CMPT 745
Software Engineering

Measurement & Performance

Nick Sumner
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Performance & Measurement

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  - Time
  - Memory
  - Open connections
  - VM instances
  - Energy consumption
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Data Structure A vs Data Structure B

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Data Structure A vs Data Structure B

How would you approach this in a data structures course?

Performance & Measurement

- Performance assessment is deceptively hard

[Demo/Exercise]

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    2) Clear evidence
    3) Correct reasoning from evidence to claims

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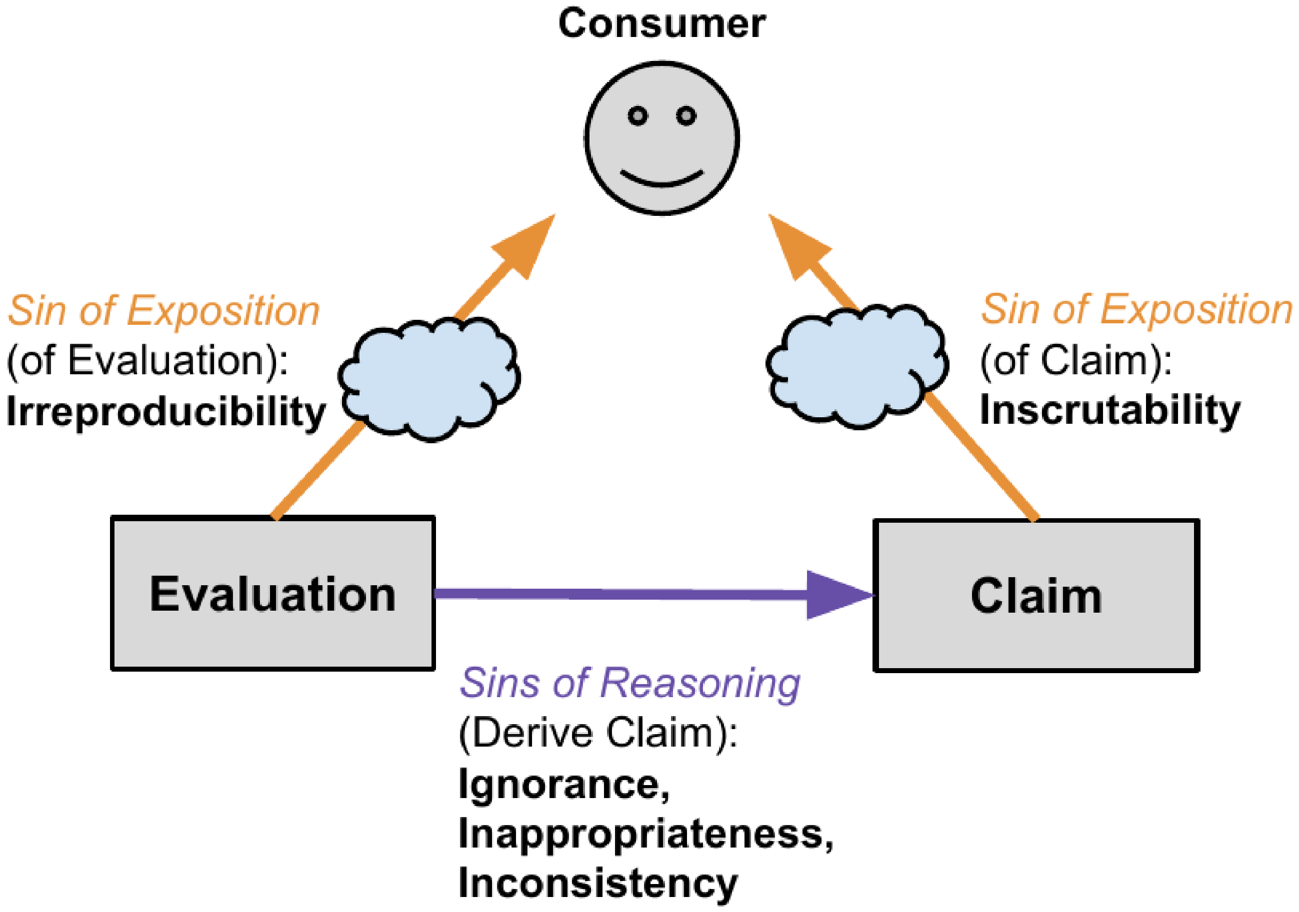
- Good performance evaluation should be rigorous & scientific
  - The same process applies in development as in ***good*** research
    1) Clear claims
    2) Clear evidence
    3) Correct reasoning from evidence to claims
  - And yet this is challenging to get right!

Performance & Measurement [Blackburn et al.]



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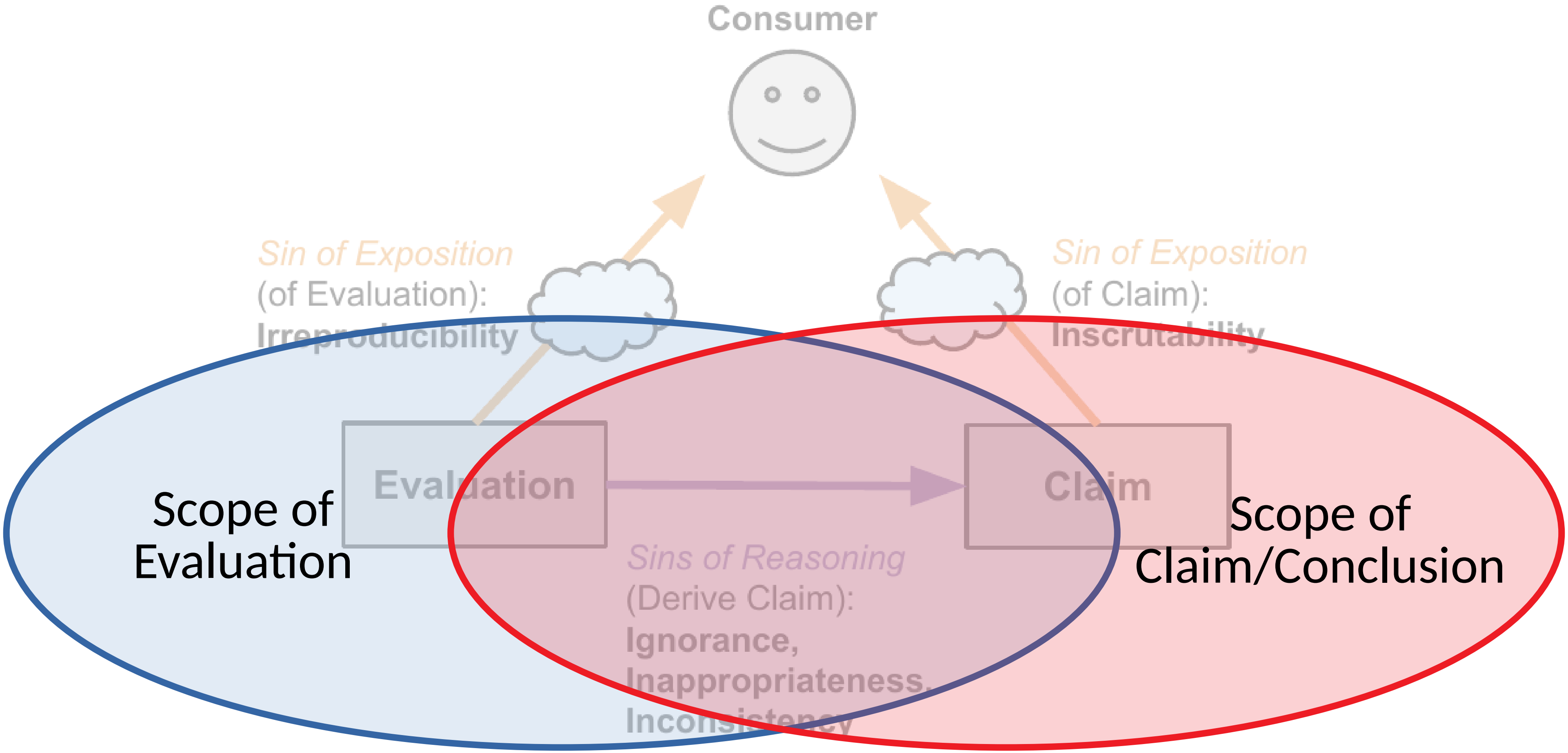

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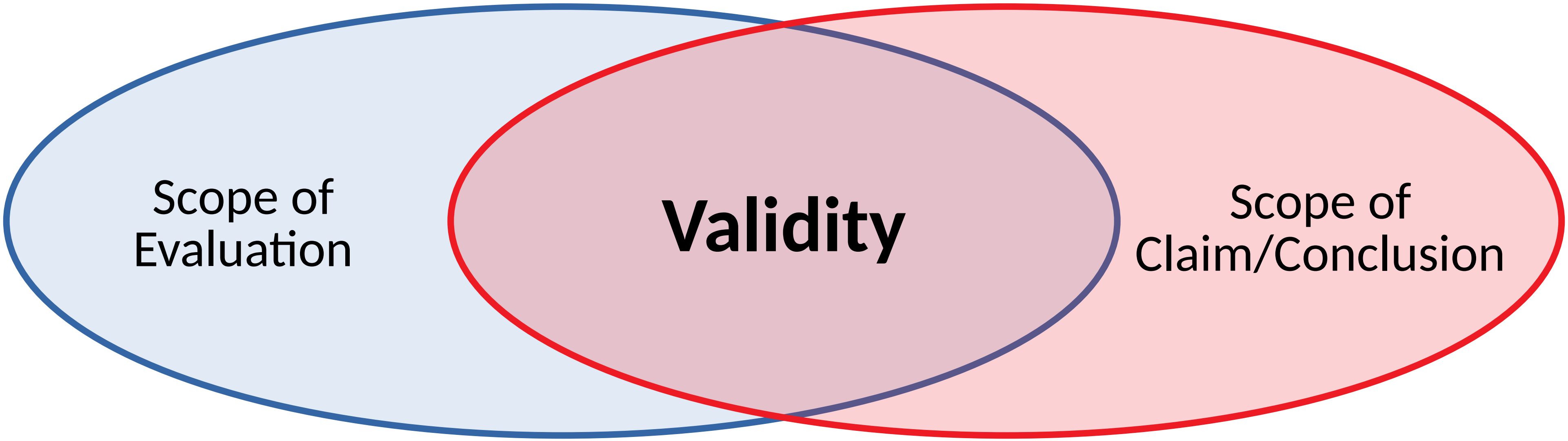

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    - Confidentiality & omission of data

Example …

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```
static int i = 0, j = 0, k = 0;
int main() {
  int g = 0, inc = 1;
  for (; g<65536; g++) {
    i += inc;
    j += inc;
    k += inc;
  }
  return 0;
}
```

Compare gcc -O2 vs -O3

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Both are right.

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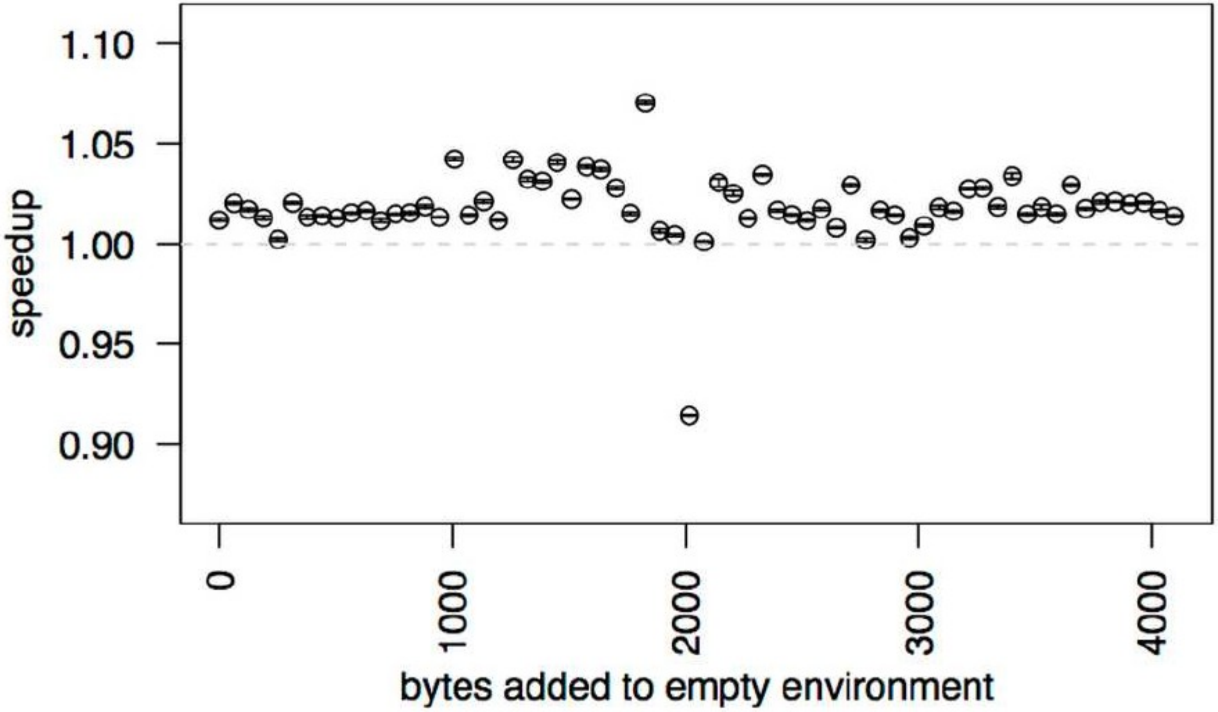

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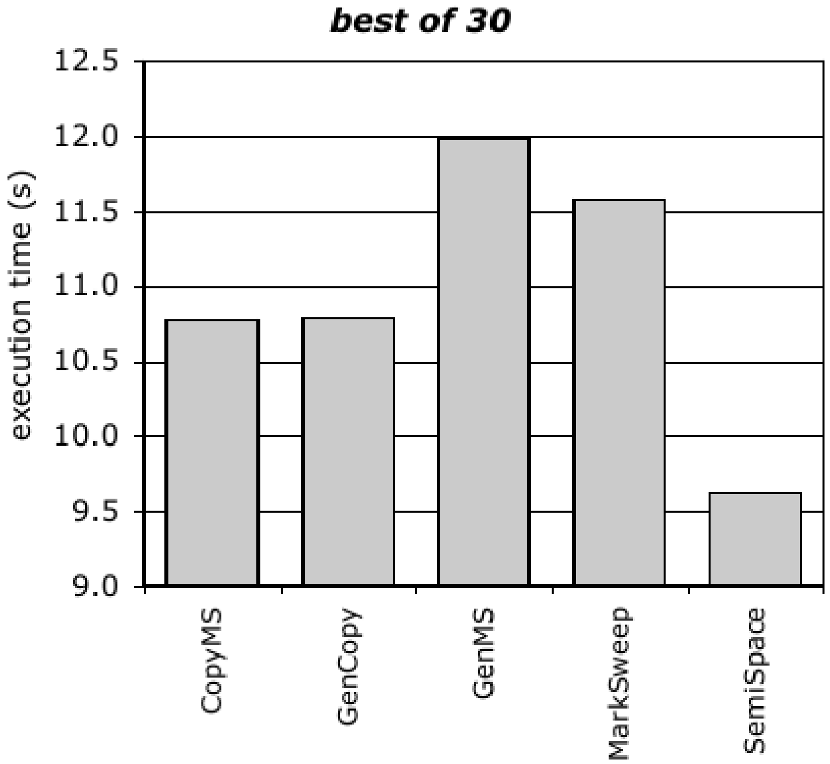

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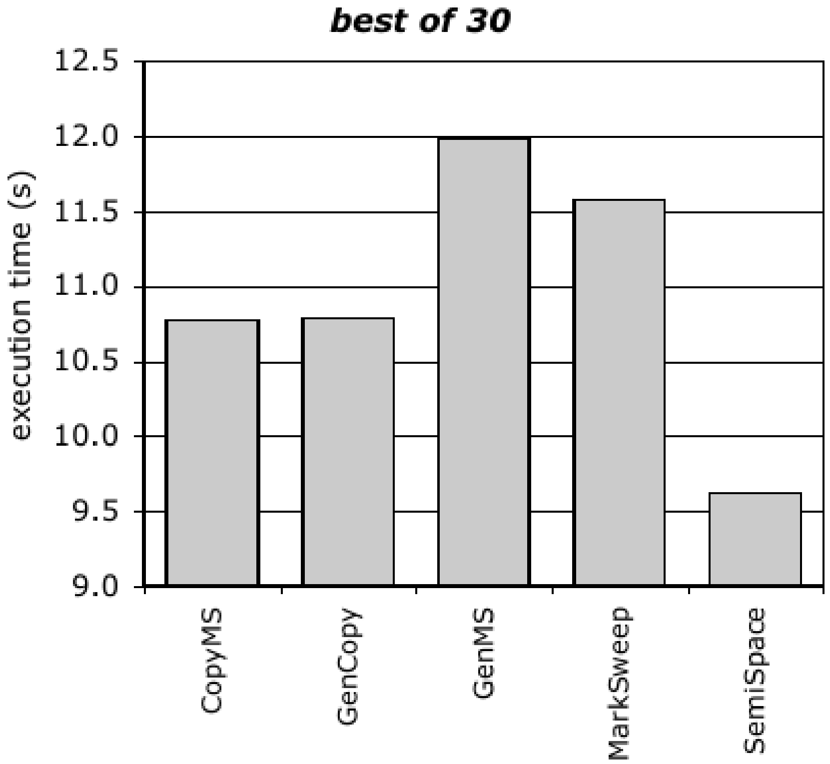

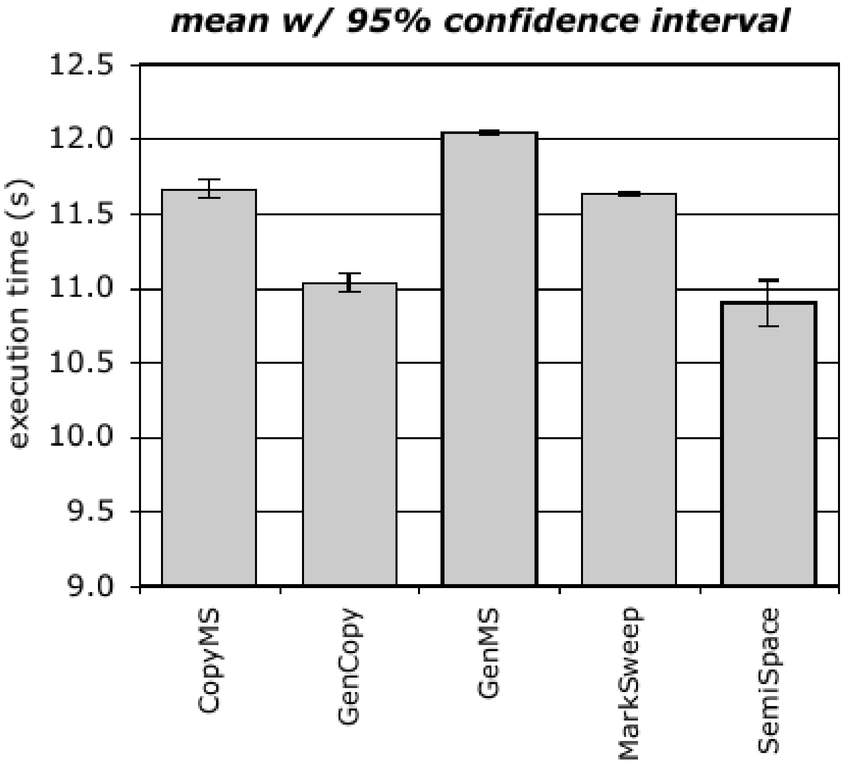

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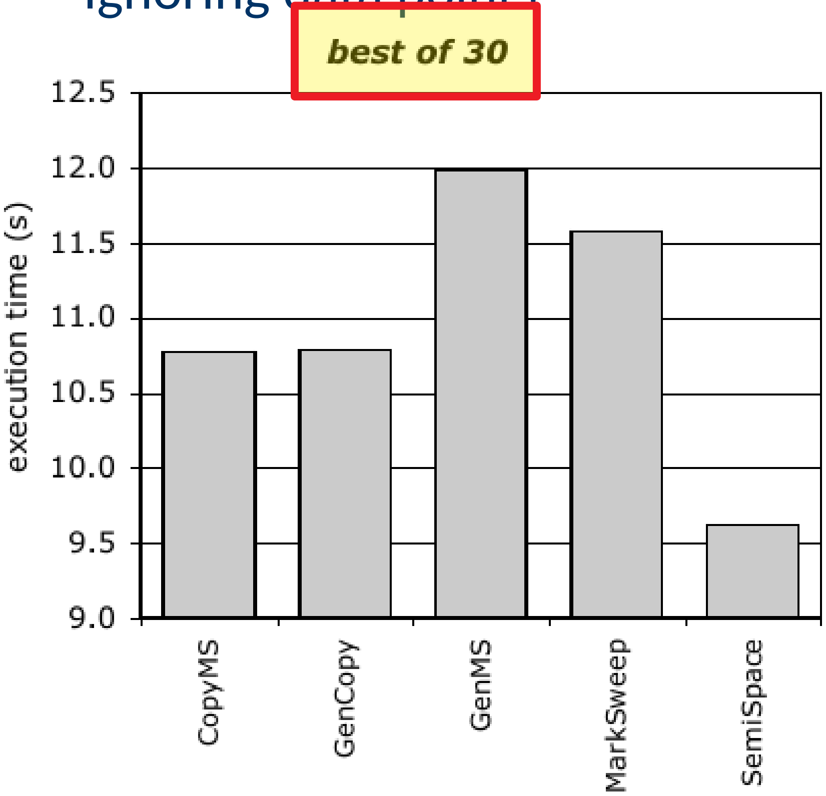

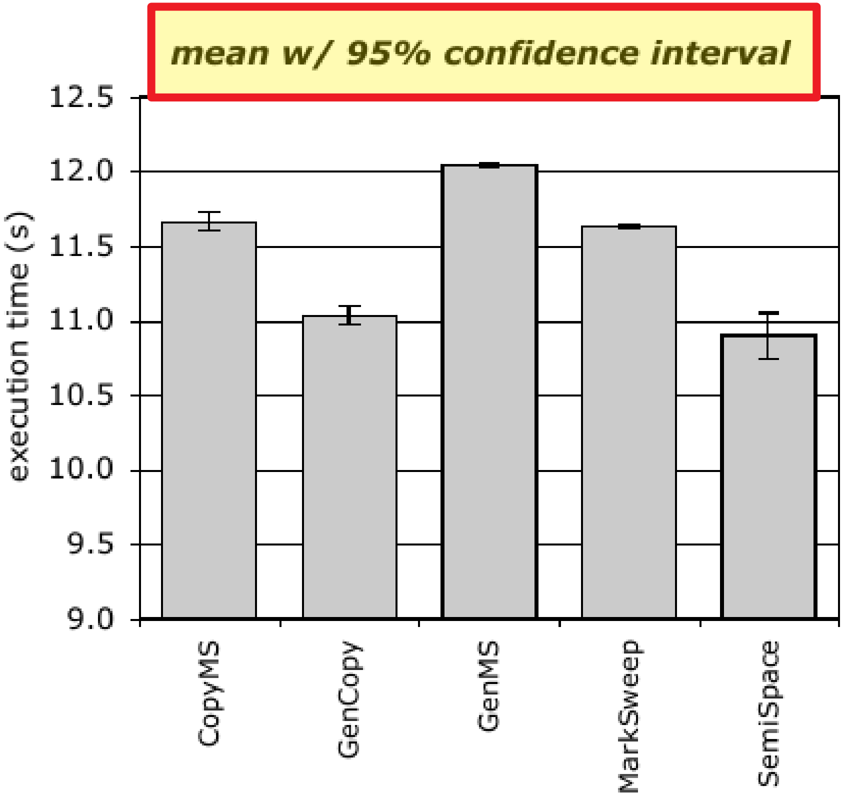

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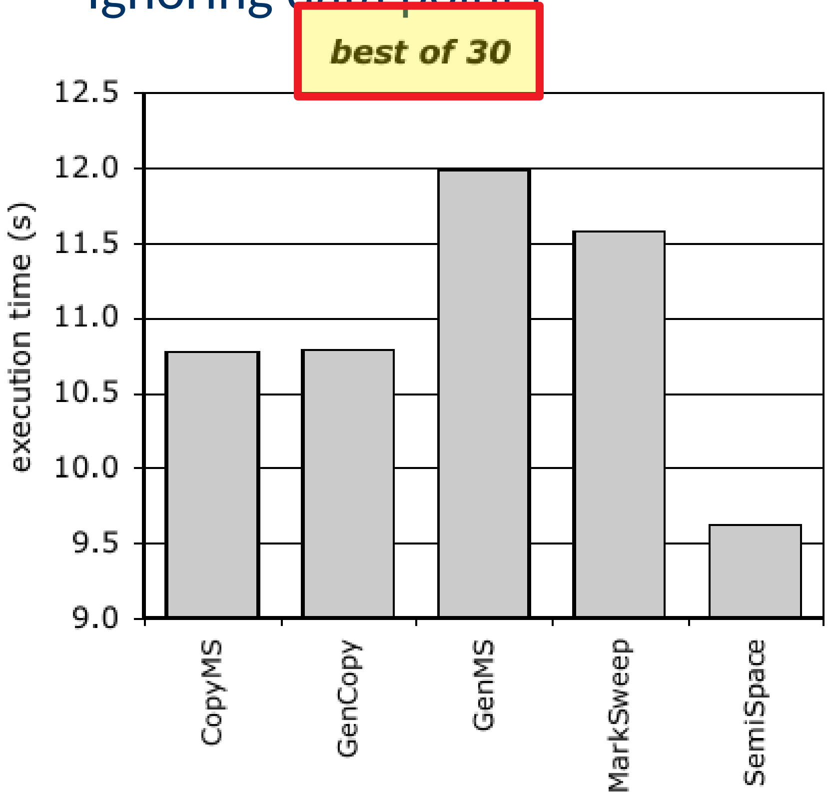

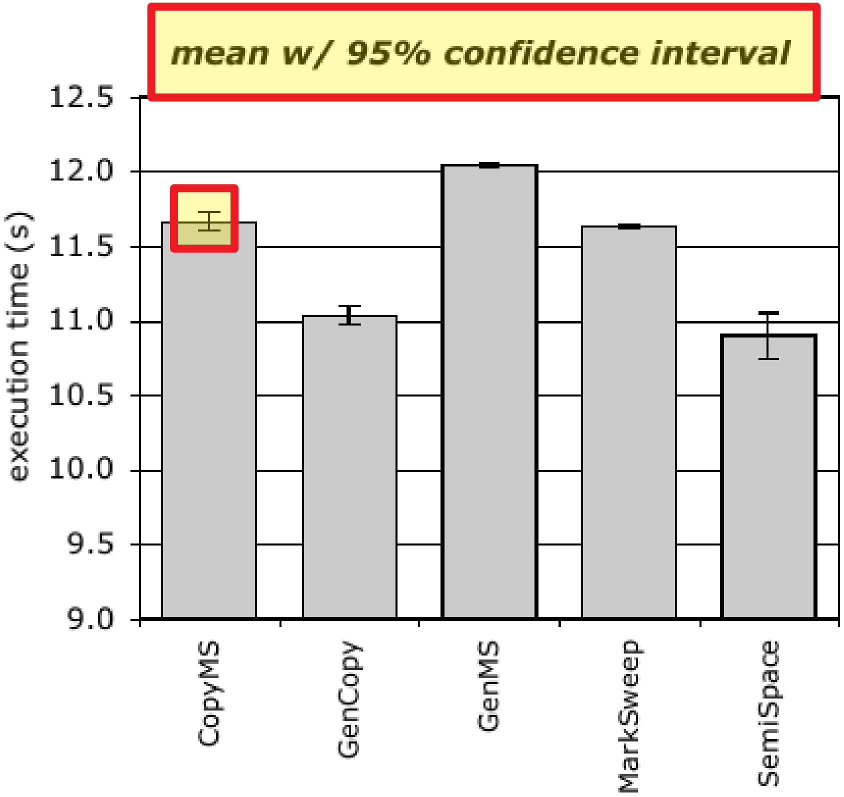

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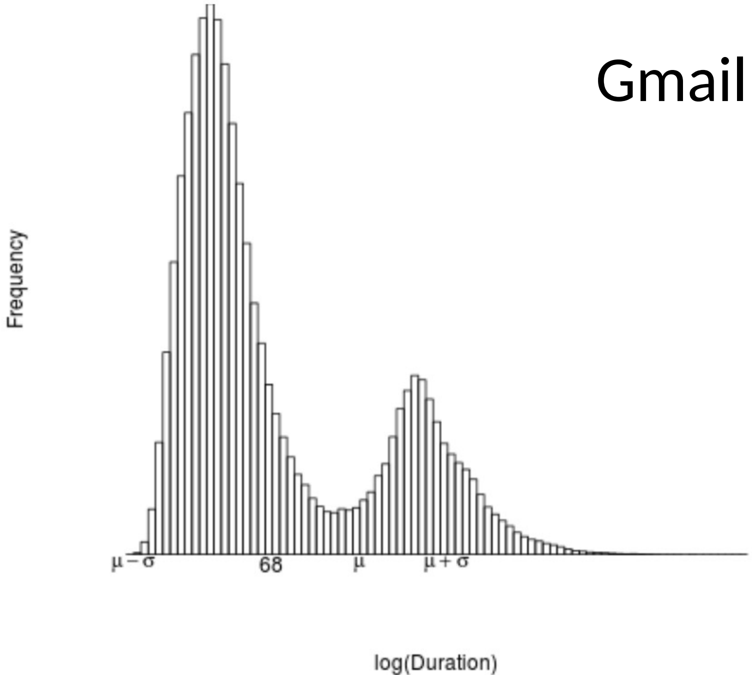

Gmail latency

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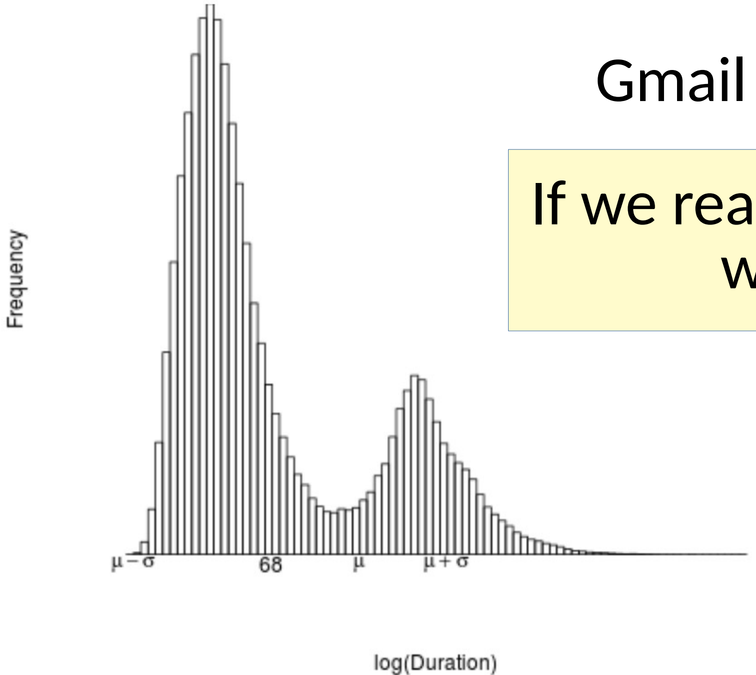

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If we reason about average latency, why is it misleading?

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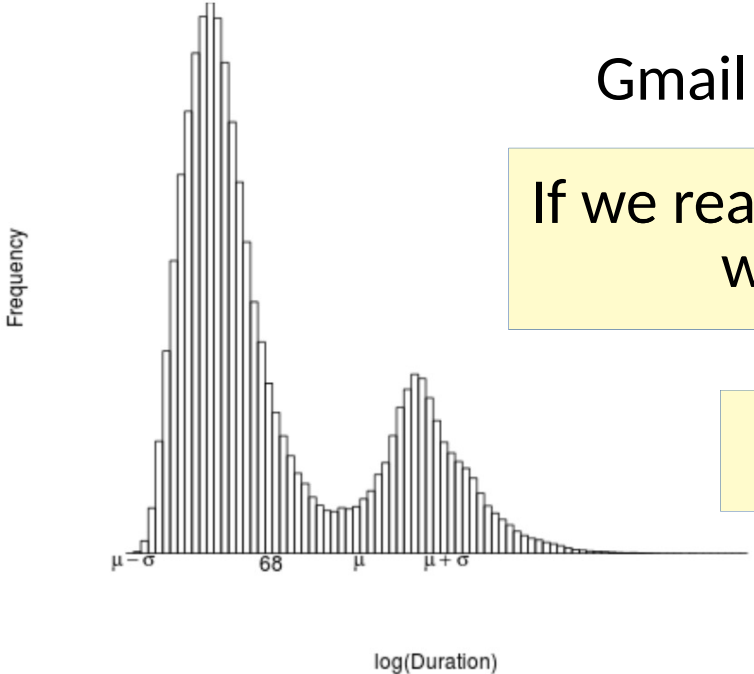

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What is better?

Performance & Measurement [Blackburn et al.]

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  - Bad metrics (e.g. execution time vs. power)

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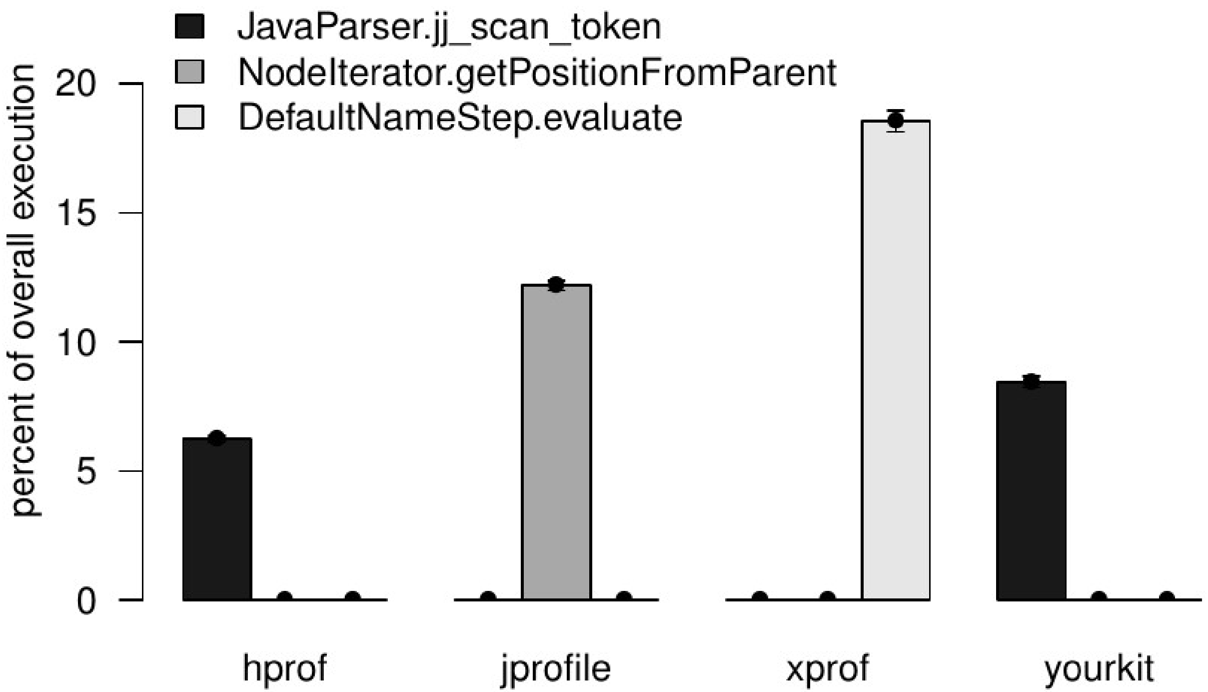

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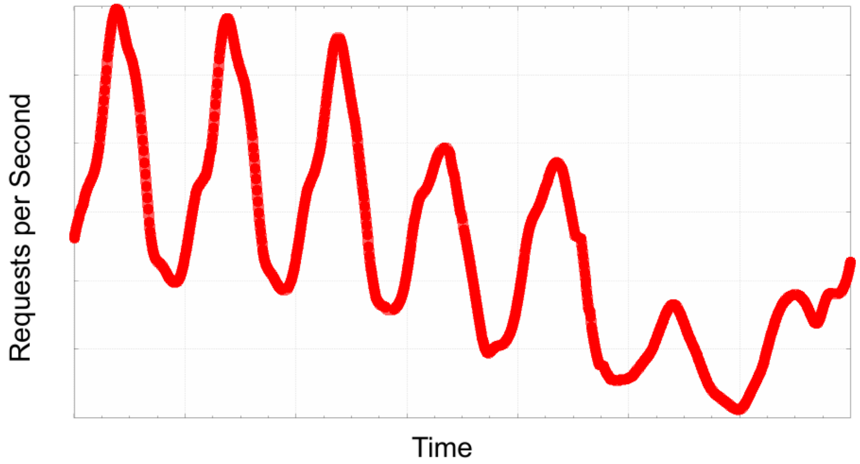
- Inconsistency – comparing apples to oranges
  - Workload variation (e.g. learner effects, time of day, day of week, …)



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- Inconsistency – comparing apples to oranges
  - Workload variation (e.g. learner effects, time of day)
  - Incompatible measures (e.g. performance counters across platforms)

Assessing Performance

Benchmarking

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  - *Microbenchmarks*
    - Focus on cost of an operation in isolation
    - Can help identify core performance details & explain causes

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Let’s dig into a common approach to consider issues

Benchmarking

- Suppose we want to run a microbenchmark

