System Software for Petascale and Beyond

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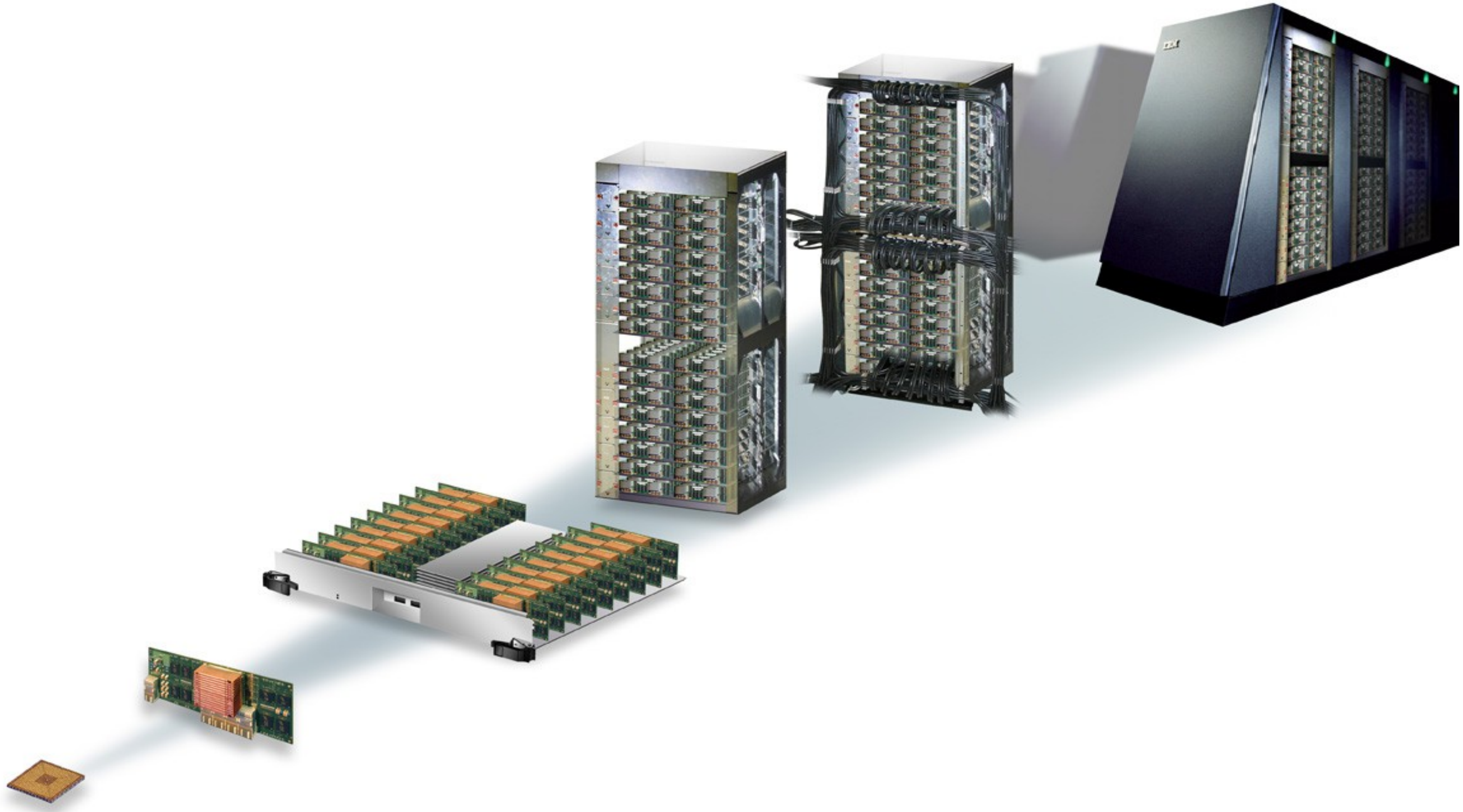
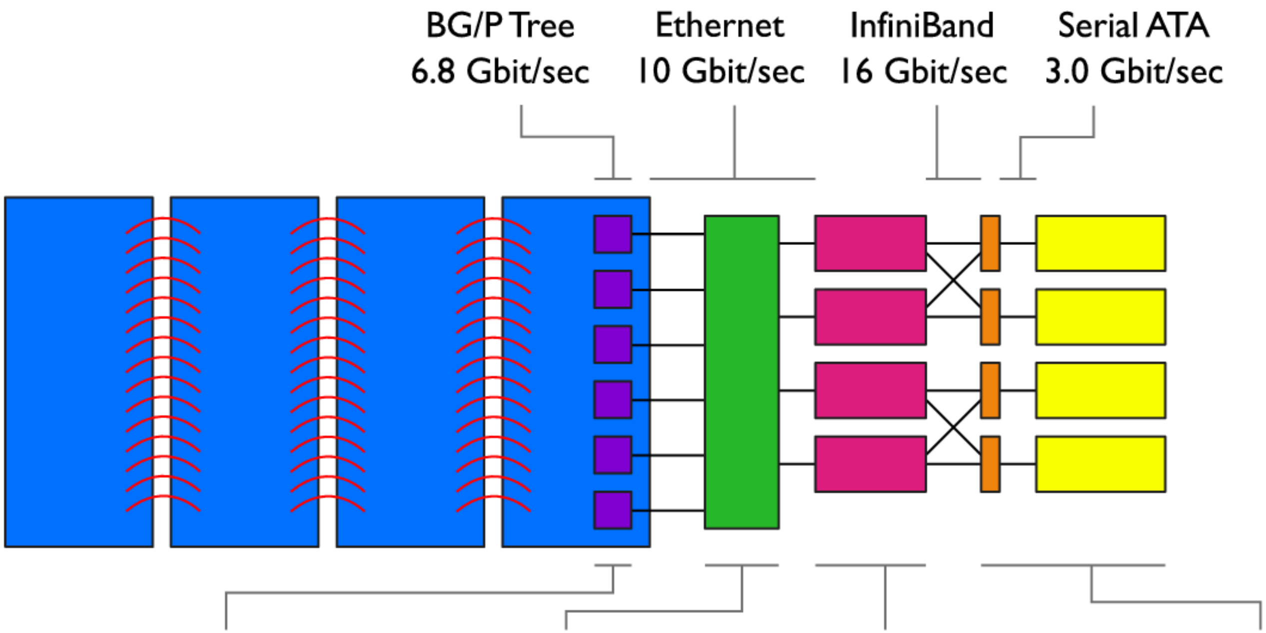
Today’s Petascale Platforms



Today's Petascale Platforms



Gateway nodes run parallel file system client software and forward I/O operations from HPC clients.

640 Quad core PowerPC 450 nodes with 2 Gbytes of RAM each

Commodity network primarily carries storage traffic.

900+ port 10 Gigabit Ethernet Myricom switch complex

Storage nodes run parallel file system software and manage incoming FS traffic from gateway nodes.

136 two dual core Opteron servers with 8 Gbytes of RAM each

Enterprise storage controllers and large racks of disks are connected via InfiniBand or Fibre Channel.

17 DataDirect S2A9900 controller pairs with 480 1 Tbyte drives and 8 InfiniBand ports per pair

Systems are Changing…

- New Constraints:
  - Transistors still scale
  - Clock leveled off (2–4 GHz)
  - Power leveled off (100–200 W)
  - ILP leveled off (2–4 ops/cycle)
- 15 years of *exponential* clock rate growth has ended
- Moore's Law reinterpreted:
  - *Parallelism* doubles every 18 months (cores or threads)

