Optimising a Real-time Audio Processing Library

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PRISM SOUND

tracktion

POWERED BY tracktion ENGINE

“Software engineering is programming integrated over time”

Titus Winters - Google

Chapters

1. Benchmarking & measurement
2. Optimisation
3. Multi-threading, CPUs and memory

1. Benchmarking & Measurement

What are Benchmarks?

- Measure code execution “time”
- Assess performance characteristics
- Structured, repeatable way
- Looking for trends:
  - ***Identify regressions***
  - ***Measure optimisation attempts***
  - ***Compare environments***

Micro vs Macro Benchmarks?

- **Micro Benchmarks:**
  - Measure a single component or task
  - Low level
    - Instructions, cache misses etc.
  - Akin to unit tests
- **Macro Benchmarks:**
  - Measure a whole system
  - Higher level
    - Throughput, execution time
  - Akin to integration tests
  - Reflect what your users will see

Measurement Metrics?

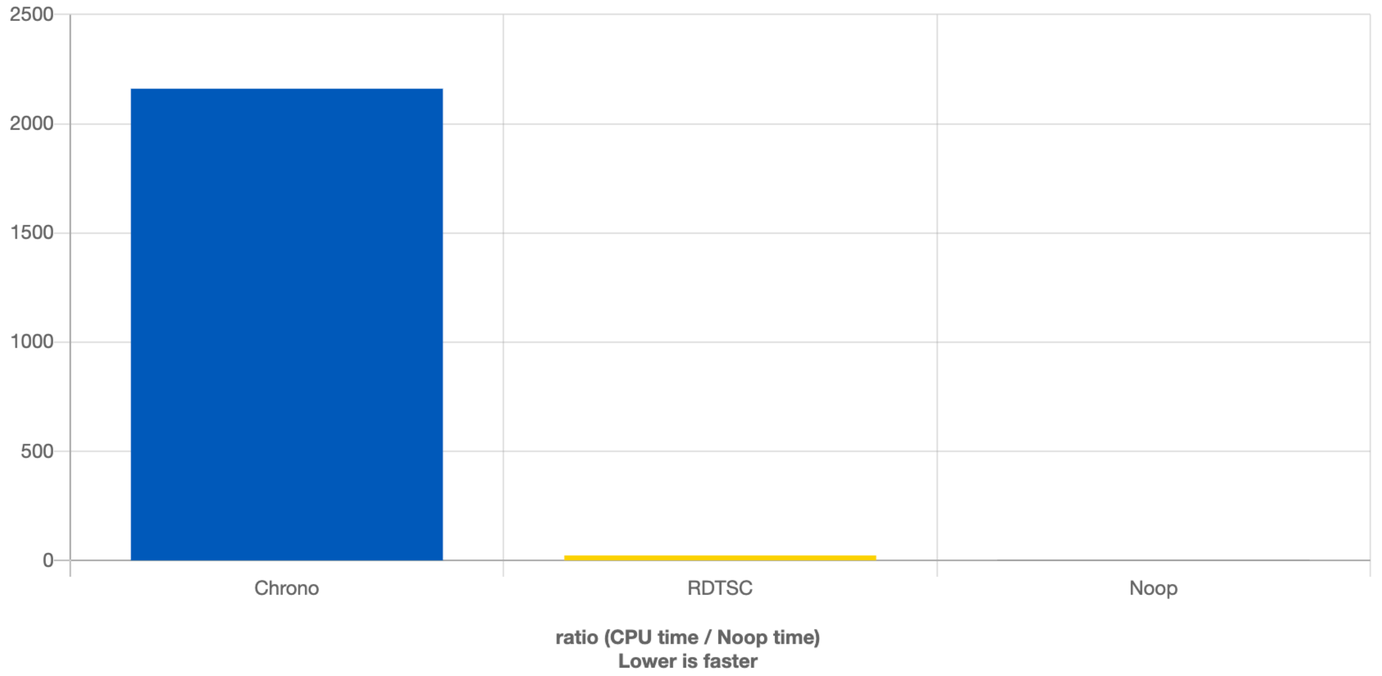
- A piece of code executing many times
- Total, min/max, mean & variance/SD
- Total execution time is useful for “macro” characteristics
- Max is useful for “worst case” scenarios
- Min informs of where you could be
- Mean gives an “expected” indication

What to Record?

- Time
  - `chrono::time_point<chrono::high_resolution_clock>`
  - Indicates what a “typical user” will experience
  - Very environment dependant
- CPU time stamp
  - Clock cycles
  - Less overhead to measure
  - Easier to compare between platforms

quick-bench.com

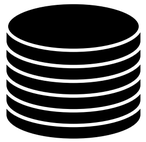
```cpp
static void Chrono(benchmark::State& state)
{
  for (auto _ : state)
  {
    auto x = std::chrono::high_resolution_clock::now();
    benchmark::DoNotOptimize(x);
  }
}
BENCHMARK(Chrono);

static void RDTSC(benchmark::State& state)
{
  for (auto _ : state)
  {
    auto x = rdtsc();
    benchmark::DoNotOptimize(x);
  }
}
BENCHMARK(RDTSC);
```



https://quick-bench.com/q/siAqIrvTsb-UB7GdpF_sJQ69v54

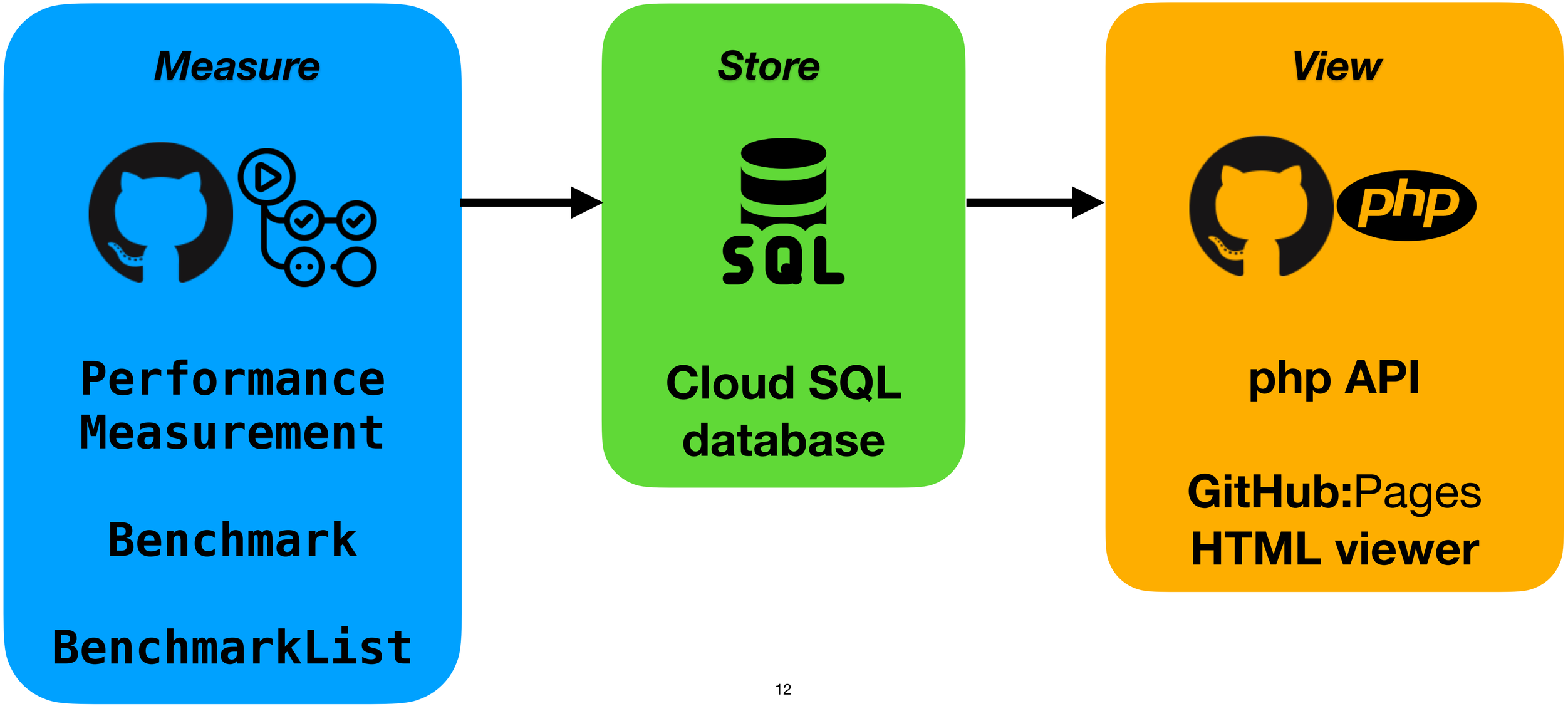
Where to Measure and Where to Store Results?

- Stable environments
  - Ideally constant machines
  - Cloud VMs provide indications



- Store results in cloud database
  - Easy to view results
  - Automatic notifications?

Benchmark System Diagram



```
//==============================================================================
class PerformanceMeasurement
{
public:
    //==============================================================================
    /** Creates a PerformanceMeasurement object.

        @param counterName      the name used when printing out the statistics
        @param runsPerPrintout  the number of start/stop iterations before calling
                                printStatistics()
    */
    PerformanceMeasurement (const std::string& counterName,
                            int runsPerPrintout = 100,
                            bool printOnDestruction = true);

    /** Destructor. */
    ~PerformanceMeasurement();

    //==============================================================================
    /** Starts timing.
        @see stop
    */
    void start() noexcept;

    /** Stops timing and prints out the results.

        The number of iterations before doing a printout of the
        results is set in the constructor.

        @see start
    */
    bool stop();

    /** Dumps the current metrics to std::cout. */
    void printStatistics();


    /** Returns a copy of the current stats. */
    Statistics getStatistics() const;
```

```
    /** Holds the current statistics. */
    struct Statistics
    {
        Statistics() noexcept = default;

        void clear() noexcept;
        double getVarianceSeconds() const;
        double getVarianceCycles() const;
        std::string toString() const;

        void addResult (double secondsElapsed, uint64_t cyclesElapsed);

        std::string name;

        double meanSeconds      = 0.0;
        double m2Seconds        = 0.0;
        double maximumSeconds   = 0.0;
        double minimumSeconds   = 0.0;
        double totalSeconds     = 0.0;

        double meanCycles       = 0.0;
        double m2Cycles         = 0.0;
        uint64_t maximumCycles  = 0;
        uint64_t minimumCycles  = 0;
        uint64_t totalCycles    = 0;

        int64_t numRuns = 0;
    };
```

```cpp
/** Describes a benchmark.
    These fields will be used to sort and group your benchmarks for comparison over time.
*/
struct BenchmarkDescription
{
    size_t hash = 0;            /**< A hash uniquely identifying this benchmark. */
    std::string category;       /**< A category for grouping. */
    std::string name;           /**< A human-readable name for the benchmark. */
    std::string description;    /**< An optional description that might include configs etc. */
    std::string platform { juce::SystemStats::getOperatingSystemName().toStdString() };
};
```

```cpp
 /** Holds the duration a benchmark took to run. */
 struct BenchmarkResult
 {
     BenchmarkDescription description;   /**< The BenchmarkDescription. */
     double totalSeconds = 0.0, meanSeconds = 0.0, minSeconds = 0.0,
            maxSeconds = 0.0, varianceSeconds = 0.0;
     uint64_t totalCycles = 0, meanCycles = 0, minCycles = 0, maxCycles = 0;
     double varianceCycles = 0.0;
     juce::Time date { juce::Time::getCurrentTime() };
 };
```

```cpp
//==============================================================================
/**
    An individual Benchmark.
    To measure a benchmark, simply create one of these with a valid description
    then before the code you are measuring call start and stop afterwards.
    Once you've done that, call getResult() to return the duration the benchmark took to run.

    To collect a set of BenchmarkResults see @BenchmarkList
*/
class Benchmark
{
public:
    /** Creates a Benchmark for a given BenchmarkDescription. */
    Benchmark (BenchmarkDescription desc)
        : description (std::move (desc))
    {
    }

    /** Starts timing the benchmark. */
    void start()
    {
        measurement.start();
    }

    /** Stops timing the benchmark. */
    void stop()
    {
        measurement.stop();
    }

    /** Returns the timing results. */
    BenchmarkResult getResult() const
    {
        return createBenchmarkResult (description, measurement.getStatistics());
    }

private:
    BenchmarkDescription description;
    tracktion::graph::PerformanceMeasurement measurement { {}, -1, false };
};
```

```
class ResamplingBenchmarks : public juce::UnitTest
{
public:
    ResamplingBenchmarks()
        : juce::UnitTest ("Resampling Benchmarks", "tracktion_benchmarks")
    {
    }

    void runTest() override
    {
        runResamplingRendering ("lagrange",     ResamplingQuality::lagrange);
        runResamplingRendering ("sincFast",     ResamplingQuality::sincFast);
        runResamplingRendering ("sincMedium",   ResamplingQuality::sincMedium);
        runResamplingRendering ("sincBest",     ResamplingQuality::sincBest);
    }

private:
    //==============================================================================
    //==============================================================================
    void runResamplingRendering (juce::String qualityName,
                                 ResamplingQuality quality)
    {
```

