The MOSIX Algorithms for Managing Cluster, Multi-Clusters and Cloud Computing Systems

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Background

Most cluster and Grid management packages evolved from batch dispatchers

- View the cluster/Grid as a set of independent nodes
  - One user per node, cluster partition for multi-users
- Use static allocation of jobs to nodes
- Place the burden of management on the users

So far a cluster/Grid OS has not been developed

- Some reasons: no industry standards, complexity of development, massive investment, architecture and OS dependency, conflicting commercial interests vs. SMPs
- May slow-down software development for next generation many-cores computers

The MOSIX project

R&D of a Multi-computer OS (MOS)

  - Formally, multi-computers are distributed memory (shared nothing) architectures: clusters, multi-cluster organizational Grids, clouds

- Geared for HPC
- Research emphasis: management algorithms
- Development: infrastructure and tools

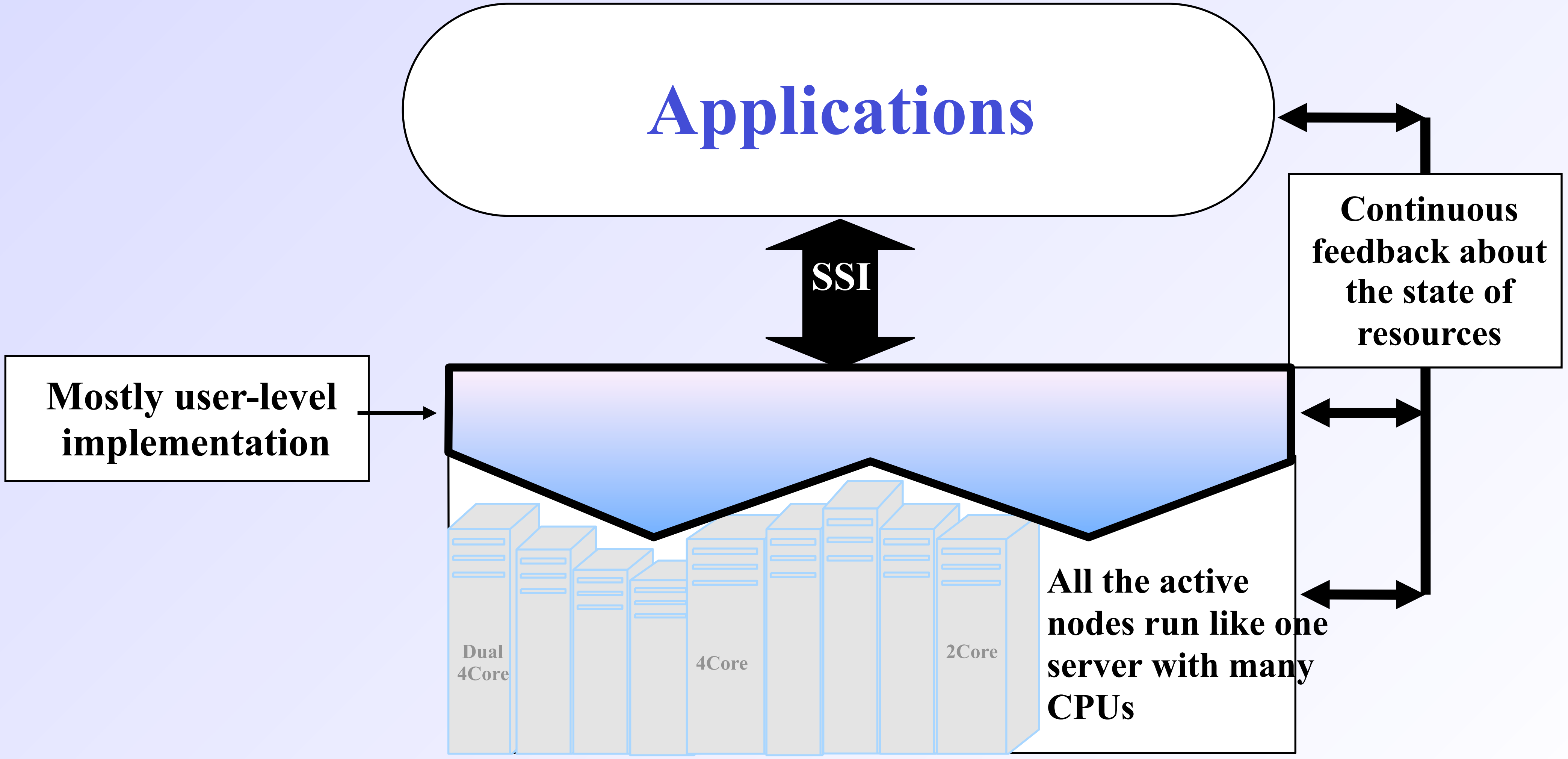
Goal: a working system that people can use

The MOS for UNIX (MOSIX)

A multi-computer OS with decentralized management

- Based on Unix (Linux)
- Provides a single-systems image
  - As if using one computer with multiple CPUs
- Geared to reduce the management complexity to users
  - The user's "login-node" environment is preserved
  - No need to "login" or copy files to remote nodes
  - No need to link applications with special libraries
  - Limited support for shared-memory

MOSIX is a unifying management layer


Applications
SSI
Mostly user-level implementation
Continuous feedback about the state of resources
All the active nodes run like one server with many CPUs
Dual 4Core
4Core
2Core

