Power and Performance Optimization at the System Level

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ACM Computing Frontiers 2005

The BlueGene/L Team

The Supercomputer Challenge

- **More Performance → More Power**
  - Systems limited by data center cooling capacity
    - New buildings for new supercomputers
  - FLOPS/W not improving from technology

→ **Traditional supercomputer design hitting power & cost limits**

- **Scaling single core performance degrades power-efficiency**

The BlueGene/L Concept

- **Parallelism can deliver higher aggregate performance**
  - Efficiency is key: (deliver performance / system power)
    - Power budget scales with peak performance
    - Application performance scales with sustained performance
- **Avoid scaling single core performance into regime with diminishing power/performance efficiency**
  - Deliver performance by exploiting application parallelism
- **Focus design effort on improving efficient MP scaling**
  - e.g., special purpose networks for synchronization and communication
- **Compute density can be achieved only with low power design approach**
  - Capacity of data center limited by cooling, not floor space

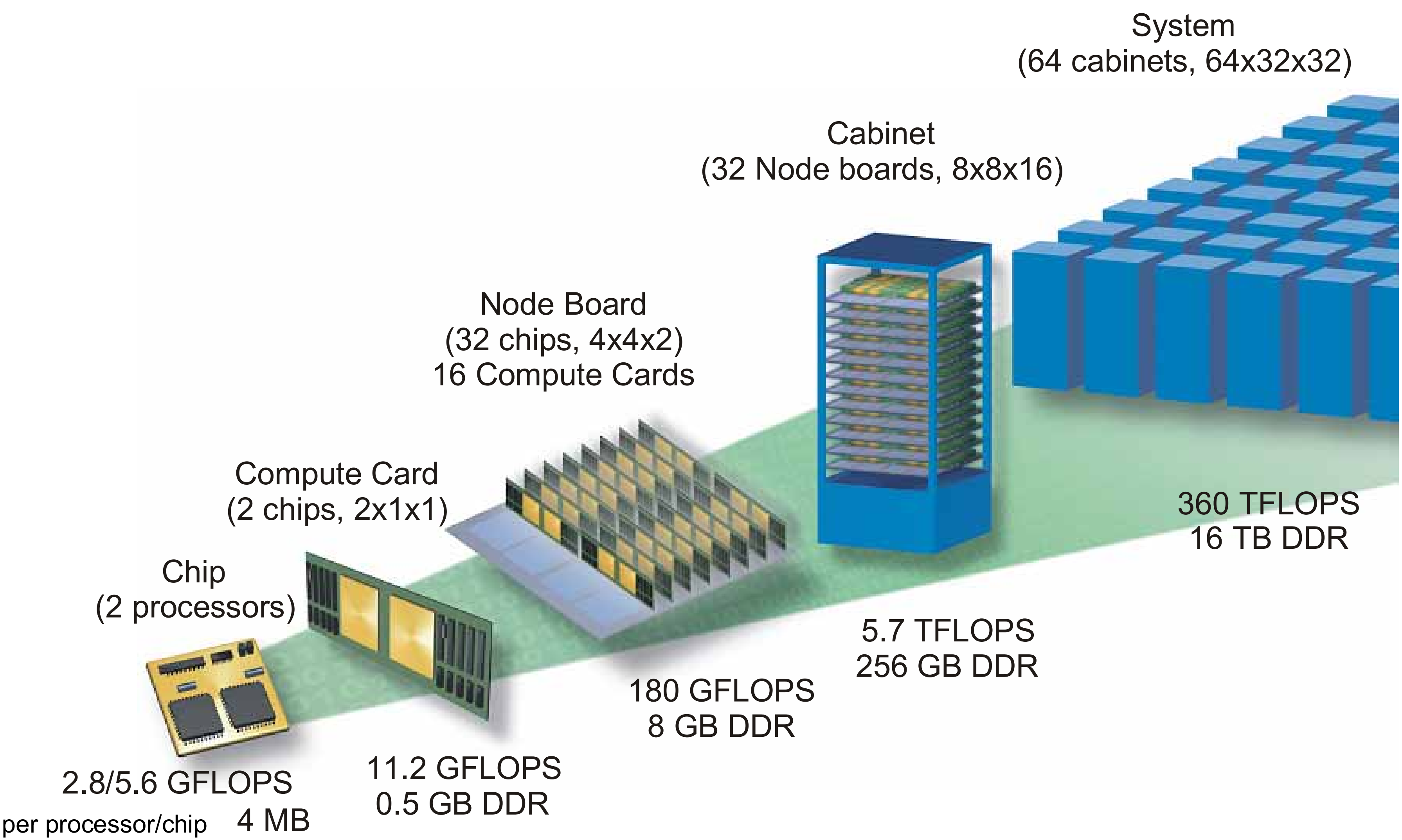
BlueGene/L Design Philosophy

- **Use standard embedded system-on-a-chip (SoC) design methodology**
- **Utilize PowerPC architecture and standard messaging interface (MPI)**
  - Standard programming model
  - Mature compiler support
- **Focus on low power**
  - Air cooling – power budget per rack 25 KW
- **Improve cost/performance (total cost/time to solution)**
  - Use & develop only two ASICs: node and link
  - Leverage industry-standard PowerPC design
- **Single-chip nodes, less complexity**
  - Enables high density

The BlueGene/L System

- **A 64k-node highly integrated supercomputer**
- **360 teraflops peak performance**
- **Strategic partnership with LLNL and high-performance computing centers**
  - Validate and optimize architecture using real applications
  - LLNL is accustomed to new architectures and experienced at application tuning to adapt to constraints
  - Help us investigate the reach of this machine
- **Focuses on numerically intensive scientific problems**
- **“Grand challenge” science projects**

BlueGene/L


System
(64 cabinets, 64x32x32)
Cabinet
(32 Node boards, 8x8x16)
Node Board
(32 chips, 4x4x2)
16 Compute Cards
Compute Card
(2 chips, 2x1x1)
Chip
(2 processors)
2.8/5.6 GFLOPS
per processor/chip
4 MB
11.2 GFLOPS
0.5 GB DDR
180 GFLOPS
8 GB DDR
5.7 TFLOPS
256 GB DDR
360 TFLOPS
16 TB DDR

System Characteristics

- **Chip multiprocessor**
  – 2 PowerPC cores per chip
- **Data parallelism**
  – Double floating point unit for advanced SIMD operations
- **High integration**
  – 2 PowerPC cores + EDRAM cache + DDR memory interface + network interfaces on a single chip
- **High performance networks**
  – Directly on chip ➔ reduce latency
  – Multiple optimized, task-specific networks
    - Synchronization, data exchange, I/O

BlueGene/L Architecture

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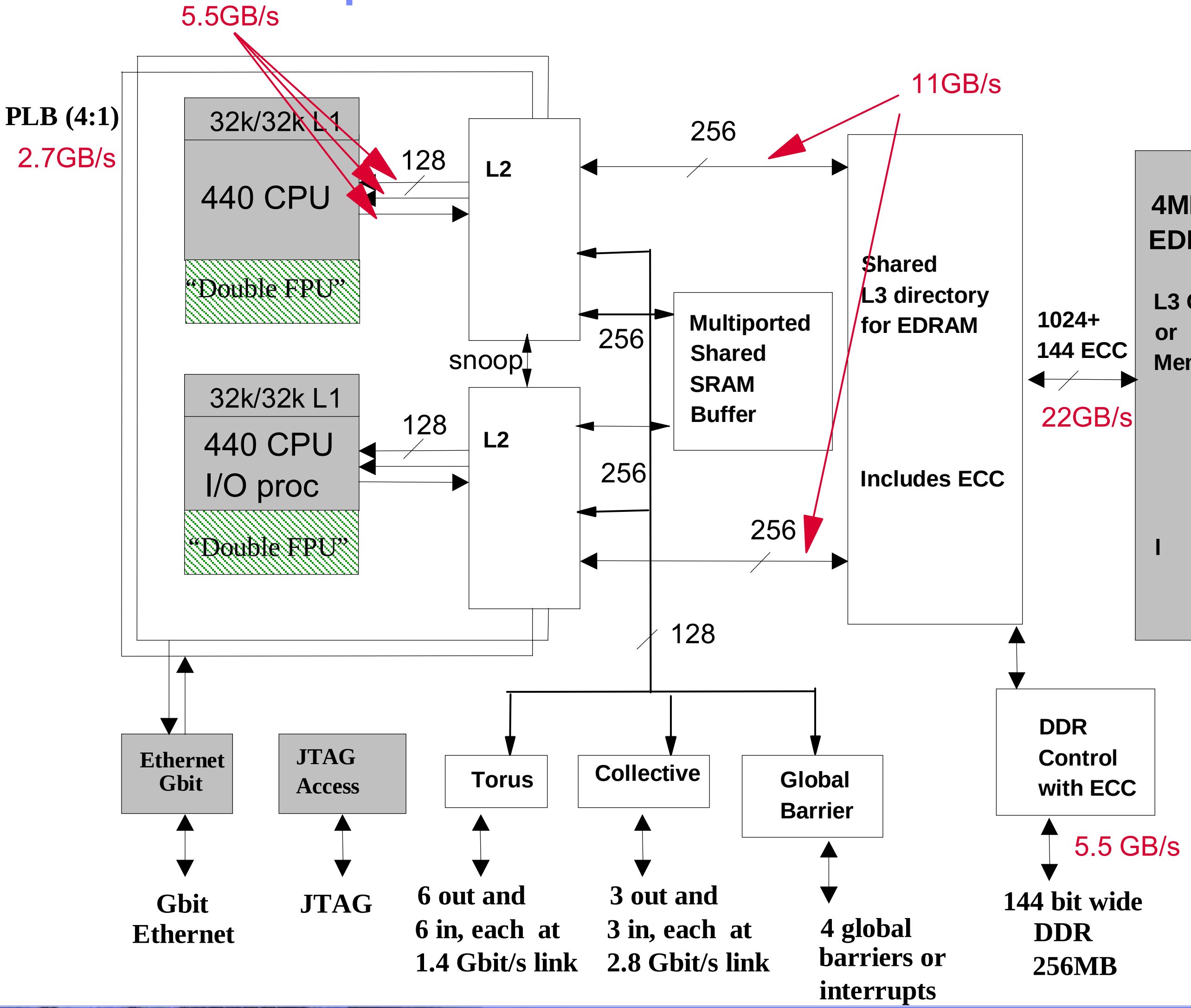
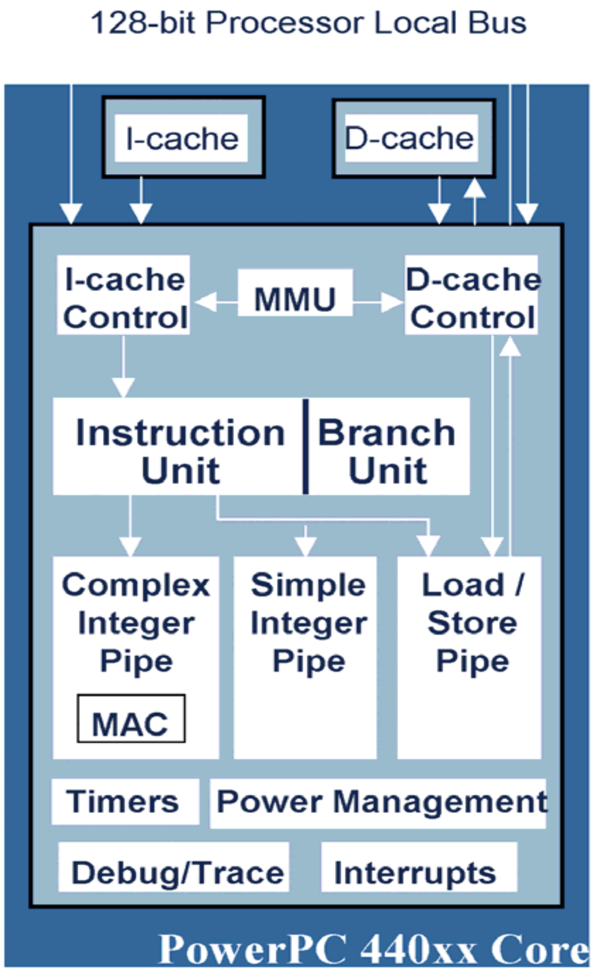
BlueGene/L Compute SoC ASIC



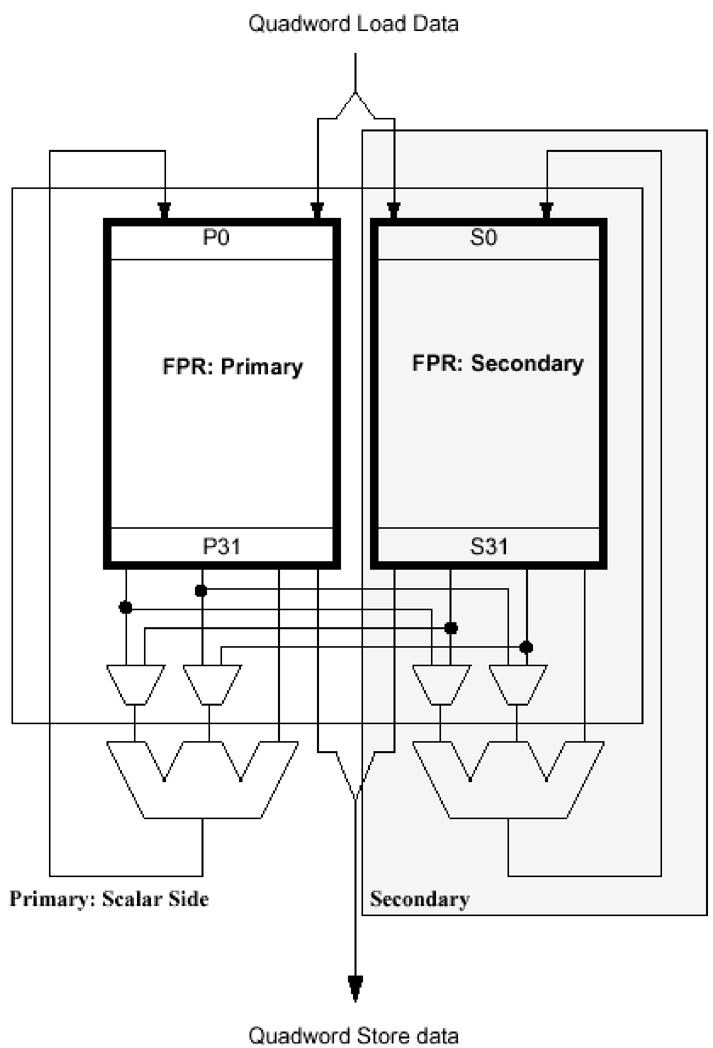
5.6GF
peak
node

PowerPC 440 Processor Core Features

- High performance embedded PowerPC core
- 2.0 DMIPS/MHz
- Book E Architecture
- Superscalar: two instructions per cycle
- Out of order issue, execution, and completion
- 7 stage pipeline
- 3 Execution pipelines
- 32 32 bit GPR
- Dynamic branch prediction
  - BHT & BTAC
- Caches
  - 32KB instruction & 32KB data cache
  - 64-way set associative, 32 byte line
- 36-bit phisical address
- 128-bit CoreConnect PLB Interface



