Linux Performance Analysis: Parallel, Serial and I/O

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Overview

- PAPI and Hardware Performance Analysis
- A Production Ready Tool Suite
- Site Wide Performance Monitoring at PDC
- IOTrack: Passively Tracking I/O

Overall Performance

"The single most important impediment to good parallel performance is still poor single-node performance."

- William Gropp

Argonne National Lab

Linux Performance Infrastructure

- Contrary to popular belief, the Linux Performance Infrastructure is well established.
- PAPI/Kernel Support is +7 years old.
- Wide complement of tools from which to choose, but few are production quality.
- Sun, IBM, Dell, HP and other major vendors are focusing on Linux Clustering and HPC.
  - More focus on performance than ever before.

The Adaptability Gap

(Thanks Bjørn)

- Until we have....
  - Hardware counter based profile directed feedback in compilers.
  - Adaptable, reconfigurable, real-time computing resources that eat C/Fortran not VHDL. (MMU's, FPGA's)
  - Matched memory, interconnect bandwidth, logic-level latencies for offboard communication.
  - Generalized zero-copy infrastructure in kernel/user space.
- We need tools and expertise to narrow it.

Hardware Performance Counters

- Performance Counters are hardware registers dedicated to counting certain types of events within the processor or system.
  - Usually a small number of these registers (2,4,8)
  - Sometimes they can count a lot of events or just a few
  - Symmetric or asymmetric
- Each register has a various modes of operation.
  - Interrupt on overflow
  - Edge detection (cycles vs. events)
  - User vs. kernel mode

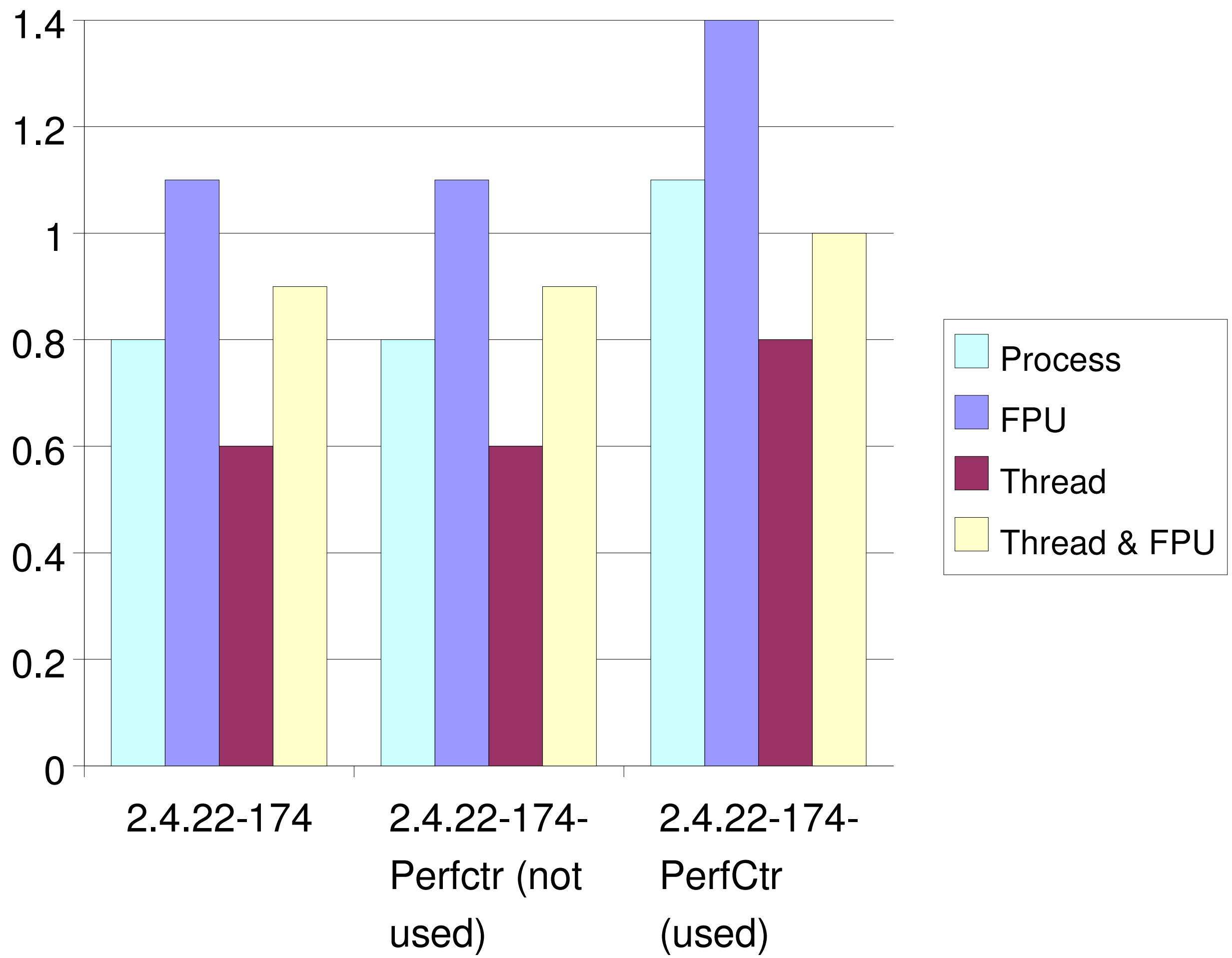
Hardware Performance Data

- Cycle count
- Instruction count
  - All instructions
  - Floating point
  - Integer
  - Load/store
- Branches
  - Taken / not taken
  - Mispredictions
- Pipeline stalls due to
  - Memory subsystem
  - Resource conflicts
- Cache
  - I/D cache misses for different levels
  - Invalidations
- TLB
  - Misses
  - Invalidations

Linux Kernel Support for PMC

- Performance counters are part of the thread context, just like FPU registers.
  - Dedicated, per-thread measurements
- Cost of switching is minimal when lazy-evaluation is used.
- Linux Kernel Integration
  - IA64: HP designed and pushed 'perfmon' into mainline by inheritance. (syscall based)
  - x86/x86_64: PerfCtr, designed by Mikael Pettersson in Uppsala. (mmap based)
    - Accepted in 2.6-mm series.

PerfCtr 2.6 Context Switches



PAPI

Performance **A**pplication **P**rogramming **I**nterface

- The purpose of PAPI is to implement a standardized portable and efficient API to access the hardware performance monitor counters found on most modern microprocessors.
- The goal of PAPI is to facilitate the optimization of parallel and serial code performance by encouraging the development of cross-platform optimization tools.

