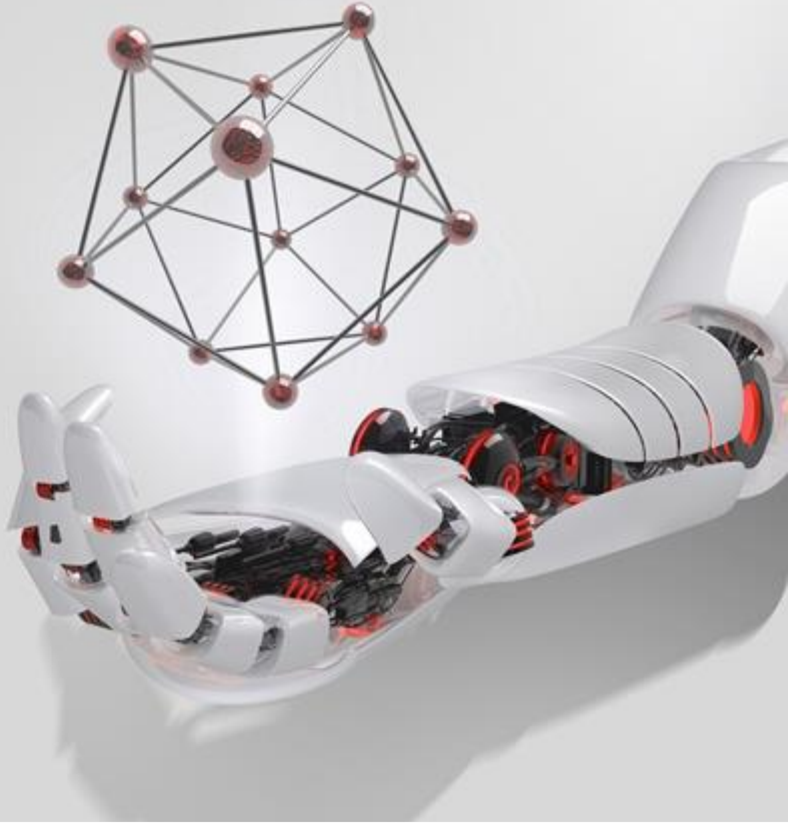
LLVM PGO Instrumentation: Example of CallSite-Aware Profiling



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Agenda

- Target of this presentation
- PGO Introduction
- Implementation details of current PGO
- Implementation details of proposed extension
- Description of llvm-profdata
- How compiler load and use profdata in optimizations.

Target of this presentation

- Make a general description of PGO
  - What is PGO?
  - When it is useful and when its not?
  - Case study
- Describe how PGO works
- Describe how to make an extension for PGO

PGO Introduction

PGO not an optimization but an approach

Pros: can improve important scenario(s)
Cons: other(s) scenarios may degrade

Profile data – describes a scenario of program usage

Possible ways for generation of profile data:

- Sampling
- Instrumentation

PGO Introduction. Sampling Pipeline

1. Build the code with source line table information
```
> clang++ -O2 -gline-tables-only code.cc -o code
```
2. Run the executable under a sampling profiler
```
> perf record -b ./code
```
3. Convert the collected profile data to LLVM format
```
> create_llvm_prof --binary=./code --out=code.prof
```
4. Build the code again using collected profile
```
> clang++ -O2 -gline-tables-only \
     -fprofile-sample-use=code.prof code.cc -o code
```

PGO Introduction. Sampling Formats

- **ASCII** text – profile info per section
- **Binary** encoding: compact format produced by autofdo create_llvm_prof tool
- **GCC** encoding: gcov compatible encoding, produced by autofdo create_gcov tool

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PGO Introduction. Instrumentation Pipeline

1. Build an instrumented version of the code

```
> clang++ -O2 -fprofile-instr-generate code.cc -o code
```

2. Run the instrumented executable with necessary inputs

```
> LLVM_PROFILE_FILE="code-%p.profraw" ./code
```

3. Combine profiles from multiple runs and convert the “raw” profile format to the input expected by clang

```
> llvm-profdata merge -output=code.profdata code-*.profraw
```

