System Software Working Group
Frontiers of Extreme Computing

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Issues

Strategic Issues – System Software and Programming Environments WG

- Advanced execution models
- Parallel programming models, methods, and tools
- Resource management, allocation, and scheduling
- Mass storage and I/O management
Questions

Questions – System Software and Programming Environments WG

• What new semantic constructs and execution models will be needed by Exascale applications and algorithms? What will the programming languages of the future look like?
• How will programmers contend with billion-way parallelism? What will the new languages look like?
• What operating system organizing strategy will effectively manage 100 million or more processing cores efficiently and reliably?
• How will compilers and runtime systems support the new classes of applications dominated by dynamic meta data structures?
• What will be the balance in the future between user direct control of resources and system automation for ease of use?
• Will programmers continue to program with arithmetic statements, or may a different paradigm become prevalent? Examples, neural networks, fuzzy logic, graph algorithms, image processing, real time?
Multiple Perspectives

• **Strategic Issues**
  - Advanced execution models
  - Parallel programming models, methods, tools
  - Resource management, allocation, scheduling
  - Mass storage and IO

• **Software Hierarchy**
  - Operating system
  - Runtime
  - Programming models, Languages, Compilers
  - IO, Storage, Mass storage
  - Programming Tools
    • Correctness
    • Performance

• **Cross-cutting Issues**
  - Power
  - Parallelism
  - Performance
  - Execution Model
  - Efficiency
  - Cost
  - Reliability
  - *Productivity*

• **Application**

• **Architecture**
Assumptions

- **Applications**
  - Use new programming models to exploit new architectural features
  - Legacy applications must work
    - Operate at performance the application designed for

- **Architecture**
  - Billions of threads
  - Globally address space
  - Multiple levels of memory with different characteristics
  - Dramatic improvements in system balance
## Discussion Summary

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Opportunities</th>
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</thead>
<tbody>
<tr>
<td>* Current OS Trends</td>
<td>* Large scale concurrency is here (100k) and growing</td>
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<td>* Traditional resource allocation mechanisms are at least 30 years old</td>
<td>* Heterogeneous computing is quickly approaching</td>
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<td>* Lack of co-design</td>
<td>* Move beyond legacy application support</td>
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<td>– Need testbeds, simulators</td>
<td>* Device technologies may inject dramatic improvements in architecture balance</td>
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<td>* Support for fault-oblivious applications</td>
<td>* Major changes in architectures are forcing reexamination of trends</td>
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<td>* Radically new architectures</td>
<td>* New programming models that expose architecture’s performance features</td>
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<td>– New ISAs, memory models</td>
<td>* Leverage community efforts to improve parallel programming for masses</td>
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<td>* Support for billion-way parallelism</td>
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<td>* Little/no interaction among OS, compiler, runtime</td>
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<td>* Programming models have not changed</td>
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<td>* Software business models</td>
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Recommendations (1)

- **New resource management strategies for processor, memory, bandwidth**
  - Current methods are insufficient
  - Scheduling
  - Flops are free; bandwidth is precious
  - ‘New’ system balances

- **New abstractions for managing heterogeneous systems** *(e.g., multiple types of processors, memory, memory models)*
  - Need access to new simulators, architectures

- **Hardware and system software co-design**
  - Use VMs to test OS at scale before system arrives
  - Need access to new simulators, architectures during design
  - Expose hardware features that allow improved performance, reliability
    - E.g., Transactional memory
      - need features in hardware for operation and performance analysis
Recommendations (2)

- Expeditions into new software systems for architectures that are $10^4$ larger than current systems
  - OS
  - Programming systems
  - ‘Programs writing programs’
  - Consider system software to be an application (‘eat our own dogfood’)
  - We can start this today – no need to wait!

- **Reliability abstractions and methods**
  - Fault-oblivious applications, programming models, ...
  - Checkpointing your exascale application will be impractical

- **IO, storage**
  - Implicit IO – need new methods for managing the n-level storage hierarchy

- **Self-evident**
  - More funding, testbeds, programs

- **Education**
Bonus Slides
Operating Systems

- Efficiency, Performance
- Reliability,
- System software resource overheads in terms of memory, time, power, heat, dollars overwhelms applications software
  – can’t afford resources to make it possible
Programming Models / Languages

- Synergy between os, runtime, and compile time
- Appropriate abstractions for levels of software stacks
Runtime
IO, Storage, Mass Storage
Execution models

- Abstract framework encompassing architecture, programming model, runtime/os, a set of governing principles interrelating them
Cross-Cutting Issues

- Power
- Parallelism
- Performance
- Execution Model
- Efficiency
- Cost
- Reliability
Power