The software architecture

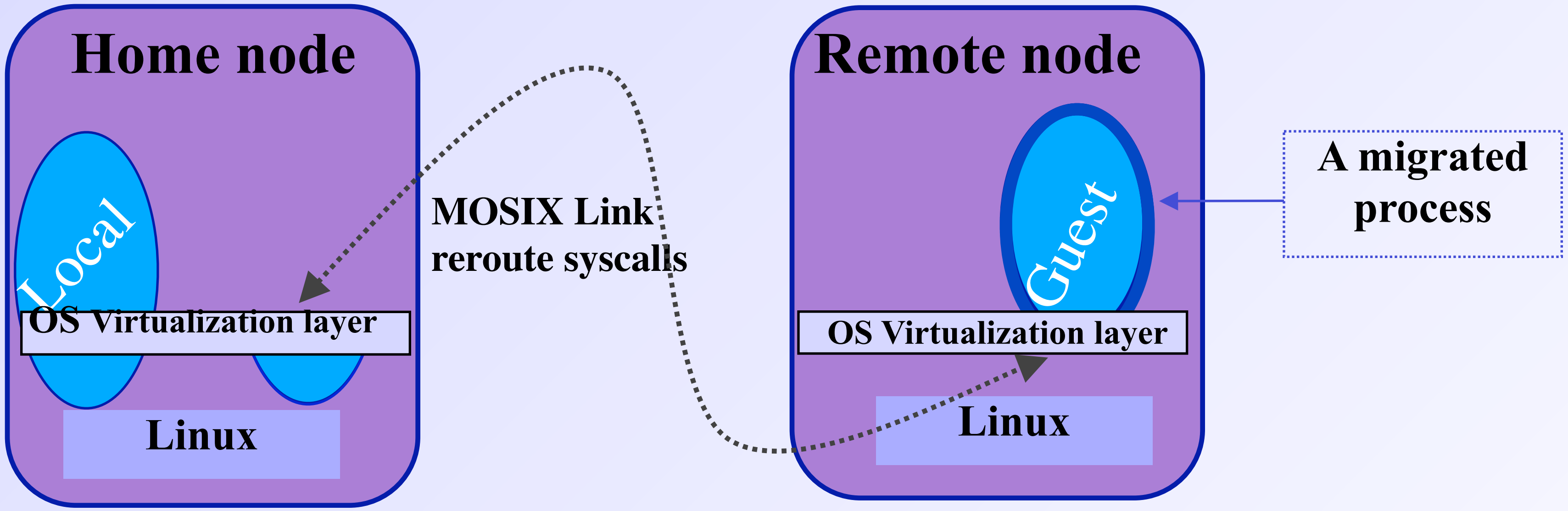
Features that are taken for granted in shared-memory systems, are not that easy to provide in a cluster

- Some features does not exist in shared-memory systems

The main components:

1. **Preemptive process migration**
   - Can migrate a running processes anytime
   - Like a course-grain context switch
     - Implication on caching, scheduling, resource utilization
2. **OS virtualization layer**
   - Allows a migrated process to run in remote nodes
3. **On-line algorithms**
   - Attempt to optimize a given goal function by process migration
     - Match between required and available resources
   - Information dissemination – based on partial knowledge

Process migration - the home node model



- Process migration – move the process context to a remote node
  - System context stay at “home” thus providing a single point of entry
- Process partition preserves the user’s run-time environment
  - Users need not care where their process are running

The OS virtualization layer

- A software layer that allows a migrated process to run in remote nodes, away from its home node
  - All system-calls are intercepted
    - Site independent sys-calls are performed locally, others are sent home
  - Migrated processes run in a sandbox
- Outcome:
  - A migrated process seems to be running in its home node
  - The cluster seems to the user as one computer
  - Run-time environment of processes are preserved - no need to change or link applications with any library, copy files or login to remote nodes
- Drawback: increased (reasonable) communication overhead
  - Multi-core latencies are expected to lower this overhead

Reasonable overhead:

Linux vs. migrated MOSIX process times (Sec.), 1Gbit-Ethernet

Application	RC	SW	JEL	BLAT
Local - Linux process (Sec.)	**723.4**	**627.9**	**601.2**	**611.6**
Total I/O (MB)	0	90	206	476
Migrated process- same cluster	**725.7**	**637.1**	**608.2**	**620.1**
slowdown	**0.32%**	**1.47%**	**1.16%**	**1.39%**
Migrated process to another cluster (1Km away)	**727.0**	**639.5**	**608.3**	**621.8**
slowdown	**0.5%**	**1.85%**	**1.18%**	**1.67%**

Sample applications:

RC = CPU-bound job
JEL = Electron motion
SW = Proteins sequences
BLAT = Protein alignments

On-line management algorithms

- Competitive algorithms for initial assignment of processes to the best available nodes (2 papers in IEEE PDS)
  - Gossip algorithm to support a distributed bulletin board (Concurrency P&E)
- Process migration
  - For load-balancing and from slower to faster nodes (several papers)
  - From nodes that run out of free memory, IPC optimizations
  - Administration of a multi-cluster (CCGrid05)
  - Parallel compression of correlated files (Cluster07)
  - Fair (proportional) share node allocation (CCGrid07)
  - Grid economy (AAMAS2008, GECON2008, Grid2008)
  - Job migration by combining process and VM migration (Cluster08)
- Research in progress
  - Overheated cores and green computing
  - Cloud computing

Resource discovery by a “gossip algorithm”

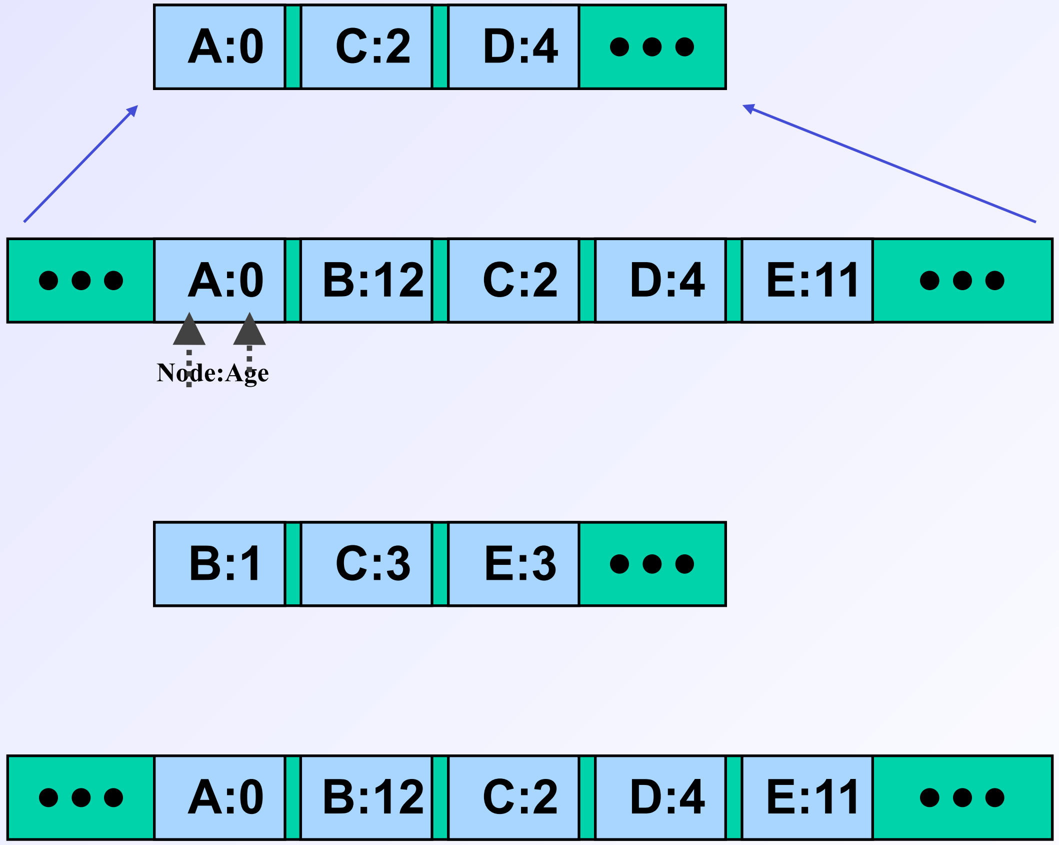
- All the nodes disseminate information about relevant resources: node allocations, CPU speed, load, memory, IPC, I/O local/remote
  - Info exchanged in a random fashion - to support scalable configurations and overcome failures
- Useful for initial allocation and process migration
  - Example: a compilation farm - assign the next job to least loaded node
- Main research issues:
  - How much/often info should be circulated
  - How to guaranteed age properties
  - How useful is old information (Mitzenmacher)
  - How it scales up

