# Quad-core Catamount and R&D in Multi-core Lightweight Kernels

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Outline

- Introduction
- Quad-core Catamount LWK results
- Open-source LWK
- Research directions
- Conclusion

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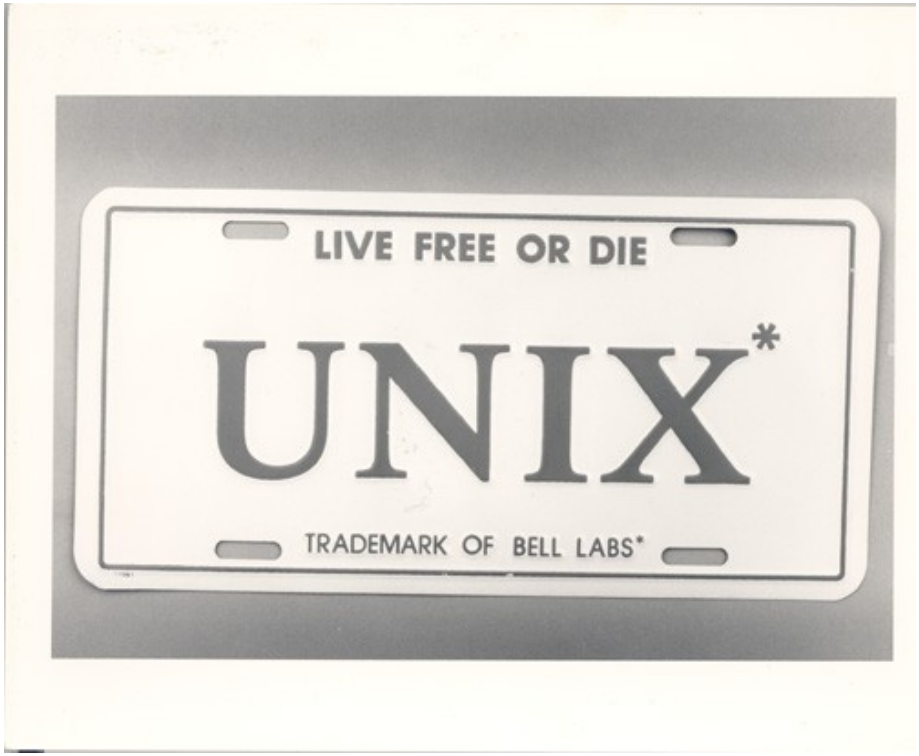
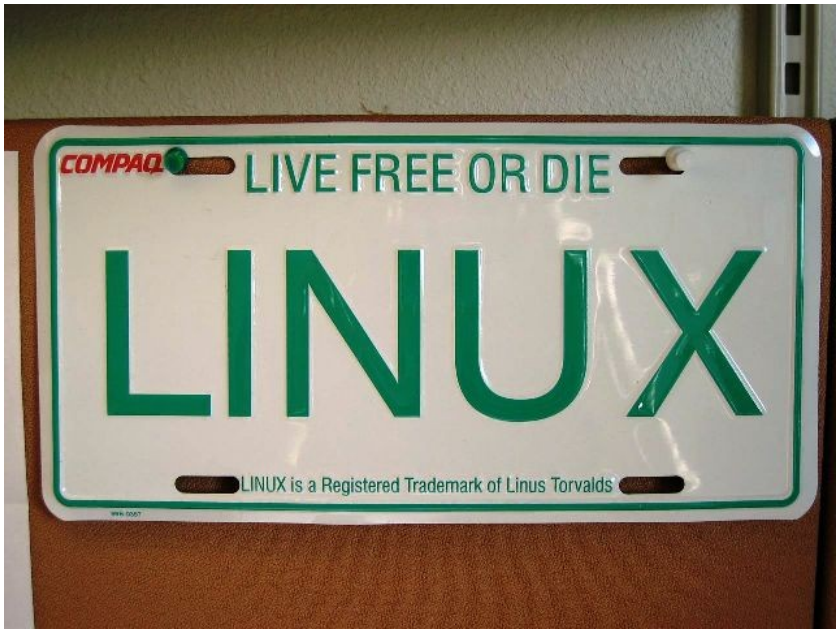
# Going on Four Decades of UNIX




**Operating System = Collection of software and APIs**
**Users care about environment, not implementation details**
**LWK is about getting details right for scalability**

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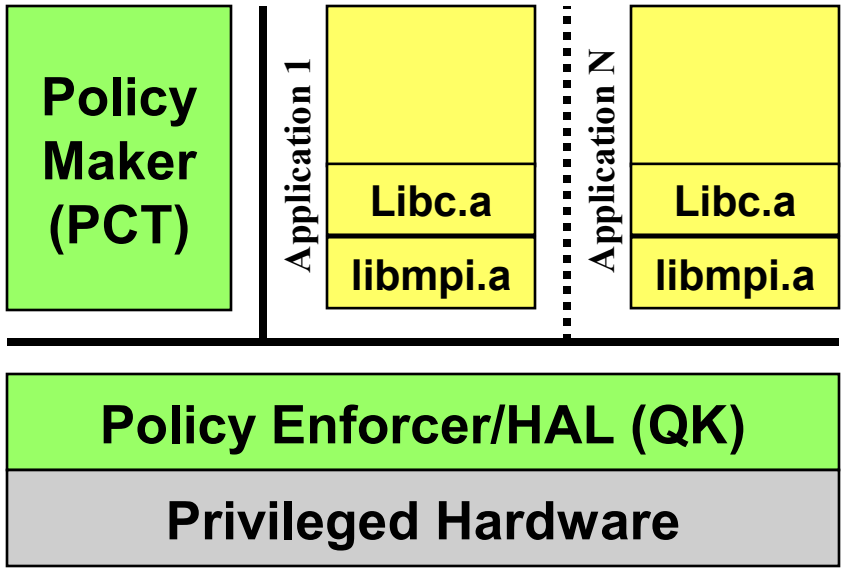
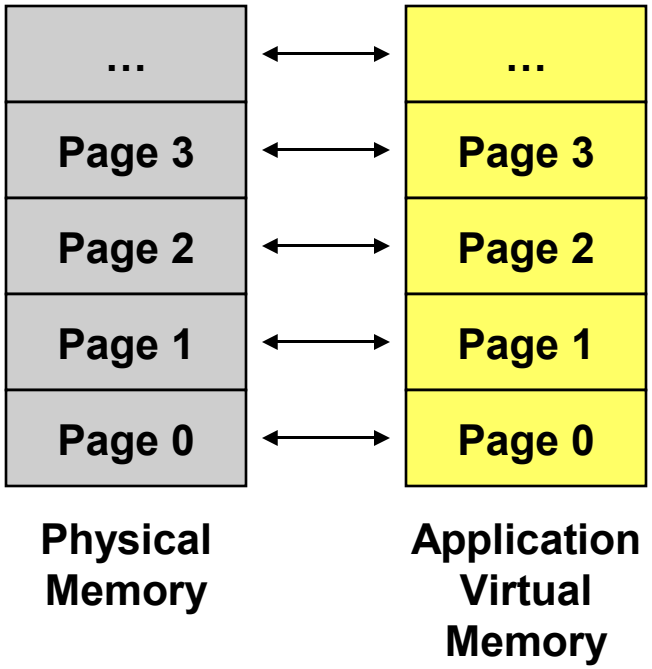
# LWK Overview

## Basic Architecture




## Memory Management




- POSIX-like environment
- Inverted resource management
- Very low noise OS noise/jitter
- Straight-forward network stack (e.g., no pinning)
- Simplicity leads to reliability

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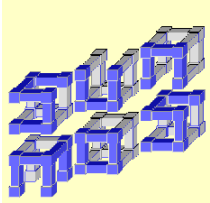
# Lightweight Kernel Timeline

**Nov 2007 Top500**
**Top 10 System**
**<u>Compute Processors:</u>**
**82% run a LWK**



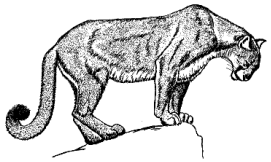
1990 – Sandia/UNM OS (SUNMOS), nCube-2

1991 – Linux 0.02

1993 – SUNMOS ported to Intel Paragon (1800 nodes)

1993 – SUNMOS experience used to design Puma

First implementation of Portals communication architecture



1994 – Linux 1.0

1995 – Puma ported to ASCI Red (4700 nodes)

Renamed Cougar, productized by Intel

Computational Plant

1997 – Stripped down Linux used on Cplant (2000 nodes)

