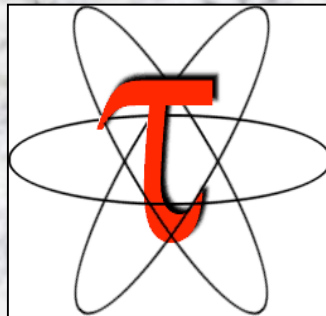


TAU Parallel Performance System

PDC Summer School in HPC



Part 1: TAU Overview and Architecture



Tutorial Outline – Part 1



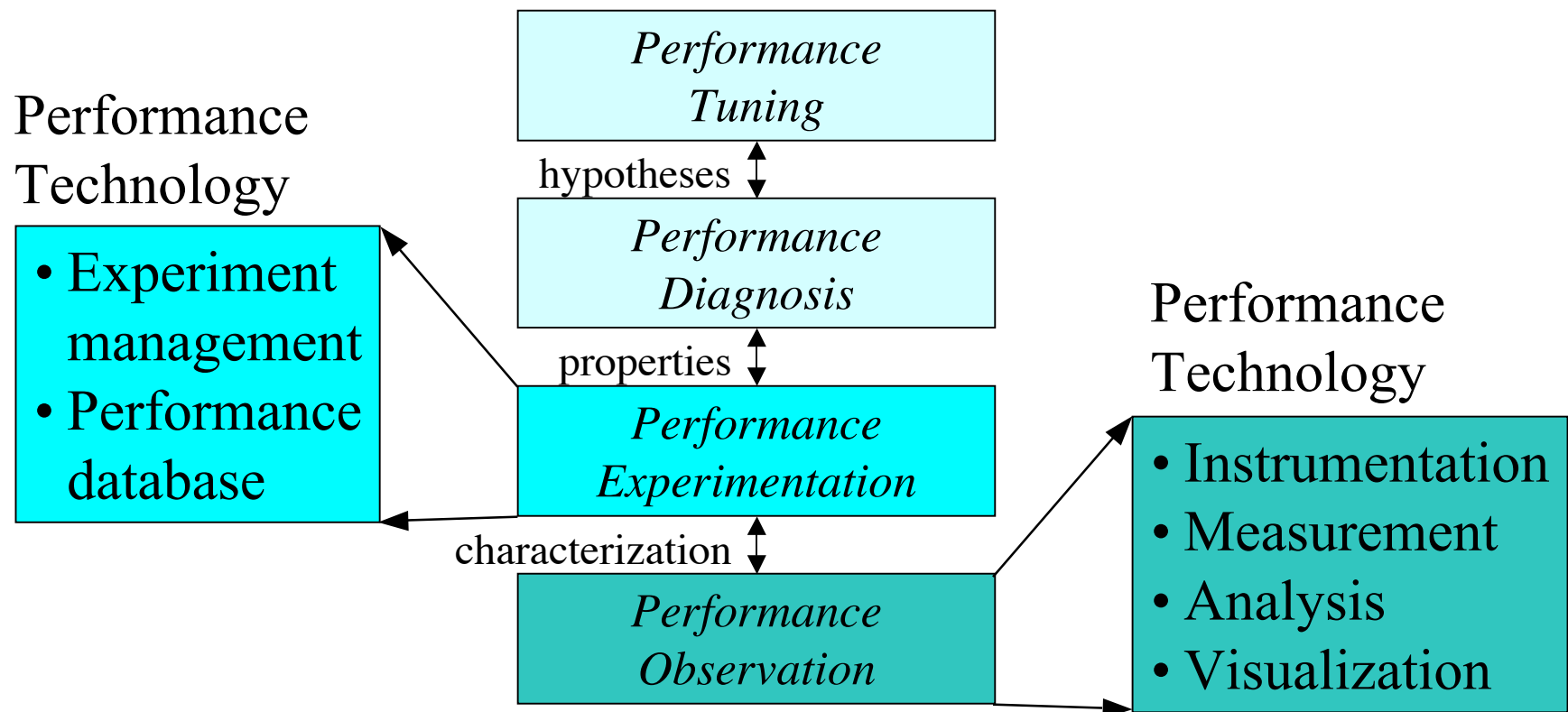
TAU Overview and Architecture

- ❑ Introduction
 - Performance technology
 - Complexity challenges and general problems
- ❑ Computation Model for Performance Technology
 - Framework for performance problem solving
- ❑ Performance analysis methods
- ❑ TAU Performance System
 - Model-oriented framework architecture
 - TAU performance system toolkit
 - TAU features, status, and application



Research Motivation

- Tools for performance problem solving
 - Empirical-based performance optimization process
 - Performance technology concerns





Complex Parallel Systems and Software

- Complexity in computing system architecture
 - Diverse parallel system architectures
 - shared / distributed memory, cluster, hybrid, NOW, ...
 - Sophisticated processor and memory architectures
 - Advanced network interface and switching architecture
- Complexity in parallel software environment
 - Diverse parallel programming paradigms
 - shared memory multi-threading, message passing, hybrid
 - Hierarchical, multi-level software architectures
 - Optimizing compilers and sophisticated runtime systems
 - Advanced numerical libraries and application frameworks



Complexity Challenges for Performance Tools

- **Computing system environment complexity**
 - Observation integration and optimization
 - Access, accuracy, and granularity constraints
 - Diverse/specialized observation capabilities/technology
 - Restricted modes limit performance problem solving
- **Sophisticated software development environments**
 - Programming paradigms and performance models
 - Performance data mapping to software abstractions
 - Uniformity of performance abstraction across platforms
 - Rich observation capabilities and flexible configuration
 - Common performance problem solving methods

Performance Needs \Leftrightarrow *Performance Technology*



- *Diverse performance observability requirements*
 - Multiple levels of software and hardware
 - Different types and detail of performance data
 - Alternative performance problem solving methods
 - Multiple targets of software and system application
- *Demands more robust performance technology*
 - Broad scope of performance observation
 - Flexible and configurable mechanisms
 - Technology integration and extension
 - Cross-platform portability
 - Open, layered, and modular framework architecture



Parallel Performance Technology

- ❑ Performance instrumentation tools
 - Different program code levels
 - Different system levels
- ❑ Performance measurement (observation) tools
 - Profiling and tracing of SW/HW performance events
 - Different software (SW) and hardware (HW) levels
- ❑ Performance analysis tools
 - Performance data analysis and presentation
 - Online and offline tools
- ❑ Performance experimentation
- ❑ Performance modeling and prediction tools



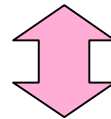
Application Problem Domain

- DOD defines leading edge parallel systems and software
 - Large-scale systems and heterogeneous platforms
 - Multi-model simulation
 - Complex, multi-layered software integration
 - Multi-language programming
 - Mixed-model parallelism
- Problem domain challenges
 - System diversity demands tool portability
 - Need for cross- and multi-language support
 - Coverage of alternative parallel computation models
 - Operate at scale

General Problems



How do we create robust and ubiquitous performance technology for the analysis and tuning of parallel and distributed software and systems in the presence of (evolving) complexity challenges?



How do we apply performance technology effectively for the variety and diversity of performance problems that arise in the context of complex parallel and distributed computer systems.



