Fault Tolerance in Distributed Systems

an introductory course

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Course Structure

- Introduction to distributed systems: foundations, main paradigms and models
- Distributed fault tolerance foundations and paradigms
- Models and systems for distributed fault-tolerant computing
- Case study: making VP'63 distributed and dependable
- Introduction to the fundamental concepts of intrusion tolerance

Pointers to course material

- Material for *distributed systems* review, and material for *fault tolerance* concepts:
  - The book Distributed Systems For System Architects, Paulo Verissimo and Luís Rodrigues, 2001, Kluwer Academic Publishers. http://www.navigators.di.fc.ul.pt/dssa
  - Further reading for these topics is described in the book, at end of each chapter.
- Material for the newer *intrusion tolerance* domain, is available from the University of Lisbon web site:
  - Intrusion-Tolerant Architectures: Concepts and Design Verissimo, P., Neves, N., and Correia, M. In: Architecting Dependable Systems. Springer-Verlag LNCS 2677 (2003). Ext. version, Tech. Rep. DI/FCUL TR03-5, Dept. of Informatics, Univ. of Lisboa (2003). http://www.navigators.di.fc.ul.pt/it/index.htm

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1

Introduction to Distributed Systems

What is a distributed system?

A computer network is not a distributed system

- *computer network*
  - infrastructure serving a set of computers interconnected through communication links of possibly diverse media and topology, and using a common set of communication protocols.
- *distributed system*
  - system composed of several computers which communicate through a *computer network*, hosting processes that use a common set of distributed protocols to assist the coherent execution of distributed activities.

Characteristics of Distributed Systems

- multiple computers
- interconnected by a network
- sharing state

- independent failures
- communication is unreliable
- has variable delays
- speed and bandwidth are moderate
- investment costs often lower than mainframes
- management costs are higher
- partial ordering of events only
- difficult to assess global state

Centralized versus Distributed Systems

- **Centralized** :
  - Accessibility
    - to resources and info
  - Homogeneity
    - of procedures and technologies
  - Manageability
    - single, domain
  - Consistency
    - global state
  - Security, due to:
    - threat reduction
- **Distributed** :
  - Scalability, helped by:
    - geographical scope
    - heterogeneity
    - modularity
  - Sharing:
    - of common resources and info
  - Reliability and availability, due to:
    - redundancy and replication
    - graceful degradation
    - failure independence
  - Security, due to:
    - vulnerability reduction
  - Low cost factor

Decentralization

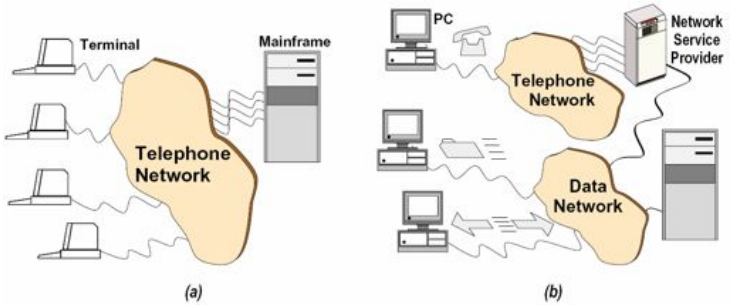
- Decentralization *is not* distribution
  - decentralization is local autonomy of means and procedures, based on local control points that contribute to the goals of a wider structure
- distribution adapts computing infrastructure to a decentralized model of activity
- strategy for decentralization?
  - decentralize control, integrate and coordinate activities
  - supply coherent system view to all loci of control
    - *common knowledge*
  - secure decentralized coordination of actions
    - *distributed algorithmic*

Distributed Systems Evolution

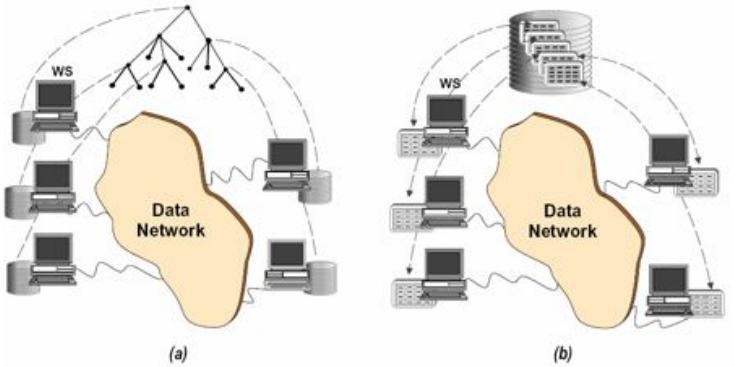
ARCHITECTURES

Remote Access Architectures:

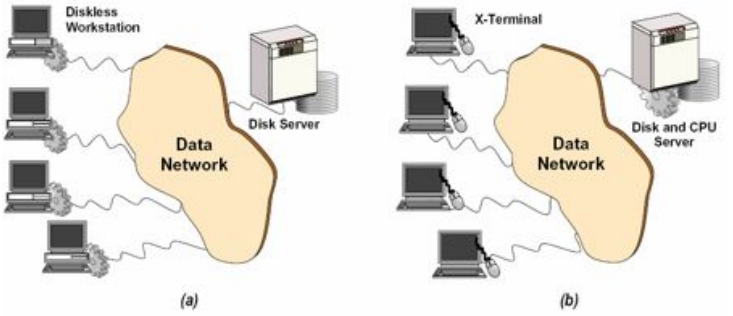
(a) Plain Telephone Line; (b) Data Network



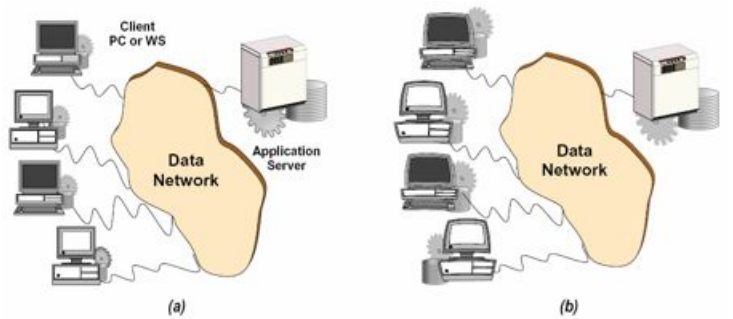
Distributed File and Memory Architect.



