Distributed Systems: Ordering and Consistent Cuts

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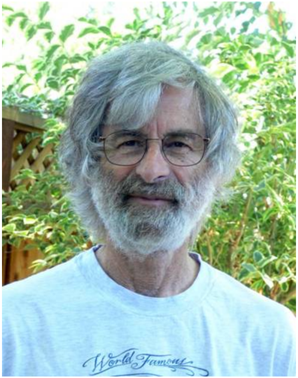
Time, Clocks and the Ordering of Events

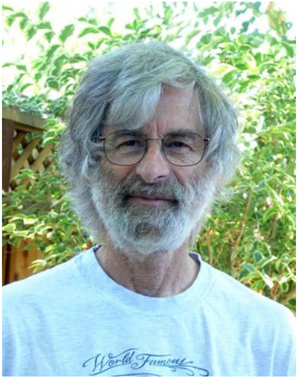
- *Time, Clocks, and the Ordering of Events in a Distributed System*



Leslie B. Lamport (1941–)

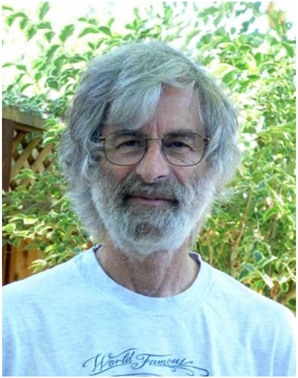
- The original author of LaTeX
- Sequential consistency
- Atomic register hierarchy
- Lamport's bakery algorithm
- Byzantine fault tolerance
- Paxos
- Lamport signature

Time, Clocks and the Ordering of Events



Leslie B. Lamport (1941–)

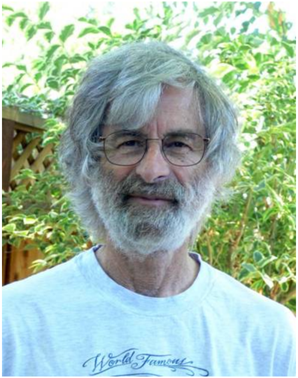
- B.S. in mathematics from MIT
- M.A. and Ph.D. in mathematics from Brandeis University
- Dijkstra Prize (2000, because of this paper, and 2005)
- IEEE Emanuel R. Piore Award (2004)
- IEEE John von Neumann Medal (2008)
- ACM A.M. Turing Award (2013)
- ACM Fellow (2014)



Leslie B. Lamport (1941–)

- “Jim Gray once told me that he had heard two different opinions of this paper: that it’s trivial and that it’s brilliant. I can’t argue with the former, and I am disinclined to argue with the latter. ”

Time, Clocks and the Ordering of Events



Leslie B. Lamport (1941–)

- “This is my most often cited paper. Many computer scientists claim to have read it. But I have rarely encountered anyone who was aware that the paper said anything about state machines … People have insisted that there is nothing about state machines in the paper. I’ve even had to go back and reread it to convince myself that I really did remember what I had written.”

Time and Systems

> *"The only reason of time is so that everything does not happen at once."*
>
> — Albert Einstein

- Something happened at 3:15: ocurred within $[3:15, 3:16)$.
- Why time is so important? Air ticket reservation, online shopping, etc.

Time and Systems

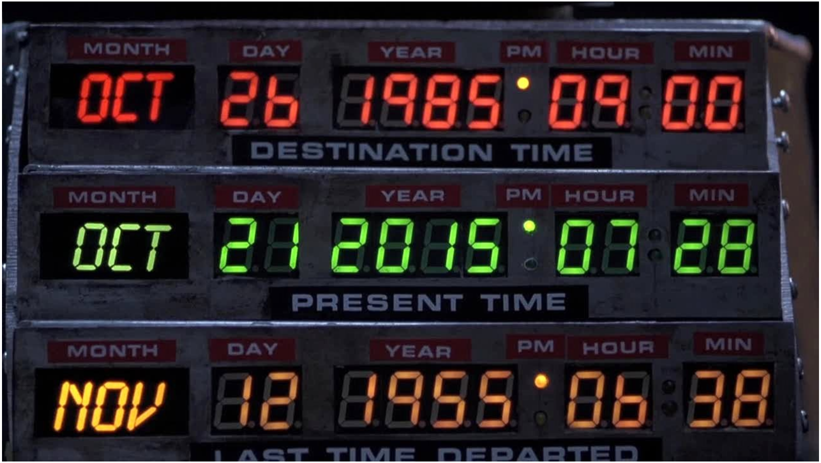
> *"The only reason of time is so that everything does not happen at once."*
>
> — Albert Einstein

