



Power and Performance Optimization at the System Level

Valentina Salapura
IBM T.J. Watson Research Center

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)

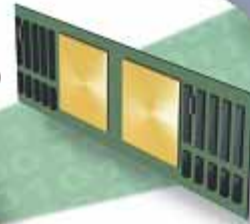
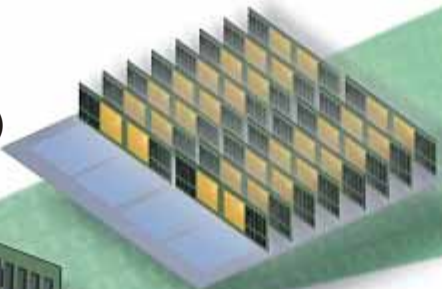
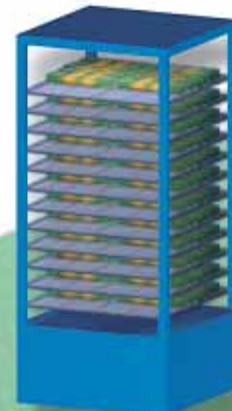
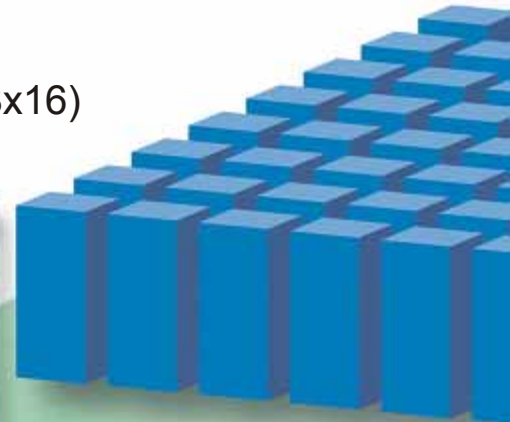
2.8/5.6 GFLOPS
per processor/chip 4 MB

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

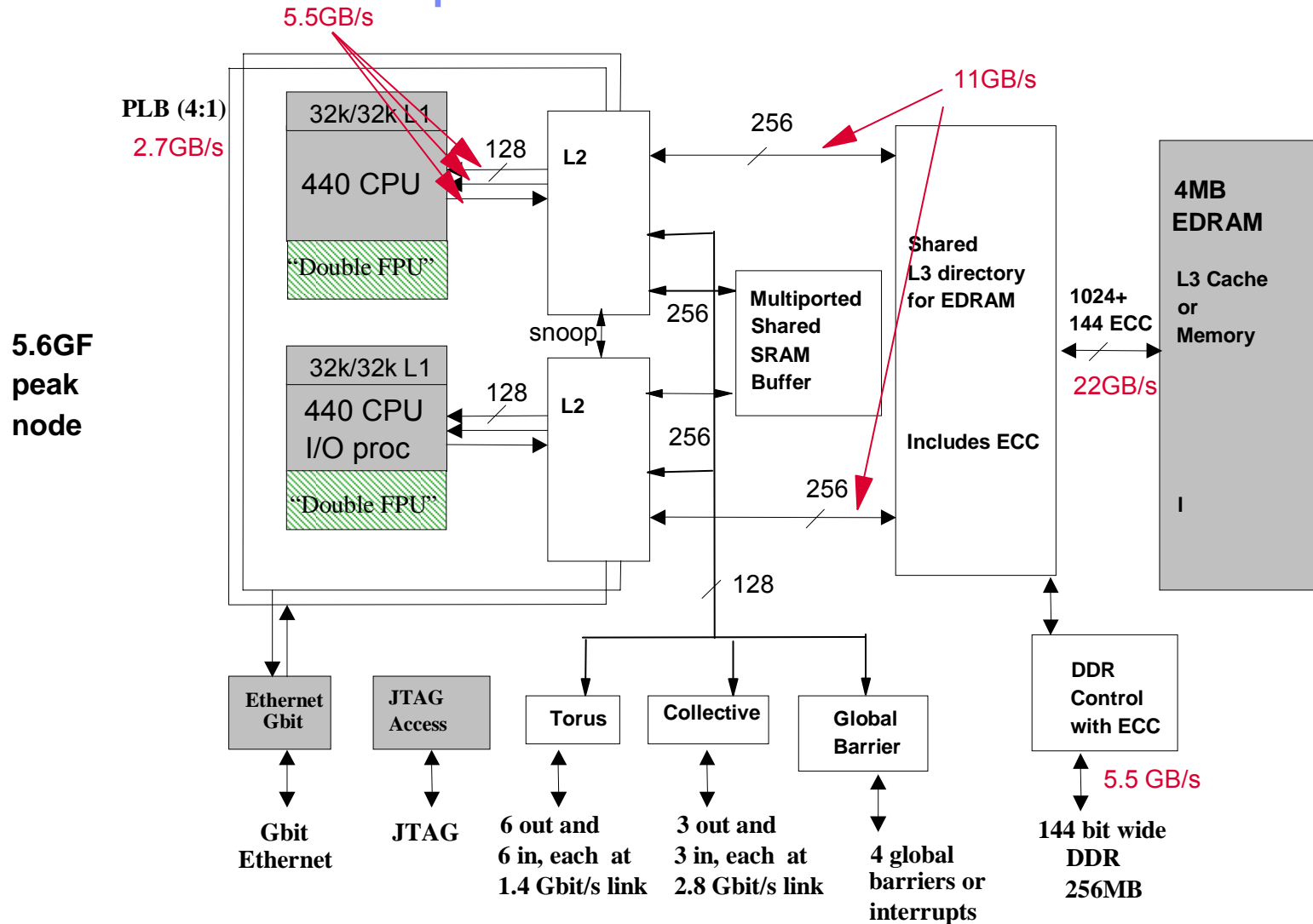


BlueGene/L Architecture



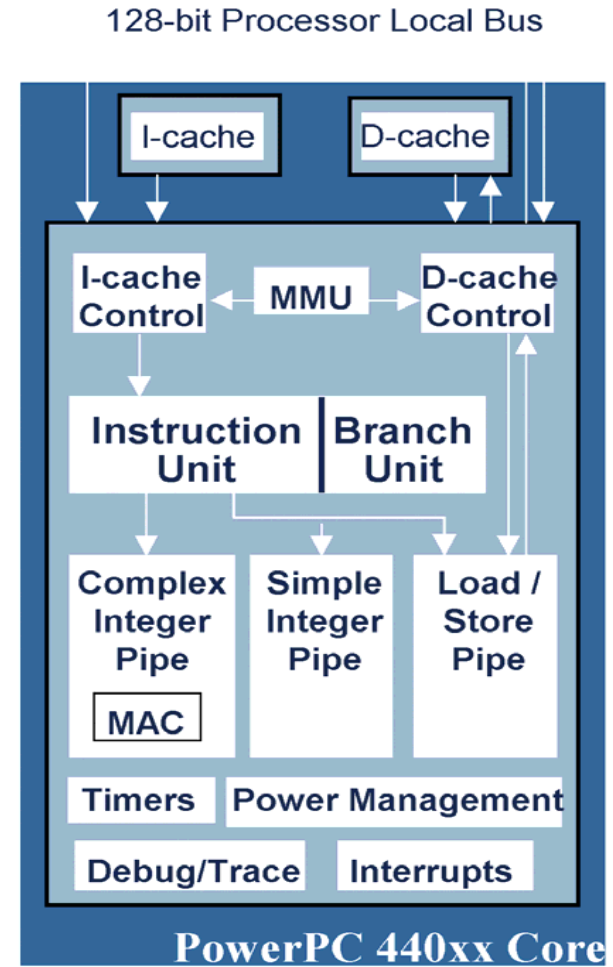
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BlueGene/L Compute SoC ASIC

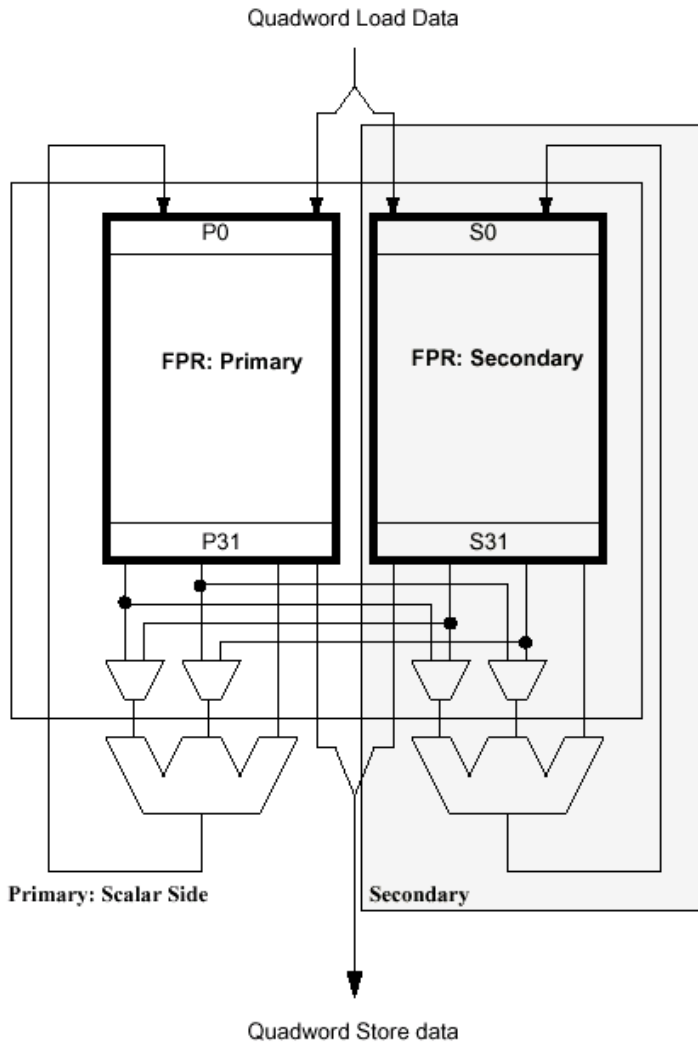


PowerPC 440 Processor Core Features

- 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
 - f* 32KB instruction & 32KB data cache
 - f* 64-way set associative, 32 byte line
- 36-bit physical address
- 128-bit CoreConnect PLB Interface



