X-Caliber & XGC System Software Research & Development

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SOS16

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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Thursday, March 15, 2012

Context

- **X-Caliber: our DARPA UHPC effort**
- **XGC: Extreme-Scale Computing Grand Challenge LDRD**
    - – (Laboratory Directed Research and Development)

- **Consistent Challenge: figure out what exascale system software looks like**
    - –Collaborate with the level above and the level below
    - –Leverage technology trends
    - –Rethink application space (what will be important in a decade?)
    - –*Be metric-focused!*
        - –Picojoules, Picojoules, Picojoules ... and time too!

X-Caliber Software Team

- **Sandia**
  - –Brian Barrett, Kyle Wheeler, Dylan Stark
- **Indiana University**
  - –Thomas Sterling
- **Louisiana State University**
  - –Hartmut Kaiser, Chirag Dekate
- **University of Illinois**
  - –William Gropp, Marc Snir
- **USC/ISI**
  - –Pedro Diniz

LSU

1867

ILLINOIS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

ISI

Information Sciences Institute

NNSA

National Nuclear Security Administration

Sandia National Laboratories

XGC Software Team

- **Sandia**
  - Brian Barrett, Ron Brightwell, Kevin Pedretti, Dylan Stark, and Kyle Wheeler
- **University of Illinois**
  - Vikram Adve, Bill Gropp, Marc Snir
- **RENCI**
  - Allan Porterfield

XGC Thrust Areas

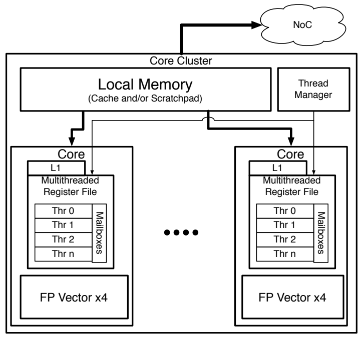
(1) Baseline - what happens if we do nothing?

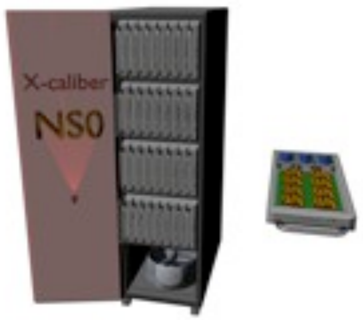
Safety and Security | **Reentry** | **Circuitry** | **Graph** | **Stream**

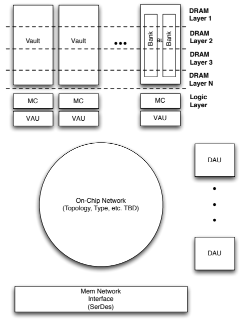
(5) Application Drivers

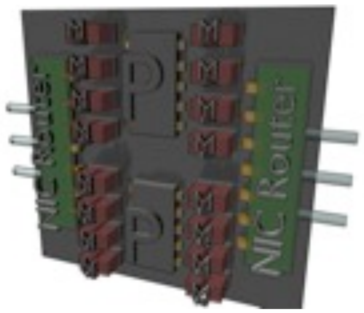
(4) System Software - enabling a new model of computation