4. Build the code again using collected profile data

```
> clang++ -O2 -fprofile-instr-use=code.profdata code.cc \
          -o code
```


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PGO Introduction. Kinds of Instrumentation

- Front-end (FE)
  `-fprofile-instr-generate`

- Middle-end (IR)
  `-fprofile-generate`

- Middle-end context sensitive (IR CS)
  `-fcs-profile-generate`

PGO Introduction. IR CS Instrumentation

```
> clang++ -O2 -fprofile-use=code.profdata \
          -fcs-profile-generate -o cs_code

> ./cs_code

> llvm-profdata merge -output=cs_code.profdata code.profdata

> clang++ -O2 -fprofile-use=cs_code.profdata
```


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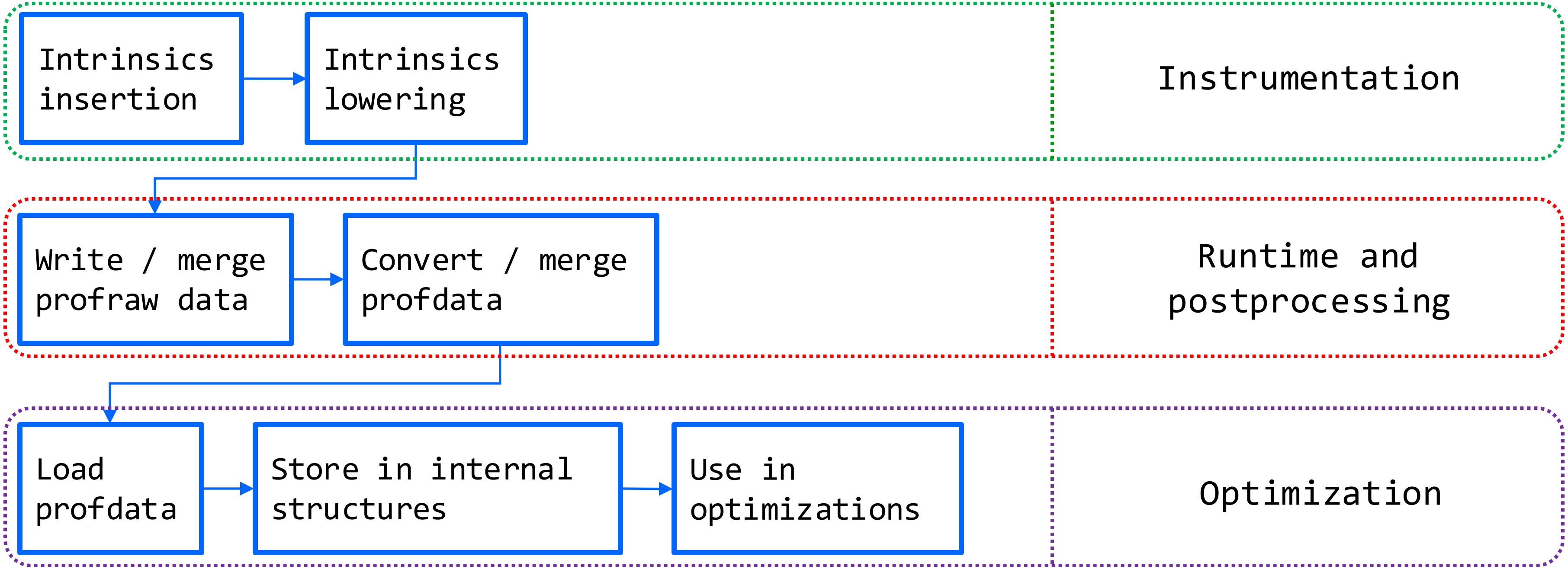
Implementation details (current state)

- All about instrumentation
  - MST-based insertion of counters
  - Insertion of value probes
  - Lowering of intrinsics
  - Compiler-rt built-in functions for PGO
    - Values updating
    - Open file, merge values and counters
  - Example
  - Format of profdata in RAM and on disc

