Time, clocks and the ordering of events

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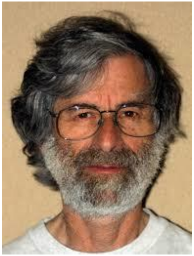
What is a Distributed System?

Distributed System

A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable.

- Leslie Lamport



What is a Distributed System?

- A set of nodes, connected by a network, which appear to its users as a single coherent system.

Distributed Algorithms

Two Generals' Problem (1/3)

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  - Messengers may be killed on their way.

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- This problem is impossible to solve!

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- Agreement is a core problem.

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- Accomplish tasks like:
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- Must work in difficult settings:
  - Concurrency: uncertainty of timing, order of events and inputs.
  - Fault-tolerance: failure and recovery of machines/processors, of communication channels.

Correctness of Distributed Algorithms

Correctness

- Always expressed in terms of
  - Safety and Liveness
  - B. Alpern and F.B. Schneider, Defining Liveness, Technical Report, 1985

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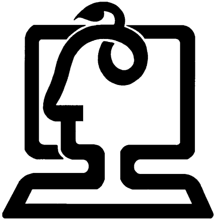
- Liveness
  - Properties that state that something good eventually happens.

Correctness Example (1/3)

- Correctness of you in this course :)



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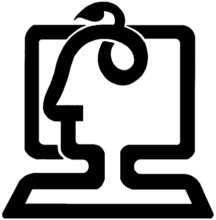

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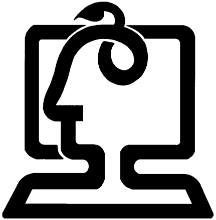

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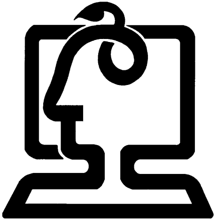

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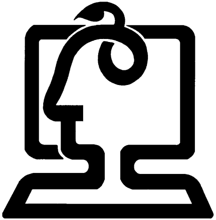

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- Safety
  - Often involves the word never, at most, cannot, ...
- Liveness
  - Often involves the word eventually: some point in future
  - Liveness is often just termination

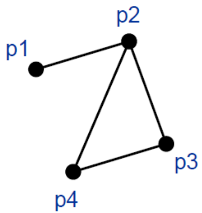
Modeling
Distributed Systems

What is a Model?

- Abstraction of relevant system properties.
- Real world is complex, model simplifies it.
- Help solving problems.
- Help analyze problems/solutions.

Modeling Distributed Systems

- What is a distributed system?
  - Bunch of nodes/processes
  - Sending messages over a network
  - To solve a common goal (algorithm)



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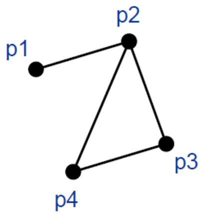
- How do we model this?



Modeling a Node

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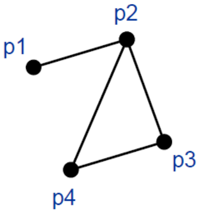

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- A single node has a bunch of neighbors.
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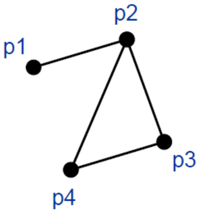

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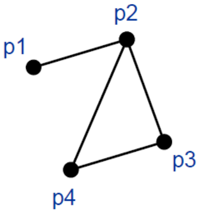

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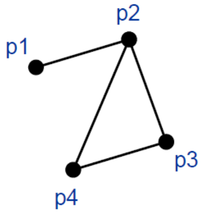

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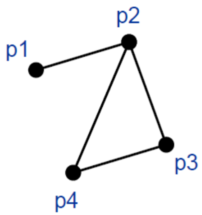


- Like a state machine: a node is in only one state at a time.
- The state of a node: input buffer, output buffer, and other data relevant to algorithm