- Needs to be managed as a precious resource (anything that consumes power)
- System software (OS, compiler, ...) needs to expose and manage power resources to applications
  - Cache management, bandwidth management, etc.
- How to model power
- Get processor developers to provide simple mechanisms
- Minimizing data movement helps
Parallelism

- Billion-way parallelism is a (the?) significant challenge
- How to express parallelism (TLP, PGAS, Data Parallel, etc.)
- OS should support arbitrary resource management policies
- System software for large-scale heterogeneous processing systems
- Ease of programming
Performance

- Reduce overhead so it is no longer a lower bound on granularity
- Don’t slow the apps down
- Abstraction for exposing architectural performance features
- Reduce operating system call overhead to the level of a procedure call
- Current approach for performance tools will not scale
Execution Models

- Must exploit synergy between OS, run-time and compile-time
- Linking the memory model with the execution model
- Lack of I/O (streaming, secondary storage) support inherent in the execution model
- How to get the “right” protocol interaction between the compiler, run-time, and OS
- Appropriate abstractions
  - For the machine and for the app developer
- Support for numerous, various architectures and applications
Efficiency

- Need new approaches to resource allocation and scheduling that do not degrade efficiency and predictability
- **Shared address space machine memory model**
  - Cache-coherency (has not) and will not scale
  - An API for exposing such parallelism
  - Pre-fetchers will not scale
- **Continuous load balancing (adaptivity)**
- **Devise a programming language for a trans-exaflops machine**
  - Language support for avoiding evil data races
  - Balance responsibilities between user and system
  - Marxist distribution of responsibilities (who’s good at what)
Productivity

- **Support for legacy applications** – new machines have to produce useful results early
- **Support for application portability**
- **Dealing with application developers’ inertia**
- **Leveraging smart applications’ people**
  - Can’t please all of the people all of the time
  - Need to work with app developers to “do the right thing”
- **Provide a sane environment for application development**
- **Need new program development environments**
  - Debuggers for billions of threads
Cost

- Lack of appropriate OS testbed resources
- Where does the money come from for system software development
  - Software may no longer be free
- Cost from uniqueness of systems?
  - Radically different system software from machine to machine
Reliability

- System software and tools need to provide an environment for the development of more robust, failure-tolerant applications
- Managing resources in the presence of failures at scale – dynamic reconfiguration
- Fault oblivious programming model
- Tools to insure system software correctness
- Invariant violation application debuggers
Design and Implementation

- Current trends in OS development are not addressing fundamental issues required for trans-exaflops computing
- Current OS’s are not structured to enable trans-exaflops computing
- Expectations of “develop on the desktop and run efficiently on the exaflop” need to be managed
- System software people are not getting it right either (automake, configure are part of the problem)
- The customer may not always be right
- System software verification on large-scale systems
  - Need real applications, real problems, and lots of time
- Leveraging disruptive technology smoothly
- Non-fixed OS (composabililty)
- What should be virtualized?
Challenges

- OS trends are not helping
- Expectation of Linux desktop environment everywhere
- Just say “no”
  - To non-scalable and/or non-predictable things
- Our apps are not Google apps
  - More strict requirements
  - But could they be more robust to failure(s)?
- There’s a right way – just do it
  - Conflicts with the business model
Challenges

- **Runtime tightly coupled with compiler?**
  - Opportunity to explore more dynamic behavior
  - Execution model has to allow asynchronous threads
  - Predictable performance
Challenges

- Sheer scale – number of things to manage
  - Billion-way parallelism
  - Reduce overhead so it is no longer a lower bound on granularity
- Current OS’s are not structured to enable trans exaflops
- Synergy between OS, run-time and compile-time
- How to express parallelism (TLP, PGAS, Data Parallel, etc.) and the corresponding execution model
- Linking the memory model with the execution model
- Managing resources in the presence of failures at scale
- Multiple definitions of an “execution model”
- Shared address space machine memory model
  - Cache-coherency (has not) and will not scale
  - An API for exposing such parallelism
  - Pre-fetchers will not scale
- Strict scaling from teraflops to trans exaflops
- Support for legacy applications
- New approaches to resource allocation and scheduling that do not degrade efficiency and predictability
Challenges

- Support for application portability
- Dealing with application developers’ inertia
- Lack of I/O (streaming, secondary storage) support inherent in the execution model
- Leveraging smart applications’ people
  - Can’t please all of the people all of the time
  - Need to work with app developers to “do the right thing”
- Lack of appropriate OS testbed resources
- OS should support arbitrary resource management policies
- Getting the OS out of the way
- Provide a sane environment for application development
- Fault oblivious programming model
- Need new program development environments
  - Debuggers for billions of threads
- System software verification on large-scale systems
  - Need real applications, real problems, and lots of time
Challenges

