Contextual Instrumented-Based Profiling for Datacenter Applications

Mircea Trofin, Google

agenda

- translate the title
- contextual instrumentation implementation (main topic)
- results
- non-server example
- plans & speculations

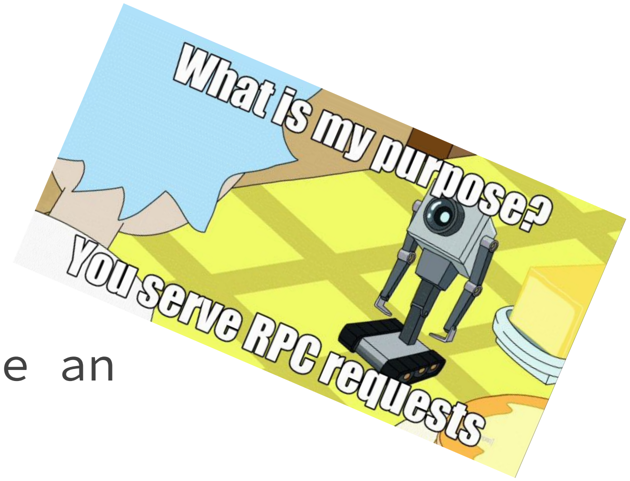
what is “instrumented…” (aka iFDO)?

- 2 builds:
  - **instrument** certain edges, before IPO:
    - `llvm.instrprof.*` intrinsics
    - identify each edge with an index (0, 1, 2..)
    - lower to counter increments in a global, per-function buffer
  - *run the program* -> counter values form the profile
    - maybe run it with a bunch of different inputs & merge profiles
  - **rebuild**: profile ingested at same position in pass pipeline as instrumentation
    - so that counter indices match
  - $ profit! $:)

- compiler-rt code for e.g. saving the globals to a file

for an in-depth dive: 2020 LLVM Developers’ Meeting: *“PGO Instrumentation: Example of CallSite-Aware Profiling”*, Pavel Kosov, Sergey Yakushkin

datacenter applications (compiler view)



- **init**: set up internal architecture
- **steady state**, threads in a pool execute an infinite loop:
  - pick up ***work*** from some queue
  - execute some synchronous ***task*** (typically short lived)
- a **task** is the analogue of “classical” **main**
  - just that the entry point is the RPC handler
  - the **most direct** impact of the optimizing compiler: **finish tasks fast**

- we collect profiles via an RPC, too!

a *profiling* problem

- we load profiles before IPO
- callee behavior can be dependent on use
  - but! profile has *averages* over all possible callers!
  - => profile quality degrades through inlining
  - poor profile => less profit :(

a measurable effect: can we estimate dynamic instruction count changes if inline policy changes -> reward signal for MLGO training

see also the CSPGO talk earlier, for the sampling-based profiling approach to this problem

contextual profiles

- keep distinct counters for different call ~~sites~~ paths
  - btw, “paths” starting from ***where***?

- challenge ***for instrumentation*** (stemming from current technique):
  - we pre-allocate counters statically
  - we don’t know the call paths - how many counter versions ***to*** allocate?
  - (...various alternatives)

key insight

Rather than think of it as a “classical binary”

Why not think of it as a “package of tasks”

(distinct entry points & call graphs)

do we know the entry points (to the tasks)?

- yes (well, the binary owner would know)
- ..or, can detect from behavior in production
  - this is just about determining main entry point *functions* (~=main RPC handlers)
  - unlikely to change too often
- they are *coarse*, *architectural* property of a binary (i.e. fairly stable over time)

implementation

high level

- pass task entry points via an LLVM flag
- main LLVM change: *how instrumentation intrinsics are lowered*
- new instrumentation intrinsic: `llvm.instrprof.callsite`
  - identifies by index a callsite in a function
  - precedes any call site that’s not inline asm or intrinsic
- lowering:
  - no global counter arrays
  - entry BB: call to `__llvm_instrprof_{get|start}_context`
    - returns a chunk of memory - the Context
  - counter update: `Context.counters[counter_index] += <step>`
  - `llvm.instrprof.callsite`:
    - save `CS.getCalledValue()` and `&Context.callsites[callsite_index]` in TLS

low(er) level Details

ContextNode


```
uint64_t Guid

ContextNode* Next

uint32_t NrCounters
uint32_t NrCallsites
--------------------
8 + 8 + 4 + 4 = 24
bytes
```

`uint64_t*`

`ContextNode**`

`NrCounters` and `NrCallsites` are function-specific, compile-time constants

passed to `__llvm_instprof_{get|start}_context`

IR, instrumented

```
define void @an_entrypoint(...) {
  call @llvm.instrprof.increment(<an_entrypoint_guid>, .., <nr_counters>, 0)
  …
  br i1 %smth label %a, label %b

a:
  call @llvm.instrprof.increment(<an_entrypoint_guid>, .., <nr_counters>, 5)
  ...
  call @llvm.instrprof.callsite(<an_entrypoint_guid>, .., <nr_callsites>, 2, %callee_1)
  call void %callee_1
  …
}


@define void @a_callee() {
  call @llvm.instrprof.increment(<a_callee_guid>, .., <nr_counters>, 0)
```