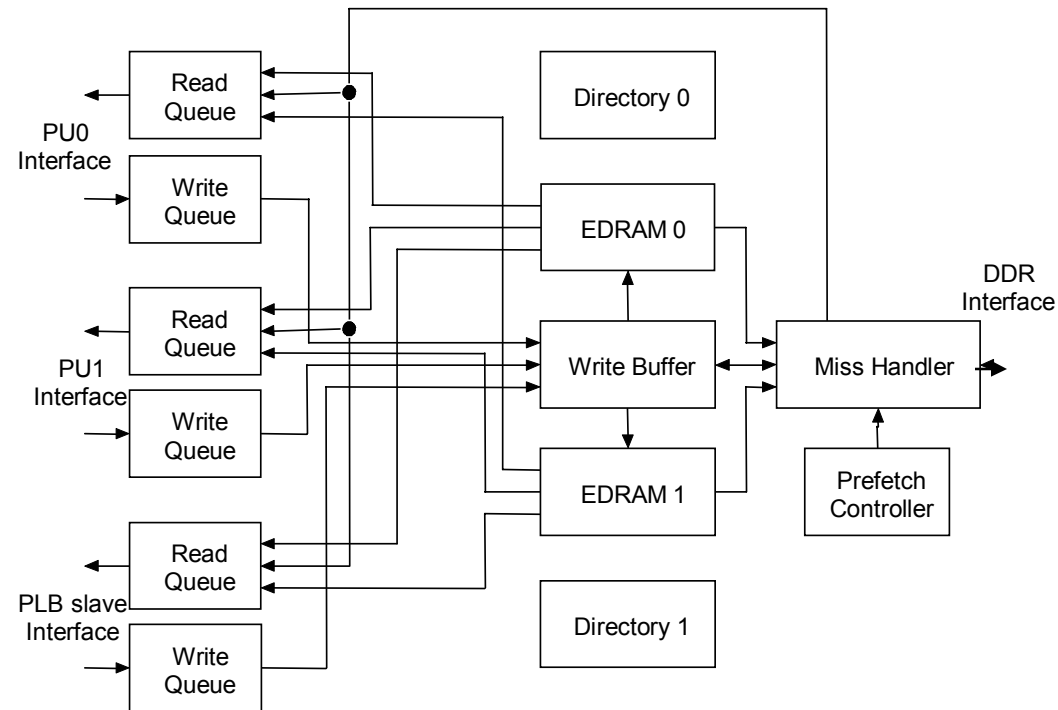
Double Hummer Floating-Point Unit



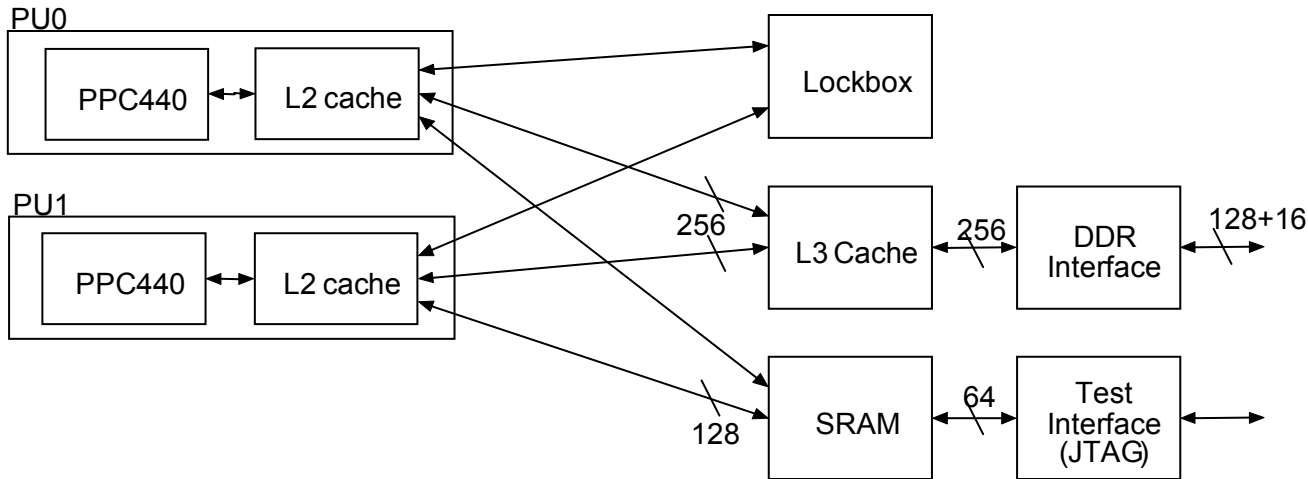
- **Two replicas of a standard single-pipe PowerPC FPU**
 - 2 x 32 64-bit registers
- **Enhanced ISA, includes instructions**
 - Executed in either pipe
 - Simultaneously execute the same operation on both sides – SIMD instructions
 - Simultaneously execute two different operations of limited types on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



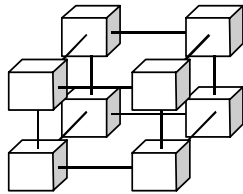
Memory Hierarchy



- **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**

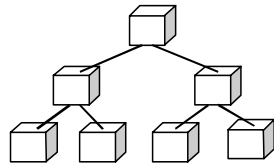
Memory Type	Latency (cycles)
L1 cache	3
L2 cache	11
L3 cache	28/36/40
Main memory	86

BlueGene/L Five Independent Networks



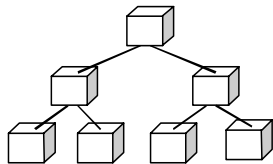
3 Dimensional Torus

- Point-to-point



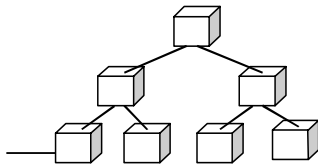
Collective Network

- Global Operations



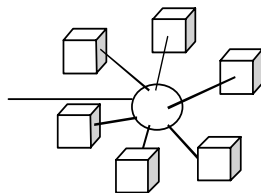
Global Barriers and Interrupts

- Low Latency Barriers and Interrupts



Gbit Ethernet

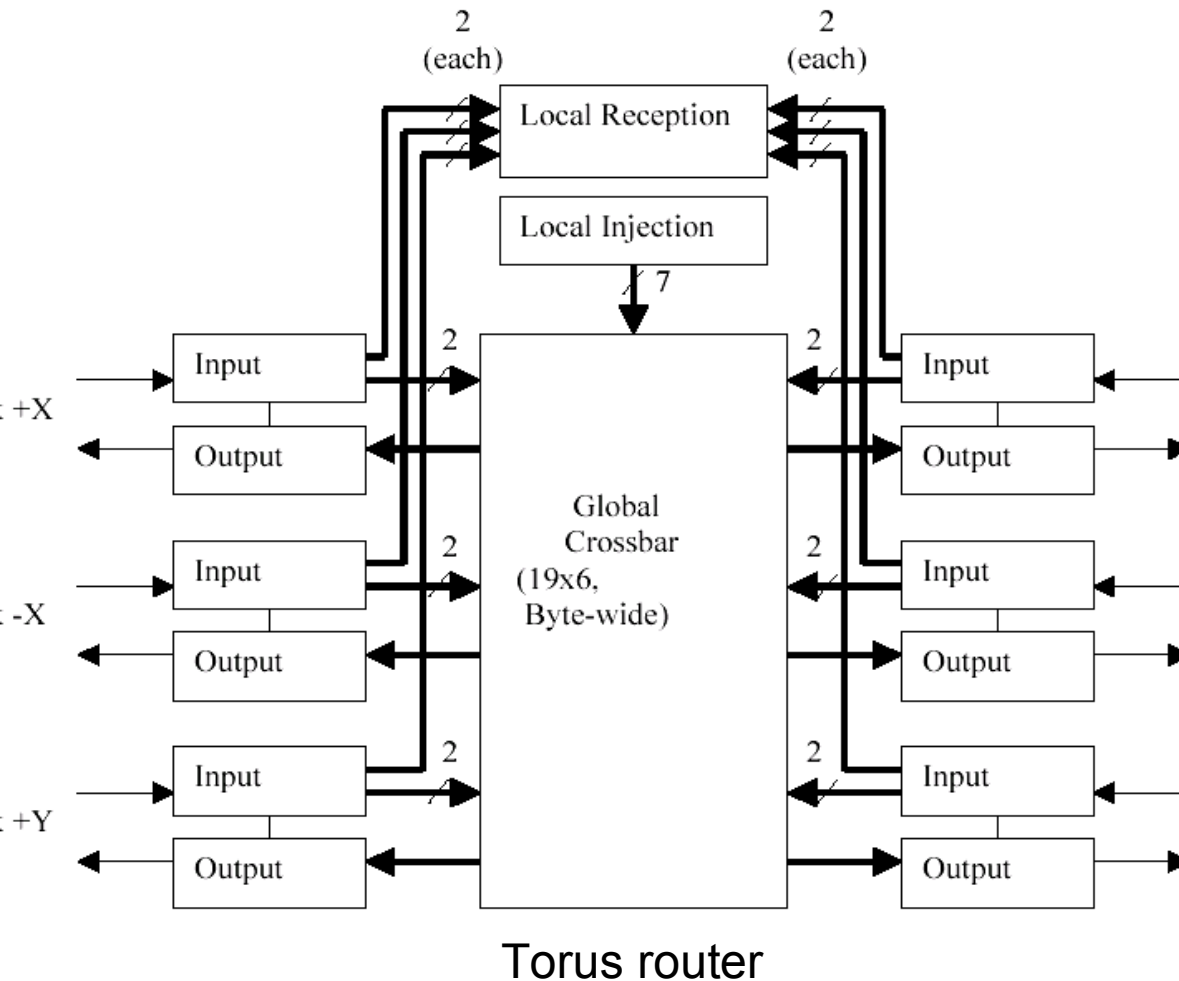
- File I/O and Host Interface



Control Network

- Boot, Monitoring and Diagnostics

Three-Dimensional Torus Network



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

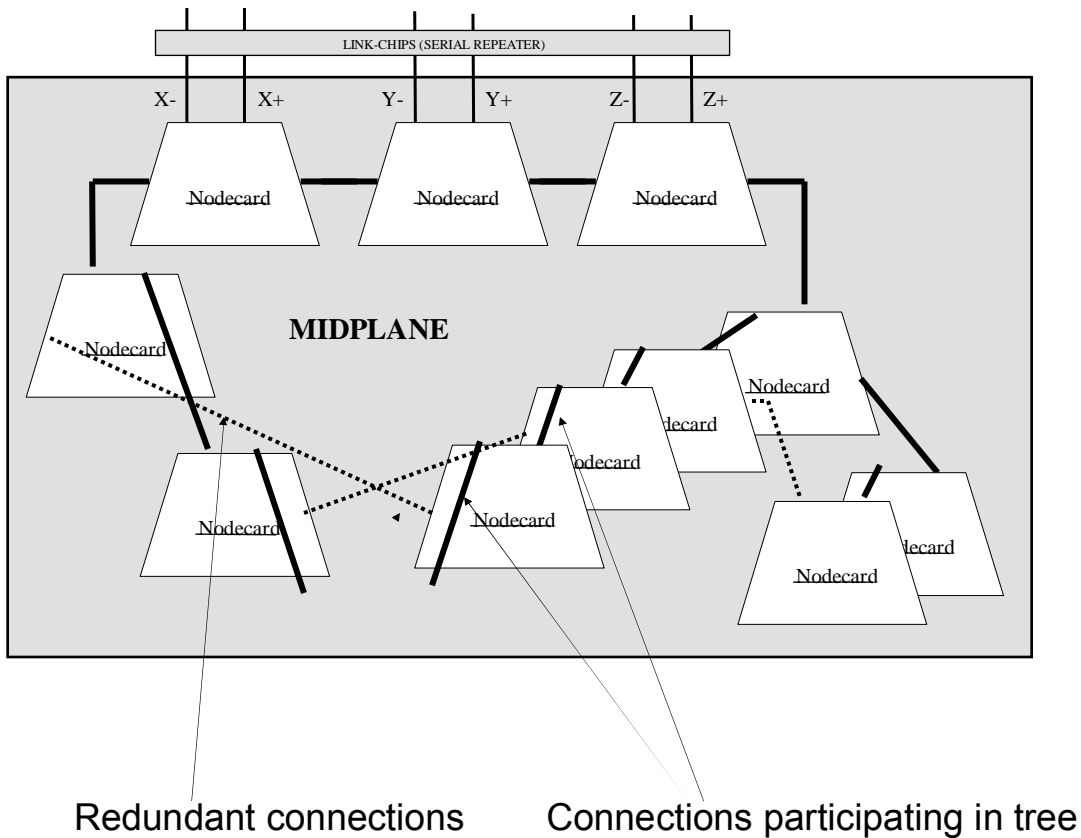
- 32–256 bytes, 4-byte trailer

Per-hop latency ~100 ns (avg.)

