Why Nobody Should Care About Operating Systems for Exascale

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Outline

- Background
- DOE Exascale Initiative
- Exascale runtime systems
- Co-Design

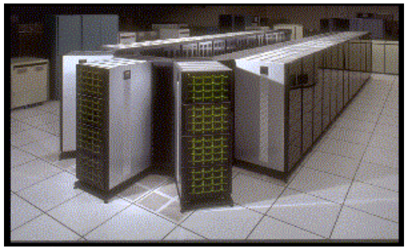
Sandia Massively Parallel Systems

1990

nCUBE2

- Sandia's first large MPP
- Achieved Gflops performance on applications

1993



Paragon

- Tens of users
- First periods processing MPP
- World record performance
- Routine 3D simulations
- SUNMOS lightweight kernel

1997

ASCI Red

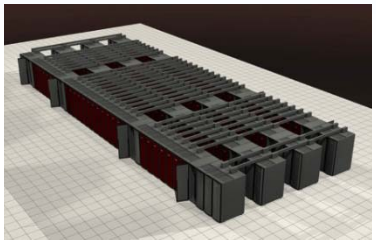
- Production MPP
- Hundreds of users
- Red & Black partitions
- Improved interconnect
- High-fidelity coupled 3-D physics
- Puma/Cougar lightweight kernel

1999

Cplant

- Commodity-based supercomputer
- Hundreds of users
- Enhanced simulation capacity
- Linux-based OS licensed for commercialization
- ~2000 nodes

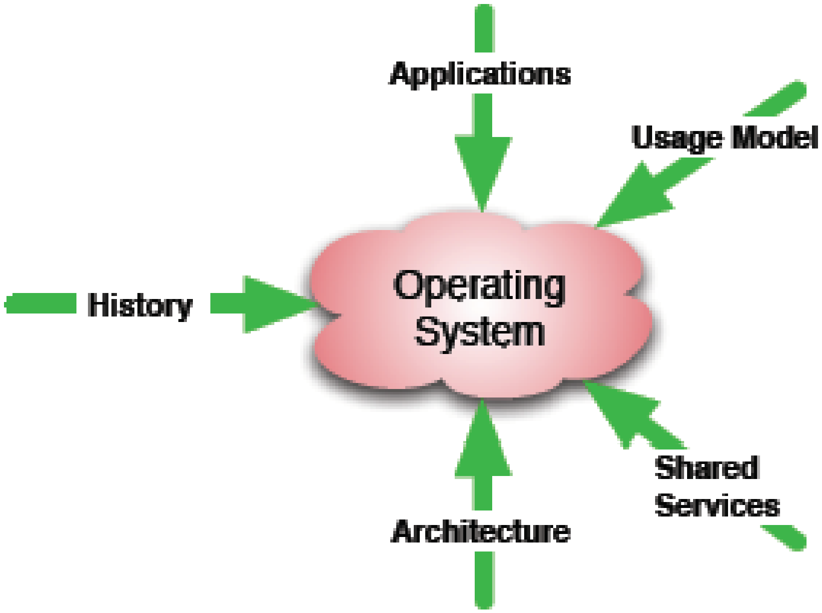
2004



Red Storm

- Prototype Cray XT
- Custom interconnect
- Purpose built RAS
- Highly balanced and scalable
- Catamount lightweight kernel
- Currently 38,400 cores (quad & dual)

Factors Influencing OS Design



- Lightweight OS
  - Small collection of apps
    - Single programming model
  - Single architecture
  - Single usage model
  - Small set of shared services
  - No history
- Puma/Cougar/Catamount
  - MPI
  - Distributed memory
  - Space-shared
  - Parallel file system
  - Batch scheduler

Sandia Lightweight Kernel Targets

- Massively parallel, extreme-scale, distributed-memory machine with a tightly-coupled network
- High-performance scientific and engineering modeling and simulation applications
- Enable fast message passing and execution
- Small memory footprint
- Persistent (fault tolerant)
- Offer a suitable development environment for parallel applications and libraries
- Emphasize efficiency over functionality
- Maximize the amount of resources (e.g. CPU, memory, and network bandwidth) allocated to the application
- Seek to minimize time to completion for the application
- Provide deterministic performance

