# Profiling Tutorial & DEMO

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2025-06-13

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# Outline

# Motivation & Background

# Modern CPUs: complex 🫠

- Complex behavior, hard to understand:
  - multi-issue: 6 Arithmetic Logic Units @ AMD Zen5
  - out-of-order
  - on-chip caches: L1 & L2
  - cache coherence: MESI ...
  - speculation
  - multiple cores

- **A black box**: need a model to predict performance

# Modern CPUs: complex 🫠

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  - out-of-order
  - on-c
  - cach
  - spec
  - mult

**Quiz Time:**
**- What is IPC as a HW-counter?**
**- In Theory, 6 ALU. But how to reach it in practice?**

- **A black box**: need a model to predict performance

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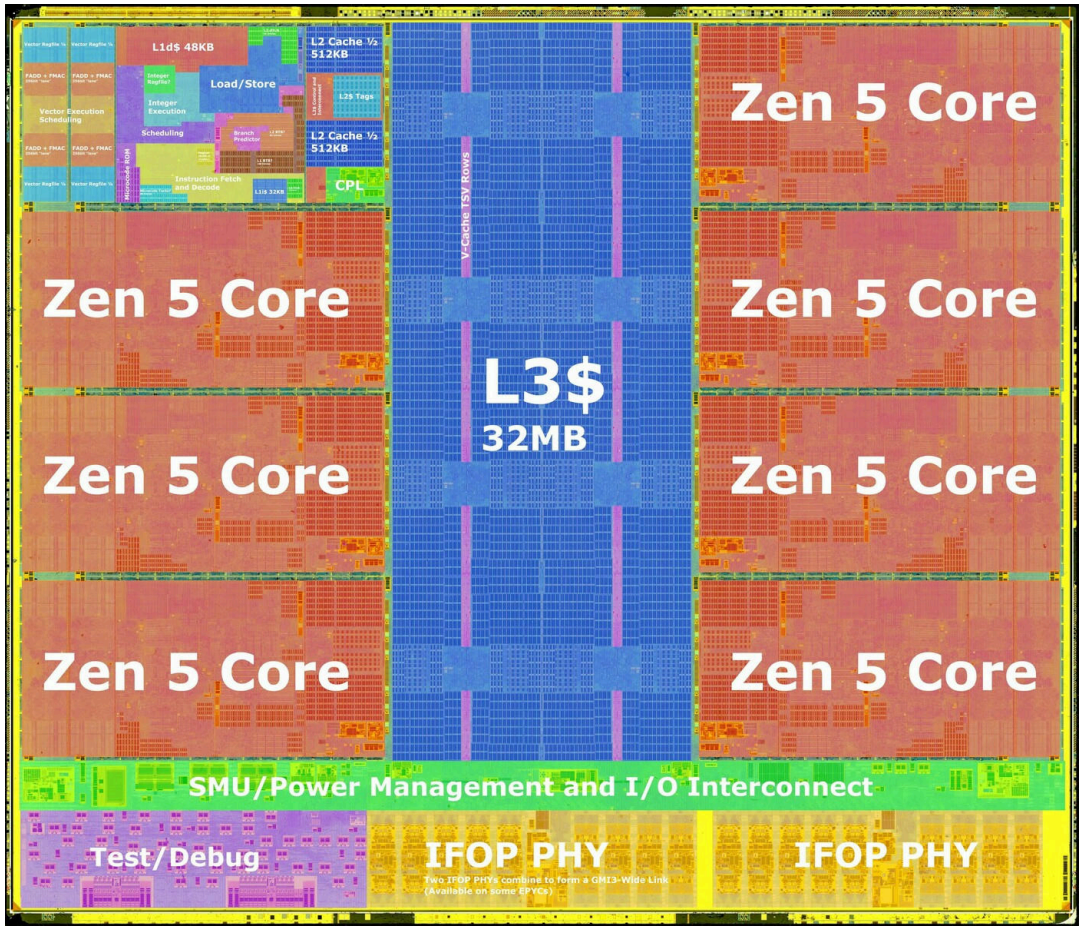
- A

