Technische Universität Darmstadt

Telecooperation Lab
Prof. Dr. Max Mühlhäuser

TK1: Distributed Systems - Programming & Algorithms

Chapter 3: Distributed Algorithms

Section 2: Synchronization – Time and State

Lecturer: **Prof. Dr. Max Mühlhäuser**

Types of Distributed Systems

TECHNISCHE UNIVERSITÄT DARMSTADT

Two types of distributed systems relevant for distributed algorithms:

- Synchronous
- Asynchronous

- **Synchronous** distributed systems are systems with known bounds on:
  1. **Message transmission delay**
  2. **Execution time (for each step of system)**
  3. **Clock drift rate**
  - Typically specify maximum and minimum bound (can be 0)
  - Measured or conservatively estimated
- **Asynchronous** system is a system where at least one of the above three conditions does not hold

Types of Systems: Remarks

TECHNISCHE UNIVERSITÄT DARMSTADT

Are **assumptions** about synchronous distributed systems **reasonable**?

Yes and maybe no

- Yes: synchronous distributed systems (as defined) *can be (and are!) built*
  - Some video-on-demand services, other special purpose / realtime systems
- Maybe no:
  - Uncertainty wrt. bounds (max - min) may be so large that system becomes *impractical*
  - *and:* the Internet as a whole **is asynchronous**
    - And still: there are many useful applications in the Internet ☺
    - why: synchronous solution may be "provably correct", lack of properties may be mitigated
- Conclusion: One can live with asynchronous systems
- But: many distributed algorithms first built for synchronous case, then extended
  - i.e. we will hear about these again later

- For now, we will focus on condition 3: "clock drift rate"
  - Leads to issues of physical clocks → HW clock synchronization, below

Hardware Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

- Physical clocks in computers are realized as crystal oscillation counters @ hardware level
  - Correspond to counter register H(t)
  - Used to generate interrupts
- Usually scaled → approximate physical time t yielding software clock C(t): $C(t) = \alpha H(t) + \beta$
  - C(t) measures time relative to some meaningful reference event
    - E.g., 64 bit counter for # of nanoseconds since last boot
    - Add "boot time" (stored somewhere) → get approximate actual time T (via OS call)
  - Programmer/user: tempted to assume C(t) = t
    - Never 100% achieved; plus: *resolution usually much lower that that of H(t)*
    - Note: values given by two consecutive clock queries will differ only if clock resolution is sufficiently smaller than processor cycle time
    - Interesting effects if one tries to measure, e.g., "execution time" of code block

Problems with Hardware Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Skew:** Disagreement in the reading of two clocks
- **Drift:** Difference in the rate at which two clocks count the time
  - Due to physical differences in crystals, plus heat, humidity, voltage, etc.
  - Accumulated drift can lead to significant skew
- **Clock drift rate:** difference in precision between a prefect reference clock and a physical clock,
  - Usually, 10^{-6} sec/sec; 10^{-7} to 10^{-8} for high precision clocks

Measuring Time

TECHNISCHE UNIVERSITÄT DARMSTADT

- Traditionally, time measured astronomically
  - Dasis: transit of the sun (highest point in the sky)
  - Yields: solar day and solar second (a 86400th of mean solar day)
- Problem: Earth's rotation is slowing down
  - Days get longer and longer
  - 300 million years ago there were 400 days in the year ;-)
- Modern way to measure time: atomic clock
  - Based on transitions in Cesium-133 atom
  - Still need to correct for Earth's rotation: leap seconds
- Result: Universal Coordinated Time (UTC)
  - UTC available via radio signal, telephone line, satellite (GPS)
  - Typical sending frequency: once per second (rarely, for a 1GHz computer!)

Synchronizing Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

- **External** synchronization
  - synchronize process clock with an authoritative external reference clock S(t) by limiting its skew to a delay bound D > 0
    - $|S(t) - C_i(t)| < D$ for all t
  - For example, synchronization with a UTC source
- **Internal** synchronization
  - Synchronize the local clocks within a distributed system to disagree by not more than a delay bound D > 0, without necessarily achieving external synchronization
    - $|C_i(t) - C_j(t)| < D$ for all i, j, t
- Obviously:
  - For a system with external synchronization bound of D, the internal synchronization is bounded by 2D

Clock Correctness

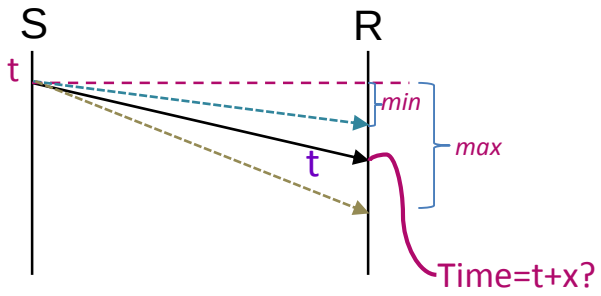
TECHNISCHE UNIVERSITÄT DARMSTADT

When is a clock correct?

1. If drift rate falls within a bound r > 0, then for any t and t' with t'>t the following error bound in measuring t and t' holds:
   - $(1-r)(t'-t) \leq H(t') - H(t) \leq (1+r)(t'-t)$
   - consequence: no jumps in HW clocks allowed → SW clock synchronization?
2. Sometimes monotonically increasing (software) clock is enough:
   - $t'>t \Rightarrow C(t') \geq C(t)$ --- but, this is insufficient for 'time keeping matters'
     (Colouris says $C(t') > C(t)$, but "ticks" of C are discrete → for small $t'-t$ this does not hold)
3. Hence: **frequently used condition** …
   - Monotonically increasing +
   - Drift rate bounded between synchronization points +
   - Clock may jump ahead (!) at synchronization points

Synchronization in Synchronous Systems

- Recall synchronous system:
  - Known bounds for: i) clock drift rate, ii) max. message transmission delay *max*, and iii) time to execute each step
- Synchronization procedure:
  1. Sender piggybacks own time t on message m
  2. Receiver sets own clock to: $t + T_{trans}$



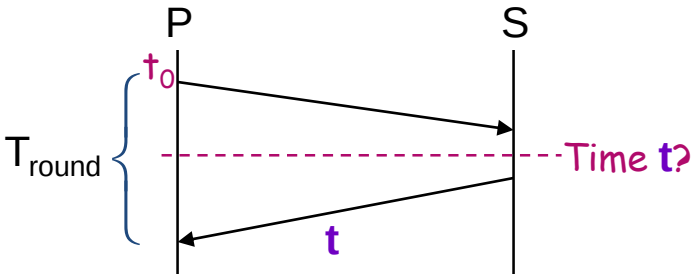
Problem: How to estimate T_{trans} ?

- Usually, it is possible to estimate minimum transmission delay *min* (or: set to 0)
  - Make conservative assumptions, also assume: no cross traffic interferes
- Let *u = max - min*
  - If receiver sets own clock to t + ½(*max*+*min*), then the skew is bounded by u/2
  - When synchronizing **N clocks**: it is possible to show that the optimum achievable bound is $u * (1 - {}^{1}/_{N})$
- Is this usable for, e.g., the Internet? No (asynch. → no *max,* plus: cross traffic)!

Christian's Algorithm (F. Christian 1989)

- Observations:
  - Round trip times between processes are often reasonably short in practice, yet theoretically unbounded
  - Practical estimate possible if round-trip times are sufficiently short in comparison to required accuracy

- Principle:
  - (assume, e.g., UTC-synchronized time server S)
  - Process P sends requests to S
  - Measures round-trip time T_{round}
    - In LAN, T_{round} often around 1 ms
    - During 1ms, a clock with a 10^{-6} sec/sec drift rate varies by at most 10^{-9} sec
    - Hence the estimate of T_{round} is reasonably accurate
  - Naive estimate: Set clock to $t + \frac{1}{2}T_{round}$



Christian's Algorithm: Analysis

TECHNISCHE UNIVERSITÄT DARMSTADT

Accuracy of estimate?

- Assumptions:
  - requests and replies via same net (same delay characteristics)
  - *min* is either known or can be estimated conservatively
- Calculation:
  - Earliest time that S can have sent reply: $t_0 + min$
  - Latest time that S can have sent reply: $t_0 + T_{round} - min$
  - Total time range for answer: $T_{round} - 2 * min$
  - Accuracy is $\pm (½T_{round} - min)$
- Discussion:
  - Really only suitable for (rather deterministic) LAN environment or Intranet
  - Problem of failure of S
    - Christian proposes redundancy through group of servers, multicast requests
    - How to choose from several replies if they vary? (byzantine agreement problems)
  - What about an imposter providing false clock readings? (authentication, attestation?)