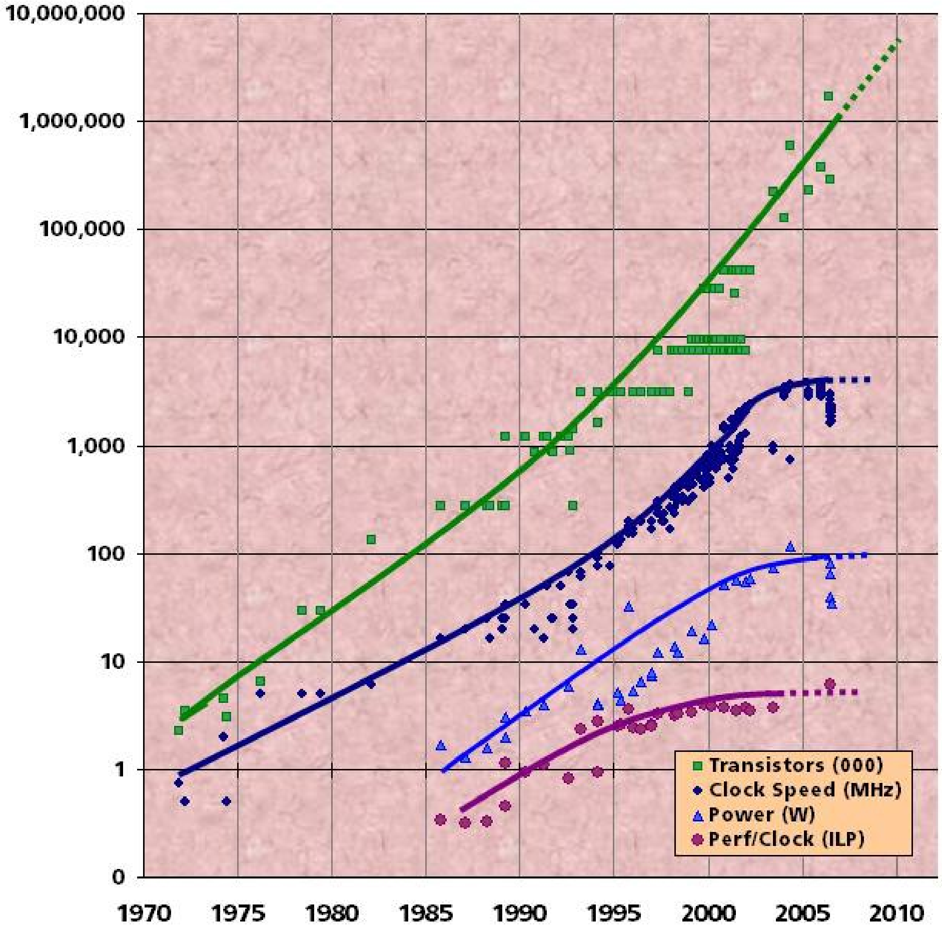


Figure courtesy of Kunle Olukotun, Lance Hammond, Herb Sutter, and Burton Smith

Key Challenges

- OS kernel
- I/O infrastructure
- Parallel programming infrastructure
- Performance analysis
- Fault tolerance
- Resource management

Two main approaches towards solving them:

- Scale an existing general-purpose solution
  - familiar to future users of the system
- Develop something from scratch
  - domain-specific, complete control

RADIX Laboratory for Scalable System Software

- OS kernel: ZeptoOS
- I/O infrastructure: PVFS2, ROMIO, IOFSL, Darshan
- Parallel programming infrastructure: MPICH2
- Performance analysis: Jumpshot, Jupiter
- Fault tolerance: CIFTS
- Resource management: Cobalt, SPRUCE

- Part of Argonne's Mathematics and Computer Science Division
  - ~15 staff
  - ~5 postdocs
  - ~15 students during the summer

radix

laboratory for scalable parallel system software

OS Kernel

Lightweight OS Kernels

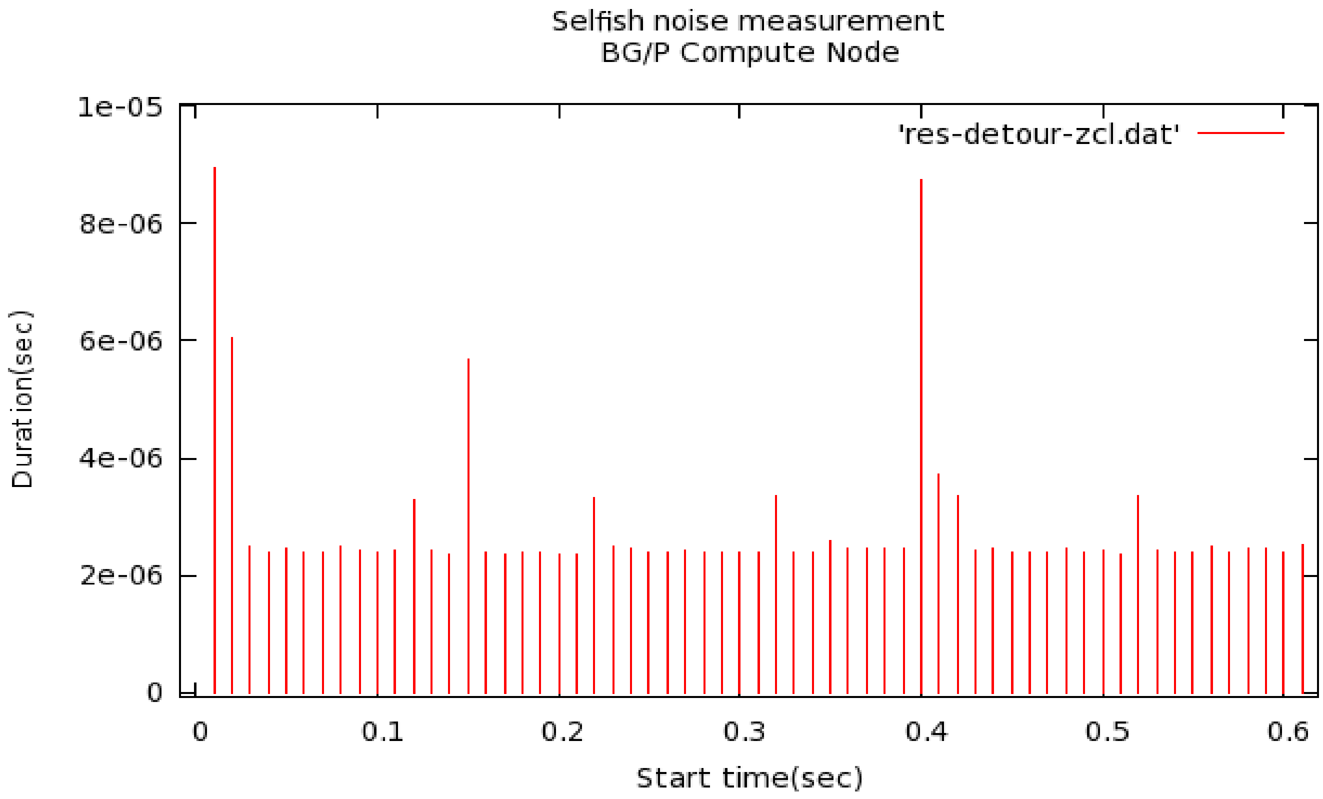
- IBM Blue Gene: CNK
  - cycle-reproducible
  - lean (can be run under the cycle simulator)
  - no virtual memory
  - no preemption, max. 4 threads/node
  - no fork/exec
- Cray XT3: Catamount
  - (similar limitations)
  - basically abandoned by now; new XTs come with Compute Node Linux
- Kitten
  - new open source kernel from Sandia

Linux on Compute Nodes

- Why do it?
  - features (threads, multitasking, shell scripts, Java, Python)
  - user familiarity in HPC environments
  - code portability
  - research platform
  - leverage large community of independent developers
- Key challenges:
  - jitter/noise
  - paged memory overhead
  - support for high-speed networks

