AMS 250: An Introduction to High Performance Computing

Parallel Performance Tools

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Outline

- Introduction to Parallel Performance Analysis and Tuning
- Performance Observation
- Performance Metrics and Measurement
  - Profiling
  - Tracing
- Performance Technologies
  - Timers
  - Counters
  - Instrumentation
- Performance Tools

Parallel Performance and Complexity

- To use a scalable parallel computer well, you must write high-performance parallel programs
- To write high-performance parallel programs, you must understand and optimize performance for the combination of programming model, algorithm, language, platform, …
- Unfortunately, parallel performance measurement, analysis and optimization can be a difficult process
- Parallel performance is complex!

Performance Factors

- Factors which determine a program's performance are complex, interrelated, and sometimes hidden
- Application related factors
  - Algorithms, dataset sizes, task granularity, memory usage patterns, load balancing, I/O communication patterns
- Hardware related factors
  - Processor architecture, memory hierarchy, I/O network
- Software related factors
  - Operating system, compiler/preprocessor, communication protocols, libraries

Utilization of Computational Resources

- Resources can be under-utilized or used inefficiently
  - Identifying these circumstances can give clues to where performance problems exist
- Resources may be “virtual”
  - Not actually a physical resource (e.g., thread, process)
- Performance analysis tools are essential to optimizing an application's performance
  - Can assist you in understanding what your program is “really doing”
  - May provide suggestions on how program performance should be improved

Performance Analysis and Tuning: The Basics

- Most important goal of performance tuning is to reduce a program's wall clock execution time
  - Iterative process to optimize efficiency
  - Efficiency is a relationship of execution time
- So, where does the time go?
- Find your program's *hot spots* and eliminate the *bottlenecks* in them
  - ***Hot spot***: an area of code within the program that uses a disproportionately high amount of processor time
  - ***Bottleneck***: an area of code within the program that uses processor resources inefficiently and therefore causes unnecessary delays
- Understand *what*, *where*, and *how* time is being spent

Sequential Performance

- Sequential performance is all about:
  - How time is distributed
  - What resources are used where and when
- “Sequential” factors
  - Computation
    - choosing the right algorithm is important
    - compilers can help
  - Memory systems and cache and memory
    - more difficult to assess and determine effects
    - modeling can help
  - Input / output

Parallel Performance

- Parallel performance is about sequential performance AND parallel interactions
  - Sequential performance is the performance within each thread of execution
  - “Parallel” factors lead to overheads
    - concurrency (threading, processes)
    - interprocess communication (message passing)
    - synchronization (both explicit and implicit)
  - Parallel interactions also lead to parallelism inefficiency
    - load imbalances

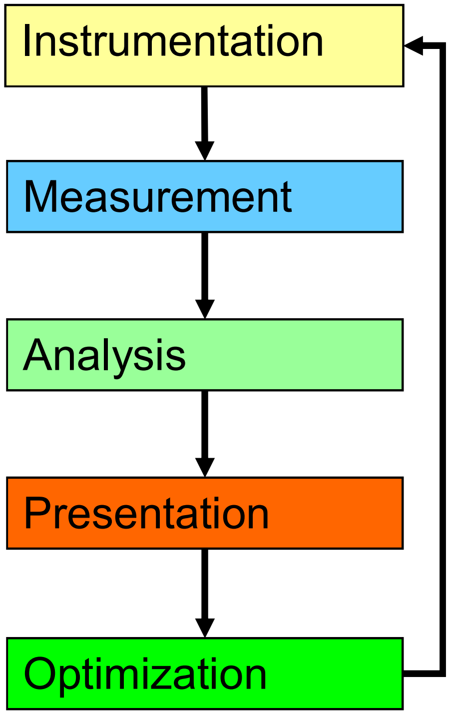
Sequential Performance Tuning

- Sequential performance tuning is a *time-driven* process
- Find the thing that takes the most time and make it take less time (i.e., make it more efficient)
- May lead to program restructuring
  - Changes in data storage and structure
  - Rearrangement of tasks and operations
- May look for opportunities for better resource utilization
  - Cache management is a big one
  - Locality, locality, locality!
  - Virtual memory management may also pay off
- May look for opportunities for better processor usage

Parallel Performance Tuning

- In contrast to sequential performance tuning, parallel performance tuning might be described as *conflict-driven* or *interaction-driven*
- Find the points of parallel interactions and determine the overheads associated with them
- Overheads can be the cost of performing the interactions
  - Transfer of data
  - Extra operations to implement coordination
- Overheads also include time spent waiting
  - Lack of work
  - Waiting for dependency to be satisfied

Performance Analysis and Optimization Cycle



Instrumentation

Measurement

Analysis

Presentation

Optimization

- Insertion of extra code (probes, hooks) into application
- Collection of data relevant to performance analysis
- Calculation of metrics, identification of performance problems
- Transformation of the results into a representation that can be easily understood by a human user
- Elimination of performance problems

Performance Observability

- Performance evaluation problems define the requirements for performance analysis methods
- Performance observability is the ability to “accurately” capture, analyze, and present (collectively observe) information about computer system/software performance
- Tools for performance observability must balance the need for performance data against the cost of obtaining it (environment complexity, performance intrusion)
  - Too little performance data makes analysis difficult
  - Too much data perturbs the measured system
- Important to understand performance observability complexity and develop technology to address it

Observation Types

- There are two types of performance observation that determine different measurement methods
    - Direct performance observation
    - Indirect performance observation
- *Direct performance observation* is based on a scientific theory of measurement that considers the cost (overhead) with respect to accuracy
- *Indirect performance observation* is based on a sampling theory of measurement that assumes some degree of statistical stationarity

Direct Performance Observation

- Execution actions exposed as events
    - In general, actions reflect some execution state
        - presence at a code location or change in data
        - occurrence in parallelism context (thread of execution)
    - Events encode actions for observation
- Observation is direct
    - Direct instrumentation of program code (*probes*)
    - Instrumentation invokes performance measurement
    - Event measurement = performance data + context
- Performance experiment
    - Actual events + performance measurements