**Quiz Time:**
**- What is IPC as a HW-counter?**
**- In Theory, 6 ALU. But how to reach it in practice?**

**“In theory there is no difference between theory and practice. In practice there is.” – Yogi Berra**

https://pubmed.ncbi.nlm.nih.gov/24320775/

# AMD Zen5 Die-Shot




https://www.techpowerup.com/327388/amd-granite-ridge-zen-5-processor-annotated

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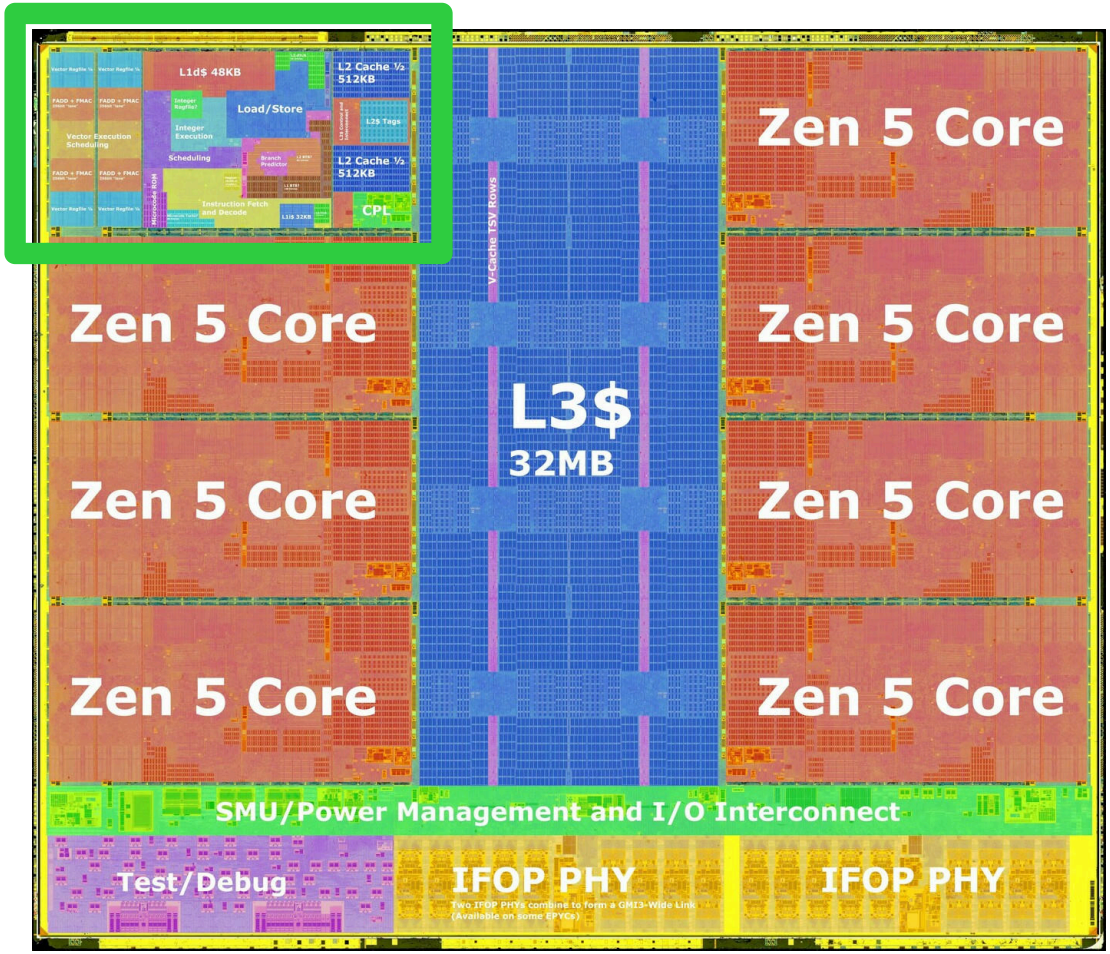


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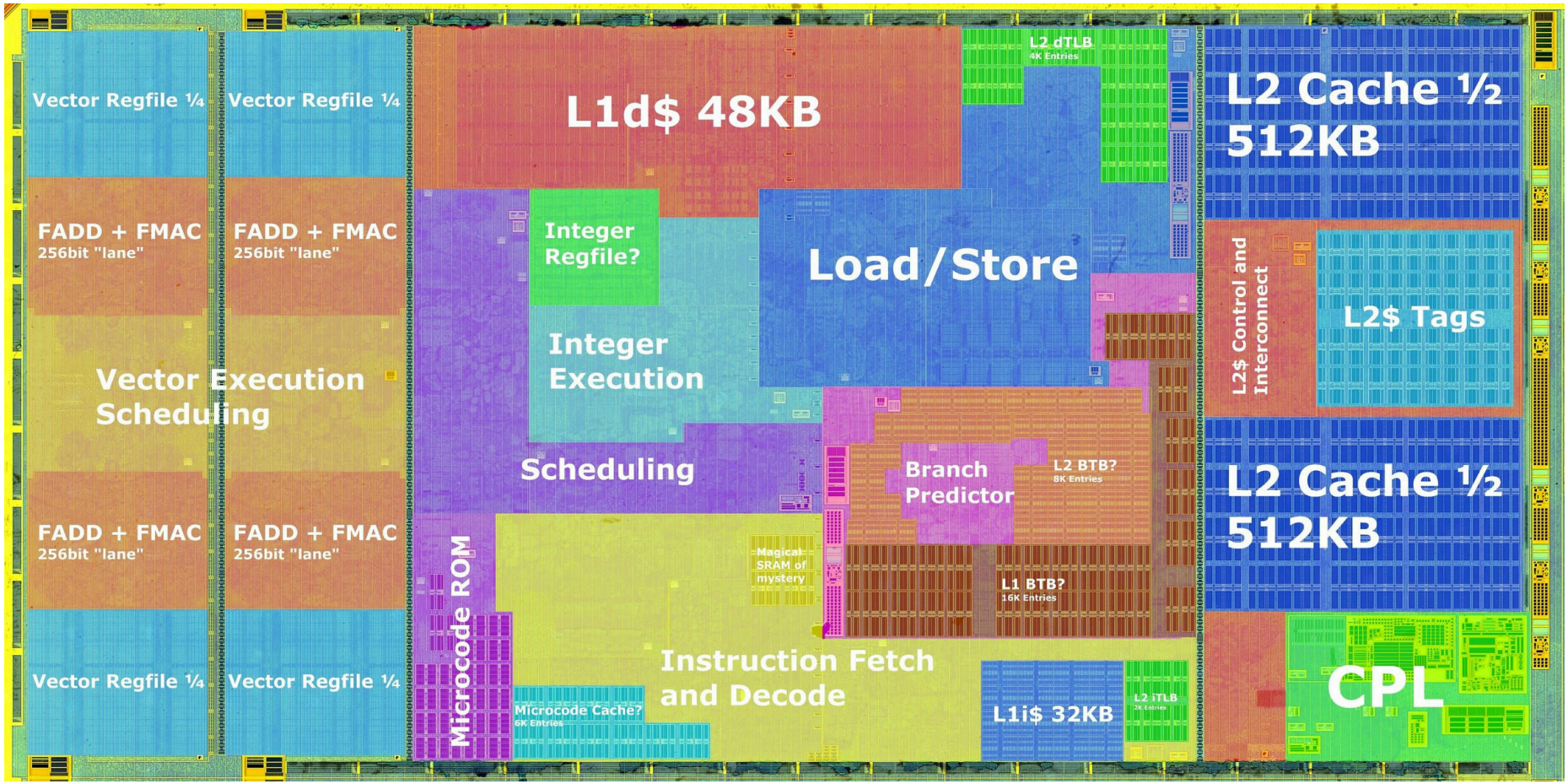
# AMD Zen5 Core-Shot: Zoom-in 🔍