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

- 6.4 μ s (64 hops)

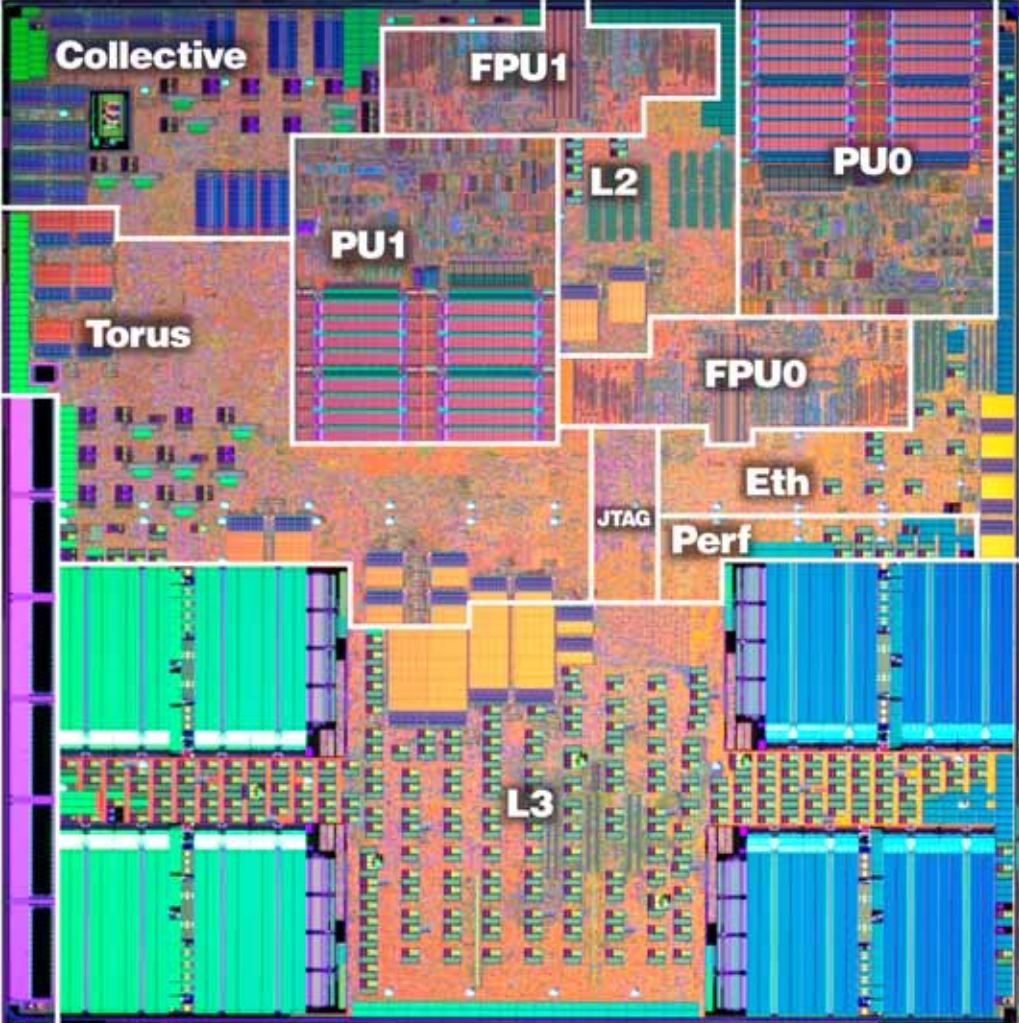
Collective Network



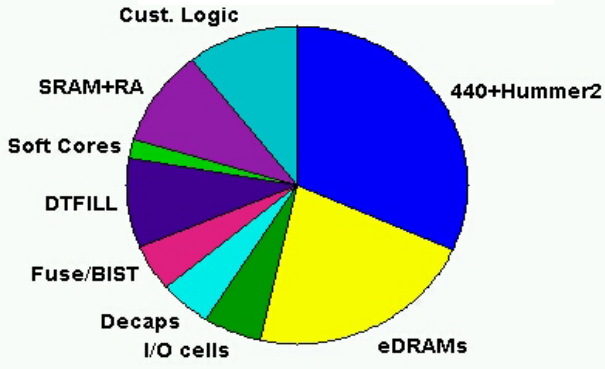
- **Global reduction support**
- **Bidirectional 3 links per node**
- **Per node bandwidth 2.1 GB/s**
- **Worst case latency (round trip) 5.0 μ s**
- **Efficient for collective communication**
 - For broadcast messages
 - Arithmetic reductions implemented in hardware
- **Fault-tolerant for tree topologies**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

BlueGene/L Chip Design Characteristics

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

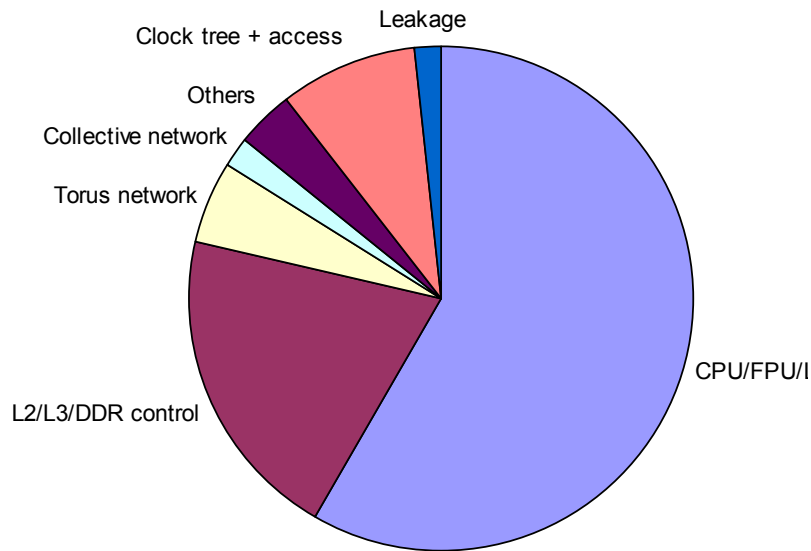


Chip Area usage

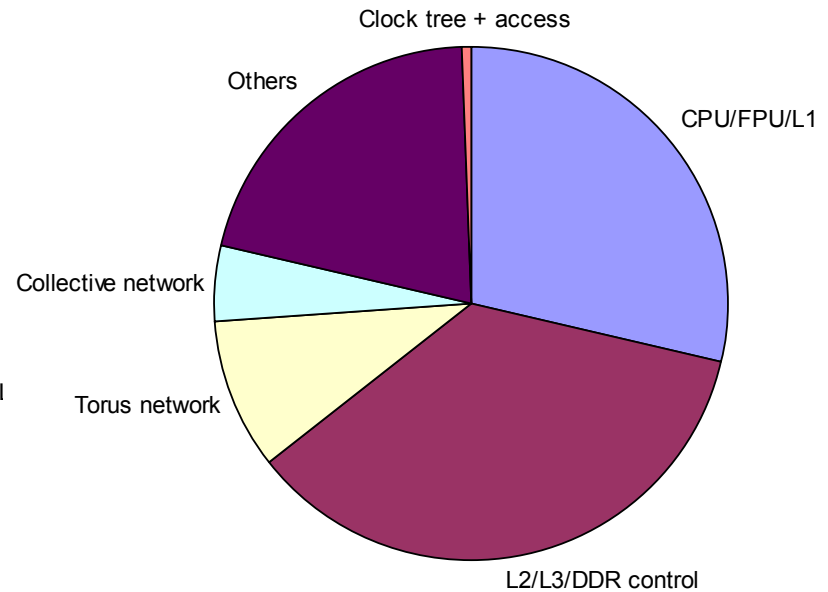


BlueGene/L Compute Chip Power and Area

Power



Area





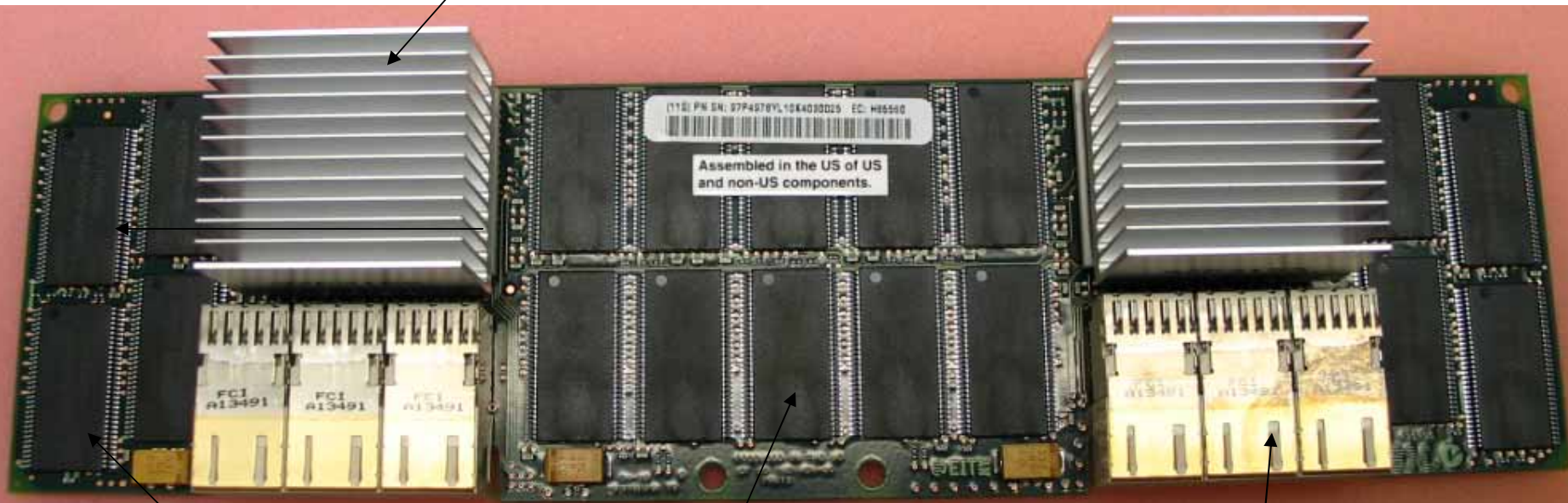
BlueGene/L System Package

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Dual Node Compute Card

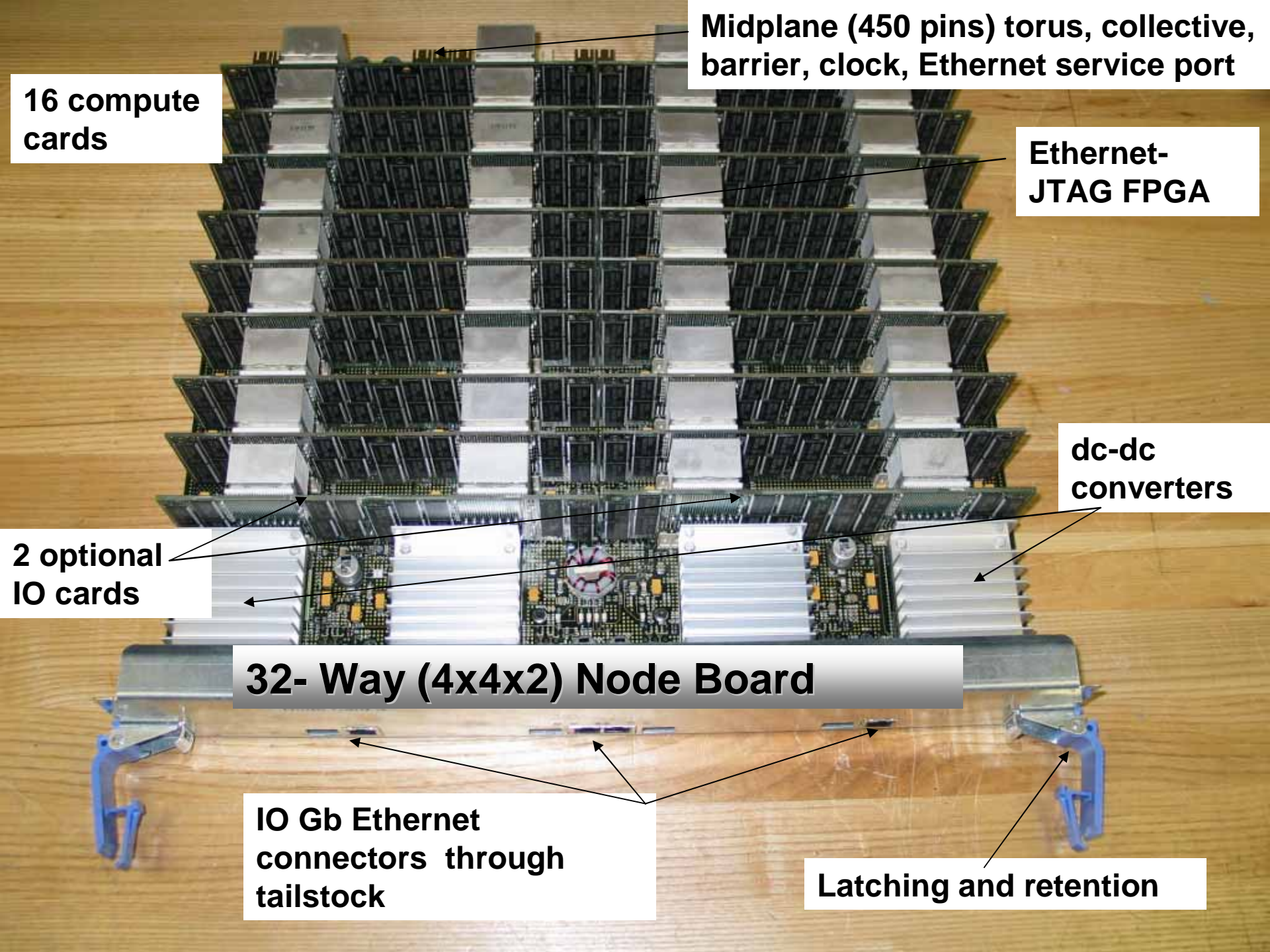
206 mm (8.125") wide, 54mm high (2.125"), 14 layers, single sided, ground referenced