- Systems: an interesting definition of "distributed": *msg. transmission delay* is NOT negligible compared to the *time between events* in a single process.
- Sometimes impossible to say any one of two occured first: *partial ordering.*

Time and Systems

> *"The only reason of time is so that everything does not happen at once."*
>
> — Albert Einstein

- "Everything does not happen at once" means *ordering*.
- An ordering can give a *happened-before* relation of events in the system.
- *Clocks* can map events to numbers, so as to give the relation.


MONTH
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DESTINATION TIME
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PRESENT TIME
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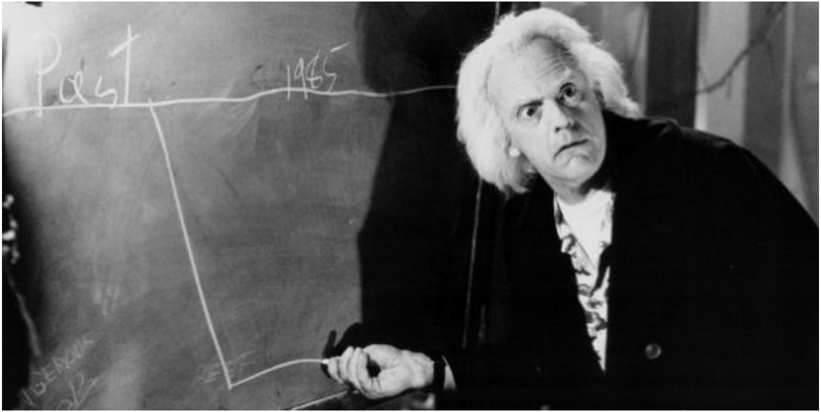
Clocks

In this paper, two clock implementations are introduced

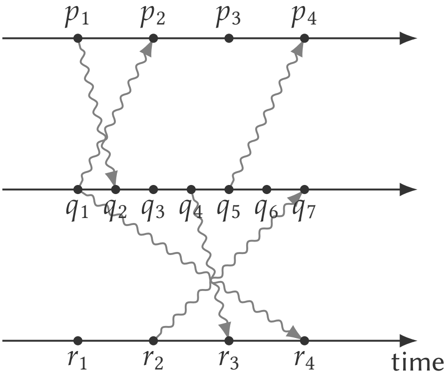
- **Logical clocks:**
  - works without the help of any physical equipment,
  - causes anomaly with external happened-before relation (the clock is confined within the system).
- **Physical clocks:**
  - works when physical clocks have certain precision,
  - but provides with strong relation.

- We have
  - A priori: total ordering of events in the same process
  - Msgs. can carry time info
- We want to archieve
  - A relation $a \to b$ that
    1. $a, b \in$ same process, a comes before $b \Longrightarrow a \to b$,
    2. a sends a msg. to $b \Longrightarrow a \to b$,
    3. $a \to b \land b \to c \Longrightarrow a \to c$.
  - Remarks:
    - a and b are *concurrent* if $a \not\to b \land b \not\to a$.
    - $a \not\to a$ (irreflexivity),
    - $a \to b \land b \to c \Longrightarrow a \to c$ (transitivity),
    - $a \to b \Longrightarrow b \not\to a$ (asymmetry).

Logical Clocks: Space-Time Diagram



Logical Clocks: Space-Time Diagram



- sending and receiving msgs. are also events,
- happened-before relation can be deduced by checking whether there is a directed path from a to b.

