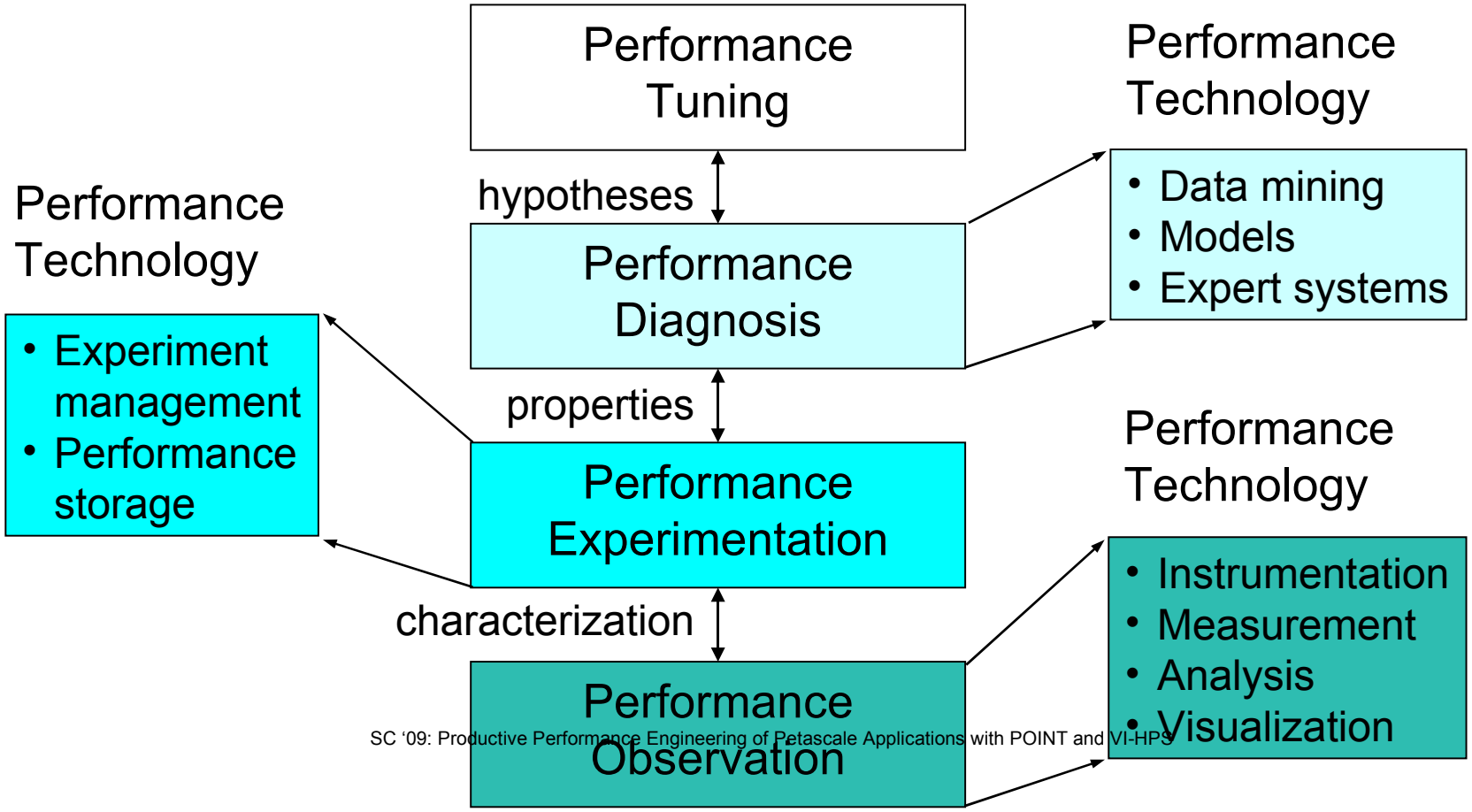
# INTRODUCTION TO PERFORMANCE ENGINEERING