Distributed bulletin board

- An n node system
  - Or a Grid with n clusters
  - Decentralized control
  - Nodes are subject to failure
- *Each node maintains a data structure (vector) with an entry for selected (or all) the nodes*
- Each entry contains:
  - State of the resources of the corresponding node, e.g. load
  - Age of the information (tune to the local clock)
- The vector is a distributed bulletin board that provides information to local requests

Information dissemination algorithm

- Each time unit:
  - Update the local information
  - Find all vector entries that are up to age *t (a window)*
  - Choose a random node
  - Send the window to that node
- Upon receiving a window
  - Update the received entries age
  - Update the entries in which the newly received information is newer



Main results

For an n node system we showed how to find

- The expected number of entries that poses information about node N with age up to T

$$X(T) = \frac{ne^{nT/(n-1)}}{n-1+e^{nT/(n-1)}}$$

- The expected average age of vector (A_w expected age of the window)

$$A_v = \frac{1}{1-(1-1/(n-1))^{X(T)}} + A_w$$

- The expected number of entries with age below t :

$$\begin{cases} X(t) & t \le T \\ n\left[1-(1-1/(n-1))^{X(T)(t-A_w)}\right] & t > T \end{cases}$$

- The expected maximal age

$$\frac{\log n + \gamma}{X(T)\log(1-1/(n-1))}$$

Outcome: we can guarantee age properties of the vector entries

Load-balancing

Heuristics: reduce variance between pairs of nodes

- **Decentralized -** pair-wise decisions
- **Responds** to load imbalances
- **Migrate** from over-loaded to under-loaded nodes or form slower to faster nodes
- **Competitive** with the optimal allocation
- **Near optimal** performance
- **Greedy**, can get to a local minimum
  - **Why: placement problem is NP-hard**

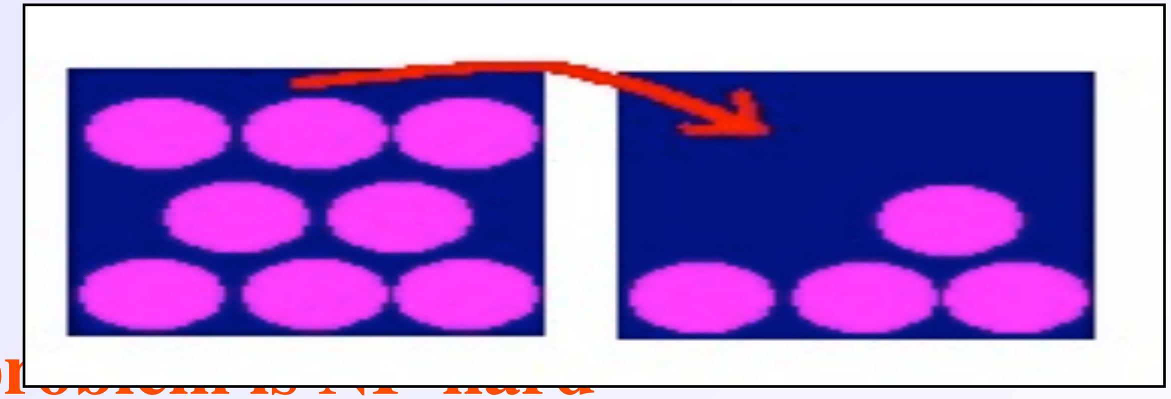
Load balancing algorithms

- **When - Load difference between a pair of nodes is above a threshold value**
- **Which - Oldest process (assumes past-repeat)**
- **Where - To the known node with the lowest load**
- **Many other heuristics**

- **Performance: benchmarks shows that the algorithm is only ~2% slower than the optimal assignment**

Memory ushering

- **Heuristics: initiate process migration from a node with no free memory to a node with available free memory**
- **Useful: when non-uniform memory usage (many users) or nodes with different memory sizes**
- **Overrides load-balancing**



- Recall: **placement problem is NP-hard**

Memory ushering algorithm

- **When** - free memory drops below a threshold value
- **Where** - the node with the lowest load, to avoid unnecessary migrations
- **Which** - smallest process that brings node under threshold
  - To reduce the communication overhead

IPC optimizations

- Reduce the communication overhead by migrating data intensive processes “near” the data
- Reduce IPC by migrating communicating processes to the same node (IPC via shared-memory)

Administrating a multi-cluster

Model: a federation of clusters, servers and workstations whose owners wish to cooperate from time to time

- Collectively administrated
  - Each owner maintains its private cluster
    - Determine the priorities vs. other clusters
  - Clusters can join or leave the Grid at any time
  - Dynamic partition of nodes to private virtual clusters
  - Users of a group access the Grid via their private cluster and workstations

