B4M36ESW: Efficient software

Lecture 2: Benchmarking

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Benchmark

Wikipedia defines benchmark as:

1. the act of running a computer program, a set of programs, or other operations, in order to **assess the relative performance** of an **object**, normally by running a number of standard tests and trials against it.
2. a benchmarking program

Object examples:

- Hardware
- Compiler
- Algorithm
- ...

Types of benchmarks:

- Micro-benchmarks (synthetic)
- Application benchmarks

How to measure software performance?

- What to measure?
  - Execution time
  - Memory consumption
  - Energy

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- What to measure?
  - Execution time
  - Memory consumption
  - Energy
- How to measure?
  - Not as easy as it sounds
  - See the rest of the lecture

Measuring energy

- Connect power meter to your computer/board
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Intel RAPL (Running Average Power Limit)

- Allows to monitor and/or limit power consumption of individual components
- Package domain, memory domain (DRAM)
- Interface via MSRs
- See Intel Software Developer's Manual: System Programming Guide

Measuring memory consumption

- Program memory (code, static data, heap, stack)
  - Stack is allocated for each thread
- Operating system memory
  - Allocated by OS kernel on behalf of the program
  - network buffers, disk and file system caches, system objects (timers, semaphores, . . .)
- Shared libraries

Outline

Measuring execution time

Timestamping

- Use system calls
  - Linux: gettimeofday, clock_gettime(CLOCK_MONITONIC)
  - Overhead – hundreds of cycles
  - Optimization: Virtual syscall

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Timestamping

- Use system calls
  - Linux: gettimeofday, clock_gettime(CLOCK_MONITONIC)
  - Overhead – hundreds of cycles
  - Optimization: Virtual syscall
- Use hardware directly (timestamp counter)

```
static inline uint64_t rdtsc()
{
    uint64_t ret;
    asm volatile ( "rdtsc" : "=A"(ret) );
    return ret;
}
```

Measuring execution time

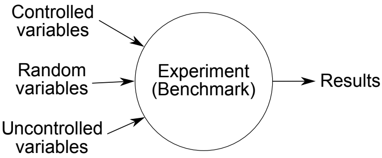
- Execution time exhibits variations
- Influenced by many factors
  - Hardware, input data, compiler, memory layout, measuring overhead, rest of the system, network load, ... you name it
  - Same factors can be controlled, others cannot
- Repeatability of measurements
- How to design benchmark experiments properly?
- How to measure *speedup*?

Example

The Challenge of Reasonable Repetition

- Variations
- Measurements must be repeated
- We want to eliminate the influence of random (non-deterministic) factors
- Statistics

Controlled variables (e.g. compiler flags, hardware, algorithm changes) – we are interested how they impact the results



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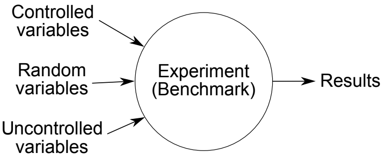

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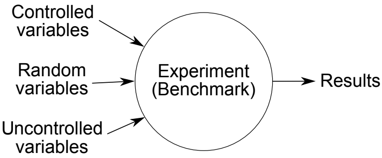
Uncontrolled variables – mostly fixed, but can cause bias of the results



Benchmark goal

- Estimate (a confidence interval for) the mean of execution time of a given benchmark on one or more platforms.
- The mean is the property of the probability distribution of the random execution times
- We can only estimate the mean value from the measurements
- Confidence interval is important
  - CI of 95% $\Rightarrow$ in 95% of cases, the true mean will be within the interval.

Levels of repetition

- Results variance occurs typically at multiple levels, e.g.:
  - (re)compilation
  - execution
  - iteration inside a program
- Sound benchmarking methodology should evaluate all the levels with random variations

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- Results variance occurs typically at multiple levels, e.g.:
  - (re)compilation
  - execution
  - iteration inside a program
- Sound benchmarking methodology should evaluate all the levels with random variations
- How many times to repeat the experiment at each level?
  - As little times as possible to not waste time
  - As many times as possible to get reasonable confidence in results
- How to summarize the results?