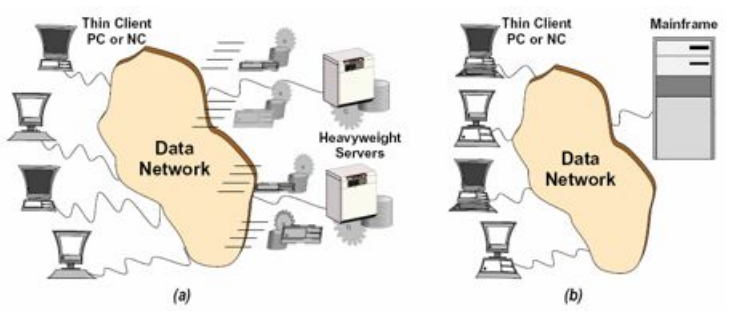
Diskless and X-Terminal Architect.
(on disk and/or CPU servers)



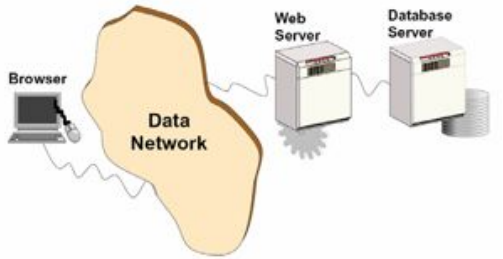
Client-Server Architectures
(Clients became "fat")



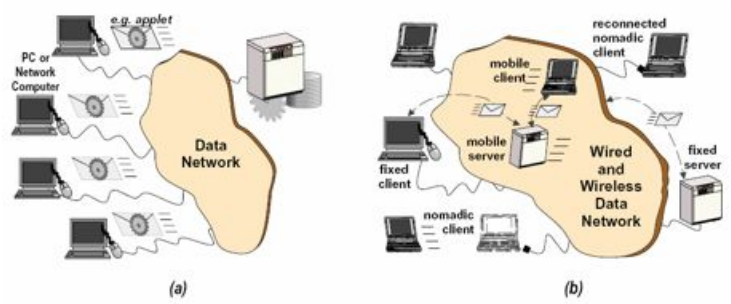
3-tier Client-Server or Thin-Client Archit.
(brought mainframes back, perhaps unnecessarily)



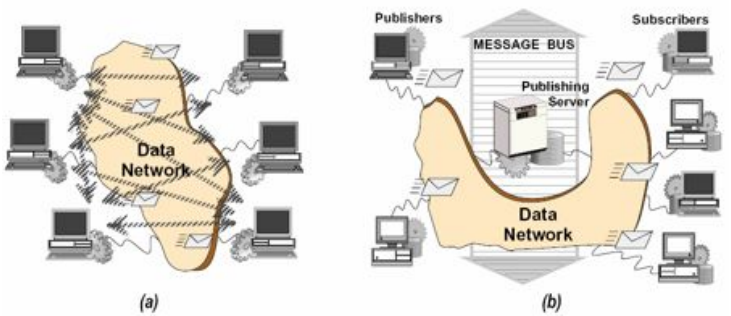
3-tier Client-Server Web-based Archit.



Mobile Code Architectures:
(a) Portable and Mobile Code; (b) Mobile Nodes



Event-based Architectures:
(a) Multipeer; (b) Publisher-subscriber



Non-functional properties of Distributed Systems

- What systems are, rather than what they do
- Some familiar names:
  - reliability and availability (fault tolerance)
  - timeliness and predictability (real-time)
  - confidentiality and integrity (security)

Some formal notions

Formal system predicates
a colloquial definition

- Objective
  - specify in a formal manner, including formulas containing logic (and, or, exists, forall), temporal logic (eventually, always) and time (until/from) operators
  - we can specify the properties of any program or protocol in terms of properties of: *safety and/or timeliness , liveness*

Formal system predicates
a colloquial definition

- Safety
  - the measure in which a service/program does not do bad things
  - safety properties specify that wrong events never take place
  - a safety property specifies that a predicate P is always true
  - example, "any delivered message is delivered to all correct participants" is a safety property
  - If it is not secured, the system becomes incorrect
  - however, it does not impose that messages are delivered at all

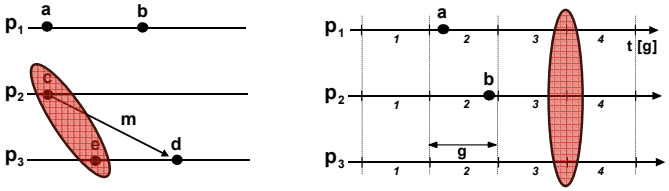
Formal system predicates
a colloquial definition

- Liveness
  - the measure in which a service/program does good things
  - liveness properties specify that good events eventually take place
  - a liveness property specifies that predicate P will eventually be true
  - example, "any message sent is delivered to at least one participant" is a liveness property
  - If it is not secured, the system may not progress (messages are not delivered)

Formal system predicates
a colloquial definition

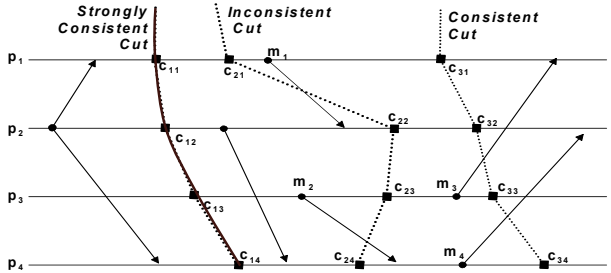
- Timeliness
  - a sub-class of safety property is timeliness, which specifies that a predicate P will be true in relation to a given instant of real time (until, before, at)
  - "any transaction completes until Tt from the start" is a timeliness property
  - to be secured, all transactions must execute within Tt time units

Space-Time and Lattice Diagrams



- Event types:
  - execution, send, receive, deliver
- Precedence:
  - a < b ; c < d
  - is c < e ?
- Time lattices:
  - based on notion of global time with granularity (tick) *g*
  - does 4:00 tick at exactly the same place everywhere?

