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PA160: Net-Centric Computing II.

Distributed Systems

Luděk Matyska

Slides by: Tomáš Rebok

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Lecture overview

Fault Tolerance in Distributed Systems I.

- single machine systems
    - failures are all or nothing
        - OS crash, disk failures, etc.
- distributed systems: multiple independent nodes
    - partial failures are also possible (some nodes fail)
    - probability of failure grows with number of independent components (nodes) in the system
- **fault tolerance:** system should provide services despite faults
    - *transient faults*
    - *intermittent faults*
    - *permanent faults*

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Fault Tolerance in Distributed Systems I.

Failure Types

Type of failure	Description
Crash failure	A server halts, but is working correctly until it halts
Omission failure	A server fails to respond to incoming requests
Receive omission	A server fails to receive incoming messages
Send omission	A server fails to send messages
Timing failure	A server's response lies outside the specified time interval
Response failure	The server's response is incorrect
Value failure	The value of the response is wrong
State transition failure	The server deviates from the correct flow of control
Arbitrary failure	A server may produce arbitrary responses at arbitrary times

Fault Tolerance in Distributed Systems II.

- *handling faulty processes:* through redundancy
- organize several processes into a group
    - all processes perform the same computation
    - all messages are sent to all the members of the particular group
    - majority needs to agree on results of a computation
    - ideally, multiple independent implementations of the application are desirable (to prevent identical bugs)
- use process groups to organize such processes

Fault Tolerance in Distributed Systems III.

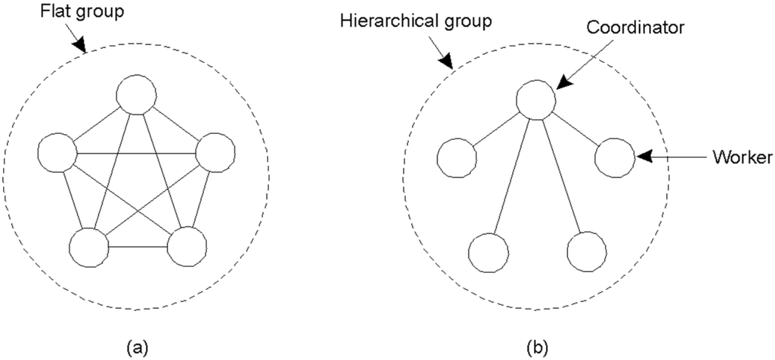

Figure: Flat Groups vs. Hierarchical Groups.

Availability in DS

- Availability is the *uptime*. i.e. fraction of time the systems works reliably
- It's usually expressed in *nines*
  - *Two nines* = 99% up = down 3.7 days/year
  - *Three nines* = 99.9% up = down 8.8 hours/year
  - *Four nines* = 99.99% up = down 53 minutes/year
  - *Five nines* = 99.999% up = down 5.3 minutes/year
- Related item is Service/Level Objective
  - 99.9% of requests are served in less than 200 ms per day

Failure detectors

- **Failure detector:** algorithm that detects whether another node is faulty
- **Perfect failure detector:** labes a node as faulty if and only if it has crashed
- Impossible without additional constraints (synchronicity, ...)
- Typical implementation
  - Heartbeats and timeouts
  - If a request is not answered within a specified amount of time, it is labeled as crashed
- Not a prfect solution
  - no way to distinguish between crashed and unresponsive (overloaded) node, lost or delayed message,

Fault Tolerance in DSs – Agreement in Faulty Systems

- How should processes agree on results of a computation?
- *K-fault tolerant:* system can survive k faults and yet function
  - assume processes fail silently
    - $\Rightarrow$ need $(k+1)$ redundancy to tolerant k faults
- *Byzantine failures:* processes run even if sick
  - produce erroneous, random or malicious replies
  - byzantine failures are most difficult to deal with

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Fault Tolerance in DSs – Agreement in Faulty Systems

Two Generals Problem:

- Two generals are in front of a city at opposite sides
  - If only one general attacks, it will be defeated
  - If both generals attack, the city will be defeated
  - They need to agree whether to attack and when
- They can communitace through messengers only
  - messengers canm be captured
- Regardless of the number of messages, it is not possible for the generals to be certain of the other general decision

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Fault Tolerance in DSs – Agreement in Faulty Systems

Byzantine Generals Problem:

