Understanding Measurement Perturbation in Trace-Based Data

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Motivation

• Instrument code to understand system behavior
  – Profile basic blocks, methods
  – Trace hardware & software metrics
• Instrumentation can perturb the system’s behavior
• How does perturbation impact the ability to reason about system behavior?
Background

• NSF Grant “Understanding the Performance of Modern Systems”
  – Amer Diwan (U of Colorado Boulder)
  – Mike Mozer (U of Colorado Boulder)
  – Peter Sweeney (IBM Research)

• Vertical profiling
  – Trace-based data
  – Reason across software and hardware components

• General belief
  – Low overhead => low perturbation
    Overhead is instruction or cycle perturbation!
Methodology

• Reason about metrics
  – Statistical correlation computes trend between two metrics
    • e.g. L1 and L2 misses
  – Compare correlation score before and after instrumentation
Infrastructure

• Extended CIL to instrument C programs
• Two types of instrumentation
  – Low level: hardware metrics
    • E.g. Cache misses, instructions executed, cycles
  – High level: software metrics
    • E.g. method calls, update global variable
• Periodically collect metric values
  – Use settimer
  – 10 to 100’s millisecond intervals
  – reads counters and writes their values to disk
Reality Check

- sjeng (SPEC CPU2006)
- Multiple runs collecting same metrics
- Graph correlation of pairs of metrics within a trace
- Minimal perturbation across runs
Inner Perturbation

- Correlate pairs of metrics within a trace
- Compare *inner* correlation scores across traces
  - E.g. compare $\text{corr}(B.H1, B.H2)$ with $\text{corr}(R.H1, R.H2)$
- Observe how correlation changes as additional instrumentation is added
Significant Inner Perturbation

- sjeng (SPEC CPU2006)
- Multiple runs collecting different software metrics
- Graph inner correlation scores of hardware metrics as instrumentation is added
- Same metrics as “Reality Check”
- Significant inner perturbation
- Small increase in instructions executed < 3%
- But recovers

Trace B

Trace R

<table>
<thead>
<tr>
<th></th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

percent increase in executed instructions
Minimal Inner Perturbation

- bzip (SPEC CPU2006)
- Multiple runs collecting different software metrics
- Graph inner correlation scores of hardware metrics as instrumentation is added
- Minimal inner perturbation
- Inner perturbation is benchmark specific
Outer Perturbation

- Correlate same metric in baseline and in another trace
- Compare *outer* correlation scores across pairs of traces
  - E.g. compare $\text{corr}(B.H1, R1.H1)$ with $\text{corr}(B.H1, R2.H1)$
- Observe how correlation changes as additional instrumentation is added
- Assumes technique to align traces
  - We use DTW
Significant Outer Perturbation

- Sim-outorder with gcc as input
- Multiple runs collecting different software metrics
- Graph outer correlation of hardware metrics as instrumentation is added
- Significant outer perturbation
- But recovers

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**Trace R1**

- S1
- H3
- H2
- H1

**Trace B**

- S2
- H3
- H2
- H1

**Trace R2**

- S1
- H3
- H2
- H1

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![Graph showing outer correlation](graph.png)

- **PAPI_L1_DCM**
- **PAPI_BR_MSP**
- **PAPI_L2_TCM**
- **PAPI_TLB_DM**

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**percent increase in executed instructions**

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**outer correlation**

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Minimal Outer Perturbation

- bzip (SPEC CPU2006)
- Multiple runs collecting with different metrics
- Graph outer correlation of hardware metrics as instrumentation is added
- Minimal outer correlation
- Outer perturbation is benchmark specific
Conclusions

• Low overhead !=> low perturbation
  – Minimal instrumentation overhead can result in significant perturbation
    • Less than 3% increase in executed instructions prevented reasoning about metrics within or across traces

• Perturbation is application specific

• Perturbation is not monotonic
  – Additional instrumentation may increase or decrease perturbation!
  – Makes impact of instrumentation hard to predict

• This is a starting point for a more in depth study!
Related Work

• Perturbation measurement [Daigle et al.]
  – Operational definition of perturbation
    • Aggregate runtime slowdown as function of instrumentation

• Perturbation management [Maloney]*
  – Use perturbation model to eliminate perturbation effects from a trace
    • Only as good as model
      – Difficult to model out-of-order superscalar machines
    • Overall program run time
Questions

• How does perturbation impact our ability to reason about system behavior?
### Inner Perturbation Details

<table>
<thead>
<tr>
<th></th>
<th>Good</th>
<th>Perturbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1_DCM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2_TCM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td><em>not measured</em></td>
</tr>
</tbody>
</table>

- Each row different metric
- “Good” is trace before perturbation
- “Perturbed” is trace after perturbation
- “S” is the software metric collected in “Perturbed” but not in “Good”
How to Evaluate Perturbation?

- Any instrumentation perturbs system behavior
- Count number of times a metric occurs
  - Hardware: no charge
  - Software: cost to increment
- Baseline trace
  - Only collect hardware metrics
    - Cost is to periodically collect metrics
  - Expect minimal perturbation, but no guarantee
  - Expect relationship between metrics are preserved
IPC over time for SPECjvm98