PAPI 3.0

- Full enumeration of platform-specific metrics
- Overflow and profiling on multiple events simultaneously
- Complete memory hierarchy information
- Complete shared library map
- Thread safe, high level API
- Efficient thread local storage and locking routines
- 32 and 64-bit profiling buckets (vs. 16-bit in SVR4/POSIX)

PAPI 3.0 Release

- Final release scheduled this week after 1 year Beta.
- Vastly lower measurement overheads.
- New support for Intel EM64T and Cray X1 (SSP/MSP)
- Updated Web Site and Documentation:
  - Links to New tools, Example codes
  - Improved Web page
  - Bugzilla Database

Open Source Tool Suite

- Mostly Orthogonal Functionality
- Well Documented
- Extensively Tested
- Actively Supported
  - Not just a research effort or a funding vehicle.
- 100% Open Source
- Expose Gaps in Research

Essential Tool Functionality

- Must work with Pthreads, OpenMP, MPI, fork() and exec().
- Passive Tools
  - Require no modification/instrumentation of source or object code.
    - Library preloading and/or name shifting.
- Active Tools
  - Instrumentation performed.
    - Binary
    - Source

Tool Methodology

- Direct Measurements read raw values of Metrics.
  - Overall/Global Measurements. (aka Quick & Dirty)
  - Site based.
    - Module/Function/Loop/Basic Block
    - Address Range

Tool Methodology

- Indirect Measurements infer values from probabilistic distributions.
- Statistical Profiling, developing a Histogram with X axis = Location, Y axis = Event Count.
- Event could equal:
  - Timer interrupts (like Gprof)
  - Hardware Counter Overflows on arbitrary Thresholds

The PDC Tool Collection

- PerfSuite from NCSA
- HPCToolkit from Rice U.
- TAU from U. Oregon.
- MpiP from LLNL
- Jumpshot/MPICH from MS State.
- IOTrack from PDC/KTH

PerfSuite from NCSA

- psrun/psprocess
- Command line tool similar to IRIX's perfex command.
- Does aggregate counting of the entire run. Also provides statistical profiling.
- Uses library preloading.
- Output is XML or Plain Text.
  - Machine information
  - Raw counter values
  - Derived metrics

PSRUN Sample Output

```
PerfSuite Hardware Performance Summary Report
Version      : 1.0
Created      : Mon Dec 30 11:31:53 AM Central Standard Time 2002
Generator    : psprocess 0.5
XML Source   : /u/ncsa/anyuser/performance/psrun-ia64.xml
Execution Information
============================================================================================
Date         : Sun Dec 15 21:01:20 2002
Host         : user01
Processor and System Information
============================================================================================
Node CPUs    : 2
Vendor       : Intel
Family       : IPF
Model        : Itanium
CPU Revision : 6
Clock (MHz)  : 800.136
                                   Memory (MB)  : 2007.16
Pagesize (KB): 16
Cache Information
============================================================================================
Cache levels : 3
--------------------------------
Level 1
Type         : data
Size (KB)    : 16
Linesize (B) : 32
Assoc        : 4
Type         : instruction
Size (KB)    : 16
Linesize (B) : 32
Assoc        : 4
--------------------------------
Level 2
Type         : unified
Size (KB)    : 96
Linesize (B) : 64
Assoc        : 6
--------------------------------
Level 3
Type         : unified
Size (KB)    : 4096
Linesize (B) : 64
Assoc        : 4
```

PSRUN Sample Output

```
Index Description                                                       Counter Value
=====================================================================================
    1 Conditional branch instructions mispredicted.....................    4831072449
    2 Conditional branch instructions correctly predicted.............   52023705122
    3 Conditional branch instructions taken...........................   47366258159
    4 Floating point instructions.....................................   86124489172
    5 Total cycles....................................................  594547754568
    6 Instructions completed.......................................... 1049339828741
    7 Level 1 data cache accesses.....................................   30238866204
    8 Level 1 data cache hits.........................................     972479062
    9 Level 1 data cache misses.......................................   29224377672
   10 Level 1 instruction cache reads.................................  221828591306
   11 Level 1 cache misses............................................   29312740738
   12 Level 2 data cache accesses.....................................  129470315862
   13 Level 2 data cache misses.......................................   15569536443
   14 Level 2 data cache reads........................................  110524791561
   15 Level 2 data cache writes.......................................   18622708948
   16 Level 2 instruction cache reads.................................     566330907
   17 Level 2 store misses............................................    1208372120
   18 Level 2 cache misses............................................   15401180750
   19 Level 3 data cache accesses.....................................    4650999018
   20 Level 3 data cache hits.........................................     186108211
   21 Level 3 data cache misses.......................................    4451199079
   22 Level 3 data cache reads........................................    4613582451
   23 Level 3 data cache writes.......................................      38456570
   24 Level 3 instruction cache misses................................       3631385
   25 Level 3 instruction cache reads.................................      17631093
   26 Level 3 cache misses............................................    4470968725
   27 Load instructions...............................................  111438431677
   28 Load/store instructions completed...............................  130391246662
   29 Cycles Stalled Waiting for memory accesses......................  256484777623
   30 Store instructions..............................................   18840914540
   31 Cycles with no instruction issue................................   61889609525
   32 Data translation lookaside buffer misses........................       2832692

Event Index
=====================================================================================
    1: PAPI_BR_MSP       2: PAPI_BR_PRC       3: PAPI_BR_TKN       4: PAPI_FP_INS
    5: PAPI_TOT_CYC      6: PAPI_TOT_INS      7: PAPI_L1_DCA       8: PAPI_L1_DCH
    9: PAPI_L1_DCM      10: PAPI_L1_ICR      11: PAPI_L1_TCM      12: PAPI_L2_DCA
   13: PAPI_L2_DCM      14: PAPI_L2_DCR      15: PAPI_L2_DCW      16: PAPI_L2_ICR
   17: PAPI_L2_STM      18: PAPI_L2_TCM      19: PAPI_L3_DCA      20: PAPI_L3_DCH
   21: PAPI_L3_DCM      22: PAPI_L3_DCR      23: PAPI_L3_DCW      24: PAPI_L3_ICM
   25: PAPI_L3_ICR      26: PAPI_L3_TCM      27: PAPI_LD_INS      28: PAPI_LST_INS
   29: PAPI_MEM_SCY     30: PAPI_SR_INS      31: PAPI_STL_ICY     32: PAPI_TLB_DM
```

PSRUN Sample Output

```
Statistics
=============================================================================================
Graduated instructions per cycle.......................................          1.765
Graduated floating point instructions per cycle........................          0.145
% graduated floating point instructions of all graduated instructions..          8.207
Graduated loads/stores per cycle.......................................          0.219
Graduated loads/stores per graduated floating point instruction........          1.514
Mispredicted branches per correctly predicted branch...................          0.093
Level 1 data cache accesses per graduated instruction..................          2.882
Graduated floating point instructions per level 1 data cache access....          2.848
Level 1 cache line reuse (data)........................................          3.462
Level 2 cache line reuse (data)........................................          0.877
Level 3 cache line reuse (data)........................................          2.498
Level 1 cache hit rate (data)..........................................          0.776
Level 2 cache hit rate (data)..........................................          0.467
Level 3 cache hit rate (data)..........................................          0.714
Level 1 cache miss ratio (instruction).................................          0.003
Level 1 cache miss ratio (data)........................................          0.966
Level 2 cache miss ratio (data)........................................          0.120
Level 3 cache miss ratio (data)........................................          0.957
Bandwidth used to level 1 cache (MB/s).................................       1262.361
Bandwidth used to level 2 cache (MB/s).................................       1326.512
Bandwidth used to level 3 cache (MB/s).................................        385.087
% cycles with no instruction issue.....................................         10.410
% cycles stalled on memory access......................................         43.139
MFLOPS (cycles)........................................................        115.905
MFLOPS (wallclock).....................................................        114.441
MIPS (cycles)..........................................................       1412.190
MIPS (wallclock).......................................................       1394.349
CPU time (seconds).....................................................        743.058
Wall clock time (seconds)..............................................        752.566
% CPU utilization......................................................         98.737
```