Summarizing benchmark results

- Significance testing
  - Is it likely that two systems have different performance?
  - This technique has significant problems, especially when used with results of computer benchmarks.
  - ministat tool (FreeBSD)

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  - ministat tool (FreeBSD)
- Visual tests
  - Do the two confidence intervals overlap?

```
+------------------------------------------------------------+
|                    +                                       |
|      x            ++                                      |
|      x  x         ++                                      |
|      xxxx         ++                        xx     x   ++  +|
||_______M_________A__________________|                      |
|            |______M__________A_________________|          |
+------------------------------------------------------------+
```

  ↑ ministat shows standard deviation, not confidence intervals!
  - No ⇒ different performance is likely
  - Yes ⇒ more statistics needed
  - Hard to estimate speedup and its confidence interval

Recommendation

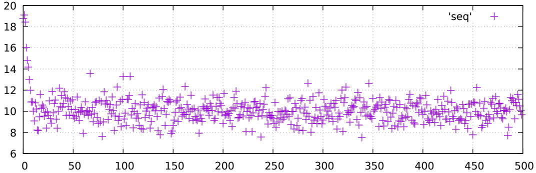
Analysis of results should be statistically rigorous and in particular should quantify any variation. Report performance changes with effect size confidence intervals.

Repeating iterations

- We are interested in *steady state performance*
- Initialization phase
  - First few iterations typically include the initialization overheads
  - Warming up caches, teaching branch predictor, memory allocations
- Independent state
  - Ideally, measurements should be *independent, identically distributed* (i.i.d.)
  - Independent: measurement does not depend on any a previous measurement
  - Independent $\Rightarrow$ initialized

When a benchmark reaches independent state?

- Manual inspection of graphs from measured data
  1. run-sequence plot ⇒ easy identification of initialization phase ⇒ strip



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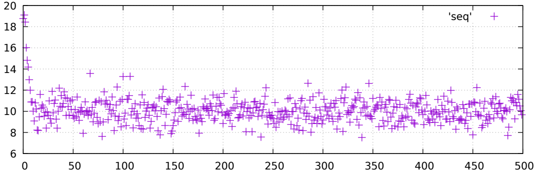
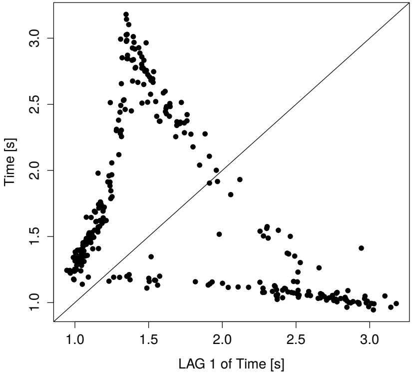
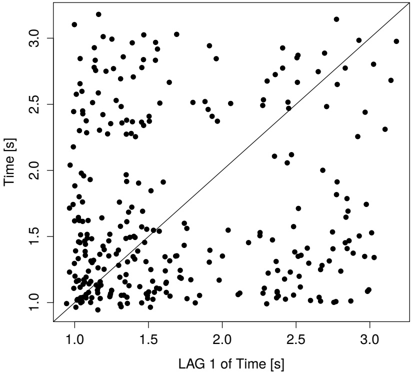


  2. Independence assessment – plot the following plots on original and randomly reordered sequence
     - lag plot (for several lags – e.g. 1–4)
     - auto-correlation function
  3. Any visible pattern suggests the measurements are not independent

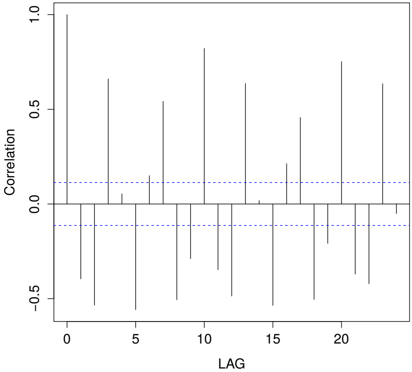
LAG

Dependency of a measured values on the previously measured value.

