Introduction to Basic Abstractions

Seif Haridi

haridi@kth.se

Need of Distributed Abstractions

- Core of any distributed system is a set of distributed algorithms
  - Implemented as a middleware between network (OS) and the application
- Reliable applications need underlying services stronger than network protocols (e.g. TCP, UDP)

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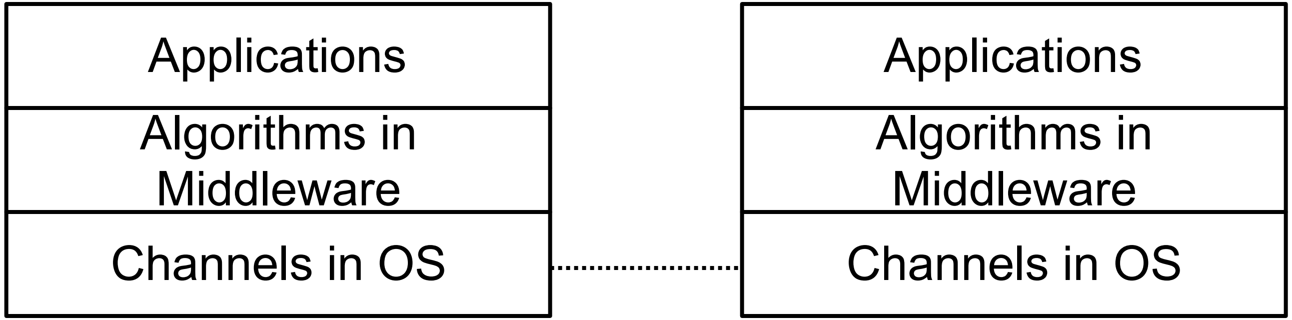

Applications

Algorithms in Middleware

Channels in OS

Applications

Algorithms in Middleware

Channels in OS

Need of Distributed Abstractions

- Network protocols aren’t enough
  - Communication
    - Reliability guarantees (e.g. TCP) only offered for one-to-one communication (client-server)
    - How to do group communication?

Abstractions in this course

Reliable broadcast
Causal order broadcast
Total order broadcast

Need of Distributed Abstractions

- Network protocols aren’t enough
  - High-level services
    - Sometimes many-to-many communication isn’t enough
    - Need reliable high-level services

Abstractions in this course

Shared memory
Consensus
Atomic commit
Replicated state machine

Reliable distributed abstractions

- Example 1: ***reliable broadcast***
  - Ensure that a message sent to a group of processes is received (delivered) by all or none
- Example 2: ***atomic commit***
  - Ensure that the processes reach the same decision on whether to commit or abort a transaction

Event-based Component Model

Distributed Computing Model

- Set of processes and a network (communication links)
- Each process runs a local algorithm (program)
- Each process makes computation steps

- The network makes computation steps
  - to store a message sent by a process
  - to deliver a message to a process

- Message delivery triggers a computation step at the receiving process

The Distributed Computing Model

- Computation step at a process
  - Receives a message (external, input)
  - Performs local computation
  - Sends one or more messages to some other processes (external, output)

- Communication step:
  - Depends on the network abstraction
  - Receives a message from a process, or
  - Delivers a message to a process

Inside a Process

- A process consists of a set of components (automata)
- Components are concurrent
- Each component receives messages through an input FIFO buffer
- Sends messages to other components
- Events are messages between components in the same process
- Events are handled by procedures (actions) called Event Handlers

Inside a Process

Event-based Programming

- Process executes program
  - Each program consists of a set of modules or component specifications
  - At runtime these are deployed as components
  - The components in general form a software stack

Event-based Programming

- Process executes program
  - Components interact via events (with attributes):
  - Handled by Event Handlers

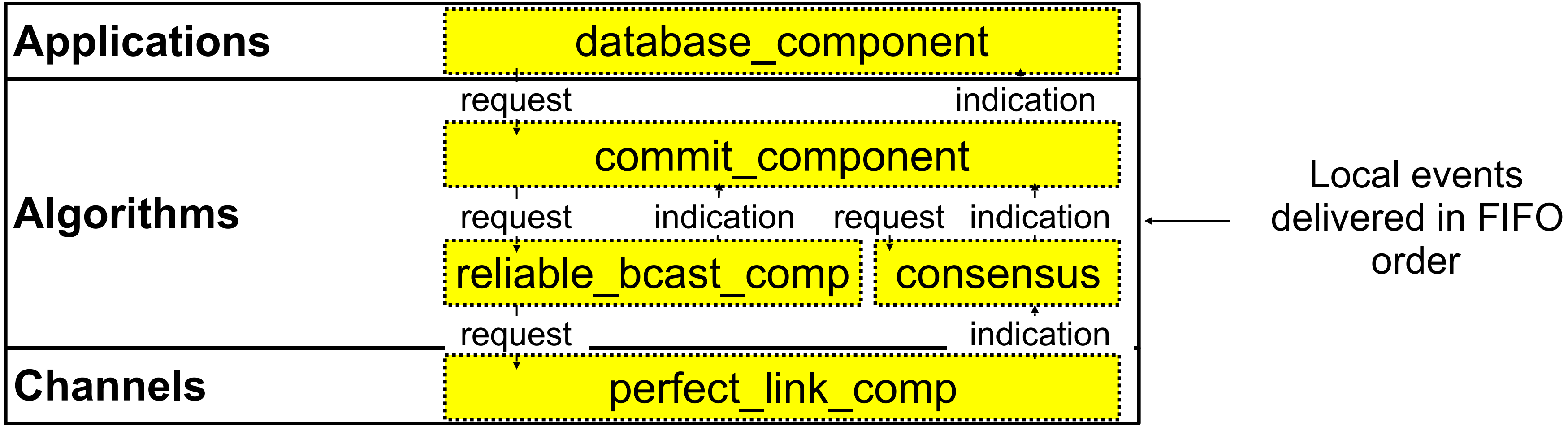
```
on event <co_i Event_1, attr1, attr2,...> do
          // local computation
          trigger <co_j Event_2, attr3, attr4,...>
```

Event-based Programming

- Events can be almost anything
  - Messages (most of the time)
  - Timers (internal event)
  - Conditions (e.g. x==5 & y<9)
- Two types of events
  - Requests
    - (flows downward) Inputs
  - Indications
    - (like responses/acks flows upward) Outputs

Components in a Process

- Stack of components in a single process



Channels as Modules

- Channels represented by modules (too)
    - Request event:
        - Send to destination some message (with data)

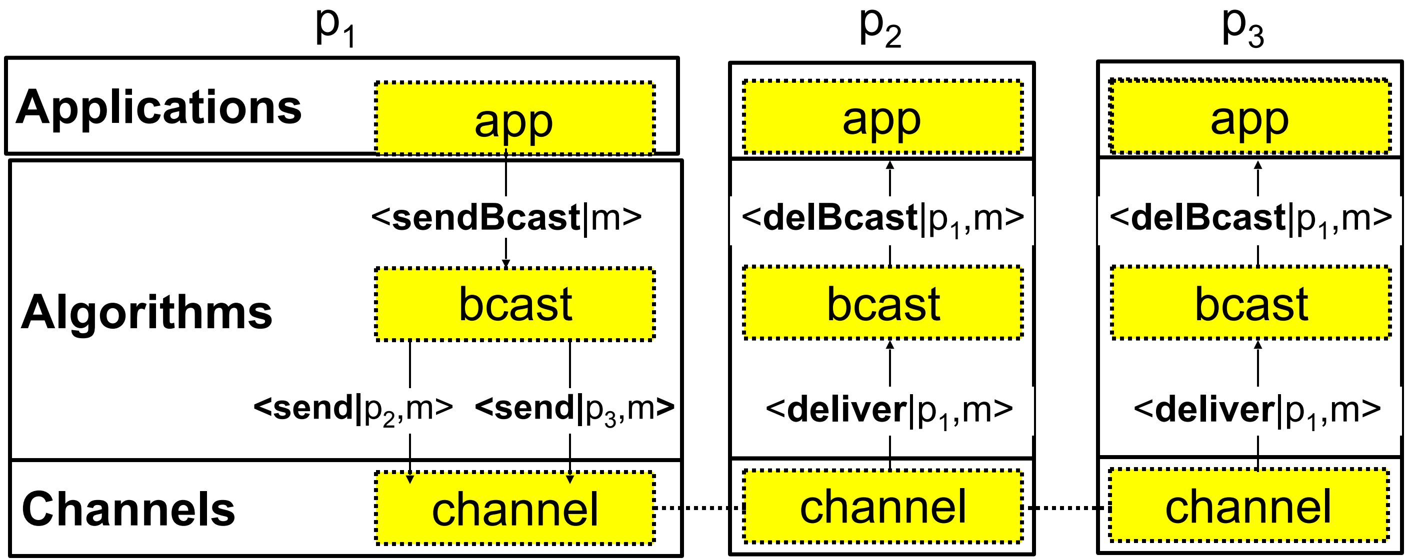
trigger <*send* | *dest*, [data1, data2, …] >