Create a 30s sin clip

```
        waveClip->setUsesProxy (false);
        waveClip->setResamplingQuality (quality);

        {
            ScopedBenchmark sb (createBenchmarkDescription ("Resampling", "WaveNode quality", "30s sin wave, 96KHz to 44.1Khz, " + qualityName.toStdString()));
            Renderer::measureStatistics ("Rendering resampling",
                                         *edit, timeRange,
                                         toBitSet ({ t }),
                                         256, playbackSampleRate);
        }
    }
};

static ResamplingBenchmarks resamplingBenchmarks;
```

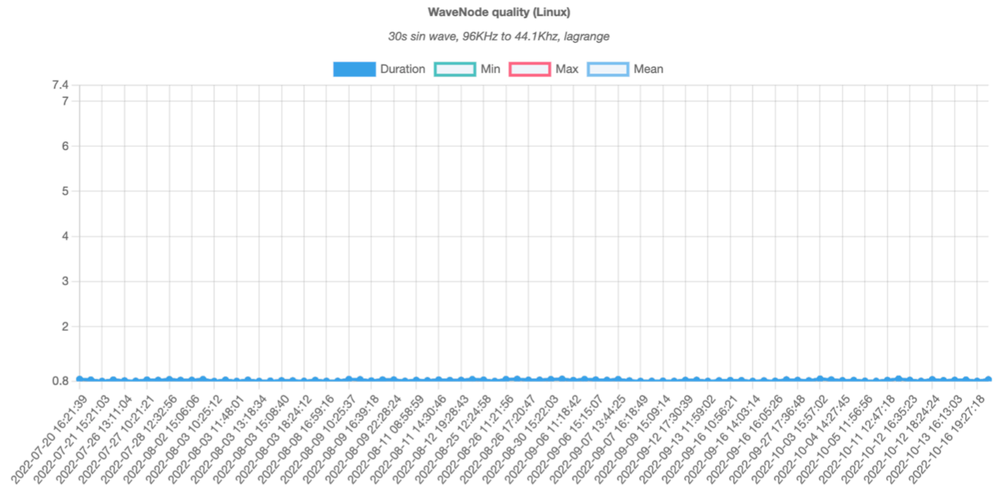
Tracktion Benchmarks

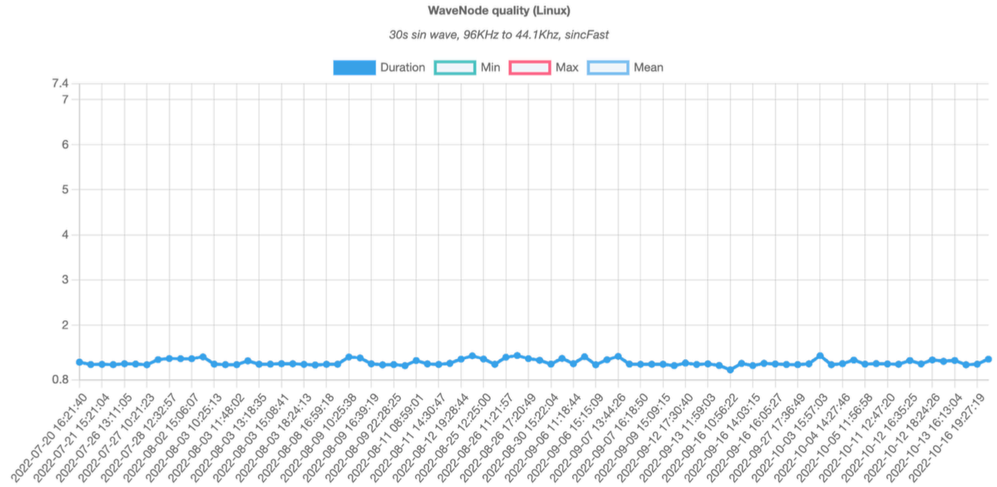
Categories: All Name: WaveNode quality Description:
All Platform: Linux

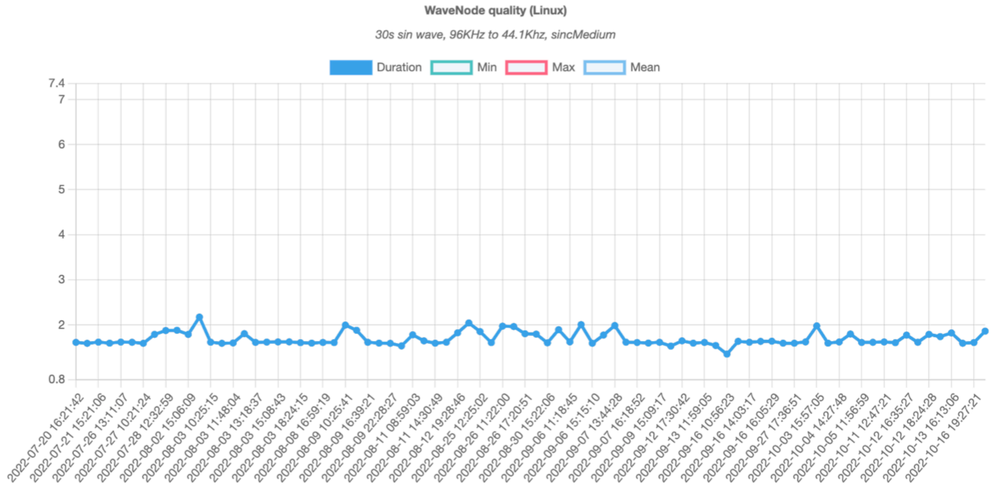
Start Date: dd/mm/yyyy End Date: dd/mm/yyyy Time Cycles

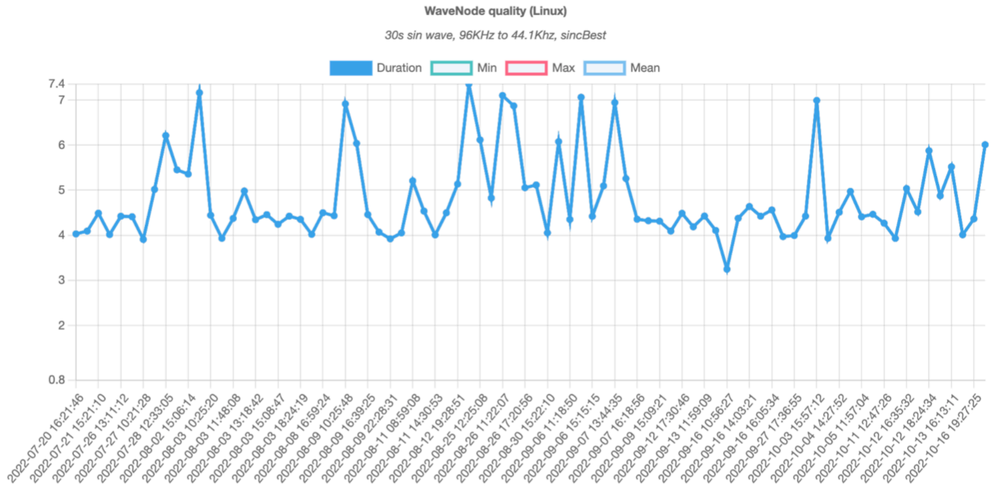
Show total Show min/max Show variance Normalise results

Update Results









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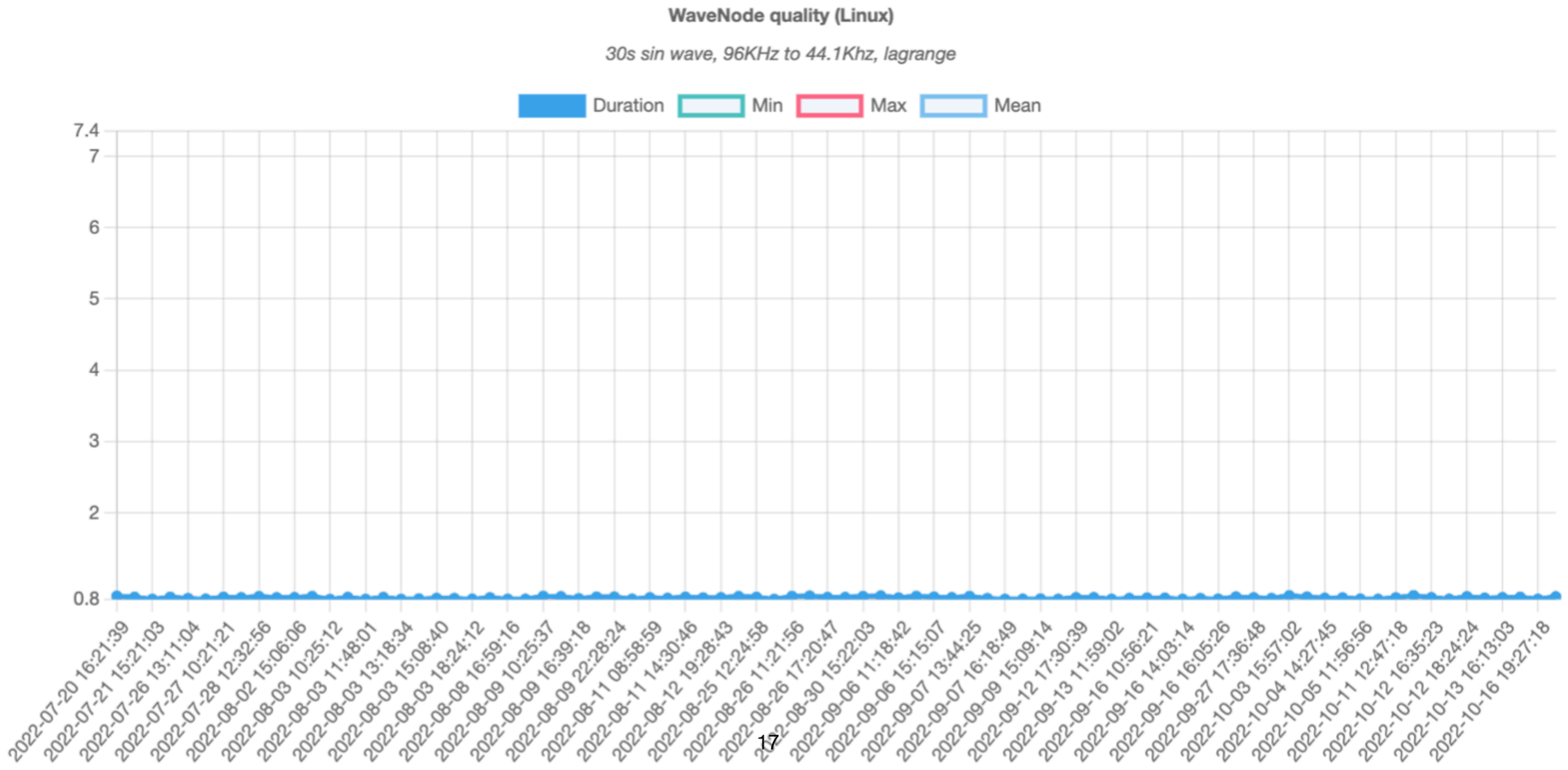

