A Container-Based Approach to OS Specialization for Exascale Computing

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Outline

- Towards exascale computing
- Overview of the Argo project
- Establishing the need for OS specialization
  - Lean OS
  - Provisioning for legacy applications
  - Provisioning for heterogeneous resources
  - Provisioning for different compute needs
- OS specialization via Compute Containers
- Single kernel, multiple OS personalities
- NodeOS and features
- Conclusion
Towards exascale computing

- Billions of execution threads
- Complex and composite workloads
- Highly heterogeneous sets of resources
  - Taking to another level the trend of mixing CPU cores, accelerators and various kinds of physical memories
- Variability
  - Changing job configuration and resource needs
- Resiliency
Overview of Argo

- A **node OS** at node level
- A user-level lightweight runtime for massive parallelism
- A System-wide signaling
- Global OS with global view.
OS Specialization

- An autonomous view of the OS meant for a specific use

- A specialization is characterized by:
  - Spanned resources
  - Set of exposed features, mechanisms and policies
  - Mandate:
    - e.g. Noise-sensitive computation
    - e.g. Heavy I/O
    - e.g. Tailored for heavy use of accelerator
    - etc.
Lean OS

Comparing Linux to a lightweight HPC OS kernel

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  - The watchdogs
  - The ksoftirqd
  - The kworkers
  - Other device-specific kernel threads (e.g. network)

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  - Other device-specific kernel threads (e.g. network) | No per-CPU core kernel thread |
| Interference in HPC application at runtime ... your mileage might vary | Extremely low interference in HPC application at runtime. |
Lean OS

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- HPC runtimes bypass lean OSes for hardware access.
OS Specialization

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- The Argo NodeOS seeks to expose most hardware resources to the HPC runtime
  - Because the runtime knows more about the Application needs than the OS
  - HPC runtime want to make their own policies and craft their own fine-tuned optimizations
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So ... is the exascale OS going to be lean?
- As of November 2014, Linux-equipped systems delivered ~98.23% of the aggregated FLOPS of the 500 most powerful supercomputers (Top500).

- Linux equipped 97% of the Top500 systems
In fact, for each ranking in the past decade, more than half the Top500 systems used Linux.

And the trend shows no change in direction!
There is basically a massive amount of existing (legacy) HPC applications that assume a Linux-like environment:

- Some well-known system calls
- POSIX
- etc.
Back to ... Comparing Linux to a lightweight HPC OS kernel (a few differences)

Linux
- ...

Blue Gene Q CNK
- ...
- Offers only 63 system calls.
  - E.g., no forking
- No sophisticated virtual to physical memory mapping
- No time-quantum
OS Specialization

Provisioning for legacy applications

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The heterogeneity will be pushed further for exascale systems:
- Massive numbers of small cores
- Big serial cores
- Accelerators
- Deeper and more complex memory hierarchies
  - Multiple NUMA domains
  - Multiple coherence domains
OS Specialization

Provisioning for heterogeneous hardware resources

- Heterogeneous sets of compute cores
- Massive intra-node parallelism

Deep and complex memory hierarchy

Coherence domain

| NUMA node | Accelerator memory 0 |
| NUMA node | Accelerator memory 1 |
| NUMA node | Accelerator memory n |

Coherence domain

| NUMA node | NVRAM |
| NUMA node | NVRAM |
| NUMA node | Other |

Coherence domain

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What features should a lean OS environment provide for a “broadly useful” supercomputer?

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- What system calls?
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OS Specialization

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OS Specialization

Provisioning for different compute needs

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NodeOS: OS Specialization via Compute Containers

The Argo NodeOS is **specialized** into a single ServiceOS and one or multiple *Compute Containers*.
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The Argo NodeOS is **specialized** into a single *ServiceOS* and one or multiple *Compute Containers*.

The Compute Containers purposely do not provide isolation; for the sake of providing seamless intra-node communication.
NodeOS: Single kernel, multiple OS personalities

- The specialization occurs over a single kernel
- The kernel is fully-fledged for the ServiceOS
- The kernel is made selectively lean for the Compute Containers
NodeOS: HPC-specific features for container specialization

- Behaviors and features exposed by a Compute Container are decided (or requested) by its “clients”
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- Examples of clients are the HPC runtimes or the Global OS

- The NodeOS interface to its clients is made of:
  - Configuration daemons, scripts or binary executables
  - New API for functionalities that were not natively exposed by the host kernel
  - Wrapped or substituted implementations for existing API functions that are expected to behave differently inside Compute Containers (e.g., making certain system calls non-blocking)
HPC runtimes want exclusive ownership of the resources that they use

e.g. physical memory
NodeOS: Compute Container specialization aspect

**Finer-grained memory units (NUMA)**

- ComputeContainer<sub>0</sub>
  - Hardware NUMA node 0
  - Hardware NUMA node 1

- ComputeContainer<sub>1</sub>
  - Hardware NUMA node 2
  - Hardware NUMA node 3

- ComputeContainer<sub>2</sub>
  - Physical memory unit

Partitioning into finer-grained memory units

ComputeContainers can have *guaranteed* page frames

Static virtual-physical mapping => Free memory pinning for faster RDMA
NodeOS: Compute Container specialization aspect

Finer-grained memory units (UMA)

ComputeContainers can have **guaranteed** page frames

Static virtual-physical mapping => Free memory pinning for faster RDMA
HPC runtimes are multiple and disparate; and some (mostly legacy) are not necessarily well-equipped for their own needs

NodeOS: Compute Container specialization aspect

e.g. scheduling behavior
NodeOS: Compute Container specialization aspect

New HPC scheduling class

- Optimized for Compute Containers with guarantees of absence of oversubscribing.
- Disables load balancing and preemption
- Reduces kernel bookkeeping
- Provides predictable performance (as much as possible) for the same workload.
HPC runtimes want some of the same functionalities provided by vanilla Linux ... without giving up their freedom.

e.g. system calls ... without ever blocking
Cooperative scheduling is “the thing” some next generation HPC concurrency runtimes are built around.
NodeOS: Compute Container specialization aspect

Completely wait-free system API

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- The user-level threads should not block; they should always yield instead
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What guarantee does the cooperative scheduling concurrency runtime provide if user-level threads can make system calls?
NodeOS: Compute Container specialization aspect

Completely wait-free system API

- System calls behaviors can be container-specific; that is, same API, different behaviors depending on the Compute Container hosting the calling process.
NodeOS: Compute Container specialization aspect

Completely wait-free system API

- System calls behaviors can be container-specific; that is, same API, different behaviors depending on the Compute Container hosting the calling process.

- Provision for all non-blocking system calls with EWOULDBLOCK or E_AGAIN returned for calling threads that have wait-freedom requirements:
  - To fulfill the concern of completely wait-free execution if desired.
  - To fulfill the need for predictability in blocking behaviors.
NodeOS: Compute Container specialization aspect

Scalability through divide and conquer

- Trade kernel-wide management of certain internal data structures with per-Compute Container approaches
- Only the subset of resources spanned by a Compute Container is considered

*e.g.*, *RCU grace periods*
Conclusion

- The Argo node operating system *specializes* a single kernel into multiple aspects that provide:
  - Lean OS environments for various OS-bypass needs and next generation HPC runtime support
  - Fully-fledged Linux environment:
    - Node booting
    - Complex resource management
    - Bulk resource allocation
    - Legacy application execution

- The specialization is fulfilled over the Linux kernel with cgroups, resource controllers and new kernel additions
- Prototype sources to be made public
Questions?