- Indication event:
    - Deliver from source some message (with data)

upon event <*deliver* | *src,* [data1,data2, …]> **do**

Example

- Application uses a Broadcast component
  - which uses channel component to broadcast



Specification

Specification of a Service

- How to specify a distributed service (abstract)?
  - Interface (aka Contract, API)
    - Requests
    - Responses
  - Correctness Properties
    - Safety
    - Liveness
  - Model
    - Assumptions on failures
    - Assumptions on timing (amount of synchrony)

declarative
specification
“what”
aka problem

……

  - Implementation
    - Composed of other services
    - Adheres to interface and satisfies correctness
    - Has internal events

imperative,
many possible
“how”

Simple Example: Job Handler

- **Module:**
  - **Name: JobHandler, instance *jh***
- **Events:**
  - **Request:** *⟨jh, Submit | job⟩ : Requests a job to be processed*
  - **Indication:** *⟨jh, Confirm | job⟩ : Confirms that the given job has been (or will be) processed*
- **Properties:**
  - *Guaranteed response: Every submitted job is eventually confirmed*

Implementation Example

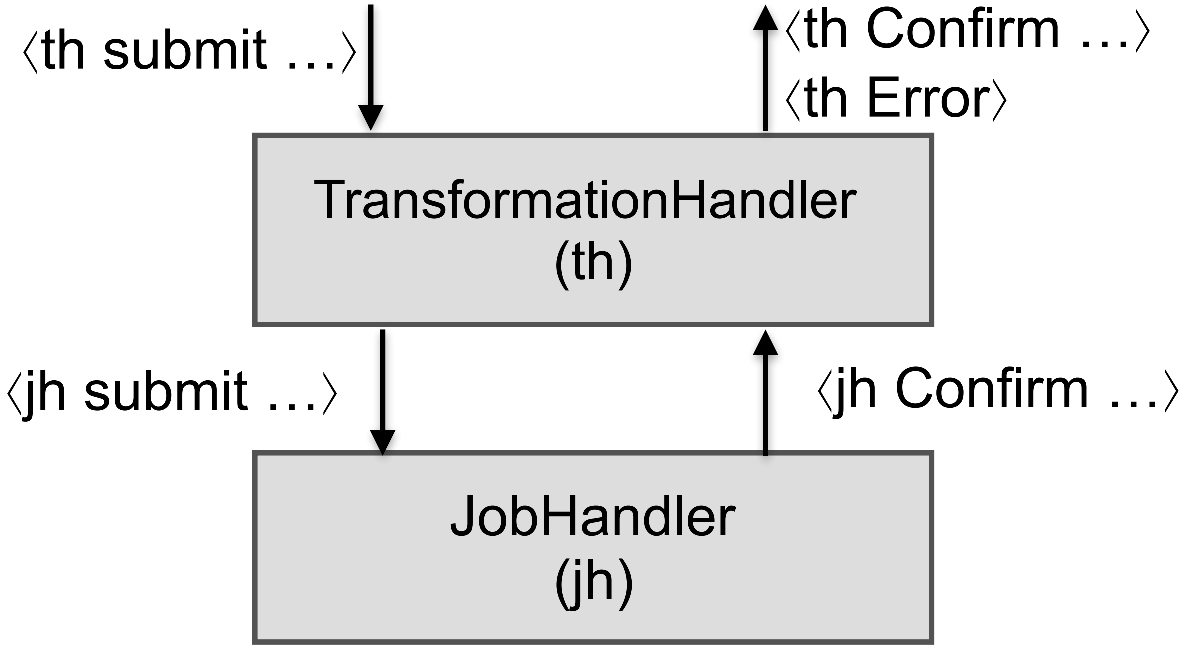
- Synchronous Job Handler
- **Implements:**
    - JobHandler, **instance *jh***
- **upon event** ⟨*jh, Submit | job*⟩ ***do***
    - process(*job)*
    - **trigger** ⟨*jh, Confirm | job*⟩

Another implementation: Asynchronous Job Handler

- **Implements:**
  - JobHandler, **instance *jh***
- **upon event** ⟨*jh, Init*⟩ ***do***
  - *buffer* := ∅
- **upon event ⟨*jh, Submit* | *job*⟩ *do***
  - *buffer* := *buffer* ∪ {*job*}
  - **trigger ⟨*jh, Confirm* | *job*⟩**
- **upon** *buffer* ≠ ∅ **do**
  - *job* := *selectjob* (*buffer*)
  - process(*job*)
  - *buffer* := *buffer* \ {*job*}

⟨..***Init***⟩ automatically generated upon component creation

Component Composition



⟨th submit …⟩

⟨th Confirm …⟩

⟨th Error⟩

TransformationHandler
(th)

⟨jh submit …⟩

⟨jh Confirm …⟩

JobHandler
(jh)

Properties
Safety and Liveness

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Correctness

- Always expressed in terms of
  - Safety and liveness
- Safety
  - Properties that state that nothing bad ever happens
- Liveness
  - Properties that state that something good eventually happens

Correctness Example

- Correctness of You in ID2203x
  - Safety
    - You should never fail the exam (marking exams costs money)
  - Liveness
    - You should eventually take the exam (university gets money when you pass)

Correctness Example (2)

- Correctness of traffic lights at intersection
  - Safety
    - Only one direction should have a green light
  - Liveness
    - Every direction should eventually get a green light

Execution and Traces (reminder)

- An execution fragment of A is sequence of alternating states and events
  - $s_0, \ \varepsilon_1, s_1, \varepsilon_2, \ldots, s_r, \varepsilon_r, \ldots$
  - $(s_k, \varepsilon_{k+1}, s_{k+1})$ transition of A for $k \geq 0$
- An execution is execution fragment where s_0 is an initial state
- A trace of an execution E, trace(E)
  - The subsequence of E consisting of all external events
  - $\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_r, \ldots$

Safety & Liveness All That Matters

- A trace property P is a function that takes a trace and returns true/false
  - i.e. P is a predicate

- Any trace property can be expressed as the conjunction of a safety property and a liveness property”

Safety Formally Defined

- The prefix of an trace T is the first *k* (for *k* ≥ 0) events of T
  - I.e. cut off the tail of T
  - I.e. finite beginning of T

- An extension of a prefix P is any trace that has P as a prefix

Safety Defined

- Informally, property P is a safety property if
  - Every trace T violating P has a bad event, s.t. every execution starting like T and behaving like T up to the bad event (including), will violate P regardless of what it does afterwards

Safety Defined

- Formally, a property P is a safety property if
  - Given any execution E such that P(trace(E)) = false,
  - There exists a prefix of E, s.t. every extension of that prefix gives an execution F s.t. P(trace(F))=false

Safety Example

- Point-to-point message communication
  - Safety P:
    - A message sent is delivered at most once

Safety Example

- Point-to-point message communication
  - Safety P:
    - A message sent is delivered at most once
  - Take an execution where a message is delivered more than once
    - Cut-off the tail after the second delivery
    - Any continuation (extension) will give an execution which also violates the required property

Liveness Formally Defined

- A property P is a liveness property if
  - Given any prefix F of an execution E,
  - There exists an extension of trace(F) for which P is true

- “As long as there is life there is hope”

Liveness Example

- Point-to-point message communication
    - Liveness P:
        - A message sent is delivered at least once

Liveness Example

- Point-to-point message communication
  - Liveness P:
    - A message sent is delivered at least once
  - Take the prefix of any execution
    - If prefix contains delivery, any extension satisfies P
    - If prefix doesn't contain the delivery, extend it so that it contains a delivery, the prefix + extended part will satisfy P