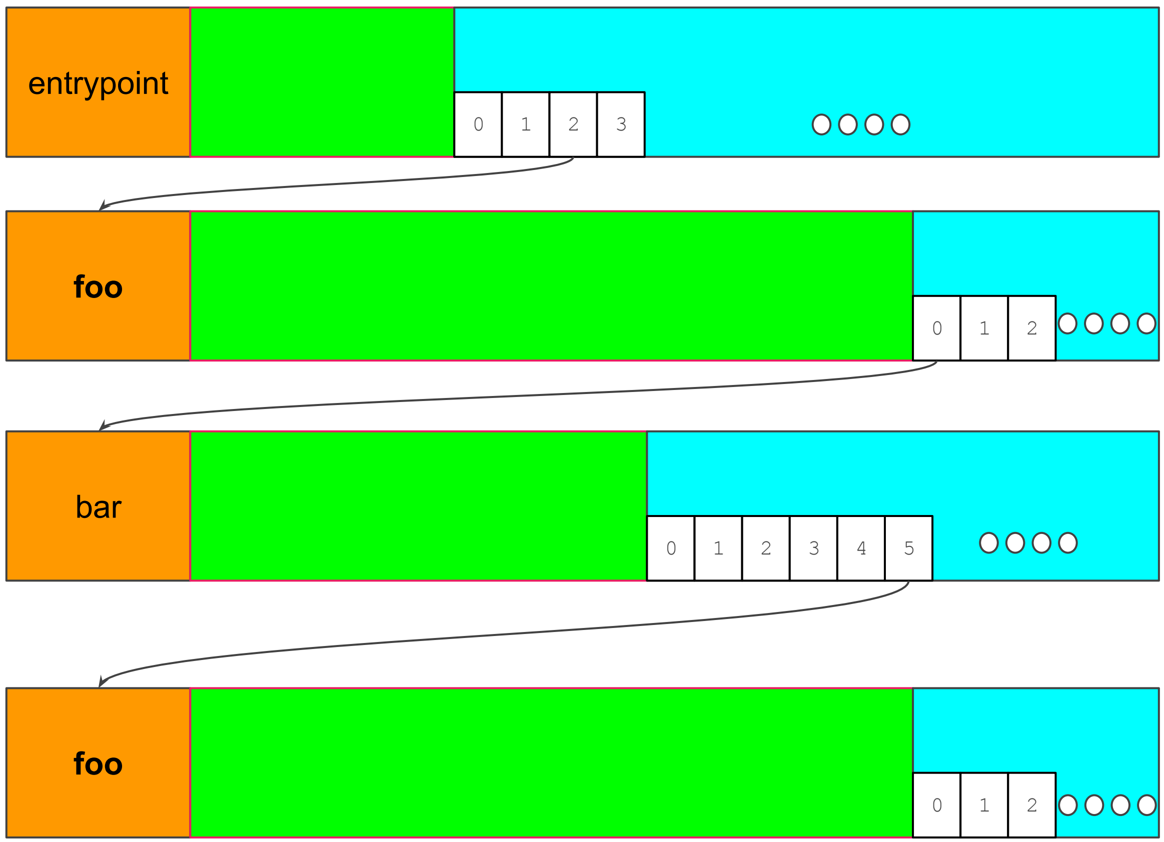
IR-ish (LLVM)

```
define void @an_entrypoint(...) {
  %ctx =
__llvm_instrprof_start_context(1234, ...)
  …
  br i1 %smth label %a, label %b

a:
  %ctx.counters[5] += 1
  ...
  _tls.expected_cs = %callee_1
  _tls.callsite_info = <gep, %ctx.callsites, 2>
  call void %callee_1
  …
}

@define void @a_callee() {
  %ctx = __llvm_instrprof_get_context(5678,
         @a_callee, nr_counters, nr_callsites)
```

C-ish (compiler-rt)

```
void __llvm_instrprof_get_context(guid,callee,
                                  ctrs, csts) {
  if (callee != _tls.expected_cs) {...}

  ContextNode **insert_pt =_tls.callsite_info;
  ContextNode *p = *insert_pt

  while (p && p->guid != guid)
    p = p->Next
  if (p)
    return p;

  p = bump_allocate(ctrs, csts);
  p->next = *insert_pt;
  *insert_pt = p;
  return p;
}
```

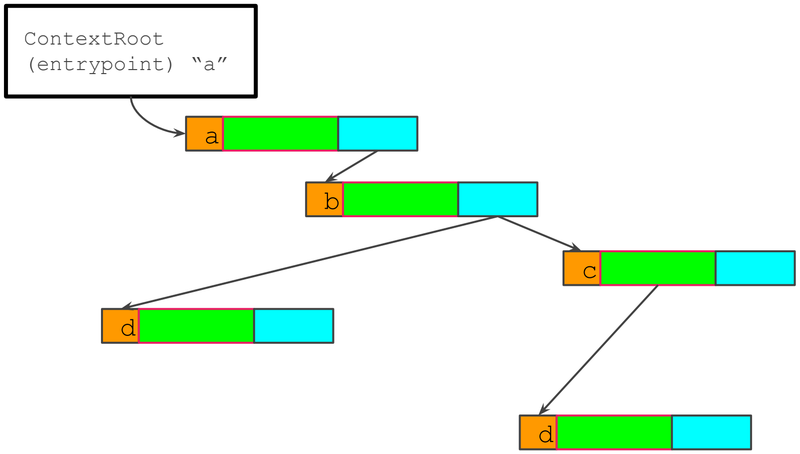
```
define void @entrypoint(...) {
  call @foo  // entrypoint id: 2
}


@define void @foo() {
  call @bar // entrypoint id: 0
}


@define void @bar() {
  call @foo // entrypoint id: 5
}
```



A function will have a different context depending on position in call graph

entry points are special

```
struct ContextRoot {
  ContextNode *FirstNode;
  Arena *FirstMemBlock;
  Arena *CurrentMem;
  __sanitizer::StaticSpinMutex Lock;
};
```



Set up and zero-initialized on LLVM side

Parameter to `__llvm_instrprof_start_context`

`Lock.tryLock()` failed? get a *"ScratchContext"* instead!

