Google Open Source

Practical Compiler Optimizations for Warehouse-Scale Applications

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Workshop Schedule

8:30 - 9:00am	Presentation: Warehouse-Scale Computing (WSC) @ Google
9:00 - 9:30am	Presentation: WSC @ Meta
9:30 - 10:00am	Presentation: WSC @ Sony
10:00 - 10:30am	Break
10:30am - 12:30pm	Open round table: Optimizing for WSC

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Warehouse-Scale Computing at Google

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Agenda

- Motivation & Workshop Goals
- Performance Characteristics of Google Workloads
- Bread-and-Butter Optimizations at Google
- Deep Dive: ThinLTO
- Feedback-Driven Optimizations (iFDO, CSFDO, AFDO, Propeller)
- Deep Dive: Propeller

Motivation & workshop goals

- Motivation
  - Warehouse-scale and desktop apps are like apples and oranges
  - Google develops optimizations for WSC, and we're far from the only ones; we'd like to hear from you!
- Goals: align with LLVM community on
    - What do WSC workloads look like?
    - What optimizations matter most for WSC?
    - Is there overlap between companies? Room for collaboration?

Google workloads from the top down

Background: top-down analysis

- Method for performance analysis & counters architecture ([A Yasin, 2014](#))

	Retiring	Front-end bound	Bad speculation	Back-end bound
471.omnetpp (SPEC CPU 2006)	16%	11%	6%	67%
search3 (Google)	14%	44%	5%	37%

Characteristics of Google workloads (spoiler: they're big)

- Massive binaries with large text sections
- Many basic blocks, most of which are cold
- Incremental builds
- Shared code/modules
- Wide dependency trees

Bread-and-butter optimizations at Google

- Cached, distributed build: Bazel w/ BuildRabbit
- Parallelized, incremental link-time optimizations: ThinLTO
- Feedback-driven compiler optimizations: FDO
- Profile-guided relinking optimizations: Propeller

- ... and many more: TCMalloc, Hugepages, Memprof (WIP)

TCMalloc

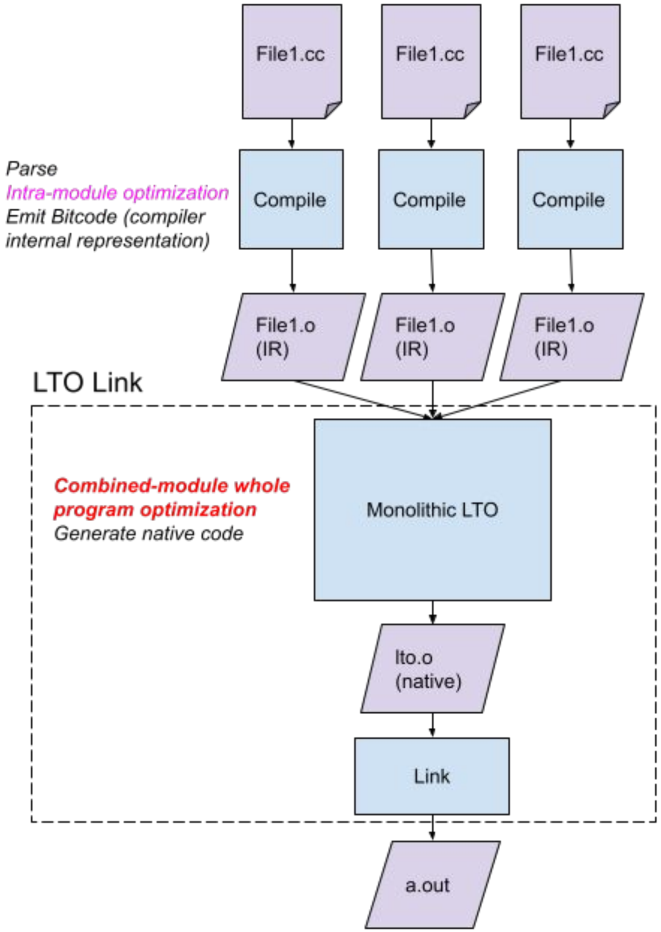
- Thread-cached memory allocation
  - Lots of threads: allocate with per-CPU caches
  - Opaque allocation: expose allocation metrics and tuning knobs
  - Place allocated memory in hugepages
  - 👍 reduce contention during alloc
  - 👍 improve TLB through hugepage placement
  - 👎 can degrade performance with bad memory allocator

```
$ # Simply add -ltcmalloc option*
$ clang -ltcmalloc -O3 example.c -o example
```