Indirect Performance Observation

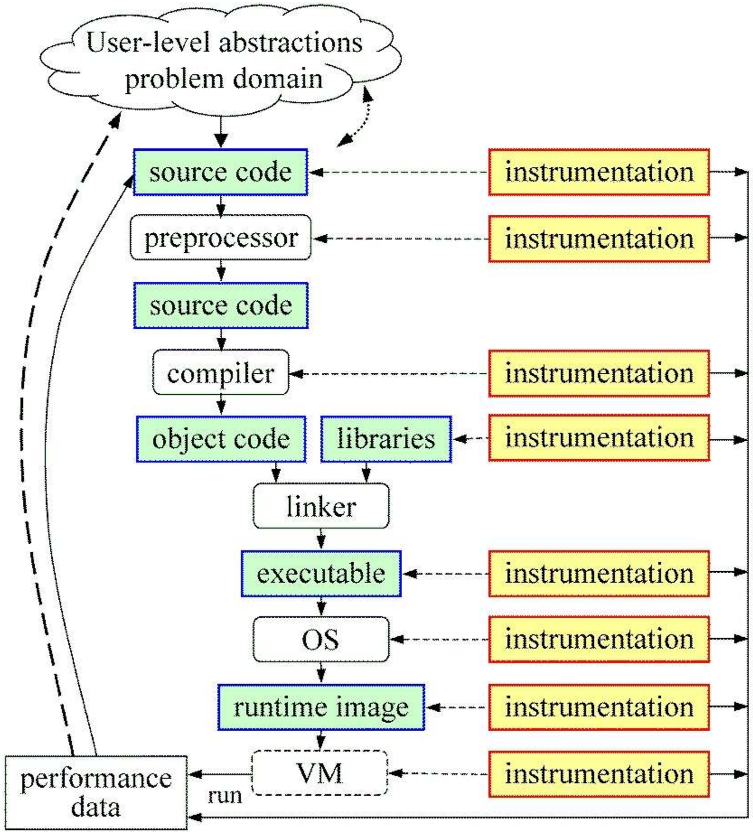
- Program code instrumentation is *not* used
- Performance is observed indirectly
  - Execution is interrupted
    - can be triggered by different events
  - Execution state is queried (sampled)
    - different performance data measured
  - *Event-based sampling* (EBS)
- Performance attribution is inferred
  - Determined by execution context (state)
  - Observation resolution determined by interrupt period
  - Performance data associated with context for period

Direct Observation: Events

- Event types
  - Interval events (begin/end events)
    - measures performance between begin and end
    - metrics monotonically increase
  - Atomic events
    - used to capture performance data state
- Code events
  - Routines, classes, templates
  - Statement-level blocks, loops
- User-defined events
  - Specified by the user
- Abstract mapping events

Direct Observation: Instrumentation

- Events defined by instrumentation access
- Instrumentation levels
  - Source code
  - Library code
  - Object code
  - Executable code
  - Runtime system
  - Operating system
- Levels provide different information / semantics
- Different tools needed for each level
- Often instrumentation on multiple levels required



Direct Observation: Techniques

- Static instrumentation
  - Program instrumented prior to execution
- Dynamic instrumentation
  - Program instrumented at runtime
- Manual and automatic mechanisms
- Tool required for automatic support
  - Source time: preprocessor, translator, compiler
  - Link time: wrapper library, preload
  - Execution time: binary rewrite, dynamic

Indirect Observation: Events/Triggers

- Events are actions external to program code
  - Timer countdown, hardware counter overflow, …
  - Consequence of program execution
  - Event frequency determined by:
    - type, setup, number enabled (exposed)
- Triggers used to invoke measurement tool
  - Traps when events occur (interrupt)
  - Associated with events
  - May add differentiation to events

Indirect Observation: Context

- When events trigger, execution context is determined at time of trap (interrupt)
  - Access to processor from interrupt frame
  - Access to information about process/thread
  - Possible access to call stack
    - requires call stack unwinder
- Assumption is that the context was the same during the preceding period
  - Between successive triggers
  - Statistical approximation valid for long running programs assuming repeated behavior

Direct / Indirect Observation Comparison

- Direct performance observation
  - ☺ Measures performance data exactly
  - ☺ Links performance data with application events
  - 😐 Requires instrumentation of code
  - ☹ Measurement overhead can cause execution intrusion and possibly performance perturbation
- Indirect performance observation
  - ☺ Argued to have less overhead and intrusion
  - ☺ Can observe finer granularity
  - ☺ No code modification required (may need symbols)
  - ☹ Inexact measurement and attribution

Performance Metrics and Measurement

- Observability depends on measurement
- A metric represents a type of measured data
  - *Count*: how often something occurred
    - calls to a routine, cache misses, messages sent, …
  - *Duration*: how long something took place
    - execution time of a routine, message communication time, …
  - Size: how big something is
    - message size, memory allocated, …
- A measurement records performance data
- Certain quantities can not be measured directly
  - *Derived metric*: calculated from metrics
    - flops per second, ...

Measurement Techniques

- When is measurement triggered?
  - External agent (indirect, asynchronous)
    - sampling via interrupts, hardware counter overflow, …
  - Internal agent (direct, synchronous)
    - through code modification (instrumentation)
- How are measurements made (data recorded)?
  - Profiling
    - summarizes performance data during execution
    - per process / thread and organized with respect to context
  - Tracing
    - trace record with performance data and timestamp
    - per process / thread

Critical Issues

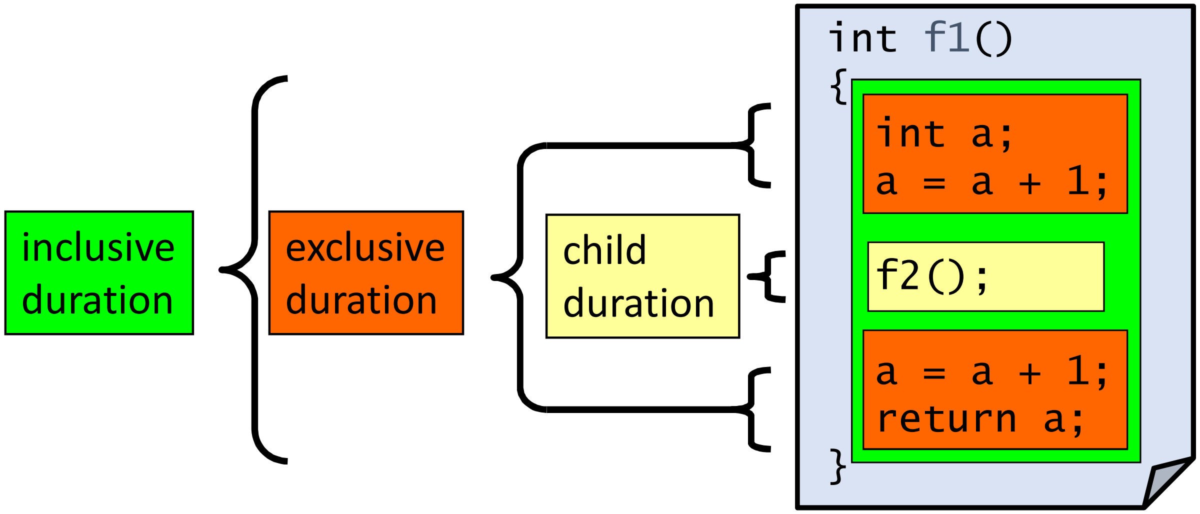
- Accuracy
  - Timing and counting accuracy depends on resolution
  - Any performance measurement generates *overhead*
    - execution on performance measurement code
  - Measurement overhead can lead to *intrusion*
  - Intrusion can cause *perturbation*
    - alters program behavior
- Granularity
  - How many measurements are made
  - How much overhead per measurement
- Tradeoff (general wisdom)
  - Accuracy is inversely correlated with granularity