Alternative Algorithm

TECHNISCHE UNIVERSITÄT DARMSTADT

Berkeley algorithm (Gusella&Zatti '89)

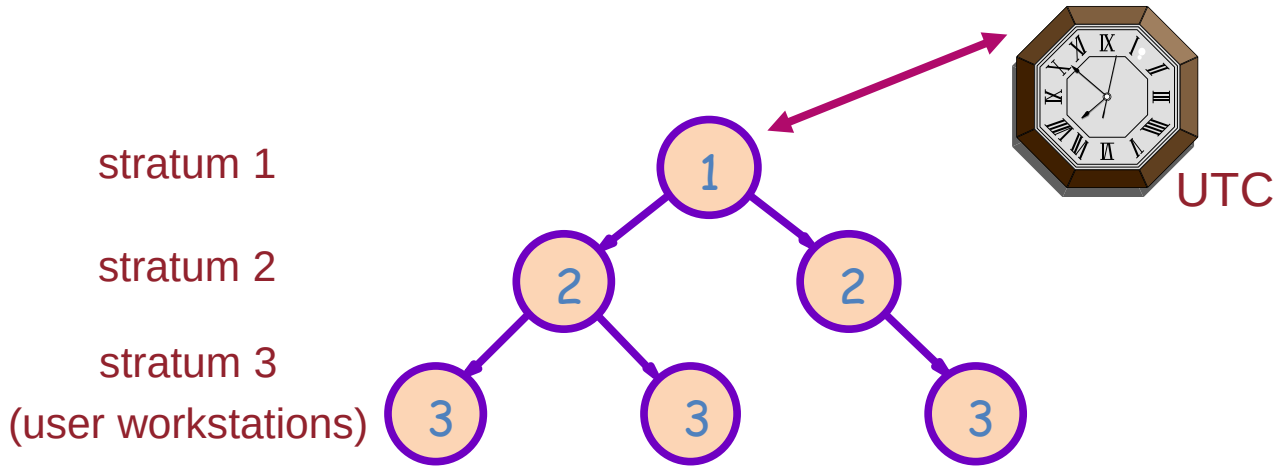
- Principle:
  - No external synchronization, but one master server (time daemon)
  - Master polls slaves periodically about **their** clock readings
  - Estimate of local clock times using Christian-like round trip estimation
  - Averages the values obtained from a group of processes
    - Cancels out individual clock's tendencies to run fast
  - Tells slave processes by which amount of time to adjust local clock
  - Master failure → find new master via election algorithm (see later)
- Experiment published:
  - 15 computers, local drift rate < 2×10^{-5}, max round-trip 10 ms
  - Clocks were synchronized to within 20-25 ms

- Note: neither algorithm really suitable for Internet where RTTs vary a lot
  (→ computing the average is bad idea)

Clock Synchronization: NTP

Internet Network Time Protocol (NTP)

- Goals:
  - Ability to externally synchronize clients via Internet to UTC
  - Provide reliable service tolerating lengthy losses of connectivity
  - Enable clients to resynchronize sufficiently frequently to offset typical HW drift rates
  - Provide protection against interference
- Synchronization subnets



Note: Arrows denote synchronization control, numbers denote strata.

Clock Synchronization: NTP (cont.)

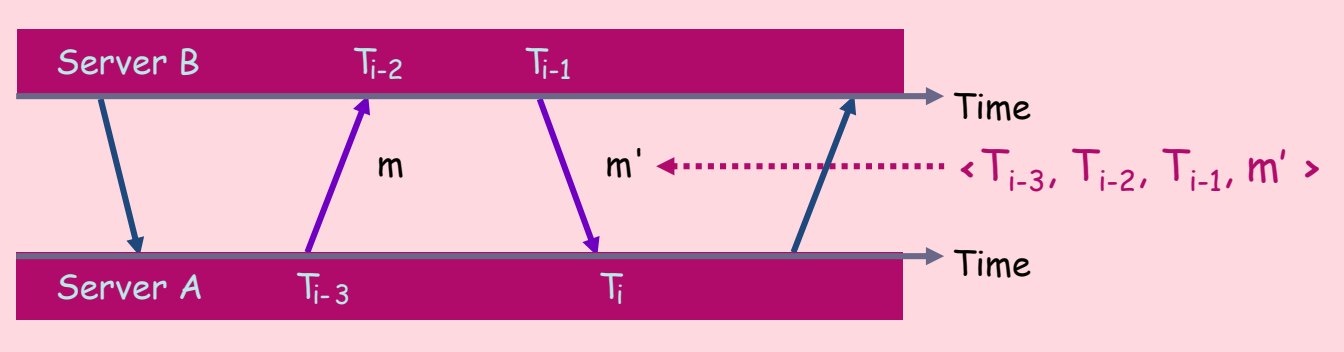
TECHNISCHE UNIVERSITÄT DARMSTADT

- Layered client-server architecture, based on UDP message passing
- Synchronization at clients with higher strata number less accurate due to increased latency to strata 1 time server
- Failure robustness: if a strata 1 server fails, it may become a strata 2 server that is being synchronized though another strata 1 server
- Modes
  - Multicast:
    - One computer periodically multicasts time info to all other computers on net
    - These adjust clock assuming a very small transmission delay
    - Only suitable for high speed LANs; yields low but usually acceptable sync.
  - procedure-call: similar to Christian's protocol
    - Server accepts requests from clients
    - Applicable where higher accuracy is needed, or where multicast is not supported by the network's hard- and software
  - Symmetric:
    - Each node is client and server (higher accuracy, more overhead, no hierarchy)

Clock Synchronization: NTP (cont.)

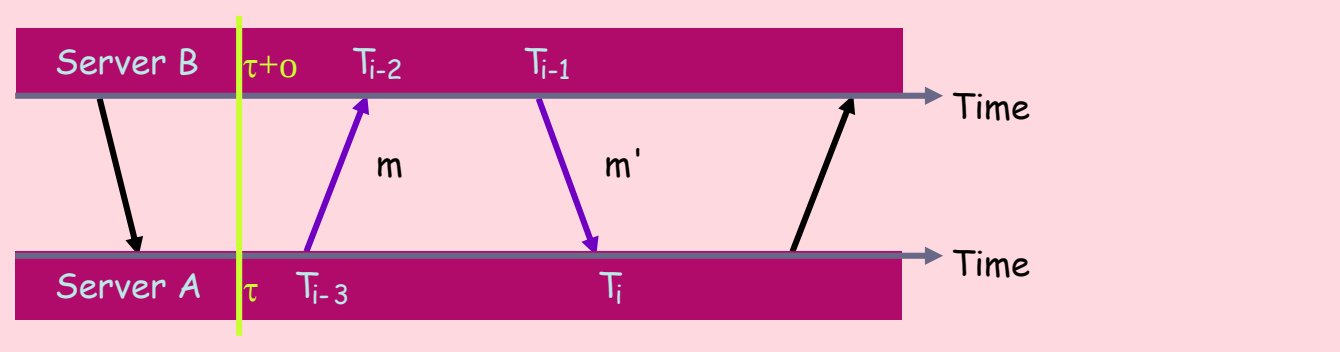
Here: protocol mechanism for procedure-call mode (symmetric mode: similar)

- All messages carry timing history information
  - Local timestamps of send and receive of *previous* NTP message
  - Local timestamp of send of *current* message



  - For each pair i of messages (m, m') exchanged between two servers the following values are being computed
    (based on 3 values carried w/ msg and 4th value obtained via local timestamp):
    - Offset o_i: estimate for the actual offset between two clocks
    - Delay d_i: true **total transmission time** for the pair of messages

Clock Synchronization: NTP (cont.)



- Let **o** the true offset of B's clock relative to A's clock (which can not be calculated), and let **t** and **t'** the true transmission times of m and m' (note: T_i, T_{i-1} ... are **not** true time!)
- Then, obviously: $T_{i-2} = T_{i-3} + t + o$ (1) and
  $T_i = T_{i-1} + t' - o$ (2)
- Adding equations (1) + (2) leads to

  delay d_i = $t + t' = T_{i-2} - T_{i-3} + T_i - T_{i-1}$ (clock errors zeroed out → **true** d)
- Offset (can't get rid of T's → estimate); e.g., subtract equations (1) – (2):

  offset **o** = $o_i + ½ (t' - t)$, where offset **estimate o_i** = $½ (T_{i-2} - T_{i-3} + T_{i-1} - T_i)$
- Accuracy (note: ½ (t - t') is error in estimate):
  for t, t' ≥ 0 it can be shown that

  $o_i - d_i/2 \leq o \leq o_i + d_i/2$

  hence, o_i is an estimate for o, and d_i is a measure for the estimate's accuracy

Clock Synchronization: NTP (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Internet Network Time Protocol (NTP): implementation, discussion:

- Statistical algorithms based on 8 most recent $<o_i, d_i>$ pairs:
  → determine quality of estimates
- The value of o_i that corresponds to the minimum d_i is chosen as an estimate for o
- Time server communicates with multiple peers,
  eliminates peers with unreliable data,
  favors peers with lower strata number
  (e.g., for primary synchronization partner selection).
- NTP phase lock loop model: modify local clock in accordance with observed drift rate
- (at times of slower LANs), experiments achieved synchronization accuracies of
  10 msecs over Internet, and 1 msec on LAN using NTP

DistSys Middleware (Platforms) usually contains „time service“ (Corba, DCE, ...), based on similar methods

Hardware Clocks: Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- Remember Problems, Terms
  - Clock register: has limited resolution, access from programming language restricted
  - Skew: disagreement in the reading of two clocks
  - Drift: difference in the rate at which two clocks count the time
    - Due to phys. differences in crystals, plus heat, humidity, voltage etc.
    - Accumulated drift can lead to significant skew
  - Clock drift rate: difference in precision: "prefect reference clock" vs. physical clock
    - Usually, 10^{-6} sec/sec, 10^{-7} to 10^{-8} for high precision clocks
  - External synchronization (wrt. "external clock", such as UTC) vs. internal sync.
  - Jumps in hardware clock? → what bounds can be guaranteed?
    - Usually, monotonicity of clock required + bounds in drift rate & jumps
- Remember Algorithms
  - In synchronous distributed systems, skew between N clocks can be bound
    - … by an "optimal algorithm" to u (1 - 1/N) where u = max – min (upper / lower transmission delay bounds)
  - in asynchronous distributed systems (Internet)
    - Algorithms by Christian and by Gusella&Zatti, both are not satisfying → NTP 'best result we can get'

Idea: what do we really need? Exact time or ordering of events?

