K42 and Blue Gene
Two Case Studies for Parallel OS

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SS 2008

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K42, Blue Gene, MosiX

K42

- Shared Memory SMP
- Emulate Linux interface
- Optimise locality and concurrency

Blue Gene

- Distributed Memory MPP
- Message Passing Interface
- Partition

MosiX

- "Clusters" with COTS networks
- Distribute Linux
- Balance Load dynamically

Overview

- Introduction and some terminology
- (Interconnect Architectures)
- Programming Models
- SMP operating systems case study: IBM K42
- MPP operating systems case Study: IBM Blue Gene

- Cluster operating system case study:
  MosiX
- An SMP technique in detail:
  RCU by Frank Mehnert

SMP: Shared Memory / Symmetric MP

- Characteristics of SMP Systems:
  - Highly optimized interconnect networks
  - Shared memory (with several levels of caches)
  - Size today: up to ~1024 CPUs
- Successful Applications:
  - Large Linux (Windows) machines: (workstations and) servers
  - Transaction-management systems
  - Unix-Workstation + Servers
- Not usually used for:
  - CPU intensive computation, massively parallel Applications

MPP: Massively Parallel Multiprocessors

- Characteristics of MPP Systems:
  - Highly optimized interconnect networks
  - Distributed memory
  - Size today: up to few 100000 CPUs

- Successful Applications:
  - CPU intensive computation, massively parallel Applications, small execution/communication ratios

- Not optimal for:
  - Transaction-management systems
  - Unix-Workstation + Servers

“Clusters”

- Characteristics of Cluster Systems:
  - Use COTS (common off the shelf) PCs and networks
  - Size: No principle limits (-> “GRID” computing)

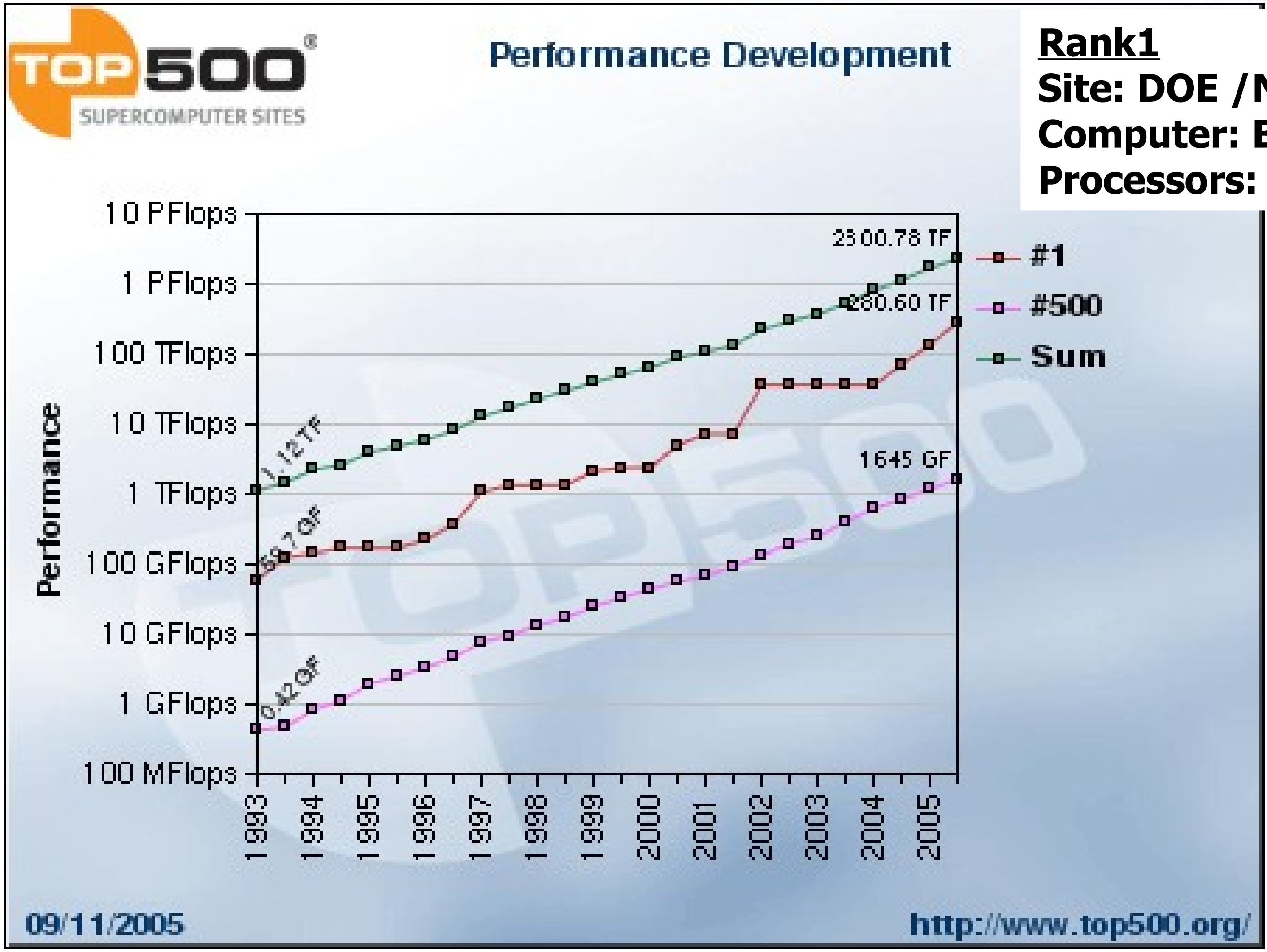
- Successful Applications:
  - CPU intensive computation, massively parallel Applications, larger execution/communication ratios
  - Cooperation between large organisations

- Not optimal for:
  - Transaction-management systems
  - Unix-Workstation + Servers

LinPack Benchmark

- Jack Dongarra
- used for Top 500 list
  - largely superceded by LAPACK
- Selection of Fortran subroutines
  - analyse and solve linear equations
    - Matrixes: general, banded, symmetric indefinite, symmetric positive definite, triangular, tridiagonal square
    - column oriented access
  - analyse and solve least-square probles
    - QR and singular value decomposition