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# Hardware Events: for performance prediction

In CPU PMUs, hardware performance counters are collected:

- instructions: x86 machine instructions executed (“retired”)
- CPU-cache hits & misses
- TLB hits & misses
- branch(-prediction) hits/misses
- IPC
- cycles & kernel-cycles (kcycles)
- ...

- up to 4 counters can be measured simultaneously
  (more require sampling/multiplexing)

# Jaja, but why do I learn profiling?

- Learn system programming
- Improve programming skills
- Understand high-performance data-intensive applications
- Get a great job

# Command-line tool: `perf`

# perf basics

```
# List of pre-defined events
$ perf list

# !Simply! gather performance counter statistics
#   statistisc are not normalized
$ perf stat <your_program>
```

# perf record & report

## Step1: record

```
# Recording Performance Data:
$ perf record <your_program>

#  for specific events:
$ perf record -e cache-misses <your_program>
```

## Step2: report

```
# Analyzing Data & view profiling results:
$ perf report
```

# Compile with debug Symbols

Preferable with symbols to match function name etc.

C++:

```
$ g++ -O3 -g -o my_program my_program.cpp
$ cmake -DCMAKE_BUILD_TYPE=RelWithDebInfo ..
```

# DEMO TIME: `perf`


https://makeameme.org/

# Comment

😊 :

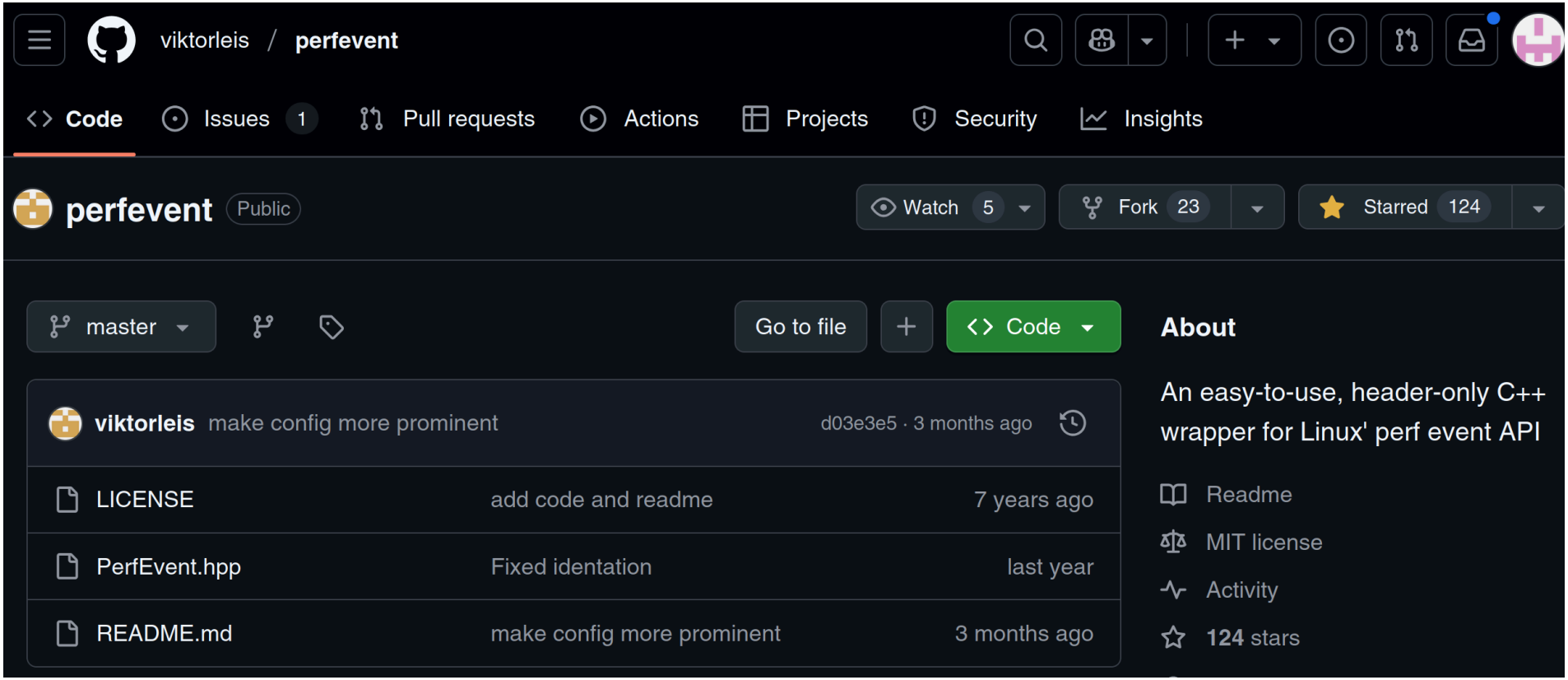
- Easy as CLI in Linux
- Out-of-box without code-changes