Heatsinks designed for 15W



9 x 512 Mb DRAM

Metral 4000 high speed differential connector (180 pins)



16 compute cards

Midplane (450 pins) torus, collective, barrier, clock, Ethernet service port

Ethernet-JTAG FPGA

dc-dc converters

2 optional IO cards

32- Way (4x4x2) Node Board

IO Gb Ethernet connectors through tailstock

Latching and retention

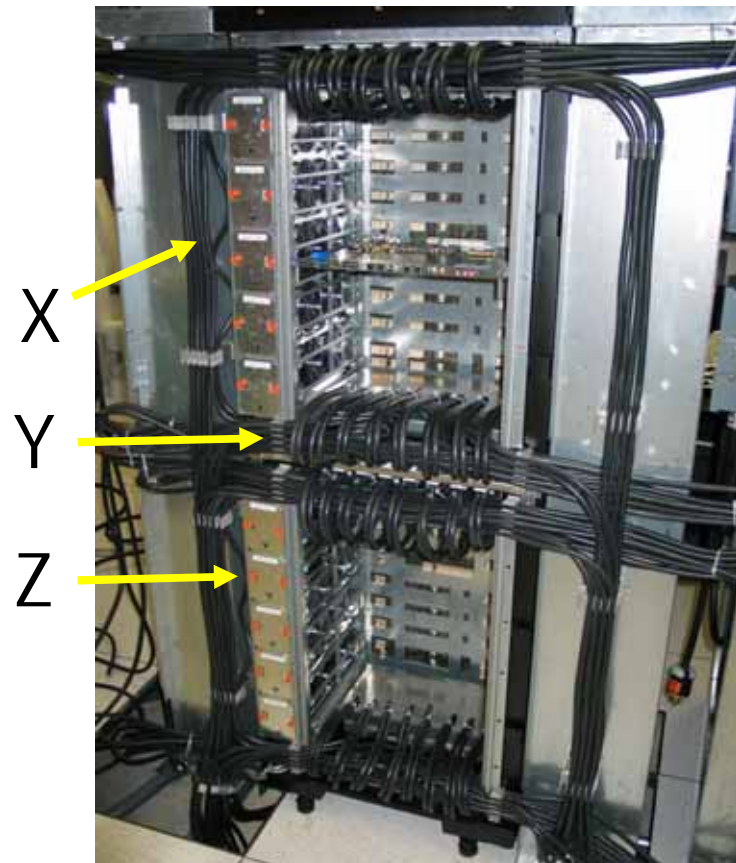
BlueGene/L Rack



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

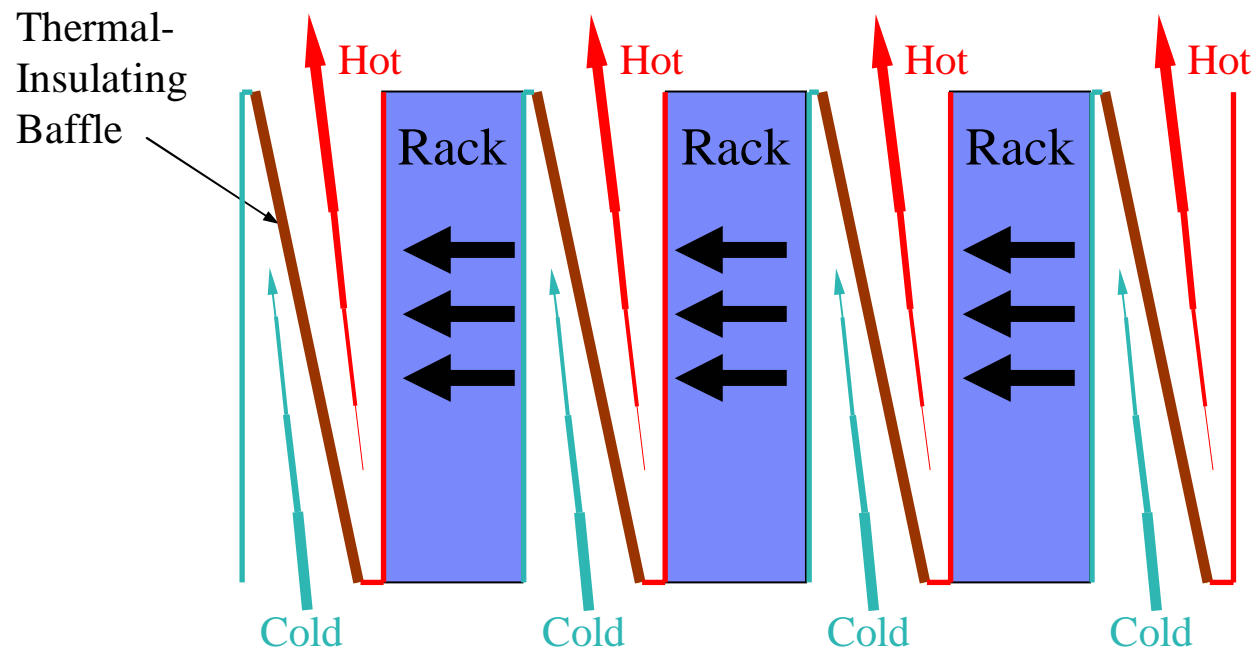
16 node boards

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



Two midplanes interconnected
with data cables

BlueGene/L Rack Ducting Scheme



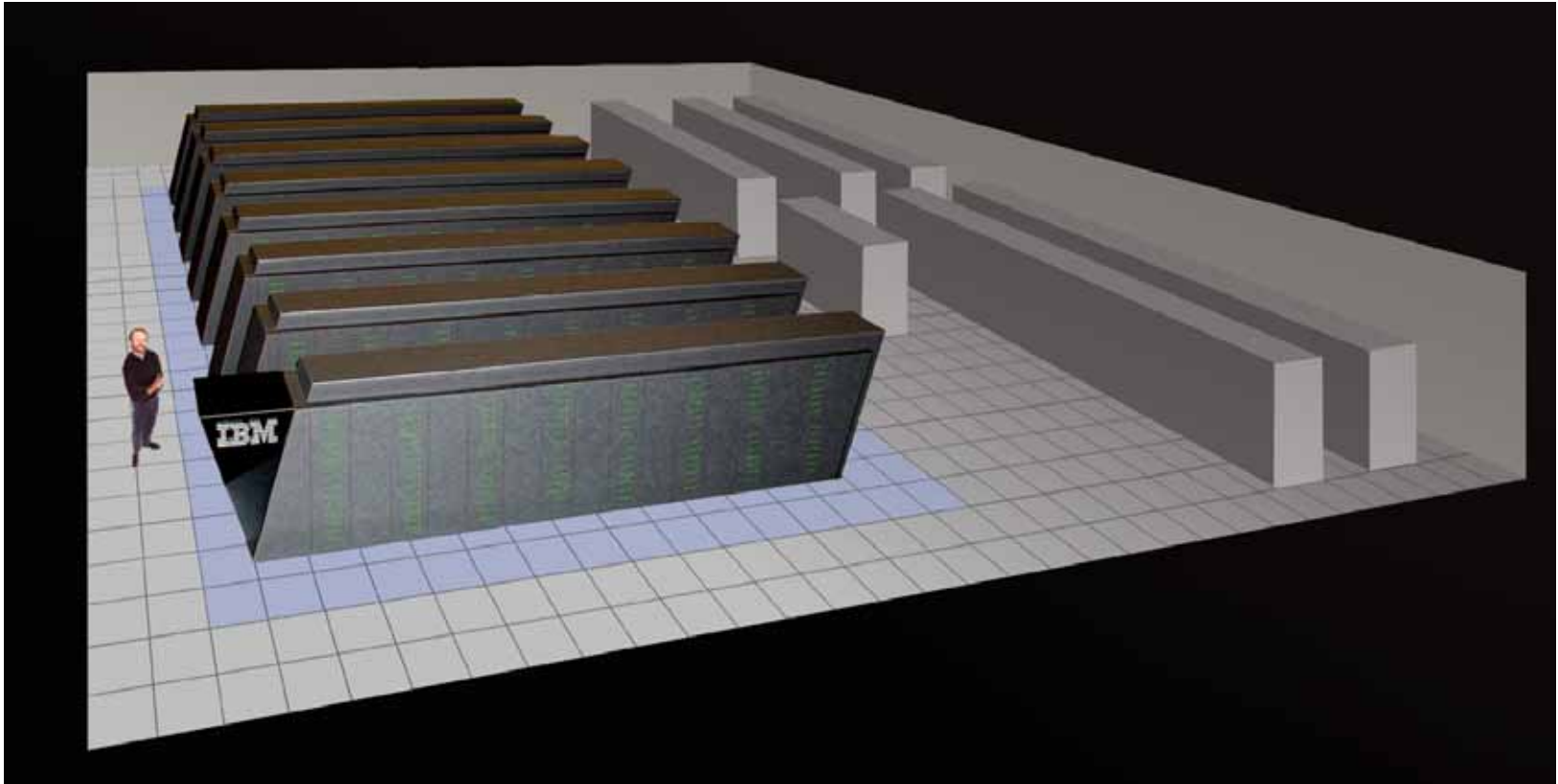
Airflow direct from raised floor

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

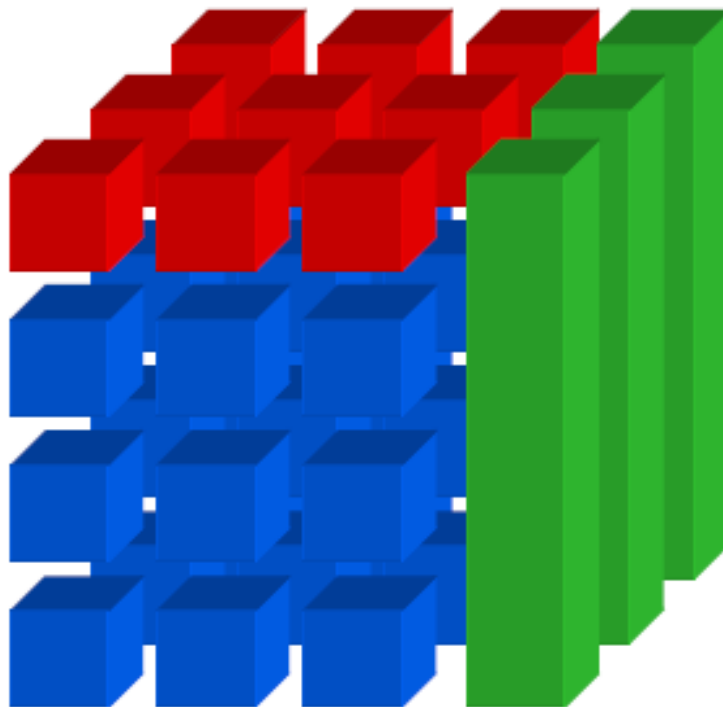
BlueGene/L System Software Main Characteristics

