System-Level Support for Composition of Applications

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The Hobbes Exascale Operating System and Runtime

- Hobbes: Composition and Virtualization as Foundations of an Extreme-Scale OS/R [Brightwell et al., ROSS ‘13]
  - Hardware challenges of exascale are systemic
  - Energy efficiency, resilience, management of heterogeneity - cannot be solved by the OS alone.
  - OS needs to provide infrastructure for exploring solutions
  - Composition and lightweight virtualization help enable systemic research
- Composition today performed at full system level, not node level
  - Decoupled applications (simulation, post-processing, analytics, etc.) add nontrivial performance overhead and consume power
  - Node level composition: move computation to data on same node
- This talk: Hobbes OS/R with support for composition of real DOE applications
Talk Roadmap

• Hobbes and the case for Composition at Extreme Scale

• Components of the Hobbes OS/R

• Evaluation of Real DOE Applications

• Conclusion
Composition Use Case: Crack Detection in Molecular Dynamics

- LAMMPS (Large Scale Atomic/Molecular Massively Parallel Simulator)
  - Used across a variety of domains relevant to DOE interests
  - Effectively, applies stress to a particular modeled material until it “cracks”
  - Periodically, outputs simulation data referring to various material characteristics (particle positions, atomic makeup, etc.)

- Bonds crack detection
  - Ingest and analyze LAMMPS output to detect and explore crack genesis

- Composition details
  - LAMMPS and Bonds built as separate binary applications
  - Data transfer accomplished via abstract communication channels. Underlying transport varies based on system capabilities
Hobbes in the Broader Exascale OS/R Spectrum

• Recent exascale OS/R efforts: Argo, McKernel, mOS, FusedOS, ...
  • Common ground: multi-enclave systems provide customized environments

• Hobbes: application composition a key capability for exascale systems
  • Data movement a bottleneck for performance and power consumption
  • Key example: tight coupling of simulation and analysis applications
  • Others: multi-materials simulation, debugging + introspection

• Performance isolation is a major requirement
  • This is a systemic problem – hardware is not the only shared resource
  • Coupling cannot come at the cost of reduced performance isolation
Hobbes Supporting a Composed Application

- Explicit support for composition via *enclaves*
- Each *enclave* customized for a particular application component
- **Performance isolation in hardware and system software**
- Consistent shared memory interface to user-level applications
Components of the Hobbes OS/R

- Operating System Components
  - Palacios and Kitten
  - Pisces lightweight co-kernel architecture

- Runtime Components
  - XEMEM: cross enclave shared memory
  - HPC library support
    - Cray/SGI XPMEM
    - ADIOS (Adaptable I/O System)
    - TCASM (Transparency Consistent Asynchronous Shared Memory) [Akkan et al., ROSS ‘13]
OS Level: Palacios VMM and Kitten LWK

- Palacios: OS-independent, embeddable virtual machine monitor
- Kitten: lightweight kernel from Sandia National Laboratories
- Established history providing scalable environments for HPC
  - Near native performance at 4096 nodes of a Cray XT3 [Lange et al., IPDPS ‘10, VEE ‘11]
  - Better than native at small scale [Kocoloski and Lange, ROSS ‘12]
- Emphasis on repeatability and consistency
  - Lack of “enterprise” features
- Allow application to get “close” to hardware

![Diagram of OS components: Application, Simulation, Analytics, Hardware, Operating System, Hobbes Runtime, XEMEM, ADIOS, TCASM, Palacios, Kitten Co-Kernel (Pisces), Linux]
OS Level: Pisces Lightweight Co-Kernel Architecture

- Supports the decomposition of a node’s hardware into independent system software environments [Ouyang et al., HPDC ‘15]

- Primary design goal: performance isolation between enclaves

- Decomposed hardware
  - CPU cores, memory blocks, I/O devices

- Internalized system software
  - Operating system, device drivers, I/O + network subsystems
Runtime Foundation: XEMEM (Cross Enclave Memory)