Single Node Perspective

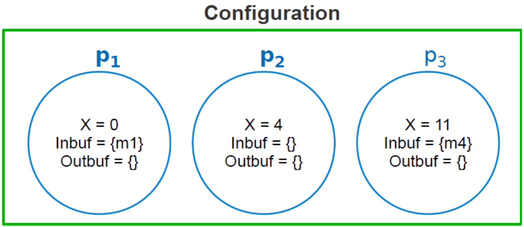
- This is how computers in a distributed system work:

1. Wait for message.
2. When received message, do some local computation, send some messages.
3. Goto 1

Single Node to a Distributed System (1/3)

- A configuration is a snapshot of state of all nodes.
  - $C = (s_0, s_1, \cdots, s_{n-1})$ where s_i is state of process p_i.

- An initial configuration is a configuration where each s_i is an initial state.



Single Node to a Distributed System (2/3)

- The system evolves through events:
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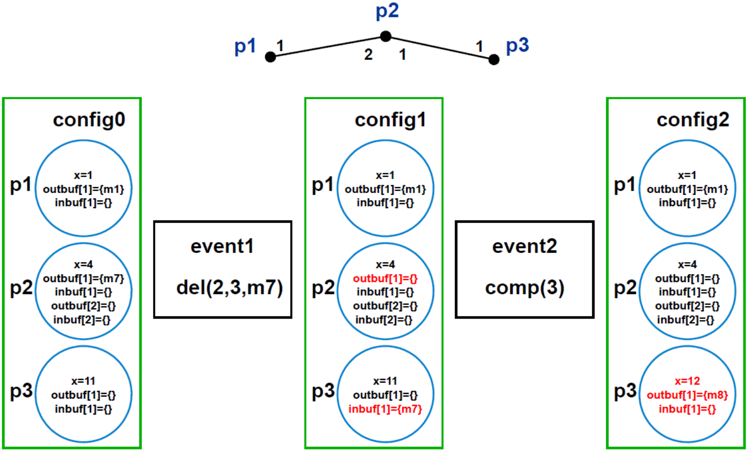
- An execution is an infinite sequence of
  - $config_0$, $event_1$, $config_1$, $event_2$, $config_2$, ...
  - $config_0$ is an initial configuration.
  - $event$ could be $comp$ or del.

Single Node to a Distributed System (3/3)

- Example execution



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- Informally, in each round:
  - Every process can send a message to each neighbor.
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- Formally, rounds consist of:
  - Deliver event for every message in all outbufs.
  - One computation event on every process.

Synchronous Systems (2/2)

- Time variance is bounded.
- Execution: bounded execution speed and time.
- Communication: bounded transmission delay.
- Clocks: bounded clock drift (and differences in clocks).

Asynchronous Systems

- Time variance is not bounded.
- Execution: different steps can have varying duration.
- Communication: transmission delays vary widely.
- Clocks: arbitrary clock drift.

Time, Clock, and Order of Events

Time

- Global time
  - Astronomical time (based on earth's rotation)
  - International Atomic Time (IAT)
  - Coordinated Universal Time (UTC)

- Local time
  - Not synchronized to a global source

Computer Clocks

- Computer clocks
  - Crystal oscillates at known frequency
  - Oscillations cause timer interrupts
  - Timer interrupts update clock

- Clock skew
  - Crystals in different computers run at slightly different rates
  - Clocks get out of sync
  - Skew: instantaneous difference
  - Drift: rate of change of skew

Synchronizing Computer Clocks

- Internal synchronization
  - Clocks synchronize locally
  - Only synchronized with each other
  - Berkeley algorithm

- Time server
  - Server that has the correct time
  - Server that calculates the correct time
  - Network Time Protocol (NTP)

Logical Clock

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- Processes need to agree on ordering of causally related events (e.g., message send and receive).

