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Distributed Systems

Chapter 2 Time and Global States

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2: Time and Global States

How can distributed processes be coordinated and synchronized, e.g.

- when accessing shared resources,
- when determining the order of triggered events?

The importance of time

- Distributed systems do not have only one clock.
- Clocks on different machines are likely to differ.
- Physical versus logical time.

2.1: Physical Time

Example; distributed software development using UNIX `make`

- Computer sets its clock back after compiling a source file
- User edits the source file
- `make` assumes the source file has not been changed since compilation
- `make` will not recompile

TAI and UTC

- International Atomic Time TAI: mean number of ticks of caesium 133 clocks since midnight Jan. 1, 1958 divided by number of ticks per second 9,192,631,770.
- Problem: 86,400 TAI seconds (corresponding to a day) are today 3 msec less than a mean solar day (because solar days are getting longer because of tidal forces).
- Solution: whenever discrepancy between TAI and solar time grows to 800 msec a leap second is added to solar time.
- The corresponding time is called Universal Coordinated Time UTC.
- UTC is broadcast every second as a short pulse by the National Institute of Standard Time NIST. It is broadcast by GPS as well.

Time in distributed systems

- Each computer p is equipped with a local clock C_p , which causes H interrupts per second. Given UTC time t , the clock value of p is given by $C_p(t)$.
- Let $C'_p(t) = \frac{dC_p}{dt}$
- Ideally, $C'_p(t) = 1$, real clocks have an error of about $\pm 10^{-5}$ (10 ppm)
- If there exists some constant ρ such that

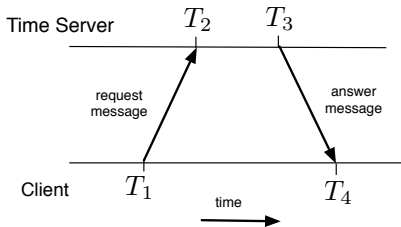
$$1 - \rho \leq \frac{dC}{dt} \leq 1 + \rho,$$

ρ is called the maximum drift rate.

- If synchronized Δt ago, two clocks may differ at most by $2\rho\Delta t$.
- To ensure synchronization within precision δ , then they need to be synchronized at least every $\frac{\delta}{2\rho}$ seconds.

Network Time Protocol NTP

- Assumption, one system C is connected to a UTC server. This system is called time-server.
- Each machine C , every $\frac{\delta}{2\rho}$ seconds, sends a time request to the time-server, which immediately responds with the current UTC.
- machine C sets its time to be T_3 ,
 - where T is the received time
 - RTT is the round trip time

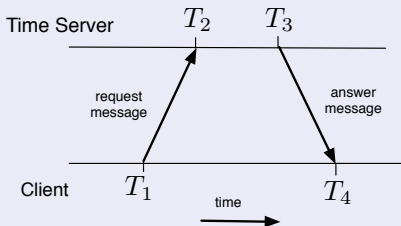


Problems and solutions

- Problem: time may run backwards!
- Solution: clocks converge to the correct time.
- Problem: Because of message delays, reported time will be outdated when received by a client.
- Solution: Try to find a good estimation for the delay.
- ... (next slide)

Problems and solutions

- Problem: Because of message delays, reported time will be outdated when received by a client.
- Solution: Try to find a good estimation for the delay.
 - **Algorithm of Flaviu Cristian**
 - Use $\frac{(T_4 - T_1)}{2}$ if no other information is available.
 - If interrupt handling time I is known, use $\frac{(T_4 - T_1 - I)}{2}$.
 - ... else ...



Problems and solutions

- Problem: Because of message delays, reported time will be outdated when received by a client.

- Solution: Try to find a good estimation for the delay

NTP: Network Time Protocol

- ... else ...
- To adjust A to B , use piggybacking:
- A sends a request to B timestamped with T_1 .
- B records the time of receipt T_2 (taken from its local clock) and returns a response timestamped with T_3 and piggybacking T_2 .
- A records the time of arrival T_4 . The propagation time from A to B is assumed to be the same as from B to A , $T_2 - T_1 \approx T_4 - T_3$.
- The offset θ of A relative to B can be estimated by A :

$$\theta = T_3 + \frac{(T_2 - T_1) + (T_4 - T_3)}{2} - T_4 = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

- If $\theta < 0$, in principle, A has to set its clock backwards.
- Take the measures several times and compute the mean while ignoring outliers.