Difficult to port Puma to COTS Alpha server

Included Portals API

2002 – Cougar ported to ASC Red Storm (13000 nodes)

Renamed Catamount, productized by Cray

Host and NIC-based Portals implementations

2004 – IBM develops LWK (CNK) for BG/L/P (106000 nodes)

2005 – IBM & ETI develop LWK (C64) for Cyclops64 (160 cores/die)

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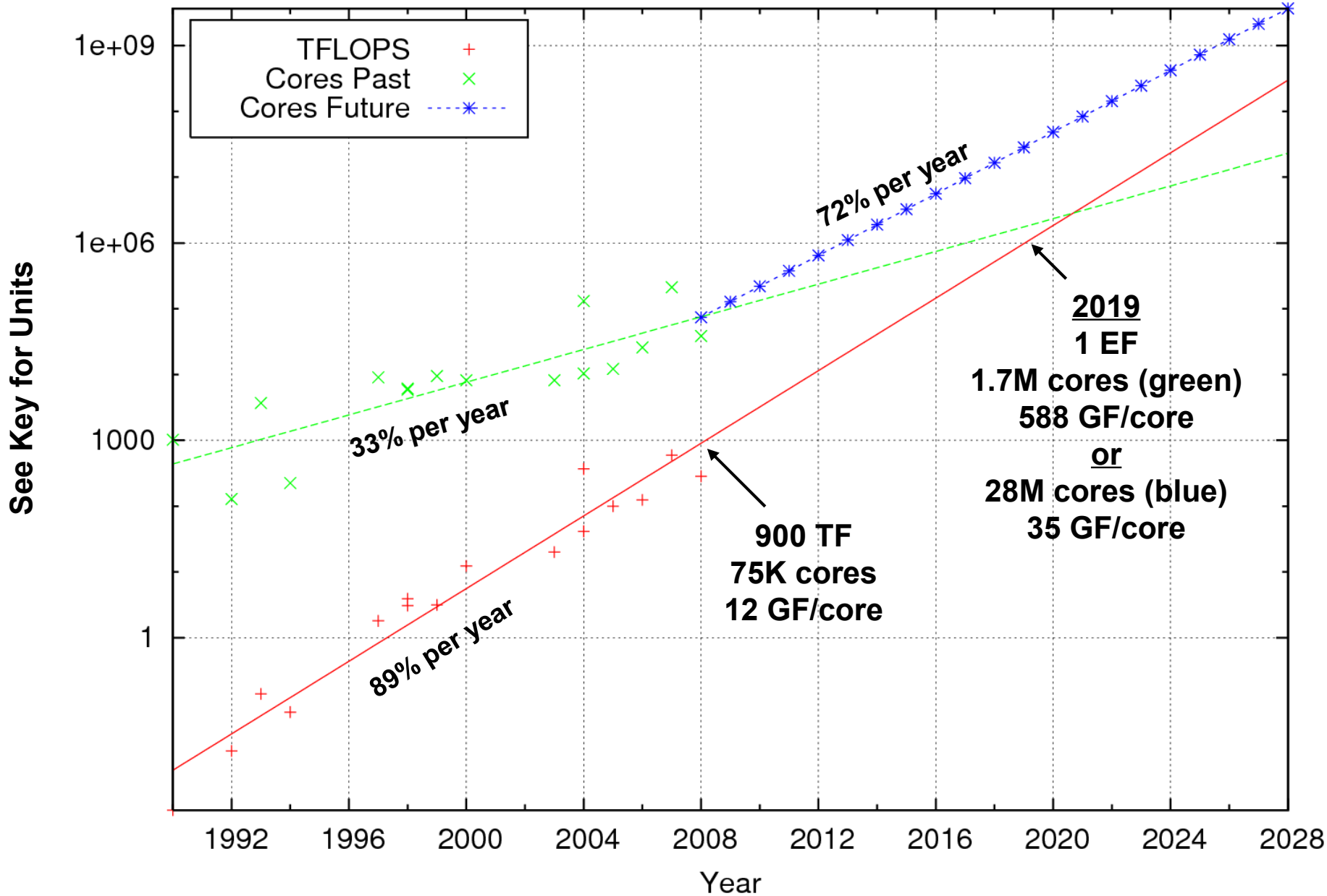
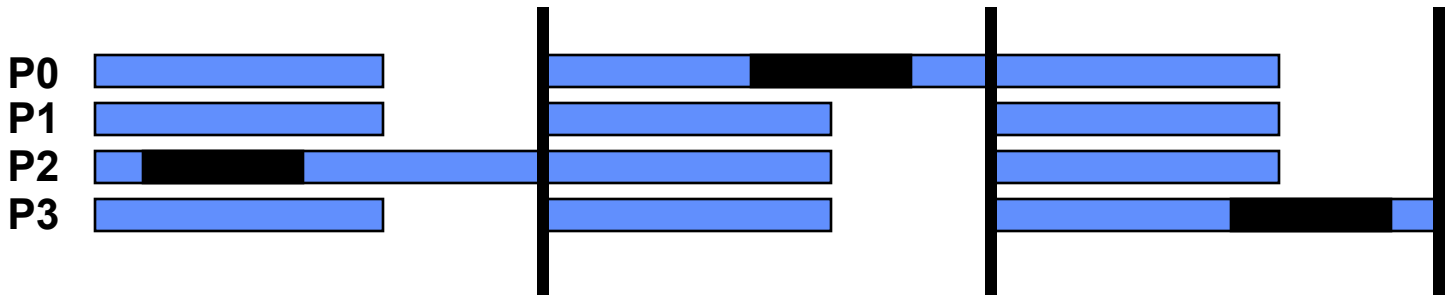
# Challenge: Exponentially Increasing Parallelism



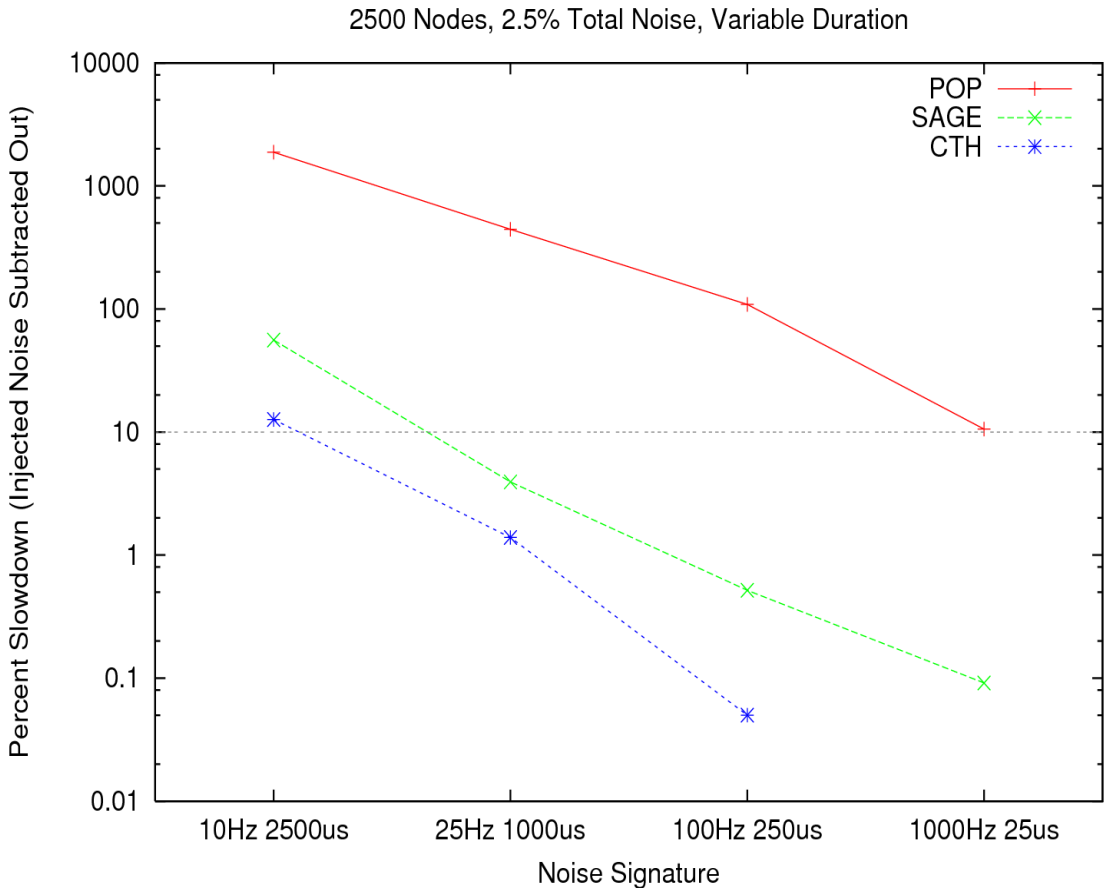
# We Know OS Noise Matters




- Impact of noise increases with scale (basic probability)
- Multi-core increases load on OS
- Idle noise measurements distort reality
  - Not asking OS to do anything
  - Micro-benchmark != real application

See "The Case of the Missing Supercomputer Performance", Petrini, et al.