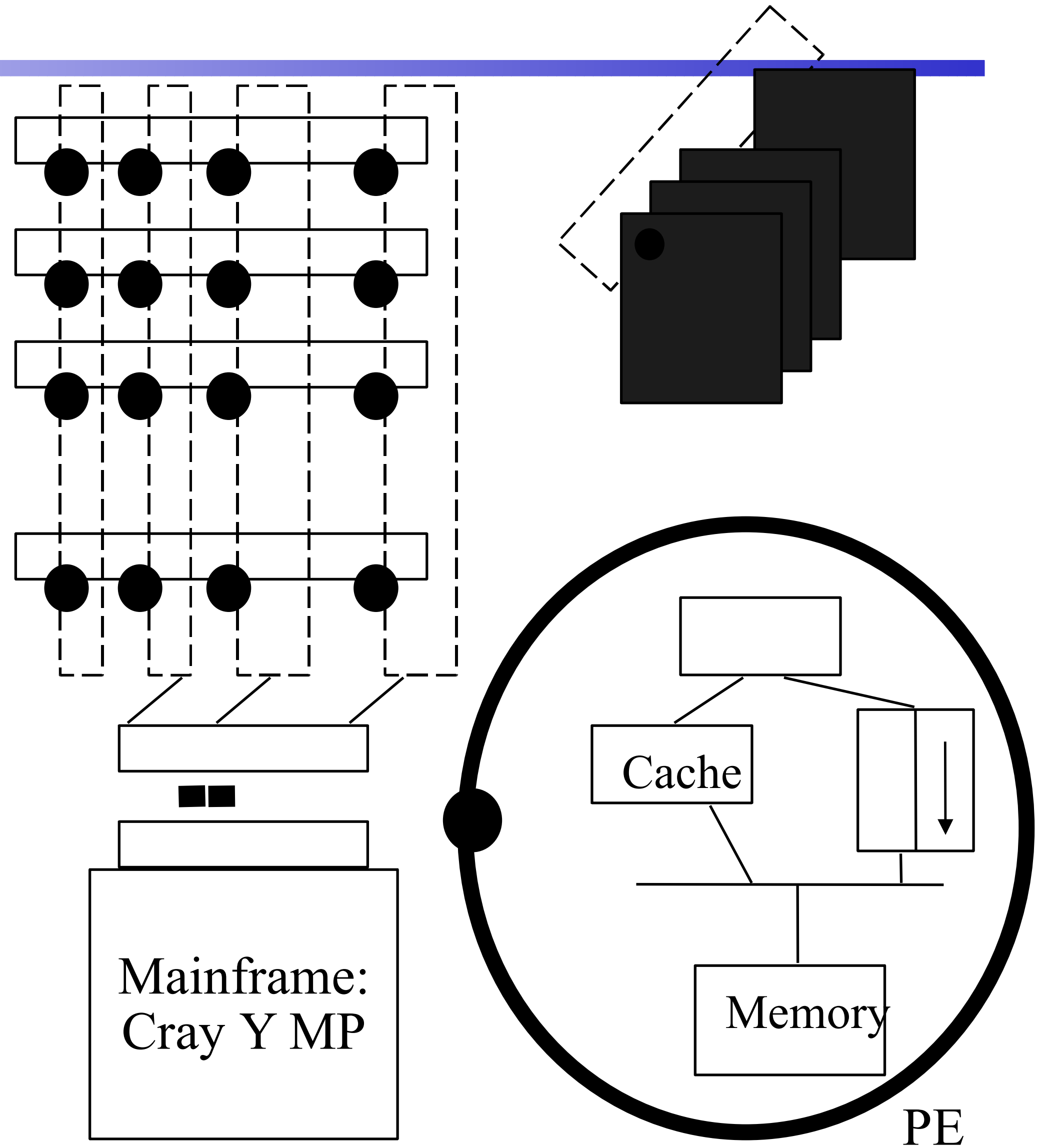
Top 500 List



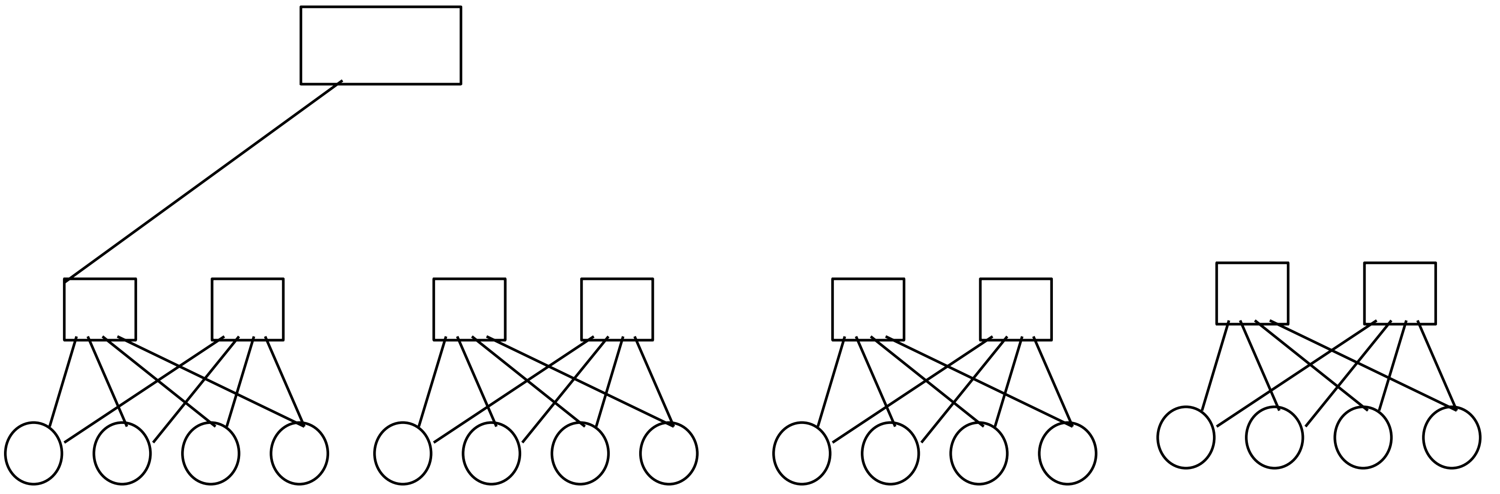
Rank1
Site: DOE /NNSA/LLNL (US)
Computer: Blue Gene/L IBM
Processors: 131072