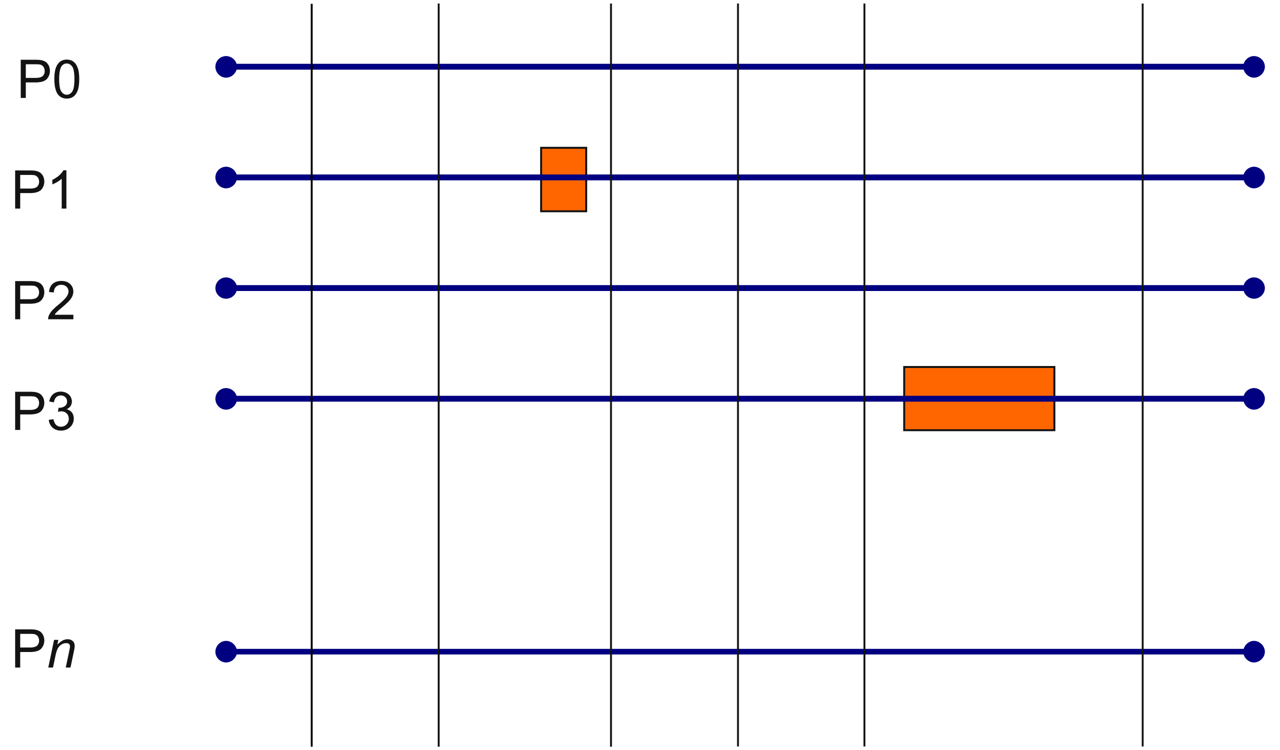
http://www.zeptoos.org/

OS Jitter



- Device interrupts
- Clocktick
- Preemptive scheduling

OS Jitter: At Scale

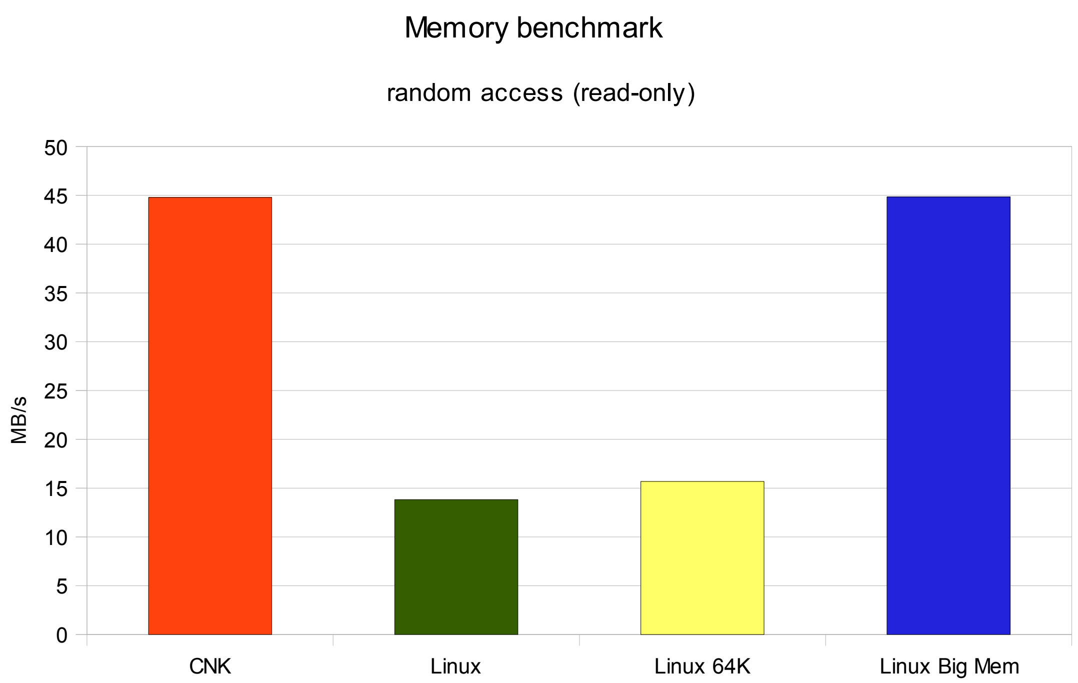


- Random detours on individual nodes delay all other nodes participating in collective operations

OS Jitter: Research Results

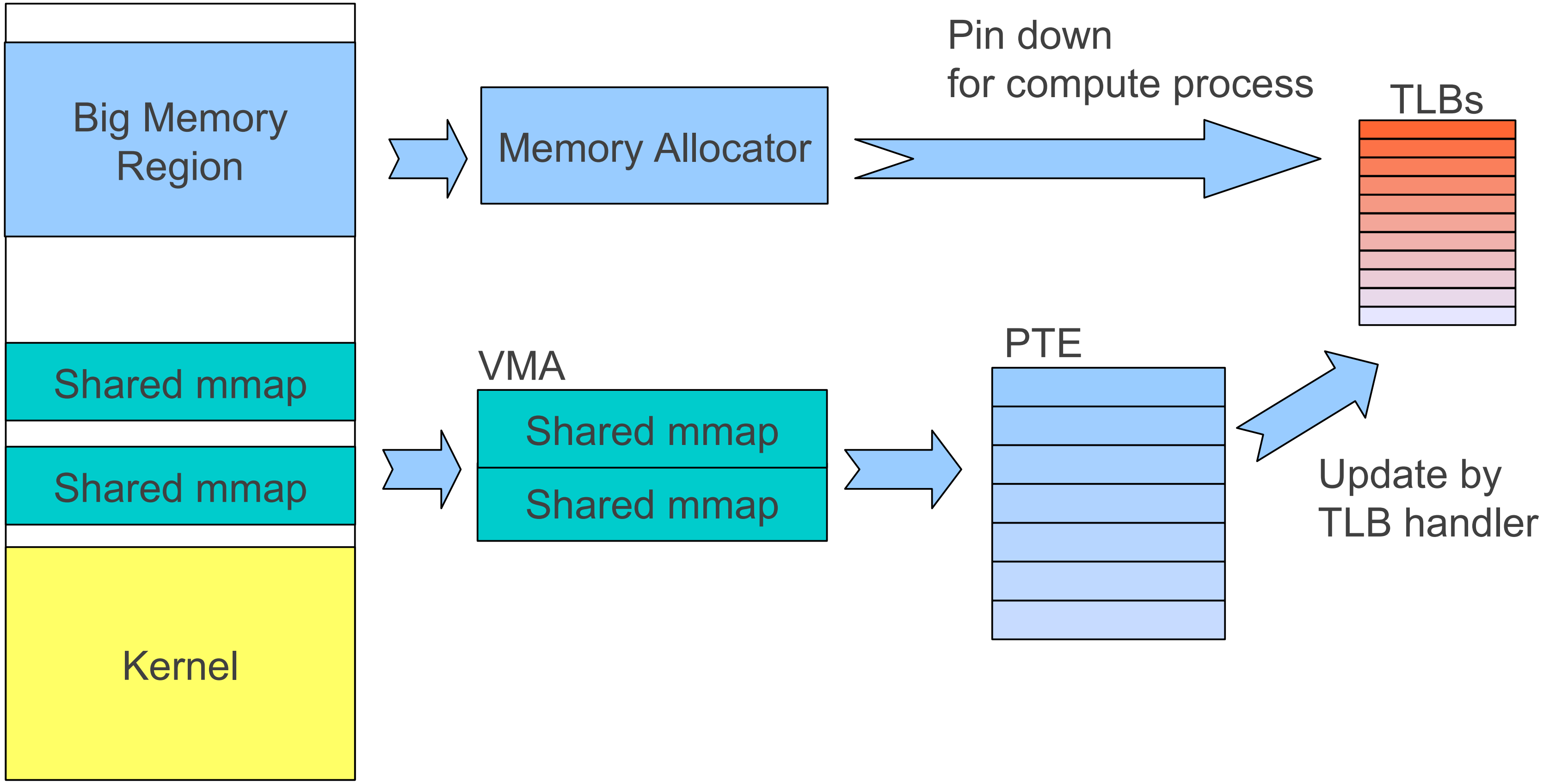
- Large-scale noise injection experiments:
  - longest detours most detrimental
  - short but frequent ones not really a problem
  - synchronizing detours across nodes eliminates the OS jitter problem
- Medium-scale experiments with Linux on BG/P:
  - OS jitter does not impede scalability
  - even on a vanilla kernel
- Future:
  - mainline developments in the area of tickless kernel

Memory Management



- Paged memory up to 6x slower than a static mapping
- Caused by a high cost of TLB misses on PPC450 CPUs

Memory Management: Big Memory



- Allocated at boot time
- Covered by large, semi-static TLBs
- Simple physical to virtual address mapping

Memory Management: Research Results

- Big Memory closes the performance gap
- This is not just a Blue Gene issue
  - *A big memory job can get a 40-50% performance improvement if it is the very first job* [after reboot, on mainstream hardware] — Don Becker, Penguin Computing
- Future:
  - short-term trends in CPUs: more flexibility (MMU in next generation BG, 1 GB pages in AMD “Barcelona”)

High Speed Networks

- Blue Gene has a high-speed 3D torus network between the compute nodes, with a DMA engine.
- The DMA engine lacks scatter/gather support required for paged memory.
- Big Memory resolves this problem by providing a physically contiguous memory region.

I/O

Compute and Storage Imbalance

A supercomputer is a device for turning compute-bound problems into I/O-bound problems — Seymour Cray/Ken Batcher

Current leadership-class machines supply only **1 GB/s of storage throughput for every 10 TF of compute performance**. This gap has grown by a factor of 10 in recent years.

