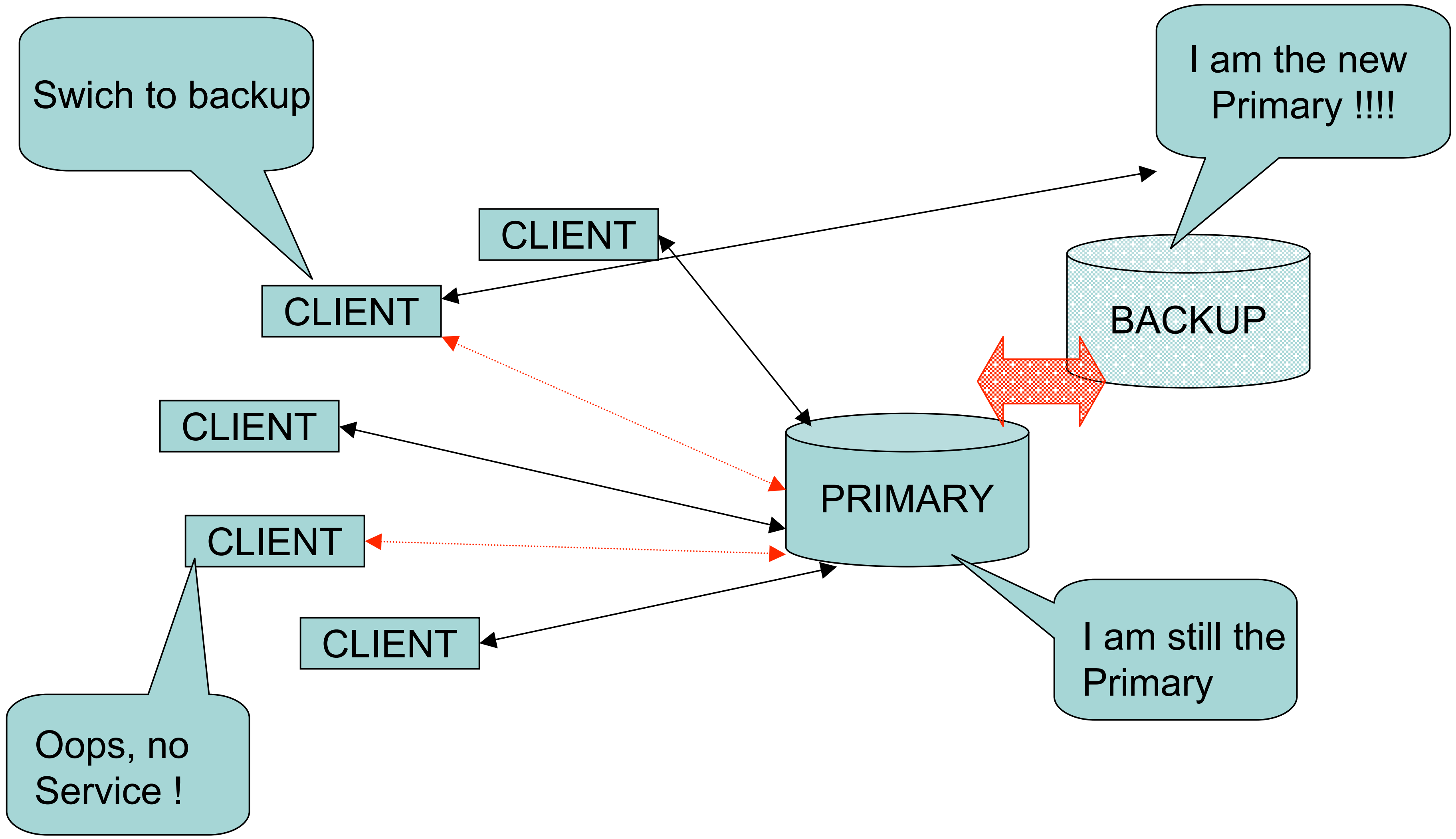
CS603: Distributed Systems

Lecture 4: Overcoming failures in distributed systems

PURDUE UNIVERSITY

Things go **very** wrong…



Outline

Processes do not have the same 'view' of the system, some perceived 'primary down', some perceived 'primary up'