Interconnects: Torus

- <u>Example: Cray T3D/T3E</u>
  - No shared memory
  - Supercomputer as front-end
  - High efficient network:
    Cache : Local : Distant
    3:27:220 Cycles
  - Embed distant memory in local address space in cache-line granularity.
  - scales up to 2K knots

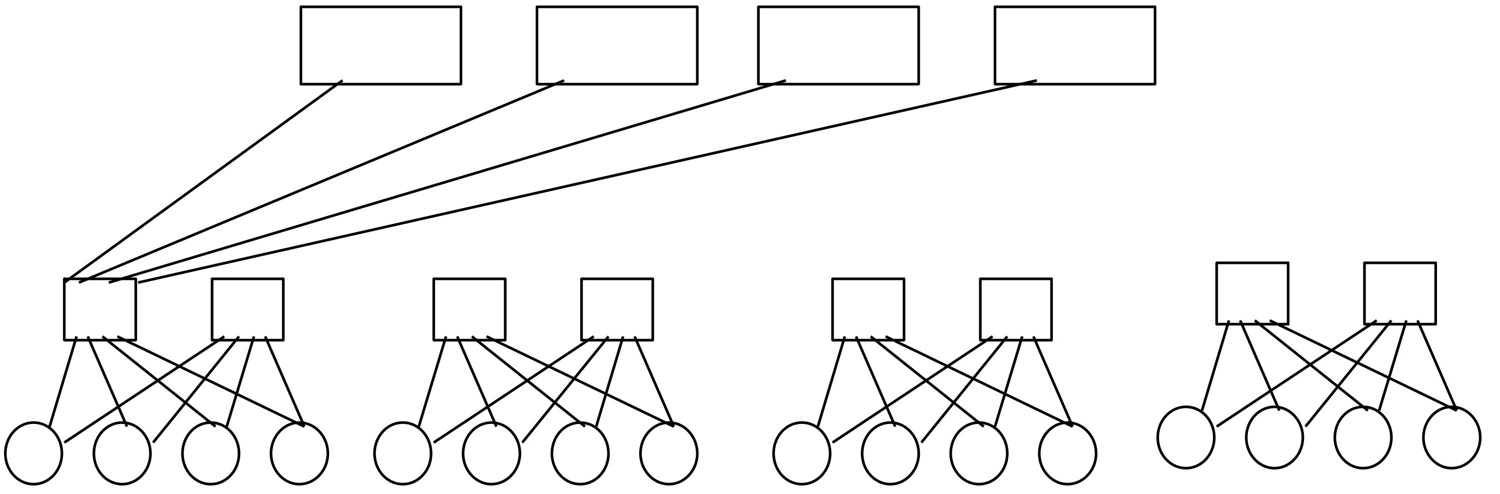


Interconnects: Fat Tree



- pioneered in Thinking Machines CM5

Interconnects: Fat Tree



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Parallel Programming Models

- Organisation of Work
  - Independent, unstructured processes (normally executing different programs) independently on nodes (make and compilers, ...), "pile of work"
  - SPMD: single program on multiple data asynchronous handling of partitioned data (SIMD: same operation on different data, old MPPs)
- Communication
  - Shared Memory, shared file system
  - Message Passing: Process cooperation through explicit message passing

Usage- and Programmingmodel

- SPMD

  while (true) {
   work
   exchange data (barrier)
  }

- Common for many MPP:
  All participating CPUs: active / inactive

- Techniques:
  - Partitioning (HW)
  - Gang Scheduling

Distributed Shared Memory

- Goal:
  - Virtually Shared Memory
- Problems:
  - false sharing
  - Overhead
- Solutions
  - Weakened consistency model
  - Replication
  - Structured Memory Models (Tupel, Objects)
- so far: no success in practice !!!

Distribution of Load

- Static
  - Place processes at startup, don't reassign
  - Requires a priori knowledge
- Dynamic Balancing
  - Process-Migration
  - Adapts dynamically to changing loads
- Problems
  - Determination of current load
  - Distribution algorithm
  - Oscillation possible
- successful in SMPs and clusters, not (yet ?) used in MPPs
- Most advanced dynamic load balancing: MosiX (next week!!!)

Messages

- Hardware – Implementation (IBM SP 2)
- Object – Systems (RPC)
- Libraries with special operations (e.g. MPI)
- Active Messages

Active Messages

- Goal:
  - Very fast process communication over the network (latency)
- Idea:
  - Message contains address of procedure to be invoked
  - Message reception leads to procedure invocation (in analogy to interrupt handler)
- Discussion
  - Very successful: speed
    (CM5: 12 microseconds Round Trip)
  - But: repair of OS limitations?

MPI, very brief overview

- Library for message-oriented parallel programming.
- Programming-model:
  - MPI program is started on all processors
  - Static allocation of processes to CPUs .
  - Processes have "Rank": 0 ... N-1
  - Each process can obtain its Rank (MPI_Comm_rank).
- Typed messages
- Communicator: collection of processes that can communicate, e.g., MPI_COMM_WORLD
- MPI_Spawn (MPI – 2)
  - Dynamically create and spread processes

MPI - Operation

- Init / Finalize
- MPI-Comm-Rank delivers “rank” of calling process, for example

  ```
  MPI_Comm_Rank(MPI_COMM_WORLD, &my-rank)

  if (my_rank != 0 )
  ...
  else ....
  ```

- MPI_barrier(comm) blocks until all processes called it
- MPI_Comm_Size how many processes in comm

MPI – Operations Send, RCV

- MPI_Send (
  void* message,
  int count,
  MPI-Datatype,
  int dest, /*rank of destination process, in */
  int tag,
  MPI_Comm comm) /* communicator*/
- MPI_RCV(
  void* message,
  int count,
  MPI-Datatype,
  int src, /* rank of source process, in */
  /* can be MPI_ANY-SRC */
  int tag, / can be MPI_ANY_TAG */
  MPI_Comm comm, /* communicator*/
  MPI_Status* status); /* source, tag, error*/