# Red Storm Noise Injection Experiments




- **Result:**
  **Noise duration is more important than frequency**
- **OS should break up work into many small & short pieces**
- **Opposite of current efforts**
  - **Linux Dynaticks**
- **Cray CNL with 10 Hz timer had to revert back to 250 Hz due to OS noise duration issues**

From Kurt Ferreira's Masters Thesis

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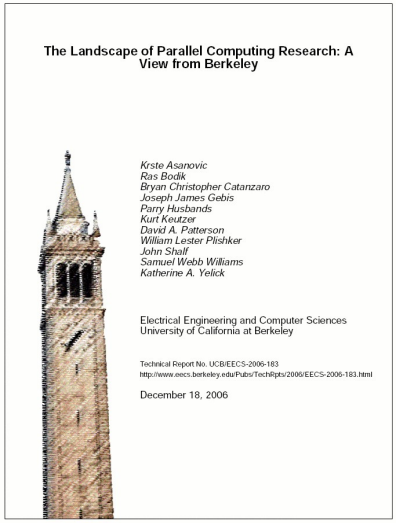
# Drivers for LWK Compute Node OS

- Practical advantages
  - Low OS noise
  - Performance – tuned for scalability
  - Determinism – inverted resource management
  - Reliability
- Research advantages
  - Small and simple
  - Freedom to innovate (see “Berkeley View”)
    - Multi-core
    - Virtualization
  - Focused on capability systems
- Can’t separate OS from node-level architecture



The Landscape of Parallel Computing Research: A View from Berkeley

*Krste Asanovic*
*Ras Bodik*
*Bryan Christopher Catanzaro*
*Joseph James Gebis*
*Parry Husbands*
*Kurt Keutzer*
*David A. Patterson*
*William Lester Plishker*
*John Shalf*
*Samuel Webb Williams*
*Katherine A. Yelick*

Electrical Engineering and Computer Sciences
University of California at Berkeley

Technical Report No. UCB/EECS-2006-183
http://www.eecs.berkeley.edu/Pubs/TechRpts/2006/EECS-2006-183.html

December 18, 2006

**Much simpler to create LWK than mainstream OS**

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# Quad-core Catamount

- **Risk mitigation for ORNL Jaguar System**
  - Plan of record: CNL + ALPS
  - Backup plan: Quad-core Catamount

- **Funded by DOE Office of Science and ORNL**
  - PI: Sue Kelly;
    John VanDyke, Courtenay Vaughan
  - Project complete, fully functional
  - Will be used for Red Storm quad-core upgrade:
    38400 cores, 284 TFLOPS

- **Results discussed:**
  - Large-scale dual-core CNL vs. Catamount
  - Small-scale quad-core performance

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# Large-scale Dual-core CNL vs. Catamount

| | CNL 2.0.03+ | Catamount 2.0.05+ | CNL vs. Catamount |
|---|---|---|---|
| | PGI 6.1.6 | PGI 6.1.3 | % CNL worse |
| **GTC** | | | |
| 1024 XT3 only | 595.6 | 584.0 | 2.0 |
| 4096 XT3 only | 614.6 | 593.8 | 3.5 |
| 20000 XT3/XT4 | 786.5 | 778.9 | 1.0 |
| **VH1** | | | |
| 1024 XT3 only | 22.7 | 20.9 | 8.6 |
| 4096 XT3 only | 137.1 | 117.4 | 16.8 |
| 20000 XT3/XT4 | 1186.0 | 981.7 | 20.8 |
| **POP** | | | |
| 4800 XT3 only | 90.6 | 77.6 | 16.8 |
| 20000 XT3/XT4 | 98.8 | 75.2 | 31.4 |

**Testing performed June 16-17, 2007 at ORNL**

- Apps important to ORNL
- Time ran out before LSMS and S3D problems diagnosed
- Catamount apps did not link with IOBUF library

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# Small-scale Quad-core CNL vs. Catamount

| Application | # MPI Ranks | Cores per Node | CNL (time units, lower better) | Catamount (time units, lower better) | (CNL/Catamount - 1) * 100% |
|---|---|---|---|---|---|
| GTC | 16 | 4 | 664.9 | 670.6 | -0.8 |
| S3D | 16 | 4 | 1949.1 | 1948.9 | 0.0 |
| POP | 16 | 4 | 153.8 | 151.9 | 1.3 |
| LSMS | 16 | 4 | 290.1 | 276.8 | 4.8 |
| SPPM | 16 | 4 | 847.8 | 845.0 | 0.3 |
| UMT | 16 | 4 | 8.4 | 7.9 | 6.4 |
| PRONTO | 16 | 4 | 241.5 | 222.0 | 8.8 |
| SAGE | 16 | 4 | 267.8 | 234.9 | 14.0 |
| CTH | 16 | 4 | 15.1 | 13.0 | 16.6 |
| PARTISN | 16 | 4 | 43.2 | 35.7 | 21.0 |

**Disclaimer: Some test problems were small**

**Testing performed April, 2008 at Sandia**

- Four nodes, 2.2 GHz quad-core, rev. B2
- UNICOS 2.0.44
- 4 KB pages CNL, 2 MB Catamount
- VH1 wouldn't run on CNL

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# Catamount Quad-core Cores Effectively Used

| Application | Utilization of each Core | Cores Effectively Used |
|---|---|---|
| PARTISN | 40% | 1.60 |
| CTH | 71% | 2.84 |
| SAGE | 74% | 2.95 |
| PRONTO | 79% | 3.18 |
| UMT2K | 91% | 3.62 |

**Disclaimer: UMT2K problem was possibly small, others reasonable**

**Calculation:**

- 4 core runs, either 1 core per node (S) or 4 cores per node (Q)
- Assume S takes 1 hr. and Q takes .85 hours
- Assume S using 100% of core
- Q is effectively using .85 * 4 = 3.4 of each core