PGO Introduction. Instrumentation Pipeline

PGO implementation steps

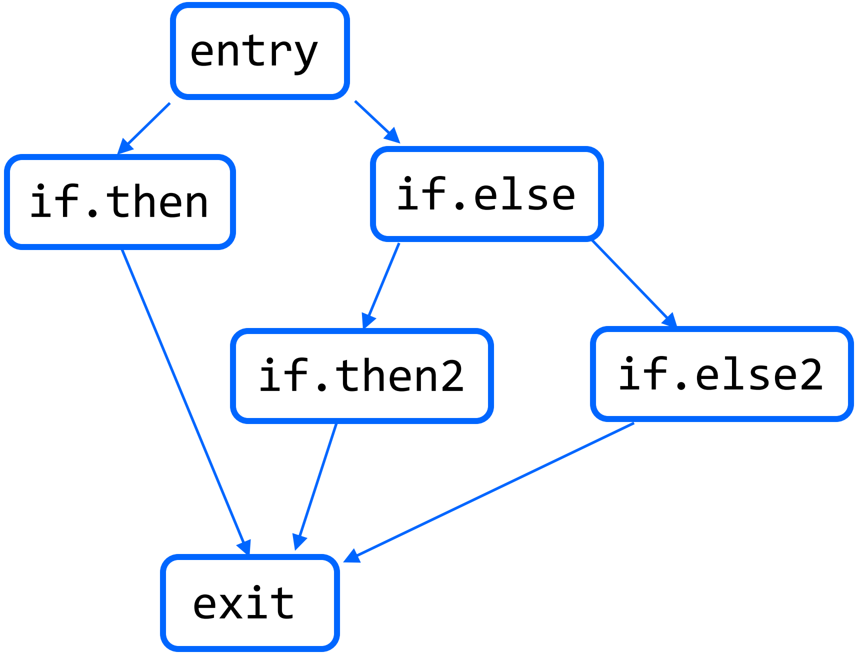


Intrinsics and its lowering

- Intrinsic is a built-in function which is inserted by compiler
- It is used to optimize:
  - Memory calls
  - Floating point operations (fadd/fmul/sin/cos …)
  - PGO counters insertion in our case
  - And more (details: include/llvm/IR/Intrinsics.td)
- When compiler meets intrinsic, it performs “lowering” – replace intrinsic with code or calls to optimized versions of some library functions