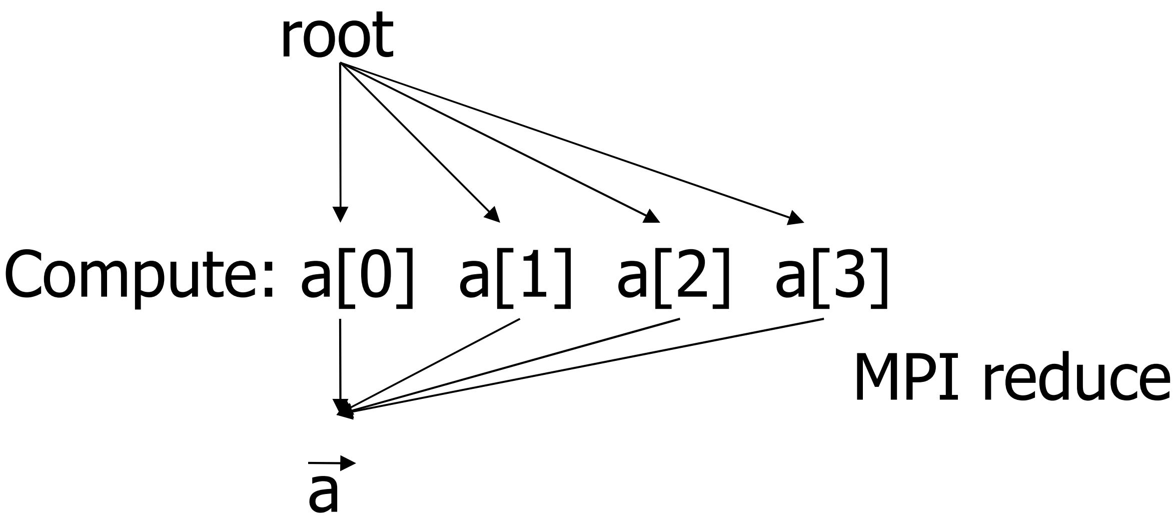
MPI – Operations Broadcast

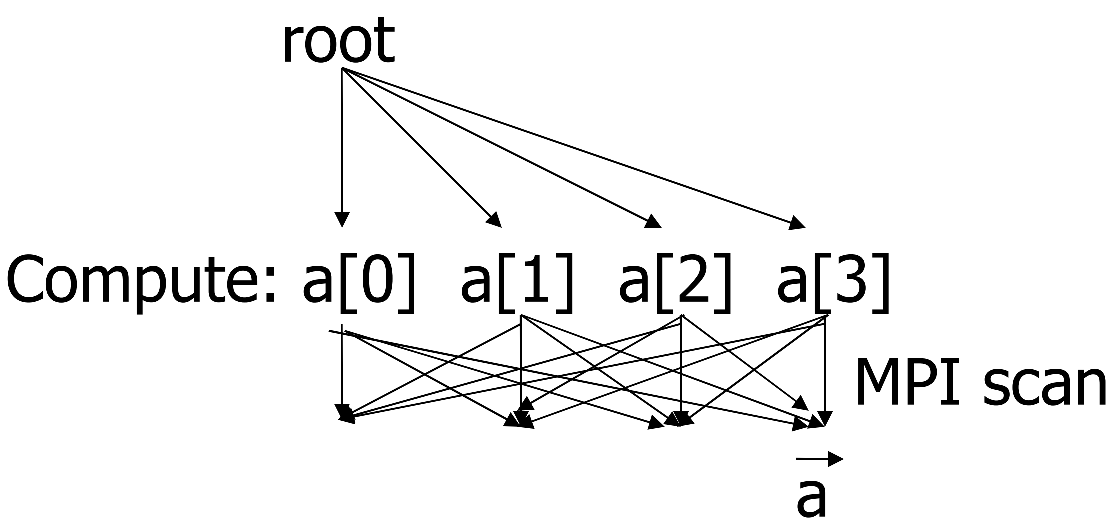
- MPI_BCAST(
  void * message,
  int count,
  MPI-Datatype,
  int root,
  MPI_Comm comm)
- process with rank == root sends,
  all others receive message
- implementation optimized for particular interconnect

MPI – Operations

- Aggregation:
  - MPI_Reduce
    - Each process holds partial value,
    - All processes reduce partial values to final result
    - Store result in RcvAddress field of <u>Root</u> process
  - MPI_Scan
    - Combine partial results into n final results and store them in RcvAddress of <u>all</u> n processes

MPI - Operations





MPI – Operations

- MPI_Reduce(

```
void* operand,    /* in*/
void * result,    /* out*/
int count,        /* in */
MP_Datatype datatype,
MPI_Op operator,
int root,
MPI_Comm comm)
```

  predefined MPI_OPs:
  sum, product, minimum, maximum, logical ops, ...

Case Study for an SMP OS: K42

- Overview:
  - Supports “pile-of-work” style,
  - common/shared object (file) system,
  - processes have many threads
  - Threads of a process run on different CPUs and share address space
  - provides Linux syscall interface
- For more see http://domino.research.ibm.com/comm/

  research_projects.nsf/pages/k42.index.html
  and paper in Eurosys 2006

Case Study: K42

- Overview:
  - Invented and/or aggressively explored many new interesting techniques (not in this lecture):
    - To support user-level thread scheduling within processes (address spaces)
    - Hot Swapping of components/implementations
    - Based on their own microkernel
  - Objective:
    migrate invented techniques into main stream Linux
- This lecture concentrates on K42's “clustered objects”

Clustered objects(CO) in K42

- Key ideas
  - Minimize sharing, maximize locality
  - Avoid global data structures and locks
  - Hide internal distribution/implementation structure
  - Per-processor “representatives” and one “root” as central entity

CO example: counter

Operations: “inc” and “getval”

alternatives: global variable ./. local reps & root counter

cases

- Inc frequent, getval infrequent:
  local rep better
- Getval frequent, inc infrequent:
  shared global variable better

(in K42: swapping even at run time)

Next few slides taken from Jonathan Appavoo with permission ...