Logical Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

- remember **why** we wanted global time: causalities, ordering of events
  - with physical clocks, skew may still be, e.g., 10^{-3} sec
- idea: use 'provable' causalities to order events, hope to infer other causalities
  - within a single process: ordering of events directly observable
  - between different processes, simplest 'provable' causality:
    sending of a message happens before receiving the same message
- is this a total or partial order?
  - actually, total order is possible, overhead / slowdown (lock-step) is considerable!
  - often, partial order is sufficient
- underlying rules:
  - If two events happen in the same process p_i, then they occurred in the order in which p_i observed them: this introduces a **local happened before relation** $\rightarrow_i$
  - for any message passing, the send event occurs before receive event

Happened Before Relation

TECHNISCHE UNIVERSITÄT DARMSTADT

Lamport's "happened before" relation
is the basic building block for ordering events

- This "happened before" relation $\rightarrow$ is defined
  based on $\rightarrow_i$ and on the send/receive causality:

HB1: for any pair of events e and e', if there is a process p_i such that e $\rightarrow_i$ e', then e $\rightarrow$ e'

HB2: for any pair of events e and e' and for any message m, if e = send(m) and e' = receive(m), then e $\rightarrow$ e'

HB3: if e, e' and e'' are events and if e $\rightarrow$ e' and e' $\rightarrow$ e'', then e $\rightarrow$ e''
(in other words, HB is identical to its transitive closure)

- *happened before* defines a partial order

Happened Before

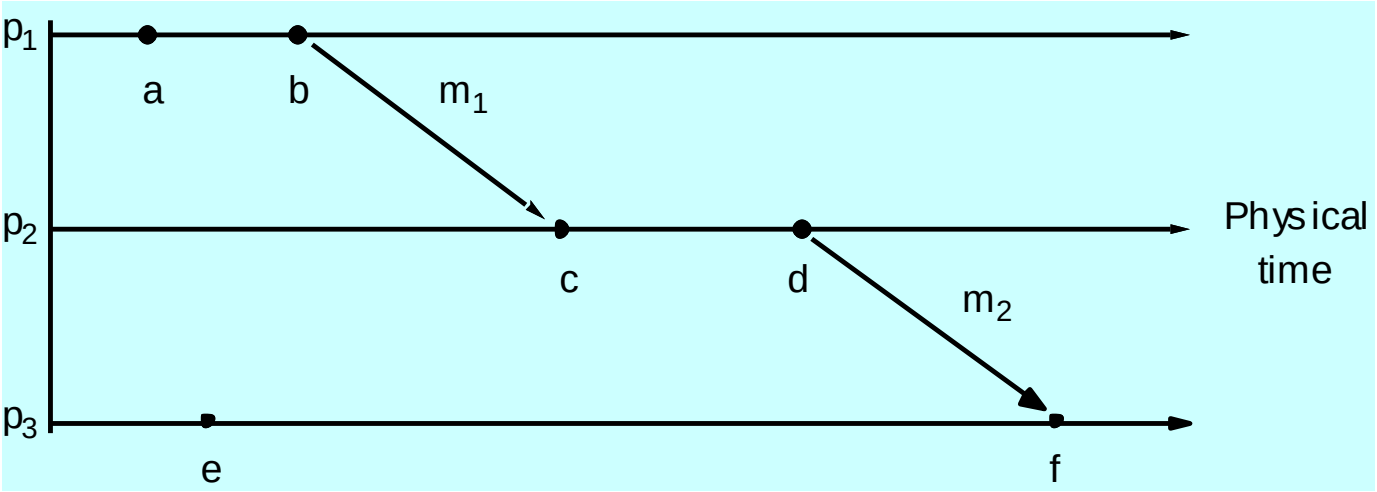
TECHNISCHE UNIVERSITÄT DARMSTADT

HB1/2/3 lead to the following:

- 'meaning' of HB: for any tuple e $\rightarrow$ e' …
  - **either** e and e' are (direct or indirect) successors *in the same process*,
  - **or** there are events e'' and e''' and a message m such that:
    e $\rightarrow$ e'' and e''' $\rightarrow$ e' and e'' = send(m) and e''' = receive(m)
    - note the recursive definition, i.e.: e $\rightarrow$ e'' may itself involve a message
- note: e $\rightarrow$ e' does not necessarily express causality between e and e'
  - causality means both *e happened before e'* AND *e was the reason for e'*
- concurrency:
  - for all e, e', if *not(e $\rightarrow$ e')* and *not(e' $\rightarrow$ e)* holds,
    then we say that e and e' are concurrent (also written as e || e')

Happened Before: Example

TECHNISCHE UNIVERSITÄT DARMSTADT



- in the above example, following holds:
  - Because of HB1: a → b, c → d, e → f
  - Because of HB2: b → c, d → f
  - … and their transitive closure
- the following events are concurrent:
  - e is concurrent to all other events except f

Lamport's Logical Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

Logical clocks …

- … are the concept & distributed algorithm corresponding to the HB relation,
- … permit inference of local event order (rather trivial)
  - monotonically increasing counters impose total order on observed events
- … and some reasoning about global event orders
  - more information comes later

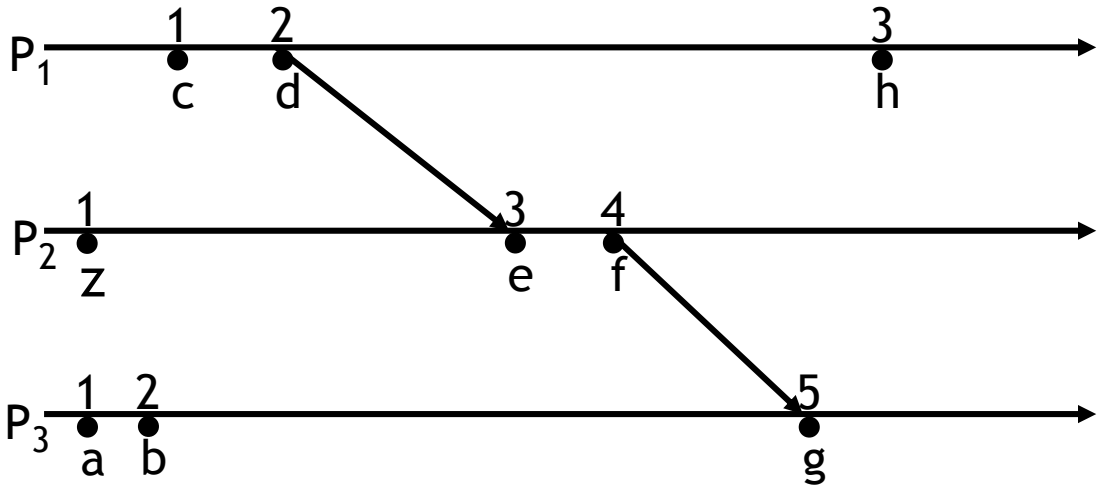
concept & distributed algorithm:

- every process p_i maintains a logical clock L_i
- $L_i(e)$ denotes the timestamp of event *e* i.e. the L_i value at its occurrence
  - Messages piggyback the timestamp of the *send* event
- algorithm ≈ rules to update logical clocks and message time stamps:

1. LC1: L_i is incremented before each event at p_i
2. LC2: A process i piggybacks L_i on every message sent, i.e. sends (m, L_i)
3. LC3: On receiving (m, t), p_j first computes $L_j = \max(L_j, t)$, then increments L_j, and then timestamps event *receive(m, t)*

Lamport's Clocks: Example

- at the beginning, timestamps are initialized (convention: to zero)
- clocks are updated according to rules LC1, LC2, and LC3
  - local events increase local timestamp
  - messages piggyback local timestamp
  - receiver of message calculates max of message and local timestamps, increases this max by 1, uses that for local timestamp



Problems

TECHNISCHE UNIVERSITÄT DARMSTADT

above algorithm has one big problem (cf. *global event orders* above)