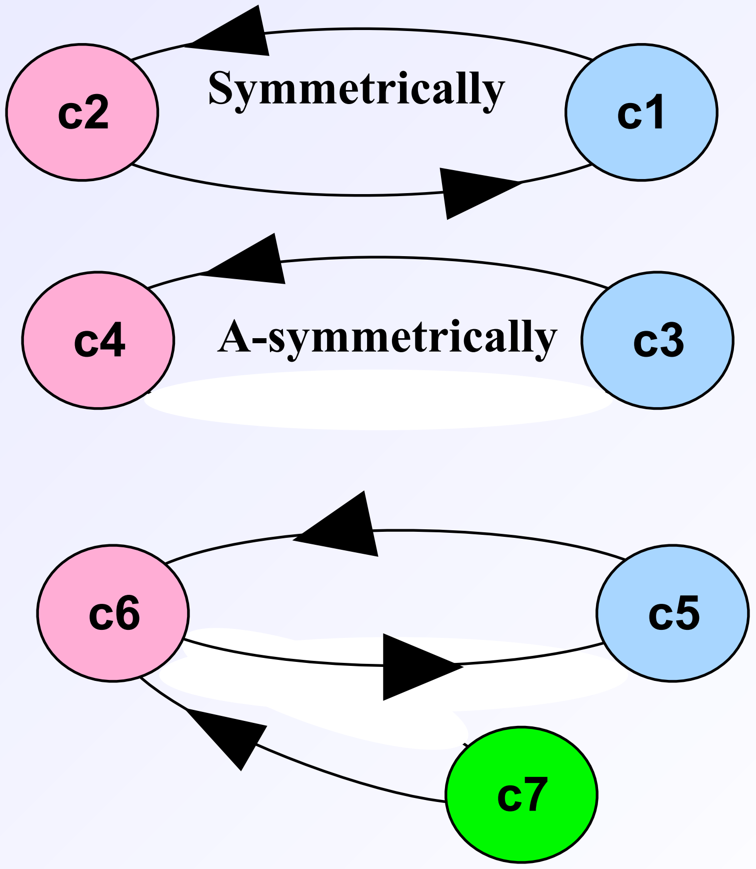
Outcome: each cluster and the whole Grid perform like a single computer with multiple processors

An "organizational" Grid: due to trust

The priority scheme

- Cluster owners can assign priorities to processes from other clusters
    - Local and higher priority processes force out lower priority processes
- Pairs of clusters could be shared, symmetrically(C1-C2) or asymmetrically(C3-C4)
- A cluster could be shared (C6) among other clusters (C5, C7) or blocked for migration from other clusters (C7)
- Dynamic partitions of nodes to private virtual clusters

Outcome: flexible use of nodes in shared clusters



When priorities are needed

- Scenario 1: one cluster, some users run many jobs, depriving other users from their fair share
- Scenario 2: some users run long jobs while other user need to run (from time to time) short jobs
- Scenario 3: several groups share a common cluster
- Solution: partition the cluster to several sub-clusters and allow each user to login to only one sub-cluster
  - Processes of local users (in each sub-cluster) has higher priority over all guest processes from other sub-clusters
  - Users in each sub-cluster can still benefit from idle nodes in the other sub-clusters

Disruptive configuration

When a cluster is disconnected:

- **All guest processes move out**
  - **To available Grid nodes or to the home cluster**
- **All migrated processes from that cluster move back**
  - **Returning processes are frozen (image stored) on disks**
    - **Try to do that for 100 2GB jobs**
  - **Frozen processes are reactivated gradually**

Outcome:

- **Long running processes are preserved**
- **No overloading of nodes**

Parallel compression of correlated files

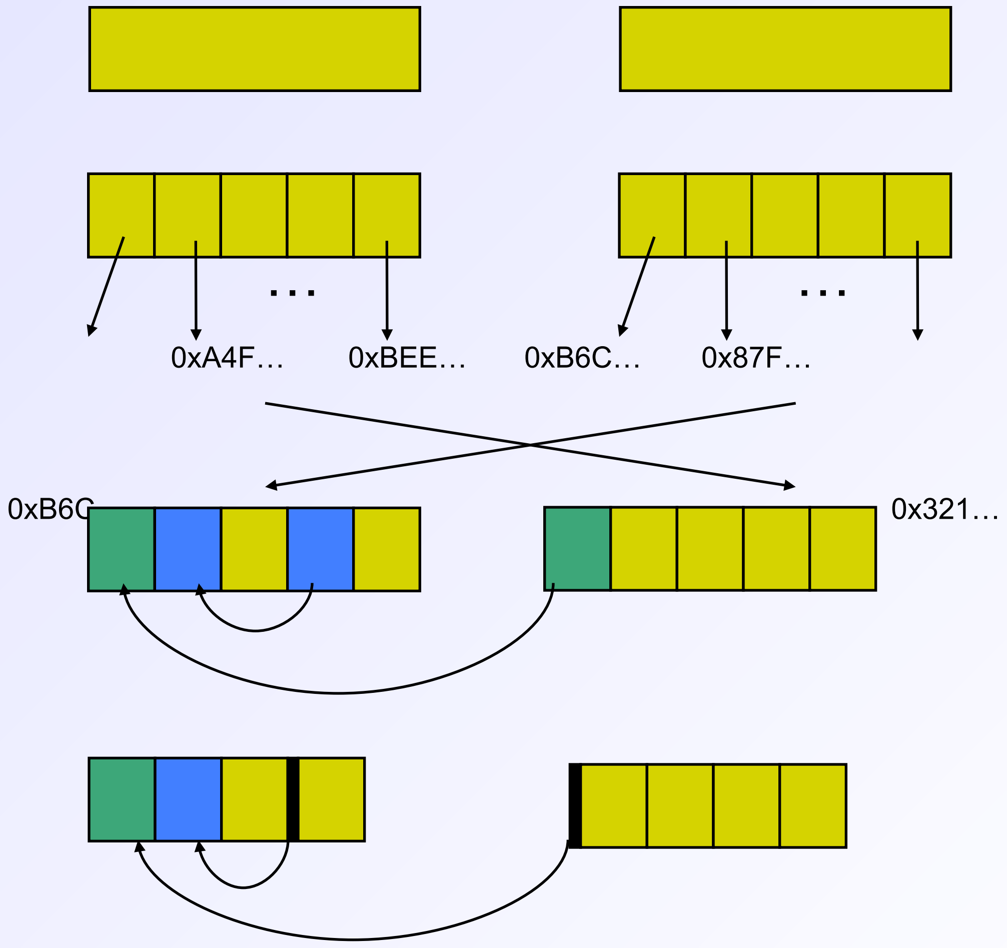
- A parallel job running in a cluster or a multi-cluster
  - One process per CPU, e.g. MPI job
- Problem: fastest way to send the memory images of a job (all processes) to a centralized repository
- Why:
  - For checkpointing
  - Dynamic node allocation in an economy-based Grid
    - New winning bids preempt old running jobs
  - Reclaiming private clusters in a multi-cluster

