Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Causality, consistency and logical time in distributed computations

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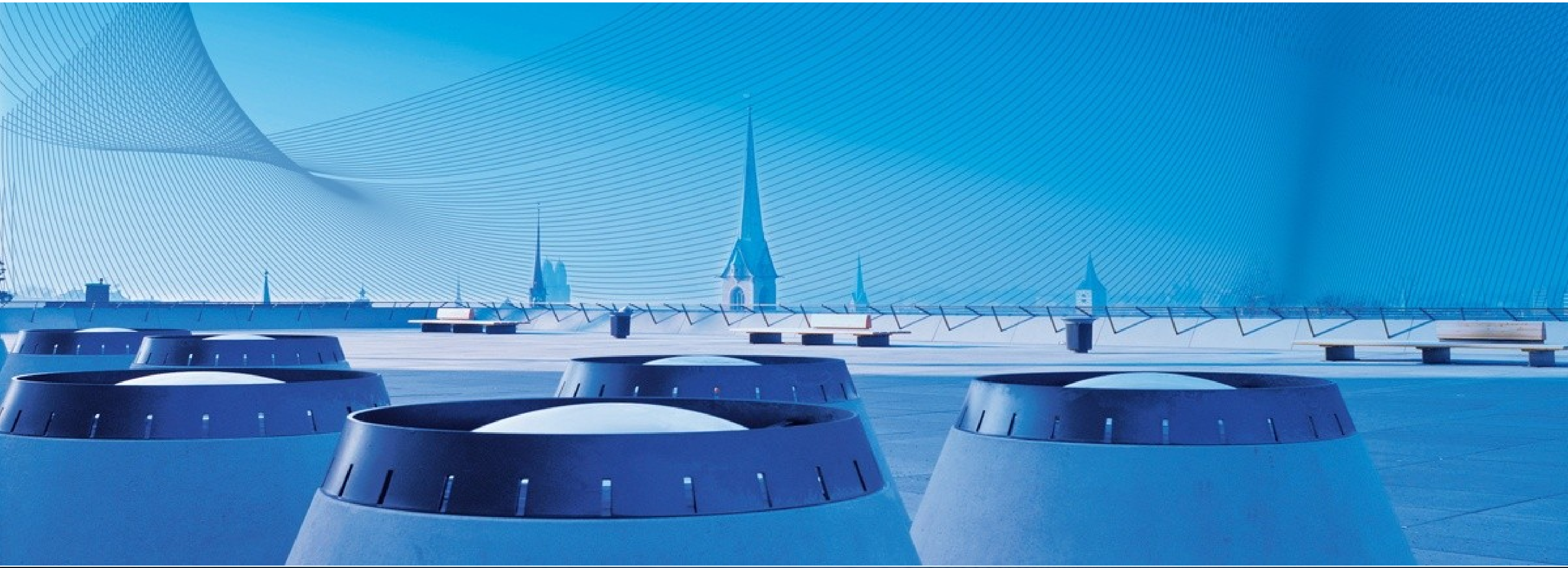


Outline

- Synchronous, asynchronous, and causally ordered communication
- Vector time
- Detecting causal relationships in distributed computations
- Conclusion

Part 1: Synchronous, asynchronous, and causally ordered communication

- A formal definition of different types of computations is needed w.r.t. causality
- Model
  - Processes form a distributed system
  - Internal-, send- and receive-events
  - Computation consists of local computations and messages
  - reliable communication

Types of computations

- A-computations
  - send and receive events are asynchronous
- FIFO-computations
  - channels have FIFO-property
- Causally ordered (NEW)
- S-computations
  - send and receive events are synchronous
  - message transmissions appear to be instantaneous

Types of computations (contd.)

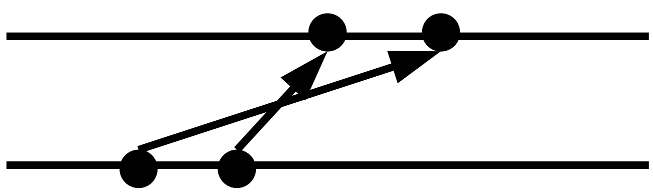
- Generally, no computation type is superior to the others
- S-computations can be simulated with A-computations and vice versa

Def: Causality relation

- $\Gamma = \{(s,r) \in C_i \times C_j$: s corresponds to r$\}$
- AS1: If a $\prec_i$ b, then a $\prec$ b
- AS2: $(s,r) \in \Gamma$, then a $\prec$ b
- AS3: If a $\prec$ b and b $\prec$ c, then a $\prec$ c

Def: A-computations

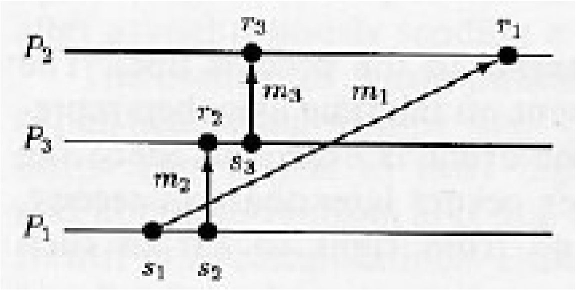
- Processes $P_1 \ldots P_n$ with a tuple $C=(C_1 \ldots C_n)$ of local computations
- A set Γ of corresponding send and receive events for which the causality relation holds