- if e $\rightarrow$ e' then L(e) < L(e')
- **but:** L(e) < L(e') does not imply e $\rightarrow$ e'
  - for example, events b and c in figure above

- Note: It is possible to augment the partial order of **timestamps** to a total order
  - simple solution: each timestamp is concatenated with process number: $L_i(e).p_i$
  - since p_i's are unique, this gives unique timestamps
  - but: this is completely artificial
  - does not solve the above problem

Logical Vector Clocks

TECHNISCHE UNIVERSITÄT DARMSTADT

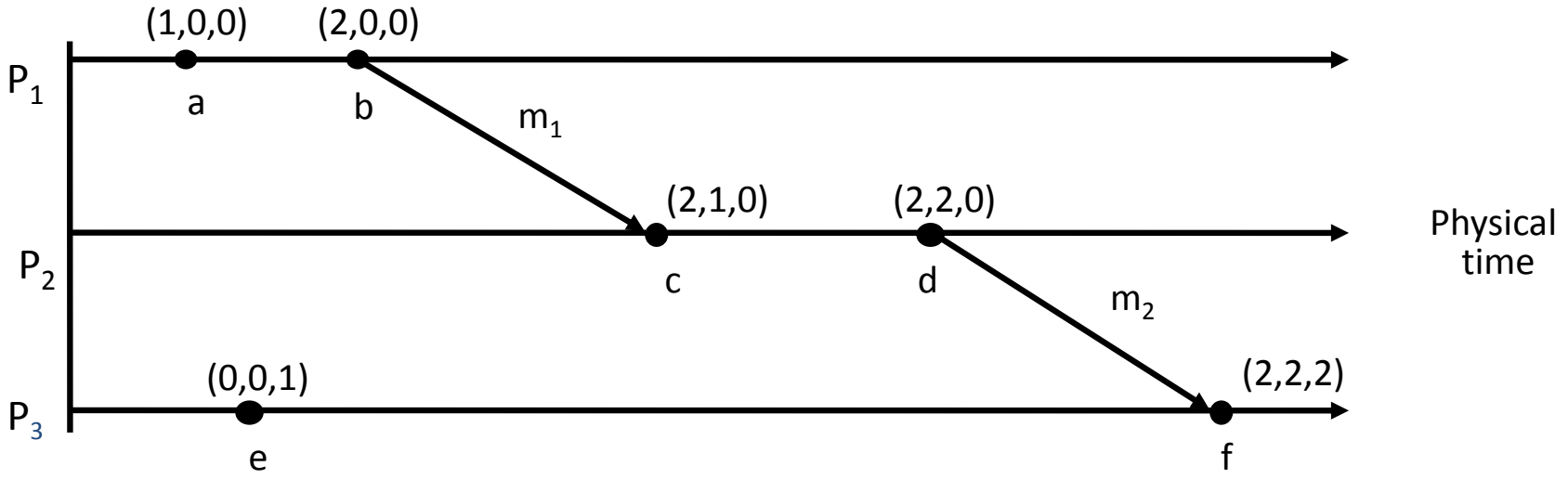
logical vector clocks solve the above problem

- vector clocks are realized as array of N (#of processes) integers
- each process i keeps its own vector clock V_i [1, ..N]
- timestamps are piggybacked as in Lamport's protocol
  - note: Timestamp is now the complete vector

again, distributed algorithm ≈ clock update rules:

1. VC1: initially, all V_i are set to [0, …, 0] (convention)
2. VC2: i sets $V_i[i] = V_i[i] + 1$ before timestamping an event
3. VC3: i includes V_i in every message (piggybacking)
4. VC4: if i receives a timestamp vector t, then i updates its V_i by means of a component-wise 'merge' similar to LC3: $V_i[j] = \max(V_i[j], t[j]), \forall j=1,..,N$

Vector Clocks: Example



- Vector clocks behave similarly to Lamport's clocks
- difference: vector clocks contain more detailed information about events in other processes
  - $V_i[j]$ is the (max) # of events in p_j that p_i has potentially been affected by
  - Lamport's clocks only *summarize* this information over all processes p_j
  - note: on the other hand, VC has higher communication complexity

Vector Clock Comparisons

- Comparison of timestamp vectors is as follows

  $V = V'$ iff $V[j] = V'[j]\ \forall j=1,..,N$

  $V \leq V'$ iff $V[j] \leq V'[j]\ \forall j=1,..,N$

  $V < V'$ iff $V \leq V'$ and $V \neq V'$
- Note: Possible to have unordered vectors
  - These imply concurrent events
- In our example:
  - $V(b) < V(d)$
  - $V(e)$ unordered to $V(d)$, i.e., $e \,||\, d$
- Theorem: $e \rightarrow e' \Leftrightarrow V(e) < V(e')$
  - This can be proven …
  - … and means: the big problem of LC is solved

now, we will move to the second corner of the ‚Bermuda Triangle'

Global States: Intro

TECHNISCHE UNIVERSITÄT DARMSTADT

Remember sample problem 'total amount of money in circulation' from intro chapter

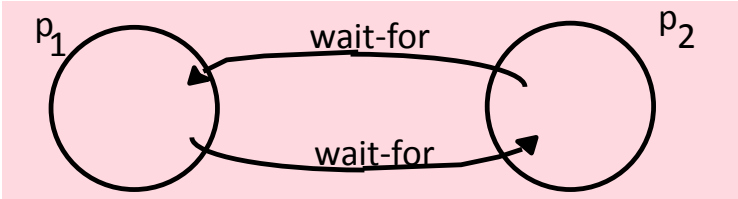
- Another sample problem that would require the view on a global state:

  Distributed deadlock detection:

  is there a cyclic 'wait-for' graph

  amongst processes and resources

  in the system?



- many other examples exist, both of general (see next slide) and of domain specific nature (e.g., in distributed simulation, …)
- remember (from intro) why a fully consistent, up-to-date global state is infeasible:
  - system state changes while we conduct observation
  - observation msgs are outdated
  - messages suffer timestamp (clock) problems

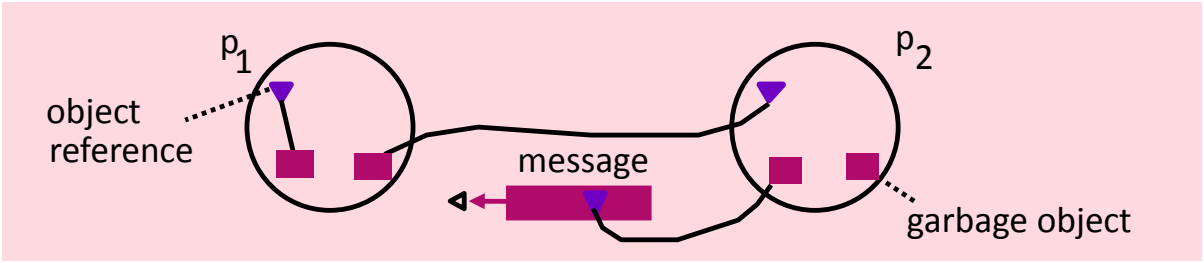
  →we may get inaccurate, inconsistent, even contradicting / false, outdated observation results

Global States: Intro (cont.)

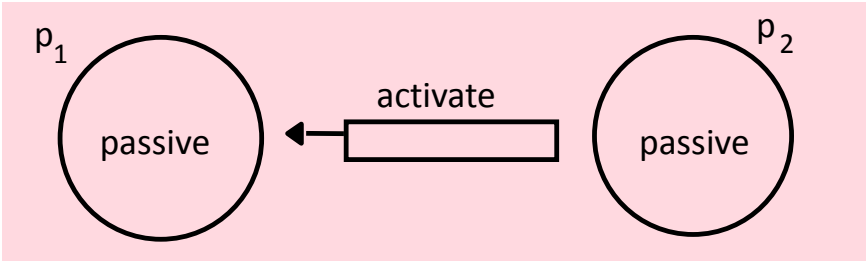
TECHNISCHE UNIVERSITÄT DARMSTADT

Further (general) problems that would require the view on a global state

- distributed garbage collection: any reference to an object left?



- distributed termination detection:
  any active process left or any process activation message in transit?