Cuts and Global States (GS)



- Types of cuts:
  - inconsistent cut: snapshot gives invalid picture of GS
  - consistent cut: snapshot gives correct but possibly incomplete picture of GS (e.g., ignores messages in transit)
  - strongly consistent cut: snapshot faithfully represents GS

Distributed systems paradigms

Naming and addressing

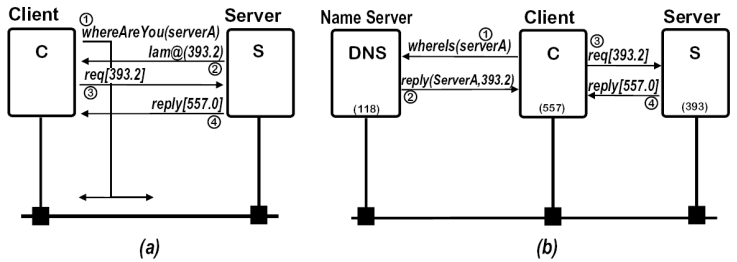


Figure 2.2. Name to Address Translation: (a) Broadcast; (b) Name Server

Message passing

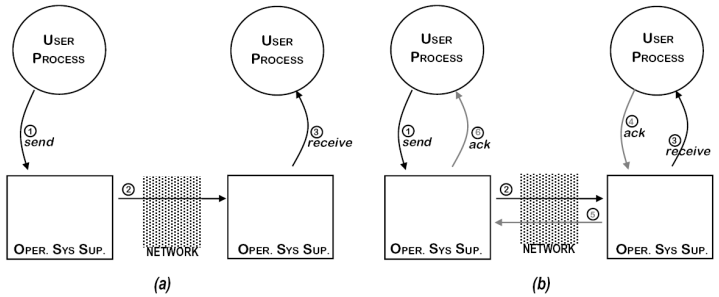


Figure 2.4. Message Passing Protocols: (a) Send-Receive;(b) Acknowledged-Send

Remote operations (contd.)

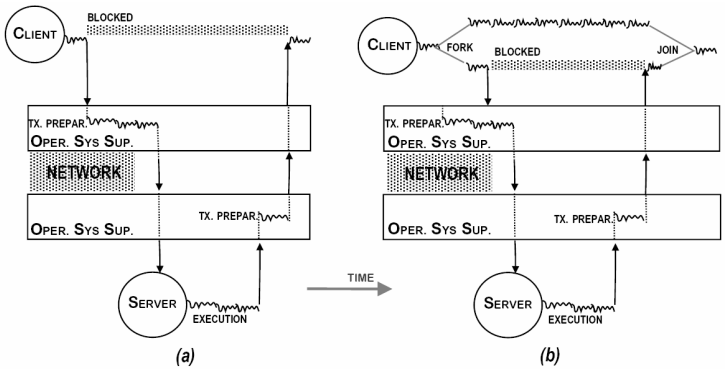


Figure 2.8. Remote Operation Interfaces: (a) Blocking; (b) Non-Blocking

Group communication

- process groups
- group communication service (multicast)
- group membership (views)
- main components of a multicast protocol:
  - routing;
  - omission tolerance;
  - flow-control;
  - ordering;
  - failure recovery.

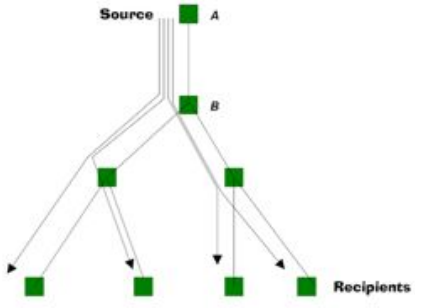


Figure 2.9. Multicast Tree

Time and synchrony

Time and Clocks

- Common uses of clocks in distributed systems:
- trigger events
- register the time at which events occurred
- measure durations
- artifact: support protocol implementation

Global Time

Why?

- trigger events
  - how do you synchronise distributed event triggering?
- register the time at which events occurred
  - how do you correlate distributed registers?
- measure durations
  - how do you measure what starts here and ends there?
- *Global Clock*:
  - abstraction: a set of mutually synchronised clocks

Absolute Time

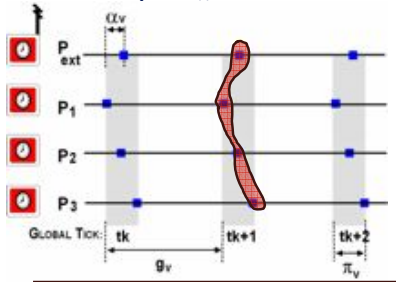
Why?