ScratchContext

- also what __llvm_instrprof_get_context returns if:
  - expected callee doesn’t match
  - there’s TLS data absent (== we’re outside any entry point)
- understood by compiler-rt:
  - if function uses ScratchContext, all callees will also use that
  - detectable because TLS will contain a ScratchContext interior pointer

(also what __llvm_instrpof_start_context returns if it can’t take the lock)

special consideration: signal handlers

- at any random point in execution, a signal handler may be called
  - it will promptly call `__llvm_instprof_get_context`! now what?
- it will discover:
  - **either** no call info on TLS (the handler in runtime “consumes” that info); **or**
  - <u>expected callee</u> is not itself; **or**
  - the call info is pointing in ScratchContext

  => return ScratchContext

other special considerations

- recursion
  - not doing anything special - just chain recursive activations
  - “it’s OK” - RPCs should finish fast

- tail calls
  - currently doing nothing special
  - could get smart and keep a “bubble” of contexts

profile format

- 2 step:
  - raw: dump the Arenas (plus a small header)
  - post-process to LLVM Bitstream

results

setup

- search binary
  - not IO bound, low/no contention -> longer running RPCs
  - 2 workloads, “large” and “small”
- reusing current instrumented profiling collection tooling

- runtime **mem** overhead: 120+25 + N_THREADS * 1MB (<=ScratchContext size)
- regular iFDO profile: 204MB (zipped: 65MB)
- *final ctx profile: 46MB (zipped: 12MB)*

profile characteristics

workload	raw profile	# ctx	# counters	# non-0 counters	max depth
large	120MB	1,118,987	9,376,222	3,201,863	89
small	25MB	279,725	2,082,311	774,796	62

binary size

section	iFDO	Contextual
.text	449MB	645MB
__llvm_prf_*	213MB (35MB are names, so “critical” is 117MB)	-
Total	964MB	960MB

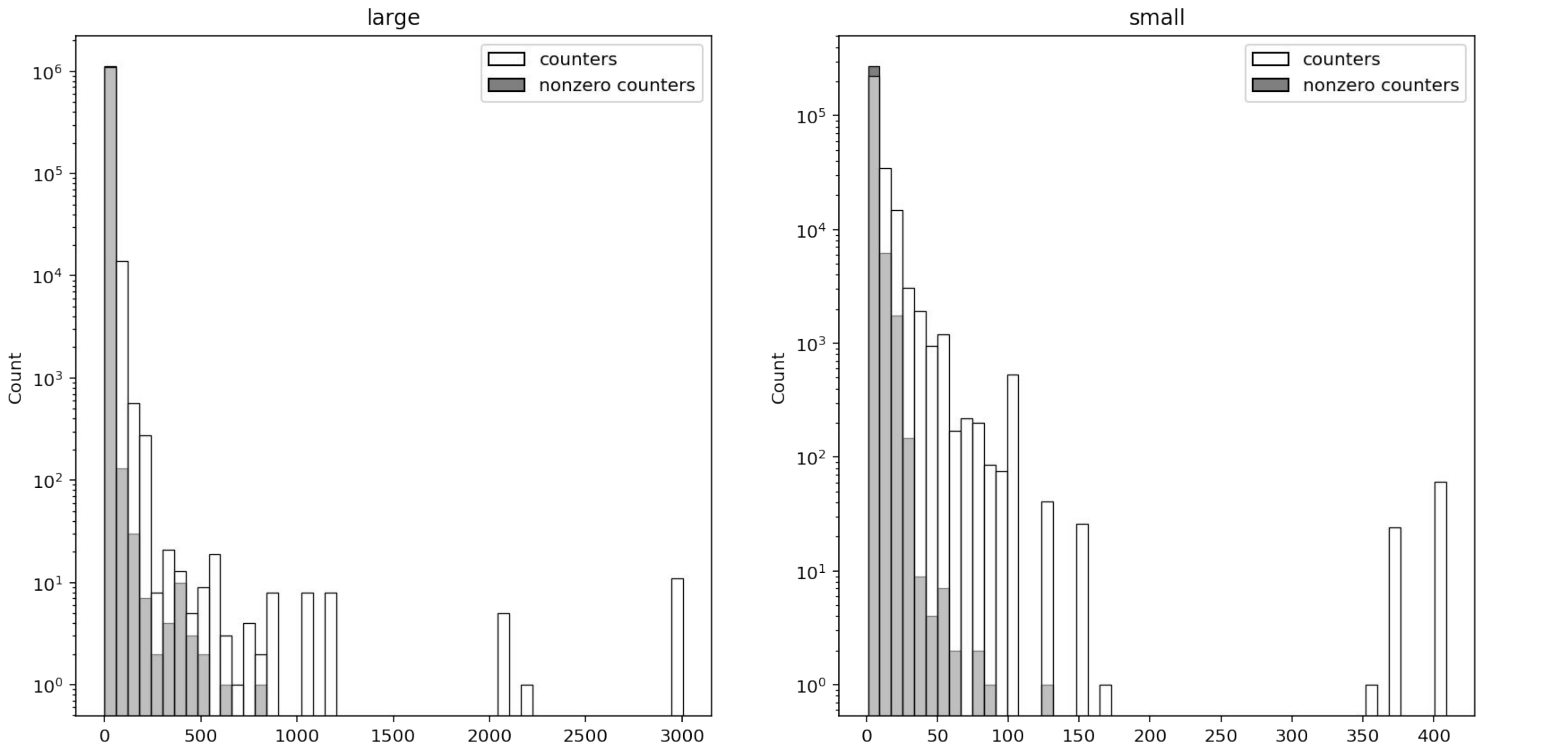
inherent .text overhead due to callsites.