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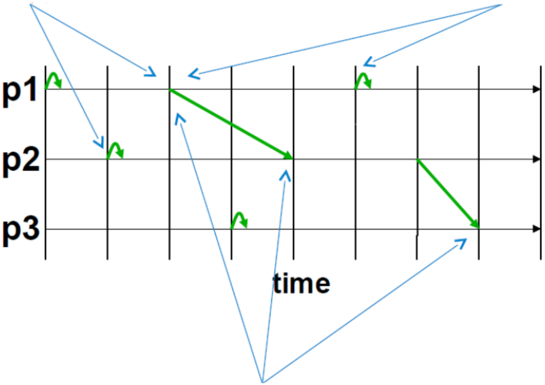
- Transitivity: if $a \rightarrow b$ and $b \rightarrow c$, then $a \rightarrow c$.
- concurrent events ($a||b$): if $a \not\rightarrow b$ and $b \not\rightarrow a$.

Causal Order Example



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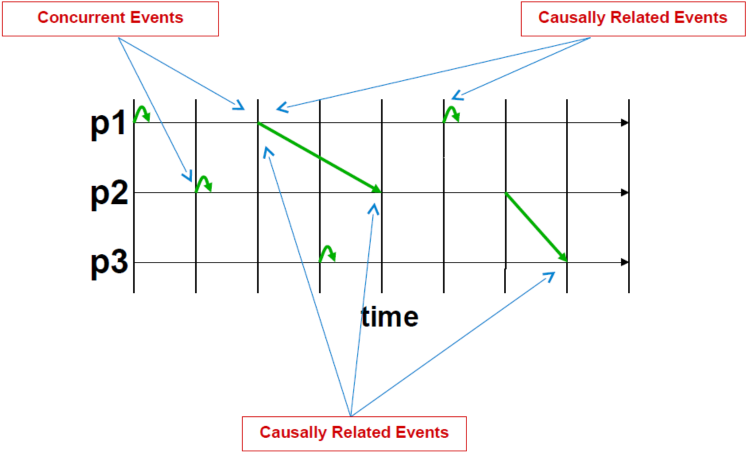

Equivalence of Executions

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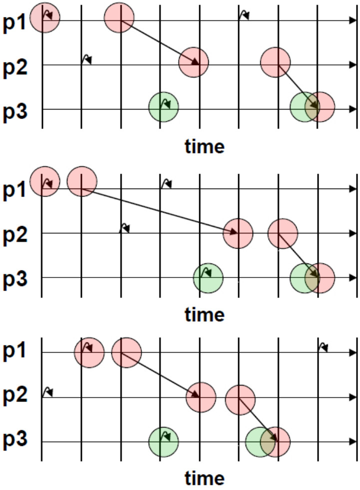
- F and E could have different permutation of events as long as causality is preserved.

Example of Similar Executions

- Same color $\sim$ Causally related



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- ... how to locally tell if two events are causally related?

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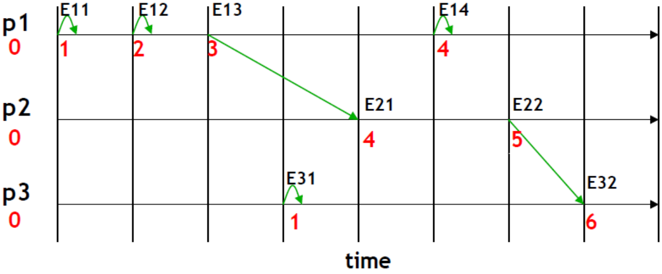
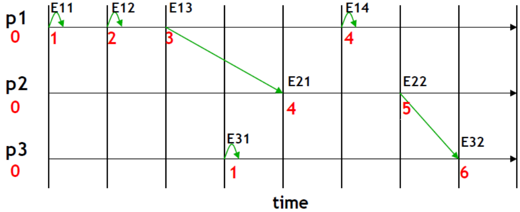
- Whenever a message m is sent from p_i to p_j:
  - p_i executes $t_i := t_i + 1$ and sends t_i with m.
  - p_j receives t_i with m and executes $t_j := max(t_j, t_i) + 1$.

Example of Lamport Logical Clock



Lamport Clocks Properties

- $a \rightarrow b$ implies $t(a) < t(b)$, where $t(a)$ is Lamport clock of event a.