- Similar setup, but there may be more generals
  - there is no messengers' capture, all messages are eventually delivered
  - they may be slow
- *Byzantine means that some generals may not be trusthworty/traitors (they lie)*
  - we seek an agreement between all honest generals
    - theory shows that the problem is solvable only if at most one third are traitors
    - to tolerate n traitors, there must be at least $3n + 1$ generals
- the problem is nontrivial even if messengers are totally reliable
  - with unreliable messengers, the problem is very complex
  - Fischer, Lynch, Paterson: in asynchronous systems, it is impossible to reach a consensus in a finite amount of time

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Fault Tolerance in DSs – Agreement in Faulty Systems

Formal definition of the agreement problem in DSs:

- let's have a set of distributed processes with initial states $\in 0, 1$
- *the goal:* all the processes have to agree on the same value
  - additional requirement: it must be possible to agree on both 0 or 1 states
- basic assumptions:
  - *system is asynchronous*
    - no bounds on processes' execution delays exist
    - no bounds on messages' delivery delay exist
    - there are no synchronized clocks
  - *no communication failures* – every process can communicate with its neighbors
  - *processes fail by crashing* – we do not consider byzantine failures

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Fault Tolerance in DSs – Agreement in Faulty Systems

Formal definition of the agreement problem in DSs: cont'd.

- *implications:*
  - ⇒ there is no deterministic algorithm which resolves the consensus problem in an asynchronous system with processes, which may fail
  - because it is impossible to distinguish the cases:
    - a process does not react, because it has failed
    - a process does not react, because it is slow
  - practically overcomed by establishing timeouts and by ignoring/killing too slow processes
    - timeouts used in so-called Failure Detectors (see later)

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Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast

- *if there was a proper type of fault-tolerant broadcast, the agreement problem would be solvable*
- various types of broadcasts:
  - *reliable broadcast*
  - *FIFO broadcast*
  - *causal broadcast*
  - *atomic broadcast* – the broadcast, which would solve the agreement problem in asynchronous systems

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Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast – Reliable Broadcast

- basic features:
  - Validity – if a correct process broadcasts *m*, then it eventually delivers *m*
  - Agreement – if a correct process delivers *m*, then all correct processes eventually deliver *m*
  - (Uniform) Integrity – *m* is delivered by a process at most once, and only if it was previously broadcasted
- possible to implement using `send`/`receive` primitives:
  - the process *p* sending the broadcast message marks the message by its identifier and sequence number
    - and sends it to all its neighbors
  - once a message is received:
    - if the message has not been previously received (based in sender's ID and sequence number), the message is delivered
    - if the particular process is not message's sender, it delivers it to all its neighbors

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Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast – FIFO Broadcast

- the reliable broadcast cannot assure the messages' ordering
  - it is possible to receive a subsequent message (from the sender's view) before the previous one is received
- *FIFO broadcast:* the messages from a single sender have to be delivered in the same order as they were sent
- FIFO broadcast $=$ Reliable broadcast $+$ FIFO ordering
  - if a process p broadcasts a message m before it broadcasts a message m', then no correct process delivers m' unless it has previously delivered m
  - $broadcast_p(m) \rightarrow broadcast_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$
- a simple extension of the reliable broadcast

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Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast – Causal Broadcast

- the FIFO broadcast is still not sufficient: it is possible to receive a message from a third party, which is a reaction to a particular message before receiving that particular message
  - $\Rightarrow$ *Causal broadcast*
- Causal broadcast = Reliable broadcast + causal ordering
  - if the broadcast of a message *m happens before* the broadcast of a message m', then no correct process delivers m' unless it has previously delivered m
  - $broadcast_p(m) \rightarrow broadcast_q(m') \Rightarrow deliver_r(m) \rightarrow deliver_r(m')$
- can be implemented as an extension of the FIFO broadcast

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Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast – Atomic Broadcast

- even the causal broadcast is still not sufficient: sometimes, it is necessary to guarantee the proper in-order delivery of all the replicas
  - two bank offices: one of them receives the information about adding an interest before adding a particular amount of money to the account, the second one receives these messages contrariwise
    - $\Rightarrow$ inconsistency
  - $\Rightarrow$ Atomic broadcast
- Atomic broadcast $=$ Reliable broadcast $+$ total ordering
  - if correct processes p and q both deliver messages m, m', then p delivers m before m' if and only if q delivers m before m'
  - $deliver_p(m) \rightarrow deliver_p(m') \Rightarrow deliver_q(m) \rightarrow deliver_q(m')$
- does not exist in asynchronous systems

Fault Tolerance in DSs – Agreement in Faulty Systems

Fault-tolerant Broadcast – Timed Reliable Broadcast

- a way to practical solution
- introduces an upper limit (time), before which every message has to be delivered
- Timed Reliable broadcast = Reliable broadcast + timeliness
  - there is a known constant Δ such that if a message is broadcasted at real-time t, then no correct (any) process delivers m after real-time $t + \Delta$
- feasible in asynchronous systems
- A kind of “approximation” of atomic broadcast

Fault Tolerance in DSs – Agreement in Faulty Systems – Failure Detectors I.