Logical Clocks: Design

- Let the clock be $C\langle e\rangle$, where e stands for an event.
- $C\langle e\rangle := C_i\langle e\rangle$, e is an event of process i.
- To satisfy "$\rightarrow$" relation, we want $\forall a, b$

$$a \rightarrow b \underbrace{\implies}_{!} C\langle a\rangle < C\langle b\rangle \quad \text{(clock cond.)}$$

-

$$\text{not vice versa: } a \rightarrow b \Leftrightarrow C\langle a\rangle < C\langle b\rangle$$

otherwise,

$$e \not\rightarrow e' \wedge e' \not\rightarrow e \implies C\langle e\rangle \not< C\langle e'\rangle \wedge C\langle e\rangle \not> C\langle e'\rangle$$
$$\implies C\langle e\rangle = C\langle e'\rangle$$

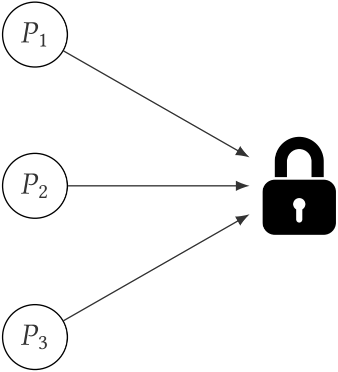
Logical Clocks: Design

- Clock condition is held if
  - C1: $a, b \in$ proc. i: a is before $b \implies C_i\langle a\rangle < C_i\langle b\rangle$.
  - C2: i sends msg. as event a to j as event b: $C_i\langle a\rangle < C_j\langle b\rangle$.
- Therefore, we can impose the following implementation rules
  - IR1: proc. i increases C_i between any two successive events.
  - IR2:
    - when i sends msg. m as an event a: m contains a timestamp $T_m = C_i\langle a\rangle$,
    - when j receives as an event b, it sets $C_j := \max\left\{C_j, T_m + 1\right\}$.

Logical Clocks: Partial to Total Ordering

- Extend the minimum partial ordering obtained above to one possible total ordering.
- Trick: use process identity ordering to *give order to all concurrent relation*.
- Example: define $a \triangleright b$ ("$\Rightarrow$" in the paper)
  - $C_i\langle a\rangle < C_j\langle b\rangle$,
  - $C_i\langle a\rangle = C_j\langle b\rangle \wedge P_i \prec P_j$.
- "$\prec$" fairness: $C_i\langle a\rangle = C_j\langle b\rangle \wedge j < i \Longrightarrow a \triangleright b$ if $j < C_i\langle a\rangle \bmod N \leq i$.

Logical Clocks: Case Study



- A unified protocol for each of processes
- Compete to acquire the lock & no pre-coordination
  1. mutex lock semantics (safety),
  2. **ordered requests**,
  3. eventual release of every processes $\implies$ every request will be granted. (liveness)

Logical Clocks: Case Study

The ordering constaint makes the design non-trival! Imagine a plausible solution using a central scheduling process P_0

- P_1 sends a request to P_0,
- P_1 sends a msg. to P_2,
- P_2 sends a request to P_0.

P1 should be granted because of the causal order.

Logical Clocks: Case Study

The solution makes use of logical clocks to reorder the requests

- assume FIFO and reliable channels
- each process has a local queue that can buffer the reorder the requests

Logical Clocks: Case Study

- Request: P_i sends "T_m: P_i requests the resouce" to every other procs. and puts onto its local queue.
- Receive (req.): on receiving "T_m: P_i req. the res.", P_j puts it into local queue and **send ACK** to P_i (not needed if it has sent a msg. to P_i with higher T'_m).
- Release: P_i removes any corresponding request msgs. from local queue and sends "T_m: P_i releases the res." to others.
- Receive (rel.): on receiving "T_m: P_i release the res.", P_j removes any corresponding request msgs. from P_i.
- When granted: (TBC).

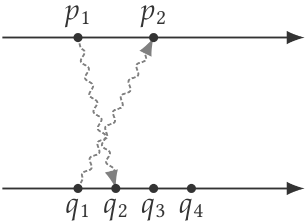
Logical Clocks: Case Study

- When granted
  - “T_m: P_i req. res.” in queue and **ordered first** (by “$\triangleright$” relation),
  - P_i received a msg. from every other procs. later than T_m (all others know about the request).