Argonne's 557 TF Blue Gene/P (Intrepid):

- 20% of the budget spent on I/O
- Full memory dump takes over 30 minutes
  - How long does it take on your laptop?

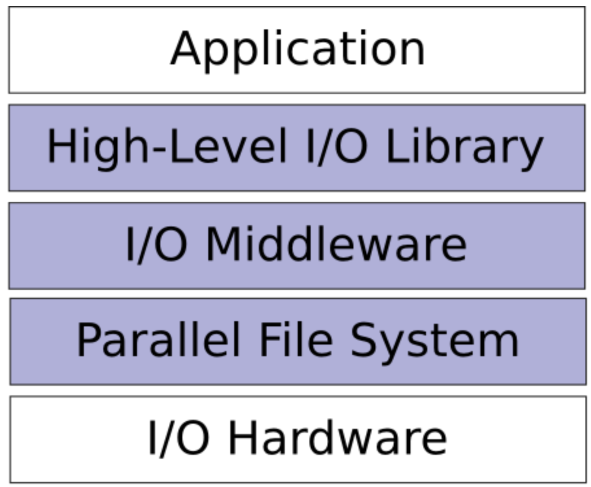
(Sad) State of the Art…

- Typical HPC file system is a scaled up version of an enterprise product
  - Very expensive at this scale
    - Big network switch needed
  - Unsuitable API
    - Who needs POSIX locks?
- Example problems:
  - Parallel mkdir takes 10 minutes!
    - GPFS with 640 clients gives 1 mkdir/s!
  - Unaligned writes orders of magnitude slower
    - Check out the PLFS work (LANL/CMU/PSC)
  - Have you ever done “svn update” of a large repo on GPFS?
- Parallel filesystem stability/performance possibly the largest problem on contemporary large-scale systems.

Software Complexity

High-Level I/O Library
maps application abstractions onto storage abstractions and provides data portability.

HDF5, Parallel netCDF, ADIOS



I/O Middleware
organizes accesses from many processes, especially those using collective I/O.

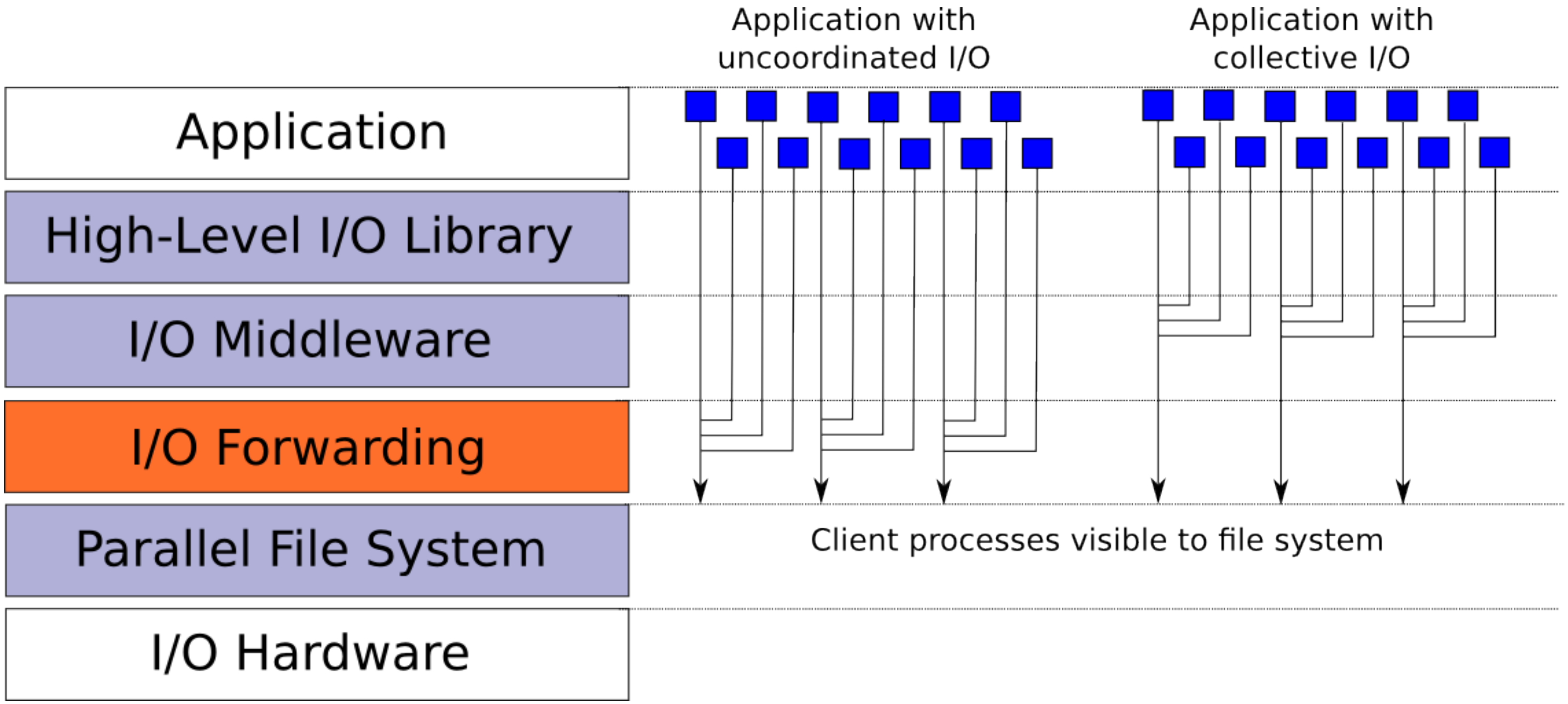
MPI-IO

Parallel File System
maintains logical space and provides efficient access to data.

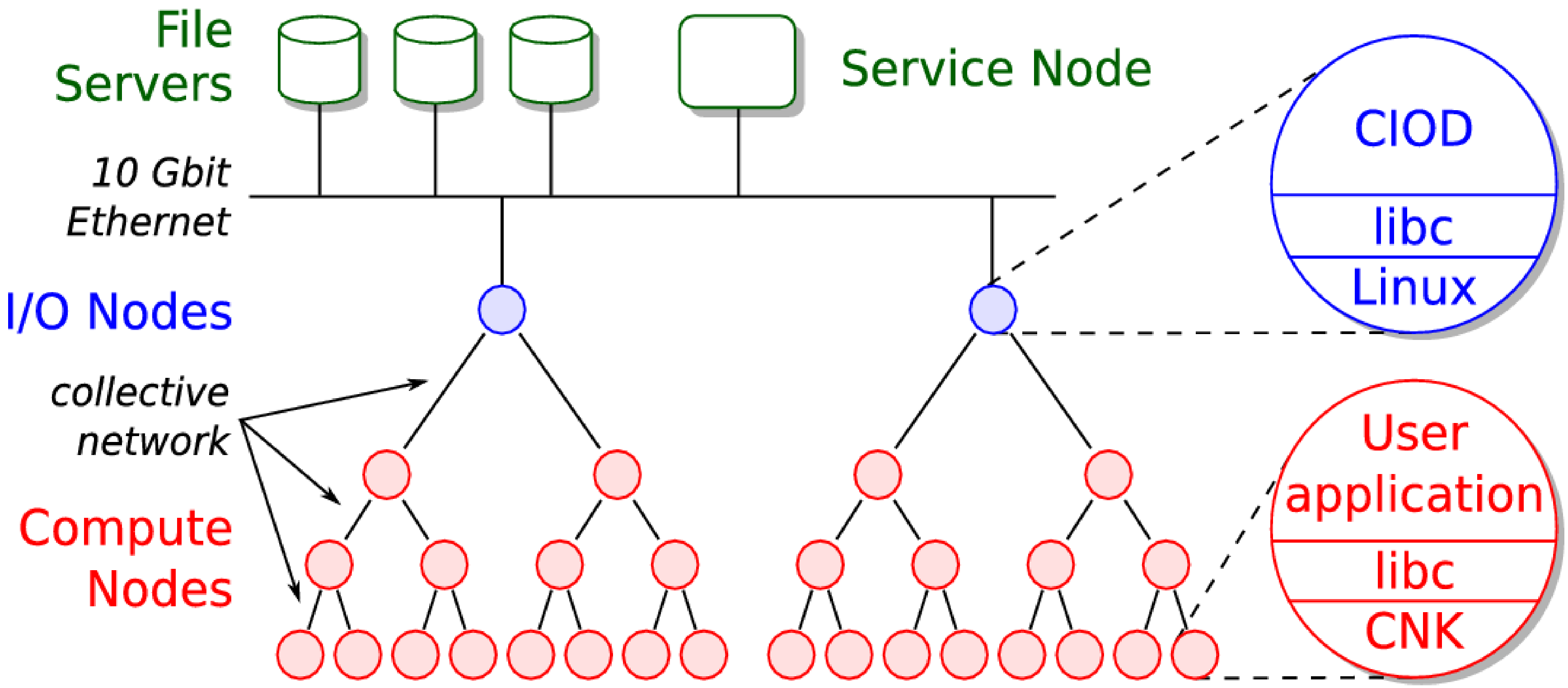
PVFS, PanFS, GPFS, Lustre

[Part of the] Solution: I/O Forwarding

- I/O Forwarding is an additional I/O software layer for leadership-class machines that bridges the gap between application process and file systems. It reduces the number of clients seen by the file system for all applications, even without collective I/O.