Profiling

- Recording of aggregated information
  - Counts, time, …
- Aggregated statistics about program and system entities
  - Functions, loops, basic blocks, …
  - Processes, threads
- Methods
  - Event-based sampling (indirect, statistical)
  - Direct measurement (deterministic)
- Example: GNU gprof
  - https://sourceware.org/binutils/docs/gprof/
  - Tutorial: http://www.thegeekstuff.com/2012/08/gprof-tutorial/

Inclusive and Exclusive Profiles

- Performance with respect to code regions
- Exclusive measurements for region only
- Inclusive measurements includes child regions



inclusive duration

exclusive duration

child duration

```
int f1()
{
  int a;
  a = a + 1;

  f2();

  a = a + 1;
  return a;
}
```

Flat and Callpath Profiles

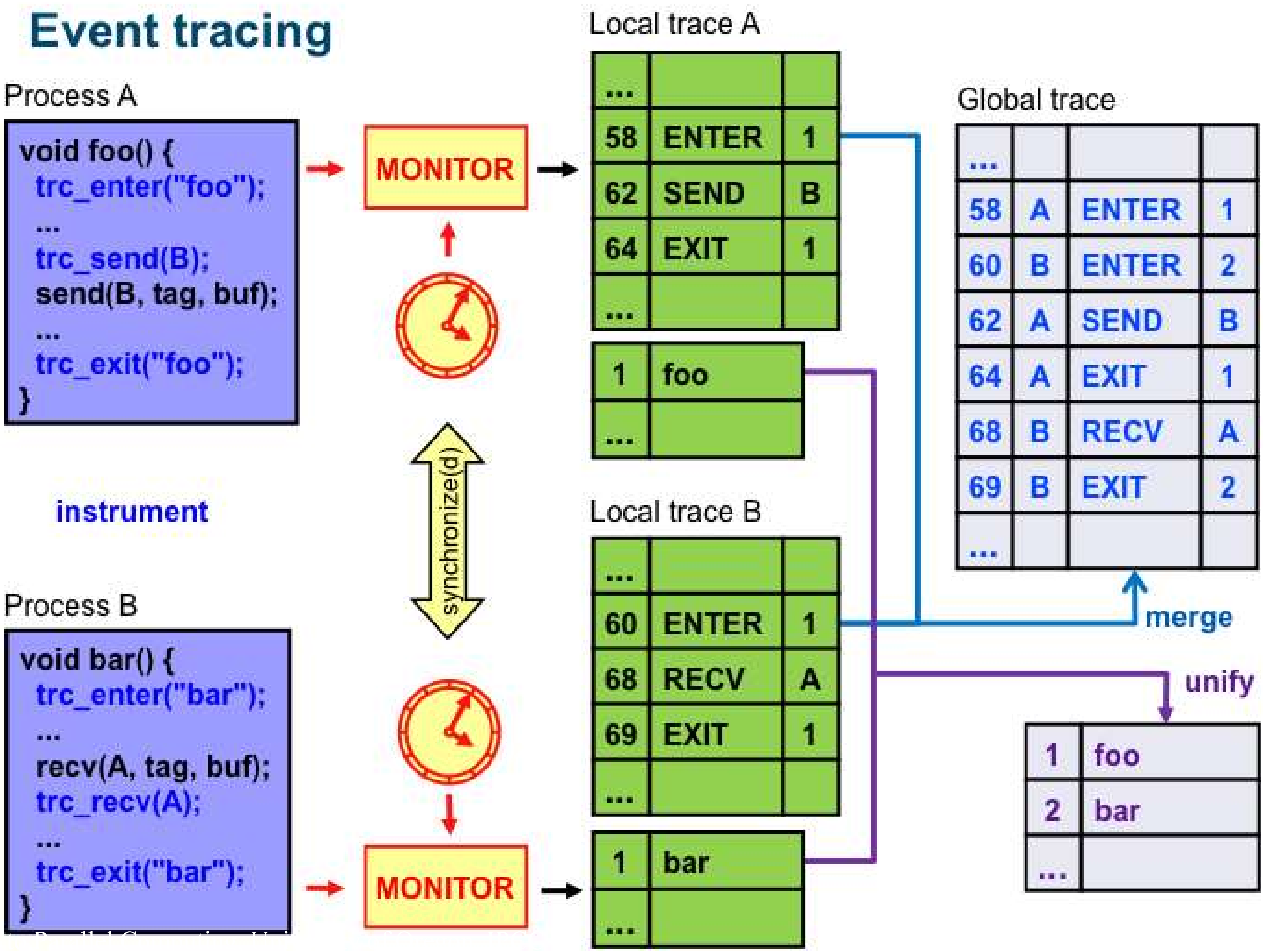
- Static call graph
  - Shows all parent-child calling relationships in a program
- Dynamic call graph
  - Reflects actual execution time calling relationships
- Flat profile
  - Performance metrics for when event is active
  - Exclusive and inclusive
- Callpath profile
  - Performance metrics for calling path (event chain)
  - Differentiate performance with respect to program execution state
  - Exclusive and inclusive

Tracing

- Recording information about significant points (events) during execution of the program
  - Enter/leave a code region (function, loop, …)
  - Send/receive a message ...
- Save information in *event record*
  - Timestamp, location ID, event type
  - Any event specific information
- An *event trace* is a stream of event records sorted by time
- Main advantage is that it can be used to reconstruct the dynamic behavior of the parallel execution
  - Abstract execution model on level of defined events

http://www.brendangregg.com/blog/2015-07-08/choosing-a-linux-tracer.html

Event Tracing



Event tracing

Process A

```
void foo() {
  trc_enter("foo");
  ...
  trc_send(B);
  send(B, tag, buf);
  ...
  trc_exit("foo");
}
```

Process B

```
void bar() {
  trc_enter("bar");
  ...
  recv(A, tag, buf);
  trc_recv(A);
  ...
  trc_exit("bar");
}
```

Local trace A

...		
58	ENTER	1
62	SEND	B
64	EXIT	1
...		