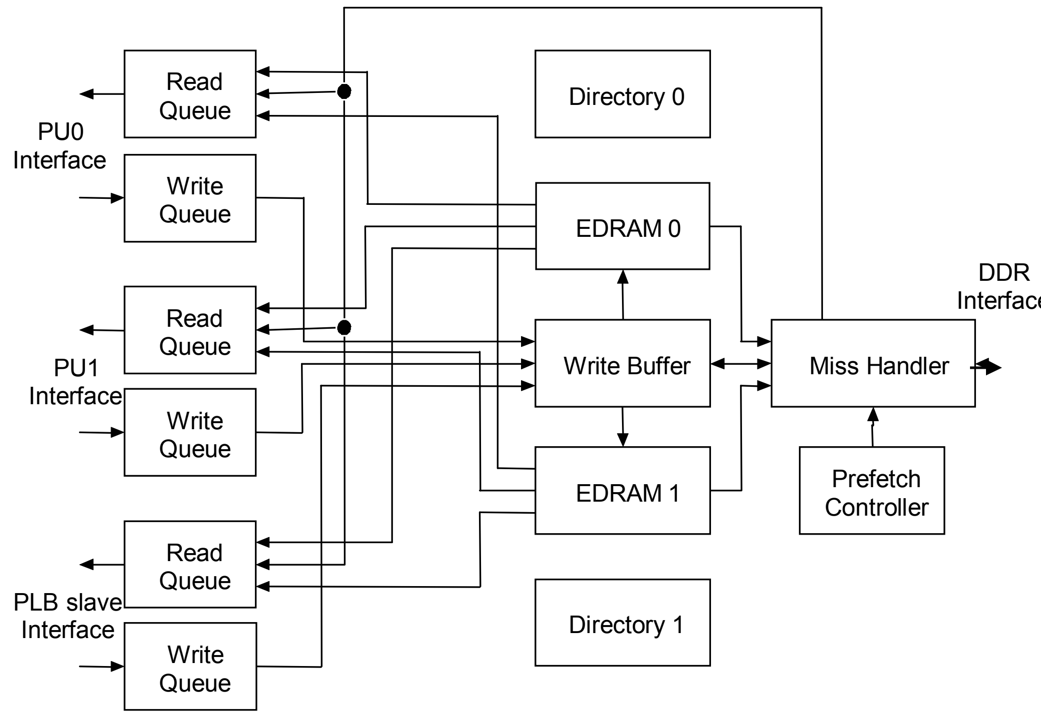
Double Hummer Floating-Point Unit



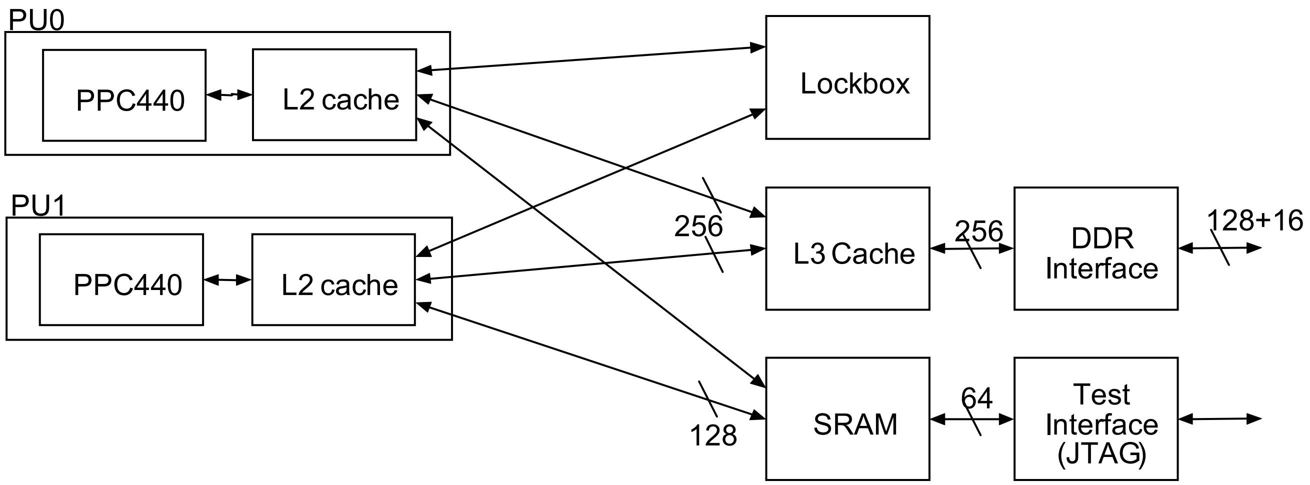
- **Two replicas of a standard single-pipe PowerPC FPU**
  - 2 x 32 64-bit registers
- **Enhanced ISA, includes instructions**
  - Executed in either pipe
  - Simultaneously execute the same operation on both sides – SIMD instructions
  - Simultaneously execute two different operations of limited types on different data
- **Two FP multiply-add operations per cycle**
  - 2.8 GFlops peak

L3 Cache Implementation

- **On-chip 4 MB L3 cache**
- **Use EDRAM**
- **Two-way interleaved**
- **2MB EDRAM per bank, 8-way set-associative, 128-byte lines**
- **ECC protected**
- **32-byte read and write bus per core @ 350MHz**
- **2 x 64-byte EDRAM access @ 175MHz**



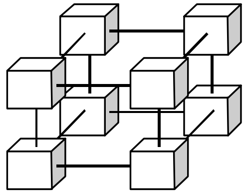
Memory Hierarchy



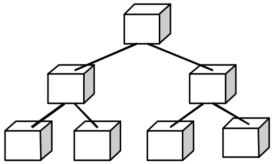
Memory Type	Latency (cycles)
L1 cache	3
L2 cache	11
L3 cache	28/36/40
Main memory	86

- **32kB D&I private cache per processor**
- **Small private L2 data prefetch caches**
  - Supports 7 streams/processor
- **On-chip 4MB L3 cache**
- **Access to main memory via L3 cache**
- **SRAM for fast exchange of control information**
- **Synchronization via lockbox semaphores**

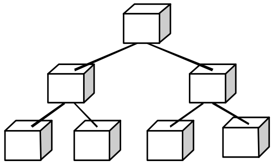
BlueGene/L Five Independent Networks



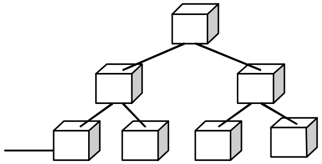
3 Dimensional Torus
- Point-to-point



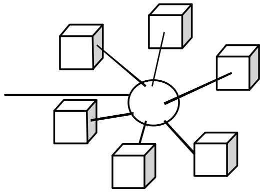
Collective Network
- Global Operations



Global Barriers and Interrupts
- Low Latency Barriers and Interrupts

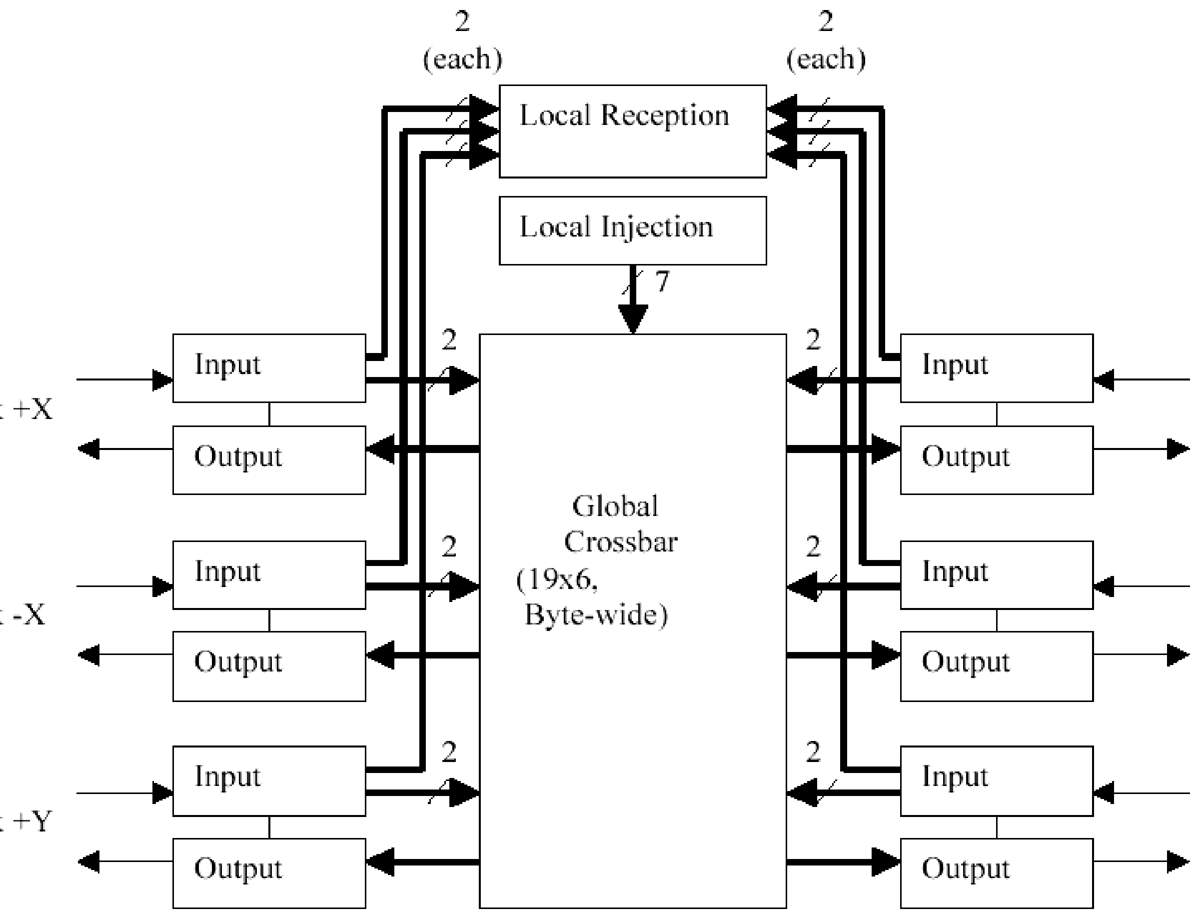


Gbit Ethernet
- File I/O and Host Interface



Control Network
- Boot, Monitoring and Diagnostics

Three-Dimensional Torus Network



Torus router

Point-to-point communication

- Nearest neighbor interconnect

Links 1 bit wide, 6 bidirectional links/chip

Per-link bandwidth 1.4Gb/s

Per-node bandwidth 2.1GB/s

Cut-through routing without software intervention

Adaptive routing

Packet length

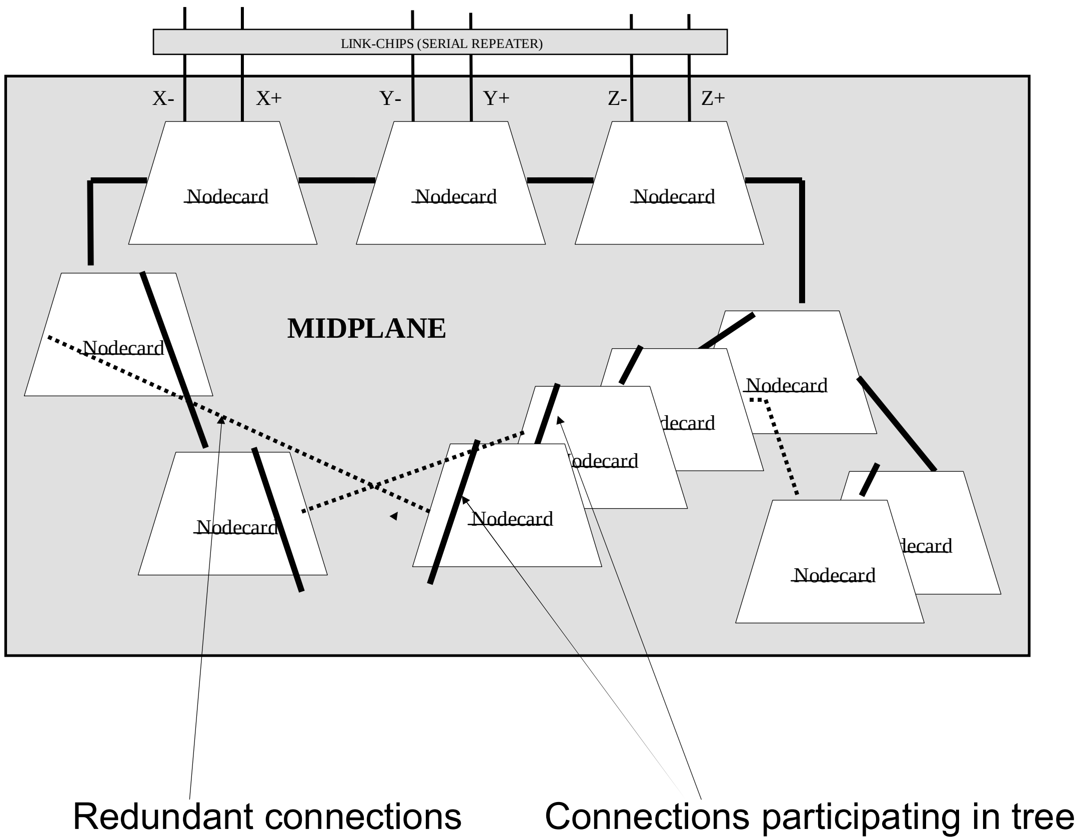
- 32–256 bytes, 4-byte trailer

Per-hop latency ~100 ns (avg.)