(3) Architecture - Coping with Concurrency and Data Movement

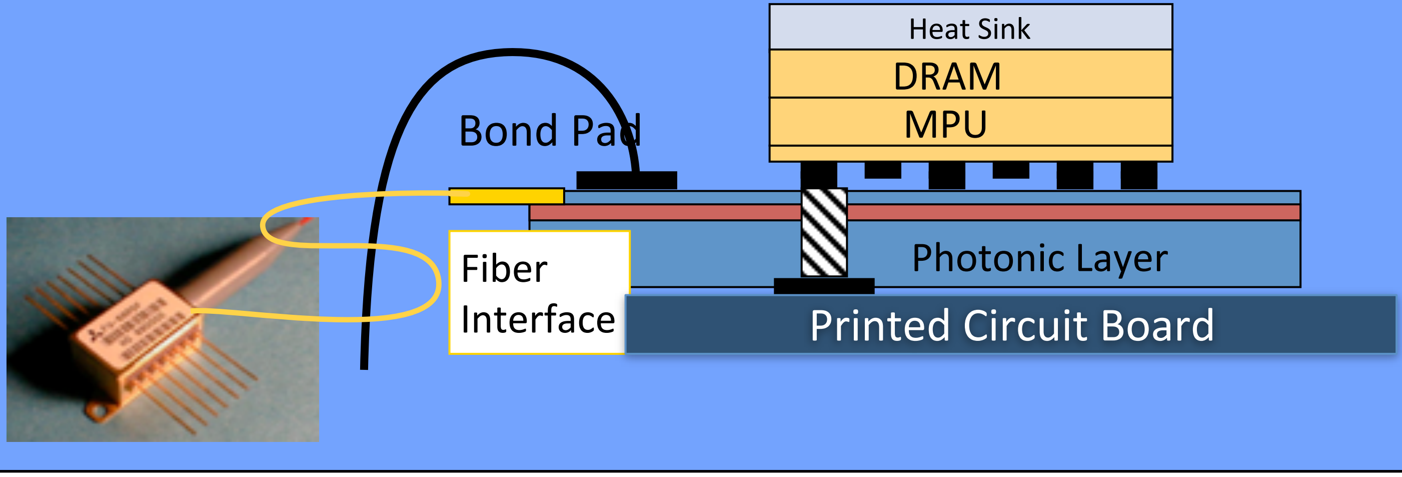


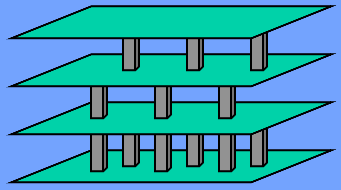






(2) Microsystems - Key Data Movement Enabling Technologies





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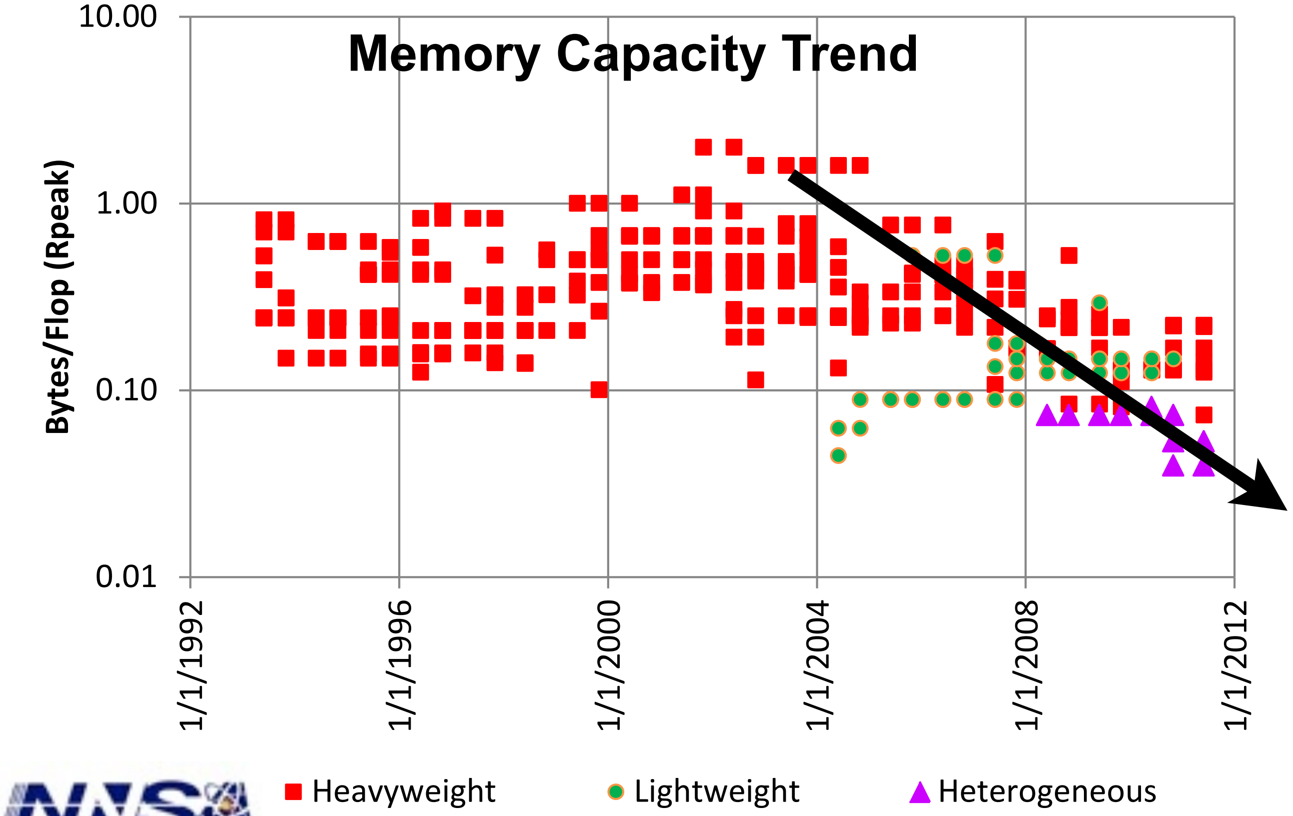
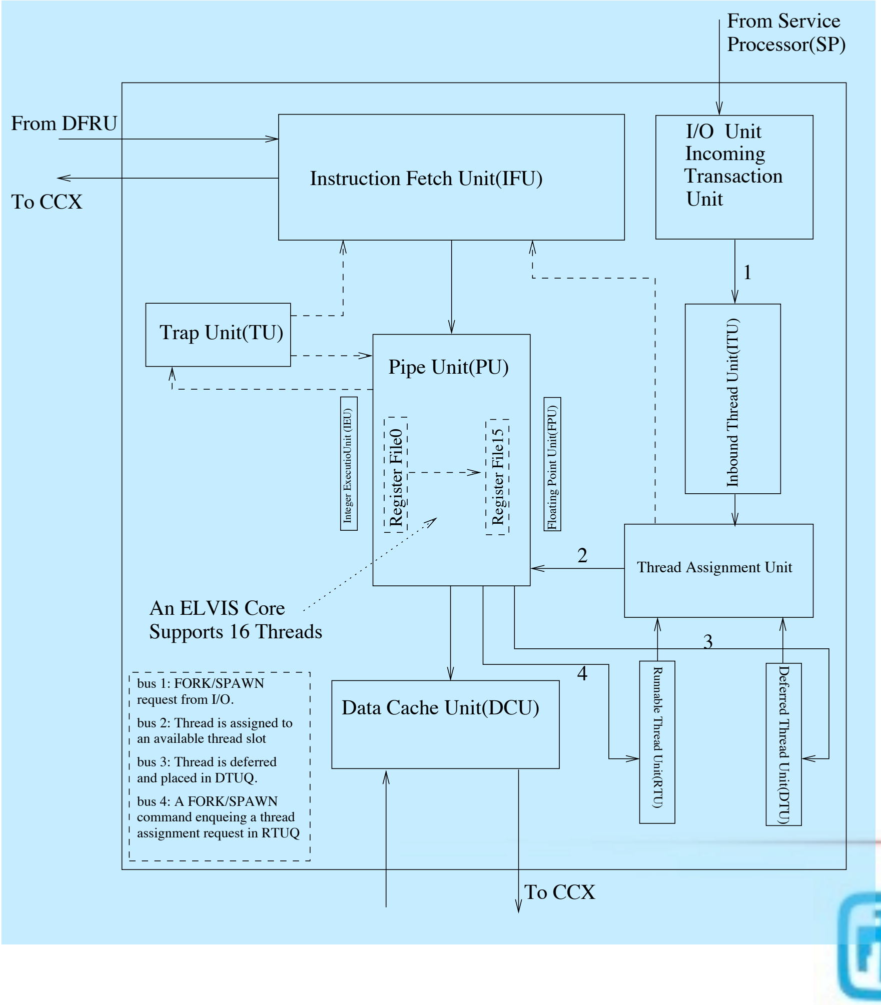
Hardware Challenges