Examples: A has to be adjusted to B .

A sends a request to B timestamped with T_1 . B records the time of receipt T_2 (taken from its local clock) and returns a response timestamped with T_3 and piggybacking T_2 . A records the time of arrival T_4 .

The offset θ of A relative to B can be estimated by A :

$$\theta = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

(a) No need for adaption detected.

$$T_1 = 10, T_2 = 12, T_3 = 14, T_4 = 16 \implies \theta = 0.$$

(b) A has to slow down.

$$T_1 = 10, T_2 = 12, T_3 = 14, T_4 = 18 \implies \theta = -1.$$

(c) A has to hurry up.

$$T_1 = 10, T_2 = 12, T_3 = 14, T_4 = 14 \implies \theta = 1.$$

On scalability of NTP (roughly)

- NTP is an Internet standard (RFC 5905).
- NTP service is provided by a network of servers.
- Primary servers are directly connected to a UTC-source.
- Secondary servers synchronize themselves with primary servers.
- This approach is applied recursively leading to several layers.
- Server A adjusts itself to server B if B is assigned a lower layer than A .
- The whole network is reconfigurable and thus is able to react on errors.

2.2: Logical Time

Why?

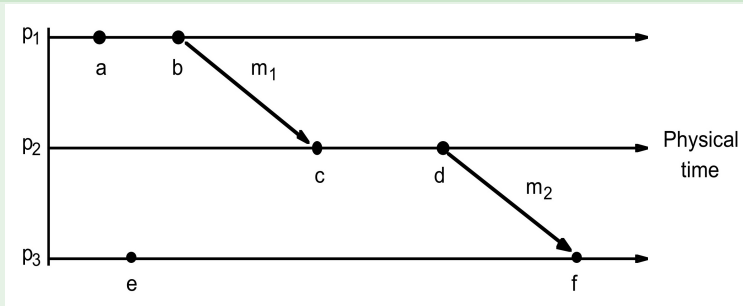
- Getting physical clocks absolutely synchronized is not possible.
- Thus it is not always possible to determine the order of two events.
- For such cases logical time can be used as a solution.
 - If two events happen in the same process they are ordered as observed.
 - If two processes interchange messages, then the sending event is always considered to be before the receiving event.

Lamport's happened-before relation (causal ordering)

- If two events a, b happen in the same process p_i they are ordered as observed and we write $a \rightarrow_i b$.
Moreover, this implies $a \rightarrow b$ systemwide.
- If two processes interchange messages, then the sending event a is always considered to be before the receiving event b , thus $a \rightarrow b$.
- Whenever $a \rightarrow b$ and $b \rightarrow c$, then also $a \rightarrow c$.

Events not being ordered by \rightarrow are called concurrent.

Example



from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

We conclude $a \rightarrow b, b \rightarrow c, c \rightarrow d, d \rightarrow f, a \rightarrow f$, however not $a \rightarrow e$; a, e are concurrent.

Algorithm of Leslie Lamport

- Let $L_i(e)$ denote the time stamp of event e at process P_i .
- When a new event a occurs in process P_i :

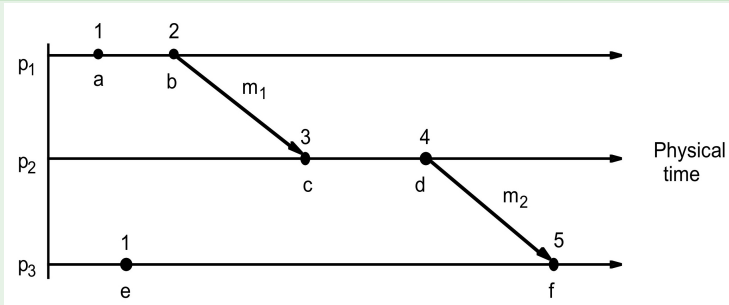
$$L_i := L_i + 1$$

- Each message m sent from P_i to P_j is piggybacked by the timestamp $L_i(a)$ of the send-event a .
- When (m, t_a) is received by P_j , P_j adjusts its logical clock L_j to the logical clock of P_j .

$$L_j := \max\{L_j, t_a\}$$

and increments L_j for the received message event.