Def: FIFO-computations

- Additionally, for all (s,r) and (s',r') $\in \Gamma$

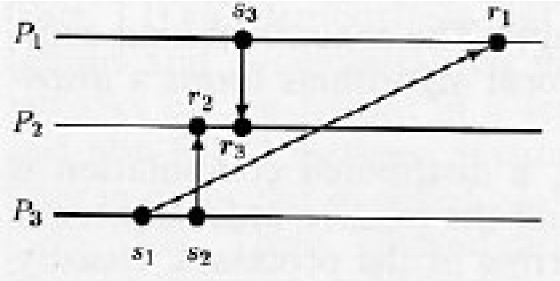
  $s \sim s' \wedge r \sim r' \wedge s \prec s' \Rightarrow r \prec r'$



Def: CO-Computations

- Additionally, for all (s,r) and (s',r') $\in \Gamma$

  $r \sim r' \wedge s \prec s' \Rightarrow r \prec r'$



Characterizations of CO-computations

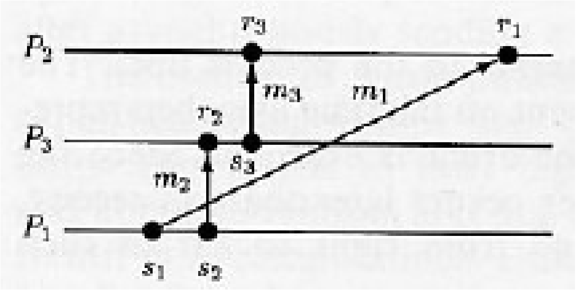
- Message ordered:

  $s \prec s' \Rightarrow \neg(r' \prec r)$

- Empty Interval:

  for each pair $(s,r) \in \Gamma$ the open interval

  $<s,r> = \{x \in C: s \prec x \prec r\}$ is empty



FIFO-computation

Characterizations of CO-computations (contd.)

- CO-computations: triangle inequality:

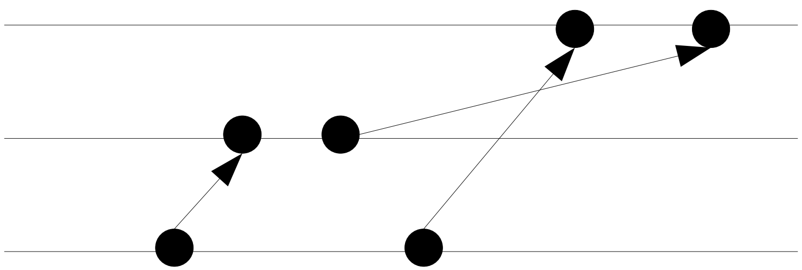
  a computation is CO iff no message is bypassed by a chain of other messages

- CO-computations: Vertical message arrow criterion

  A computation C is CO iff for every m in C there exists a space-time diagram for C such that m can be drawn as a vertical message arrow and no arrows go from right to left

Def: RSC-computations

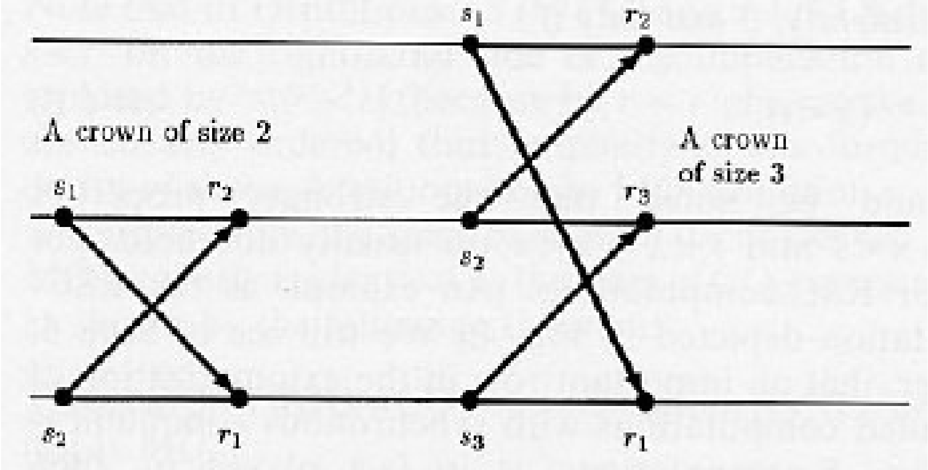
- RSC-computations: Realizable with Synchronous Communication
- A computation is called RSC if there exists a non-separated linear extension of $(C, \prec)$



Characterizations of RSC-computations

- Crowns: A crown is a sequence of pairs of corresponding send and receive events such that

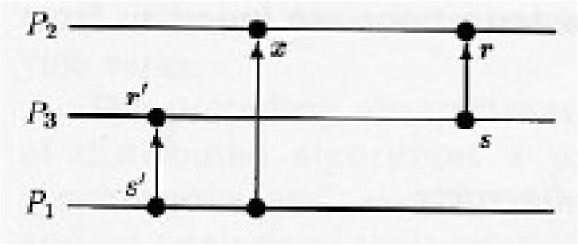
  $s_1 \prec r_2,\ s_2 \prec r_3,\ \ldots,\ s_{k-1} \prec r_k,\ s_k \prec r_1$



- A computation is RSC iff it contains no crown

Characterizations of RSC-computations (contd.)