Common MPP Operating-System-Model

- PE: compute intensive part of application
  - Micro-Kernel
  - Start + Synchronization of Application
  - elementary Memory Management (no demand paging)

- all other OS functionality on separate Servers or dedicated nodes
- strict space sharing:
  only one application active per partition at a time

Space Sharing

- Assign partition from field of PEs
  - Applications are pair wise isolated
  - Applications self responsible for PEs
  - shared segments for processes within partition (Cray)
- Problems:
  - debugging (relatively long stop-times)
  - Long-running jobs block shorter jobs
- Isolation of application with respect to:
  - Security
  - Efficiency
- Buzzword: “eliminate the OS from the critical path"

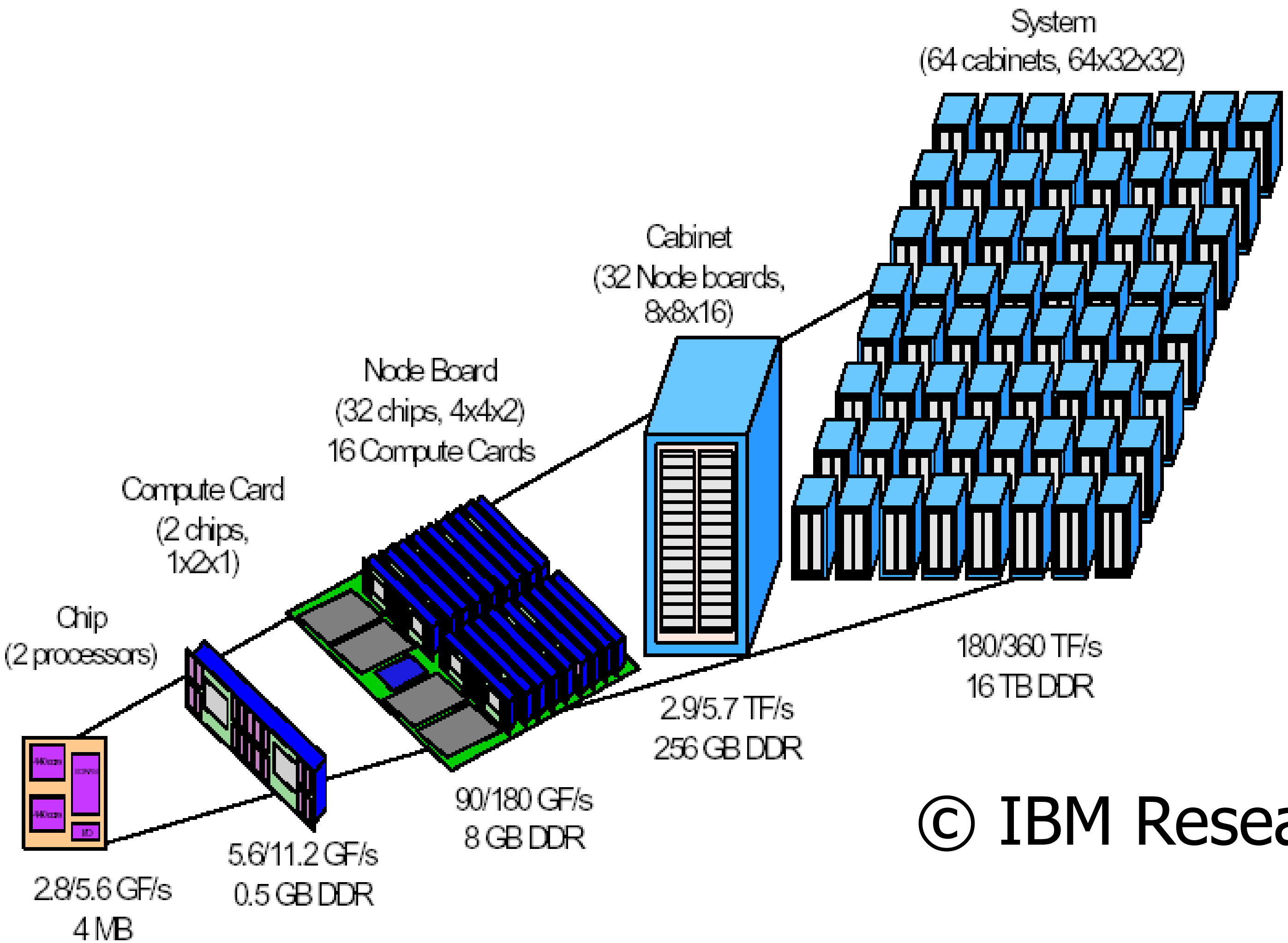
Space Sharing

- Hardware-Supported assignment of nodes to applications
- Partitions
  - static at configuration
    Installed by operator for longer period of time
  - Variable(Blue Gene/L):
    Selections and setup on start of Job
    established by “scheduler”
  - Very flexible (not in any MPP I know):
    - increase and shrink during operation
    - Applications need to deal with varying CPU numbers

Case Study: IBM – Blue Gene/L

- www.research.ibm.com/bluegene
- Applications:
  - Storm prediction
  - Protein folding
  - ...
- Requirements:
  - Fold large protein:
    - 1 Year computation on Petaflop computer
- Ranking 1 in Top 500
  using 16384 compute nodes (possible 65536)

IBM – Blue Gene Hardware



Functional HW organisation

- compute nodes:
  applications only, up to 65 536
- i/o nodes:
  IO, file system interaction, ...
  up to 1024
- separate file servers
- service nodes

compute and IO-Nodes: newly developed, identical

Compute and IO Nodes

- 2 32 bit PowerPC 700 MH with two 64 bit FPU each
- L1 cache (not coherent),
  2KB L2 and 4MB L3 cache (coherent)
  L2 hit 10 cycles, L3 hit 25 cycles, L3 miss 75 cycles
- some SRAM buffers for intranode communication
- GB ethernet,
- torus, tree, interrupt/barrier control
  (additional ASIC for cross plane communication)
- very low power

