OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

High Availability for Ultra-Scale Scientific High-End Computing

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Overview

- Research at Oak Ridge National Laboratory.
- Fault-tolerant heterogeneous metacomputing.
- High availability system software framework.
- Super-scalable algorithms for computing on 100,000 processors.

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Oak Ridge National Laboratory

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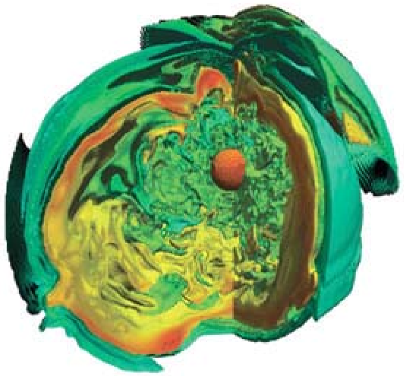
- Multiprogram science and technology laboratory.
- Privately managed for the U.S. Department of Energy.
- Basic and applied research and development.
- In biological, chemical, computational, engineering, environmental, physical, and social sciences.
- Staff: 3800 total, 1500 scientists and engineers
- Budget: $1.06 billion, 75% from DOE.
- Total land area: 58mi^2 (150km^2).
- ~3000 guest researchers each year.
- ~30,000 visitors each year.



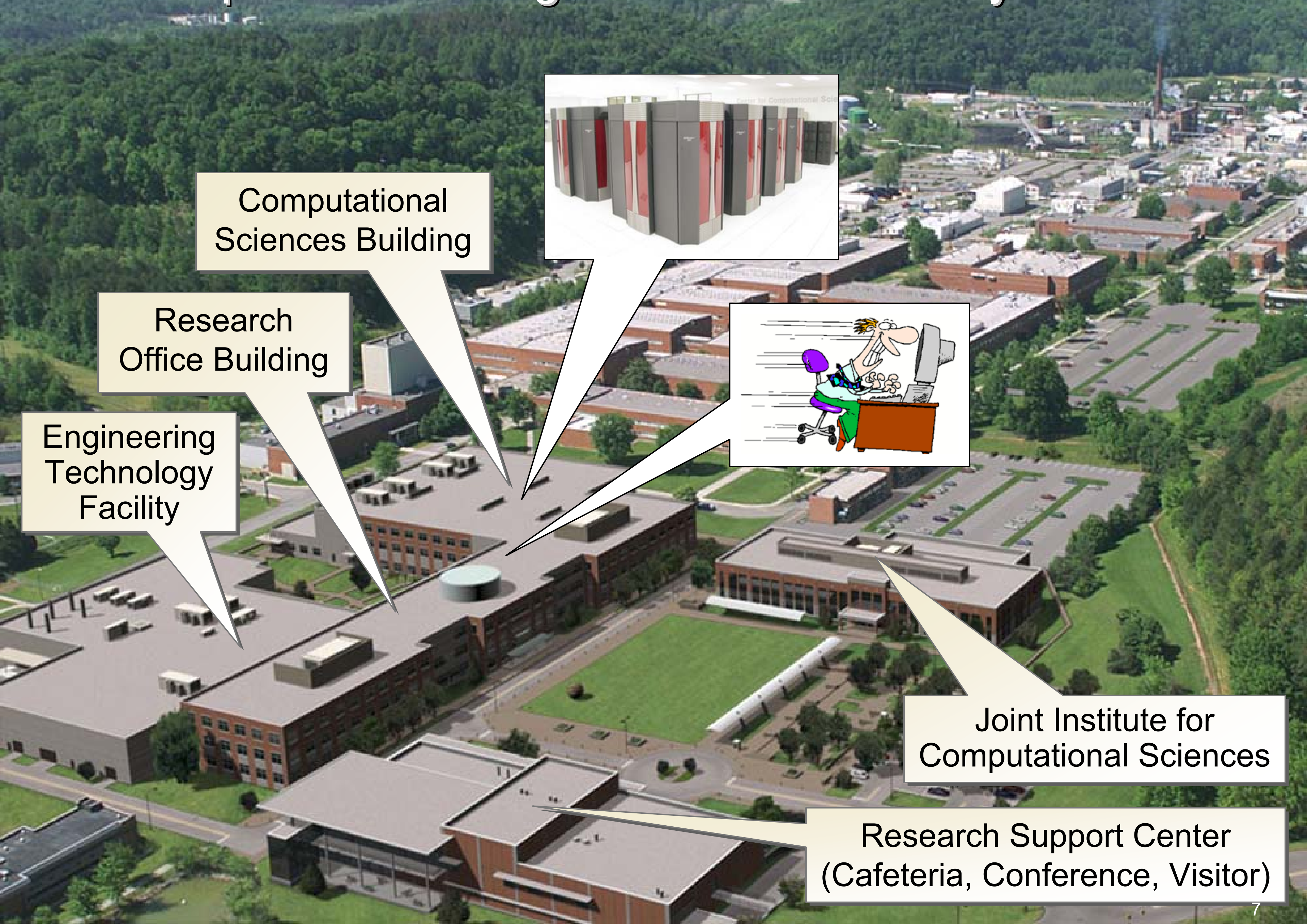
Laboratories and Research Centers

- Oak Ridge Electron Linear Accelerator (ORELA).
- Holifield Radioactive Ion Beam Facility (HRIBF).
- High Flux Isotope Reactor (HFIR).
- Spallation Neutron Source (SNS), *see next slide*.
- High Temperature Materials Laboratory (HTML).
- National Transportation Research Center (NTRC).
- ...
- Joint Institute for Computational Science (JICS).
- National Leadership Computing Facility (NLCF).

Spallation Neutron Source at Oak Ridge National Laboratory

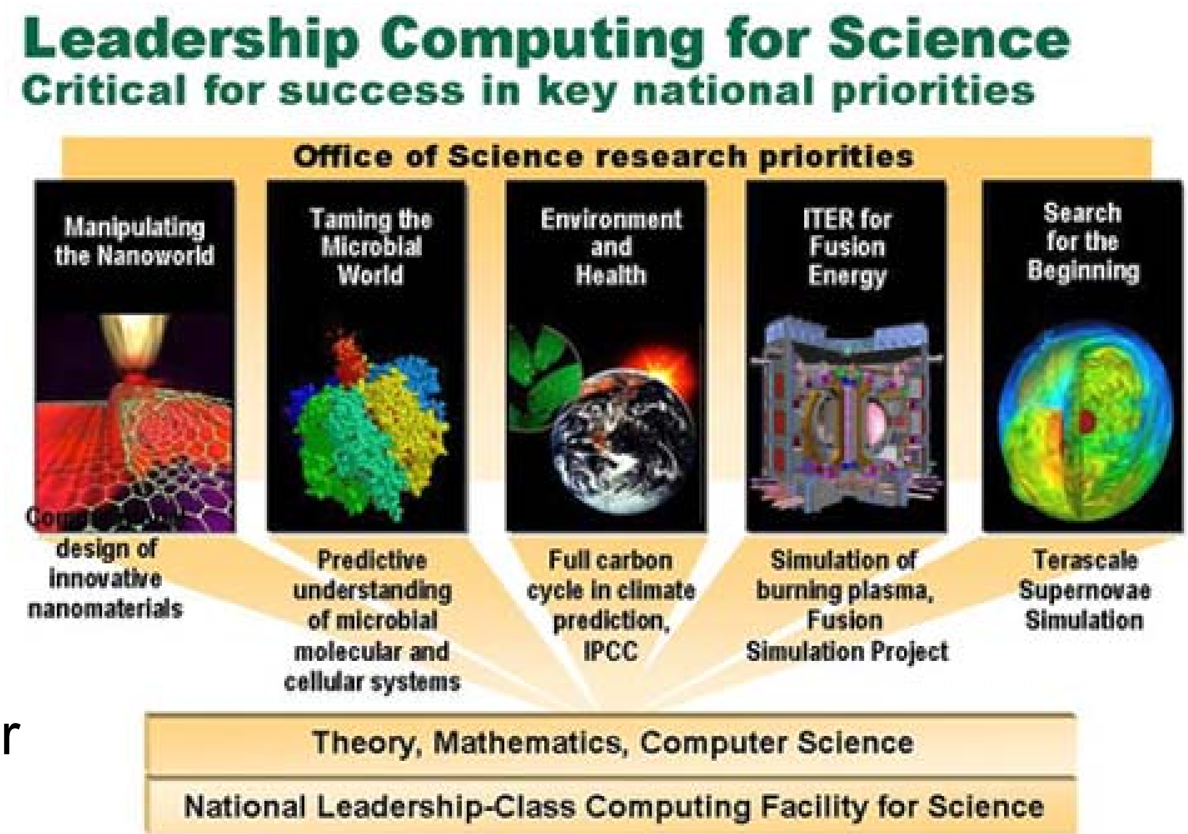
Operational in 2006
Construction cost of $1.4 billion

East Campus of Oak Ridge National Laboratory



National Leadership Computing Facility

- Established in 2004.
- $25M from US DOE.
- Lead by Oak Ridge National Laboratory.
- Collaboration with other laboratories and universities.
- Using capability over capacity computing.
- Advancing the race for scientific discovery.



More information: www.nlcf.gov

Center for Computational Sciences

- Computer center with 40,000 ft^2 (3700m^2) floor space.
- 4 systems in the Top 500 List of Supercomputer Sites:
  - 11. Cray XT3, MPP with 5212P, 10TB ⇨ 25 TFLOPS.
  - 50. Cray X1, Vector with 1024P, 4TB ⇨ 18 TFLOPS.
  - 143. IBM Power 4, Cluster with 864P, 1TB ⇨ 4.5 TFLOPS.
  - 362. SGI Altix, SSI with 256P, 2TB ⇨ 1.4 TFLOPS.