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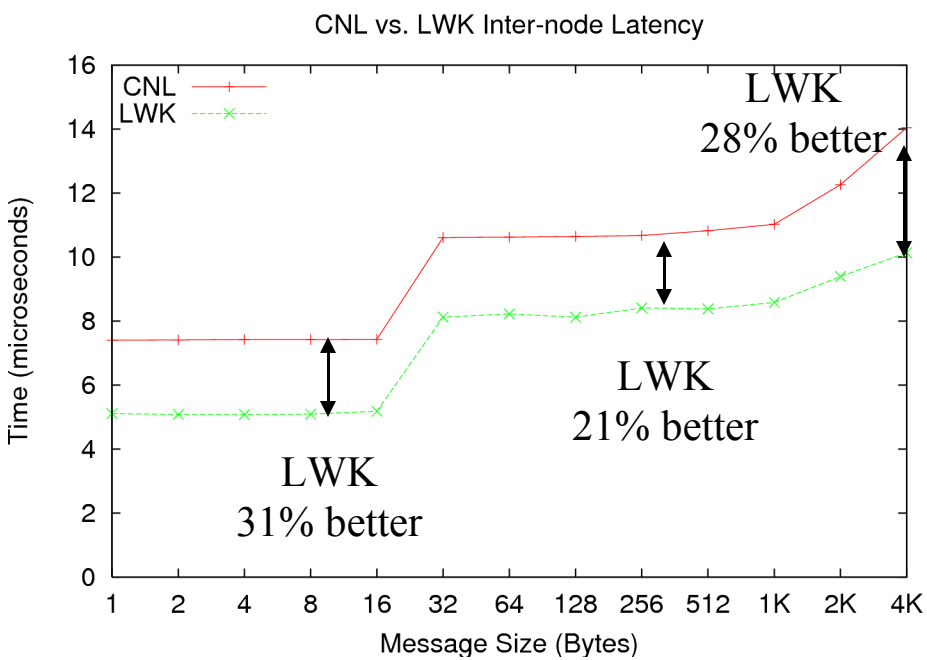
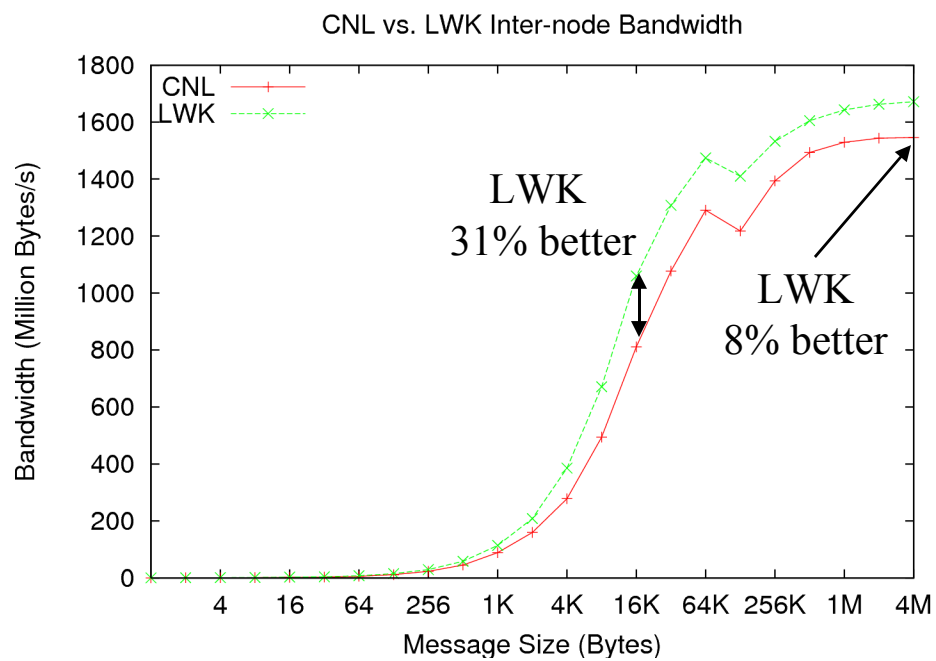
# Quad-Core Catamount Network Stack Performance

- **LWK's static, contiguous memory layout simplifies network stack**
  - **No pinning/unpinning overhead**
  - **Send address/length to SeaStar NIC**




Host-based Network Stack (Generic Portals)
Testing Performed April 2008 at Sandia, UNICOS 2.0.44

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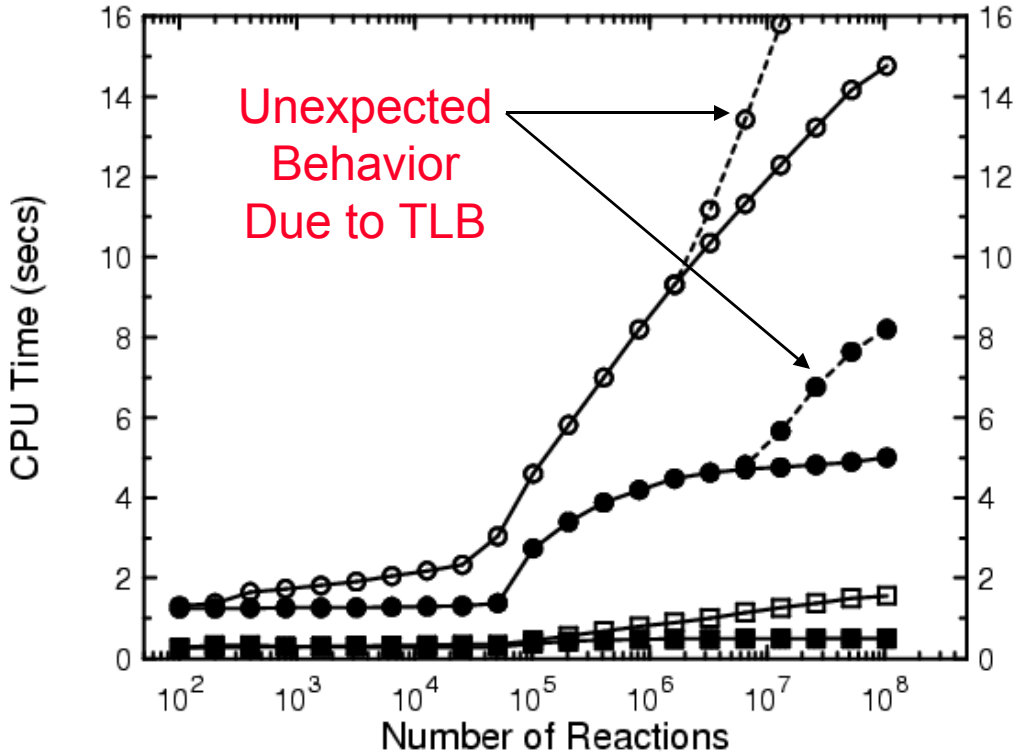
# TLB Gets in Way of Algorithm Research




Dashed Line =
Small pages

Solid Line =
Large pages
(Dual-core Opteron)

Open Shapes =
Existing Logarithmic Algorithm
(Gibson/Bruck)

Solid Shapes =
New Constant-Time Algorithm
(Slepoy, Thompson, Plimpton)

**TLB misses increased with large pages,**
**but time to service miss decreased dramatically (10x).**
**Page table fits in L1! (vs. 2MB per GB with small pages)**

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# Project Kitten

- Creating modern open-source LWK platform
  - Multi-core becoming MPP on a chip, requires innovation
  - Leverage hardware virtualization for flexibility
- Retain scalability and determinism of Catamount
- Better match user and vendor expectations

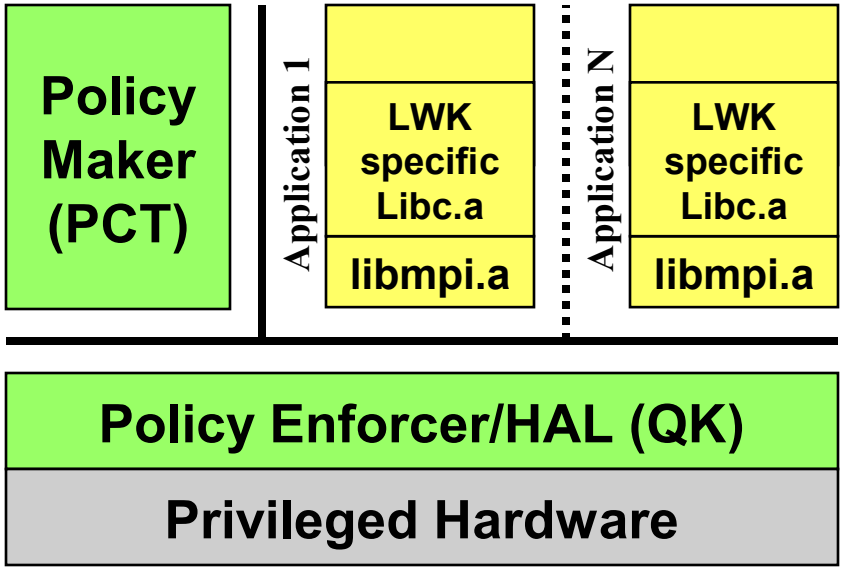
| Linux, Solaris, AIX, Windows | Cplant, Cray CNL, Bproc/XCPU | Plan9, K42, L4 | Catamount, BGL/CNK, BGP/CNK | Cyclops |
|---|---|---|---|---|
| COTS | Lightweight Linux | "Rightweight" | LWK | Exotic |

