An Introduction to HPC Tools Research

Karen L. Karavanic

Research Scientist

New Mexico Consortium

and

Associate Professor of Computer Science

Portland State University

Subliminal Slide: You want to go to graduate school here…

In the Beginning…

- 1991 I started graduate school at U Wisconsin
- 1993 I started working with the Paradyn Parallel Performance Tools Group

Parallel Performance Tools

1. Goal: Locate the Bottleneck
   Applications large/long running
   – Profiling
2. Problem: Synchronization
   – MPI applications:
     - one MPI rank waiting to receive a message
     - Barrier: EVERYONE waiting for slow rank to reach barrier
   – Tracing
3. Scaling
   – Intel Paragon: 1-4000 Processors/Nodes !!
   – How to measure all of the nodes??
   – Perturbation: we can no longer measure everything

Paradyn Parallel Performance Tools

- Key insight (Hollingsworth/Miller 1994): *what if we could insert and remove instrumentation on the fly, as the application runs??*
- Dynamic instrumentation
- Automated Performance Diagnosis
  - Define common problems and "hypotheses"
  - Search through the space of all possible problems ("why") places in the code ("where") and phases throughout the long run ("when")
- First Demo: SC Exhibit Hall
- My Dissertation: Using historical data to make this more efficient

1993 to present: Never Boring...

- Threading
  - Scalability Challenges: 1,000s-10,000 of threads
    - How to measure all of the threads for each node??
    - New bottlenecks: locking
    - How to visualize??
- Multicore
  - Scalability Challenges: 2-8x cores/processor
    - How to measure all of the cores for each processor??
    - Perturbation
    - New Bottlenecks: shift to memory

1993 to present: Never Boring...

- Manycore
  - Example: General Purpose GPU Computing
    - 1000s of low power compute cores
    - Used as "accelerators" to CPUs
    - High level directives: how to explain problem to programmer?
- Power/Cooling
  - Great Berkeley Quote: You can't cause more climate problems powering your data center than you solve with your science
  - Exascale Reality: We cannot generate enough power to simply expand our systems
  - New Challenge for tools: measure/report power/heat

Trinity @LANL

- Architecture Cray XC30
- Memory capacity >2 PB of DDR4 DRAM
- Peak performance >40 PF
- Number of compute nodes >19,000
- Processor architecture Intel Haswell & Knights Landing
  - 60 cores/processor
- Parallel file system capacity (usable) >80 PB
- Parallel file system bandwidth (sustained) 1.45 TB/s
- Burst buffer storage capacity (usable) 3.7 PB
- Burst buffer bandwidth (sustained) 3.3 TB/s
- Footprint <5,200 sq ft
- Power requirement <10 MW