- All message arrows in a diagram can be drawn vertical



- RSC-computations are equivalent to S-computations

Informal view: A-computations and S-computations

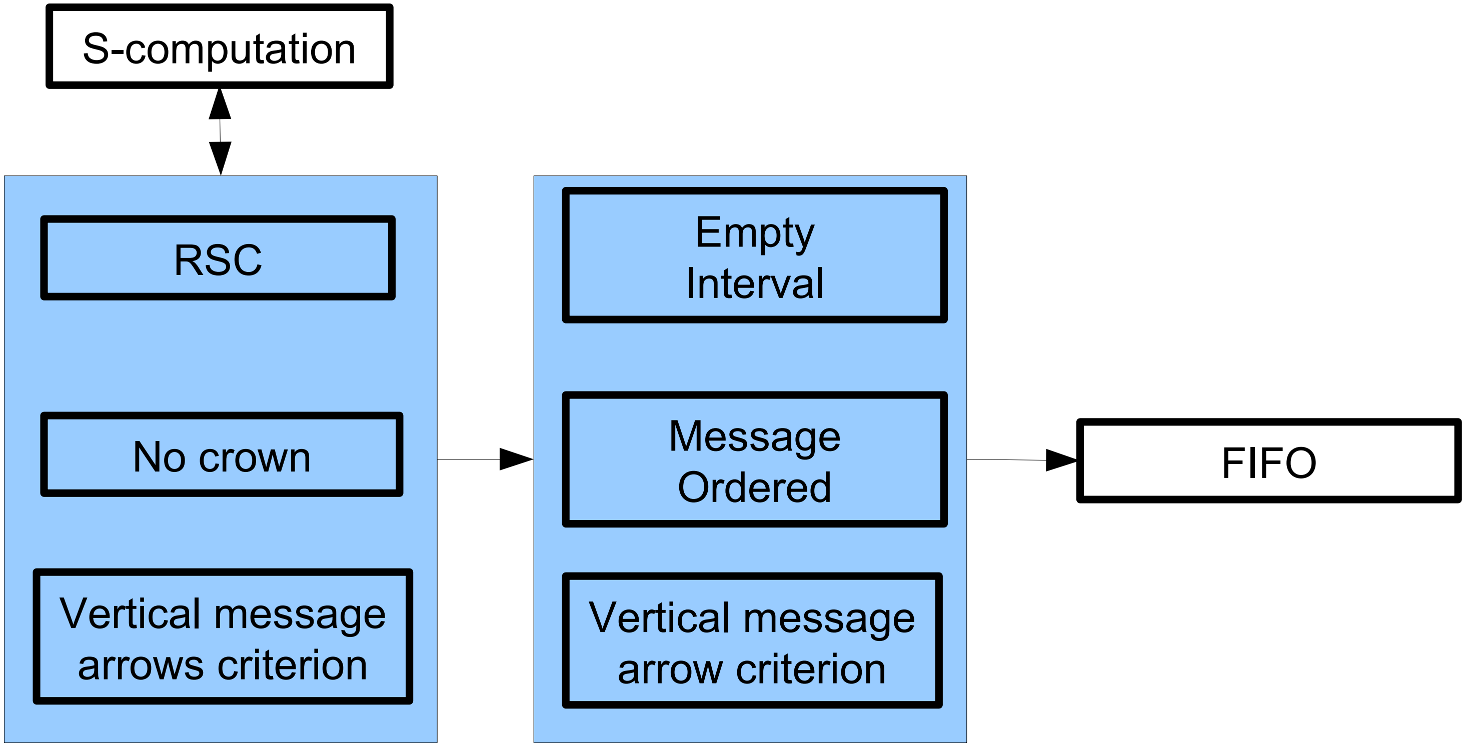
- S-computations are often regarded as a special case of A-computations (A-computations with empty channels)
- Proofs of algorithms for A-computations hold with rules for S-computations
- (but algorithms could deadlock in synchronous case)

Hierarchy of computations

- The paper shows a hierarchy of computations with different characteristics: synchronous, asynchronous, FIFO, causally ordered

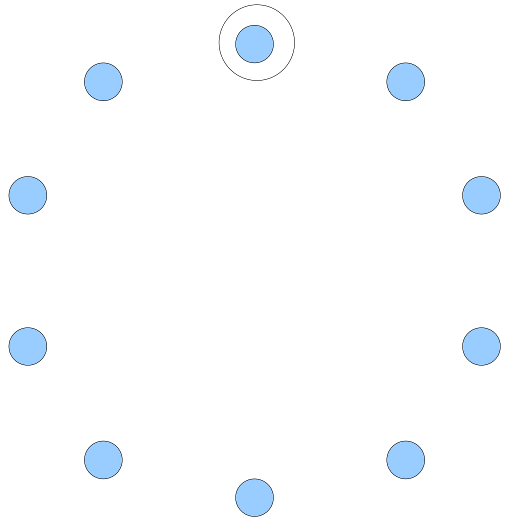
  S-computations $\subset$ CO-computations $\subset$ FIFO-computations $\subset$ A-computations

Hierarchy


S-computation
RSC
No crown
Vertical message arrows criterion
Empty Interval
Message Ordered
Vertical message arrow criterion
FIFO

Termination detection algorithm revisited

- Processes $P_0...P_{n-1}$, passive or active
- Send a token along a virtual ring