- Exponential increase in node-level parallelism
- Lower memory capacity per core
  - –Weak scaling will be insufficient
- Significantly lower network to memory bandwidth ratios
- Need for system software to have finer control of hardware resources




From Service Processor(SP)
From DFRU
To CCX
Instruction Fetch Unit(IFU)
I/O Unit Incoming Transaction Unit
1
Trap Unit(TU)
Pipe Unit(PU)
Inbound Thread Unit(ITU)
Integer ExecutioUnit (IEU)
Register File0
Register File15
Floating Point Unit(FPU)
2
Thread Assignment Unit
An ELVIS Core Supports 16 Threads
3
4
Data Cache Unit(DCU)
Runnable Thread Unit(RTU)
Deferred Thread Unit(DTU)
To CCX

bus 1: FORK/SPAWN request from I/O.

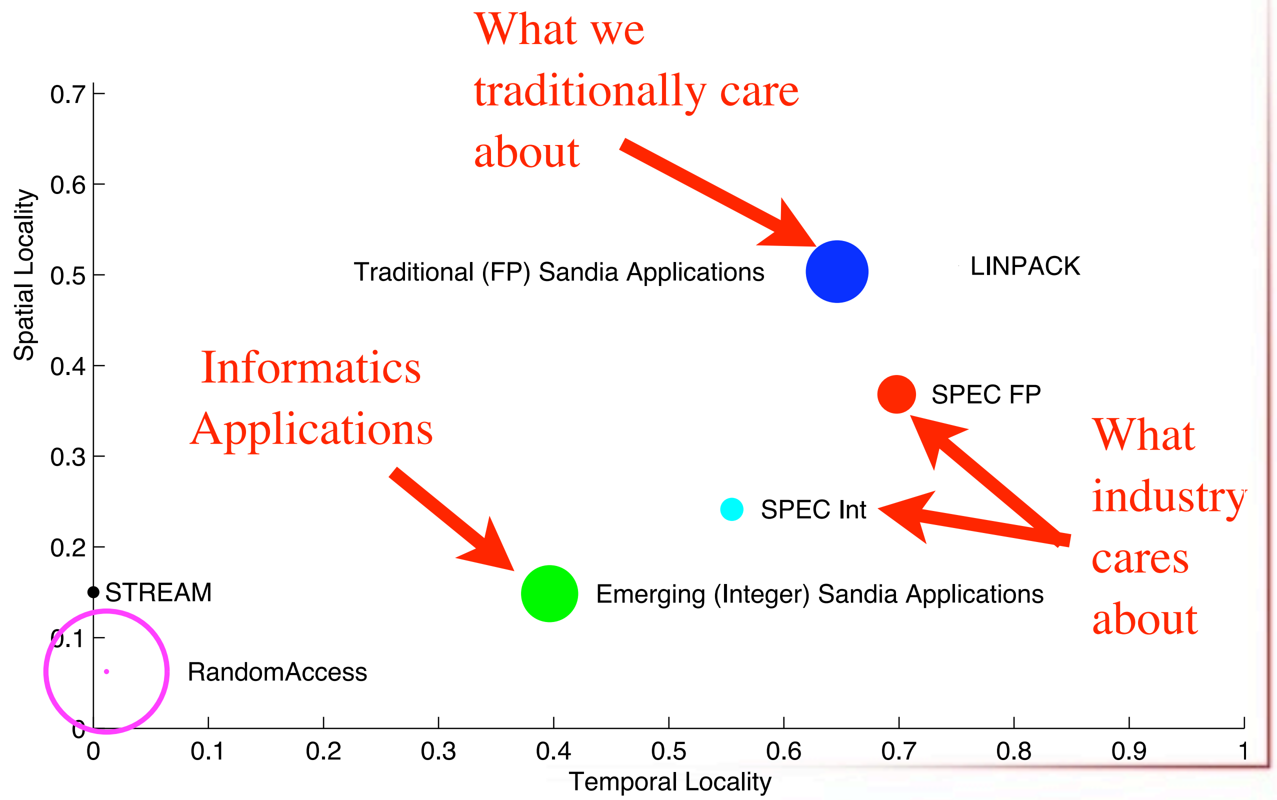
bus 2: Thread is assigned to an available thread slot

bus 3: Thread is deferred and placed in DTUQ.

bus 4: A FORK/SPAWN command enqueing a thread assignment request in RTUQ

Application Challenges

- **Huge variety in programming models and run-times emerging**
  - Evolutionary BSP-originated applications
  - Revolutionary programming models
    - Everyone’s got one, and they’re all the best
    - 101+ actively developed parallel programming languages
  - Lots of new application varieties
  - Flexibility key
- **Multiple optimization points**
  - Time to solution
  - Energy to solution
  - Money to solution
  - Total system efficiency



What we traditionally care about

Informatics Applications

What industry cares about

From: Murphy and Kogge, *On The Memory Access Patterns of Supercomputer Applications: Benchmark Selection and Its Implications*, IEEE T. on Computers, July 2007

Foundational Knowledge

- **Distributed systems scaling determined by:**
  - –Ability to move data
  - –Synchronization

- **Lightweight System Software WORKS**
  - –ASCI Red, ASC Red Storm, BG/{L,P,Q}
  - –Low perturbation of applications

- **Synchronization Costs**
  - –Local and remote
  - –Explicit and implicit

Research Questions

- **How will threads evolve to be more lightweight and match hardware semantics?**
  - What will hardware threading semantics be?

- **What synchronization primitives are necessary for highly asynchronous applications?**
  - Free, Fast, Infinite

- **What memory consistency models are necessary?**
  - ... or even useful?

- **What communication primitives are necessary for evolving applications?**
  - Probably not six-function MPI

Necessity is the Mother of Invention

- **Need insight into:**
  - Trade-offs between different data/work movement strategies
  - Cost of synchronization/protection mechanisms with real applications
  - How much automaticity/adaptivity is necessary in large scale applications?