1	foo
...	

Local trace B

...		
60	ENTER	1
68	RECV	A
69	EXIT	1
...		

1	bar
...	

Global trace

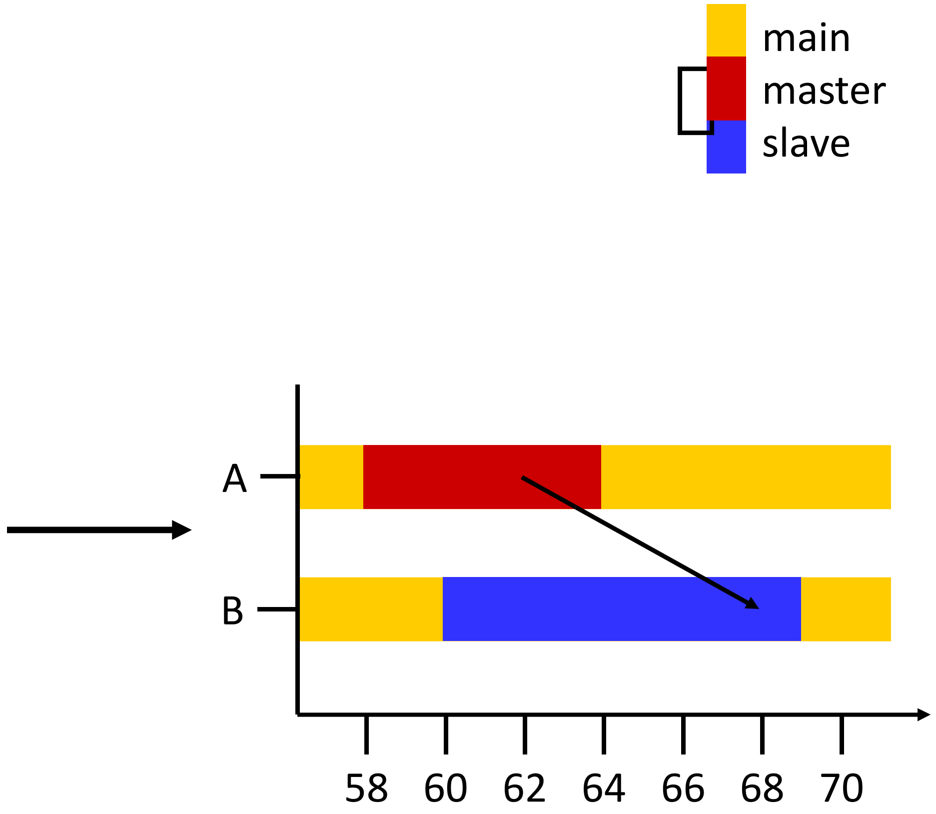
...			
58	A	ENTER	1
60	B	ENTER	2
62	A	SEND	B
64	A	EXIT	1
68	B	RECV	A
69	B	EXIT	2
...			

1	foo
2	bar
...	

Tracing: Time-line 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
...			



Trace File Formats

- There have been a variety of tracing formats developed over the years and supported in different tools
- Vampir
  - https://www.vampir.eu/
  - *VTF*: family of historical ASCII and binary formats
- MPICH / JumpShot
  - http://www.mcs.anl.gov/research/projects/perfvis/software/viewers/
  - *ALOG, CLOG, SLOG, SLOG-2*
- Scalasca
  - http://www.scalasca.org/
  - *EPILOG* (Jülich open-source trace format)
- Paraver
  - http://www.bsc.es/computer-sciences/performance-tools/paraver
- TAU Performance System
  - http://www.cs.uoregon.edu/research/tau/home.php
- Convergence on *Open Trace Format (OTF)*
  - http://www.paratools.com/otf

Profiling / Tracing Comparison

- Profiling
  - ☺ Finite, bounded performance data size
  - ☺ Applicable to both direct and indirect methods
  - 😐 Loses time dimension (not entirely)
  - ☹ Lacks ability to fully describe process interaction
- Tracing
  - ☺ Temporal and spatial dimension to performance data
  - ☺ Capture parallel dynamics and process interaction
  - ☺ Can derive parallel profiles for any time region
  - 😐 Some inconsistencies with indirect methods
  - ☹ Unbounded performance data size (large)
  - ☹ Complex event buffering and clock synchronization

Performance Analysis and Visualization

- Gathering performance data is not enough
- Need to analyze the data to derive performance understanding
- Need to present the performance information in meaningful ways for investigation and insight
- Single-experiment performance analysis
  - Identifies performance behavior within an execution
- Multi-experiment performance analysis
  - Compares and correlates across different runs to expose key factors and relationships

Performance Technologies

- Timers
- Counters
- Instrumentation
  - Source level
  - Library wrapping (PMPI)
  - Compiler instrumentation
  - Binary (Dyninst, PEBIL, MAQAO)
  - Runtime Interfaces
- Program address resolution
- Stack Walking
- Heterogeneous (accelerator) timers and counters

Time

- How is time measured in a computer system?
- How do we derive time from a clock?
- What clock/time technologies are available to a measurement system?
- How are clocks synchronized in a parallel computer in order to provide a “global time” common between nodes?
- Different technologies are available
    - Issues of resolution and accuracy

Execution Time

- There are different types of time
- ***Wall-clock time***
  - Based on realtime clock (continuously running)
  - Includes time spent in all activities
- ***Virtual process time*** (aka *CPU time*)
  - Time when process is executing (CPU is active)
    - user time and system time
  - Does not include time when process is inherently waiting
- ***Parallel execution time***
  - Runs whenever *any* parallel part is executing
  - Need to define a global time basis

Timer: gettimeofday()

- UNIX function
- Returns wall-clock time in seconds and microseconds
- Actual resolution is hardware-dependent
- Base value is 00:00 UTC, January 1, 1970
- Some implementations also return the timezone

```c
#include <sys/time.h>

struct timeval tv;
double walltime;  /* seconds */

gettimeofday(&tv, NULL);
walltime = tv.tv_sec + tv.tv_usec * 1.0e-6;
```

Timer: clock_gettime()

- POSIX function
- For *clock_id* **CLOCK_REALTIME** it returns wall-clock time in seconds and nanoseconds
- More clocks may be implemented but are not standardized
- Actual resolution is hardware-dependent

```
#include <time.h>

struct timespec tv;
double walltime;  /* seconds */

Clock_gettime(CLOCK_REALTIME, &tv);
walltime = tv.tv_sec + tv.tv_nsec * 1.0e-9;
```