```
startTime = getCurrentTimeInSeconds();
doWorkloadOfInterest();
endTime = getCurrentTimeInSeconds();
reportResult(endTime – startTime);
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Benchmarking

- Suppose we want to run a microbenchmark

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What possible issues do you observe?

Benchmarking

- Suppose we want to run a microbenchmark

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startTime = getCurrentTimeInSeconds();
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  - Granularity of measurement
  - Warm up effects
  - Nondeterminism
  - Size of workload
  - System interference
  - Frequency scaling?
  - Interference of other workloads?
  - Alignment?

Benchmarking

- Granularity & Units
  - Why is granularity a problem?
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Benchmarking

- Granularity & Units
  - Why is granularity a problem?
  - What are alternatives to `getCurrentTimeInSeconds()`?
  - What if I want to predict performance on a different machine?
    - Using *cycles* instead of wall clock time can be useful, but has its own limitations
    - Remember the sins of measurement

Benchmarking

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  - Why is warm up time necessary *in general*?

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Quiescence? Post-JIT hooks? …?

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Quiescence? Post-JIT hooks? …?
It is ***complicated***. [Tratt 2018]

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Benchmarking

- Nondeterministic behavior
  - Will `getCurrentTimeInSeconds()` always return the same number?

Why/why not?

Benchmarking

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    - Hint: The Law of Large Numbers!
- By running the same test many times,
  the sample arithmetic mean will converge on the real one

Is this always what you want?

Benchmarking

- A revised (informal) approach:

```
for (…) doWorkloadOfInterest();
startTime = getCurrentTimeInNanos();
for (…) doWorkloadOfInterest();
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Benchmarking

- A revised (informal) approach:

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startTime = getCurrentTimeInNanos();
for (…) doWorkloadOfInterest();
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```

- This still does not solve everything
  - Frequency scaling?
  - Interference of other workloads?
  - Alignment?

Benchmarking

- Now we have a benchmark, how do we interpret/report it?
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  - We must ***compare***
    - Benchmark vs expectation/mental model
    - Different solutions
    - Over time
    - Results are often normalized against the baseline

Benchmarking

- Now we have a benchmark, how do we interpret/report it?
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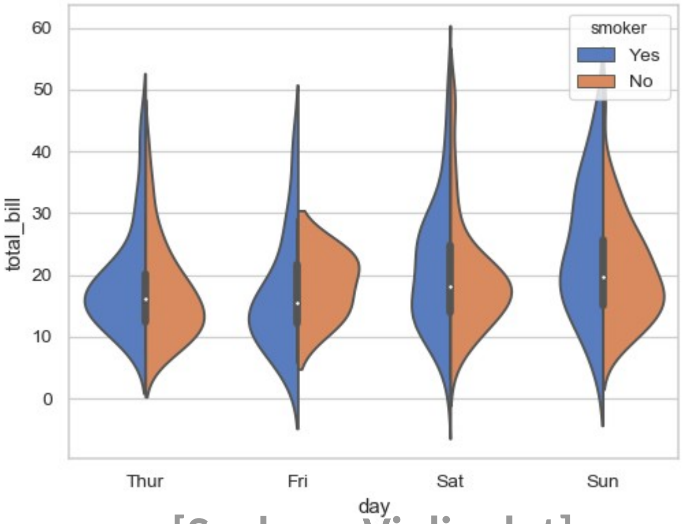

[Seaborn Violinplot]

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- Now we have a benchmark, how do we interpret/report it?
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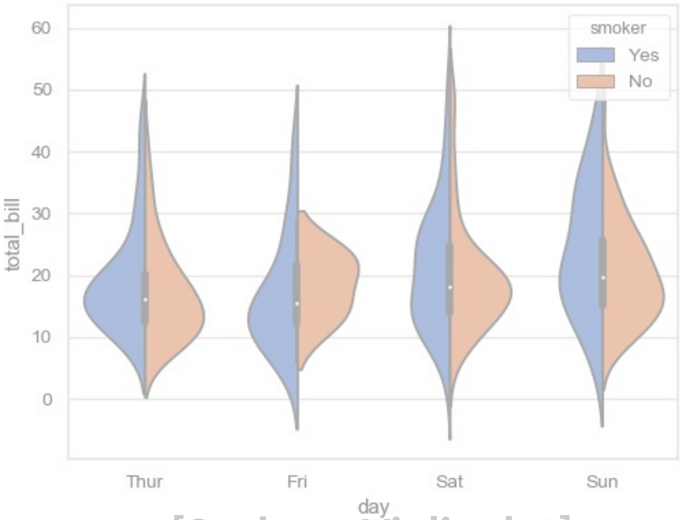
    - Show the distribution (e.g. violin plots)
    - Summarize the distribution (e.g. mean and confidence intervals, box & whisker)



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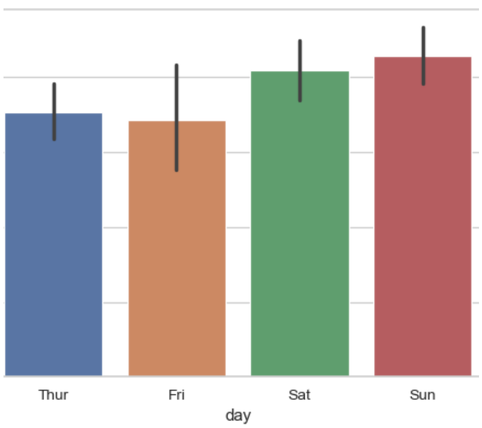
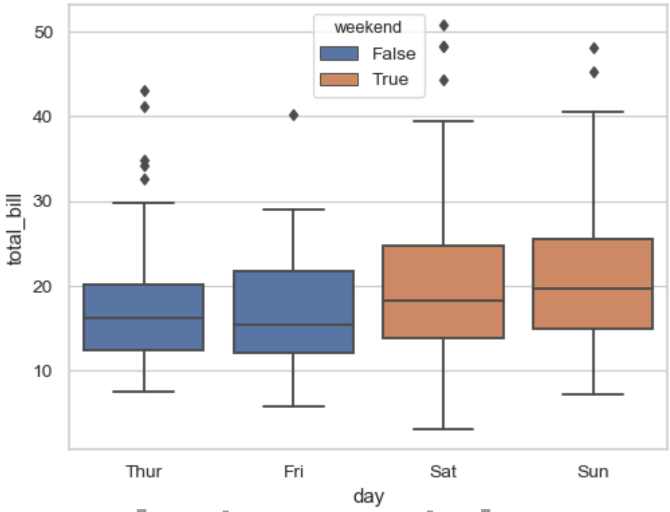


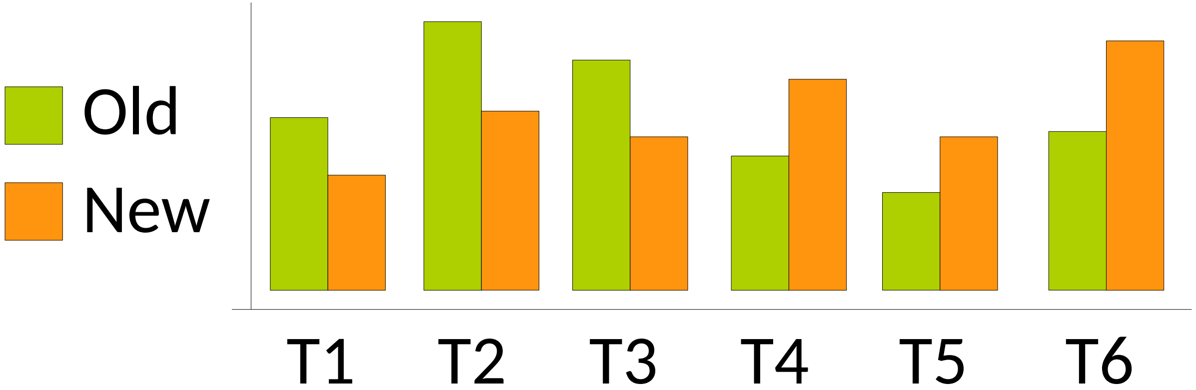
[Seaborn Barplot]



[Seaborn Boxplot]

Benchmarking

- A ***benchmark suite*** comprises multiple benchmarks



Benchmarking

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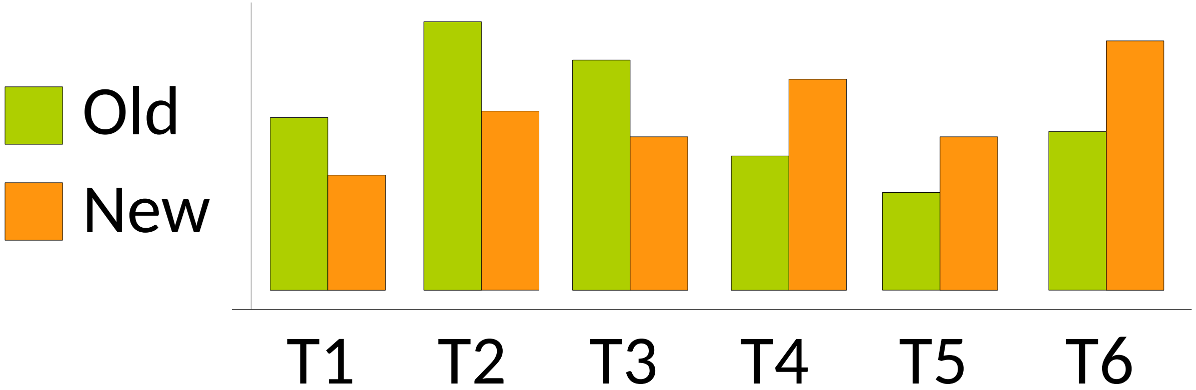

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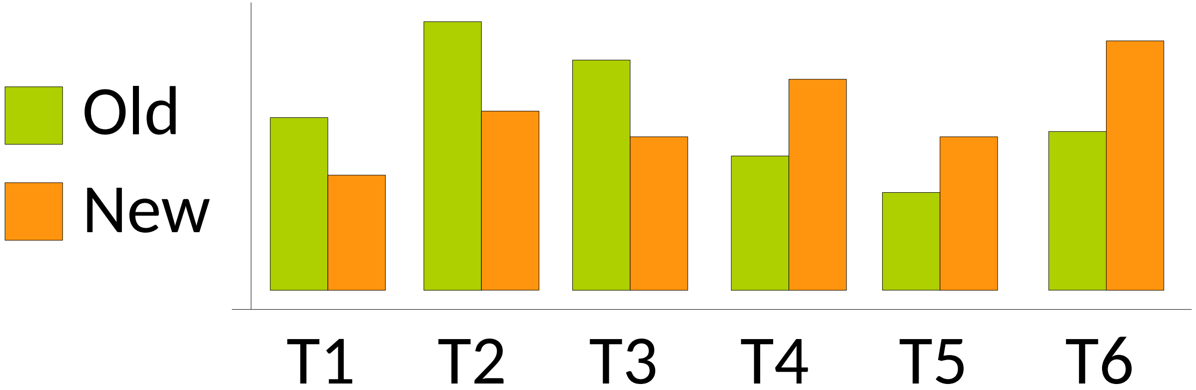
    - *Hypothesis testing*
      - Is solution A different than B?



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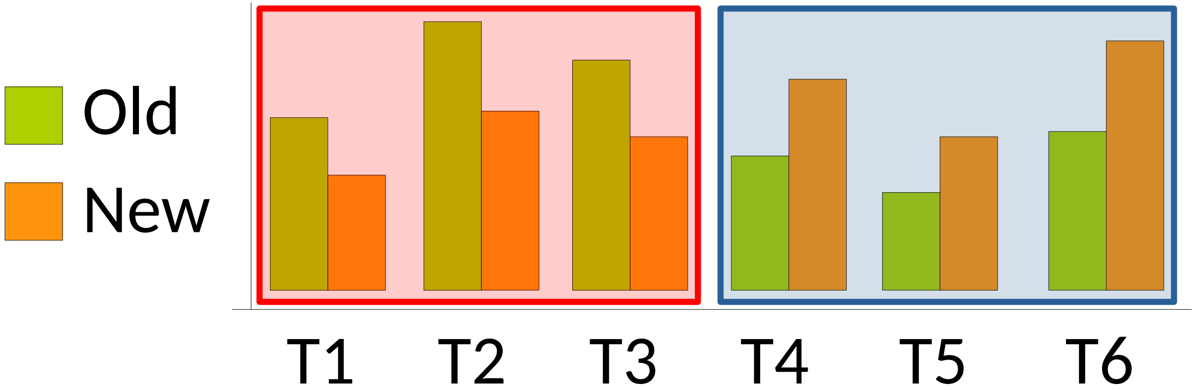

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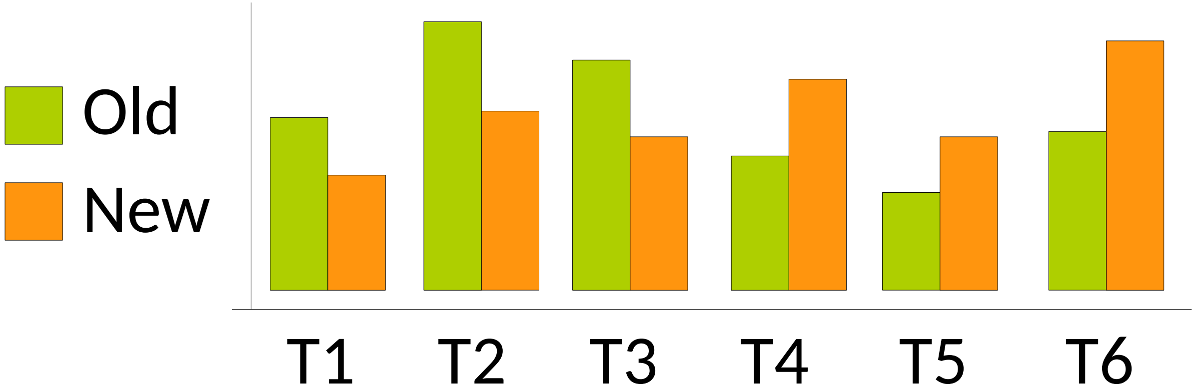
      - Is solution A different than B?
      - You can use ANOVA



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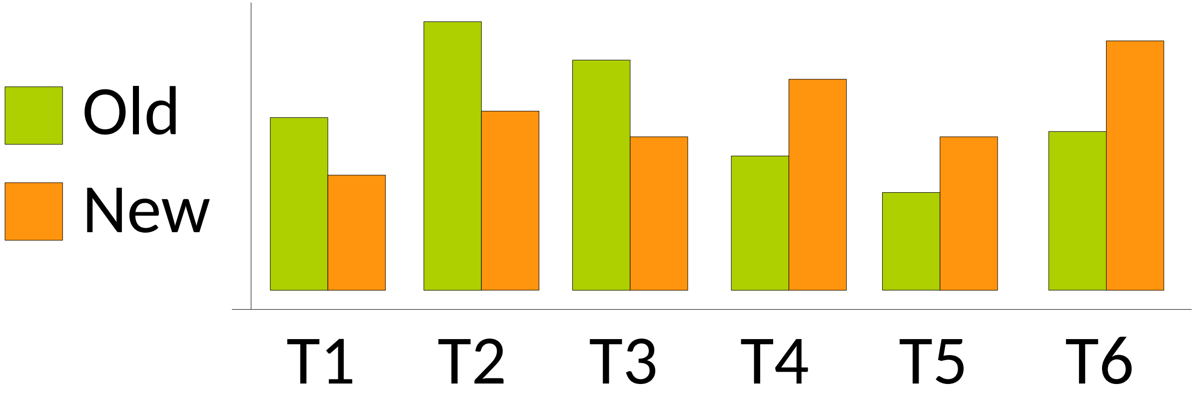

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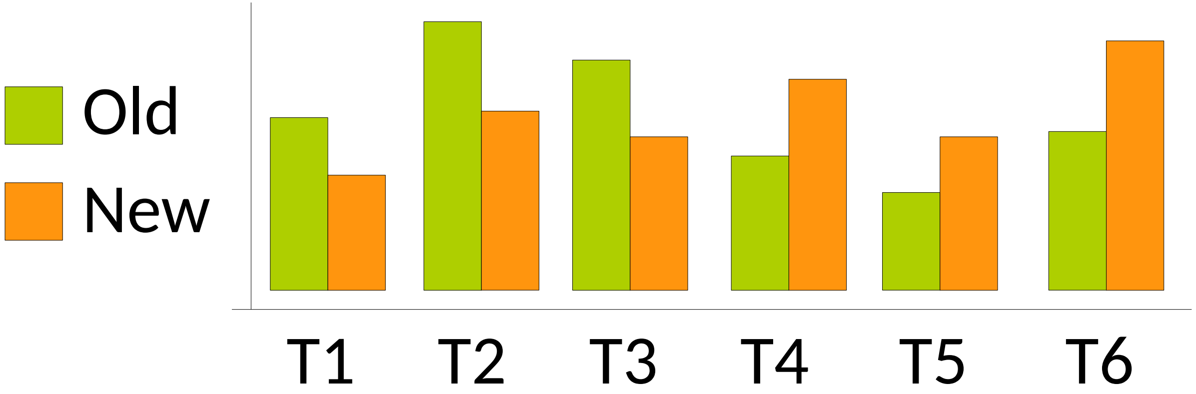
      - Condensing a suite to a single number
      - Intrinsically lossy, but can still be useful



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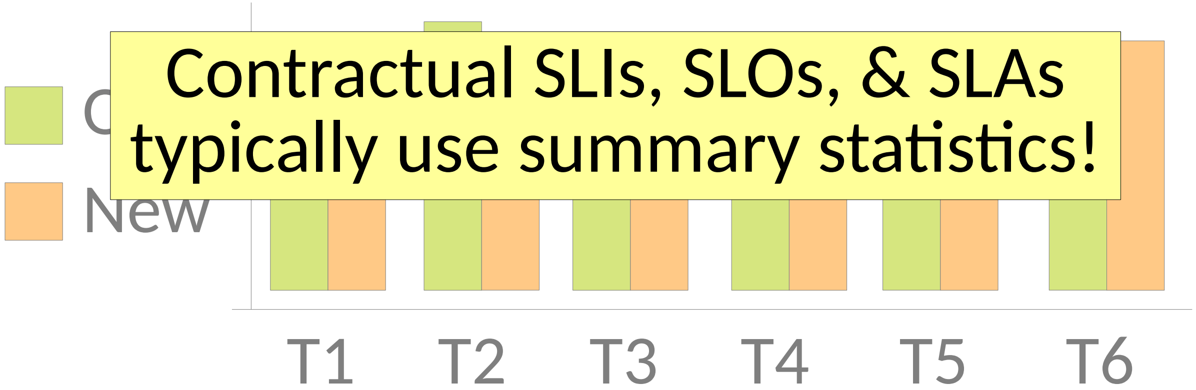


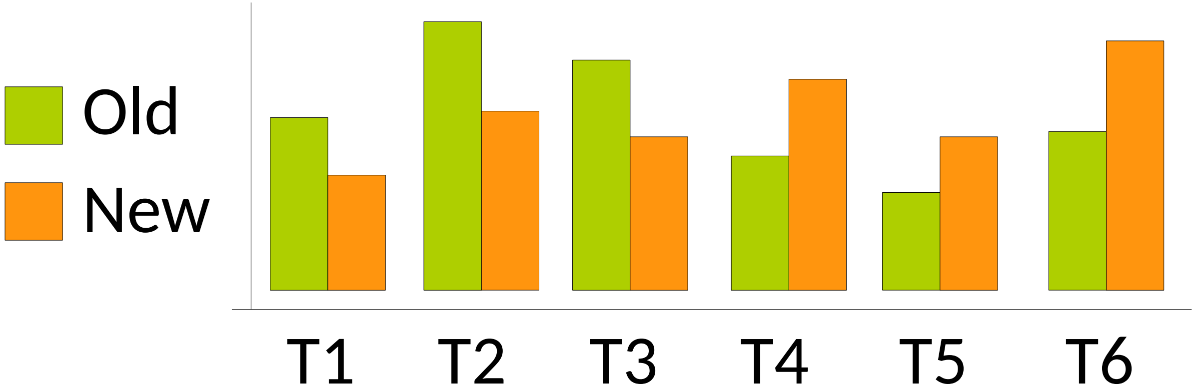
Contractual SLIs, SLOs, & SLAs typically use summary statistics!

Benchmarking

- A benchmark suite comprises multiple benchmarks
- Now we have multiple results, how should we consider them?
  - 2 major senarios
    - *Hypothesis testing*
    - *Summary statistics*
      - Condensing a suite to a single number
      - Intrinsically lossy, but can still be useful

Old: ?
New: ?

$\frac{New}{Old}$: ?



Summary Statistics

Averages of $r_1, r_2, \ldots, r_N$

- Many ways to measure *expectation* or *tendency*

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Each type means something different and has valid uses

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Handling Nondeterminism