- **Research is slowed by lack of experimental platform**

- **Use both clusters and simulation as foundational experimental platforms!**

- **Combine Kitten, Portals, and Qthreads to build a multi-node multi-threaded runtime for experimentation (SPR)**

Scalable Parallel Runtime (SPR)

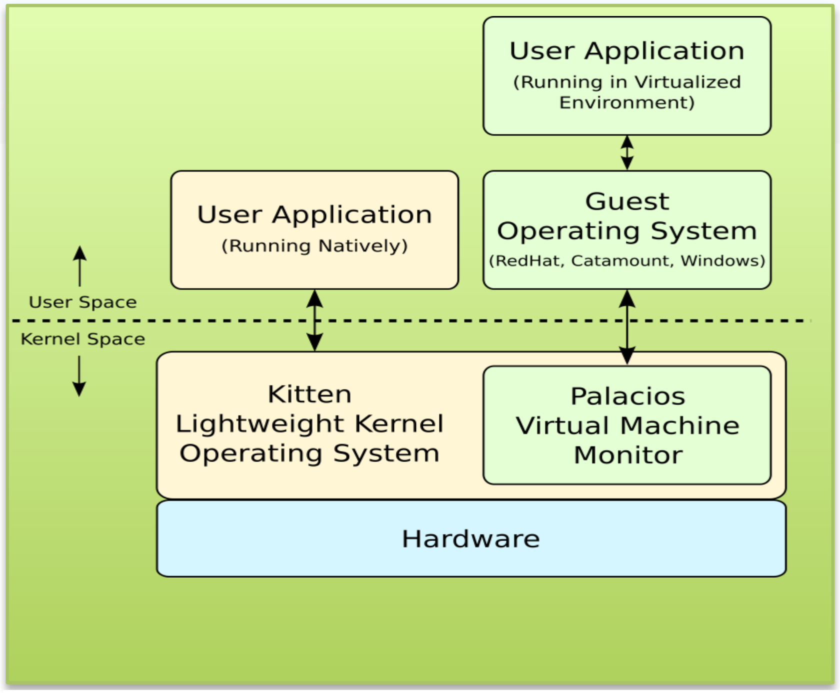
- **Qthreads: Lightweight threading interface**
  - –Scalable, lightweight scheduling on NUMA platforms
  - –Supports a variety of synchronization mechanisms, including Full/Empty bits and atomic operations
  - –Potential for direct hardware mapping
- **Portals 4: Lightweight networking API**
  - –Semantics for supporting both one-sided and tagged message passing
  - –Small set of primitives, allows offload from main CPU
  - –Supports direct hardware mapping
- **Kitten: Lightweight OS kernel**
  - –Builds on lessons from ASCI Red, Cplant, Red Storm
  - –Utilizes scalable parts of Linux environment
  - –Primarily supports direct hardware mapping

Kitten Lightweight Kernel

- **Simple compute node OS**
  - Tool for OS+runtime research
  - Looks like Linux to applications and tools
- **Current R&D**
  - Job launch via OpenMPI ORTE / mpirun
  - Support for Intel MIC, Arthur cluster at Sandia
  - System-call forwarding
  - Low-overhead task migration

Operating System	Round-Trip Task Migration Time (task on core A migrates to core B, then back to A
Linux 2.6.35.7	4435 ns
Kitten 1.3	2630 ns

Core-switching performance between two cores in the same Intel X5570 2.93 GHz processor. Kitten achieves a speedup of 1.7 compared to Linux, due to simpler implementation.



User Application (Running in Virtualized Environment)

User Application (Running Natively)

Guest Operating System (RedHat, Catamount, Windows)