- Order of events in distributed systems
- Failure detection
- Membership

THE BAD NEWS

- We can not detect failures in a trustworthy, consistent manner
- We can not reach a state of “common knowledge” concerning something not agreed upon in the first place
- We can not guarantee agreement on things (election of a leader, update to a replicated variable) in a way certain to tolerate failures

CAN WE DO ANYTHING?

System Model Dimensions

- Non-deterministic processes
- Communication is through messages
- Network can be a clique or a graph, not every machine can connect to every other machine
- Network packets can be lost, duplicated, delivered very late or out of order, spied upon, replayed, corrupted, source or destination address can lie
- Communication can be authenticated or not
- Execution model can be
  - Asynchronous: no synchronized clocks or time-bounds on message delays.
  - Synchronous: execution is partitioned in rounds, all messages send in a round are delivered in that round

Execution, Configuration, Events

- Set of processes p_i, each process with a state s_i
- Configuration C_t: set of state of each process at some moment
- Events: send and deliver, events can change the state at a process
- Execution: sequence of configuration and events

Safety and Liveness

- Safety: a condition that must hold in every finite prefix of a sequence (from an execution)

  "nothing bad happens"

- Liveness: a condition that must hold a certain number of times

  "something good happens"

Ordering of Events

- Order of events, particularly causality helps in reasoning or analyzing a system
- Single process: follow the sequence of events, each event has a timestamp and the causality relation between events is given by time
- Distributed processes: many events generated at different processes, how to order events?
- Time is essential for ordering events in a distributed system
  - Physical time: local clock; global clock
  - Logical time: partial ordering, total ordering

From Theory to Practice

- What does it take to synchronize many computers across several networks?
- NTP
- How does NTP protocols relate to the protocols described before?
- A good source is:
- www.eecis.udel.edu/~mills/database/brief/overview/overview.ppt