More on Safety

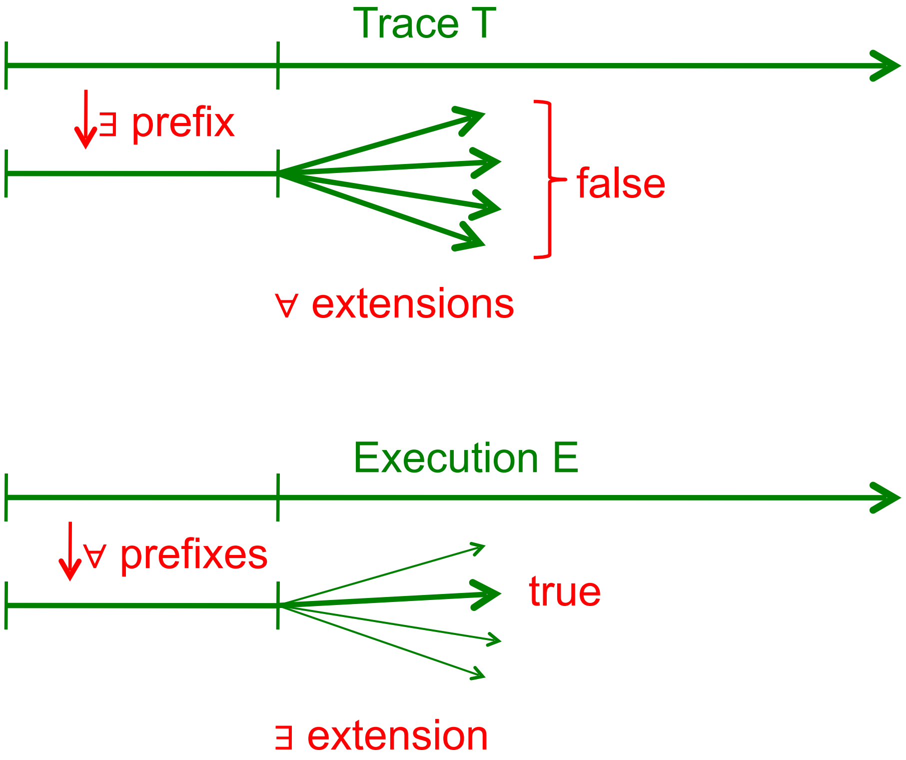
- Safety can only be
  - satisfied in infinite time (you’re never safe)
  - violated in finite time (when the bad happens)

- Often involves the word “never”, “at most”, “cannot”,…
- Sometimes called “partial correctness”

More on Liveness

- Liveness can only be
  - satisfied in finite time (when the good happens)
  - violated in infinite time (there's always hope)
- Often involves the words eventually, or must
  - Eventually means at some (often unknown) point in "future"
- Liveness is often just "termination"

Formal Definitions Visually



- Safety can always be made false in finite time
- Safety is false for an execution E if there exists a prefix such that all extensions are false
- Liveness can always be made true in finite time
- Liveness is true for an execution E if for all prefixes there exists an extension that is true

Pondering Safety and Liveness

- Is really every property either liveness or safety?
  - Every message should be delivered exactly 1 time [d]

- Every message is delivered at most once and
- Every message is delivered at least once

Process Failure Model

Specification of a Service

- How to specify a distributed service (abstract)?
  - Interface (aka Contract, API)
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  - Model
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- Implementation
  - Composed of other services
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Model/Assumptions

- Specification needs to specify the distributed computing model
  - Assumptions needed for the algorithm to be correct

- Model includes assumptions on
  - Failure behavior of processes & channels
  - Timing behavior of processes & channel

Process failures

- Processes may fail in four ways:
  - Crash-stop
  - Omissions
  - Crash-recovery
  - Byzantine/Arbitrary
- Processes that don’t fail in an execution are correct

Crash-stop failures

- Crash-stop failure
  - Process stops taking steps
    - Not sending messages
    - Nor receiving messages

- Default failure model is crash-stop
    - Hence, do not recover
    - But processes are not allowed to recover? [d]

Omission failures

- Process omits sending or receiving messages
  - Some differentiate between
    - Send omission
      - Not sending messages the process has to send according to its algorithm
    - Receive omission
      - Not receiving messages that have been sent to the process
  - For us, omission failure covers both types

Crash-recovery Failures

- The process might crash
  - It stops taking steps, not receiving and sending messages
- It may recover after crashing
  - Special <Recovery> event automatically generated
  - Restarting in some initial recovery state
- Has access to stable storage
  - May read/write (expensive) to permanent storage device
  - Storage survives crashes
  - E.g., save state to storage, crash, recover, read saved state

Crash-recovery Failures

- Failure is different in crash-recovery model
  - A process is faulty in an execution if
    - It crashes and never recovers, or
    - It crashes and recovers infinitely often (unstable)
  - Hence, a correct process may crash and recover
    - As long as it is a finite number of time

Byzantine failures

- Byzantine/Arbitrary failures
  - A process may behave arbitrarily
    - Sending messages not specified by its algorithm
    - Updating its state as not specified by its algorithm

  - May behave maliciously, attacking the system
    - Several malicious processes might collude

Fault-tolerance Hierarchy

Fault-tolerance Hierarchy

- Is there a hierarchy among the failure types
  - Which one is a special case of which? [d]
  - An algorithm that works correctly under a general form of failure, works correctly under a special form of failure

- Crash special case of Omission
  - Omission restricted to omitting everything after a certain event

Fault-tolerance Hierarchy

- In Crash-recovery
  - Under assumption that processes use stable storage as their main memory

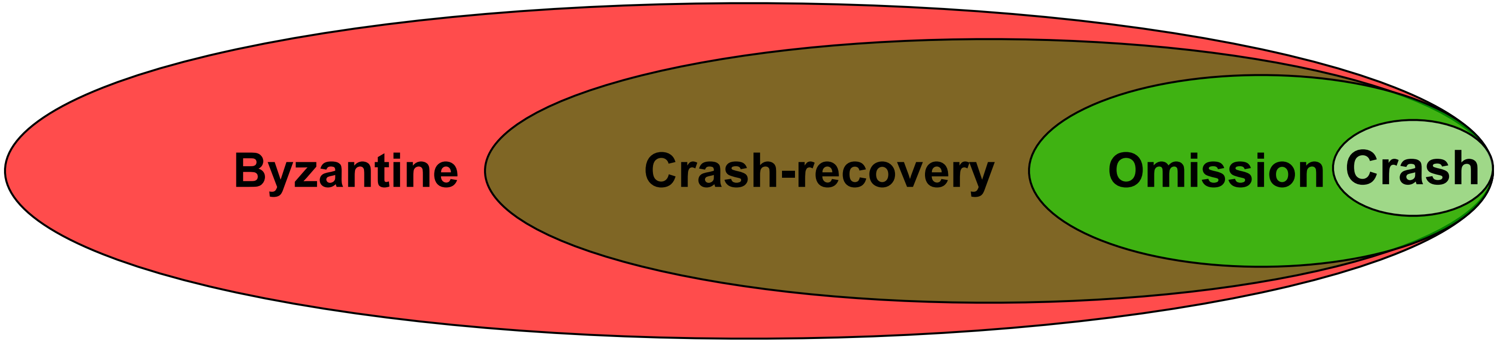
- Crash-recovery is identical to omission
  - Crashing, recovering, and reading last state from storage
  - Just same as omitting send/receiving while being crashed

Fault-tolerance Hierarchy

- In crash-recovery it is possible to use volatile memory
  - Then recovered nodes might not be able to restore all of state
  - Thus crash-recovery extends omission with amnesia
- Omission is special case of Crash-recovery
    - Crash-recovery , not allowing for amnesia

Fault-tolerance Hierarchy

- Crash-recovery special case of Byzantine
  - Since Byzantine allows anything
- Byzantine tolerance → crash-recovery tolerance
  - Crash-recovery → omission, omission → crash-stop



Channel Behavior (failures)

Specification of a Service

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Channel failure modes

- Fair-Loss Links
  - Channels delivers any message sent with non-zero probability (no network partitions)
- Stubborn Links
  - Channels delivers any message sent infinitely many times
- Perfect Links
  - Channels that delivers any message sent exactly once

Channel failure modes

- Logged Perfect Links
  - Channels delivers any message into a receiver’s persistent store (message log)