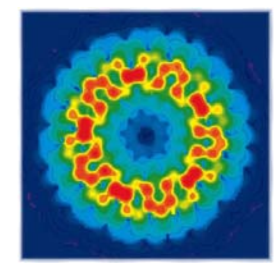
Leadership Computing Roadmap

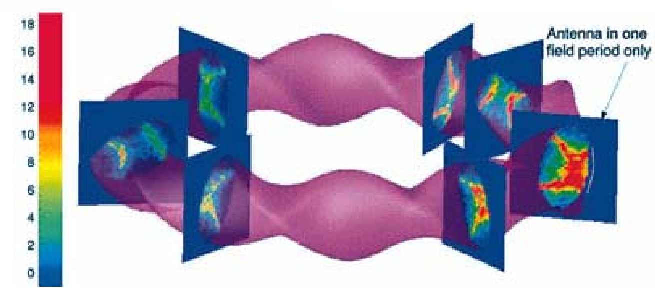
- Planned upgrades next year:
  - Cray XT3 to 20000P/40TB ⇨ 100 TFLOPS.
- Future roadmap:
  - ~ 2007 Upgrade Cray X1e to X2.
  - ~ 2007 Upgrade Cray XT3 to 250 TFLOPS.
  - ~ 2009 Installation of a 1 PFLOP system.

Cray Center of Excellence at ORNL

Computer Science Research Groups

- Computer Science and Mathematics (CSM) Division.
  - Applied research focused on computational sciences, intelligent systems, and information technologies.
- CSM Research Groups:
  - Climate Dynamics
  - Computational Biology
  - Computational Chemical Sciences
  - Computational Materials Science
  - Computational Mathematics
  - ...
  - *Network and Cluster Computing (~23 researchers)*





Network & Cluster Computing Projects

- Parallel Virtual Machine (PVM).
- MPI Specification, FT-MPI and Open MPI.
- Common Component Architecture (CCA).
- Open Source Cluster Application Resources (OSCAR).
- Scalable Systems Software (SSS).
- …
- Fault-tolerant metacomputing (HARNESS).
- High availability for high-end computing (RAS-MOLAR).
- Super-scalable algorithms research.

Ultra-scale Scientific High-End Computing

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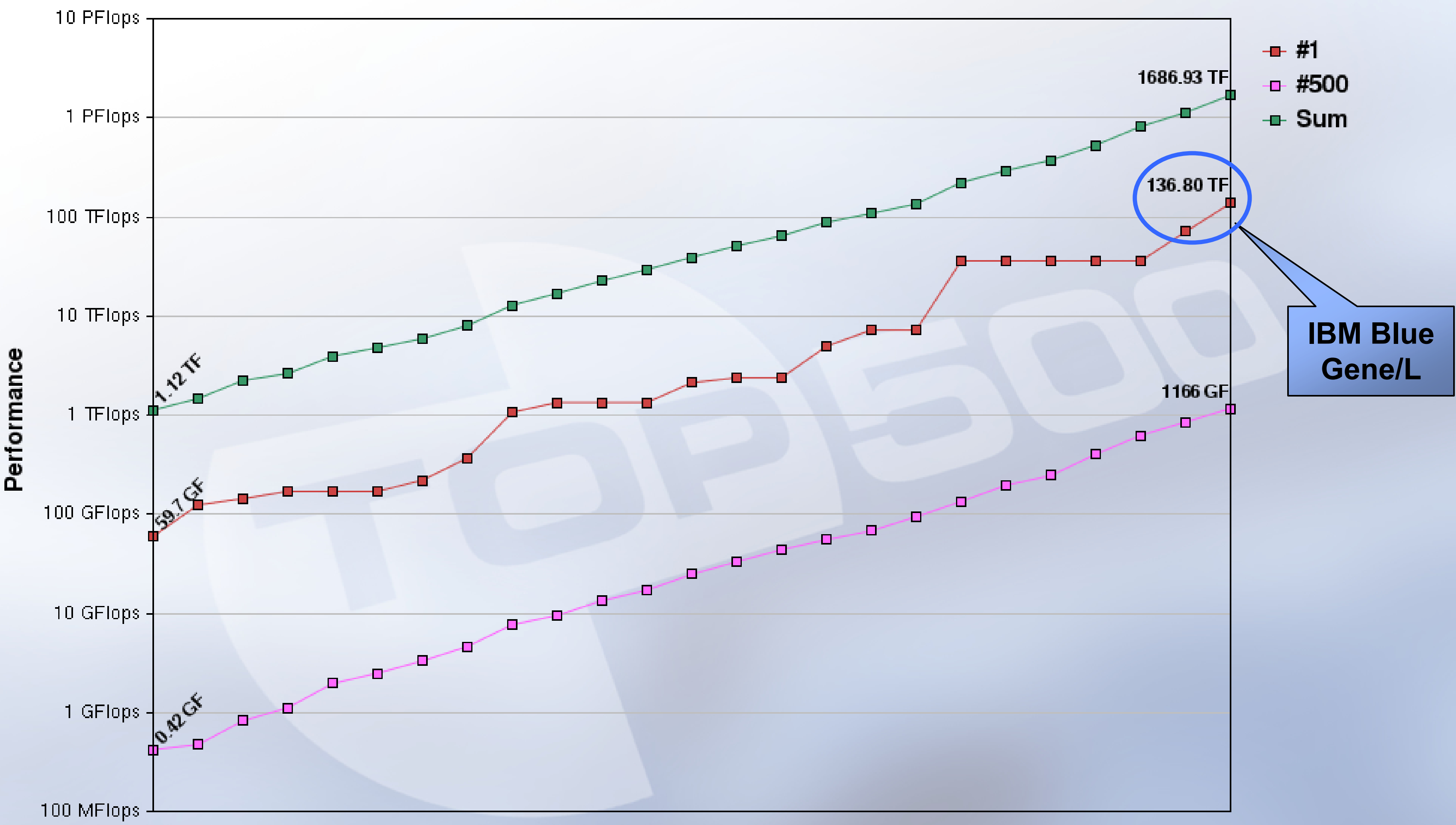
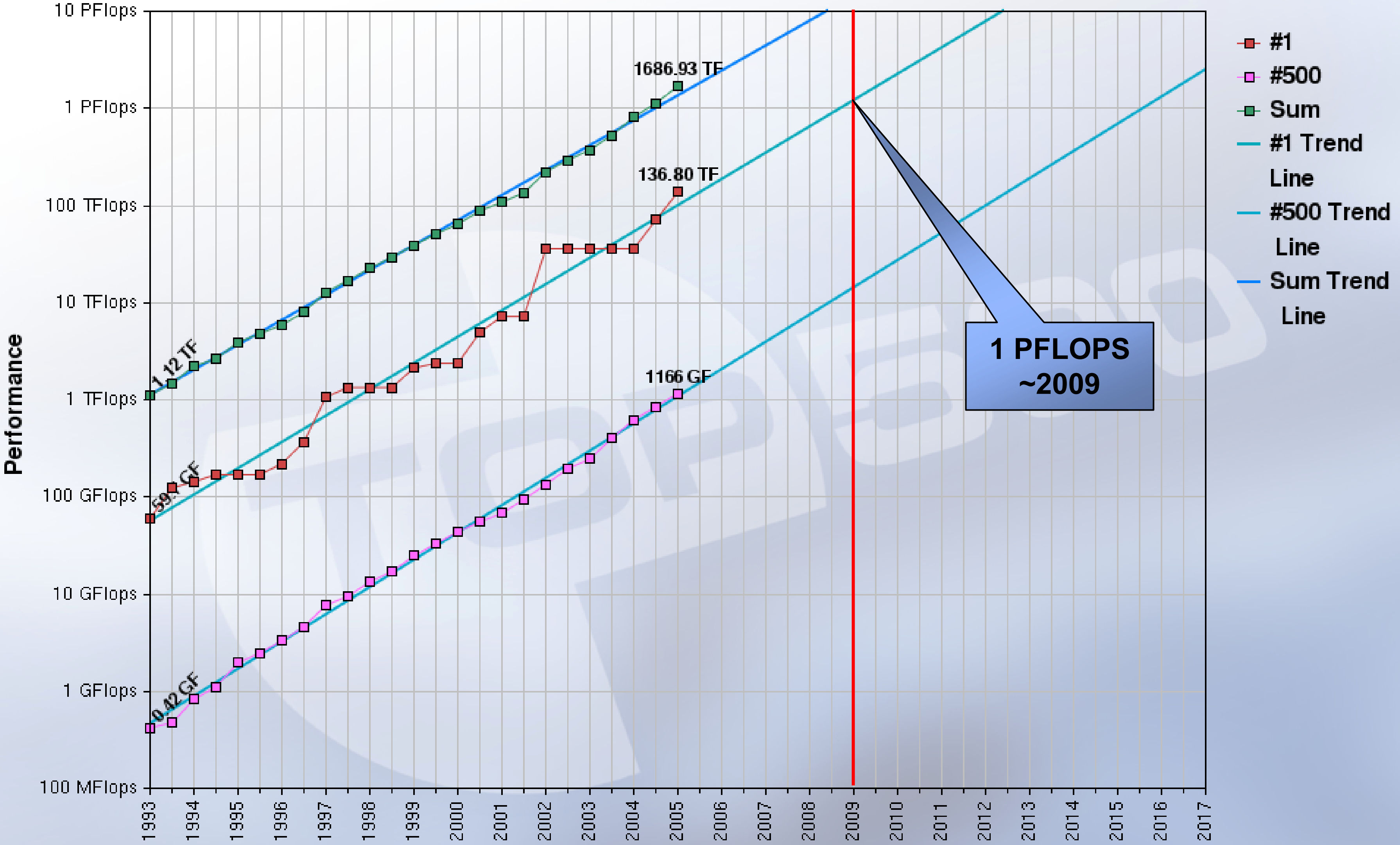
Scientific High-End Computing

- Next generation supercomputing.
  - Large-scale cluster, parallel, distributed and vector systems.
  - 131,072 processors for computation in IBM Blue Gene/L.
- Computationally and data intensive applications.
  - Many research areas: (multi-)physics, chemistry, biology…
  - Climate, supernovae (stellar explosions), nuclear fusion, material science and nanotechnology simulations.
- Ultra-scale = upper end of processor count (+5,000).
  - 25+ TeraFLOPS (25,000,000,000,000 FLOPS and more).