Lightweight Kernel Approach

- Separate policy decision from policy enforcement
- Move resource management as close to application as possible
- Protect applications from each other
- Let user processes manage resources (via libraries)
- Get out of the way

Reasons for A Specialized Approach

- Maximize available compute node resources
  - Maximize CPU cycles delivered to application
    - Minimize time taken away from application process
    - No daemons
    - No paging
    - Deterministic performance
  - Maximize memory given to application
    - Minimize the amount of memory used for message passing
    - Kernel size is static
    - Somewhat less important but still can be significant on large-scale systems
  - Maximize memory bandwidth
    - Uses large page sizes to avoid TLB flushing
  - Maximize network resources
    - Physically contiguous memory model
    - Simple address translation and validation
      - No NIC address mappings to manage
- Increase reliability
  - Relatively small amount of source code
  - Reduced complexity
  - Support for small number of devices

Basic Principles

- Logical partitioning of nodes
- Compute nodes should be independent
  - Communicate only when absolutely necessary
- Limit resource use as much as possible
  - Expose low-level details to the application-level
  - Move complexity to application-level libraries
- KISS
  - Massively parallel computing is inherently complex
  - Reduce and eliminate complexity wherever possible

Quintessential Kernel (QK)

- Policy enforcer
- Initializes hardware
- Handles interrupts and exceptions
- Maintains hardware virtual addressing
- No virtual memory support
- Static size
- Non-blocking
- Small number of well-defined entry points

Process Control Thread (PCT)

- Runs in user space
- More privileged than user applications
- Policy maker
  - Process loading
  - Process scheduling
  - Virtual address space management
  - Fault handling
  - Signals
- Customizable
  - Singletasking or multitasking
  - Round robin or priority scheduling
  - High performance, debugging, or profiling version
- Changes behavior of OS without changing the kernel

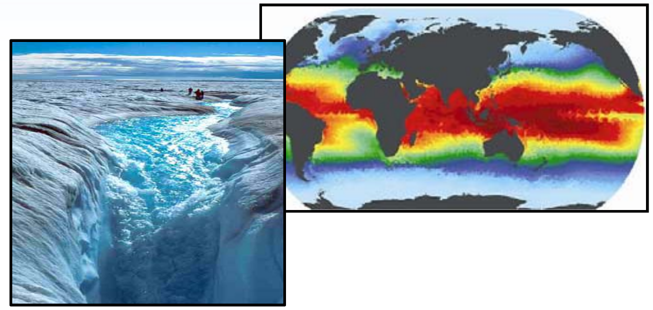
LWK Key Ideas

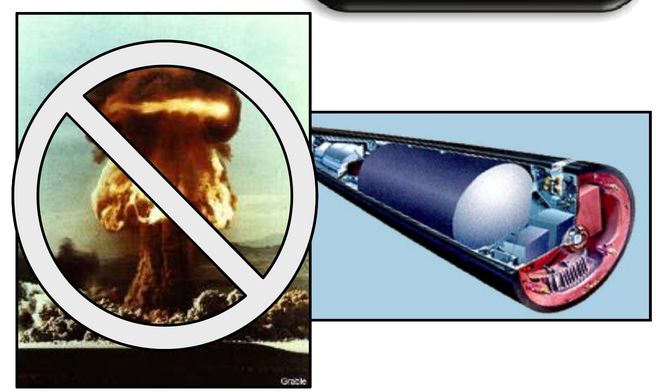
- Protection
  - Levels of trust
- Kernel is small
  - Very reliable
- Kernel is static
  - No structures depend on how many processes are running
- Resource management pushed out to application processes, libraries, and runtime system
- Services pushed out of kernel to PCT and runtime system

DOE Exascale Initiative

DOE mission imperatives require simulation and analysis for policy and decision making

- *Climate Change*: Understanding, mitigating and adapting to the effects of global warming
  - Sea level rise
  - Severe weather
  - Regional climate change
  - Geologic carbon sequestration
- *Energy*: Reducing U.S. reliance on foreign energy sources and reducing the carbon footprint of energy production
  - Reducing time and cost of reactor design and deployment
  - Improving the efficiency of combustion energy systems
- *National Nuclear Security*: Maintaining a safe, secure and reliable nuclear stockpile
  - Stockpile certification
  - Predictive scientific challenges
  - Real-time evaluation of urban nuclear detonation





Accomplishing these missions requires exascale resources.