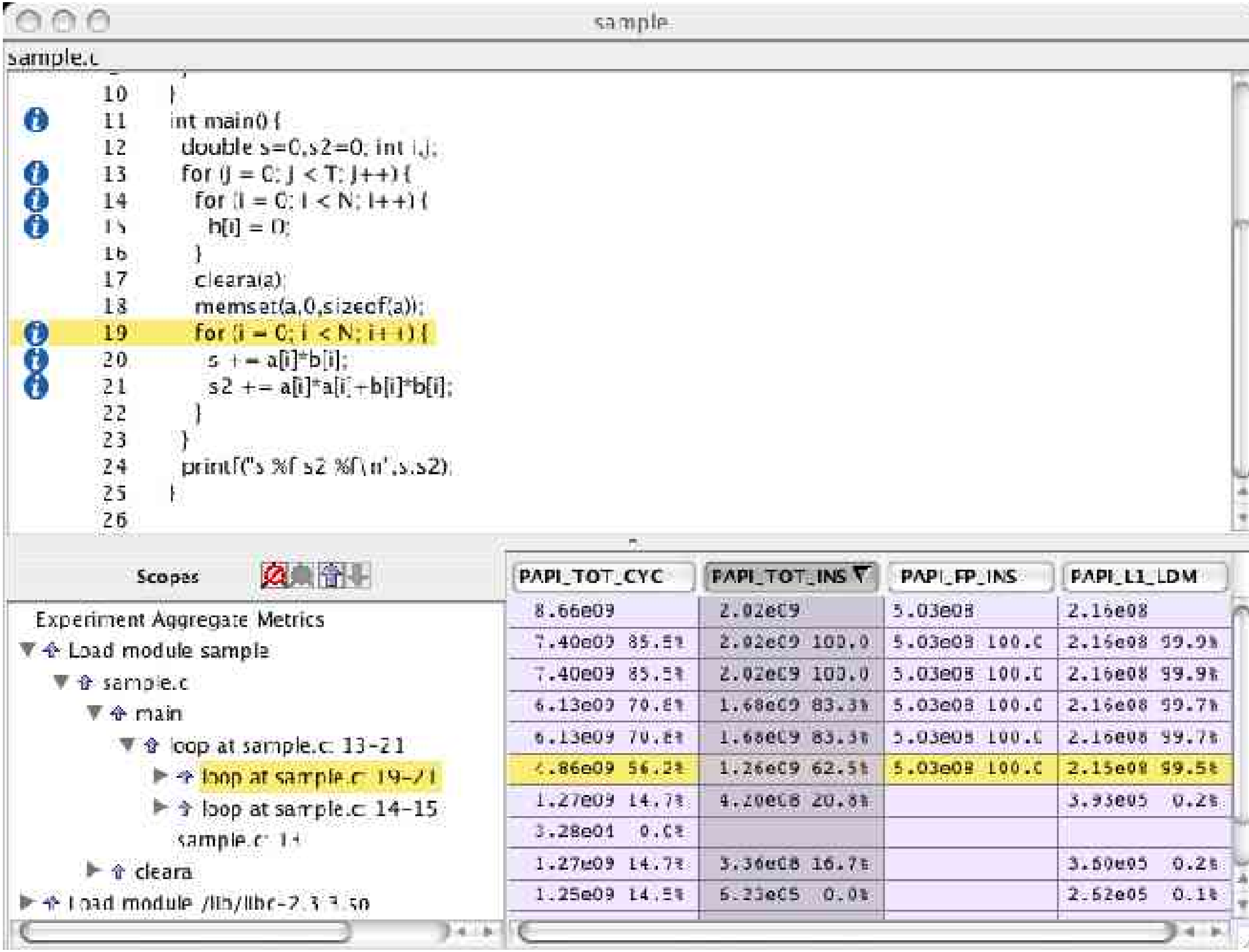
HPCToolkit from Rice U.

- Use event-based sampling and statistical profiling to profile unmodified applications: hpcrun
- Interpret program counter histograms: hpcprof
- Correlate source code, structure and performance metrics: hpcview/hpcquick
- Explore and analyze performance databases: hpcviewer
- Linux IA32, x86_64, IA64

HPCToolkit Goals

- Support large, multi-lingual applications
  - Fortran, C, C++, external libraries (possibly binary only) with thousands of procedures, hundreds of thousands of lines
  - Avoid
    - Manual instrumentation
    - Significantly altering the build process
    - Frequent recompilation
- Collect execution measurements scalably and efficiently
  - Don’t excessively dilate or perturb execution
  - Avoid large trace files for long running codes
- Support measurement and analysis of serial and parallel codes
- Present analysis results effectively
  - Top down analysis to cope with complex programs
  - Intuitive enough for physicists and engineers to use
  - Detailed enough to meet the needs of compiler writers
- Support a wide range of computer platforms

HPCToolkit Sample Output



OProfile

- Oprofile is a statistical profiler put into RedHat kernels and adopted by other Linux vendors.
- Implementation is good for overall system tuning, but useless for production environments.
  - No aggregate counter support
  - Must be configured by root
  - Non-existent API

TAU from U. Oregon

- Tuning and Analysis Utilities (11+ year project effort)
- Integrated toolkit for parallel and serial performance instrumentation, measurement, analysis, and visualization
- Open software approach with technology integration
- Robust timing and hardware performance support using PAPI
- TAU supports both profiling and tracing models.

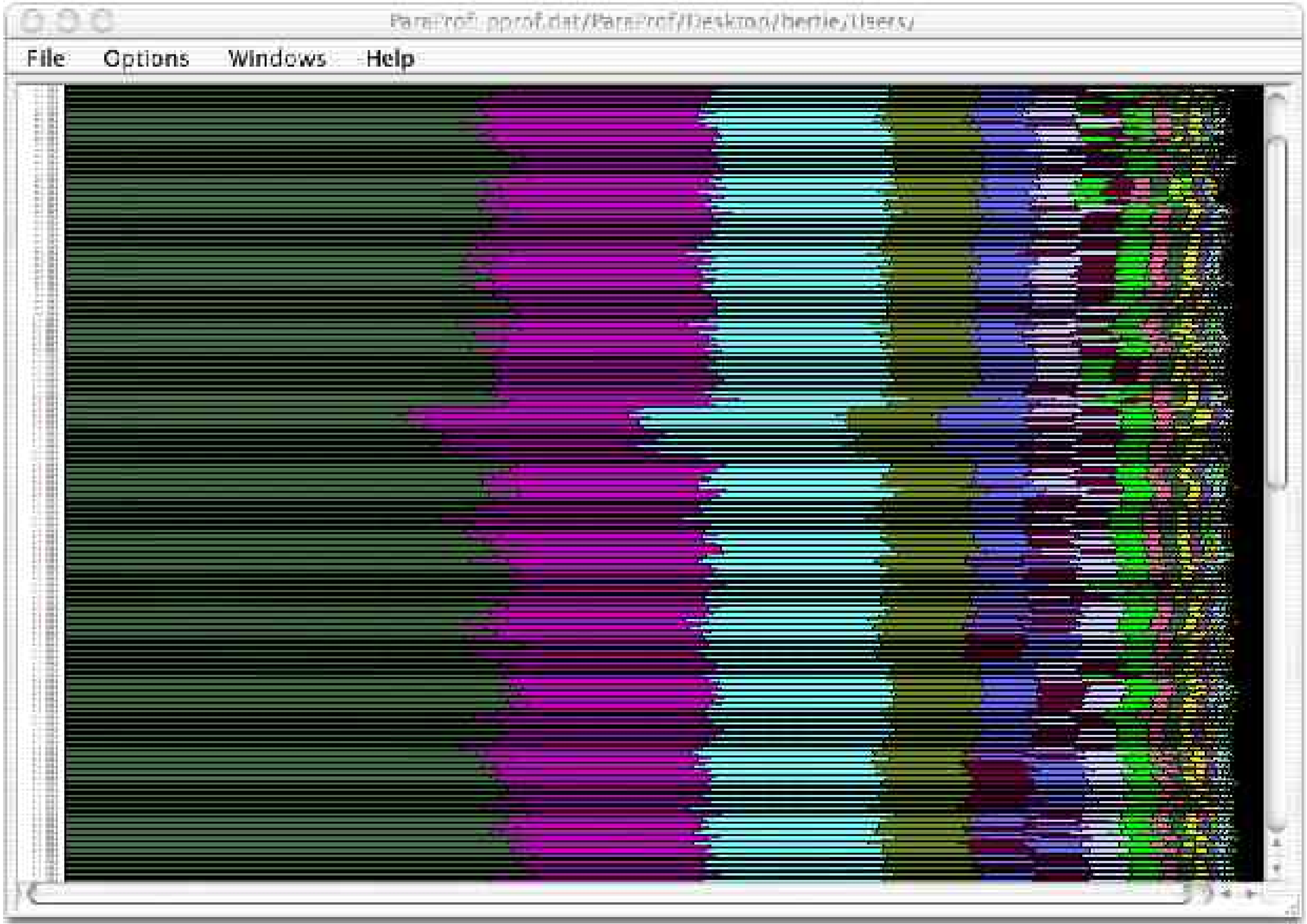
Some TAU Features

- Function-level, block-level, statement-level
- Support for callgraph and callpath profiling
- Parallel profiling and Inter-process communication events
- Supports user-defined events
- Trace merging and format conversion