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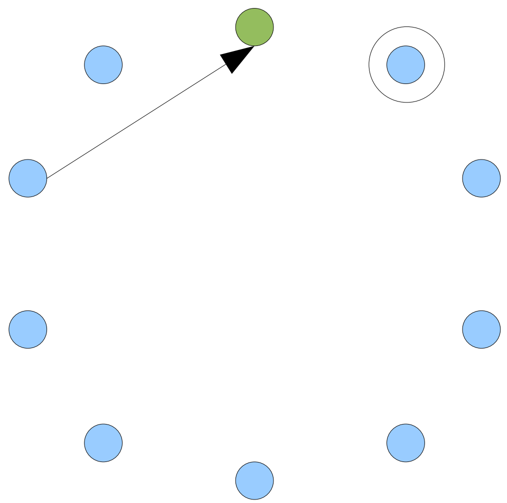

Termination detection algorithm revisited

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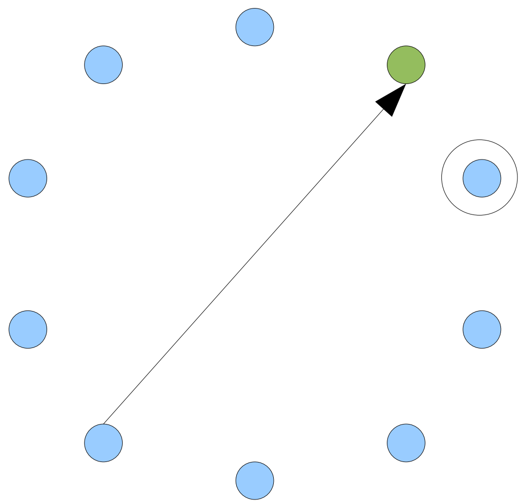

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Termination detection algorithm revisited

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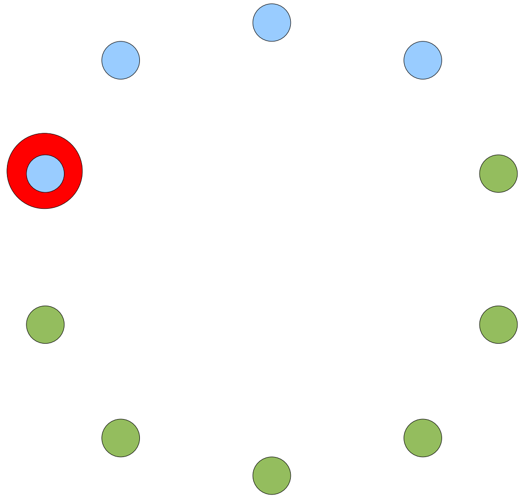


Part 2: Vector time

- Calculation of global state in a system without real-time clocks
- Calculate potential causality between events.

- One can try to simulate a synchronous system on an asynchronous system
- ... simulate global time
- ... simulate global state

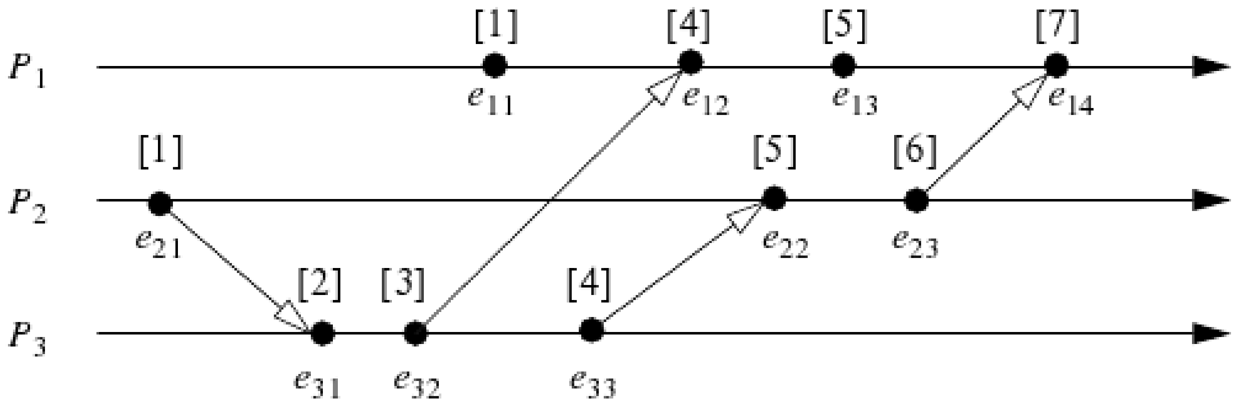
and build algorithms on top

Virtual time

- Simulate global time by Lamport:
- Every process stores the „global time“
- Before a send event, a process increases its value of the global time and attaches the new value to the message
- If a process receives a message with a timestamp attached that is greater than its own value, it updates its local clock

Lamport Time

- Insufficient in some cases, it loses information by mapping events to integers:
- Events happening at the same time can get different timestamps...