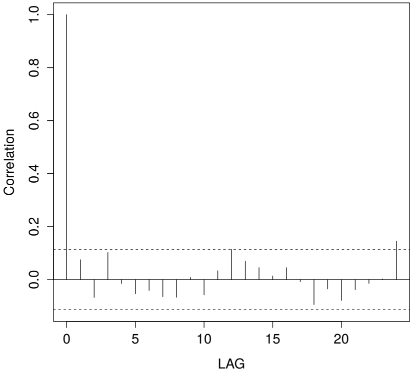




Auto-correlation function



dependent



independent

Recommendations

Use this manual procedure just once to find how many iterations each benchmark, VM and platform combination requires to reach an independent state.

If a benchmark does not reach an independent state in a reasonable time, take the same iteration from each run.

Repeating executions

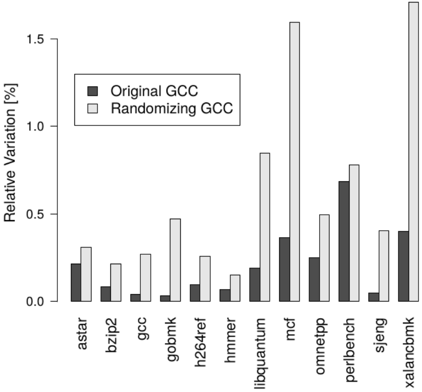
- What if different executions exhibit higher variance than iterations?

	bloat6	eclipse9	lusearch9	tradebeans9	tradesoap9	xalan6	xalan9
Iteration	14.1	0.8	3.3	1.5	0.8	7.0	3.5
Execution	3.7	0.4	30.3	0.4	0.4	9.1	1.0

- Determine initialized and independent state as before.

Repeating compilation

- Sometimes even a compiler can influences the benchmark results.
- Code layout generated by the compiler: original vs. randomized



- Why code layout makes a difference?
- If you cannot control the factor, make it random.

Multi-level repetition

- We have to repeat the experiments to narrow confidence interval
- If the variance occurs at higher levels (execution, compilation), we need to repeat at least at that level.
- Repeating at lower level may be cheaper (no execution overhead, compilation overhead, etc.)
  - Time can be saved by repeating at lower levels.
- How to find required number of repetitions at each level to reach given confidence interval?
- Can be formulated mathematically.

Notation

- Levels
  - Lowest level (iteration) $= 1$
  - Highest level (e.g. compilation) $= n$
- *Initial experiment*
  - bold letters
  - $\mathbf{r_1}, \mathbf{c_1}$
- *Real experiment*
  - normal letters
  - r_1, c_1

Initial experiment

Goal is to find the required number of iterations at each level.

- Select number of repetitions (exclusive of warm-up) $\mathbf{r_1}, \mathbf{r_2}, \ldots$ to be arbitrary but sufficient value, say 20.
- Gather the cost of repetition at each level (time added exclusively by that level, e.g. compile time)
  - $\mathbf{c_1}$ iteration duration
  - $\mathbf{c_2}$ time to gen an execution (time to independent state)
  - $\mathbf{c_3}$ compilation time
- Measurement times: $\mathbf{Y_{j_n \ldots j_1}}, \quad j_1 = 1 \ldots r_1,\ j_2 = 1 \ldots r_2,\ \ldots$
- Calculate arithmetic means for different levels:
  $\bar{\mathbf{Y}}_{j_n \bullet \cdots \bullet}$