2 methods

- Method 1: concurrent serial compressors - simultaneously compress the memory images at each node, then send to the repository
  - Problem: takes longer to compress and send a memory image than sending it uncompressed
- Method 2: Assumption: memory images of a parallel job are correlated:
  - The processes use the same code and libraries
  - Typically, these processes share the same database
  - It is expected that there are large substrings common to these images.
    - Inter-file redundancy
- Idea: Eliminate inter-file redundancy

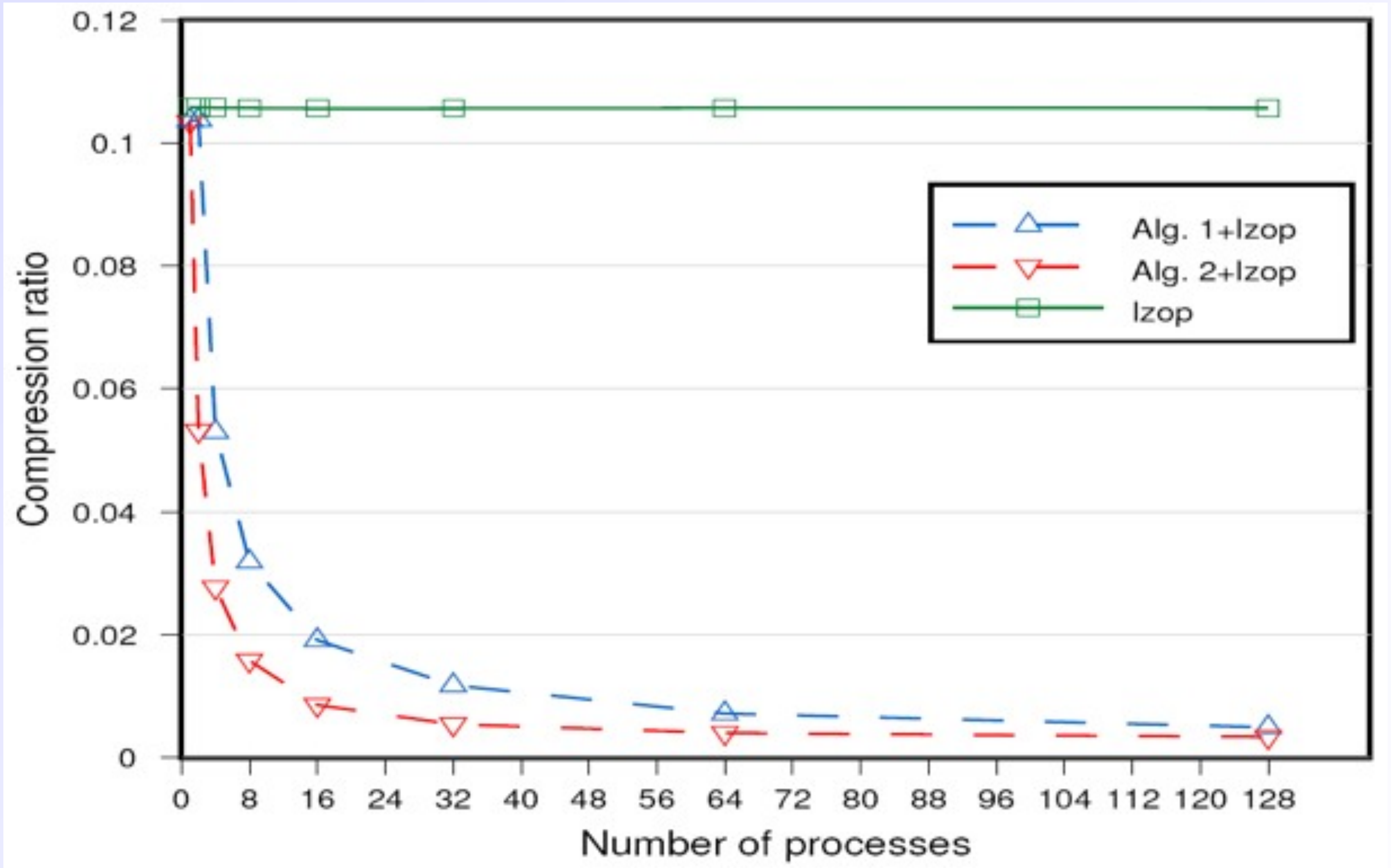
Parallel algorithm

- **For each memory image:**
  - **Partition the file into equal chunks**
  - **Obtain hash value for each chunk**
  - **Exchange hash values with the other nodes to find duplicate chunks**
  - **Compress the file, replacing duplicate chunks with pointers**
    - Advantage: no need to transfer the whole file to compare chunks, just the hash values
    - The basis of the rsync protocol
- **Improvement: use serial compressors on results to further compress each file**



RxRySpace compression ratios

- **A medical application that creates 2D projections of 3D CT data**
- ***Average image size: 509MB, Total size 99GB***
- ***Run on 64 dual-core nodes with 2GB RAM***