MST-based insertion of counters

CFG



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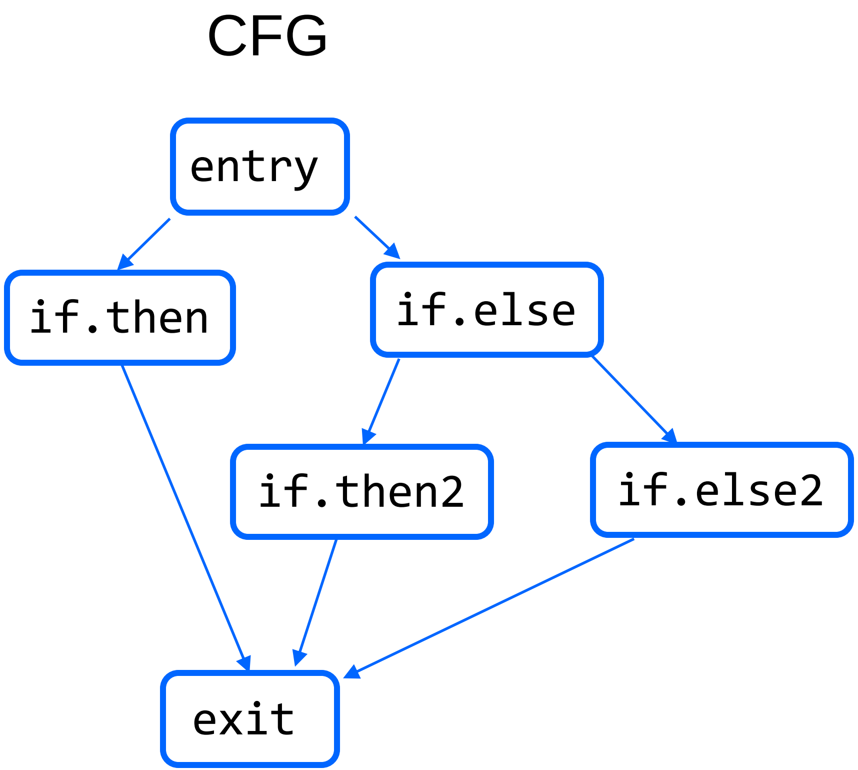
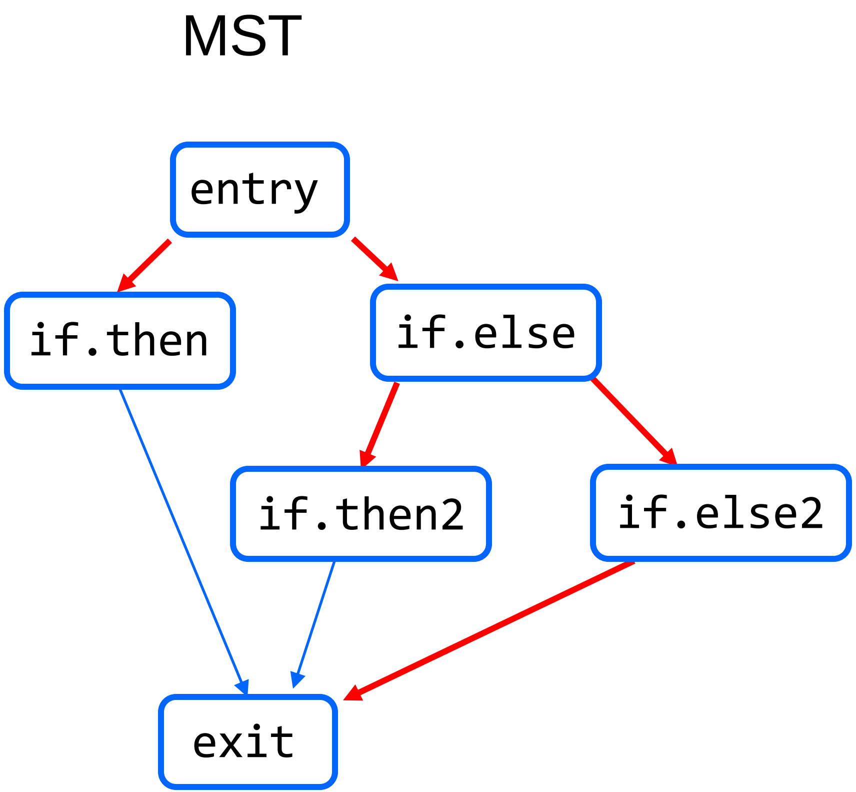
MST-based insertion of counters