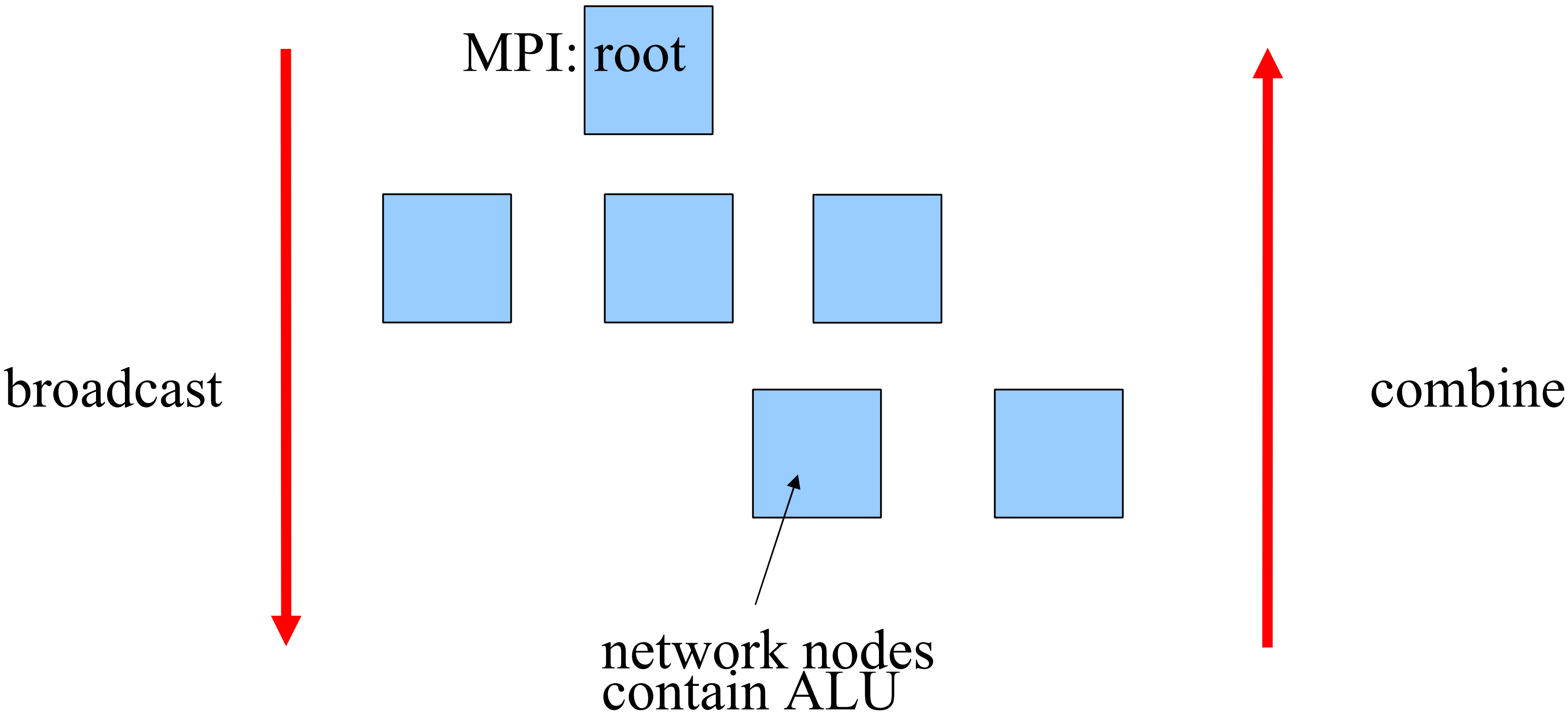
IBM – Blue Gene Interconnect

- 5 Networks:
  - 3D Torus   64 (cabinet) x 32 (midplane) x 32 (cpu card)
    only used by compute nodes
    memory mapped:
    "local injection FIFO" and "local reception FIFO"
    can be partitioned
    175 MB/sec per link

IBM – Blue Gene Interconnect

- 5 Networks:
  - Tree Network
    used Combine and Broadcast (network contains ALUs)
    interaction with IO/Nodes
  - Barrier + Interrupt Network
  - GBIT Ethernet to JTAG (machine control)
  - GBIT Ethernet to outside
    (communication with other systems, file servers)

Broadcast and Combine Tree Network



ca 2 microseconds latency for complete tree

IBM – Blue Gene Interconnect

- **“psets”**:
  - can be assembled as needed (with restrictions)
  - e.g.: 1:8, 1:128, 1:1024 (compute:io)

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System Software Overview

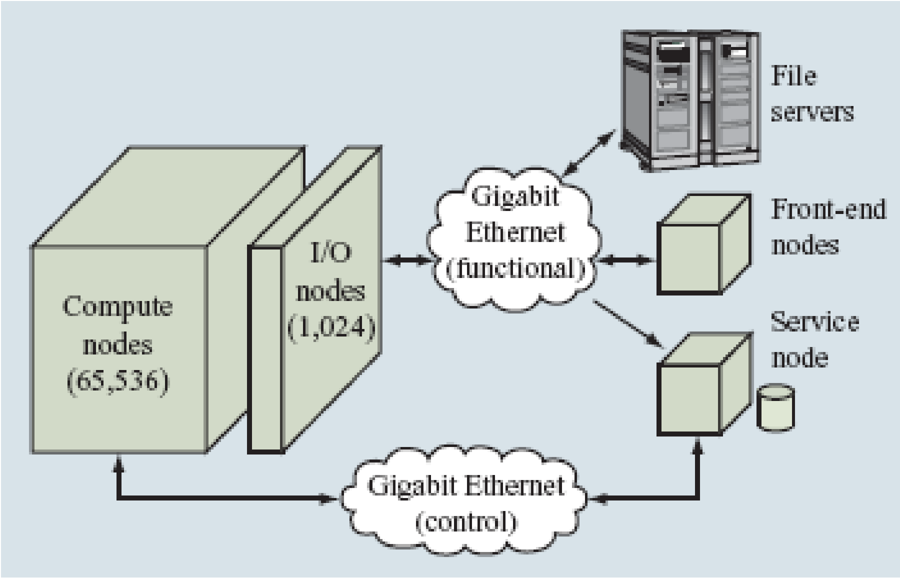


Figure 1

High-level architectural view of a complete Blue Gene/L system.