Definitions: Instrumentation

- ❑ Inserting extra code (hooks) into program
- ❑ Source code instrumentation
 - Manual
 - Automatic by compiler or source-to-source translator
- ❑ Object code instrumentation
 - “Re-writing” the executable to insert hooks
- ❑ Dynamic code instrumentation
 - Object code instrumentation while program is running
- ❑ Pre-instrumented library
 - Typically used for MPI and PVM program analysis
- ❑ Passive vs. active instrumentation



Definitions: Measurement

- ❑ Capturing performance data about system and software
- ❑ Triggered by events
 - Active and passive
 - Obtain execution control to make measurement
- ❑ Profile-based
- ❑ Trace-based
- ❑ Multiple performance data
 - Execution time
 - System and hardware statistics
- ❑ Runtime vs. online access



Definitions: Measurement – Profiling

□ Profiling

- Recording of summary information during execution
 - inclusive, exclusive time, # calls, hardware statistics, ...
- Reflects performance behavior of program entities
 - functions, loops, basic blocks
 - user-defined “semantic” entities
- Very good for low-cost performance assessment
- Helps to expose performance bottlenecks and hotspots
- Implemented through
 - **sampling**: periodic OS interrupts or hardware counter traps
 - **instrumentation**: direct insertion of measurement code



Definitions: Measurement – Tracing

□ Tracing

- Recording data at significant points (**events**)
 - entering/exiting code region (function, loop, block, ...)
 - thread/process interactions (e.g., send/receive message)
- Save information in **event record**
 - timestamp
 - CPU identifier, thread identifier
 - event type and event-specific information
- **Event trace** is a time-sequenced stream of event records
- Can be used to reconstruct dynamic program behavior
- Typically requires code instrumentation



Event Tracing: *Instrumentation*, *Monitor*, *Trace*

CPU A:

```

void master {
  trace(ENTER, 1);
  ...
  trace(SEND, B);
  send(B, tag, buf);
  ...
  trace(EXIT, 1);
}

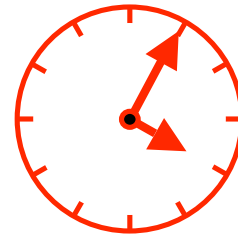
```

CPU B:

```

void slave {
  trace(ENTER, 2);
  ...
  recv(A, tag, buf);
  trace(RECV, A);
  ...
  trace(EXIT, 2);
}

```



timestamp



Event definition

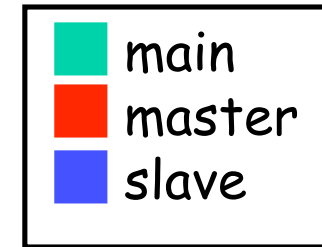
1	master
2	slave
3	...

...			
58	A	ENTER	1
60	B	ENTER	2
62	A	SEND	B
64	A	EXIT	1
68	B	RECV	A
69	B	EXIT	2
...			

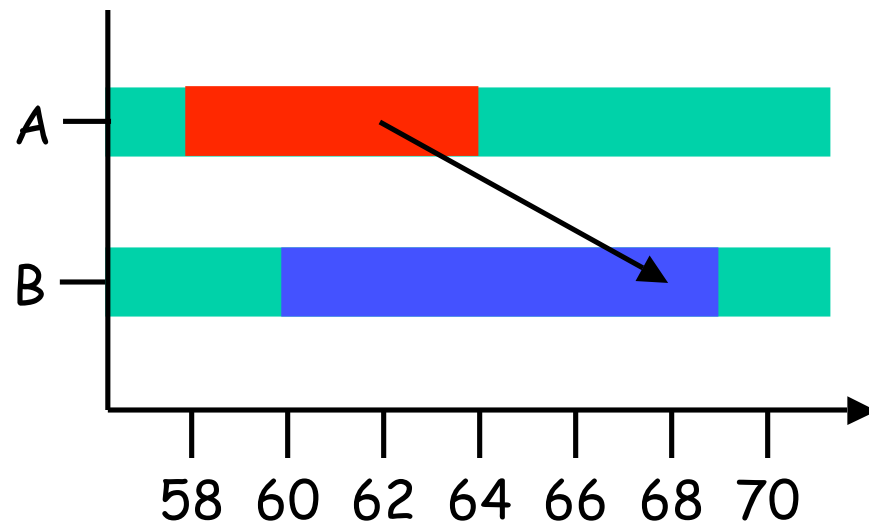


Event Tracing: "Timeline" Visualization

1	master
2	slave
3	...



...			
58	A	ENTER	1
60	B	ENTER	2
62	A	SEND	B
64	A	EXIT	1
68	B	RECV	A
69	B	EXIT	2
...			





Unix Profiling Tools (prof)

❑ Classical Unix profiling tools

- *prof* and *gprof*

❑ *prof*

- Sample-based measurement
 - samples program counter (PC) at timer interrupts or traps
 - match PC with code sections (routines) using symbol table
- Keeps time histogram
 - assumes all time since last sample spent in routine
 - accumulates time per routine
- Needs large enough samples to obtain statistical accuracy
- Requires program to be compiled for profiling
 - need to produce symbol table



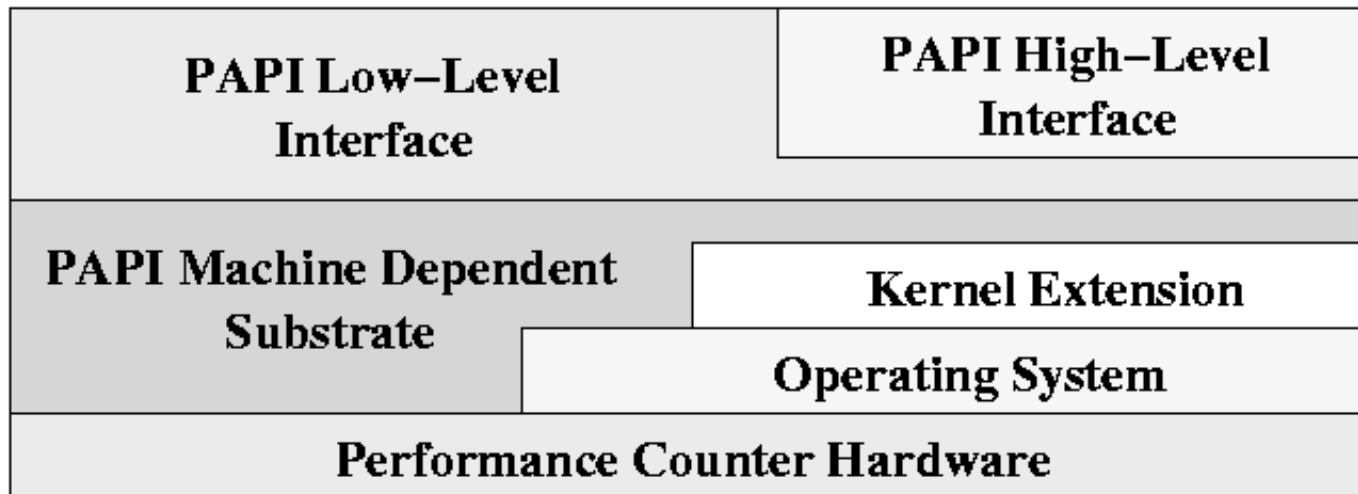
Unix Profiling Tools (gprof)

- ❑ Interested in seeing routine calling relationships
 - *Callpath profiling*
- ❑ *gprof*
 - Sample-based measurement
 - samples program counter (PC) at timer interrupts or traps
 - match PC with code sections (routines) using symbol table
 - looks on stack for calling PC and matches to calling routine
 - Keeps time histogram
 - assumes all time since last sample spent in routine
 - accumulates time per routine and caller
 - Needs large enough samples to obtain statistical accuracy
 - Requires program to be compiled for profiling



Performance API (PAPI, UTK)

- ❑ Time is not the only thing of interest
- ❑ Access to hardware counters on modern microprocessors



- ❑ *papiprof*
 - Profiling using PAPI counter measurements
- ❑ Program Counter Library (PCL, Research Center Juelich)



What about Parallel Profiling?