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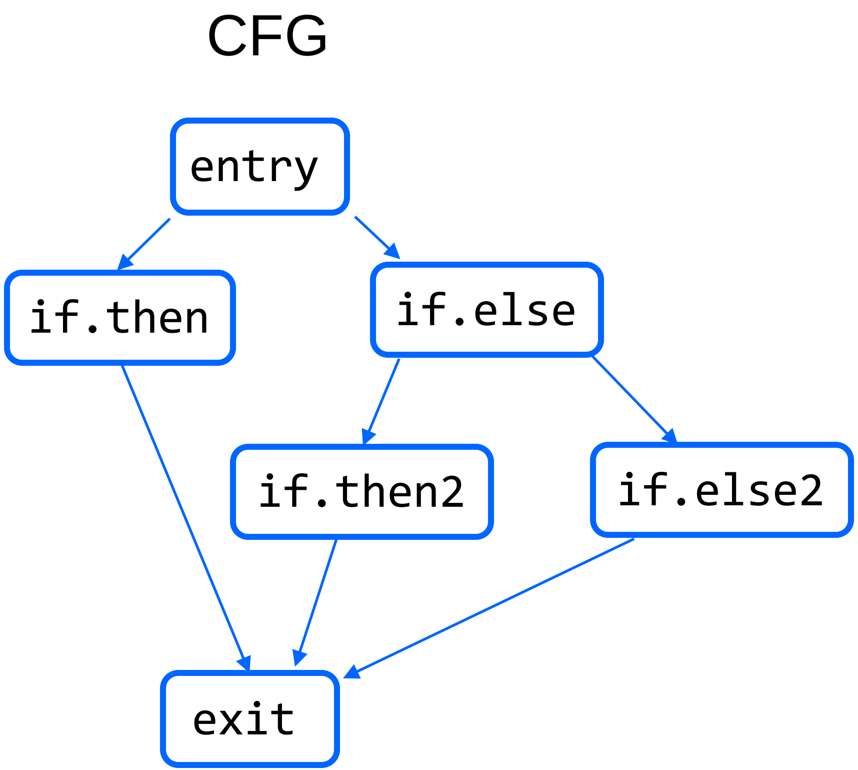
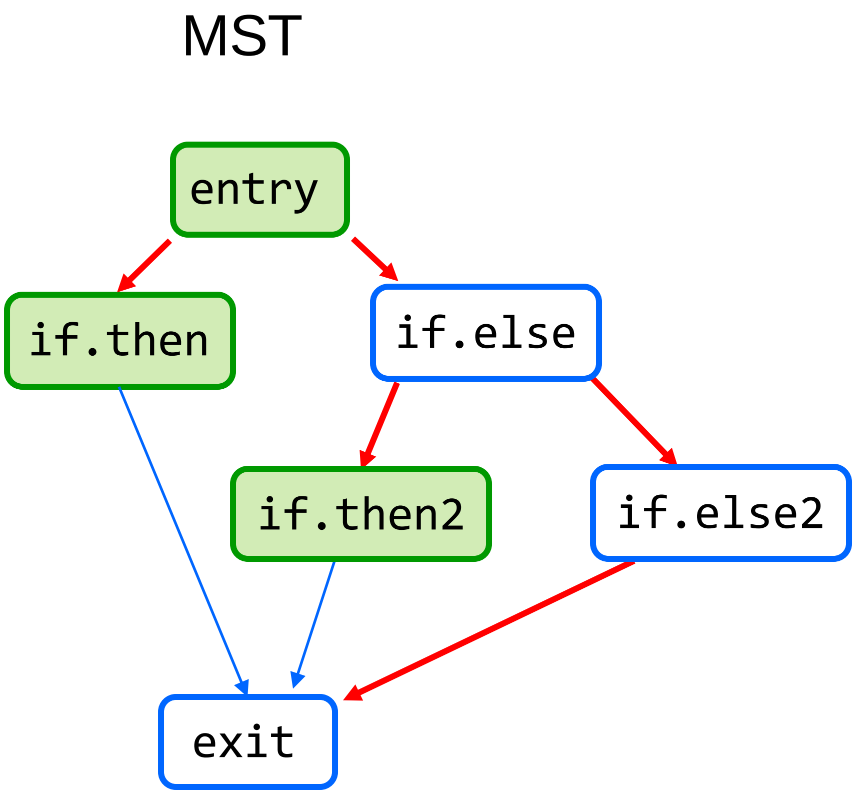
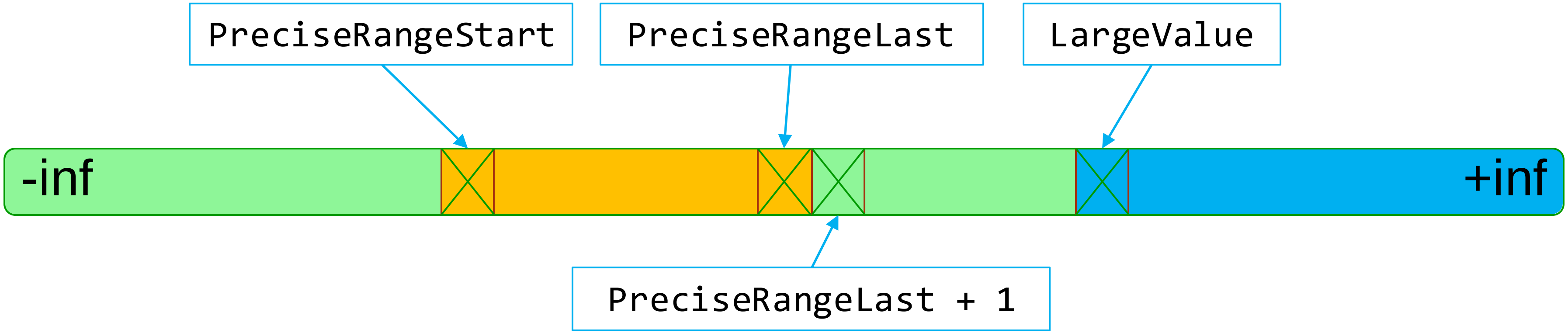
MST-based insertion of counters