😔 :

- Does profiling really start with reading assembly?
- No (or bad) mapping to code-segment
- What-if:
  Dataset-generation burning cycles, but no need to optimize?

# Header: perf-event

# Single-Header




https://github.com/viktorleis/perfevent

# Instrument CPU counters in source code

```
#include "PerfEvent.hpp"

BenchmarkParameters params; // Define global params
params.setParam("name","MyBenchmark");

/// Burning Cycles: dataset loading, generation ...
for (int th = 1; th < maxThreads; ++th) {
  params.setParam("threads",numThreads); // Change local parameters
  {
    PerfEventBlock e(n,params,printHeader);
    // Counter are started in constructor
    yourBenchmark(); // !Profiling ONLY HERE!
    // Benchmark counters are automatically stopped
    // and printed on destruction of e
  }
}
```

# DEMO TIME: perf-event


https://makeameme.org/

# Comment

😊 :

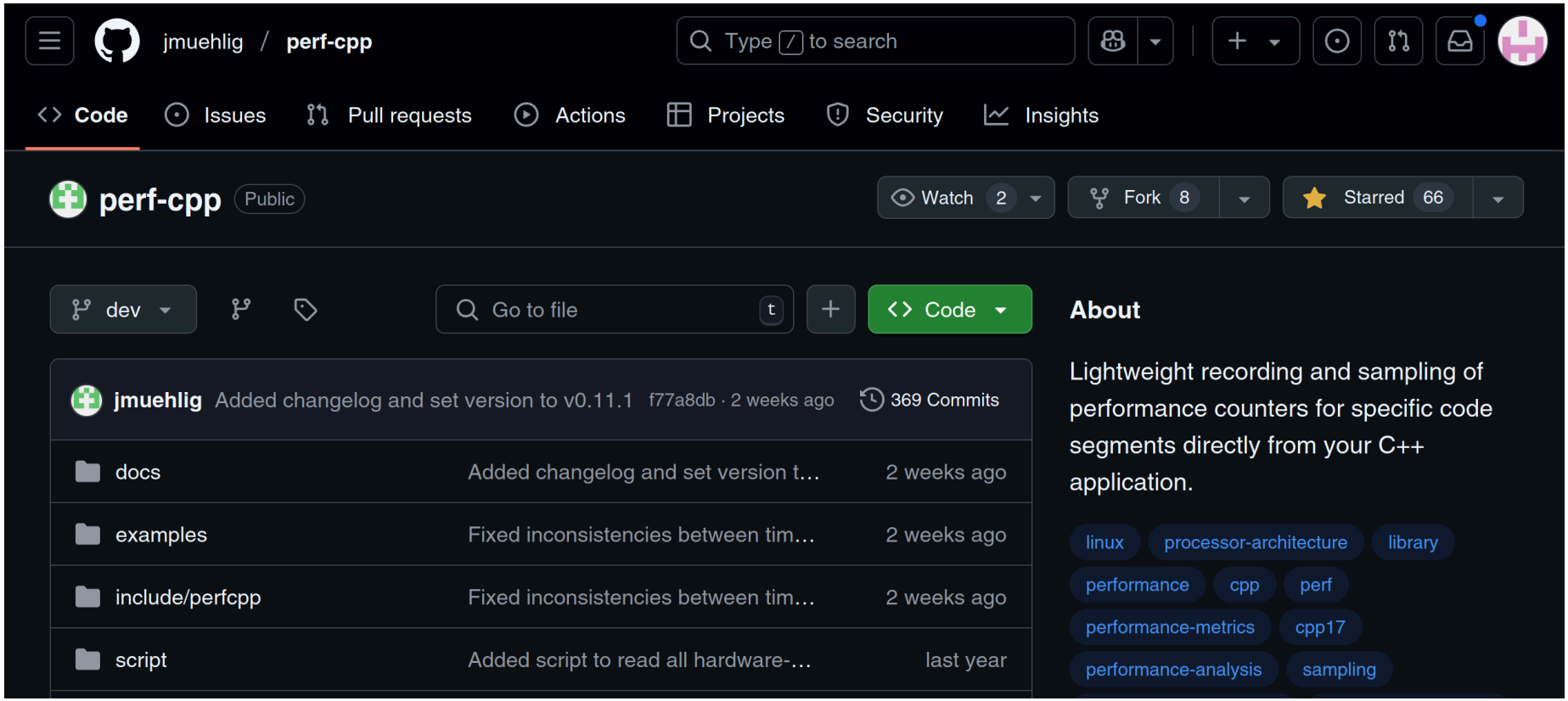
- Only needed code-segment benchmarked!
- Easy with header-only
- Simple code-changes