- ❑ Unix profiling tools are sequential profilers
 - Process-oriented
- ❑ What does parallel profiling mean?
 - Capture profiles for all “threads of execution”
 - shared-memory threads for a process
 - multiple (Unix) processes
 - What about interactions between “threads of execution”?
 - synchronization between threads
 - communication between processes
 - How to correctly save profiles for analysis?
 - How to do the analysis and interpret results ?
- ❑ Parallel profiling scalability



MPI “Profiling” Interface (PMPI)

- ❑ How to capture message communication events?
- ❑ MPI standard defined an interface for instrumentation
 - Alternative entry points to each MPI routine
 - “Standard” routine entry linked to instrumented library
 - Instrumented library performs measurement then calls alternative entry point for corresponding routine
 - library interposition
 - wrapper library
- ❑ PMPI used for most MPI performance measurement
- ❑ PMPI also can be used for debugging
- ❑ PERUSE (LLNL) project is a follow-on project



Computation Model for Performance Technology

□ How to address dual performance technology goals?

- Robust capabilities + widely available methods
- Contend with problems of system diversity
- Flexible tool composition/configuration/integration

□ Approaches

○ Restrict computation types / performance problems

- machines, languages, instrumentation technique, ...
- limited performance technology coverage and application

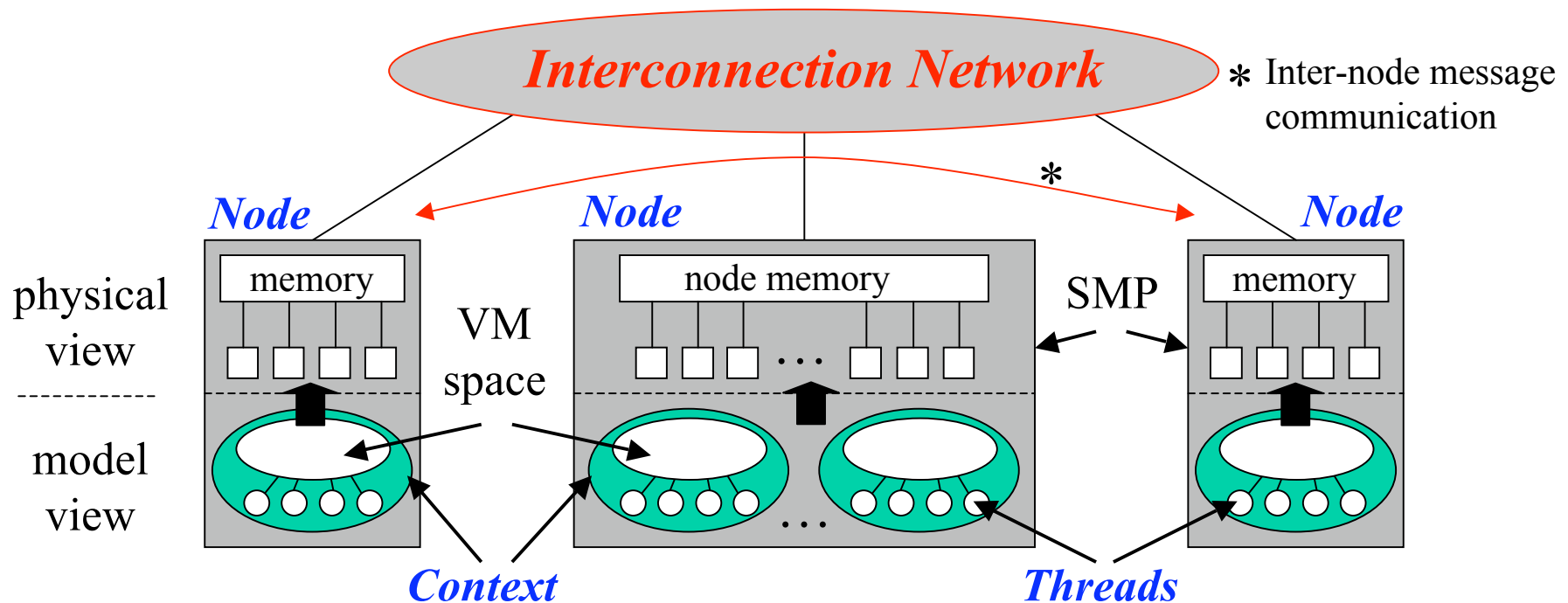
○ Base technology on abstract computation model

- general architecture and software execution features
- map features/methods to existing complex system types
- develop capabilities that can be adapted and optimized



General Complex System Computation Model

- ❑ **Node**: physically distinct shared memory machine
 - Message passing *node interconnection network*
- ❑ **Context**: distinct virtual memory space within node
- ❑ **Thread**: execution threads (user/system) in context





TAU Performance System

- ❑ Tuning and Analysis Utilities (12+ year project effort)
- ❑ *Performance system framework* for scalable parallel and distributed high-performance computing
- ❑ Targets a general complex system computation model
 - nodes / contexts / threads
 - Multi-level: system / software / parallelism
 - Measurement and analysis abstraction
- ❑ *Integrated toolkit* for performance instrumentation, measurement, analysis, and visualization
 - Portable performance profiling and tracing facility
 - Open software approach with technology integration
- ❑ University of Oregon , Forschungszentrum Jülich, LANL