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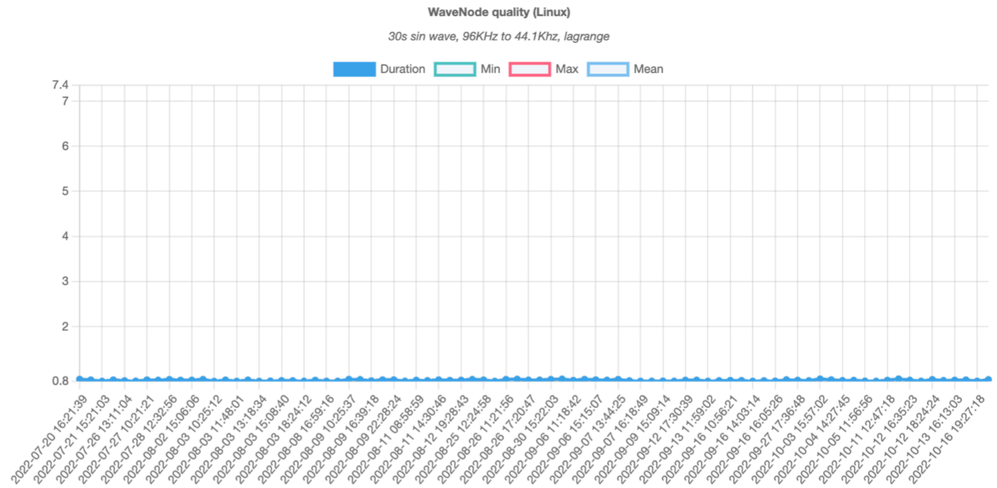
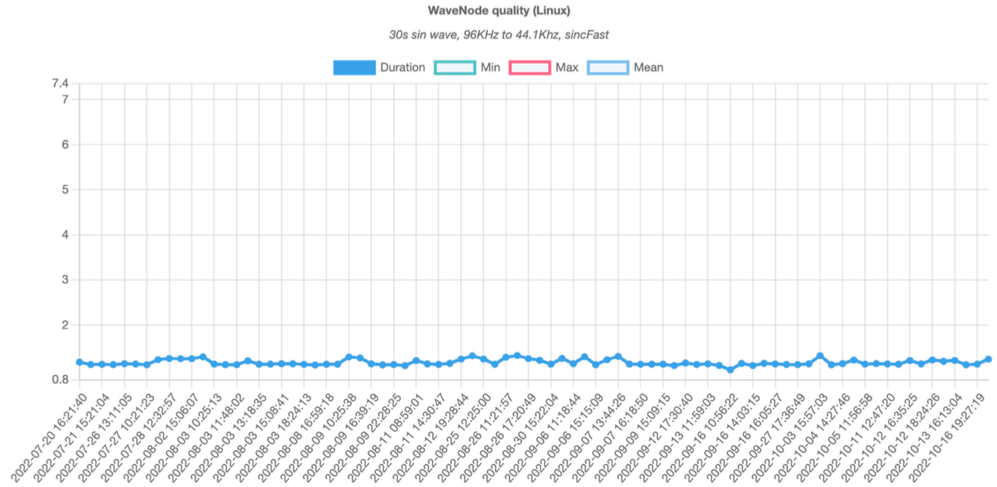
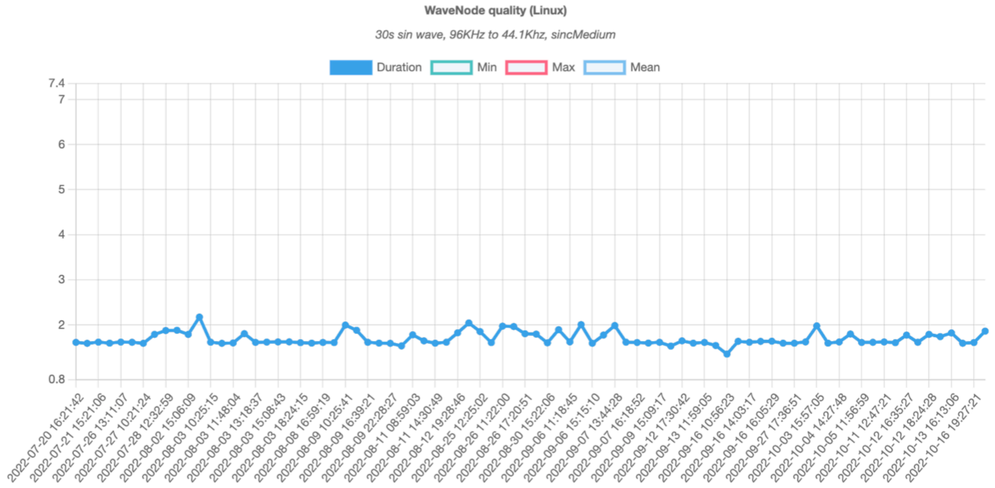
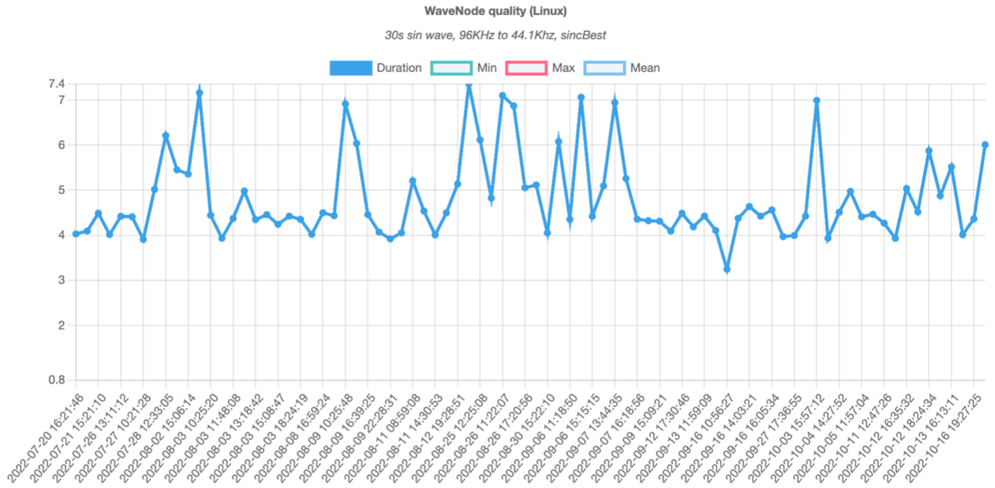








When to add benchmarks to your suite?

- New features
- QA/user reports
- When you see benchmark regressions

2. Optimisation

Identifying Areas for Optimisation

- Run a specific benchmark under a tool to get a picture of what is going on

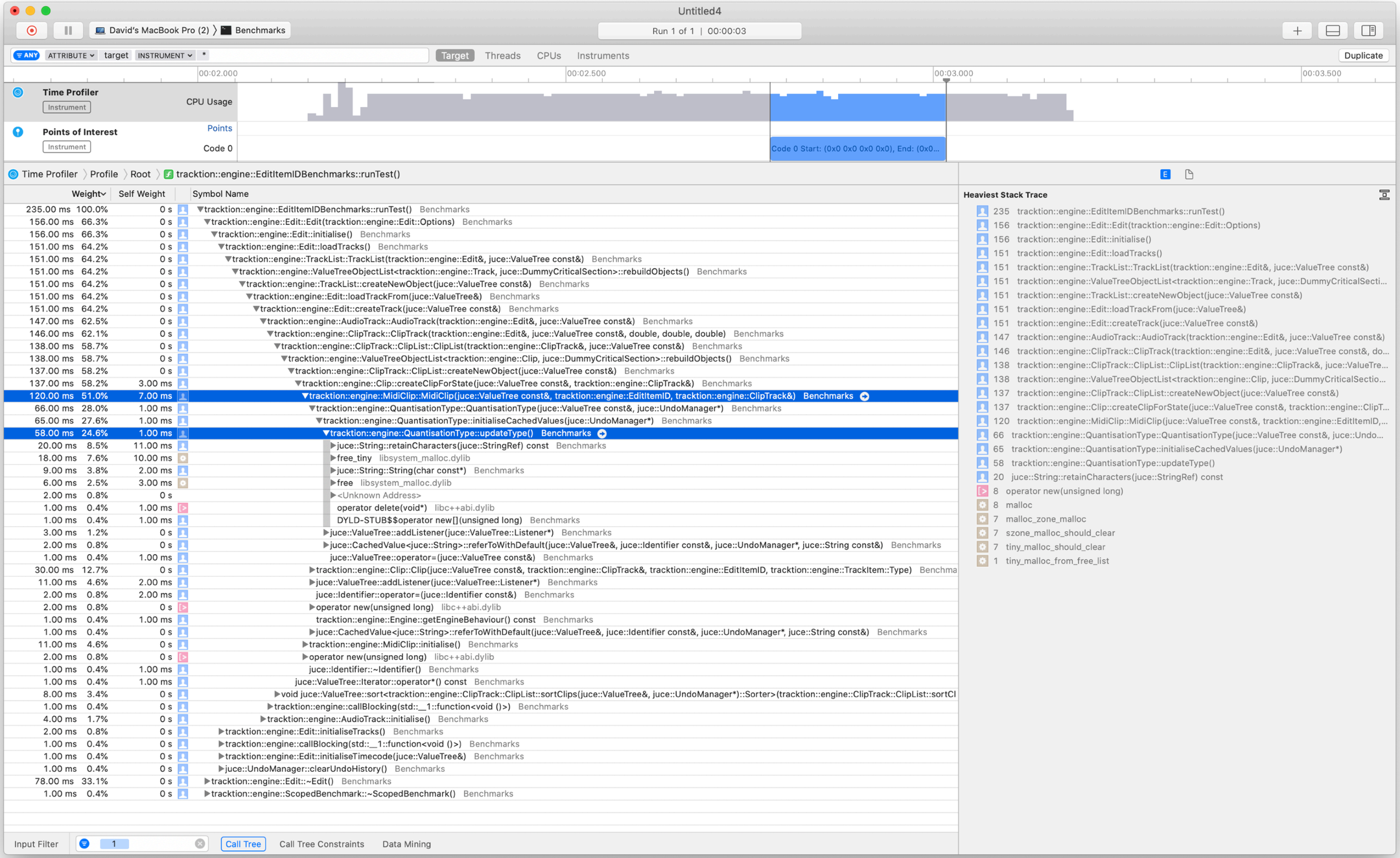
Profiling Tools

- Time profilers:
  - Give you a tree of time spent in functions
  - Can be used to identify hotspots
  - Xcode Instruments - Time Profiler, VS Profile, Intel VTune
- System Tracers:
  - Show events such as system calls, memory management, thread interruptions etc.
  - Xcode Instruments - System Trace, DTrace/strace
- Performance counters:
  - Reads CPU hardware registers for things like branch mis-predictions, cache misses etc.
  - Xcode Instruments - Counters, Linux - perf
- **Always profile release builds!**

