Distributed Systems — Time and Global State

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Distributed Systems — Time and Global State

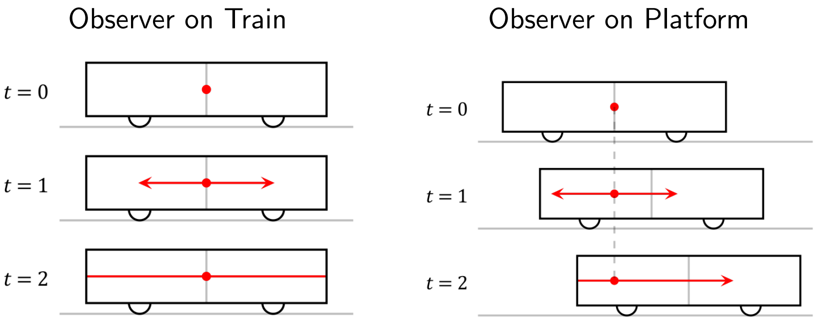
Introduction In this part of the course we will cover:

- Why time is such an issue for distributed computing
- The problem of maintaining a global state
- Consequences of these two main ideas
- Methods to get around these problems

Global Notion of Time

- Einstein  showed that the speed of light is constant for all observers regardless of their own velocity
- He (and others) have shown that this forced several other (sometimes counter-intuitive) properties including:
  1. length contraction
  2. time dilation
  3. relativity of simultaneity
     - Contradicting the classical notion that the duration of the time interval between two events is equal for all observers
     - It is impossible to say whether two events occur at the same time, if those two events are separated by space
     - A drum beat in Japan and a car crash in Brazil
     - However, if the two events are causally connected — if A causes B — the RoS preserves the causal order

Global Notion of Time



- However, if the two events are causally connected — if A causes B — the relativity of simultaneity preserves the causal order
- In this case, the flash of light happens before the light reaches either end of the carriage for all observers

Global Notion of Time

In Our World

- We operate as if this were not true, that is, as if there were some global notion of time
- People may tell you that this is because:
- On the scale of the differences in our frames of references, the effect of relativity is negligible

Global Notion of Time

In Our World

- We operate as if this were not true, that is, as if there were some global notion of time
- People may tell you that this is because:
- On the scale of the differences in our frames of references, the effect of relativity is negligible
- It's true that on our scales the effects of relativity are negligible
- But that's not really why we operate as if there was a global notion of time
- Even if our theortical clocks are well synchronised, or mechanical ones are not
- We just accept this inherent inaccuracy build that into our (social) protocols

Global Notion of Time

Physical Clocks

- Computer clocks tend to rely on the oscillations occuring in a crystal
- The difference between the instantaneous readings of two separate clocks is termed their *"skew"*
- The *"drift"* between any two clocks is the difference in the rates at which they are progressing. The rate of change of the skew
- The *drift* rate of a given clock is the drift from a nominal "perfect" clock, for quartz crystal clocks this is about 10^{-6}
- Meaning it will drift from a perfect clock by about 1 second every 1 million seconds — 11 and a half days.

Global Notion of Time

Coordinated Universal Time and French

- The most accurate clocks are based on atomic oscillators
- Atomic clocks are used as the basis for the international standard *International Atomic Time*
- Abbreviated to TAI from the French Temps Atomique International
- Since 1967 a standard second is defined as 9,192,631,770 periods of transition between the two hyperfine levels of the ground state of Caesium-133 (Cs^{133}).
- Time was originally bound to astronomical time, but astronomical and atomic time tend to get out of step
- Coordinated Universal Time — basically the same as TAI but with *leap seconds* inserted
- Abbreviated to UTC again from the French Temps Universel Coordonné

Global Notion of Time

Correctness of Clocks

- What does it mean for a clock to be correct?
- The operating system reads the node's hardware clock value, $H(t)$, scales it and adds an offset so as to produce a software clock $C(t) = \alpha H(t) + \beta$ which measures real, physical time t
- Suppose we have two *real* times t and t' such that $t < t'$
- A physical clock, H, is correct with respect to a given bound 'p' if:
- $(1 - p)(t' - t) \leq H(t') - H(t) \leq (1 + p)(t' - t)$
-
  - $(t' - t)$ — The true length of the interval
  - The measured length of the interval
  - The smallest acceptable length of the interval
  - The largest acceptable length of the interval

Global Notion of Time

Correctness of Clocks

$(1 - p)(t' - t) \leq H(t') - H(t) \leq (1 + p)(t' - t)$

- An important feature of this definition is that it is monotonic
- Meaning that:
- If $t < t'$ then $H(t) < H(t')$
- Assuming that $t < t'$ with respect to the precision of the hardware clock

Global Notion of Time

Monotonicity

- What happens when a clock is determined to be running fast?
- We could just set the clock back:
- but that would break monotonicity
- Instead, we retain monotonicity:
  - $C_i(t) = \alpha H(t) + \beta$
  - decreasing β such that $C_i(t) \leq C_i(t')$ for all $t < t'$

Global Notion of Time

External vs Internal Synchronisation

- Intuitively, multiple clocks may be synchronised with respect to each other, or with respect to an external source.
- Formally, for a synchronisation bound $D > 0$ and external source S:
  - Internal Syncronisation
    - $| C_i(t) - C_j(t) | < D$
    - No two clocks disagree by D or more
  - External Syncronisation
    - $| C_i(t) - S(t) | < D$
    - No clock disagrees with external source S by D or more
- Internally synchronised clocks may not be very accurate at all with respect to some external source
- Clocks which are externally synchronised to a bound of D though are automatically internally synchronised to a bound of $2 \times D$.