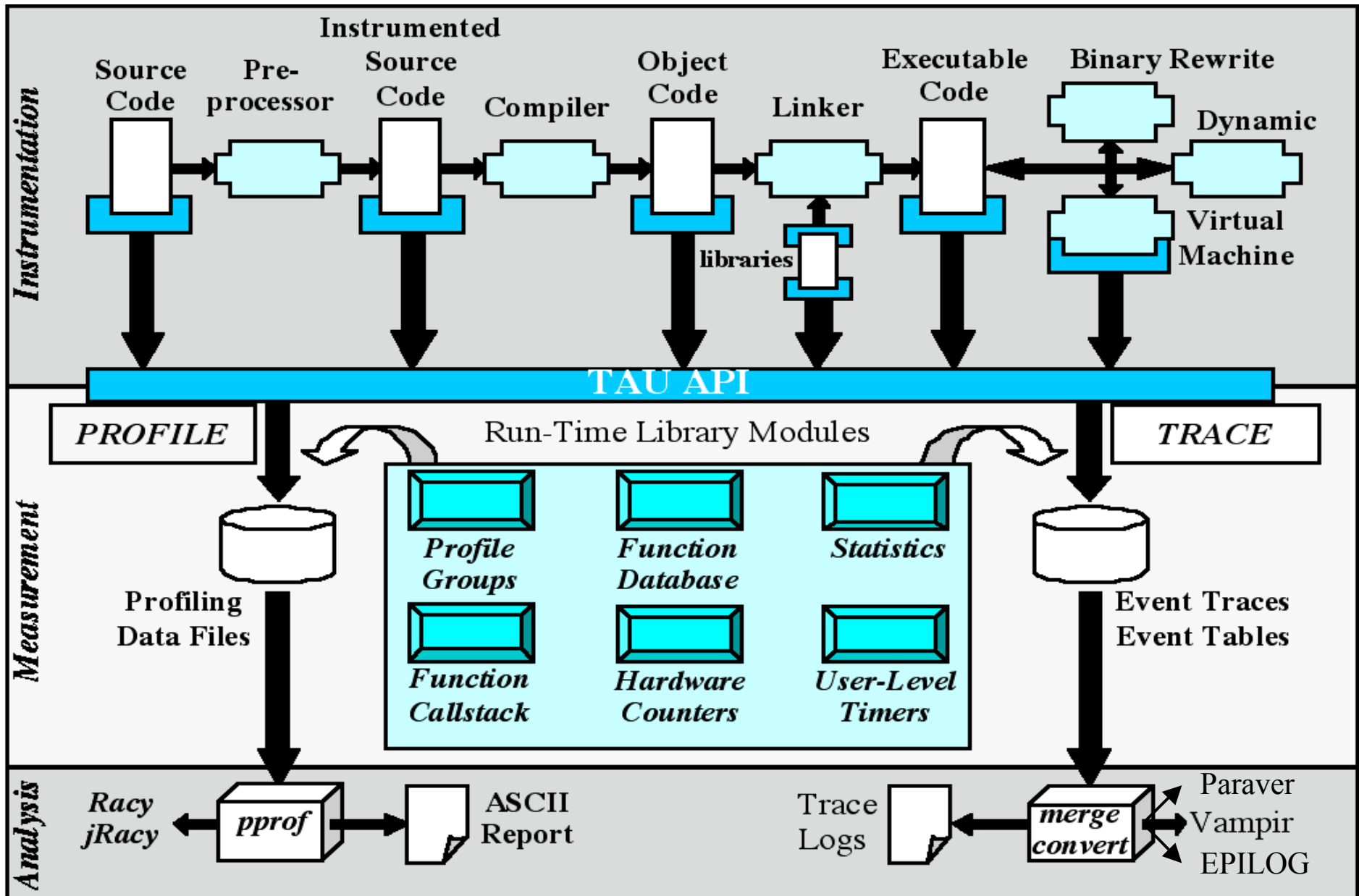


TAU Performance Systems Goals

- ❑ Multi-level performance instrumentation
 - Multi-language automatic source instrumentation
- ❑ Flexible and configurable performance measurement
- ❑ Widely-ported parallel performance profiling system
 - Computer system architectures and operating systems
 - Different programming languages and compilers
- ❑ Support for multiple parallel programming paradigms
 - Multi-threading, message passing, mixed-mode, hybrid
- ❑ Support for performance mapping
- ❑ Support for object-oriented and generic programming
- ❑ Integration in complex software systems and applications



TAU Performance System Architecture





Definitions: Instrumentation

□ Instrumentation

- Insertion of extra code (hooks) into program

- **Source** instrumentation

- done by compiler, source-to-source translator, or manually
- + portable
- + links back to program code
- re-compile is necessary for (change in) instrumentation
- requires source to be available
- hard to use in standard way for mix-language programs
- source-to-source translators hard to develop (e.g., C++, F90)

- **Object code** instrumentation

- “re-writing” the executable to insert hooks



Definitions – Instrumentation (continued)

- **Dynamic** code instrumentation
 - a debugger-like instrumentation approach
 - executable code instrumentation on running program
 - *Dyninst* and *DPCL* are examples
 - +/- opposite compared to source instrumentation
- **Pre-instrumented** library
 - typically used for MPI and PVM program analysis
 - supported by link-time **library interposition**
 - + easy to use since only re-linking is necessary
 - can only record information about library entities



TAU Instrumentation Approach

- ❑ Support for standard program events
 - Routines
 - Classes and templates
 - Statement-level blocks
- ❑ Support for user-defined events
 - Begin/End events (“user-defined timers”)
 - Atomic events (e.g., size of memory allocated/freed)
 - Selection of event statistics
- ❑ Support definition of “semantic” entities for mapping
- ❑ Support for event groups
- ❑ Instrumentation optimization

TAU Instrumentation



- Flexible instrumentation mechanisms at multiple levels
 - Source code
 - manual
 - 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*)
 - statically-linked and dynamically-linked (e.g., Python)
 - Executable code
 - dynamic instrumentation (pre-execution) (*Dyninst*)
 - virtual machine instrumentation (e.g., Java using *JVMPI*)



Multi-Level Instrumentation

- ❑ Targets common measurement interface
 - *TAU API*
- ❑ Multiple instrumentation interfaces
 - Simultaneously active
- ❑ Information sharing between interfaces
 - Utilizes instrumentation knowledge between levels
- ❑ Selective instrumentation
 - Available at each level
 - Cross-level selection
- ❑ Targets a common performance model
- ❑ Presents a unified view of execution
 - Consistent performance events



Code Transformation and Instrumentation

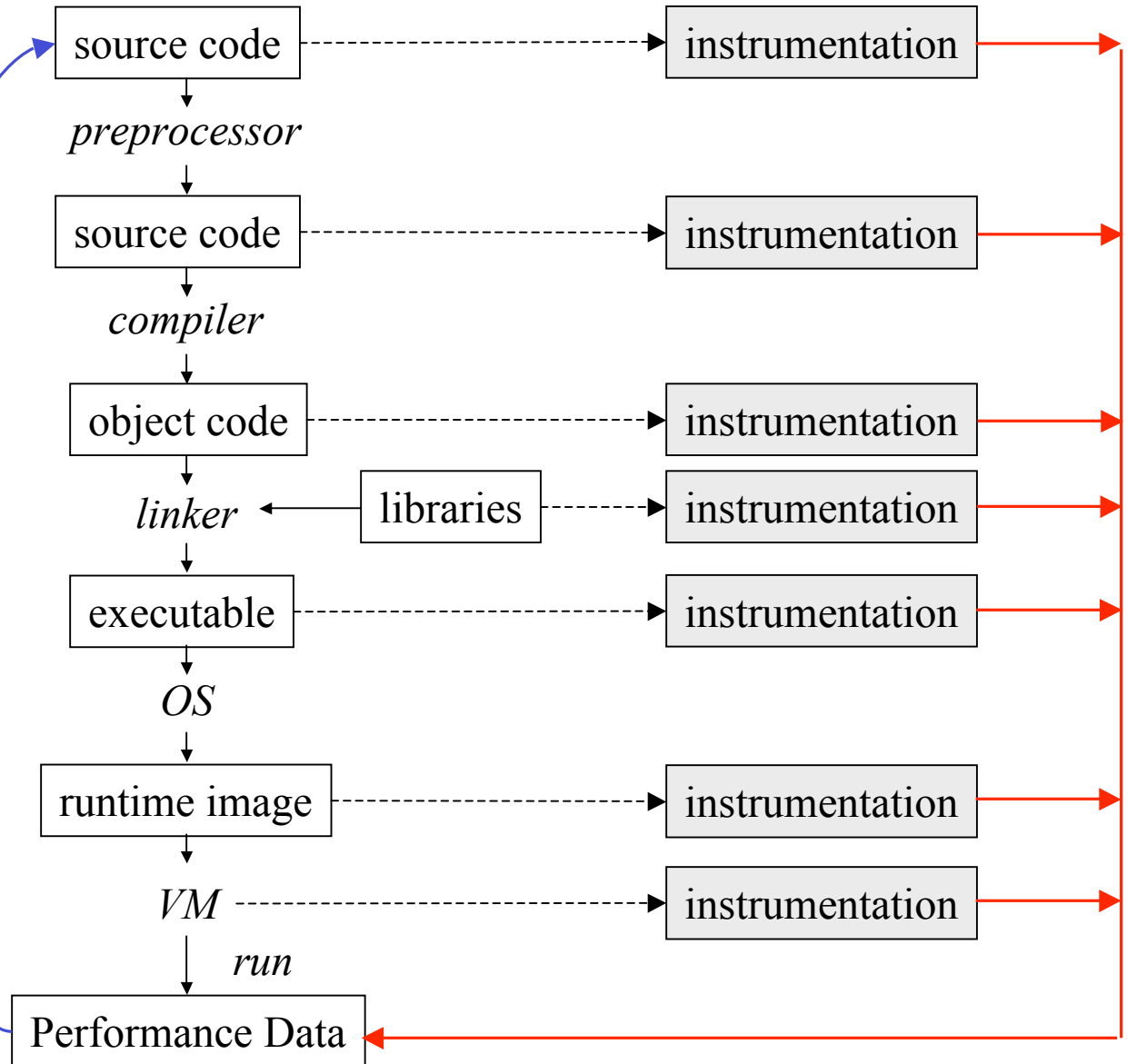
- Program information flows through stages of compilation/linking/execution
 - Different information is accessible at different stages
 - Each level poses different constraints and opportunities for extracting information