Performance Development



Projected Performance Development



Ultra-scale Software Research Issues

- Capability computing applications require ultra-scale systems and long runtimes (weeks or even months).
- However, larger and more complex systems result in an increase of failure rates and system downtimes.
- Furthermore, application efficiency drops off with increased system scale due to Amdahl's Law.

➔ Application software fault-tolerance.
➔ High availability system software.
➔ Super-scalable algorithms for 100,000 processors.

Fault-tolerant Heterogeneous Metacomputing with Harness

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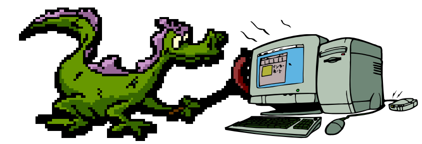
What is Harness

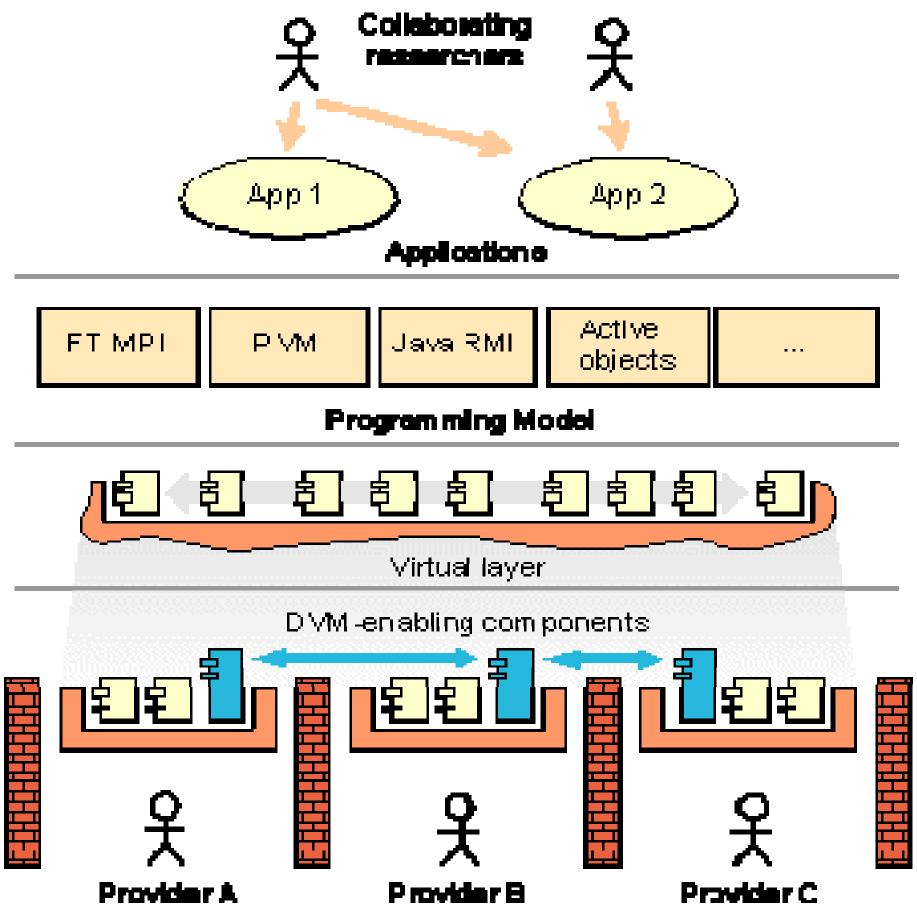
- A pluggable, reconfigurable, adaptive framework for heterogeneous distributed computing.
- Allows aggregation of resources into high-capacity distributed virtual machines.
- Provides runtime customization of computing environment to suit applications needs.
- Enables dynamic assembly of scientific applications from (third party) plug-ins.
- Offers highly available distributed virtual machines through distributed control.

Harness Research Areas



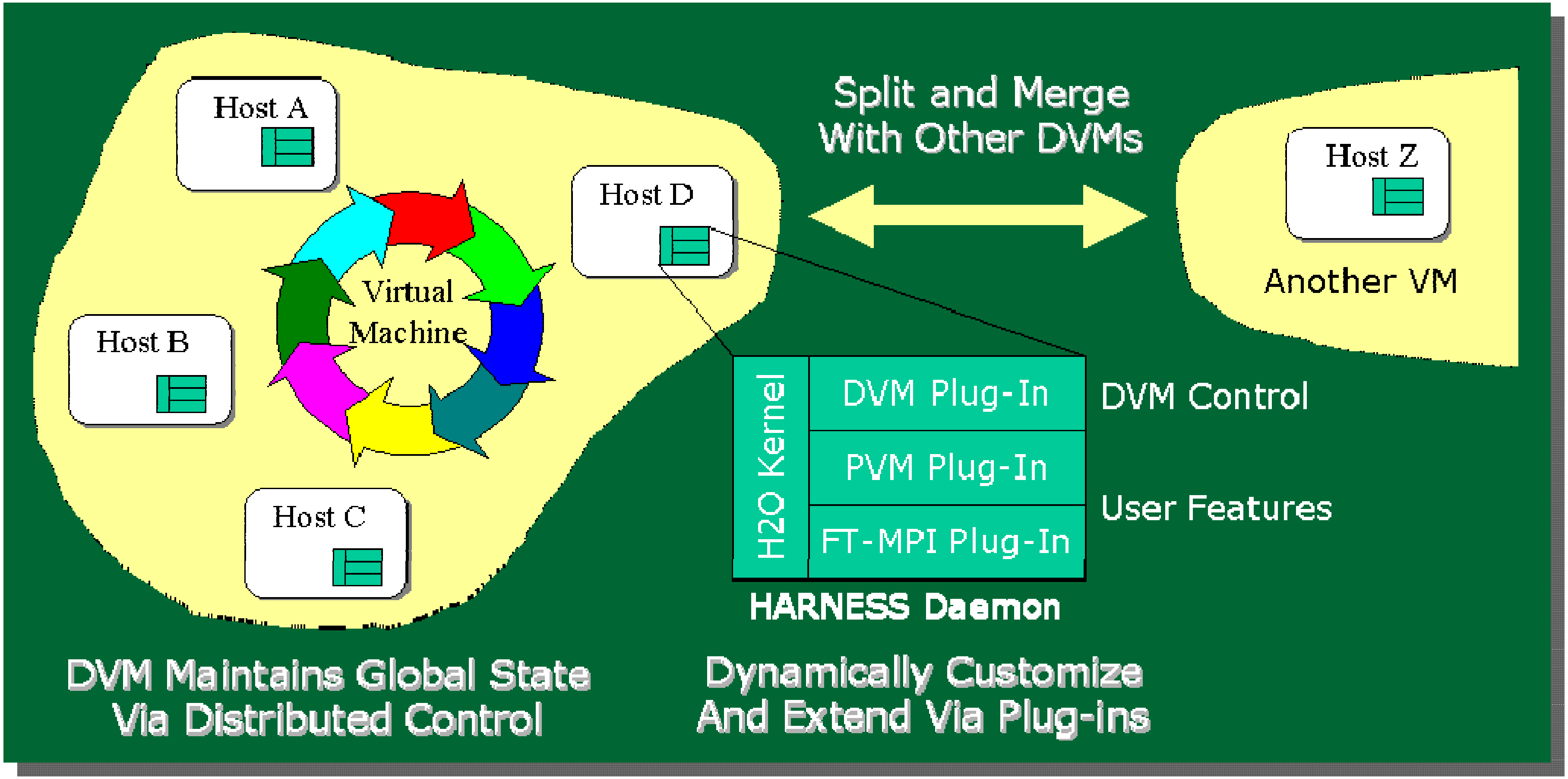
- Lightweight, pluggable software frameworks.
- Adaptive, reconfigurable runtime environments.
- Parallel plug-ins and diverse programming paradigms.
- Highly available distributed virtual machines (DVMs).
- Advanced ultra-scale approaches for fault tolerance.
- Fault-tolerant message passing (FT-MPI).
- Mechanisms for configurable security levels.
- Dynamic, heterogeneous, reconfigurable communication frameworks (RMIX).

Harness Architecture



- Light-weight kernels share their resources.
- Plug-ins offer services.
- Support for diverse programming models.
- Distributed Virtual Machine (DVM) layer.
- Highly available DVM.
- Highly available plug-in services via DVM.

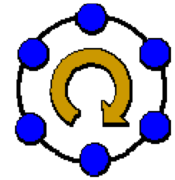
Harness DVM Architecture



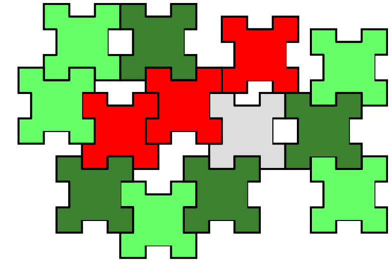
Harness Plug-ins

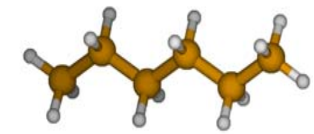
- PVM emulation plug-in:
  - Replaces the PVM daemon.
  - Allows users a seamless transition to Harness.
  - Plug-ins and applications just link libpvm.
  - PVM is controlled with the Harness console.
- Fault-tolerant MPI (FT-MPI) plug-in:
  - Combines several FT-MPI services in one plug-in.
  - Plug-ins and applications just use ftmpiCC.
  - FT-MPI is controlled with the Harness console.