System Software: Overview

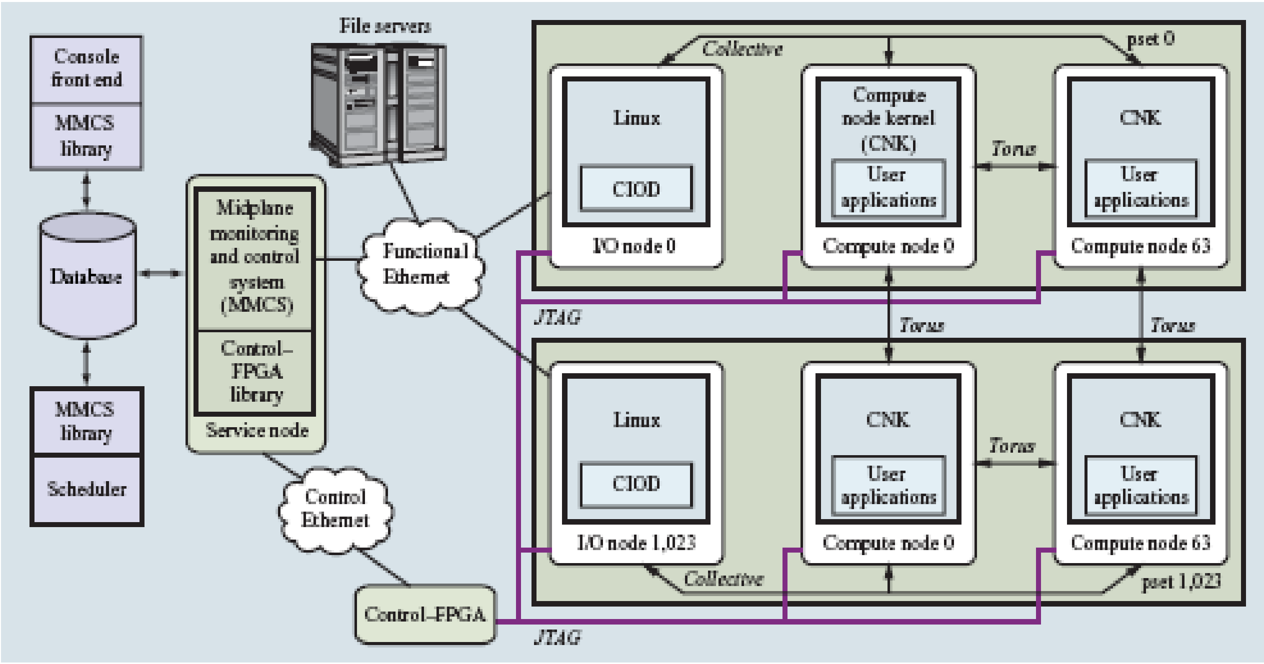


Figure 2

High-level view of the Blue Gene/L system software architecture.

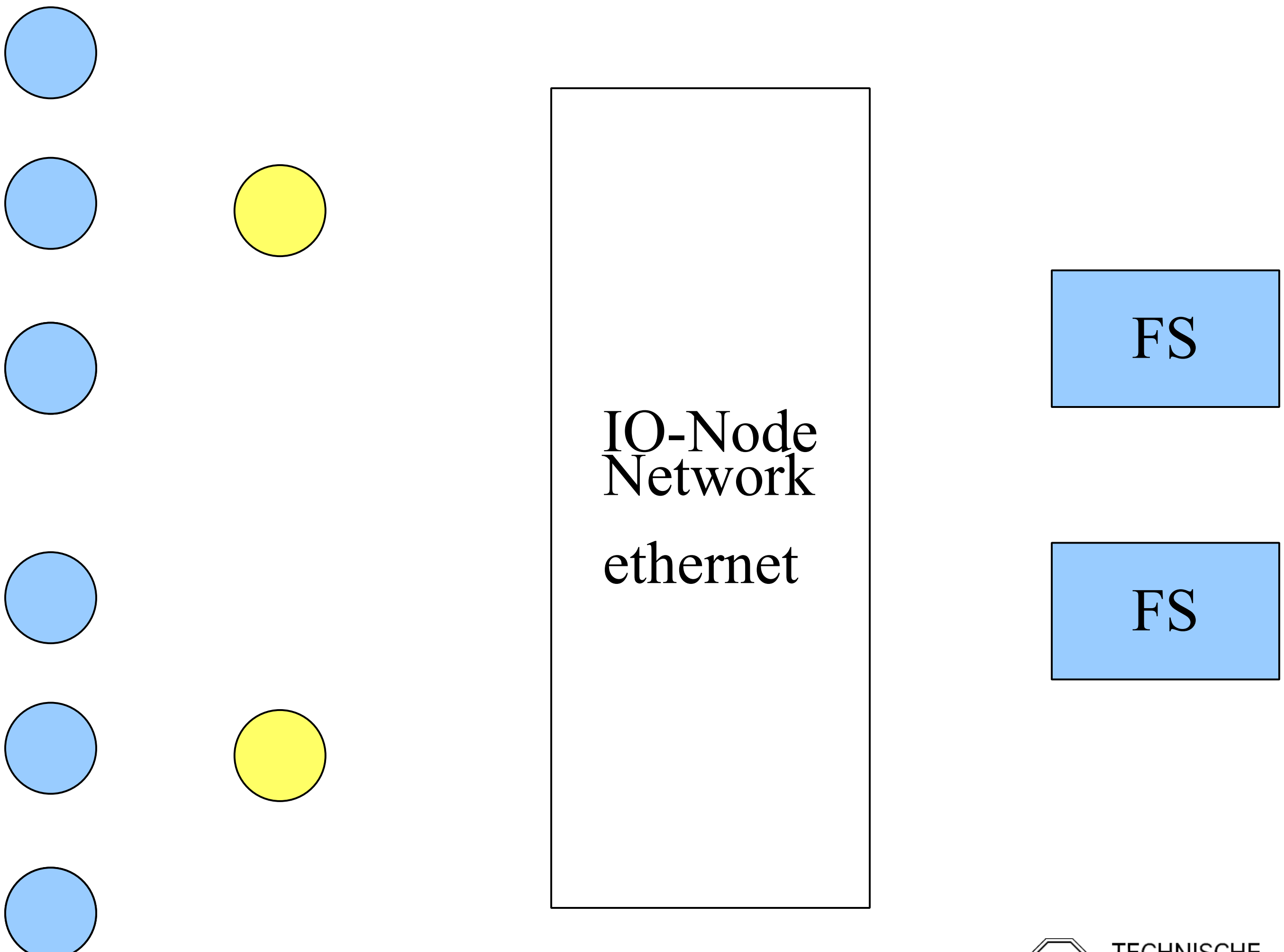
Principle Decisions

- strict space sharing
  one application per partition at a time
  enables user-mode communication without protection problems
- one application thread per compute node
- no demand paging:
  to avoid page faults and TLB misses