*alternatively, see [TCMalloc Quickstart]

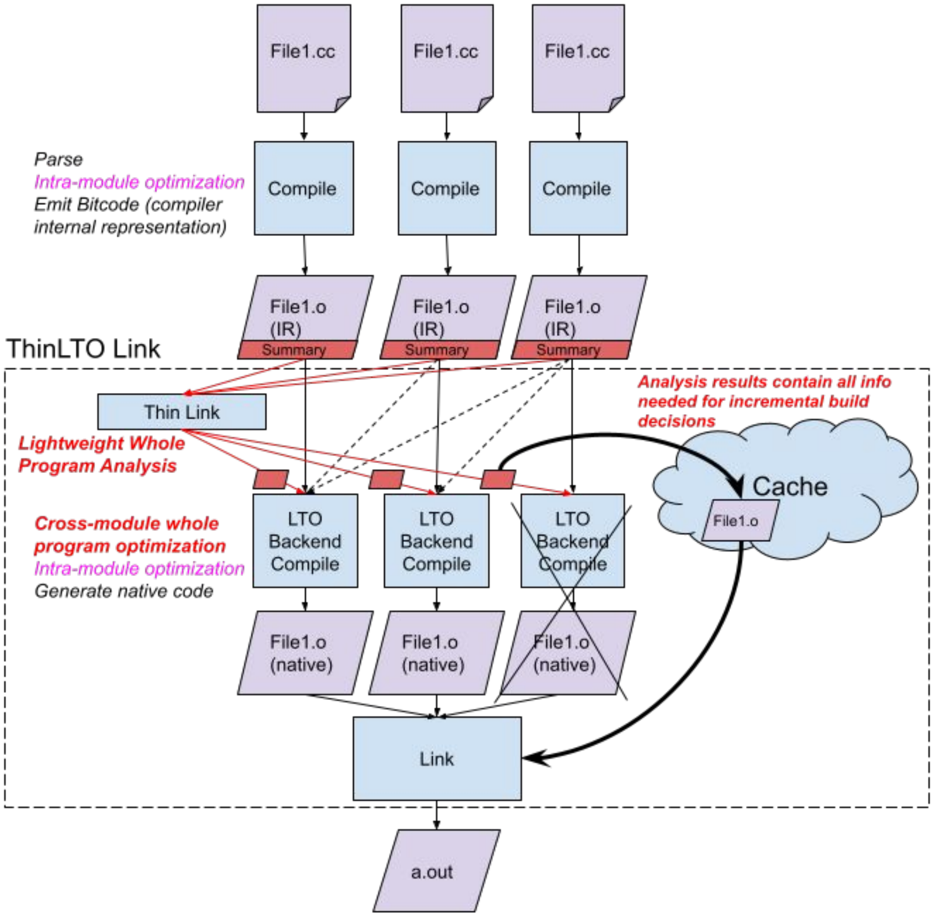
Deep dive: ThinLTO

Monolithic LTO



- First part of compile is fully parallel
- First part of compile is fully incremental
- Enables cross-module whole program optimization
- LTO compilation is not parallel
- LTO compilation is not incremental
- LTO compilation does not scale in memory

ThinLTO



- First part of compile is fully parallel
- First part of compile is fully incremental
- Enables cross-module whole program optimization
- LTO Thin Link summary-based analysis is serial but very lightweight (memory, time)
- LTO backend compilation is fully parallel
- LTO backend compilations can be distributed
- LTO backend compilation is fully incremental
- LTO backend compilation scales in memory

ThinLTO

- After compilation:
  - Generate bitcode summaries in parallel
  - Perform LTO IR optimizations and codegen in parallel
- Read indexed summaries and perform serial whole program optimization
- 👍 far superior scaling than LLVM/GCC LTO
- 👍 incremental and distributed build friendly
- 👍 safe for always-on optimization, doesn't degrade performance
- 👎 not quite as effective as standard LTO

```
$ # Simply add -flto=thin option
$ clang -flto=thin -O2 file1.o file2.o -o a.out
```

Feedback-Driven Optimization (FDO)