Allen D. Malony
Performance Research Laboratory
University of Oregon

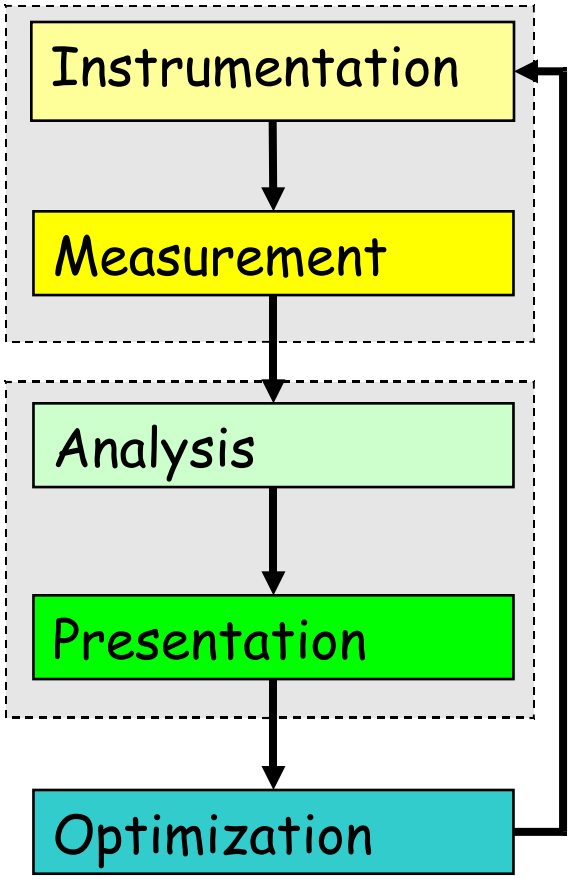
# Performance Engineering

- Optimization process
- Effective use of performance technology



# Performance Optimization Cycle

- Expose factors
- Collect performance data
- Calculate metrics
- Analyze results
- Visualize results
- Identify problems
- Tune performance



# Parallel Performance Properties

- Parallel code performance is influenced by both sequential and parallel factors?
- Sequential factors
  - Computation and memory use
  - Input / output
- Parallel factors
  - Thread / process interactions
  - Communication and synchronization

# Performance Observation

- Understanding performance requires observation of performance properties
- Performance tools and methodologies are primarily distinguished by what observations are made and how
  - What aspects of performance factors are seen
  - What performance data is obtained
- Tools and methods cover broad range

# Metrics and Measurement

- Observability depends on measurement
- A metric represents a type of measured data
  - Count, time, hardware counters
- A measurement records performance data
  - Associates with program execution aspects
- Derived metrics are computed
  - Rates (e.g., flops)
- Metrics / measurements decided by need

# Execution Time

- Wall-clock time
  - Based on realtime clock
- Virtual process time
  - Time when process is executing
    - ser time and system time
  - Does not include time when process is stalled
- Parallel execution time
  - Runs whenever any parallel part is executing
  - Global time basis

# 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

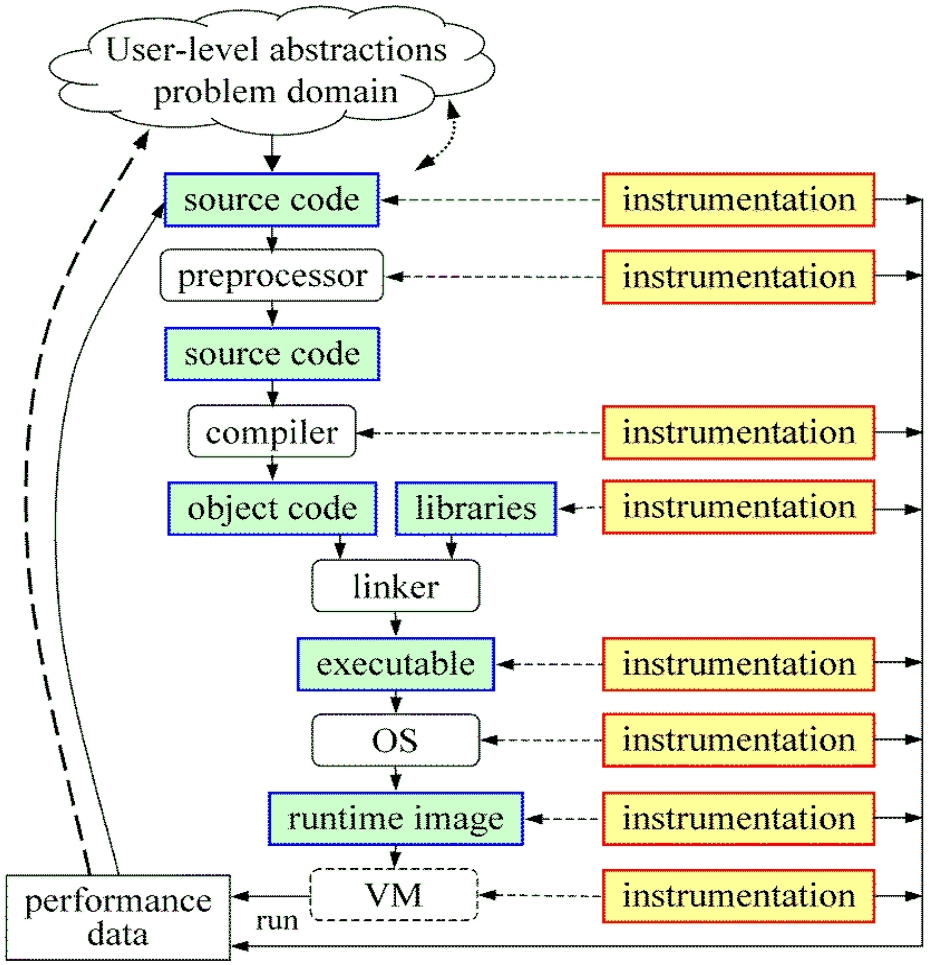
- Events defined by instrumentation access
- Instrumentation levels
  - Source code
  - Object code
  - Runtime system
  - Library code
  - Executable code
  - Operating system
- Different levels provide different information
- Different tools needed for each level
- Levels can have different granularity