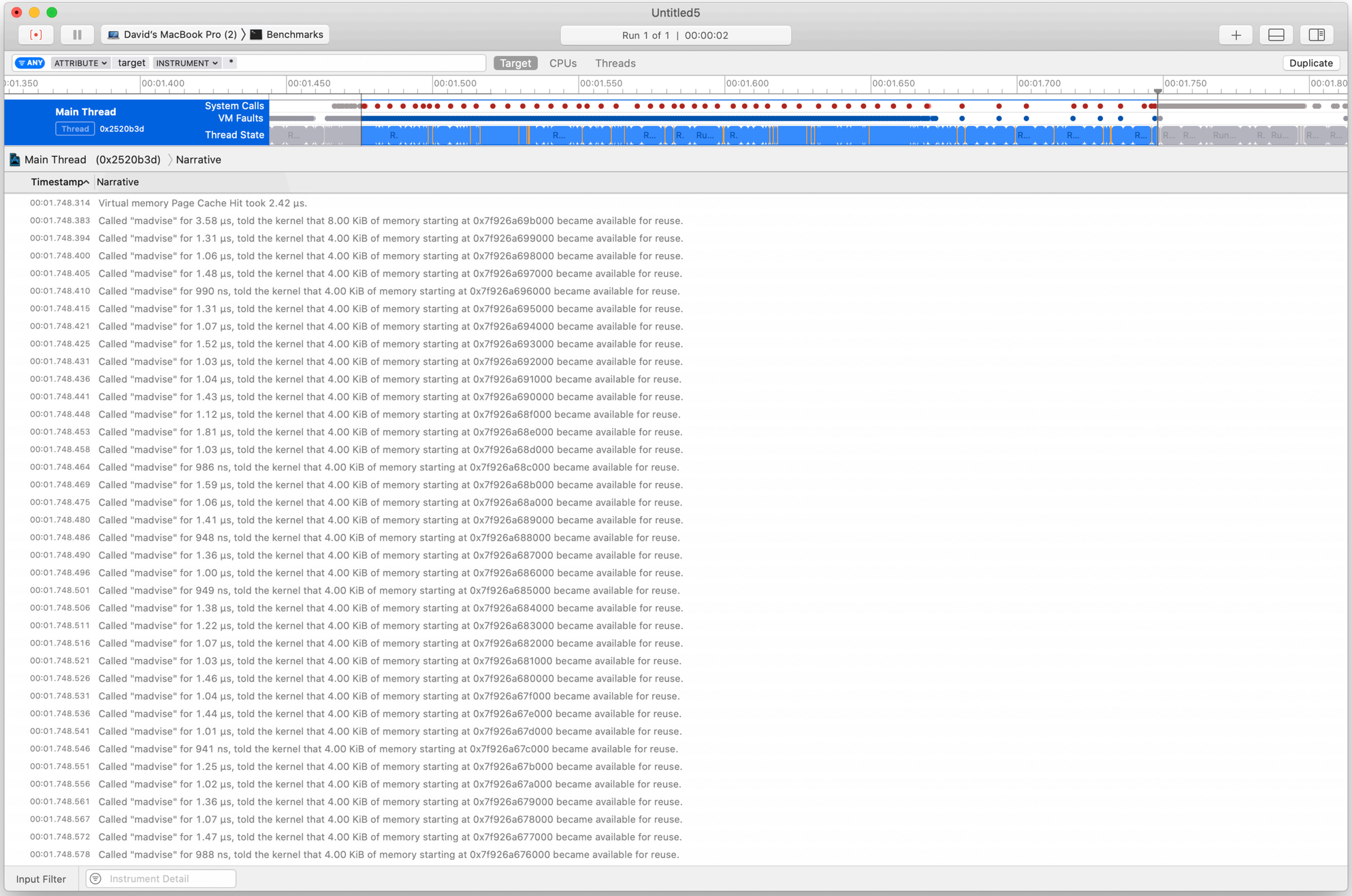




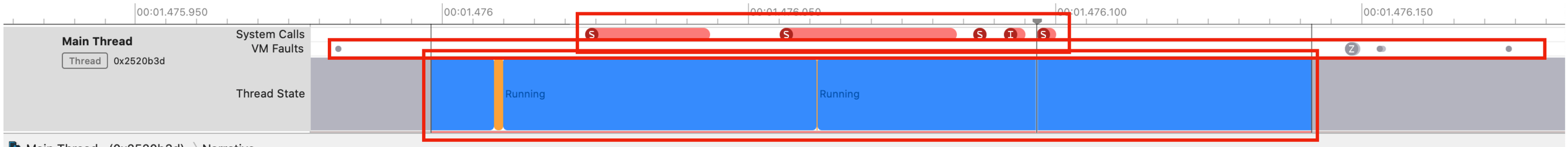


Time Profiler

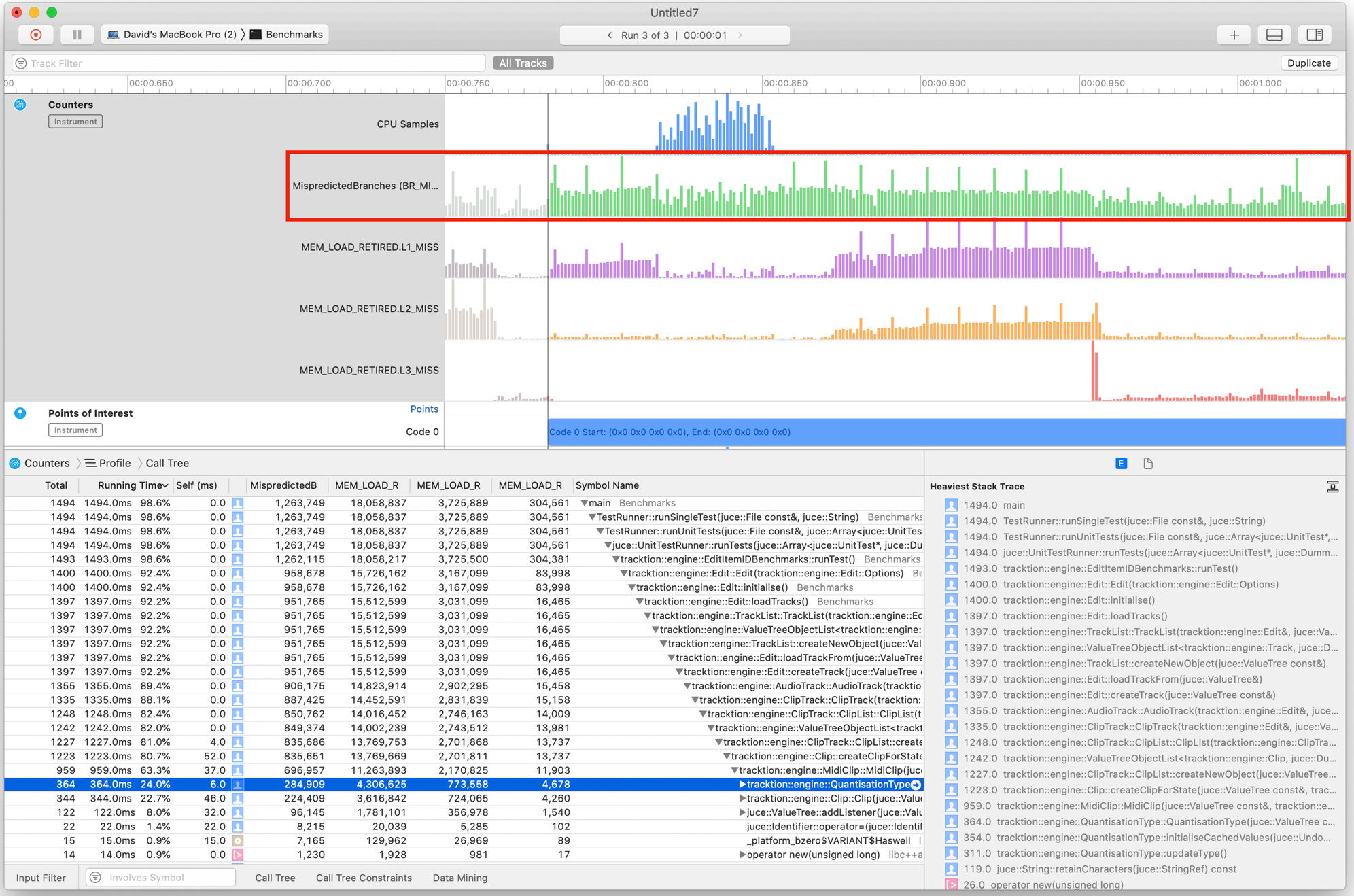


System Trace



Main Thread (0x2520b3d) 〉 Narrative

Timestamp	Narrative
00:01.475.954	Virtual memory Zero Fill took 901 ns.
00:01.475.960	Virtual memory Zero Fill took 1.12 µs.
00:01.475.963	Virtual memory Zero Fill took 1.28 µs.
00:01.475.970	Virtual memory Zero Fill took 614 ns.
00:01.475.976	Virtual memory Zero Fill took 959 ns.
00:01.475.982	Virtual memory Zero Fill took 819 ns.
00:01.476.008	Interrupted for 1.76 µs while CPU 0 serviced an interrupt handler.
00:01.476.010	Ran for 50.90 µs on CPU 0 at priority 31.
00:01.476.023	Called "stat64" for 20.40 µs.
00:01.476.055	Called "open" for 28.85 µs.
00:01.476.060	Interrupted for 274 ns (0.9% of open's duration) while CPU 0 serviced an interrupt handler.
00:01.476.061	Ran for 125.63 µs on CPU 0 at priority 31.
00:01.476.086	Called "fstat64" for 2.06 µs.
00:01.476.091	Called "read" for 3.50 µs.
00:01.476.097	Called "close" for 3.12 µs.



Performance Counters

Memory Access


Pioneer

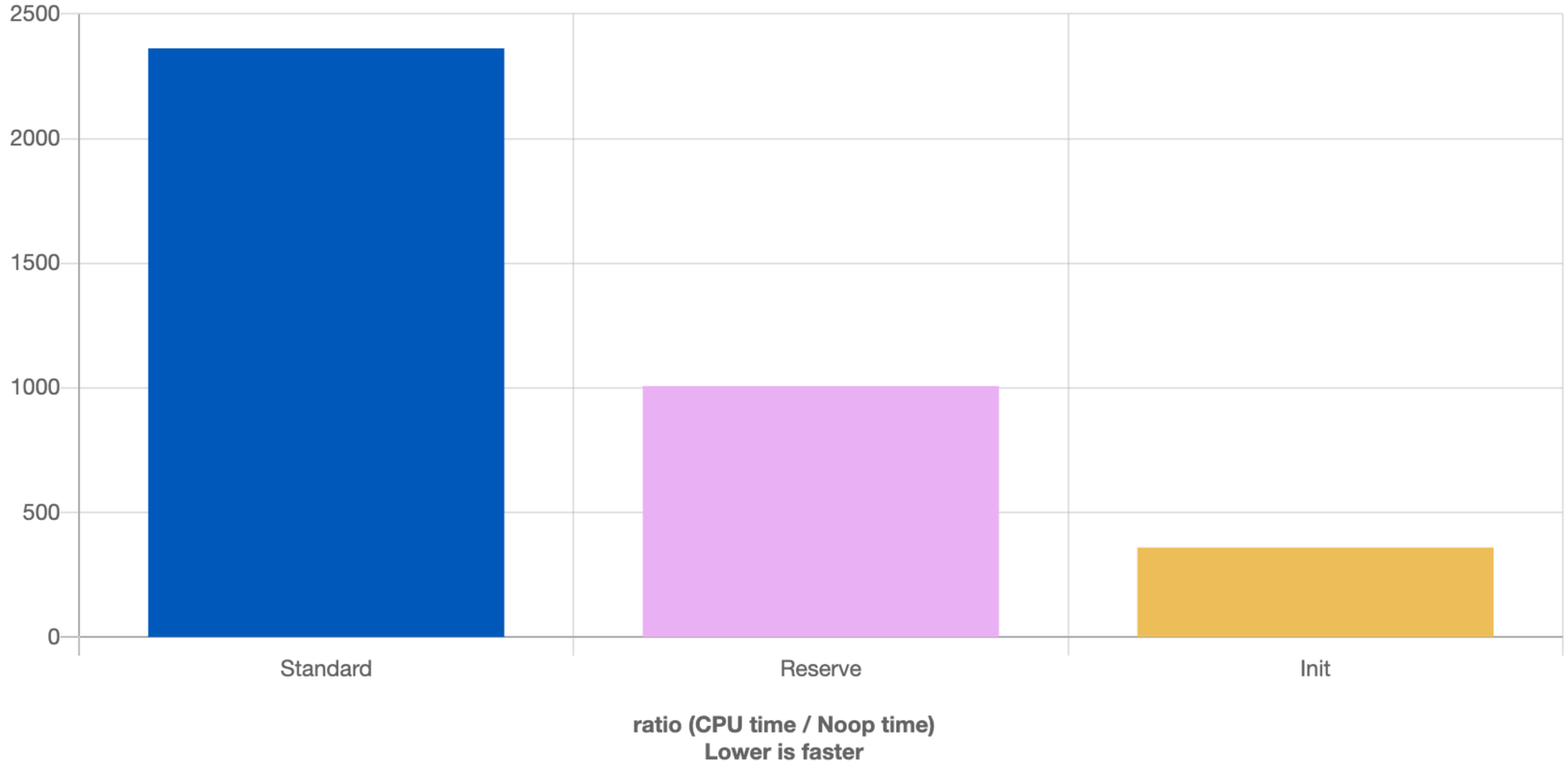
Techniques for Optimisation

Techniques for Optimisation

1. Identifying work that can be removed

- The simplest form of optimisation is not doing some work
- Use a profile trace to identify sections of code that don’t need to be run
  - E.g. reducing the number of memory allocations by reserving
- You may need to think of an alternative approach in order to remove a chunk of code
  - Evaluate lazily
  - Evaluate asynchronously

```cpp
#include <vector>

std::vector<double> vec;

for (int i = 0; i < 1'000; ++i)
  vec.push_back (0.0);

std::vector<double> vec;
vec.reserve (1'000);

for (int i = 0; i < 1'000; ++i)
  vec.push_back (0.0);

std::vector<double> vec (1'000, 0.0);
```