Potential System Architecture Targets

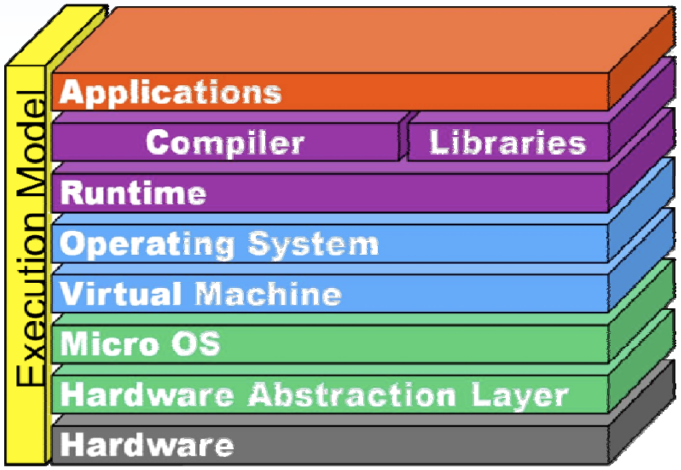
System attributes	2010	"2015-2018"		"2018-2020"	
System peak	2 Peta	200 Petaflop/sec		1 Exaflop/sec	
Power	6 MW	15 MW		20 MW	
System memory	0.3 PB	5 PB		32-64 PB	
Node performance	125 GF	0.5 TF	7 TF	1 TF	10 TF
Node memory BW	25 GB/s	0.1 TB/sec	1 TB/sec	0.4 TB/sec	4 TB/sec
Node concurrency	12	O(100)	O(1,000)	O(1,000)	O(10,000)
System size (nodes)	18,700	50,000	5,000	1,000,000	100,000
Total Node Interconnect BW	1.5 GB/s	20 GB/sec		200 GB/sec	
MTTI	days	O(1day)		O(1 day)	

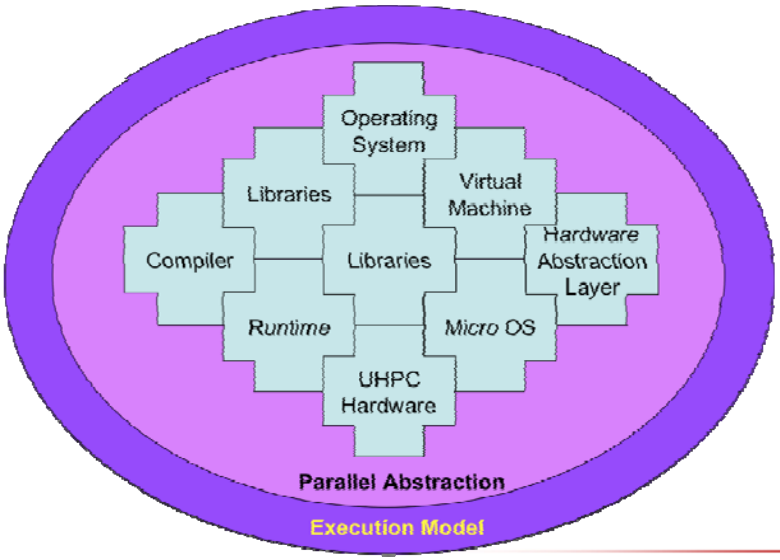
Investment in Critical Technologies is Needed for Exascale

- **System power** is a first class constraint on exascale system performance and effectiveness.
- **Memory** is an important component of meeting exascale power and applications goals.
- Early investment in several efforts to decide in 2013 on exascale **programming model**, allowing exemplar applications effective access to 2015 system for both mission and science.
- Investment in exascale **processor design** to achieve an exascale-like system in 2015.
- **Operating System** strategy for exascale is critical for node performance at scale and for efficient support of new programming models and run time systems.
- **Reliability and resiliency** are critical at this scale and require applications neutral movement of the file system (for check pointing, in particular) closer to the running apps.
- **HPC co-design strategy** and implementation requires a set of a hierarchical performance models and simulators as well as commitment from apps, software and architecture communities.