```
for (x in 0 to ...)
  times[x] = doWorkloadOfInterest();
```

E(time) = arithmean(times)

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CAVEAT: If the size of each workload changes, a weighted harmonic mean is required!

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$$\sqrt[N]{\prod_{i=1}^{N} r_i}$$

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Any idea why it may be useful here?
(A bit of a thought experiment)

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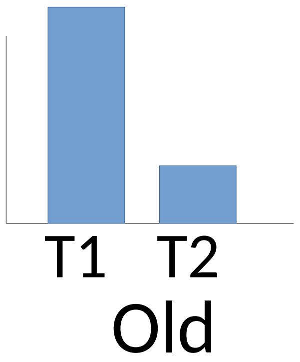

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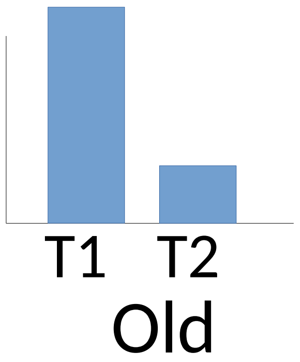

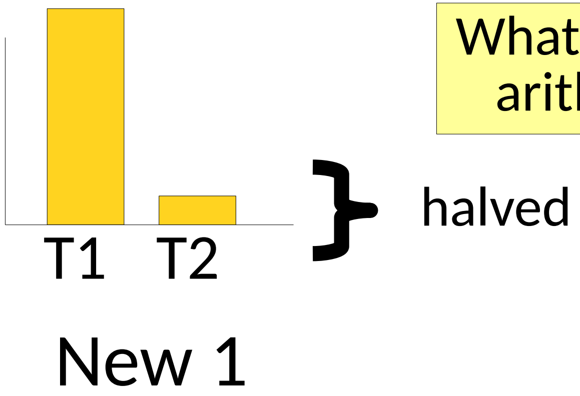

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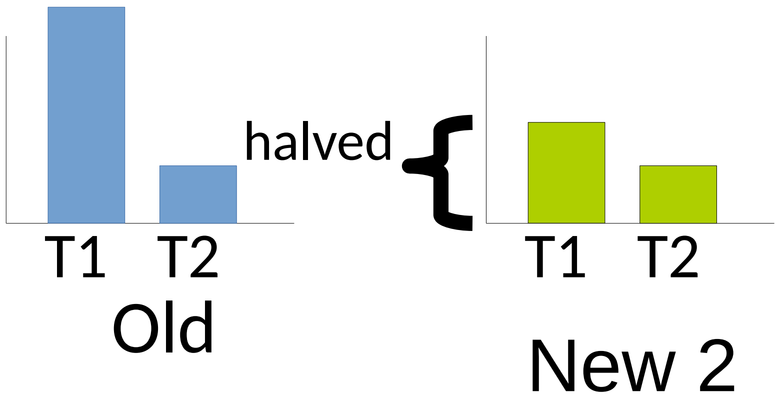

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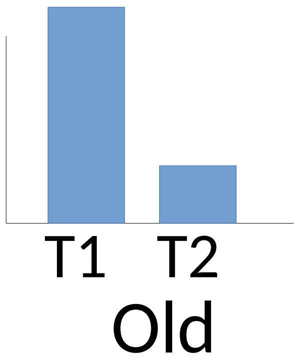

The (non) change to T1 dominates any behavior for T2!

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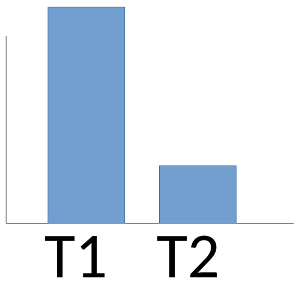

Old

Geometric:

$$\sqrt{r_1 \times r_2}$$

Old

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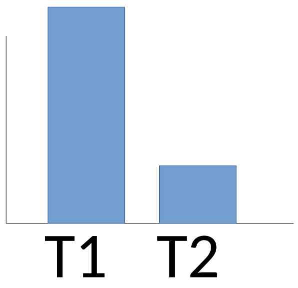

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$$\sqrt{r_1 \times (\frac{1}{2} r_2)}$$

New 1

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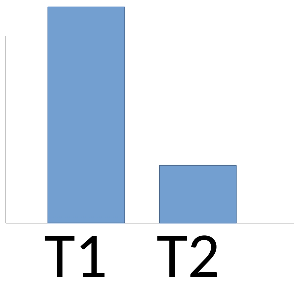

Old

Geometric:

$$\sqrt{r_1 \times r_2}$$

Old

$$\sqrt{r_1 \times (\frac{1}{2} r_2)}$$

New 1

$$\sqrt{(\frac{1}{2} r_1) \times r_2}$$

New 2

Summary Statistics

- Geometric Mean
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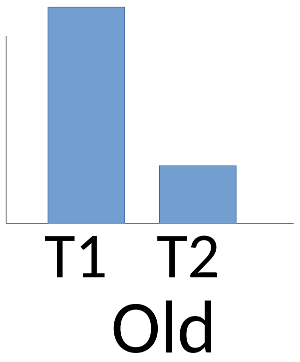
$$\sqrt[N]{\prod_{i=1}^{N} r_i}$$



Geometric:

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$$\sqrt{r_1 \times (\frac{1}{2} r_2)} = \sqrt{\frac{1}{2} \times r_1 \times r_2} = \sqrt{(\frac{1}{2} r_1) \times r_2}$$

New 1

New 2

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  - Good for reporting results that mean different things
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  - A 10% difference in any benchmark affects the final value the same way

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Note: It doesn't have an *intuitive* meaning!
It does provides a balanced *score* of performance.

See [Mashey 2004] for deeper insights.

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Again, these are commonly tied to SLAs!

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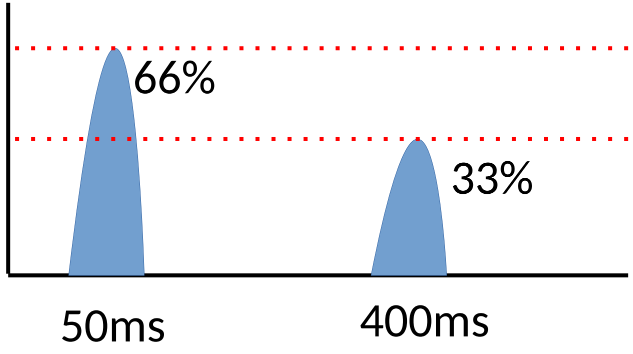

Suppose <200ms response is okay.

An arithmetic mean yields **167ms**.

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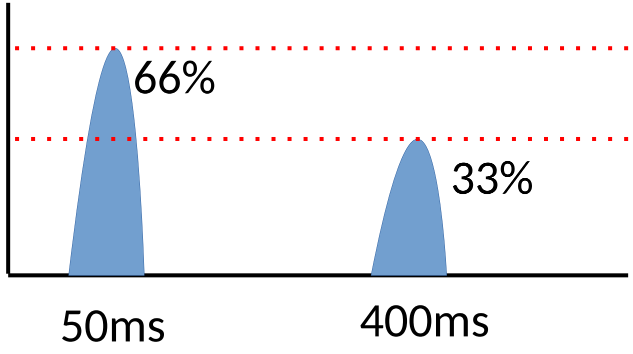

Suppose <200ms response is okay.

An arithmetic mean yields 167ms.

But **1/3** of responses are bad!

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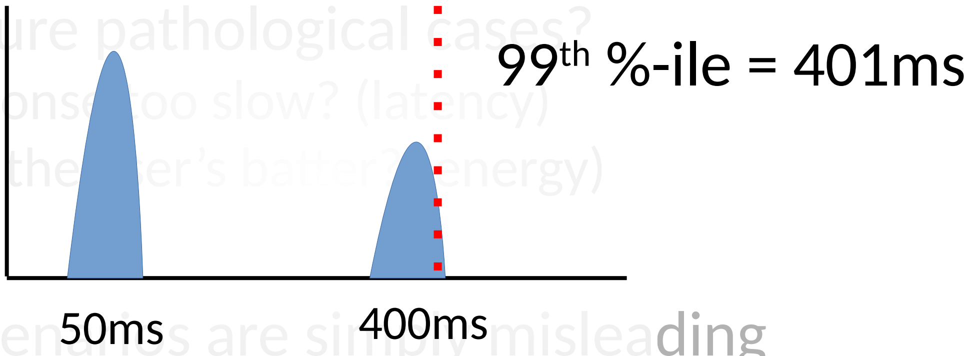

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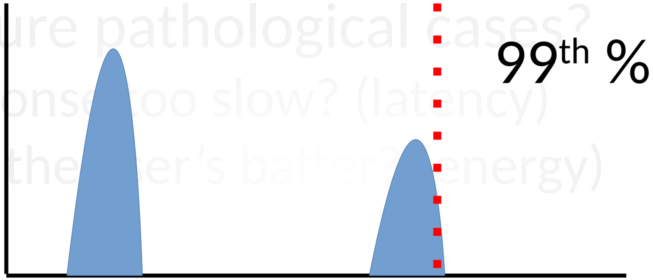

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Percentiles better capture adherence to minimum standards.

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Median of 69-75 [Hubspot 2019]

p(99th %-ile experience) = $1-0.99^{75}$ ~ **0.5**

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How many server requests does a web page make?

How do you measure percentiles over time?

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For more see:

How not to measure latency
Latency SLOs Done Right

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- *Percentiles*
  - n^{th} percentile - The score below which n% of a population resides
- Even percentiles can be misleading when misused
- Typical SLIs, SLOs, & SLAs are driven by percentiles.
  - These become your contractual obligations!

Summary Statistics

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  you cannot sit down and follow a boilerplate process.

Summary Statistics

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  you cannot sit down and follow a boilerplate process.
- Assess the goal. Assess the data. Determine what is meaningful.

Benchmarking

- In practice applying good benchmarking & statistics is made easier via frameworks
  - Google benchmark (C & C++)
  - Google Caliper (Java)
  - JMH (Java)
  - Nonius
  - Celero
  - Easybench
  - Pyperf
  - …

Investigating Performance

Profiling

- When benchmark results do not make sense, you should investigate ***why***

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You should already be familiar with tools like gprof or jprofile.
We'll examine some more advanced profilers now.

Heap profiling

- Suppose I have a task and it consumes all memory
  - **Note:** This is not hypothetical. This often happens with grad students!

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Some people mistakenly believe that using managed languages like Java prevents these.

In practice, they look different….

leaks, …

bloat, latency spikes, OutOfMemoryError

Heap profiling

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Effective Java Item 7
Eliminate obsolete object references.

  - **Note:** This is not hypothetical. This often happens with grad students!
  - If I can ide… emediate
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- Heap profile… m
  & their prove…
  - Can identi… …

```
public Integer pop() {
  if (size == 0) {
    throw new EmptyStackException();
  }
  size -= 1;
  Integer result = data[size];
  data[size] = null;
  return result
}
```

managed languages like Java prevents these.

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Very common defect in callbacks & caches
(nullification & deregistration)

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- Heap profilers track the allocated memory in a program & their provenance
  - Can identify hotspots, bloat, leaks, short lived allocations, ...
  - Commonly *sample* based, but sometimes *event* based
  - e.g. Massif, Heaptrack, ...

Heap profiling

```
int
main() {
  std::vector<std::unique_ptr<long[]>> data{DATA_SIZE};

  for (auto &element : data) {
    element = std::make_unique<long[]>(BLOCK_SIZE);
    // do something with element
    std::this_thread::sleep_for(std::chrono::milliseconds(100));
  }

  std::this_thread::sleep_for(std::chrono::seconds(1));
  return 0;
}
```

Heap profiling

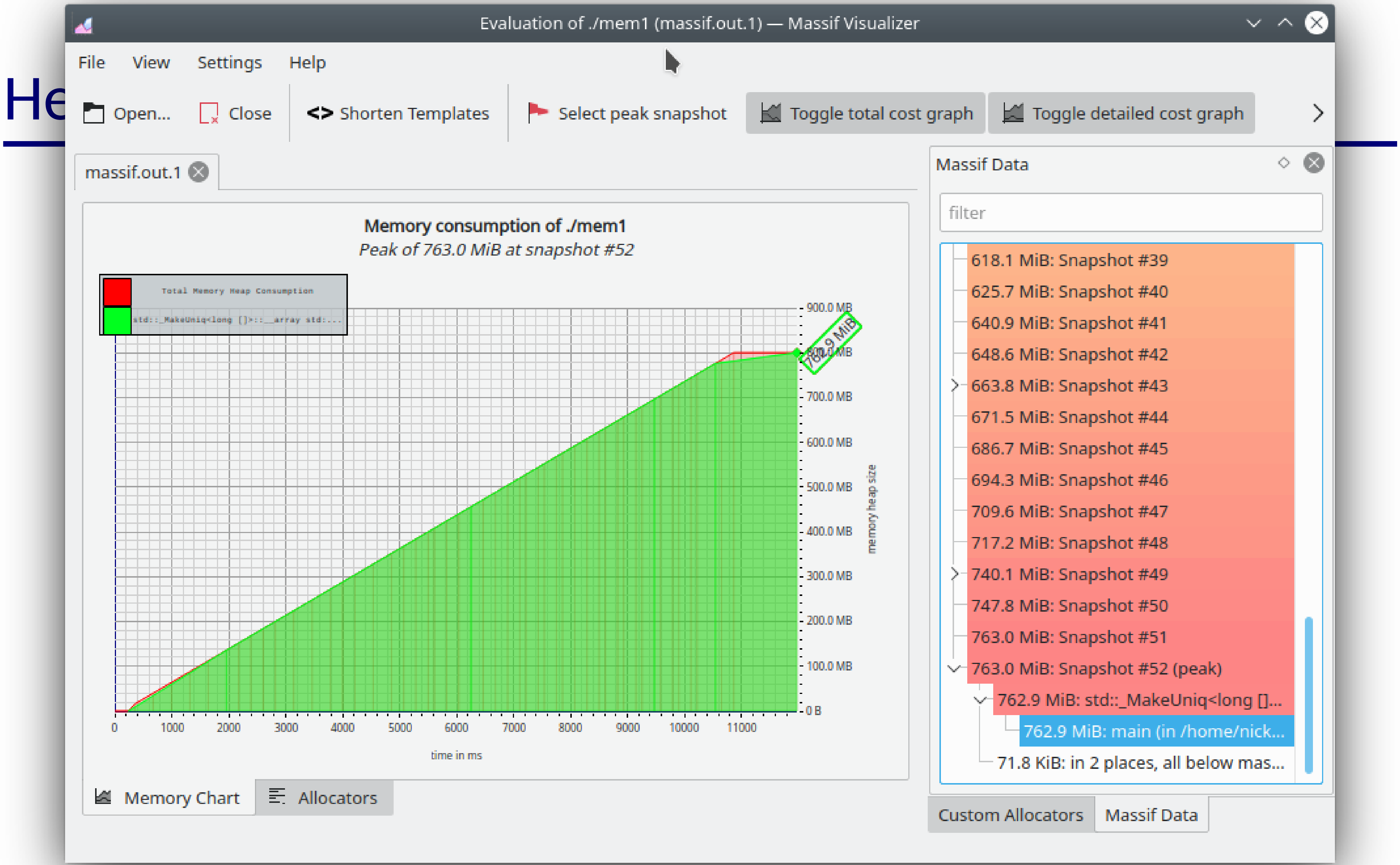
```
int
main() {
  std::vector<std::unique_ptr<long[]>> data{DATA_SIZE};

  for (auto &element : data) {
    element = std::make_unique<long[]>(BLOCK_SIZE);
    // do something with element
    std::this_thread::sleep_for(std::chrono::milliseconds(100));
  }