https://quick-bench.com/q/9uTY-mY6yFS1gIE7hIDBFjU5uNw

Techniques for Optimisation

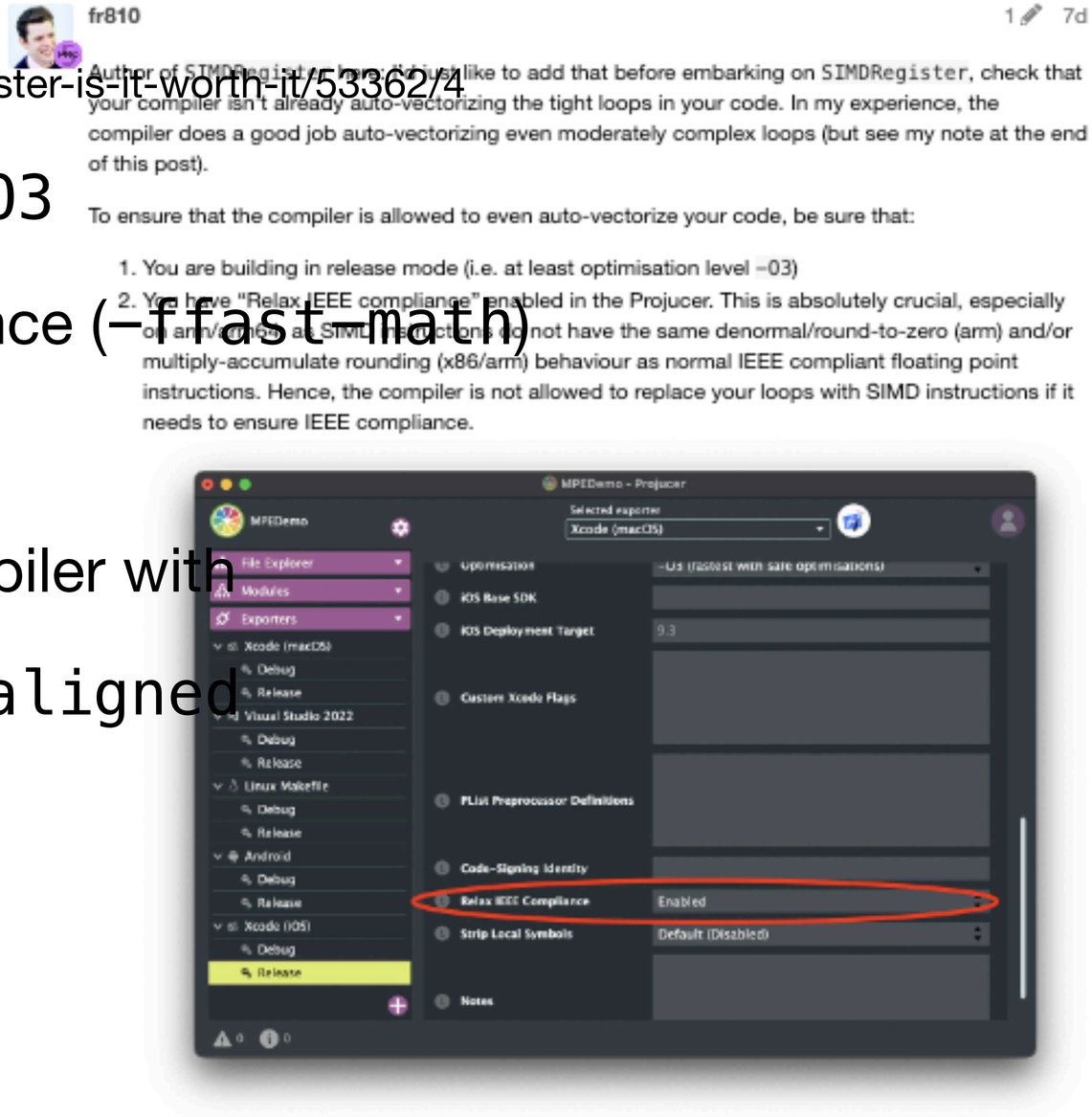
2. Identifying work that can be combined

- Combine work in time:
  - Evaluate in parallel
  - Execute using SIMD instructions (single instruction, multiple data)
- Combine work in an algorithm:
  - `std::min_element` + `std::max_element` ≈ `std::minmax_element`

Credit to Fabian:

https://forum.juce.com/t/simdregister-is-it-worth-it/53362/4

- Build with at least `-O3`
- Relax IEEE compliance (`-ffast-math`)
  - `-Ofast`
- Optionally help compiler with
  - `std::assumed_aligned`



fr810 1 7d

Author of SIMDRegister here. I'd just like to add that before embarking on `SIMDRegister`, check that your compiler isn't already auto-vectorizing the tight loops in your code. In my experience, the compiler does a good job auto-vectorizing even moderately complex loops (but see my note at the end of this post).

To ensure that the compiler is allowed to even auto-vectorize your code, be sure that:

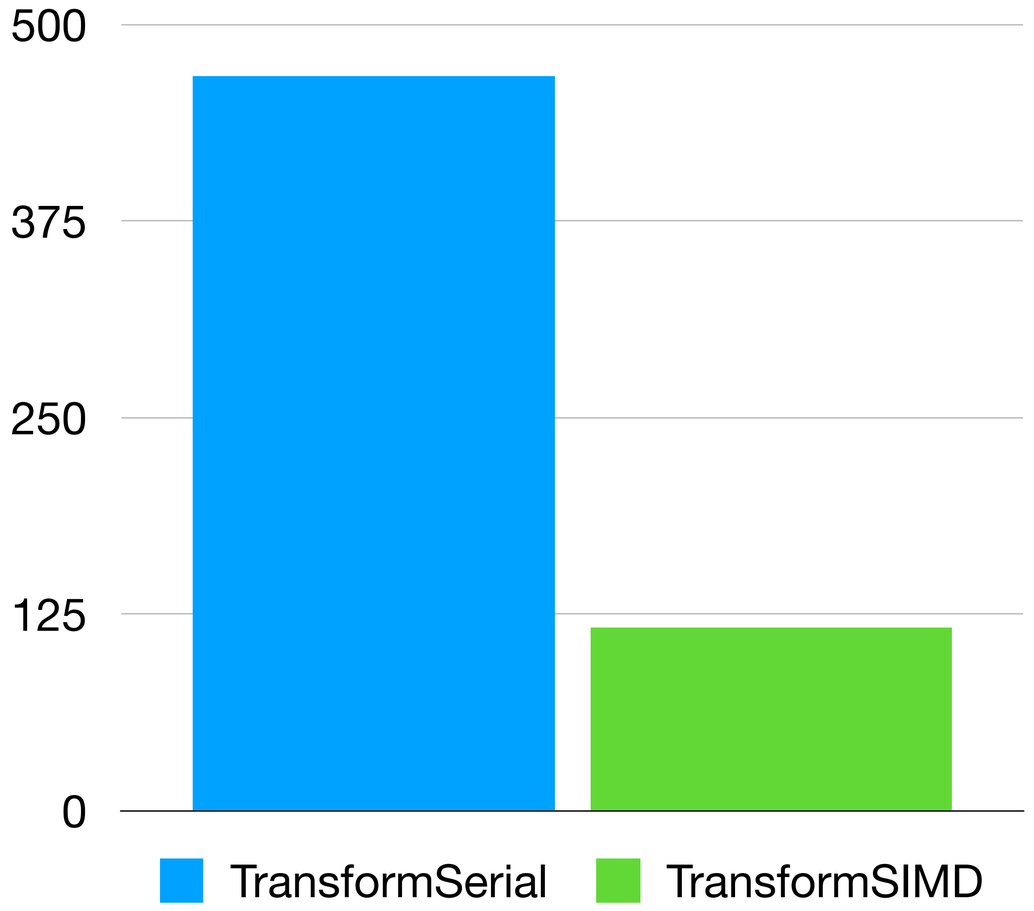
1. You are building in release mode (i.e. at least optimisation level `-O3`)
2. You have "Relax IEEE compliance" enabled in the Projucer. This is absolutely crucial, especially on arm/aarch64 as SIMD instructions do not have the same denormal/round-to-zero (arm) and/or multiply-accumulate rounding (x86/arm) behaviour as normal IEEE compliant floating point instructions. Hence, the compiler is not allowed to replace your loops with SIMD instructions if it needs to ensure IEEE compliance.

> Note if you are compiling with `-Ofast` then "Relax IEEE compliance" will be enabled regardless of the Projucer setting.

To check if your code is being auto-vectorized, you need to look at the assembly. I recommend doing this, even when using `SIMDRegister`, as you will often have unexpected results.

I highly recommend `godbolt.org` for this; `godbolt.org` has the advantage that you can change

```cpp
// Return 256 random floats +-1.0f
static const std::vector<float>& getBufferData();

static void TransformXXX(benchmark::State& state)
{
  const auto& v = getBufferData();
  auto copy = v;

  for (auto _ : state)
  {
    std::transform (v.begin(), v.end(), copy.begin(), copy.end(),
                    [] (auto v1, auto v2) { return v1 + v2; });
  }
}
BENCHMARK(TransformXXX);
```