# 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
- Advantages / disadvantages

# Direct Observation: Mapping

- Associate performance data with high-level semantic abstractions
- Abstract events at user-level provide semantic context



# Indirect Observation: Events/Triggers

- Events are actions external to program code
  - Timer countdown, HW 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 determined at time of trap (interrupt)
  - Access to PC 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

# Direct / Indirect 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

# Measurement Techniques

- When is measurement triggered?
  - External agent (indirect, asynchronous)
    - interrupts, hardware counter overflow, …
  - Internal agent (direct, synchronous)
    - through code modification
- How are measurements made?
  - 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

# Measured Performance

- Counts
- Durations
- Communication costs
- Synchronization costs
- Memory use
- Hardware counts
- System calls

# Critical issues

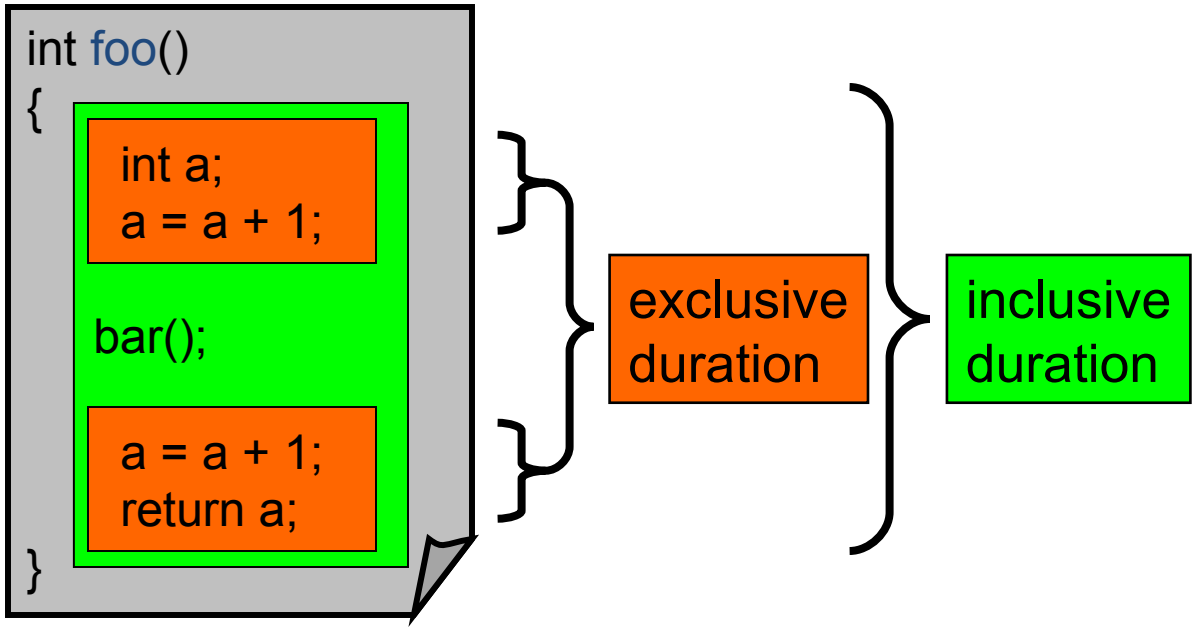
- Accuracy
  - Timing and counting accuracy depends on resolution
  - Any performance measurement generates overhead
    - Execution on performance measurement code
  - Measurement overhead can lead to intrusion
  - Intrusion can cause perturbation
    - alters program behavior
- Granularity
  - How 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, …
- … about program and system entities
  - Functions, loops, basic blocks, …
  - Processes, threads
- Methods
  - Event-based sampling (indirect, statistical)
  - Direct measurement (deterministic)