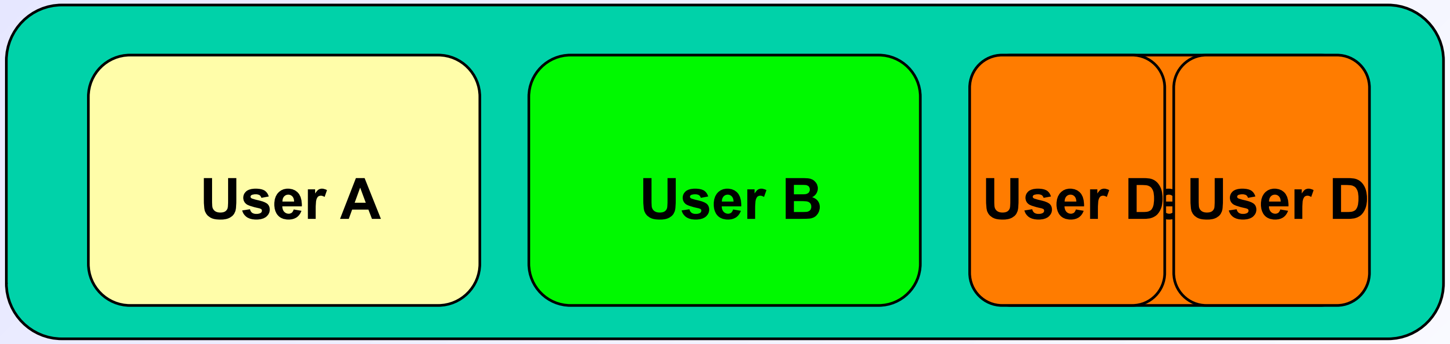


Fair-share node allocation

- **Most cluster and Grid management systems do not provide adequate means for fair share allocation, e.g. as in single-node systems**
  - **New users may need to wait a long time until scheduled to run**
- We developed on-line algorithms and a runtime environment for fair share scheduling in a cluster

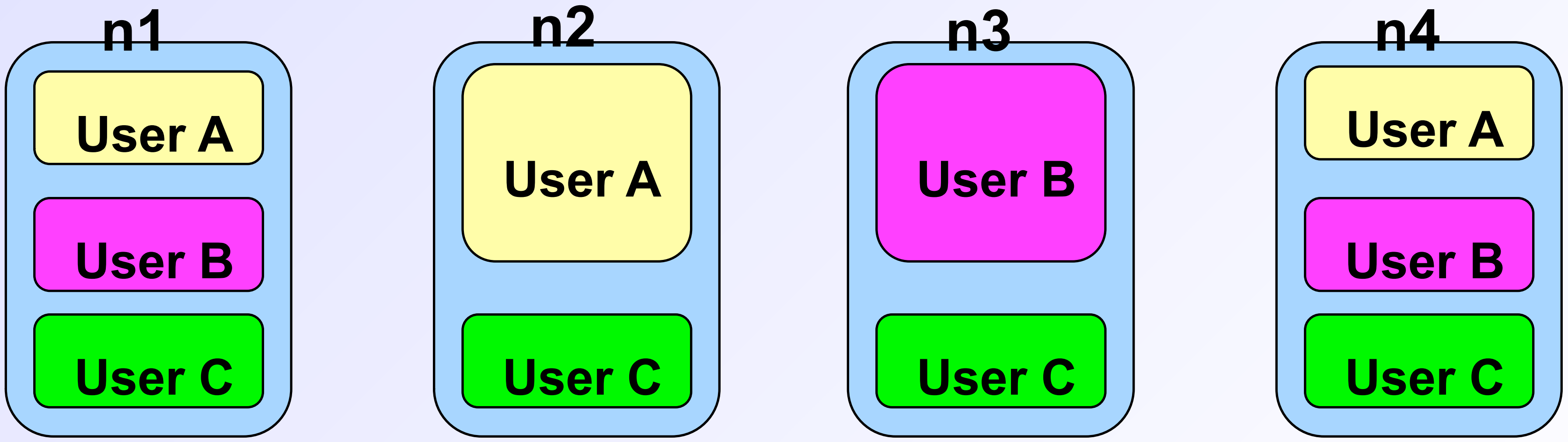
Single-node Fair-Share (FS) scheduling

- A scheduling strategy for proportional allocation of the CPU to users
  - Users get a predefined percentage of the CPU
  - As opposed to the OS default which is equal distribution among processes
  - *Lottery* and *Stride* are two well known algorithms for FS scheduling in a single-node
  - VMware & Xen supports proportional share scheduling of VMs



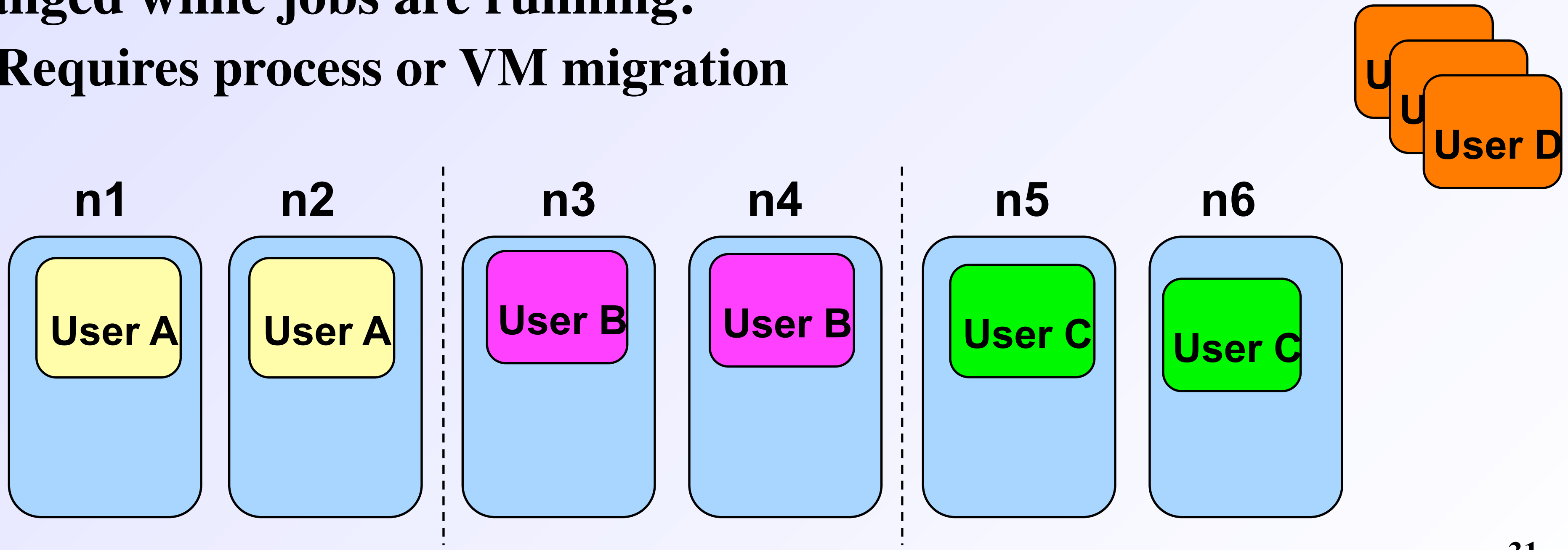
Cluster FS by time-sharing *(Horizontal Partitioning)*