Value probes

- Record indirect calls
- Record sizes for memcpy / memmove / memset



- If target value is in green area, then it is set to PreciseRangeLast+1
- If target value is in blue area, then it is set to LargeValue
- Otherwise it is recorded with its real value

Compiler-rt builtin functions

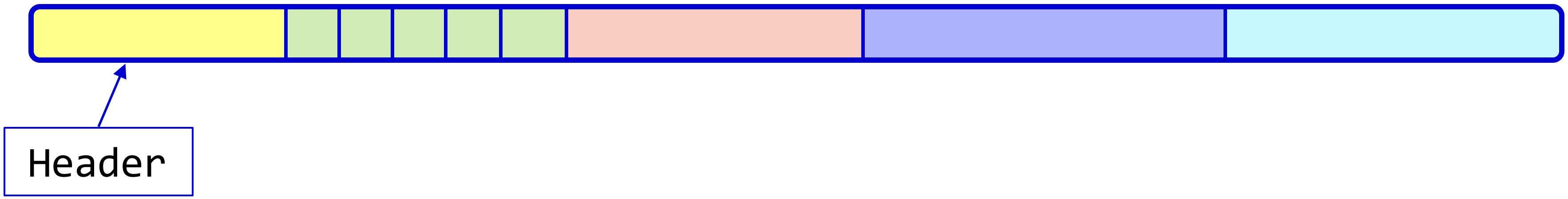
- Builtins for profiling
  - __llvm_profile_get_magic
  - __llvm_profile_get_version
  - __llvm_profile_instrument_target
  - __llvm_profile_instrument_memop
  - __llvm_profile_write_file
  - __llvm_profile_dump
  - __llvm_profile_reset_counters
  - and much more (details in compiler-rt/lib/profile)

Instrumentation example

```
void foo(char* buf, int num) {
    memset(buf, 0, num);
}
```

```
define dso_local void @foo(i8* nocapture %0, i64 %1) {
  %3 = load i64, i64* getelementptr inbounds ([1 x i64], [1 x i64]* @__profc_foo,
                                               i64 0, i64 0)
  %4 = add i64 %3, 1
  store i64 %4, i64* getelementptr inbounds ([1 x i64], [1 x i64]* @__profc_foo,
                                              i64 0, i64 0)
  tail call void @__llvm_profile_instrument_memop(i64 %1,
        i8* bitcast ({ i64, i64, i64*, i8*, i8*, i32, [2 x i16] }
                      * @__profd_foo to i8*), i32 0)
  tail call void @llvm.memset.p0i8.i64(i8* align 1 %0, i8 0, i64 %1, i1 false)
  ret void
}
```