Synchronising Clocks

Synchronising in a synchronous system

- Imagine trying to synchronise watches using text messaging
- Except that you have bounds for how long a text message will take
- How would you do this?
  1. Mario sends the time t on his watch to Luigi in a message m
  2. Luigi should set his watch to $t + T_{trans}$ where T_{trans} is the time taken to transmit and receive the message m
  3. Unfortunately T_{trans} is only bound, it is not known
  4. We do know that $min \leq T_{trans} \leq max$
  5. We can therefore acheive a bound of $u = max - min$ if the Luigi sets his watch to $t + min$ or $t + max$
  6. We can do a bit better an achieve a bound of $u = \frac{max - min}{2}$ if Luigi sets his watch to $t + \frac{max + min}{2}$
  7. More generally if there are N clocks (Mario, Luigi, Peach, Toad, ...) we can achieve a bound of $(max - min)(1 - \frac{1}{N})$
  8. Or more simply we make Mario an external source and the bound is then $max - min$ (or $2 \times \frac{max - min}{2}$)

Synchronising Clocks

Cristian's Method

- The previous method does not work where we have no upper bound on message delivery time, i.e. in an asynchronous system
- Cristian's method is a method to synchronise clocks to an external source.
- This could be used to provide external or internal synchronisation as before, depending on whether the source is itself externally synchronised or not.
- The key idea is that while we might not have an upper bound on how long a single message takes, we can have an upper bound on how long a round-trip took.
- However it requires that the round-trip time is sufficiently short as compared to the required accuracy.

Synchronising Clocks

Cristian's Method

- Luigi sends Mario (our source/server) a message m_r requesting the current time, and records the time T_{sent} at which m_r was sent according to Luigi's current clock
- Upon receiving Luigi's request message m_r Mario responds with the current time according to his clock in the message m_t.
- When Luigi receives Mario's time t in message m_t, at time T_{rec} according to his own clock the round trip took $T_{round} = T_{rec} - T_{sent}$
- Luigi then sets his clock to $t + \frac{T_{round}}{2}$
- Which assumes that the elapsed time was split evenly between the exchange of the two messages.

Cristian's Method

- How accurate is this?
- We often don't have accurate upper bounds for message delivery times but frequently we can at least guess conservative lower bounds
- Assume that messages take at least *min* time to be delivered
- The earliest time at which Mario could have placed his time into the response message m_t is *min* after Luigi sent his request message m_r.
- The latest time at which Mario could have done this was *min* before Luigi receives the response message m_t.
- The time on Mario's watch when Luigi receives the response m_t is:
  - At least $t + min$
  - At most $t + T_{round} - min$
  - Hence the width is $T_{round} - (2 \times min)$
- The accuracy is therefore $\frac{T_{round}}{2} - min$

Synchronising Clocks

The Berkley Algorithm

- Like Cristian's algorithm this provides either external synchronisation to a known server, or internal synchronisation via choosing one of the players to be the master
- Unlike Cristian's algorithm though, the master in this case does not wait for requests from the other clocks to be synchronised, rather it periodically polls the other clocks.
- The other's then reply with a message containing their current time.
- The master, estimates the slaves current times using the round trip time in a similar way to Cristian's algorithm
- It then averages those clock readings together with its own to determine what should be the current time.
- It then replies to each of the other players with the amount by which they should adjust their clocks

Synchronising Clocks

The Berkley Algorithm

- If a straight forward average is taken a faulty clock could shift this average by a large amount, and therefore a *fault tolerant average* is taken
- This is exactly as it sounds, it averages all the clocks that do not differ by a chosen maximum amount.

Network Time Protocol

Pairwise synchronisation

- Similar to Cristian's method however:
- Four times are recorded as measured by the clock of the process at which the event occurs:
  1. T_{i-3} — Time of sending of the request message m_r
  2. T_{i-2} — Time of receiving of the request message m_r
  3. T_{i-1} — Time of sending of the response message m_t
  4. T_i — Time of receiving of the response message m_t
- So if Luigi is requesting the time from Mario, then T_{i-3} and T_i are recorded by Luigi and T_{i-2} and T_{i-1} are recorded by Mario
- Note that because Mario records the time at which the request message was received and the time at which the response message is sent, there can be a non-neglible delay between both
- In particular then messages may be dropped

Network Time Protocol

Pairwise synchronisation

- If we assume that the true offset between the two clocks is O_{true}:
- And that the actual transmission times for the messages m_r and m_t are t and t' respectively then:
- $T_{i-2} = T_{i-3} + t + O_{true}$ and
- $T_i = T_{i-1} + t' - O_{true}$
- $T_{round} = (t + t') = (T_i - T_{i-3}) - (T_{i-1} - T_{i-2})$
- $O_{guess} = \frac{(T_{i-2} - T_{i-3}) + (T_{i-1} - Ti)}{2}$

Network Time Protocol

Pairwise synchronisation

- This is the non-trivial line:
- $O_{guess} = \frac{(T_{i-2} - T_{i-3}) + (T_{i-1} - T_i)}{2}$
- $$\begin{array}{lcl} T_{i-2} - T_{i-3} & = & t + O_{true} \\ T_{i-1} - T_i & = & O_{true} - t' \\ \hline & = & (t - t') + (2 \times O_{true}) \end{array}$$
- $O_{guess} = \frac{t - t'}{2} + O_{true}$
- $O_{true} = O_{guess} + \frac{(t - t')}{2}$

Since we know that $T_{round} > \mid t - t' \mid$:

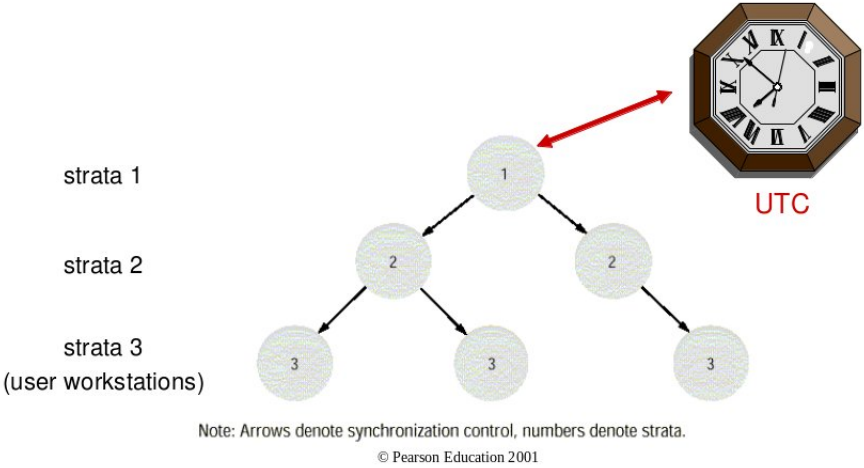
- $O_{guess} - \frac{T_{round}}{2} \leq O_{true} \leq O_{guess} + \frac{T_{round}}{2}$
- O_{guess} is the guess as to the offset
- T_{round} is the measure of how accurate it is which is essentially based on how long the messages were in transit

Synchronising Clocks

Network Time Protocol

- Network Time Protocol (actually abbreviated was NTP) is designed to allow clients to synchronise with UTC over the Internet.
- NTP is provided by a network of servers located across the Internet.
- Primary servers are connected directly to a time source such as a radio clock receiving UTC.
- Other servers are connected in a tree, with their *strata* determined by how many branches are between them and a primary server
- Strata N servers synchronise with Strata N - 1 servers
- Eventually a server is within a user's workstation
- Errors may be introduced at each level of synchronisation and they are cumulative, so the higher the strata number the less accurate is the server

Network Time Protocol



Note: this picture does not show synchronisation between servers at the same strata, but this does occur

Synchronising Clocks

Network Time Protocol

- NTP servers synchronise in one of three ways:
  1. Multicast mode
     - Not considered very accurate
     - Intended for use on a high-speed LAN
     - Can be accurate enough nonetheless for some purposes
  2. Procedure call mode
     - Similar to Cristian's method
     - Servers respond to requests from higher-strata servers
     - Who use round-trip times to calculate the current time to some degree of accuracy
     - Used for example in network file servers which wish to keep as accurate as possible file access times
  3. Symmetric mode
     - Used where the highest accuracies are required
     - In particular between servers nearest the primary sources, that is the lower strata servers
     - Essentially similar to procedure-call mode except that the communicating servers retain timing information to improve their accuracy over time

Network Time Protocol

Overview

- In all three modes messages are delivered using the standard UDP protocol
- Hence message delivery is unreliable
- At the higher strata servers can synchronise to high degree of accuracy over time
- But in general NTP is useful for synchronising accurately to UTC, whereby accurate is at the human level of accuracy
- Wall clocks, clocks at stations etc
- In summary: we can synchronise clocks to a bounded level of accuracy, but for many applications the bound is simply not tight enough

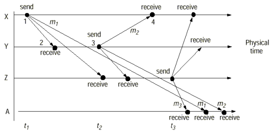
Logical Clocks

Asynchronous Orderings

- So we can achieve some measure of synchronisation between physical clocks located at different sites
- Ultimately though we will never be able to synchronise clocks to arbitrary precision
- For some applications low precision is enough, for others it is not.
- Where we cannot guarantee a high enough order of precision for synchronisation, we are forced to operate in the asynchronous world
- Despite this we can still provide a *logical* ordering on events, which may useful for certain applications

Logical Clocks

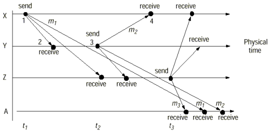
Logical Ordering



- Logical orderings attempt to give an order to events similar to physical causal ordering of reality but applied to distributed processes
- Logical clocks are based on the simple principles:
- Any process can order the events which it observes/executes
- Any message must be sent before it is received

Logical Clocks

Logical Ordering — Happened Before



- More formally we define the *happened-before* relation $\rightarrow$ by the three rules:
  1. If e_1 and e_2 are two events that happen in a single process and e_1 proceeds e_2 then $e_1 \rightarrow e_2$
  2. If e_1 is the sending of message m and e_2 is the receiving of the same message m then $e_1 \rightarrow e_2$
  3. If $e_1 \rightarrow e_2$ and $e_2 \rightarrow e_3$ then $e_1 \rightarrow e_3$

Logical Clocks

Logical Ordering — A Logical Clock

- Lamport designed an algorithm whereby events in a logical order can be given a numerical value
- This is a *logical clock*, similar to a program counter except that there is no backward jumping, and so it is monotonically increasing
- Each process P_i maintains its internal logical clock L_i
- So in order to record the logical ordering of events, each process does the following:
  - L_i is incremented immediately before each event is issued at P_i
  - When the process P_i sends a messsage m it attaches the value of its logical clock $t = L_i(m)$.
  - Upon receiving a message (m, t) process P_j computes the new value of L_j as $max(L_j, t)$