profile collection performance

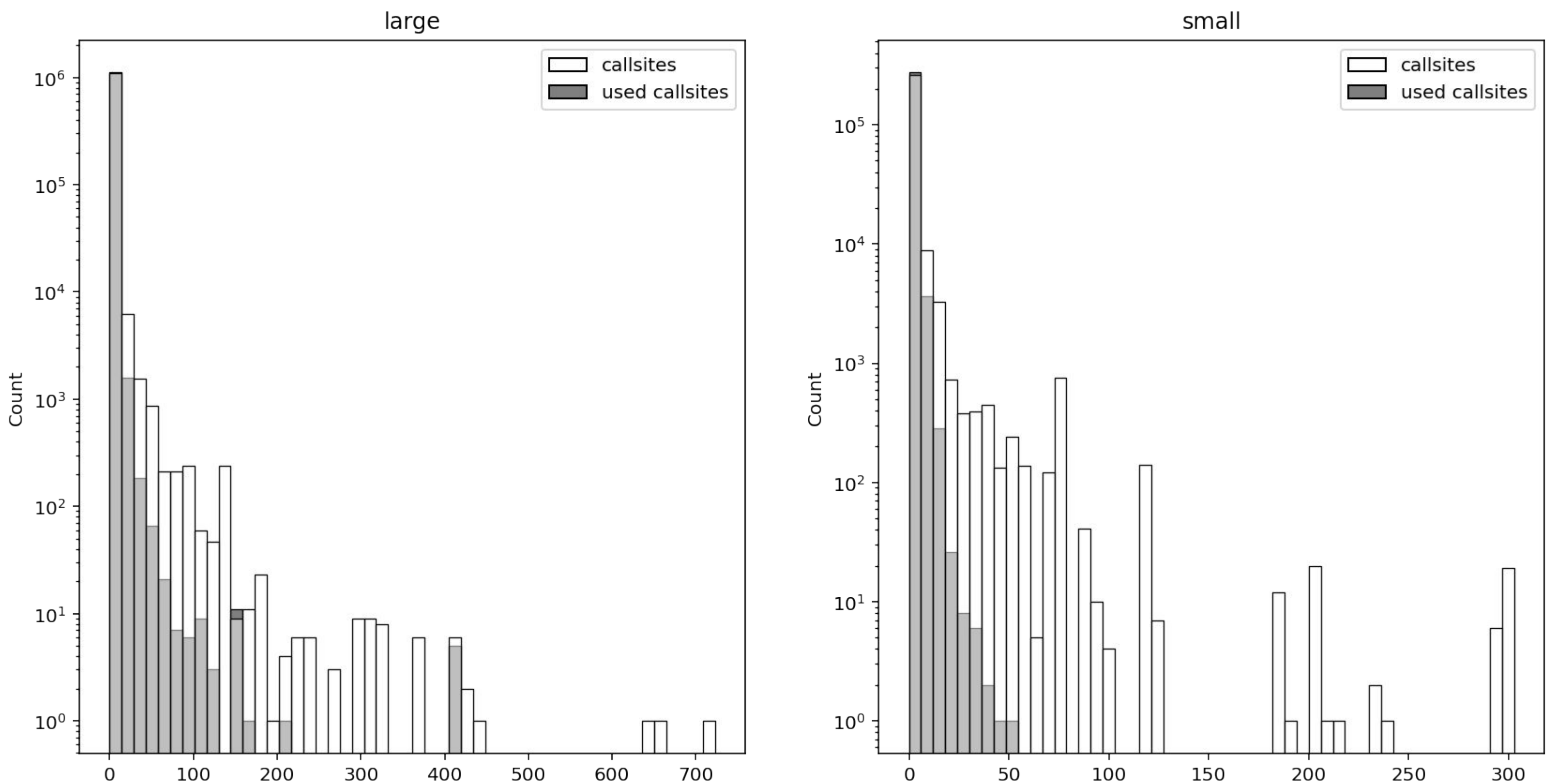
Metric	iFDO	contextual	improv. *__multiplier__*
"TOTAL":QPS:	3,456.95	18,399.70	5.32
"SMALL":avg_cpu_kcycles:	49,112.96	10,699.07	4.59
"SMALL":99.9%ile_server_latency_usec:	1,152,165.00	166,625.00	6.91
"SMALL":avg_round_trip_latency_usec:	54,970.23	11,297.49	4.87
"LARGE":avg_cpu_kcycles:	91,293.63	13,937.04	6.55
"LARGE":99.9%ile_server_latency_usec:	634,050.00	75,521.00	8.40
"LARGE":avg_round_trip_latency_usec:	65,588.55	10,403.51	6.30

- (absence of) shared writes
  - anecdote: if the null context were shared => **20x slowdown** compared to normal iFDO! (yes, without any concurrency control)
- steady-state overhead is just around callsites
  - i.e. decaying occurrence of any (bump-)allocation