Timer: getrusage()

- UNIX function
- Provides a variety of different information
  - Including user time, system time, memory usage, page faults, and other *resource use* information
  - Information provided system-dependent!

```
#include <sys/resource.h>

struct rusage ru;
double usrtime;  /* seconds */
int memused;

getrusage(RUSAGE_SELF, &ru);
usrtime = ru.ru_utime.tv_sec +
          ru.ru_utime.tv_usec * 1.0e-6;
memused = ru.ru_maxrss;
```

Timer: MPI & OpenMP

- MPI provides portable MPI wall-clock timer

```
#include <mpi.h>
double walltime;   /* seconds */

walltime = MPI_Wtime();
```

  - Not required to be consistent/synchronized across ranks!
- OpenMP 2.0 also provides a library function

```
#include <omp.h>
double walltime;   /* seconds */

walltime = omp_get_wtime();
```

- Hybrid MPI/OpenMP programming?
  - Interactions between both standards (yet) undefined

Timer: Others

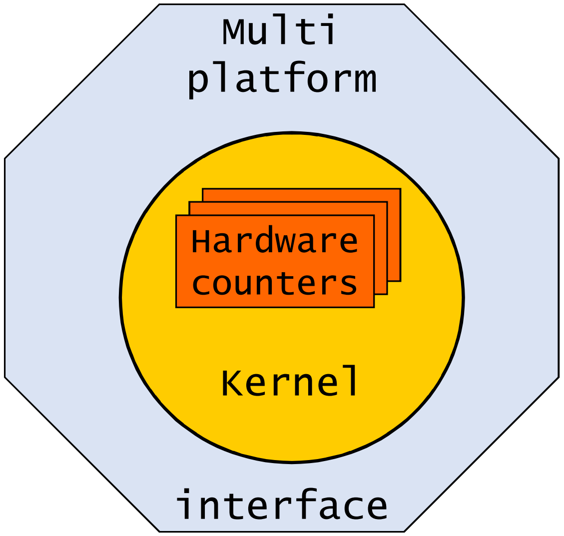
- Fortran 90 intrinsic subroutines
  - cpu_time()
  - system_clock()
- Hardware counter libraries typically provide “timers” because underlying them are cycle counters
  - Vendor APIs
    - PMAPI, HWPC, libhpm, libpfm, libperf, …
  - PAPI (Performance API)
    - http://icl.cs.utk.edu/papi/

What Are Performance Counters

- Extra processor logic inserted to count specific events
- Updated at every cycle (or when some event occurs)
- Strengths
  - Non-intrusive
  - Very accurate
  - Low overhead
- Weaknesses
  - Provides only hard counts
  - Specific for each processor
  - Access is not appropriate for the end user
    - nor is it well documented
  - Lack of standard on what is counted

Hardware Counters Interfaces

- Kernel level
  - Handling of overflows
  - Thread accumulation
  - Thread migration
  - State inheritance
  - Multiplexing
  - Overhead
  - Atomicity
- Multi-platform interfaces
  - Performance API (*PAPI*)
    - University of Tennessee, USA
    - http://icl.cs.utk.edu/papi/
  - Lightweight Performance Tools (*LIKWID*)
    - University of Erlangen, Germany
    - https://github.com/RRZE-HPC/likwid



Hardware Measurement

Typical measured events account for:

- Functional units status
  - float point operations
  - fixed point operations
  - load/stores
- Access to memory hierarchy
- Cache coherence protocol events
- Cycles and instructions counts
- Speculative execution information
  - instructions dispatched
  - branches mispredicted

Hardware Metrics

Typical hardware counter	**Useful derived metrics**
Cycles / Instructions	IPC
Floating point instructions	FLOPS
Integer instructions	computation intensity
Load/stores	instructions per load/store
Cache misses	load/stores per cache miss
Cache misses	cache hit rate
Cache misses	loads per load miss
TLB misses	loads per TLB miss

- Derived metrics allow users to correlate the behavior of the application to hardware components
- Define threshold values acceptable for metrics and take actions regarding optimization when below/above thresholds

Hardware Counters Access on Linux

- perf
  - Linux profiling with performance counters: https://perf.wiki.kernel.org/index.php/Main_Page
  - Available from Linux kernel 2.6.31
  - Comprised of performance counters subsystem in kernel and userspace utility
  - Can instrument CPU performance counters, tracepoints, kprobes, and uprobes (dynamic tracing)
  - Capable of statistical profiling of the entire system (both kernel and userland code)
- Intel Performance Counter Monitor
  - https://software.intel.com/en-us/articles/intel-performance-counter-monitor

PAPI – Performance API

- Middleware to provide a consistent and portable API for the performance counter hardware in microprocessors
- Countable events are defined in two ways:
  - Platform-neutral *preset* events
  - Platform-dependent *native* events
- Presets can be derived from multiple native events
- Two interfaces to the underlying counter hardware:
  - *High-level* interface simply provides the ability to start, stop and read the counters for a specified list of events
  - Low-level interface manages hardware events in user defined groups called *EventSets*
- Events can be multiplexed if counters are limited

http://icl.cs.utk.edu/papi/

PAPI High Level API

- Meant for application programmers wanting simple but accurate measurements
- Calls the lower level API
- Allows only PAPI preset events
- 10 functions:
    - *PAPI_accum_counters*
    - *PAPI_num_counters*
    - *PAPI_num_components*
    - *PAPI_start_counters, PAPI_stop_counters*
    - *PAPI_read_counters*
    - *PAPI_flips, PAPI_flops*
    - *PAPI_ipc, PAPI_epc*

http://icl.cs.utk.edu/papi/docs/db/d93/group__high__api.html

PAPI Low Level API

- Increased efficiency and functionality over the high level PAPI interface
- Access to native events
- Obtain information about the executable, the hardware, and memory
- Set options for multiplexing and overflow handling
- System V style sampling (profil())
- Thread safe