User Space

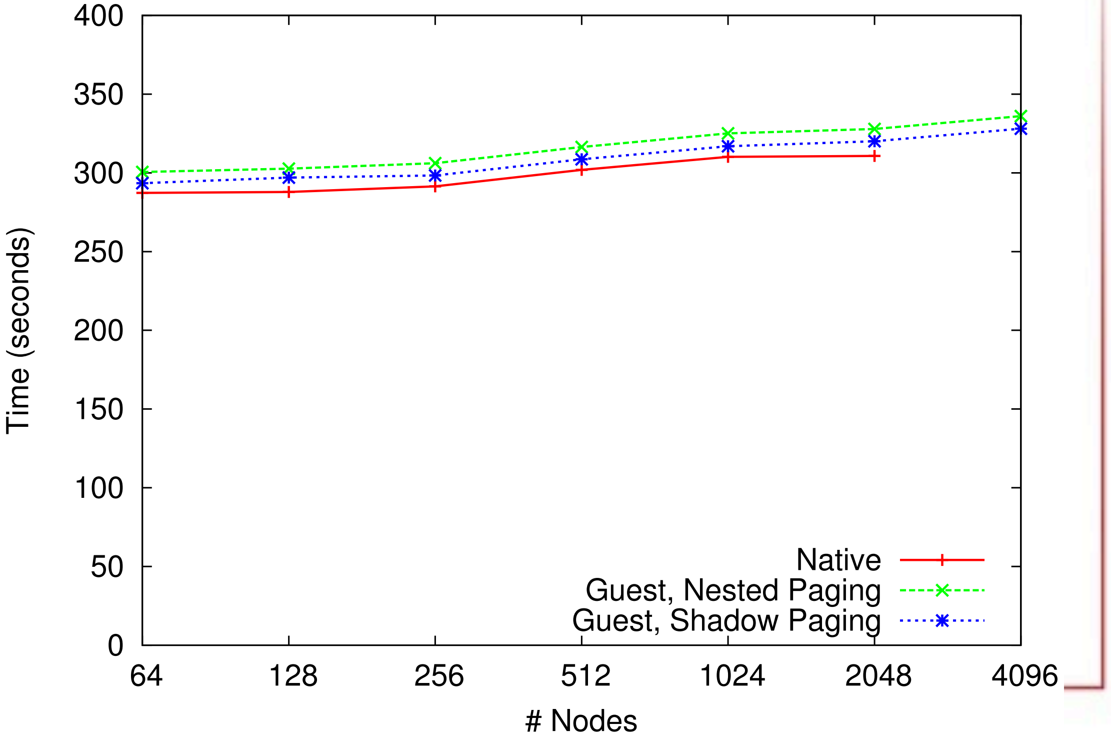
Kernel Space

Kitten Lightweight Kernel Operating System

Palacios Virtual Machine Monitor

Hardware

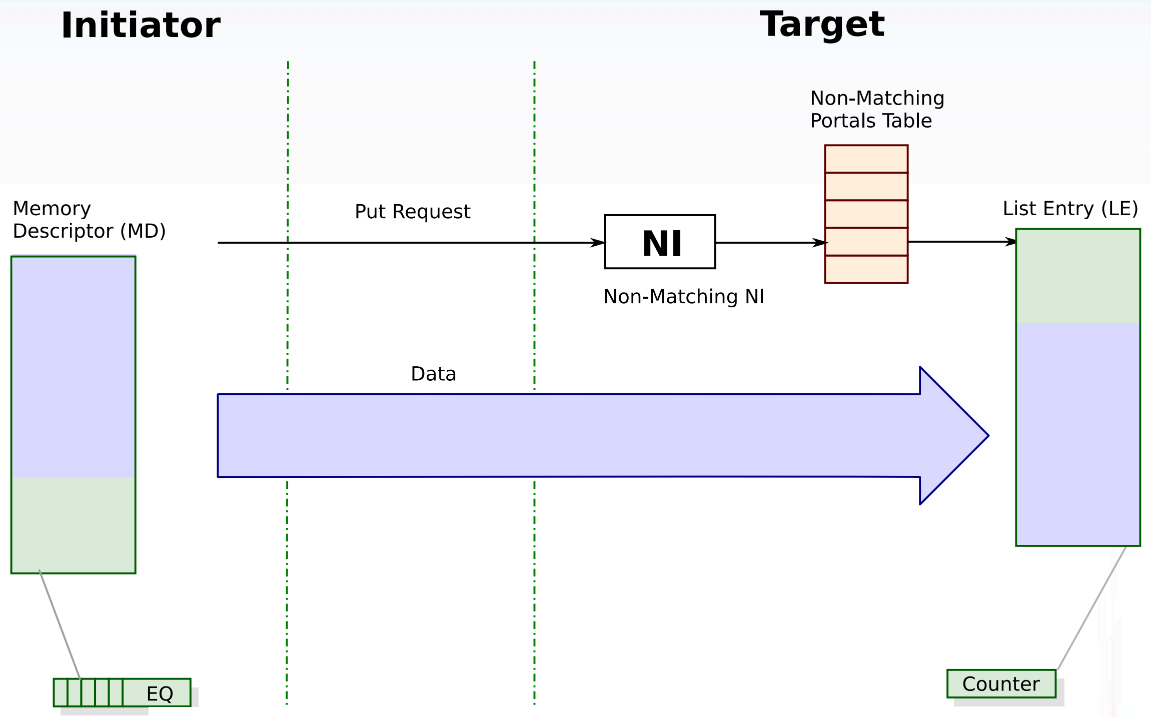
Kitten LWK supports running native applications alongside guest OSes.



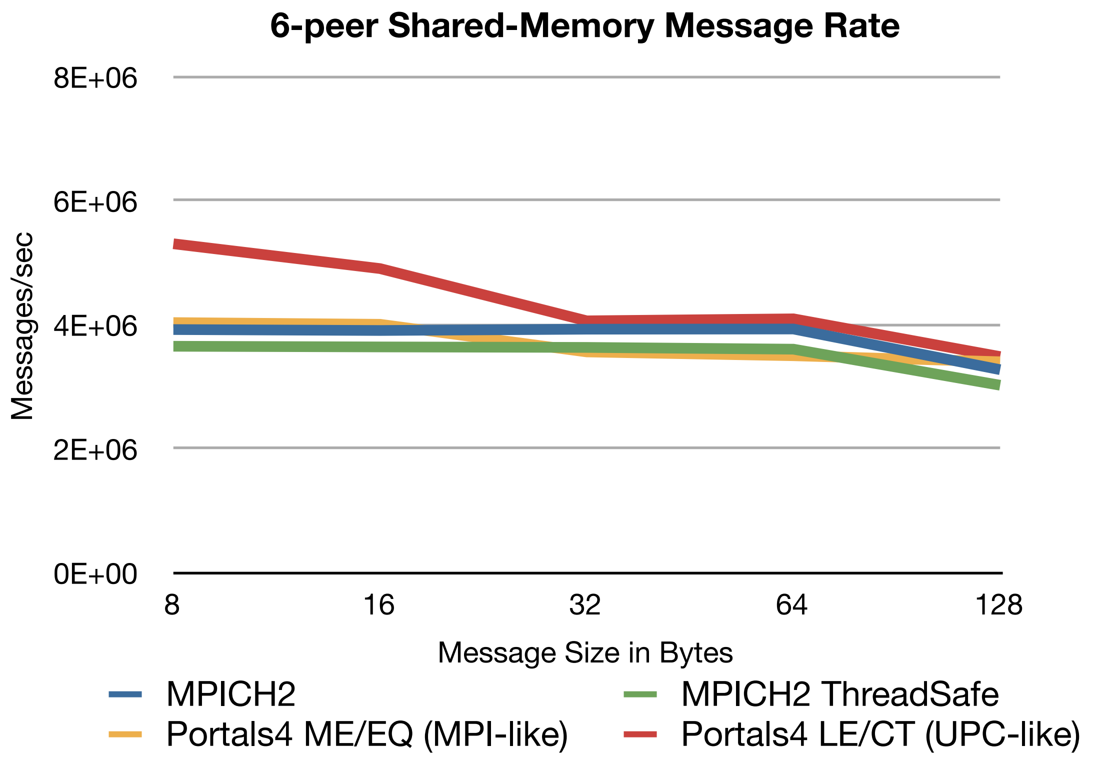
Weak scaling performance of Catamount guest OS is within 5% of Catamount native OS at 4096 nodes

Portals4 Lightweight Comm.