Worst case latency for 64k machine (64 x 32 x 32)

- 6.4 μs (64 hops)

Collective Network

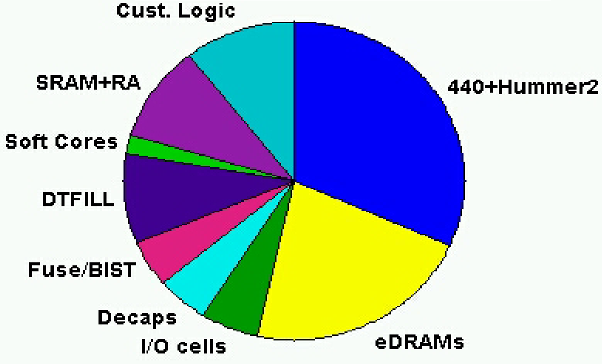


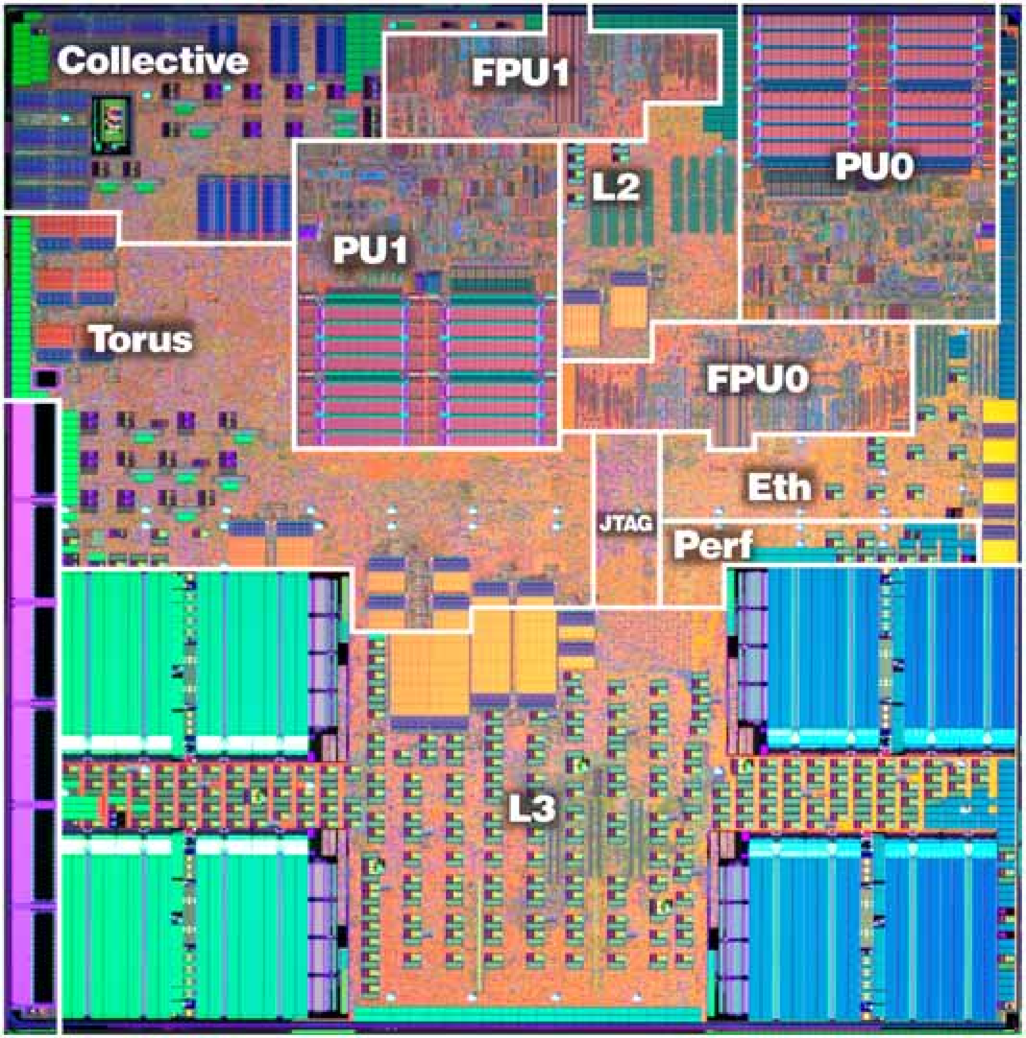
- **Global reduction support**
- **Bidirectional 3 links per node**
- **Per node bandwidth 2.1 GB/s**
- **Worst case latency (round trip) 5.0μs**
- **Efficient for collective communication**
  - For broadcast messages
  - Arithmetic reductions implemented in hardware
- **Fault-tolerant for tree topologies**
- **Connect every node to I/O node for file system**

BlueGene/L Chip Design Characteristics

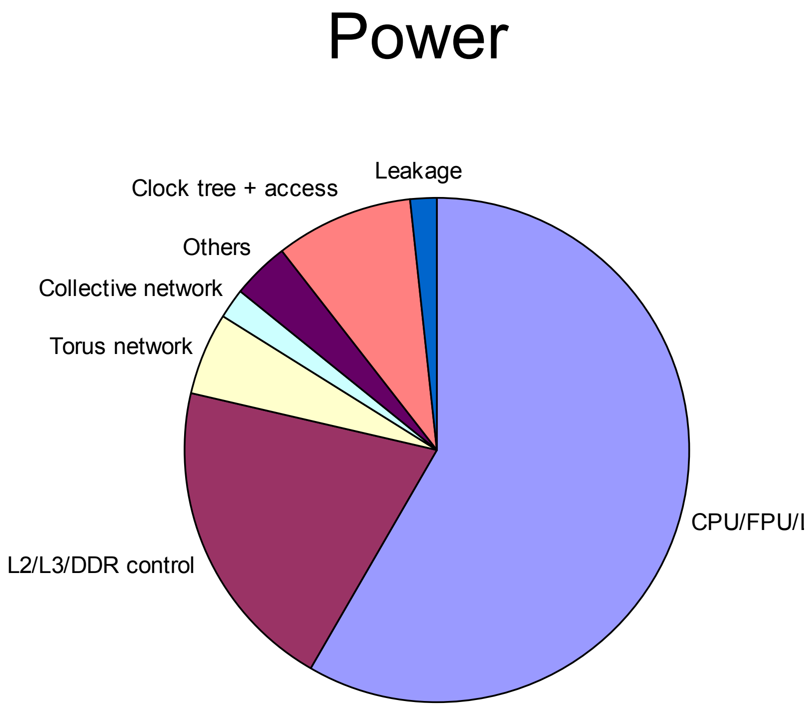
- **IBM Cu-11 0.13µ CMOS ASIC process technology**
- **11 x 11 mm die size**
- **95M transistors**
- **1.5/2.5V**
- **12.9W**
- **CBGA package, 474 pins**

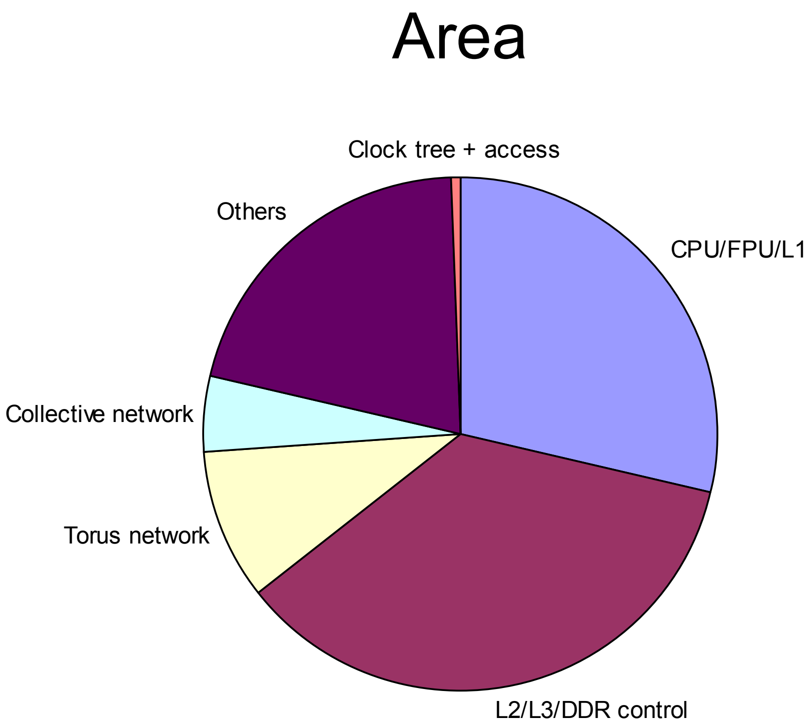
Chip Area usage





BlueGene/L Compute Chip Power and Area





BlueGene/L System Package

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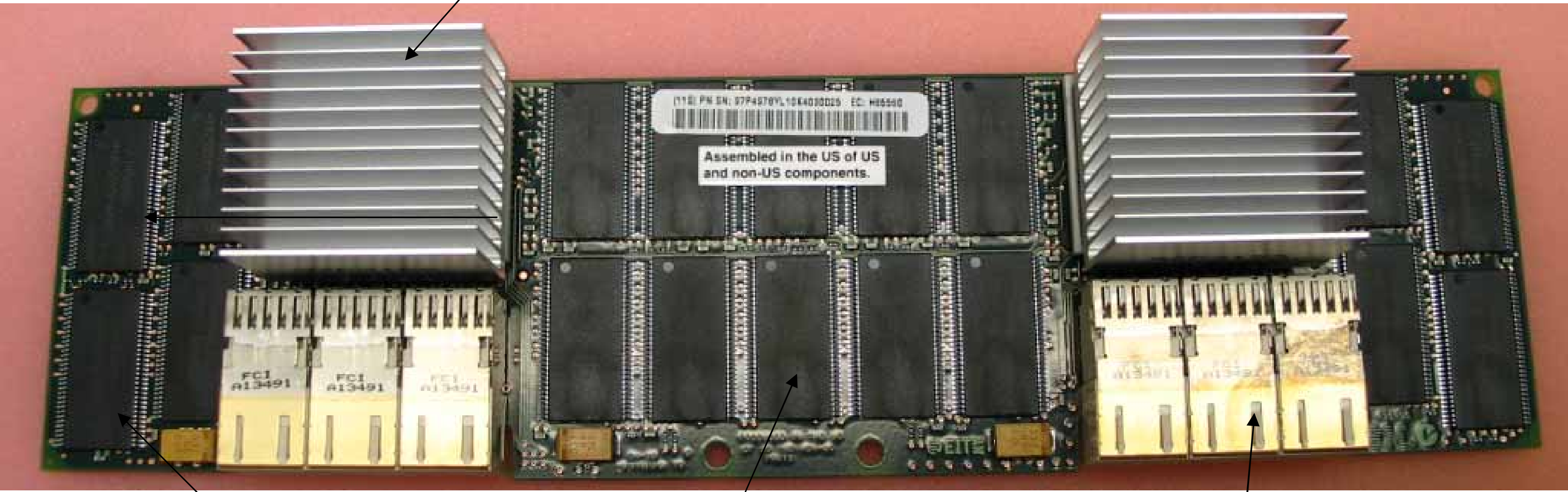
Dual Node Compute Card