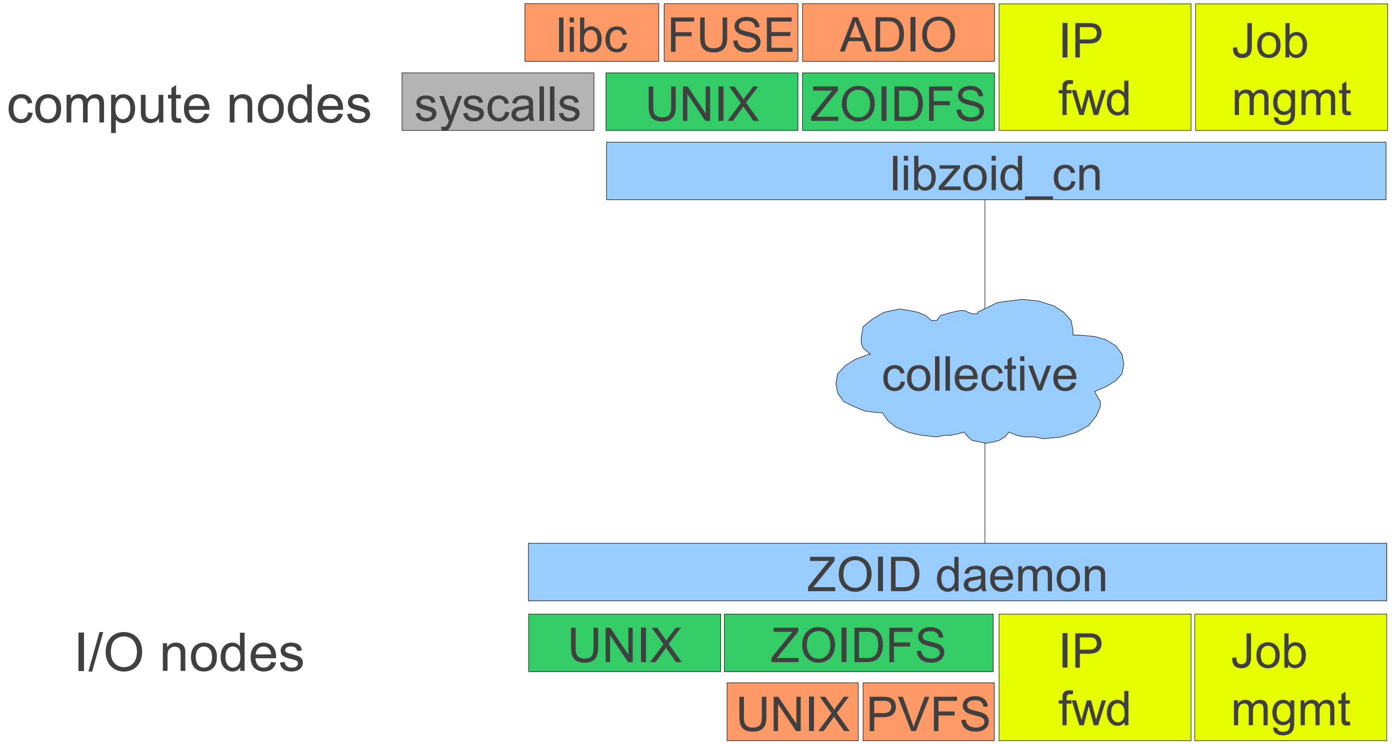


I/O Forwarding on Blue Gene



- POSIX-only
- No aggregation, no caching
- Not extensible

ZOID: Low-Level Function Shipping Infrastructure



The IOFSL Project

Design, build, and distribute a scalable, unified high-end computing I/O forwarding software layer that would be adopted and supported by DOE Office of Science and NNSA.

- Reduce the number of file system operations/clients that the parallel file system sees
- Provide function shipping at the file system interface level
- Offload file system functions from simple or full OS client processes to a variety of targets
- Support multiple parallel file system solutions and networks
- Integrate with MPI-IO and any hardware features designed to support efficient parallel I/O

http://www.iofsl.org/

ZOIDFS Protocol

- Opaque handles used to reference files
  - Portable across nodes
- Flexible read and write operations
  - Vectors of memory buffers and file regions
- Minimizes state to improve scalability
- Reduces the number of I/O operations
- Enables middleware optimizations
- Example call:

```
int zoidfs_read(const zoidfs_handle_t *handle,
                zoidfs_size_t mem_count,
                void *mem_starts[],
                const zoidfs_size_t mem_sizes[],
                zoidfs_size_t file_count,
                const zoidfs_ofs_t file_starts[],
                zoidfs_size_t file_sizes[]);
```

IOFSL: Performance Optimizations

- Reduced number of metadata operations
  - Lookup a handle from one process, broadcast to others via MPI
- Reduced number of file data operations
  - Complex datatypes can be handled with a single call
- Pipelining
  - Large I/O operations exposed to the forwarding server
  - Simultaneous transfer of data between CN-ION and ION-FS
- Aggregation
  - Reduce the number of requests
- Caching of file data and metadata

Results

ZeptoOS Matches the Performance of CNK…

- NAS Parallel Benchmarks (class C / 1024 nodes)

	CNK (Mop/s)	Zepto (Mop/s)	Zepto/CNK
IS	3990.92	4009.76	1.005
CG	15749.35	15706.83	0.997
MG	134955.02	134380.19	0.996
FT	96594.32	96385.49	0.998
LU	40889.58	40616.70	0.993
EP	2503.11	2499.84	0.999
SP	106009.42	105708.94	0.997
BT	165240.30	164777.07	0.997

- NAS Parallel Benchmarks FT (class D)

	CNK (Mop/s)	Zepto (Mop/s)	Zepto/CNK
1024	217666.44	216916.86	0.997
4096	371444.68	372516.63	1.003
8192	768919.56	768431.17	0.999

… And Sometimes Exceeds It

- Parallel Ocean Program

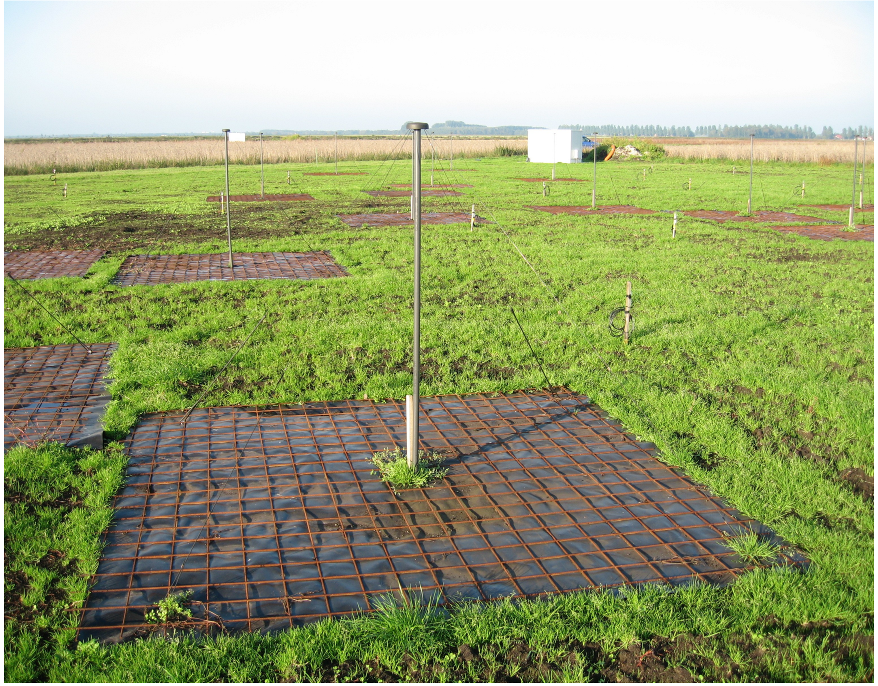
	CNK (s)	Zepto (s)	CNK/Zepto
64	196.62	197.26	0.997
128	105.69	105.59	1.001
256	57.37	57	1.006
512	34.98	34.49	1.014
1024	22.37	21.89	1.022
2048	16.74	16.32	1.026
4096	14.54	14.10	1.031