- impossibility of consensus caused by inability to detect slow process and a failed process
  - synchronous systems: let's use timeouts to determine whether a process has crashed
  - $\Rightarrow$ Failure Detectors

Failure Detectors (FDs):

- a distributed oracle that provides hints about the operational status of processes (which processes had failed)
  - FDs communicate via atomic/time reliable broadcast
- every process maintains its own FD
  - and asks just it to determine, whether a process had failed
- however:
  - hints may be incorrect
  - FD may give different hints to different processes
  - FD may change its mind (over & over) about the operational status of a process

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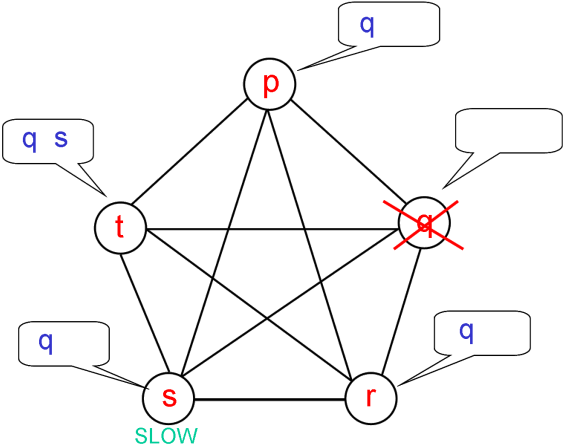
Fault Tolerance in DSs – Agreement in Faulty Systems – Failure Detectors II.



Fault Tolerance in DSs – Agreement in Faulty Systems

Perfect Failure Detector:

- properties:
  - Eventual Strong Completeness – eventually every process that has crashed is permanently suspected by all non-crashed processes
  - Eventual Strong Accuracy – no correct process is ever suspected
- hard to implement
- is perfect failure detection necessary for consensus? **No.**
  - $\Rightarrow$ weaker Failure Detector

weaker **Failure Detector:**

- properties:
  - Strong Completeness – there is a time after which every faulty process is suspected by every correct process
  - Eventual Strong Accuracy – there is a time after which no correct process is suspected
- can be used to solve the consensus
  - this is the weakest FD that can be used to solve the consensus

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Scheduling/Load-balancing in Distributed Systems

For concurrent execution of interacting processes:

- **communication** and **synchronization between processes** are the two essential system components

Before the processes can execute, they need to be:

- **scheduled** and
- allocated with resources

Why scheduling in distributed systems is of special interest?

- because of the issues that are different from those in traditional multiprocessor systems:
  - *the communication overhead is significant*
  - *the effect of underlying architecture cannot be ignored*
  - *the dynamic behaviour of the system must be addressed*
- local scheduling (on each node) + global scheduling

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Scheduling/Load-balancing in Distributed Systems

- let's have a pool of jobs
  - there are some inter-dependencies among them
- and a set of nodes (processors) able to reciprocally communicate

Load-balancing

The term **load-balancing** means assigning the jobs to the processors in the way, which minimizes the time/communication overhead necessary to compute them.

- load-balancing – divides the jobs among the processors
- scheduling – defines execution order of the jobs (on each processor)
  - load-balancing and planning are tightly-coupled (synonyms in DSs)
- **objectives:**
  - enhance overall system performance metric
    - process completion time and processor utilization
  - location and performance transparency

Scheduling/Load-balancing in Distributed Systems

- the scheduling/load-balancing task can be represented using graph theory:
  - the pool of N jobs with dependencies can be described as a graph $G(V, U)$, where
    - the nodes represent the jobs (processes)
    - the edges represent the dependencies among the jobs/processes (e.g., an edge from i to j requires that the process i has to complete before j can start executing)
- the graph G has to be split into p parts, so that:
  - $N = N_1 \cup N_2 \cup \cdots \cup N_p$
  - which satisfy the condition, that $|N_i| \approx \frac{|N|}{p}$, where
    - $|N_i|$ is the number of jobs assigned to the processor i, and
    - p is the number of processors, and
    - the number/cost of the edges connecting the parts is minimal
  - the objectives:
    - uniform jobs' load-balancing
    - minimizing the communication (the minimal number of edges among the parts)
- the splitting problem is NP-complete
  - the heuristic approaches have to be used