- **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

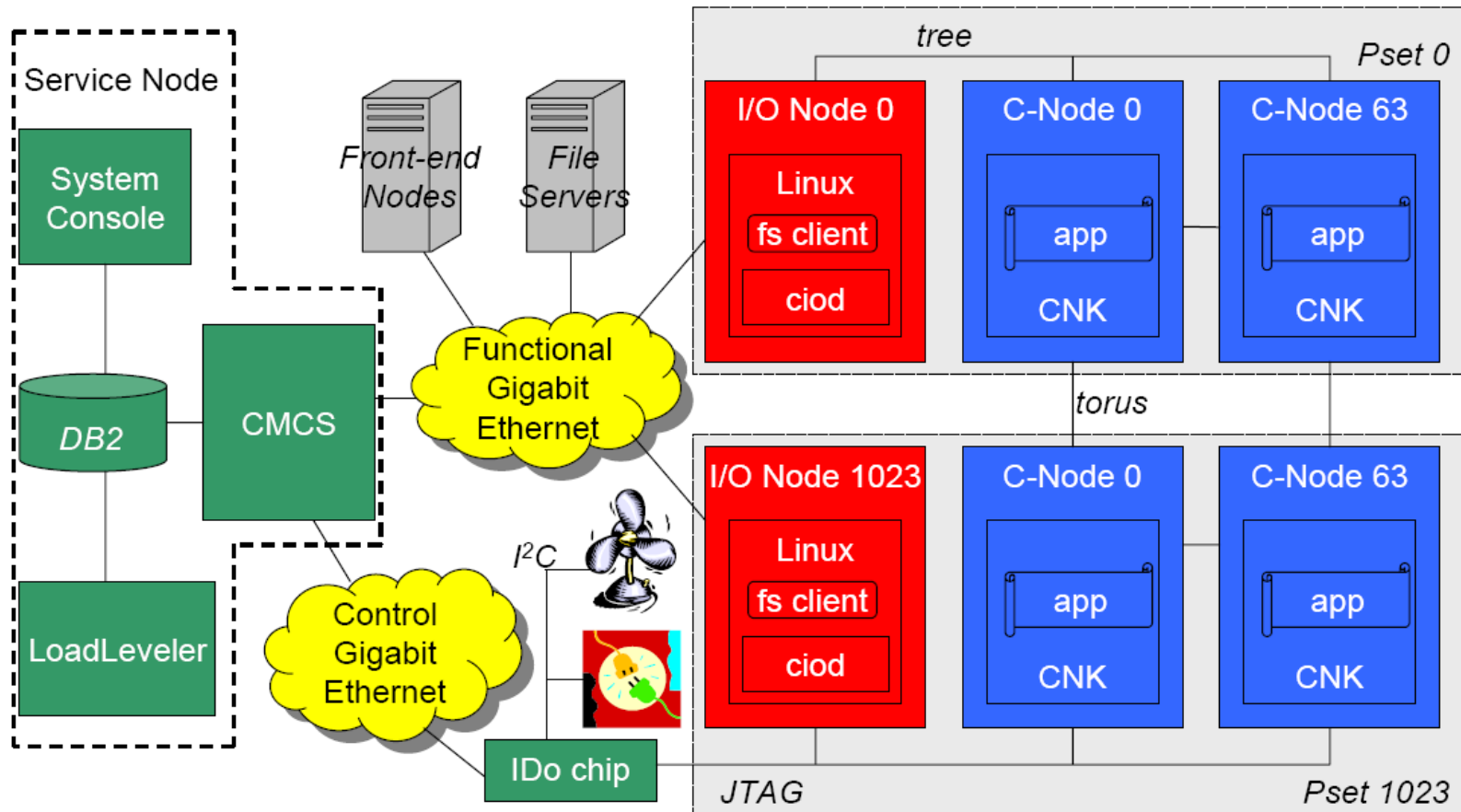
- **blrts operating system**
 - Linux compatible minimalist kernel
 - Single user single program operation
 - Minimal operating system interference
- **Virtual memory constrained to physical memory size**
 - Implies no demand paging
- **Torus memory mapped in the user address space**
 - no operating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

BlueGene/L System Software Architecture



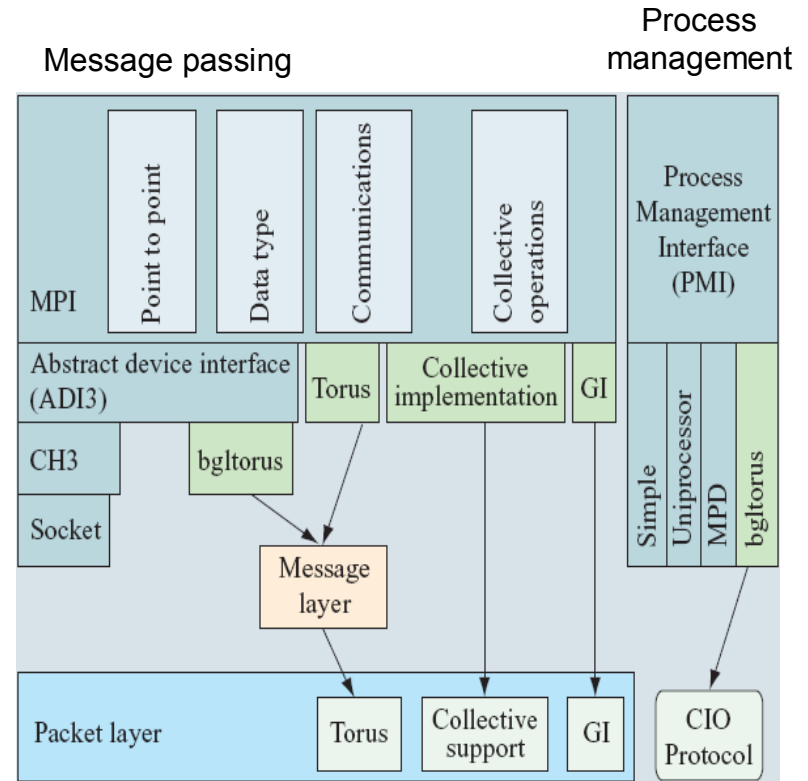
- **Compute nodes** for user applications
 - Simple Compute Node Kernel
 - Connected by 3D torus and collective network
- **I/O nodes** for interaction with the outside world
 - Run Linux
 - Provide OS services – file access, process launch/termination, debugging
 - Tree network and Gigabit Ethernet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



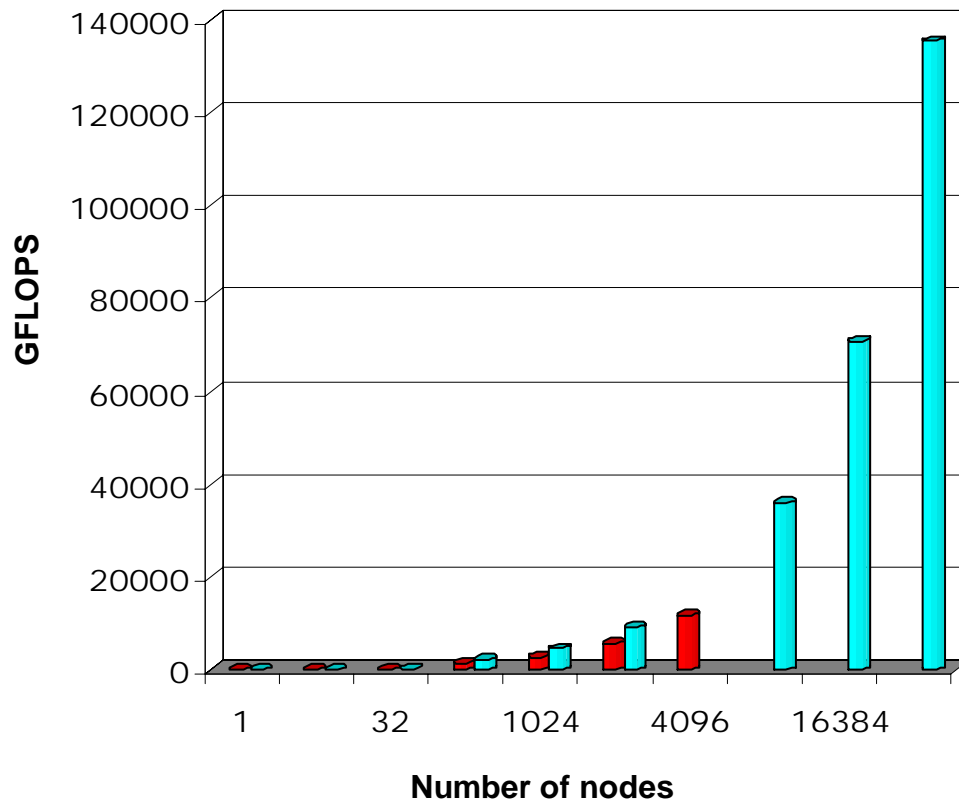


BlueGene/L Application Performance and Power Analysis



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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