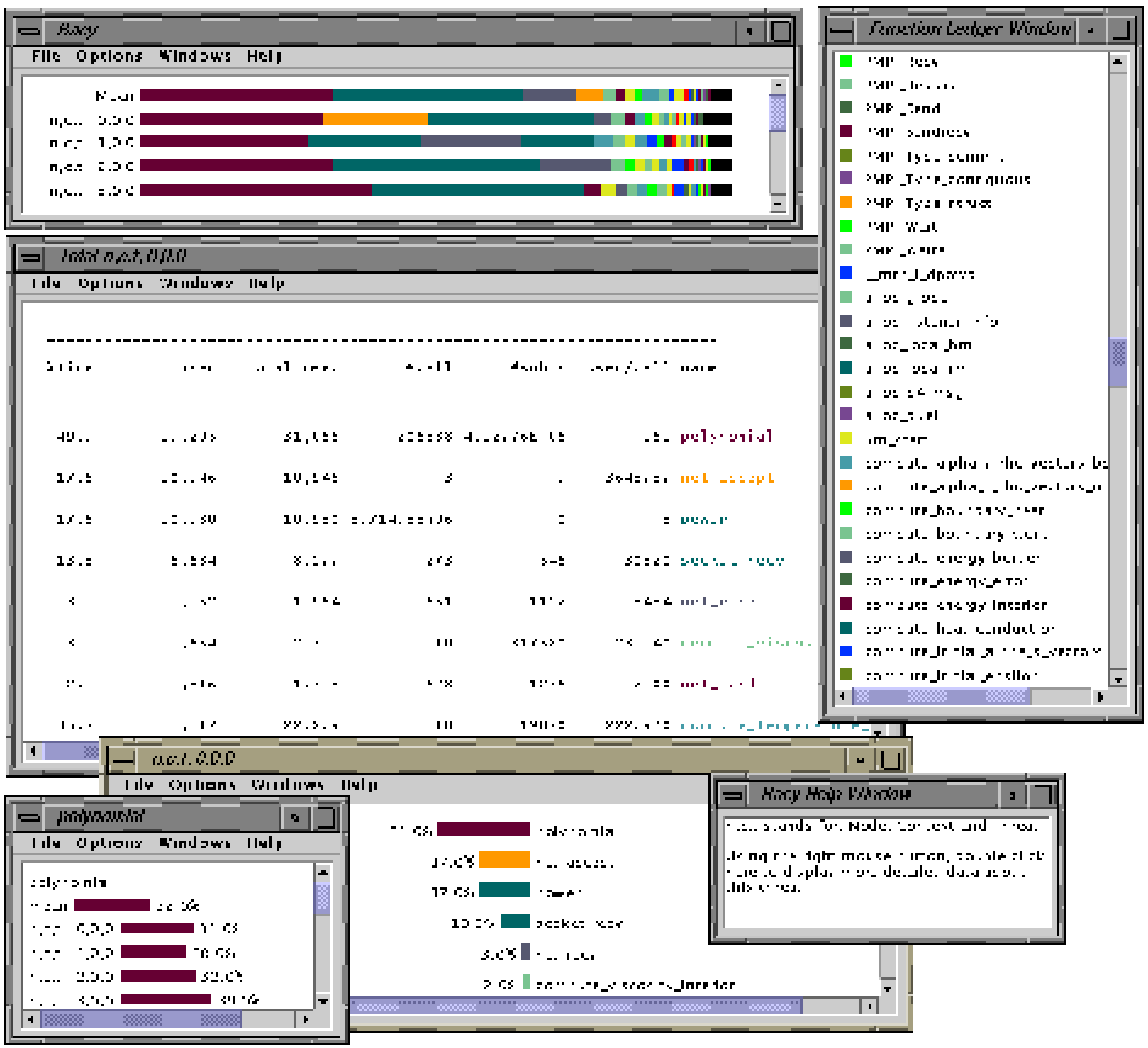
TAU Instrumentation

- Flexible mechanisms:
  - Source code both manual and automatic.
    - C, C++, F77/90/95 (Program Database Toolkit (PDT))
    - OpenMP (directive rewriting (Opari), POMP spec)
  - Object code
    - pre-instrumented libraries (e.g., MPI using PMPI)
  - Executable code
    - dynamic instrumentation (pre-execution) (DynInstAPI)

TAU Parallel Display



TAU Program Display



MPI Profiling

- How much time we are spending in communication.
  - Load balance
  - Algorithm design
  - Synchronization and scaling
- MPI tools to do this via the MPI profiling interface.
  - MpiP for aggregate statistics and call site information.
  - Jumpshot-4 for trace generation and visualization.

MpiP: Lightweight MPI Profiling

- Trace generation of MPI calls is Heavyweight!
- Trace is generated but reduced at runtime
- Short text summary is generated at the end of execution.
- Traces:
  - MPI I/O
  - Callsite and callstack (optional)
  - Controlled scope with MPI_Pcontrol().

MpiP: Lightweight MPI Profiling

- MPIP is a lightweight, scalable profiling tool for gathering timing information about MPI applications
  - Records cumulative time for each MPI callsite
  - Tested up to 4,096 processors
  - Output data size is time-invariant
  - Timing information provides first order approximation of performance problems
- Short text summary is generated at the end of execution.

MpiP Tracing

- No large tracefiles or large perturbation on application
- Traces:
  - MPI 1 and MPI 2 Calls
  - MPI I/O
  - Callsite and callstack (optional)
  - Controlled scope with MPI_Pcontrol().

MpiP v2.7 Output

```
@ Command : /afs/pdc.kth.se/home/m/mucci/mpiP-
2.7/testing/./sweep-ops-stack.exe
/tmp/SPnodes-mucci-0
@ Version                    : 2.7
@ MPIP Build date            : Aug 17 2004, 17:04:36
@ Start time                 : 2004 08 17 17:08:48
@ Stop time                  : 2004 08 17 17:08:48
@ MPIP env var               : [null]
@ Collector Rank             : 0
@ Collector PID              : 17412
@ Final Output Dir           : .
@ MPI Task Assignment        : 0 h05n05-e.pdc.kth.se
@ MPI Task Assignment        : 1 h05n35-e.pdc.kth.se
@ MPI Task Assignment        : 2 h05n05-e.pdc.kth.se
@ MPI Task Assignment        : 3 h05n35-e.pdc.kth.se

@--- MPI Time (seconds)
---------------------------------------------------
---------------------------------------------------------------
------------
Task    AppTime    MPITime     MPI%
   0      0.084     0.0523    62.21
   1     0.0481      0.015    31.19
   2      0.087     0.0567    65.20
   3     0.0495     0.0149    29.98
   *      0.269      0.139    51.69

@--- Aggregate Time (top twenty, descending, milliseconds)
----------------
---------------------------------------------------------------
------------
Call                Site       Time     App%    MPI%
```

