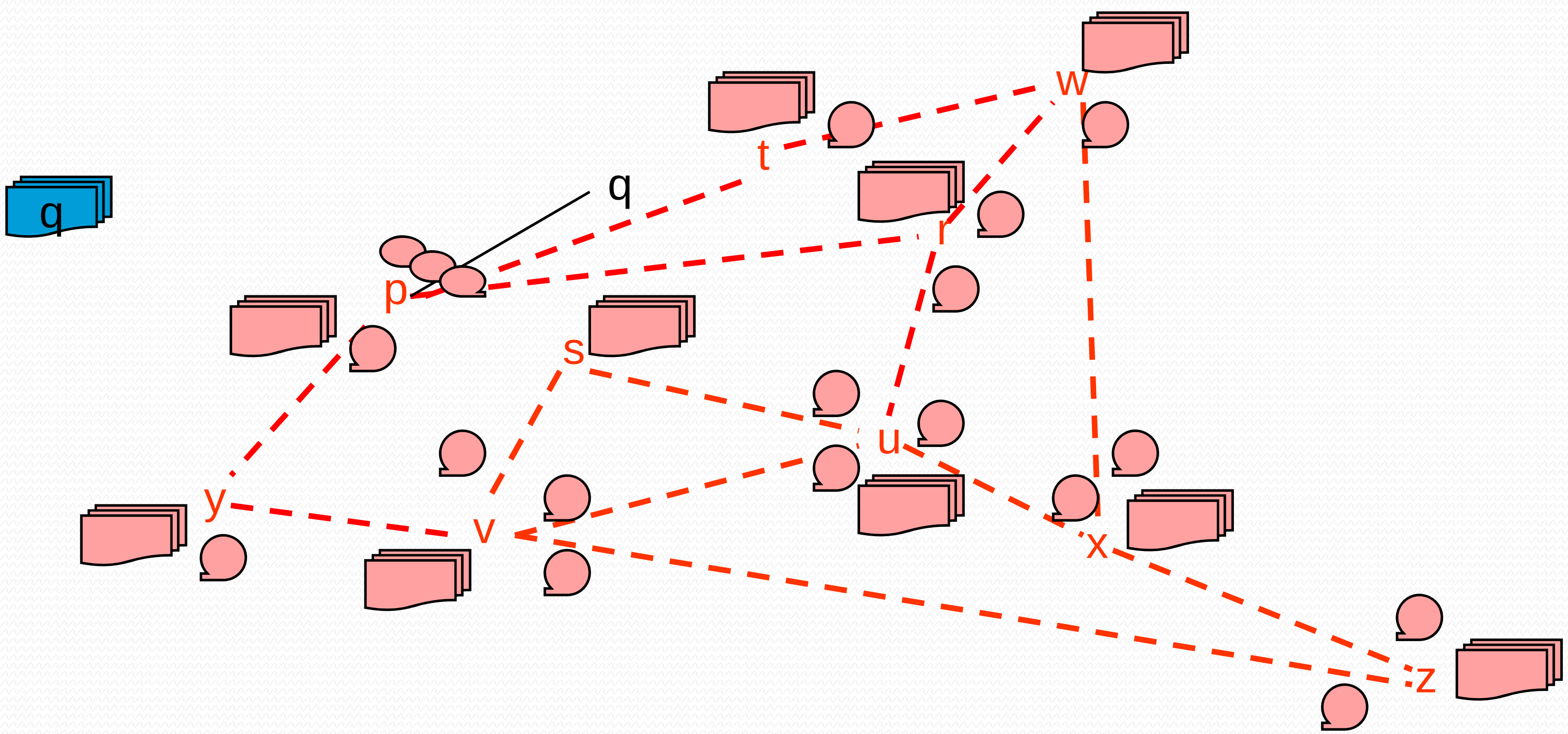