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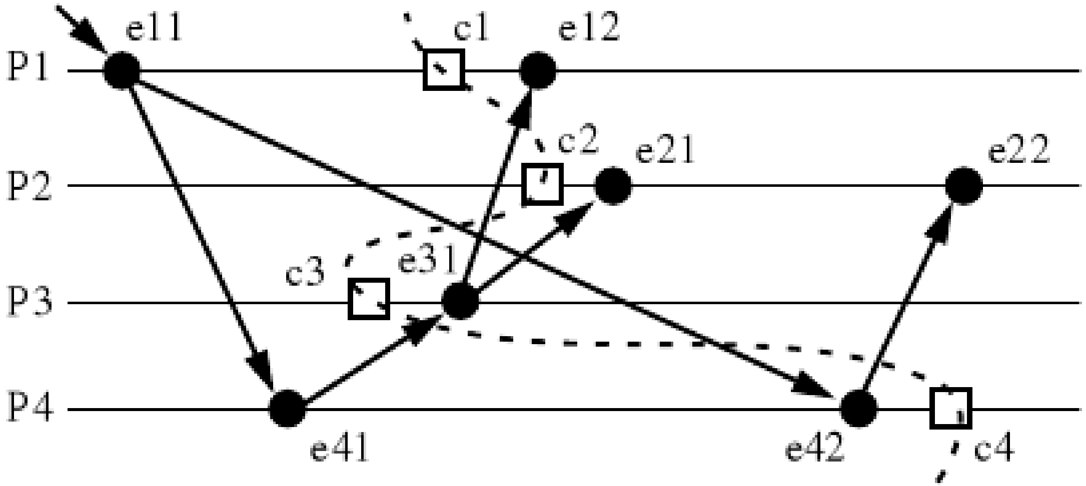
Cuts

- Subset of events; Graphically, a zigzag line which cuts the diagram into two parts



- Cuts the diagram into past and future

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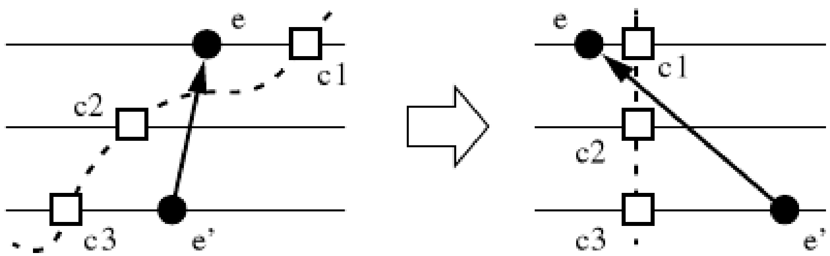
Consistent Cuts

- A Cut is consistent if every message received was sent
- Inconsistent cuts yield „invalid“ space-time diagrams



- Can be seen as an instant in time
- One could use a cut to compute a global state

Vector Time

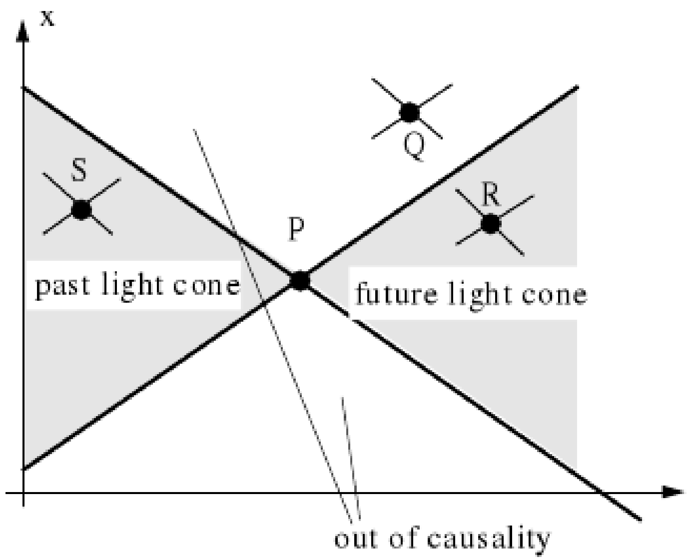
- Every process has a local clock
- Before a receive- or send-event a process increases its local clock
- Every process saves the most recent values it knows from all processes in a vector V_i
- A process attaches its local vector to the message
- If a process receives a message it updates its local vector

Properties of Vector Time

- The lattice of consistent cuts and the lattice of time vectors are isomorphic
- Vector time is able to model concurrency

Minkowski's space-time

- Maybe a better model of time than the „standard“ model
- Event P can only affect event b if b lies in the future light cone of P



- Close analogy to vector time

Snapshot algorithm

- P_i wants to request a global snapshot
- P_i fixes a time $s = V_i + (0,\ldots,0,1,0,\ldots,0)$
- P_i broadcasts s to all other processes and freezes until it knows that all other processes know s
- P_i „ticks“ again, takes a local snapshot and broadcasts a dummy message, so all processes advance their clocks to some value ≥ s
- If a process' local clock becomes ≥ s, it takes a local snapshot and sends it to P_i

Snapshot algorithm (contd.)

- The algorithm can be made much simpler and more efficient
  - External process
  - No need for whole vectors to be sent

Part 3: Detecting Causal Relationships in Distributed Computations

- In Search of The Holy Grail
- Debugging
- Consistent recovery
- Detecting deadlocks