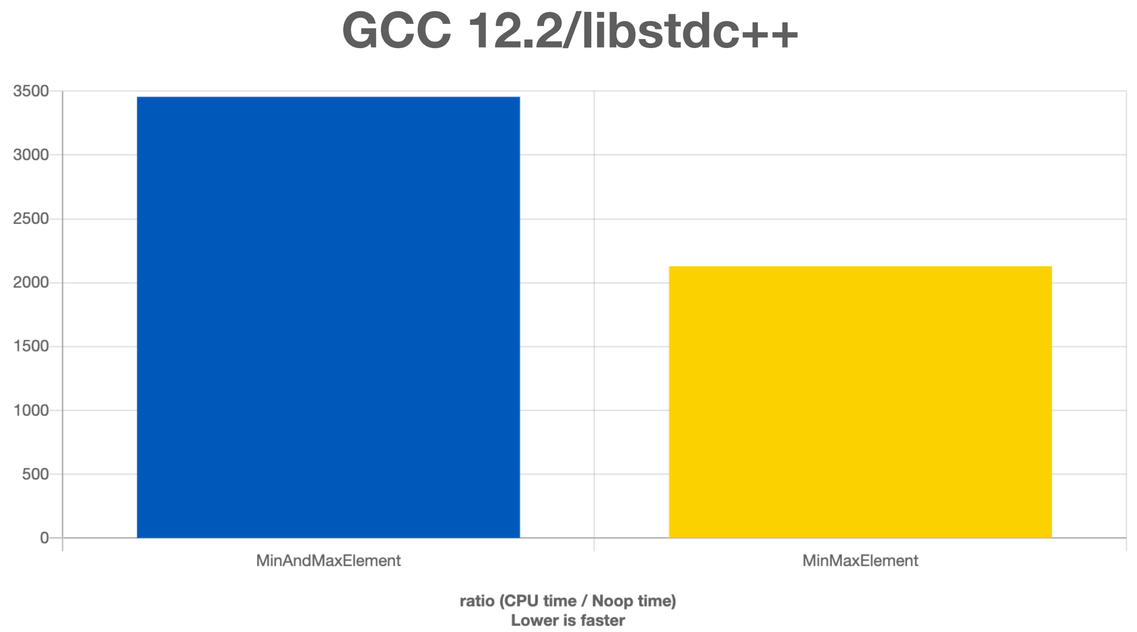
4x Faster

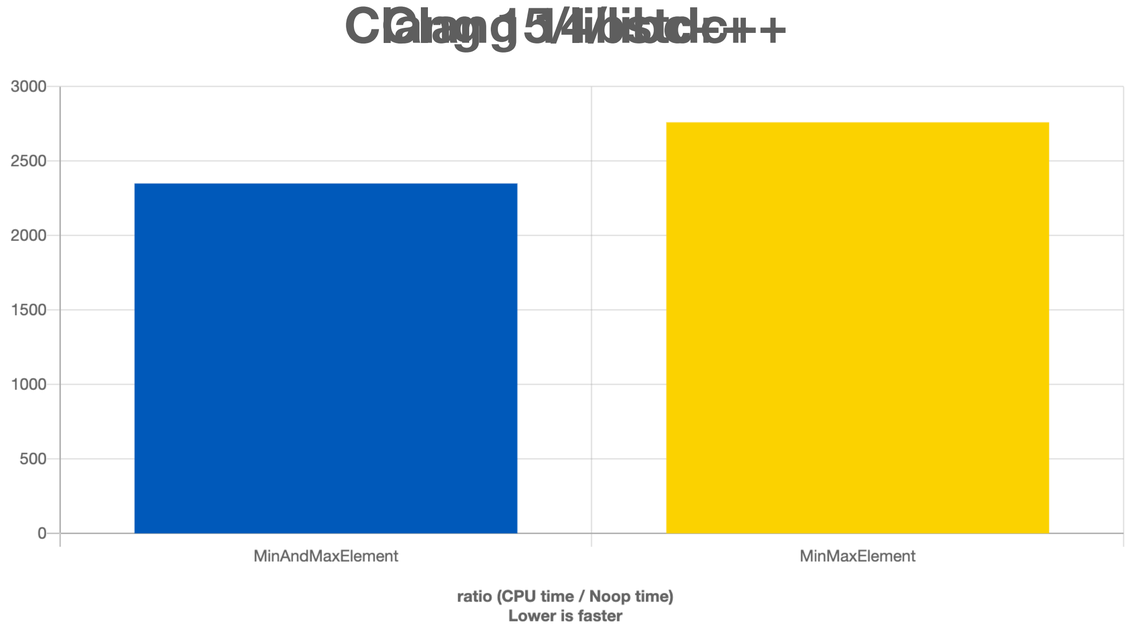
https://quick-bench.com/q/p0J2y_b8quwaJ560iDSBL_SgjzI

```cpp
#include <algorithm>

const auto v = { 566, … };
```

```cpp
const auto min = std::min_element (begin(v), end(v));
const auto max = std::max_element (begin(v), end(v));
```

```cpp
const auto [min, max] = std::minmax_element (begin(v), end(v));
```





https://quick-bench.com/q/QnasARJ8vPBHjkdkCUpxW-4m5f0

Techniques for Optimisation

3. Reducing algorithmic complexity

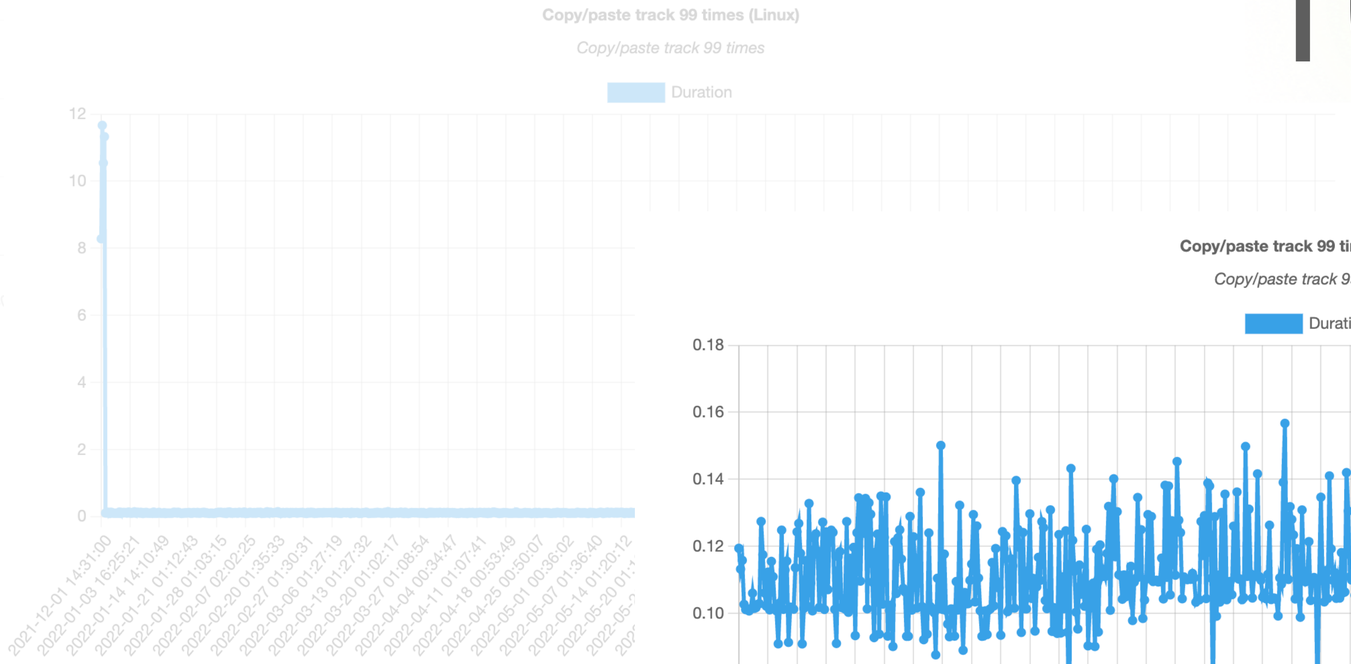
- Identify hotspots from profilers
- Rework algorithms to reduce complexity
- Big O notation
  - O(1), O(log n), O(n), O(n^2) etc.
- Ensure your algorithm works the same way
  - Including contracts!
  - Testing saves you!

Example: `Edit::createNewItemID`

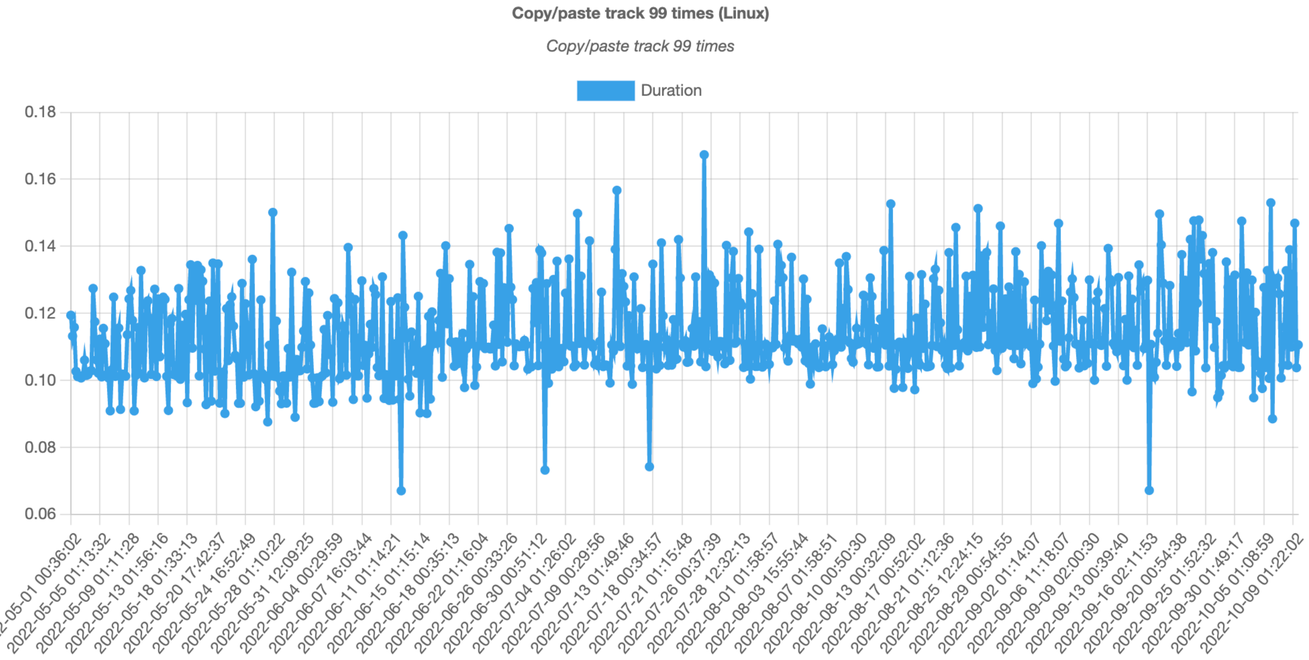
```
EditItemID Edit::createNewItemID (const std::vector<EditItemID>& idsToAvoid) const
{
    // TODO: This *may* be slow under heavy load - keep an eye open for this
    // in case a smarter caching system is needed
    auto existingIDs = EditItemID::findAllIDs (state);

    existingIDs.insert (existingIDs.end(), idsToAvoid.begin(), idsToAvoid.end());
    existingIDs.insert (existingIDs.end(), usedIDs.begin(), usedIDs.end());

    trackCache.visitItems ([&] (auto i)  { existingIDs.push_back (i->itemID); });
    clipCache.visitItems ([&] (auto i)   { existingIDs.push_back (i->itemID); });

    std::sort (existingIDs.begin(), existingIDs.end());
    auto newID = EditItemID::findFirstIDNotIn (existingIDs);
    jassert (usedIDs.find (newID) == usedIDs.end());
    usedIDs.insert (newID);

    return newID;
}

std::vector<EditItemID> EditItemID::findAllIDs (const juce::ValueTree& v)
{
    std::vector<EditItemID> ids;

    IDRemapping::visitAllIDDecls (v, [&] (const juce::var& oldID)
    {
        auto i = EditItemID::fromVar (oldID);

        if (i.isValid())
            ids.push_back (i);
    });

    return ids;
}


    template <typename Visitor>
    static void visitAllIDDecls (const juce::ValueTree& v, Visitor&& visitor)
    {
        for (int i = 0; i < v.getNumProperties(); ++i)
        {
            auto propName = v.getPropertyName (i);

            if (isIDDeclaration (propName))
                visitor (v.getProperty (propName));
        }

        for (const auto& child : v)
            visitAllIDDecls (child, visitor);
    }
```

```
EditItemID Edit::createNewItemID (const std::vector<EditItemID>& idsToAvoid) const
{
    if (nextID == 0)
    {
        auto existingIDs = EditItemID::findAllIDs (state);

        existingIDs.insert (existingIDs.end(), idsToAvoid.begin(), idsToAvoid.end());

        trackCache.visitItems ([&] (auto i)  { existingIDs.push_back (i->itemID); });
        clipCache.visitItems ([&] (auto i)   { existingIDs.push_back (i->itemID); });

        std::sort (existingIDs.begin(), existingIDs.end());
        nextID = existingIDs.empty() ? 1001 : (existingIDs.back().getRawID() + 1);

       #if JUCE_DEBUG
        usedIDs.insert (existingIDs.begin(), existingIDs.end());
       #endif
    }

    auto newID = EditItemID::fromRawID (nextID++);

#if JUCE_DEBUG
    jassert (usedIDs.find (newID) == usedIDs.end());
    usedIDs.insert (newID);
#endif

    return newID;
}
```