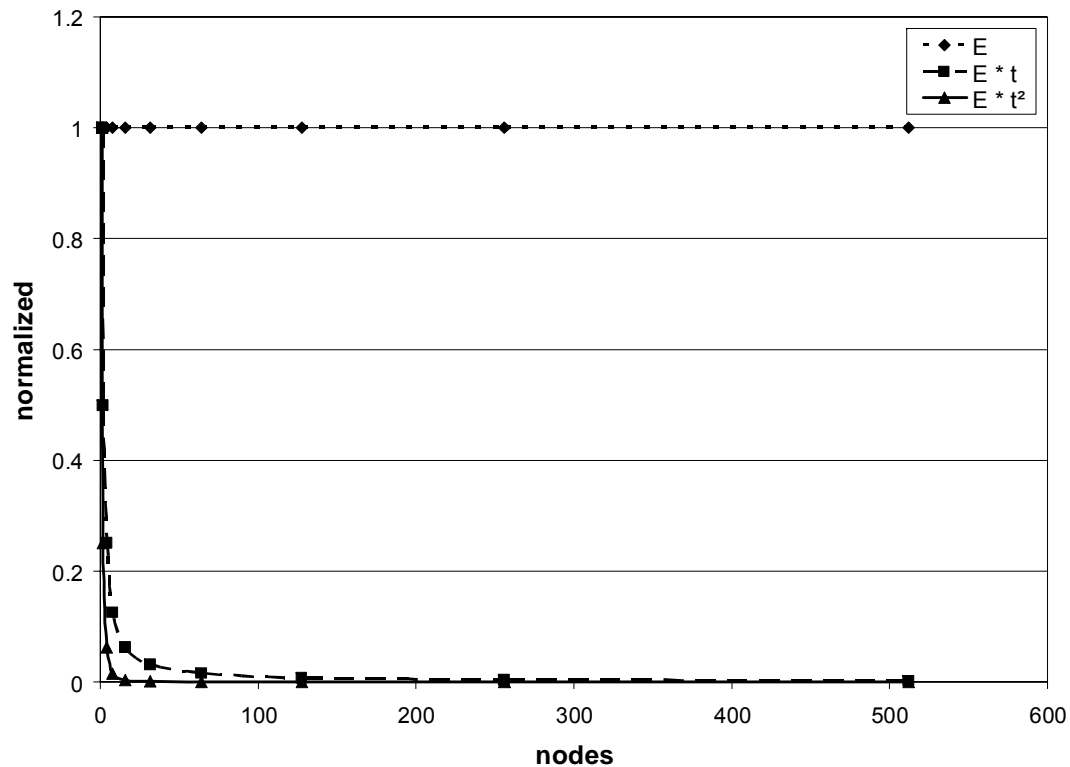
77% of peak

Application Performance and Power Efficiency

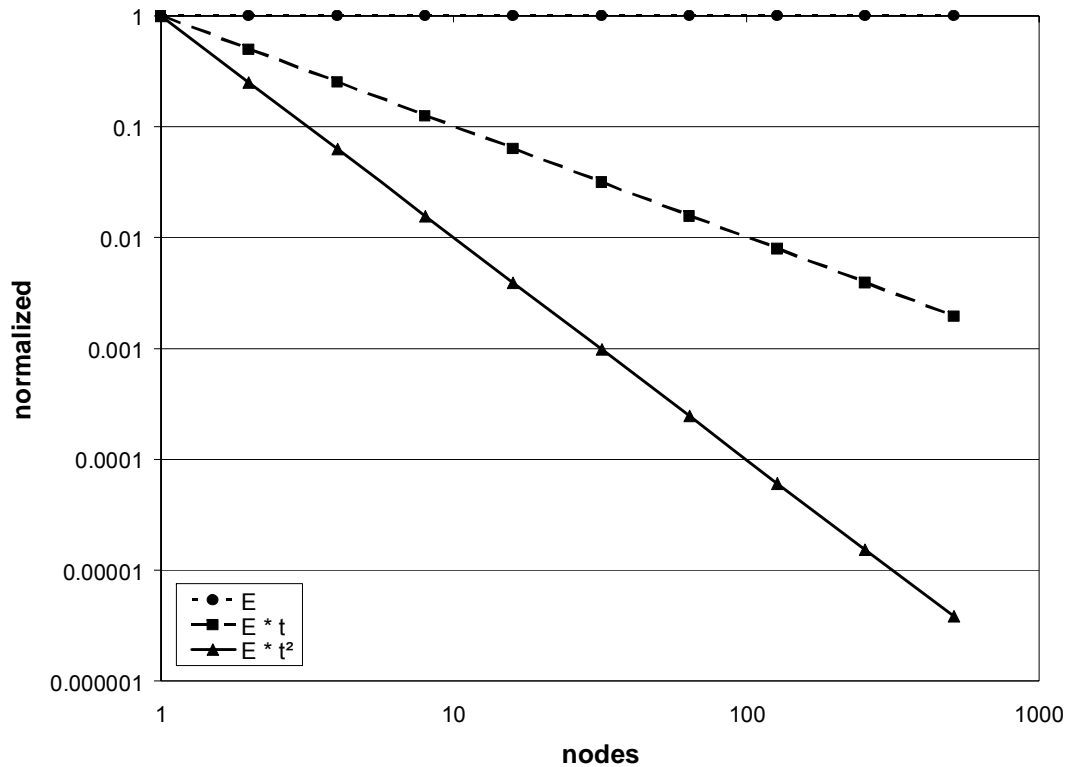
■ Figures of merit

- 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

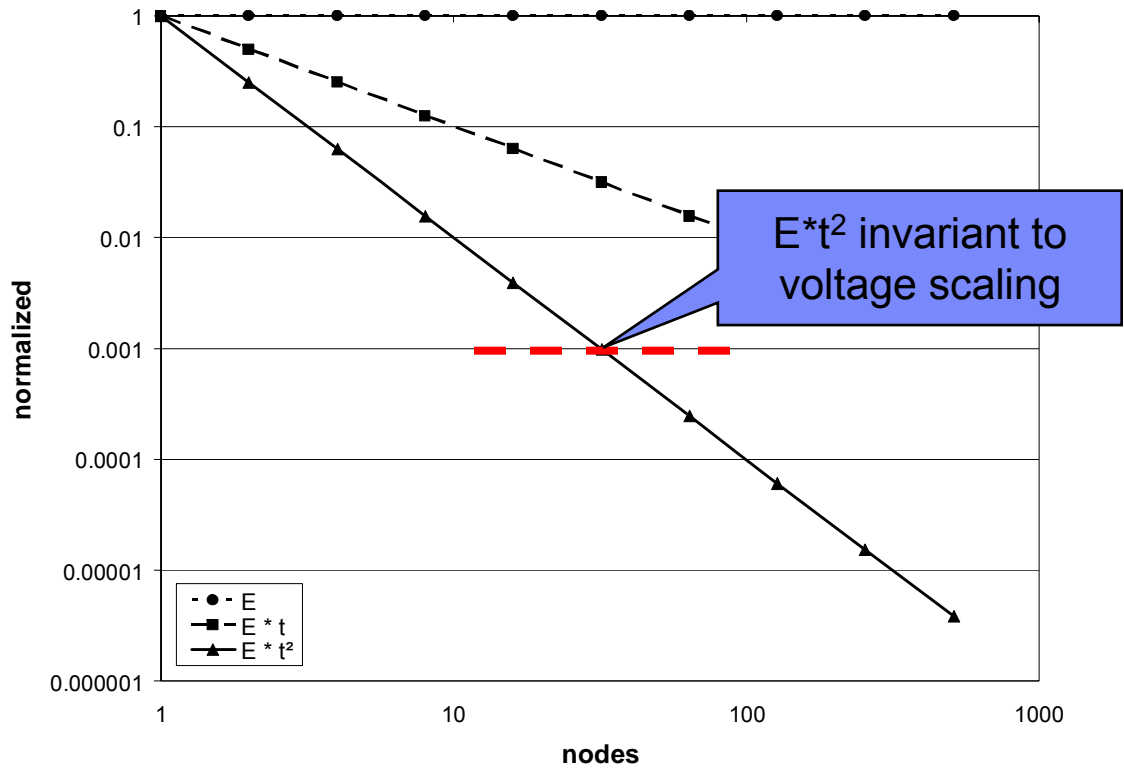
Low Power - High Performance System Concept



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



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

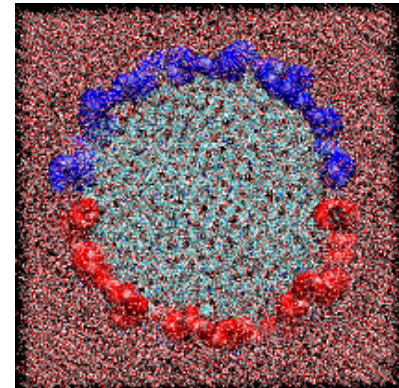


Applying Metrics to Actual Applications

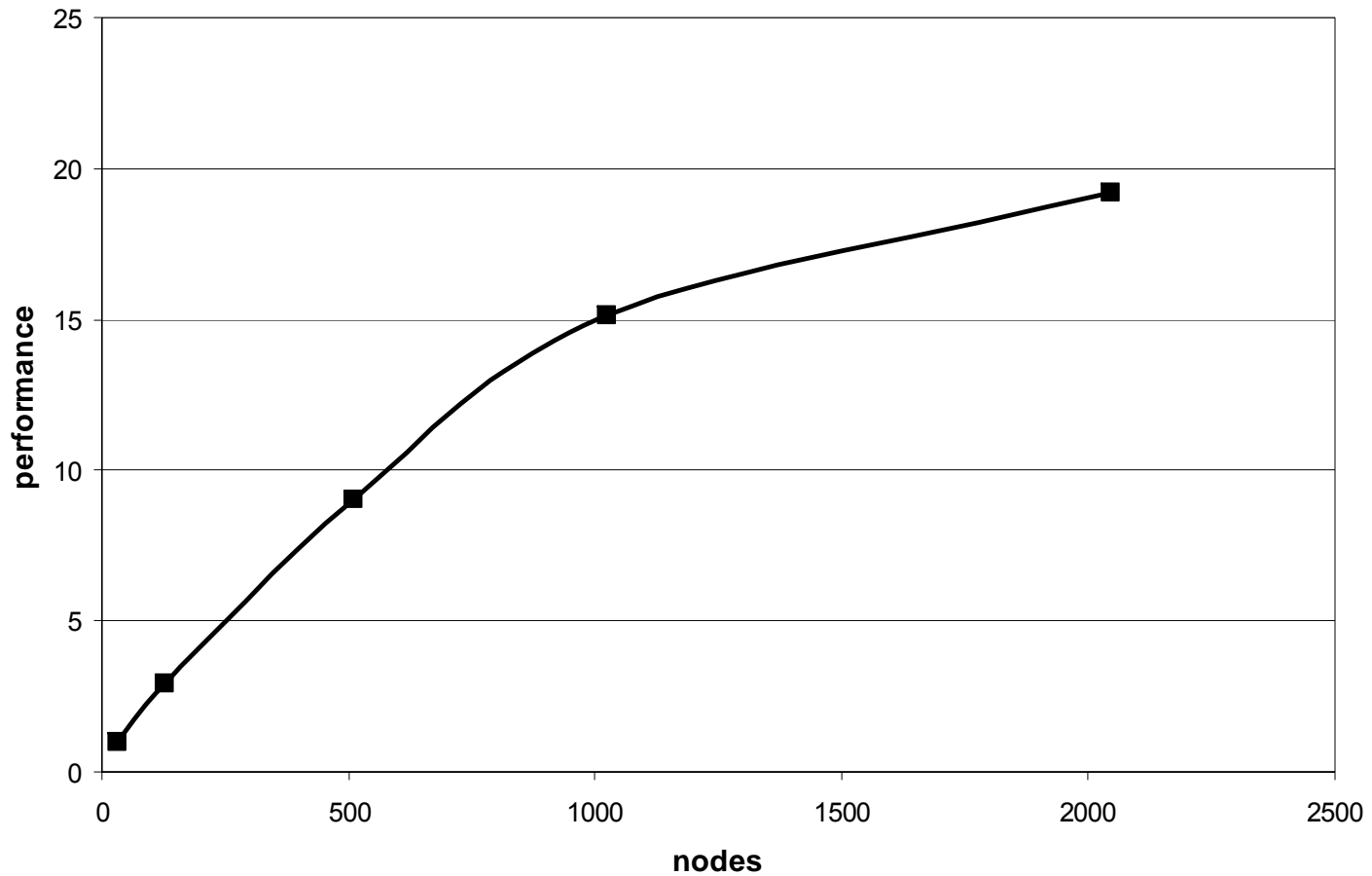
- **LINPACK highly parallel – follows 77% of peak performance**
 - Problem size matches the size of the system
 - Weak scaling
- **Many applications require constant amount of computation regardless of the size of the system**
 - Fixed sized problems
 - Strong scaling
 - More conservative performance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