Logical Clocks: Case Study Generalization

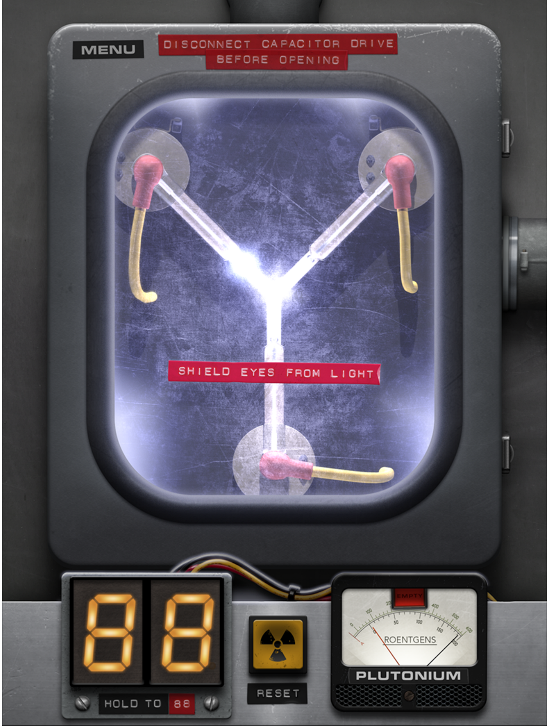
- Request or release the resource $\Longrightarrow$ operations on a global state.
- State machine:
  - states: $s \in S$,
  - commands: $c \in C$,
  - events that cause state transition: $e : C \times S \rightarrow S$, $e(c, s) = s'$.
- In the previous case: $C = \{P_i \text{ requests}\} \cup \{P_i \text{ releases}\}$
- Each process has a local running instance of the state machine.
- The order of executing commands is consistent.
- State machine replication without fault tolerance.

Logical Clocks: Anomalous Behavior

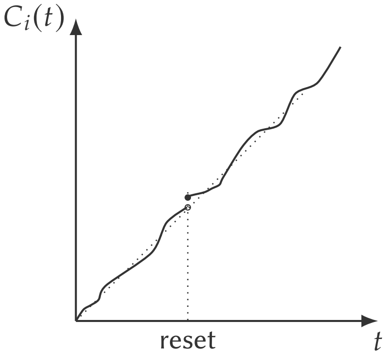


How to address the issue?

- Give the user the responsibility for avoiding anomalous behavior (to express the external causality with manual timestamp).
- Introduce stronger clock condition:
  - Let "$\boldsymbol{\rightarrow}$" denote the happened-before relation for the set of *all* systems events (including "external" events).
  - $\forall a, b : a \boldsymbol{\rightarrow} b \implies C\langle a \rangle < C\langle b \rangle$.


MENU
DISCONNECT CAPACITOR DRIVE
BEFORE OPENING
SHIELD EYES FROM LIGHT
88
HOLD TO 88
RESET
EMPTY
ROENTGENS
PLUTONIUM

Physical Clocks



- $C_i(t)$ is differentiable function of t except for isolated jump discontinuities where the clock is reset.
- True physical clock: $\mathrm{d}C_i(t)/\mathrm{d}t \approx 1$.

Physical Clocks

- PC1: $\exists$ constant $\kappa \ll 1 : \forall i, |\mathrm{d}C_i(t)/\mathrm{d}t - 1| < \kappa$. (physical property of a specific clock C_i)
- PC2: $\forall i, j : |C_i(t) - C_j(t)| < \epsilon$. (guaranteed by a carefully chosen protocol)

Physical Clocks

- Let μ be a number: $\forall i, j, a \to b \implies$
  - $a \in$ process i,
  - $b \in$ process j,
  - a occurs at t,
  - b occurs later than $t + \mu$.
- μ is less than the shortest transmission time for interprocess messaging.
- To avoid anomalous behavior: $\forall i, j, t : C_i(t + \mu) - C_j(t) > 0$.