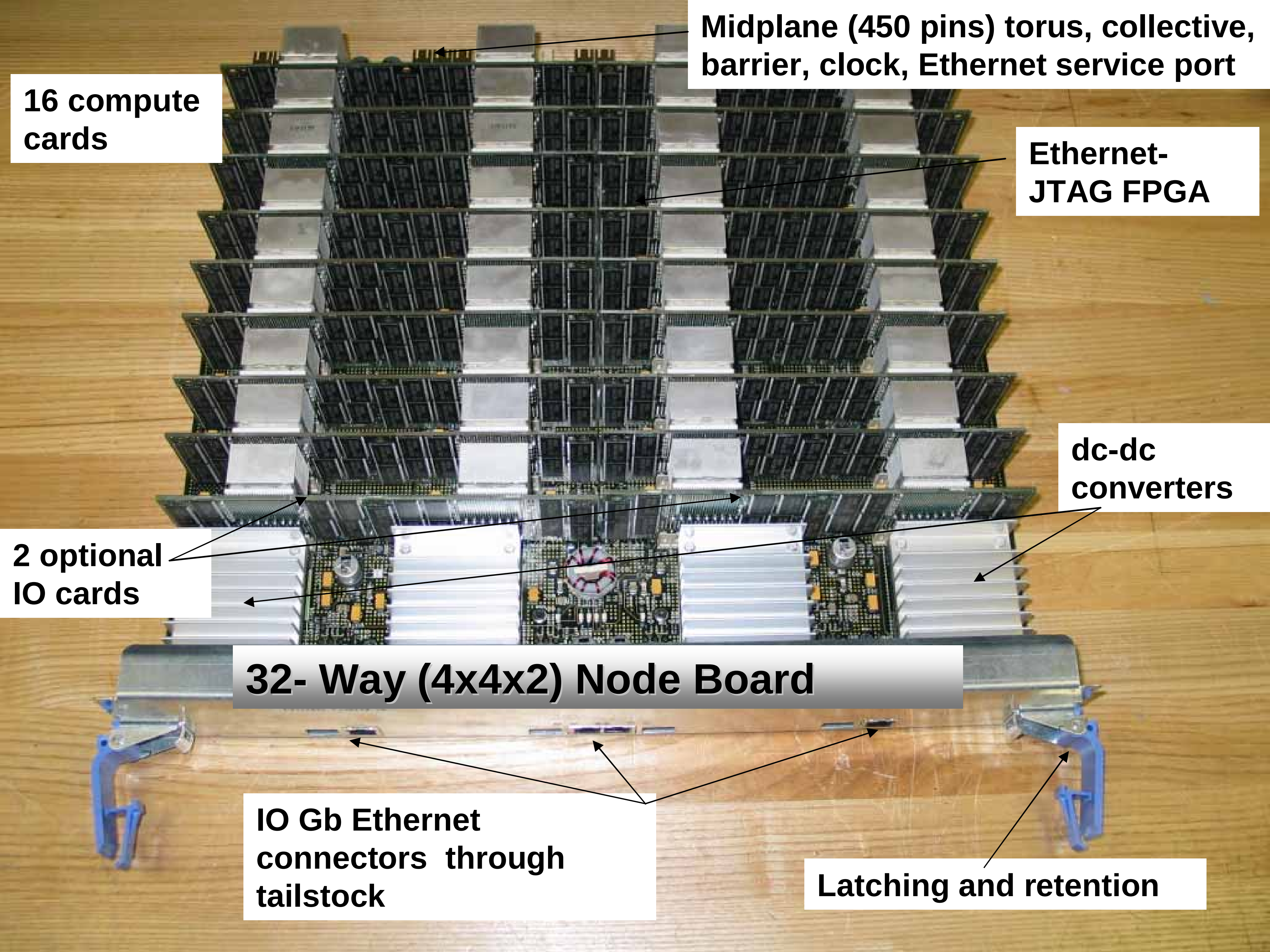
206 mm (8.125”) wide, 54mm high (2.125”), 14 layers, single sided, ground referenced

Heatsinks designed for 15W



9 x 512 Mb DRAM

Metral 4000 high speed differential connector (180 pins)

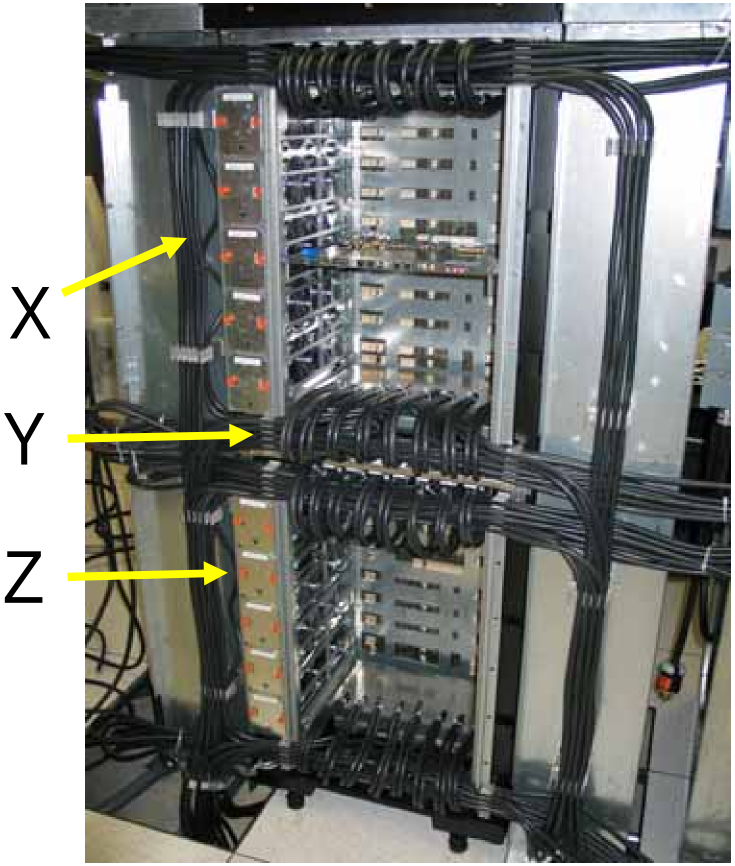

Midplane (450 pins) torus, collective, barrier, clock, Ethernet service port
16 compute cards
Ethernet-JTAG FPGA
dc-dc converters
2 optional IO cards
32- Way (4x4x2) Node Board
IO Gb Ethernet connectors through tailstock
Latching and retention

BlueGene/L Rack

512 – way (8 x 8 x 8) “midplane” (half-cabinet)

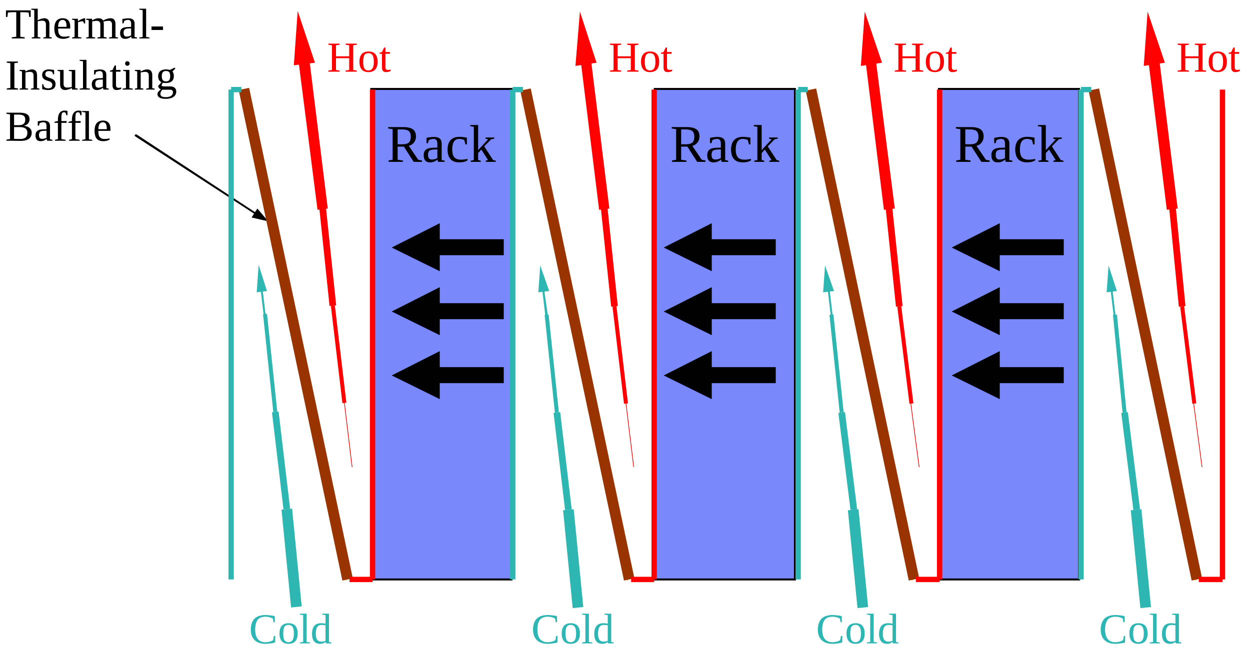
16 node boards

All wiring up to this level (>90%) card-level



Two midplanes interconnected with data cables

BlueGene/L Rack Ducting Scheme

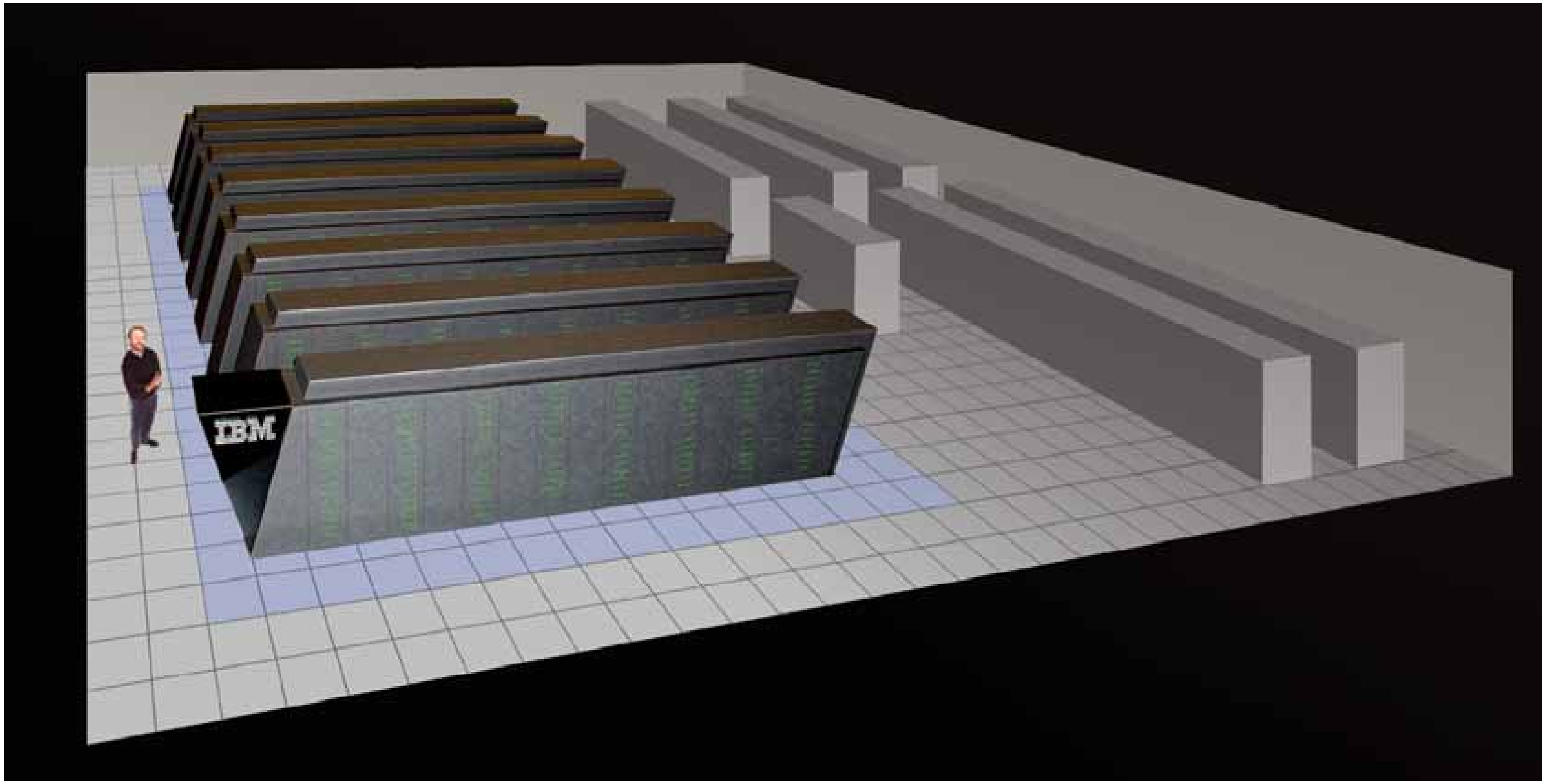


Airflow direct from raised floor

BlueGene/L 16-Rack System at IBM Rochester

16384 + 256 BLC chips. About 400 kW

BlueGene/L System



BlueGene/L System Software

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BlueGene/L – Familiar Software Environment

- **Fortran, C, C++ with MPI**
  - Full language support
  - Automatic SIMD FPU exploitation
- **Linux development environment**
  - Cross-compilers and other cross-tools execute on Linux front-end nodes
  - Users interact with system from front-end nodes
- **Tools support**
  - debuggers, hardware performance monitors, trace based visualization

BlueGene/L – Familiar Software Environment

- **Programmer's view: Nearly identical software stack/interface to pSeries**
  - Compilers: IBM XLF, XLC, VA C++, hosted on PPC/Linux
  - Operating System: Linux-compatible kernel with some restrictions
  - Message passing library: MPI
  - Math libraries: ESSL, MASS, MASSV
  - Parallel file system: GPFS
  - Job scheduler: LoadLeveler
- **System administrator's view**
  - Look and feel of a PPC Linux cluster managed from a PPC/Linux host, but diskless
  - Managed by a novel control system

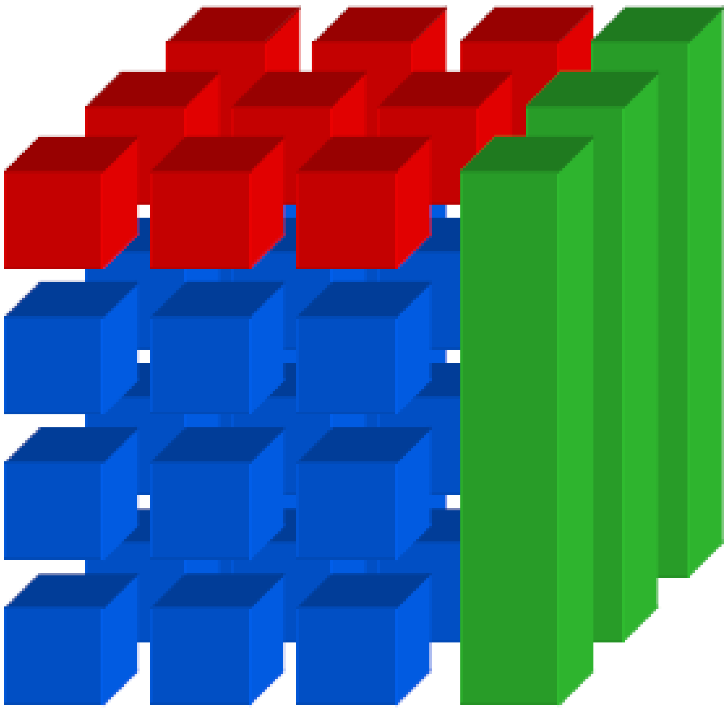
BlueGene/L System Software Main Characteristics