Causal History

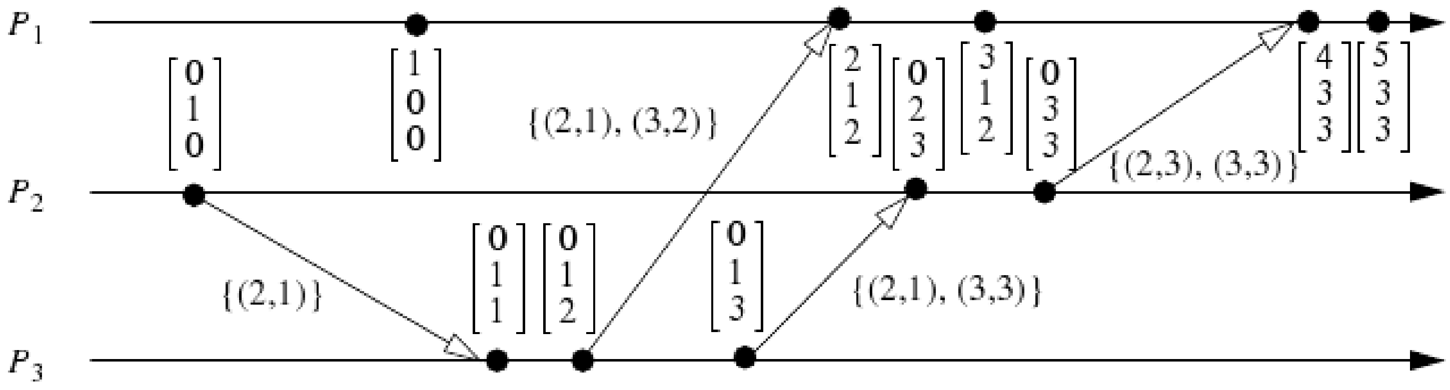
- Assign complete history to each event
  - Too expensive
- Can be reduced to vector time
  - Lamport time does not characterize causality

Efficient Vector time

- Attaching vector time to each message is unacceptable
  - Vector timestamps can become large
- Typically, only a few processes communicate directly

Efficient Vector time (contd.)

- Store LS (last sent) and LU (last update)



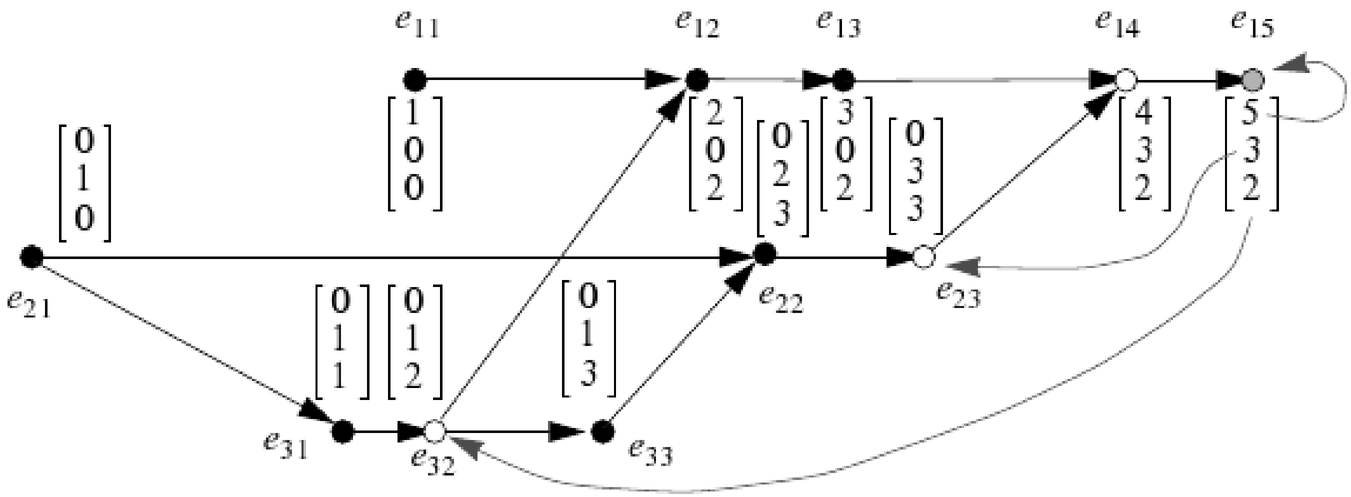
- FIFO is required

The size of vector time

- Unfortunately, causal order is in general of order N
- Application of vector time is substantially limited

Realizations for Offline Analysis

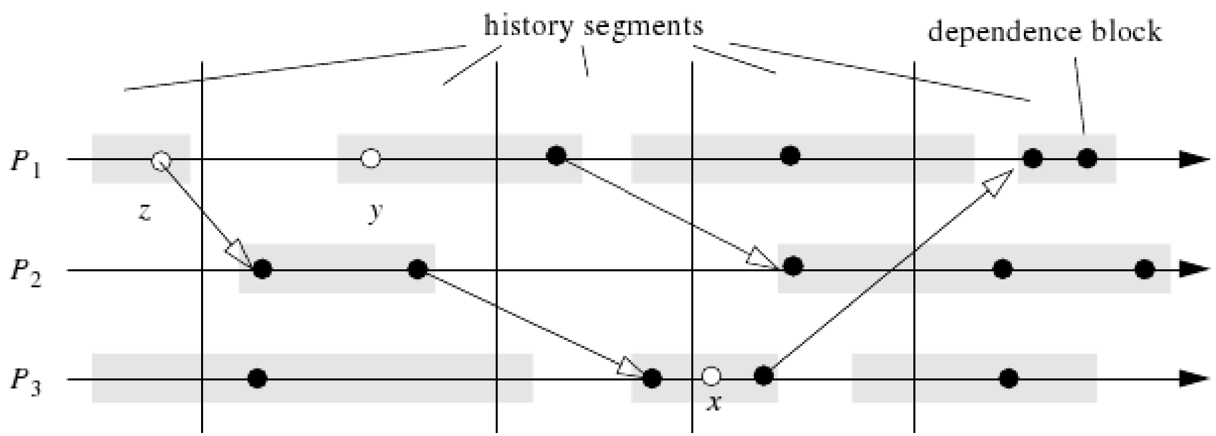
- Depth-first search algorithm to get complete causal history
  - Each event has at most 2 direct predecessors
- Store *direct* dependencies of each event