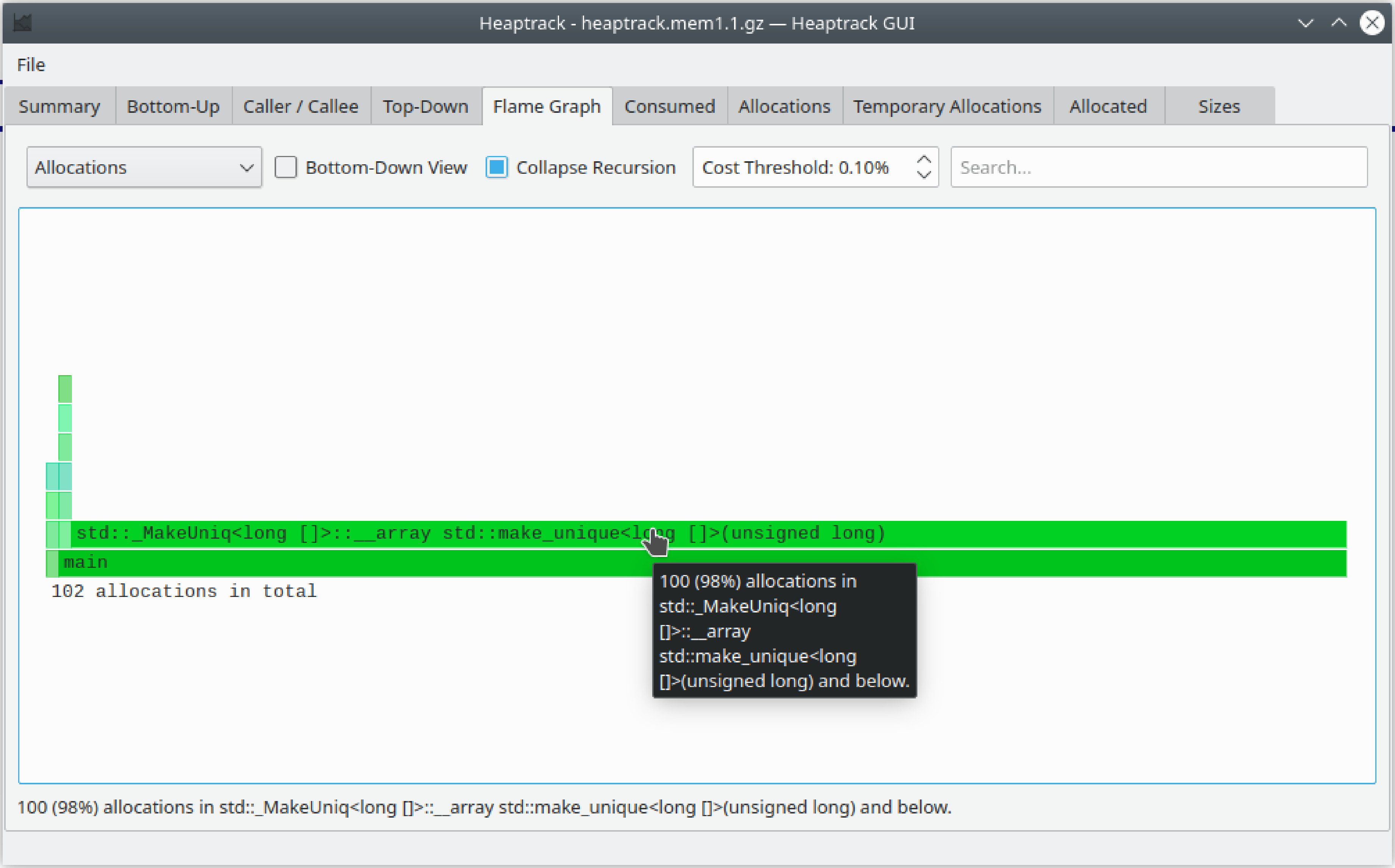
  std::this_thread::sleep_for(std::chrono::seconds(1));
  return 0;
}
```

valgrind --time-unit=ms --tool=massif <program invocation>
heaptrack <program invocation>

massif-visualizer massif.out.<PID>
heaptrack_gui <path to data>


He
Evaluation of ./mem1 (massif.out.1) — Massif Visualizer
File
View
Settings
Help
Open...
Close
Shorten Templates
Select peak snapshot
Toggle total cost graph
Toggle detailed cost graph
massif.out.1
Memory consumption of ./mem1
Peak of 763.0 MiB at snapshot #52
Total Memory Heap Consumption
std::_MakeUniq<long []>::__array std::...
762.9 MiB
900.0 MB
800.0 MB
700.0 MB
600.0 MB
500.0 MB
400.0 MB
300.0 MB
200.0 MB
100.0 MB
0 B
memory heap size
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
time in ms
Memory Chart
Allocators
Massif Data
filter
618.1 MiB: Snapshot #39
625.7 MiB: Snapshot #40
640.9 MiB: Snapshot #41
648.6 MiB: Snapshot #42
663.8 MiB: Snapshot #43
671.5 MiB: Snapshot #44
686.7 MiB: Snapshot #45
694.3 MiB: Snapshot #46
709.6 MiB: Snapshot #47
717.2 MiB: Snapshot #48
740.1 MiB: Snapshot #49
747.8 MiB: Snapshot #50
763.0 MiB: Snapshot #51
763.0 MiB: Snapshot #52 (peak)
762.9 MiB: std::_MakeUniq<long []...
762.9 MiB: main (in /home/nick...
71.8 KiB: in 2 places, all below mas...
Custom Allocators
Massif Data

Heaptrack - heaptrack.mem1.1.gz — Heaptrack GUI
File
Summary
Bottom-Up
Caller / Callee
Top-Down
Flame Graph
Consumed
Allocations
Temporary Allocations
Allocated
Sizes
900.0 MB
800.0 MB
700.0 MB
600.0 MB
500.0 MB
400.0 MB
300.0 MB
200.0 MB
100.0 MB
0 B
Memory Consumed
0s
1s
2s
3s
4s
5s
6s
7s
8s
9s
10s
11s
12s
Elapsed Time


Heaptrack - heaptrack.mem1.1.gz — Heaptrack GUI
File
Summary
Bottom-Up
Caller / Callee
Top-Down
Flame Graph
Consumed
Allocations
Temporary Allocations
Allocated
Sizes
Allocations
Bottom-Down View
Collapse Recursion
Cost Threshold: 0.10%
Search...
std::_MakeUniq<long []>::__array std::make_unique<long []>(unsigned long)
main
102 allocations in total
100 (98%) allocations in std::_MakeUniq<long []>::__array std::make_unique<long []>(unsigned long) and below.
100 (98%) allocations in std::_MakeUniq<long []>::__array std::make_unique<long []>(unsigned long) and below.

Heap profiling

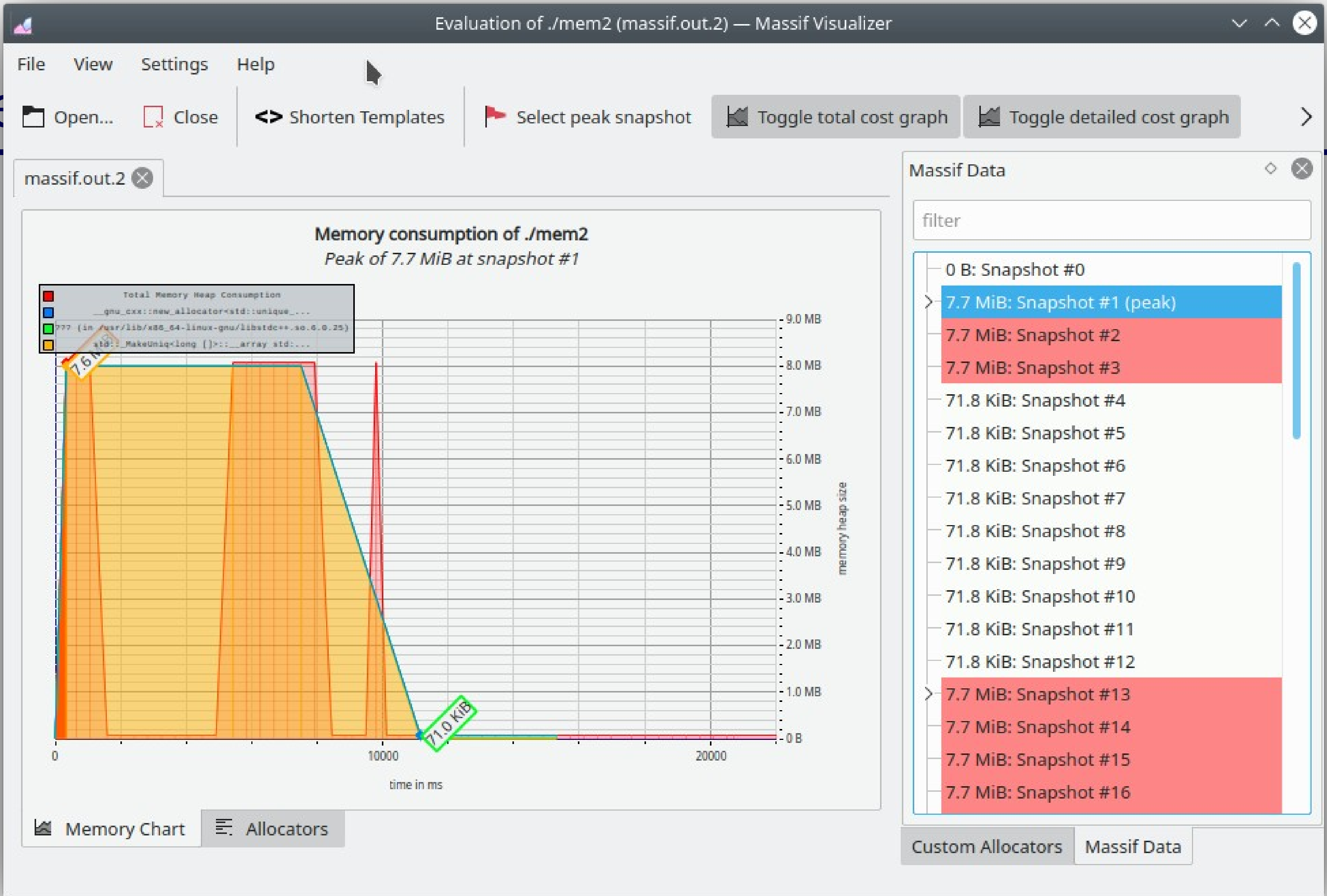
```
int
main() {
  std::vector<std::unique_ptr<long[]>> data{DATA_SIZE};

  for (auto &element : data) {
    element = std::make_unique<long[]>(BLOCK_SIZE);
    // do something with element
    std::this_thread::sleep_for(std::chrono::milliseconds(100));
    element.reset();
    std::this_thread::sleep_for(std::chrono::milliseconds(100));
  }

  std::this_thread::sleep_for(std::chrono::seconds(1));
  return 0;
}
```

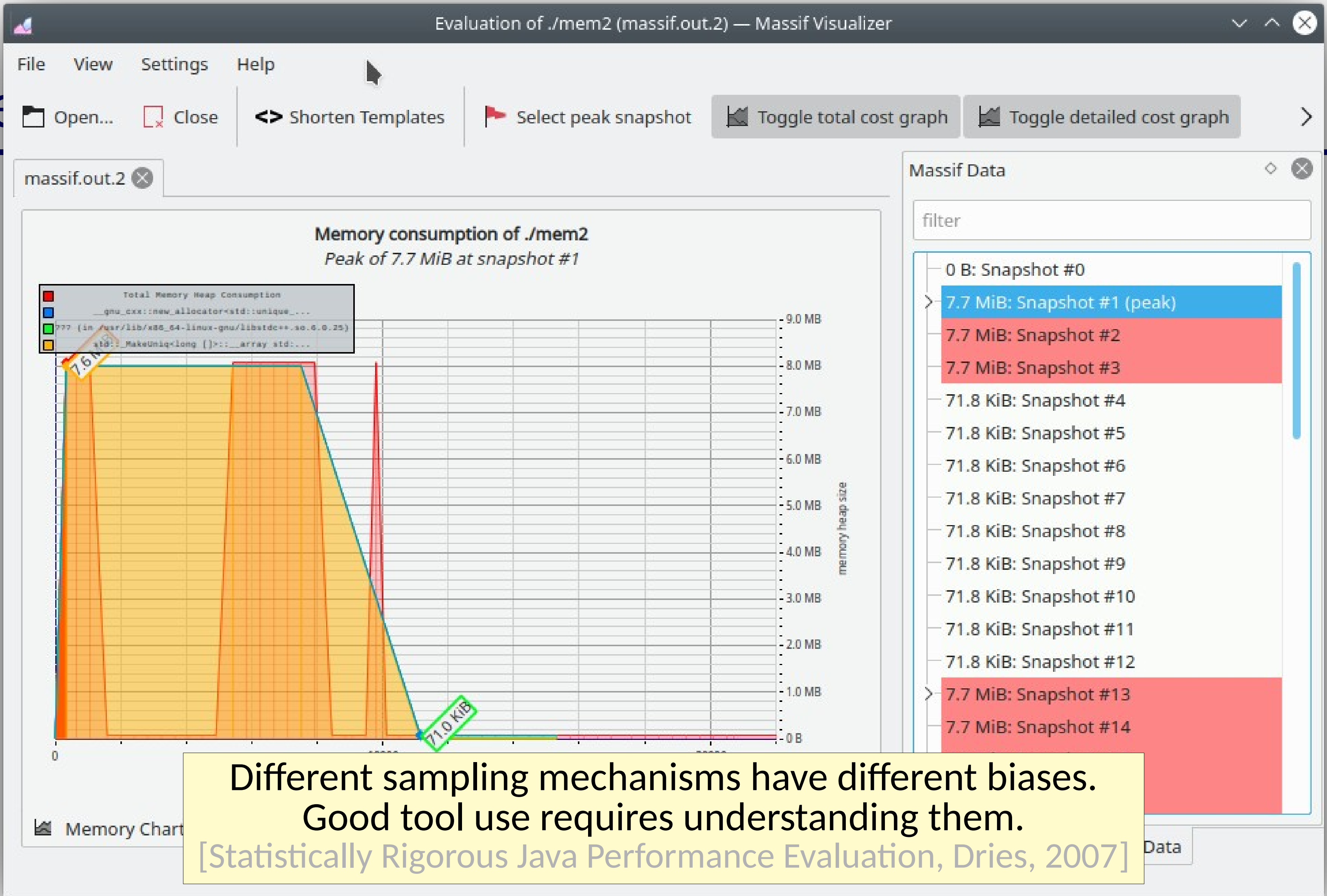
How do we expect this to differ?

He

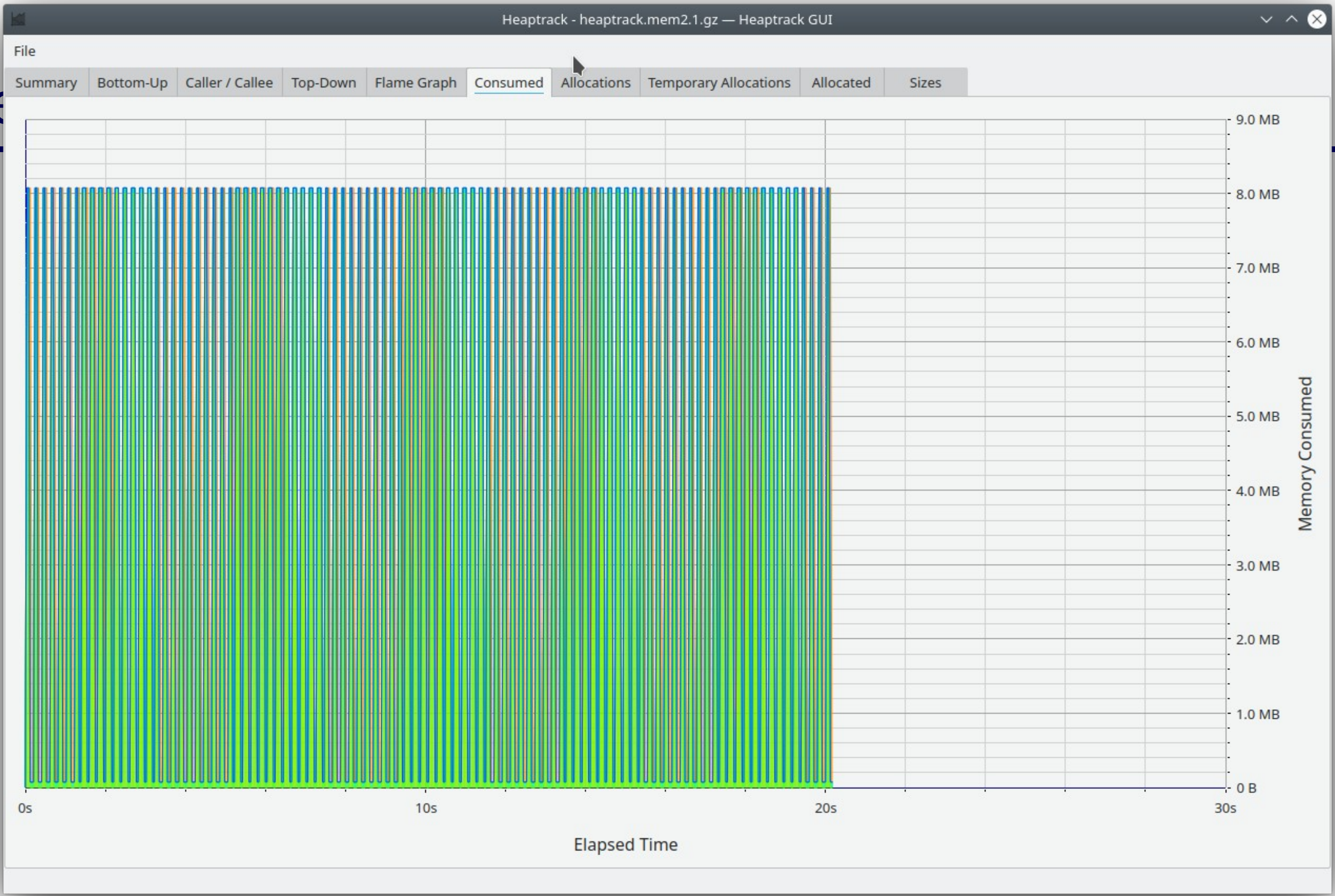


Evaluation of ./mem2 (massif.out.2) — Massif Visualizer
File View Settings Help
Open... Close Shorten Templates Select peak snapshot Toggle total cost graph Toggle detailed cost graph
massif.out.2
Memory consumption of ./mem2
Peak of 7.7 MiB at snapshot #1
Total Memory Heap Consumption
7.6 MiB
71.0 KiB
9.0 MB
8.0 MB
7.0 MB
6.0 MB
5.0 MB
4.0 MB
3.0 MB
2.0 MB
1.0 MB
0 B
memory heap size
0
10000
20000
time in ms
Memory Chart
Allocators
Massif Data
filter
0 B: Snapshot #0
7.7 MiB: Snapshot #1 (peak)
7.7 MiB: Snapshot #2
7.7 MiB: Snapshot #3
71.8 KiB: Snapshot #4
71.8 KiB: Snapshot #5
71.8 KiB: Snapshot #6
71.8 KiB: Snapshot #7
71.8 KiB: Snapshot #8
71.8 KiB: Snapshot #9
71.8 KiB: Snapshot #10
71.8 KiB: Snapshot #11
71.8 KiB: Snapshot #12
7.7 MiB: Snapshot #13
7.7 MiB: Snapshot #14
7.7 MiB: Snapshot #15
7.7 MiB: Snapshot #16
Custom Allocators
Massif Data

He



Different sampling mechanisms have different biases.
Good tool use requires understanding them.
[Statistically Rigorous Java Performance Evaluation, Dries, 2007]



Heaptrack - heaptrack.mem2.1.gz — Heaptrack GUI
File
Summary
Bottom-Up
Caller / Callee
Top-Down
Flame Graph
Consumed
Allocations
Temporary Allocations
Allocated
Sizes
9.0 MB
8.0 MB
7.0 MB
6.0 MB
5.0 MB
4.0 MB
3.0 MB
2.0 MB
1.0 MB
0 B
Memory Consumed
0s
10s
20s
30s
Elapsed Time

CPU Profiling & Flame Graphs

- When CPU is the resource, investigate where the CPU is spent
  - Classic profilers – gprof, oprofile, jprof, …

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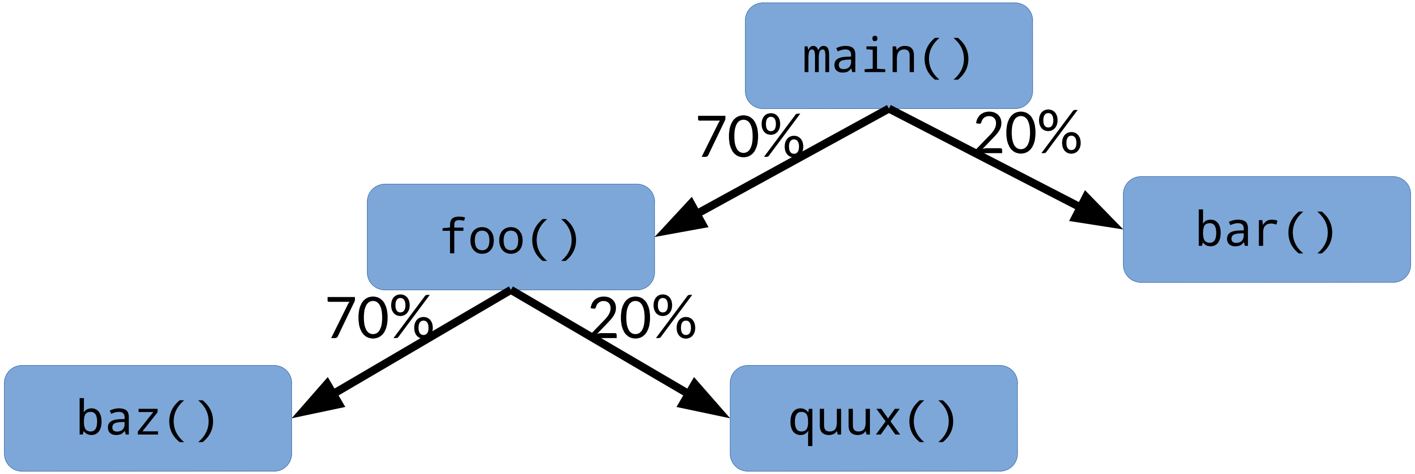

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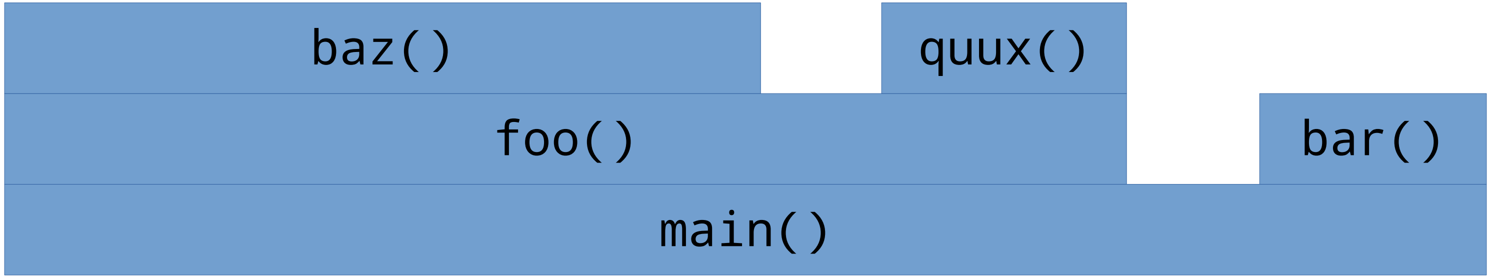

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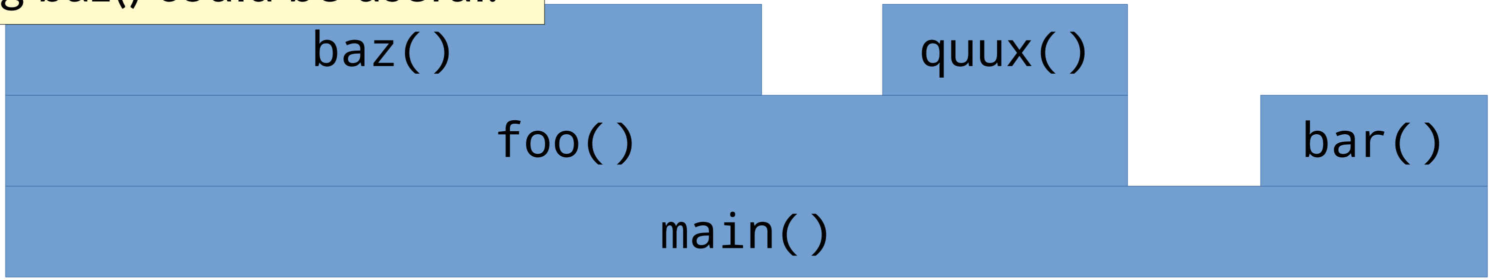
It is easier to see that optimizing baz() could be useful.



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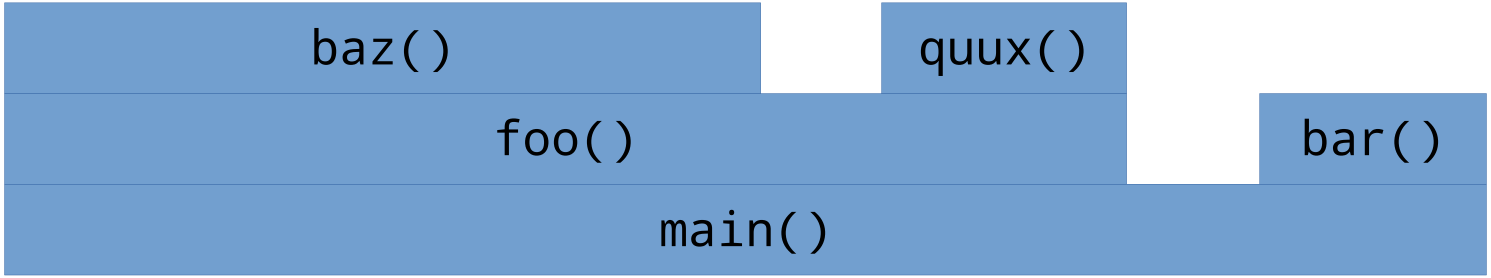

CPU Profiling & Flame Graphs

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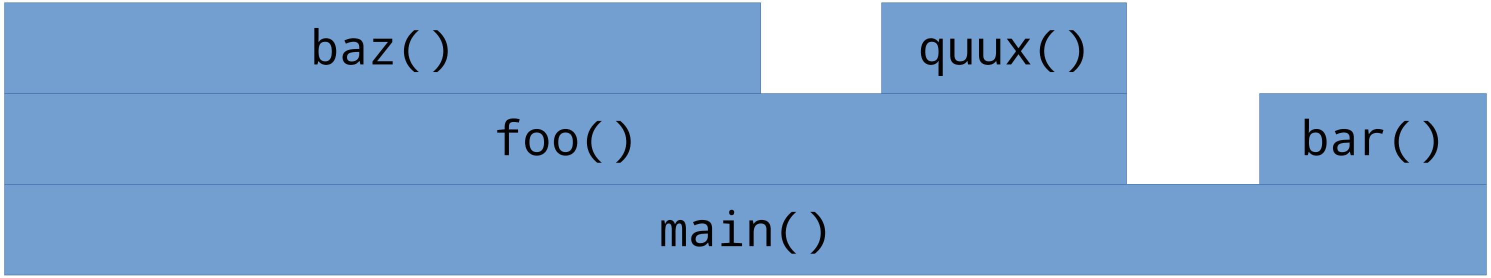
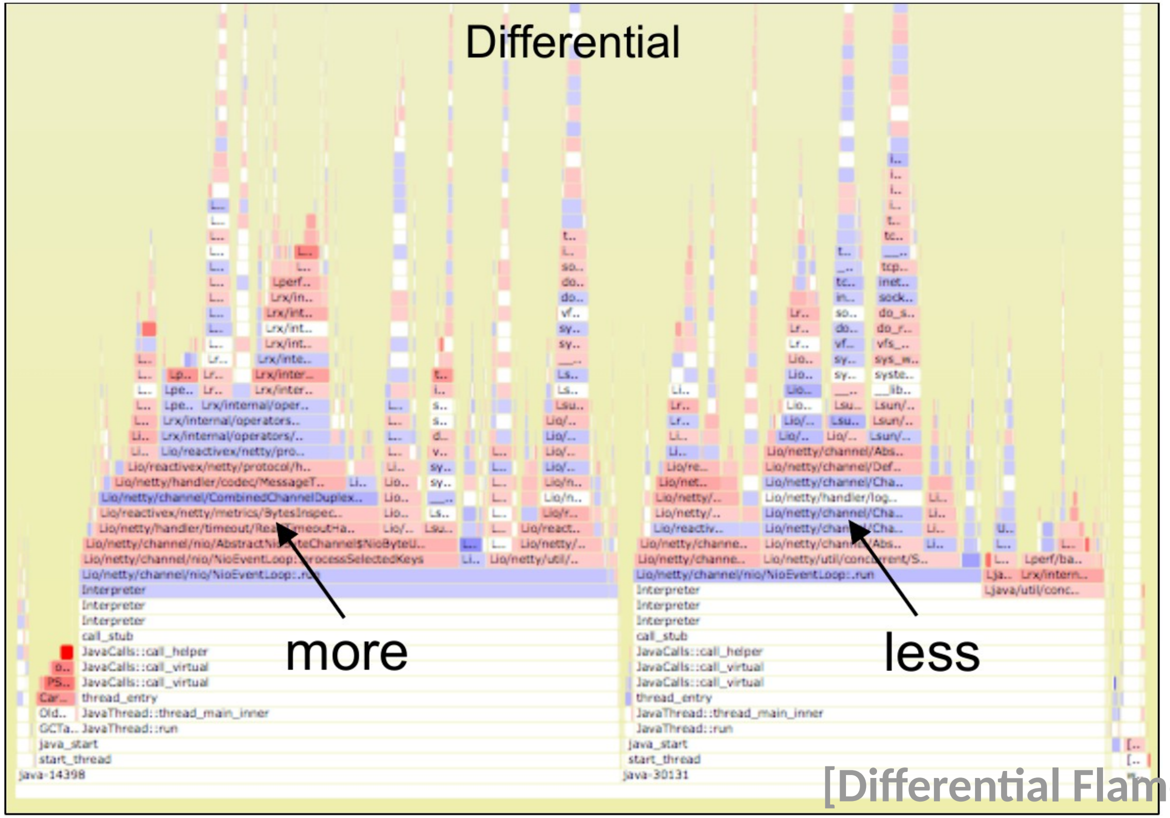
- Flame graphs provide a way of structuring and visualizing substantial profiling information
  - Consumers of CPU on top
  - ancestry, proportions, components can all be clearly identified



CPU Profiling & Flame Graphs

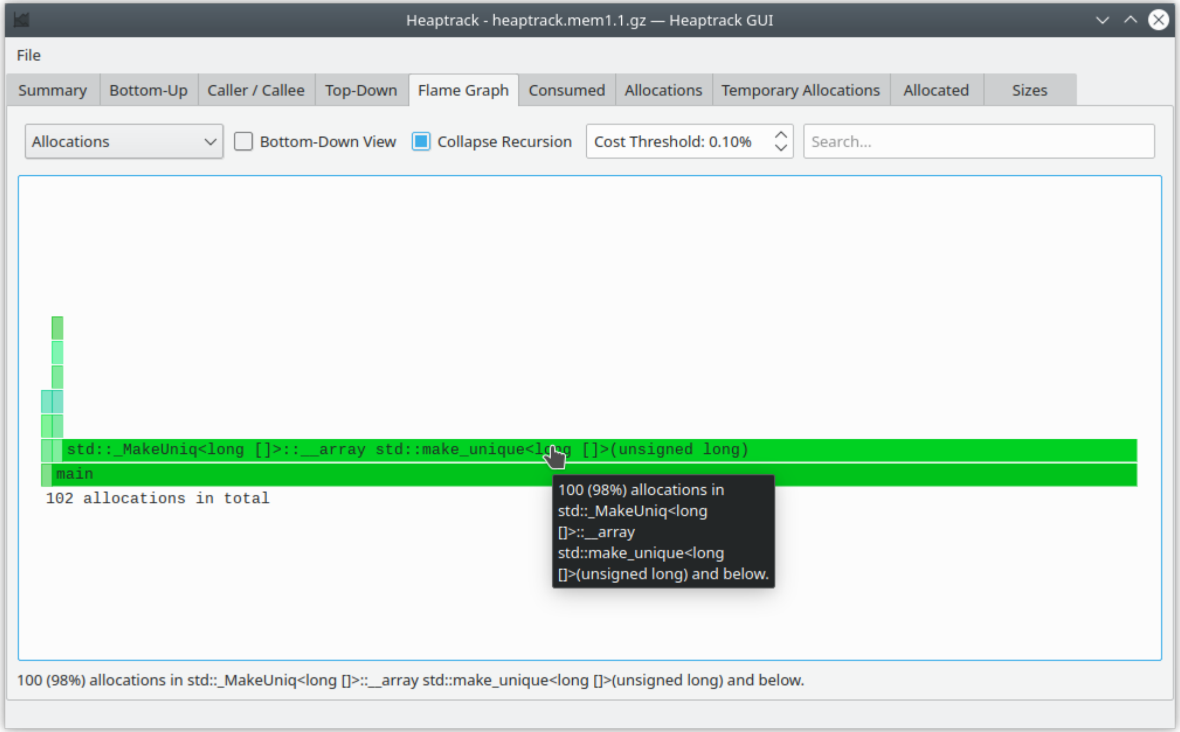
- Can extract rich information by embedding interesting things in colors



[Gregg, ATC 2017]
[Differential Flame Graphs, Gregg, 2014]

CPU Profiling & Flame Graphs

- Flame graphs are not just limited to CPU time!
  - Any countable resource or event can be organized & visualized



CPU Profiling & Flame Graphs

- Flame graphs are not just limited to CPU time!
  - Any countable resource or event can be organized & visualized
- You can also automatically generate them with clang & chrome
  - See project X-Ray in clang
  - See Chrome Trace Viewer

Perf & event profiling

- Sometimes low-level architectural effects determine the performance
  - Cache misses
  - Misspeculations
  - TLB misses

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```
perf stat -e <events> <command>
perf record -e <events> -g <command>
perf report
perf annotate
perf list
```