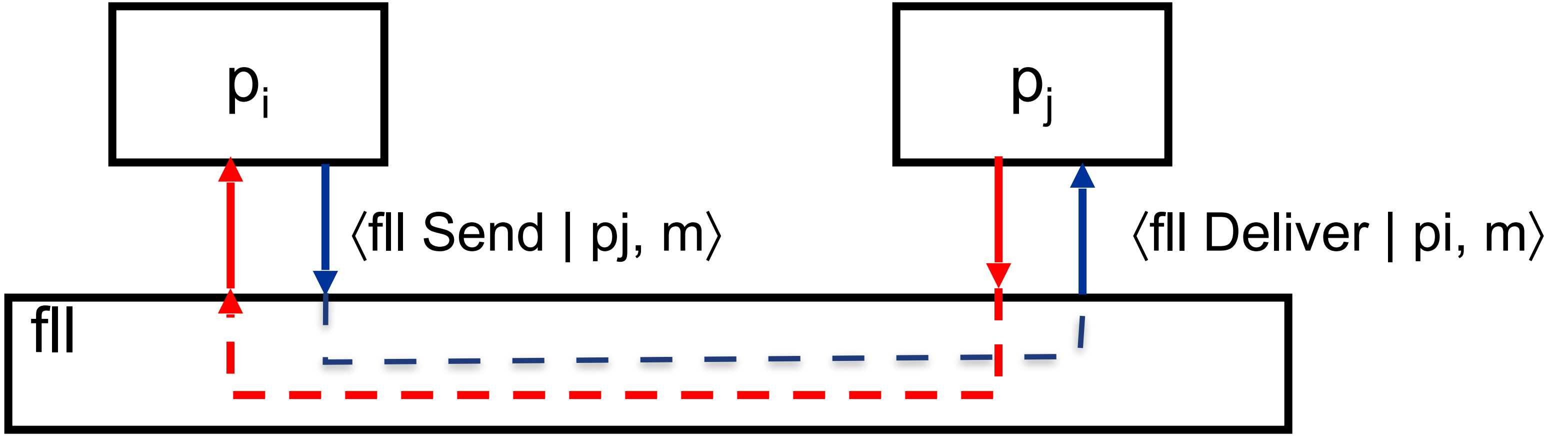
- Authenticated Perfect Links
  - Channels delivers any message m sent from process p to process q, that guarantees the m is actually sent from p to q

Fair Loss Links

Channel failure modes

- Fair-Loss Links
  - Channels delivers any message sent with non-zero probability (no network partitions)

Fair Loss Links (fll)



⟨fll Send | pj, m⟩

⟨fll Deliver | pi, m⟩

Fair-loss links: Interfaces

- **Module:**
  - Name: FairLossPointToPointLink **instance** fll
- **Events:**
  - **Request**: ⟨fll, Send | dest, m⟩
    - Request transmission of message m to process dest
  - **Indication**:⟨fll, Deliver | src, m⟩
    - Deliver message m sent by process src

- **Properties:**
  - ***FL1, FL2, FL3.***

Fair-loss links

- Properties
  - ***FL1. Fair-loss***: If m is sent infinitely often by p_i to p_j, and neither crash, then m is delivered infinitely often by p_j
  - ***FL2. Finite duplication:*** If a m is sent a finite number of times by p_i to p_j, then it is delivered at most a finite number of times by p_j
    - I.e. a message cannot be duplicated infinitely many times
  - ***FL3. No creation:*** No message is delivered unless it was sent

Stubborn Link

Channel failure modes

- Stubborn Links
  - Channels delivers any message sent infinitely many times

Stubborn links: interface

- **Module:**
  - Name: StubbornPointToPointLink **instance** sl
- **Events:**
  - **Request**: ⟨sl, Send | dest, m⟩
    - Request the transmission of message m to process dest
  - **Indication**:⟨sl, Deliver src, m⟩
    - deliver message m sent by process src
- **Properties:**
  - ***SL1, SL2***

Stubborn Links: interface

- **Module:**
  - Name: StubbornPointToPointLink
    instance sl
- **Events:**
  - **Request**: ⟨sl, Send | dest, m⟩
    - Request the transmission of message m to process dest
  - **Indication**:⟨sl, Deliver src, m⟩
    - deliver message m sent by process src
- **Properties:**
  - ***SL1, SL2***

Stubborn Links

- Properties
  - ***SL1. Stubborn delivery***: if a correct process p_i sends a message m to a correct process p_j, then p_j delivers m an infinite number of times
  - ***SL2. No creation:*** if a message m is delivered by some process p_j, then m was previously sent by some process p_i

Implementing Stubborn Links

- Implementation
  - Use the Lossy link
  - Sender stores every message it sends in **sent**
  - It periodically resends all messages in **sent**

Algorithm (sl)

```
Implements: StubbornLinks instance sl
Uses: FairLossLinks, instance all
• upon event ⟨sl, Init⟩ do
    • sent := ∅
    • startTimer(TimeDelay)

• upon event ⟨Timeout⟩ do
    • forall (dest, m) ∈ sent do
        • trigger ⟨fl, Send | dest, m⟩
    • startTimer(TimeDelay)

upon event ⟨sl, Send | dest, m⟩ do
    • trigger ⟨fll, Send | src, m⟩
    • sent := sent ∪ { (dest, m) }
upon event ⟨fll, Deliver | src, m⟩ do
    • trigger ⟨sl Deliver | src, m⟩
```

Implementing Stubborn Links

- Implementation
  - Use the Lossy link
  - Sender stores every message it sends in **sent**
  - It periodically resends all messages in **sent**
- Correctness
  - ***SL1. Stubborn delivery***
    - If process doesn’t crash, it will send every message infinitely many times. Messages will be delivered infinitely many times. Lossy link may only drop a (large) fraction.
  - ***SL2. No creation***
    - Guaranteed by the Lossy link

Perfect Links

Channel failure modes

- Perfect Links
  - Channels that delivers any message sent exactly once

Perfect links: interface

- **Module:**
  - Name: PerfectPointToPointLink, **instance** pl
- **Events:**
  - **Request**: ⟨pl, Send | dest, m⟩
    - Request the transmission of message m to node dest
  - **Indication**: ⟨pl, Deliver | src, m⟩
    - deliver message m sent by node src
- **Properties:**
  - ***PL1, PL2, PL3***

Perfect links (Reliable links)

- ***Properties***
  - ***PL1. Reliable Delivery***: If p_i and p_j are correct, then every message sent by p_i to p_j is eventually delivered by p_j
  - ***PL2. No duplication:*** Every message is delivered at most once
  - ***PL3. No creation:*** No message is delivered unless it was sent

Perfect links (Reliable links)

- Which one is safety/liveness/neither
- ***PL1. Reliable Delivery***: If neither p_i nor p_j crashes, then every message sent by p_i to p_j is eventually delivered by p_j

(liveness)

- ***PL2. No duplication:*** Every message is delivered at most once (safety)
- ***PL3. No creation:*** No message is delivered unless it was sent

(safety)

Perfect Link Implementation

- Implementation
  - Use Stubborn links
  - Receiver keeps log of all received messages in **Delivered**
    - Only deliver (perfect link Deliver) messages that weren't delivered before
- Correctness
  - *PL1. Reliable Delivery*
    - Guaranteed by Stubborn link. In fact the Stubborn link will deliver it infinite number of times
  - *PL2. No duplication*
    - Guaranteed by our log mechanism
  - *PL3. No creation*
    - Guaranteed by Stubborn link (and its lossy link? [D])

FIFO Perfect links (Reliable links)

- ***Properties***
  - ***PL1. Reliable Delivery***:
  - ***PL2. No duplication:***
  - ***PL3. No creation:*** No message is delivered unless it was sent
  - ***FFPL. Ordered Delivery***: if m_1 is sent before m_2 by p_i to p_j and m_2 is delivered by p_j then m_1 is delivered by p_j before m_2

Internet TCP vs. FIFO Perfect Links

- TCP provides reliable delivery of packets
- TCP reliability is so called “session based”
- Uses sequence numbers
  - ACK: “I have received everything up to byte X”
- Implementing Perfect Link abstraction on TCP requires reconciling messages between the sender and receiver when reestablishing connection after a session break

Default Assumptions in Course

- We assume perfect links (aka reliable) most of time in the course (unless specified otherwise)
- Roughly, reliable links ensure messages exchanged between correct are delivered exactly once
- NB. Messages are uniquely identified and
  - the message identifier includes the sender’s identifier
  - i.e. if “same” message sent twice, it’s considered as two different messages

- Many algorithm for crash-recovery process model assume either a Stubborn link, or Logged perfect link

Timing Assumptions

Specification of a Service

- How to specify a distributed service (abstract)?
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Timing Assumptions

- Timing assumptions
  - Processes
    - bounds on time to make a computation step
  - Network
    - Bounds on time to transmit a message between a sender and a receiver
  - Clocks:
    - Lower and upper bounds on clock rate-drift and clock skew w.r.t. real time

Asynchronous Model and Causality

Asynchronous Systems

- No timing assumption on processes and channels
  - Processing time varies arbitrarily
  - No bound on transmission time
  - Clocks of different processes are not synchronized
- Reasoning in this model is based on which events may cause other events
  - Causality
- Total order of event not observable locally, no access to global clocks

Causal Order (happen before)

- The relation $\rightarrow_\beta$ on the events of an execution (or trace β), called also causal order, is defined as follows
  - If a occurs before b on the same process, then $a \rightarrow_\beta b$
  - If a is a send(m) and b deliver(m), then $a \rightarrow_\beta b$
  - $a \rightarrow_\beta b$ is transitive
    - i.e. If $a \rightarrow_\beta b$ and $b \rightarrow_\beta c$ then $a \rightarrow_\beta c$