System software as currently implemented is not suitable for exascale system

- Barriers
  - System management SW not parallel
  - Current OS stack designed to manage only O(10) cores on node
  - Unprepared for industry shift to NVRAM
  - OS management of I/O has hit a wall
  - Not prepared for massive concurrency
- Technical Focus Areas
  - Design HPC OS to partition and manage node resources to support massively concurrency
  - I/O system to support on-chip NVRAM
  - Co-design messaging system with new hardware to achieve required message rates
- Technical gaps
  - 10X: in affordable I/O rates
  - 10X: in on-node message injection rates
  - 100X: in concurrency of on-chip messaging hardware/software
  - 10X: in OS resource management





Software challenges in extreme scale systems, *Sarkar, 2010*

NNSA National Nuclear Security Administration

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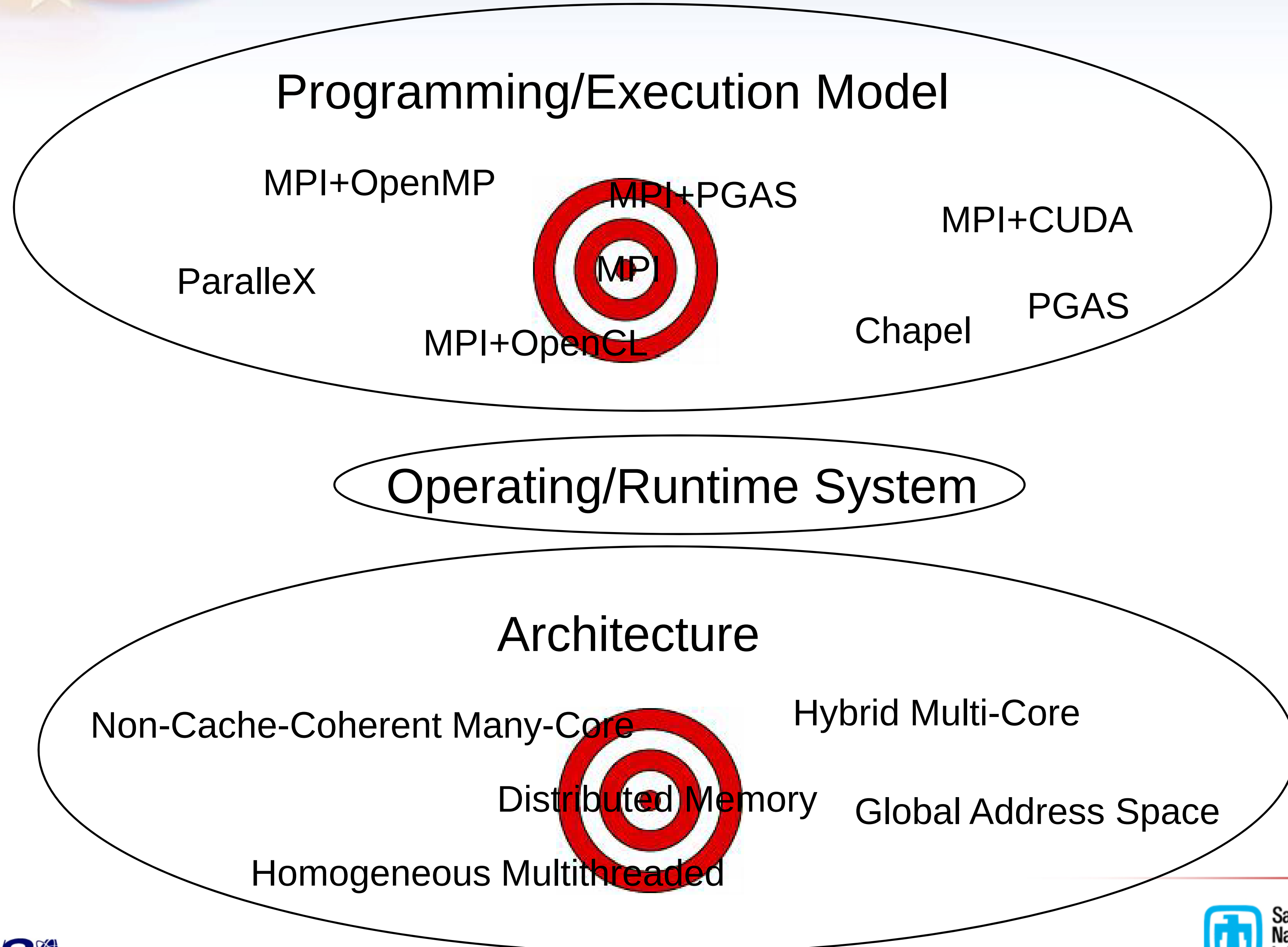
Exascale Challenge for System Software