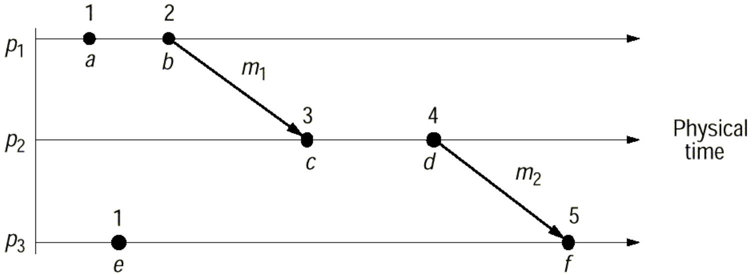
Logical Clocks

Properties

- Key point: using induction we can show that:
- $e_1 \rightarrow e_2$ implies that $L(e_1) < L(e_2)$
- However, the converse is not true, that is:
- $L(e_1) < L(e_2)$ does not imply that $e_1 \rightarrow e_2$
- It is easy to see why, consider two processes, P_1 and P_2 which each perform two steps prior to any communication.
- The two steps on the first process P_1 are concurrent with both of the two steps on process P_2.
- In particular $P_1(e_2)$ is concurrent with $P_2(e_1)$ but $L(P_1(e_2)) = 2$ and $L(P_2(e_1)) = 1$

Logical Clocks

Lamport Clocks — No reverse implication



- Here event $L(e) < L(b) < L(c) < L(d) < L(f)$
- but only $e \rightarrow f$
- e is concurrent with b, c and d.

Logical Clocks

Total Ordering

- Just as the happened-before relation is a partial ordering
- So to are the numerical Lamport stamps attached to each event
- That is, some events have the same number attached.
- However we can make it a total ordering by considering the process identifier at which the event took place
- In this case $L_i(e_1) < L_j(e_2)$ if either:
    1. $L_i(e_1) < L_j(e_2)$ OR
    2. $L_i(e_1) = L_j(e_2)$ AND $i < j$
- This has no physical meaning but can sometimes be useful

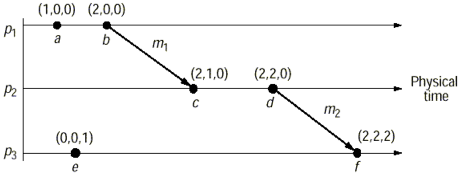
Vector Clocks

Vector Clocks augment Logical Clocks

- Vector clocks were developed (by Mattern and Fidge) to overcome the problem of the lack of a reversed implication
- That is: $L(e_1) < L(e_2)$ does not imply $e_1 \rightarrow e_2$
- Each process keeps it own vector clock V_i (an array of Lamport clocks, one for every process)
- The vector clocks are updated according to the following rules:
  1. Initially $V_i[j] = 0$
  2. As with Lamport clocks before each event at process P_i it updates its own Lamport clock within its own vector clock: $V_i[i] = V_i[i] + 1$
  3. Every message P_i sends includes its entire vector clock $t = V_i$
  4. When P_i receives a timestamp V_x then it updates all of its vector clocks with: $V_i[j] = max(V_i[j], V_x[j])$

Vector Clocks

Vector Clocks augment Logical Clocks



- Vector clocks (or timestamps) are compared as follows:
  1. $V_x = V_y$ *iff* $V_x[i] = V_y[i] \quad \forall i, 1 \dots N$
  2. $V_x \leq V_y$ *iff* $V_x[i] \leq V_y[i] \quad \forall i, 1 \dots N$
  3. $V_x < V_y$ *iff* $V_x[i] < V_y[i] \quad \forall i, 1 \dots N$
- As with logical clocks: $e_1 \rightarrow e_2$ implies $V(e_1) < V(e_2)$
- In contrast with logical clocks the reverse is also true: $V(e_1) < V(e_2)$ implies $e_1 \rightarrow e_2$

Vector Clocks

Vector Clocks augment Logical Clocks

- Of course vector clocks achieve this at the cost of larger time stamps attached to each message
- In particular the size of the timestamps grows proportionally with the number of communicating processes

Summary of Logical Clocks

- Since we cannot achieve arbitrary precision of synchronisation between remote clocks via message passing
- We are forced to accept that some events are concurrent, meaning that we have no way to determine which occured first
- Despite this we can still achieve a logical ordering of events that is useful for many applications

Global State

- Correctness of distributed systems frequently hinges upon satisfying some global system invariant
- Even for applications in which you do not expect your algorithm to be correct at all times, it may still be desirable that it is "good enough" at all times
- For example our distributed algorithm maybe maintaining a record of all transactions
  - In this case it might be okay if some processes are behind other processes and thus do not know about the most recent transactions
  - But we would never want it to be the case that some process is in an inconsistent state, say applying a single transaction twice.

Global State

- Motivating examples:
  1. Distributed garbage collection
  2. Distributed deadlock detection
  3. Distributed termination detection
  4. Distributed debugging

Global State — Absence of a Global Time

You may have thought you got away from global time discussions

- Consider what happens to each of our distributed problems should we have a global time
- Distributed Garbage Collection
  - Agree a global time for each process to check whether a reference exists to a given object
  - This leaves the problem that a reference may be in transit between processes
  - But each process can say which references they have sent before the agreed time and compare that to the references received at the agreed time

Global State — Absence of a Global Time

You may have thought you got away from global time discussions

- Consider what happens to each of our distributed problems should we have a global time
- Distributed Deadlock Detection
  - Somewhat depends upon the problem in question, however:
  - At an agreed time all processes send to some master process the processes or resources for which they are waiting
  - The master process then simply checks for a loop in the resulting graph

Global State — Absence of a Global Time

You may have thought you got away from global time discussions

- Consider what happens to each of our distributed problems should we have a global time
- Distributed Termination Detection
  - At an agreed time each process sends whether or not they have completed to a master process
  - Again this leaves the problem that a message may be in transit at that time
  - Again though, we should be able to work out which messages are still in transit

Global State — Absence of a Global Time

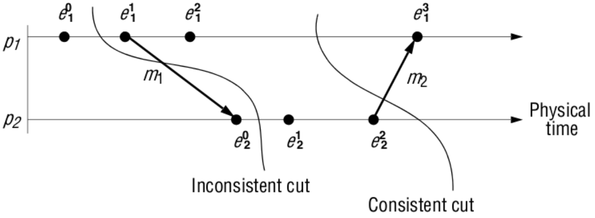
You may have thought you got away from global time discussions