- Caused by `gettimeofday()` being 7x more expensive under CNK

LOFAR

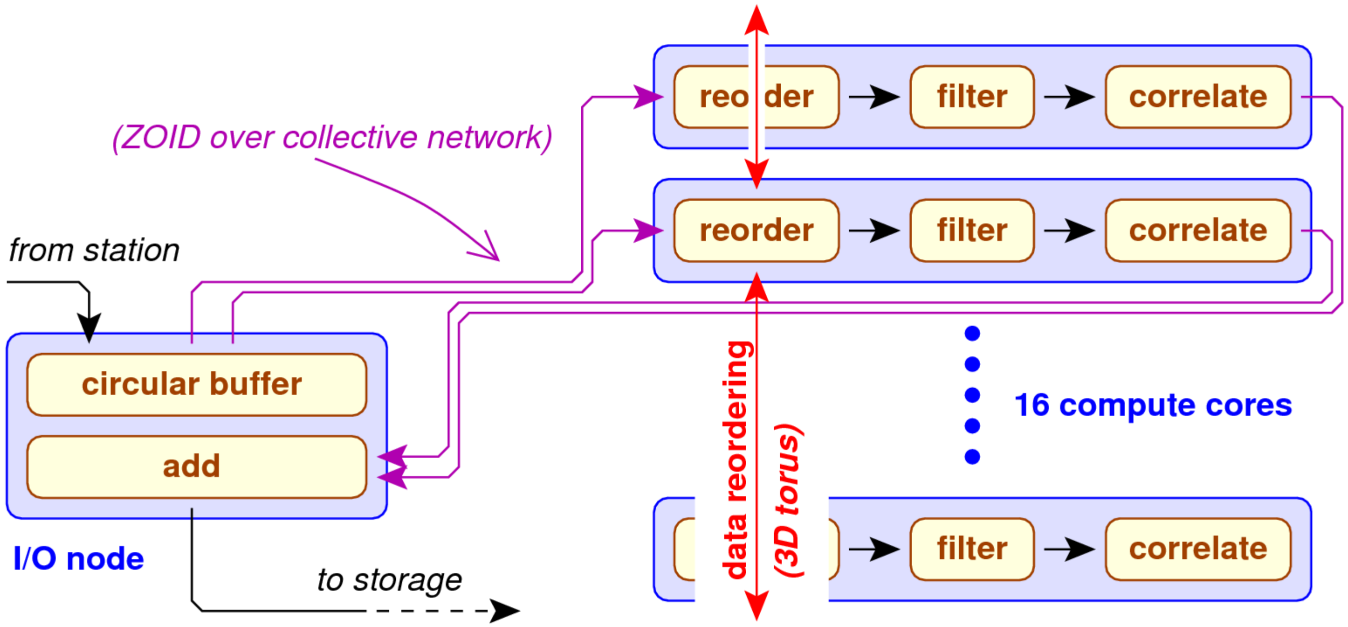
LOw Frequency Array

- revolutionary radio telescope
  - no dishes
  - *O*(10000) receivers
  - omni-directional
- central processing
  - real time
  - *software*
  - BG/P supercomputer



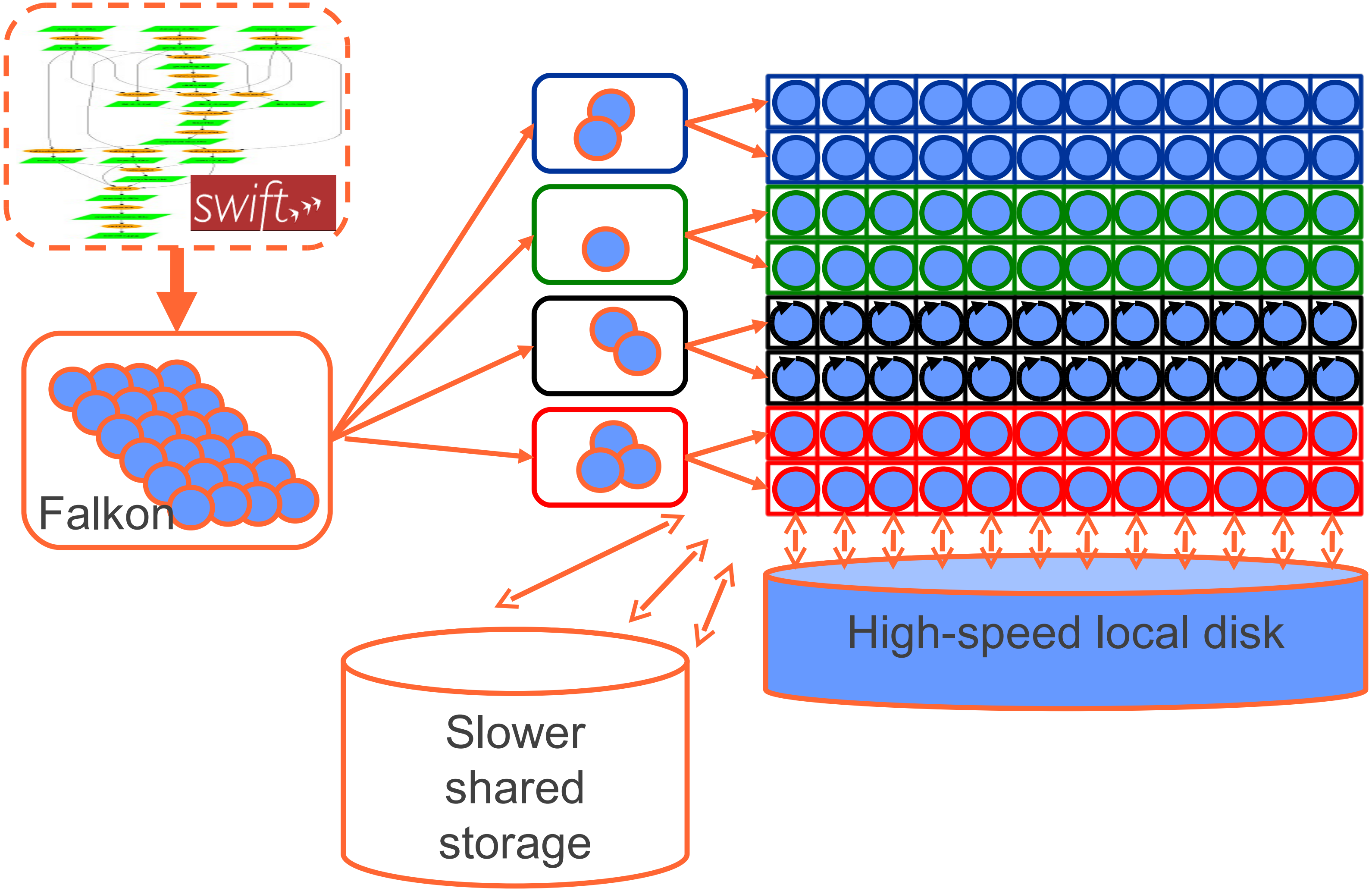
LOFAR BG/L Processing with ZOID

- reorder, filter, correlate data
- use ZOID plug-in on I/O node

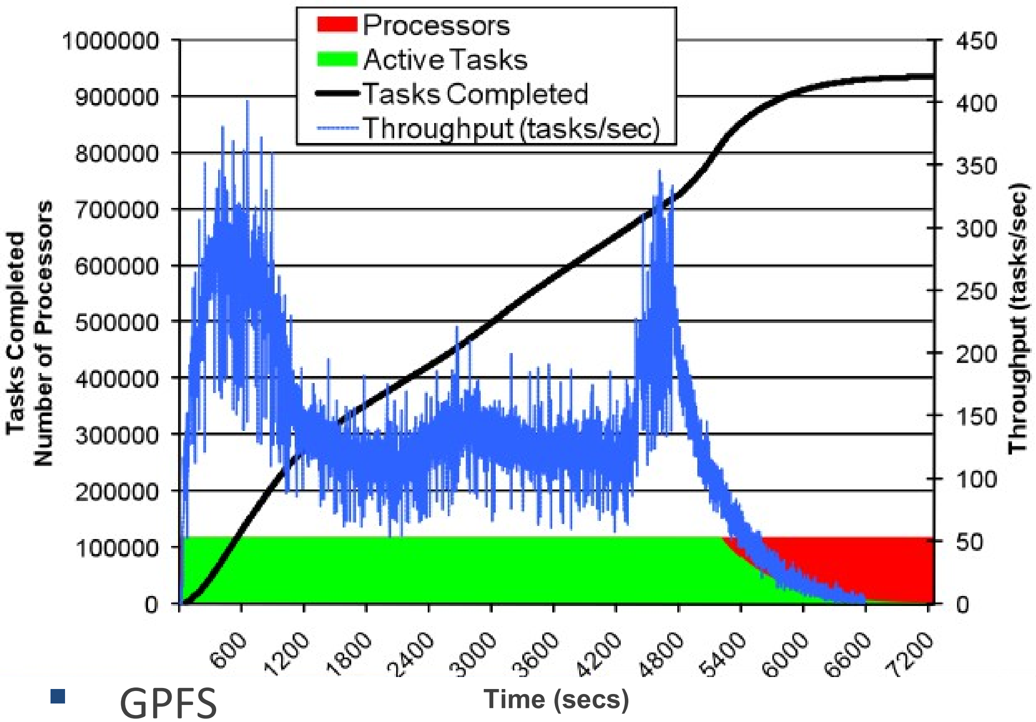


- application on I/O node: no need for input cluster

Falkon: Managing 160,000 CPUs



DOCK on BG/P: ~1M Tasks on 118,000 CPUs



- CPU cores: 118784
- Tasks: 934803
- Elapsed time: 7257 sec
- Compute time: 21.43 CPU years
- Average task time: 667 sec
- Relative Efficiency: 99.7%
  - (from 16 to 32 racks)
- Utilization:
  - Sustained: 99.6%
  - Overall: 78.3%