Harness Plug-ins

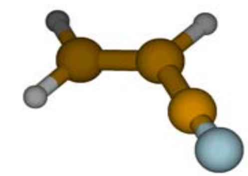


Distributed Control



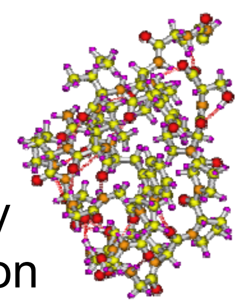


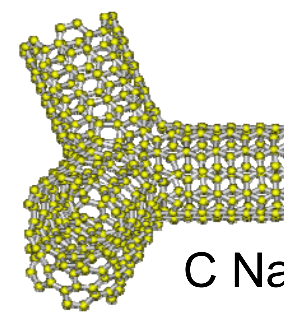
SCC-DFTB



- DVM plug-in:
  - Allows to aggregate multiple Harness kernels.
- Distributed control plug-in:
  - Provides high availability through virtual synchrony.
- RMIX plug-in:
  - Offers multi-protocol RMI (JRMPX, SOAP and RPC).
- Several application plug-ins:
  - Molecular dynamics.
  - Quantum chemistry.

Geometry Optimization





C Nanotubes

High Availability System Software Framework

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Research Motivation

- Today's supercomputers typically need to reboot to recover from a single failure.
- Entire systems go down (regularly and unscheduled) for any maintenance or repair.
- Compute nodes sit idle while their head node or one of their service nodes is down.
- Availability will get worse in the future as the MTBI decreases with growing system size.

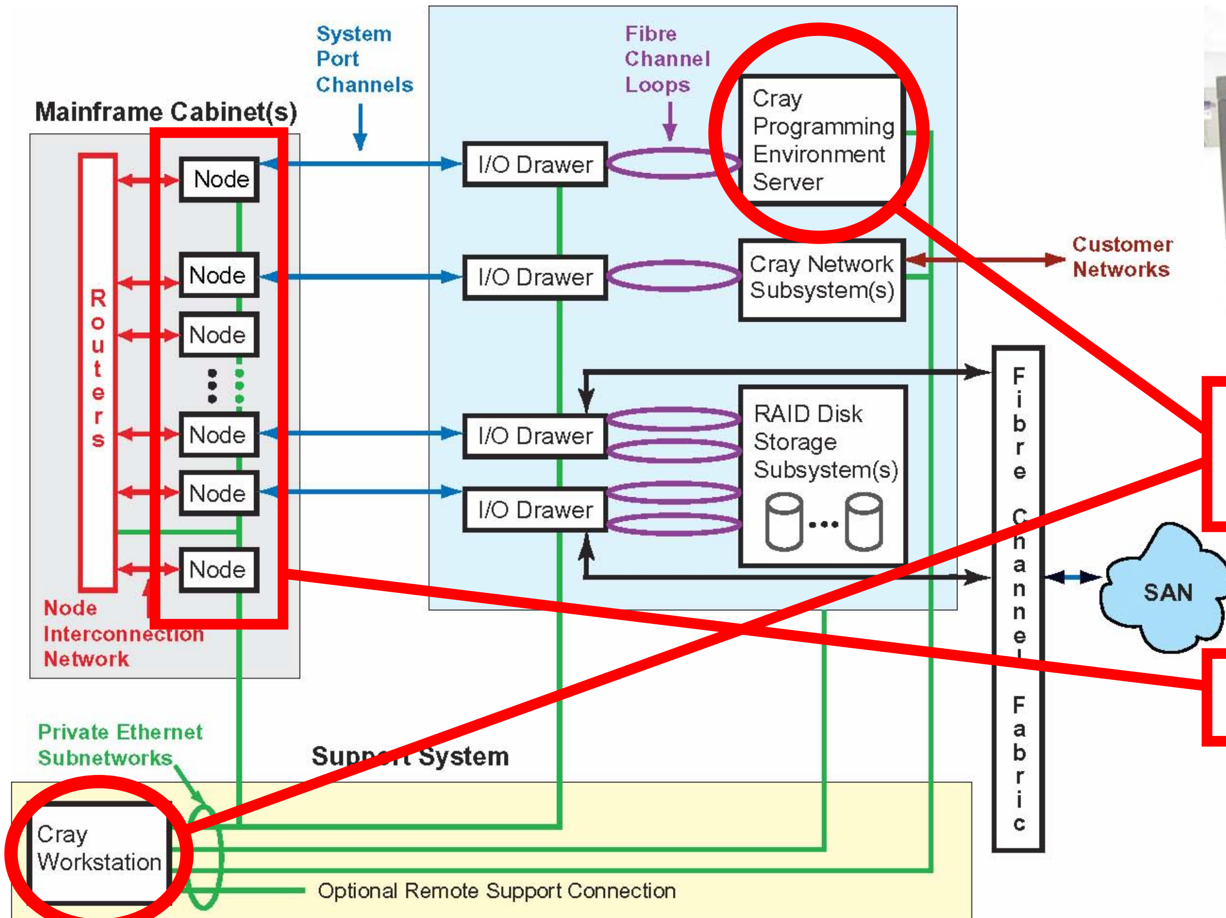
➢ *Why do we accept such significant system outages due to failures, maintenance or repair?*

Availability Measured by the Nines

9's	Availability	Downtime/Year	Examples
1	90.0%	36 days, 12 hours	Personal Computers
2	99.0%	87 hours, 36 min	Entry Level Business
3	99.9%	8 hours, 45.6 min	ISPs, Mainstream Business
4	99.99%	52 min, 33.6 sec	Data Centers
5	99.999%	5 min, 15.4 sec	Banking, Medical
6	99.9999%	31.5 seconds	Military Defense

- Enterprise-class hardware + Stable Linux kernel = 5+
- Substandard hardware + Good high availability package = 2-3
- Today's supercomputers = 1-2
- My desktop = 1-2

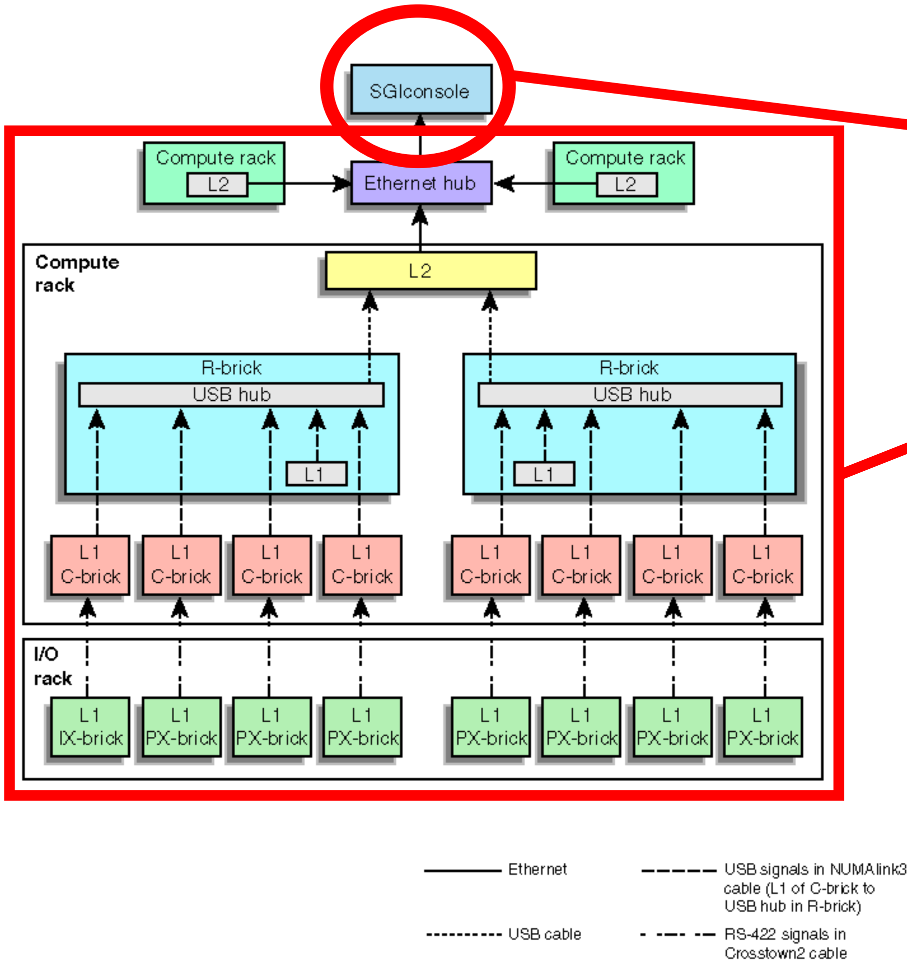
Vector Machines: Cray X1 (Phoenix)