- Consider what happens to each of our distributed problems should we have a global time
- Distributed Debugging
  - At each point in time we can reconstruct the global state
  - We can also record the entire history of events in the exact order in which they ocurred.
  - Allowing us to replay them and inspect the global state to see where things have gone wrong as with traditional debugging

Global State — Consistent Cuts

- So, if we had synchronised clocks, we could agree on a time for each process to record its state
- The combination of local states and the states of the communication channels would be an actual global state
- Since we cannot do that we attempt to find a "*cut*"
- A cut is a partition of events into those occurring before the cut and those occurring after the cut
- The goal is to assemble a meaningful global state from the the local states of processes recorded at different times

Global State — Consistent Cuts



- A consistent cut is one which does not violate the happens before relation $\rightarrow$
- If $e_1 \rightarrow e_2$ then either:
  - both e_1 and e_2 are before the cut or
  - both e_1 and e_2 are after the cut or
  - e_1 is before the cut and e_2 is after the cut
  - but not
  - e_1 is after the cut and e_2 is before the cut

Global State — Consistent Cuts

Runs and Linearisations

- A *consistent global state* is one which corresponds to a consistent cut
- A "*run*" is a total ordering of all events in a global history which is consistent with the local history of each process
- A "*linearisation*" is a total ordering of all events in the global history which is consistent with the happens-before relation $\rightarrow$
- So all linearisations are also runs
- Not all runs pass through consistent global states but all linearisations pass only through consistent global states

Global State — Safety and Liveness

- When we attempt to examine the global state, we are often concerned with whether or not a property holds
- Some properties, B, are properties we hope never hold and some properties, G, are properties we hope always hold
- *Safety* is the property that a bad property B does not hold for any reachable state
- *Liveness* is the property that a good property G holds for all reachable states

Global State — Stable and Unstable properties

- Some properties we wish to establish are *stable* properties
- Such properties may never become true, but once they do they remain true
- Our four example properties:
  - Garbage is *stable*: once an object has no valid references (at a process or in transit) will never have any valid references
  - Deadlock is *stable*: once a set of processes are deadlocked they will always be deadlocked without external intervention
  - Termination is *stable*: once a set of processes have terminated they will remain terminated without external intervention
  - Debugging is not really a property but the properties we may look for whilst debugging are likely *non-stable*

Global State — Snapshot

Chandy and Lamport

- The goal is to record a snapshot, or global state, of a set of processes
- The algorithm is such that the combination of recorded states may never have occured simultaneously
- However the computed global state is always a consistent one
- The state is recorded locally at each process
- The algorithm also does not address the issue of *gathering* the recorded global state.
- Though generally the locally recorded state can then be sent to some pre-agreed master process.

Global State — Chandy and Lamport

Assumptions

- There is a path between any two pairs of processes, in both directions
- Any process may initiate a global snapshot at any time
- The processes may continue their execution and send/receive normal messages whilst the snapshot takes place

Global State — Chandy and Lamport

Assumptions

- There is a path between any two pairs of processes, in both directions
- Any process may initiate a global snapshot at any time
- The processes may continue their execution and send/receive normal messages whilst the snapshot takes place
- Neither channels nor processes fail
- Communication is reliable such that every message that is sent arrives at its destination exactly once
- Channels are unidirectional and provide FIFO-ordered message delivery.

Global State — Chandy and Lamport

Algorithm — Receiver

Receiving rule for process p_i

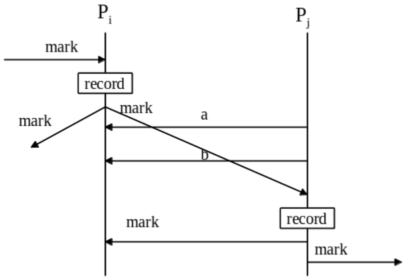
1. On receipt of a Marker message over channel c:
2.   if p_i has not yet recorded state:
3.   record process state now
4.   record the state of c as the empty set
5.   turn on recording of messages arriving on all other channels
6.   else
7.   records the state of c as the set of messages it has recorded since p_i first recorded its state

Global State — Chandy and Lamport

Algorithm — Sender

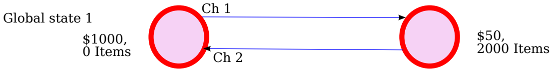
Sending rule for process p_i

1. After p_i has recorded its state:
2. p_i sends a marker message for each outgoing channel c
3. before it sends any other messages over c



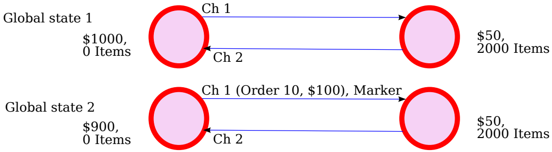
Global State — Chandy and Lamport Example

We begin in this global state, where both channels are empty, the states of the processes are as shown, but we say nothing about what has gone before.



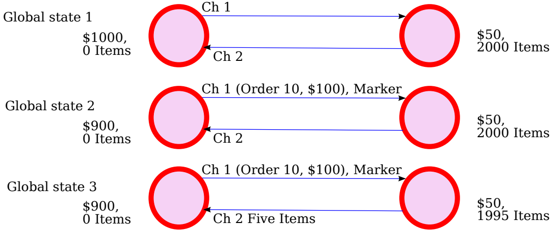
Global State — Chandy and Lamport Example

The left process decides to begin the snapshot algorithm and sends a Marker message over channel 1 to the left process. It then decides to send a request for 10 items at $10 each.