Three clocks with application of Lamport's algorithm.



from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

Totally ordered logical clocks

- Extend the Lamport clock for each process P_i :
- Clock values must be systemwide unique
 - for this the clock value L_i is referred to with the process id i , i.e. (L_i, i)
 - all distinct clocks L_i can be unified into a system clock L .
- Define the total ordering

$$(T_i, i) < (T_j, j) \quad :\Leftrightarrow \quad \begin{cases} i < j & \text{if } T_i = T_j \\ T_i < T_j & \text{else} \end{cases}$$

- So, we translate a partial ordering into a total ordering
- However from the total ordering $L(a) < L(b)$ one cannot conclude $a \rightarrow b$.

Mattern's Vector Clocks

- Vector clock for a system of n processes: array of n integers.
- Each process P_i keeps its own vector clock V_i which is used to timestamp local events.
- Processes piggyback their own vector clock on messages they send.
- Update rules for vector clocks:

VC1: Initially, $V_i[j] := 0$ for $i, j \in \{1, \dots, n\}$

VC2: P_i timestamps prior to each event: $V_i[i] := V_i[i] + 1$.

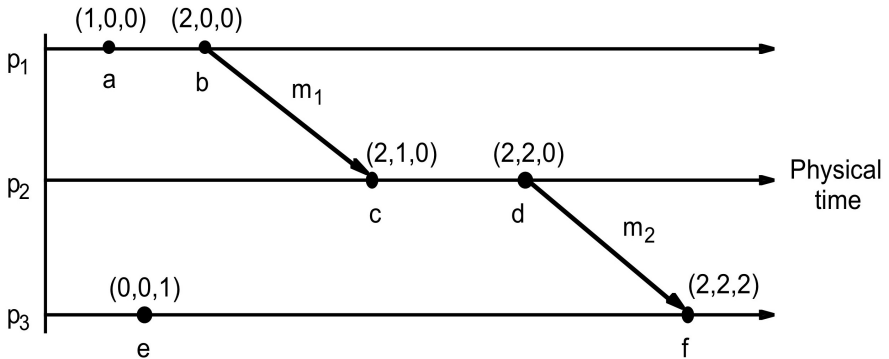
VC3: P_i sends the value $t = V_i$ with each message.

VC4: When P_i receives some message piggybacked with timestamp t , it sets

$$V_i[j] := \max\{V_i[j], t[j]\} \quad \text{for } i = 1, 2, \dots, n$$

- $V_i[j]$ is the number of events that P_i has timestamped.
- $V_i[j]$ for $i \neq j$ is the number of events that have occurred at P_j to the knowledge of P_i .

Vector Clock Example



from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

Comparing vector timestamps

- The clock vectors define a partial ordering
 - $V = V'$ iff $V[j] = V'[j]$ for all $j \in \{1, \dots, n\}$
 - $V \leq V'$ iff $V[j] \leq V'[j]$ for all $j \in \{1, \dots, n\}$
 - $V < V'$ iff $V \leq V' \wedge V \neq V'$.
- If for events a, b neither $V(a) \leq V(b)$ nor $V(a) \geq V(b)$ the events are called concurrent, i.e. $a || b$

Comparing vector timestamps

$V(a)$	$V(b)$	Relation	
$(2, 1, 0)$	$(2, 1, 0)$	$V(a) = V(b)$	all entries are the same
$(1, 2, 3)$	$(2, 3, 4)$	$V(a) < V(b)$	all entries of V are prior to V'
$(1, 2, 3)$	$(3, 2, 1)$	$a b$	two events are concurrent