😔 :

- Bad mapping to Code/Application-Knowledge:
  - Let’s say nodes in a OLC-Btree?

# Library: perf-cpp

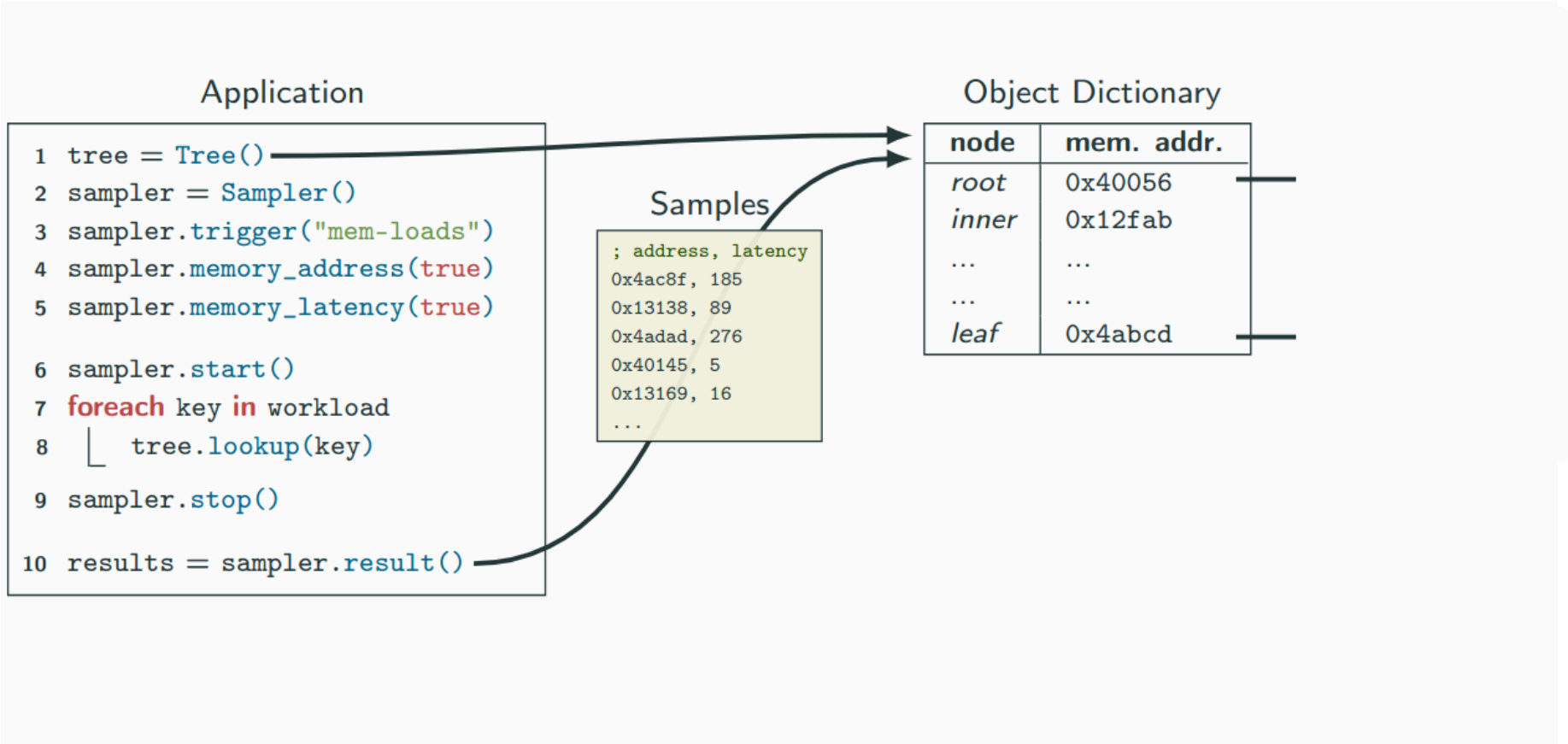
# A library: static or shared



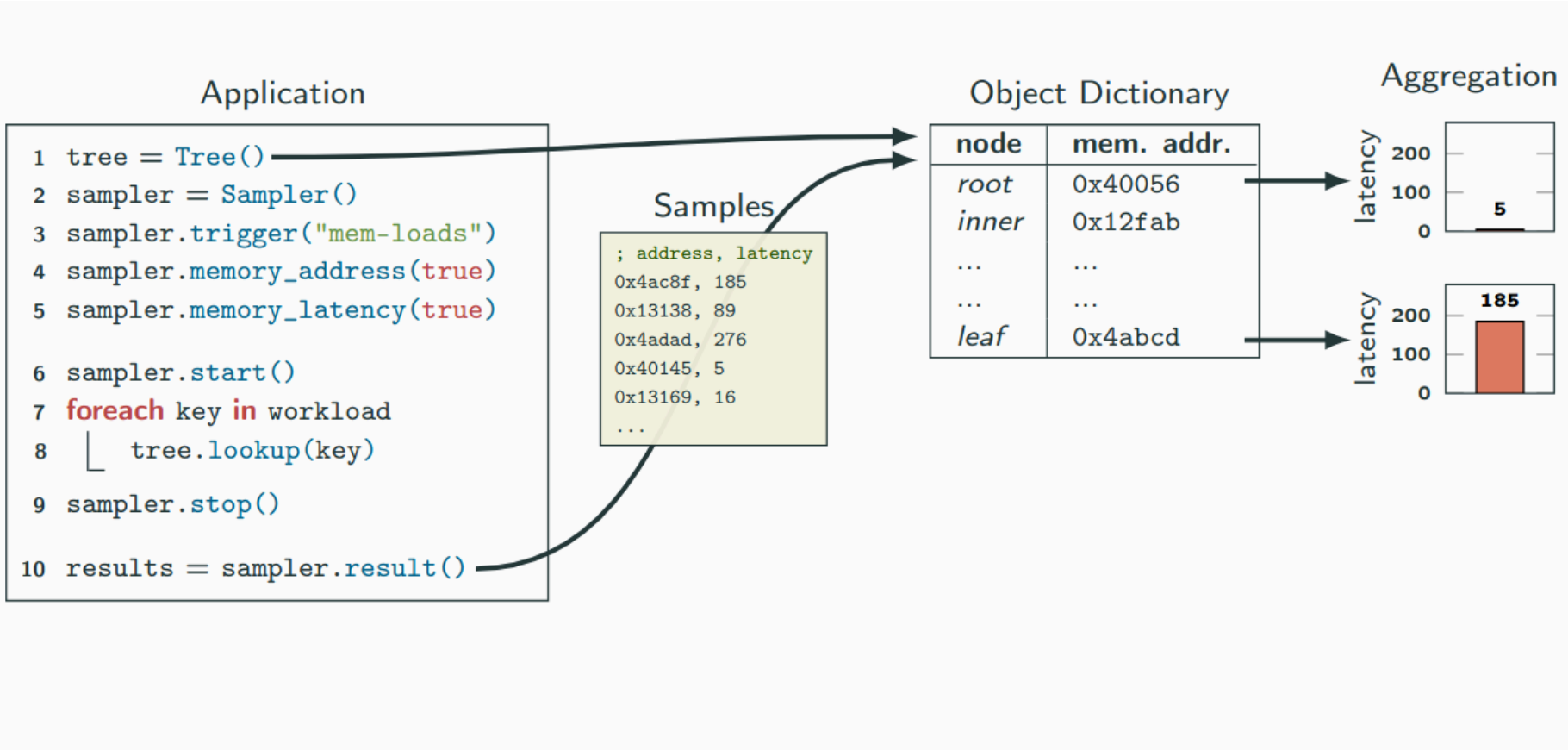

https://github.com/jmuehlig/perf-cpp

https://github.com/jmuehlig/nodmc25-profiling-tutorial

# Profiling with Knowledge of OLC B+tree: Node-mapping



# Profiling with Knowledge of OLC B+tree: Node-mapping



# Profiling with Knowledge of OLC B+tree: Results

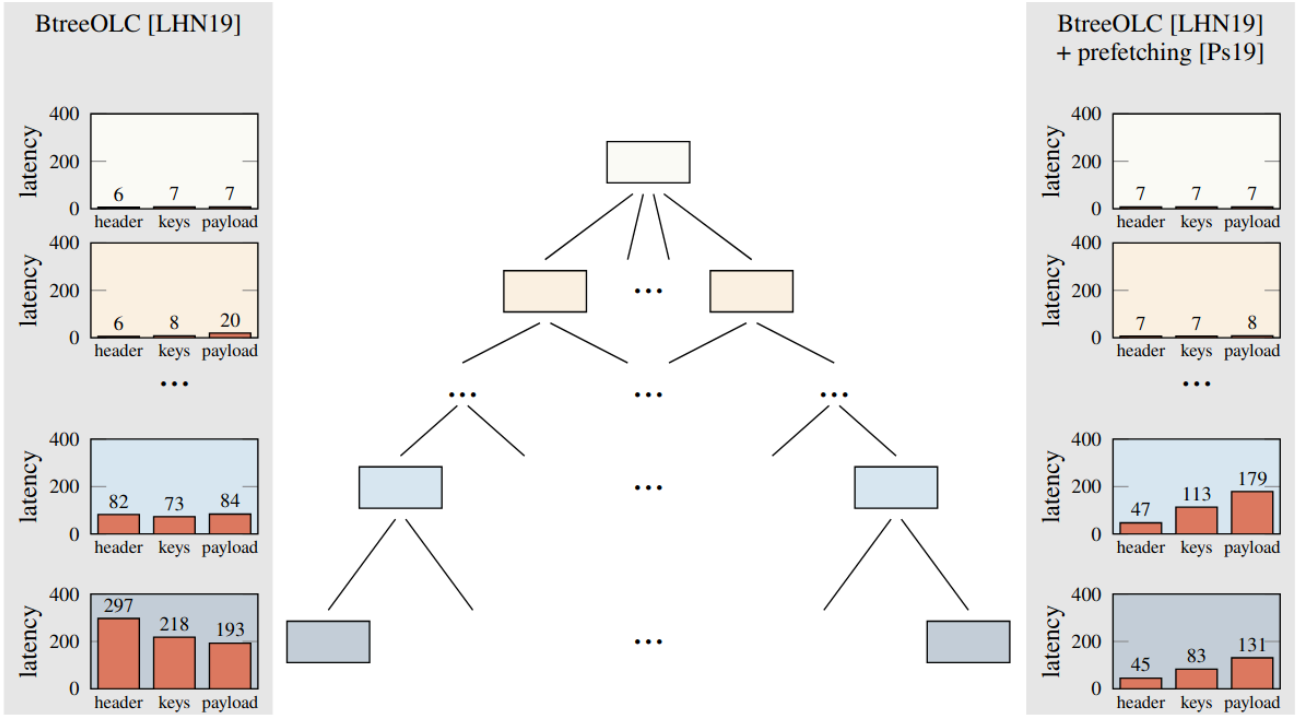



Fig. 4: Memory access latency for different node-segments (header, keys, payloads) in various tree levels derived from sampling—*without* prefetching (left) and *with* software-based prefetching (right).