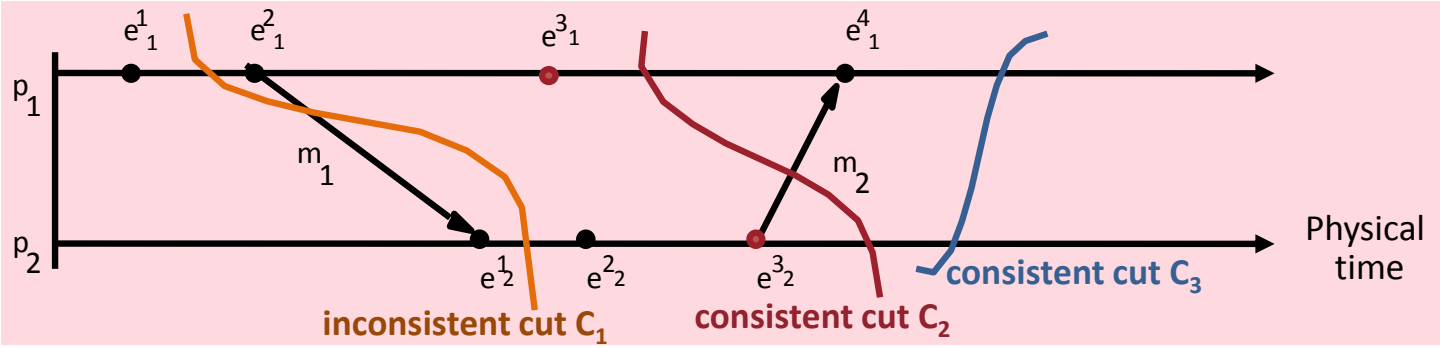
Cuts as Approximation of Global States

compute an up-to-date global state - how close can we get? remember *observation issues:*

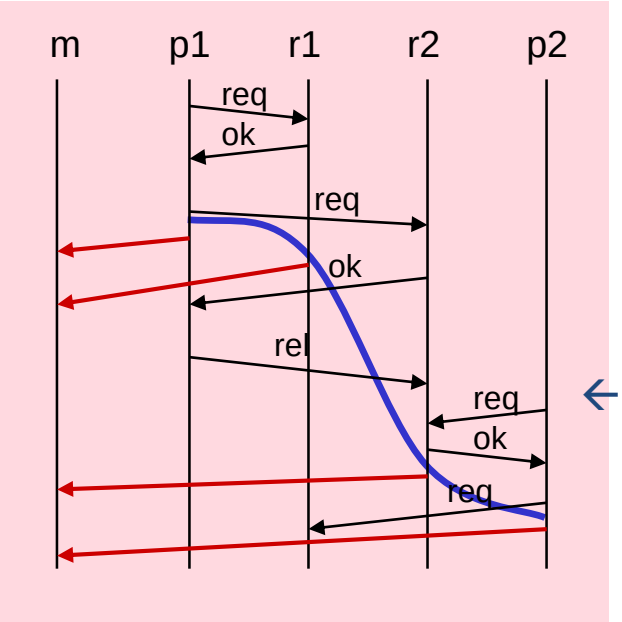
- what can/should be observed? *process events → states* and *communication events → channel states*
- why is it difficult? interrelated 'Bermuda triangle' problems
  - an important sub-issue, see distributed termination & garbage collections: messages-in-transit? (cf. 'channel states')
- a first idea: **observe** events & states of local processes, **infer** 'channel' states i.e. messages-in-transit
  accept that only **out-dated states** can be 'reconstructed' – but **how well?**

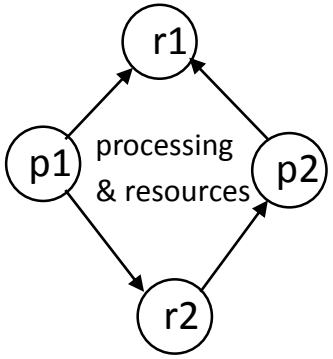
this first idea leads to: **cuts**

- compute an assumed former global state from state information of the processes,
  such that the resulting "cut" through the system is **consistent:**
  - the cut includes no events that are the effect of another event without that
    the 'causing events' be also part of the cut (cf. „→" relation), see C_2 below
  - the idea: only events that could have happened 'simultaneously' appear as the-most-recent-event-per-process
    - 'concurrent events' in the sense of HB, such as e^3_1 and e^3_2 for C_2 , or
    - 'causal events' such as e^3_2 and e^4_1 for C_3



Global States: Cuts (cont.)



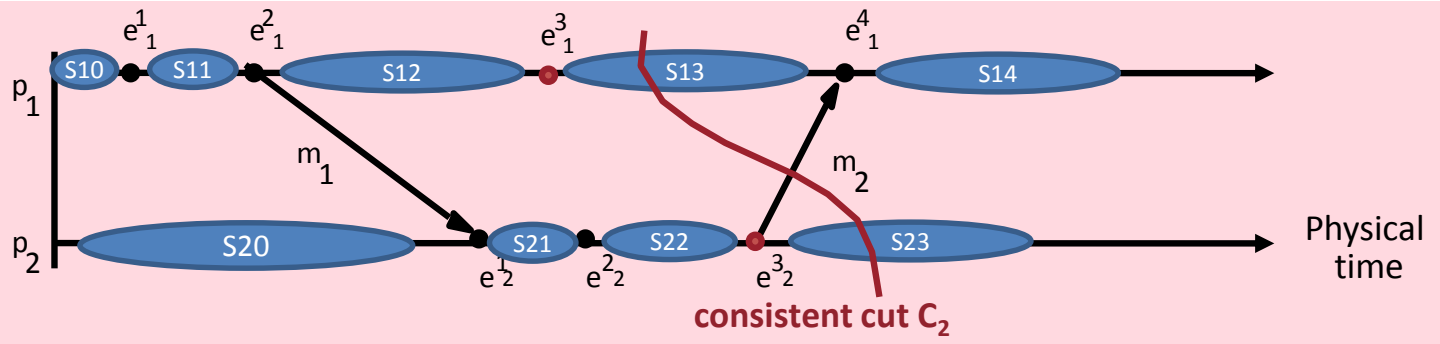


← another example of an inconsistent cut, involving 5 processes:
2 processing (p), 2 resource mgmt. (r), 1 monitoring
why inconsistent? „rel“ (p1→r2):
receive event ∈ cut, but send event ∉cut
in this case, a „phantom message“ would be detected

Inlet about the concept *history:*

- history of process p_i : $h_i = < e_i^1, e_i^2, ... >$
  - each e_i^k corresponds to either a send, receive, or internal action
- s_i^k then denotes the state of process i immediately after the k-th event e_i^k
- (remember idea: record send/receive events as part of state ⇒ channel info recoverable)
- global history: $H = (h_1, h_2, .., h_N)$

Global States: Cuts (cont.)



local states (blue ellipses) indicated here for explanation purposes

Definitions:

1. cut C:== (h_1^{c1}, h_2^{c2}, .., h_N^{cN}) such that ($\forall$i: h_i^{ci} a prefix of h_i)

- prefix: history 'that may be outdated', i.e. 'except 0…n *last* events'
- this means: each process' history is just divided into past and future

2. consistent cut: cut C for which $\forall e \in C: f \rightarrow e \Rightarrow f \in C$

- state of s_i in C is that of p_i immediately succeeding last event processed by p_i in C (i.e., e_i^{ci})
- global system state S = (s_1, s_2, .., s_N) – set of local states
- consistent global state: corresponds to consistent cut
  - considered potentially possible [past] global state
  - e.g., state (S12, S22) could have happened (but did not, in the picture above – which a DistSys cannot see)

Global States

TECHNISCHE UNIVERSITÄT DARMSTADT

Global state sequence

- consider a system as evolving in a sequence of global state transitions

  $S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow \ldots$

  - precisely 1 process performs local transition in every step of sequence
  - turns the partial order of all events in the system into a total order, concurrent events can be thought of as having happened in some total order (linearization) that is consistent with the partial order described through $\rightarrow$
  - S' called reachable from state S if there is a linearization passing thru S then S'
  - possible to further formalize these concepts
- Definitions:
  - Run = ordering of all events (in a global history) consistent with $\rightarrow_i$ for each p_i i.e. with each local history's ordering
  - Linearization (also known as 'consistent run') = Run *and* consistent with "$\rightarrow$" (in addition to $\rightarrow_i$, all related send and receive events are in order)
  - S' reachable from S: $\exists$ linearization: …➔ S ➔ … ➔ S' ➔…

Global States vs. Properties

TECHNISCHE UNIVERSITÄT DARMSTADT

remember properties from intro chapter! here: → state properties

- express syst. properties by defining predicates π evaluated on states
  - e.g., $x(S_i) = 5$
  - e.g., $num\_crit(S_i) \leq 1$
- safety properties: “No bad thing will ever happen”, e.g.
  - system never deadlocked
    - (note: a *required* deadlock would be a *liveness* and even a *stability* predicate: once deadlocked, sys. will remain so forever)
  - the sum of money in the electronic payment system is constant i.e. never changes
  - there is never more than one process in critical section
- liveness properties: “Eventually something good will happen”, e.g.
  - the system will eventually make progress
  - the system will eventually terminate
  - every sent message will eventually be received (leadsto)
  - if a process requests access to the critical section infinitely often, it will be granted access infinitely often (strong fairness)

Global States (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Kinds of global state predicates:

- Stability

ω= true in S
$\forall S'$, S ➔ … ➔ S' $\Rightarrow$ ω= true in S'

- Safety

α = undesirable property
S_0 = initial state of system
$\forall S$, S_0 ➔ … ➔ S $\Rightarrow$ α = false in S

- Liveness

β = desirable property
S_0 = initial state of system
$\exists S$, S_0 ➔ … ➔ S $\Rightarrow$ β = true in S