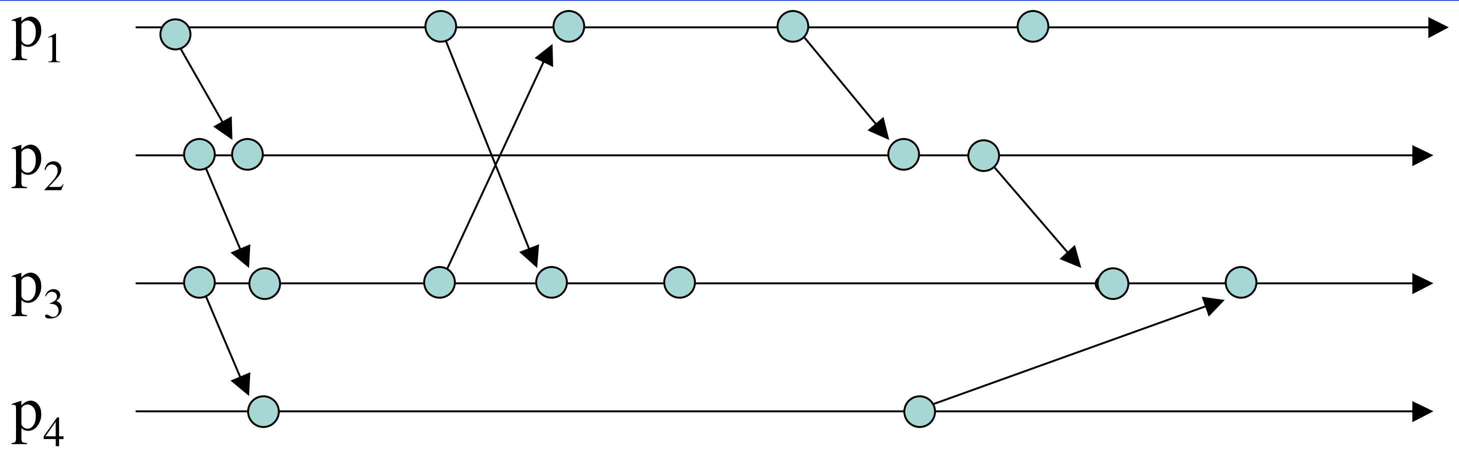
From Theory to Practice

- Consider a sensor network
- Communication is expensive (even if a node does not have any data to receive, just listening consumes power)
- Power is limited
- Synchronization is important because
  - Nodes can sleep and save battery
  - Communication may be avoided

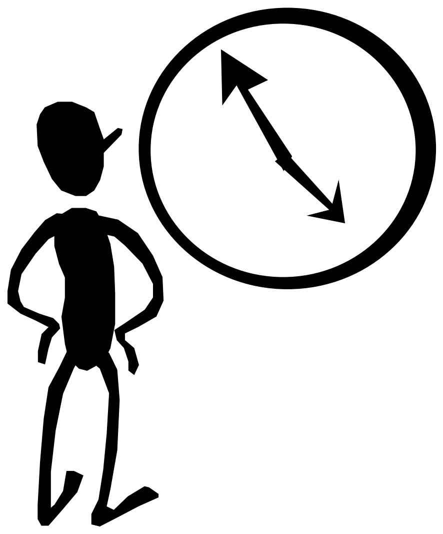
From Physical Clocks to Logical Clocks

- Synchronized clocks are great if we have them, but
- Why do we need the time anyway?
- In distributed systems we care about ‘what happened before what’

``HAPPENED BEFORE''



- If events a and b take place at the same process and a **occurs before** b
  a □ b
- If a is send event at p1 and b is deliver event at p2, p1 ≠ p2
  a □ b
- If a □ b and b □ c then a □ c



Logical Clocks: Lamport Clocks

- Each process maintains his own clock C_i (a counter)
- Clock Condition: for any events *a* and *b* in process p_i

if a □ b then $C_i(a) < C_i(b)$

- Implementation:
  - each process p_i increments C_i between any successive events
  - on send event *a*, attach to the message *m* local clock

$Tm = C_i(a)$

  - on receive of message *m* process P_k sets C_k to

$C_k = \max(C_k, T_m) + 1$

Lamport Clocks: Total Order

- Logical Clocks only provide partial order
- Create Total Order by breaking the ties
- Example to break ties, use process identifiers, have on order on process identifiers:

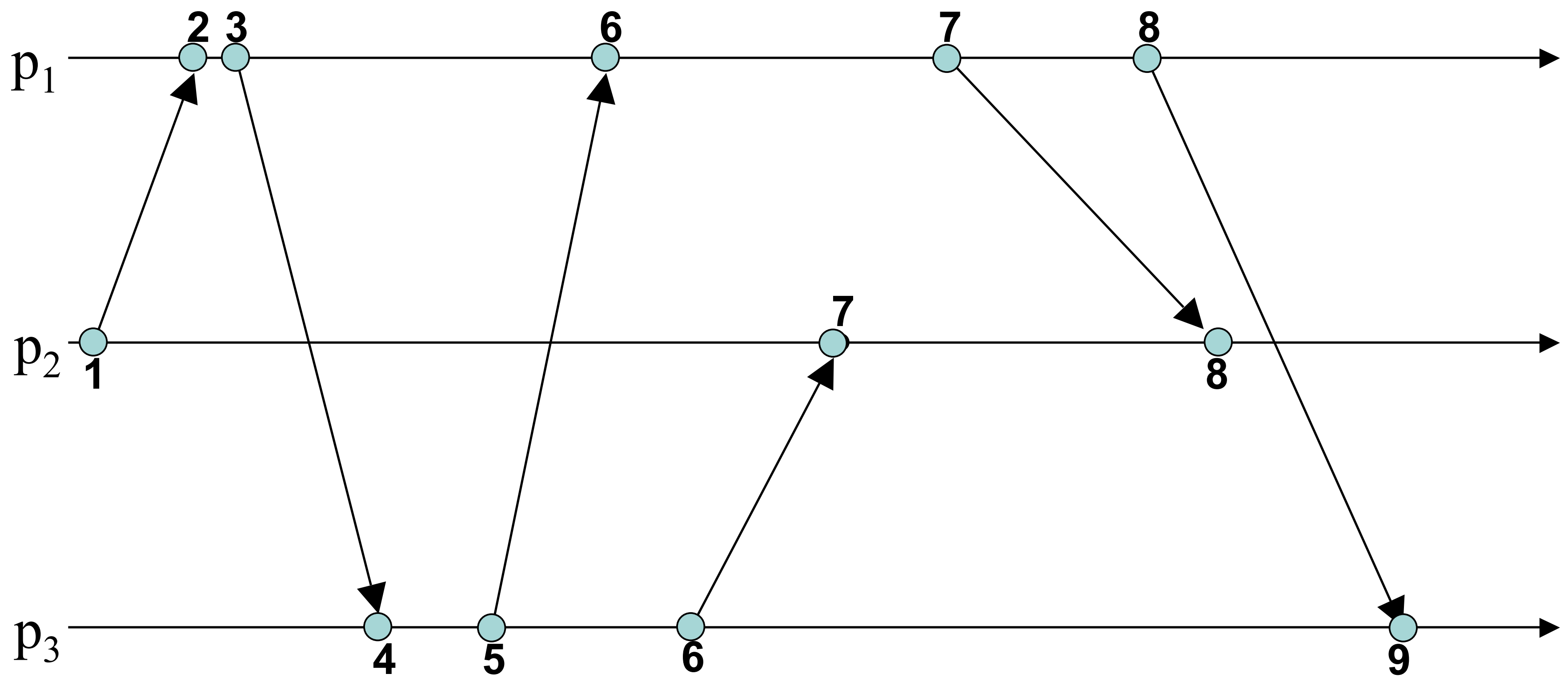
  If a is event in p_i and b is event in p then

  $$a \;\square\; b \quad \text{iff}$$

  $C_i(a) < C_j(b)$ or

  $C_i(a) = C_j(b)$ and $p_i < p_j$

Lamport Clocks: Example



Reminder: Partial and Total Order

- **Definition:** A relation R over a set S is a partial order iff for each *a*, *b*, and *c* in S:

  *a*R*a* (reflexive).

  *a*R*b* $\wedge$ *b*R*a* $\Rightarrow$ *a* = *b* (antisymmetric).

  *a*R*b* $\wedge$ *b*R*c* $\Rightarrow$ *a*R*c* (transitive).

- **Definition:** A relation R over a set S is total order if for each distinct *a* and *b* in S, R is antisymmetric, transitive and either *a*R*b* or *b*R*a*.

Concurrent Events

- Concurrent events:

  If a □ b and b □ a then
  a and b are concurrent

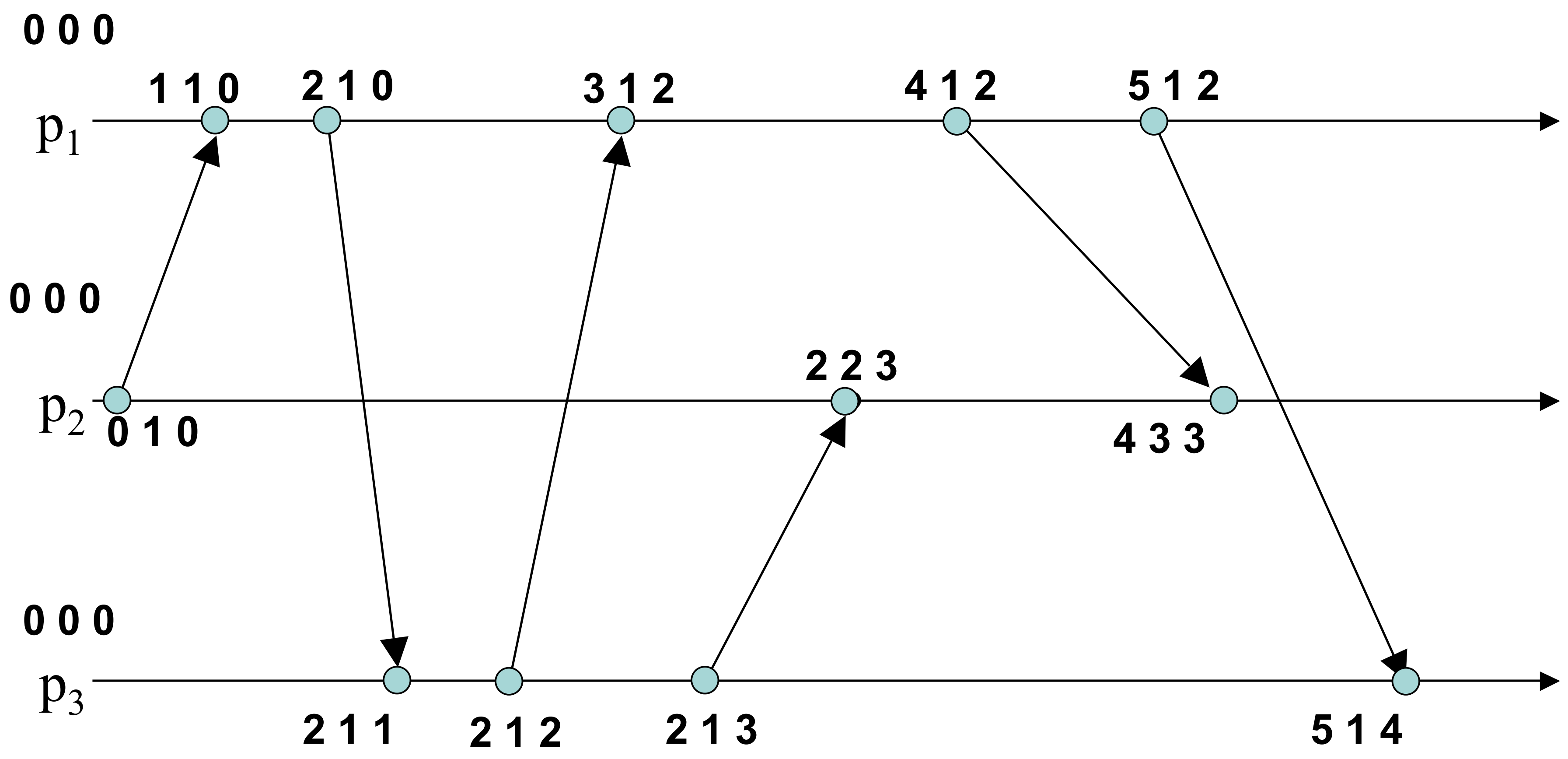
- Logical clocks assigns order to events that are causally independent, in other words events that are causally independent appear as if they happened in a certain order

- We need a ‘vector time’

Vector Clocks

- Each process maintains a vector C_i initially [0, 0, ..., 0].
- When p_i executes an event, it increments $C_i[i]$
- When p_i sends a message m to p_j, it piggybacks C_i on m.
- When p_i receives a message m,
  $\square$ j: 1 $\square$ j $\square$ n, $j \neq i$: $C_i[j] = \max(C_i[j], m.C[j])$
  $C_i[i] = C_i[i] + 1$.