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```
perf stat -e <events> <command>
perf record -e <events> -g <command>
perf report
perf annotate
perf list
```

events like

```
task-clock,context-switches,cpu-migrations,page-faults,
cycles,branches,branch-misses,cache-misses,
cycle_activity.stalls_mem_any,icache_64b.iftag_stall
```

Perf & event profiling

```
Sequence s;
size_t count = // size of workload
auto value = randomInts.begin();

while (count) {
  const auto &v = *value;
  auto pos = std::find_if(s.begin(), s.end(),
    [&v] (auto elt) { return !(elt < v); });
  s.insert(pos, v);
  ++value;
  --count;
}
```

Perf & event profiling

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  ++value;
  --count;
}
```

Perf & event profiling

```
perf stat -e ... bin/sequenceTest  --benchmark_filter=vector
```

```
 Performance counter stats for 'bin/sequenceTest --benchmark_filter=vector':

               203      page-faults                    #    0.216 K/sec
     3,633,972,445      cycles                         #    3.871 GHz
    11,103,176,853      instructions                   #    3.06  insn per cycle
     3,878,166,469      branches                       # 4130.852 M/sec
            938.83 msec task-clock                     #    0.981 CPUs utilized
                 3      context-switches               #    0.003 K/sec
                 0      cpu-migrations                 #    0.000 K/sec
         1,895,927      branch-misses                  #    0.05% of all branches
           398,844      cache-misses
       135,089,499      cycle_activity.stalls_total #  143.891 M/sec
```

805K insertions/sec @~1 second

Perf & event profiling

```
perf stat -e ... bin/sequenceTest  --benchmark_filter=list
```

```
 Performance counter stats for 'bin/sequenceTest --benchmark_filter=list':

              302      page-faults                      #    0.015 K/sec
   78,686,515,379      cycles                           #    3.953 GHz
   11,813,349,494      instructions                     #    0.15  insn per cycle
    4,695,891,137      branches                         #  235.899 M/sec
        19,906.35 msec task-clock                       #    0.999 CPUs utilized
               76      context-switches                 #    0.004 K/sec
                0      cpu-migrations                   #    0.000 K/sec
        1,344,413      branch-misses                    #    0.03% of all branches
        2,949,410      cache-misses
   73,920,774,866      cycle_activity.stalls_total # 3713.427 M/sec
```

28.7K insertions/sec @~20 seconds

Perf & event profiling

```
perf record -e ... -g bin/sequenceTest  --benchmark_filter=list
perf annotate
```

```
Samples: 177  of event 'cache-misses', 4000 Hz, Event count (approx.): 268564

Percent│      [&v] (auto elt) { return !(elt < v); });
       │        mov        0x0(%r13),%eax
       │      operator()<int>():
       │        nop
       │      __find_if<std::_List_iterator<int>, __gnu_cxx::__ops::_Iter_pred<testNaiveInsert<s
  1.48 │        cmp        %eax,0x10(%rbp)
       │      → jge        17a30 <void testNaiveInsert<std::__cxx11::list<int, std::allocator<in
       │       ZNSt14 List iteratorIiEppEv():
       │       _M_node = _M_node->_M_next;
 85.01 │        mov        0x0(%rbp),%rbp
       │      __find_if<std::_List_iterator<int>, __gnu_cxx::__ops::_Iter_pred<testNaiveInsert<s
 12.13 │        cmp        %r12,%rbp
       │      → jne        17a70 <void testNaiveInsert<std::__cxx11::list<int, std::allocator<in
Press 'h' for help on key
```

85-97% of stalls are on the linked list traversal

Similar profilers across languages

- These sorts of profiling concerns are not just for native code
  - Python – scalene (https://github.com/emeryberger/scalene)
  - Javascript – Chrome Dev Tools, Firebug, JitProf, …
  - Java – VisualVM, Mission Control, XRebel, …
  - …

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  - …

What *events* you care about may change, but the need for profiling is ubiquitous.

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  figuring out *what* to profile &
  developing new profiling tools is critical

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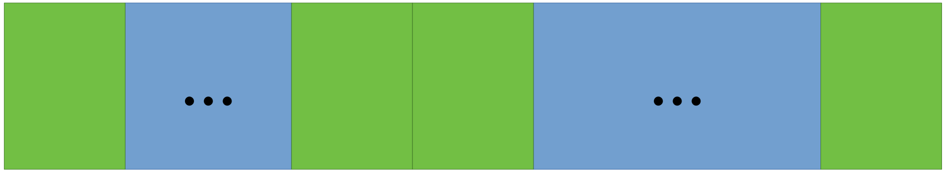
  - Java – VisualVM, Mission Control, XRebel, …
  - …
- As new languages and use cases emerge,
  figuring out *what* to profile &
  developing new profiling tools is critical
- Whatever event, resource, or problem you are interested in,
  a custom profiler can provide a useful investigative tool

Profiling for *opportunities*

- Causal profiling (e.g. Coz)



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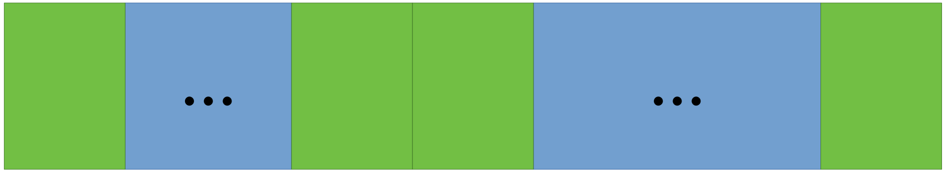

What should I look at to speed things up?

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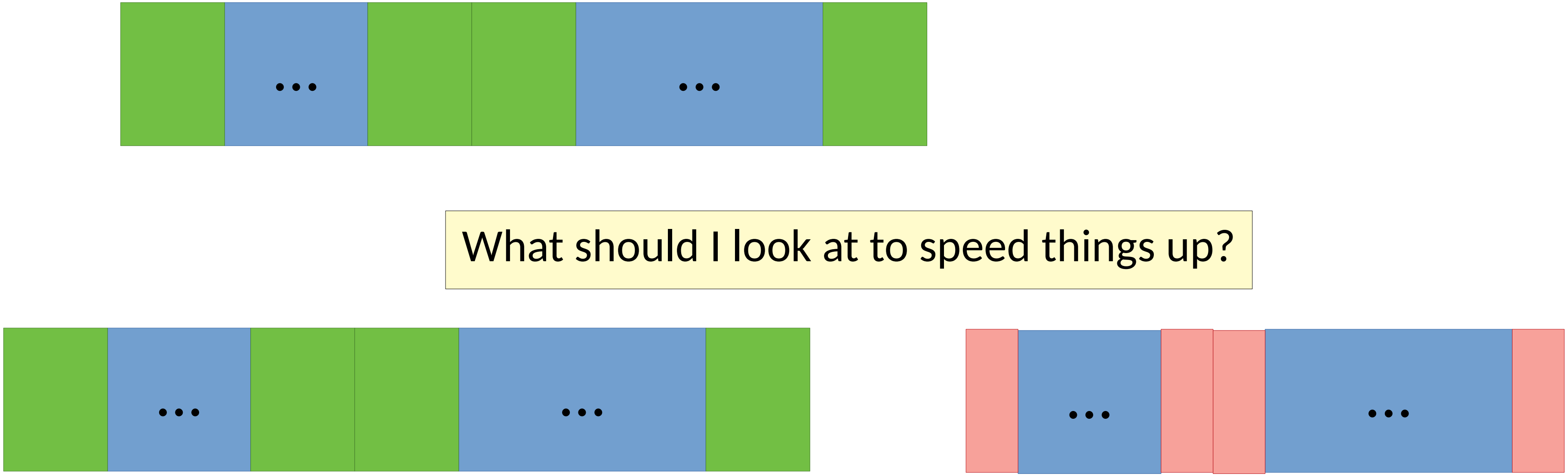

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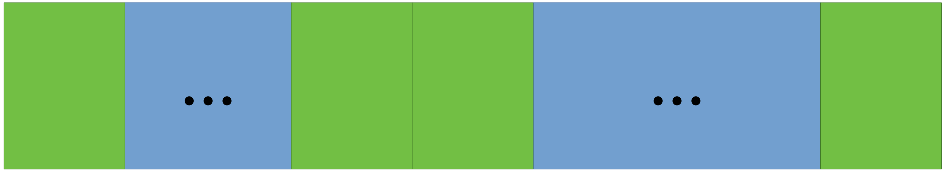

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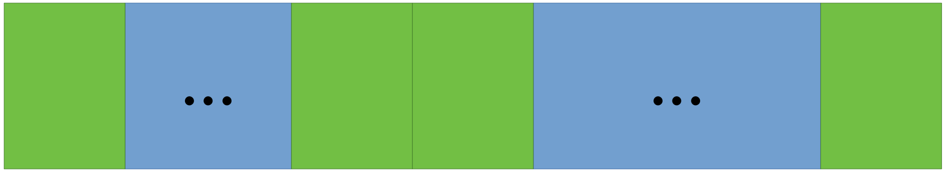

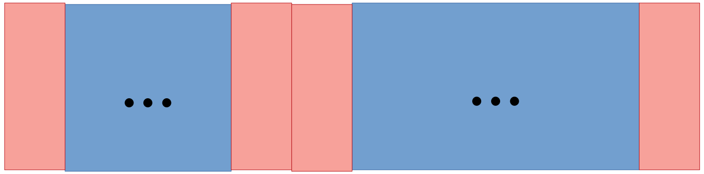

How would you implement such a tool?

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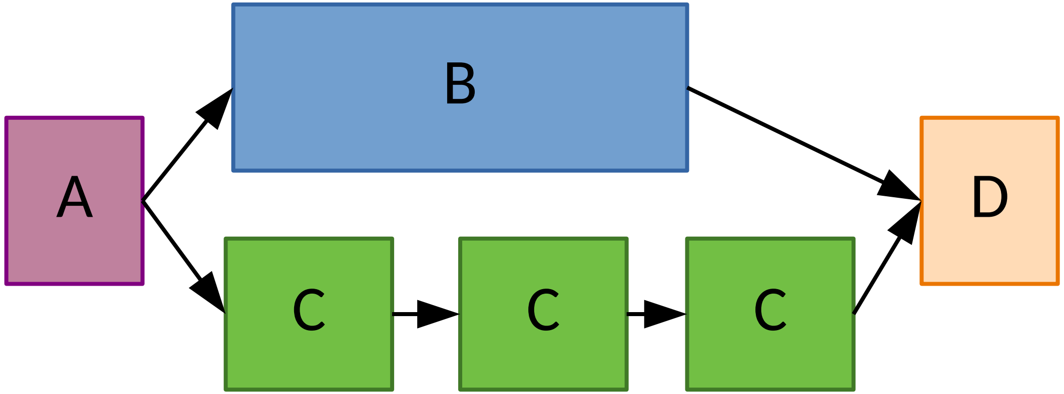

What about parallel code?

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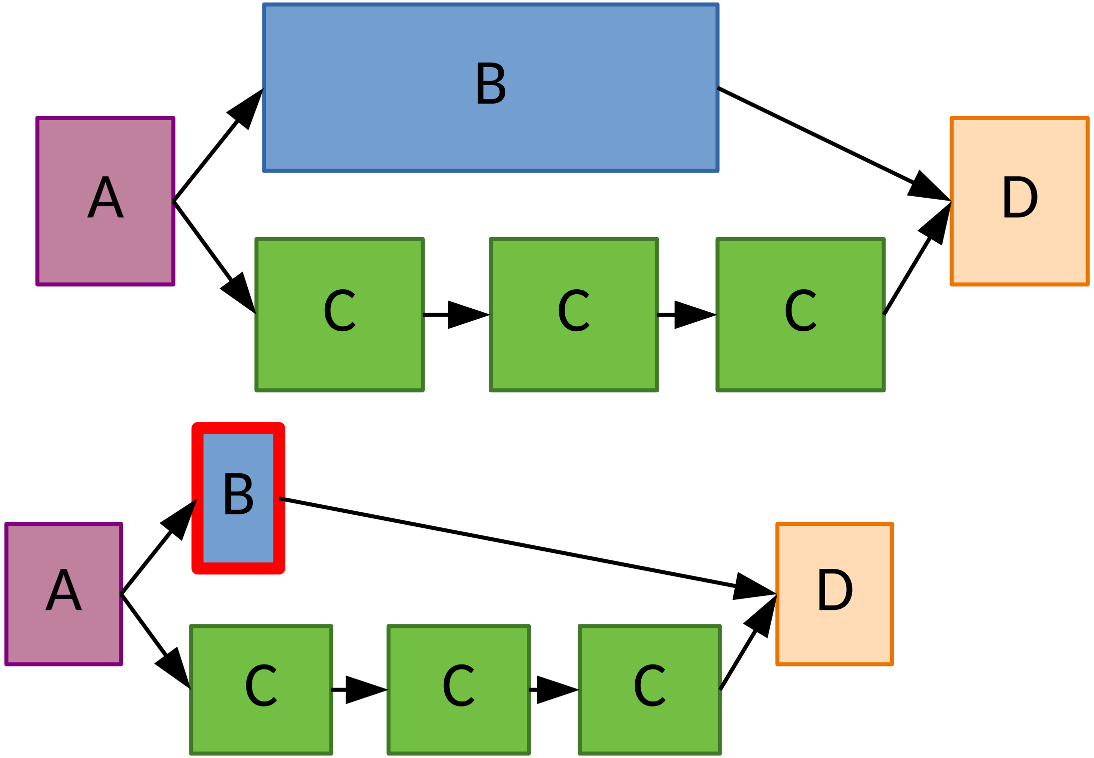

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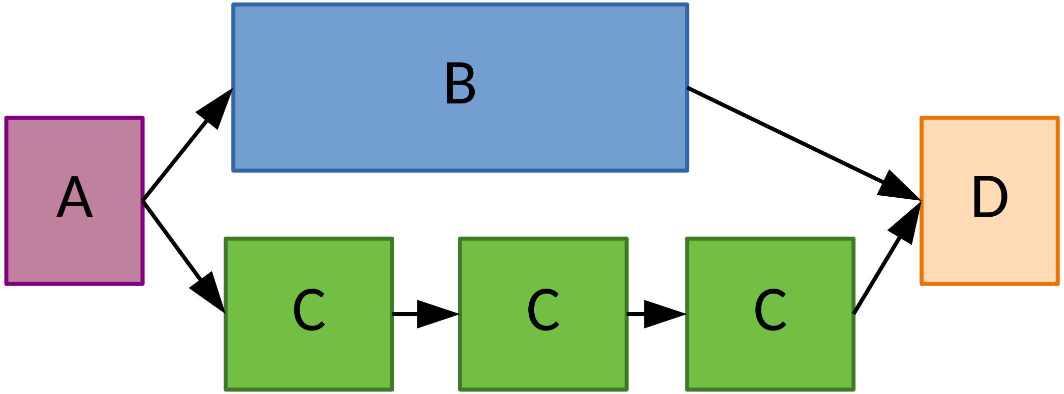
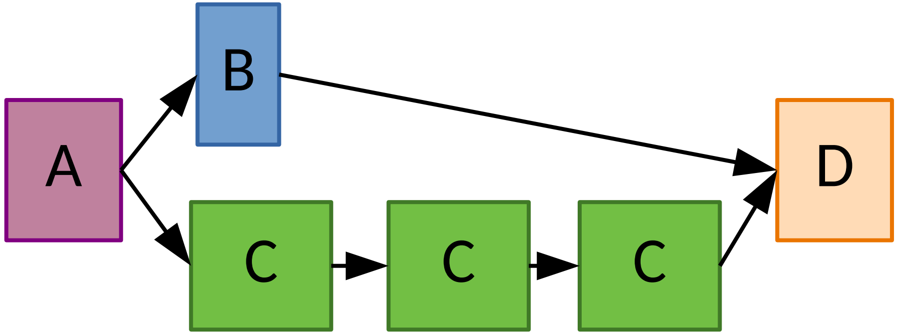
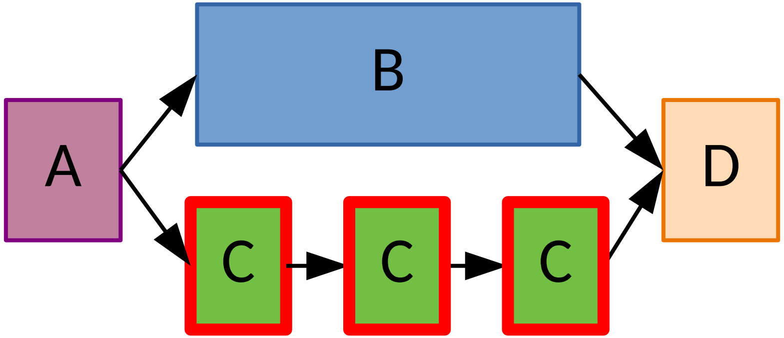
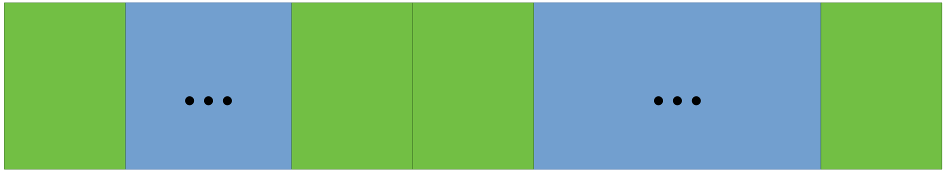






Profiling for *opportunities*

- Causal profiling
- Profiling *for parallelism* (1, 2, 3, 4, 5, …)