Trinity@LANL

Tools Challenges for Trinity

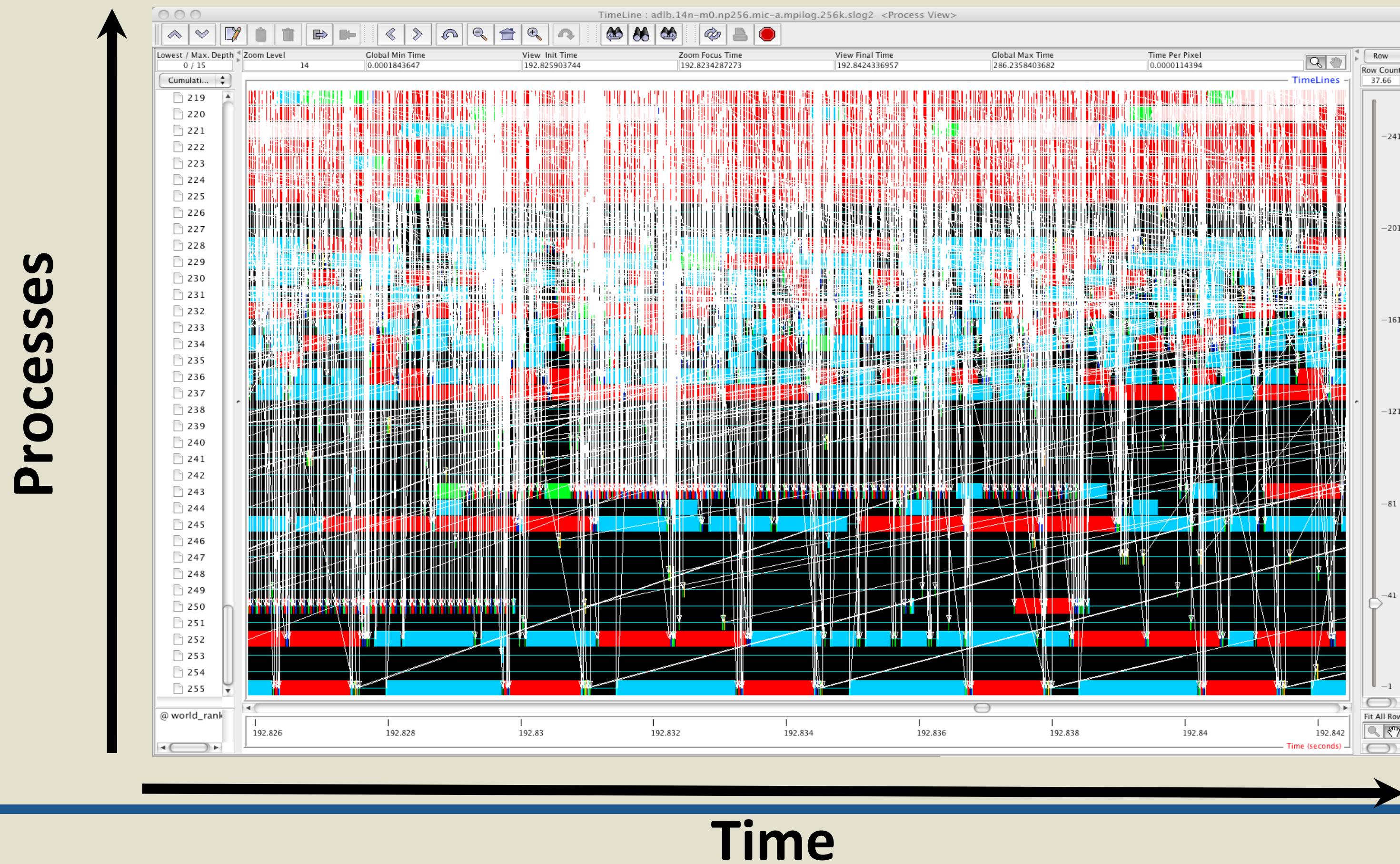
- We still have perturbation limits…. Only worse
- We still can't collect all of the data into a huge tracefile… only worse
- Now we can't move all of the data through the interconnect
- We have to worry about how much power our tools need ("power cap")
- Simple aggregation may hide performance problems

Current Status

MPI Tracing

- Collect MPI traces: comm type, participants
- Visualize traces with various tools, e.g. Jumpshot (ANL)

Jumpshot: Asynchronous Dynamic Load Balancing



Instruction-level Analysis

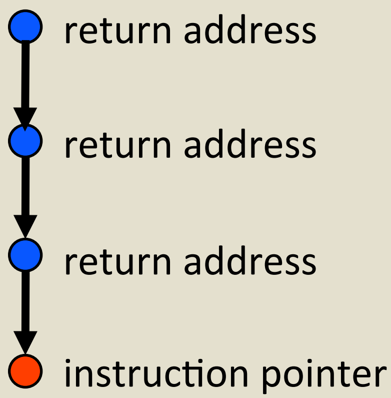
- Analyze dynamic characteristics of applications using a binary instrumentation framework, e.g., Valgrind, Pin
- Sample analyses
  - instruction mix (e.g. floating point, integer, branch, memory)
  - computational intensity (flops per memory access)
  - percentage of floating point ops that are vectorized (SIMD)
  - reuse distance
    - unique cache lines touched between two accesses to same cache line
    - gathered using detailed simulation of caches in your CPU
    - pinpoint sources of cache misses in your code