Variance estimators

- After initial experiments, n unbiased variance estimators $\mathbf{T_1^2}, \ldots, \mathbf{T_n^2}$ is calculated
- They describe how much each level contributes independently to variability in the results.
- Start with calculating $\mathbf{S_i^2}$ – biased estimator of the variance at each level $i, 1 \leq i \leq n$:

$$\mathbf{S_i^2} = \frac{1}{\prod_{k=i+1}^{n} \mathbf{r_k}} \frac{1}{\mathbf{r_i} - 1} \sum_{j_n=1}^{r_n} \cdots \sum_{j_i=1}^{r_i} \left(\bar{\mathbf{Y}}_{j_n \ldots j_i \bullet \cdots \bullet} - \bar{\mathbf{Y}}_{j_n \ldots j_{i+1} \bullet \cdots \bullet} \right)^2$$

- Then obtain T_i^2:

$$\begin{aligned} T_1^2 &= \mathbf{S}_1^2 \\ \forall i, 1 < i \leq n, T_i^2 &= \mathbf{S}_i^2 - \frac{\mathbf{S}_{i-1}^2}{\mathbf{r_{i-1}}} \end{aligned}$$

- If $T_i^2 \leq 0$, this level induces little variation and repetitions can be skipped.

Real Experiment: Confidence Interval

- Optimum number of repetitions at different levels $r_1, \ldots, r_{n-1}$ can be calculated as:

$$\forall i, 1 \leq i < n, \quad r_i = \left\lceil \sqrt{\frac{c_{i+1}}{c_i} \frac{T_i^2}{T_{i+1}^2}} \right\rceil$$

- Then recalculate: S_n^2 and $\bar{Y}_{j_n \bullet \ldots \bullet}$ as before but with data from real experiment.
- Asymptotic confidence interval with confidence $(1 - \alpha)$ is:

$$\bar{Y} \pm t_{1-\frac{\alpha}{2},\nu} \sqrt{\frac{S_n^2}{r_n}}$$

where $t_{1-\frac{\alpha}{2},\nu}$ is $(1 - \frac{\alpha}{2})$-quantile of the t-distribution with $\nu = r_n - 1$ degrees of freedom.

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Recommendation

For each benchmark/VM/platform, conduct a dimensioning experiment to establish the optimal repetition counts for each but the top level of the real experiment. Re-dimension only if the benchmark/VM/platform changes.

Outline

Measuring speedup

- Speedup is a ratio of two execution times (random variables)
- What is the speedup confidence interval?
- How many times to repeat the speedup experiments?

Speedup confidence interval

- $\bar{Y}$ – old system execution time
- $\bar{Y}'$ – new system execution time
- Speedup: $\bar{Y}'/\bar{Y}$

$$\frac{\bar{Y}\cdot\bar{Y}' \pm \sqrt{(\bar{Y}\cdot\bar{Y}')^2 - (\bar{Y}^2 - h^2)(\bar{Y}'^2 - h'^2)}}{\bar{Y}^2 - h^2}$$

$$h = \sqrt{t^2_{\frac{\alpha}{2},\nu}\frac{S_n^2}{r_n}} \quad h' = \sqrt{t^2_{\frac{\alpha}{2},\nu}\frac{S_n'^2}{r_n}}$$

Repetition count

- Relation of confidence interval of the speedup to confidence interval on individual measurements:

$$\mathbf{e} \approx \frac{\bar{Y}'}{\bar{Y}} \sqrt{e^2 + e'^2}$$

- e, e' half-width of the old resp. new confidence interval

Recommendation

Always provide effect size confidence intervals for results. Either for single systems or for speedups.

References

- Kalibera, Tomas and Jones, Richard E. (2013) **Rigorous Benchmarking in Reasonable Time**. In: ACM SIGPLAN International Symposium on Memory Management (ISMM 2013), 20–12 June, 2013, Seattle, Washington, USA. http://kar.kent.ac.uk/33611/