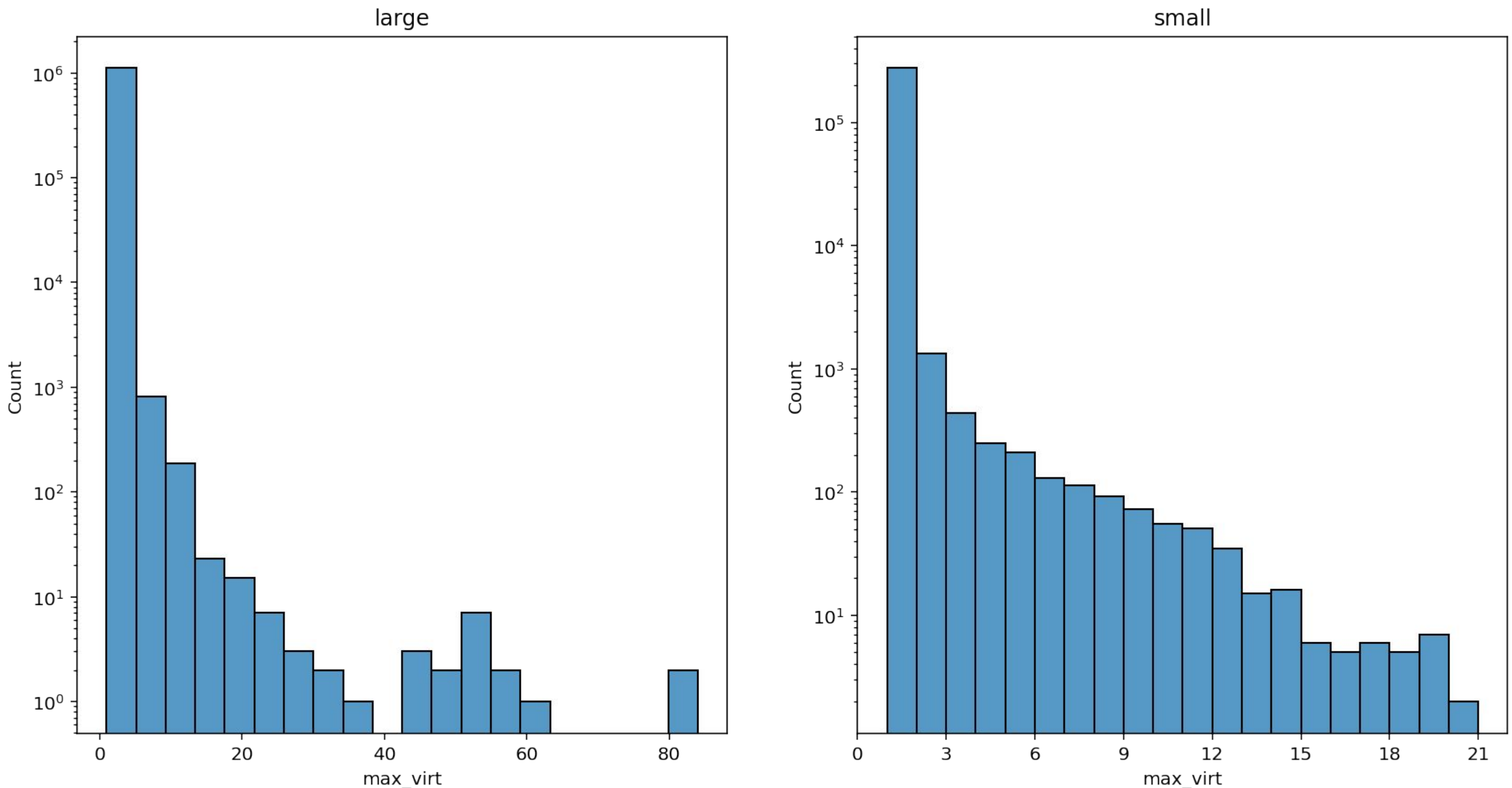
Distribution of nr of counters per ctx (y: log scale)



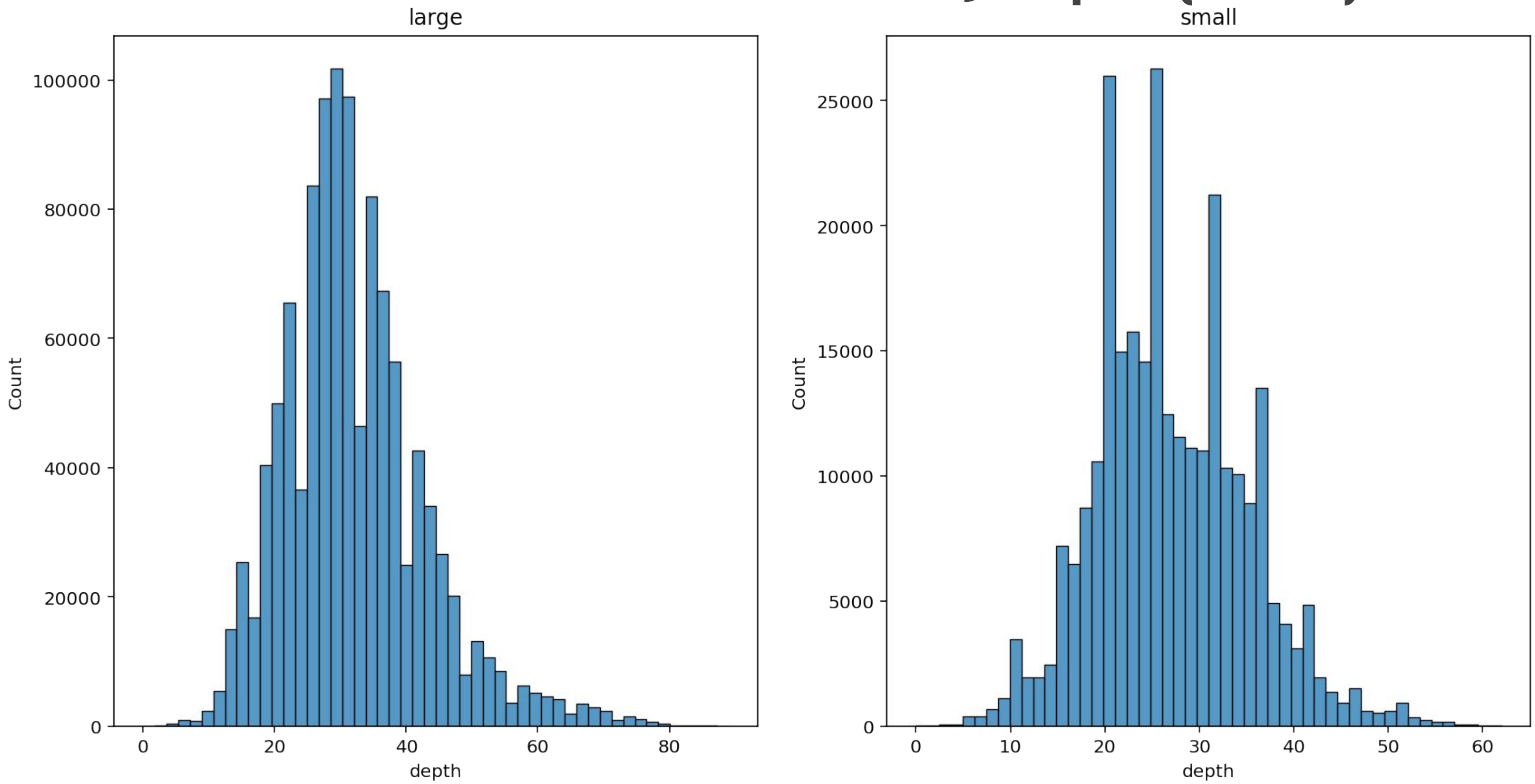
Distribution of nr of callsites per ctx (y: log scale)