- GPFS
  - 1 script (~5KB)
  - 2 file read (~10KB)
  - 1 file write (~10KB)
- RAM (cached from GPFS on first task per node)
  - 1 binary (~7MB)
  - static input data (~45MB)

Other Issues

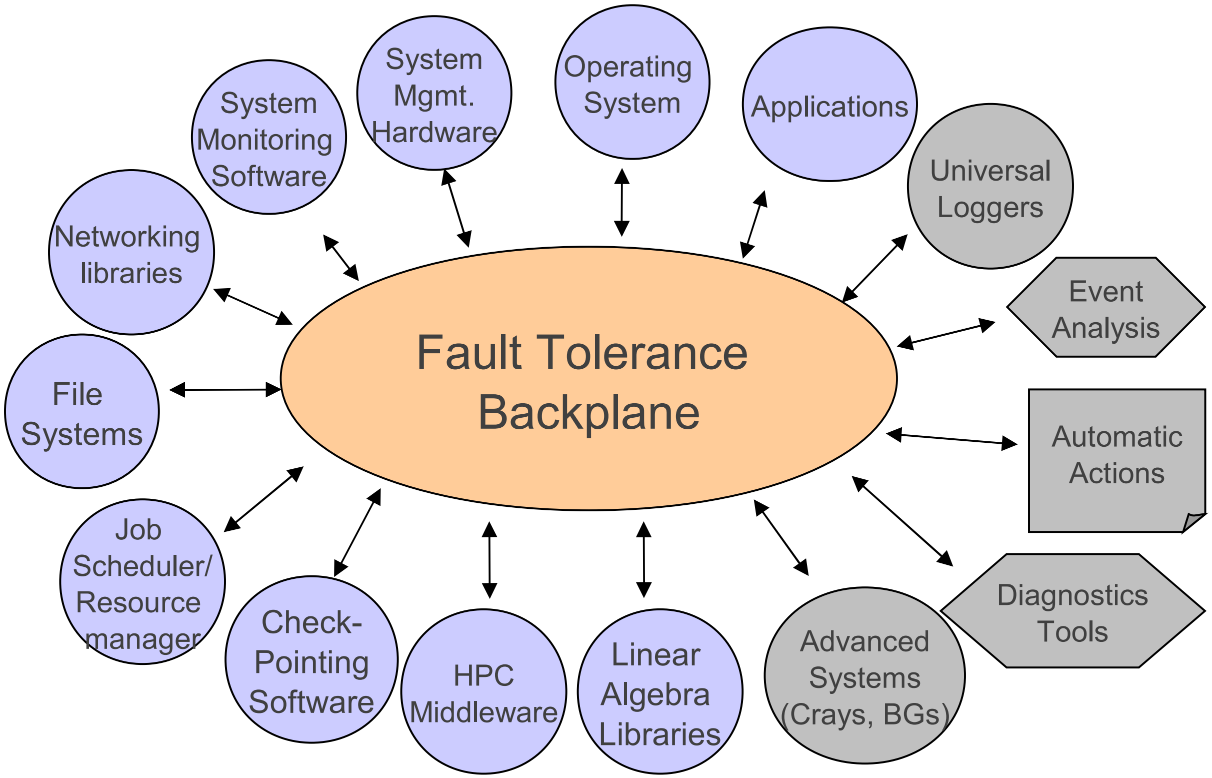
Fault tolerance: CIFTS

Coordinated Infrastructure for Fault Tolerant Systems

- Traditional fault tolerance is handled by individual components
- No coordination between them
- No sharing of fault information
- Components don't know the reason for system-wide faults
  - Did the application exit due to an inherent error in the code?
  - Did it exit due to a system failure?

http://www.mcs.anl.gov/research/cifts/

CIFTS



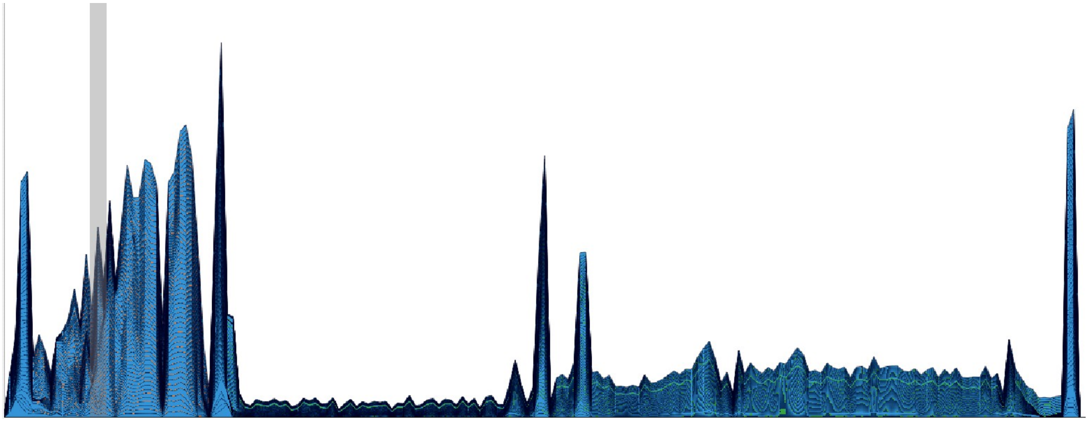
- Fault Tolerance Backplane:
  - Provides a scalable framework to exchange fault-related information
  - Exposes a standard interface that can be used by any component
  - Provides a uniform event handling and notification mechanism

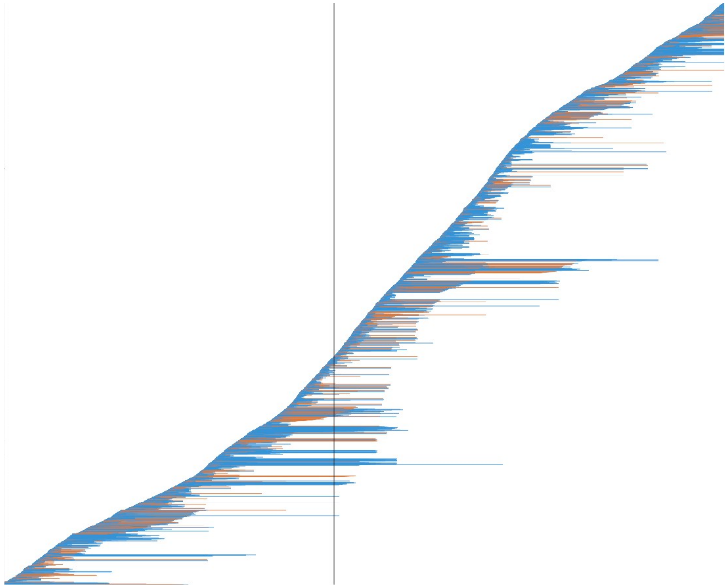
Performance Analysis: Jupiter

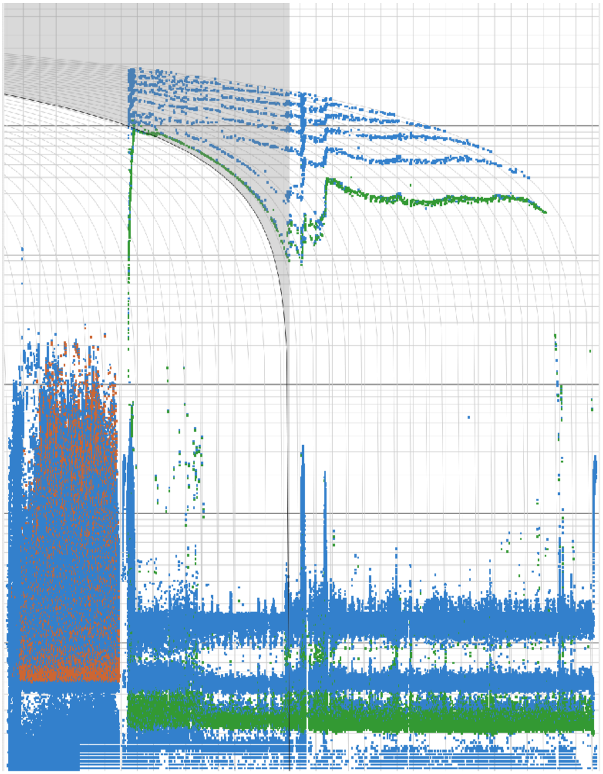
Visual Characterization of I/O System Behavior for High-End Computing