Snapshots

TECHNISCHE UNIVERSITÄT DARMSTADT

Definitions ok! Goal now: observation of global states
i.e. distributed algorithms for computing global states

- impossibility to obtain up-to-date global state information →
- goal: take "snapshots" i.e. observe
  consistent global states: states that correspond to consistent cuts
  - no ordering violation within processes
  - no causality violation for send/receive message events
  - local states comprised in consistent global state *could* have occurred all at the same time
- naive logical time based snapshot algorithm
  - given time t known to all processes 1.. N for which snapshot is sought
    - determine state of each process
      after events with timestamp less than or equal to t
    - for every pair (x, y) of processes determine, according to the local event history for x and y, which messages have been sent but are not yet received at time t - those messages are part of the state
  - problem: requires logical clocks

Snapshots

TECHNISCHE UNIVERSITÄT DARMSTADT

Chandy-Lamport algorithm: determination of consistent global states

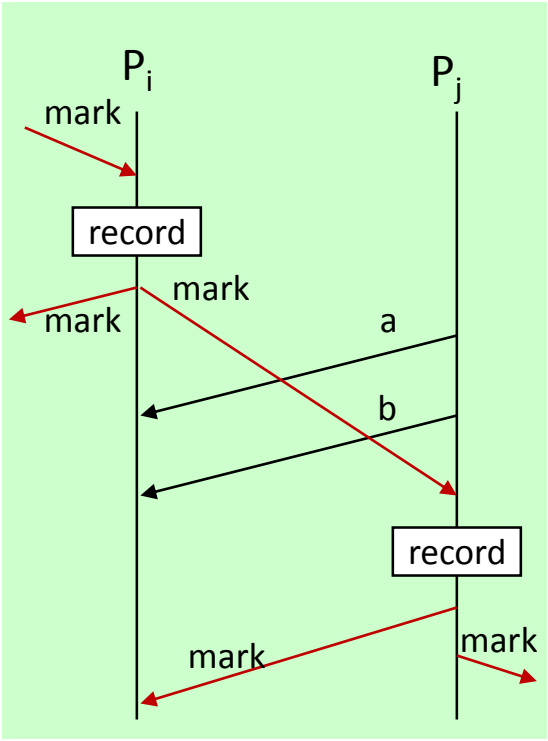
- goal:
  observe consistent global states w/o maintenance of logical clocks
- idea:
  - use marker messages broadcasted in the (fully connected) distributed system to distinguish messages sent before or at t from those after t
  - causes processes to locate local and channel state information, does not (yet) include gathering of local state info to form global state
- assumptions:
  - perfect communication: no loss, corruption, reordering or duplication of messages occurs, and messages sent will eventually be delivered
  - unidirectional FIFO channels
  - processes fully meshed, virtually
    (there's a „path" from every process to every other process; e.g., TCP)
  - any process may initiate a snapshot-taking at any time (!!)
  - normal system execution continues during snapshot-taking

Snapshots: Chandy-Lamport

TECHNISCHE UNIVERSITÄT DARMSTADT

First sketch of Chandy-Lamport snapshot algorithm:

- Elements:
  - Players: processes P_i with
    - Incoming channels
    - Outgoing channels
  - Concept: „flood“ channels with (broadcast) marker messages
  - 2 Rules: Marker sending / receiving rule; rough sketch:
    - upon receipt of 1st marker:
      - record own state
      - turn on recording of incoming msgs on every channel;
        for channel $P_j \rightarrow P_j$: record msgs until P_j has recorded its state → sends marker
        → we receive it (these msgs are considered „in transit“ in channel $P_j \rightarrow P_i$ for cut)
      - send markers on all outbound channels
    - upon receipt of further markers:
      - stop to record incoming msgs on corresp. channel (as above for $P_j \rightarrow P_i$)
      - if markers rcvd. on all channels: send all info to initiator (its ID travels in marker msg)
    - processes may record their state at different points in time, but
      the differential is always accounted for by the state of the corr. channel
- Start of algorithm
  - a process acts as if it received a marker message



Snapshots: Chandy-Lamport (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

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) *then* 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.

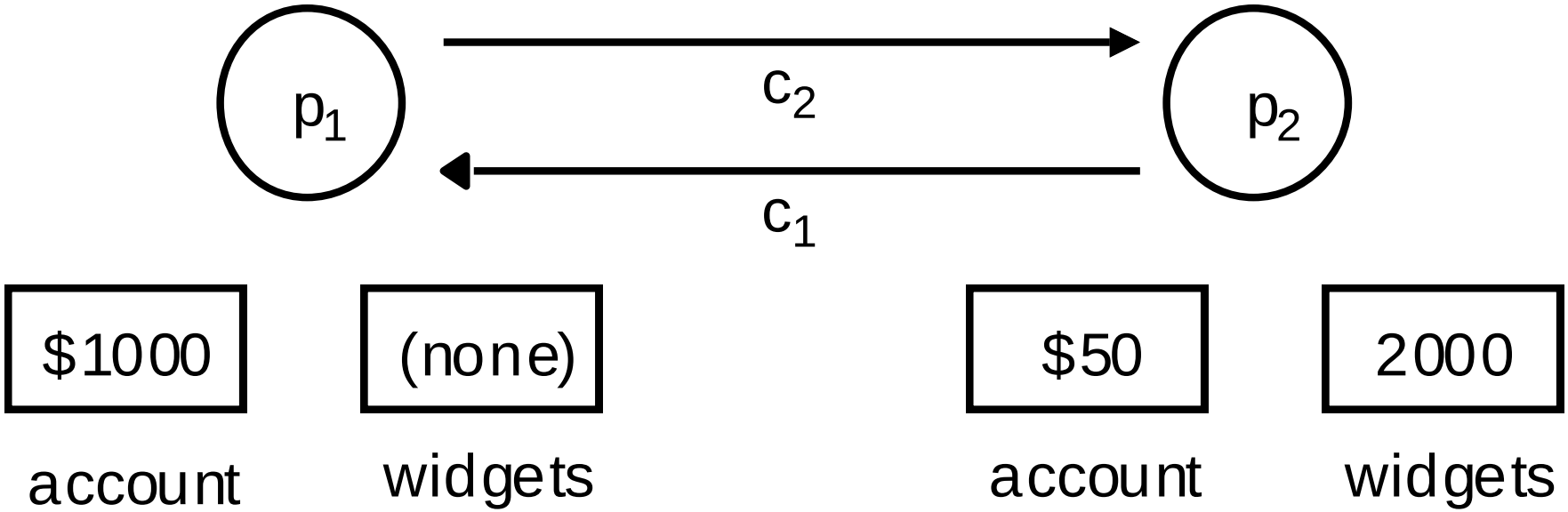
end if

Marker sending rule for process p_i

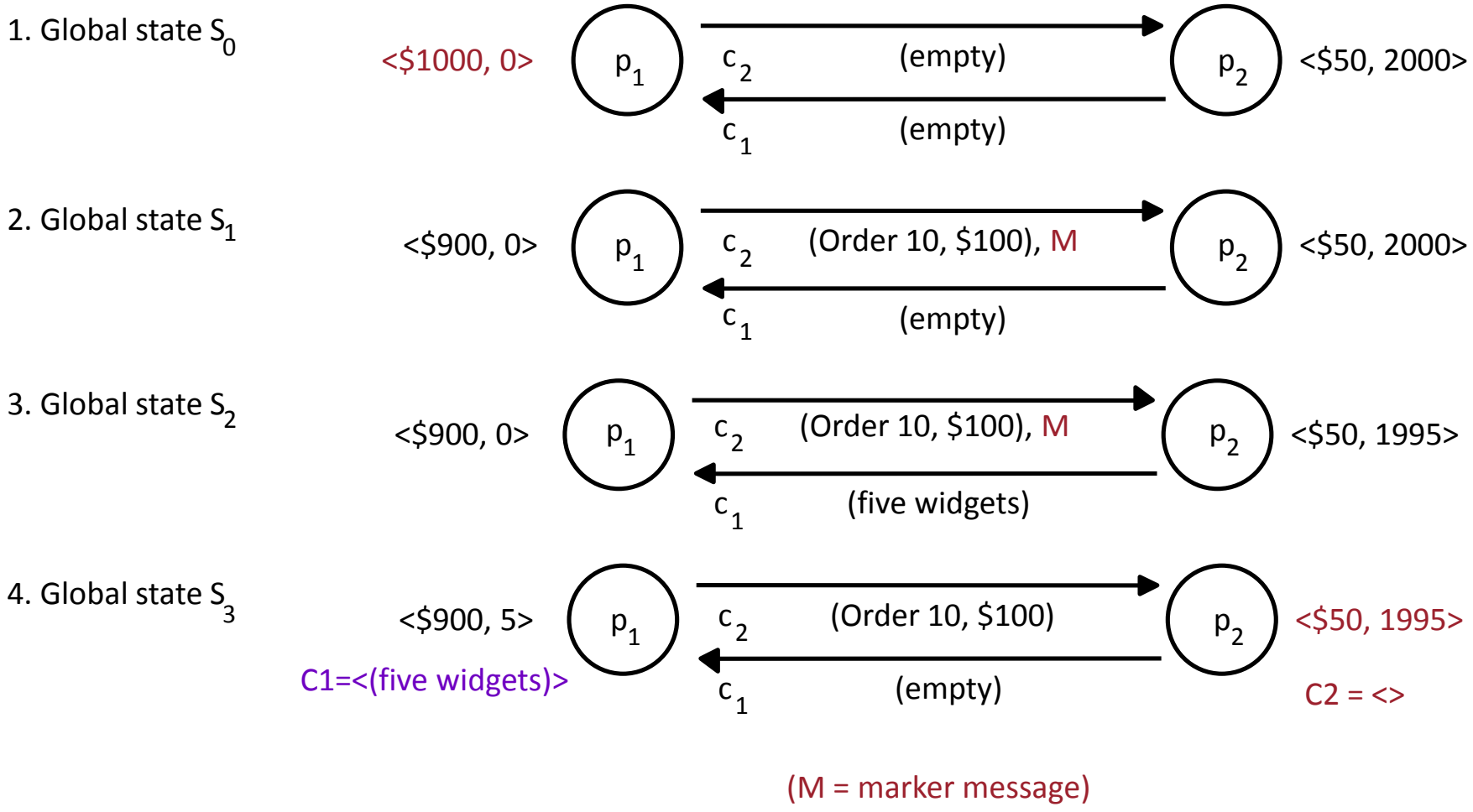
After p_i has recorded its state, for each outgoing channel *c*:
p_i sends one marker message over *c*
(before it sends any other message over *c*).