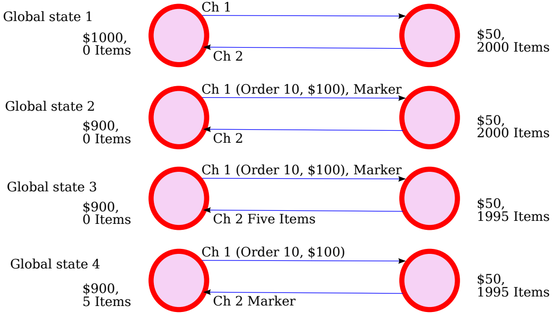
Global State — Chandy and Lamport Example

Meanwhile, the right process responds to an earlier request and sends 5 items to the left process over channel 2.

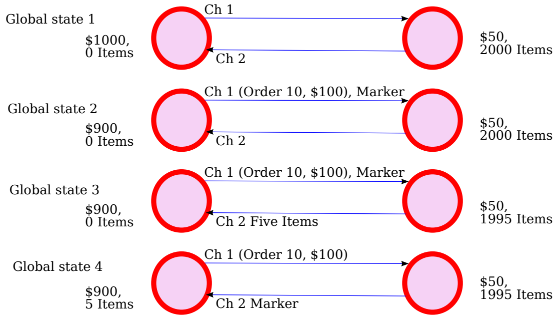


Global State — Chandy and Lamport Example

Finally the right process receives the Marker message, and in doing so records its state and sends the left process a Marker message over channel 2. When the left process receives this Marker message it records the state of channel two as containing the 5 items it has received since recording its own state.



Global State — Chandy and Lamport Example



The final recorded state is:

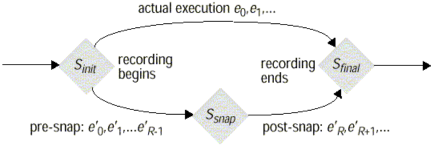
Left Process	$1000, 0
Right Process	$50, 1995
Channel 1	empty
Channel 2	Five Items

Global State — Chandy and Lamport

Reachability

- The cut found by the Chandy and Lamport algorithm is always a consistent cut
- This means that the global state which is characterised by the algorithm is a consistent global state
- Though it may not be one that ever occurred
- We can though define a reachability relation:
  - This is defined via the initial, observed and final global states when the algorithm is run
  - Assume that the events globally occurred in an order $Sys = e_1, e_2 \ldots$
  - Let S_{init} be the global state immediately before the algorithm commences and S_{final} be the global state immediately after it terminates. Finally S_{snap} is the recorded global state
  - We can find a permutation of Sys called Sys' which:
    - contains all three states: S_{init}, S_{snap} and S_{final}
    - Does not break the happens-before relationship on the events in Sys

Global State — Chandy and Lamport — Reachability



- It may be that there are two events in *Sys*, e_n and e_{n+1} such that e_n is a post-snap event and e_{n+1} is a pre-snap event
- However we can swap the order of e_n and e_{n+1} since it cannot be that $e_n \rightarrow e_{n+1}$
- We continue to swap adjacent pairs of events until all pre-snap events are ordered before all post-snap events. This gives us the the linearisation Sys'
- The reachability property of the snapshot algorithm is useful for recording stable properties
- However any non-stable predicate which is True in the snapshot may or may not be true in any other state
- Since the snapshot may not have actually occured

Global State — Chandy and Lamport

Use Cases

- No work which depends upon the global state is done until the snapshot has been gathered
- They are therefore useful for:
  1. Evaluating after the kind of change that happens infrequently
  2. Stable changes, since the property that you detect to have been true "when" the snapshot was taken will still be true once the snapshot has been gathered
  3. The kind of property that has a correct or an incorrect answer rather than a range of increasingly appropriate answers: Routing vs Garbage Collection
  4. Properties that need not be detected and acted upon immediately, for example garbage collection.

Distributed Debugging

- Distributed debugging was the application of our four example applications that stood out for being concerned with unstable properties
- This is a problem for our global snap-shot technique since its main usefulness is derived from our reachability relation which in turn means little for a non-stable property
- Distributed debugging is in a sense a combination of logical/vector clocks and global snapshots

Example Non-Stable Condition

- Suppose we are implementing an online poker game
- There is a process representing each player and one representing the pot in the centre of the table
- Players can "send chips" to the pot, and once winners have been decided the pot may send chips back to some of the players.
- We wish to make sure that the total amount of chips in the game never exceeds the initial amount
- It may be less than the initial amount since some chips may be in transit between a player and the centre pot.
- But it cannot be more than the initial amount.

Distributed Debugging

- Suppose that we have a history H of events $e_1, \ldots, e_n$
- $H(e_1, \ldots e_n)$ is therefore the true order of events as they actually occurred in our system
- Recall then that a *run* is any ordering of those events in which each event occurs exactly once
- But a *linearisation* is a consistent run
  - A consistent run is one in which the "happens-before" relation is satisfied for all pairs of events e_i, e_j
  - If $e_i \rightarrow e_j$ then any linearisation (or consistent run) will order e_i before e_j.
  - Importantly then, all linearisations only pass through consistent states

Distributed Debugging

The possibly relation

- Any linearisation *Lin* of our history of events *H* must therefore pass through only consistent states
- A property P that is true in any state through which *Lin* passes, was conceivably true at some global state through which *H* passed
- If this is the case for some property p and some linearisation we say $\textit{possibly}(p)$
- Note: suppose we had taken a global snapshot during the set of events *H* to determine if the property p was true and determined that it was: $\textit{Snap}(p)$ evaluates to true.
- This would imply that p was possible.
- However the reverse is not true, so:
  - $\textit{Snap}(p) \implies \textit{possibly}(p)$
  - $\textit{possibly}(p) \not\Longrightarrow \textit{Snap}(p)$

The definitely relation

- The sister relation to the *possibly* relation is the *definitely* relation
- This states that for any linearisation *Lin* of *H*, *Lin* must pass through some consistent global state *S* for which the candidate property is true
- Since *H* is a linearisation of itself, then the candidate property was certainly true at some point in the history of events.