- **Logical partitioning (LPAR) of the system for multiple concurrent users**
  - Link chip partitions the system into logically separate systems
- **Strictly space sharing**
  - One parallel job (user) per partition of machine
  - One process per processor of compute node
- **Intra-chip communication**
  - MPI message passing programming model
- **Modes of operation**
  - Co-processor mode
    - Compute processor + communication off-load engine
  - Virtual node mode
    - Symmetric processors

BlueGene/L Operating Environment

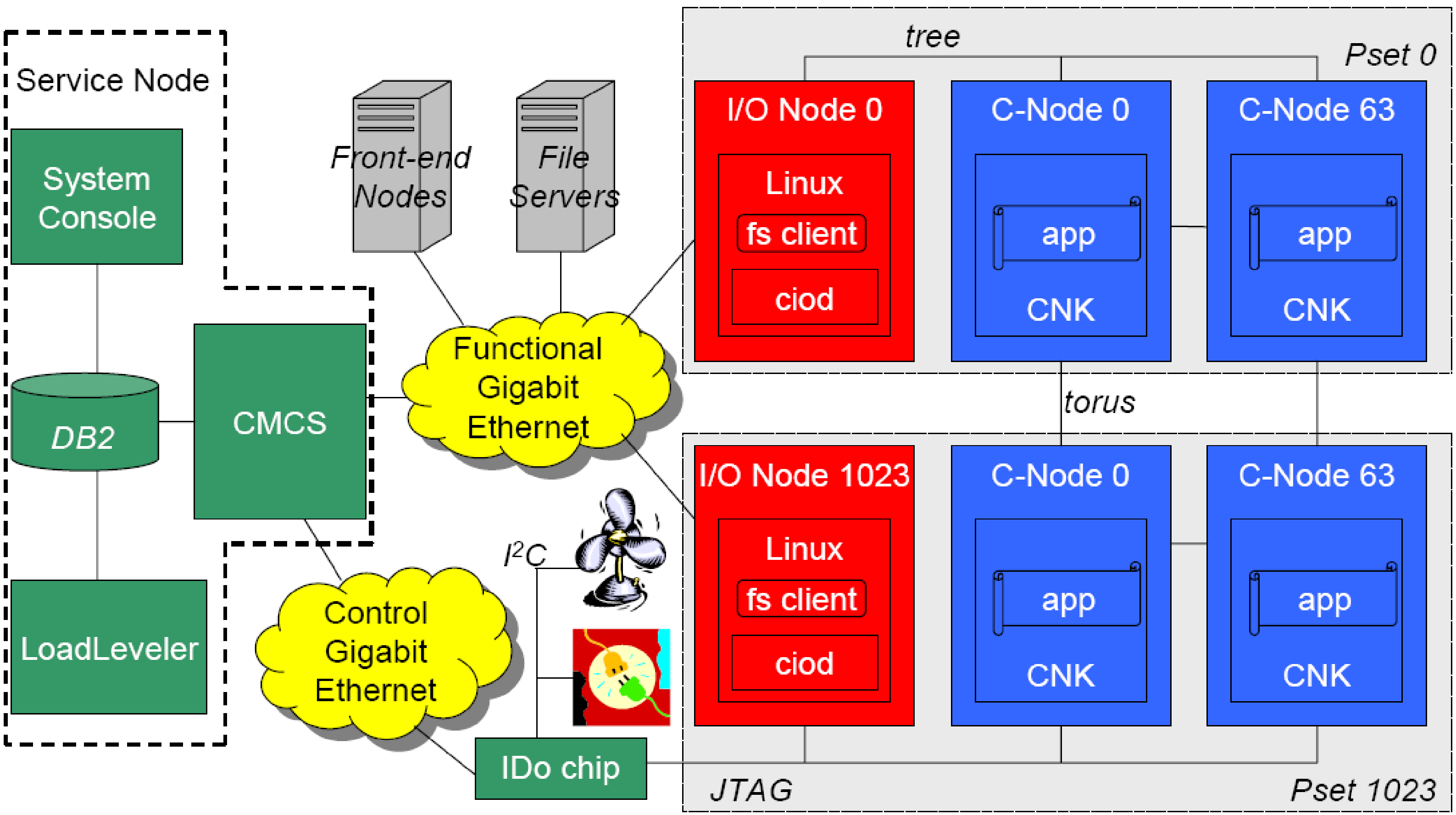
- **blrts operating system**
  - Linux compatible minimalist kernel
  - Single user single program operation
    - Minimal operating system interference
- **Virtual memory constrained to physical memory size**
  - Implies no demand paging
- **Torus memory mapped in the user address space**
  - no operating system calls needed for application communication

BlueGene/L System Software Architecture



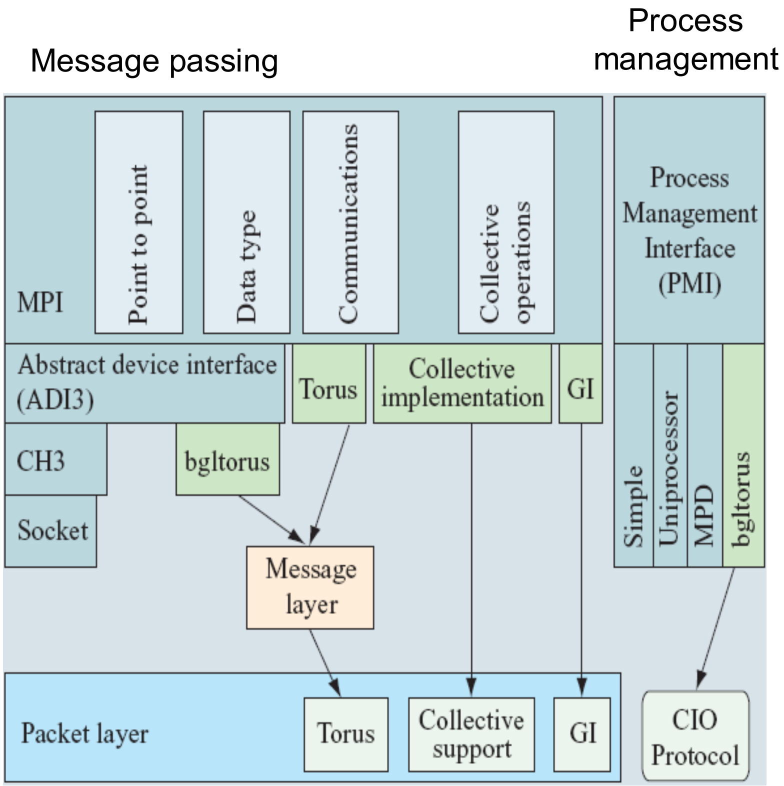
- **Compute nodes for user applications**
  - Simple Compute Node Kernel
  - Connected by 3D torus and collective network
- **I/O nodes for interaction with the outside world**
  - Run Linux
  - Provide OS services – file access, process launch/termination, debugging
  - Tree network and Gigabit Ethernet
- **Service nodes for machine monitoring and control**
  - Linux cluster
  - Custom components for booting, partitioning, configuration

Blue Gene/L System Architecture



MPI

- **MPI 1.1 compatible implementation for message passing between compute nodes**
  - Only the most widely used features of MPI implemented
- **Based on MPICH2 from ANL**
- **Point-to-point**
  - Utilizes Torus
  - Implements a BlueGene/L version ADI3 on top of message layer
- **Global operations**
  - Utilizes both torus and collective network
- **Process management**
  - Use BlueGene/L's control system rather than MPICH's process managers



BlueGene/L Application Performance and Power Analysis

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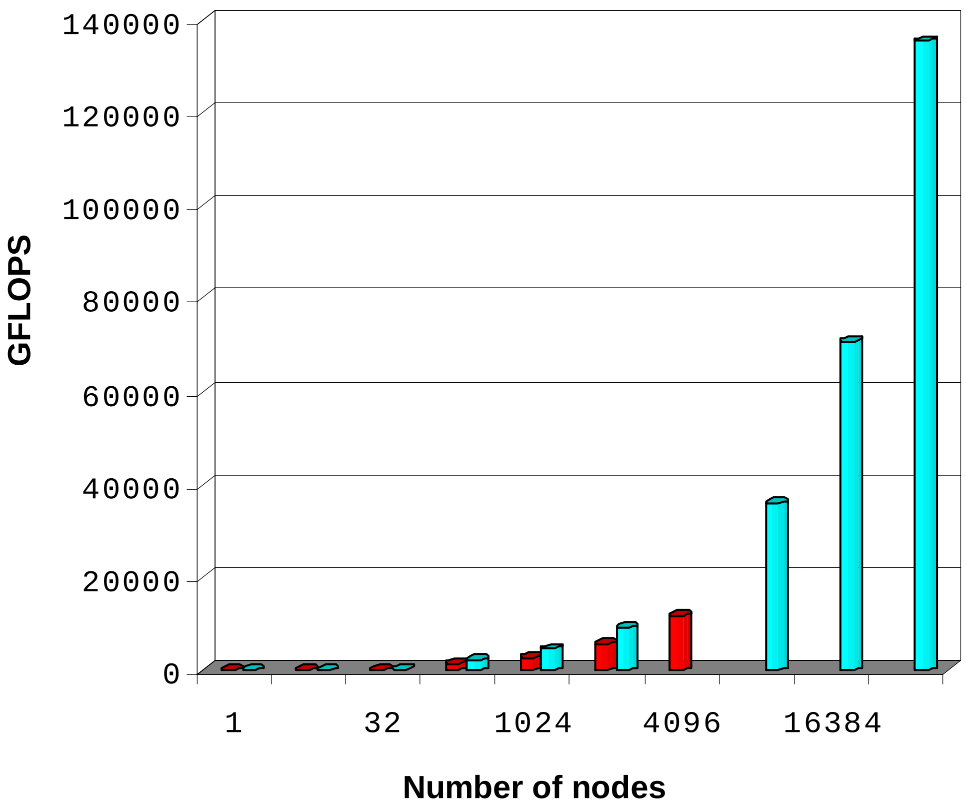
LINPACK Performance



DD1 hardware @ 500 MHz

#4 on June 2004 TOP500 list

11.68 TFLOP/s on 4K nodes

DD2 hardware @ 700 MHz

#1 on Nov 2004 TOP500 list

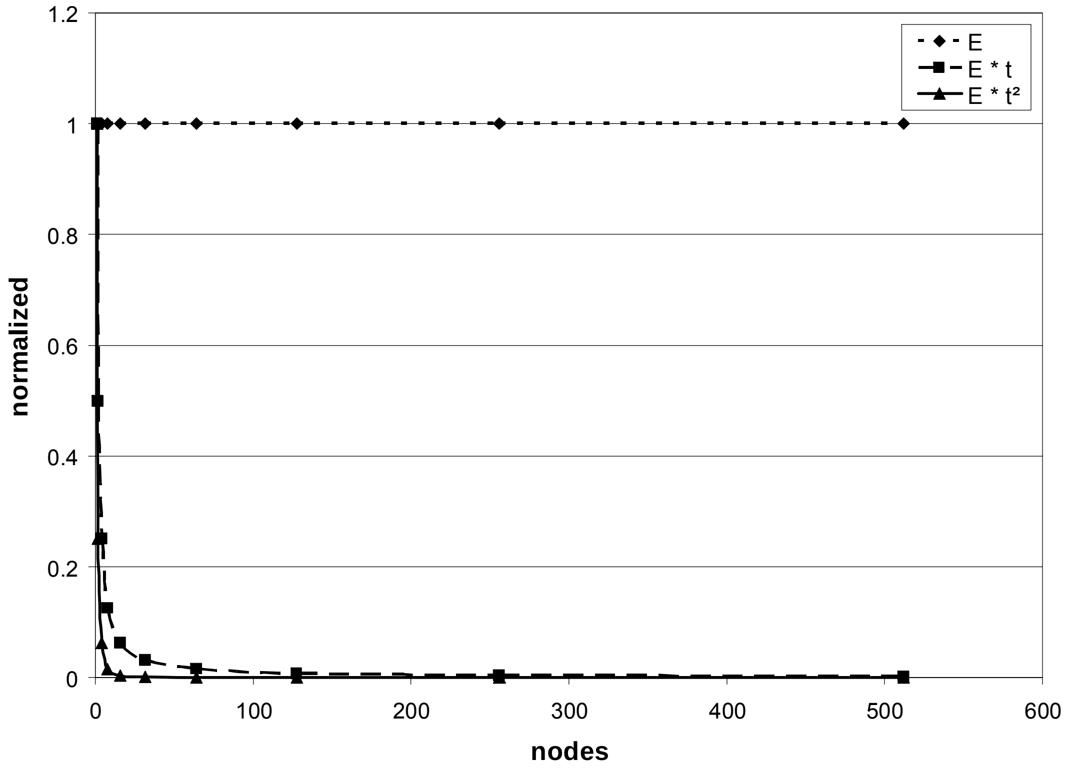
70.72 TFLOP/s on 16K nodes

77% of peak

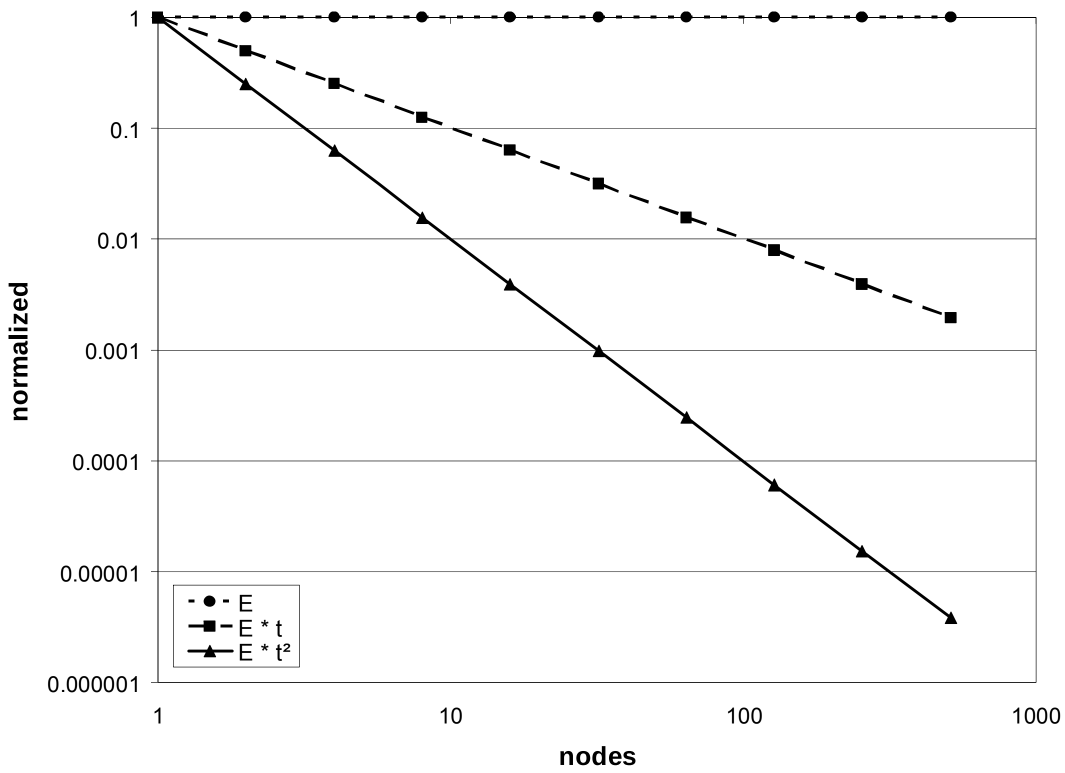
Application Performance and Power Efficiency