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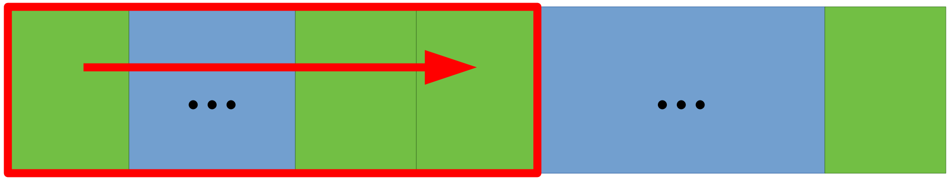

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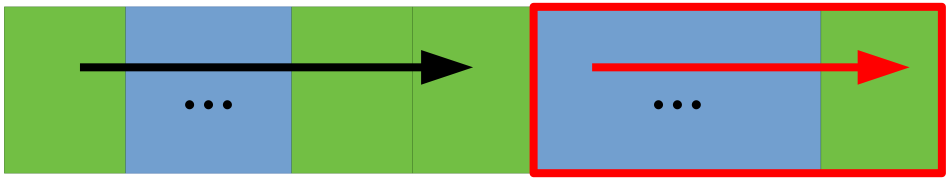

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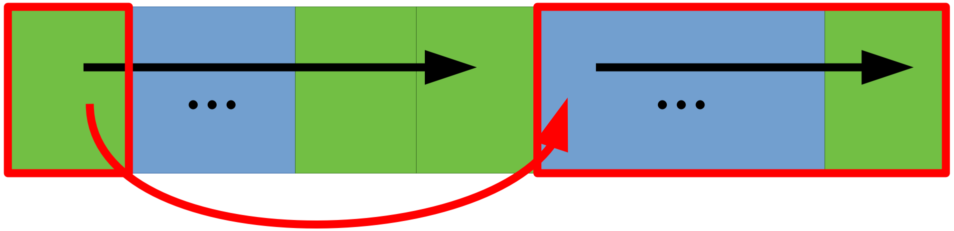
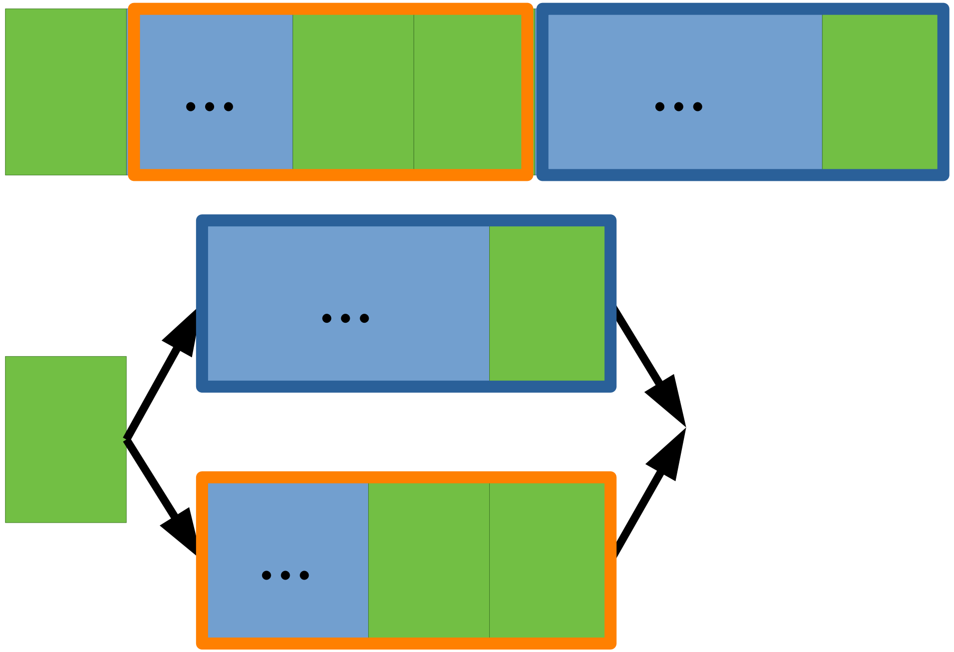


Profiling for *opportunities*

- Causal profiling
- Profiling for parallelism (1, 2, 3, 4, 5, ...)



Improving Performance

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  - Compilers & tuning the build process

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- Optimizing cold code can *hurt* software
  - You need to understand your trade offs, goals, & business value
  - But also *do not ignore* basic performance awareness

Compiling for performance

- Enabling optimizations…

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- LTO (Link Time Optimization / Whole Program Optimization)

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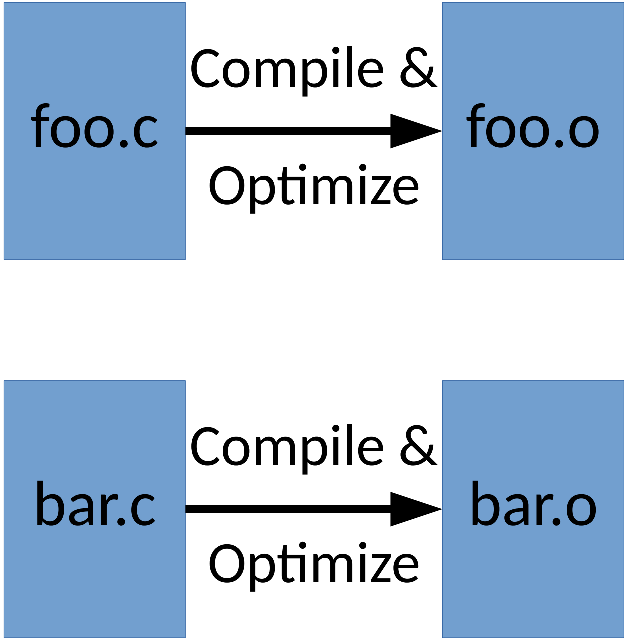

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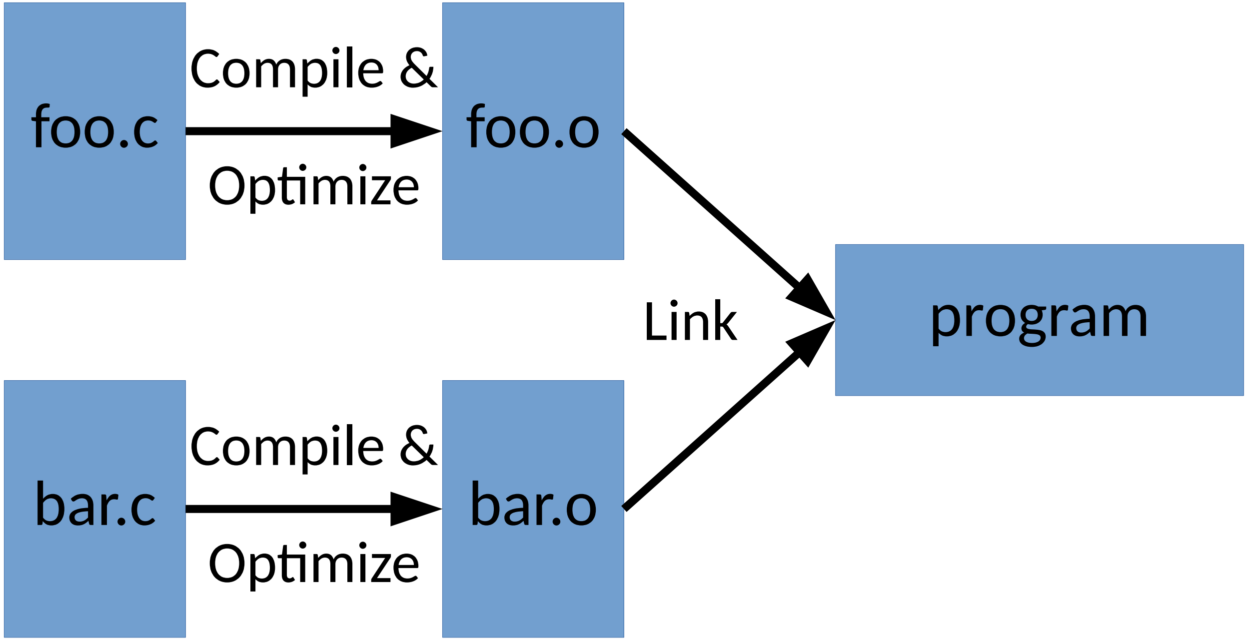

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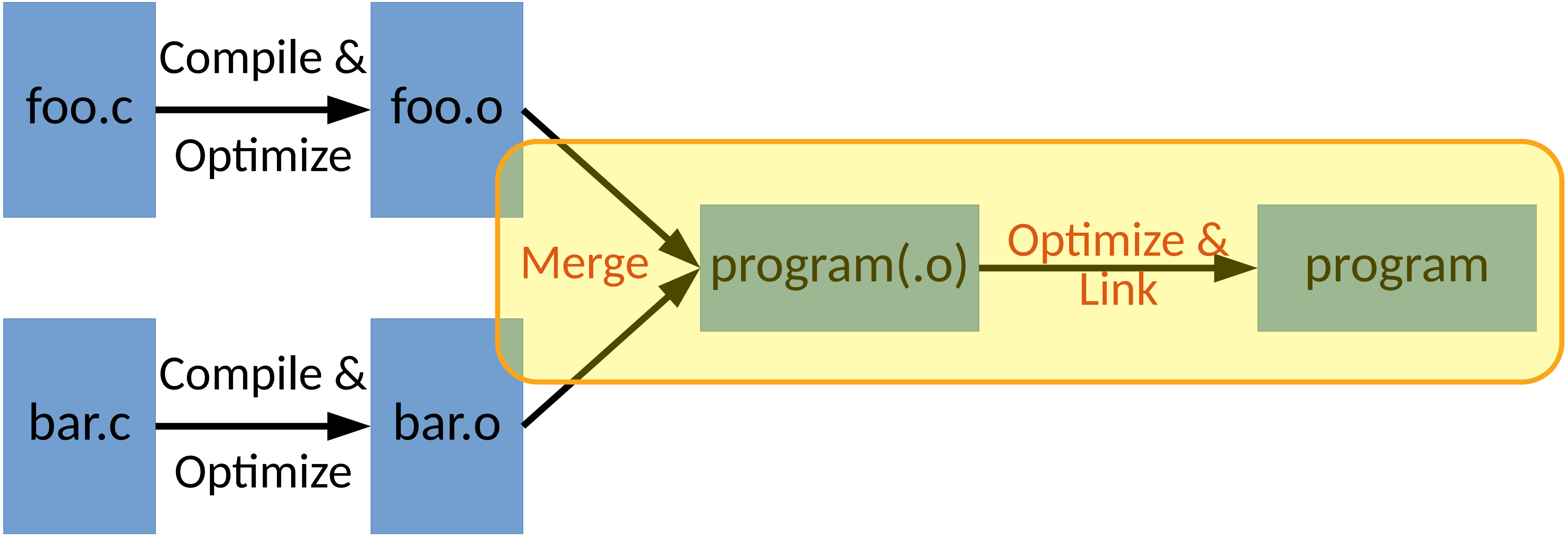

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funPtr = ?
      …
funPtr()
```

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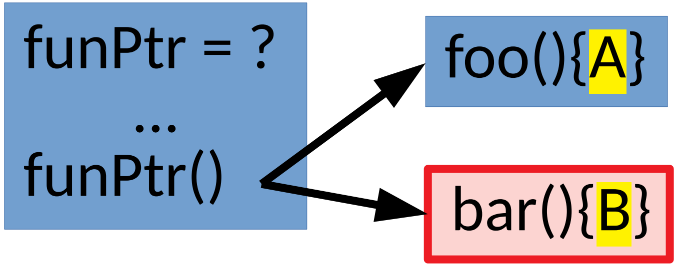

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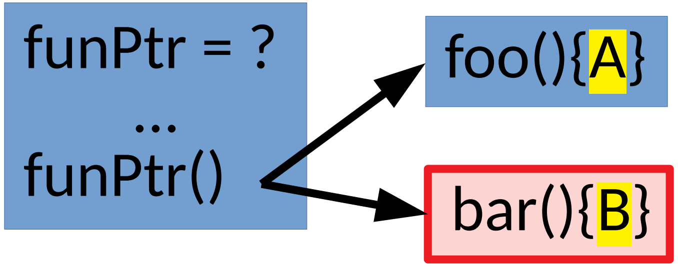


```
funPtr = ?
      …
if funPtr == bar:
    B'
else:
    funPtr()
```

Compiling for performance

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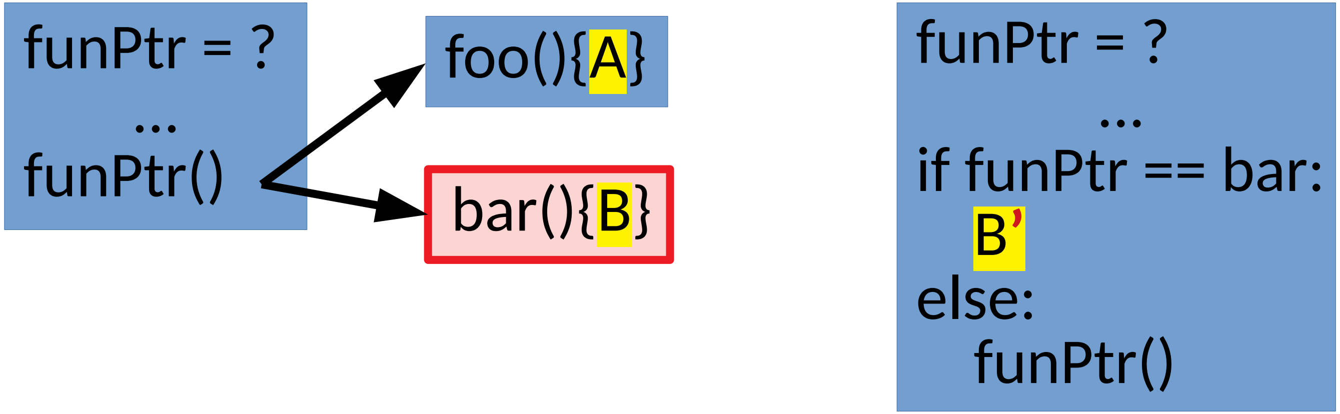

[Visual Studio profile guided optimizations]

Compiling for performance

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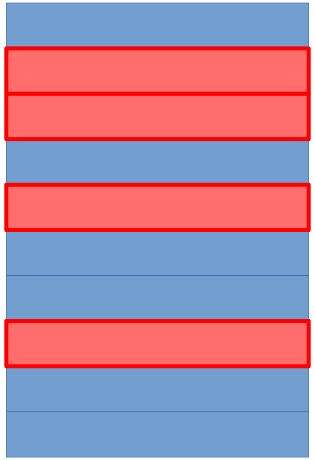

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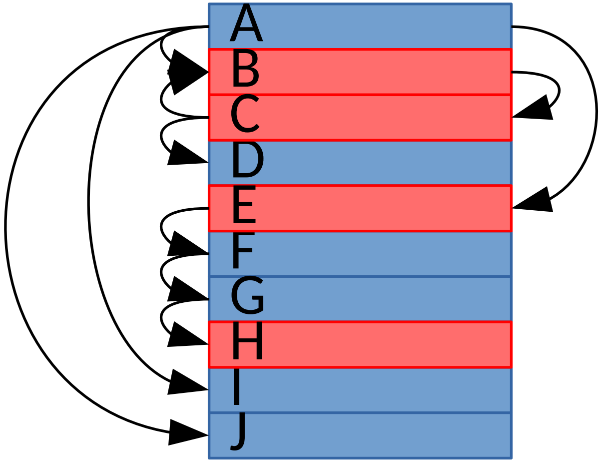

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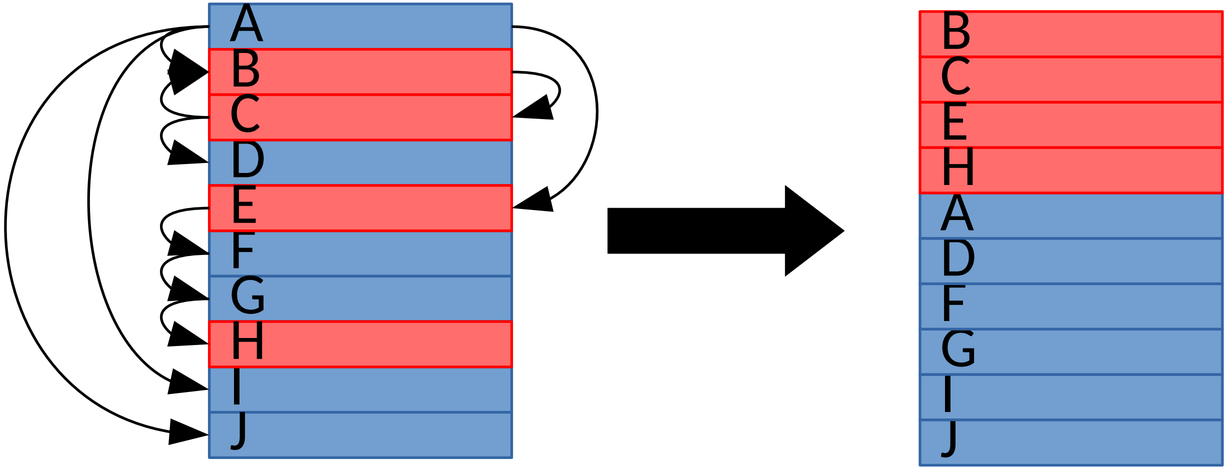

Compiling for performance

- Enabling optimizations…
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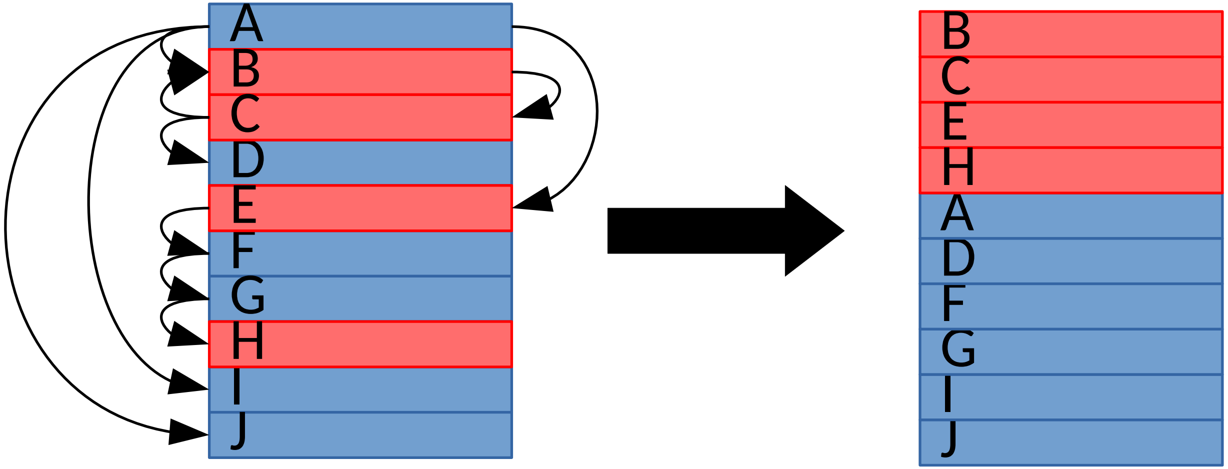
Google & Facebook found it useful on servers.
Apple has found it useful in embedded devices & apps.
Why? [Hot-Cold Splitting in LLVM]



Compiling for performance

- Enabling optimizations…
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- Polyhedral analysis, tiling, etc.
  - Transforming complex operations on, e.g., matrices to maximize locality

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- Polyhedral analysis, tiling, etc.
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Even for web apps, these techniques make a difference when applied to the hot path.
[Google Developer Updates]

Optimizing Your Data

- The basic directions of data optimizations

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- The basic directions of data optimizations
  - Ensure the data you *want* is *available* for the tasks you have

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Several aspects of high level design may be in tension with these

Optimizing Your Data

- Basic structure packing
  - Smaller aggregates consume less cache

```
struct S1 {
  char a;
};
```

sizeof(S1) == 1

```
struct S2 {
  uint32_t b;
};
```

sizeof(S2) == 4

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```
struct S3 {
  char a;
  uint32_t b;
  char c;
};
```

sizeof(S3) == ?

Optimizing Your Data

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struct S1 {
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struct S3 {
  char a;
  uint32_t b;
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```

sizeof(S3) == **12**

uint32_t must be 4 byte aligned.
Padding is inserted!

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sizeof(S2) == 4

```
struct S3 {
  char a;
  uint32_t b;
  char c;
};
```

sizeof(S3) == 12

```
struct S4 {
  char a;
  char c;
  uint32_t b;
};
```

sizeof(S3) == **8**

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Careful ordering improves cache utilization

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```
template <class PointedTo>
class PointerValuePair<PointedTo,int> {
  uintptr_t compact;
  PointedTo* getP() {
    return reinterpret_cast<PointedTo*>(compact & ~0xFFFFFFF8);
  }
  Value getV() { return compact & 0x00000007; }
};
```

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Optimizing Your Data

- Managing indirection
  - Pointers and indirection can stall the CPU while waiting on memory

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```
std::list numbers = ...
for (auto& i : numbers) {
   ...
}
```

We already saw this.
Traversing a linked list is expensive!

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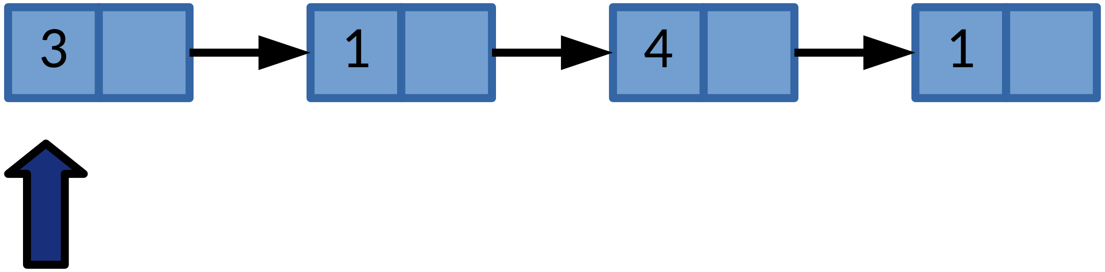

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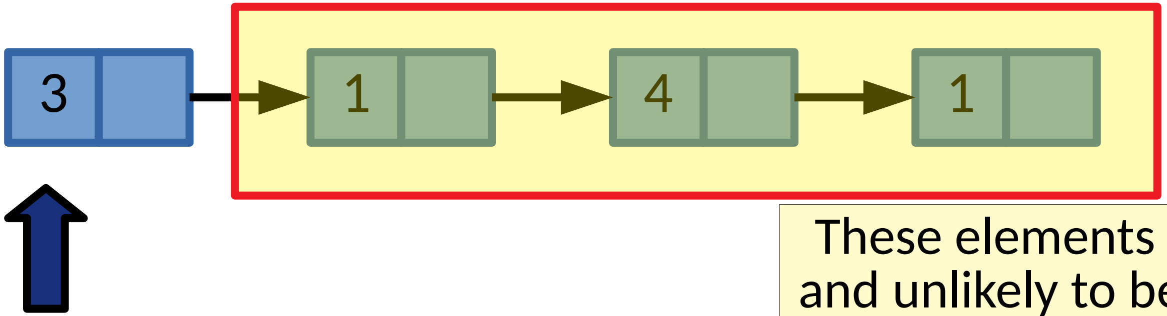

These elements are unlikely to be in cache and unlikely to be prefetched automatically.