- $t(a) < t(b)$ does not necessarily imply $a \rightarrow b$
- $t(E31) < t(E13)$, but $E31 \not\rightarrow E13$

Shortcoming of Lamport Clocks

- Main shortcoming of Lamport's clocks:
  - $t(a) < t(b)$ does not necessarily imply $a \rightarrow b$
  - We cannot deduce causal dependencies from time stamps.

- Why?
  - Clocks advance independently or via messages.
  - There is no history as to where advances come from.

Vector Clocks

- At each process, maintain a clock for every other process.
  - Each clock V_i is a vector of size N.
  - $V_i[j]$ contains process p_is knowledge about process p_j's clock.
  - Initially, $V_i[j] := 0$ for $i, j \in \{1, \cdots, N\}$.

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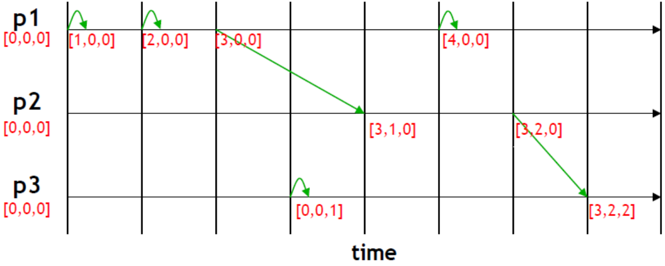
- Whenever a message m is sent from p_i to p_j:
  - p_i executes $V_i[i] := V_i[i] + 1$ and sends V_i with m.
  - p_j receives V_i with m and merges the vector clocks V_i and V_j:

$$V_j[k] = \begin{cases} max(V_j[k], V_i[k]) + 1 & \text{if } j = k \\ max(V_j[k], V_i[k]) & \text{otherwise} \end{cases}$$

Example of Vector Clock

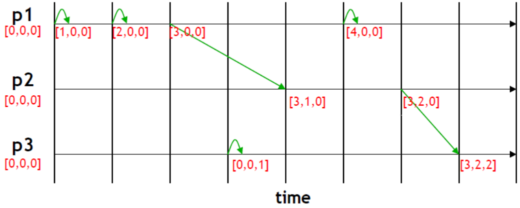


Comparing Vector Clocks

- $V = V'$ iff $V[i] = V'[i]$ for $i \in \{1, \cdots, N\}$
- $V \leq V'$ iff $V[i] \leq V'[i]$ for $i \in \{1, \cdots, N\}$
- $V||V'$ iff $V \leq V' \wedge V' \leq V$

Vector Clocks Properties

- $a \to b$ implies $V(a) < V(b)$
- $V(a) < V(b)$ implies $a \to b$



Logical Clock vs. Vector Clock

- Logical clock
  - If $a \rightarrow b$ then $t(a) < t(b)$
- Vector clock
  - If $a \rightarrow b$ then $V(a) < V(b)$
  - If $V(a) < V(b)$ then $a \rightarrow b$
  - Sending extra information: vector with size N, for N processes.

Global State

Global State

- Determining global properties
- Distributed checkpoint
  - What is a correct state of the system to save?
- Distributed garbage collection
  - Do any references exist to a given object?
- ...

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- May be finite or infinite.

- Each event e_i^j is either a local event or a communication event.

Local and Global State

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- The local state s_i^k records all events included in the history h_i^k.
- The global state, S, of a distributed computation is an N-tuple of local states $(s_1, s_2, \cdots, s_N)$, one for each process.

Cuts

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- A cut, C, of a distributed computation is the union of N partial histories, one for each process: $C = \bigcup_{i=1}^{N} h_i^{c_i}$

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- Each cut C has a corresponding global state: $S = (s_1, s_2, \cdots, s_N)$.