Vector Clocks: Example



How to Order with Vector Clocks

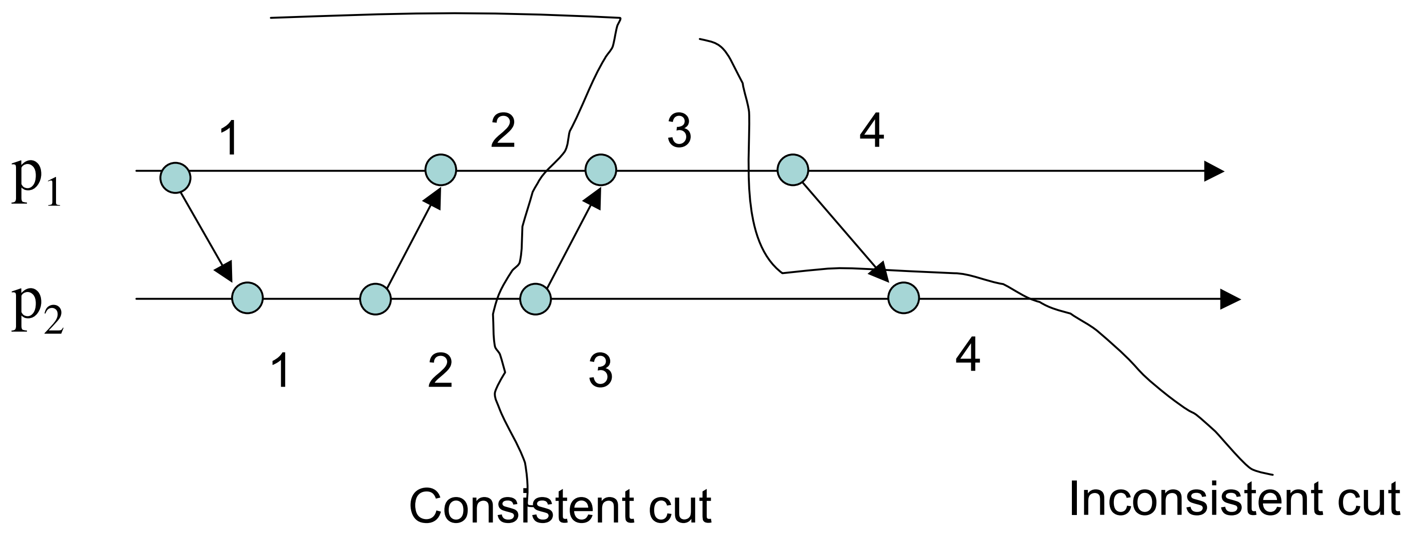
- Given two events a and b, $a \rightarrow b$ if and only if
- b has a counter value for the process in which a occurred greater than or equal to the value of that process at event a inclusive, and
- a has a counter value for the process in which b occurred strictly less than the value of that process at event b inclusive.

$$b \rightarrow a \equiv \forall i: 1 \leq i \leq n: V(b)[i] \leq V(a)[i]$$
$$\wedge \exists i: 1 \leq i \leq n: V(b)[i] < V(a)[i]$$

$$b \parallel a \equiv \exists i: 1 \leq i \leq n: V(b)[i] < V(a)[i]$$
$$\wedge \exists i: 1 \leq i \leq n: V(a)[i] < V(b)[i]$$

Using Ordering…: Consistent Cuts

- There is no outside observer that can look at the system and detect problems, for example a deadlock
- Cut: n-vector $(k_0, \dots k_{n-1})$ of positive integers
- Consistent cut: if for all i, j, $(k_i + 1)$ event at process p_i did not ‘happened before’ k_j event at p_j



Detecting failures

- Impossibility result: it is impossible to design an asynchronous fault-tolerant consensus algorithm, even when only one process can crash. (FLP85)
- Proof Idea: It is shown how an infinite sequence of events can be constructed such that the algorithm never terminates (stays indecisive forever).
- The impossibility comes from the fact that in an asynchronous system, it is impossible to distinguish between a faulty-process and a slow process.