- Plenty of research on application performance analysis and debugging tools
- The needs of system software developers often overlooked
  - a high-scale parallel filesystem is a complex parallel application
- Develop/improve/deploy:
  - end-to-end, scalable tracing integrated into the I/O system (MPI-IO, I/O forwarding, file systems),
  - new visual representations and analysis techniques for inspecting traces and extracting knowledge, scalable to very large systems and integrable with existing techniques

Jupiter

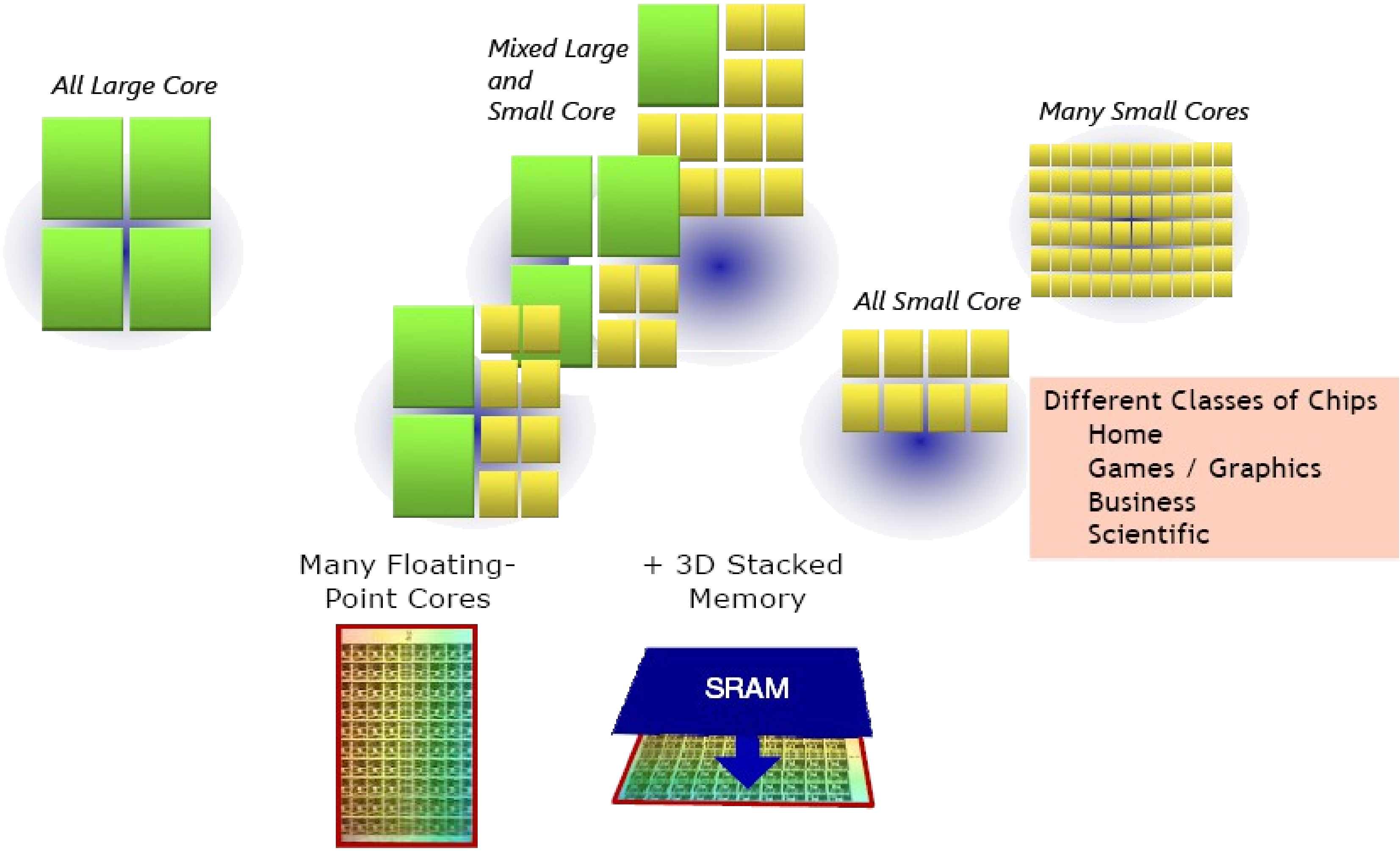






Conclusion

What’s Next?



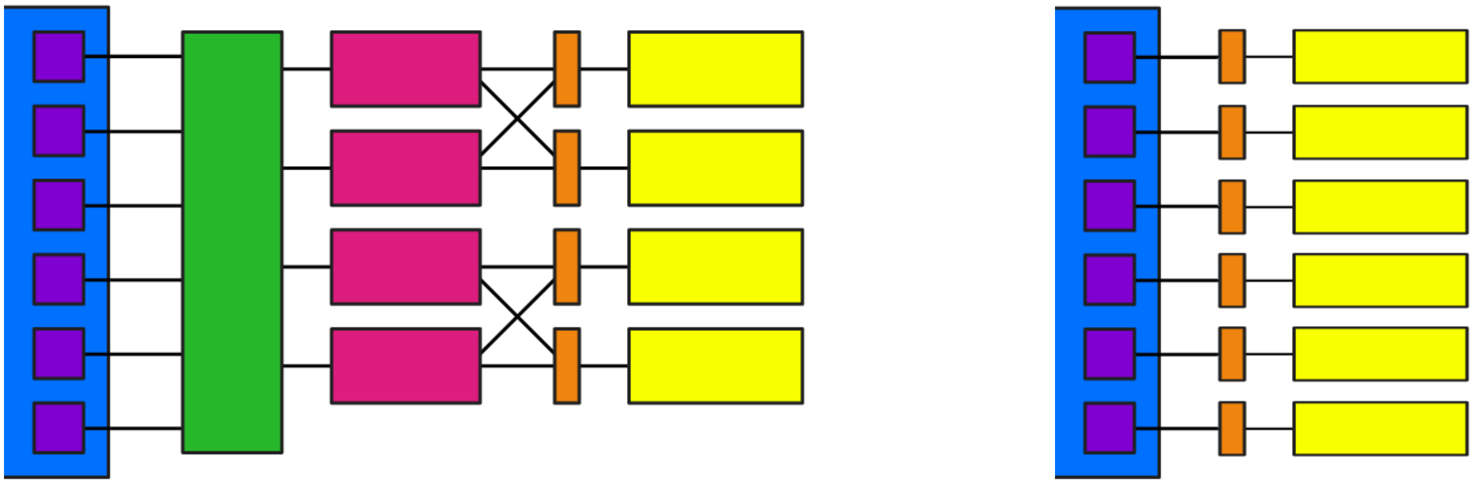
Source: Jack Dongarra, ISC 2008

The Big Questions

- Extreme-scale operating systems will be even more challenging on emerging next-generation hardware
  - Large multi-core
  - Heterogeneous cores
  - Hierarchical
- What should the OS stack look like?
  - virtualization/partitioning?
    - For example: should we partition OS services to n–1th core?
  - I/O forwarding inside each compute node?

Could We Get Rid of Enterprise Storage in HPC?

- What if we collapse I/O forwarding nodes and file server nodes?



- What is the difference?
  - no external network switch
  - high-speed HPC network used instead

Collaborators

- RADIX: Kazutomo Yoshii, Harish Naik, Pete Beckman, Dries Kimpe, Jason Cope, Rob Ross, Phil Carns, Sam Lang, Rob Latham, Rinku Gupta, Rusty Lusk
- Project partners:
  - University of Oregon: Allen Malony, Sameer Shende, Aroon Nataraj, Alan Morris
  - Los Alamos: James Nunez, John Bent, Gary Grider, Sean Blanchard, Latchesar Ionkov, Hugh Greenberg
  - Oak Ridge: Steve Poole, Terry Jones
  - Sandia: Lee Ward
  - UC Davis: Kwan-Liu Ma, Chris Muelder
- External collaborators:
  - ASTRON (Netherlands Institute for Radio Astronomy): John W. Romein, P. Chris Broekema
  - University of Chicago: Michael Wilde, Zhao Zhang, Ioan Raicu, Allan Espinoza
  - University of Delaware: Guang R. Gao, Handong Ye
- Summer students: Nawab Ali, Ivan Beschastnikh, Peter Boonstoppel, Hajime Fujita, Valerie Galluzzi, Jason Kotenko, Alex Nagelberg, Kazuki Ohta, Satya Popuri, Taku Shimosawa, Zichen Xu, Kazunori Yamamoto