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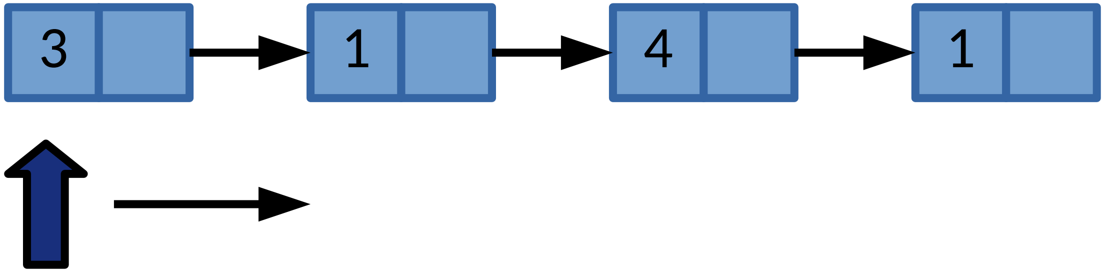

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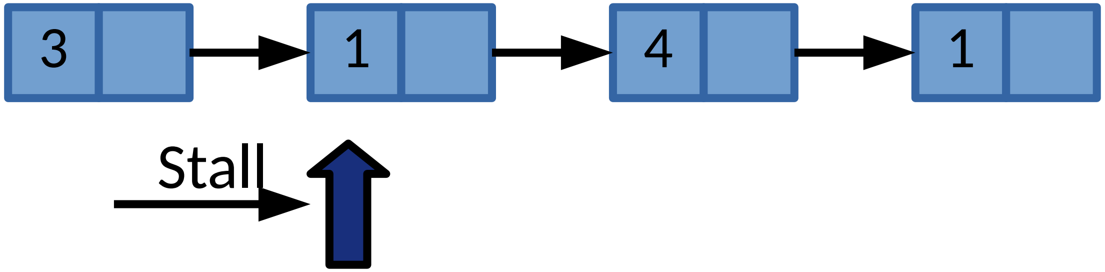

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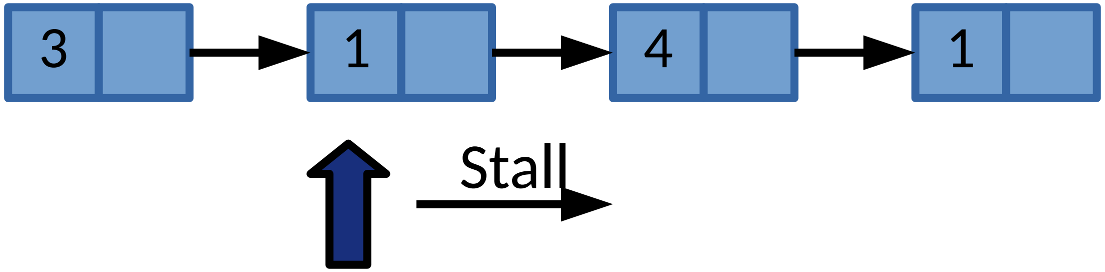

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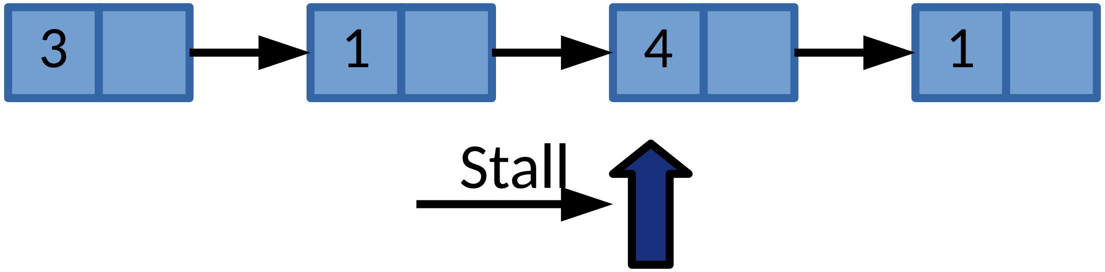

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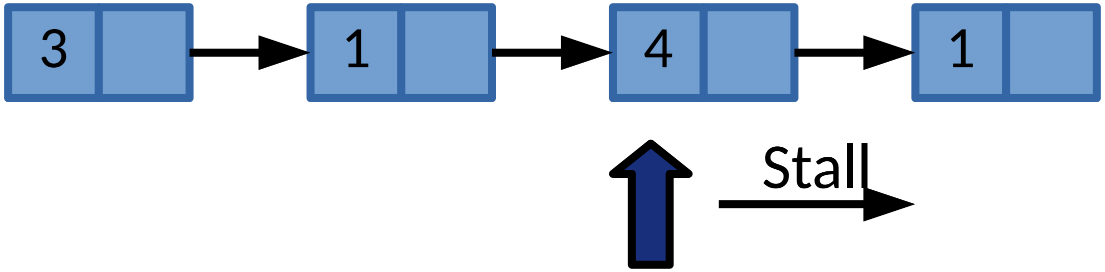

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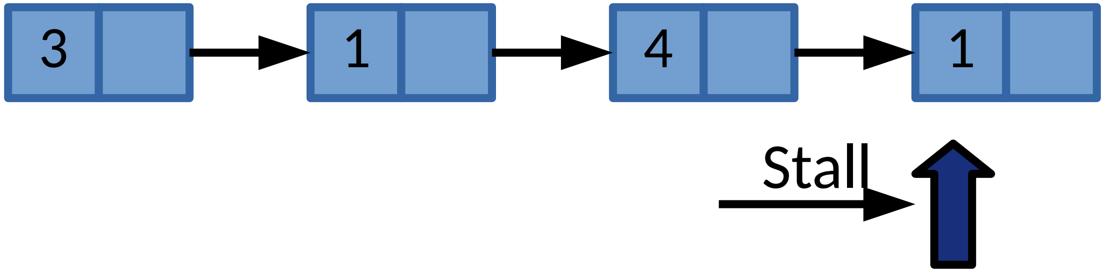

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How does this relate to
design tools that we have seen?

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How does this relate to
design tools that we have seen?

How does this relate to
language selection & performance?

Optimizing Your Data

- Grouping things that are accessed together
  - Guiding spatial design by temporal locality can improve cache utilization

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```
for (Dog& d : dogs) {
  play(d.friendliness, d.hobby);
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```

We can try to push the cold fields out of the cache

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};
```

```
for (Dog& d : dogs) {
  play(d.friendliness, d.hobby);
}
```

```
struct HotDog {
  double friendliness;
  std::string hobby;
  unique_ptr<Cold> cold;
};
```

```
struct Cold {
  uint32_t age;
  uint32_t ownerID;
  Food treats[10];
};
```

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Benefits depend on
the size of Cold & the access patterns

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Benefits depend on
the size of Cold & the access patterns

Again, profilers can guide the process.
[Le, 2019]

Optimizing Your Data

- Grouping things that are accessed together
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  - Cold field outlining
  - AoS vs SoA (Array of Structs vs Struct of Arrays)

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struct Dog {
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  uint32_t ownerID;
  std::string hobby;
  Food treats[10];
};
```

```
struct DogManager {
  std::vector<uint32_t> friendliness;
  std::vector<uint32_t> age;
  std::vector<uint32_t> ownerID;
  std::vector<std::string> hobby;
  std::vector<std::array<Food,10>> treats;
};
```

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};
```

```
for (auto i : range(dogs)) {
  play(friendliness[i], hobby[i]);
}
```

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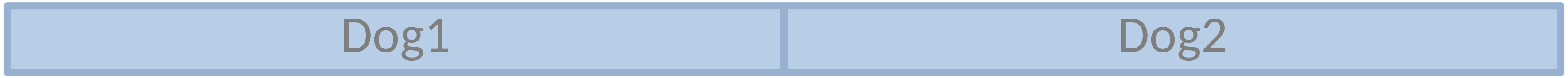

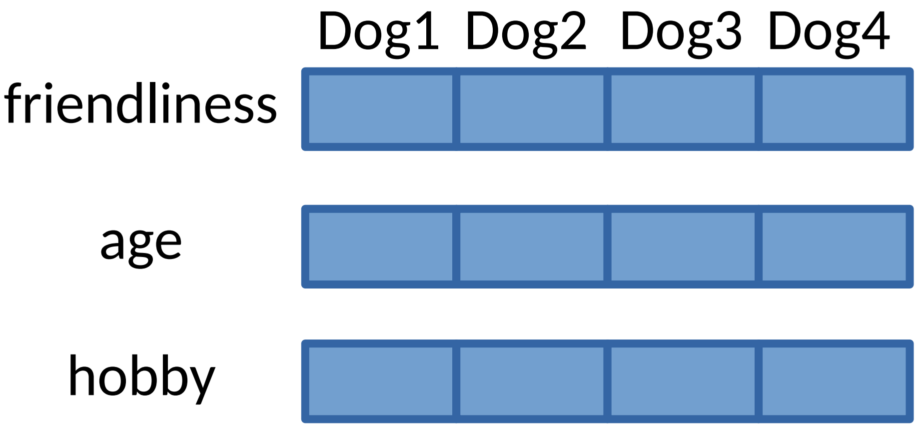

Optimizing Your Data

- Grouping things that are accessed together
  - Guiding spatial design by temporal locality can improve cache utilization
  - Cold field outlining
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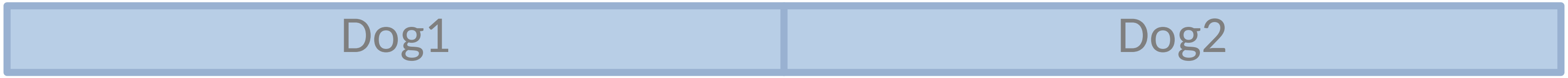

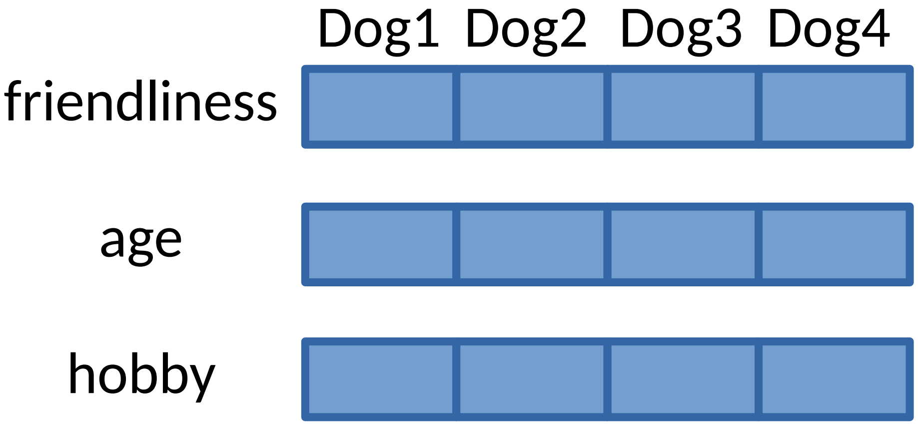

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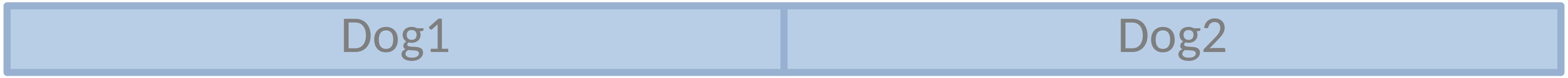

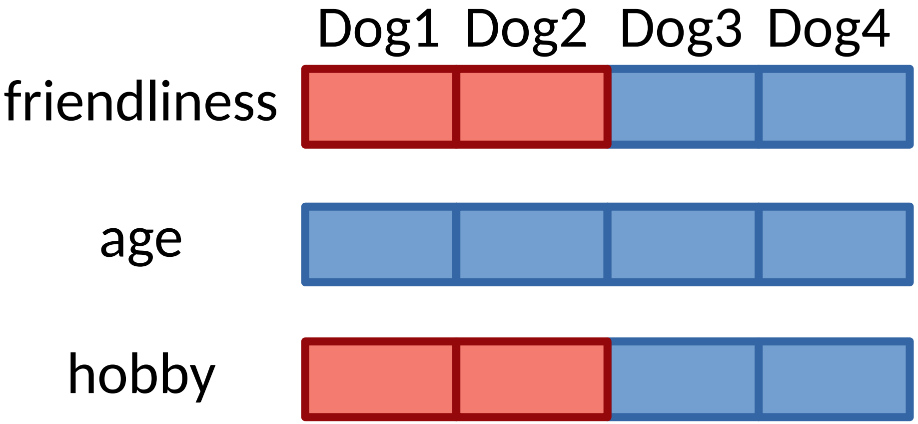

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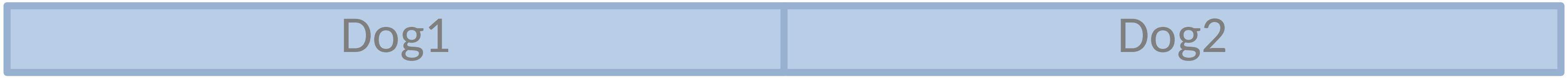

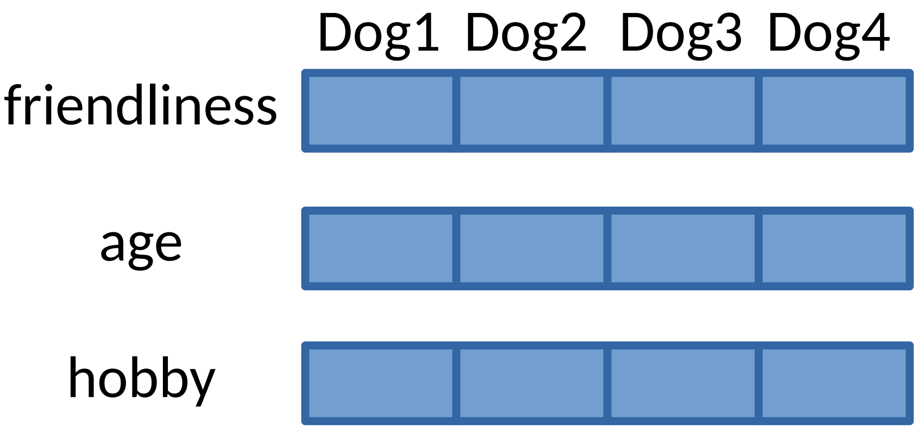

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Easier for compilers to vectorize

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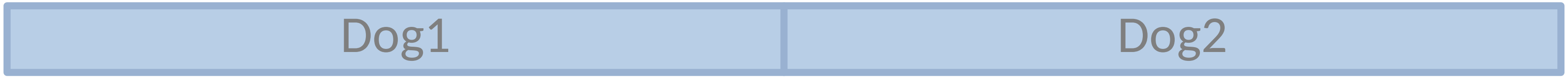

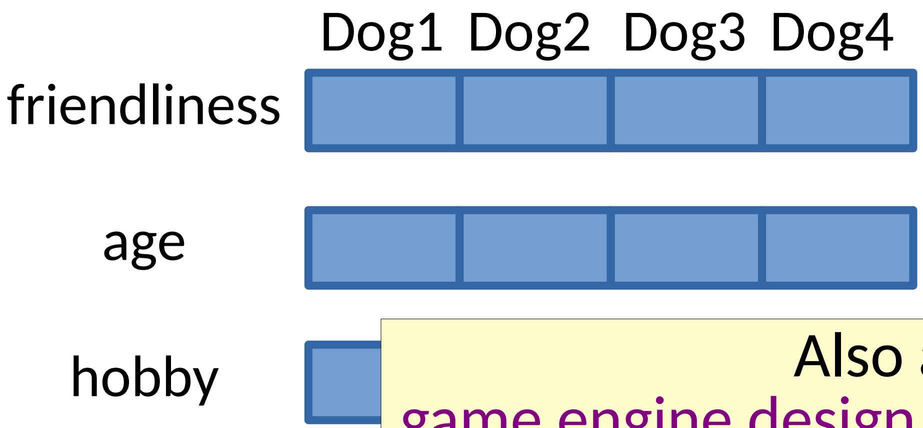

You can pick and choose while still getting good locality

Easier for compilers to vectorize

Also a foundation of modern game engine design (ECS) & data processing (columnar DB)

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  - Compilers automate this but cannot always succeed (LICM)

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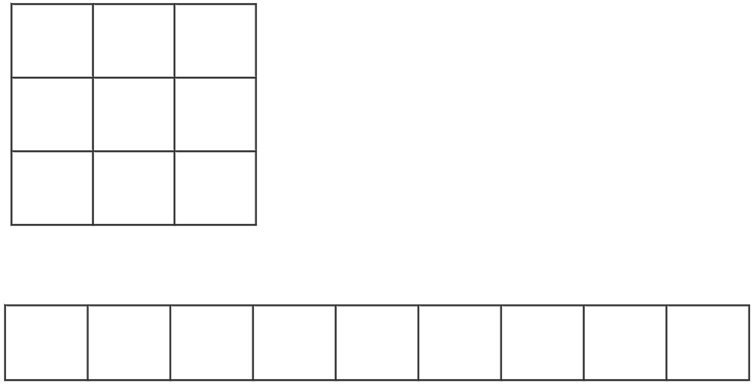

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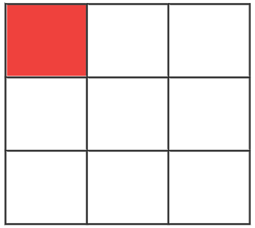

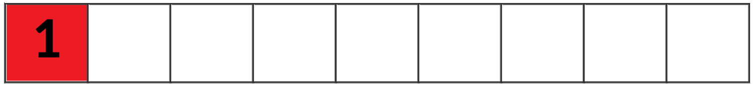

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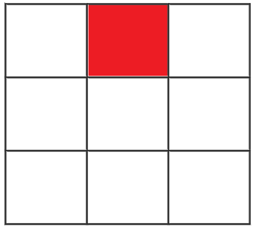

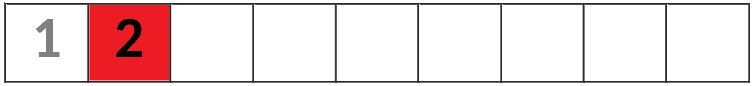

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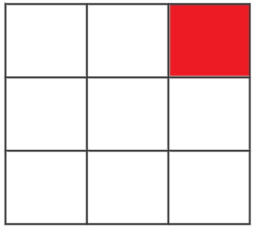

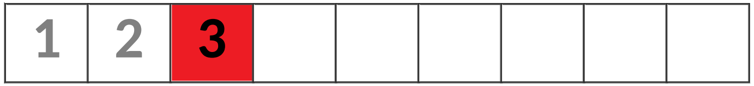

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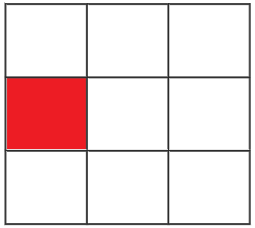

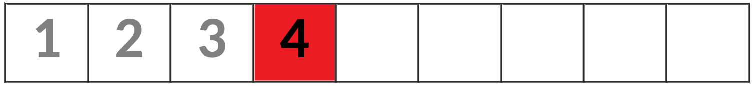

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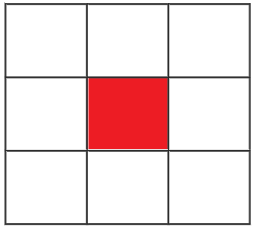

Memory accesses are consecutive!


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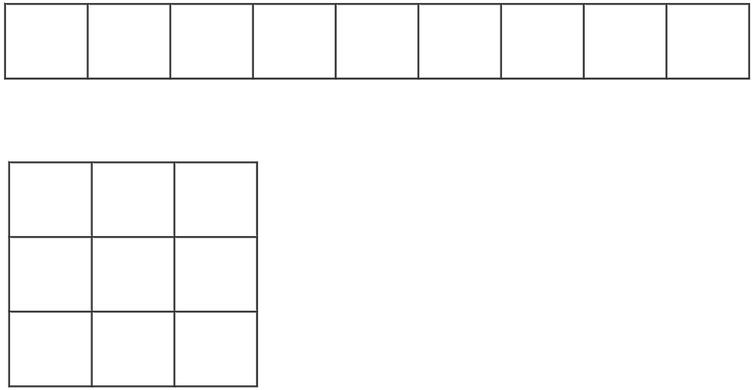

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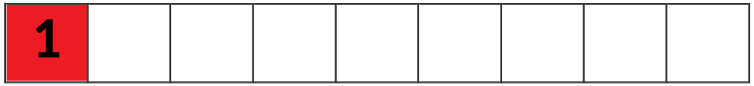

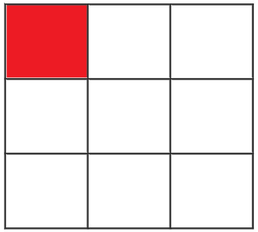

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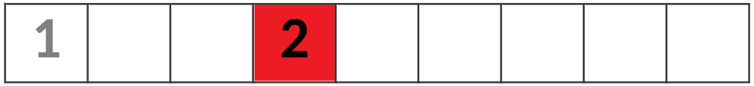

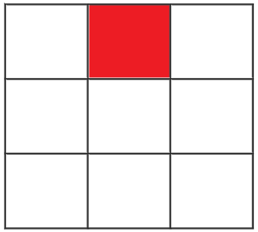

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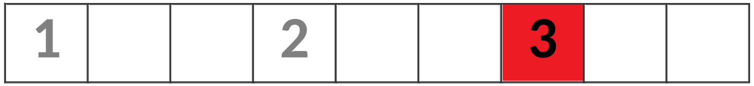

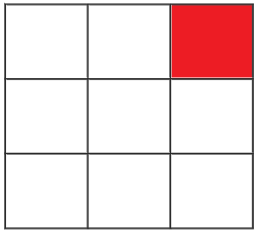

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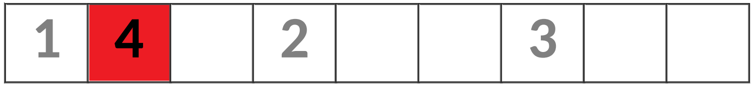

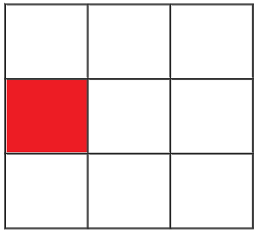

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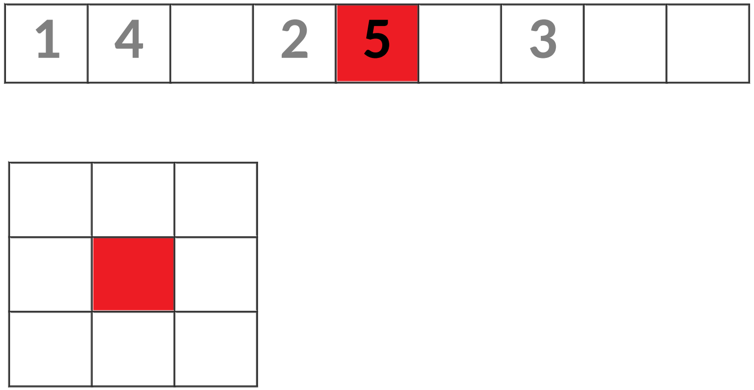

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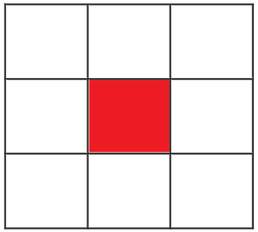

Memory accesses jump around & thrash the cache!

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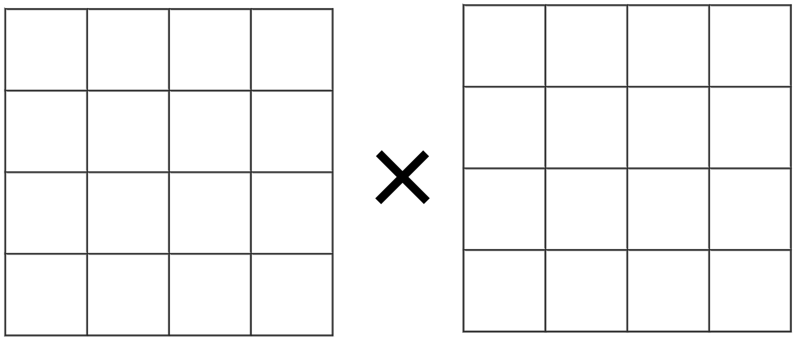

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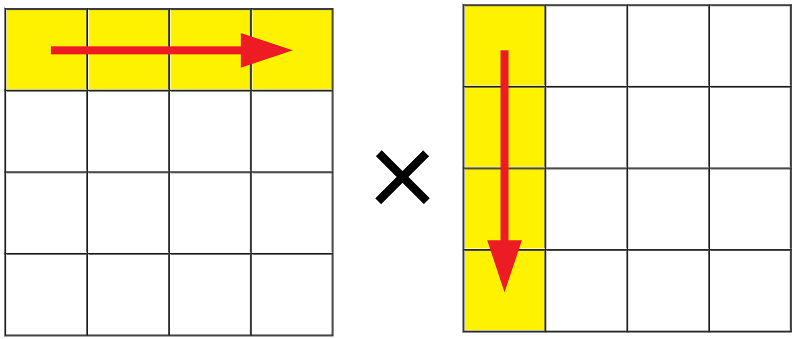

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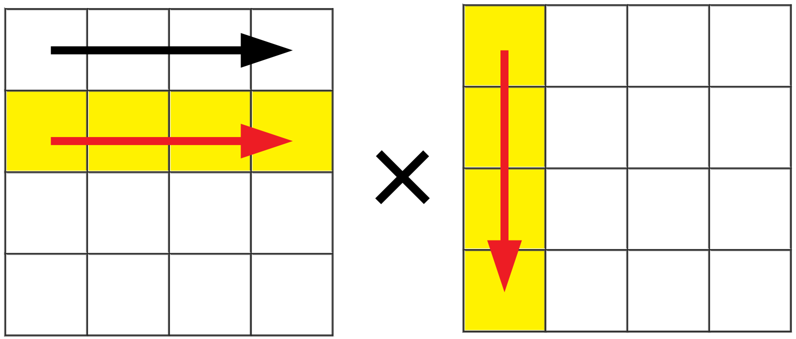

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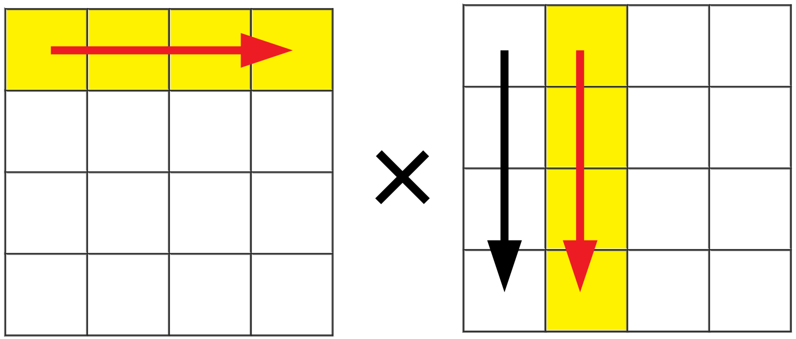

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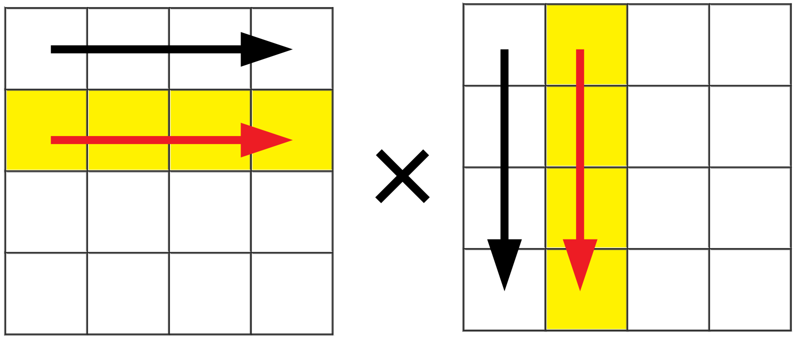

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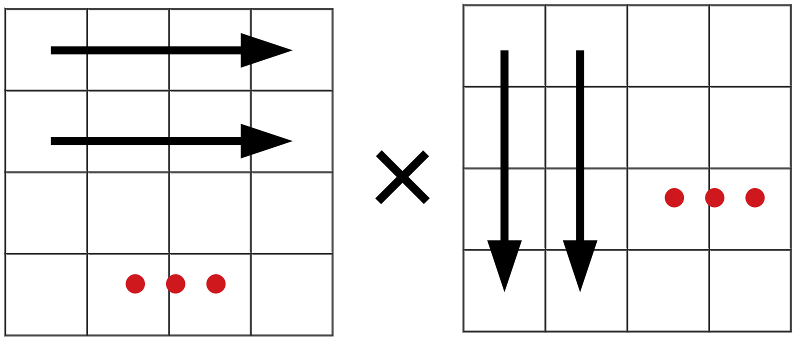

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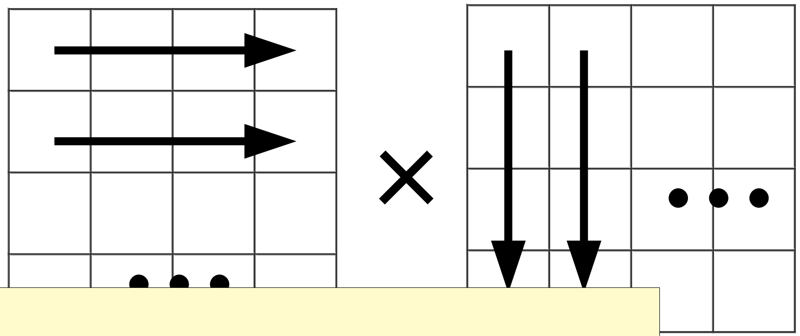

Problem:
Using the same layout creates bad locality.

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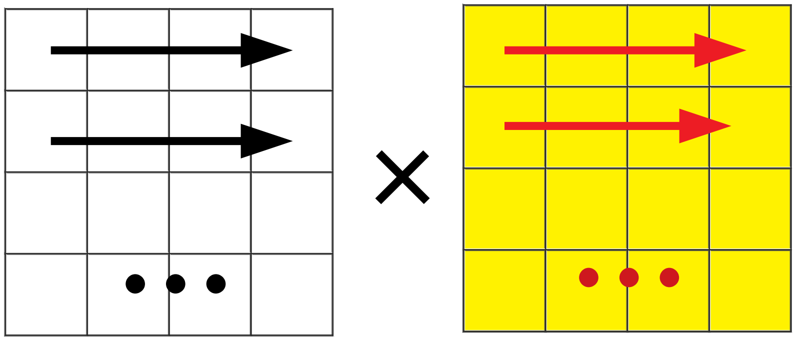

Solution: Transpose first.
Implement over the transpose instead.

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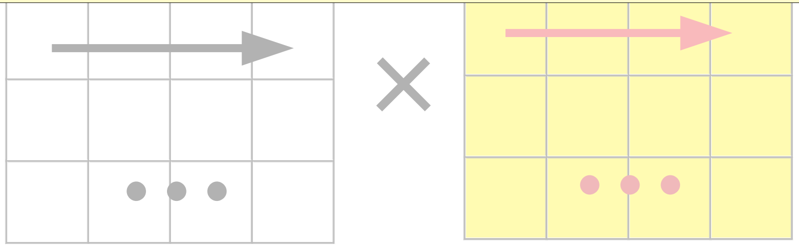
Note: Better solutions further leverage layout & parallelization.



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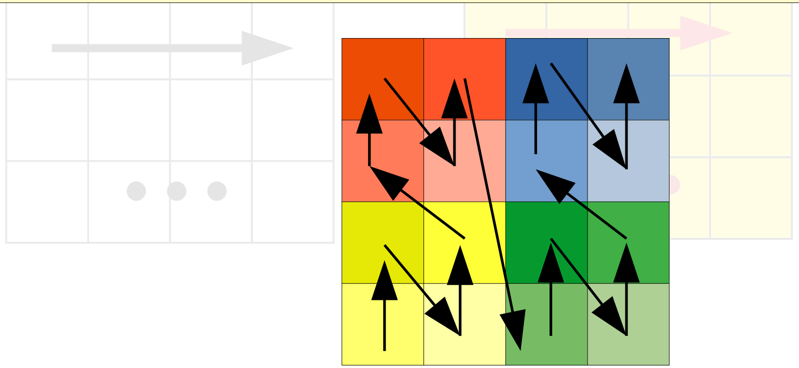

tiling, polyhedral analysis, …

[polyhedral.info]

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- Memory management effects
  - Data structure packing & access patterns affect deeper system behavior

Optimizing Your Data

- Memory management effects
  - Data structure packing & access patterns affect deeper system behavior
    - What about virtual memory, page tables, & the TLB?

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    - What about virtual memory, page tables, & the TLB?
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Optimizing Your Data

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Object/Memory pools?

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      Object/Memory pools?
      Per class allocation?

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      Region based allocation?

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      Object/Memory pools?
      Per class allocation?
      Region based allocation?
      Bump pointer allocators?
      Cyclic buffers?
      Precomputed allocation requirements & scheduling?

Optimizing Your Data

- Memory management effects
  - Data structure packing & access patterns affect deeper system behavior
    - What about virtual memory, page tables, & the TLB?
    - What about allocation strategies & fragmentation?
  - Data structure inlining
    - folly::small_vector
      absl::InlinedVector
      rust-smallvec
      …

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    - folly::small_vector
      absl::InlinedVector
      rust-smallvec
      …