Single Points of Failure, Single Points of Control

Single Points of Failure

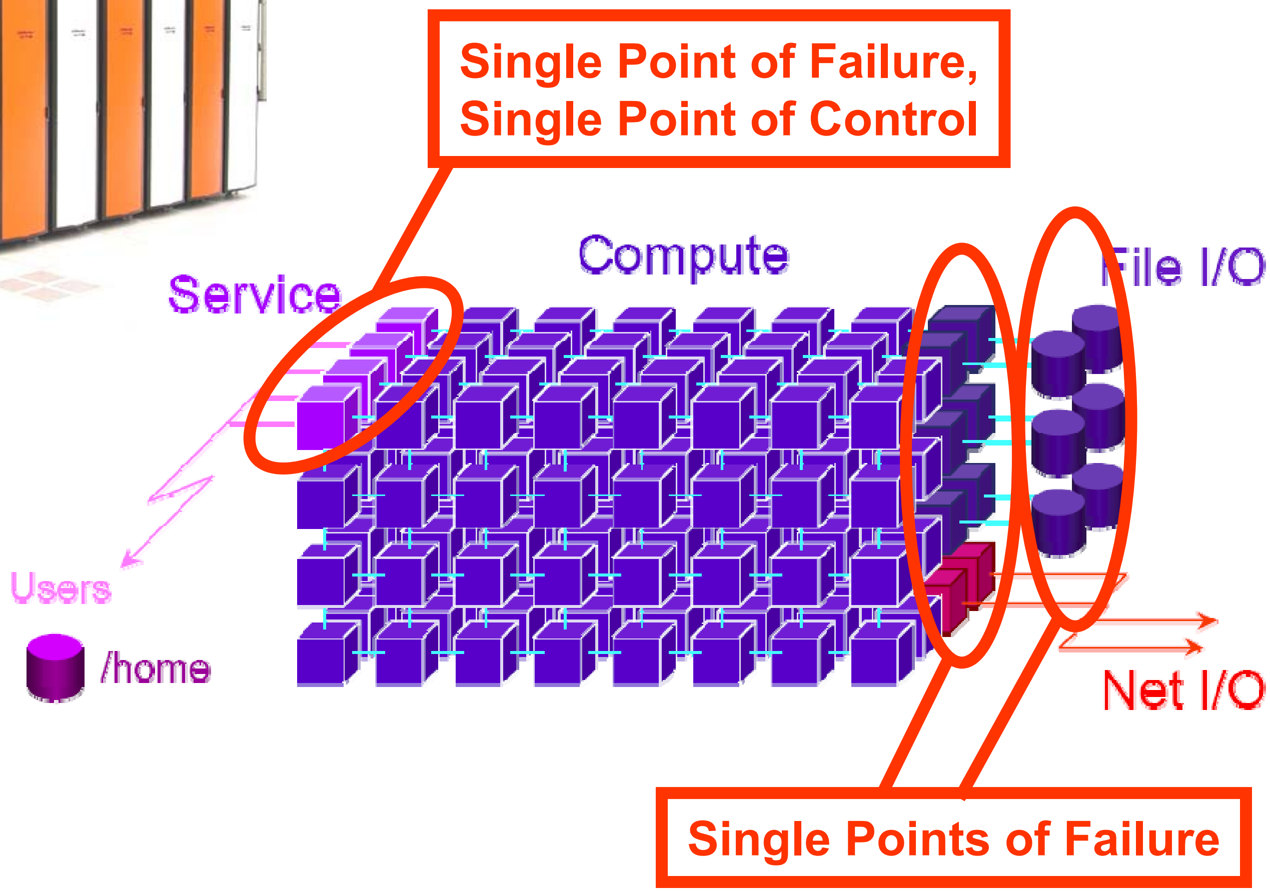
SSI Systems: SGI Altix (Ram)



Single Point of Failure, Single Point of Control

Single Points of Failure

MPPs: Cray XT3 (Jaguar)



Research Goals

- Provide high-level RAS capabilities similar to the IT/telecommunication industry (3-4 nines).
- Eliminate many of the numerous single-points of failure and control in today's terascale systems.
- Improve scalability and access to systems and data.
- *Development of techniques to enable terascale systems to run computational jobs 24x7.*
- *Development of proof-of-concept implementations as blueprint for production-type RAS solutions.*

High Availability Methods

Active/Hot-Standby:

- Single active head node.
- Backup to shared storage.
- Simple checkpoint/restart.
- Rollback to backup.
- Idle standby head node(s).
- Service interruption for the time of the fail-over.
- Service interruption for the time of restore-over.
- Possible loss of state.

Active/Active:

- Many active head nodes.
- Work load distribution.
- Symmetric replication between participating nodes.
- Continuous service.
- Always up-to-date.
- No restore-over necessary.
- Virtual synchrony model.
- Complex algorithms.

High Availability Technology

Active/Hot-Standby:

- HA-OSCAR with active/hot-standby head node.
- Similar projects: HA Linux…
- Cluster system software.
- No support for multiple active/active head nodes.
- No application support.

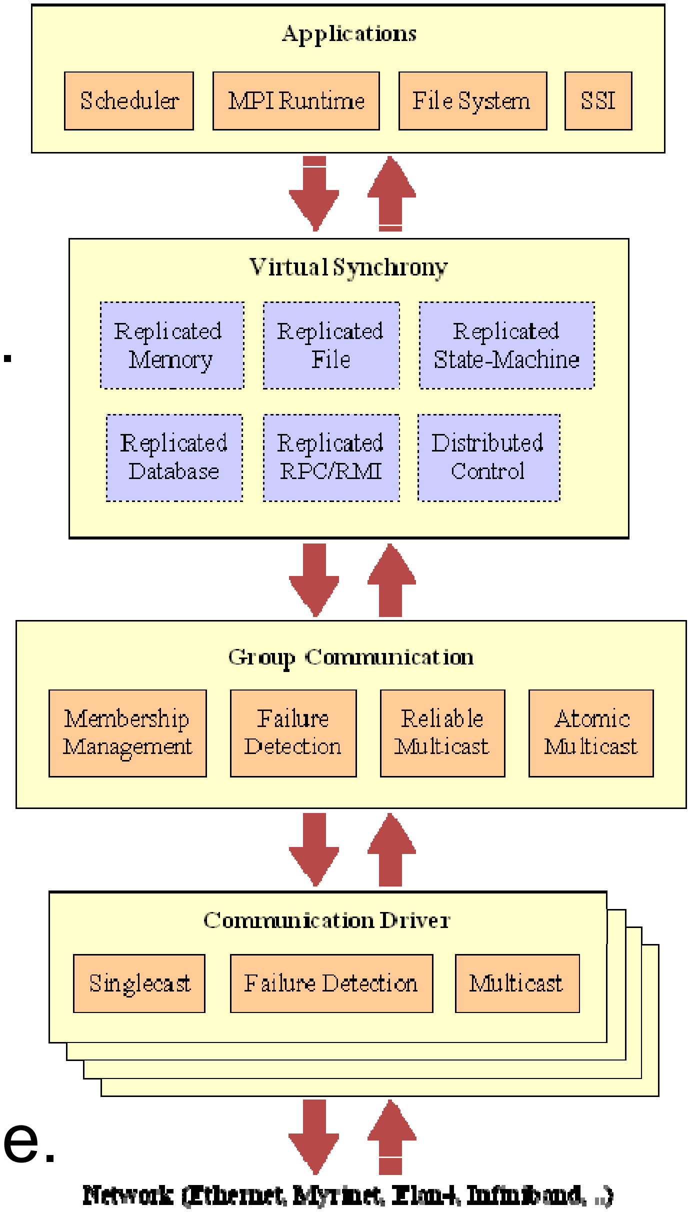
Active/Active:

- HARNESS with symmetric distributed virtual machine.
- Similar projects: Cactus …
- Heterogeneous adaptable distributed middleware.
- No system level support.
- Solutions not flexible enough.

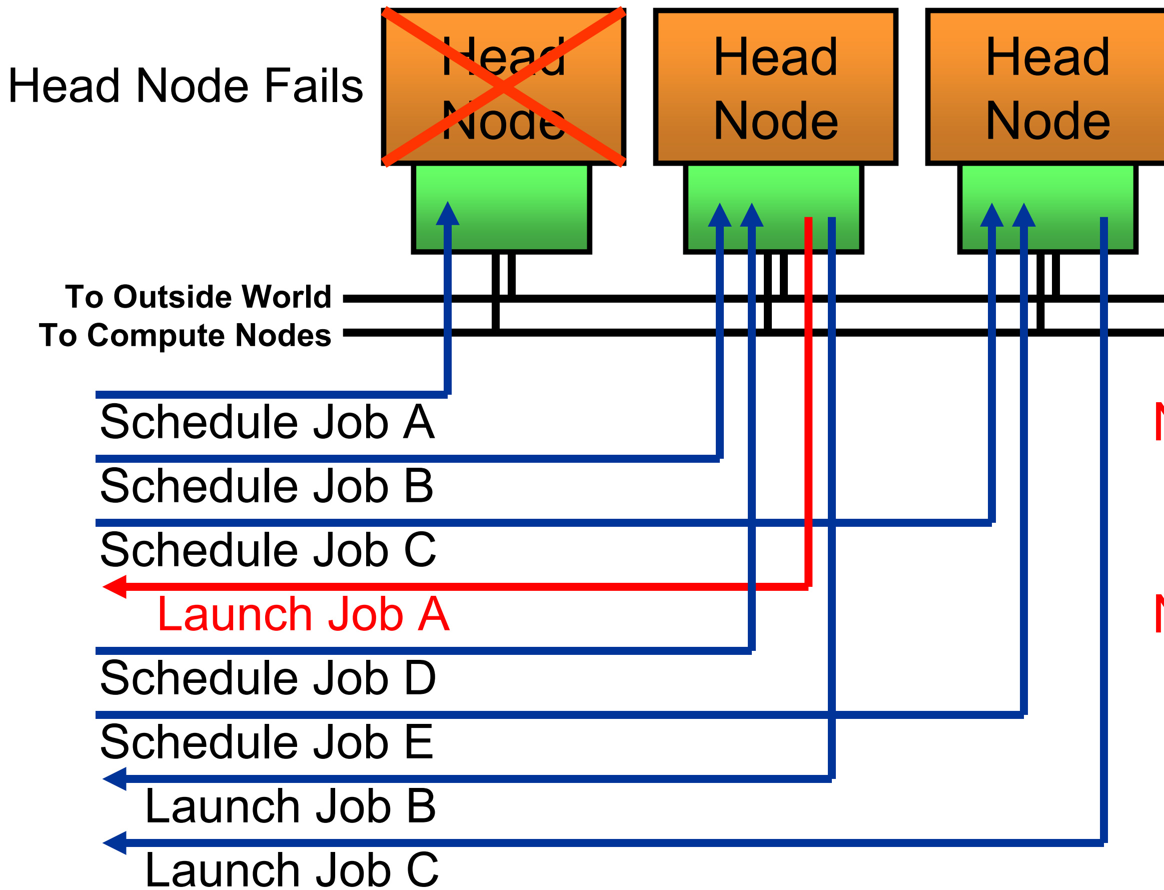
- ➢ *System-level data replication and distributed control service needed for active/active head node solution.*
- ➢ *Reconfigurable framework similar to HARNESS needed to adapt to system properties and application needs.*

RAS Framework

- Pluggable component framework.
  - Communication drivers.
  - Group communication.
  - Virtual synchrony.
  - *Applications.*
- Interchangeable components.
- Adaptation to application needs, such as level of consistency.
- Adaptation to system properties, such as network and system scale.