More formally:

- The statement $possibly(p)$ means that there is a consistent global state S through which at least one linearisation of H passes such that $S(p)$ is true.
- The statement $definitely(p)$ means that for all linearisations L of H, there is a consistent global state S through which L passes such that $S(p)$ is True

Distributed Debugging

Possibly vs Definitely

- You may think that the possibly relation is useless
- Since I knew before we started that some predicate was potentially true at some point.
- However, $\neg(\mathit{possibly}(p)) \implies \mathit{definitely}(\neg p)$
- But, from $\mathit{definitely}(\neg p)$ we cannot conclude $\neg(\mathit{possibly}(p))$.
- $\mathit{definitely}(\neg p)$ means that there is at least one state in all linearisations of H such that p is not true, but not all states.
- $\neg(\mathit{possibly}(p))$ however would require that $\neg(p)$ was true in all states in all linearisations
- Another way to put this is that $\mathit{definitely}(p)$ and $\mathit{definitely}(\neg p)$ may be true simultaneously but $\mathit{possibly}(p)$ and $\neg(\mathit{possibly}(p))$ cannot.

Distributed Debugging

Basic Outline

- The processes must all send messages recording their local state to a master process
- The master process collates these and extracts the consistent global states
- From this information the *possibly*(p) and *definitely*(p) relations may be computed.

Distributed Debugging

Collecting The Global States

- Each process sends their initial state to the master process in a state message and thereafter periodically send their local state.
- The preparing and sending of these state messages may delay the normal operation of the distributed system but does not otherwise affect it: so debugging may be turned on and off.
- "Periodically" is better defined in terms of the predicate for which we are debugging.
- So we do not send a state message to the master process other than, initially and whenever our local state changes.
- The local state need only change with respect to the predicate in question. We can concurrently check for separate predicates as well by marking our state messages appropriately.
- Additionally even if the local state changes we need only send a state message if that update could have altered the value of the predicate.

Distributed Debugging

State Message Stamps

- In order that the master process can assemble the set of consistent states from the set of state messages the individual processes send it ..
- Each state message is stamped with the Vector clock value at the local process sending the state message: $\{s_i, V(s_i)\}$
- If $S = \{s_1, \ldots s_n\}$ is a set of state messages received by the master process, and $V(s_i)$ be the vector time stamp of the particular local state s_i
- Then it is known that S is a consistent global state *iff*:
- $V_i[i] >= V_j[i] \quad \forall i, j1, ...N$

State Message Stamps

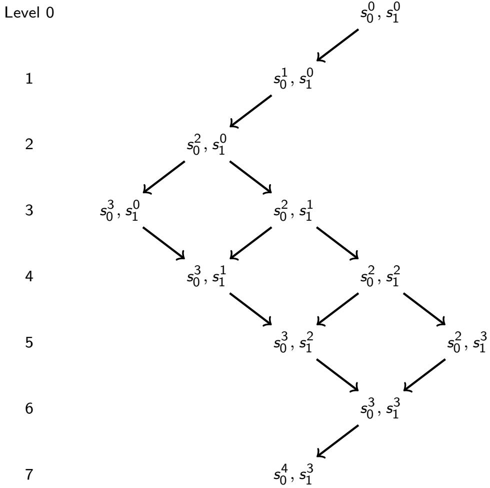
Assembled Consistent Global States

- S is a consistent global state *iff*:
- $V_i[i] >= V_j[i] \quad \forall i, j 1, ...N$
- This says that the number of p_i's events known at p_j when it sent s_j is no more than the number of events that had occurred at p_i when it sent s_i.
- In other words, if the state of one process depends upon another (according to happened-before ordering), then the global state also encompasses the state upon which it depends.

Assembling Consistent Global States

- Imagine the simplest case of 2 communicating processes.
- A plausible global state is $S(s_0^x, s_1^y)$
- The subscripts, 0 and 1, refer to the process index
- The superscripts x and y refer to the number of events which have occurred at the particular process.
- The "level" of a given state is $x + y$, which is number of events which have occurred globally to give rise to the particular global state S.

Assembling Consistent Global States



Evaluating Possibly and Definitely

1. A state $S' = \{s_0^{x_0'}, \ldots s_N^{x_N'}\}$ is reachable from a state $S = \{s_0^{x_0}, \ldots s_N^{x_N}\}$
2. If
   - S' is a consistent state
   - The level of S' is 1 plus the level of S and:
   - $x_{i'} = x_i$ or $x_{i'} = 1 + x_i \quad \forall 0 \leq i \leq N$

Evaluating Possibly

1. Level = 0
2. States = $\{(s_0^0, \ldots s_N^0)\}$
3. while (States is not empty)
   - Level = Level + 1
   - Reachable = {}
   - for S' where level(S') = Level
     - if S' is reachable from some state in States
     - then if p(S') then output possibly(p) is True and quit
     - else place S' in Reachable
   - States = Reachable
4. output possibly(p) is false