- coordination of systems that do not communicate directly
- bounding the error in lenghty duration measurement
- *Absolute global clock*:
  - abstraction: a set of clocks synchronised individually to a common reference
  - e.g., UTC- Universal Time Coordinated; TAI- Temps Atomique Internacional

Time and clocks

Properties of a Global Clock System

- Physical Granularity
  - $pc^{tk+1} - pc^{tk} = g$
- Virtual Granularity
  - $vc^{tk+1} - vc^{tk} = g_v$
- Convergence
  - $| vc_k(t^0) - vc_l(t^0) | \leq \delta_v$
- Precision
  - $| vc_k(t) - vc_l(t) | \leq \pi_v$, forall $0 \leq t$
- Rate
  - $1 - \rho_v \leq [\, t(vc_k^{tk+1}) - t(vc_k^{tk}) \,] / g_v \leq 1 + \rho_v$, forall $0 \leq tk < tk+1$
- Accuracy
  - $| vc_k(t) - t | \leq \alpha_v$, forall $0 \leq t$, t from an abs ref



So, does 4:00 tick at exactly the same place everywhere?

Time and clocks
Properties of a Global Clock System

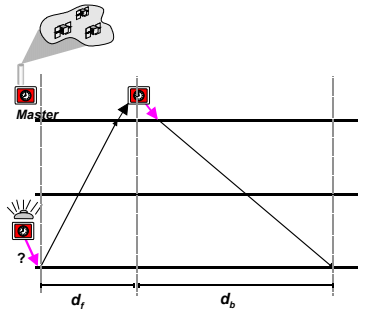
- Physical Granularity (g)
  - fundamental tick or pulse of hardware clock.
- Virtual Granularity (gv)
  - tick of the virtual clock, submultiple of g
- Convergence (δv)
  - measures how close virtual clocks are to each other immediately after the synchronization algorithm terminates.
- Precision (Πv)
  - measures how closely virtual clocks remain synchronized to each other at any time.
- Rate (ρv)
  - instantaneous rate of drift of virtual clocks.
- Envelope Rate ($\rho\alpha$)
  - long-term, or average rate of drift.
- Accuracy (αv)
  - measures how closely virtual clocks are synchronized to an absolute real time reference, provided externally.

Clock synchronisation

- Hardware clocks drift with time
  - some (e.g. cesium or rubidium GPS clocks) are extremely stable
  - but PC and workstation HW clocks are bad (worst than 1ppm)
- so they have to be synchronised periodically
  - *clock synchronisation protocols*
- Internal synchronisation:
  - ensures precision
  - normally clocks cooperatively readjust (*agreement or convergence based*)
- External synchronisation:
  - ensures accuracy and precision ($\pi_v = 2\ \alpha_v$)
  - normally clocks read from an external master (*round-trip-based*)

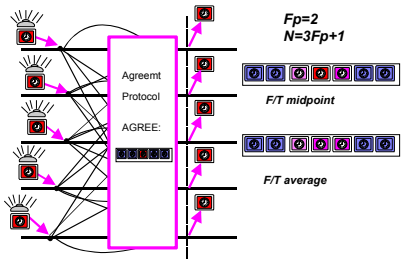
Clock synchronisation
(master- ou round-trip based)

- external synchronization :
  - based on round-trip measurement from central master clock
- Accuracy:
  - assessed by measuring round-trip delay
  - depends on delay symmetry
  - (df+db)/2 best run
- Precision:
  - precision is twice the accuracy ($\pi_v = 2\ \alpha_v$)



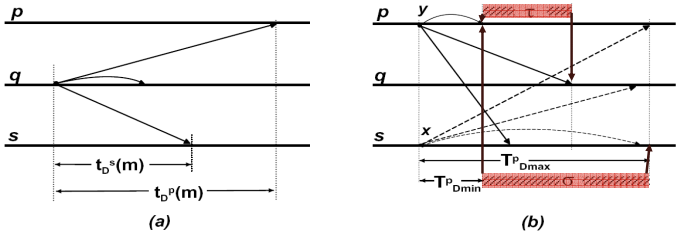
Clock synchronisation
agreement-based

- Agreement based:
  - convergence based on F/T average or median
  - clocks are Byzantine
- Precision:
  - precision depends on clock reading error
  - processors compute common value to set clocks to
  - time for agreement is in critical path of precision



Synchronism

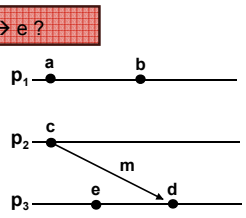
- synchronism means (w.r.t. messages):
  - known and bounded message delivery delay
- synchronism metrics of quality:
- Steadiness (σ)
  - $\sigma = \max_p(T_{Dmax} - T_{Dmin})$ (variance of delivery delay across execs)
- Tightness (τ)
  - $\tau = \max_{m,p,q}(t_D^p(m) - t_D^q(m))$ (variance of delivery delay in same exec)

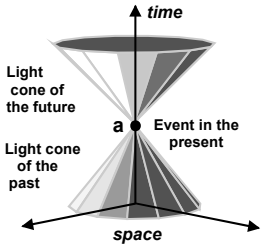


Ordering

Causal Order

So, is c → e ?





- **happened-before relation :**
  - ***a*** **--> *b* iff:**
  - ***a*** **before *b* locally**
  - ***a*** **send and *b*** **reception of *a***

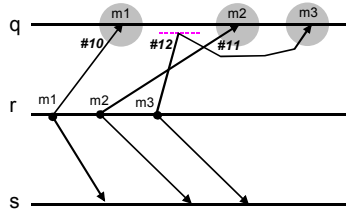
- cause-effect order:
  - natural universe order
- a partial order:
  - depends of time-like and space-like separation of events
  - relativistic effect due to speed difference between local and message events

Ordering

- Causal Delivery
  - for any two messages M1 and M2, sent by p and q, delivered to any correct processes, if *send(M1) --> send(M2),* then *deliver(M1) --> deliver(M2)*
  - Example: clients compete over a server to schedule a trip, buy some stock, and communicate between them at the same time; only causal reflects the inter-client relations on the server requests
- FIFO Delivery (*first-in-first-out*)
  - for any two messages M1 and M2, sent by p, delivered to any correct processes, if *send(M1) --> send(M2),* then *deliver(M1) --> deliver(M2)*
  - Example: this is a reduction of the general causal order to messages originated from only one sender (e.g. TCP ordering)