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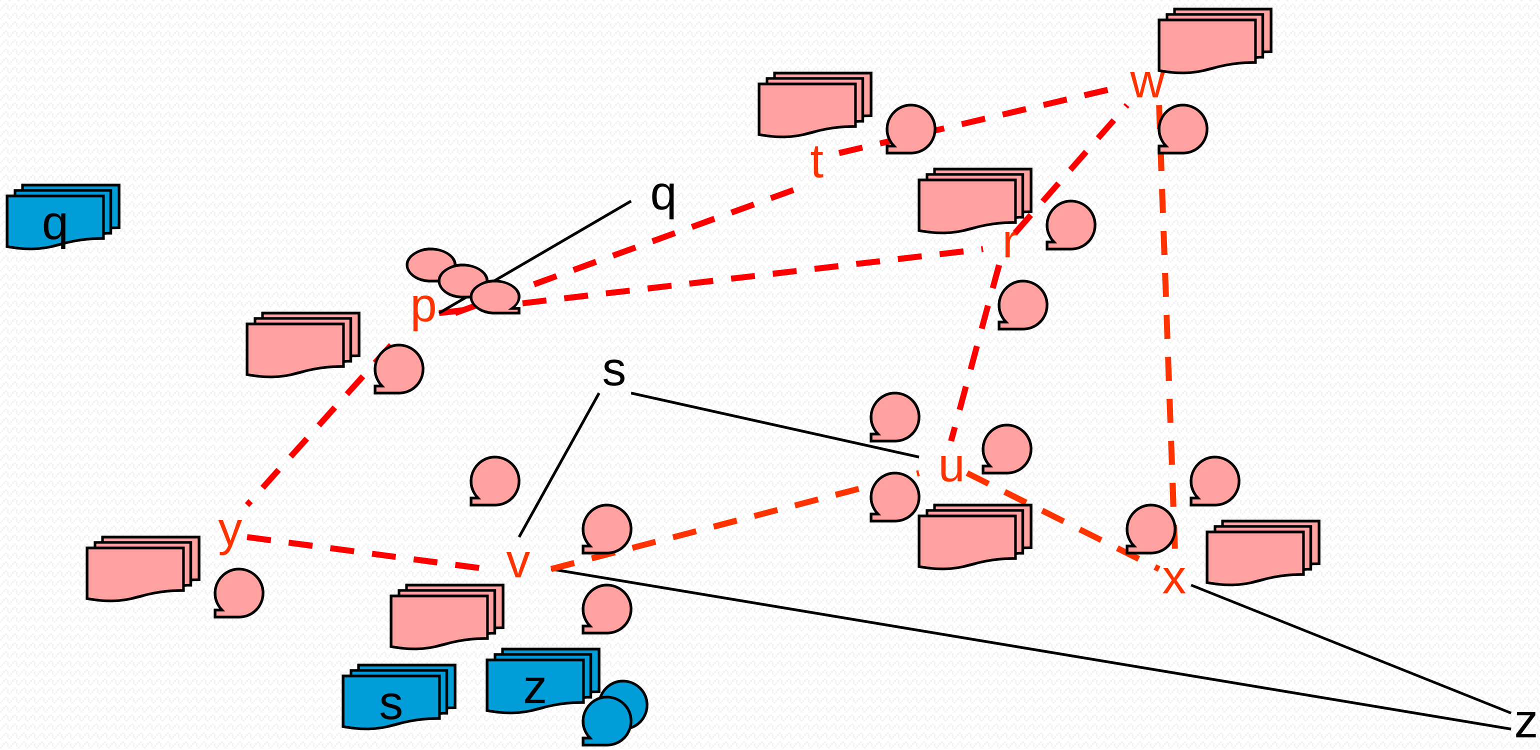