Copy/paste track 99 times (Linux)
Copy/paste track 99 times
Duration
Min
Max
Mean
12
10
8
6
4
2
0
2021-12-01 14:31:00
2021-12-01 14:46:00
2021-12-01 15:12:00
2021-12-01 16:44:00


Copy/paste track 99 times (Linux)
Copy/paste track 99 times
Duration
12
10
8
6
4
2
0

100x


Copy/paste track 99 times (Linux)
Copy/paste track 99 times
Duration
0.18
0.16
0.14
0.12
0.10
0.08
0.06

- Reduced complexity from O(2n) to O(1)
- Behaviour has changed
  - ID now always increases
  - Could wrap if called `std::numeric_limits<int64_t>::max()` times
    - 9223372036854775807 (9.2x10^18)
    - That’s quite a lot of tracks/clips/plugins
- Contract has stayed the same - returns a unique ID
  - Checked with an assertion

Techniques for Optimisation

4. Caching appropriate data

- If data is accessed and manipulated in the same way frequently, it may be faster to store the manipulated data somewhere
- Difficulties involve:
  - Keeping track of the cache/dirty state
  - Knowing when to clean up the cache
- Uses additional memory

Example:
`MidiClip::getSequenceLooped()`

```
class MidiClip  : public Clip
{
private:
    mutable std::unique_ptr<MidiList> cachedLoopedSequence;
```

```
MidiList& MidiClip::getSequenceLooped() const
{
   if (! isLooping())
        return getSequence();

    if (cachedLoopedSequence == nullptr)
        cachedLoopedSequence = createSequenceLooped (getSequence());

    return *cachedLoopedSequence;
}
```

Techniques for Optimisation

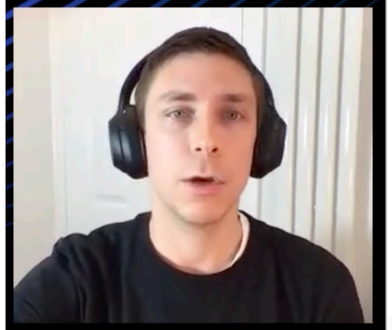
5. Reducing memory footprint

- Cache misses stall the CPU effectively wasting cycles
- Reducing the amount of memory a performance sensitive section of code uses can reduce the time to execute. Why?
  - Memory is more likely to be in lower cache levels
  - Lower cache levels are MUCH faster
- If possible, use contiguous memory