# DEMO TIME: perf-cpp


https://makeameme.org/

# Comment

😊 :

- Yes. Application-Knowledge!
- Nice functionality

😔 :

- (In my experience) Hard to compile&run it on:
  - diff. CPU: Intel and AMD
  - diff. Kernel versions

# EXTRA: “AI-HW Profiler” for CPU-code

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With “AI-HW”, I mean GPUs.

## NVIDIA Nsight Systems

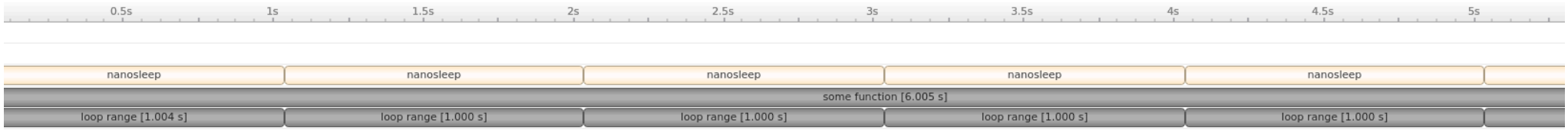
NVIDIA Nsight™ Systems is a system-wide performance analysis tool designed to visualize an application's algorithms, identify the largest opportunities to optimize, and tune to scale efficiently across any quantity or size of CPUs and GPUs, from large servers to our smallest systems-on-a-chip (SoCs).

https://docs.nvidia.com/nsight-systems/UserGuide/index.html#cpu-profiling-on-linux

# Runtime Breakdown with NVTX

```cpp
#include <nvtx3/nvtx3.hpp>

void some_function() {
    NVTX3_FUNC_RANGE();  // Range around the whole function
    for (int i = 0; i < 6; ++i) {
        nvtx3::scoped_range loop{"loop range"};  // Range for iteration
        std::this_thread::sleep_for(std::chrono::seconds{1}); // Sleep 1s
    }
}
```




https://github.com/NVIDIA/NVTX

# DEMO TIME: NSYS


https://makeameme.org/

# Comment

😊 :

- GUI showing overview and runtime-breakdown
- C++ (Header-only) & Python (import-only)
- Bus Monitoring: PCIe (SSD, Network), NVLink...

- (I use it everyday. But what I do everyday?)

😔 :

- Limited CPU metrics.
- Need to install it via NVIDIA.