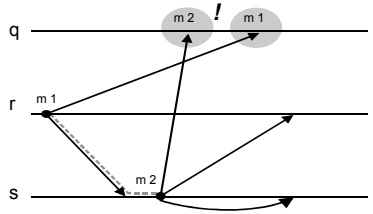
operations in FIFO order

(the most intuitive ordering)



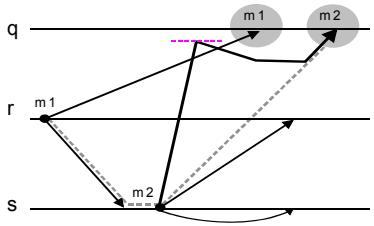
- r is solving problem by executing 3 modules in sequence
- he disseminates intermediate results (m1, m2, m3) to s and q, who perform the second phase, which depends on the sequence order.
- q got m1 with #10 and then m3 with #12, he knows m2 with #11 is missing and **delays** delivery of m3 until m2 arrives and only then it delivers messages m2 and m3 in that sequence.
- NB: in complex protocols, **reception** often different from **delivery**

when FIFO order is insufficient



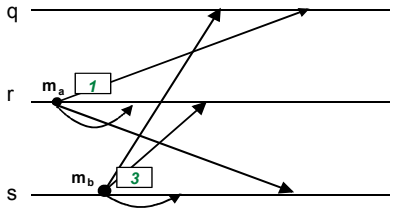
- problem was complex, so r breaks his job in steps, asking s to perform step 2 after he does step 1, which he signals with m1
- s executes step 2 when m1 arrives, after which it send m2
- problem: m1 got delayed, it will be delivered to q after m2
- since q waits for messages in the order they were issued to perform the second phase, the **application fails**
- what went wrong is that FIFO protocol does not capture m1 -> m2 causal relation and order inversion takes place
- cannot be used if competing senders also exchange messages

Solution: causal order



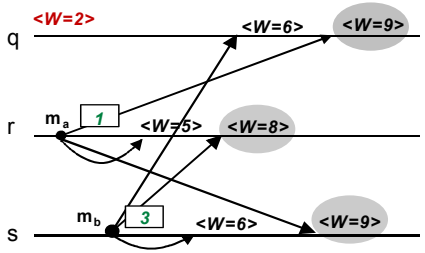
- FIFO is expanded to causal and englobes all nodes: m1 -> m2 is now recognised
- m1 is delayed to q, but q delays delivery of m2, to fulfil causal delivery

operations in causal order



- r leads a team work performing some computations
- result is accumulated in variable W, update function compares W previous state to new result, takes greatest and adds 3
- errors in previous works make r request all steps done in parallel by r, q and s, and results disseminated to all, to compare results and replicate W. Any one finishing a step posts result to all including himself, in **causal order**.
- if everybody is doing the same steps, it is expected for W to be the same everywhere.

when causal order is insufficient

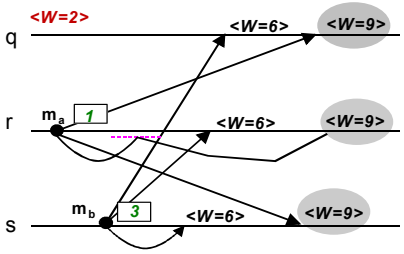


- initially W=2, and r and s disseminate their results concurrently
- so causal order protocol does not order them:
- ma = <1> is received first at r, W=2+3=5, then mb = <3> is received and W=5+3=8. mb = <3> is received first at q, W=3+3=6, then mb = <3> is received and W=6+3=9
- this violates replicated computation correctness subsequent steps depending on the value of W will not be consistent

Total ordering implementations

- Total ordering
  - Any two messages delivered to any pair of participants are delivered in the same order to both participants
  - Example: sending operation or update requests to replicas of a server, so that they execute them inthe same order and produce the same result and/or assume the same state

Solution: total order

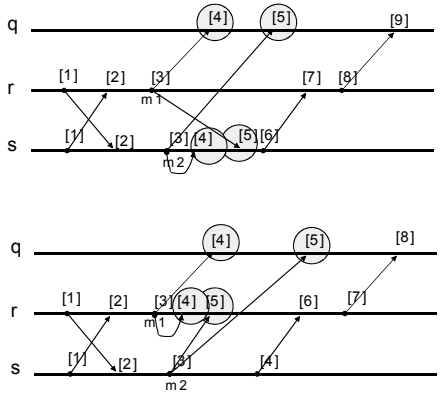


- previous problem is solved with total order
- active replica management requires total order, be it causal or not
- in which cases can we do active replicas without total order ?
- *think....*

Ordering mechanisms and algorithms

Causal ordering with logical clocks

- ***Objective:***
  - **order events by cause-effect or precedence (e1 --> e2)**
- ***Implementation rules:***
  - **initially: LCi=0 forall i;**
  - **at each *e* local to *p*: incr. LCp**
  - **at each send, timestamp *m* with LC value: LC(m) = LCp**
  - **at each reception at *q*, incr. LCq, and update LCq with max [LCq,LC(m)]**
- ***Ordering rules:***
  - **e1 --> e2 ==> LC(e1) < LC(e2)**

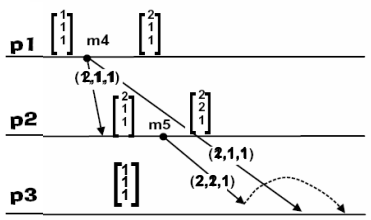


Causal ordering with vector clocks in action

(ISIS CBCAST protocol)