- Where should performance instrumentation be done?
 - At what level?
 - Instrumentation at different levels
 - Cooperative



Code Transformation Levels and Instrumentation

- Instrumentation relevant to code aspects
- Capture knowledge of code relationships
- Relate performance data to source-level view





TAU Source Instrumentation

- ❑ Automatic source instrumentation (*tau_instrumentor*)
 - Routine entry/exit and class method entry/exit
 - Block entry/exit and statement level (to be added)
 - Uses an instrumentation specification file
 - include/exclude list for events and files
 - Uses command line options for group selection
- ❑ Instrumentation event selection (*tau_select*)
 - Automatic generation of instrumentation specification file
 - Instrumentation language to describe event constraints
 - event identity and location
 - event performance properties (e.g., overhead analysis)
 - Create TAUselect scripts for performance experiments



TAU Performance Measurement

- ❑ TAU supports profiling and tracing measurement
- ❑ Robust timing and hardware performance support
- ❑ Support for online performance monitoring
 - Profile and trace performance data export to file system
 - Selective exporting
- ❑ Extension of TAU measurement for multiple counters
 - Creation of user-defined TAU counters
 - Access to system-level metrics
- ❑ Support for callpath measurement
- ❑ Integration with system-level performance data
 - Operating system statistics (e.g., /proc file system)

TAU Measurement



□ Performance information

- Performance events
- High-resolution *timer library* (real-time / virtual clocks)
- General *software counter library* (user-defined events)
- Hardware performance counters
 - *PAPI* (Performance API) (UTK, Ptools Consortium)
 - consistent, portable API

□ Organization

- Node, context, thread levels
- *Profile groups* for collective events (runtime selective)
- Performance data *mapping* between software levels



TAU Measurement with Multiple Counters

- ❑ **Extend event measurement to capture multiple metrics**
 - Begin/end (interval) events
 - User-defined (atomic) events
 - Multiple performance data sources can be queried
- ❑ **Associate counter function list to event**
 - Defined statically or dynamically
 - Different counter sources
 - timers and hardware counters
 - user-defined counters (application specified)
 - system-level counters
 - Monotonically increasing required for begin/end events
- ❑ **Extend user-defined counters to system-level counter**

TAU Measurement Options



□ Parallel profiling

- Function-level, block-level, statement-level
- Supports user-defined events
- TAU parallel profile data stored during execution
- Hardware counts values and support for multiple counters
- Support for callgraph and callpath profiling

□ Tracing

- All profile-level events
- Inter-process communication events
- Trace merging and format conversion

□ Configurable measurement library



Grouping Performance Data in TAU

□ Profile Groups

- A group of related routines forms a profile group
- Statically defined
 - TAU_DEFAULT, TAU_USER[1-5], TAU_MESSAGE, TAU_IO, ...
- Dynamically defined
 - group name based on string, such as “**mpi**” or “**particles**”
 - runtime lookup in a map to get unique group identifier
 - uses *tau_instrumentor* to instrument
- Ability to change group names at runtime
- Group-based instrumentation and measurement control



Performance Analysis and Visualization

- ❑ Analysis of parallel profile and trace measurement
- ❑ Parallel profile analysis
 - *Pprof* : parallel profiler with text-based display
 - *ParaProf* : graphical, scalable parallel profile analysis
 - *ParaVis* : profile visualization
- ❑ Performance Data Management Framework (*PerfDMF*)
- ❑ Parallel trace analysis
 - Format conversion (ALOG, VTF 3.0, Paraver, EPILOG)
 - Trace visualization using *Vampir* (Pallas/Intel)
 - Parallel profile generation from trace data
- ❑ Online parallel analysis and visualization



Pprof Command

- `pprof [-c|-b|-m|-t|-e|-i] [-r] [-s] [-n num] [-f file] [-l] [nodes]`
 - **-c** Sort according to number of calls
 - **-b** Sort according to number of subroutines called
 - **-m** Sort according to msec (exclusive time total)
 - **-t** Sort according to total msec (inclusive time total)
 - **-e** Sort according to exclusive time per call
 - **-i** Sort according to inclusive time per call
 - **-v** Sort according to standard deviation (exclusive usec)
 - **-r** Reverse sorting order
 - **-s** Print only summary profile information
 - **-n num** Print only first number of functions
 - **-f file** Specify full path and filename without node ids
 - **-l** List all functions and exit



Pprof Output (NAS Parallel Benchmark – LU)

- ❑ Intel Quad
PIII Xeon
- ❑ F90 +
MPICH
- ❑ Profile
 - Node
 - Context
 - Thread
- ❑ Events
 - code
 - MPI

emac@neutron.cs.uoregon.edu

Buffers Files Tools Edit Search Mule Help

Reading Profile files in profile.*

NODE: 0; CONTEXT: 0; THREAD: 0;

%Time	Exclusive msec	Inclusive total msec	#Call	#Subrs	Inclusive usec/call	Name
100.0	1	3:11.293	1	15	191293269	applu
99.6	3,667	3:10.463	3	37517	63487925	bcast_inputs
67.1	491	2:08.326	37200	37200	3450	exchange_1
44.5	6,461	1:25.159	9300	18600	9157	buts
41.0	1:18.436	1:18.436	18600	0	4217	MPI_Recv()
29.5	6,778	56,407	9300	18600	6065	blts
26.2	50,142	50,142	19204	0	2611	MPI_Send()
16.2	24,451	31,031	301	602	103096	rhs
3.9	7,501	7,501	9300	0	807	jacltd
3.4	838	6,594	604	1812	10918	exchange_3
3.4	6,590	6,590	9300	0	709	jacu
2.6	4,989	4,989	608	0	8206	MPI_Wait()
0.2	0.44	400	1	4	400081	init_comm
0.2	398	399	1	39	399634	MPI_Init()
0.1	140	247	1	47616	247086	setiv
0.1	131	131	57252	0	2	exact
0.1	89	103	1	2	103168	erhs
0.1	0.966	96	1	2	96458	read_input
0.0	95	95	9	0	10603	MPI_Bcast()
0.0	26	44	1	7937	44878	error
0.0	24	24	608	0	40	MPI_Irecv()
0.0	15	15	1	5	15630	MPI_Finalize()
0.0	4	12	1	1700	12335	setbv
0.0	7	8	3	3	2893	l2norm
0.0	3	3	8	0	491	MPI_Allreduce()
0.0	1	3	1	6	3874	pintgr
0.0	1	1	1	0	1007	MPI_Barrier()
0.0	0.116	0.837	1	4	837	exchange_4
0.0	0.512	0.512	1	0	512	MPI_Keyval_create()
0.0	0.121	0.353	1	2	353	exchange_5
0.0	0.024	0.191	1	2	191	exchange_6
0.0	0.103	0.103	6	0	17	MPI_Type_contiguous()

