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

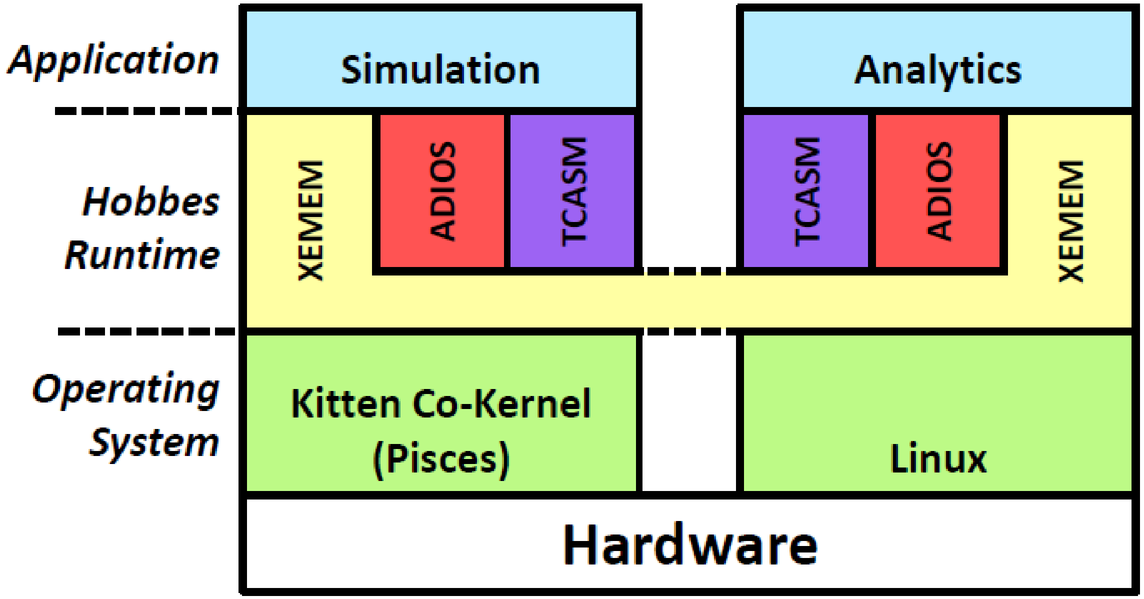
Hobbes in the Broader Exascale OS/R Spectrum

- 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

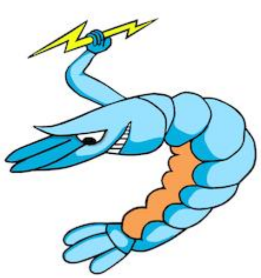
Components of the Hobbes OS/R

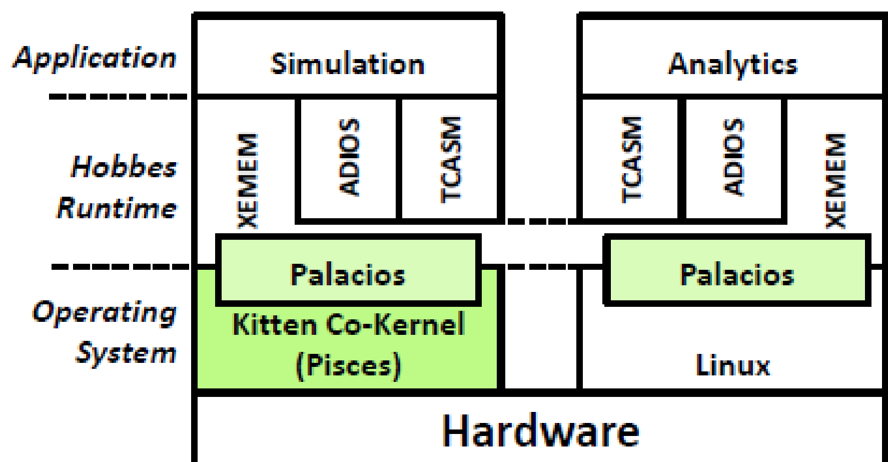
- Operating System Components
  - Palacios and Kitten
  - Pisces lightweight co-kernel architecture

- Runtime Components
  - XEMEM: cross enclave shared memory
  - HPC library support
    - Cray/SGI XPMEM
    - ADIOS (Adaptable I/O System)
    - TCASM (Transparently Consistent Asynchronous Shared Memory) **[Akkan et al., ROSS '13]**