- **Figures of merit**
  - t -- time (delay)
    - application execution time
  - E -- energy (W/MIPS)
    - energy dissipated to execute application
  - E * t -- energy-delay [Gonzalez Horowitz 1996]
    - energy and delay are equally weighted
  - E * t^2 -- energy-delay squared [Martin *et al.* 2001]
    - metric invariant on the assumption of voltage scaling

Low Power - High Performance System Concept



Low Power - High Performance System Concept (log-log)



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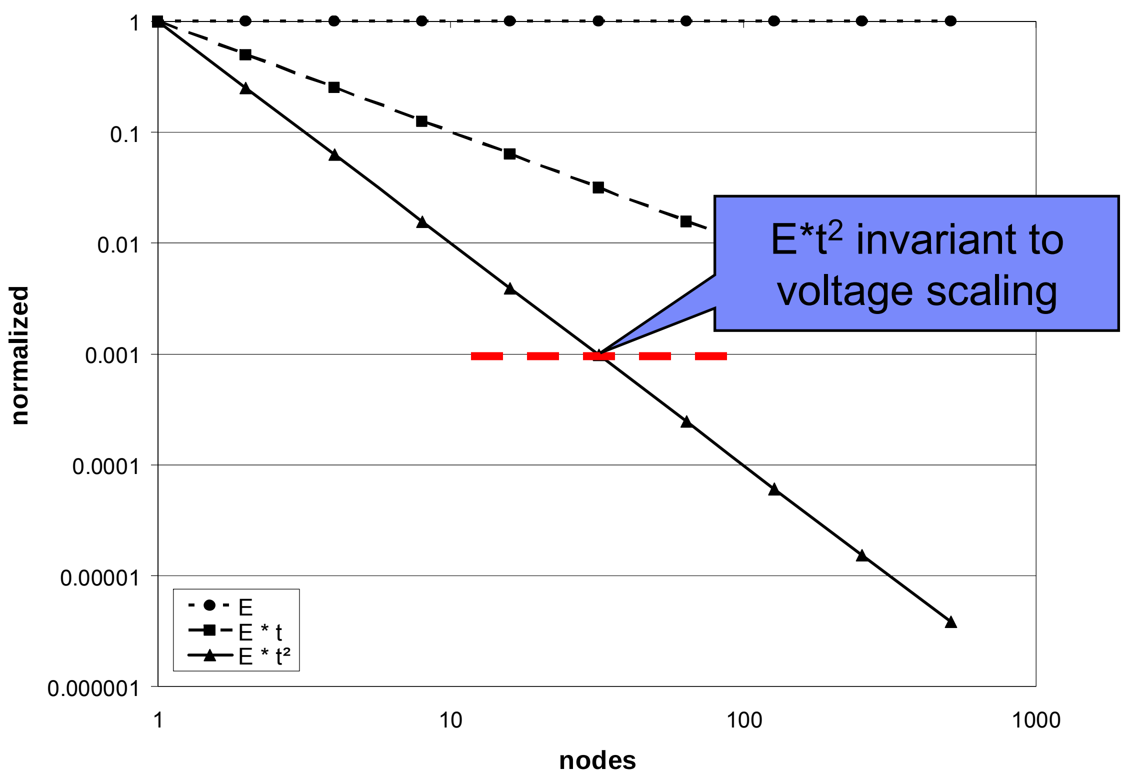
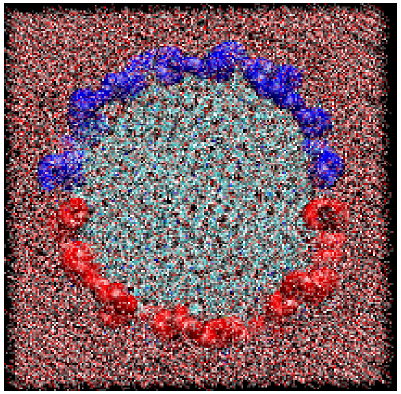


Applying Metrics to Actual Applications

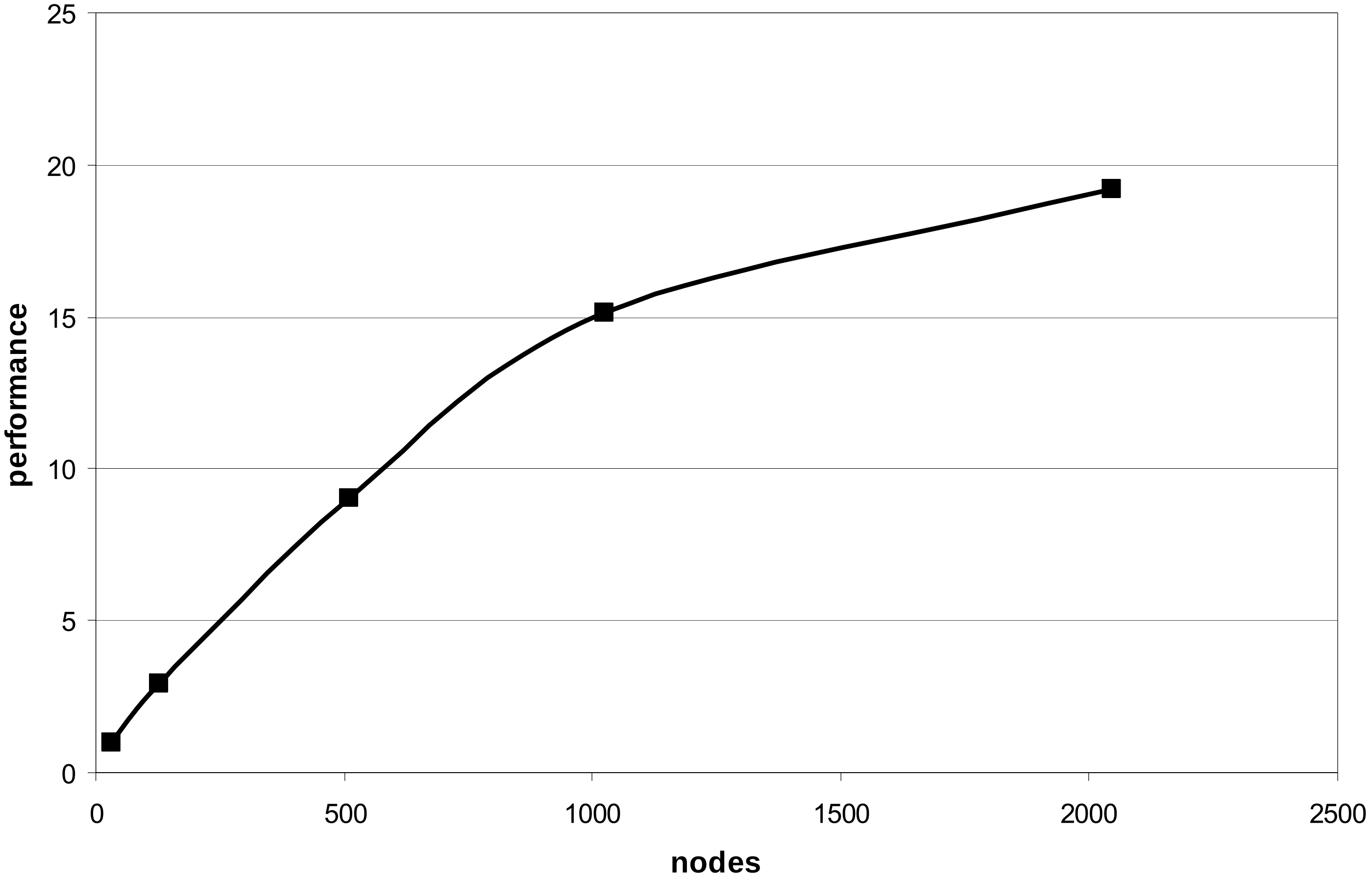
- **LINPACK highly parallel – follows 77% of peak performance**
  - Problem size matches the size of the system
  - Weak scaling
- **Many applications require constant amount of computation regardless of the size of the system**
  - Fixed sized problems
  - Strong scaling
  - More conservative performance evaluation
- **Apply metrics for several applications and problems**
  - e.g., NAMD, UMT2K

NAMD

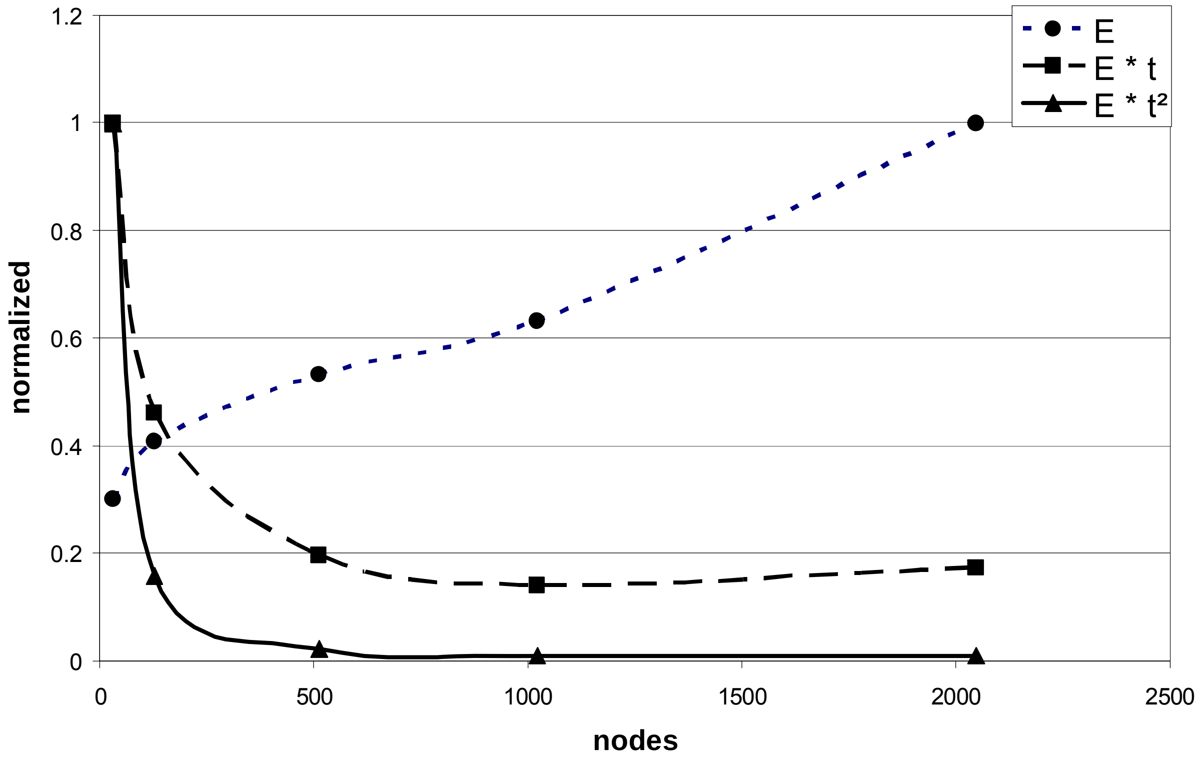
- **Parallel, object-oriented molecular dynamics code designed for high-performance simulation of large biomolecular systems**
  - Developed by the Theoretical Biophysics Group in the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign
- **Distributed free of charge with source code**
  - Based on Charm++ parallel objects
- **NAMD benchmark**
  - Box with one molecule of apoprotein A1 solvated in water
- **Fixed size problem on 92,224 atoms**