# Comment

😊 :

- GUI showing overview and runtime-breakdown
- C++ (Header-only) & Python (import-only)
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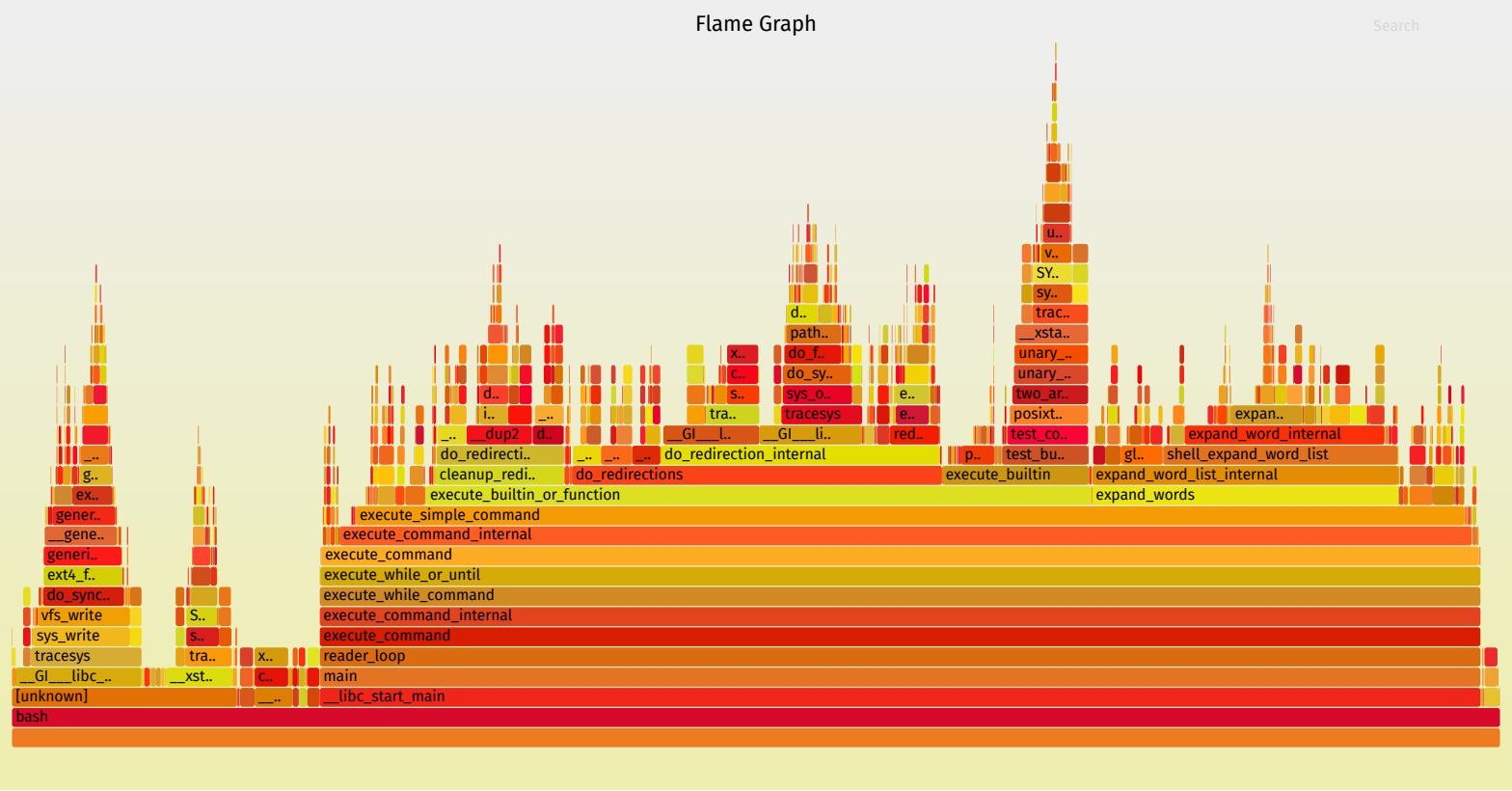
Lab2 Hint: Runtime breakdown. Everything is memory-bound there. 🚀

# More?

# Not covered, but also important

- Details about profiling: PMUs, Samping, Abstractions... Read the NoDMC paper & `perf-cpp` documentations
- Debugging & Profiling:
  - Compiler Explorer: https://godbolt.org/
  - `valgrind` & `gdb`
- CPU:
  - `lscpu` , `lstopo`
  - `/proc/{meminfo, cpuinfo}`, `dmidecode -t {memory,cache}`
  - `perf` Flamegraph
  - NUMA with `numactl`
  - perfetto for GUI: https://perfetto.dev/docs/quickstart/linux-tracing
- Discussion? 😀

# Backup: Flamegraph




https://github.com/brendangregg/FlameGraph

His website and books are also very nice!

# Resources

- Understanding Application Performance on Modern Hardware: Profiling Foundations and Advanced Techniques - Mühlig, Jan; Kühn, Roland; Teubner, Jens (TU Dortmund, NoDMC@BTW25)
- https://github.com/jmuehlig/perf-cpp?tab=readme-ov-file#resources-about-perf--profiling
- Ulrich Drepper's What Every Programmer Should Know About Memory
- Agner Fog's Software optimization resources
- Intel's Top-Down Microarchitectural Analysis Method

Many thanks to Jan Mühlig for perf-cpp and sharing the slide, Matthias Jasny and Tobias Ziegler for sharing ADMS slides, Viktor Leis for perf-event, and all mentioned resources!