- Two events, a and b, are concurrent if not $a \rightarrow_\beta b$ and not $b \rightarrow_\beta a$
- $a \| b$

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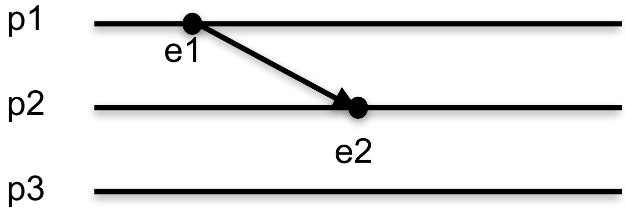
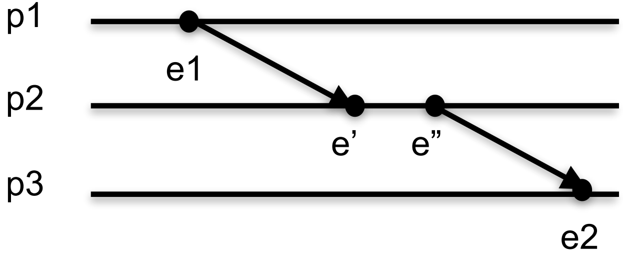
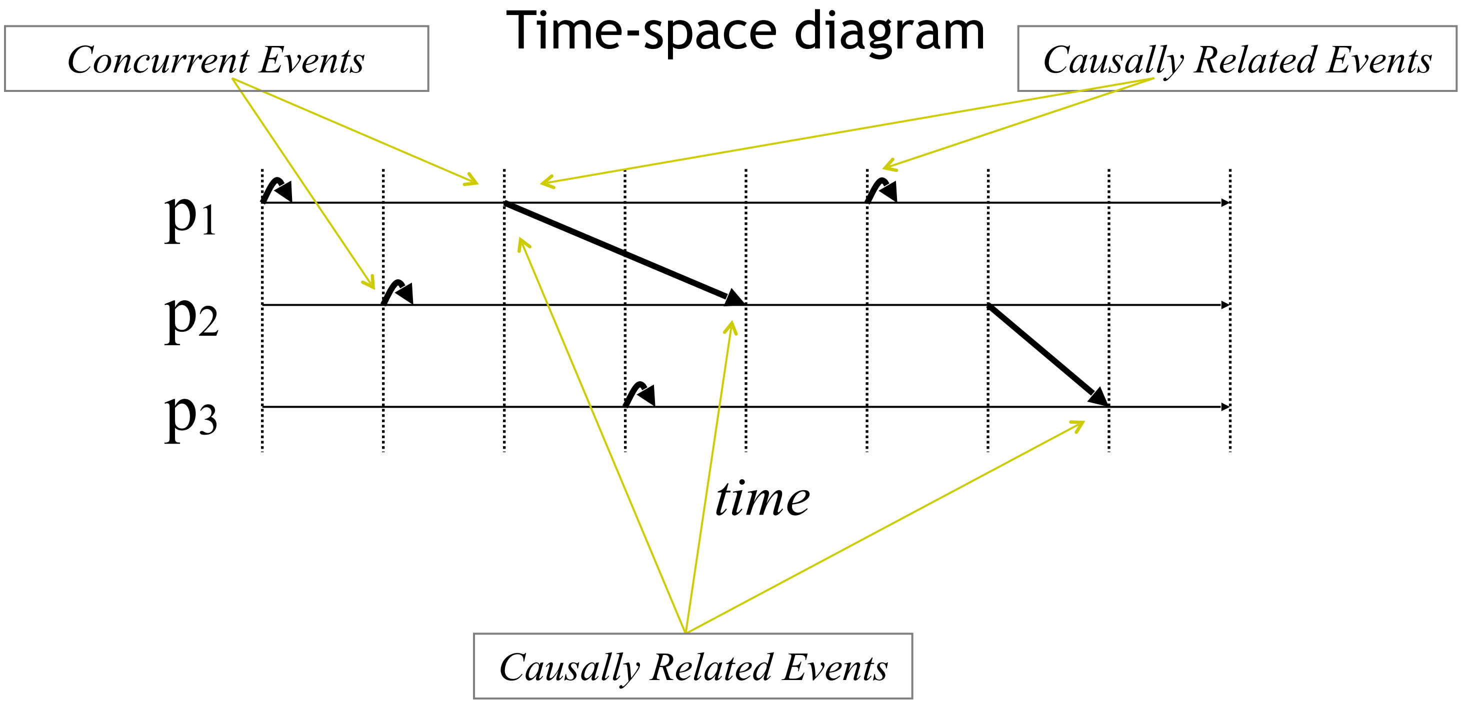




Example of Causally Related events



Similarity of executions

- The view of p_i in E, denoted $E|p_i$, is
  - the subsequence of execution E restricted to events and state of p_i
- Two executions E and F are similar w.r.t p_i if
  - $E|p_i = F|p_i$
- Two executions E and F are similar if
  - E and F are similar w.r.t every process

Equivalence of Executions

- **Computation Theorem:**
  - Let E be an execution (c_0,e_1,c_1,e_2,c_2,…), and V the trace of events (e_1,e_2,e_3,…)
  - Let P be a permutation of V, preserving causal order
    - P=(f_1, f_2, f_3…) preserves the causal order of V when for every pair of events $f_i \rightarrow_V f_j$ implies f_i is before f_j in P
  - Then E is similar to the execution starting in c_0 with trace P

Equivalence of executions

- If two executions F and E have the same collection of events, and their causal order is preserved, F and E are said to be similar executions, written $F{\sim}E$
  - F and E could have different permutation of events as long as causality is preserved!

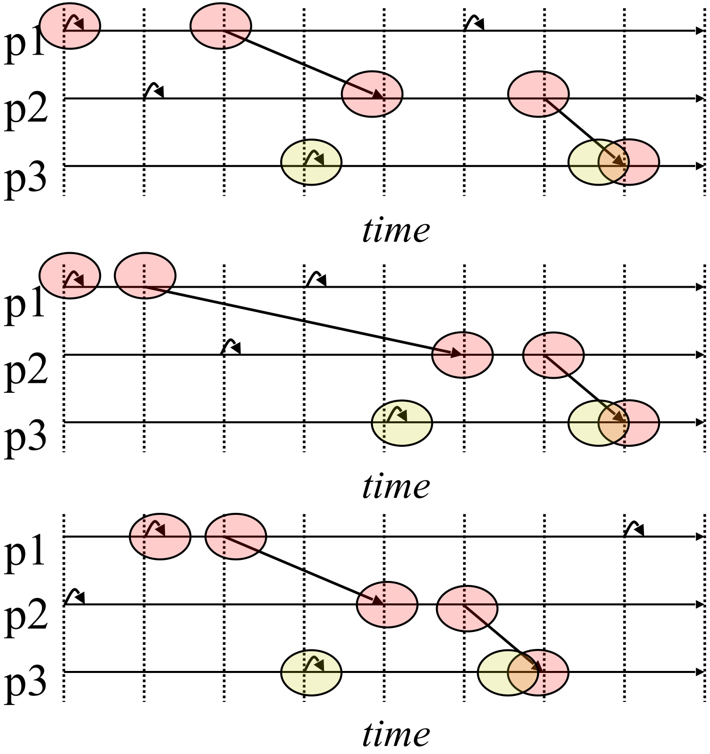
Computations

- Similar executions form equivalence classes where every execution in a class is similar to the other executions in the same class

- I.e. the following always holds for executions:
  - ~ is reflexive
    - I.e. a~ a for any execution
  - ~ is symmetric
    - I.e. If a~b then b~a for any executions a and b
  - ~ is transitive
    - If a~b and b~c, then a~c, for any executions a, b, c

- Equivalence classes are called computations of executions

Example of similar executions



🟨 🟥 *Same color ~ Causally related*

- All three executions are part of the same computation, as causality is preserved

Two important results (1)

- **Computation theorem gives two important results**
- **Result 1:** There is no algorithm in the asynchronous system model that can observe the order of the sequence of events (that can “see” the time-space diagram, or the trace) for all executions

Two important results (1)

- Proof:
  - Assume such an algorithm exists. Assume p knows the order in the final (repeated) configuration
  - Take two distinct similar executions of algorithm preserving causality
  - Computation theorem says their final repeated configurations are the same, then the algorithm cannot have observed the actual order of events as they differ

Two important results (2)

- Result 2: The computation theorem does not hold if the model is extended such that each process can read a local hardware clock

- Proof:
    - Similarly, assume a distributed algorithm in which each process reads the local clock each time a local event occurs
    - The final (repeated) configuration of different causality preserving executions will have different clock values, which would contradict the computation theorem