Lamport Relationship and Vector Clocks

Theorem

For any two events e_j, e_i :

$$e_j \rightarrow e_i \iff V(e_j) < V(e_i) .$$

Proof sketch

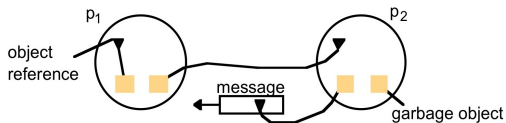
- $e_j \rightarrow e_i \implies V_j < V_i$.
 - If the events occur on the same process then $V_j < V_i$ follow directly.
 - $e_j \rightarrow e_i$ implies a message is sent after e_j to the process with event e_i or two succeeding events of a process
 - Since each entry of the receiving process is updated to the at least the maximum of the entries of the sending processes, $V_j < V_i$
- $e_j \rightarrow e_i \longleftarrow V_j < V_i$.
 - If both events occur on the same process, $e_j \rightarrow e_i$ follows straightforward.
 - An increase of the i -th row can only be caused by a message path sent from the process of e_j to e_i
- complete proof is left as exercise

2.3. Global System States

Distributed Garbage Collection

- Non-referenced objects need to be erased
- p_2 has an object referenced in a message to p_1
- p_1 has an object referenced by p_2
- Neither one can be erased

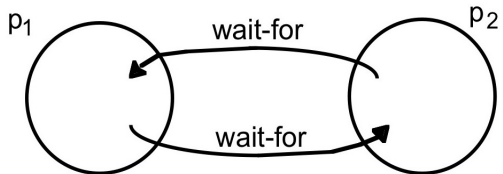
- How to determine a global state in the absence of global time



2.3. Global System States

Distributed Deadlock Detection

- occurs when processes wait for each other to send a message
- and the processes form a cycle

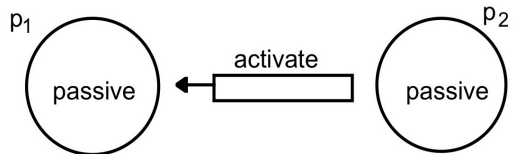


from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

2.3. Global System States

Distributed Termination Detection

- How to detect that a distributed algorithm has terminated
- Assume p_1 and p_2 request values from the other
- If they wait for a value they are passive, otherwise active
- Assume both processes are passive. Can we conclude the system has terminated?
- No, since there might be an activating message on its way



2.3. Global System States

Distributed Debugging

- Distributed systems are difficult to debug
- e.g. consider a program where each process has a changing variable x_i
- All variables are required to be in range $|x_i - x_j| \leq 1$.
- How to be sure that this will never be violated?

Cuts

- Consider system \mathcal{P} of n processes p_i for $i = 1, \dots, n$.
- The execution of a process is characterized by its history (of events e_i^t)

$$\text{history}(p_i) = h_i = \langle e_i^0, e_i^1, e_i^2, \dots \rangle$$

- We denote a finite prefix

$$h_i^k = \langle e_i^0, e_i^1, \dots, e_i^k \rangle$$

- An event is either

- an internal action or
- sending a message or
- receiving a message

- Let s_i^k denote the state of process p_i immediately before event e_i^k .

- The global history H is

$$H = h_1 \cup h_2 \cup \dots \cup h_n$$

- A *cut* C of the system's execution is a set of prefaces

$$C = h_1^{c_1} \cup h_2^{c_2} \cup \dots \cup h_n^{c_n}$$

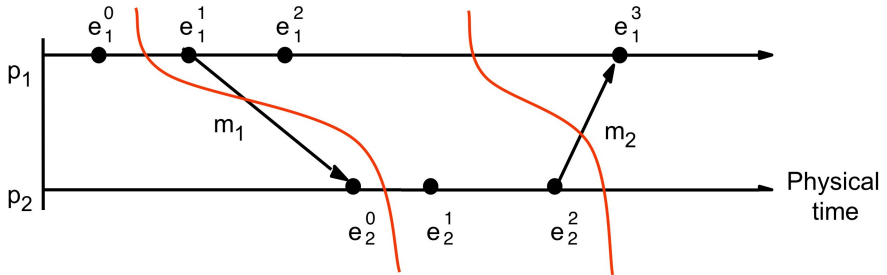


Consistent Cuts

- A cut C is consistent if,

$$\text{For all events } e \in C : f \rightarrow e \implies f \in C .$$

- i.e. for each event it also contains all the events that happened-before the event.