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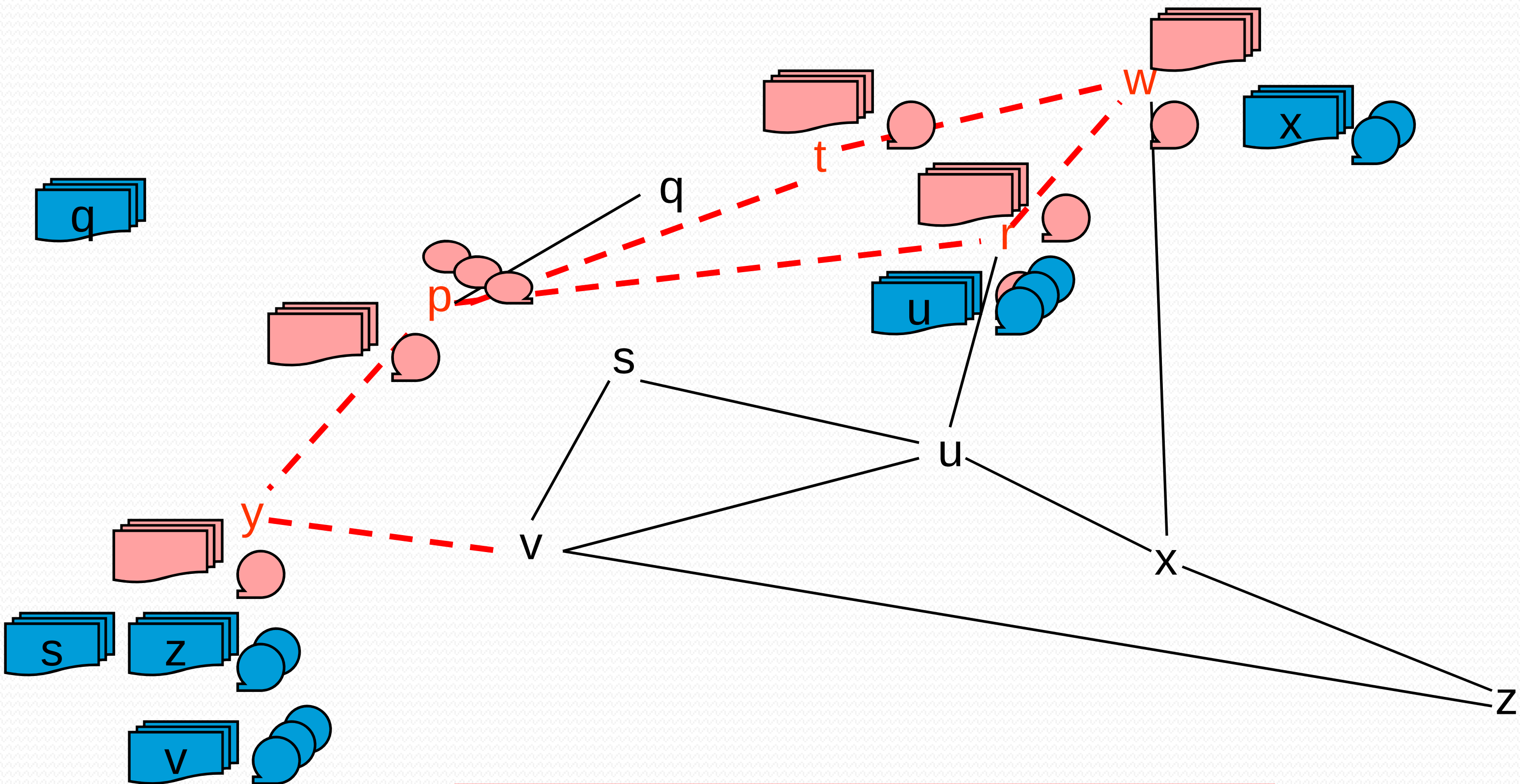