--:-- NPB_LU.out (Fundamental)--L8--Top--



Profile Terminology – Example

- ❑ Routine “int main()”
- ❑ Inclusive time
 - 100 secs
- ❑ Exclusive time
 - $100 - 20 - 50 - 20 = 10$ secs
- ❑ #Calls
 - 1 call
- ❑ #Subrs
 - Child routines called
 - 3
- ❑ Inclusive time/call
 - 100secs

```
int main( )
{ /* takes 100 secs */

    f1 (); /* takes 20 secs */
    f2 (); /* takes 50 secs */
    f1 (); /* takes 20 secs */

    /* other work */

}

/*
Time can be replaced by counts
*/
```

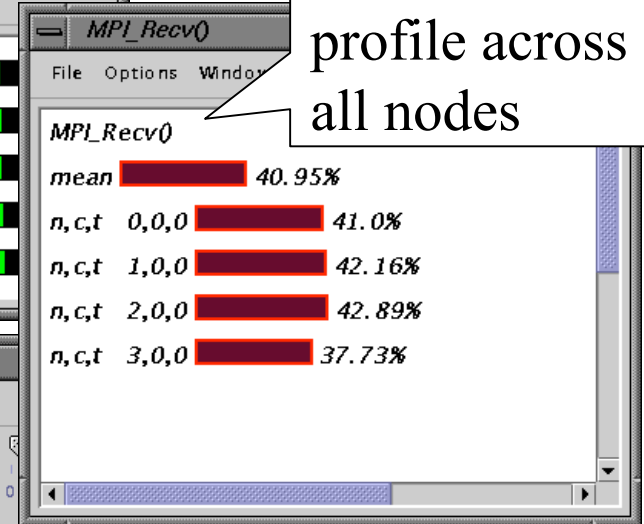
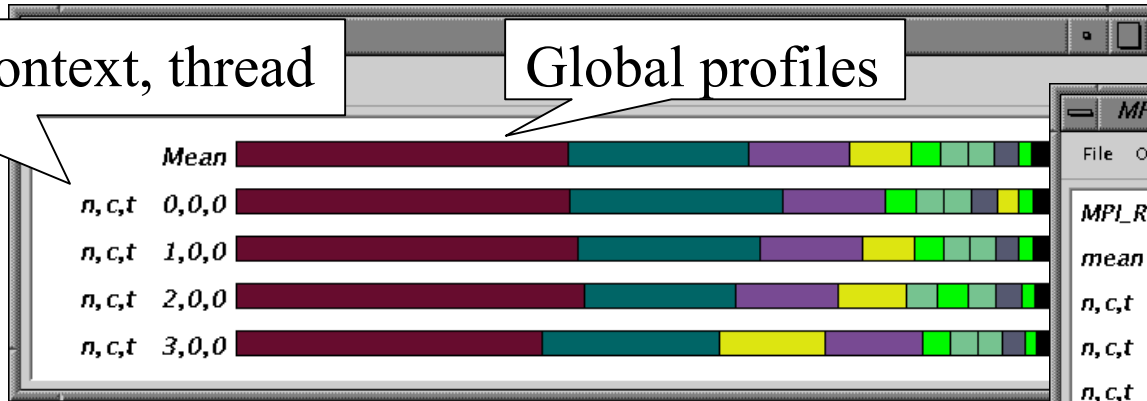


ParaProf (NAS Parallel Benchmark – LU)