WSC applications typically

miss [L2 icache] in the range of 5-20 MPKI,

an **order of magnitude** more frequently

than the **worst cases** in SPEC CPU2006

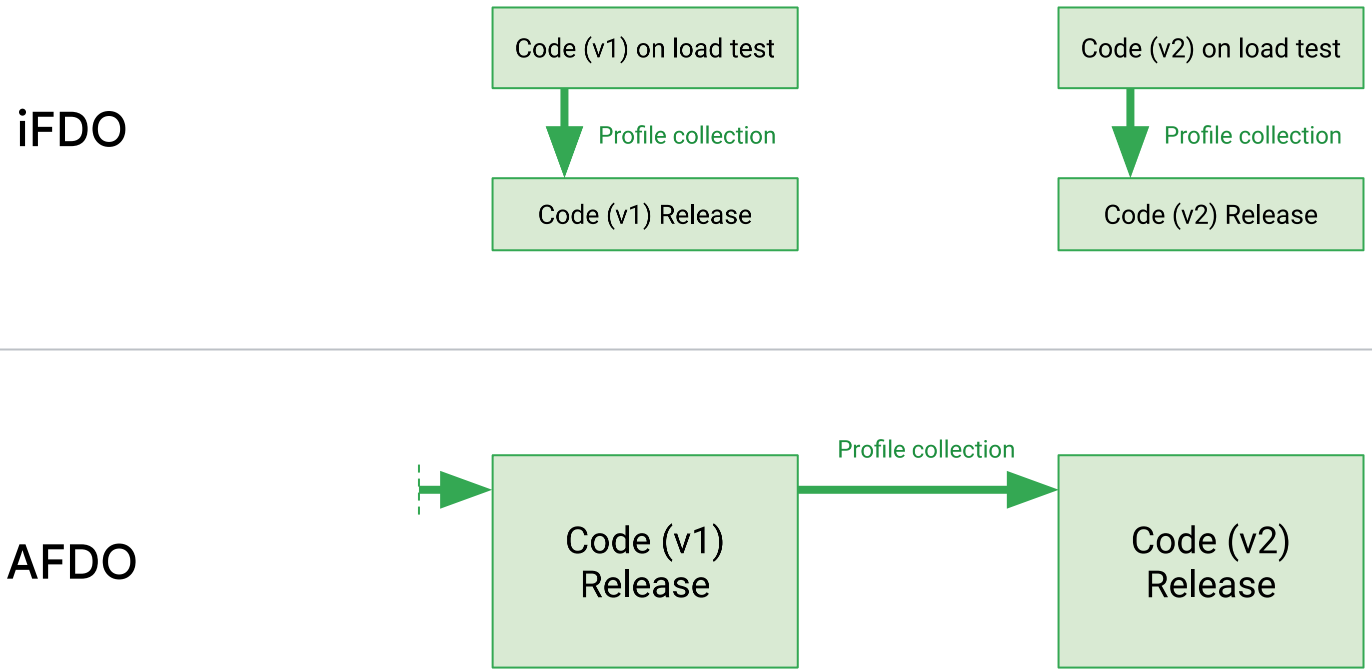
Profiling a warehouse-scale computer

S. Kanev, et. al, 2014

FDO at a glance

- Motivation: short basic blocks, most of which are cold
- Solution: use profile data to drive optimization decisions
    - Function & basic block layout
    - Function splitting
    - Function inlining
    - Loop unrolling, branch optimization
    - Speculative code motion, hoisting
    - And many more!

Traditional vs AutoFDO



Lowering the bar

- AutoFDO: automatic profile collection from production workloads
  - FDO requires representative load test
  - Instead, profile the workload directly
  - 👍 implicitly representative profiles
  - 👍 low bar to entry
  - 👎 vulnerable to source drift
  - 👎 relies on debug info for sample attribution

Quality profiles from the fleet

- FSAFDO: flow-sensitive AutoFDO
  - AFDO profiles merge samples from cloned basic blocks
  - Add hierarchical metadata to discriminate between cloned blocks
  - 👍👍 gains profile granularity
  - 👎 increases profile size and compile time (≤5%)
  - 👎 doesn't handle ambiguous profiles

Refining profile quality with *FDO

- Instrumented FDO: enables sample-to-block mapping beyond debug info
  - AFDO requires debug info to identify blocks
  - Use instrumentation to recover control flow
  - 👍 stable speedup 👍 high sample -> block correlation
  - 👎 requires representative loadtest
- CSFDO: context-specific profiles
  - FDO has ambiguity between `f(x)` inlined by `g(x)` vs by `h(x)`
  - Collect another round of profiles after inlining
  - 👍 increases profile quality 👎 requires additional profiling

In practice

- AutoFDO

```
$ clang -O3 example.c -o example # Build 1
$ perf record -b ... ; create_llvm_prof ... # Profile
$ clang -fprofile-sample-use=profile example.c -o example # Build 2
```