OS Level: Palacios VMM and Kitten LWK

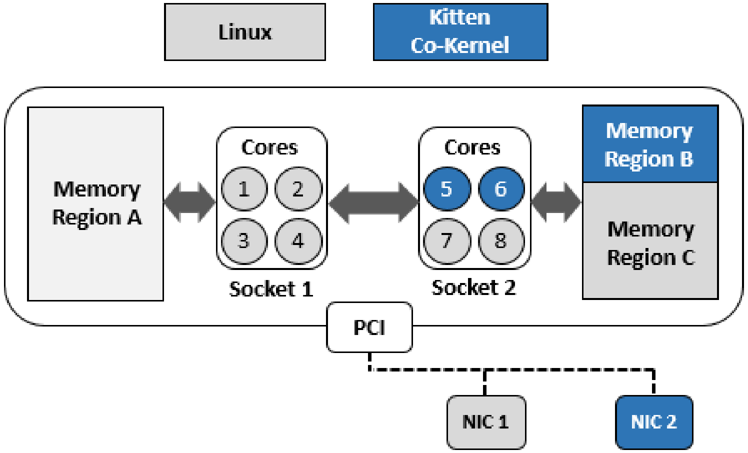
- Palacios: OS-independent, embeddable virtual machine monitor
- Kitten: lightweight kernel from Sandia National Laboratories
- Established history providing scalable environments for HPC
  - **Near native performance at 4096 nodes of a Cray XT3 [Lange et al., IPDPS '10, VEE '11]**
  - **Better than 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

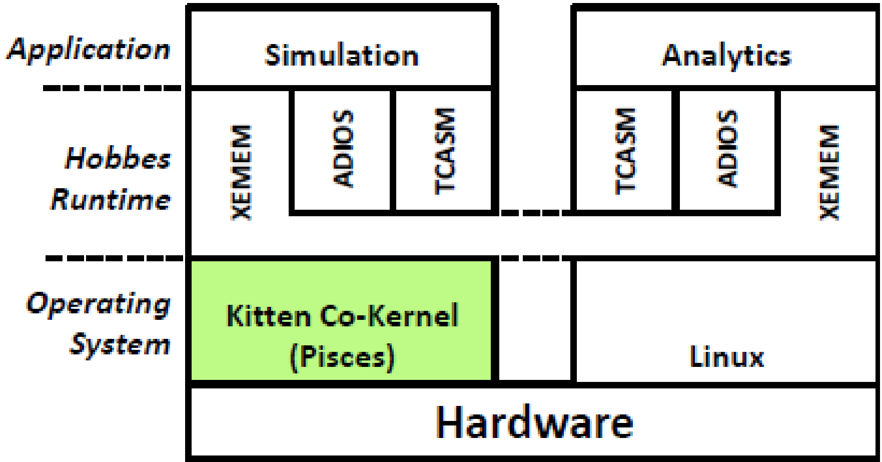




OS Level: Pisces Lightweight Co-Kernel Architecture

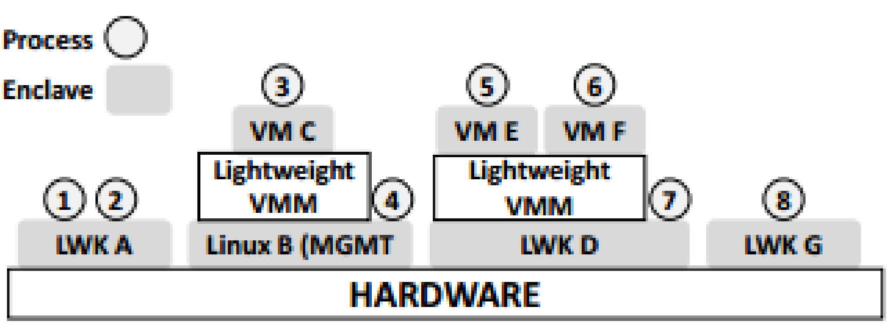
- Supports the decomposition of a node's hardware into independent system software environments **[Ouyang et al., HPDC '15]** **(Talk Thursday!)**
- **Primary design goal: performance isolation between enclaves**
- Decomposed hardware
  - **CPU cores, memory blocks, I/O devices**
- Internalized system software
  - **Operating system, device drivers, I/O + network subsystems**