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Scheduling/Load-balancing in Distributed Systems

An illustration

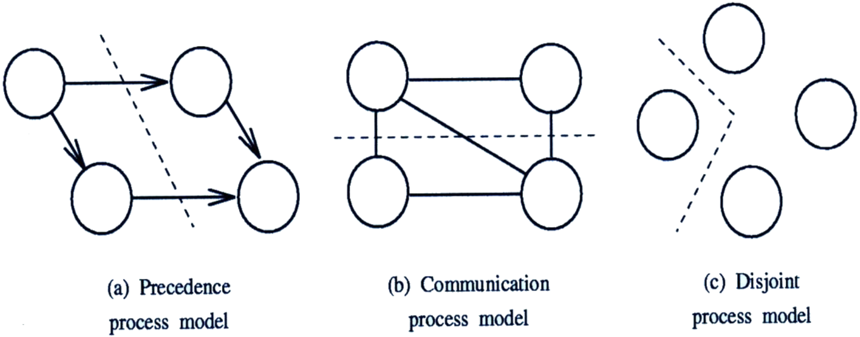

Figure: An illustration of splitting 4 jobs onto 2 processors.

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Scheduling/Load-balancing in Distributed Systems

- the “proper” approach to the scheduling/load-balancing problem depends on the following criteria:
  - *jobs’ cost*
  - *dependencies among the jobs*
  - *jobs’ locality*

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Scheduling/Load-balancing in Distributed Systems

Jobs' Cost

- the job's cost may be known:
  - before the whole problem set's execution
  - during problem's execution, but before the particular job's execution
  - just after the particular job finishes
- *cost's variability* – all the jobs may have (more or less) the same cost or the costs may differ
- the problem classes based on jobs' cost:
  - all the jobs have the same cost: *easy*
  - the costs are variable, but, known: *more complex*
  - the costs are unknown in advance: *the most complex*

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Scheduling/Load-balancing in Distributed Systems

Dependencies Among the Jobs

- is the order of jobs' execution important?
- the dependencies among the jobs may be known:
  - before the whole problem set's execution
  - during problem's execution, but before the particular job's execution
  - are fully dynamic
- the problem classes based on jobs' dependencies:
  - the jobs are fully independent on each other: *easy*
  - the dependencies are known or predictable: *more complex*
    - flooding
    - in-trees, out-trees (balanced or unbalanced)
    - generic oriented trees (DAG)
  - the dependencies dynamically change: *the most complex*
    - e.g., searching/lookup problems

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Scheduling/Load-balancing in Distributed Systems

Locality

- communicate all the jobs in the same/similar way?
- is it suitable/necessary to execute some jobs “close” to each other?
- when the job’s communication dependencies are known?

- the problem classes based on jobs’ locality:
  - the jobs do not communicate (at most during initialization): *easy*
  - the communications are known/predictable: *more complex*
    - regular (e.g., a grid) or irregular
  - the communications are unknown in advance: *the most complex*
    - e.g., a discrete events’ simulation

Scheduling/Load-balancing in DSs – Solving Methods

- in general, the "proper" solving method depends on the time, when the particular information is known
- basic solving algorithms' classes:
  - *static* – offline algorithms
  - *semi-static* – hybrid approaches
  - *dynamic* – online algorithms
- some (but not all) variants:
  - static load-balancing
  - semi-static load-balancing
  - self-scheduling
  - distributed queues
  - DAG planning

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Scheduling/Load-balancing in DSs – Solving Methods

Semi-static load-balancing

- suitable for problem sets with slow changes in parameters, and with locality importance
- iterative approach
  - uses static algorithm
  - the result (from the static algorithm) is used for several steps (slight unbalance is accepted)
  - after the steps, the problem set is recalculated with the static algorithm again
- often used for:
  - particle simulation
  - calculations of slowly-changing grids (but in a different sense than in the previous lectures)

Scheduling/Load-balancing in DSs – Solving Methods

Self-scheduling I.