- Cluster-wide proportional resource allocation to all users
- Time sharing *[Arpaci-Dusseau et al PDPTA 1997]*
  - Resources are allocated proportionally within each node using a single node scheduler (like *stride*)
  - Based on the desired proportions and the current allocation, a supervisor algorithm determines the local proportion allocated to each user on each machine



Cluster FS by space-sharing (vertical partitioning)

- Proportional allocation of disjoint sets of nodes to users (one user per node)
  - Non-preemptive: size of sets can be changed only when jobs are started or finished
    - Common in batch systems
  - Preemptive space-sharing: size of sets can be dynamically changed while jobs are running.
    - Requires process or VM migration

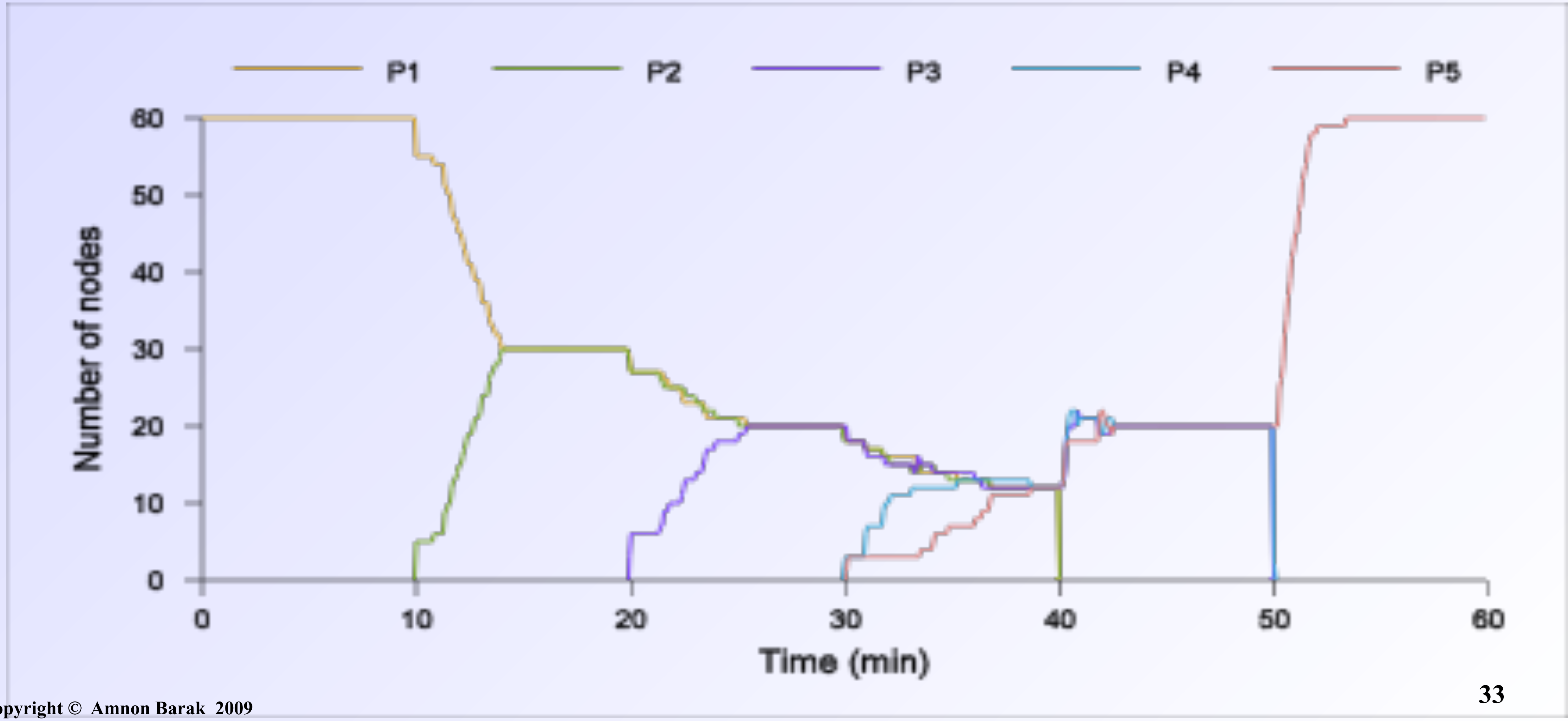


A distributed dynamic proportional share scheduler

- A distributed, preemptive space sharing scheduler was developed
- A central algorithm, maintains one queue for all the users
- Our distributed algorithm (without a single queue)
  - Each node continuously monitors the current allocation of nodes to users
  - The nodes with the highest id that is already allocated to a user which is using more nodes than its entitled share becomes a potential candidates to be reallocated
    - This node adjust the local MOSIX priority to allow users which deserve more nodes to obtain nodes if in need
  - In case of non integer shares, the algorithm circulate some nodes among different users
    - 2 users 3 nodes

Example on a 60 nodes cluster

- Gradually adding up to 5 users
- Then gradually removing 2 partners at a time



Benefits of migration for market based scheduling

- **Market based schedulers allocates nodes according to economic considerations**
  - **Goal: the more you pay the more you get**
- In a static allocation – running jobs are not interrupted
  - Scheduling only upon job completion
- In a dynamic scheduler (using migration) scheduling decisions can be done at any time
  - Can potentially improve the allocation

→ Research: What is the benefit of using migrations from an **economic/performance point of view**

  → From a theoretic point of view we defined 3 natural fairness properties and showed that only with migration such properties can be fulfilled