# Inclusive and Exclusive Profiles

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



# 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

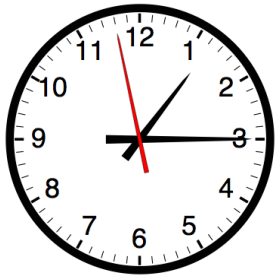
# Tracing Measurement

**Process A:**

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

**Process B:**

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



MONITOR

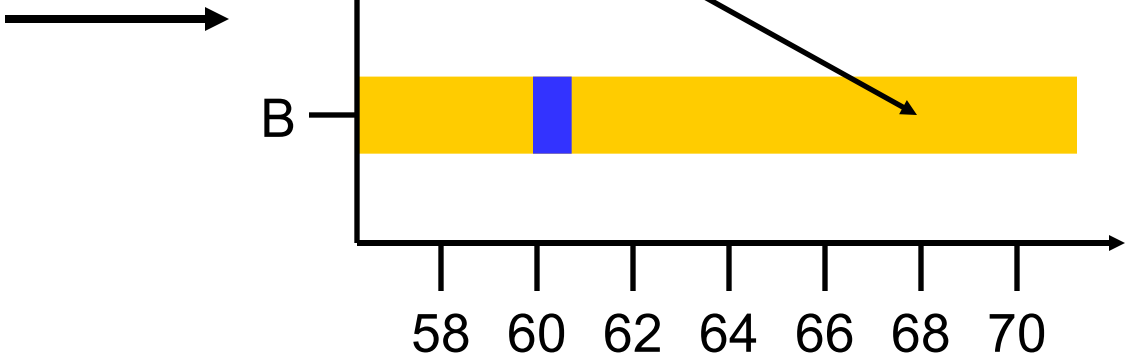
| | |
|---|---|
| 1 | master |
| 2 | worker |
| 3 | ... |

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

# Tracing Analysis and Visualization

| | |
|---|---|
| 1 | master |
| 2 | worker |
| 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 Formats

- Different tools produce different formats
  - Differ by event types supported
  - Differ by ASCII and binary representations
    - Vampir Trace Format (VTF)
    - KOJAK (EPILOG)
    - Jumpshot (SLOG-2)
    - Paraver
- Open Trace Format (OTF)
  - Supports interoperation between tracing tools

# 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
  - 😐 Some inconsistencies with indirect methods
  - ☹ Unbounded performance data size (large)
  - ☹ Complex event buffering and clock synchronization