- **Simple low-level communication layer**
  - Tool for communication+runtime research
  - Thread-safe by design
  - Supports legacy and next-gen applications and tools
  - Common substrate to allow efficient use and sharing of resources among higher-level protocols
- **Current R&D**
  - Shared InfiniBand and SMP multi-core progress engines
  - Efficient blocking/waiting mechanisms



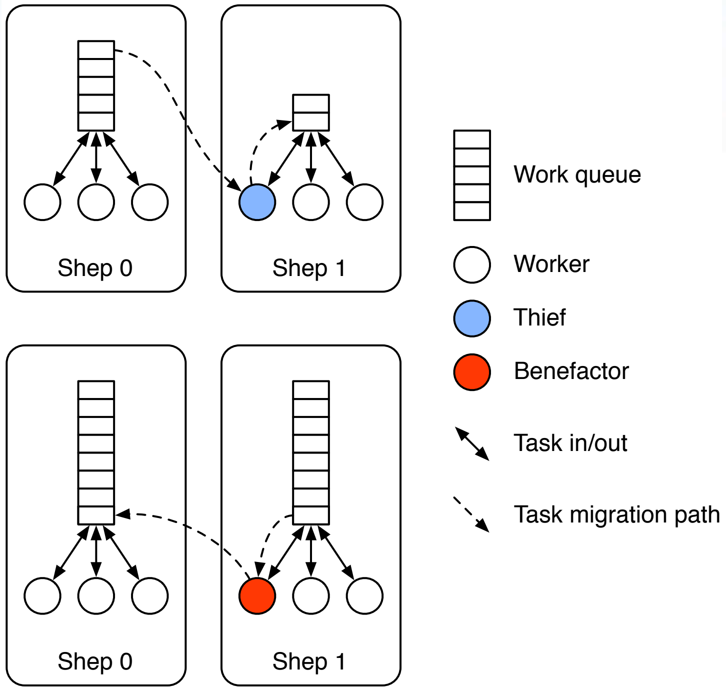
Much of the potential complexity gets out of the way for basic operations.



Message rates for small messages match MPICH2 performance under MPI-like conditions, and can even beat it for UPC-like conditions.

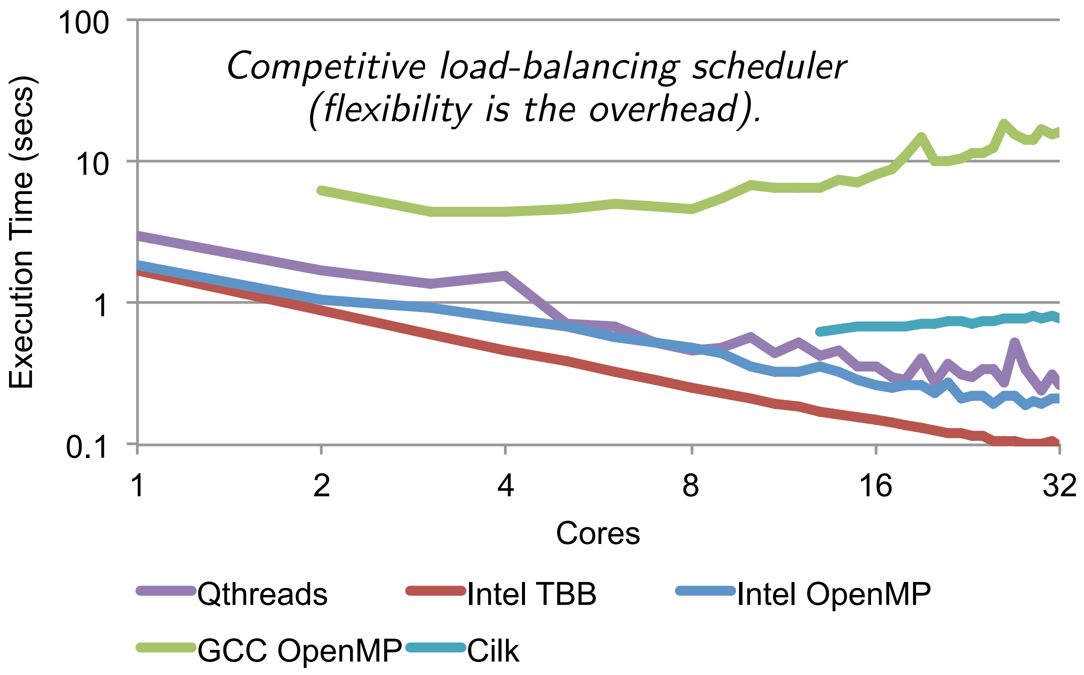
Qthreads Lightweight Threading

- **Simple task-based runtime**
  - Tool for programming model research
  - Supports both OpenMP-like models and more complex Chapel-like models
  - Presents simplified model of system to the application
  - High-performance scheduler
- **Current Qthreads R&D**
  - Task team and eureka support
  - Efficient, flexible collective operations
  - Remote task launch