Distribution of max indirect calls in a ctx (y: log scale)



Distribution of number of contexts by depth (linear)



a non-server use

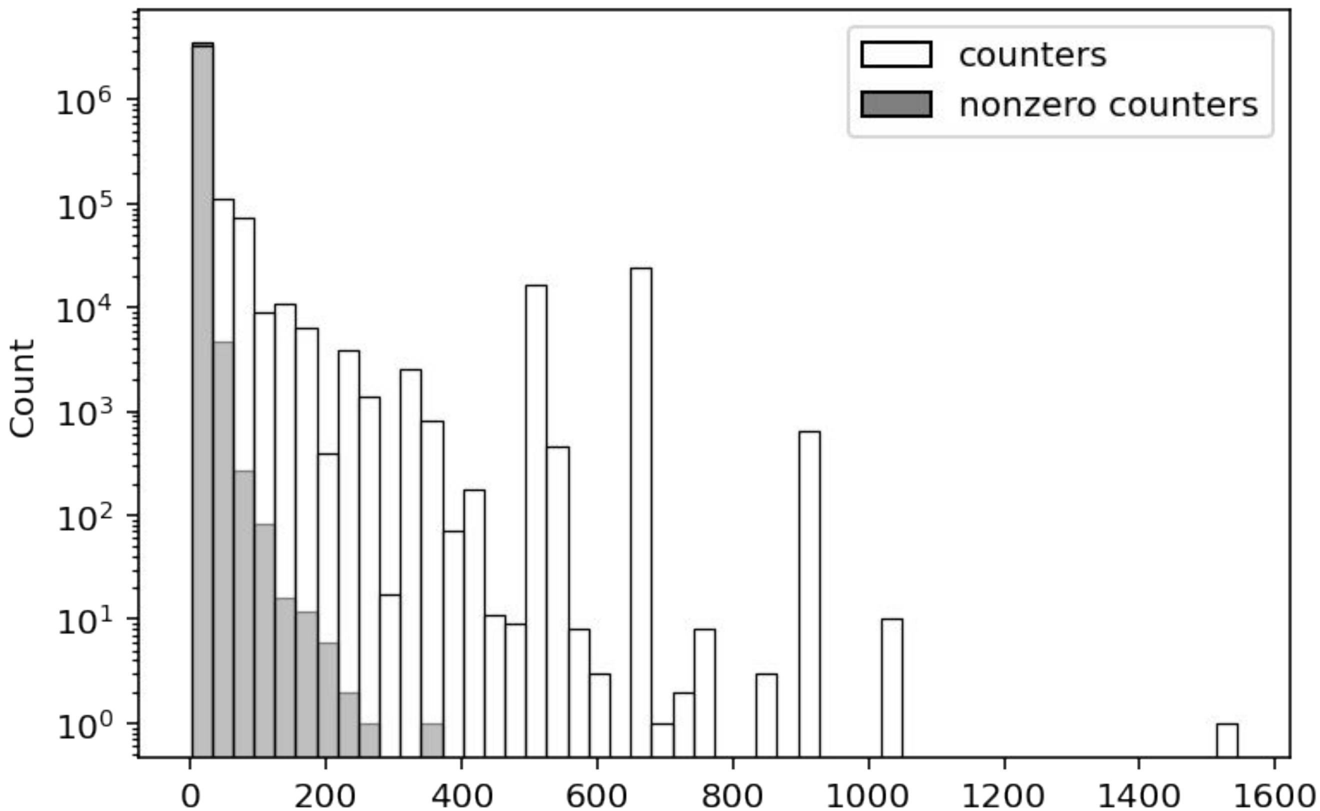
opt

- collected the IR of PassBuilder.cpp (~8MB)
- opt --passes='default<O2>'