Modular HA Framework on Active/Active Head Nodes: Scheduler Example

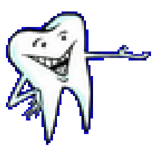


No Single Point of Failure

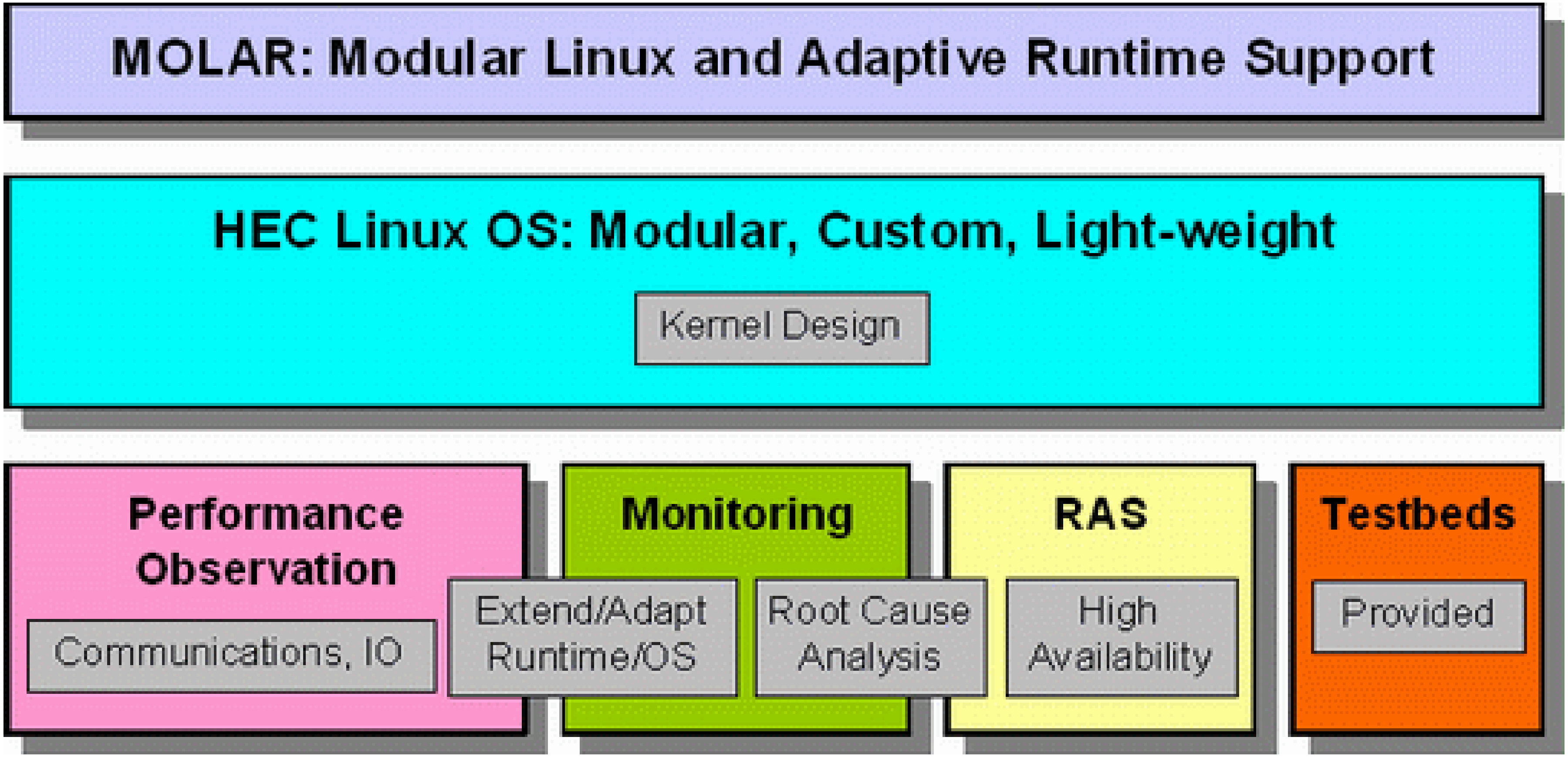
No Single Point of Control

MOLAR: Modular Linux and Adaptive Runtime Support for High-end Computing Operating and Runtime Systems

- The HA Framework is part of the MOLAR project.
- MOLAR addresses the challenges for operating and runtime systems to run large applications efficiently on future ultra-scale high-end computers.
- MOLAR is a collaborative effort:



MOLAR: HEC OS/R Research Map



Super-Scalable Algorithms for Computing on 100,000 Processors

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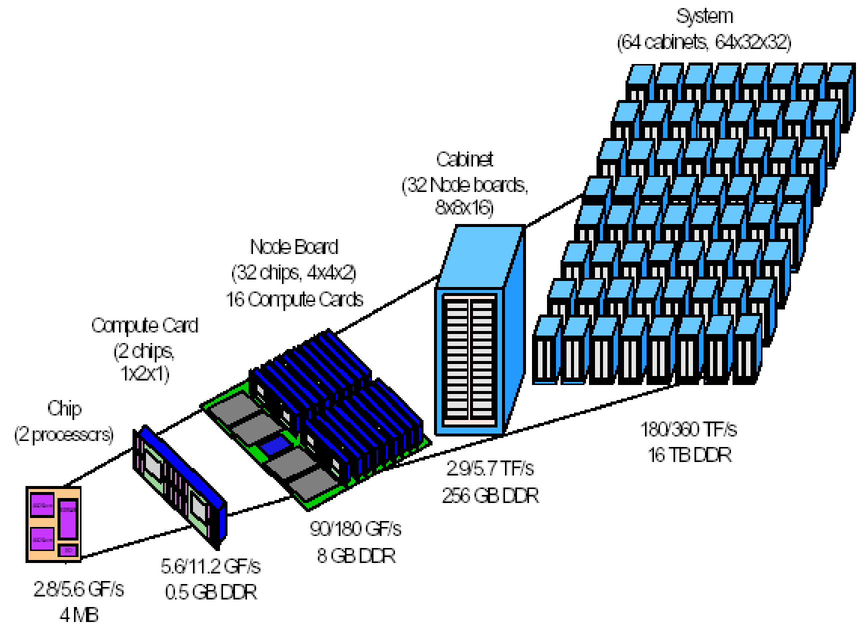
Super-Scale Architectures

- Current tera-scale supercomputers have up to 10,000 processors.
- Next generation peta-scale systems will have 100,000 processors and more.
- Such machines may easily scale up to 1,000,000 processors in the next decade.
- IBM is currently deploying the Blue Gene/L system at research institutions world-wide.

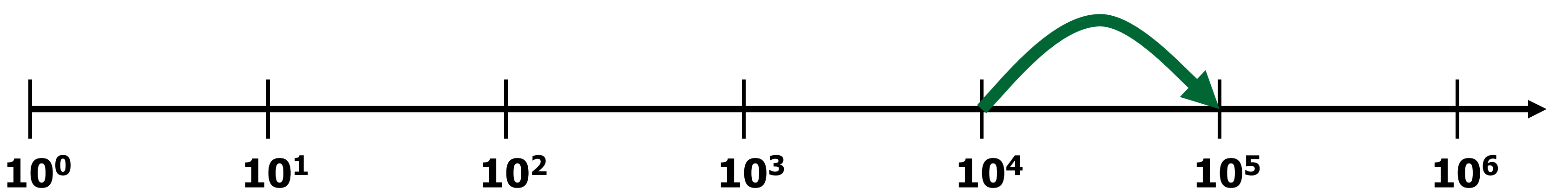
IBM Blue Gene/L

- 64K diskless nodes with 2 processors per node.
- 512MB RAM per node.
- Additional service nodes.
- 360 Tera FLOPS.
- Over 150k processors.
- Various networks.
- Operational in 2005.
- Partition (512 nodes) outages on single failure.
- MTBF = hours, minutes?



Scalability Issues

- How to make use of 100,000 processors?
- System scale jumps by a magnitude.
- Current algorithms do not scale well on existing 10,000-processor systems.
- Next generation super-scale systems are useless if efficiency drops by a magnitude.

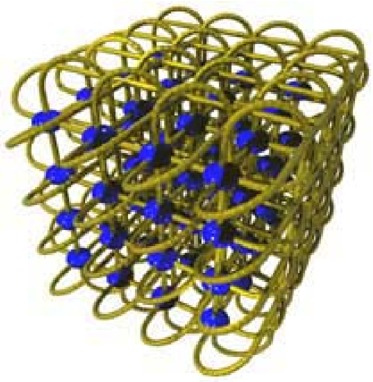


Fault-tolerance Issues

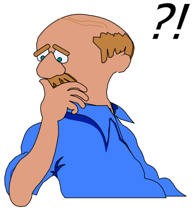
- How to survive on 100,000 processors?
- Failure rate grows with the system size.
- Mean time between failures (MBTF) may be a few hours or just a few minutes.
- Current solutions for fault-tolerance rely on checkpoint/restart mechanisms.
- Checkpointing 100,000 processors to central stable storage is not feasible anymore.