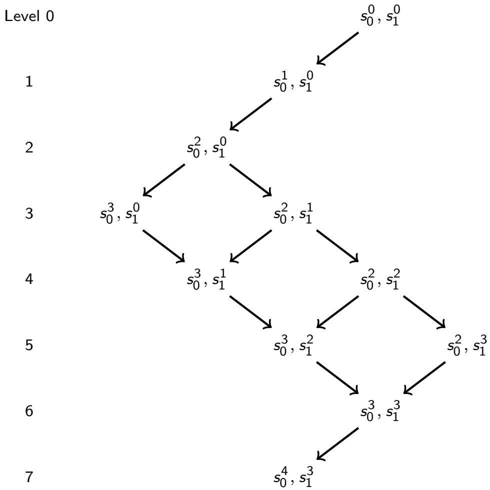
Evaluating Definitely

1. Level = 0
2. States = $\{(s_0^0, \ldots s_N^0)\}$
3. while (States is not empty)
    - Level = Level + 1
    - Reachable = {}
    - for S' where level(S') = Level
        - if S' is reachable from some state in States
        - then if $\neg(p(S'))$ then place S' in Reachable
    - States = Reachable
4. if Level is the maximum level recorded
5. then output definitely(p) is false
6. else output definitely(p) is true

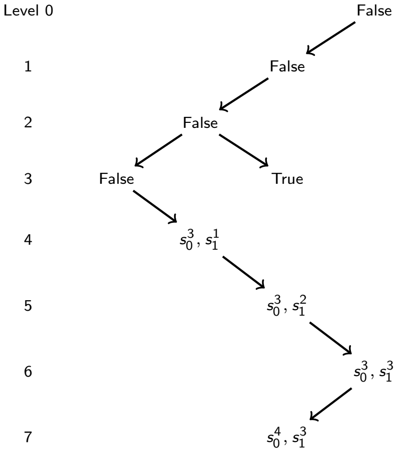
Note: Should also check if it is true in the initial state

Evaluating Definitely

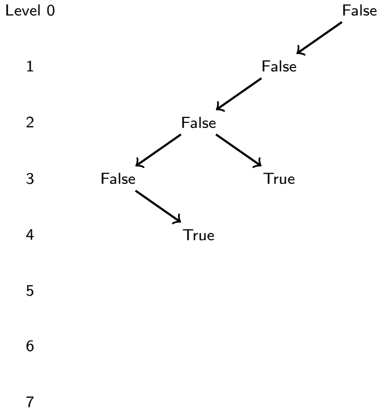
Recall:



Evaluating Definitely



Evaluating Definitely



Definitely(p) is True

Evaluating Possibly and Definitely

- Note that the number of states that must be evaluated is potentially huge
- In the worse case, there is no communication between processes, and the property is False for all states
- We must evaluate all permutations of states in which each local history is preserved
- This system therefore works better if there is a lot of communication and few local updates (which affect the predicate under investigation)

Distributed Debuggin

In a synchronous system

- We have so far considered debugging within an asynchronous system
- Our notion of a consistent global state is one which could potentially have occurred
- In a synchronous system we have a little more information to make that judgement
- Suppose each process has a clock internally synchronised with the each other to a bound of D.
- With each state message, each process additionally time stamps the message with their local time at which the state was observed.
- For a single process with two state messages (s_i^x, V_i, t_i) and (s_i^{x+1}, V_i', t_i') we know that the local state s_i^x was valid between the time interval:
- $t_i - D$ to $t_i' + D$

Distributed Debugging

In a synchronous system

- Recall our condition for a consistent global state:
- $V_i[i] >= V_j[i] \quad \forall i, j1, ...N$
- We can add to that:
- $t_i - D \leq t_j \leq t_i' + D$ and vice versa forall i,j
- Note, this makes use of the bounds imposed in a synchronous system but speaks nothing of the time taken for a message to be delivered
- Therefore obtaining useful bounds is rather plausible
- But if there is a lot of communication then we may not prune the number of states which must be checked

Distributed Debugging

Summary

- Each process sends to a monitor process state update messages whenever a significant event occurs.
- From this the monitor can build up a set of consistent global states which may have occurred in the true history of events
- This can be used to evaluate whether some predicate was possibly true at some point, or definitely true at some point

Summary

- We noted that even in the real world there is no global notion of time
- We extended this to computer systems noting that the clocks associated with separate machines are subject to differences between them known as the *skew* and the *drift*.
- We nevertheless described algorithms for attempting the synchronisation between remote computers
  - Cristian's method
  - The Berkely Algorithm
  - Pairwise synchronisation in NTP
- Despite these algorithms to synchronise clocks it is still impossible to determine for two arbitrary events which occurred before the other.
- We therefore looked at ways in which we can impose a meaningful order on remote events and this took us to logical orderings

Summary

- Lamport and Vector clocks were introduced:
  - Lamport clocks are relatively lightweight provide us with the following $e_1 \rightarrow e_2 \implies L(e_1) < L(e_2)$
  - Vector clocks improve on this by additionally providing the reverse implication $V(e_1) < V(e_2) \implies e_1 \rightarrow e_2$
  - Meaning we can entirely determine whether $e_1 \rightarrow e_2$ or $e_2 \rightarrow e_1$ or the two events are concurrent.
  - But do so at the cost of message length and scalability
- The concept of a true history of events as opposed to *runs* and *linearisations* was introduced
- We looked at Chandy and Lamport's algorithm for recording a global snapshot of the system
- Crucially we defined a notion of reachability such that the snapshot algorithm could be usefully deployed in ascerting whether some stable property has become true.

Summary

- Finally the use of consistent cuts and linearisations was used in Marzullo and Neiger's algorithm
- Used in the debugging of distributed systems it allows us to ascertain whether some transient property was possibly true at some point or definitely true at some point.
- We compare these asynchronous techniques with the obvious synchronous techniques
- We observe that while the synchronous techniques would be more accurate often, they will occasionally be wrong
- The asynchronous techniques are frequently conservative in that they may be imprecise but never wrong
- For example two events may be deemed concurrent meaning that we do not know which occurred first, but we will never erroneously ascertain that e_1 occurred before e_2

Any Questions

Any Questions?