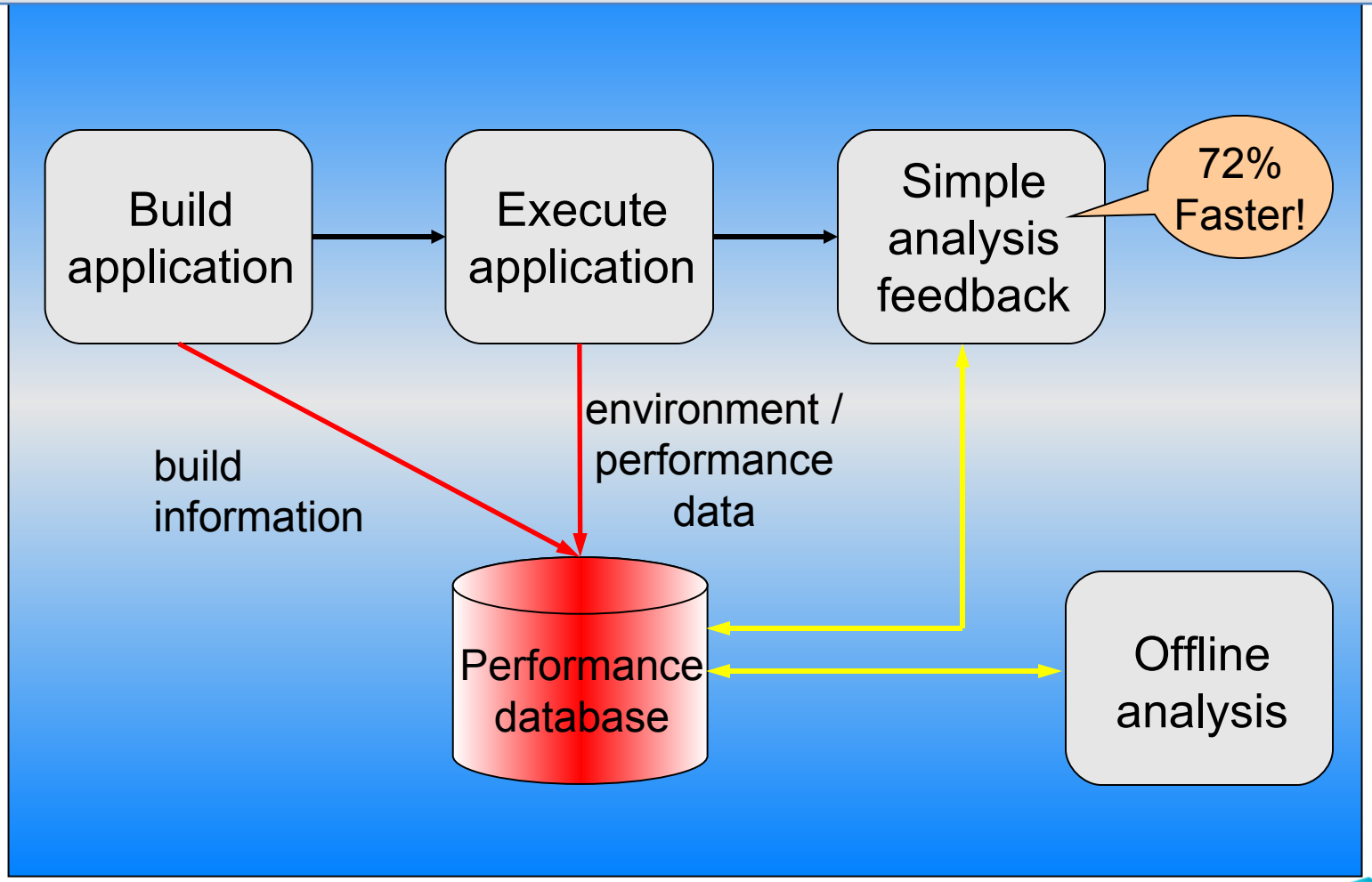
# Performance Problem Solving Goals

- Answer questions at multiple levels of interest
  - High-level performance data spanning dimensions
    - machine, applications, code revisions, data sets
    - examine broad performance trends
  - Data from low-level measurements
    - use to predict application performance
- Discover general correlations
  - performance and features of external environment
  - Identify primary performance factors
- Benchmarking analysis for application prediction
- Workload analysis for machine assessment

# Performance Analysis Questions

- How does performance vary with different compilers?
- Is poor performance correlated with certain OS features?
- Has a recent change caused unanticipated performance?
- How does performance vary with MPI variants?
- Why is one application version faster than another?
- What is the reason for the observed scaling behavior?
- Did two runs exhibit similar performance?
- How are performance data related to application events?
- Which machines will run my code the fastest and why?
- Which benchmarks predict my code performance best?

# Automatic Performance Analysis



# Performance Data Management

- Performance diagnosis and optimization involves multiple performance experiments
- Support for common performance data management tasks augments tool use
  - Performance experiment data and metadata storage
  - Performance database and query
- What type of performance data should be stored?
  - Parallel profiles or parallel traces
  - Storage size will dictate
  - Experiment metadata helps in meta analysis tasks
- Serves tool integration objectives

# Metadata Collection

- Integration of metadata with each parallel profile
  - Separate information from performance data
- Three ways to incorporate metadata
  - Measured hardware/system information
    - CPU speed, memory in GB, MPI node IDs, …
  - Application instrumentation (application-specific)
    - Application parameters, input data, domain decomposition
    - Capture arbitrary name/value pair and save with experiment
  - Data management tools can read additional metadata
    - Compiler flags, submission scripts, input files, …
    - Before or after execution
- Enhances analysis capabilities