Synchronous Systems

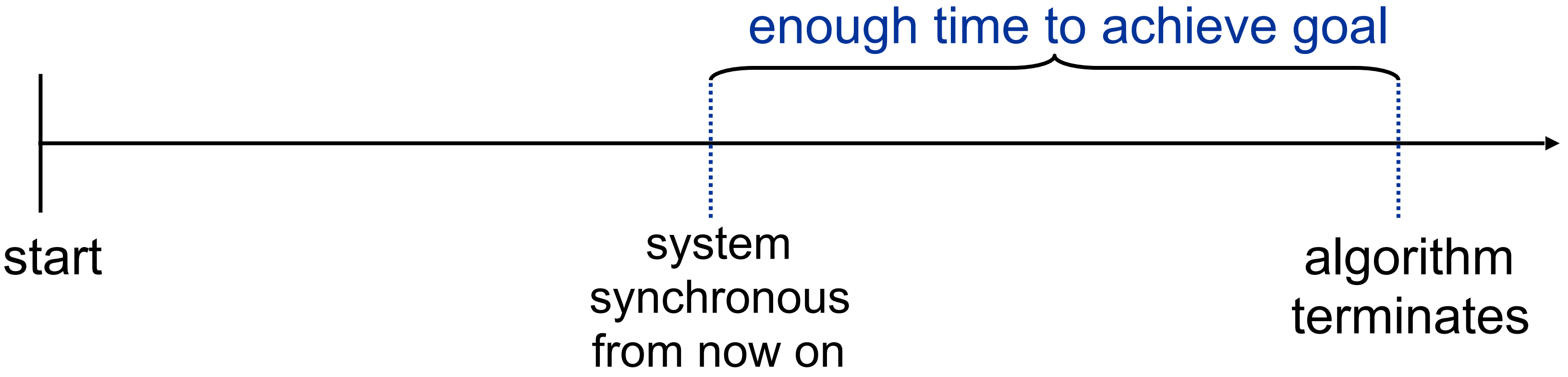
- Model assumes
  - Synchronous computation
    - Known upper bound on how long it takes to perform computation
  - Synchronous communication
    - Known upper bound on message transmission delay
  - Synchronous physical clocks
    - Nodes have local physical clock
    - Known upper bound clock-drift rate and clock skew
- Why study synchronous systems? [d]

Partial Synchrony

- Asynchronous system
  - Which eventually becomes synchronous
    - Cannot know when, but in every execution, some bounds eventually will hold
- It’s just a way to formalize the following
  - *Your algorithm will have a long enough time window, where everything behaves nicely (synchrony), so that it can achieve its goal*
- Are there such systems? [d]

Partial Synchrony

- *Your algorithm will have a long enough time window, where everything behaves nicely (synchrony), so that it can achieve its goal*
  - Useful for proving liveness properties of algorithms



enough time to achieve goal

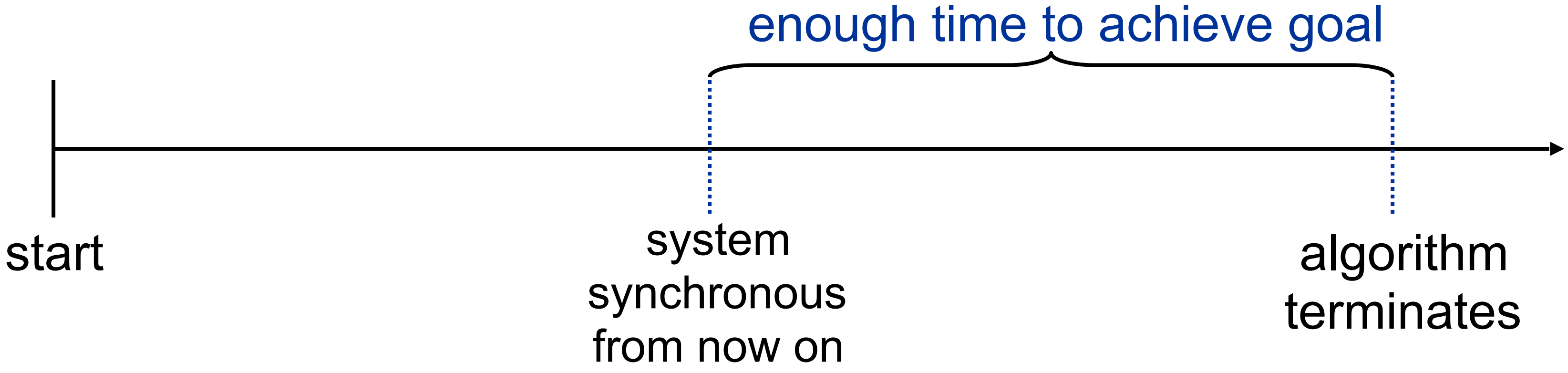
start

system synchronous from now on

algorithm terminates

Partial Synchrony

- Notice the time at which a system behaves synchronously is unknown
- To prove safety properties we need to assume that the system is asynchronous
- To prove liveness we use the partial synchrony assumption



enough time to achieve goal

start

system synchronous from now on

algorithm terminates

Timed Asynchronous Systems

- No timing assumption on processes and channels
  - Processing time varies arbitrarily
  - No bound on transmission time
- Bounds on Clocks drift-rate and clock skews
  - Interval clocks
  - At real-time t, clock of process P is in interval $(t-\rho, t+\rho)$
  - ρ depends on P

Logical Clocks

Logical Clocks

- A clock is function **t** from the events to a totally order set such that for events *a* and *b*
  - if $a \rightarrow b$ then $\mathbf{t}(a) < \mathbf{t}(b)$

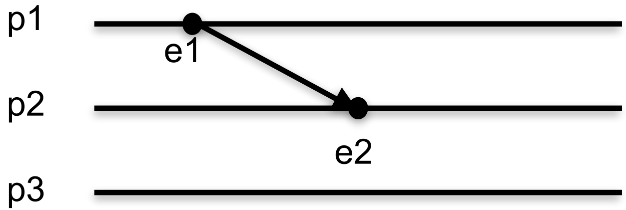
- We are interested in → being the happen-before relation

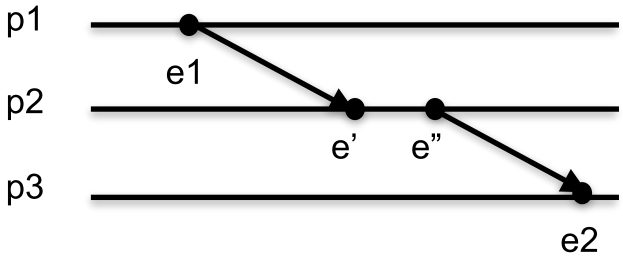
Causal Order (happen before)

- The relation $\rightarrow_\beta$ on the events of an execution (or trace β), called also causal order, is defined as follows
  - If a occurs before b on the same process, then $a \rightarrow_\beta b$
  - If a is a send(m) and b deliver(m), then $a \rightarrow_\beta b$
  - $a \rightarrow_\beta b$ is transitive
    - i.e. If $a \rightarrow_\beta b$ and $b \rightarrow_\beta c$ then $a \rightarrow_\beta c$

- Two events, a and b, are concurrent if not $a \rightarrow_\beta b$ and not $b \rightarrow_\beta a$
- $a || b$

Causal Order (happen before)





Observing Causality

- So causality is all that matters…
- …how to locally tell if two events are causally related?

Lamport Clocks at process p

- Each process has a local logical clock, kept in variable $\mathbf{t_p}$, initially $\mathbf{t_p} = 0$
  - A process p piggybacks ($\mathbf{t_p}$, p) on every message sent
- On internal event *a*:
  - $\mathbf{t_p} := \mathbf{t_p} + 1$; perform internal event *a*
- On send event message m:
  - $\mathbf{t_p} := \mathbf{t_p} + 1$; send(m, ($\mathbf{t_p}$, p))
- On delivery event *a* of m with timestamp (t_q, q) from q:
  - $\mathbf{t_p} := \max(\mathbf{t_p}, \mathbf{t_q}) + 1$; perform delivery event *a*

Lamport Clocks (2)