Inconsistent cut

Consistent cut

Global States

- A *consistent global state* corresponds to a consistent cut.
- A run is a total ordering of all events in a global history that is consistent with each local history's ordering (\rightarrow_i , for $i = 1, \dots, n$).
- A consistent run (linearization) is an ordering of the events in the global history that is consistent with the happened-before-relation (\rightarrow) on H .
- Consistent runs pass only through consistent global states.

Global State Predicates, Stability, Safety and Liveness

- A *global state predicate* is a function that maps from the set of global states to `{true, false}`.
- *Stability* of a global state predicate: A global state predicate is *stable* if once it has reached `true` it remains in this state for all states reachable from this state.
- *Safety* is the assertion that an undesired state predicate evaluates to `false` to all states S reachable from the starting state S_0 .
- *Liveness* is the assertion that a desired state predicate evaluates to `true` to all states S reachable from the starting state S_0 .

How to detect and record a global state

'Snapshot' algorithm of Chandy and Lamport

- Goal
 - record a set of events corresponding to a global state (consistent cut)
 - in a living system during run-time
 - without extra process
- Requirements
 - channels, processes do not fail. Communication is reliable
 - channels are uni-directional and have FIFO message delivery
 - graph of processes and channels is strongly connected
 - any process may initiate a snapshot
 - processes continue their execution (including messages)
- Notations
 - p_i 's incoming channel: where all messages for p_i arrive
 - p_i 's outgoing channel: where p_i sends all messages to other processes
 - Marker message: a special message distinct from every other message

Distributed Snapshot of Chandy and Lamport

Marker receiving rule for process p_i

On p_i 's receipt of a *marker* message over channel c :

if (p_i has not yet recorded its state) it

records its process state now;

records the state of c as the empty set;

turns on recording of messages arriving over other incoming channels;

else

p_i records the state of c as the set of messages it has received over c since it saved its state.

end if

Marker sending rule for process p_i

After p_i has recorded its state, for each outgoing channel c :

p_i sends one marker message over c

(before it sends any other message over c).

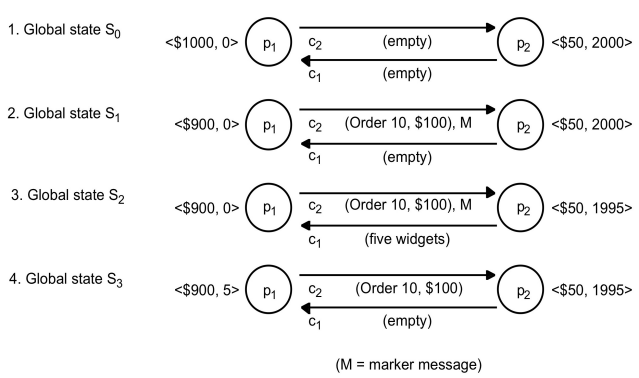
from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

General remarks

A snapshot consists of the state of a process and states of all incoming channels.

- Starting a snapshot:
 - Any process P can start a snapshot.
 - 1 Create a local snapshot of P 's state.
 - 2 Send marker message over all channels.
 - Upon receipt of a marker message, other processes participate in the snapshot.
- Collecting the snapshot:
 - Every process has created a local snapshot.
 - The local snapshot can be sent to a collector process.
- Terminating a snapshot:
 - If marker message has been received on all channels, the process the snapshot terminates
 - Then the snapshot can be sent to a collector process.

