CIS 631
Parallel Processing

Lecture 4: Parallel Performance Analysis and Engineering

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Outline

- Review
- Parallel performance analysis problem
- Parallel performance analysis methodology
- Measurement and analysis techniques
- Performance engineering approach
Parallel Programming

- To use a scalable parallel computer, you must be able to write parallel programs
- You must understand the programming model and the programming languages, libraries, and systems software used to implement it
- Unfortunately, parallel programming is not easy
Parallel Programming: Are we having fun yet?

Source: Bernd Mohr
Parallel Programming Models

- Two general models of parallel program
  - Task parallel
    - Problem is broken down into tasks to be performed
    - Individual tasks are created and communicate to coordinate operations
  - Data parallel
    - Problem is viewed as operations of parallel data
    - Data distributed across processes and computed locally

- Characteristics of scalable parallel programs
  - Data domain decomposition to improve data locality
  - Communication and latency do not grow significantly
Shared Memory Parallel Programming

- Shared memory address space
- (Typically) easier to program
  - Implicit communication via (shared) data
  - Explicit synchronization to access data
- Programming methodology
  - Manual
    - Multi-threading using standard thread libraries
  - Automatic
    - Parallelizing compilers
    - OpenMP parallelism directives
  - Explicit threading (e.g. POSIX threads)
Parallel Programming Model: Threads

- Global style
- Shared and private data
- Work distribution onto threads for global operations
- Domain decomposition determines work distribution
Distributed Memory Parallel Programming

- Distributed memory address space
- (Relatively) harder to program
  - Explicit data distribution
  - Explicit communication via messages
  - Explicit synchronization via messages
- Programming methodology
  - Message passing
    - Plenty of libraries to chose from (MPI dominates)
    - Send-receive, one-sided, active messages
  - Data parallelism
  - Shared virtual memory
Paralle Programming Model: Message Passing

- Local style
- Domain decomposition leads to data distribution
- Explicit communication and synchronization
- Higher programming overhead
- Message passing libraries
Basic Parallel Programming Paradigm: SPMD

- SPMD: Single Program Multiple Data
- One program executes on all processors
- Basic paradigm for implementing parallel programs
- Process-dependent cases are handled inside the program

```c
if (processor == 42) then
    call do_something()
else
    call do_something_else()
endif
```

- Parallelism is “programmed in”
- Easier to manage program for scalability
Parallel Programming: Still a Problem?
Parallel Computing and Scalability

- Scalability in parallel architecture
  - Processor numbers
  - Memory architecture
  - Interconnection network
  - Avoid critical architecture bottlenecks
- Scalability in computational problem
  - Problem size
  - Computational algorithms
    - Computation to memory access ratio
    - Computation to communication ratio
- Parallel programming models and tools
- Performance scalability
Amdahl’s Law

- $T_{seq}$: sequential execution time that cannot be parallelized
- $T_{par}$: sequential execution time that can be parallelized
- $T_1 = T_{seq} + T_{par} \Rightarrow T_{par} = T_1 - T_{seq}$
- $T_p = T_{seq} + T_{par} / p$ (assume fully parallelized)
- As $p \to \infty$, $T_p \to T_{seq}$
- Let $f_{seq}$ be the fraction $T_{seq} / T_1$ and $S_p = T_1 / T_p$
- Speedup = $S_p = T_1 / T_p = T_1 / (T_{seq} + T_{par} / p)$
  $= 1 / (f_{seq} + T_{par} / pT_1) = 1 / (f_{seq} + (1-f_{seq})/ p)$
  - As $p \to \infty$, $S_p = S_\infty \to 1 / f_{seq}$
- Speedup bound is determined by the degree of sequential execution time in the computation, not # processors!!!
**Amdahl’s Law and Scaled Speedup**

- Amdahl’s Law makes it hard to obtain good speedup

  \[ f_{seq} \times 100\% \quad 10\% \quad 5\% \quad 2\% \quad 1\% \quad .1\% \]

  \[ S_{\infty} \quad 10 \quad 20 \quad 50 \quad 100 \quad 1000 \]

- Change perspective on the problem
- Consider scaling of problem size as \# processors scale
- \( T_{seq} \): sequential execution time (1 and \( p \) processors)
- \( T_{par} \): execution time in parallel mode on \( p \) processors

  \[ T_{p} = T_{seq} + T_{par}, \quad T_{1} = T_{seq} + pT_{par} \]

- Let \( f_{par} \) be the fraction \( T_{par} / T_{p} \)
- Scaled speedup \( = S_{p} = 1 + (p-1)T_{par} / T_{p} = 1 + (p-1)f_{par} \)
Parallel Performance

- To use a scalable parallel computer well, you must be able to write high-performance parallel programs.