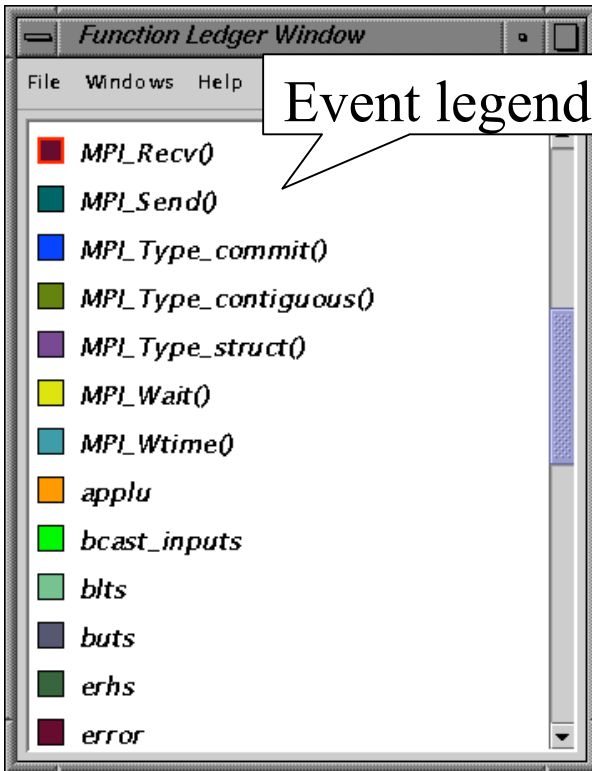
node,context, thread

Global profiles

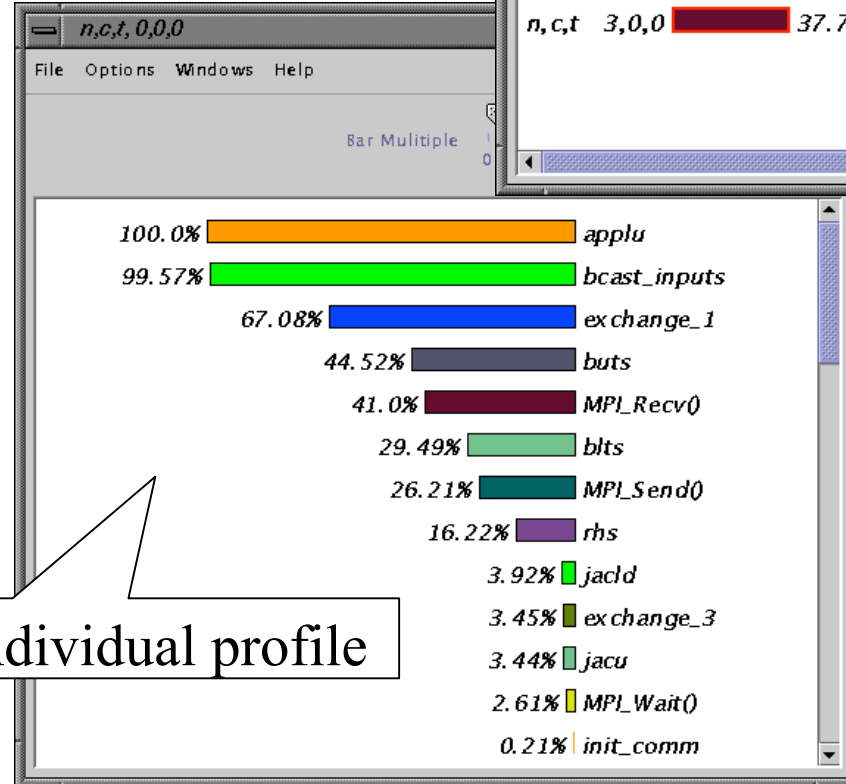
Routine profile across all nodes



Event legend



Individual profile

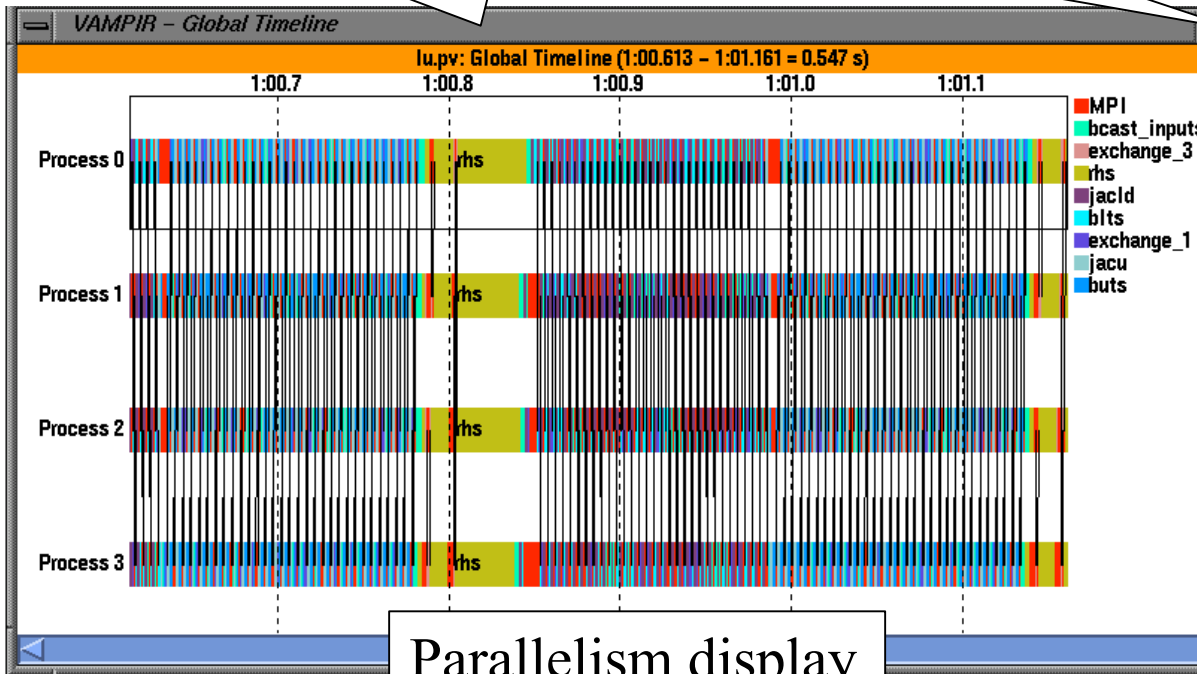




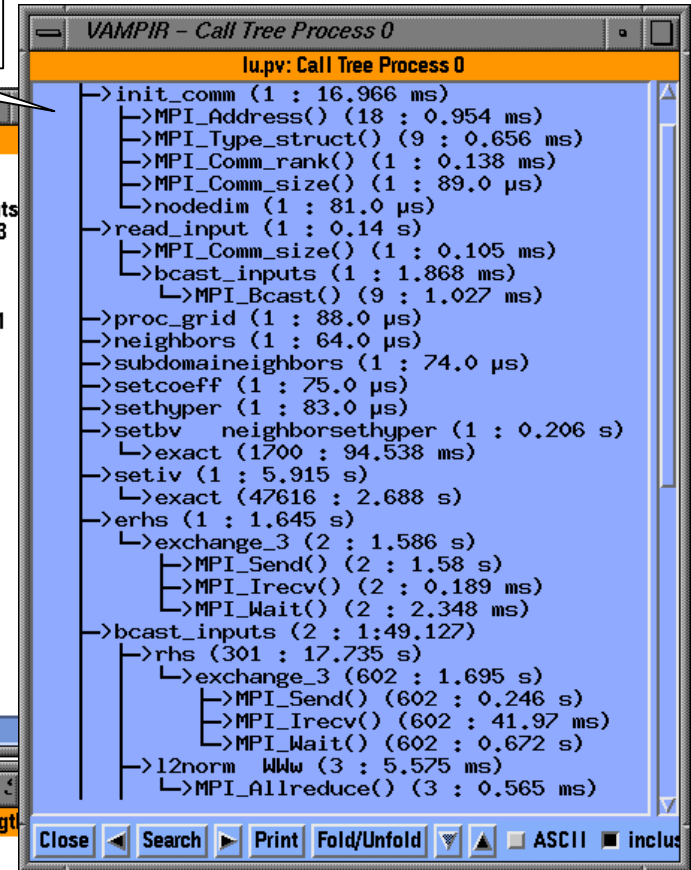
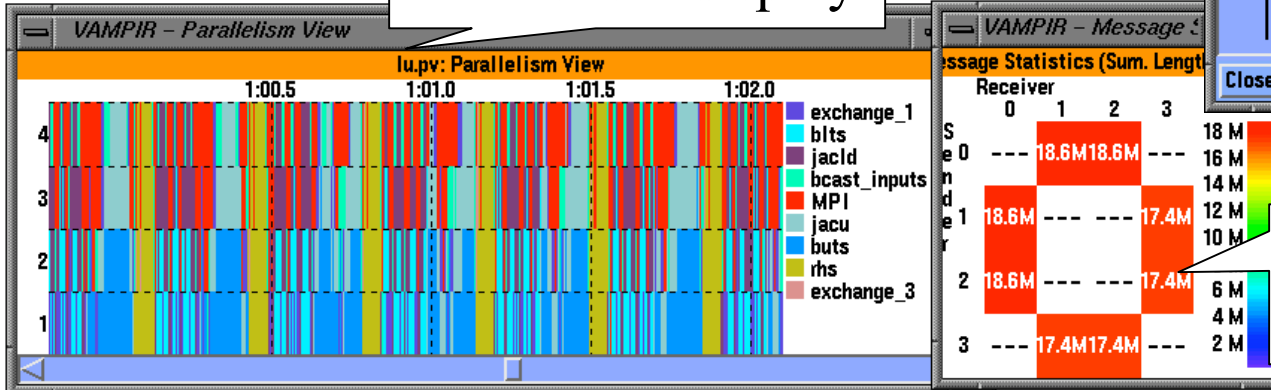
TAU + Vampir (NAS Parallel Benchmark – LU)