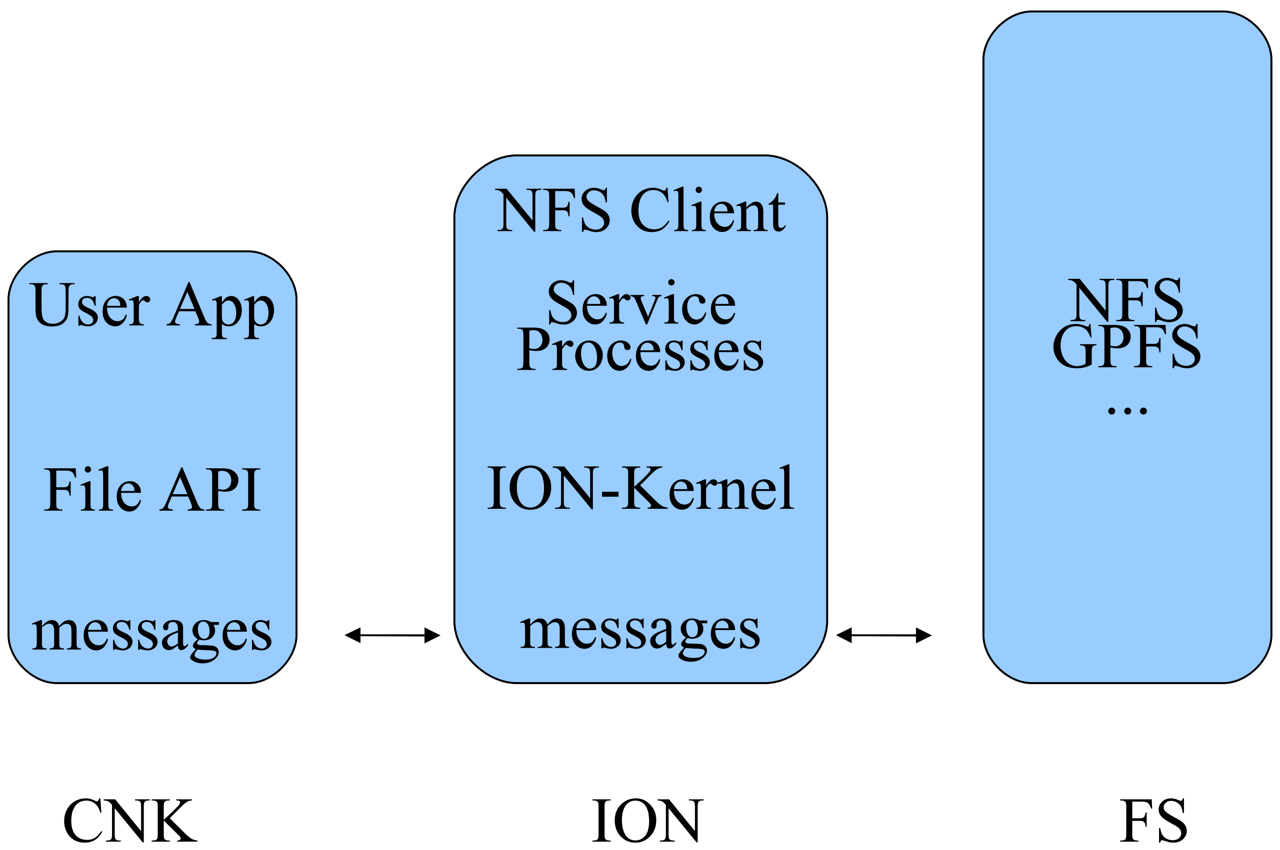
System Software

- compute node kernel: newly developed (CNK)
- io-nodes: Linux
- front end: compilers etc
- overall: MPI exploiting the communication hardware of compute nodes
- service node:
  control of the whole machine, DB2

Organization



Node and Roles



IO-Nodes

- all outside communication of compute nodes goes thru IO-Nodes
- Job launch and control for their “psets”
- provide system services needed by application
  no user application code on IO-Nodes
- diskless; boot image via RAM-Disk
- only one of the two CPUs are used by Linux
  (L1 cache not coherent)
- CIOD (control and io daemon):
  program launch, signaling, termination, IO
  point to point messaging with compute nodes

Compute Node Kernel

- single-user dual threaded minimal kernel
- flat fixed-size 512MB address space
- kernel protected using MMU
- physical resources are partitioned between user and kernel
- access to torus from user mode
- glibc runtime; no fork exec etc
  IO shipped to IO-Nodes

Compute Node Kernel

Messages, three layers

- HAL packet: delivery of packets
- messages: arbitrary size, reordering
- MPI
  specific support for reduction, broadcast, processes

packets and messages: “active messages”

Compute Node Kernel, 2 modes of op.

- coprocessor mode,
  dual threaded process sharing complete address space
  - One CPU:
    main application thread, non preemtable
  - Other CPU as "coprocessor":
    e.g., message passing services,
    but also computation in coroutine model
    co_start starts a computation
    co_join waits for completion

  all coherence must be handled by user program
- virtual node mode (next slide)

Compute Node Kernel, 2 modes of op.

- coprocessor mode
- virtual node mode
  2 single threaded processes, bound to CPUs
  - each process has access to half of the memory
  - share access to communication
  - can communicate only via message passing

Service Node

Core Management and Control System (CMCS), acts as global OS:

- makes all long-term policy decisions
- in coop with IO-Nodes performs/controls system management:
  monitoring, booting, temperature control, configuration registers

Job Execution: Init and Boot

- partition allocation: identify set of unused nodes
- compute “personality” for each node
  view of torus etc
- boot image for
  - CNK ca 128KB
  - IO-Node ca 0.5 MB + RAM Disk
- configuration info loaded into “Personality Area” of each node
- IO-Node mounts file systems etc as needed

Summary

- Workstations, Server and Supercomputers with low number of CPUs:
  State of the Art
- Symmetric Parallel Computers with X- CPUs:
  Successful application at OLTP
- Massively Parallel Computers X-hundred to x-thousand CPUs:
  promising (since a long time ...)

References

- **Dave Culler, Jaswinder Sing,**
  Parallel Computer Architecture – A HW/SW-Approach
  99, Morgan Kaufmann

- Kai Hwang, Zhiwei Xu,
  Scalable Parallel Computing
  97, McGraw-Hill

- Curt Schimmel, Unix Systems for Modern Architectures
  94, Addisson Wesley

References

- Blue Gene/L programming and operating environment
  by J. E. Moreira, G. Almasi, C. Archer, R. Bellofatto, P. Bergner, J. R. Brunheroto, M. Brutman, J. G. Castanos, P. G. Crumley, M. Gupta, T. Inglett, D. Lieber, D. Limpert, P. McCarthy, M. Megerian, M. Mendell, M. Mundy, D. Reed, R. K. Sahoo, A. Sanomiya, R. Shok, B. Smith, G. G. Stewart

  IBM Journal of Research and Development
  Volume 49, Number 2/3, Page 367 (2005)
- MPI Tutorial
  http://www-unix.mcs.anl.gov/mpi/learning.html