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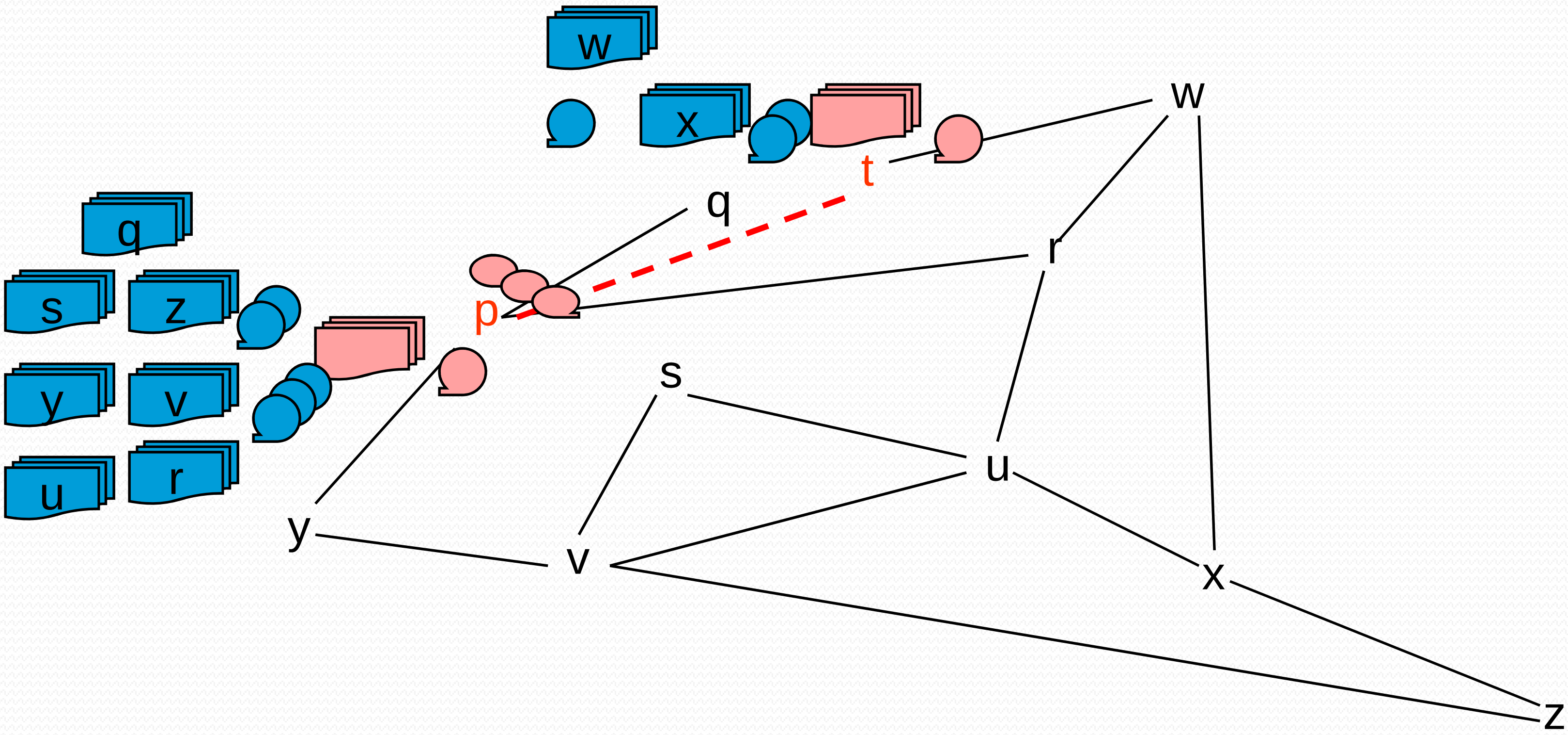