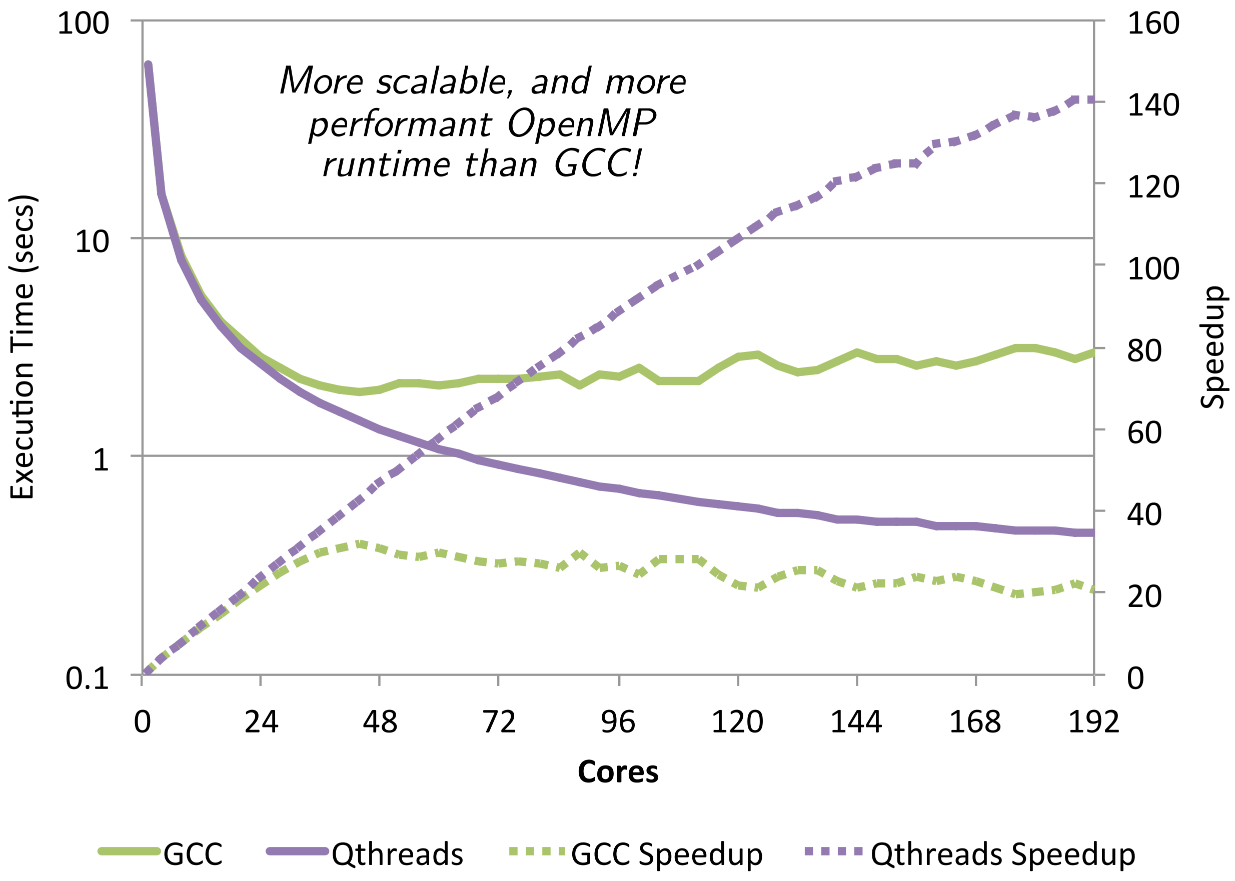
High performance "sherwood" work-stealing scheduler effectively balances cache efficiency with load balancing.

Unbalanced Tree Search Benchmark



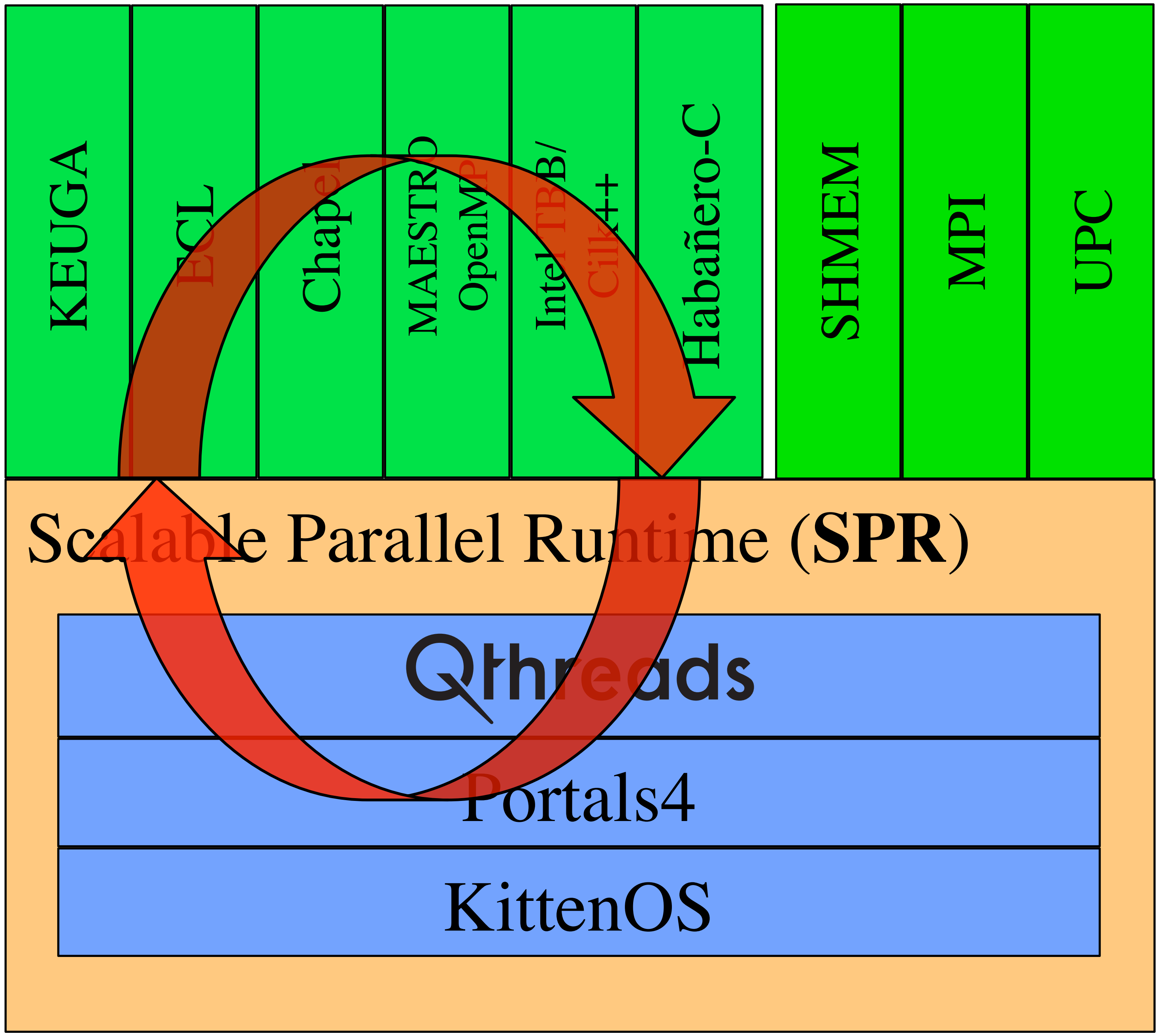
Competitive load-balancing scheduler (flexibility is the overhead).