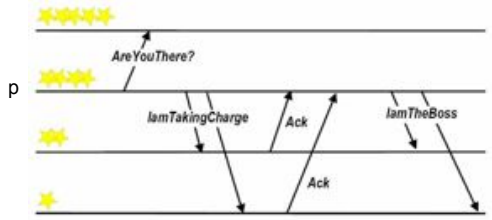
- ***Implementation rules (Pi -> Pj):***
- **initially:** VTi[k]=0 forall i,k
- ***at each send m*:**
- incr. VTi[i] and timestamp *m* with VTi: VT(m)
- ***at each Rx at Pj delay delivery until*:**
- msg m-1 from Pi seen : VT(Pj)[i]=VT(m)[i]-1 and
- all msgs preceding m delivered at Pi,

  also delivered at Pj : VT(m)[k]≤VT(Pj)[k] , forall k
- ***Pi does not delay msgs to itself***
- ***upon each delivery:***
- update VT(Pj) w/ max[VT(Pj)[k],VT(m)[k]] forall k
- ***Example:***
- **when p3 receives m5, VT3=[1,1,1]**
- **since VT(m) =[2,2,1], msg from p1 is missing at p3**
- **wait until rx m4, which sets VT3=[2,1,1], and deliver m5, setting VT3=[2,2,1]**



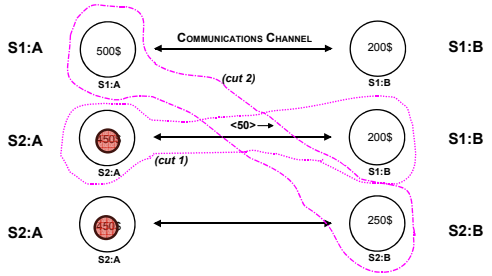
Coordination and Consistency

Leader election *(bully algorithm)*



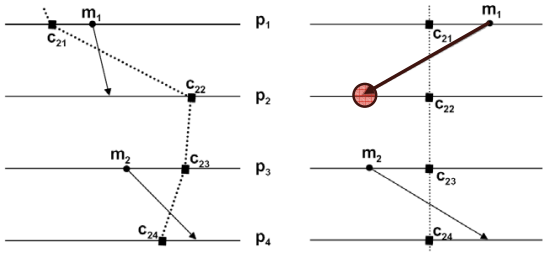
- always elects the highest ranked active candidate (i.e., process with the lowest identier)
- instead of sending a message to every process, process p trying to become leader just sends *AreYouThere?* to higher ranks, if someone replies, p silently gives up
- if nobody replies, p tells all lower ranks of his intention, sending *IAmTakingCharge*, and waits for ack from each
- when all acks come (or a timeout occurrs, since some of the processes with lower rank may have crashed), p assumes the leadership by sending *IAmTheBoss* to all processes.

Consistent Global States
(issues with Ad-hoc State Snapshots)



- total=700$; money transfer A-> B, 50$; during transfer, ad-hoc snapshot is done, from external node sending messages to A and B.
- cut 1: <S2:A=450$, S1:B=200$>=650$! (msg sent, not received!)
- cut 2: <S1:A=500$, S2:B=250$>=750$! (msg received, not sent!)
- a correct snapshot protocol will flush the channels to ensure consistency

Inconsistent Cuts



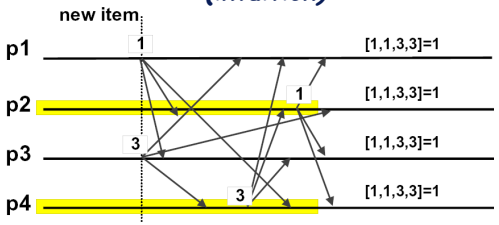
- what you get if you don't use the right algorithm:
  - is there anything strange with message m1?
  - and now?
  - a correct snapshot protocol will discard messages "not sent" to ensure consistency

Consensus

- Validity
  - if a process decides v, then v was proposed by some process
  - no process decides more than once
- Agreement
  - No two correct processes decide differently
- Termination
  - Every correct process eventually decides

- Consensus is equivalent to atomic broadcast
  - That is, one can implement one with the other
  - Does not mean that all such implementations are efficient!

Distributed consensus
(intuition)



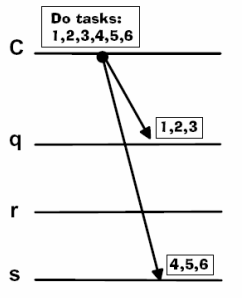
- set of processes must agree on one action, in a decentralized way: decide who keeps each new item that arrives, all send their votes to all
- new item arrives, p2 and p4 are busy, so only p1 and p3 offer to pick it
- p2 receives the proposal from p1 in the first place, thus it supports p1, while for the same reason p4 supports p3.
- when all votes are collected, all have same vector to decide from (1,1,3,3)
- any agreed deterministic function will do, ex:
  - "winner is the one with more votes, in case of tie, the smaller ID wins"
- the item is assigned to p1.

Membership

- group membership
  - set of processes belonging to the group at a given point in time
- membership service:
  - keeps track of membership and provides info to group members
- group view:
  - subset of members mutually reachable at a given point
- group membership is often dynamic:
  - in response to user demand or changes in the runtime environment (load, failures, etc)
  - it may grow, by letting new processes join the group
  - it may shrink, by letting members leave the group
  - view changes when processes fail or when they recover

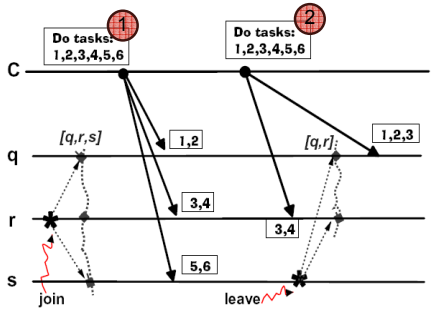
Agreement on Membership
(decentralized applications)