ORNL/IBM Collaboration

- Development of biology and material science applications for super-scale systems.
- Exploration of super-scalable algorithms.
  - Natural fault-tolerance.
  - Scale invariance.
- Focus on test and demonstration tool.

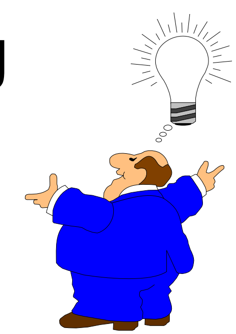


- <u>Get scientists to think about scalability and fault-tolerance in super-scale systems!</u>



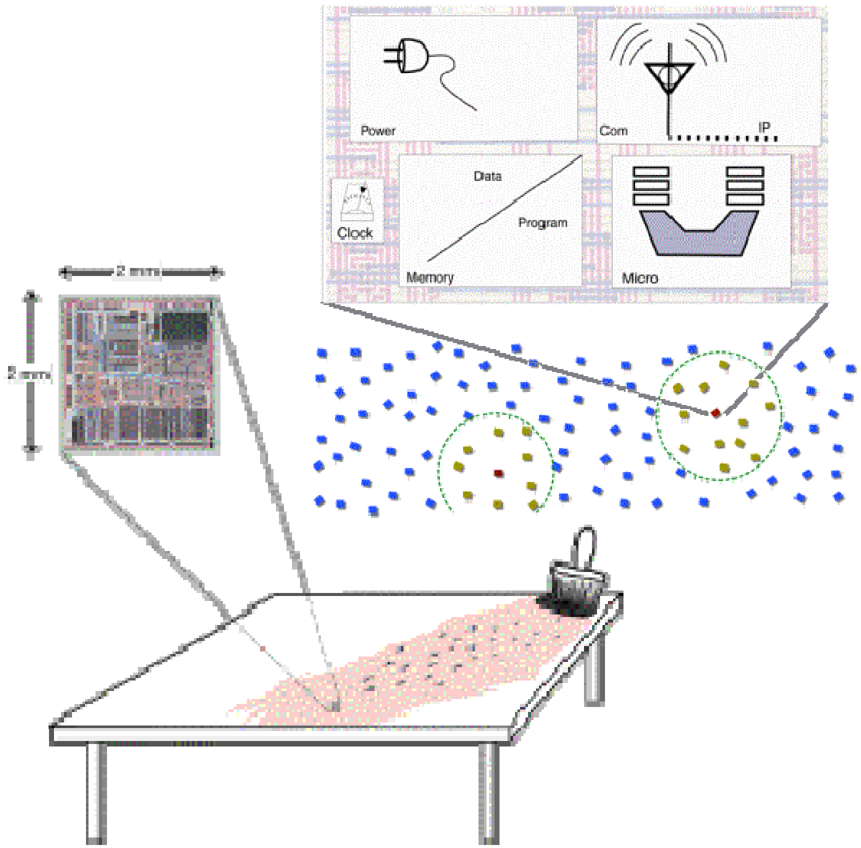
Cellular Algorithms Theory

- Processes have only limited knowledge mostly about other processes in their neighborhood.
- Application is composed of local algorithms.
- Less inter-process dependencies, e.g not everyone needs to know when a process dies.
- Peer-to-peer communication with overlapping neighborhoods promotes scalability.



- MIT Media Lab. Research: Paintable Computing.

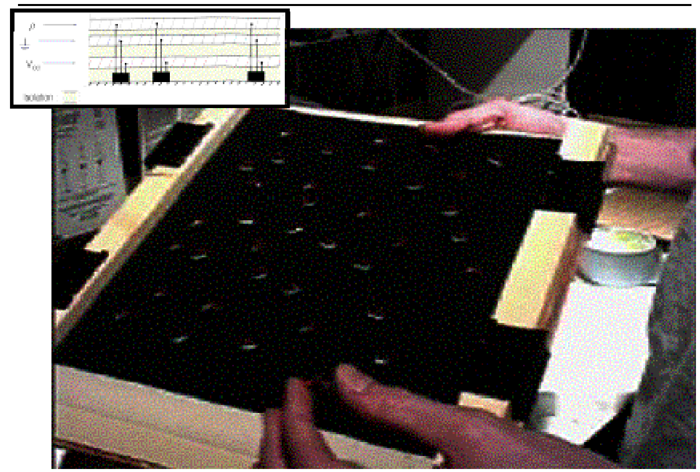
MIT Research: Paintable Computing

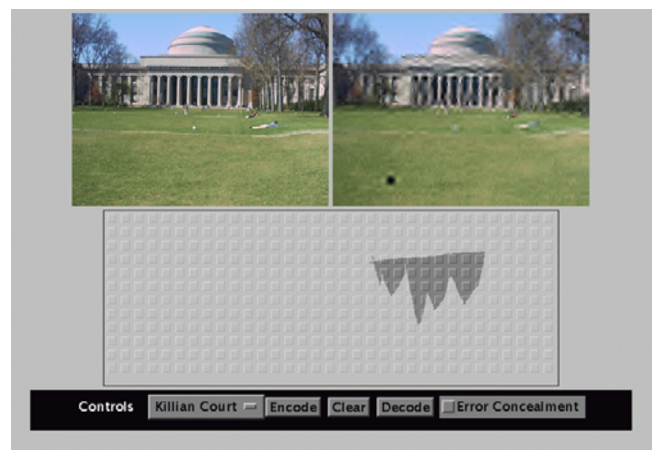


- In the future, embedded computers with a radio device will get as small as a paint pigment.
- Supercomputers can be easily assembled by just painting a wall of embedded computers.
- Applications are driven by cellular algorithms.

MIT Research: Pushpin Computing

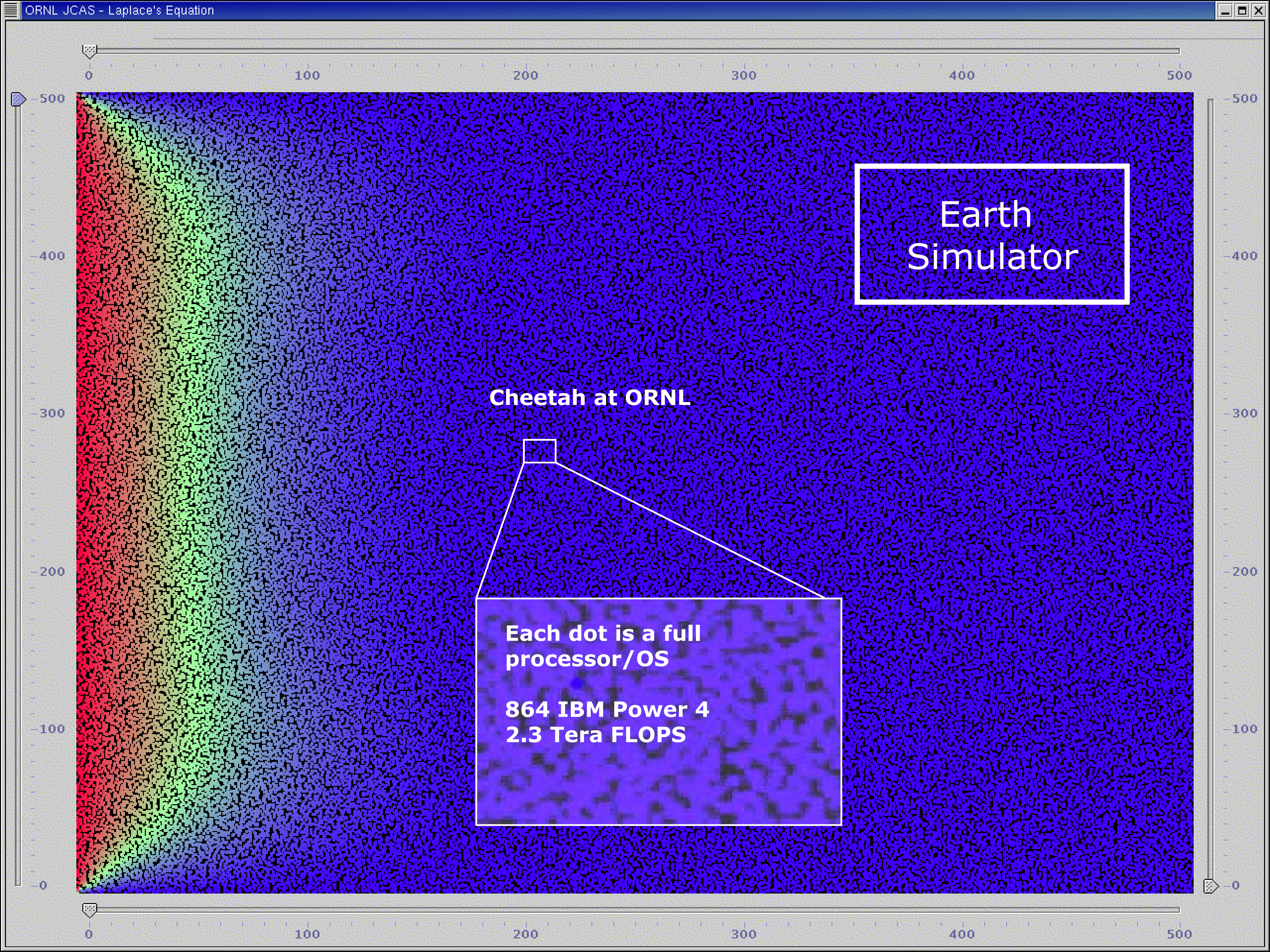
- 100 embedded nodes.
- 1.25m x 1.25m pushpin board provides power.
- Initial applications:
  - Distributed audio stream storage.
  - Fault-tolerant holistic data (image) storage.
- Ongoing research:
  - Sensor networks.