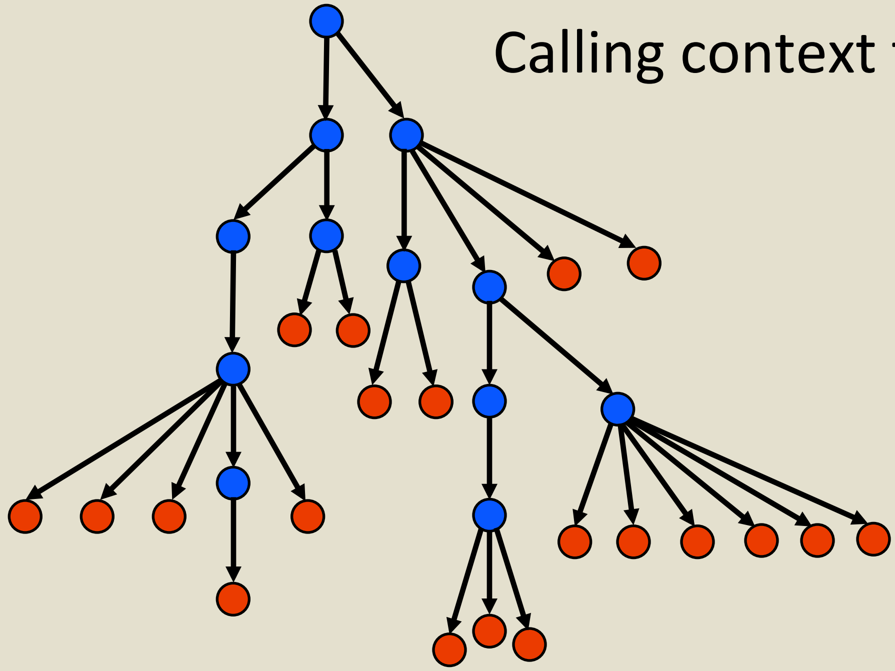
Call Path Profiling

Measure and attribute costs in context

- sample timer or hardware counter overflows
- gather calling context using stack unwinding