# Leverage Linux and Open Source

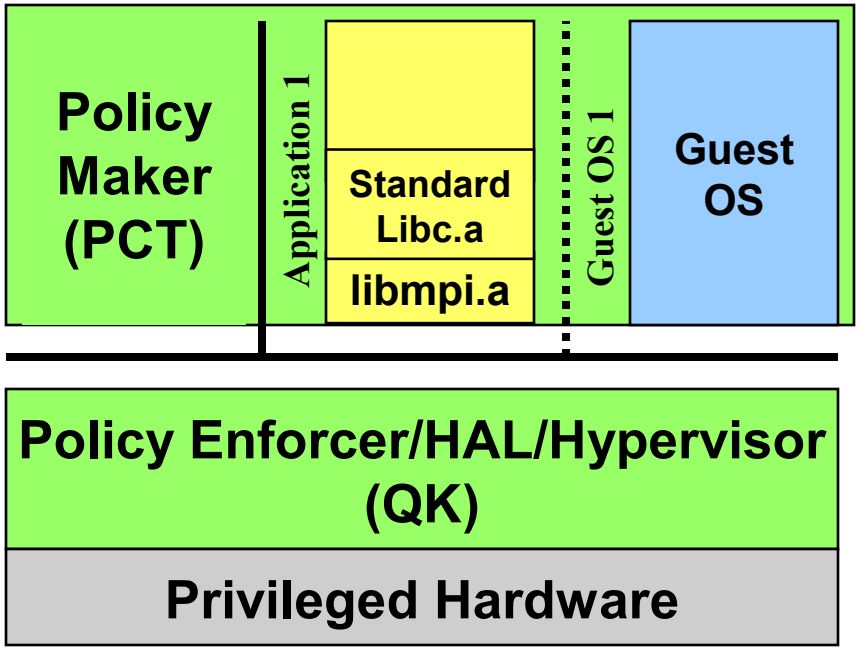
- **Repurpose basic functionality from Linux Kernel**
  - Hardware bootstrap
  - Basic OS kernel primitives
- **Innovate in key areas**
  - Memory management (Catamount-like)
  - Network stack
  - Fully tick-less operation, but short duration OS work
- **Aim for drop-in replacement for CNL**
- **Open platform more attractive to collaborators**
  - Northwestern and UNM adding their V3VEE lightweight hypervisor to Kitten (NSF funded)
  - Potential for wider impact

# LWK Architecture

## Catamount




## Kitten




**Major changes:**

- QK includes hypervisor functionality
- QK provides Linux ABI interface, relay to PCT
- PCT provides function shipping, rather than special libc.a

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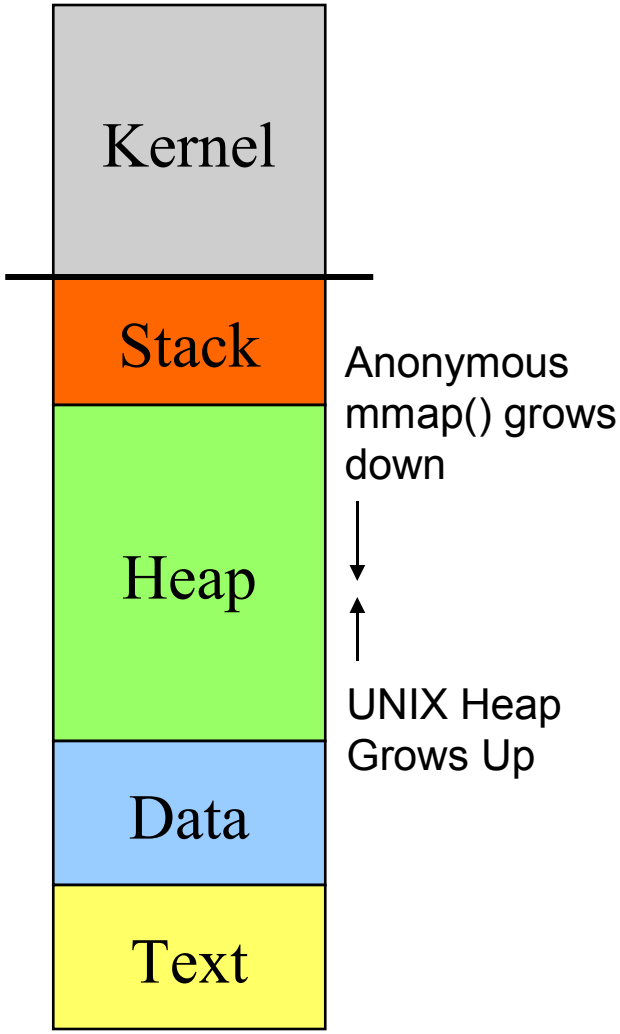
# Status




- **X86-64 support**
- **Linux ABI**
  - **Basic system calls**
  - **Initial user-stack setup**
  - **Thread Local Storage (TLS)**
  - **Virtual system calls**
- **Boots on Red Storm**
  - **Drop-in CNL replacement**
  - **Console I/O**
  - **Portals network stack**
- **Initrd treated as PCT (ELF image)**
- **Runs STREAM compiled with standard Linux toolchain**
- **DOE approved for open source release (GPL)**

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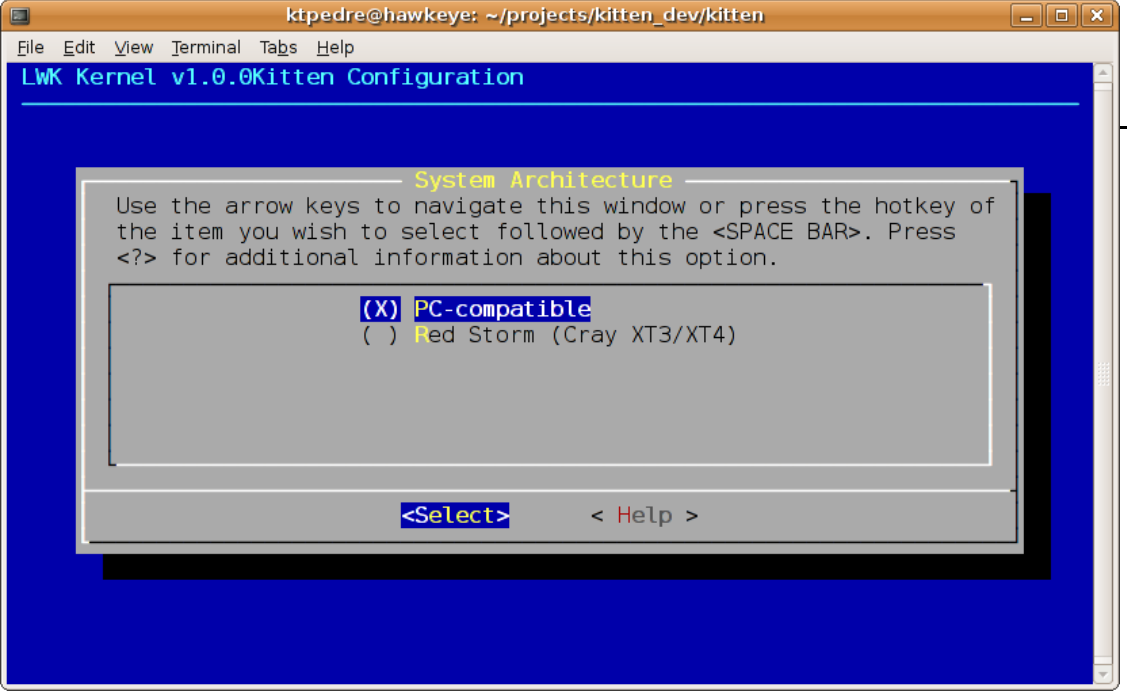
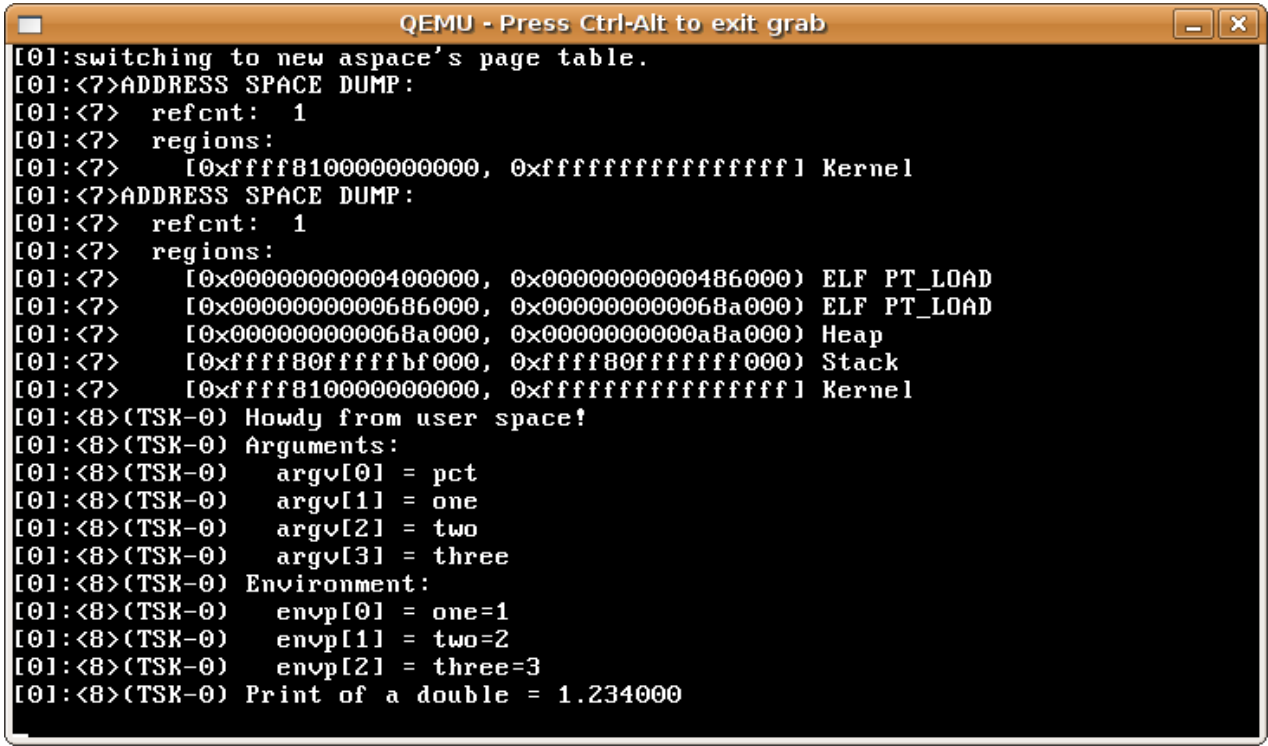



```
make bzImage
make isoimage
```