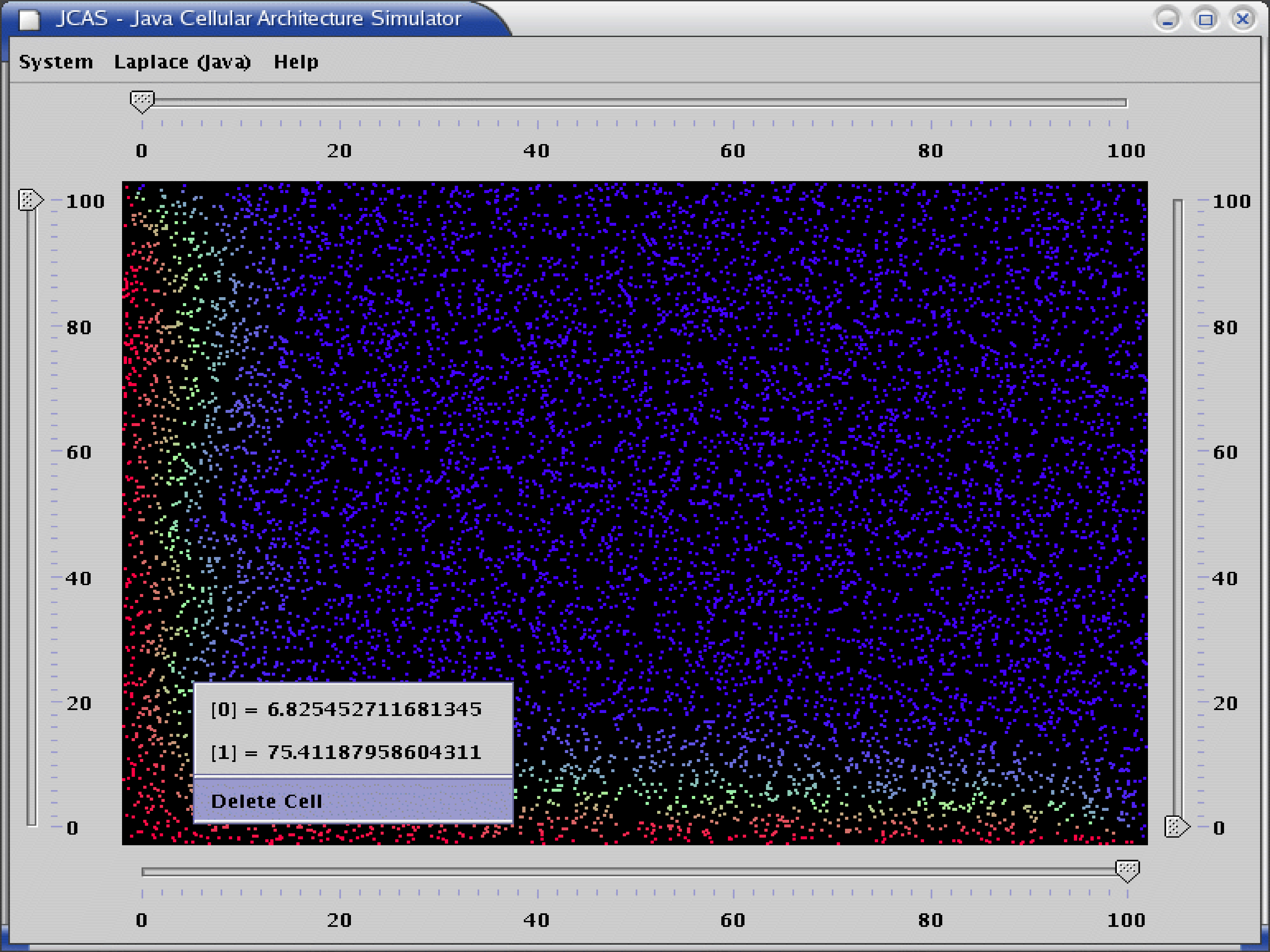




Cellular Architecture Simulator

- Developed at ORNL in Java with native C and Fortran application support using JNI.
- Runs as standalone or distributed application.
- Lightweight framework simulates up to 1,000,000 lightweight processes on 9 real processors.
- Standard and experimental networks:
  - Multi-dimensional mesh/torus.
  - Nearest/Random neighbors.
- Message driven simulation is not in real-time.
- Primitive fault-tolerant MPI support.


ORNL JCAS - Laplace's Equation
0
100
200
300
400
500
Earth Simulator
Cheetah at ORNL
Each dot is a full processor/OS
864 IBM Power 4
2.3 Tera FLOPS


JCAS - Java Cellular Architecture Simulator
System
Laplace (Java)
Help
0
20
40
60
80
100
[0] = 6.825452711681345
[1] = 75.41187958604311
Delete Cell

Super-scalable Algorithms Research

- Extending the cellular algorithms theory to real world scientific applications.
- Exploring super-scale properties:
  - Scale invariance – fixed scaling factor that is independent from system and application size.
  - Natural fault-tolerance – algorithms get the correct answer despite failures without checkpointing.
- Gaining experience in programming models for computing on 100,000 processors.

Explored Super-scalable Algorithms

- Local information exchange:
  - Local peer-to-peer updates of values.
  - Mesh-free chaotic relaxation (Laplace/Poisson).
  - Finite difference/element methods.
  - Dynamic adaptive refinement at runtime.
  - Asynchronous multi-grid with controlled or independent updates between different layers.
- Global information exchange:
  - Global peer-to-peer broadcasts of values.
  - Global maximum/optimum search.

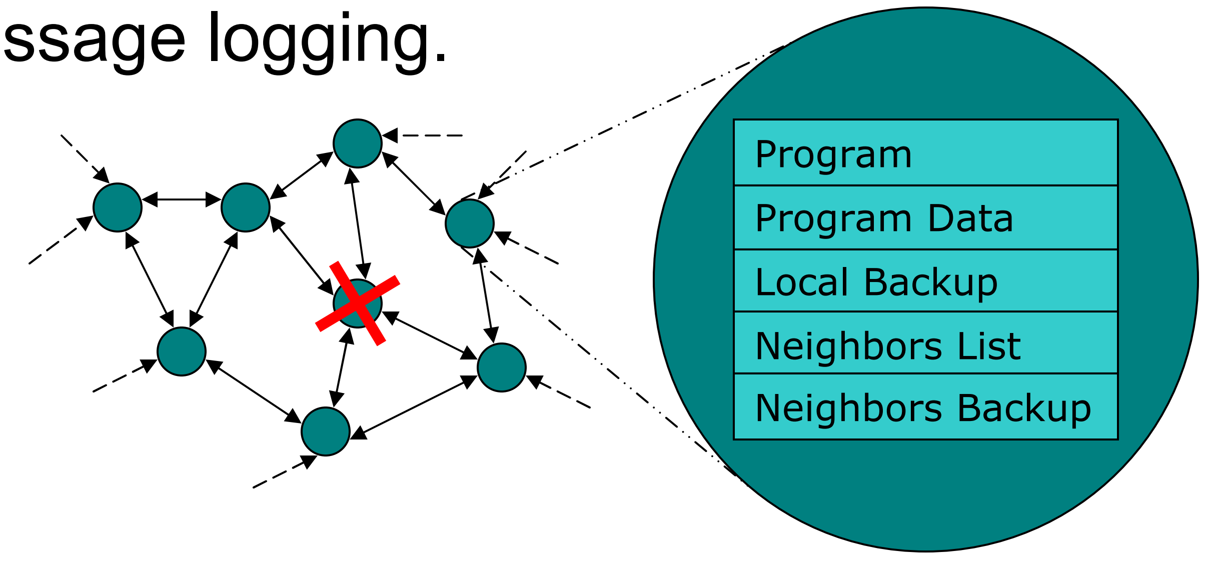
Super-scalable Fault Tolerance

- For non-naturally fault tolerant algorithms.
- Does it makes sense to restart all 100,000 processes because of one failure?
- The mean time between failures (MTBF) is likely to be a few hours or just a few minutes.
- Traditional centralized checkpointing and message logging are limited by bandwidth (bottleneck).

→ Frequent checkpointing decreases app. efficiency.
→ The failure rate is going to outrun the recovery rate.

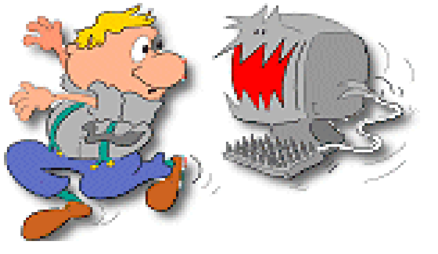
Super-scalable Diskless Checkpointing

- Decentralized peer-to-peer checkpointing.
- Processors hold backups of neighbors.
- Local checkpoint and restart algorithm.
- Coordination of local checkpoints.
- Localized message logging.



Super-scalable Algorithms Research

- Super-scale systems with 100,000 and more processors become reality very soon.
- Super-scalable algorithms that are scale invariant and naturally fault-tolerant do exist.
- Diskless peer-to-peer checkpointing provides an alternative to natural fault-tolerance.
- A lot of research still needs to be done.



Conclusions

- Oak Ridge National Laboratory performs basic and applied research in various areas.
- Capability computing is ORNLs path to world-class leadership computing.
- Next generation ultra-scale scientific high-end computing is a research challenge for:
  - Application software fault-tolerance.
  - High availability system software.
  - Super-scalable algorithms.

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High Availability for Ultra-Scale High-End Scientific Computing

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