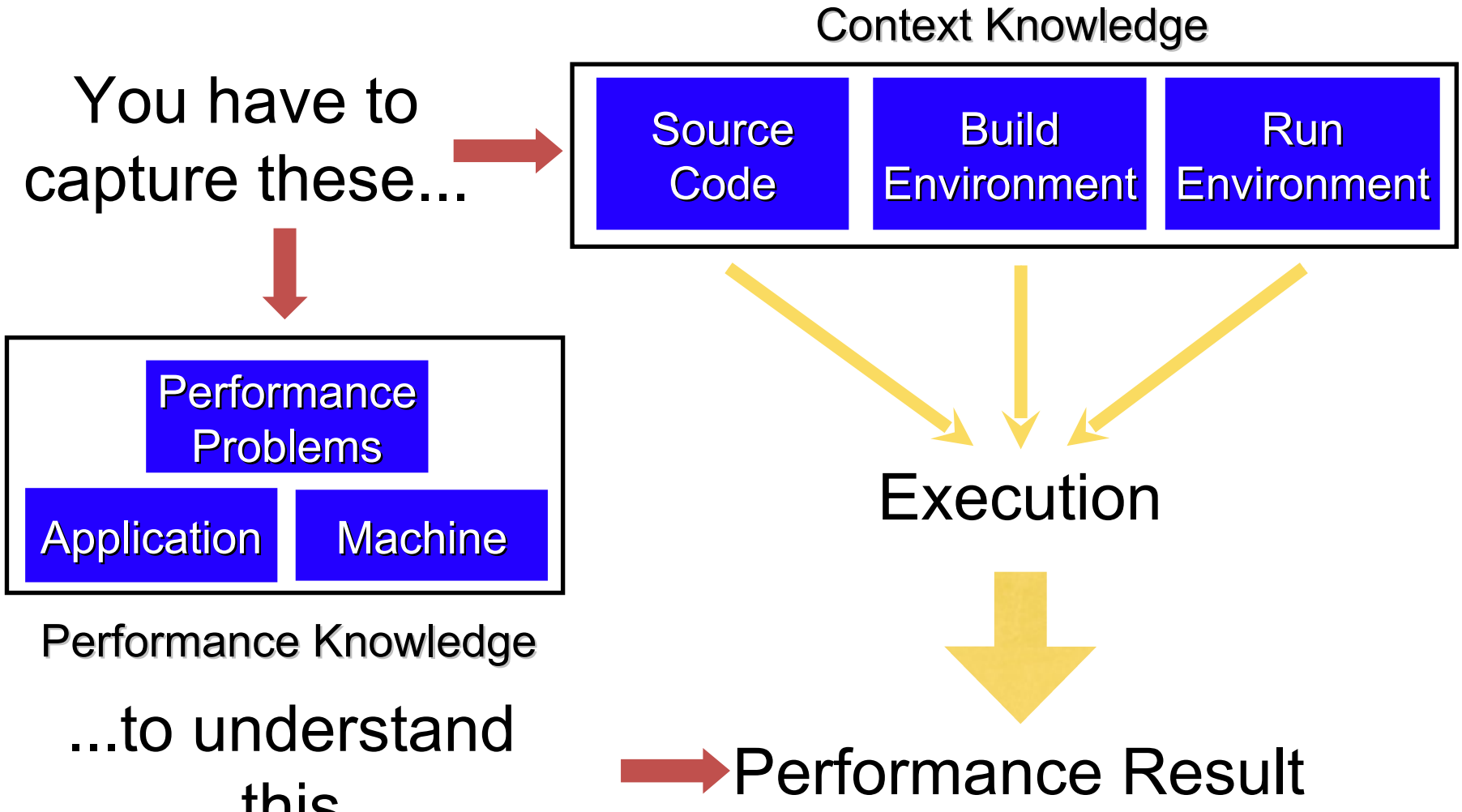
# Performance Data Mining

- Conduct parallel performance analysis in a systematic, collaborative and reusable manner
  - Manage performance complexity and automate process
  - Discover performance relationship and properties
  - Multi-experiment performance analysis
- Data mining applied to parallel performance data
  - Comparative, clustering, correlation, characterization, …
  - Large-scale performance data reduction
- Implement extensible analysis framework
  - Abstraction / automation of data mining operations
  - Interface to existing analysis and data mining tools