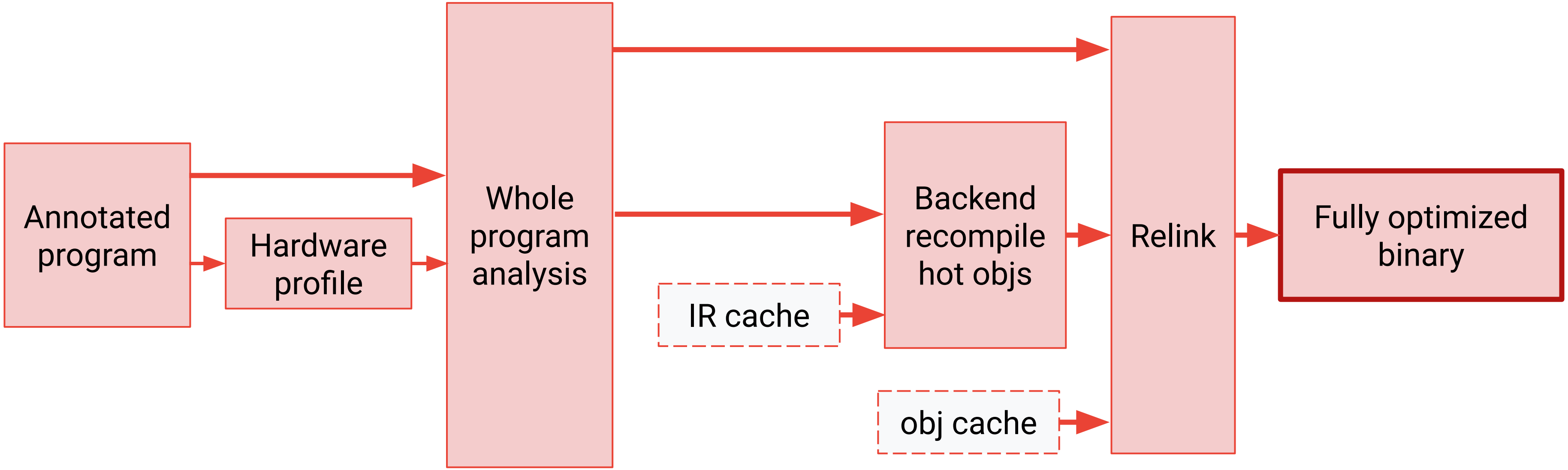
- CSFDO

```
$ clang -fprofile-generate=$FDO_DIR example.c -o example # FDO-instrumented build
$ ./example # FDO profile
$ llvm-profdata merge -output=example.profdata $FDO_DIR
$ clang -fprofile-use=example.profdata -fcs-profile-generate=$CSFDO_DIR \
        example.c -o fdo_example # CSFDO-instrumented build
$ ./fdo_example # CSFDO profile
$ llvm-profdata merge -output=fdo_example.profdata $CSFDO_DIR example.profdata
$ clang -fprofile-use=fdo_example.profdata \
      example.c -o cs_example # CSFDO-optimized build
```

Deep dive: Propeller

Propeller: "A Framework for Post Link Optimizations"

- Propeller: "A Framework for Post Link Optimizations"
  - *FDO has limited view of the program



Near ground truth profiles with Propeller

- 👍 precise profiles don't require propagation
- 👍 whole-program block-level layout
- 👍 scalable & incremental due to IR and obj caching
- 👎 requires an additional round of profiling

In practice

```
$ # Propeller-annotated build
$ clang -fprofile-use=example.profdata -fbasic-block-sections=labels \
        example.c -o fdo_example
$ # Propeller profile
$ perf record -b ./fdo_example
$ create_llvm_prof --format=propeller --binary=fdo_example \
        --profile=perf.data --out=$PROP_DIR/cc_profile.txt \
        --propeller_symorder=$PROP_DIR/ld_profile.txt
$ # Propeller-optimized build
$ clang -fprofile-use=example.profdata \
      -fbasic-block-sections=list=propeller_cc_profile \
      --Wl,--symbol-ordering-file=propeller_ld_profile \
      example.c -o prop_example
```

Conclusion

Summary & Implications

- Google WSC workloads are massive
    - Higher **icache miss rates** than desktop applications
    - **Distributed build** necessitates **distributed**, **incremental** optimizations
    - **FDO** is a <u>must</u> for performance-sensitive applications
- Important considerations for future server-side optimization work
    - Preserve **debug info** and **branch profile** information
    - Prioritize optimization **scalability** and **safety**
- We'd love to hear your experiences!

Thank you!

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We'll be right back!

(discussion at 10:40 AM)

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