↓

```
kvm -cdrom image.iso
```

↓



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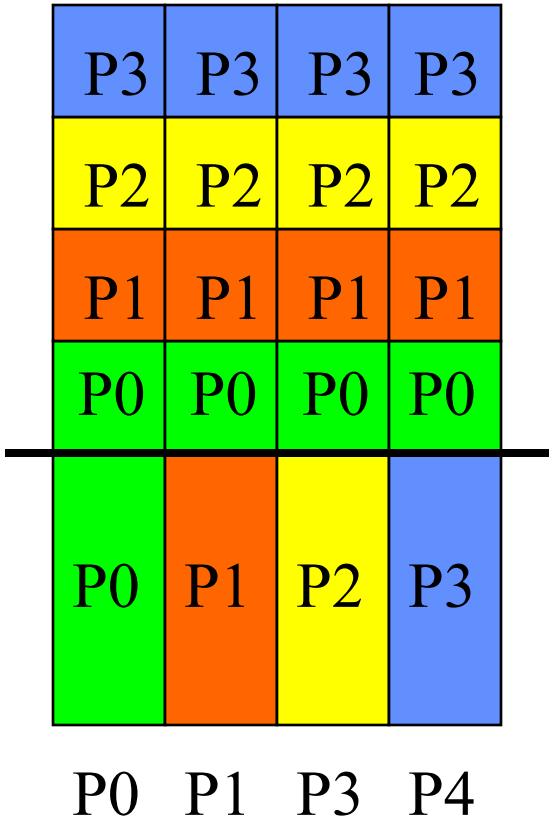
# SMARTMAP: Simple Mapping of Address Region Tables for Multi-core Aware Programming

Ron Brightwell, Trammell Hudson, Kevin Pedretti

- Leverages LWK memory management model
- Allows all of the processes on a multi-core processor to access each others' memory directly
  - User-space to user-space
  - No serialization through the OS
  - Access to remote address by flipping a bit
- Each process still has a separate virtual address space
- Allows MPI to minimize memory-to-memory copies on node
  - No copying for non-contiguous MPI datatypes
  - More efficient collective operations
    - Reductions can operate directly on user buffer

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# Complexity of a Lightweight OS

## LWK Code

```
static void
initialize_shared_memory( void )
{
    extern page_table_t *pml4_table_cpu[];
    int cpu;
    for ( cpu=0; cpu < MAX_NUM_CPUS; cpu++ )
    {
        page_table_t *pml4 = pml4_table_cpu[ cpu ];
        if ( !pml4 )
            continue;
        pcb_t * kpcb = cur_kpcb_ptr[cpu];
        if ( !kpcb )
            continue;
        page_table_entry_t dirbase = (
            phys_addr( kpcb->kpcb_dirbase )
            | PDE_P
            | PDE_W
            | PDE_U
        );
        int other;
        for ( other=0; other < MAX_NUM_CPUS; other++ )
        {
            page_table_t *other_pml4 = pml4_table_cpu[other];
            if ( !other_pml4 )
                continue;
            other_pml4[ cpu+1 ] = dirbase;
        }
    }
}
```

## User Code

```
static inline void *
remote_address(
    unsigned core,
    volatile void * vaddr)
{
    uintptr_t addr = (uintptr_t) vaddr;
    addr |= ((uintptr_t) (core+1)) << 39;
    return (void*) addr;
}
```

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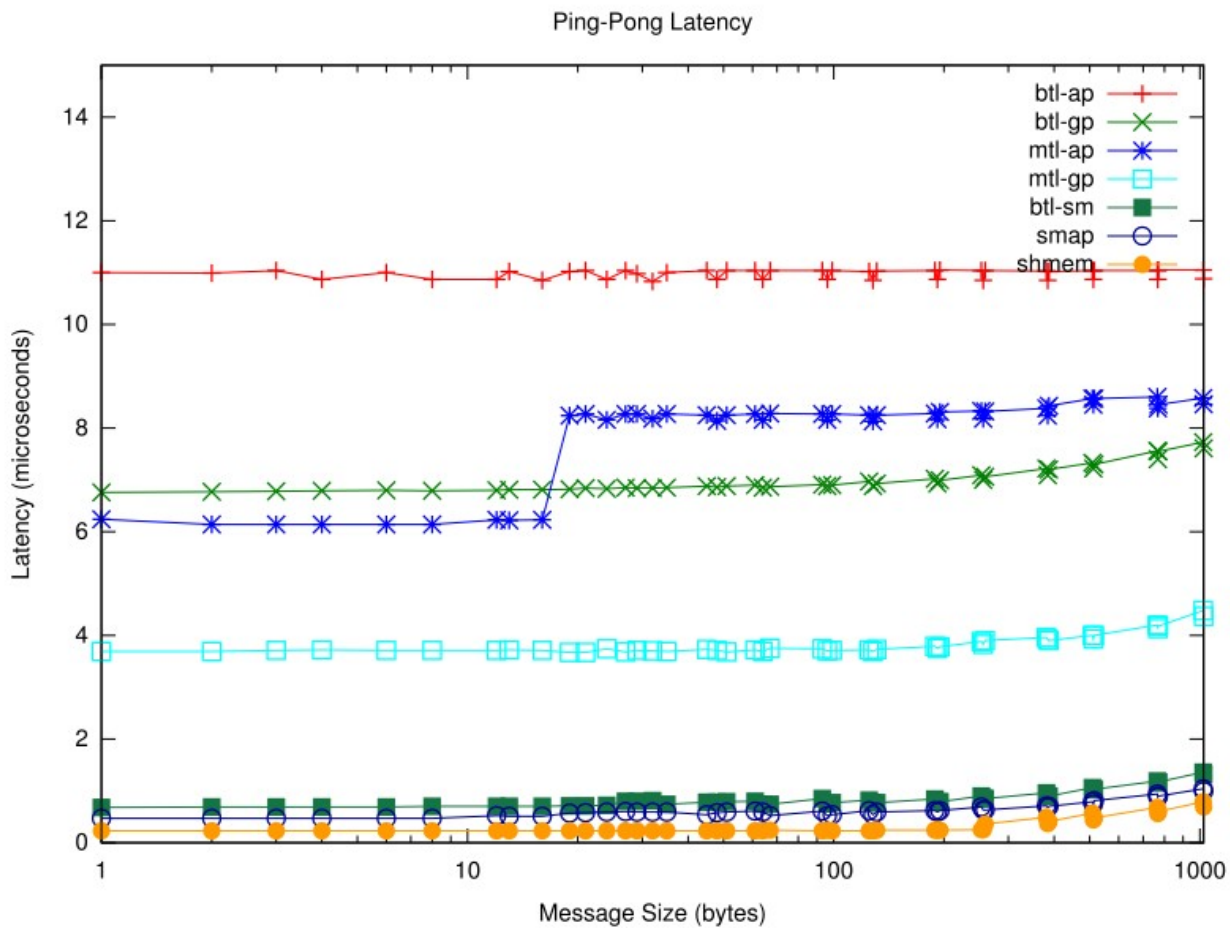
# PingPong Latency