Physical Clocks

- To avoid anomalous behavior: $\forall i, j, t : C_i(t + \mu) - C_j(t) > 0$.
- Resetting clocks: clocks are always reset forward. (why?)
- If PC1 and PC2 are guaranteed
  - From PC1, we have for same process i: $C_i(t + \mu) - C_i(t) > (1 - \kappa)\mu$.
  - Combining with PC2, we have:

$$\epsilon \leq \mu(1 - \kappa) \Longrightarrow \mu \geq \frac{\epsilon}{1 - \kappa}$$

Physical Clocks

- Combining with PC2, we have:

$$\epsilon \leq \mu(1-\kappa) \Longrightarrow \mu \geq \frac{\epsilon}{1-\kappa}$$

- How to guarantee PC2?
- What ϵ can we get when ensuring PC2?

Physical Clocks

- Define total delay: $v_m = t' - t$.
- Minimum delay: $\mu_m \geq 0 : \mu_m \leq v_m$.
- Define unpredicatable delay: $\xi_m = v_m - \mu_m$.

Physical Clocks

- IR1': $\forall i$, P_i does not receive msg. at $t \implies C_i$ is differentiable at t and $\mathrm{d}C_i(t)/\mathrm{d}t > 0$ (> 0 is trivial because clocks never go backward).
- IR2':
  - P_i sends msg. at t that contains $T_m = C_i(t)$,
  - Upon receiving m at t', P_j sets $C_j(t')$ equal to

$$\max\left\{\lim_{\delta\to 0} C_j(t' - |\delta|), T_m + \mu_m\right\}$$

Physical Clocks

- Theorem (proof is in Appendix A of the paper):

$$\epsilon \approx d \cdot (2\kappa\tau + \xi) \quad \forall t \gtrsim t_0 + \tau d \quad \text{(assuming } \mu + \xi \ll \tau\text{)}$$

- d: the diameter of the communication graph among the processes.
- τ: at least 1 msg. sent between $(t, t + \tau)$.
- Recall: given

$$\mu \geq \frac{\epsilon}{1 - \kappa}$$

then the anomalous behavior cannot happen.

Distributed Snapshots

- *Distributed Snapshots: Determining Global States of Distributed Systems*

K. Mani Chandy (1944–)

- Dining philosophers problem.
- Chandy-Lamport algorithm.
- Three books and over a hundred papers on distributed computing, verification of concurrent programs, parallel programming languages and performance models of computing & communication systems.

K. Mani Chandy (1944–)

- B.Tech. from Indian Institute of Technology.
- M.S. from Polytechnic Institute of Brooklyn.
- Ph.D. in Electrical Engineering from MIT.
- Simon Ramo Professor of Computer Science at Caltech.
- Memeber of National Academy of Engineering.
- A. A. Michelson Award (1985).
- IEEE Koji Kobayashi Award (1987).

K. Mani Chandy (1944–)

- Worked for Honeywell and IBM.
- Was in CS department of UT Austin, serving as chair in 1978–79 and 1983–85.
- Story of the Chandy-Lamport algorithm according to Lamport's website.

Taking snapshots: What?

- Assumption: a process can
  - record its own state and the msgs. it sends and receives,
  - nothing else!
- A process p must enlist the cooperation of other procs. that must record their local states and send the recorded states to p.
- What makes a “snapshot”: a global state is a set of
  - process states
  - channel states: the buffered messages

Taking snapshots: How?

- How to make snapshot: anology to taking a panorama photo.

Taking snapshots: How?

- How to make snapshot: anology to taking a panorama photo.
- Different moments in different pieces, but together make a reasonable photo.
- Define "making sense" for distributed snapshots?