Consistent Cuts (1/2)

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  $(e' \in C) \wedge (e \rightarrow e') \Rightarrow e \in C$

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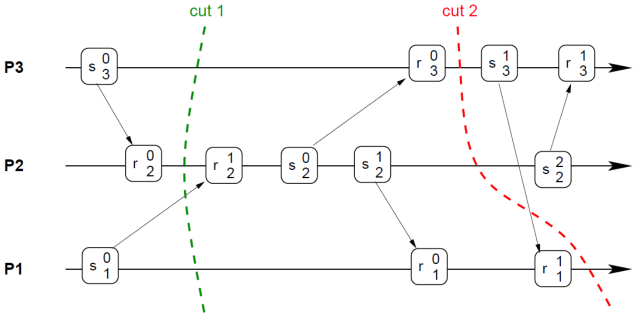

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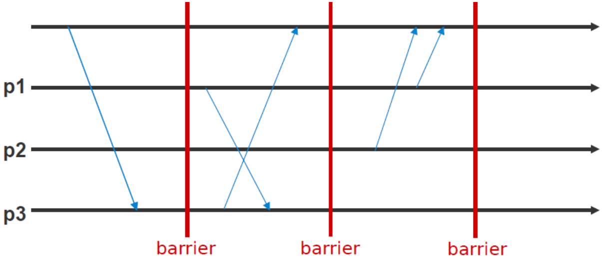
- A global state is consistent if it corresponds to a consistent cut.

Possible Solutions

- Coordinated blocking
- Coordinated non-blocking

Coordinated Blocking

- At barrier, all processes take their checkpoints.
- Bulk-Synchronous Parallel (BSP)



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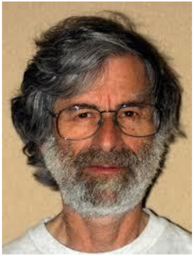
- Chandy and Lamport's snapshot

Chandy and Lamport's Snapshot

- Determines a consistent global state.
- Takes care of messages that are in transit.

Model of a Distributed System

- Process: one process initiates taking of global snapshot
- Channels: directed, FIFO, reliable
- Process graph: fixed topology, strongly connected component

Chandy and Lamport's Snapshot Algorithm (1/3)

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- The algorithm terminates after each process has received a marker on all of its incoming channels.
- All the local snapshots get disseminated to all other processes and all the processes can determine the global state.

Chandy and Lamport's Snapshot Algorithm (2/3)

- Marker Sending Rule for process p_i:
  - Process p_i records its state.
  - For each outgoing channel c on which a marker has not been sent, p_i sends a marker along c before p_i sends further messages along c.

Chandy and Lamport's Snapshot Algorithm (3/3)

- Marker Receiving Rule for process p_j on receiving a marker along channel c:
  - If p_j has not recorded its state, it records the state of channel c as the empty set, and follows the Marker Sending Rule.
  - Otherwise, it records the state of c as the set of messages received along c after p_j's state was recorded and before p_j received the marker along c.

Correctness of the Algorithm (1/2)

- Condition 1: any message that is sent by a process before recording its snapshot, must be recorded in the cut.

- When a process p_j receives message m_{ij} from p_i that precedes the marker on channel c_{ij}, it acts as follows: if process p_j has not taken its snapshot yet, then it includes m_{ij} in its recorded snapshot. Otherwise, it records m_{ij} in the state of the channel c_{ij}. Thus, condition Condition 1 is satisfied.

Correctness of the Algorithm (2/2)

- Condition 2: any message that is sent by a process after recording its snapshot, must not be recorded in the cut.

- Due to FIFO property of channels, it follows that no message sent after the marker on that channel is recorded in the channel state. Thus, condition Condition 2 is satisfied.

Summary

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- Correctness of distributed algorithms: safety + liveness
- Casual order
- Logical clock and Vector clock
- Global state: Chandy and Lamport's algorithm

References:

- L. Lamport, Time, clocks, and the ordering of events in a distributed system. ACM Communications, 1978
- K.M. Chandy and L. Lamport, Distributed snapshots: determining global states of distributed systems. ACM Transactions on Computer Systems, 1985.
- B. Alpern and F.B. Schneider, Defining Liveness. Technical Report, 1984.

Questions?

Acknowledgements

Some slides were derived from Seif Haridi slides (KTH University).