- Shared memory architecture supporting user-level shared memory across enclaves [Kocoloski and Lange, HPDC ‘15] (Talk tomorrow!)
- Supports shared memory between Linux host enclave, Kitten co-kernels, and guest OSes in Palacios VMs
- **Arbitrary enclave topologies**
  - Common namespace for exported memory regions
  - Protocol based on cross enclave page frame shipping
- **Backwards compatible API with Cray/SGI XPMEM**
ADIOS (Adaptable I/O System)

- High performance middleware enabling flexible data movement
  - Abstracts Data-at-Rest to Data-in-Motion
- Established history enabling composition
  - Multi-physics [F. Zheng et. al., IPDPS ’10]
  - Interactive visualization [Dayal et al., CCGrid ’14]
- Multiple transport methods which leverage a common API
- Novel memory / network transports can be integrated quickly
Evaluation Methodology

• Main goal: proof of concept experimental demonstration
  • Support of real DOE applications
  • Demonstration of functionality and flexibility in underlying enclave configurations

• Two applications, both highly relevant to DOE
  • LAMMPS coupled via ADIOS with Bonds
    • From the SmartPointer analytics toolkit
  • GTC (Gyrokinetic Toroidal Code) coupled via ADIOS with PreData
    • Performs sorting of particle data and histogram generation for visualization

• Main performance goal: effective performance isolation through low application variance across multiple runs
Evaluation Details

• Evaluation Environment
  • Single compute node of Sandia’s “Curie” Cray XK7 testbed
  • Node consists of 16-core 2.1 GHz AMD Opteron CPU, 32 GB DDR3
  • Baseline environment: Compute Node Linux (CNL)

• Enclave configurations
  • Single Linux OS running Cray CNL
  • Multi-enclave environments utilizing Pisces co-kernels running Kitten LWK.
  • Some configurations utilize Palacios embedded with Kitten to provide Linux in VMs.
  • Coupling performed via ADIOS’ XEMEM and POSIX file-based transports
Results

- Collected average and standard deviation of at least 5 runs in each enclave configuration

### LAMMPS + Bonds

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- LAMMPS in Kitten reduces standard deviation

- GTC performance comparable with analysis in VM
Conclusion

• **Application composition is an emerging requirement for extreme scale applications**

• The Hobbes OS/R provides explicit support for application composition
  • Multi-enclave OS/R supports heterogeneous application components
  • Performance isolation a key design requirement
  • High performance I/O/middleware libraries support higher-level behavior of unmodified application components

• **The Hobbes OS/R adds no overhead to applications on single node and limits application variance through effective performance isolation**
Upcoming Talks from the Hobbes Team

• **From the Hobbes team:**
  • Oscar Mondragon: Quantifying Scheduling Challenges for Exascale System Software (ROSS, right now!)
  • Kyle Hale: A Case for Transforming Parallel Run-times into Operating System Kernels (HPDC, Wednesday 10:50 AM)

• **XEMEM, Pisces talks:**
  • Brian Kocoloski: XEMEM: Efficient Shared Memory for Composed Applications on Multi-OS/R Exascale Systems (HPDC, Wednesday 4:35 PM)
  • Jiannan Ouyang: Achieving Performance Isolation with Lightweight Co-kernels (HPDC, Thursday 2:00 PM)
Thank You

• Brian Kocoloski
  • briankoco@cs.pitt.edu
  • http://people.cs.pitt.edu/~briankoco

• Source available
  • The Prognostic Lab @ U. Pittsburgh
  • http://www.prognosticlab.org

• The Hobbes project
  • http://xstack.sandia.gov/hobbes/
TCASM (Transparently Consistent Asynchronous Shared Memory)

• **Producer consumer model, designed for coupled applications (simulation + analytics, debugging)** [Akkan et al., ROSS ‘13]
  - Simulation + analytics/visualization
  - Debugging

• Leverages copy-on-write (COW) semantics to create multiple views of shared memory pages
  - No wasted memory – copies only made when needed
  - No application-level synchronization

• In Hobbes, XEMEM shares read only snapshots across enclave boundaries