Timeline display

Callgraph display



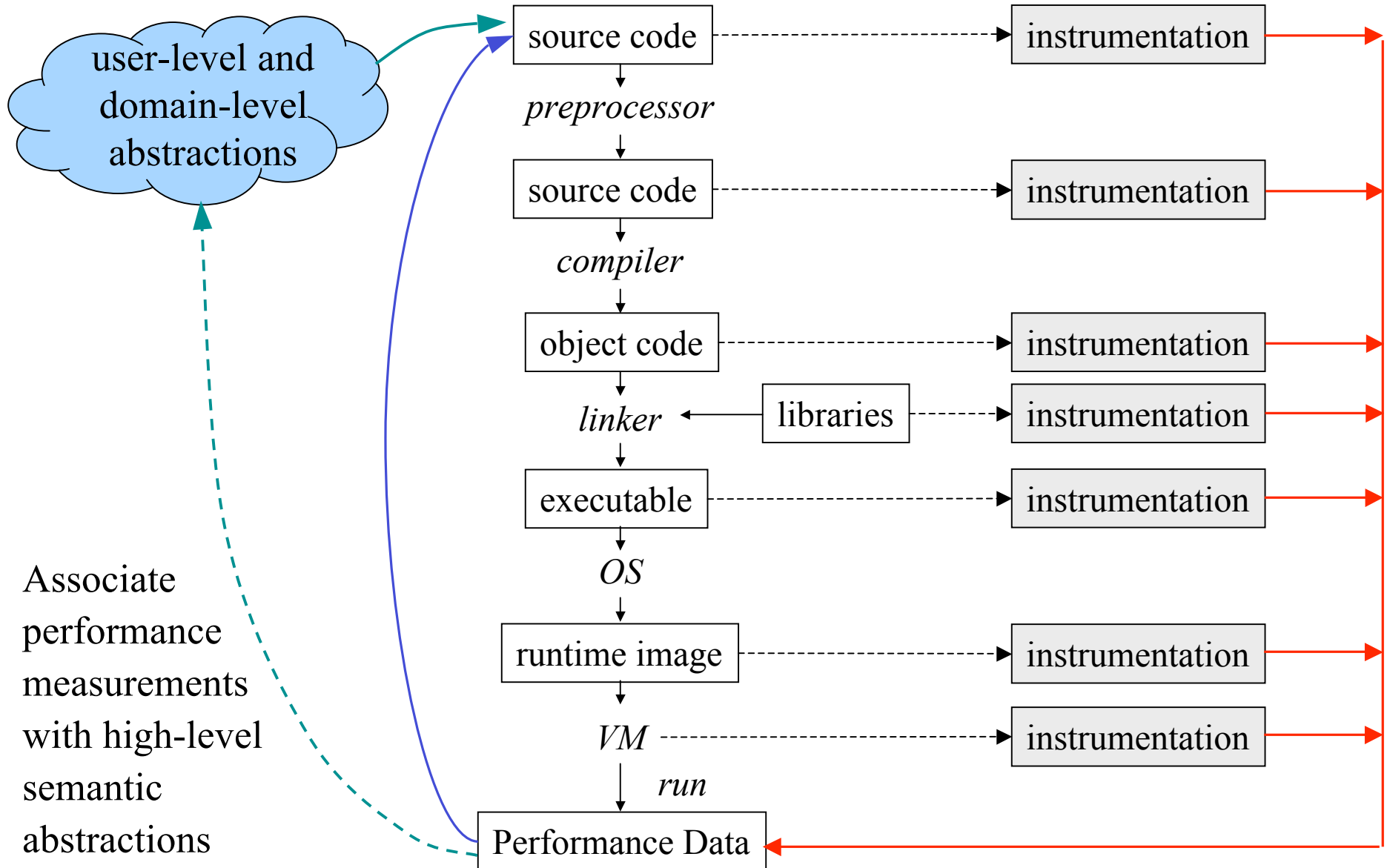
Parallelism display



Communications display



Semantic Performance Mapping





Strategies for Empirical Performance Evaluation

- Empirical performance evaluation as a series of performance experiments
 - Experiment trials describing instrumentation and measurement requirements
 - **Where/When/How** axes of empirical performance space
 - where are performance measurements made in program
 - when is performance instrumentation done
 - how are performance measurement/instrumentation chosen
- Strategies for achieving flexibility and portability goals
 - Limited performance methods restrict evaluation scope
 - Non-portable methods force use of different techniques
 - Integration and combination of strategies

TAU Performance System Status



❑ Computing platforms (selected)

- IBM SP / pSeries, SGI Origin 2K/3K, Cray T3E / SV-1 / X1, HP (Compaq) SC (Tru64), Sun, Hitachi SR8000, NEC SX-5/6, Linux clusters (IA-32/64, Alpha, PPC, PA-RISC, Power, Opteron), Apple (G4/5, OS X), Windows

❑ Programming languages

- C, C++, Fortran 77/90/95, HPF, Java, OpenMP, Python

❑ Thread libraries

- pthreads, SGI sproc, Java, Windows, OpenMP

❑ Compilers (selected)

- Intel KAI (KCC, KAP/Pro), PGI, GNU, Fujitsu, Sun, Microsoft, SGI, Cray, IBM (xlc, xlf), Compaq, NEC, Intel



Selected Applications of TAU

- ❑ Center for Simulation of Accidental Fires and Explosion
 - University of Utah, ASCI ASAP Center, C-SAFE
 - Uintah Computational Framework (UCF) (C++)
- ❑ Center for Simulation of Dynamic Response of Materials
 - California Institute of Technology, ASCI ASAP Center
 - Virtual Testshock Facility (VTF) (Python, Fortran 90)
- ❑ Los Alamos National Lab
 - Monte Carlo transport (MCNP)
 - full code automatic instrumentation and profiling
 - ASCI Q validation and scaling
 - SAIC's Adaptive Grid Eulerian (SAGE)
 - Fortran 90 automatic instrumentation and profiling



Selected Applications of TAU (continued)

□ Lawrence Livermore National Lab

- Overture object-oriented PDE package (C++)
- Radiation diffusion (KULL)
 - C++ automatic instrumentation, callpath profiling

□ Sandia National Lab

- DOE CCTTSS SciDAC project
- Common component architecture (CCA) integration
- Combustion code (C++, Fortran 90, GrACE, MPI)

□ Center for Astrophysical Thermonuclear Flashes

- University of Chicago / Argonne, ASCI ASAP Center
- FLASH code (C, Fortran 90, MPI)



Selected Applications of TAU (continued)

□ Argonne National Lab

- PETSc (C, C++, Fortran 90, MPI)
 - Portable, Extensible Toolkit for Scientific Computation

□ National Center for Atmospheric Research (NCAR)

- Earth System Modeling Framework (ESMF)
 - C++, components

□ DOD PET (Avi Purkayastha, TACC)

- HYCOM (Hybrid Coordinate Ocean Model) (NAVO)
 - Climate/Weather/Ocean (CWO) Modeling and Simulation
- AVUS (Air Vehicles Unstructured Solver)
- MACH3 3D magnetohydrodynamic (MHD) code
- OVERFLOW-D Navier-Stokes solver (NASA)



Concluding Remarks

- ❑ Complex parallel systems and software pose challenging performance analysis problems that require robust methodologies and tools
- ❑ To build more sophisticated performance tools, existing proven performance technology must be utilized
- ❑ Performance tools must be integrated with software and systems models and technology
 - Performance engineered software
 - Function consistently and coherently in software and system environments
- ❑ TAU performance system offers robust performance technology that can be broadly integrated



Supporting Agencies

□ Department of Energy (DOE)

- Office of Advanced Scientific Computing Research (OASCR), MICS Division
 - DOE 2000 ACTS contract
 - “Performance Technology for Tera-class Parallel Computer Systems: Evolution of the TAU Performance System”
 - “Performance Analysis of Parallel Component Software”



- National Nuclear Security Administration (NNSA), Office of Advanced Simulation and Computing (ASC)



- University of Utah DOE ASCI Level 1 sub-contract
- DOE ASCI Level 3 (LANL, LLNL)





Supporting (continued)

□ National Science Foundation

- NSF National Young Investigator (NYI)



□ Research Centre Juelich

- John von Neumann Institute for Computing
- Dr. Bernd Mohr



□ Los Alamos National Laboratory



□ University of Oregon