# How to explain performance?

- Should not just redescribe performance results
- Should explain performance phenomena
  - What are the causes for performance observed?
  - What are the factors and how do they interrelate?
  - Performance analytics, forensics, and decision support
- Add *knowledge* to do more intelligent things
  - Automated analysis needs good informed feedback
  - Performance model generation requires interpretation
- Performance knowledge discovery framework
  - Integrating meta-information
  - Knowledge-based performance problem solving

# Metadata and Knowledge Role



# Performance Optimization Process

- Performance characterization
  - Identify major performance contributors
  - Identify sources of performance inefficiency
  - Utilize timing and hardware measures
- Performance diagnosis (Performance Debugging)
  - Look for conditions of performance problems
  - Determine if conditions are met and their severity
  - What and where are the performance bottlenecks
- Performance tuning
  - Focus on dominant performance contributors
  - Eliminate main performance bottlenecks

# POINT Project

- "High-Productivity Performance Engineering (Tools, Methods, Training) for NSF HPC Applications"
  - NSF SDCI, Software Improvement and Support
  - University of Oregon, University of Tennessee, National Center for Supercomputing Applications, Pittsburgh Supercomputing Center
- POINT project
  - Petascale Productivity from Open, Integrated Tools
  - http://www.nic.uoregon.edu/point

# Motivation

- Promise of HPC through scalable scientific and engineering applications
- Performance optimization through effective performance engineering methods
  - Performance analysis / tuning “best practices”
- Productive petascale HPC will require
  - Robust parallel performance tools
  - Training good performance problem solvers

# Objectives

- Robust parallel performance environment
  - Uniformly available across NSF HPC platforms
- Promote performance engineering
  - Training in performance tools and methods
  - Leverage NSF TeraGrid EOT
- Work with petascale applications teams
- Community building

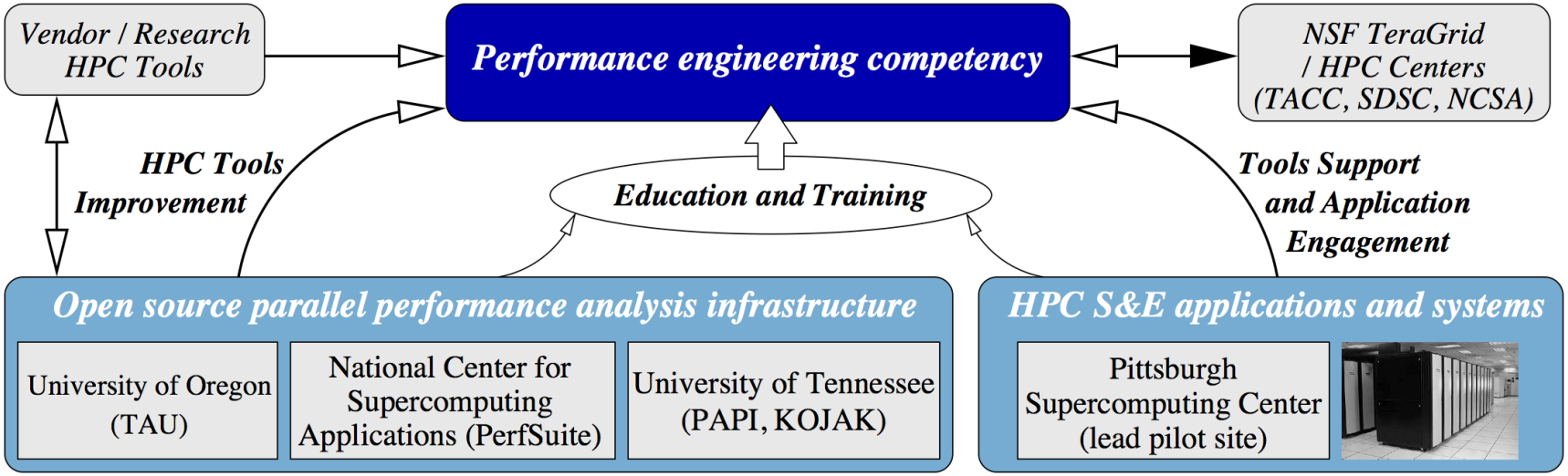
# Challenges

- Consistent performance tool environment
  - Tool integration, interoperation, and scalability
  - Uniform deployment across NSF HPC platforms
- Useful evaluation metrics and process
  - Make part of code development routine
  - Recording performance engineering history
- Develop performance engineering culture
  - Proceed beyond “hand holding” engagements