- How to get the “right” protocol interaction between the compiler, run-time, and OS
- Appropriate abstractions
  - For the machine and for the app developer
- Leveraging disruptive technology smoothly
- Continuous load balancing (adaptivity)
- Support for numerous, various architectures and applications
- Non-fixed OS (composability)
- System software for large-scale heterogeneous processing systems
- Devise a programming language for a trans-exaflops machine
  - Language support for avoiding evil data races
  - Balance responsibilities between user and system
  - Marxist distribution of responsibilities (who’s good at what)
Opportunities

- Decent programming models
  - Expressiveness, generality, performance, productivity
- Influence architectures – co-design
  - E.g., FEB on network messages
- Initiate OS expeditions to explore these new design spaces
- Neil – look at the largest systems we have and highlight successes
- Moving beyond legacy applications
- Give applications developers tools to manage parallelism and locality easily
- Develop massive parallel asynchronous fine grained execution model
  - Tnt is not asynchronous
- Reassigning responsibility throughout the software stack
Opportunities

- Funding for system software NRE
- Resilient computing – computation that continues to completion in spite of failures – fault oblivious computing
- User challenge → parallelism is not easy
- Leverage hardware developments in multicore and many-core
  - HPC’s problems are now the world’s problems 😊
- Photonics should ease traditional burdens on software
- Help apps developers manage locality
  - Tools for doing so
- Allow experts to manage software system explicitly and inject domain knowledge into the system
  - Conservative defaults, heroic overrides
- Feedback-driven or adaptive compilers
  - Redefine role of compiler
  - Heterogeneous systems
  - Autotuning
  - Interactive optimization
- Beefeaters is Thomas’ favorite drink
- Opportunity to establish a new relationship between runtime and OS; where the compiler is a conduit from the programming model to the runtime
  - Hardware <-> Runtime Systems <->
  - Dynamic system for managing parallelism
- Metrics for evaluating system software capabilities
- Revisiting system software design choices in light of light
Viable Paths Forward

• **Education**
  – Careers in HPC
  – Labs need to emphasize intellectual freedom
  – Adequate investments
  – Beowulf boot camp

• **Market size – consequences of open source**
Viable Paths Forward

• **TS Operating System**
  – Lightweight kernels
  – Emerging behavior from LWKs
  – Development time is relatively small
  – Single machine that is self-regulating
  – Lightweight synergistic types of constructs that are symbiotic
    • Small group in short amount of time
Viable Paths Forward

- **Development environments**
  - Virtualization for experimentation
    - Scaling
- **Limitations from legacy application’s constraints**
  - Accommodate legacy applications
  - Refactor for optimal performance
  - Well defined migration path
- **System software resource overheads in terms of memory, time, power, heat, dollars**
  - Overpowers applications software
- **Mass storage**
  - Software for mass storage should be this new programming model
  - Fault oblivious, full use of tlp
- **Tools for performance and correctness**
  - Usability at scale
System software resource overheads in terms of memory, time, power, heat, dollars overwhelms applications software
  – can’t afford resources to make it possible

Demand paging will not occur

Support for new architectural constructs or models
  – Don’t assume uniformity of system resources in a specific application
  – Multiple levels of memory, different characteristics
    • Need a new memory model
    • One physical port
    • vNUMA

Threads / Scheduling
  – Don’t want kernel level threads scheduling
  – Need predictability
  – Preemption in alternative devices
  – Performance variability across different memory hierarchies, devices

Can’t drop a process on a raw processor w/o OS, protection domains
Programming Languages / Compilers

- Programs that write programs
- Components
- Correctness
- Expressiveness
- Should functional programming remerge
  - Erlang, haskell,
- New languages: X10, Chapel, Fortress
- Languages that allow application to specify multi-grained parallelism and locality
  - Different synchronization mechanisms
- Transparency v. visibility
- Mainstream and elite users
- Data structures, affinity, distributions
IO and Storage

- **Storage is a parallel application**
  - Same problems: distributed data, parallelism, failures
  - Same tools for 30 years
    - C, Unix-like OS

- **Performance and scaling**
  - N-way to one scaling
  - Same load balancing problems

- **IO/storage is often under-provisioned**

- **Checkpointing (1 EB)**
  - Checkpointing needs more work
    - This isn’t your grandfather’s checkpointing
Runtime

- Control flow migration in runtime
  - Continuations
  - Latency hiding opportunities
- Runtime will have fluctuating resource demands on system
- Runtime will have a shorter ‘wavelength’ than OS
- No protection, lightweight
- Triumph of user-level runtime
- Transparent support for correctness and performance analysis