Call path sample

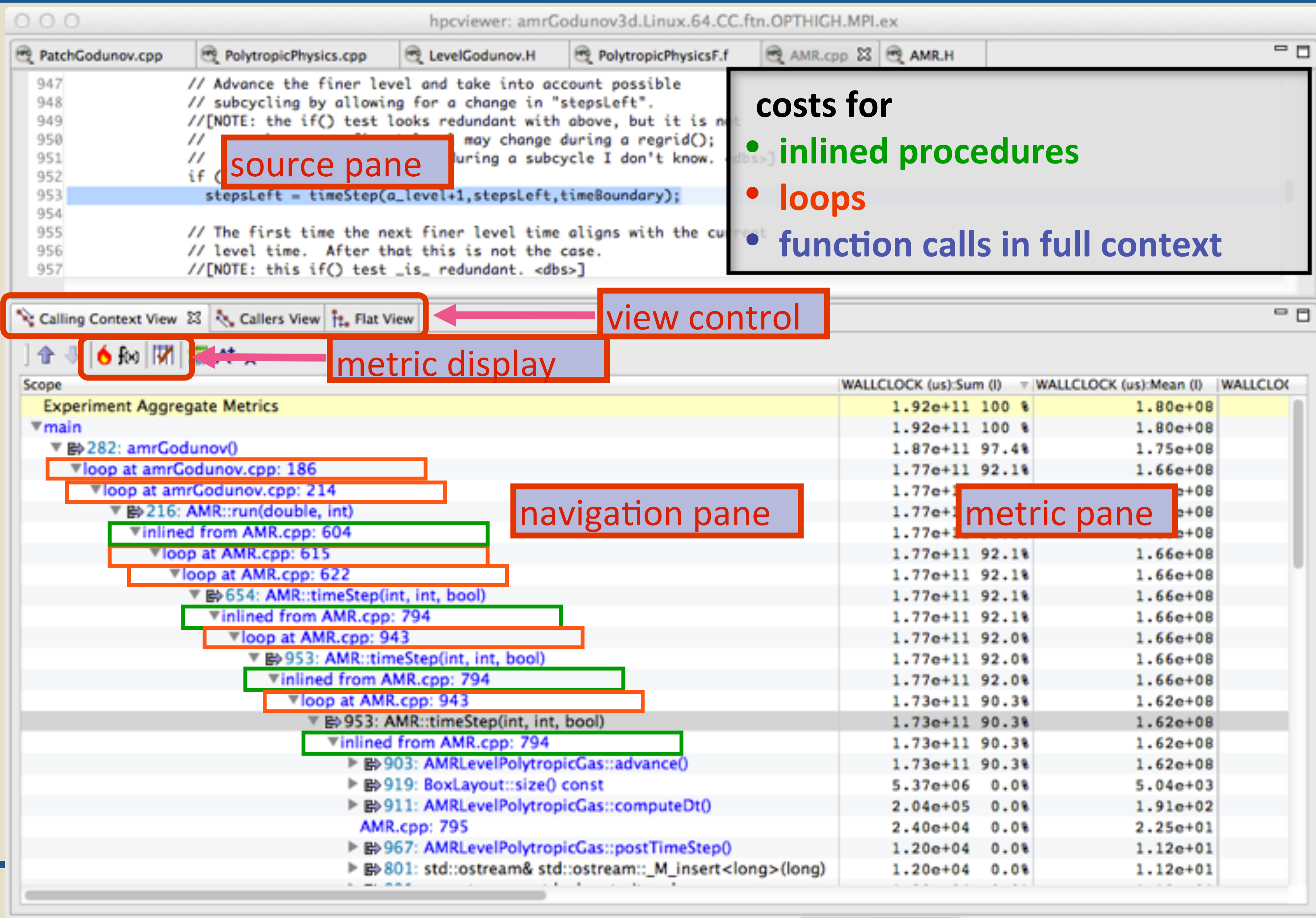




Calling context tree

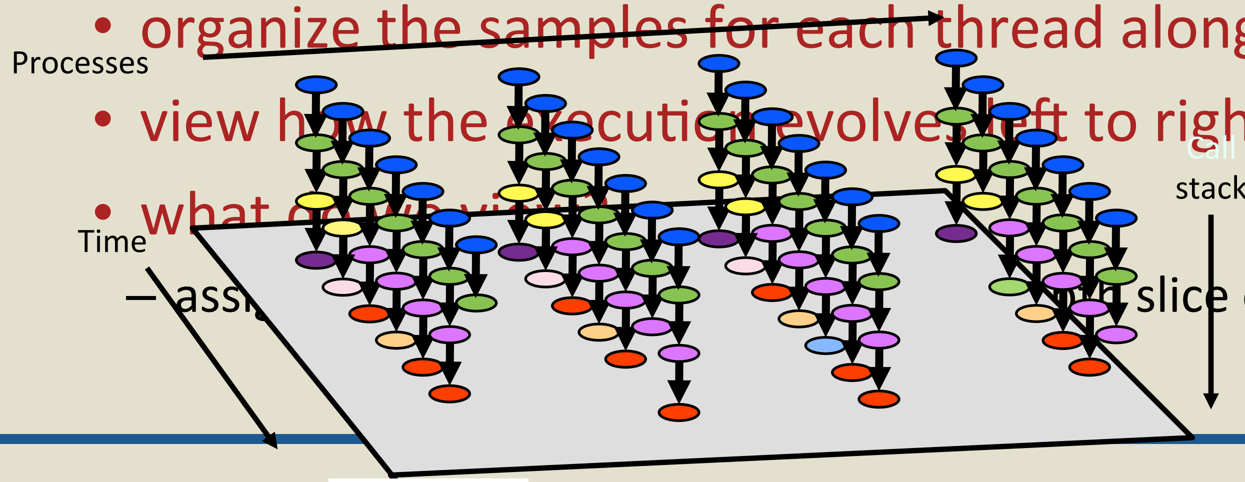
Overhead proportional to sampling frequency...
...not call frequency