Example



from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

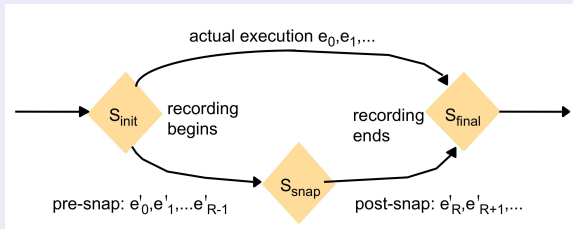
Termination of the snapshot algorithm

- If marker message has been received on all channels, the process the snapshot terminates
- If the communication graph induced by the messages is strongly connected
- then the marker eventually reaches all nodes
- \Rightarrow only a finite number of messages need to be recorded

The snapshot algorithm selects a Consistent Cut

- Consider two events $e_i \rightarrow e_j$ on processes p_i and p_j
- If e_j is in the cut of the snapshot, then e_i should be, too
- If e_j occurred before p_j taking its snapshot, then e_i should have occurred before p_i has taking its snapshot
- If $p_i = p_j$ this is obvious.
- Now we consider $p_i \neq p_j$ and assume (*) that e_i is not in the cut and e_j is within the cut.
- Consider messages m_1, m_2, \dots, m_h causing the *happened-before* relationship $e_i \rightarrow e_j$.
- So, m_1 must have sent after the snapshot, and m_2 , and so forth. Each of this messages must have been sent after the marker message occurred on each channel (because of FIFO rules on the channel).
- Then, e_j cannot be in the cut. This contradicts (*) and proves the claim.

Reachability of the snapshot algorithm selects a Consistent Cut



from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

- A snapshot characterizes events into two types
 - 1 pre-snap: An event happening before marking the corresponding process
 - 2 post-snap: An event happening after marking
- Note that pre-snap events can take place after post-snap events
- It is impossible that $e_i \rightarrow e_j$ if e_i is a post-snap event and e_j is a pre-snap event

Distributed Debugging

Goal of algorithm of Marzullo and Neiger

- Testing properties post-hoc, e.g. safety conditions
- Capture traces rather than snapshots
- Gathered by a monitoring process (outside the system)
- How are process states collected
- How to extract consistent global states
- How to evaluate safety, stability and liveness conditions

Distributed Debugging

Temporal operators

Consider all linearizations of H

- \circ *possible* ϕ There exists a consistent global state S through a linearization such that $\phi(S)$ is true.
- \circ *definitely* ϕ For all linearizations a consistent global state will be passed such that $\phi(S)$ is true.

Relationship of Definitely and Possibly

$$1 \quad \forall S \in H : \phi(S) \implies \textit{definitely } \phi$$

$$2 \quad \forall S \in H : \phi(S) \implies \textit{possibly } \phi$$

$$3 \quad \forall S \in H : \neg\phi(S) \implies \neg\textit{definitely } \phi$$

$$4 \quad \forall S \in H : \neg\phi(S) \implies \neg\textit{possibly } \phi$$

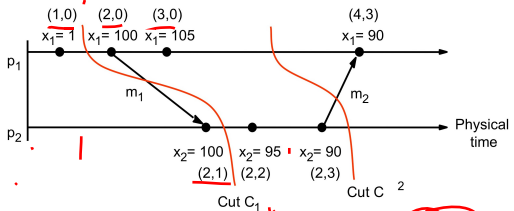
$$5 \quad \textit{definitely } \phi \implies \textit{possibly } \phi$$

$$6 \quad \neg\textit{possibly } \phi \implies \textit{definitely } \neg\phi$$

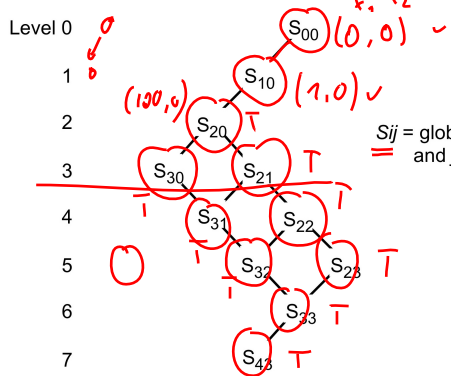
$$7 \quad \textit{definitely } \neg\phi \not\implies \neg\textit{possibly } \phi$$