- 2.2 GHz Quad-core AMD Opteron
- Catamount N-Way (CNW) 2.0.41
- PGI 7.1.4
- GNU 3.3.3
- Open MPI subversion head

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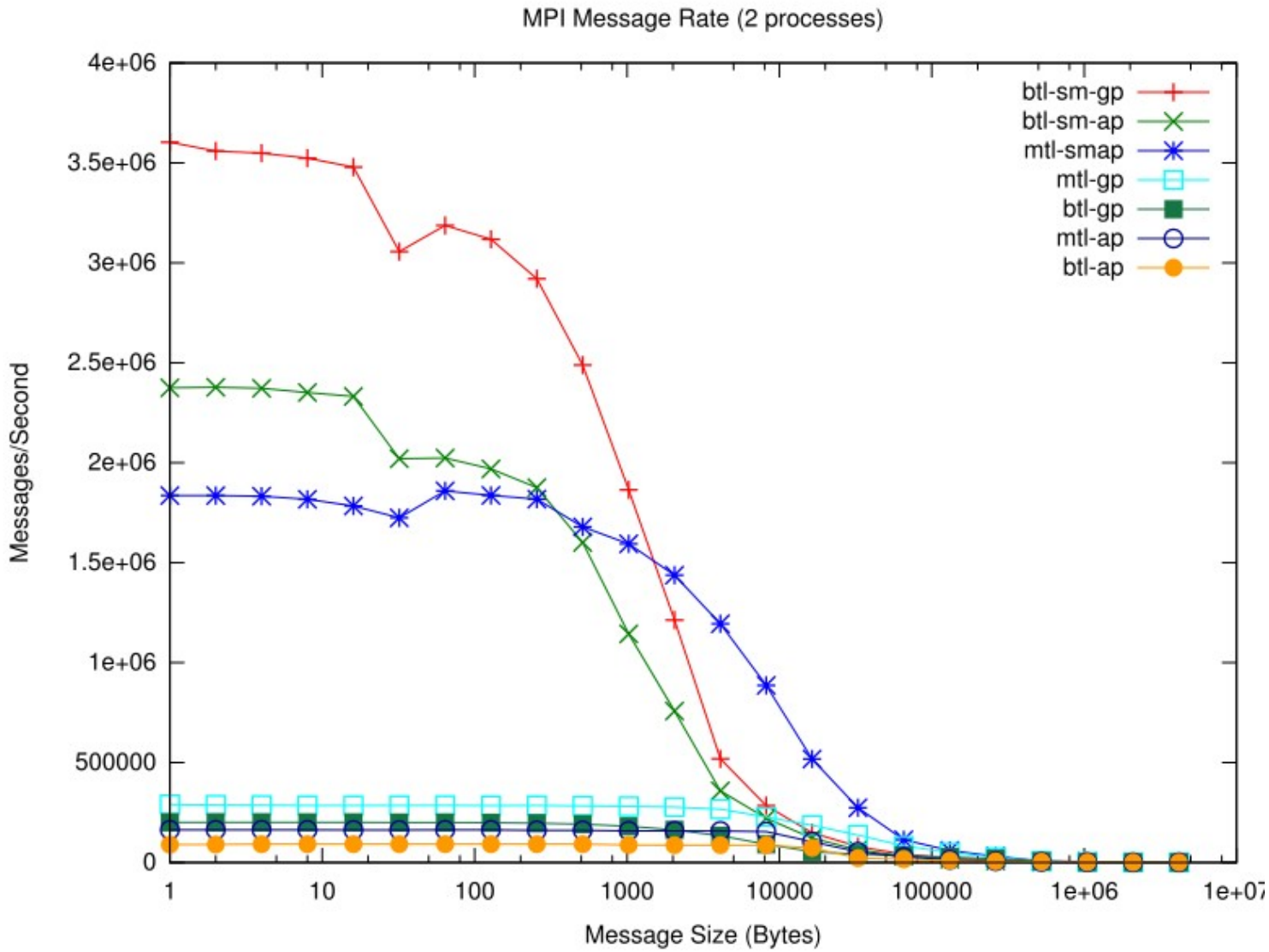


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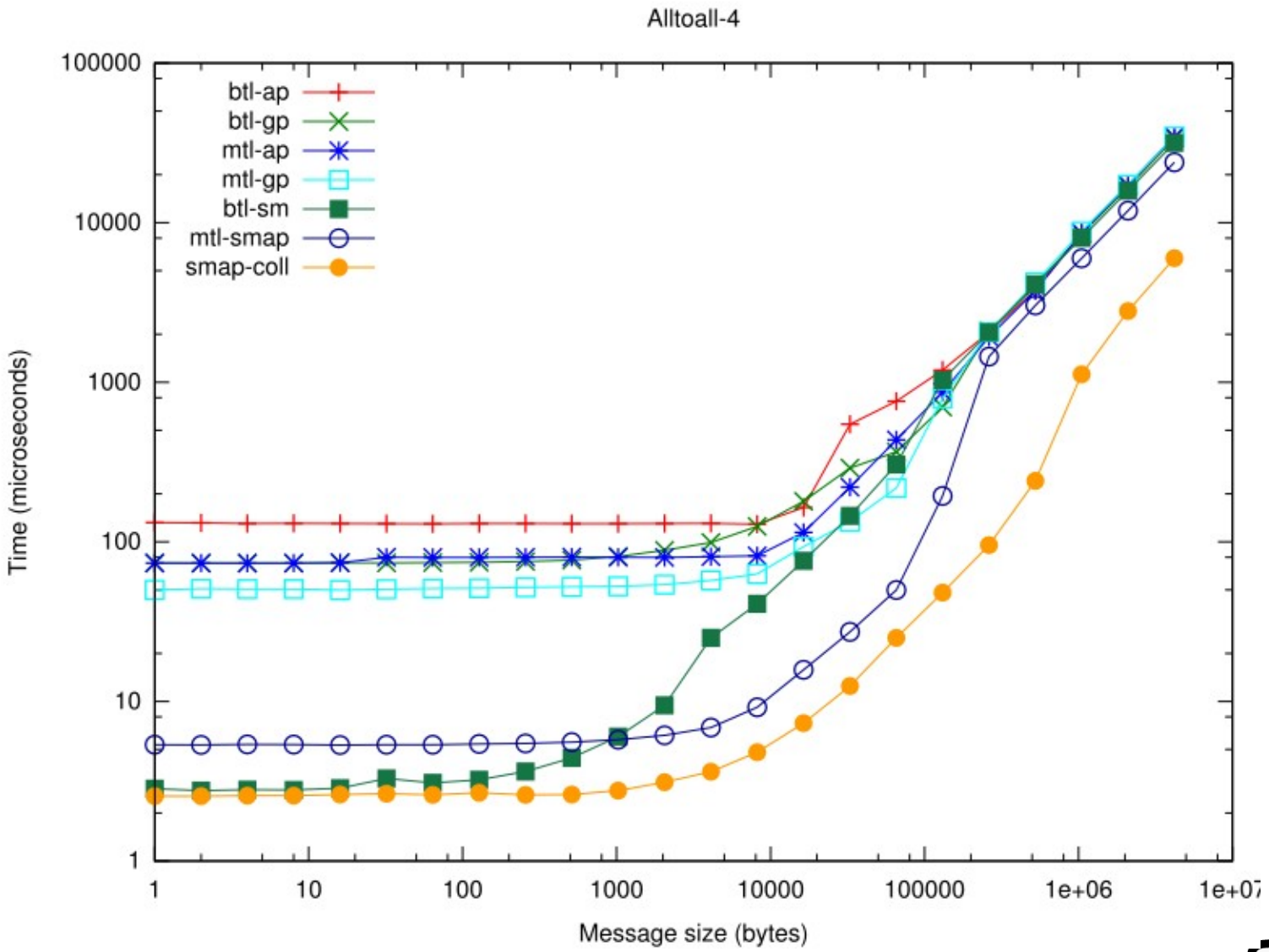