- a centralized pool of jobs
- idle processors pick the jobs from the pool
- new (sub)jobs are added to the pool
- \+ ease of implementation
- suitable for:
  - a set of independent jobs
  - jobs with unknown costs
  - jobs where locality does not matter
- unsuitable for too small jobs – due to the communication overhead
  - $\Rightarrow$ coupling jobs into bulks
    - fixed size
    - controlled coupling
    - tapering
    - weighted distribution

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Scheduling/Load-balancing in DSs – Solving Methods

Self-scheduling II. – Fixed size & Controlled coupling

Fixed size

- typical offline algorithm
- requires much information (number and cost of each job, ...)
- it is possible to find the optimal solution
- theoretically important, not suitable for practical solutions

Controlled coupling

- uses bigger bulks in the beginning of the execution, smaller bulks in the end of the execution
  - lower overhead in the beginning, finer coupling in the end
- the bulk's size is computed as: $K_i = \lceil \frac{R_i}{p} \rceil$
  where:
  - R_i ...the number of remaining jobs
  - p ...the number of processors

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Scheduling/Load-balancing in DSs – Solving Methods

Self-scheduling II. – Tapering & Weighted distribution

Tapering

- analogical to the Controlled coupling, but the bulks' size is further a function of jobs' variation
- uses historical information
  - low variance ⇒ bigger bulks
  - high variance ⇒ smaller bulks

Weighted distribution

- considers the nodes' computational power
- suitable for heterogenous systems
- uses historical information as well

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Scheduling/Load-balancing in DSs – Solving Methods

Distributed Queues

- $\approx$ self-scheduling for distributed memory
- instead of a centralized pool, a queue on each node is used (per-processor queues)
- suitable for:
  - distributed systems, where the locality does not matter
  - for both static and dynamic dependencies
  - for unknown costs
- an example: diffuse approach
  - in every step, the cost of jobs remaining on each processor is computed
  - processors exchange this information and perform the balancing
  - locality must not be important

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Scheduling/Load-balancing in DSs – Solving Methods

Centralised Pool vs. Distributed Queues

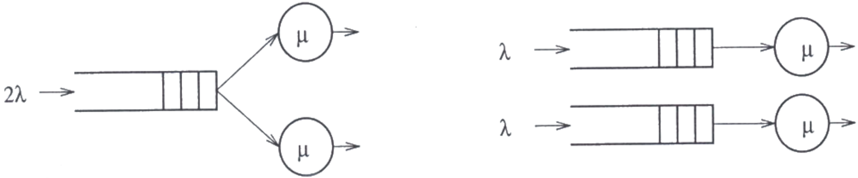

Figure: Centralised Pool (left) vs. Distributed Queues (right).

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Scheduling/Load-balancing in DSs – Solving Methods

DAG Planning

DAG Planning

- another graph model
  - the nodes represent the jobs (possibly weighted)
  - the edges represent the dependencies and/or the communication (may be also weighted)
- e.g., suitable for digital signal processing
- basic strategy – divide the DAG so that the communication and the processors' occupation (time) is minimized
  - NP-complete problem
  - takes the dependencies among the jobs into account

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Scheduling/Load-balancing in DSs – Design Issues I.

When the scheduling/load-balancing is necessary?

- for middle-loaded systems
  - lowly-loaded systems – rarely job waiting (there's always an idle processor)
  - highly-loaded systems – little benefit (the load-balancing cannot help)

What is the performance metric?

- mean response time

What is the measure of load?

- must be easy to measure
- must reflect performance improvement
- example: queue lengths at CPU, CPU utilization

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Scheduling/Load-balancing in DSs – Design Issues I.

Types of policies:

- *static* (decisions hardwired into system), *dynamic* (uses load information), *adaptive* (policy varies according to load)

Policies:

- *Transfer policy:* when to transfer a process?
  - threshold-based policies are common and easy
- *Selection policy:* which process to transfer?
  - prefer new processes
  - transfer cost should be small compared to execution cost
    - $\Rightarrow$ select processes with long execution times
- *Location policy:* where to transfer the process?
  - polling, random, nearest neighbor, etc.
- *Information policy:* when and from where?
  - demand driven (only a sender/receiver may ask for), time-driven (periodic), state-change-driven (send update if load changes)

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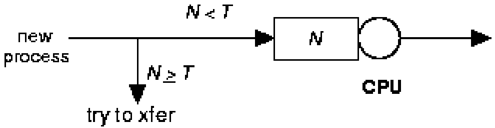
Scheduling/Load-balancing in DSs – Design Issues II.