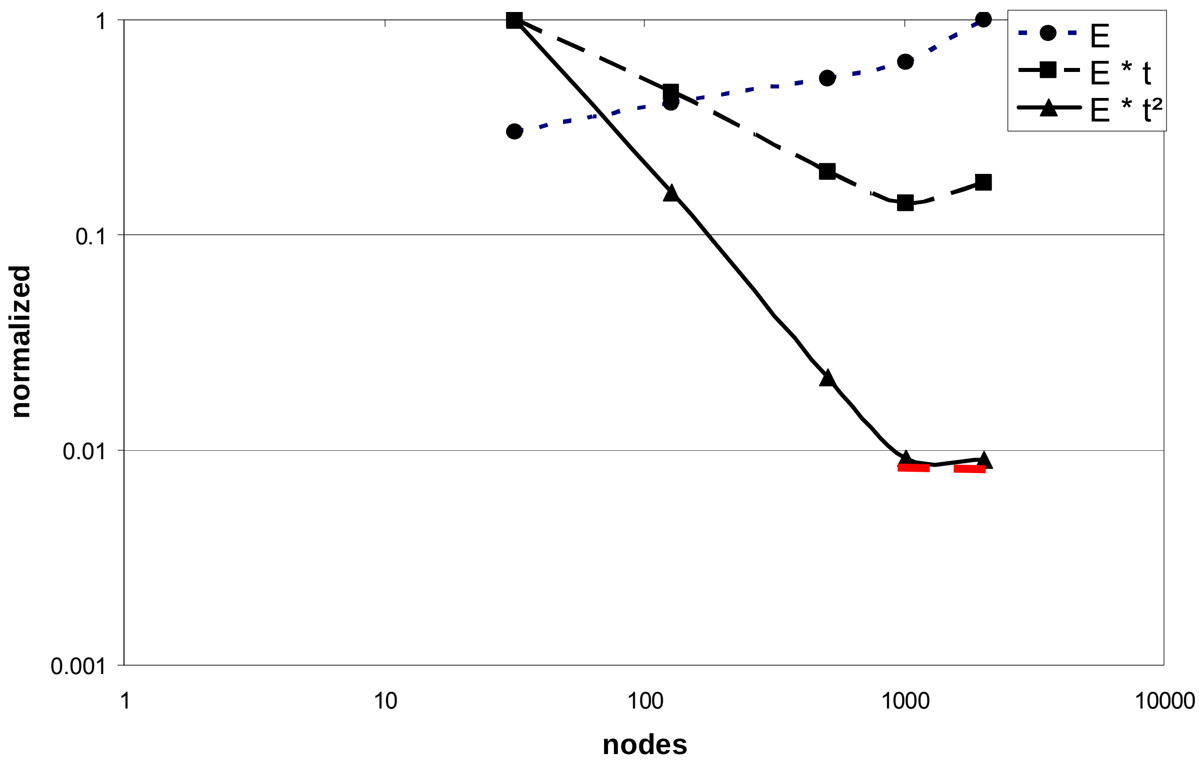
NAMD Performance Scaling



NAMD Power and Power Performance

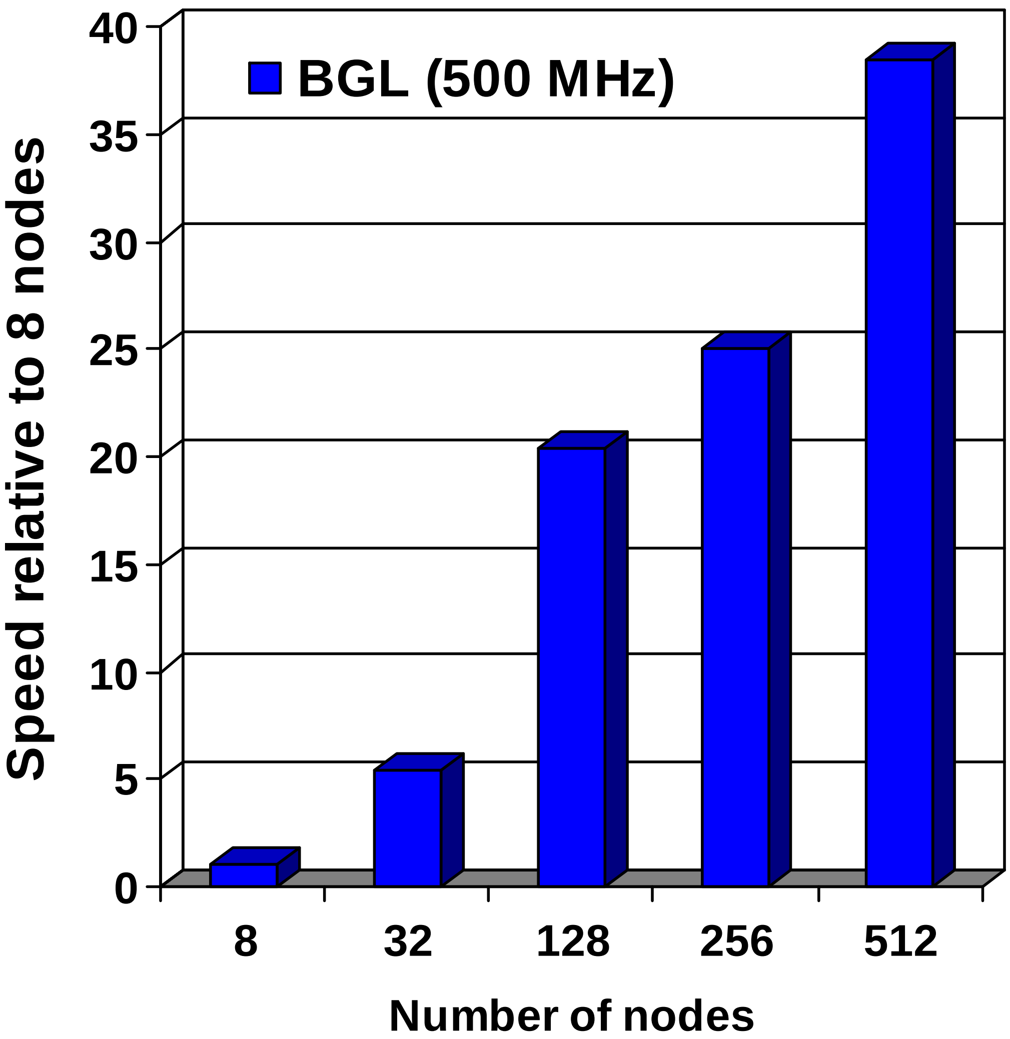


NAMD Power and Power Performance on log-log

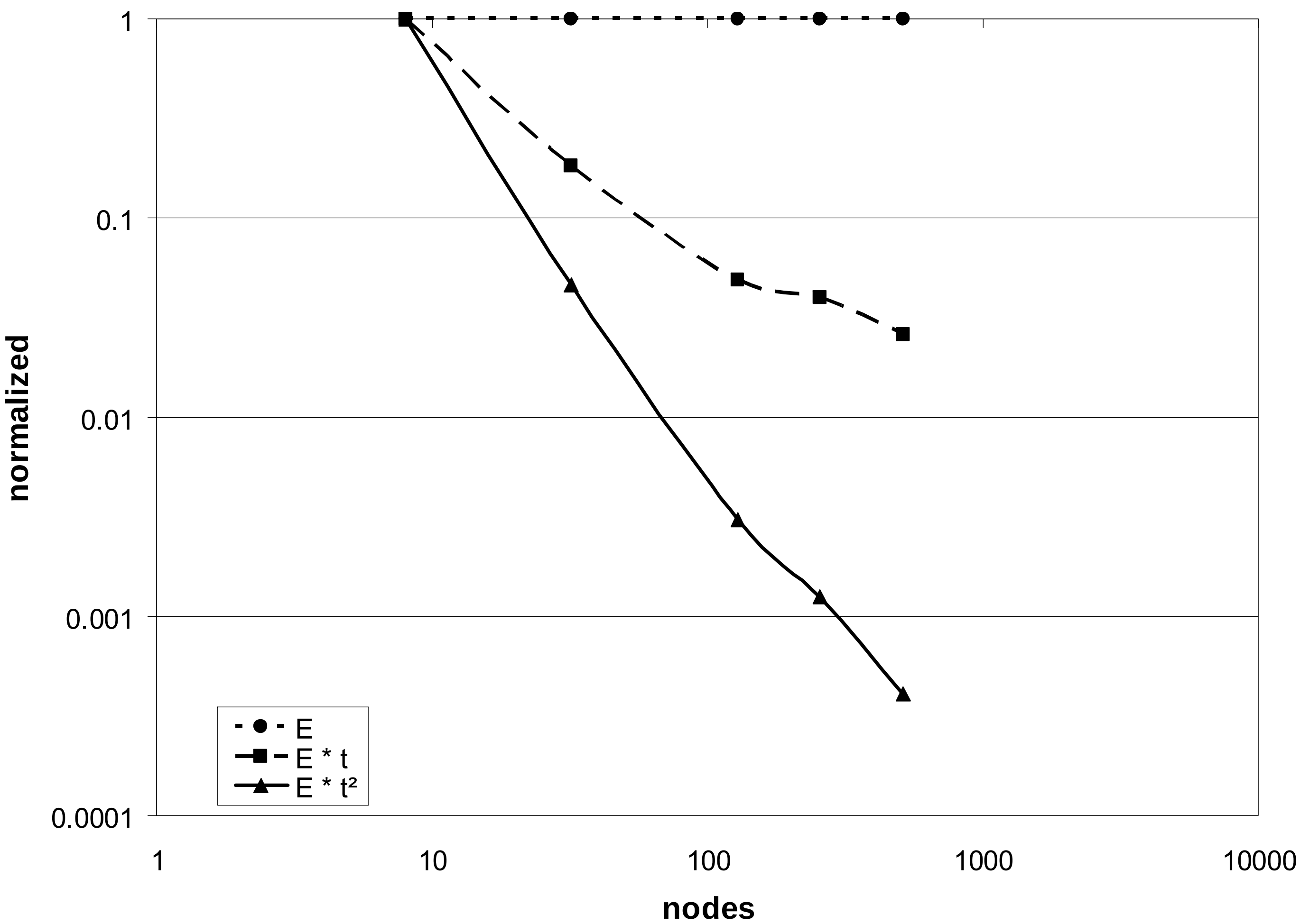


ASCI Purple Benchmarks – UMT2K

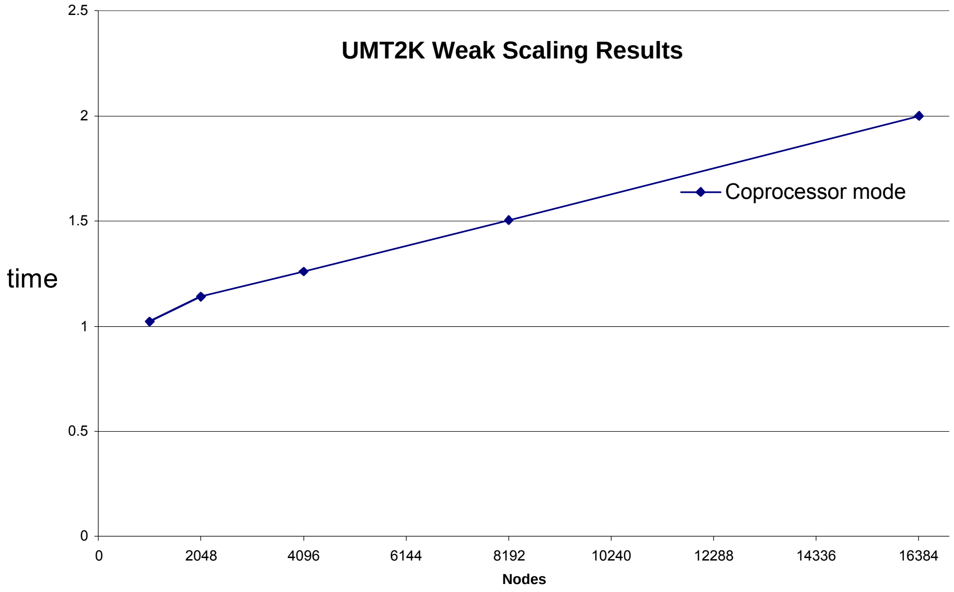
- **UMT2K – Unstructured mesh radiation transport**
- **Problem size fixed**
- **Excellent scalability up to mid-sized configurations**
  - Load balancing problems when scaling to 2000 or more nodes
  - Needed algorithmic changes in original program
  - Tuned UMT2K version scales well beyond 8000 BlueGene/L nodes