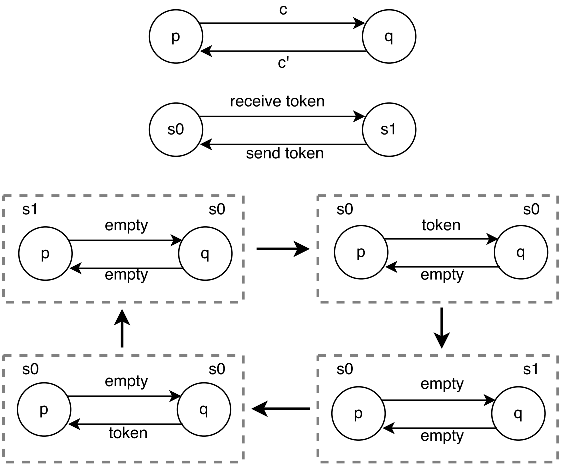
Taking snapshots: Why?

- Detect stable property of a predicate y in the system D.
- Stable: $y(S) \longrightarrow y(S')$, $\forall S'$ of D reachable from S.
- y is true $\Longrightarrow$ y is *always* true.

Model

- Processes.
- Channels with
  - infinite buffer,
  - no error,
  - FIFO.
- Delay is arbitrary but finte.
- Events are
  - Atomic
  - $e = \langle p, s, s', M, c \rangle$
- Global state S consist of
  - Process states: $s_1, s_2, \ldots$
  - Channel states: a sequence of msgs. $M_1, M_2, \ldots$

Model: Example



Algorithm

- Motivation: see 3.1 of the paper.
- Some processes spontaneously start to *record their states.*
- For each process p: sends one *marker* along c (the channel directed away from p) *after* recoding its state and *before* it sends further msgs.
- For each process q receiving a marker from channel c
  - if q has not recorded its state
    - q records its state,
    - q records the state of c as empty;
  - otherwise, q records the state of c as the sequence of msgs. received along c
    - after q's state was recoreded,
    - before q received the marker along c.

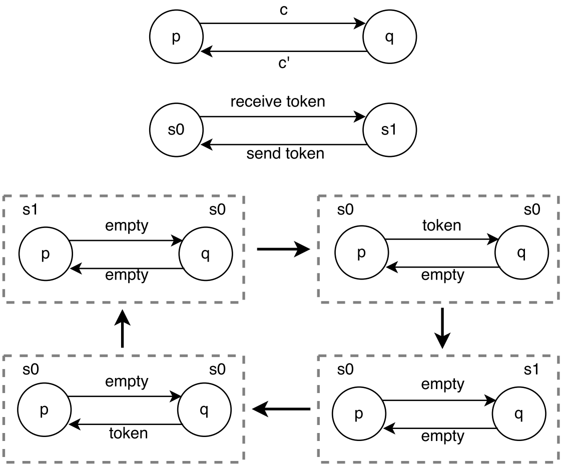
Algorithm: Discuss

- Termination?
- Has the recorded global state ever happened in the system?

Algorithm: Discuss

- Has the recorded global state ever happened in the system? (Not always)
- Locally “consistent” $\neq$ globally “consistent”.

Algorithm: Discuss



Algorithm: Discuss

- Define “happened”?

Algorithm: Properties and Proof

- Let seq $= (e_i, 0 \leq i)$ be a distributed *computation*.
- $S_{i-1} \xrightarrow{e_{i-1}} S_i$.
- Initiated in S_ι, terminated in S_ϕ.
- Show that for the captured snapshot S^*
  - S^* is reachable from S_ι,
  - S_ϕ is reachable from S^*.

Algorithm: Proof

- Show that for the captured snapshot S^*
  - S^* is reachable from S_ι,
  - S_ϕ is reachable from S^*.
- $\exists\,\mathrm{seq}'$
  - seq' is a permutation of seq,
  - $S_\iota = S^*$ or S_ι occurs earlier than S^*,
  - $S_\phi = S^*$ or S^* occurs ealier than S_ϕ.

Algorithm: Proof

- Define e_i is
  - "prerecording" (pre.) iff. e_i is in proc. p and p records its state after e_i (somewhere) in seq.
  - "postrecording" (post.) o.w.
- If not ALL pre. preceds post. $\exists j$
  - $\ldots, \overbrace{e_{j-1}}^{\text{post.}}, \overbrace{e_j}^{\text{pre.}}, \ldots$
  - then $\ldots, e_j, e_{j-1}, \ldots$ is also a computation.