Failure Detectors as an Abstraction

- **Failure detector**: distributed oracle that makes guesses about process failures
- Accuracy: the failure detector makes no mistakes when labeling processes as faulty.
- Completeness: the failure detector "eventually" (after some time) suspects every process that actually crashes.
- Classified based on their properties
- Used to solve different distributed systems problems

Completeness

- **Strong Completeness**: There is a time after which every process that crashes is suspected by **EVERY** correct process.
- **Weak Completeness**: There is a time after which every process that crashes is permanently suspected by **SOME** correct process.

Accuracy

- **Strong Accuracy**: No process is suspected before it crashes.
- **Weak Accuracy**: Some correct process is never suspected. (at least one correct process is never suspected)
- **Eventual Strong Accuracy**: *There is a time* after which correct processes are not suspected by any correct process.
- **Eventual Weak Accuracy**: *There is a time* after which some correct process is never suspected by any correct process.

Perfect Failure Detector

- A perfect failure detector has strong accuracy and strong completeness
- THIS IS AN ABSTRACTION
- IT IS IMPOSSIBLE TO HAVE A PERFECT FAILURE DETECTOR
- We have to live with … unreliable failures detectors…

Unreliable Failure Detectors

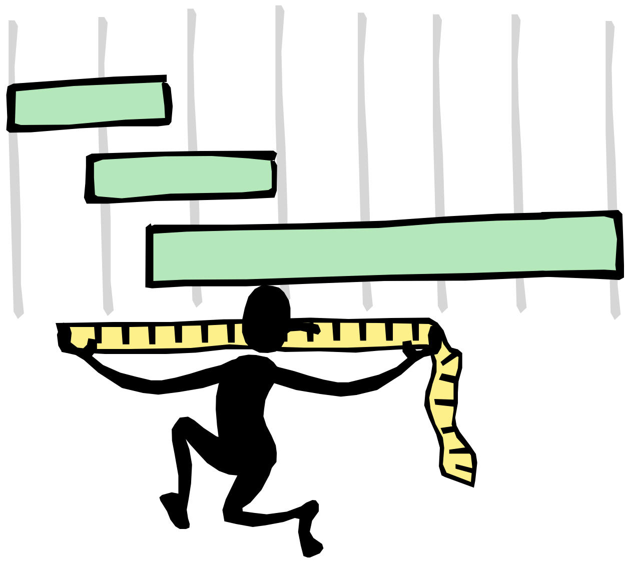
- Unreliable failure detectors can make mistakes
- A process is suspected that it was faulty, that can be true or false, if false the list of alive processes is modified.
- Failure detectors can add/remove processed from the list of suspects; different processes have different lists.
- The assumptions are that:
  - After a while the network becomes stable so the failure detector does not make mistakes anymore.
  - In the unstable period, the failure detector can make mistakes.

Failure Detection Implementation

- Push: processes keep sending heartbeats "I am alive" to the monitor. If no message is received for awhile from some process, that process is suspecte as being dead.
- Pull: monitor asks the processes "Are you alive?", and process will respond "Yes, I am alive". If no answer is received from some process, the process is suspected as being dead.
- What are advantages and disadvantages of these two models?

Metrics for Failure Detectors

- Detection time
- Mistake recurrence time
- Mistake duration
- Average mistake rate
- Query accuracy probability
- Good period duration
- Network load



Failure Detectors Implementation

- Every process must know about who failed
- How to disseminate the information
- How about if not every node can communicate directly with another node?

REQUIRED READING

- Leslie Lamport for "Time, Clocks, and the Ordering of Events in a Distributed System," Communications of the ACM, July 1978, 21(7):558-565.
- Michael J. Fischer, Nancy A. Lynch, and Michael S. Paterson for "Impossibility of Distributed Consensus with One Faulty Process," Journal of the ACM, April 1985, 32(2):374-382.
- Unreliable Failure Detectors for Reliable Distributed Systems, T. Chandra and S. Toueg. 1996.