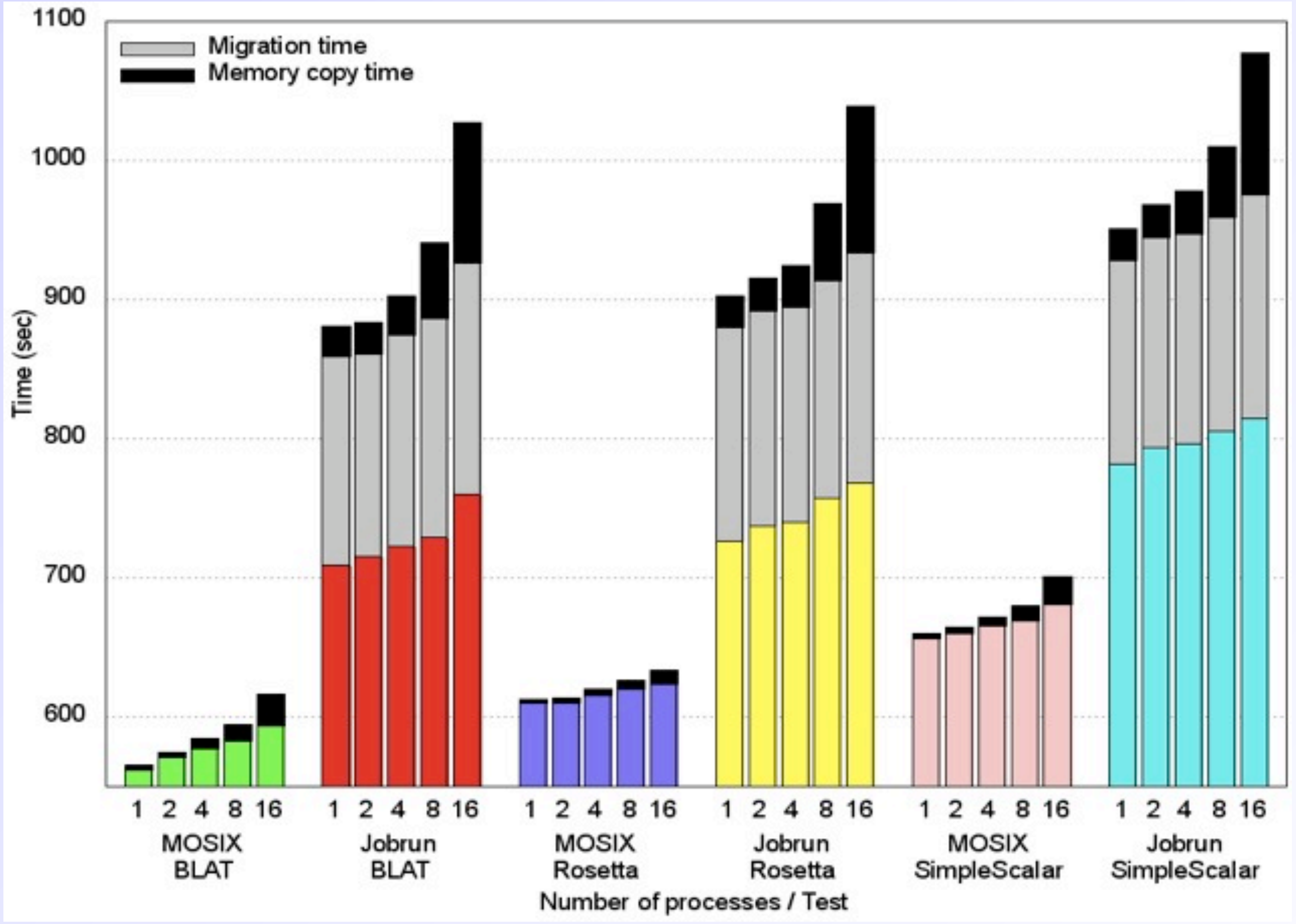
  → On the empirical side, we used real workloads and demonstrated that migration deliver better performance when prices are increasing and that it makes the system simpler allowing the user not to report the run time of the job

→ On going EU project

VM vs. Process migration

- Determine the viability of using VMs for HPC
- Measure the performance of MOSIX vs. VMware Server
- Combine process migration with VM migration
- Tested several real-life applications:
  - Linux processes (distributed using SSH)
  - MOSIX processes with individual home-nodes
  - VM-Linux / MOSIX –inside VMs, with a native head / home node
  - VHN-Linux / MOSIX – same, but with a virtual head / home node
  - WVM-Linux / MOSIX – same, but over Windows XP

Results



- ➢**Migrate x proc. 5 minutes into runtime (after I/O is done)**
- ➢**Fixed VM migration time (Dump-Restore)**
- ➢**MOSIX memory-copy time is much shorter**
- ✓**Only copies actual process memory**

Overheated cores, green computing (in progress)

- Process migration to cooler cores
  - Hardware automatically lower clock rate of overheated cores
  - Today – all cores; Future – individual cores
- Resolve by:
  - Reserve “spare” cores – how many ?
  - Exchange CPU and I/O processes among cores

Green computing:

- Reallocate processes to optimize power usage
- Group processes in fewer nodes vs. even load

Reach the clouds

Cloud computing allows user to run applications and store data on remote clusters/data-centers via the internet

- Some providers: Amazon, Google, IBM, Sun
- Relevant issues: cost, convenience, trust
- The MOSIX "reach the clouds" (MRC) tools:
  - Allows users to launch applications on the local workstation, then run in clouds, while still using local files
    - By exporting local file systems to remote clusters
    - No need to store or copy files in the clouds

Cloud computing

- Algorithm determine when to run locally or in the cloud
    - Based on latencies and rate of remote interactions
- Users can:
    - Reserve remote nodes
    - Bid for nodes on different clusters
    - Dynamic manage remote nodes

Our campus Grid (HUGI)

- 16 production MOSIX clusters ~430 nodes, ~650 CPUs
  - In life-sciences, med-school, chemistry and computer science
  - Priorities among users from different departments
- Sample applications:
  - Nano-technology
  - Molecular dynamics
  - Protein folding, Genomics (BLAT, SW)
  - Weather forecasting
  - Navier-Stokes equations and turbulence (CFD)
  - CPU simulator of new hardware design (SimpleScalar)
- Potential growth: VMs in Windows machines in student labs

Conclusions and current activities

- Migration is a key tech to manage multi-CPU systems
  - Next frontier: large scale multi-cores
- On going research projects
  - Migratable sockets for direct communication between migrated parallel processes
  - On-line algorithms for Grid economy
    - Centralized vs. distributed spot market
  - Run in VM’s on Windows and Linux
    - Tools for multi-cluster configuration, administration and monitoring

Current status

- **Mature technology: 10 major releases were developed for Unix, BSD, BDSI and Linux-2.2, 2.4, 2.6**
  - **Production installations since 1989**
  - **Based on Linux since 1998**
  - **Current implementation:**
    - **Mostly at user level**
    - **Almost independent of the Linux kernel**

Further info (shortly including a new version of a White Paper)

at http://www.MOSIX.org