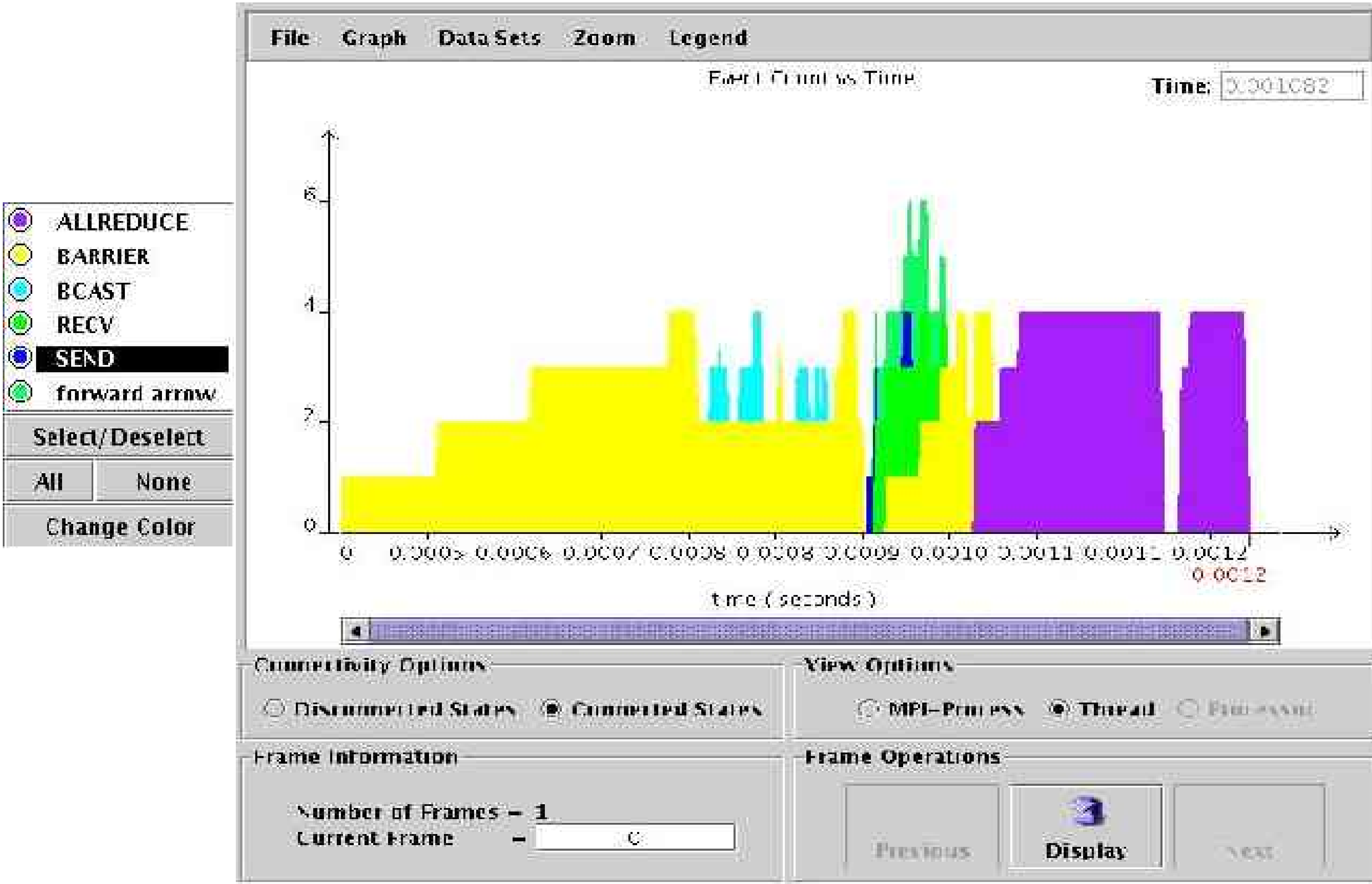
MpiP v2.7 Output 2

```
---------------------------------------------------------------
---------------
@--- Callsite Time statistics (all, milliseconds): 16
---------------------
---------------------------------------------------------------
---------------
Name                 Site Rank   Count       Max      Mean
Min    App%   MPI%
Allreduce               1    0       2     0.105     0.087
0.069   0.21   0.33
Allreduce               1    1       2     0.118      0.08
0.042   0.33   1.07
Allreduce               1    2       2      0.11     0.078
0.046   0.18   0.27
Allreduce               1    3       2     0.102     0.072
0.042   0.29   0.97
Barrier                 1    0       3      51.9      17.3
0.015  61.86  99.44
Barrier                 1    1       3     0.073    0.0457
0.016   0.29   0.91
Barrier                 1    2       3      54.9      18.8
0.031  64.90  99.53
Barrier                 1    3       3      1.56      1.02
0.035   6.20  20.68
Bcast                   1    0       2     0.073    0.0535
0.034   0.13   0.20
Bcast                   1    1       2     0.037     0.023
0.009   0.10   0.31
Bcast                   1    2       2     0.084     0.046
0.008   0.11   0.16
Bcast                   1    3       2      0.03    0.0275
0.025   0.11   0.37
```