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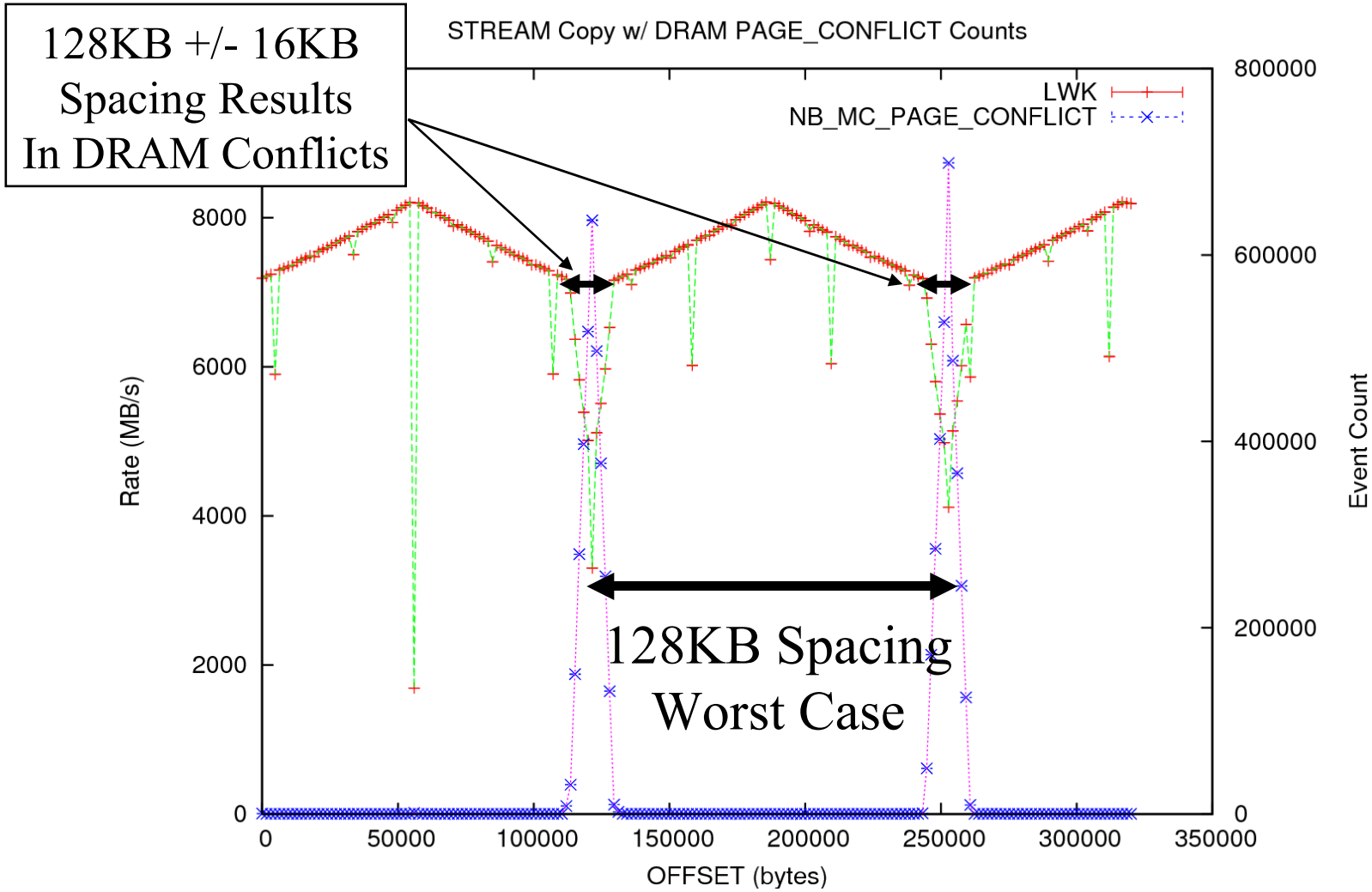
# Future Work

- Lots of MPI work
- Expose node/network topology through MPI communicators
  - MPI_COMM_NODE
  - MPI_COMM_NETWORK
- Explore ways for applications to use directly
  - Compiler (BEC)?
  - Libraries (LibSM)?

# Mitigating DRAM Bank Conflicts

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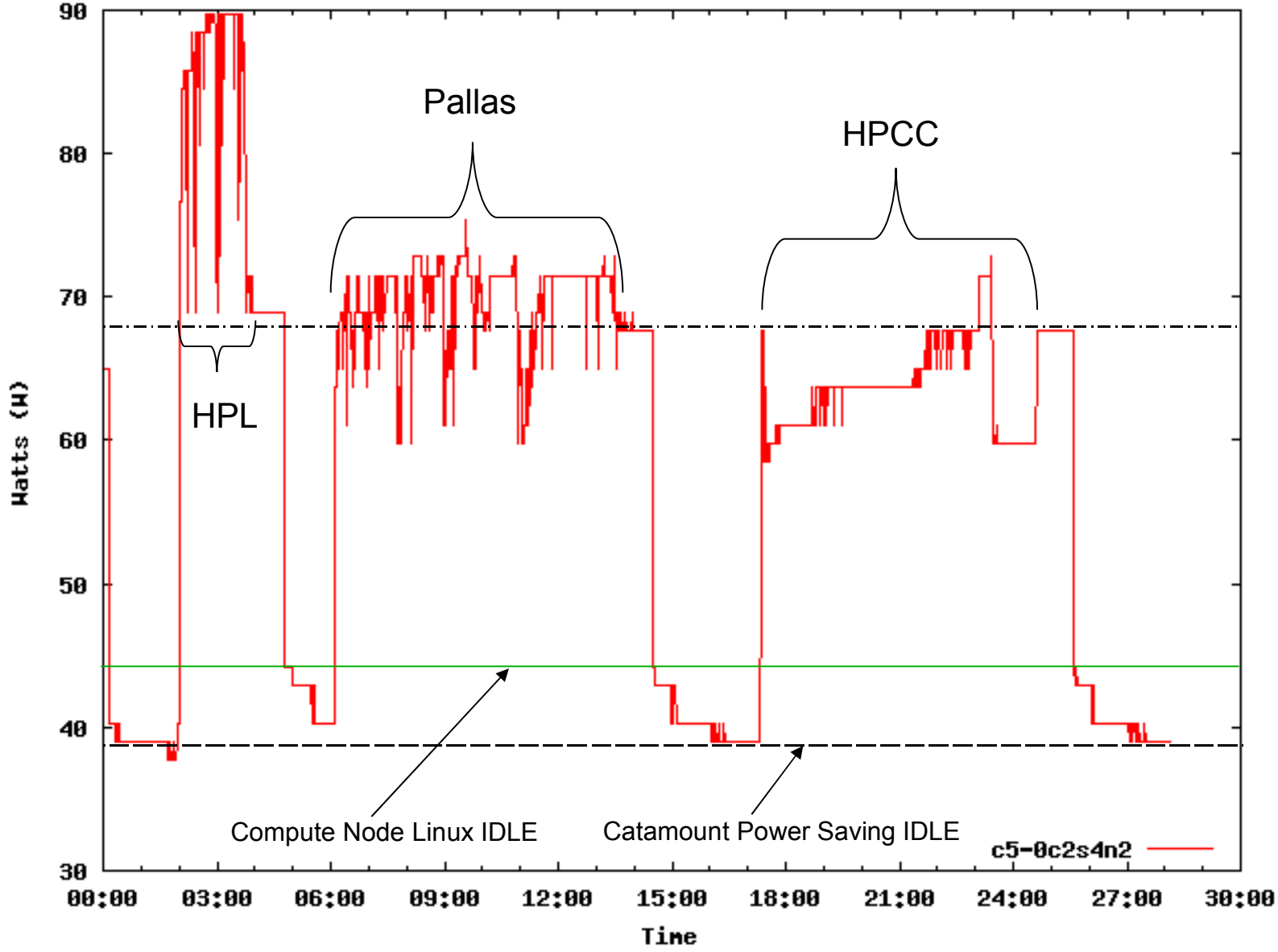
# Application Power Signatures



# Conclusion

- Sandia focusing on needs of capability systems
- Quad-core Catamount ready for action
  - Risk mitigation for ORNL Jaguar
  - Will be used for Red Storm upgrade: 38400 cores, 284 TFLOPS
- Kitten LWK in development
  - Open source
  - Multi-core and hardware virtualization
- Leveraging LWK for system software research

# Acknowledgments


- Quad-core Catamount
  - Office of Science and ORNL
  - Sue Kelly, John VanDyke, Courtenay Vaughan, Jim Tomkins
- Kitten LWK
  - Kurt Ferreira, Trammell Hudson, Sue Kelly, Michael Levenhagen, John VanDyke
- SMARTMAP
  - Ron Brightwell, Trammell Hudson
- DRAM Bank Conflicts
  - Kurt Ferreira, Courtenay Vaughan
- Power Signatures
  - Jim Laros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