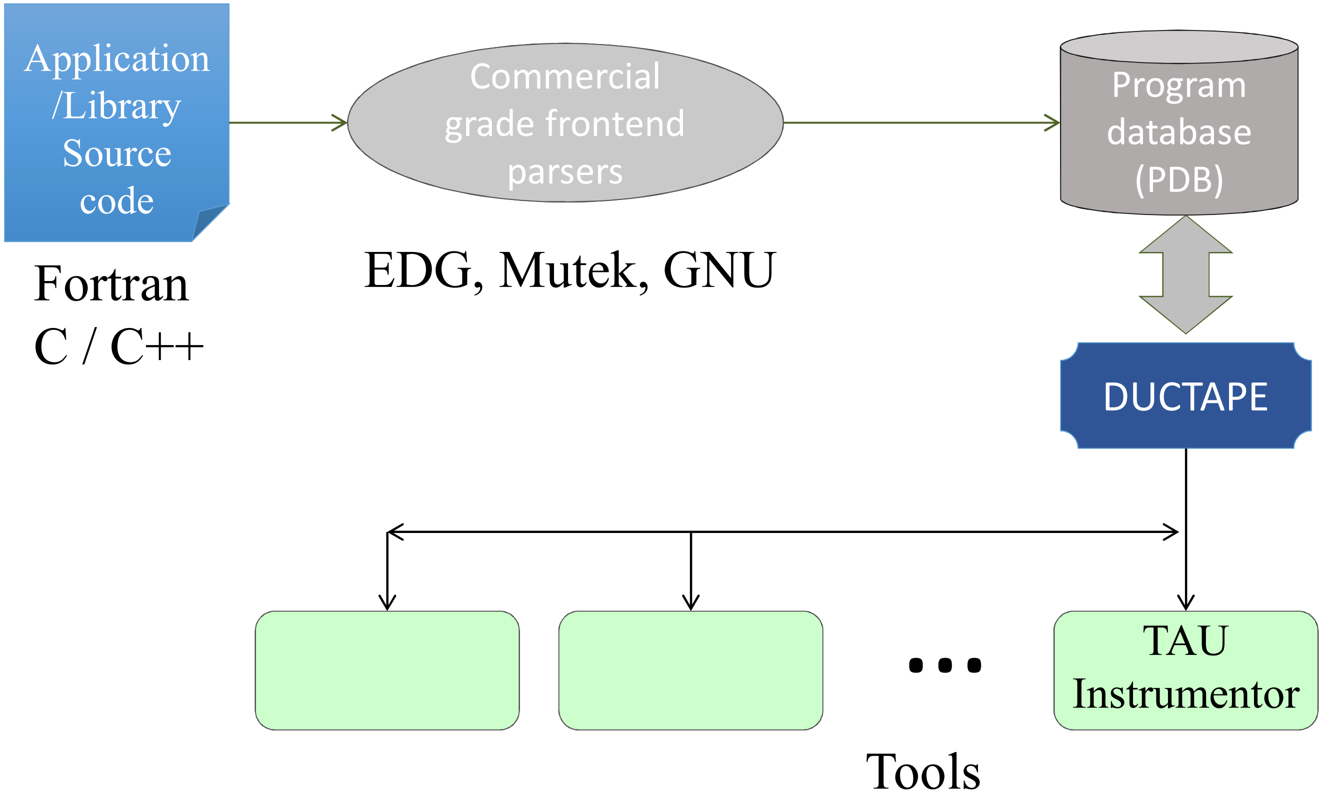
Source Instrumentation with Timers

- Measuring performance using *timers* requires instrumentation
  - Have to uniquely identify code region (name)
  - Have to add code for timer start and stop
  - Have to compute delta and accumulate statistics
- Hand-instrumentation becomes tedious very quickly, even for small software projects
- Also a requirement for enabling instrumentation only when wanted
  - Avoids unnecessary overheads when not needed

Program Database Toolkit (PDT)

- https://www.cs.uoregon.edu/research/pdt/home.php
- Used to automate instrumentation of C/C++, Fortran source code
- Source code parser(s) identify blocks such as function boundaries, loop boundaries, …
- Instrumentor uses parse results to insert API calls into source code files at block enter/exit, outputs an instrumented code file
- Instrumented source passed to compiler
- Linker links application with measurement library

PDT Architecture



Application /Library Source code

Fortran
C / C++

Commercial grade frontend parsers

EDG, Mutek, GNU

Program database (PDB)

DUCTAPE

…

TAU Instrumentor

Tools

PMPI – MPI Standard Profiling Interface

- The **MPI** (Message Passing Interface) standard defines a mechanism for instrumenting all API calls in an MPI implementation
- Each **MPI_*** function call is actually a *weakly defined* interface that can be re-defined by performance tools
- Each **MPI_*** function call eventually calls a corresponding **PMPI_*** function call which provides the expected MPI functionality
- Performance tools can redefine **MPI_*** calls

PMPI Example

- Original MPI_Send() definition:

```
int __attribute__((weak))
MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest,
         int tag, MPI_Comm comm) {
    PMPI_Send(buf, count, datatype, dest, tag, comm);
}
```

- *Possible* Performance tool definition:

```
int MPI_Send(void *buf, int count, MPI_Datatype datatype,
             int dest, int tag, MPI_Comm comm) {
    MYTOOL_Timer_Start(“MPI_Send”);
    PMPI_Send(buf, count, datatype, dest, tag, comm);
    MYTOOL_Timer_Stop(“MPI_Send”);
    MYTOOL_Message_Size(“MPI_Send”, count * sizeof(datatype));
}
```

Compiler Instrumentation

- Modern compilers provide the ability to instrument functions at compile time
- Can exclude files and/or functions
- GCC example:
  - Use the compiler option `-finstrument-functions`
  - Instrument function entry and exit

```
void __cyg_profile_func_enter (void *this_fn,
                               void *call_site);
void __cyg_profile_func_exit  (void *this_fn,
                               void *call_site);
```

Trace and profile function calls with GCC:
https://balau82.wordpress.com/2010/10/06/trace-and-profile-function-calls-with-gcc/

Compiler Instrumentation – Tool Interface

- Measurement libraries have to implement those two functions:

```
void __cyg_profile_func_enter (void *this_fn,
                               void *call_site);
void __cyg_profile_func_exit  (void *this_fn,
                               void *call_site);
```

- The function and call site pointers are instruction addresses
- How to resolve those addresses to source code locations?
  - Binutils: libbfd, libiberty

Binary Instrumentation

- Source Instrumentation not possible in all cases
  - Exotic / Domain Specific Languages (no parser support)
  - Pre-compiled system libraries
  - Utility libraries without source available
- Binary instrumentation modifies the existing executable and all libraries, adding user-specified function entry/exit API calls
- Can be done once, or as first step of execution

Binary Instrumentation Tools

- **Dyninst API**
  - http://www.dyninst.org/dyninst
  - Dynamic binary instrumentation for runtime code patching
- **PEBIL**
  - http://www.sdsc.edu/pmac/tools/pebil.html
  - Static binary instrumentation for x86/Linux
  - Lightweight binary instrumentation tool that can be used to capture information about the behavior of a running executable
- **MAQAO**
  - http://www.maqao.org/
  - Tool for analyzing and optimizing binary codes
  - Provides an API to insert user code at any point of the binary