- To get high-performance parallel programs, you must understand and optimize performance for the combination of programming model, algorithm, language, platform, …

- Unfortunately, parallel performance analysis and optimization is not an easy process.
Parallel Performance Evaluation

- Study of performance in parallel systems
  - Models and behaviors
  - Evaluative techniques
- Evaluation methodologies
  - Analytical modeling and statistical modeling
  - Simulation-based modeling
  - Empirical measurement, analysis, and modeling
- Purposes
  - Planning
  - Diagnosis
  - Tuning
Performance Observability (My Guiding Thesis)

- 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.
(Parallel) Performance Analysis Process

Implementation

Preparation

Performance Analysis

Program Tuning

Production

Measurement

Refinement

Analysis

Ranking

Production
Parallel Performance Analysis Environment

- **Parallel System**
- **Parallel Program**

**Stored Performance Knowledge**
- General performance results add to performance knowledge base

**Experimental Performance Data**
- Analysis, modeling, and presentation of empirical data

**Performance Hypothesis**
- Hypothesis refinement from empirical results

**Performance Observation**
- Constraints on observational capabilities, invocation of measurement tools

- System/program characteristics plus performance knowledge used for initial hypothesis

Lecture 4

CIS 631 - Parallel Processing
Performance Analysis and Tuning

- Successful parallel performance tuning process
  - Characterization: finding critical performance problems
  - Diagnosis: determining performance problem causes
  - Hypothesis testing: selection of performance optimization
  - Hypothesis validation: analyzing tuning results

- Reasoning and intuition only take you so far

- Need to make empirical observations
  - Performance instrumentation tools
  - Performance measurement tools
  - Performance analysis tools
Factors which determine a program's performance are complex, interrelated, and sometimes hidden.

Application related factors:
- Algorithms dataset sizes
- Memory usage patterns
- I/O communication patterns

Hardware related factors:
- Processor architecture
- Memory hierarchy

Software related factors:
- Operating system
- Compiler preprocessor
- Task Granularity
- Load Balancing
- Amdahl's Law
- I/O network
- Communication protocols
- Libraries
Utilization of Computational Resources

- Often resources are under-utilized or used inefficiently
- Identifying these circumstances can give clues to where performance problems exist
- Resources may be “virtual” (i.e., not a physical resource)
  - Thread or 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 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 versus Parallel Performance

- Sequential performance is all about how time is distributed and what resources are used where and when.
- Parallel performance is about sequential performance AND parallel interactions.
  - Sequential performance is the performance within each thread of execution (i.e., its sequential performance).
  - Parallel interactions lead to overheads:
    - synchronization
    - communication
  - 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 versus Sequential

- 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
Interesting Performance Phenomena

- Superlinear speedup
  - Speedup in parallel execution is greater than linear
  - $S_p > p$
  - How can this happen?

- Need to keep in mind the relationship of performance and resource usage

- Computation time (i.e., real work) is not simply a linear distribution to parallel threads of execution

- Resource utilization thresholds can lead to performance inflections
How Is Time Measured?

- How do we determine where the time goes?
- "A person with one clock knows what time it is, a person with two clocks is never sure."
  - Confucious
- "Define time."
  - Bill Clinton (attributed)
- Time is only as good (accurate) as the clock we use
- Clocks are not the same and, thus, time is not the same
  - Wallclock time – measured against “real” time
  - CPU (virtual) time – time accumulates (i.e., “ticks”) only when process is executing
  - Clocks have different resolutions and overheads for access
    - affects accuracy
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
    - user 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
  - Library code
  - Object code
  - Executable code
  - Runtime system
  - 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:
```c
void master {
    trace(EXIT, 1);
    ...
    trace(SEND, B);
    send(B, tag, buf);
    ...
    trace(EXIT, 1);
}
```

Process B:
```c
void worker {
    trace(EXIT, 2);
    ...
    recv(A, tag, buf);
    trace(RECV, A);
    ...
    trace(EXIT, 2);
}
```
Tracing Analysis and Visualization

```
<table>
<thead>
<tr>
<th></th>
<th>master</th>
<th>worker</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>master</td>
<td>worker</td>
</tr>
<tr>
<td>2</td>
<td>master</td>
<td>worker</td>
</tr>
<tr>
<td>3</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
```

```
... 
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

- Build application
- Execute application
- Simple analysis feedback
- Performance database
- Offline analysis
- 72% Faster!
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

You have to capture these...

Performance Problems
Application
Machine

Performance Knowledge

Context Knowledge
Source Code
Build Environment
Run Environment

Execution

...to understand this

Performance Result
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](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
POINT Project Organization

Vendor / Research HPC Tools

HPC Tools Improvement

Performance engineering competency

Education and Training

NSF TeraGrid / HPC Centers (TACC, SDSC, NCSA)

Tools Support and Application Engagement

Open source parallel performance analysis infrastructure

University of Oregon (TAU)

National Center for Supercomputing Applications (PerfSuite)

University of Tennessee (PAPI, KOJAK)

HPC S&E applications and systems

Pittsburgh Supercomputing Center (lead pilot site)

Performance Technology Expertise

Source instrumentation

Binary and dynamic instrumentation

Library interposition

Runtime control

Scalable profile and trace analysis

Scalable performance visualization

Automatic performance diagnosis

Performance data mining

Application and workload characterization

Memory access / usage analysis

Hardware counter access

Statistical profiling

Memory and I/O measurement

Kernel-level measurement

Performance database

Web-based portal

Automatic configuration

Testing and validation

Performance Engineering Process

Level 2 (Advanced)

Level 1 (Intermediate)

Level 0 (Entry)

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
Next Class

- Parallel performance tools
- TAU Performance System