Distributed Debugging: Definitely $|x_1 - x_2| \leq 50$

DFS
BFS

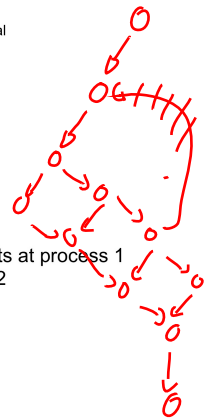


DAG



S_{ij} = global state after i events at process 1 and j events at process 2

Directed
Acyclic
Graph



Algorithm of Marzullo & Neiger

Collecting the states

- ④ All initial states are sent to the monitor
- ④ All state changes are sent to the monitor
- ④ If only a predicate is monitored ϕ then only states are sent where ϕ changes
 - With the states the corresponding vector clock is sent to the monitor
 - The vector clocks will be used to establish the \rightarrow -relationship
 - The monitor computes the DAG corresponding to the *happened-before*-relationship
 - Arrange the graph in levels $L = 0, 1, \dots$ such that no global state in level happened before a state in lower level.
 - In Level 0 there is only the initial state.

1. Evaluating possibly ϕ for global history H of N processes

$L := 0$;

States := $\{ (s_1^0, s_2^0, \dots, s_N^0) \}$;

while ($\phi(S) = \text{False}$ for all $S \in \text{States}$)

$L := L + 1$;

Reachable := $\{ S' : S' \text{ reachable in } H \text{ from some } S \in \text{States} \wedge \text{level}(S') = L \}$;

States := Reachable

end while

output "possibly ϕ ";

from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

2. Evaluating definitely ϕ for global history H of N processes

```

-→ L := 0;
-→ if ( $\phi(s_1^0, s_2^0, \dots, s_N^0)$ ) then States := {} else States := { (s_1^0, s_2^0, \dots, s_N^0) };
  while (States  $\neq$  {})
    -→ L := L + 1;
      Reachable := { S': S' reachable in H from some S  $\in$  States  $\wedge$  level(S') = L };
      States := { S  $\in$  Reachable:  $\phi(S) = \text{False}$  }
    end while
  output "definitely  $\phi$ ";

```

from *Distributed Systems – Concepts and Design*, Coulouris, Dollimore, Kindberg

Evaluating Definitely $\phi(S)$

Cost

Let n be the number of processes with k events each

- Time: ~~$O(k^n)$~~ $O(k^n \cdot n)$
- Space: ~~$O(kn)$~~ $O(k^n)$

S_{000}

S_{001} S_{010} S_{100}
 S_{002}

Level 0

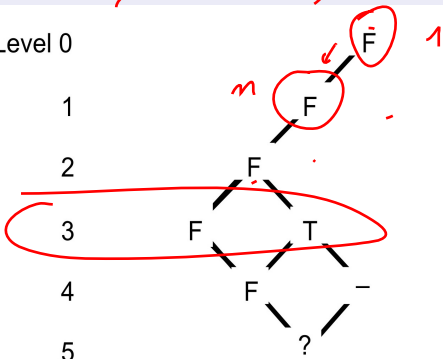
1

2

3

4

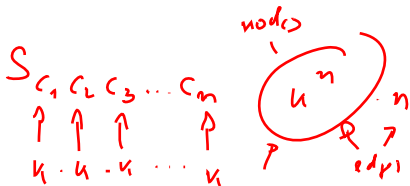
5

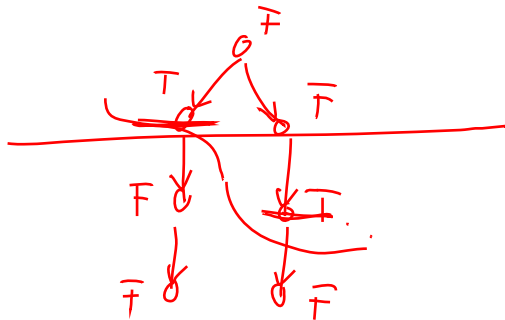


BFS

Dijkstra

$F = (\phi(S) = \text{False}); T = (\phi(S) = \text{True})$





End of Section 2