- Breadth-first search to get vector time

Concurrency Regions

- Regions of events which share the same causal past and future



- Characterizing causality is reducible to characterizing concurrency

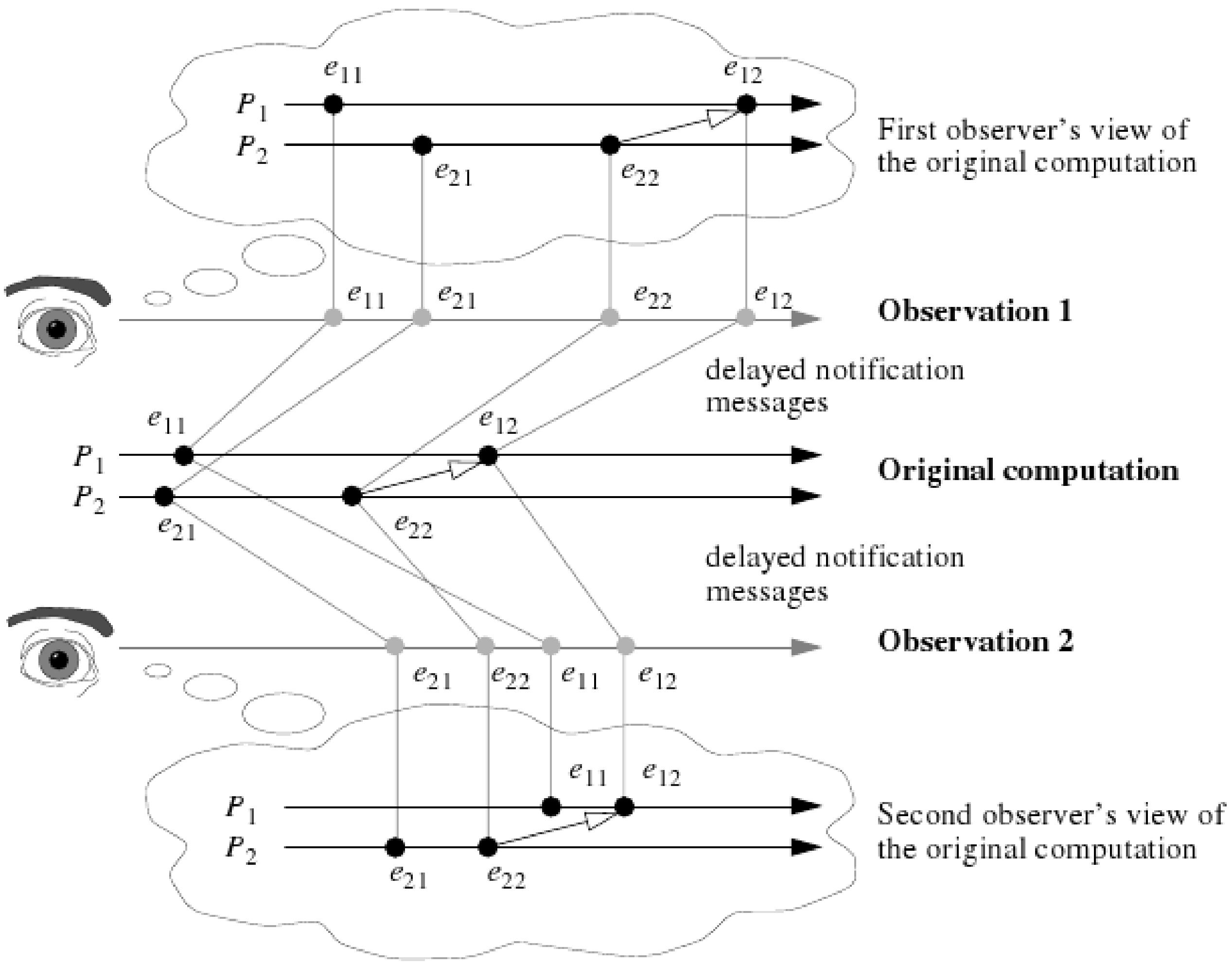
Global predicates

- Important for debugging
- Not all observers of a computation establish the truth for a given predicate

Observers

- Report every event to an external observer
- Use causal delivery protocol
  - Preserves causality relation
- All observations are valid
- One observer may claim that a predicate has been established while another claims that the predicate wasn't satisfied during the computation

Observers (contd.)



Possibly and Definitely

- Possibly: There is an instant in an observation at which the predicate holds
- Definitely: In every complete observation there is an instant at which the predicate holds

- Stable predicates: A predicate which eventually in every observation

Detecting definitely

- Based on vector time
- Compute the set A_i of intersection points of level i for each level; $i \in \{0...l\}$, $l=|E|$
  - All intersection points in A_{k-1} are accessible by a path on which the predicate is never satisfied on lower levels
- If A_l is empty, the predicate definitely holds
- Similar for Possibly
- Costly