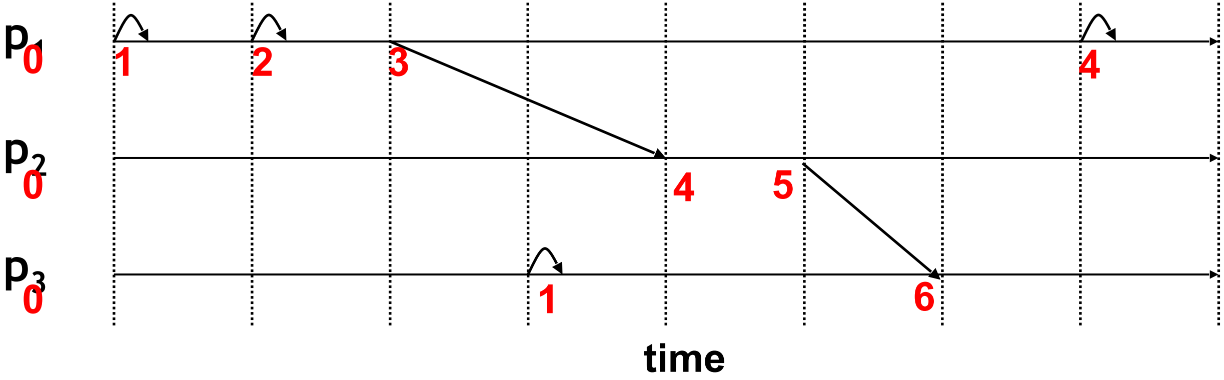
- Observe the timestamp (t, p) is unique
- Comparing two timestamps (t_p,p) and (t_q,q)
  - $(t_p,p)<(t_q,q)$ iff $(t_p<t_q$ or $(t_p=t_q$ and $p<q))$
  - i.e. break ties using process identifiers
  - e.g. $(5,p_5) < (7,p_2)$, $(4,p_2) < (4,p_3)$

Lamport Clocks (2)

- Lamport logical clocks guarantee that:
  - If $a \rightarrow_\beta b$, then $\mathbf{t}(a) < \mathbf{t}(b)$,
    - where $\mathbf{t}(a)$ is Lamport clock of event a

- events a and b are on the same process p, t_p is strictly increasing, so if a is before b, then t(a) < t(b)
- a is a send event with t_q and b is deliver event, t(b) is at least one larger than t_q (t(a))
- transitivity of t(a) < t(b) < t(c) implies the transitivity condition of the happen before relation

Lamport logical clocks



- Lamport logical clocks guarantee that:
  - If $a \rightarrow_\beta b$, then $\mathbf{t}(a) < \mathbf{t}(b)$,
  - if $\mathbf{t}(a) \geq \mathbf{t}(b)$, then not $(a \rightarrow_\beta b)$

Vector Clocks

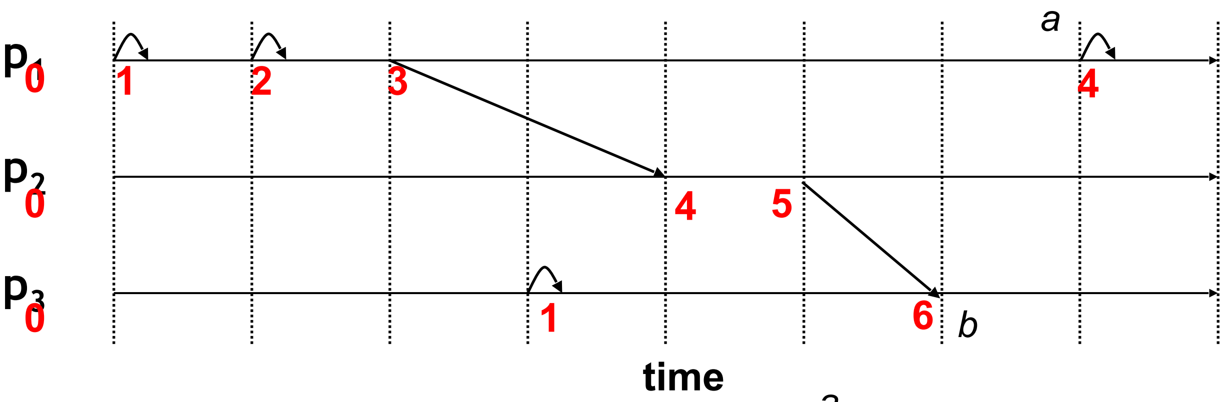
Vector clocks

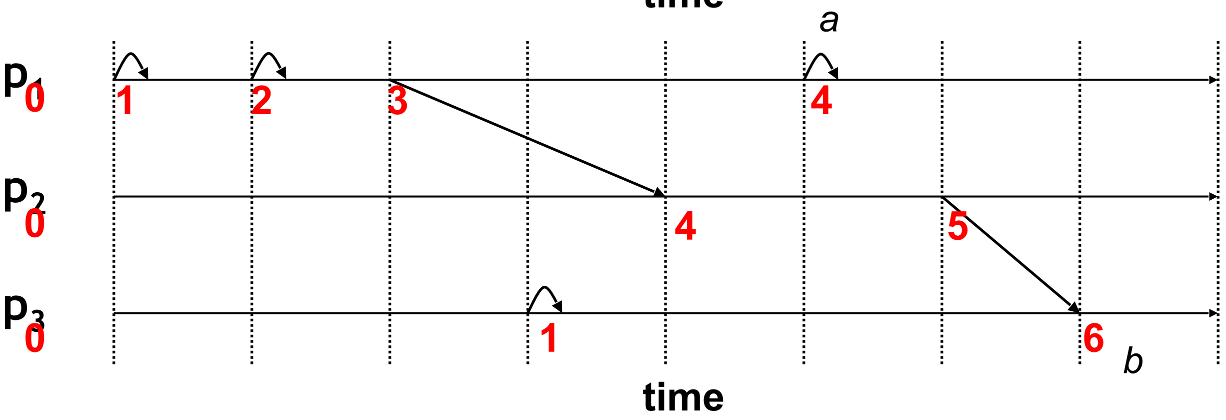
- The happen-before relation is a partial order
- In contrast logical clocks are total
  - Information about non-causality is lost
    - We cannot tell by looking to the timestamps of event *a* and *b* whether there is a causal relation between the events, or they are concurrent
- Vector clocks guarantee that:
  - if $\mathbf{v}(a) < \mathbf{v}(b)$ then $a \rightarrow_{\beta} b$, in addition to
  - if $a \rightarrow_{\beta} b$ then $\mathbf{v}(a) < \mathbf{v}(b)$
    - where $\mathbf{v}(a)$ is a vector clock of event *a*

Non-causality and Concurrent events

- Two events *a* and *b* are concurrent ($a \parallel_\beta b$) in an execution E (trace(E) = β) if
  - **not** $a \rightarrow_\beta b$ and **not** $b \rightarrow_\beta a$
- Computation theorem implies that if ($a \parallel_\beta b$) in β then there are two executions (with traces β_1 and β_2) that are similar where *a* occurs before *b* in β_1, *b* occurs before *a* in β_2

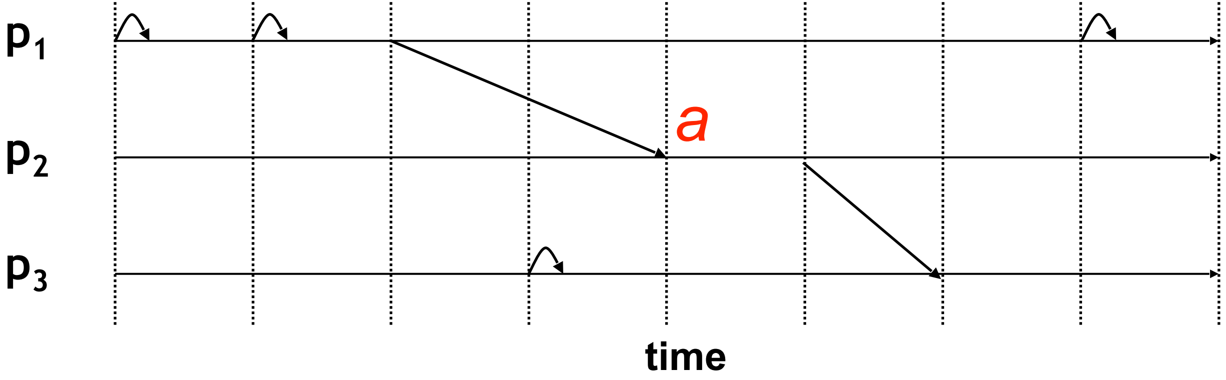
Non-causality and Concurrent events





Vector clock definition

- Vector clock for an event ***a***
  - **v**(a) = ($x_1, \ldots, x_n$)
  - x_i is the number of events at p_i that happens-before a
  - for each such event e: e → a



Vector Timestamps

- Processes $p_1, \ldots, p_n$
- Each process p_i has local vector **v** of size **n** (number of processes)
  - **v**[i] = 0 for all i in 1…n
  - Piggyback **v** on every sent message
- For each transition (on each event) update local **v** at p_i:
  - **v**[i] := **v**[i] + 1 (internal, send or deliver)
  - **v**[j] := max(**v**[j], $\mathbf{v_q}$[j]), for all j ≠ i (deliver)
    - where $\mathbf{v_q}$ is clock in message received from process q