3. Multi-threading, CPUs and memory

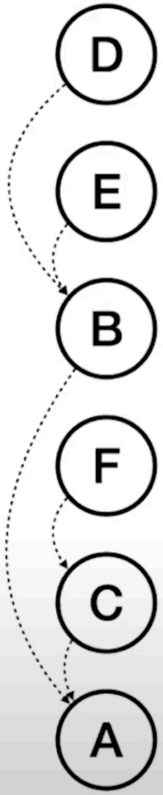
Introduction to Tracktion Graph

ADC20
AUDIO DEVELOPER CONFERENCE

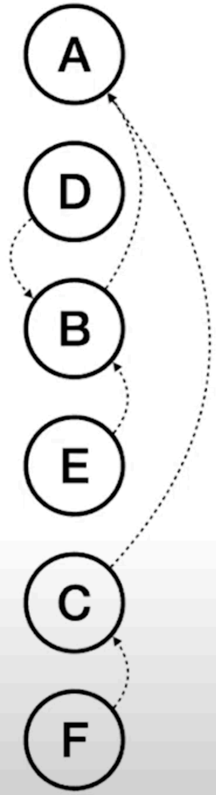


Dave Rowland

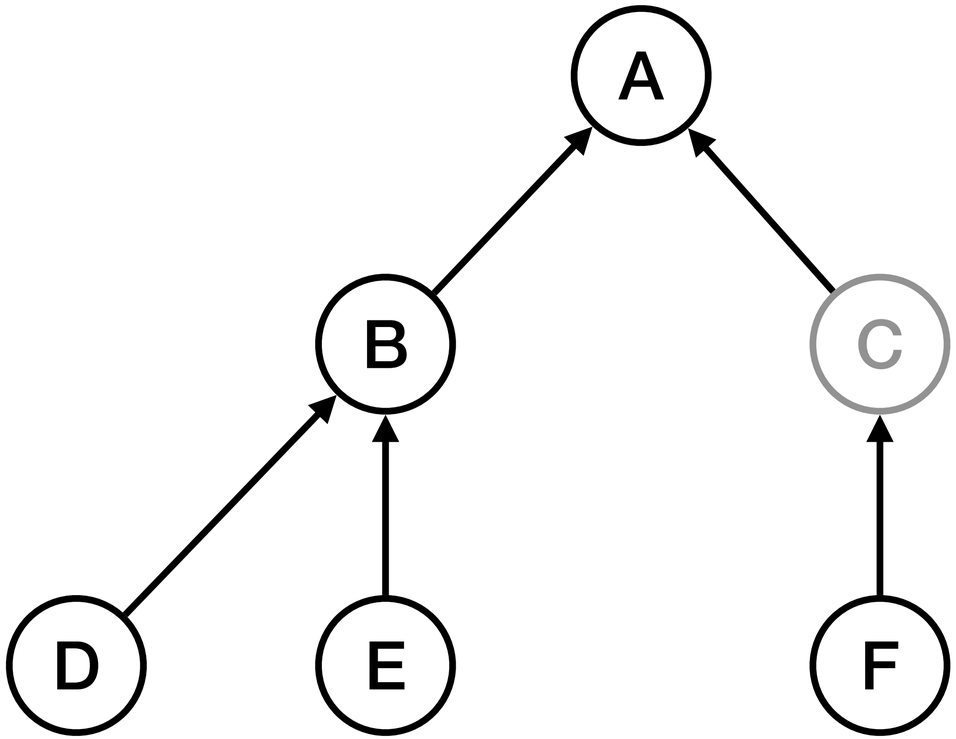
Post-ordered DFS: ✅



Pre-ordered DFS: ❌

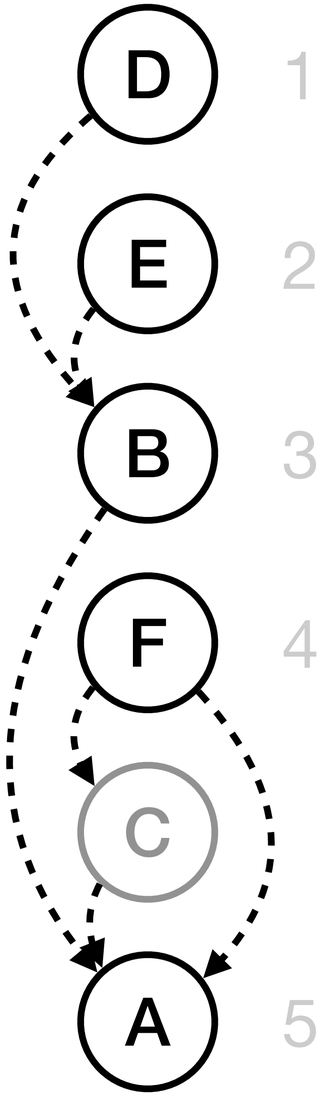


18

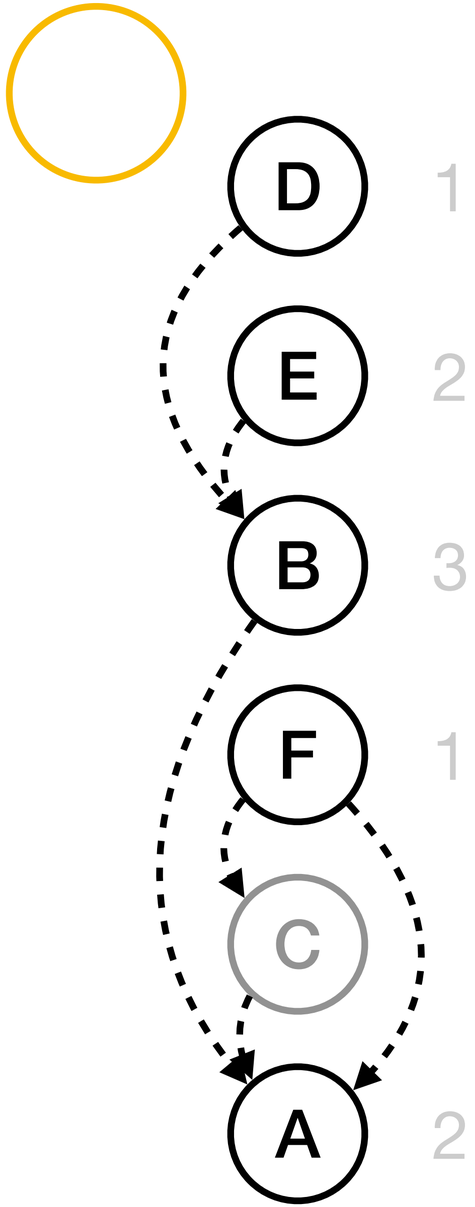


Directed Acyclic Graph

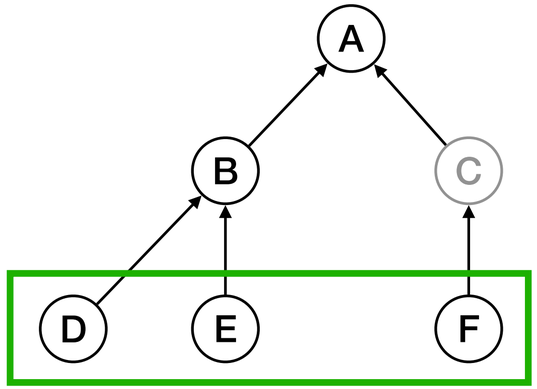
Per-node Assignment

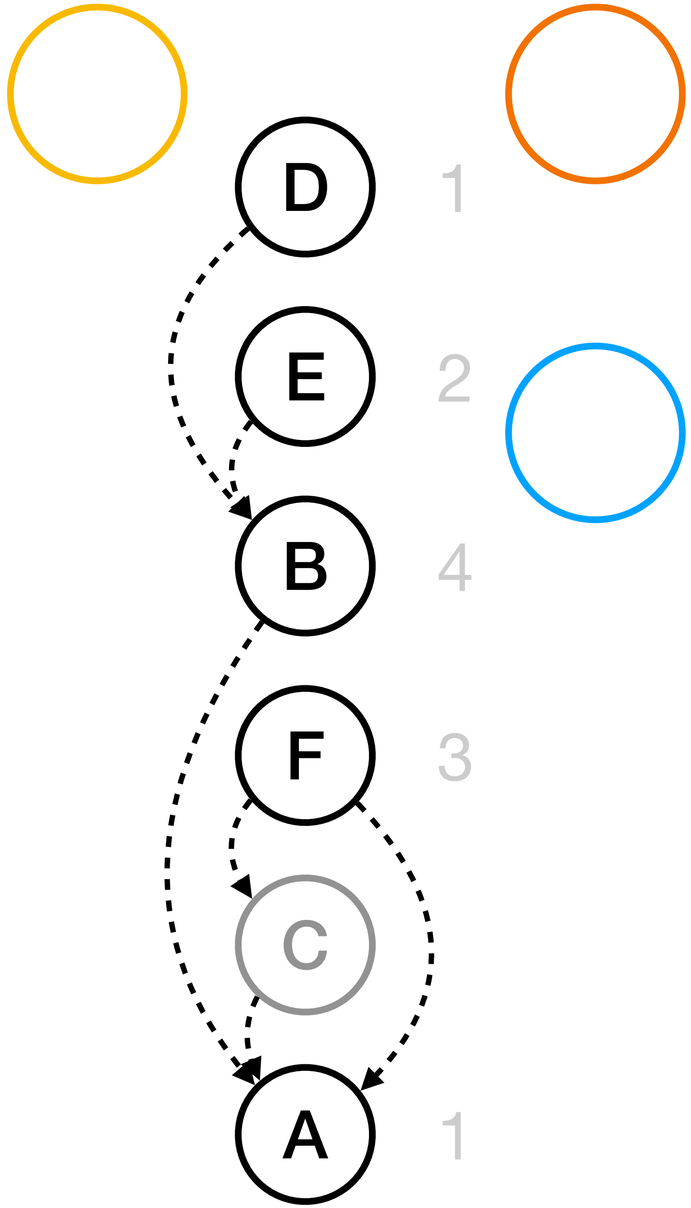


Single Threaded Analysis

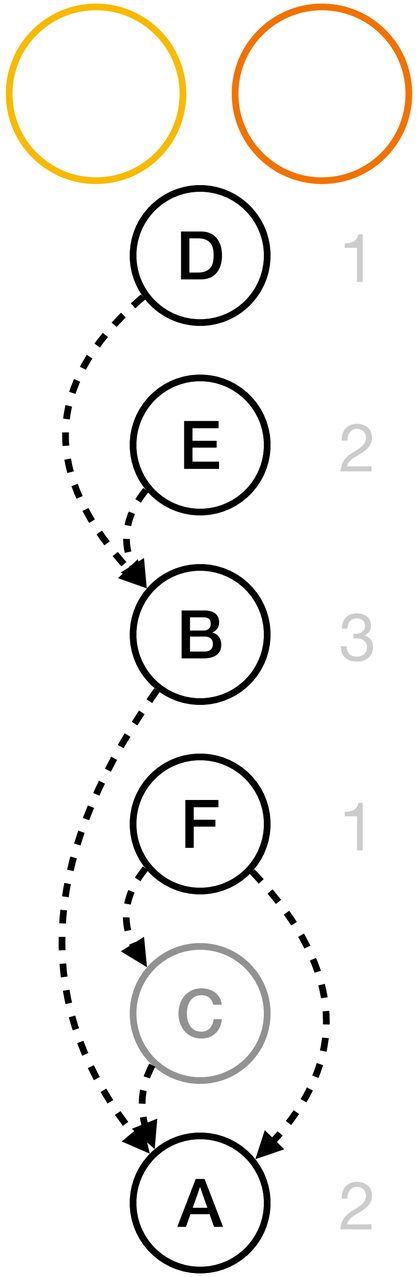


Multi Threaded Pre-process Analysis



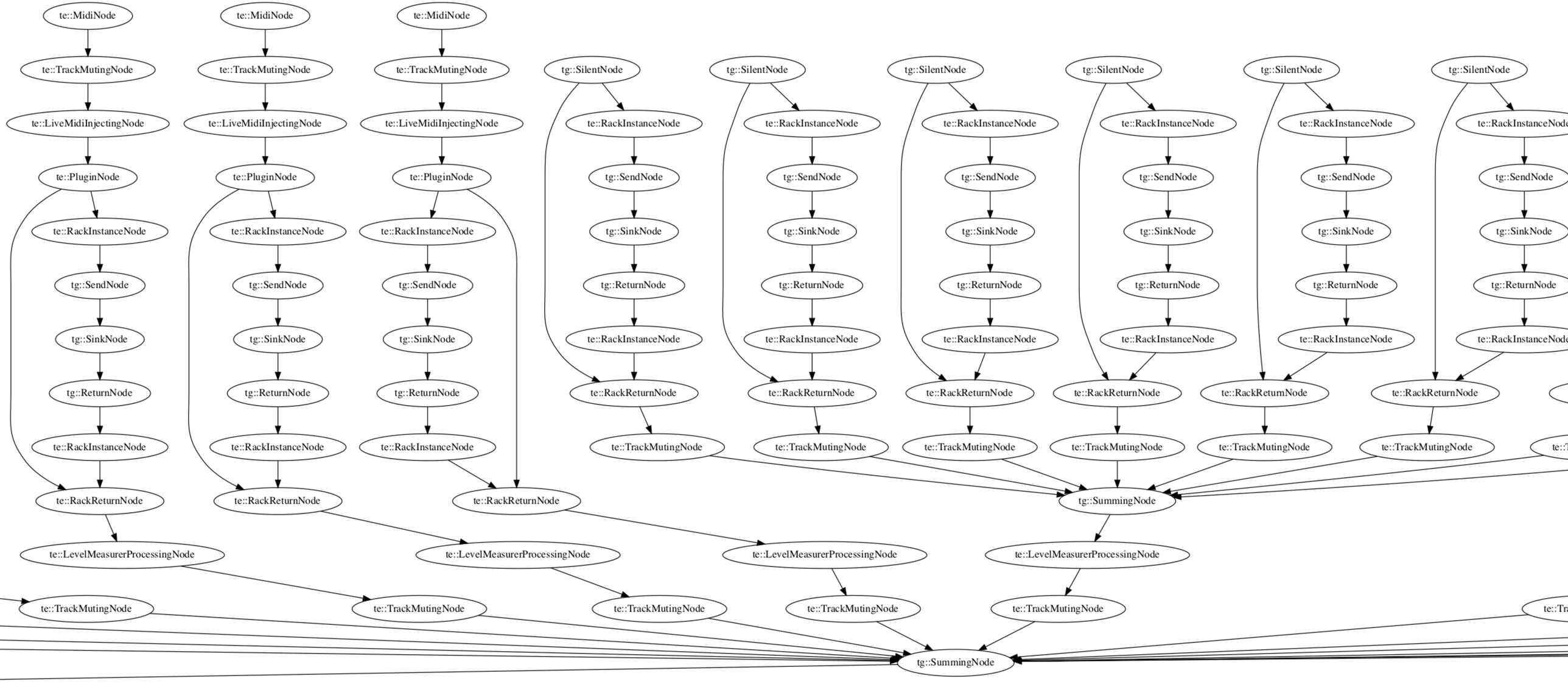


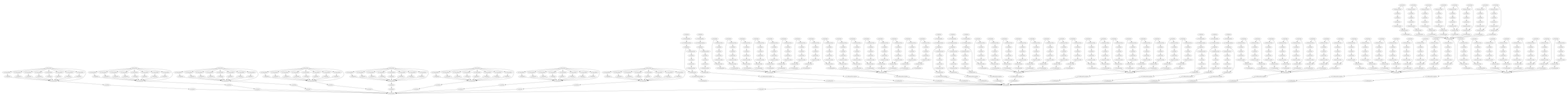
Multi Threaded Run-time Memory Assignment



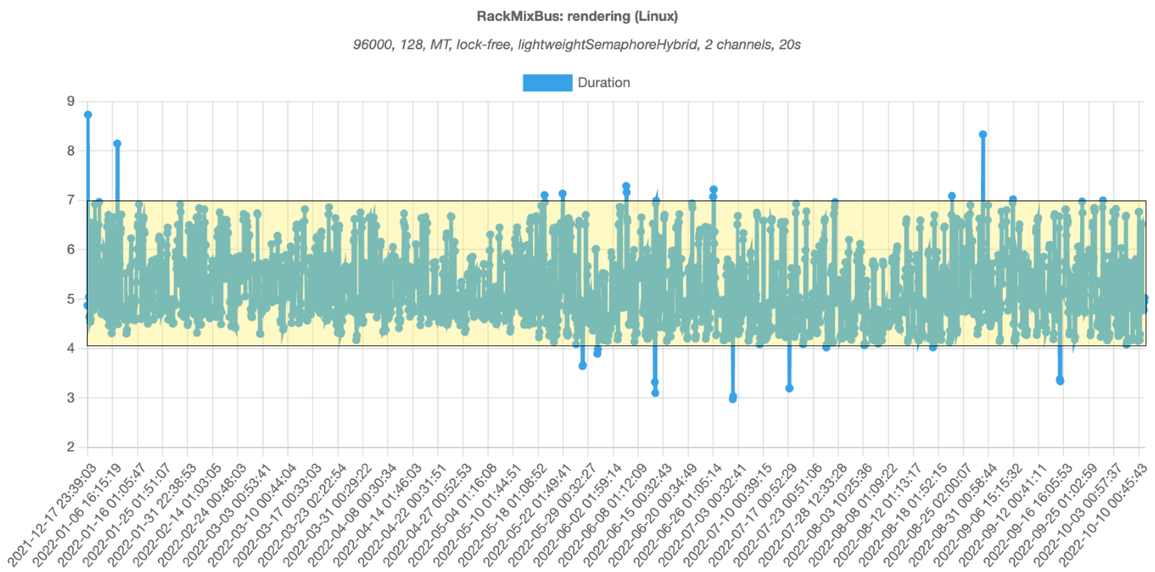
Multi-threaded Assignment

- Difficult to reason about
- Varies a lot depending on:
  - Graph size
  - Graph structure
  - Number of threads
- **Need to measure/benchmark!**

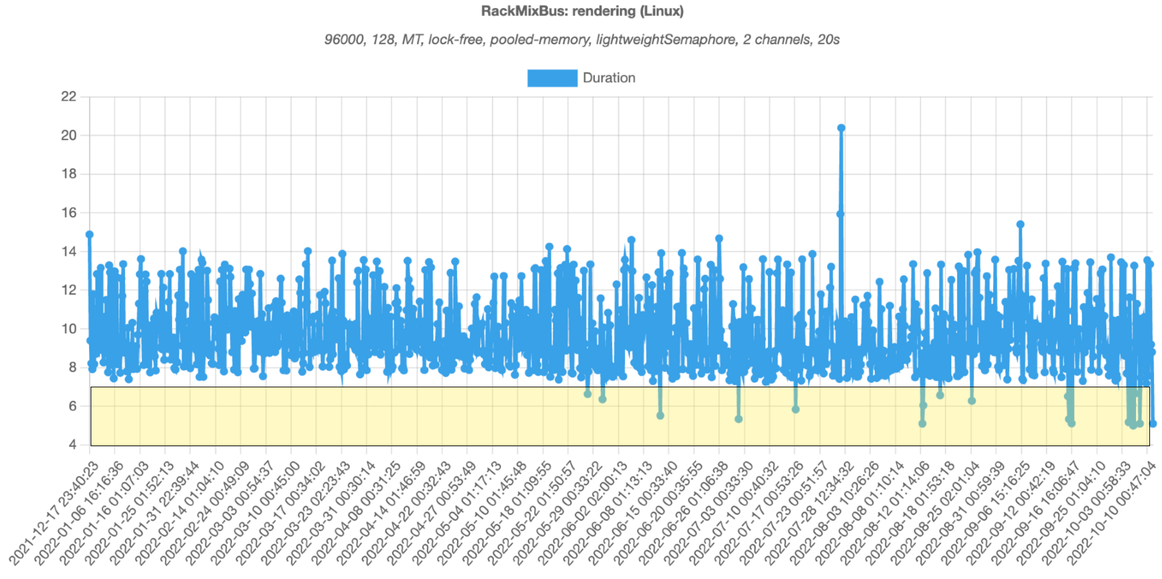

te::MidiNode
te::TrackMutingNode
te::LiveMidiInjectingNode
te::PluginNode
te::RackInstanceNode
tg::SendNode
tg::SinkNode
tg::ReturnNode
te::RackInstanceNode
te::RackReturnNode
te::LevelMeasurerProcessingNode
te::TrackMutingNode
tg::SilentNode
te::RackInstanceNode
tg::SendNode
tg::SinkNode
tg::ReturnNode
te::RackInstanceNode
te::RackReturnNode
te::TrackMutingNode
tg::SummingNode
te::LevelMeasurerProcessingNode
te::TrackMutingNode
tg::SummingNode



Each Node Has its Own Memory



Run-time Memory Assignment



- The overhead of using less memory outweighed the cache benefits
  - Complexity in run-time assignment of memory
- Might be different on more constrained platforms
- Or different graph configurations
  - E.g. more nodes, larger channel counts, larger buffer sizes etc.
- May need some heuristics of when to adapt

Optimising a Real-time Audio Processing Library

David Rowland

@drowaudio

Slides/video:

github.com/drowaudio/presentations

tracktion code:

github.com/Tracktion/tracktion_engine