Analyzing Chombo@1024PE with hpcviewer



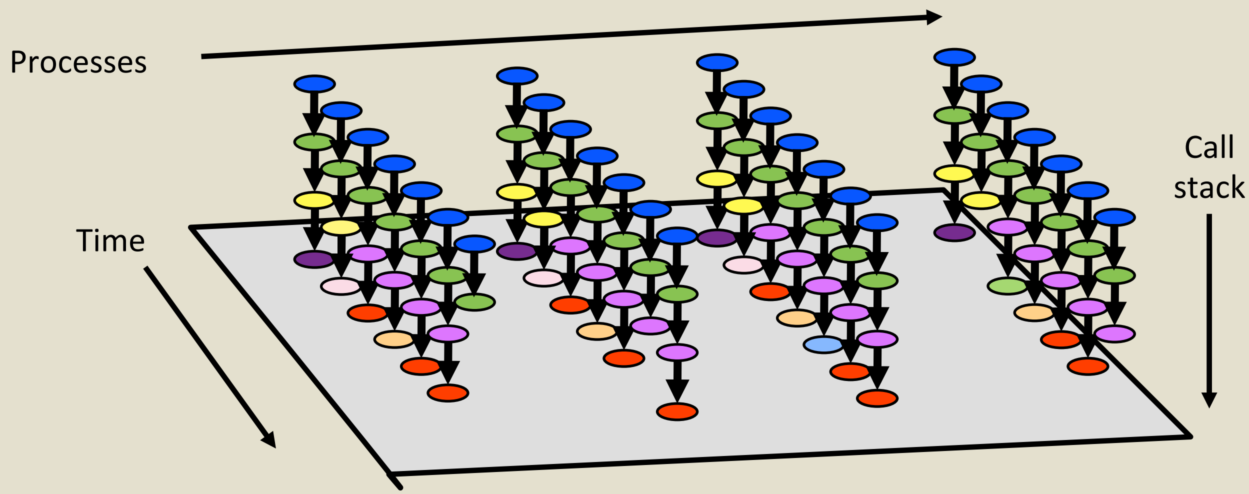
Understanding Temporal Behavior

- Profiling compresses out the temporal dimension
  - temporal patterns, e.g. serialization, are invisible in profiles
- What can we do? Trace call path samples
  - sketch:
    - N times per second, take a call path sample of each thread
    - organize the samples for each thread along a time line
    - view how the execution evolves left to right
    - what do we view?
  - assi… slice of an execution