- coherent notion of membership useful for a number of applications
- e.g. decentralized dispatcher
  - group of workers (set of parallel processors) divide a task requested by client by the current number of elements
  - dispatch is local, split is dynamic: processors may come and go



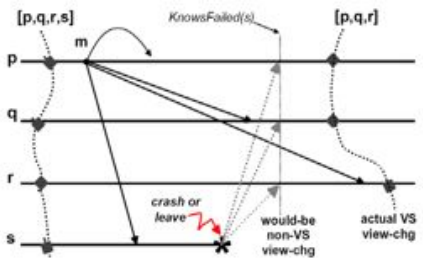
Agreement on Membership
(issues with ad-hoc view change)

- r joins group, view is {q,r,s}, then s leaves
- change notification not consistent:
  - r gets request 2 in view {q,r,s}, so picks <3,4>
  - q gets request 2 in view {q,r}, so picks <1,2,3>
- what went wrong:
  - <3> is performed twice
  - <5,6> are not performed



View Synchrony
view-synchronous view change

- solution to previous problem:
  - membership changes notified consistently with message flow !
  - if a message m is delivered to a process p in view Vi, then for all q in Vi, m is also delivered to q in view Vi.
- how to ensure all processes deliver same messages in same view?
  - flush messages until a consistent cut

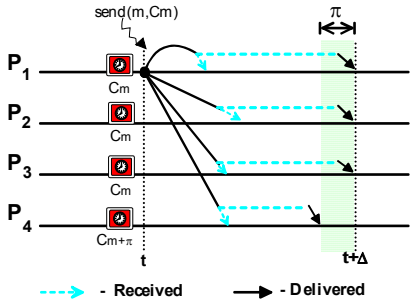


Atomic Broadcast
properties

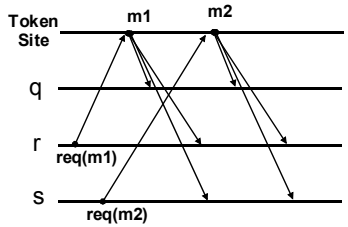
- Validity
  - If a correct processor broadcasts a message M, then some correct processor eventually delivers M.
- Agreement
  - If a correct processor delivers a message M, then all correct processors eventually deliver M.
- Integrity
  - For any message M, every correct process *p* delivers M at most once
  - If process *p* delivers M and *sender*(*M*) is correct, then M was previously broadcast by *sender*(*M*).
- Total order
  - If two correct processors deliver two messages *M*1 and *M*2 then both processors deliver the two messages in the same order.

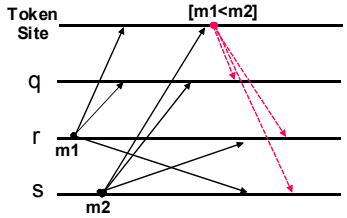
Atomic Broadcast
(symmetric approach - intuition)

- reliability through space redundancy or tx-w-resp
- total causal ordering through physical clock timestamps
- delivers by message timestamp order
- disambiguates e.g. by UID or MAC address, etc.
- i.e. msg(Cm) after Cm-1 and before Cm+1 everywhere
- can be done with logical timestamps



Atomic Broadcast
(asymmetric approach - intuition)





- reliability by tx-w-resp w/ store-and-forward or diffusion w/ negative ack
- token-based: sequencer decides ordering and propagates to all
- total non-causal order

Replicated computations

- distributed applications may run replicated pieces of code which should behave in the same way (e.g. fault tolerance, performance)
- atomic broadcast guarantees, in a decentralized way, that replicas receive the same sequence of inputs:
  - same requests, in the same order

Concurrency and Atomicity

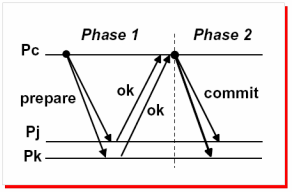
Atomicity

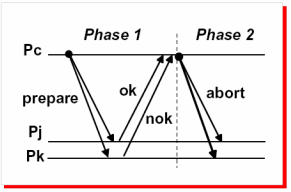
- atomicity is the property of an indivisible operation
- transactional atomicity is that property extended to a set of operations that are made look like indivisible
- atomic transaction is an operation exhibiting that property
- several techniques concur to achieve it:
  - either all operations are performed, or the whole transaction is aborted
  - intermediate results cannot be seen before the end
  - results must be stored in non-volatile memory to be persistent

Distributed Atomicity

- how to ensure atomicity of transactions that run across several nodes?
- Problem:
  - partial failure of nodes, and partitions, leading to inconsistent termination
- Solution:
  - distributed atomic commitment
  - most used protocol - *two-phase commit*

2-phase Distributed Atomic Commitment





- Two-phase commit
  - commit
  - abort
- Problem:
  - subject to blocking

Distributed systems models

Synchrony models

Table 3.2. Synchronous Model Properties

• Processing delays have a known bound
• Message delivery delays have a known bound
• Rate of drift of local clocks has a known bound
• Difference between local clocks has a known bound

- The last property species the existence of synchronized clocks.
- Whilst not required of every synchronous system, the first three properties make it possible.

Synchrony models

Table 3.1. Asynchronous Model Properties

• Processing delays are unbounded or unknown
• Message delivery delays are unbounded or unknown
• Rate of drift of local clocks is unbounded or unknown
• Difference between local clocks is unbounded or unknown

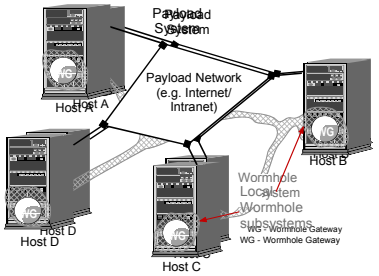
- The last two are essentially equivalent:
- since a local clock in a time-free system is nothing more than a sequence counter, synchronized clocks are also impossible in an asynchronous system.
- however, they are listed for a better comparison with synchronous models.