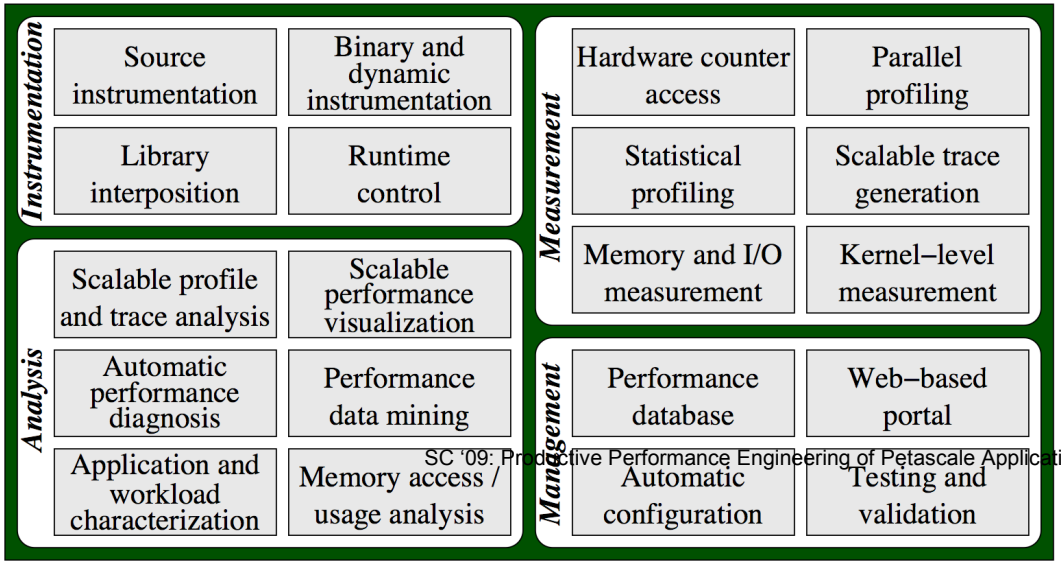
# Performance Engineering Levels

- Target different performance tool users
  - Different levels of expertise
  - Different performance problem solving needs
- Level 0 (entry)
  - Simpler tool use, limited performance data
- Level 1 (intermediate)
  - More tool sophistication, increased information
- Level 2 (advanced)
  - Access to powerful performance techniques

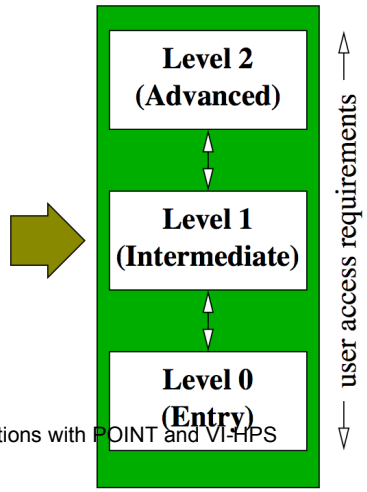
# POINT Project Organization




**Performance Technology Expertise**




**Performance Engineering Process**

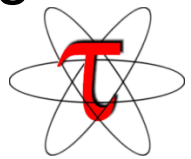



Testbed Apps
ENZO
NAMD
NEMO3D

# Parallel Performance Technology

- PAPI
  - University of Tennessee, Knoxville
- PerfSuite
  - National Center for Supercomputing Applications
- TAU Performance System
  - University of Oregon
- Kojak / Scalasca
  - Research Centre Juelich
- Vampir and VampirTrace
  - T.U. Dresden






# Parallel Engineering Training

- User engagement
- User support in TeraGrid
- Training workshops
- Quantify tool impact
- POINT lead pilot site
  - Pittsburgh Supercomputing Center
  - NSF TeraGrid site

# Testbed Applications

- ENZO
  - Adaptive mesh refinement (AMR), grid-based hybrid code (hydro+Nbody) designed to do simulations of cosmological structure formation
- NAMD
  - Mature community parallel molecular dynamics application deployed for research in large-scale biomolecular systems
- NEMO3D
  - Quantum mechanical based simulation tool created to provide quantitative predictions for nanometer-scale semiconductor devices