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Exascale Runtime Systems

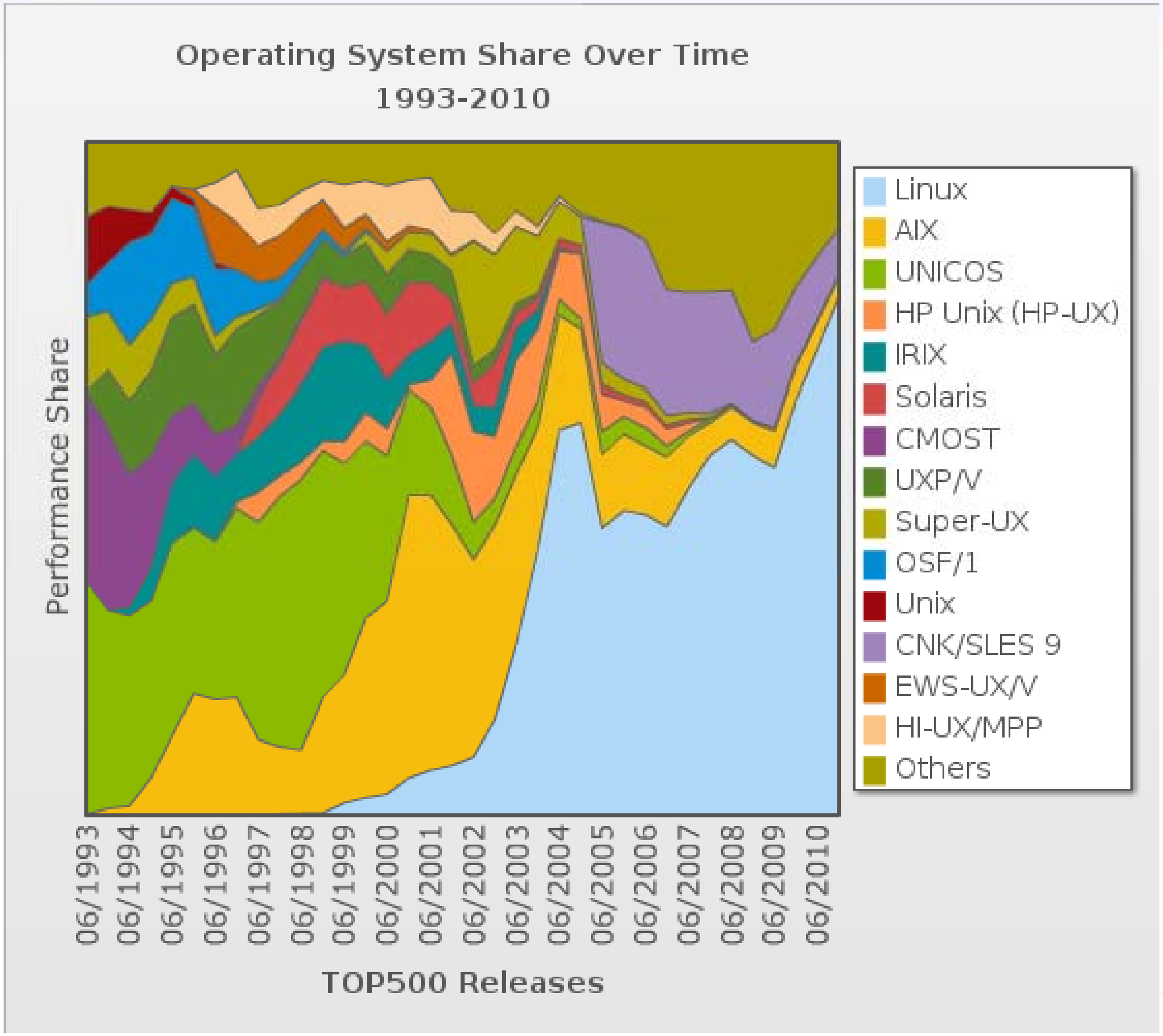
Pros and Cons of LWK Approach (From a Runtime Perspective)