Synchrony models in between

- *synchrony or asynchrony are not homogeneous properties of systems*:
  - they may vary with time
  - they may vary with the part of the system being considered
- that is, sometimes
  - the system is not always asynchronous, and/or
  - the system is not asynchronous everywhere
- intermediate models attempting best of both worlds
  - asynchronous with failure detectors
  - timed asynchronous
  - quasi-synchronous
  - wormholes

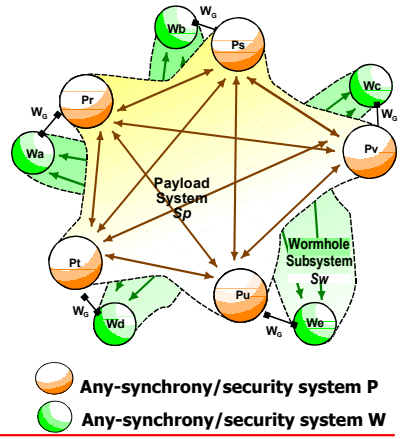
Wormhole models

- New design philosophy for distributed systems:
  - constructs with privileged properties which endow systems with the capability of evading the uncertainty of environment ("taking a shortcut") for certain crucial steps of their operation,
  - this allows achieving some predictability (the required "hard properties")
- Based on hybrid distributed systems models

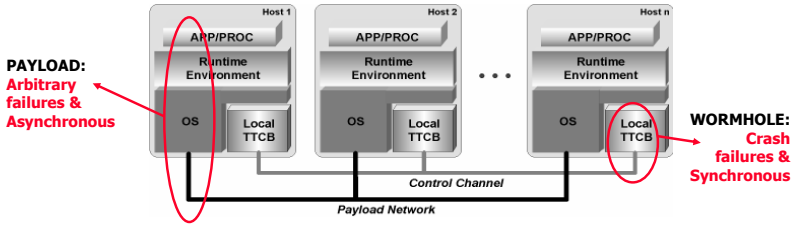


Hybrid distributed systems models
(a.k.a. Wormhole models)

- models in between
  - system is neither synchronous nor asynchronous
  - it is both, at the same time, different places
- concept may be extended to fault model:
  - system is neither fail-silent (crash) nor fail-arbitrary (Byzantine)
  - it is both, at the same time, different places



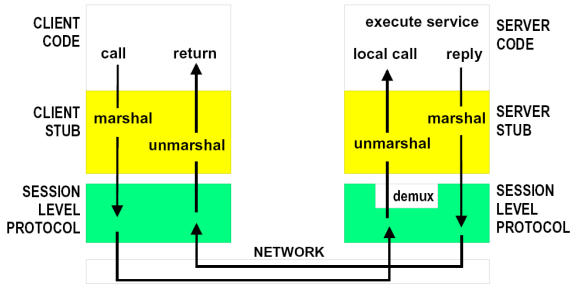
Example system with wormhole



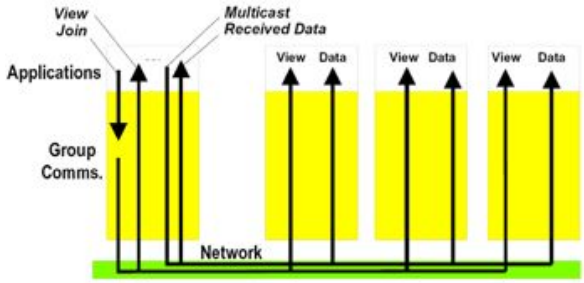
- the example system (TTCB) is a distributed real-time and security kernel providing a minimal set of trusted/timely services
  - failure detection
  - local authentication
  - agreement on a fixed sized block of data (TBA)
  - trustworthy global timestamps and random numbers

Distributed Computing models

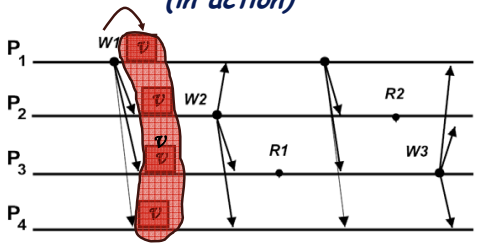
Client-server with RPC
(in action)



Group-oriented
(in action)

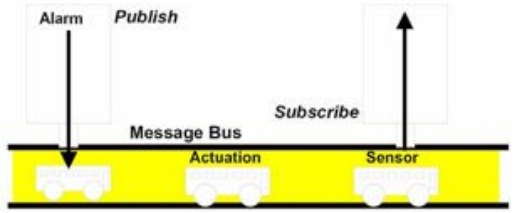


Distributed Shared Memory (DSM)
(in action)



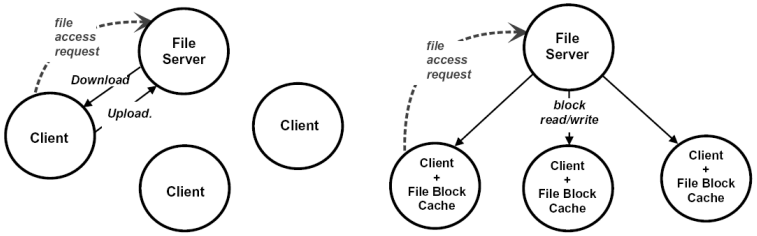
- simulating a shared data item in local memory, over a distributed and/or possibly replicated memory

Message bus
(in action)



- publisher-subscriber
- oriented to event processing
- supported by event-based communication

Distributed File systems
(in action)



- Download-Upload
  - retrieving and storing the whole file from/to the file server
- Remote Access
  - clients cache file blocks that they request from the server
  - files remain remote on the server

Object-oriented
(in action)