Snapshots: Chandy-Lamport (cont.)

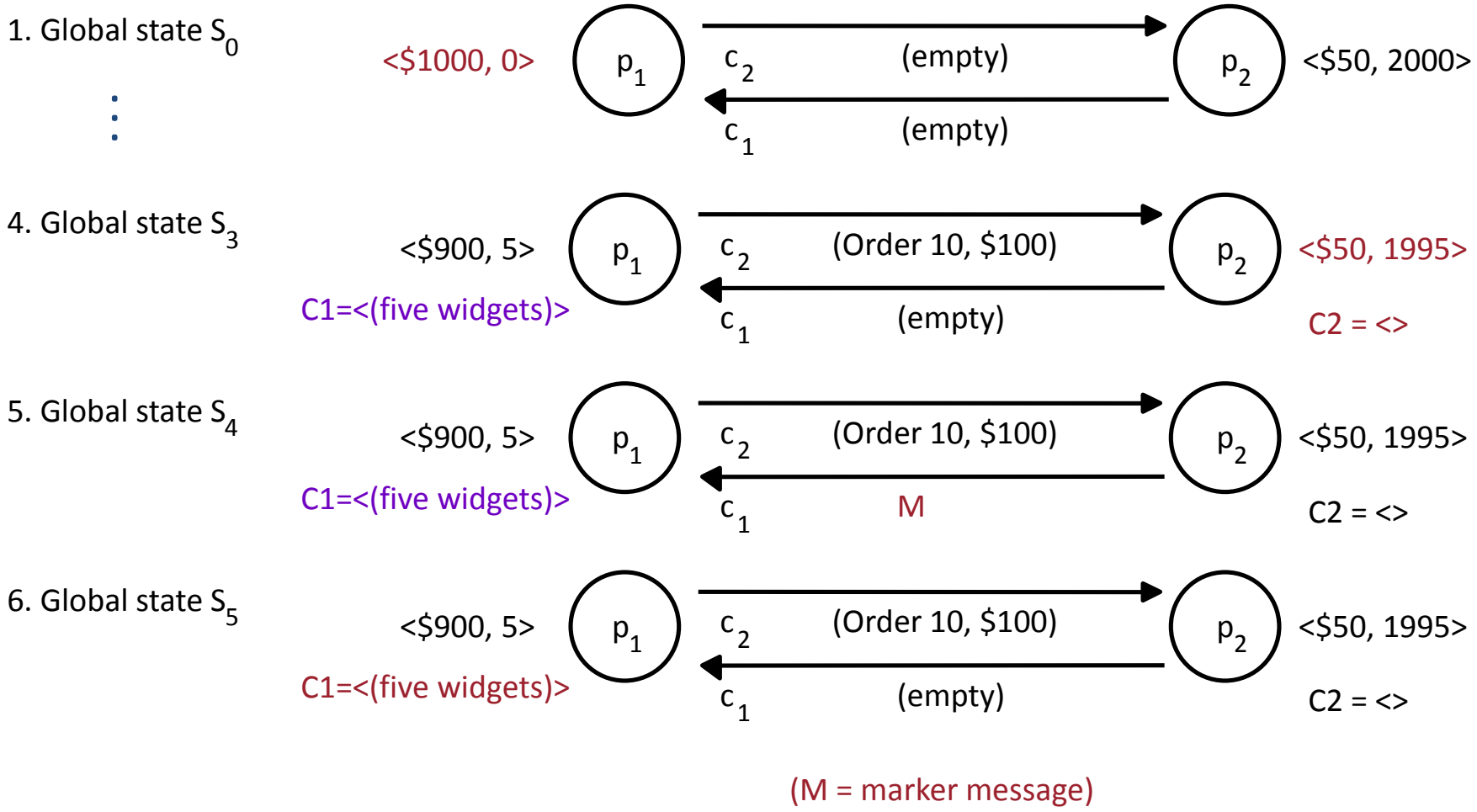
- Example: „electronic commerce“



Snapshots: Chandy-Lamport (cont.)

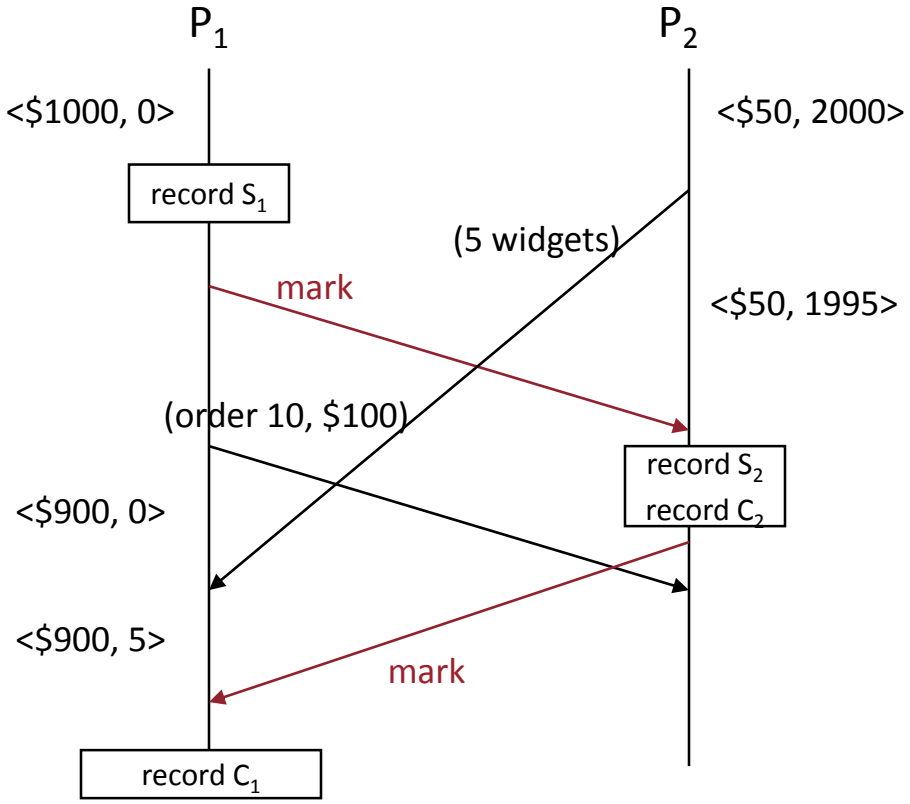


Snapshots: Chandy-Lamport (cont.)



Snapshots: Chandy-Lamport (cont.)

MSC (message sequence chart) for example:



- recorded state

  P_1: <$1000, 0>, P_2: <$50, 1995>, c_2: <>, c_1: <(5 widgets)>

Snapshots: Chandy-Lamport (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Theorem: The Chandy-Lamport Algorithm terminates

- Proof sketch:
  - Assumption: a process receiving a marker message will record its state and send marker messages via each outgoing channel in finite period of time.
  - If there is a communication path from p_i to p_k, then p_k will record its state a finite period of time after p_i
  - Since the communication graph is strongly connected, all processes in the graph will have terminated recording their state and the state of incoming channels a finite time after some process initiated snapshot taking.

Snapshots: Chandy-Lamport (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Theorem: Snapshots taken by the Chandy-Lamport Algorithm correspond to consistent global states

- Proof:

  Let e_i and e_k be events at P_i and P_k, and let $e_i \rightarrow e_k$.

  Then (we have to prove), if e_k is in the cut, so is e_i.