- Cons
  - Node-level resource allocation and management is static
    - Memory allocation happens at application load time
    - Bad for shared memory on NUMA systems
  - Runtime components only communicate on set-up and tear-down
- Pros
  - Supports an application-specific runtime
    - Never happened in practice
    - OSFA worked for MPI applications
  - User-level networking
    - Runtime system can use same network interface as applications
    - No need for communication stack inside the OS
  - Memory management and scheduling are greatly simplified
    - User processes are allocated out of PCT heap

Forces Driving Exascale System Software

- Energy constraints and power management
  - Reduced data movement
- Resiliency
  - More frequent failures
- Concurrency
  - O(1k – 10k) threads per node
- Heterogeneity
  - Different types of cores
  - Non-coherent shared memory
  - Deeper memory hierarchies
- Highly unbalanced systems
  - Compute performance will dominate
- More complex applications
  - Dynamic, data-dependent algorithms
- Support for legacy interfaces and tools

Linux is the Dominant OS on the Top 500



Are These Really Linux Supercomputers?

- #1 - Tianhe-1A
  - 14,336 6-core Intel Xeons
    - 86,016
    - 3%
  - 7168 448-core Nvidia GPUs
    - 3,211,264 total cores
    - 97%

- #7 - Roadrunner
  - 6120 2-core AMD Opterons
    - 13,824 cores
    - 11%
  - 12,240 9-core IBM PowerXCell 8is
    - 116,640 cores
    - 89%

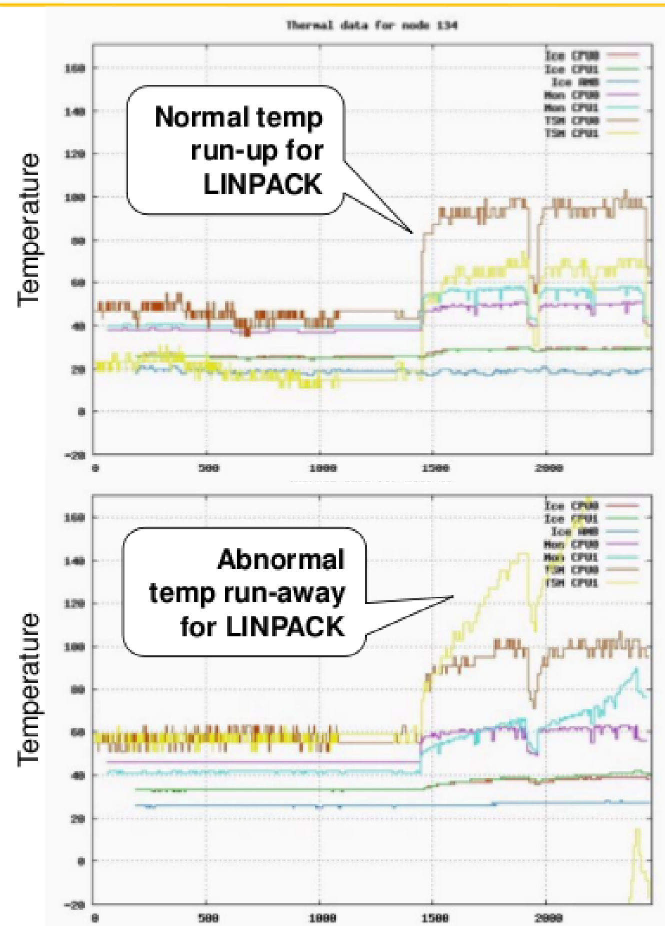
- Maybe ASCI Red really was a VxWorks machine…

Doctor, It Hurts When I use Linux…

U.S. DEPARTMENT OF ENERGY

The rate and effect of undetected (aka silent) errors must be better understood.