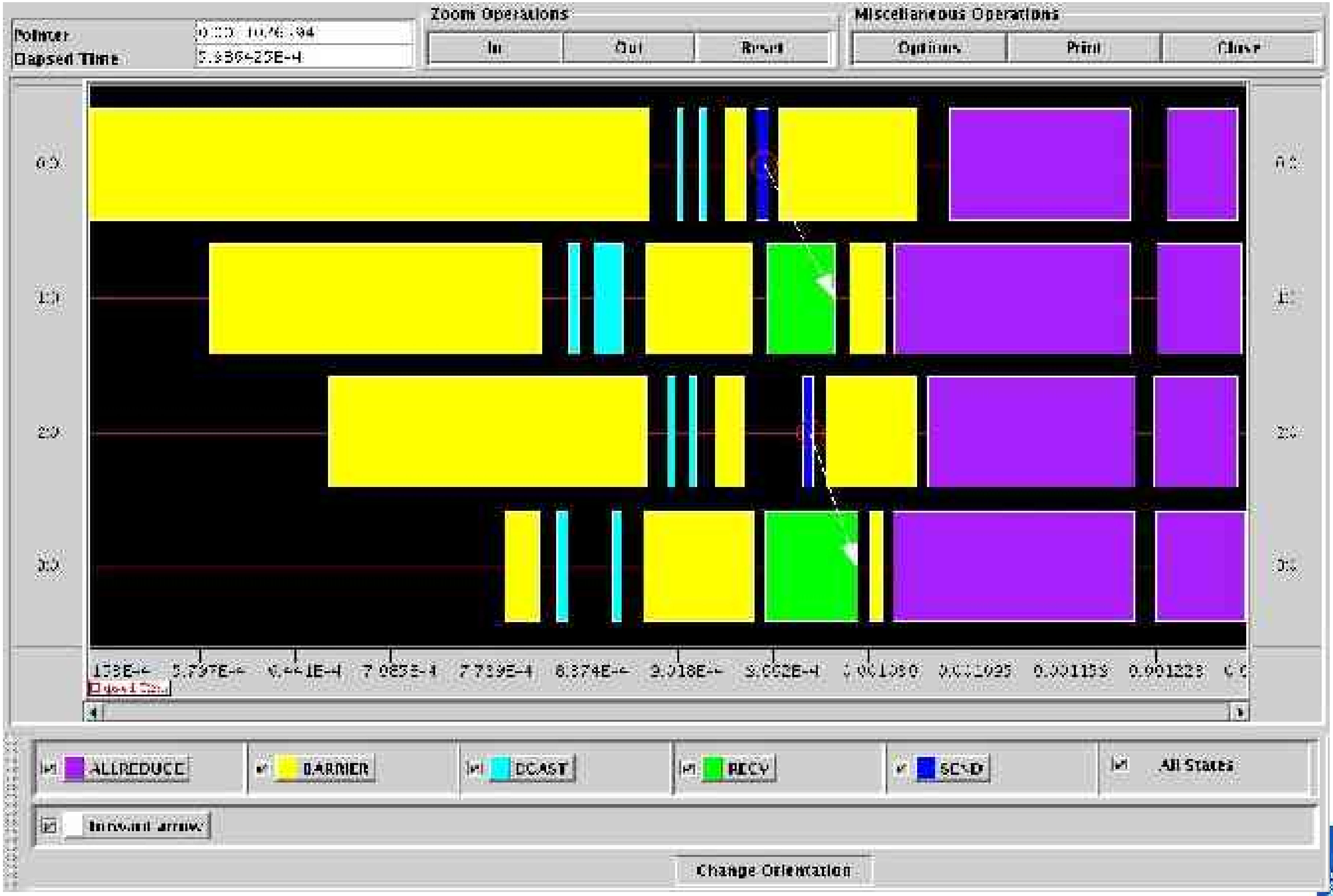
Jumpshot: MPI Visualization

- If we need to see the exact sequence of messages exchanged between processes.
- MPI tracing by relinking our application using the Jumpshot MPE libraries that can be used with **any** MPI.
- Jumpshot-3 included with MPICH 1.2.6.
- Jumpshot-4 is a separate release.

Jumpshot-3 Main Window



Jumpshot-3 Timeline



Performance Work at PDC

- Long History of Focus on Performance
  - Early use of Hardware Counters on the SP2 in Batch System for per CPU collection
- Collaboration with PAPI group from ICL/University of Tennessee
  - Work on Itanium 2, Opteron port and involved in the design of PAPI 3
- Development of custom monitoring scripts for the Itanium 2 cluster: “Lucidor”.
- Performance Analysis and Optimization Workshop of 2003: Brought researchers in the field from all around Scandinavia

Site Wide Performance Monitoring at PDC

- Integrate complete job monitoring in the batch system itself.
- Track every cluster, group, user, job, node all the way down to individual threads.
- Zero overhead monitoring, no source code modifications.
- Near 100% accuracy.

Site Wide Performance Monitoring at PDC

- Allow performance characterization of all aspects of a technical compute center:
  - Application Workloads
  - System Performance
  - Resource Utilization
- Provide users, managers and administrators with a quick and easy way to track and visualize performance of their jobs/system.
- Complete integration from batch system to database to PHP web interface.
- Motivated by work at PDC & NCSA.

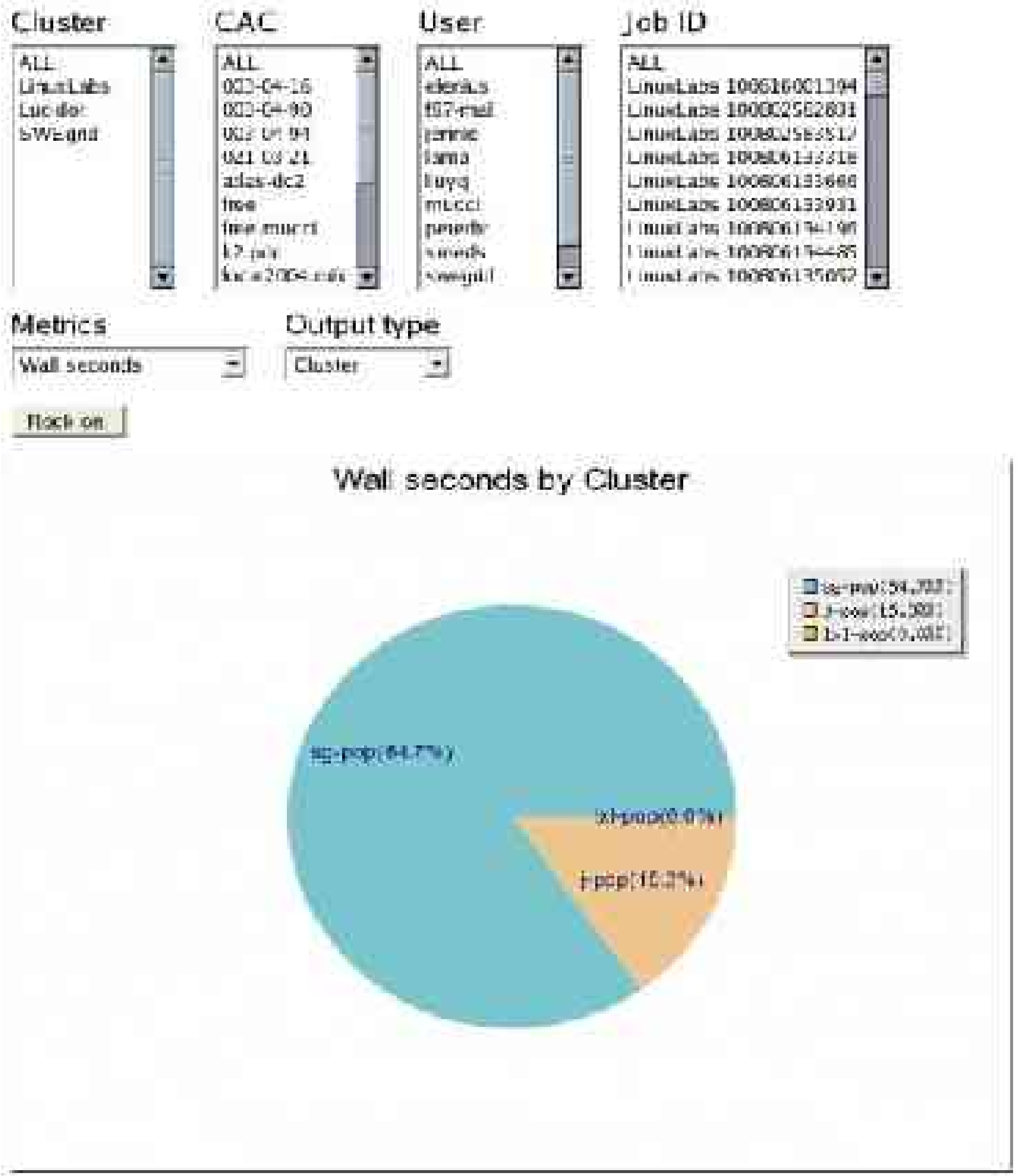
The PDC System: Front End

- PDC Runs a modified EASY Scheduler.
- Easy runs a:
  - Preamble/Postamble on the front end that prepares the data directory and some state.
  - Easy works by editing remote /etc/passwd.
  - Reserved nodes get their real shell running under 'papiex', a PSRUN like tool that uses LD_PRELOAD to see everything.
  - Data is dumped when processes exit into private area.