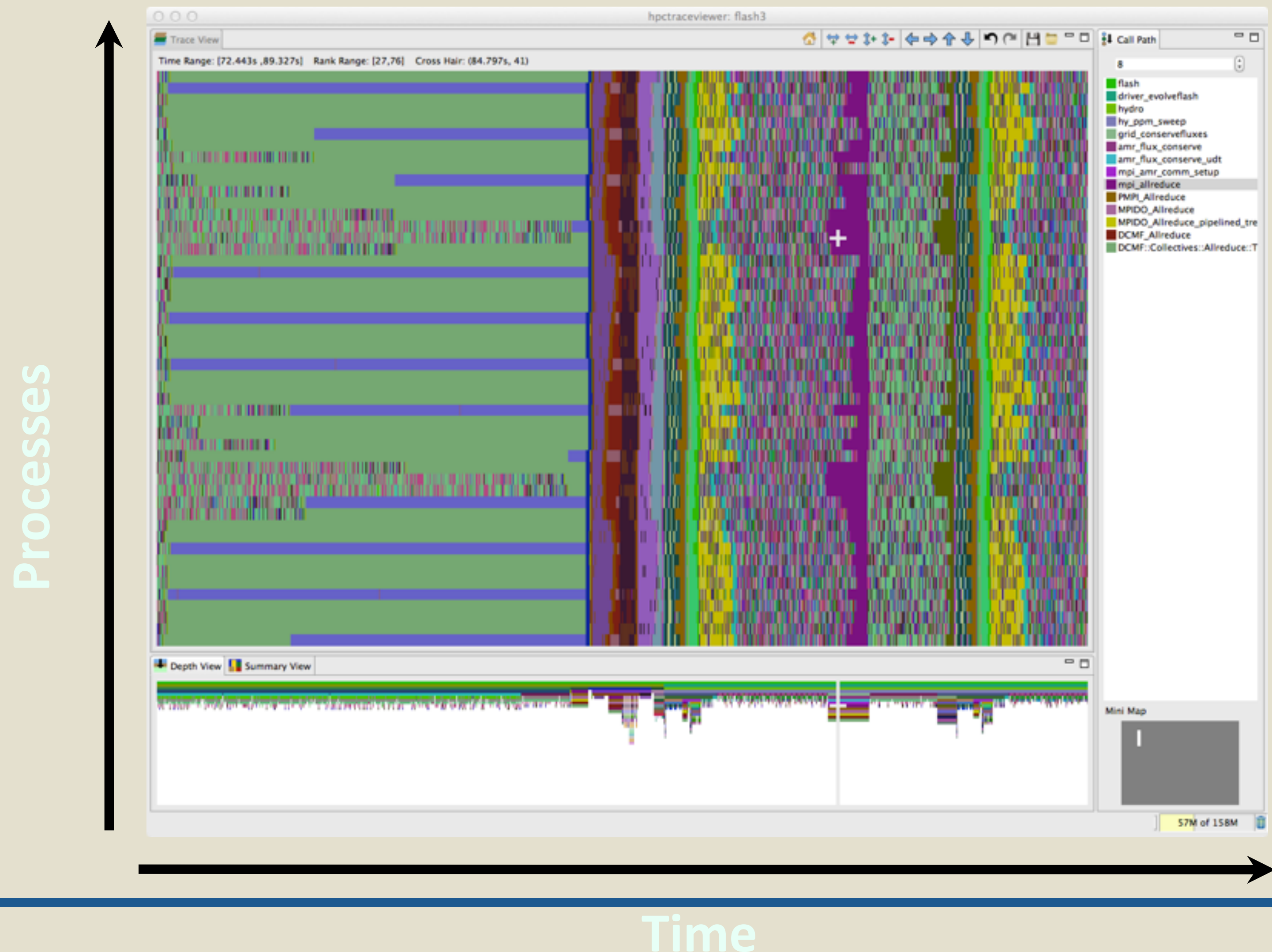
Understanding Temporal Behavior

- Profiling compresses out the temporal dimension
  - temporal patterns, e.g. serialization, are invisible in profiles
- What can we do? Trace call path samples
  - sketch:



hpctraceviewer: detail of FLASH3@256PE

Load imbalance among threads appears as different lengths of colored bands along the x axis



Formal Verification: Model Checking

Example tool: Spin (http://spinroot.com)

- Formal verification of parallel software
  - performs on-the-fly exploration of execution state spaces
- Used to identify logical design errors in parallel programs
  - e.g., communication and synchronization protocols, data structures
- Supports multiple communication models
  - message passing: both rendezvous and buffered
  - communication through shared memory
- Checks logical consistency of a specification
  - reports deadlocks, race conditions, incompleteness
  - identifies assumptions about relative speeds of processes
- Verifies properties specified with linear temporal logic
- Specify system descriptions in PROMELA modeling language