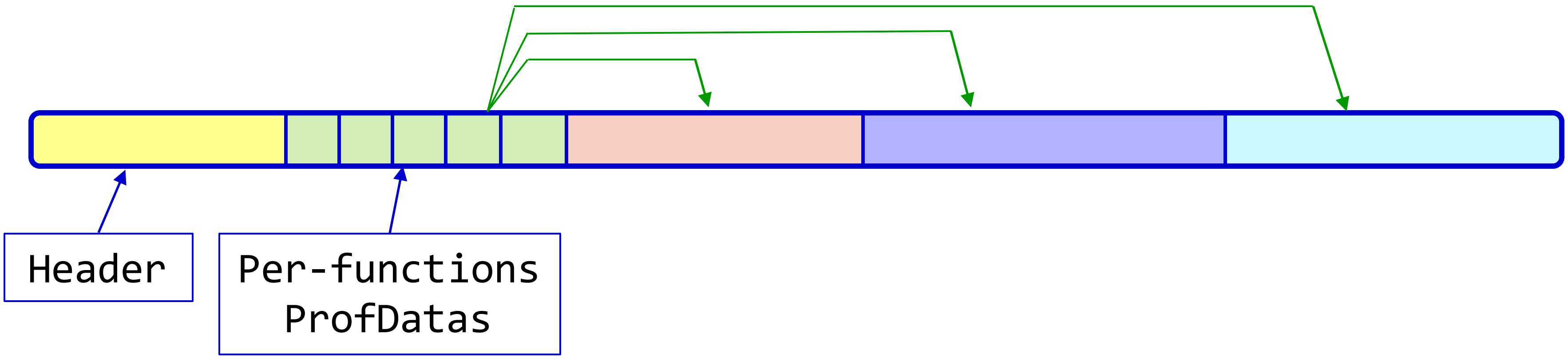
Format of profdata



<u>Header:</u>

- Magic / version
- Paddings
- Sizes of all sections

Format of profdata



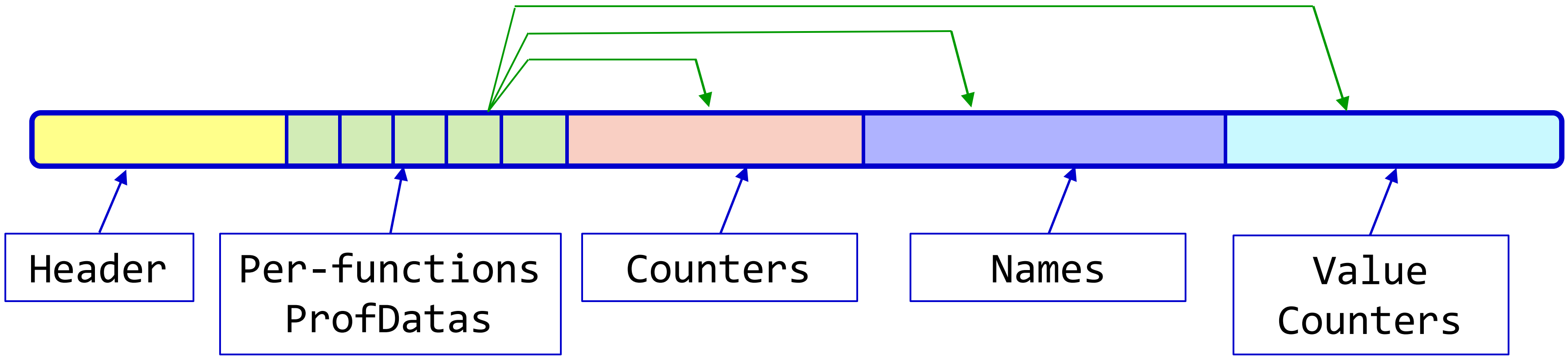
Header:

- Magic / version
- Paddings
- Sizes of all sections

ProfData:

- FuncHash, FuncNameMD5
- Pointers (offsets) to related data in sections
- Number of counters