Comparing Vector Clocks

- $v_p \leq v_q$ iff
  - $v_p[i] \leq v_q[i]$ for all i
- $v_p < v_q$ iff
  - $v_p \leq v_q$ and for some i, $v_p[i] < v_q[i]$
- v_p and v_q are concurrent ($v_p \| v_q$) iff
  - not $v_p < v_q$, and not $v_q < v_p$

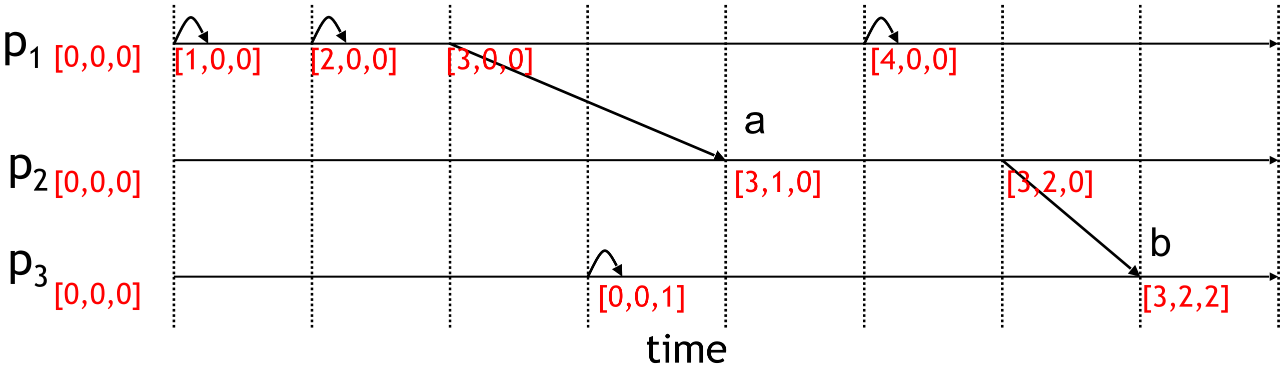
$(3,0,0) \leq (3,1,0)$

$[3,0,0] < [3,1,0]$

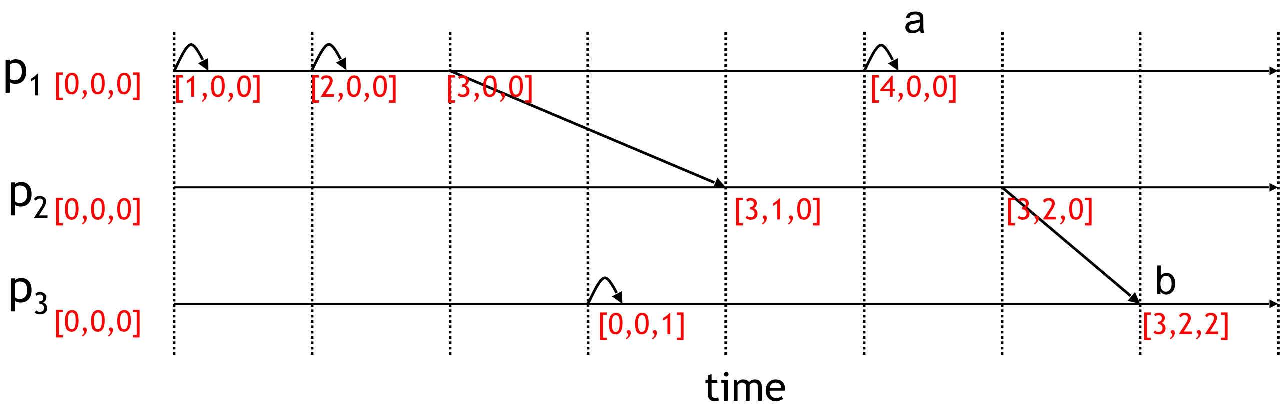
$[3,1,0] <> [4,0,0]$

- Vector clocks guarantee
  - If $v(a) < v(b)$ then $a \rightarrow b$, and
  - If $a \rightarrow b$, then $v(a) < v(b)$
    - where v(a) is the vector clock of event a

Example of Vector Timestamps

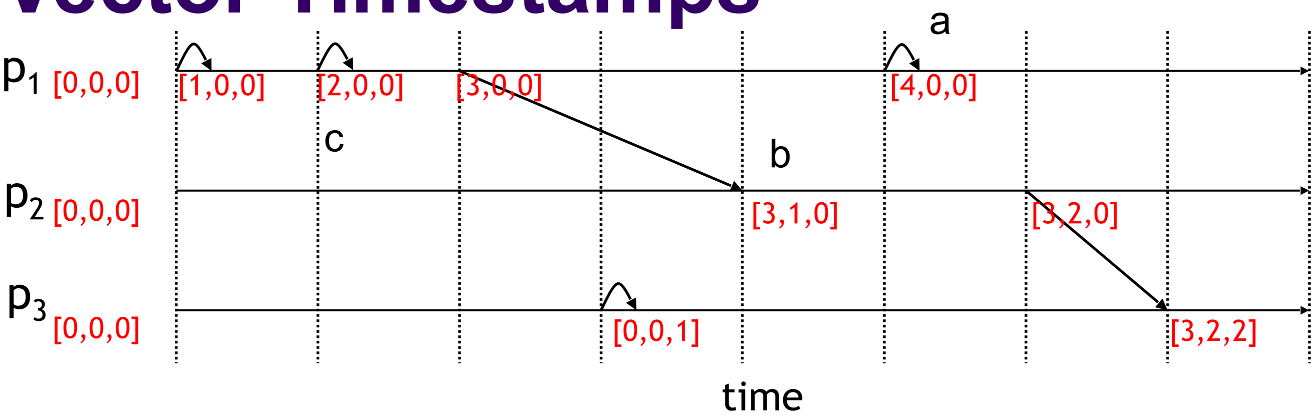


v(a) < v(b) implies a → b



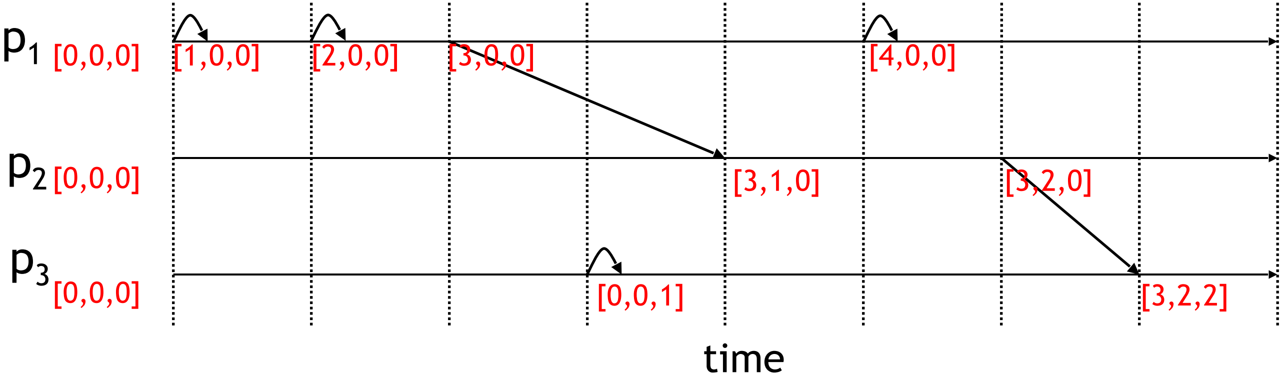
v(a) <> v(b) implies a || b

Vector Timestamps



- For any events a and b, and trace β :
  - **v**(a) and **v**(b) are incomparable if and only if a||b
  - **v**(a) < **v**(b) if and only if a → b

Example of Vector Timestamps



Great! But cannot be done with smaller vectors than size n, for n nodes

Partial and Total Orders

- Only a partial order or a total order? [d]
  - the relation $\rightarrow_\beta$ on events in executions
    - Partial: $\rightarrow_\beta$ doesn't order concurrent events
  - the relation < on Lamport logical clocks
    - Total: any two distinct clock values are ordered (adding pid)
  - the relation < on vector timestamps
    - Partial: timestamp of concurrent events not ordered

Logical clock vs. Vector clock

- **Logical clock**
  - If $a \rightarrow_{\beta} b$ then $t(a) < t(b)$ (1)

- **Vector clock**
  - If $a \rightarrow_{\beta} b$ then $v(a) < v(b)$ (1)
  - If $v(a) < v(b)$ then $a \rightarrow_{\beta} b$ (2)

- Which of (1) and (2) is more useful? [d]

- What extra information do vector clocks give? [d]