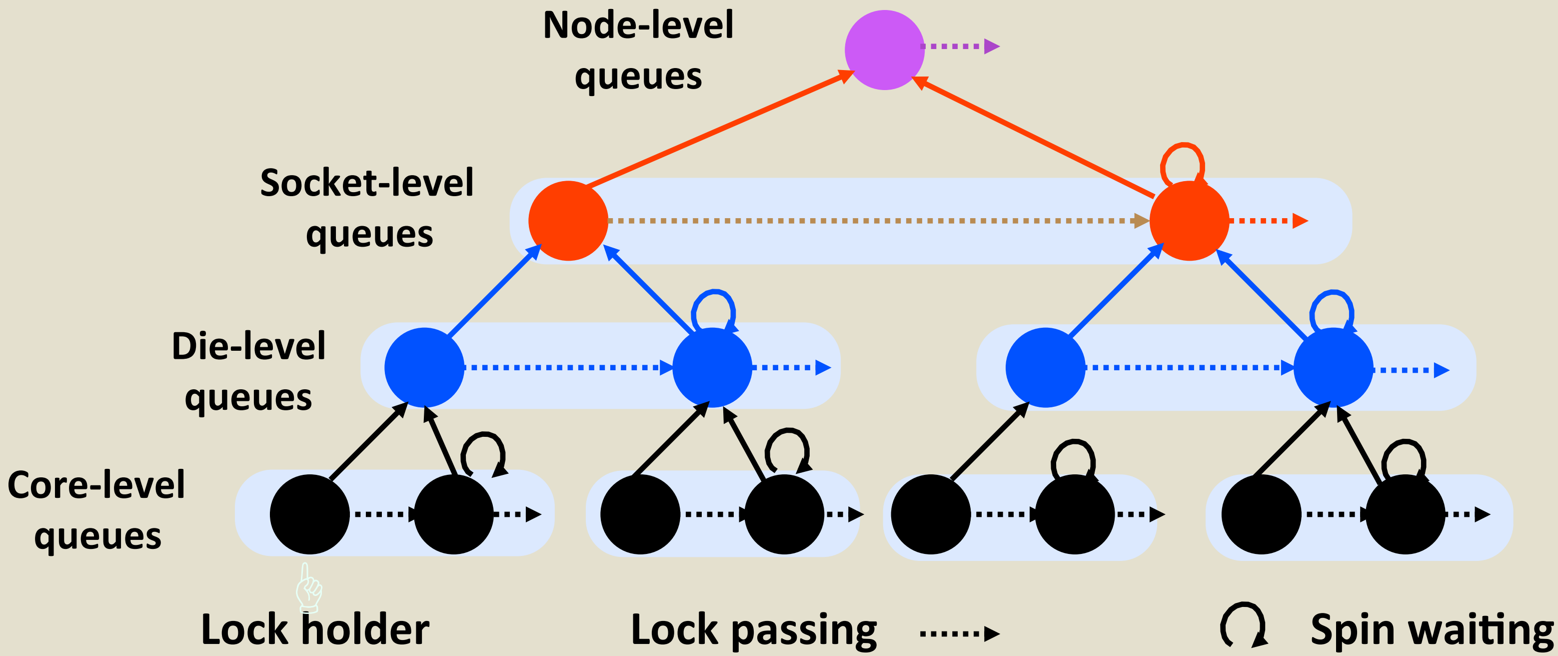
Dynamic Analysis

- Valgrind: framework for dynamic analysis tools
  http://valgrind.org
  - two useful valgrind tools
    - memcheck: detects memory-management problems
      - accesses memory it shouldn't
        - areas not yet allocated, areas that have been freed, areas past the end of heap blocks, inaccessible areas of the stack
      - reads uninitialized values
      - leaks memory
      - performs double or mismatched frees of heap blocks
    - helgrind: finds data races in multithreaded programs
      - memory locations accessed by >1 thread, unprotected by a lock
- A notable race detector: cilkscreen

Nicholas Nethercote and Julian Seward. Valgrind: A Framework for Heavyweight Dynamic Binary Instrumentation. Proceedings of ACM SIGPLAN PLDI 2007.

G.-I. Cheng, M. Feng, C. E. Leiserson, K. H. Randall, and A. F. Stark. Detecting data races in Cilk programs that use locks. Proceedings of SPAA 1998.

A Sophisticated Shared-Memory Synchronization Algorithm



- High performance locking protocol for NUMA machines
  - lock-holder typically passes lock to a “nearby” lock-waiter
    - improves locality of shared data
  - limit lock passing to nearby threads to avoid starvation
- Accesses shared variables with RMW operations, loads,

Milind Chabbi, Michael Fagan, John Mellor-Crummey. High Performance Locks for Multi-level NUMA Systems. PPoPP 2015. San Francisco, CA. Feb, 2015. To appear.

Features of the Algorithm

- Tree-structured organization of queuing locks at each level
- Recursive protocol (in both acquisition and release)
- Complex interactions between participating threads at various level of hierarchy
  - Needs precise ordering of memory updates
- Generous use of
  - read-modify-write operations (compare-and-swap and swap)
  - reads and writes to shared variables
- Support for thread abort at any point in the protocol
  - protocol is "state-full"

A Concurrency Bug!

- Symptom: multiple threads simultaneously in the critical section
- Investigation
  - – no obvious flaw in the algorithm
  - – no obvious issue in the implementation
  - – code+algorithm reviewed by multiple synchronization experts
- Traditional debugging efforts failed
  - – debugging with assertions
    - assertions trigger long after the bug occurs
    - can't backtrack to see thread interleaving that leads to assertion failure
  - – single stepping in the debugger (gdb)
    - bug sporadically appears only with > 9 threads
    - does not appear when closely observed (a "Heisenbug")

PinPlay: Deterministic Replay of Parallel Programs

Buggy multi-threaded program → PinPlay (Recorder) → PinBall(Log)

1. Record a log of “buggy” execution

(Leave overnight with multiple runs to hit assertion / segfault)

records access order (RAW, WAR, and WAW) to shared memory locations

2. Replay the execution with “buggy” thread interleaving

PinBall(Log) → PinPlay (Replay Engine) / Analysis tools + debugger interface → execution w/ original interleaving ← Debugger

H. Patil, C. Pereira, M. Stallcup, G. Lueck, J. Cownie. PinPlay: A Framework for Deterministic Replay and Reproducible Analysis of Parallel Programs; CGO 2010. Best Paper Award.

PinPlay: Key Features

- PinPlay records and replays
  - access order (RAW, WAR, and WAW) of shared memory locations
  - a myriad of other details needed for execution replay
  - Single-threaded, multi-threaded, and multi-process programs
- Logger: slowdown up to 147X
- Replay: slowdown up to 36X

g++ Code Generation Bug Corrupts Algorithm!