Algorithm: Proof

- If not ALL pre. precedes post. $\exists j$
  - $\ldots, \overbrace{e_{j-1}}^{\text{post.}}, \overbrace{e_j}^{\text{pre.}}, \ldots$
  - then $\ldots, e_j, e_{j-1}, \ldots$ is also a computation.
- e_{j-1} and e_j must be on different procs. (because e_{j-1} is post., $j-1 < j$).
- Assume e_{j-1} occurs at p, e_j occurs at q, and $p \neq q$.
- There CANNOT be a msg. sent at e_{j-1} and received at e_j
  - a msg. sent along c when e_{j-1} occurs $\Longrightarrow$ a marker must have been sent long c before e_{j-1} (by definition of post. events).
  - a msg. received along c when e_j occurs $\Longrightarrow$ a marker must have been received long c before e_j (FIFO) $\Longrightarrow$ e_j is post. too (on receiving a marker, a process records its state). Contradiction!

Algorithm: Proof

- Assume e_{j-1} occurs at p, e_j occurs at q, and $p \neq q$.
- There CANNOT be a msg. sent at e_{j-1} and received at e_j. (proved, channel state is unchanged)
- State of q is not altered by the occurence of e_{j-1}: because of different procs.
  - If e_j at q receives M along c, then M must have been the msg. at the head of c before $e_{j-1} \implies e_j$ can occur in S_{j-1}.
- State of p is not altered by the occurence of e_j
  - e_j happens after p and at a different process $\implies e_{j-1}$ can occur after e_j.

Algorithm: Proof

- Therefore
  - $\ldots, e_{j-2}, \boldsymbol{e}_j, \boldsymbol{e}_{j-1}, \ldots$ is a valid computation,
  - the global state after $e_1, \ldots, e_{j-2}, \boldsymbol{e}_j, \boldsymbol{e}_{j-1}$ is the same as $e_1, \ldots, e_{j-2}, \boldsymbol{e}_{j-1}, \boldsymbol{e}_j$.
- With the invariants held, such swapping can be done repetitively, until
  - all pre. events precede post. events,
  - seq is a computation,
  - $\forall i, i < \iota$ or $i \geq \phi : e'_i = e_i$, and
  - $\forall i, i \leq \iota$ or $i \geq \phi : S'_i = S_i$.

Algorithm: Proof

- With the invariants held, such swapping can be done repetitively, until
  - all pre. events precede post. events,
  - seq is a computation,
  - $\forall i, i < \iota$ or $i \geq \phi : e'_i = e_i$, and
  - $\forall i, i \leq \iota$ or $i \geq \phi : S'_i = S_i$.
- Finally, we need to show the state $\bar{S}$ in the middle (after all pre. before all post.) is S^* (recorded snapshot).
- Equivalently
  - the state of $\forall p$ is the same,
  - the state of $\forall c$ is the same.

Algorithm: Proof

- Equivalently
  - the state of $\forall p$ is the same,
    - by noticing the state of a process can only be changed by events,
    - all posts. events are after the state $\bar{S}$;
  - the state of $\forall c$ is the same:

$$(\text{msgs. of pre. send of } c) - (\text{msgs. of pre. receive of } c)$$
$$= \text{msgs. taken in the snapshot of } c$$

    - msgs. of pre. send of c =
      (i) msgs. sent by p before sending a marker,
    - msgs. of pre. receive of c =
      (ii) msgs. received by q before recording,
    - (i) – (ii) = msgs. in the snapshot.

Distributed Snapshot: Stability Detection

- Input: a stable property y
- Output: A booleam value definite with the property
  - $y(S_\iota) \longrightarrow \text{definite}$
  - $\text{definite} \longrightarrow y(S_\phi)$
- Implementation
  - record a global state S^*,
  - $\text{definite} \coloneqq y(S^*)$.
- Correctness
  - $S*$ is reachable from S_ι,
  - S_ϕ is reachable from S^*, and
  - $y(S) \longrightarrow y(S') \quad \forall S'$ reachable from S (definition of a stable property).

Thank you!

Q & A