```
small_vector<int,2> vec;
vec.push_back(0); // Stored in-place on stack
vec.push_back(1); // Still on the stack
vec.push_back(2); // Switches to heap buffer
```

[facebook's small_vector]

Optimizing Your Data

- Designing with clear ownership policies in mind

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  - Resource acquisition should not happen in hot code

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  - Use APIs that express intent & prevent copying

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“std::string is responsible for almost half of all allocations in the Chrome”

```
foo(const std::string& s) {
  bar(s.c_str());
}
```

```
bar(const char* s) {
  baz(std::string{s});
}
```

```
baz(const std::string& s) {
  quux(s.c_str());
}
```

```
quux(const char* s) {
  quuz(std::string{s});
}
```

Optimizing Your Data

- Designing with clear ownership policies in mind
  - Resource acquisition should not happen in hot code
  - Use APIs that express intent & prevent copying

"std::string is responsible for almost half of all allocations in the Chrome"

```
template<class E>
struct Span {
    template<class E, auto N>
    Span(const std::array<E,N>& c);

    template<class E>
    Span(const std::vector<E>& c);

    E* first;
    size_t count;
};
```

Optimizing Your Code

- Basic ideas for code optimization (we'll walk through examples shortly)

Optimizing Your Code

- Basic ideas for code optimization
  - Avoid branching whenever possible

Optimizing Your Code

- Basic ideas for code optimization
  - Avoid branching whenever possible

Mis-speculating over a branch is costly

Optimizing Your Code

- Basic ideas for code optimization
  - Avoid branching whenever possible
  - Make code that does the same thing occur close together temporally

Optimizing Your Code

- Basic ideas for code optimization
  - Avoid branching whenever possible
  - Make code that does the same thing occur close together temporally

Leverage the instruction cache if you can

Optimizing Your Code

- Branch prediction & speculation

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements

```
for (...) {
  if (foo(c)) {
    bar();  A
  } else {
    baz();  B
  }
}
```

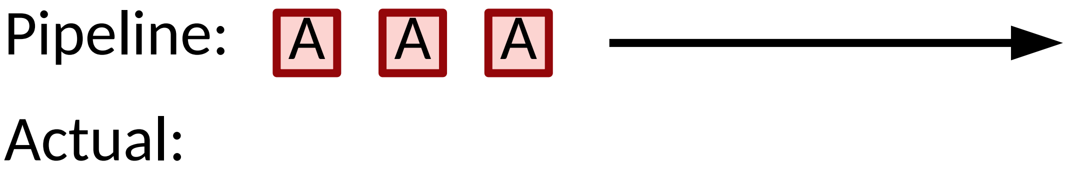
90%

10%

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements

```
for (...) {
  if (foo(c)) {
    bar();    A    90%
  } else {
    baz();    B    10%
  }
}
```



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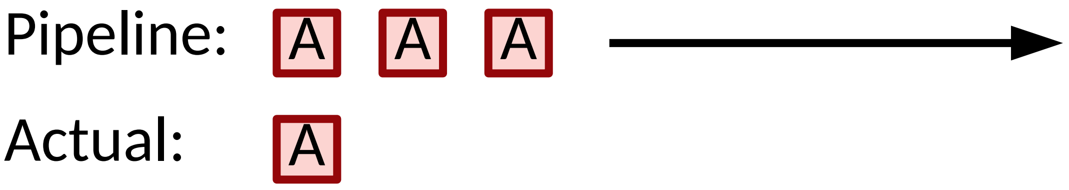

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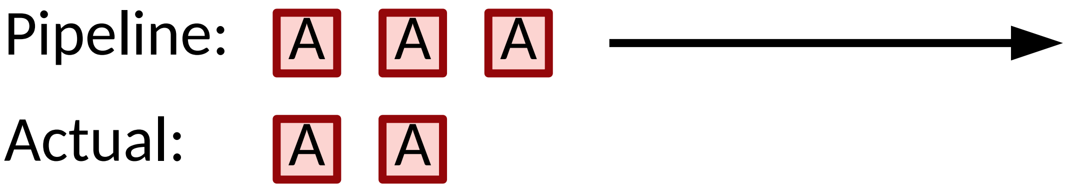

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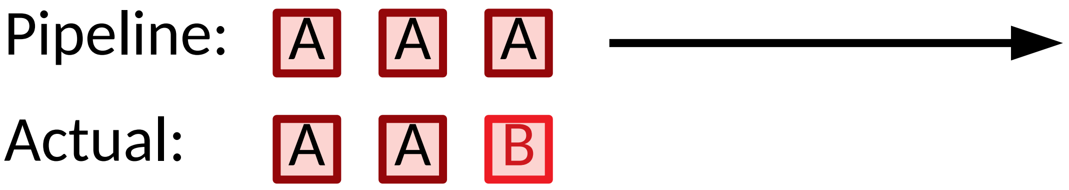
A 90%

B 10%



Optimizing Your Code

- Branch prediction & speculation
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```
for (...) {
  if (foo(c)) {
    bar();  [A]
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```

90%

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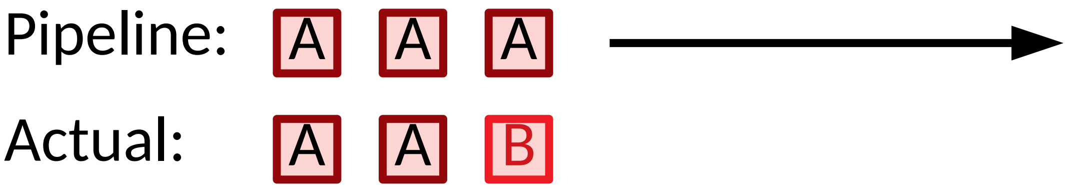

Stall, but relatively infrequently

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements

```
for (...) {
  if (foo(c)) {
    bar(); A
  } else {
    baz(); B
  }
}
```

51%

49%

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements

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for (...) {
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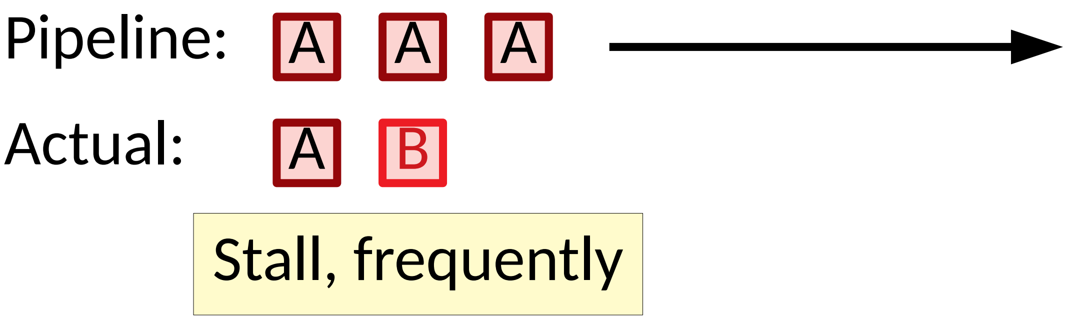
51%

49%



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```
for (...) {
  if (foo(c)) {
    bar();    A
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}
```

51%

49%

Pipeline: A A A →

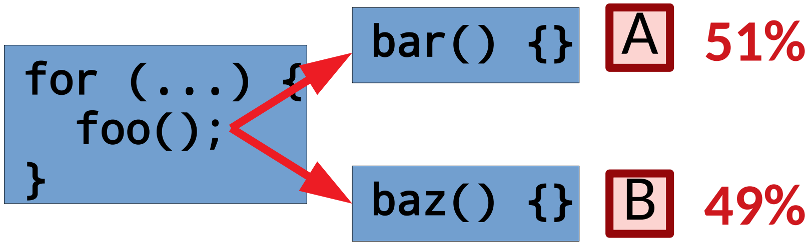
Actual: A B

Stall, frequently

How would you fix it?

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements
  - On function pointers!



Optimizing Your Code

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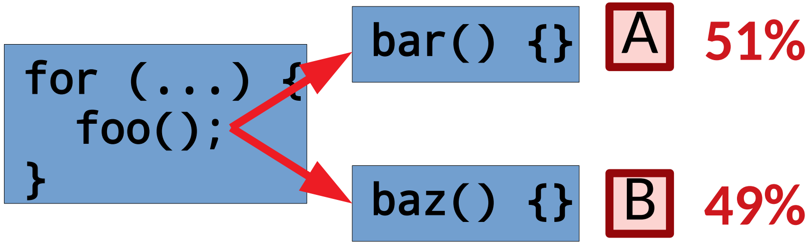

The same problems arise

Optimizing Your Code

- Branch prediction & speculation
  - On `if` statements
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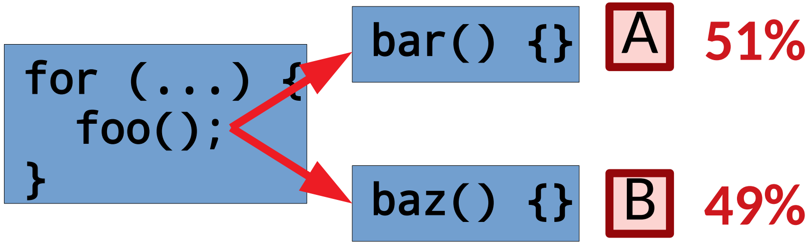

The same problems arise

Consistent call targets perform better

Optimizing Your Code

- Designing away checks
  - Repeated checks can be removed by maintaining invariants

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```
i ← 1
while i < length(A)
    j ← i
    while j > 0 and A[j-1] > A[j]
        swap A[j] and A[j-1]
        j ← j - 1
    i ← i + 1
```

[Wikipedia’s Insertion Sort]

Optimizing Your Code

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Can we turn the semantic check into a bounds check?

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We just guarantee that **A** starts with the smallest element!

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[Wikipedia's Insertion Sort]

```
k ← find_smallest(A)
swap A[0] and A[k]
i ← 1
while i < length(A)
    j ← i
    while A[j-1] > A[j]
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```

On an Intel i7@ 2.20GHz, uniformly random data

8192 elements:	269k items/s	415k items/s
32768 elements:	68k items/s	104k items/s
131072 elements:	17k items/s	26k items/s

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```

[Wikipedia’s Insertion Sort]

```
A[-1] ← MIN_VALUE
i ← 1
while i < length(A)
    j ← i
    while A[j-1] > A[j]
        swap A[j] and A[j-1]
        j ← j - 1
    i ← i + 1
```

Extra domain knowledge may allow this in different ways.

Values that do not appear?
Shape & distribution?
…

Optimizing Algorithms

- Improving real world algorithmic performance comes from recognizing the ***interplay*** between ***theory*** and ***hardware***

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  - Can you determine data & behaviors early?
  - Can you fetch/perform them during an early lull?

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e.g., determine resources for a web page,
& fetch them when initially loading
[Mickens 2010, Netravali 2018, Ko 2021]

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- Better performance modeling & algorithms
  - The core approaches we use have not adapted to changing contexts

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A ***uniform cost model***
throws necessary information away

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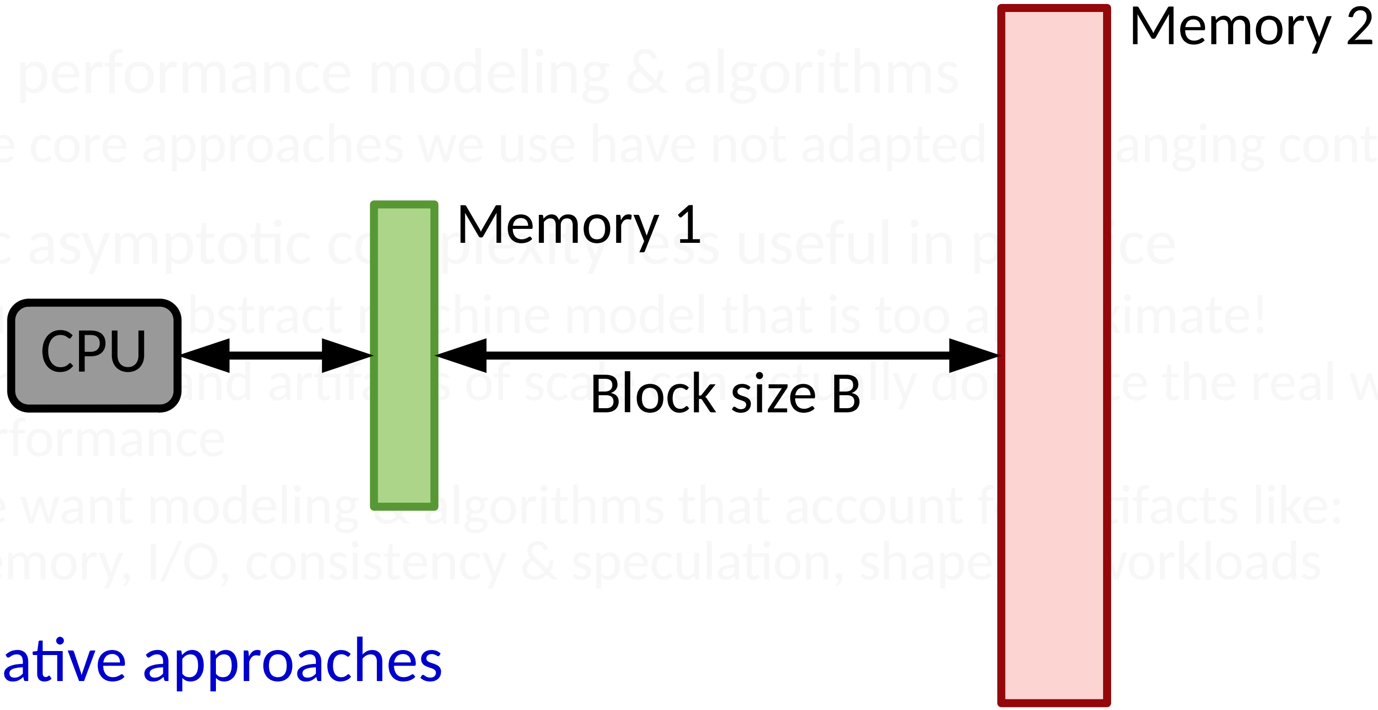

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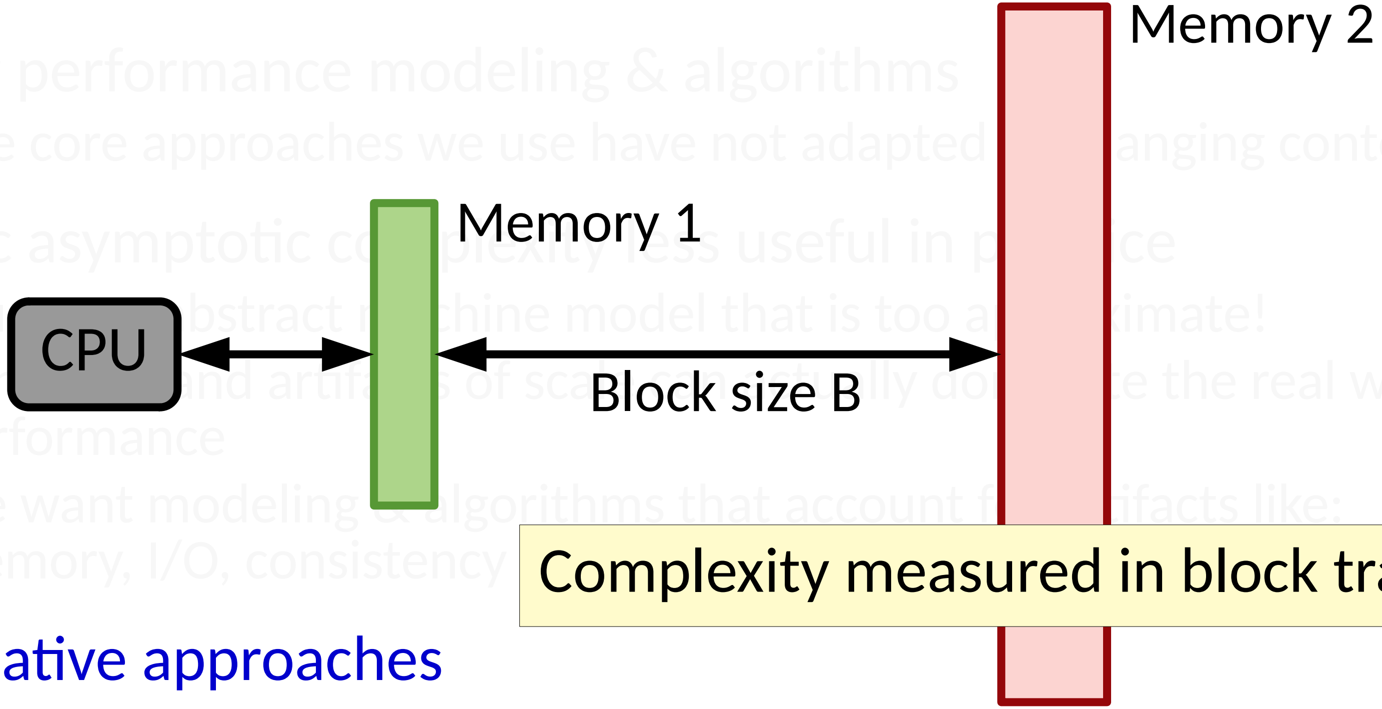
Optimizing Algorithms



Complexity measured in block transfers

- Alternative approaches
  - I/O complexity, I/O efficiency and cache awareness

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Similar to I/O, but agnostic to block size

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  - Parameterized complexity

Optimizing Algorithms

- Classic design mistakes [Lu 2012]

Optimizing Algorithms

- Classic design mistakes [Lu 2012]
  - Uncoordinated functions (e.g. lack of batching)

```
for (auto& action : actions) {
  action.do()
}
```

```
Action::do() {
  acquire(mutex)
  ...
  release(mutex)
}
```

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VS

```
acquire(mutex)
for (auto& action : actions) {
  action.do()
}
release(mutex)
```

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  - Skippable functions (e.g. transparent draws)

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```
foo() {
  bar()
}
```

```
bar() {
  baz()
}
```

```
baz() {
  quux()
}
```

```
quux() {
  random()
}
```

```
random() {
  acquire(mutex)
  ...
  release(mutex)
}
```

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random() {
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Consider
shallow, broad, & explicit designs, or
designing the resource away.

Optimizing Algorithms

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This sounds simple,
but it can become quite challenging.
[Loncaric 2016, Idreos 2018, Loncaric 2018]

Summary

- Reasoning rigorously about performance is challenging

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- Good tooling can allow you to investigate performance well

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- Reasoning rigorously about performance is challenging
- Good tooling can allow you to investigate performance well
- We can improve performance through
  - compilers
  - managing data
  - managing code
  - better algorithmic thinking