NAMD

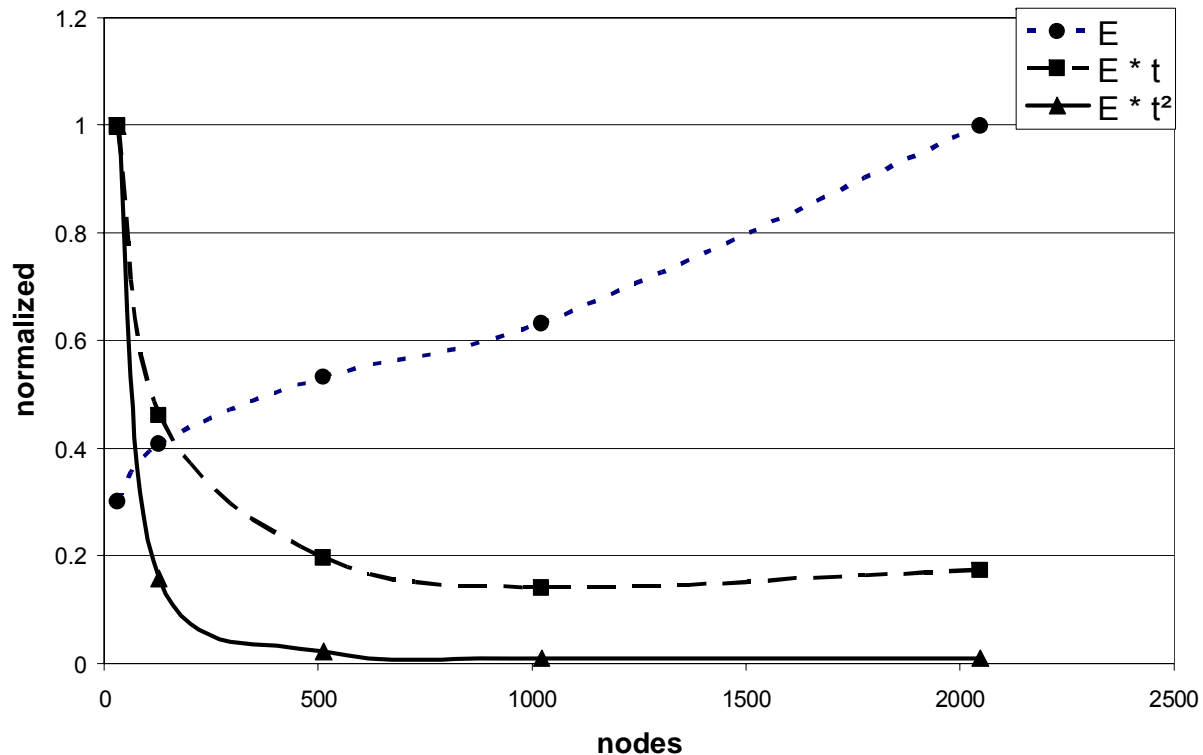
- **Parallel, object-oriented molecular dynamics code designed for high-performance simulation of large biomolecular systems**
 - Developed by the Theoretical Biophysics Group in the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign
- **Distributed 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**