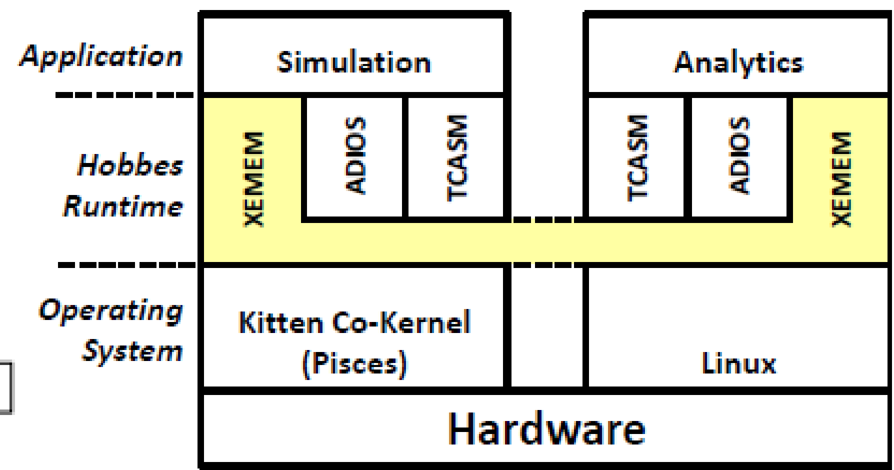




Runtime Foundation: XEMEM (Cross Enclave Memory)

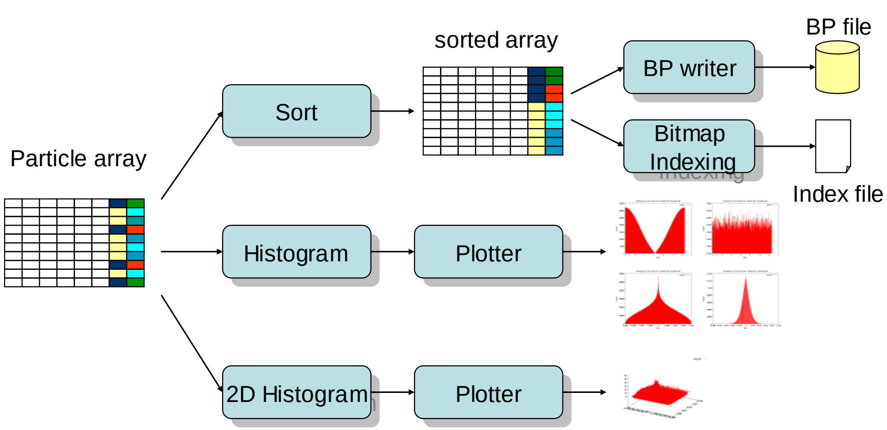
- Shared memory architecture supporting user-level shared memory across enclaves **[Kocoloski and Lange, HPDC '15]** **(Talk tomorrow!)**
- Supports shared memory between Linux host enclave, Kitten co-kernels, and guest OSes in Palacios VMs
- **Arbitrary enclave topologies**
  - Common namespace for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

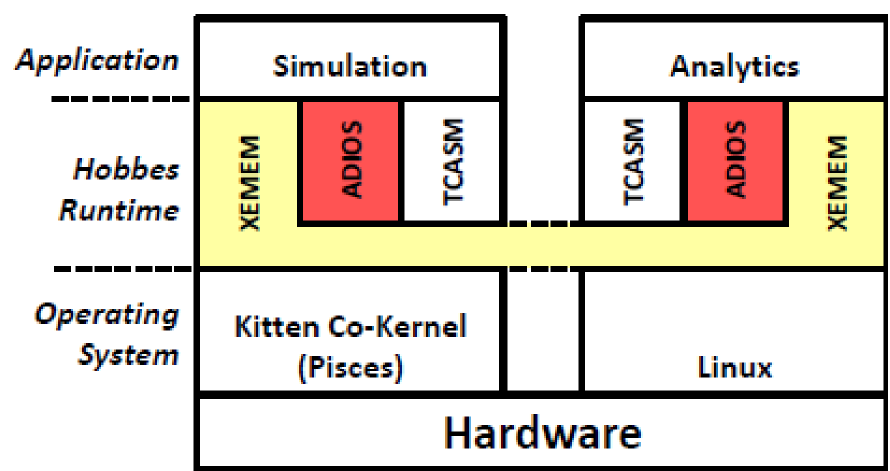




ADIOS (Adaptable I/O System)

- 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

LAMMPS Enclave	Bonds Enclave	Average	StdDev
Cray-Linux (POSIX)		165.02	0.20
Cray-Linux (XEMEM)		153.48	0.08
Cray-Linux	Kitten	153.50	0.15
Kitten	Cray-Linux	153.91	0.04
Cray-Linux	Linux-VM	153.35	0.17
Linux-VM	Cray-Linux	156.10	0.15
Kitten-Enclave1	Kitten-Enclave2	153.83	0.03

GTC + PreData

GTC Enclave	Analysis Enclave	Average	StdDev
Cray-Linux (POSIX)		148.42	0.12
Cray-Linux (XEMEM)		147.40	0.09
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- **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/

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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