- During acceptance, RR experienced intermittent, but relatively frequent (20 microhertz) silent errors on HPL
- The issue was eventually tracked to an entire MPI transfer filled with zeroes
  - But data on the sending side was confirmed to be correct
- Root cause was a policy misunderstanding between
  - System: *when I move pinned memory, I will tell you*
  - MPI: *you won't move pinned memory, so I won't listen*



*Slide courtesy of Andy White (LANL)

OS/R is Really a Set of APIs

- glibc and toolchain is what most application developers care about
  - Lightweight kernels can be Linux API and ABI compatible
- System programmers care about the OS
  - Tool developers drive the need for OS functionality more than applications
    - ptrace and signals are not ideal
- Observing application experience with accelerators is interesting
  - Proprietary hardware
  - Custom programming language
  - Cross-compile environment
  - Limited debugging support
  - Explicit memory management
  - No system calls
  - Dealing with a lightweight kernel should be easy after programming for accelerators

What's Driving the Need for More Advanced Runtime Systems?

- Dynamic local resource management
  - Massive on-node parallelism
    - Large numbers of threads that must be created, synchronized, and destroyed
  - Resilience
    - Node-level resources may come and go
  - Locality management
    - Reduce data movement to manage power
    - Potentially moving work to data
  - Scalability
    - Need to move away from bulk synchronous approach
    - Jitter will be pervasive
  - Hybrid programming models
    - Interoperability between different models
      - Distributed memory, shared memory, heterogeneous cores
    - Efficient phase change
      - Managing resources when moving between models
- Responding to non-local events
  - Resilience
    - System-level resources may come and go

Co-Design

Co-design is a key element of the Exascale strategy

- Architectures are undergoing a major change
  - Single thread performance is remaining relatively constant and on chip parallelism is increasing rapidly
  - Hierarchical parallelism, heterogeneity
  - Massive multithreading
  - NVRAM for caching I/O
- Applications will need to change in response to architectural changes
  - Manage locality and extreme scalability (billion-way parallelism)
  - Potentially tolerate latency
  - Resilience?
- Unprecedented opportunity for applications/algorithms to influence architectures, system software and the next programming model
  - Hardware R&D is needed to reach exascale
- We will not be able to solve all of the exascale problems through architectures work only
- Co-design has become a buzzword for identifying challenges

Fundamental Capabilities for Co-Design

- Software agility
  - Applications
    - Need to identify an important, representative subset
    - Application code must be small and malleable
  - System software
    - Smaller is better
    - Lightweight is ideal
    - Toolchain is always a huge issue
- Hardware simulation tools
  - Sandia SST
  - Virtualization
    - Leverage virtual machine capability to emulate new hardware capability
- Need mechanisms to know the impact of co-design quickly
- Integrated teams
  - Co-design centers

Hardware Support for Run-Time Systems

- Network hardware support for thread activation
  - Run-time system components must communicate across nodes
  - Message reception in current networks occurs by recognizing change in memory
    - Leads to polling
  - Need hardware mechanism to block/unblock threads on network events
  - Active message model only makes sense with hardware support
    - Waiting until there's nothing to do to notice incoming messages is bad
- More advanced network functions (eureka, dynamic hierarchy)
- More sophisticated mode switch / protection hardware
- Hardware performance information
  - Dynamic resource management decisions will need performance info
  - Current performance counters only capture a subset of what is needed
- Thread scheduling
  - Hardware support for efficient scheduling and synchronization
  - Must be flexible (programmable?)
  - Should allow for operating on groups of threads

Processor Protection Rings

- Current scalable HPC applications don't make system calls
  - Allows the ratio of full-featured service nodes to lightweight nodes to be small
  - All "real" system calls on Sandia LWK were serialized through one process
- Current run-time systems don't make system calls either
  - Only at set-up and tear-down
- Probably only need a small subset of cores with ring 0 capability
  - System calls will turn into run-time thread activation response
- May need to have more sophisticated network protection mechanism
  - Would like to have run-time system threads invoked on message arrival

Limited Coupling at OS Layer

- This is part of what defines the OS and differentiates run-time system
  - The lowest level of local hardware management
- Need hierarchical structure to allow for scalability
- Exascale will require tighter coupling between some components
  - Runtime system components
  - RAS system and runtime system
  - Application and runtime system
- Need to provide information while minimizing dependencies
  - Use all information but limit required information
  - OS shouldn't require non-local information

Acknowledgments

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