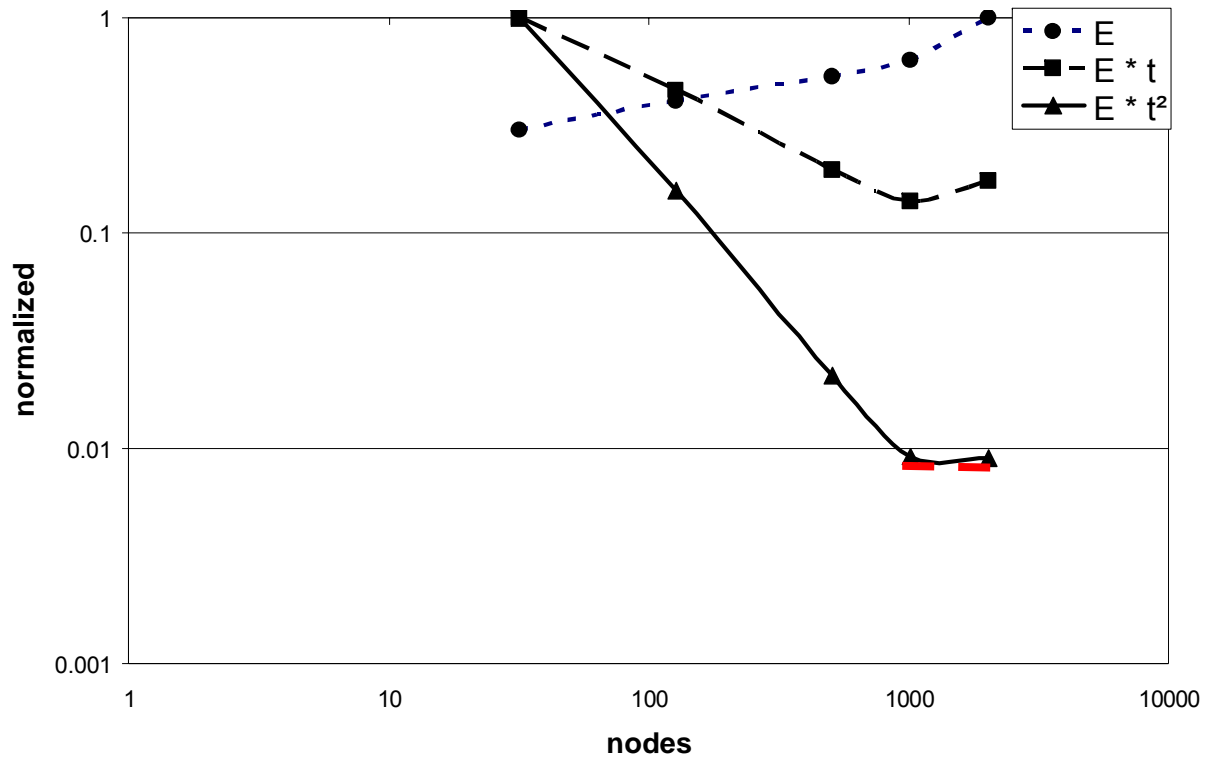
NAMD Performance Scaling



NAMD Power and Power Performance

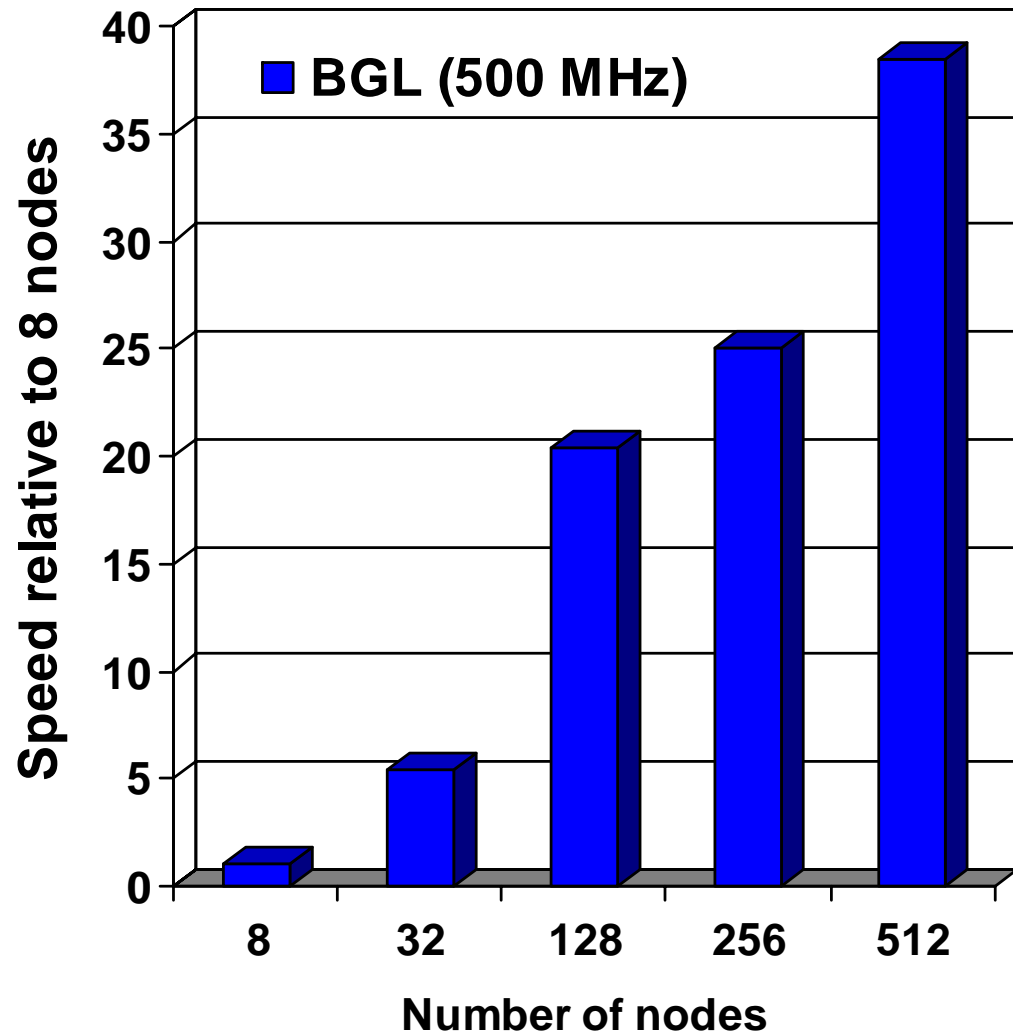


NAMD Power and Power Performance on log-log

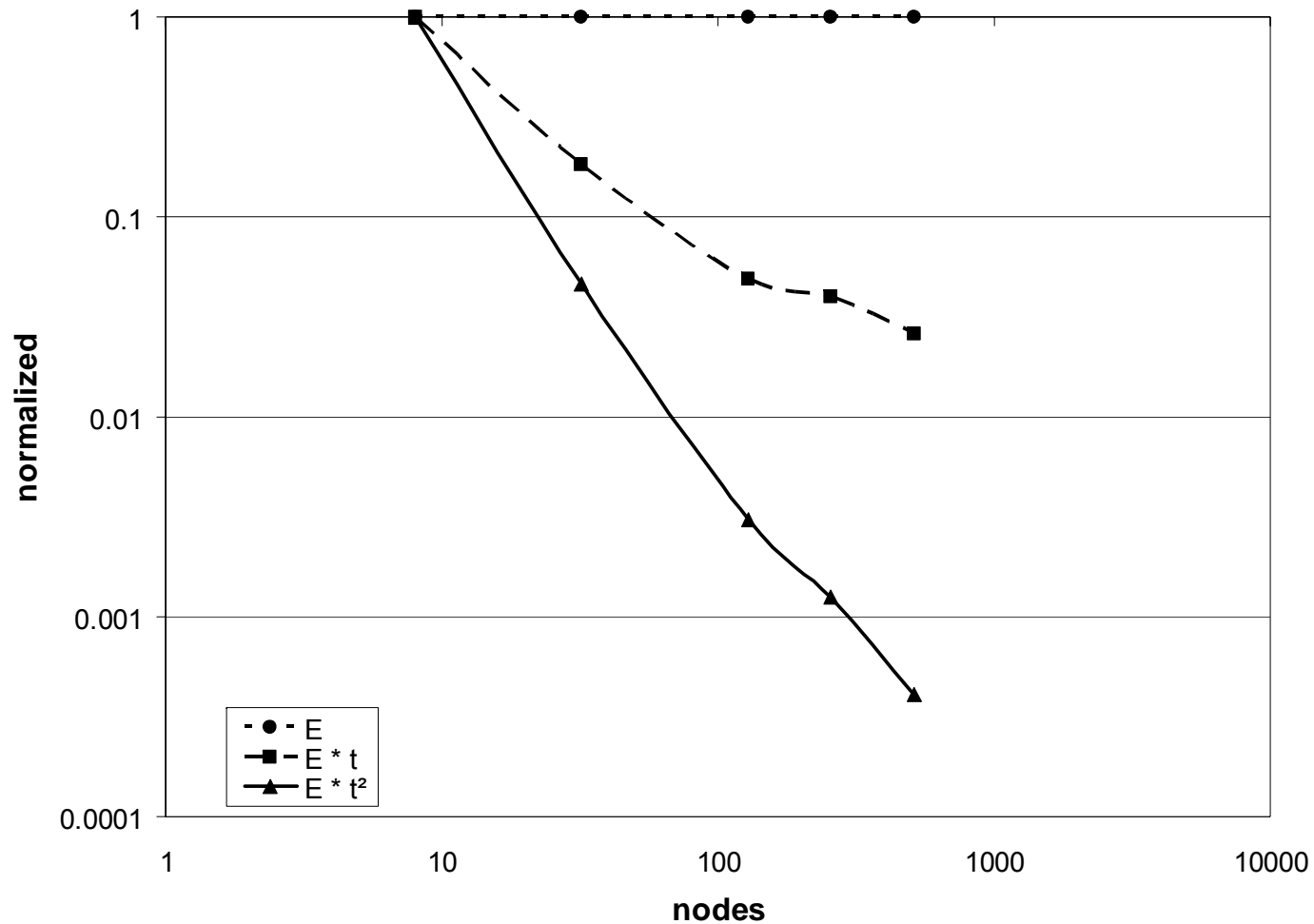


ASCI Purple Benchmarks – UMT2K

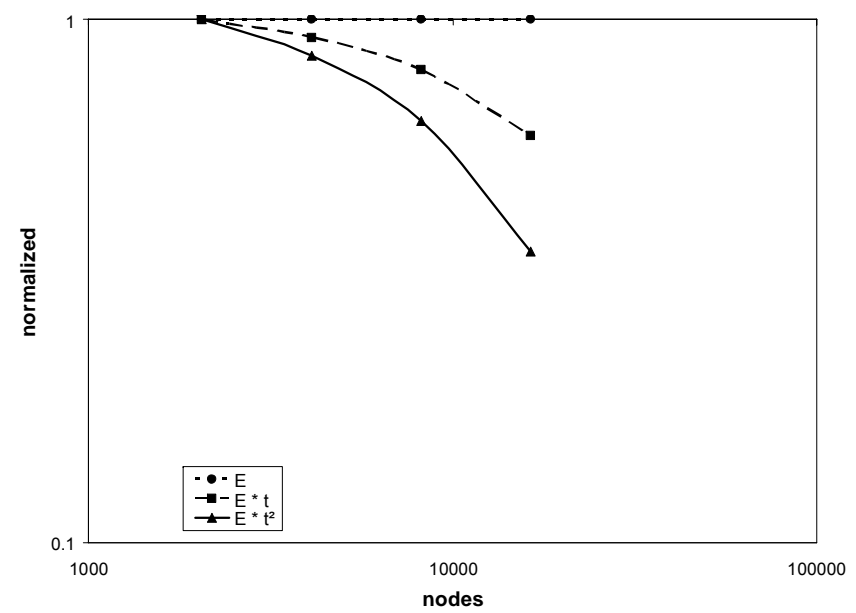
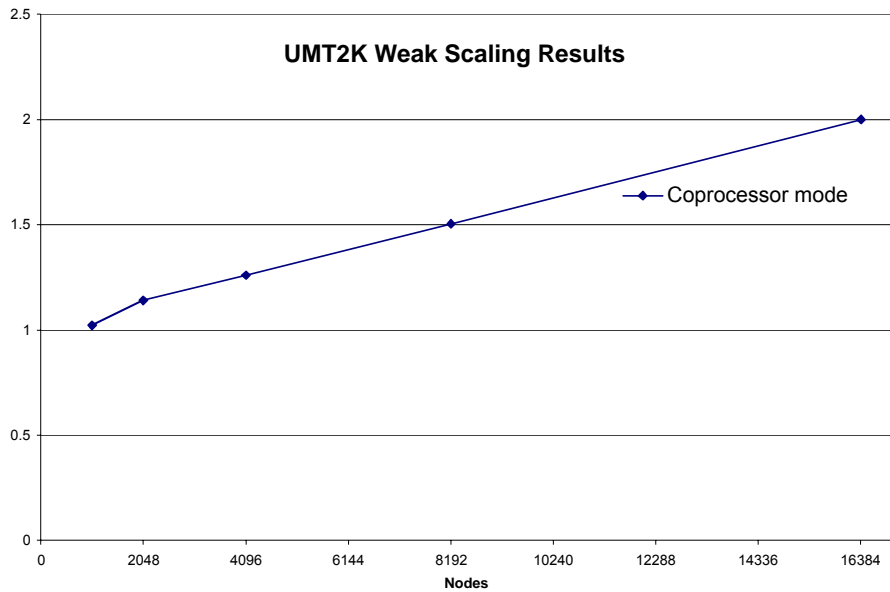
- **UMT2K – Unstructured mesh radiation transport**
- **Problem size fixed**
- **Excellent scalability up to mid-sized configurations**
 - Load balancing problems when scaling to 2000 or more nodes
 - Needed algorithmic changes in original program
 - Tuned UMT2K version scales well beyond 8000 BlueGene/L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



UMT2K Power and Power Performance



Recent UMT2K Runs Demonstrate Good Performance

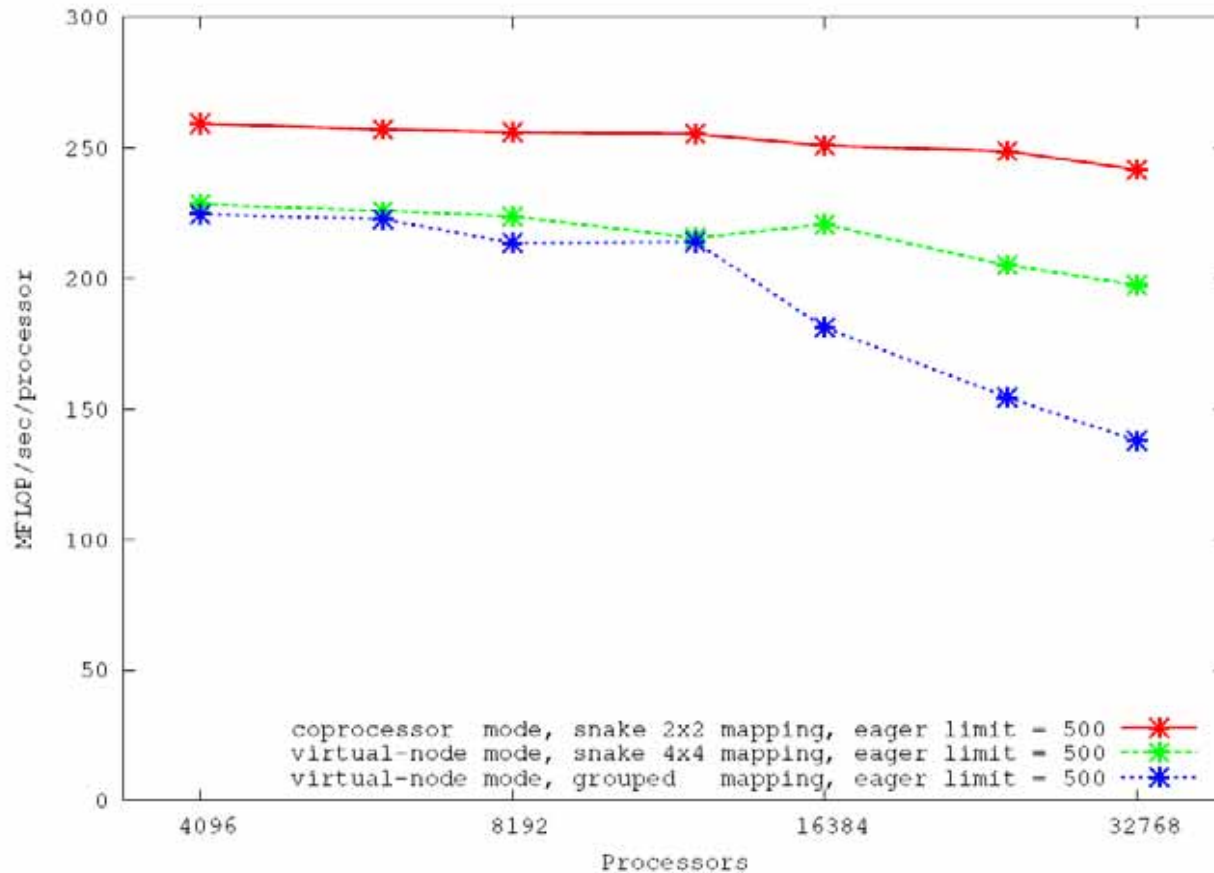


Nearest neighbor communication consistent
 Load balance unchanged from 1K to 8K

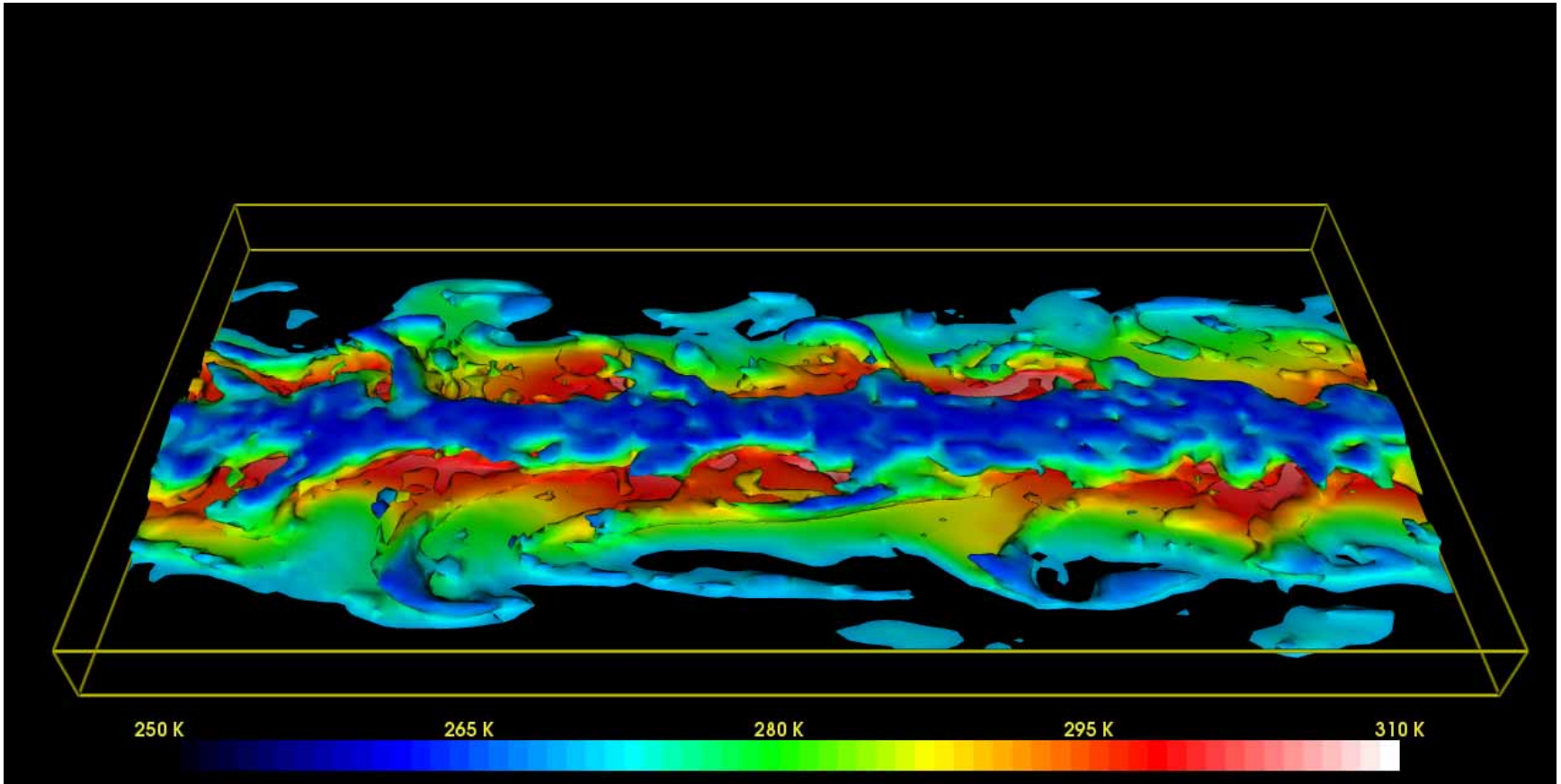
HOMME

- **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 (Coprocesor 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