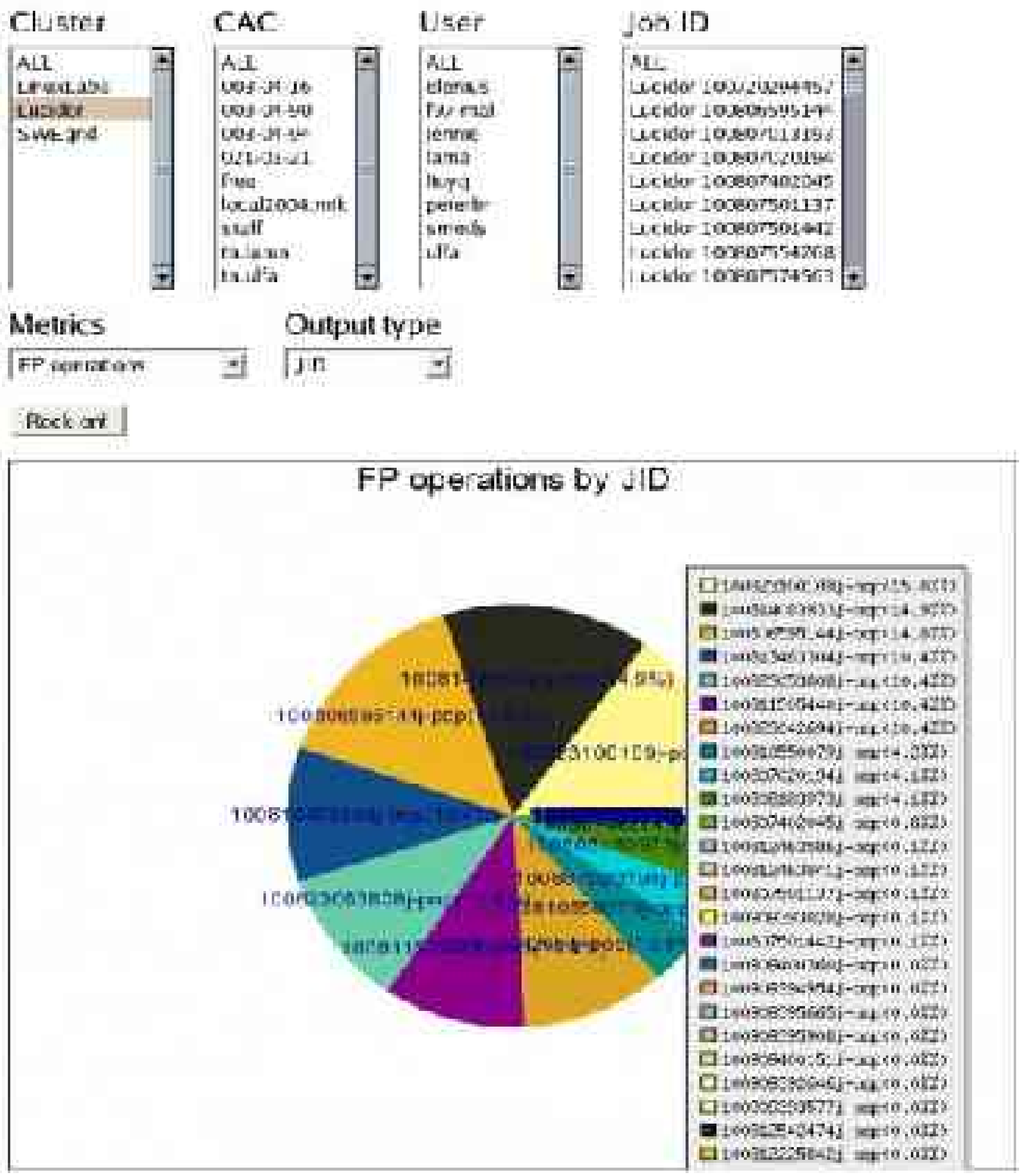
The PDC System: Back End

- Perl scripts walk the data directory and insert the data into a Postgres database using the DBI interface.
- Interface is run on webserver with PHP scripts and JPGraph.