- Source code

```
// Expect atomic 64-bit write
cacheline_aligned_64_bit_var = 0xdffffffffffffffd;
```

- GNU g++ 4.4.5 generated machine code

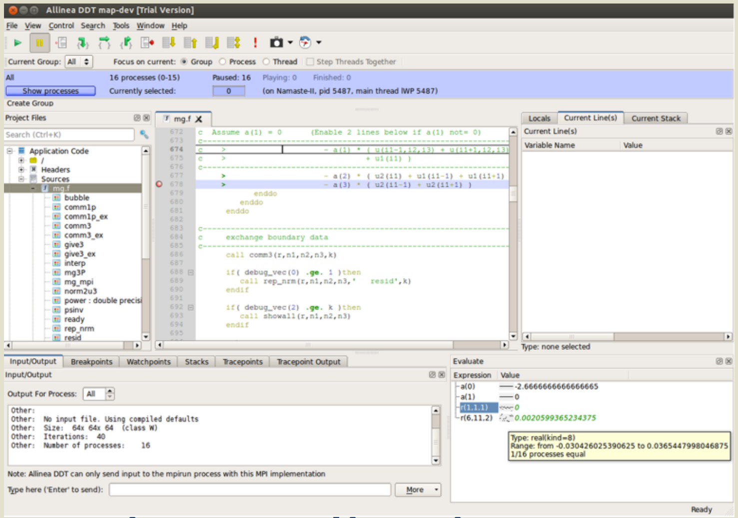
Bad interleaving

```
movl   $0xfffffffd,(%rax)    // write low 32-bits
movl   $0xdfffffff,0x4(%rax) // write high 32-bits
```

- Splitting this 64-bit write into two parts creates *a small window of inconsistent state*
- Bug was not noticeable at source (the point of write)
- Bug was not noticeable at sync (read a clobbered, yet valid, 64-bit value)
- Required a record/replay tool to step through the execution under debugger to identify the inconsistent state

Interactive Debugging

- Popular tools: TotalView (Rogue Wave), DDT (Allinea)
- What can be debugged?
  - MPI applications
  - multithreaded processes
  - accelerated codes



- Laptops to supercomputers
  - debug over 100K processes
- Integrated GUI for controlling entire application
  - variable value inspection in different processes
  - data visualization
- Reverse debugging with Totalview's Replay Engine
  - records orderings and state changes as program executes
  - recovers prior states on demand with "backward stepping"

Figure credit: http://www.allinea.com/sites/default/files/uploads/products/sparkline.png

Summary

- Lots of tools available
- Existing tools address diverse needs
  - proving parallel code correct
  - detecting data races
  - repeating intricate thread interleavings for debugging
  - interactive debugging of huge process counts
  - understanding MPI communication by tracing and visualization
  - profiling to understand where an application spends its time
  - visualizing sample traces to understand behavior over time
- Tool frameworks for building custom tools
- Challenges
  - better tools for accelerated computing
  - tools for correctness checking, debugging, and performance analysis of a billion dynamic tasks!
    - measurement, analysis, attribution, presentation

References

- Spin: http://spinroot.com
- valgrind: http://valgrind.org
- Pin: http://pintool.org
- Pinplay: http://pinplay.org
- cilkscreen: http://www.cilkplus.org
- totalview: http://www.roguewave.com
- ddt: http://www.allinea.com
- jumpshot: http://www.mcs.anl.gov/research/projects/perfvis/software/viewers/
  - HPCToolkit: http://hpctoolkit.org

Acknowledgments

- Tools slides courtesy of John Mellor-Crummey, Department of Computer Science, Rice University
- Jumpshot figure: Rusky Lusk

Want to Learn More about Tools?

- At SC15:
  - Exhibit Floor Tools Demos:
    - IBM, The Portland Group, NVIDIA, Intel, … also the major labs
  - Research Posters Exhibit
    - Tonight 5-7pm
  - Tech Papers
    - Wed 1:30 – 3pm Performance Tools Session
- Interested in internship/job at New Mexico Consortium? Contact: karavan@pdx.edu
- Interested in graduate school at Portland State University? Contact: karavan@pdx.edu
  - www.cs.pdx.edu/~karavan