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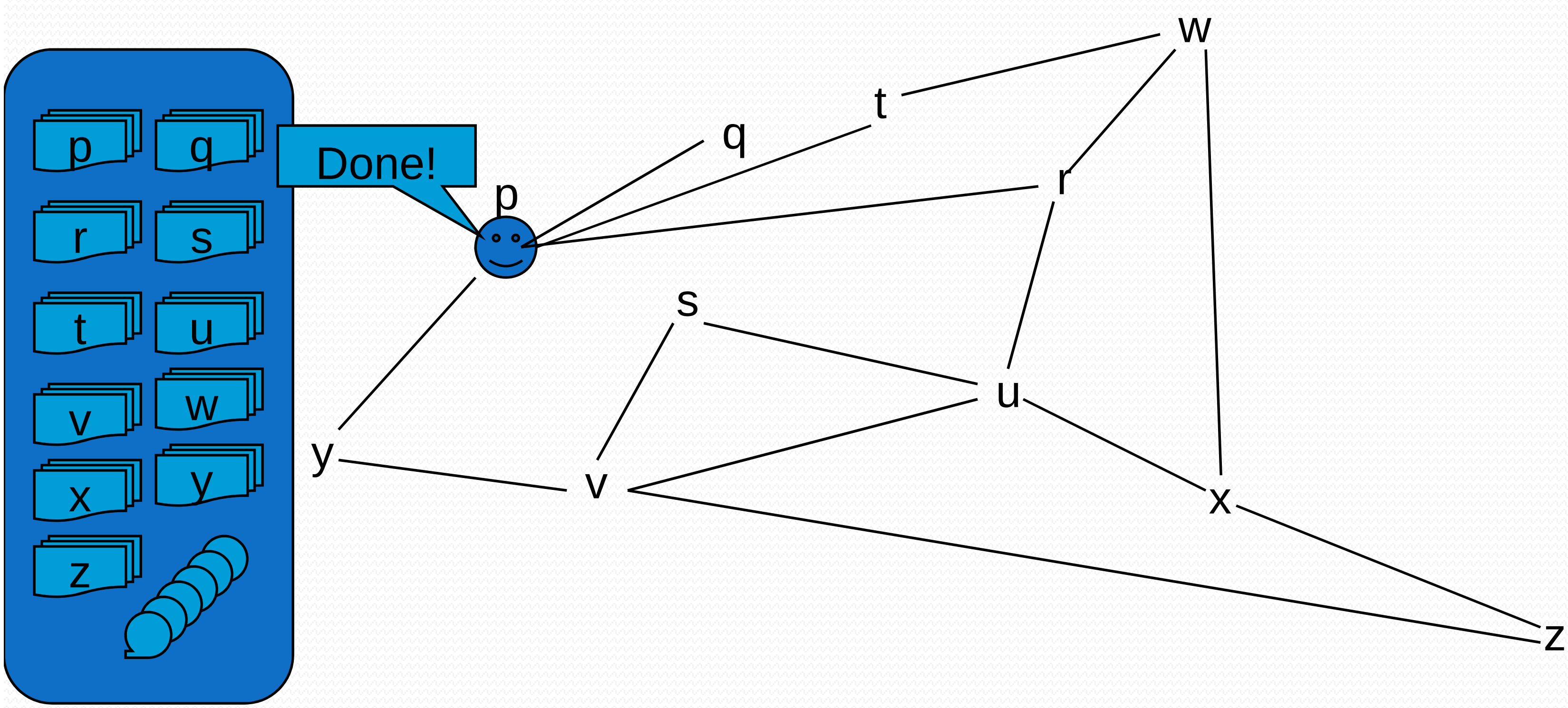

A snapshot of a network

Using logical clocks for cuts

- Application could also set a logical clock WAY ahead
- Rule: *each time the clock reaches a multiple of 100,000,000 write down your state*
  - So: node p sets clock ahead to 1,000,001 (and writes down its state). Then floods the network
  - As the message reaches nodes, each records its state

Summary

- We've seen that true clocks are "tricky" in distributed systems but that we can use simple integers or vectors of integers to capture event ordering
  - Logical clocks capture just part of the ordering
  - Vector clocks are larger but capture all the useful info.
- Then we looked at how one can interpret "simultaneous" as a distributed concept
  - Consistent snapshots or cuts (cuts being the "front line" of a snapshot, which includes channel state too)