More efficient algorithms

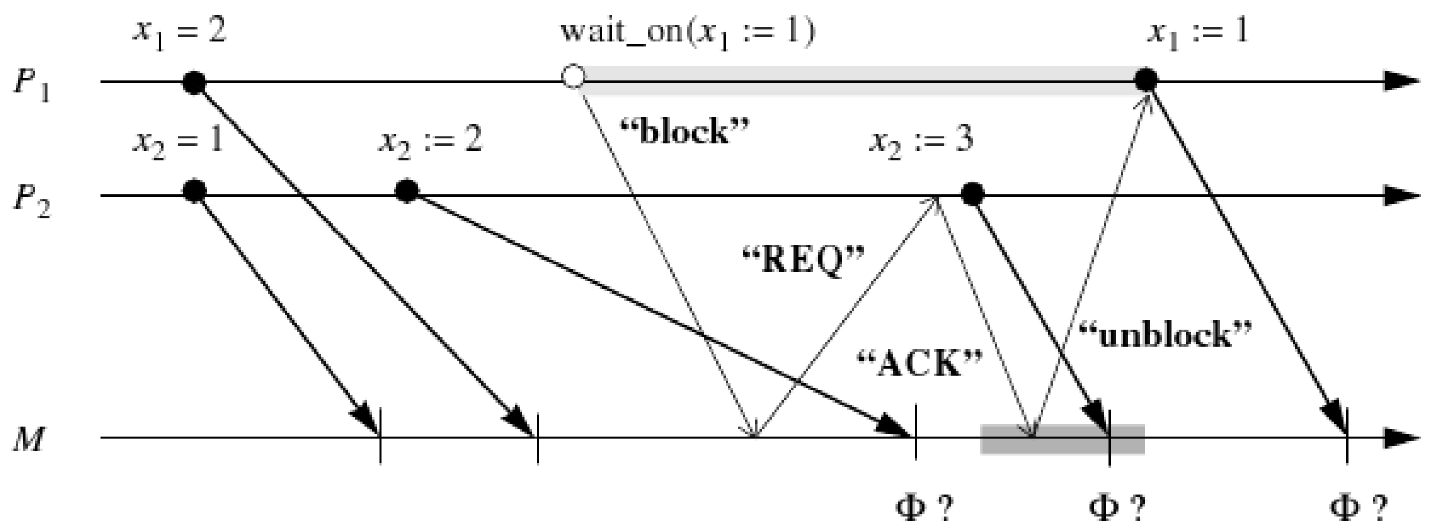
- Decomposable predicates are easier to detect
- Establish parts of the global predicate
- Go into one direction until parts of the predicate are satisfied

Computation replay

- Record non-deterministic events
- Replay with recorded decisions

Currently

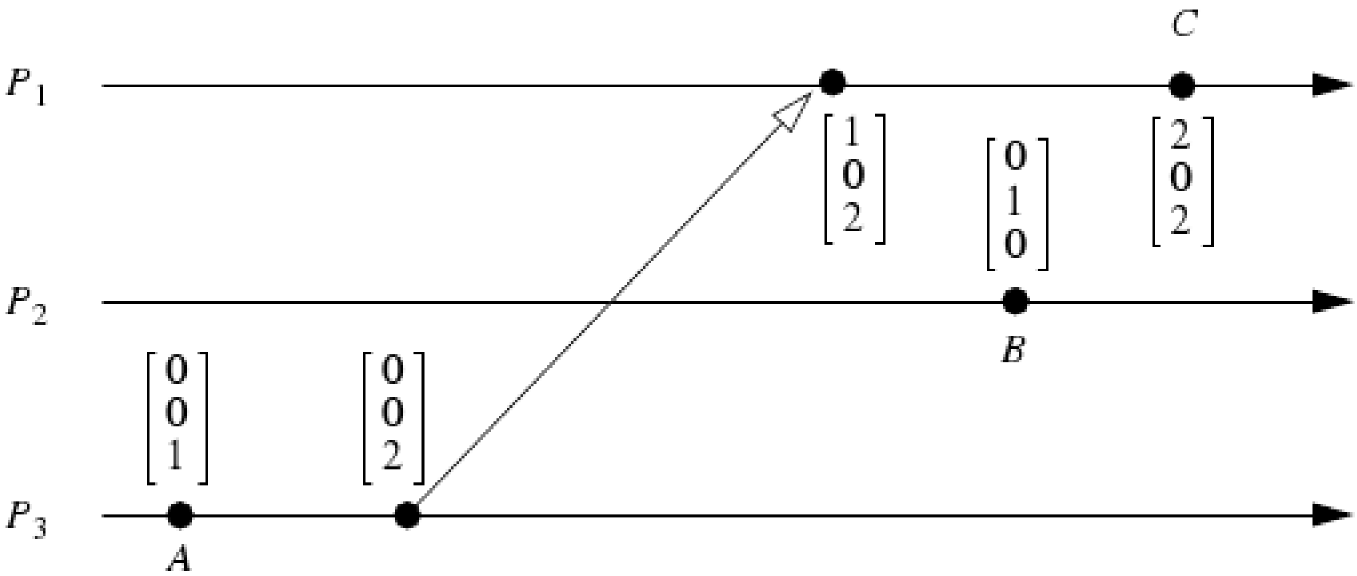
- Evaluate predicate on the real-time order of the events
  - Must use a powerful observer
  - Intrusive: block at each invalidating event



- Might miss some predicates

Behavioral patterns

- Classes of events, each event belongs to a class
- Combine classes to patterns: A happens between B and C



- What timestamps should be assigned to combined events?
  - (A||B) $\rightarrow$ C

Conclusion

- Hierarchy of computation types
- Vector time is interesting
  - limited application
- Detection requires much effort

Questions?