Performance Tools

- Intel Vtune Amplifier
- Intel Trace Analyzer and Collector
- Open|SpeedShop: https://openspeedshop.org/
- HPCToolkit: http://hpctoolkit.org/
- Vampir: https://www.vampir.eu/
- Scalasca: http://www.scalasca.org/
- TAU: https://www.cs.uoregon.edu/research/tau/home.php
- Periscope Tuning Framework: http://periscope.in.tum.de/
- mpiP: http://mpip.sourceforge.net/
- Paraver: http://www.bsc.es/computer-sciences/performance-tools/paraver/
- PerfExpert: https://www.tacc.utexas.edu/research-development/tacc-projects/perfexpert

Intel Vtune Amplifier

- A commercial **Performance Profiler** for serial and multithreaded applications
  - GUI: **amplxe-gui**
  - CLI: **amplxe-cl**
- Use Vtune Amplifier to locate or determine the following:
  - The most time-consuming (*hot*) functions in your application and/or on the whole system
  - Sections of code that do not effectively utilize available processor time
  - The best sections of code to optimize for sequential performance and for threaded performance
  - Synchronization objects that affect the application performance
  - Whether, where, and why your application spends time on input/output operations
  - The performance impact of different synchronization methods, different numbers of threads, or different algorithms
  - Thread activity and transitions
  - Hardware-related issues in your code such as data sharing, cache misses, branch misprediction, and others
- Tutorials:

  https://software.intel.com/en-us/articles/intel-vtune-amplifier-tutorials

Intel Trace Analyzer and Collector

- Intel **Trace Analyzer and Collector** is a graphical tool for understanding MPI application behavior, quickly finding bottlenecks, improving correctness, and achieving high performance for parallel cluster applications.
- Trace Collector
  - intercepts all MPI calls and generates tracefiles (.*stf*)
  - can also trace non-MPI applications, like socket communication in distributed applications or serial programs
  - formerly known as Vampirtrace (VT)
- Trace Analyzer
  - GUI tool that analyzes the tracefiles (.*stf*): **traceanalyzer**
- Documentation:

  https://software.intel.com/en-us/articles/intel-trace-analyzer-and-collector-documentation

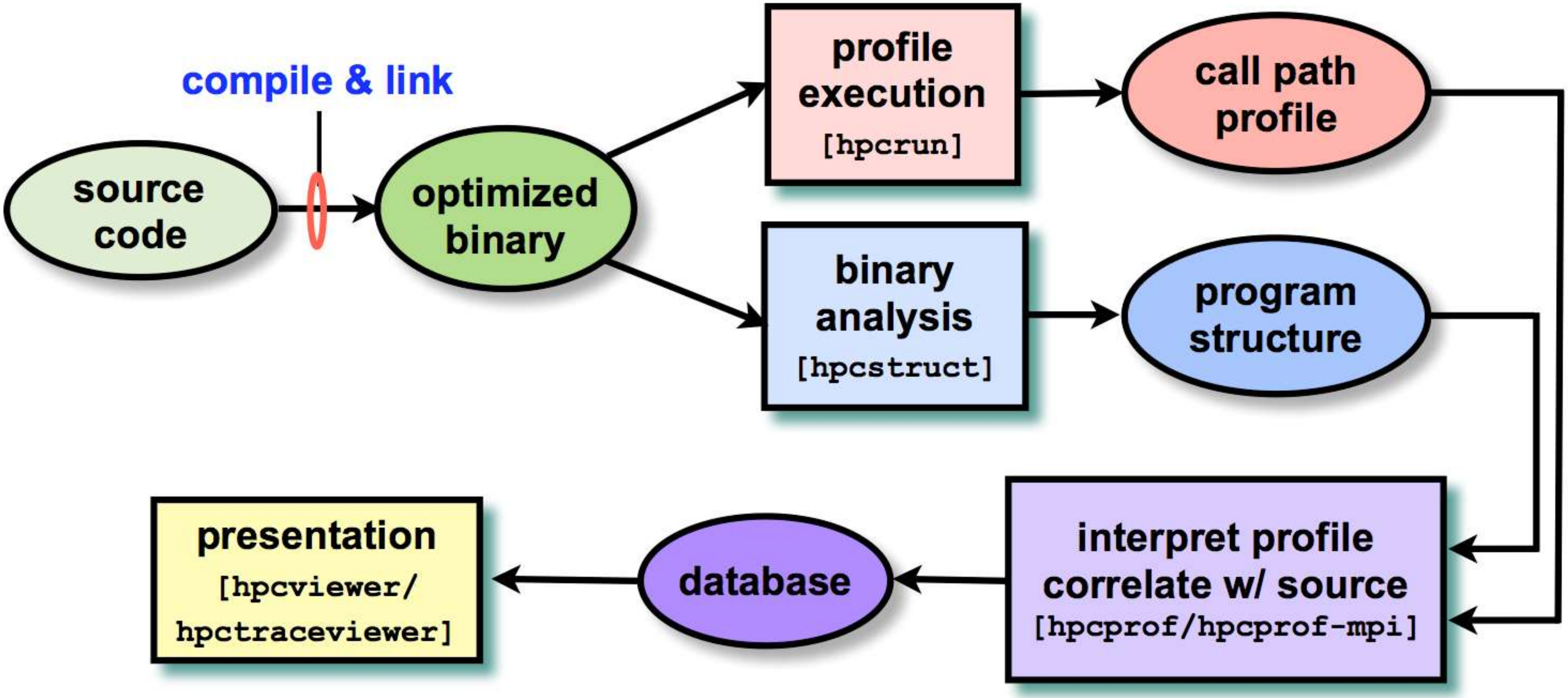
Open|SpeedShop

- https://openspeedshop.org/
- Base functionality include:
  - Program Counter Sampling
  - Support for Callstack Analysis
  - Hardware Performance Counter Sampling and Threshold based
  - MPI Lightweight Profiling and Tracing
  - I/O Lightweight Profiling and Tracing
  - Floating Point Exception Analysis
  - Memory Trace Analysis
  - POSIX Thread Trace Analysis
- Tutorials: https://openspeedshop.org/category/tutorials/

HPCToolkit

- http://hpctoolkit.org/
- Integrated suite of tools for measurement and analysis of program performance
- Uses statistical sampling of timers and hardware performance counters
- Works with multilingual, fully optimized applications that are statically or dynamically linked
- Supports measurement and analysis of serial codes, threaded codes (e.g., pthreads, OpenMP), MPI, and hybrid (MPI+threads) parallel codes
- Documentation: http://hpctoolkit.org/documentation.html