  That means, if e_k occurred before P_k recorded its state, then e_i must have occurred before P_i recorded its state

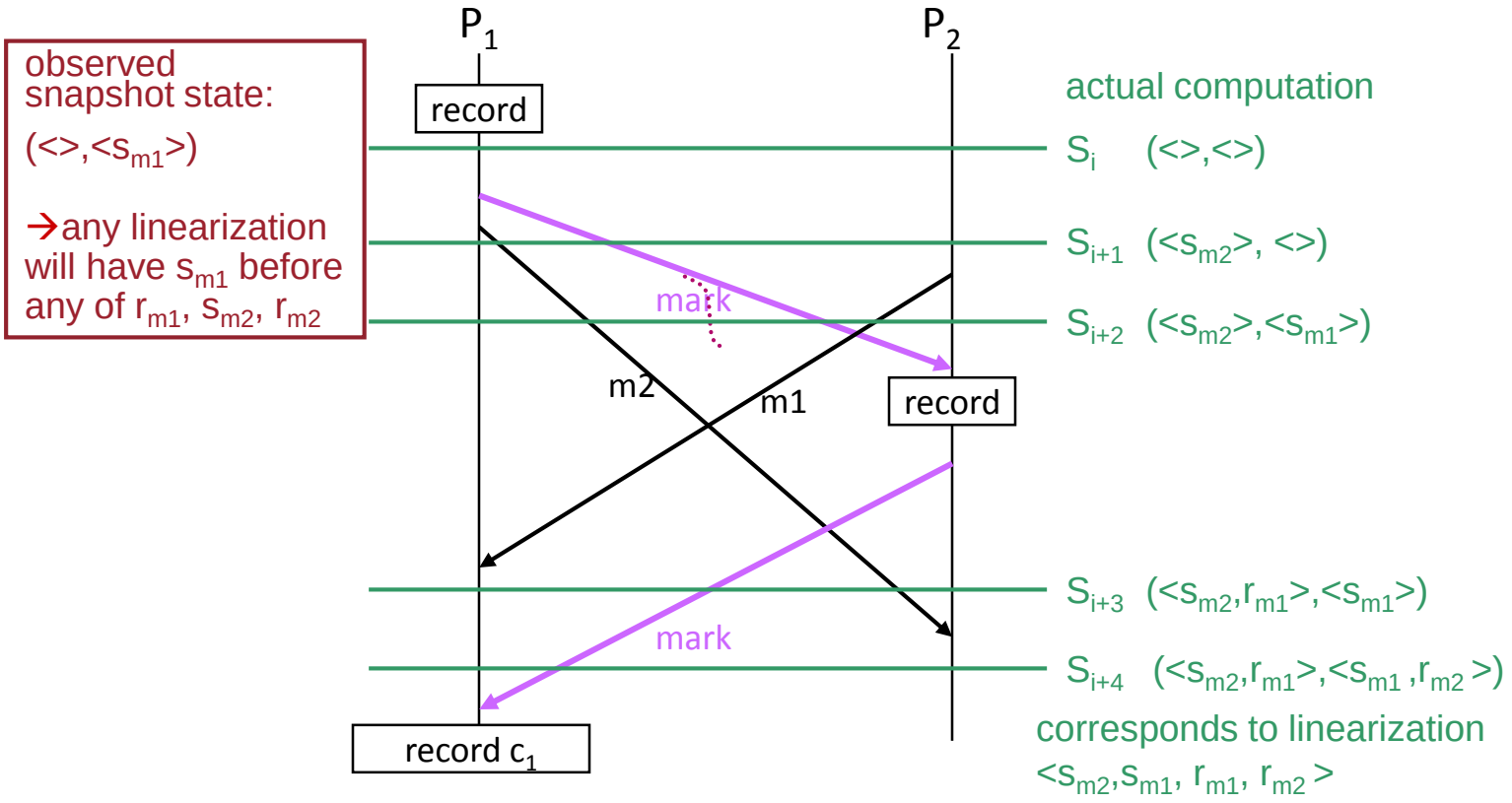
  $k=i$: obvious.

  $k \neq i$: assume P_i recorded its state before e_i occurred

  - as $k \neq i$ there must be a finite sequence of messages $m_1,..., m_n$ that induced $e_i \rightarrow e_k$
  - then, before any of the $m_1,..., m_n$ had arrived, a marker must have arrived at the corresponding receiver (at P_k before m_n), and P_k must have recorded it's state before e_k occurred, hence a contradiction

Snapshots: Chandy-Lamport (cont.)

- as expected: Chandy-Lamport algorithm records a possible global system state, but the actual execution of the system that 'took' the snapshot may never have reached it.
- shown here by example: (s_{mi}/r_{mi} denotes send/receive event for msg m_i)



Snapshots: Chandy-Lamport (cont.)

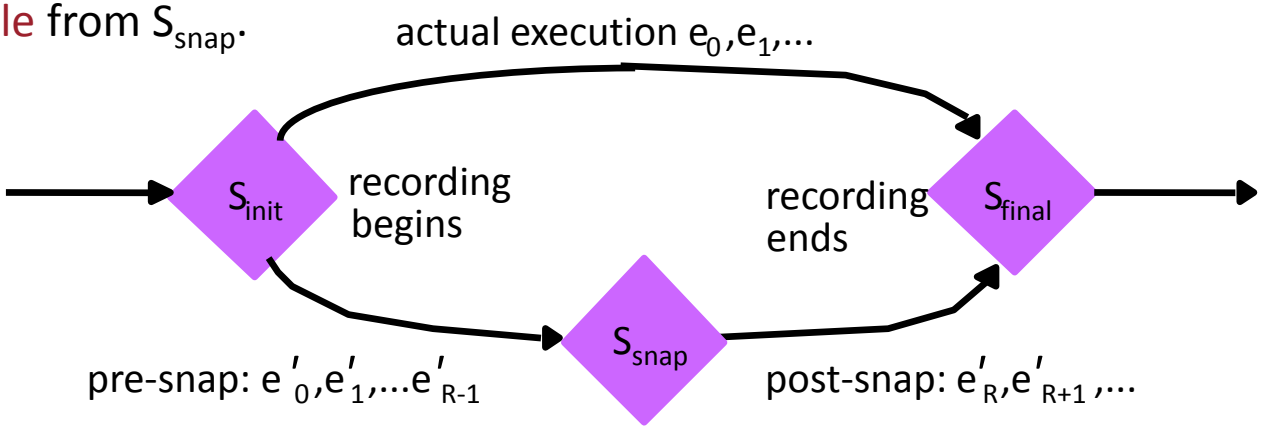
Reachability Theorem: let Sys = e_0, e_1, .. the linearization of a sys. execution

Let:

- S_{init} the initial global state of the system immediately before Chandy-Lamport snapshot-taking was initiated by the first process,
- S_{snap} the recorded snapshot state, and
- S_{final} the global system state after the algorithm terminated.

Then: there is a permutation (and still: linearization) Sys'= e'_0, e'_1, .. of Sys such that

- S_{init}, S_{snap} and S_{final} occur in Sys' and
- S_{snap} is reachable from S_{init}, and
- S_{final} is reachable from S_{snap}.



Snapshots: Chandy-Lamport (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Proof:

- split events in Sys in
  - pre-snap events: occurred before respective process (where event occurred) recorded its state
  - post-snap events: all other events
- how to order events in order to obtain Sys'?
  - assume e_j post-snap event at one process, e_{j+1} pre-snap in *different* process
    - *not*($e_j \rightarrow e_{j+1}$), since otherwise they would be send and receive of same msg, $\Rightarrow$ they would be either both post- or both pre-snap

      $\Rightarrow$ e_j and e_{j+1} may be swapped in Sys'
    - swap adjacent events, if necessary and possible, until Sys' is so that all pre-snap events precede all post-snap events
  - let e'_0, e'_1, .. e'_{R-1} denote the prefix of pre-snap events in Sys', hence the set of events prior to state recording for each process, hence all events leading from S_{init} up to the state recorded as S_{snap}
  - S_{init} & S_{final} unchanged $\Rightarrow$ reachability relationship established

Snapshots: Chandy-Lamport (cont.)

TECHNISCHE UNIVERSITÄT DARMSTADT

Conclusion:

- Reachability property and system property specification
  - S_{snap} may never have occurred in an actual system execution
  - hence, for an arbitrary state predicate P, $P(S_{snap})$ = true says nothing about the actual system run
- However, let P a stable predicate (stability property), then

  $P(S_{snap}) \Rightarrow P(S_{final})$; $\neg P(S_{snap}) \Rightarrow \neg P(S_{init})$

Consequences for Distributed Debugging:

- Properties
  - typically, user is interested in invariant safety properties
    - the system does not reach a deadlock state
    - the difference between variables x and y is always non-zero
    - the valves v_1 and v_2 may never be open at the same time
  - above snapshot algo. can at best prove violation of these properties
    - works well if the violation is a stability property:
      example again: deadlock - once true (as a debugging issue), it remains true
  - interested in a monitoring algorithm that records system traces in order to decide whether safety properties were, or may have been, violated in a given system run