BOTS NQueens Benchmark (Altix 3600)



More scalable, and more performant OpenMP runtime than GCC!

Runtime Architecture / Experimental Platform



KEUGA

ECL

Chapel

MAESTRO OpenMP

Intel TBB/ Cilk++

Habañero-C

SHMEM

MPI

UPC

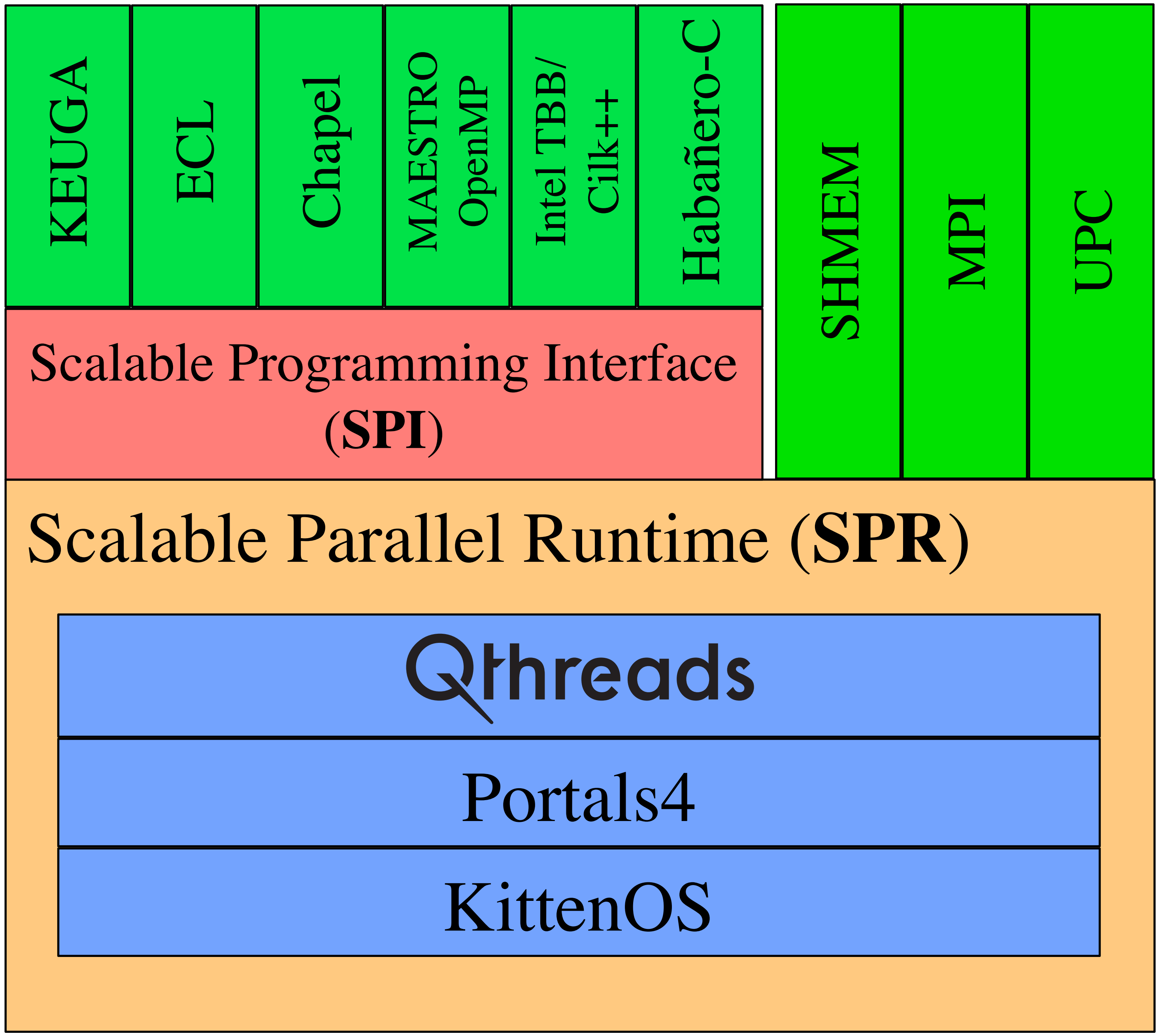
Scalable Parallel Runtime (**SPR**)

Qthreads

Portals4

KittenOS

Runtime Architecture / Experimental Platform



The Lime in the Coconut

- **Research slowed by lack of applications**
  - Apps need programming environment vision
  - ...and an API, if possible
- **Experiment-driven SPI (Scalable Programming Interface) design-points:**
  - Environmental description (local vs global topology)
  - Naming needs (GIDs vs handles vs ?)
  - How much detail is necessary from the application to specify performant data/work movement?
  - How much detail from the runtime is necessary to enable specification of performant data/work movement?
  - What synchronization semantics are needed and/or useful? (Futures vs mutexes vs FEBs vs ?)
- **Use both experimental results and application programming effort to guide API development**

Current Status

- **Download Today!**
  - –Kitten: http://code.google.com/p/kitten/
  - –Portals4: http://code.google.com/p/portal4/
  - –Qthreads: http://code.google.com/p/qthreads/

- **Stacked components work**
  - –Portals4 on Kitten (with InfiniBand)
  - –Qthreads on Kitten
  - –Qthreads on Portals4

- **Multinode Threading Environment**
  - –Remote spawn/sync
  - –Multinode UTS, without work-stealing

Thank You!