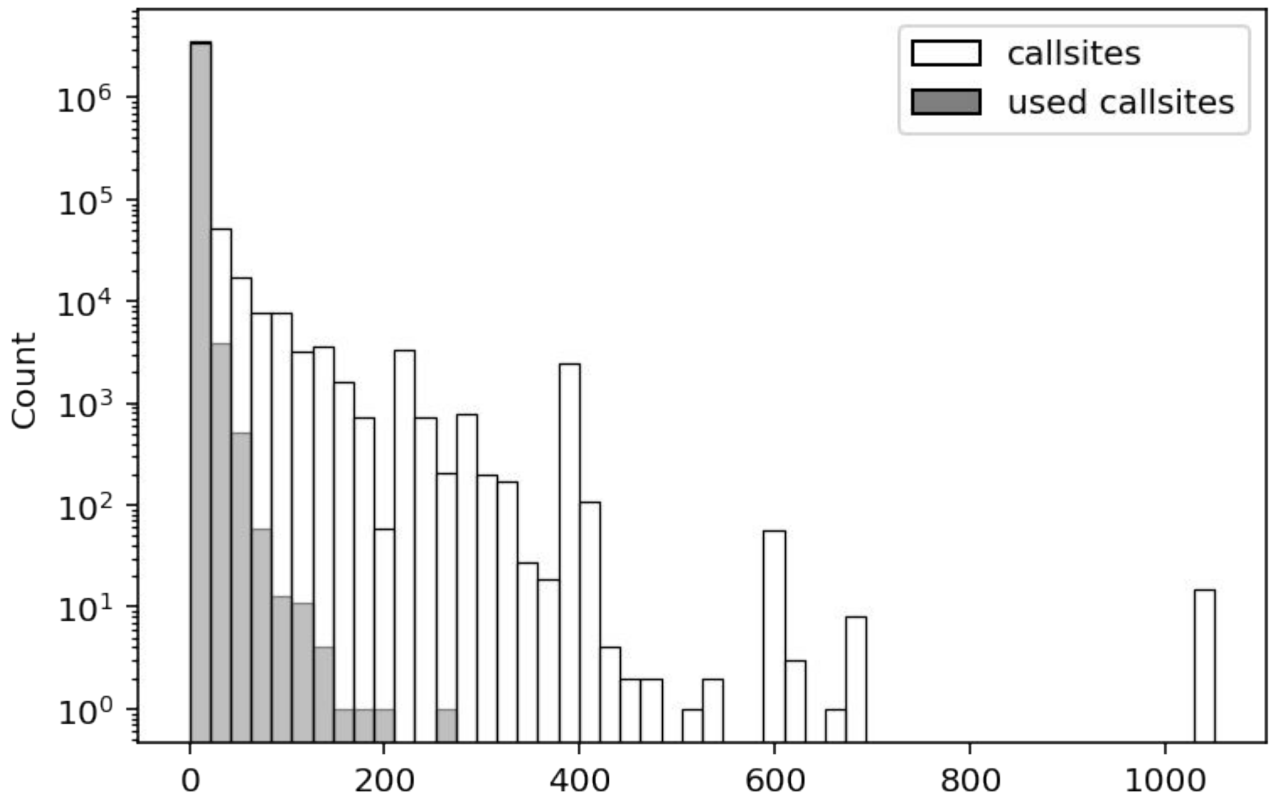
metric	iFDO	Contextual
time	**12.51s***	**30.29s***
profile size	19MB	138MB
#counters		66M
#contexts		3.5M
runtime mem usage		868MB

**(for reference: ~9s non-instr)*

Distribution of nr of counters per context (y: log scale)



Distribution of nr of callsites per ctx (y: log scale)



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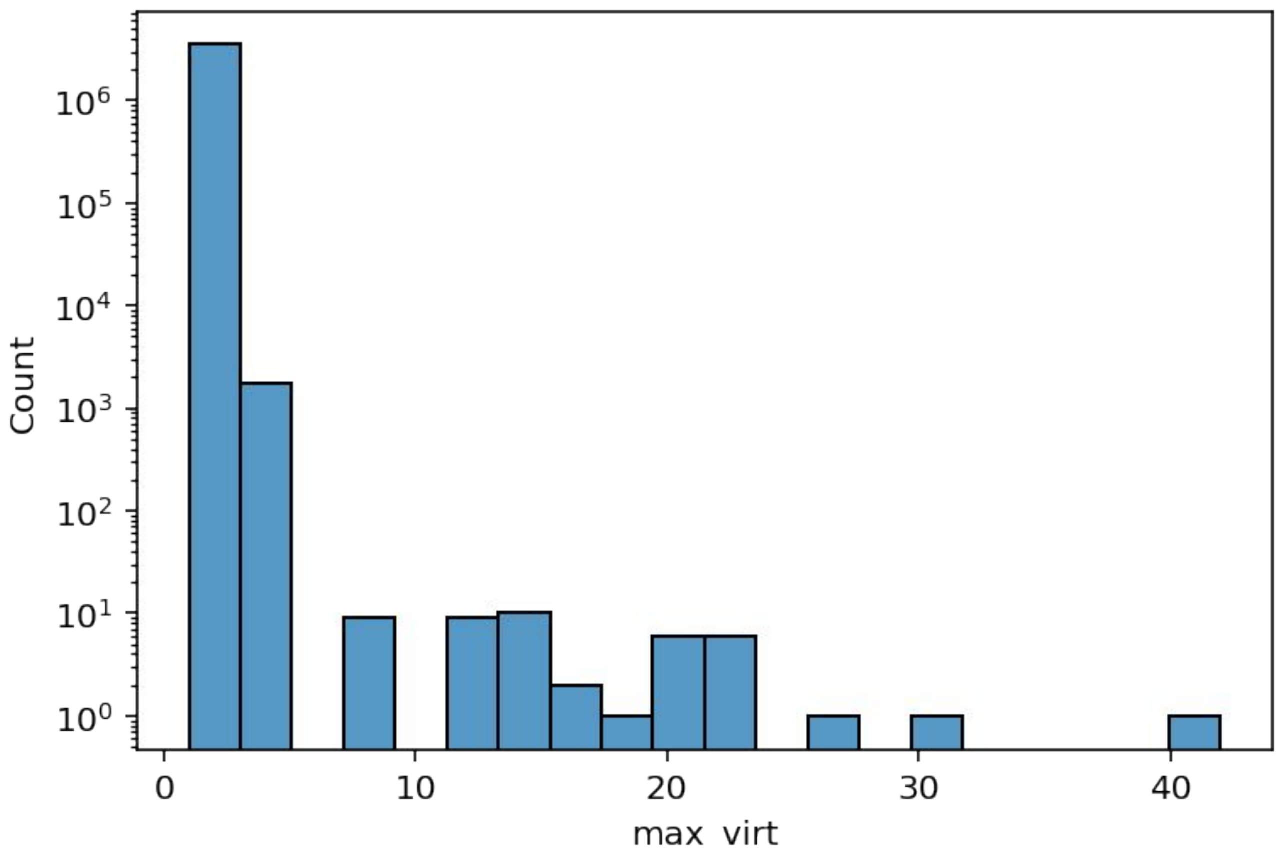