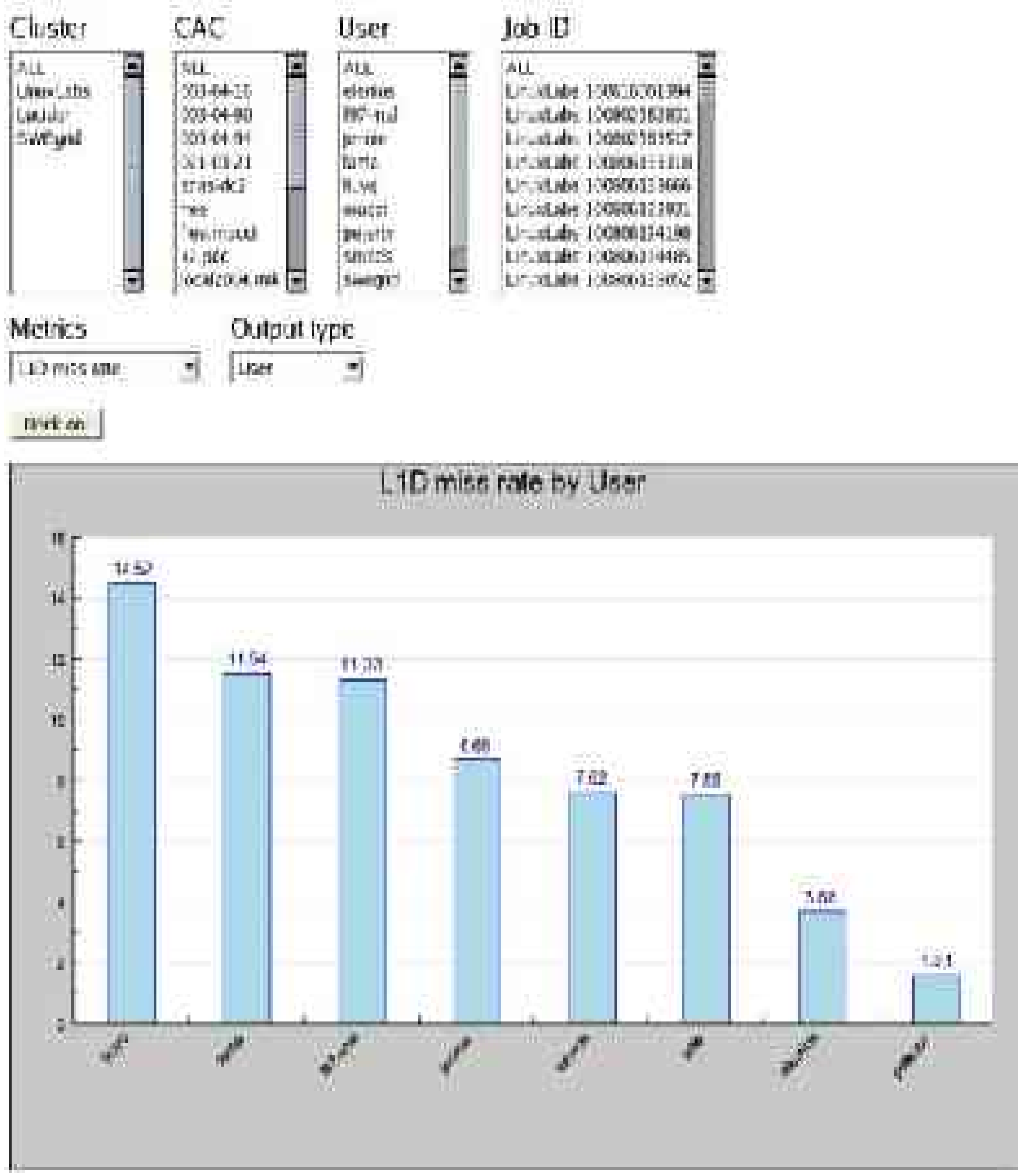
PDC Performance Miner
Main Window



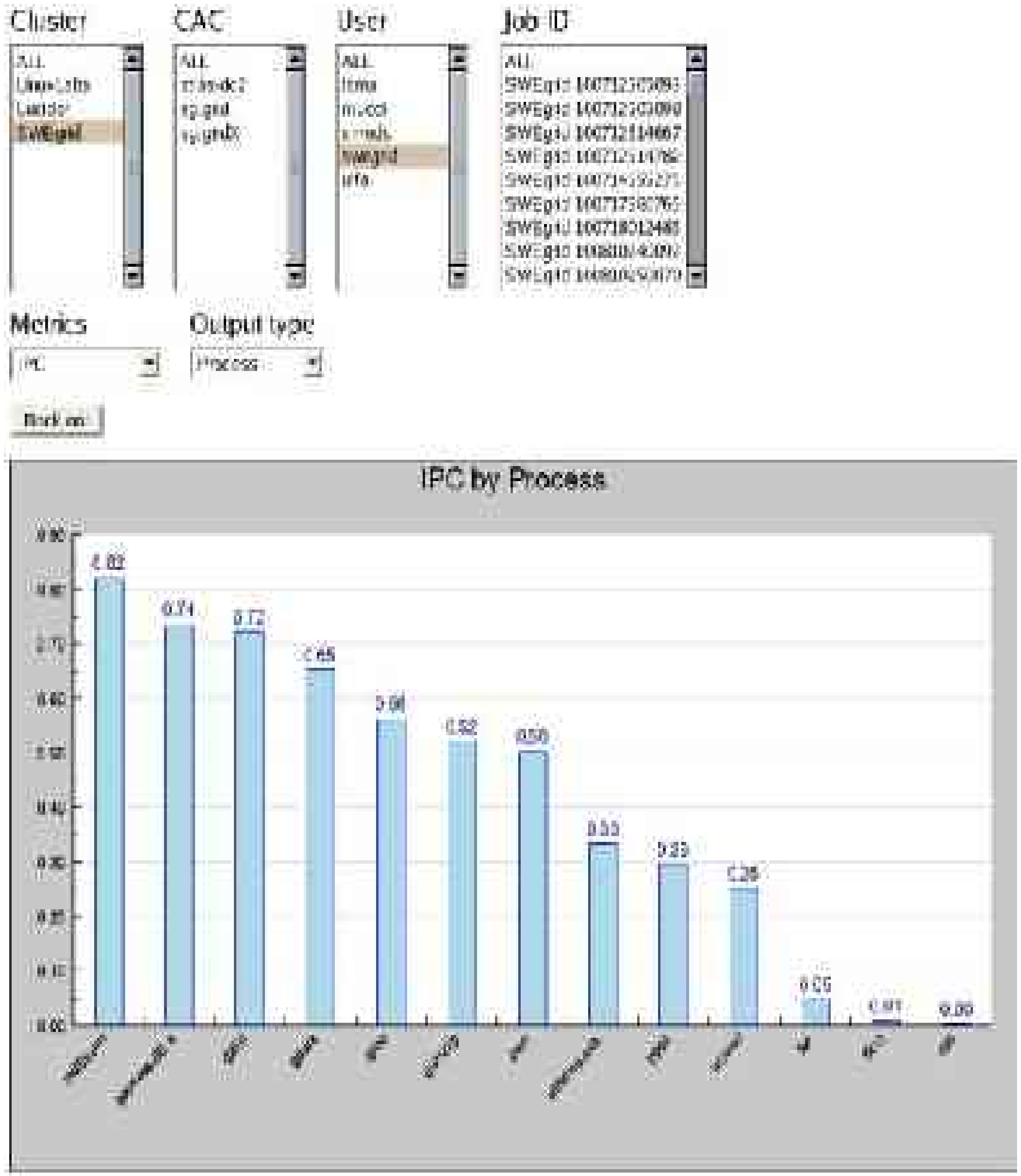
PDC Performance Miner
FP Ops by Job ID



PDC Performance Miner
L1 Miss Rate by User



PDC Performance Miner
IPC by Process for SweGrid



IO Track Goals

- Understand application I/O patterns in order to:
  - Direct optimization efforts for applications
  - Direct system design and tuning
  - Give a better understanding of I/O needs in general
- Provide an infrastructure for automatic I/O tuning

IO Track Overview

- IOtrack consists of three components:
  - iowrap - A preloaded library that traps calls to libc and creates log-files for each process.
  - logread - A tool to analyze iowrap log-files. (not yet finished)
  - iotrack - A driver program.

Iowrap Internals

- iowrap traps I/O calls to libc using function replacement.
  - File descriptor creation/close:
    - open/close/creat/dup/socket/accept/fcntl
  - I/O on File descriptors:
    - read/write/readv/writev/send/recv/sendto recvfrom/lseek/sendmsg/recvmsg
  - Stream I/O
    - fopen/fclose/fdopen/fread/fwrite/fprintf/fscanf
- mmap-based I/O is not handled: If the user knows enough to use mmap, we probably don't need to help.

Logfile Format

- Currently ASCII, may change in the future.

```
0.607013:LIBRARY LOADED:pid 3082:ppid
 3738:process /usr/bin/head:args /etc/passwd
0.607375:OPEN:new fd 4:/etc/passwd
0.607444:READ:fd 4:request size 4096:I/O size 4096
0.607480:LSEEK:fd 4:offset -3356:whence -1:new pos 1
0.607663:CLOSE:fd 4
0.607714:CLOSE:fd 3
```

Data from Log File

- Size of I/Os
- Which files are accessed?
- Location of I/Os within files
- I/O tracing withing files
- Redundant operations

Performance Impact

- Not well characterized as of yet, but generally depends on:
  - The granularity of IO
  - The amount of buffering performed in IOTrack.
- Data without buffering using 'sob' filesystem benchmark.
  - 1% overhead on reading 10 128MB files with 32MB block size.
  - 47% overhead on reading 16k 128kB files with 4kB block size.

Gaussian03 C02 Data test653

- Runtime is 31 minutes on 900Mhz Itanium2
- Profiling overhead was 3.5%
- 3 processes
  - 29 executions of 15 binaries
- 180 opens on 13 files
- Essentially all I/O goes to $GAUSS_SCRDIR, a temporary storage area on local disk
- Aggregate I/O is 14GB writes and 68GB reads

Gaussian03 C02 Data test653

- Total # of read/write calls is 3.4M
- Average I/O write size is 23.7kB
- Average I/O read size is 25.4kB
- 90% writes are 16kB
- 33% reads are 18.75kB
- 33% reads are 12.5kB
- 33% reads are 37.5kB

IOTrack Information

- This is a work in progress!
- Developed as part of a SNIC project on storage led by NSC.
- Code at http://www.pdc.kth.se/~pek/iotrack
- Contact:
  - Per Ekman, pek@pdc.kth.se
  - Philip J. Mucci, mucci@cs.utk.edu

Links

- PAPI
  - http://icl.cs.utk.edu/projects/papi
  - PerfCtr
    - http://user.it.uu.se/~mikpe/linux/perfctr/2.6
  - Perfmon
    - http://www.hpl.hp.com/research/linux/perfmon
- IOTrack
  - http://www.pdc.kth.se/~pek/iotrack
- HPCToolkit
  - http://www.hipersoft.rice.edu/hpctoolkit

Links

- PerfSuite
  - http://perfsuite.ncsa.uiuc.edu
- TAU
  - http://www.cs.uoregon.edu/research/paracomp/tau/tautools
- MPIP
  - http://www.llnl.gov/CASC/mpip
- Jumpshot-4
  - http://www-unix.mcs.anl.gov/perfvis/software/viewers

Credits

- PDC
  - http://www.pdc.kth.se
- ICL/UTK
  - http://icl.cs.utk.edu
- Additional work on PDC Performance Miner:
  - Daniel Ahlin, Johan Danielsson, Lars Malinowski, Ulf Andersson, Nils Smeds
- Work funded in part by:
  - US: DoE MICS, DoE SciDAC, NSF PACI Alliance
  - Sweden: SNIC