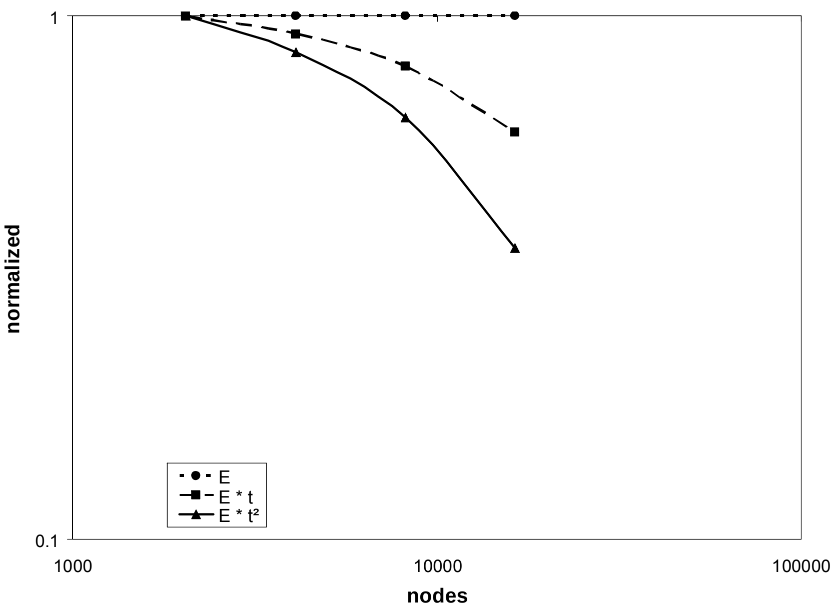


UMT2K Power and Power Performance



Recent UMT2K Runs Demonstrate Good Performance



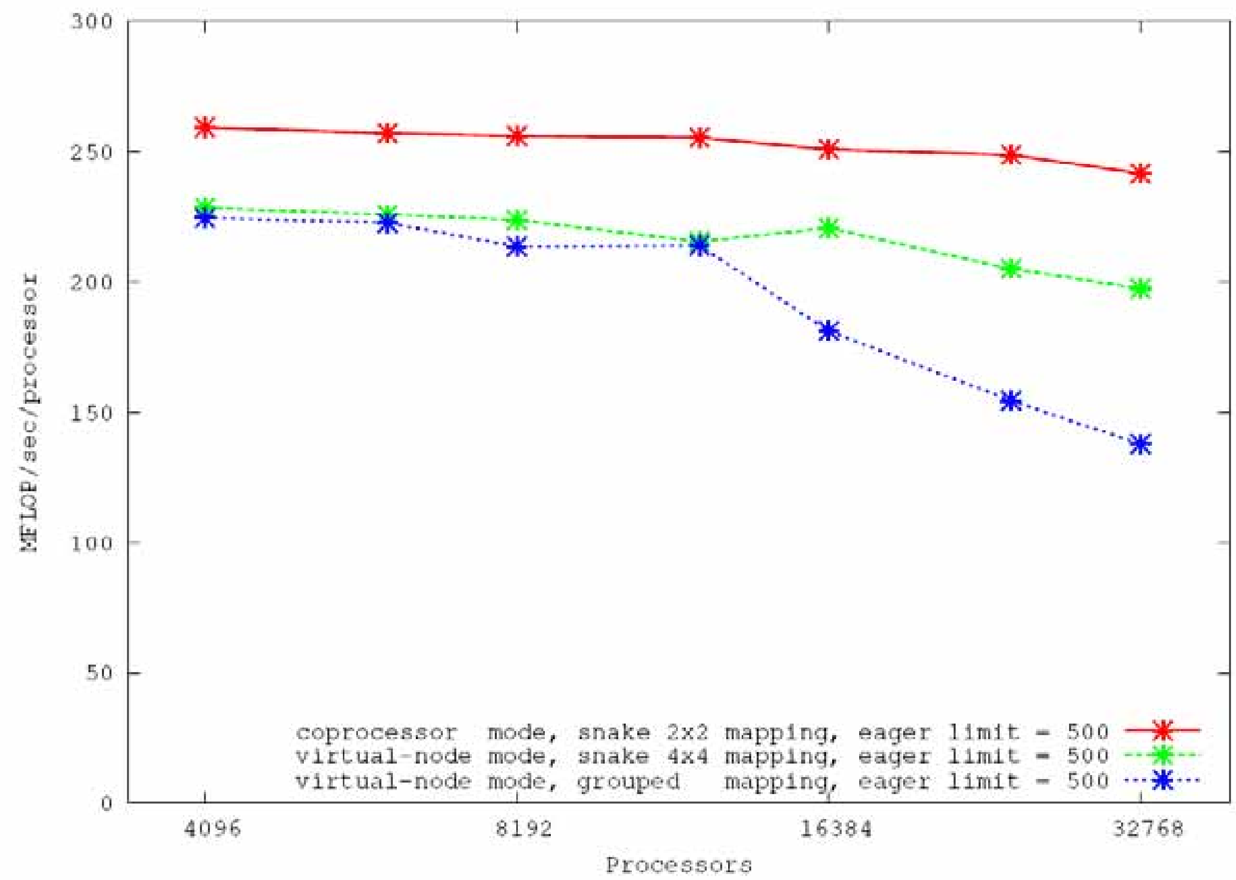


Nearest neighbor communication consistent
Load balance unchanged from 1K to 8K

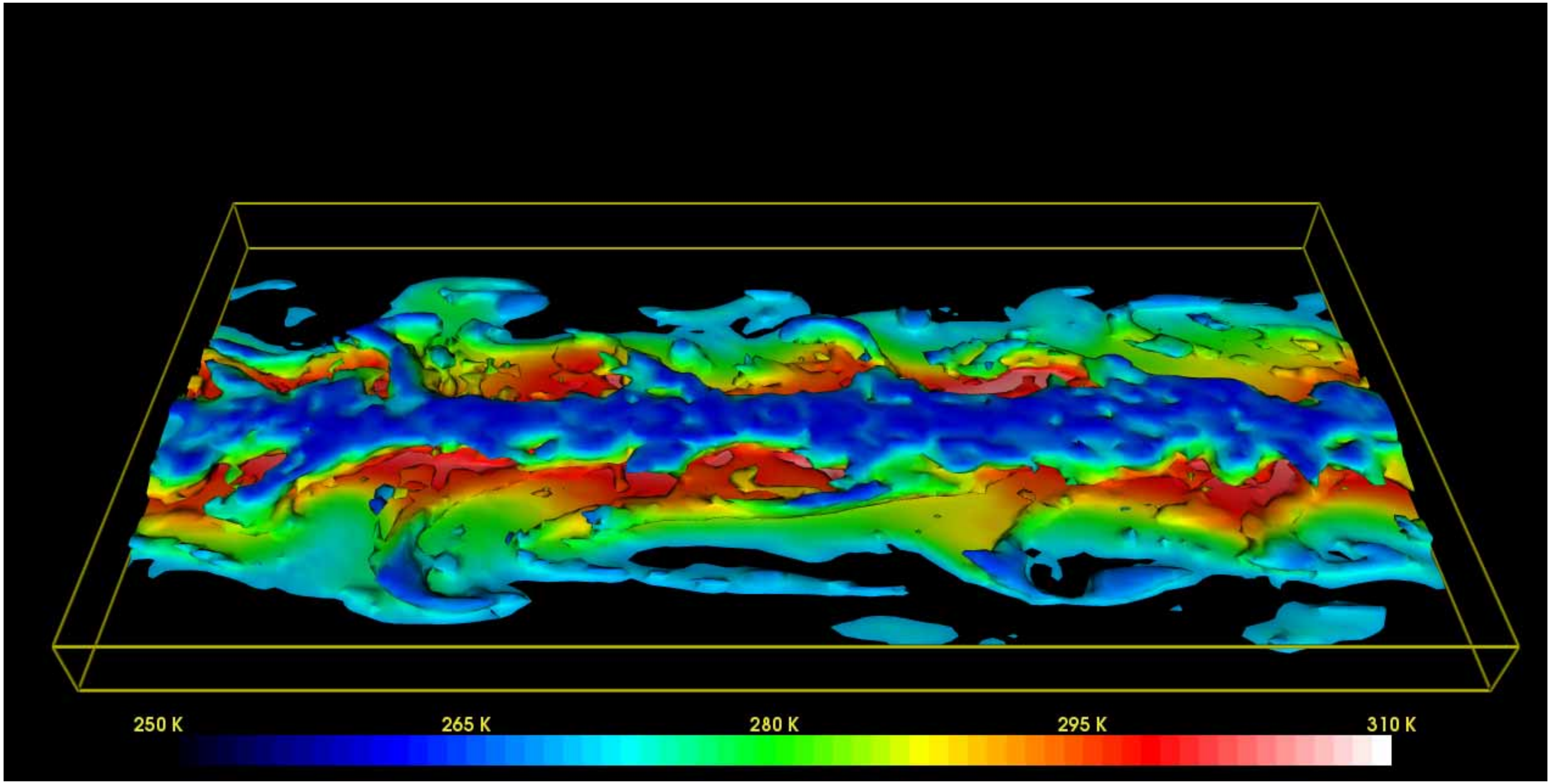
HOMME

- **National Center for Atmospheric Research**
  - Cooperation NCAR, Boulder and IBM
- **Moist Held-Suarez test**
  - Atmospheric moist processes fundamental component of atmospheric dynamics
    - Most uncertain aspect of climate change research
  - Moisture injected into the system at a constant rate from the surface
- **Importance of problem**
  - Moist processes must be included for relevant weather model
    - Formation of clouds and the development and fallout of precipitation
  - Requires high horizontal and vertical resolution
    - Order of 1 kilometer
  - Key to a better scientific understanding of global climate change

HOMME – Strong Scaling



HOMME – Visualization



BlueGene/L-Tuned Applications

- **Amber7**: Classical molecular dynamics used by AIST and IBM Blue Matter.
- **Blue Matter**: (IBM: Robert Germain et al) Classical molecular dynamics for protein folding and lipids.
- **CPMD**: (Car-Parrinello (ab initio) quantum molecular dynamics by IBM) Strong scaling of SiC 216 atoms & 1000 atoms.
- **ddcMD**: (LLNL: Classical molecular dynamics; Fred Streitz, Jim Glosli, Mehul Patel)
- **Enzo:** (UC San Diego) simulation of galaxies, has performance problem on every platform.
- **Flash**: (University of Chicago & Argonne) Collapse of stellar core and envelope explosion. Supernova simulation.
- **GAMESS**: Quantum Chemistry
- **HOMME**: (NCAR, Richard Loft) Climate code, 2d model of cloud physics.
- **HPCMW** (RIST): Solver for finite elements
- **LJ** (Caltech): Lennard Jones molecular dynamics
- **LSMS**: (Oak Ridge National Lab: Thomas Schulthess and Mark Fahey) First principles Material Science.
- **MDCASK**: (LLNL: Classical molecular dynamics; Alison Kutoba, Tom Spelce)
- **Miranda** (LLNL: instability/turbulence; Andy Cook, Bill Cabot, Peter Williams, Jeff Hagelberg)
- **MM5** from NCAR: meso-scale weather prediction
- **NAMD**: Molecular Dynamics
- **NIWS** (Nissei): Financial/Insurance Portfolio Simulation
- **PAM-CRASH**: (ESI) Automobile crash simulation.
- **ParaDis**: (LLNL: dislocation dynamics;Vasily Bulatov, Gregg Hommes)
- **Polycrystal**: (Caltech) material science
- **Qbox**: Quantum Chemistry, ab initio quantum molecular dynamical calculation.
- **Quarks** (Boston University, Joe Howard)
- **Raptor** (LLNL: instability/turbulence; Jeff Greenough, Charles Rendleman)
- **QCD**: (IBM Pavlos Vranas) sustained 1 TF/s on one rack. 19% uni efficiency.
- **QMC**: (Caltech) Quantum Chemistry
- **SAGE**: (LANL: SAIC's Adaptive Grid Eulerian Code) AMR hydrodynamics. Heat and radiation transport with AMR.
- **SPHOT**: (LLNL) 2D photon transport
- **SPPM**: **S**implified **P**iecewise **P**arabolic Method. 3-D gas dynamics on a uniform Cartesian grid.
- **Sweep3d**: (LANL) 3-d neutron transport
- **TBLE**: magnetohydrodynamics
- **UMT2K**: (LLNL) photon transport 3d Boltzmann on unstructured grid

BlueGene/L Performance and Density

Performance Metric	Single Rack Blue Gene
Peak Teraflops (Virtual Node mode)	5.73
Peak Teraflops **(**Coprocessor mode)	2.86
Linpack Teraflops	4.53

Metric	ASCI White	ASCI Q	Earth Simulator	BG/L
Memory/Space (GB/m^2)	8.6	17	3.1	***140***
Speed/Space ($GFlops/m^2$)	13	16	13	***1600***
Speed/Power (GFlops/kW)	12	7.9	4	***300***

BlueGene/L - Paradigm Shift for Supercomputers

- **Aggregate performance is important**
  - Not performance of individual chip
- **Simple building block**
  - High integration on a single chip
    - Processors, memory, interconnect subsystems
  - Low power → allows high density packaging
  - Cost-effective solution

→ As a result, breakthrough in compute power
  - Per Watt
  - Per square meter of floor space
  - Per dollar

→ BlueGene/L enables
  - New unparalleled application performance
  - Breakthroughs in science by providing unprecedented compute power

BlueGene/L on the Web

www.research.ibm.com/bluegene

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System Features		BG/L
Node Properties	Node Processors	2 × PowerPC440
	Processor Frequency	700MHz
	L1 Cache (private) I+D	32+32KB/processor
	L2 Cache (private)	14 (7) stream prefetching
	L3 Cache size (shared)	4MB
	Main Store	256MB/512MB/1GB
	Main Store Bandwidth	5.6GB/s
	Peak Performance	5.6GF/node
Torus Network	Bandwidth (per node)	6*2*175MB/s=2.1GB/s
	Hardware Latency (Nearest Neighbor)	200ns (32B packet) 1.6µs (256B packet)
	Hardware Latency (Worst Case)	6.4µs (64 hops)
Collective Network	Bandwidth (per node)	3*2*350MB/s=2.1GB/s
	Hardware Latency (round trip worst case)	5.0µs

BlueGene/L at a Glance

Attribute	Details	Benefits
Processor	PowerPC 440 700MHz; two per node	Low power allows dense packaging; better processor-memory balance
Memory	512 MB SDRAM-DDR per node	
Networks	3D Torus - 175MB/sec in each direction Collective Network – 350MB/sec; 1.5 usec latency Global Barrier/Interrupt Gigabit Ethernet (machine control and outside connectivity)	Special networks speed up internode communications; designed for MPI programming constructs; improve systems management
Compute Nodes	Dual processor; 1024 per rack	Double FPU improves performance
I/O Nodes	Dual processor; 16 per rack (additional nodes optional)	Strengthens systems management
Operating Systems	Compute Node – Lightweight proprietary kernel I/O Node – Embedded Linux Front End and Service Nodes – SuSE SLES 9 Linux	Kernel tailored to processor design; industry-standard distribution preserves familiarity to end user
Performance	Peak per rack (virtual node mode) – 5.73 teraflops Peak per rack (coprocessor mode) – 2.86 teraflops Linpack per rack – 4.53 teraflops	Highest available performance benefits capability customers
Power	28.14 kW power consumption per rack (maximum) 208 VAC 3-phase; 100 amp service per rack	Low power draw enables dense packaging
Cooling	Air conditioning 8 tons/rack (minimum) 2800 CFM (compute rack); 350 CFM (power supplies)	Low cooling requirements enable extreme scale-up
Acoustics	9.0 LwAD and 8.7 LwAm	
Dimensions (includes air duct)	Height – 1958 mm Width – 915 mm Depth – 915 mm Weight – 750 Kg	Design allows "brickwall" layout for better floor space utilization