HPCToolkit Workflow



compile & link

source code

optimized binary

profile execution [hpcrun]

call path profile

binary analysis [hpcstruct]

program structure

interpret profile correlate w/ source [hpcprof/hpcprof-mpi]

database

presentation [hpcviewer/ hpctraceviewer]

Vampir

- https://www.vampir.eu/
- Mission: Visualization of dynamics of complex parallel processes
- Requires two components
  - Monitor/Collector (**Score-P**)
  - Charts/Browser (**Vampir**)
- Typical questions that Vampir helps to answer:
  - What happens in my application execution during a given time in a given process or thread?
  - How do the communication patterns of my application execute on a real system?
  - Are there any imbalances in computation, I/O or memory usage and how do they affect the parallel execution of my application?

https://www.alcf.anl.gov/files/Vampir.pdf

Scalasca

- http://www.scalasca.org/
- Scalable parallel performance analysis toolset
  - Focus on communication and synchronization
- Integrated performance analysis process
  - Callpath profiling
  - Event tracing
- Supported programming models
  - MPI-1, MPI-2 one-sided communication
  - OpenMP
  - Hybrid (MPI + OpenMP)
- Available for all major HPC platforms
- Documentation:
  http://www.scalasca.org/software/scalasca-2.x/documentation.html

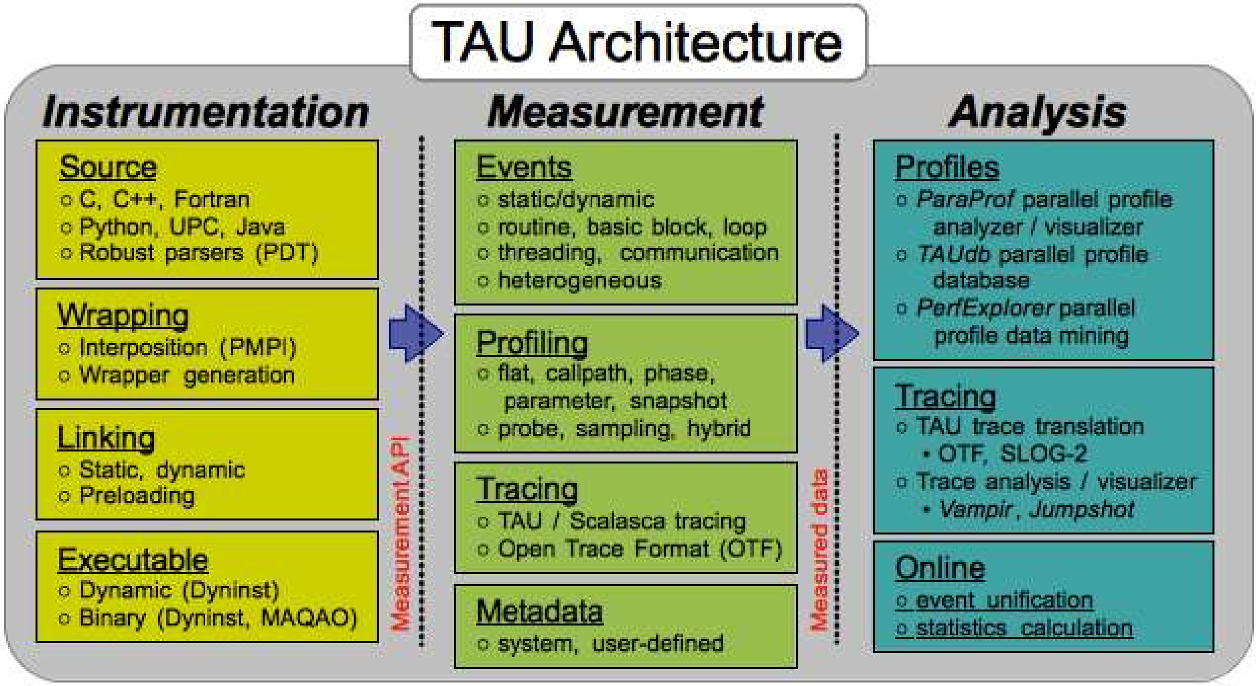
TAU Performance System

- https://www.cs.uoregon.edu/research/tau/home.php
- A portable profiling and tracing toolkit for performance analysis of parallel programs written in Fortran, C, C++, UPC, Java, Python
- Capable of gathering performance information through instrumentation of functions, methods, basic blocks, and statements as well as event-based sampling
- Tutorial: http://tau.uoregon.edu/tau.ppt
- Documentation: https://www.cs.uoregon.edu/research/tau/docs.php

TAU Architecture

- TAU is a parallel performance framework and toolkit
- Software architecture provides separation of concerns

  Instrumentation | Measurement | Analysis



TAU Architecture

Instrumentation

Source
- C, C++, Fortran
- Python, UPC, Java
- Robust parsers (PDT)

Wrapping
- Interposition (PMPI)
- Wrapper generation

Linking
- Static, dynamic
- Preloading

Executable
- Dynamic (Dyninst)
- Binary (Dyninst, MAQAO)

Measurement

Events
- static/dynamic
- routine, basic block, loop
- threading, communication
- heterogeneous

Profiling
- flat, callpath, phase, parameter, snapshot
- probe, sampling, hybrid

Tracing
- TAU / Scalasca tracing
- Open Trace Format (OTF)

Metadata
- system, user-defined

Analysis

Profiles
- *ParaProf* parallel profile analyzer / visualizer
- *TAUdb* parallel profile database
- *PerfExplorer* parallel profile data mining

Tracing
- TAU trace translation
  - OTF, SLOG-2
- Trace analysis / visualizer
  - *Vampir*, *Jumpshot*

Online
- event unification
- statistics calculation

TAU Components

- Instrumentation
  - Fortran, C, C++, OpenMP, Python, Java, UPC, Chapel
  - Source, compiler, library wrapping, binary rewriting
  - Automatic instrumentation
- Measurement
  - Internode: MPI, OpenSHMEM, ARMCI, PGAS, DMAPP
  - Intranode: Pthreads, OpenMP, hybrid, …
  - Heterogeneous: GPU, MIC, CUDA, OpenCL, OpenACC, …
  - Performance data (timing, counters) and metadata
  - Parallel profiling and tracing (with **Score-P** integration)
- Analysis
  - Parallel profile analysis and visualization (**ParaProf**)
  - Performance data mining / machine learning (**PerfExplorer**)
  - Performance database technology (**TAUdb**)
  - Empirical autotuning