Sender-initiated Policy

- Transfer policy



- Selection policy: newly arrived process
- Location policy: three variations
  - Random – may generate lots of transfers
    - ⇒ necessary to limit max transfers
  - Threshold – probe n nodes sequentially
    - transfer to the first node below the threshold, if none, keep job
  - Shortest – poll N_p nodes in parallel
    - choose least loaded node below T
    - if none, keep the job

Scheduling/Load-balancing in DSs – Design Issues II.

Receiver-initiated Policy

- *Transfer policy:* if departing process causes load $< T$, find a process from elsewhere
- *Selection policy:* newly arrived or partially executed process
- *Location policy:*
  - Threshold – probe up to N_p other nodes sequentially
    - transfer from first one above the threshold; if none, do nothing
  - Shortest – poll n nodes in parallel
    - choose the node with heaviest load above T

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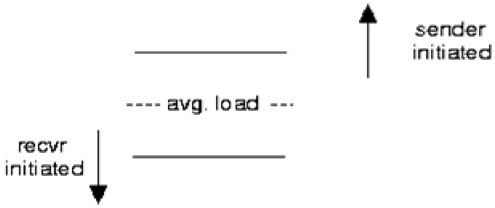
Scheduling/Load-balancing in DSs – Design Issues II.

Symmetric Policy

- combines previous two policies without change
  - nodes act as both senders and receivers
- uses average load as the threshold



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Scheduling/Load-balancing in DSs – Case study

V-System (Stanford)

- state-change driven information policy
  - significant change in CPU/memory utilization is broadcast to all other nodes
- *M* least loaded nodes are receivers, others are senders
- sender-initiated with new job selection policy
- *Location policy:*
  - probe random receiver
  - if still receiver (below the threshold), transfer the job
  - otherwise try another

Scheduling/Load-balancing in DSs – Case study

Sprite (Berkeley) I.

- *Centralized information policy:* coordinator keeps info
  - state-change driven information policy
  - Receiver: workstation with no keyboard/mouse activity for the defined time period (30 seconds) and below the limit (active processes $<$ number of processors)
- *Selection policy:* manually done by user $\Rightarrow$ workstation becomes sender
- *Location policy:* sender queries coordinator
- the workstation with the foreign process becomes sender if user becomes active

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Scheduling/Load-balancing in DSs – Case study

Sprite (Berkeley) II.

- *Sprite process migration:*
  - facilitated by the Sprite file system
  - state transfer:
    - swap everything out
    - send page tables and file descriptors to the receiver
    - create/establish the process on the receiver and load the necessary pages
    - pass the control
  - the only problem: communication-dependencies
    - solution: redirect the communication from the workstation to the receiver

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Scheduling/Load-balancing in DSs

Code and Process Migration

- key reasons: *performance* and *flexibility*
- flexibility:
  - dynamic configuration of distributed system
  - clients don't need preinstalled software (download on demand)
- process migration (*strong mobility*)
  - process $=$ code $+$ data $+$ stack
  - examples: Condor, DQS
- code migration (*weak mobility*)
  - transferred program always starts from its initial state
- *migration in heterogeneous systems:*
  - only weak mobility is supported in common systems (recompile code, no run time information)
  - the virtual machines may be used: interpreters (scripts) or intermediate code (Java)

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Lecture overview

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Distributed Systems – Further Information

- **FI courses:**
  - PA150: Advanced Operating Sytems Concepts (doc. Staudek)
  - PA053: Distributed Systems and Middleware (doc. Tůma)
  - PA039: Supercomputer Architecture and Intensive Computations (prof. Matyska)
  - PA177: High Performance Computing (LSU, prof. Sterling)
  - IV100: Parallel and distributed computations (doc. Královič)
  - IB109: Design and Implementation of Parallel Systems (dr. Barnat)
  - etc.
- **(Used) Literature:**

  - W. Jia and W. Zhou. Distributed Network Systems: From concepts to implementations. Springer, 2005.
  - A. S. Tanenbaum and M. V. Steen. Distributed Systems: Principles and paradigms. Pearson Prencite Hall, 2007.
  - G. Coulouris, J. Dollimore, and T. Kindberg. Distributed Systems: Concepts and design. Addison-Wesley publishers, 2001.
  - Z. Tari and O. Bukhres. Fundamentals of Distributed Object Systems: The CORBA perspective. John Wiley & Sons, 2001.
  - etc.