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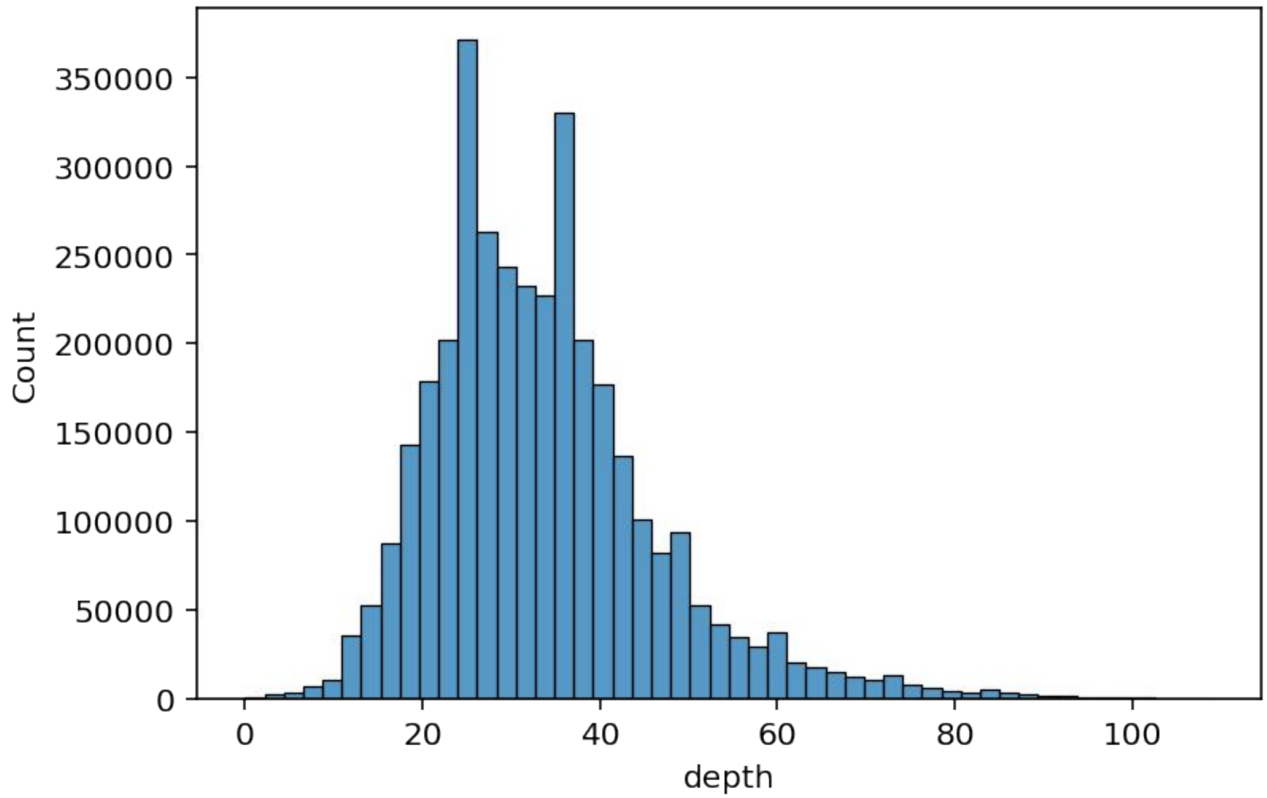

some differences

- max counter ***values*** (relative to entry):
  - large: 4K
  - small: 16K
  - opt: 24M

- it’s why opt’s profile is *relatively small*
  - spends more time in loops

plans & speculations

profile ingestion (use)

- interplay with ThinLTO
- ThinLTO ingestion builds on existing “Workload Definitions” (PR [#74545])
  - ingest all of a graph into one module
- post-link opt leverages `ModuleInliner`:
  - do all IPO first, *and then* function simplification
  - ICP, Inliner awareness about ctx profiling
  - this can be relaxed, piecemeal, for passes in the function simplification pipeline, as necessary

possible commonalities with CSPGO

- let's first iterate a bit, risk of "too early abstractions"

- Realistic goal *(I think)*:
  - a common "`ContextualProfileAnalysis`"
  - or at least an abstraction
  - **goal is to make "contextual awareness" for a pass a technique-independent change**

in closing

- RFC -> after EuroLLVM
- "showcase" PR #86036
- the "task-based", "pass the entry points" approach may be more general
  - `main` isn't what it used to be
  - lots of other programs are event-driven (browsers. phone apps.)
  - focus analysis, optimizations… (*"optimizing, but to what end?"*)