Format of profdata



<u>Header:</u>

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<u>ProfDatas:</u>

- FuncHash, FuncNameMD5
- Pointers (offsets) to related data in sections
- Number of counters

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Implementation details for extension

- Overview of proposed extension
  - Example. Pros and cons

- New intrinsics and its lowering

- Change in profdata format

- Extension of internal structures

Overview of Callsite-Aware PGO

- Main difference between original PGO and this one – separate counters for every callsite. It can be useful for several optimizations like Inlining

- Pros: compiler can get more info for enhance optimizations

- Cons: code size, compile time, runtime memory and performance overhead

Overview of callsite-aware PGO

Original PGO

Array of counters

```
void foo() {
   if (cond) {
      counter1++;
      block1;
   } else {
      counter2++;
      block2;
   }
}
```

Callsite-aware PGO

Set of arrays of counters

Array of counters for CS

```
void foo() {
   choose_cs_set;
   if (cond) {
      counter1++;
      block1;
   } else {
      counter2++;
      block2;
   }
}
```


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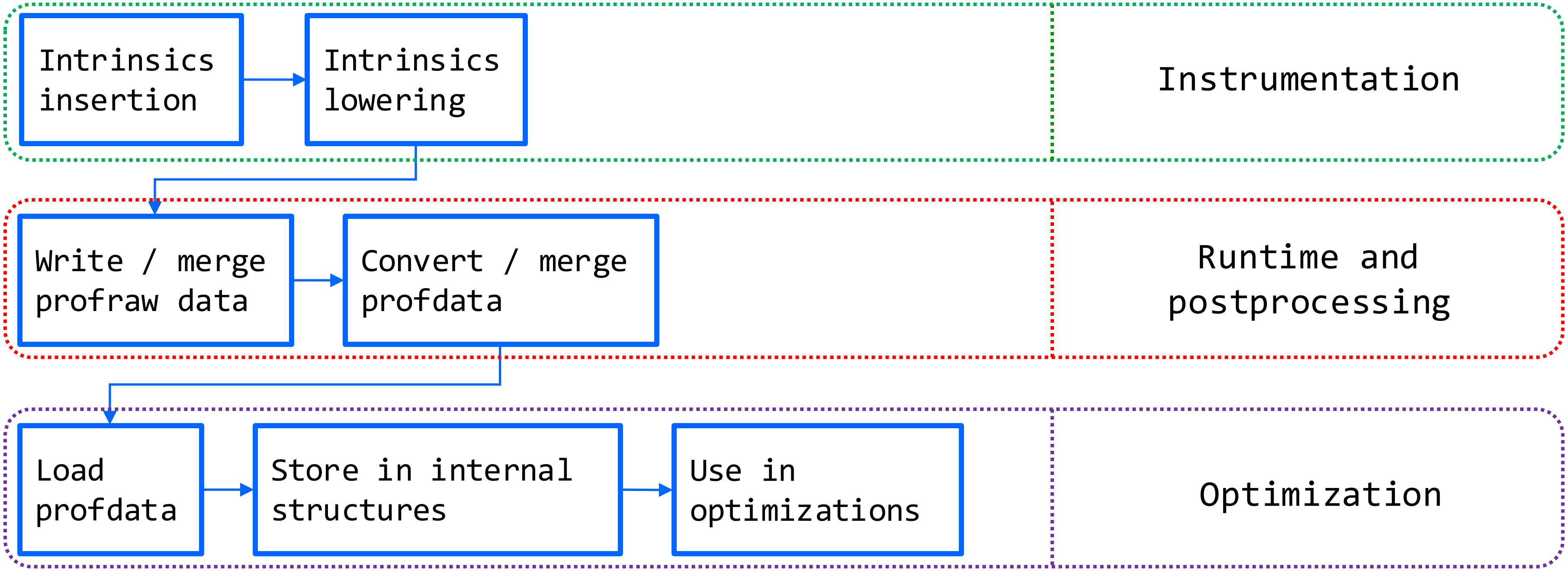
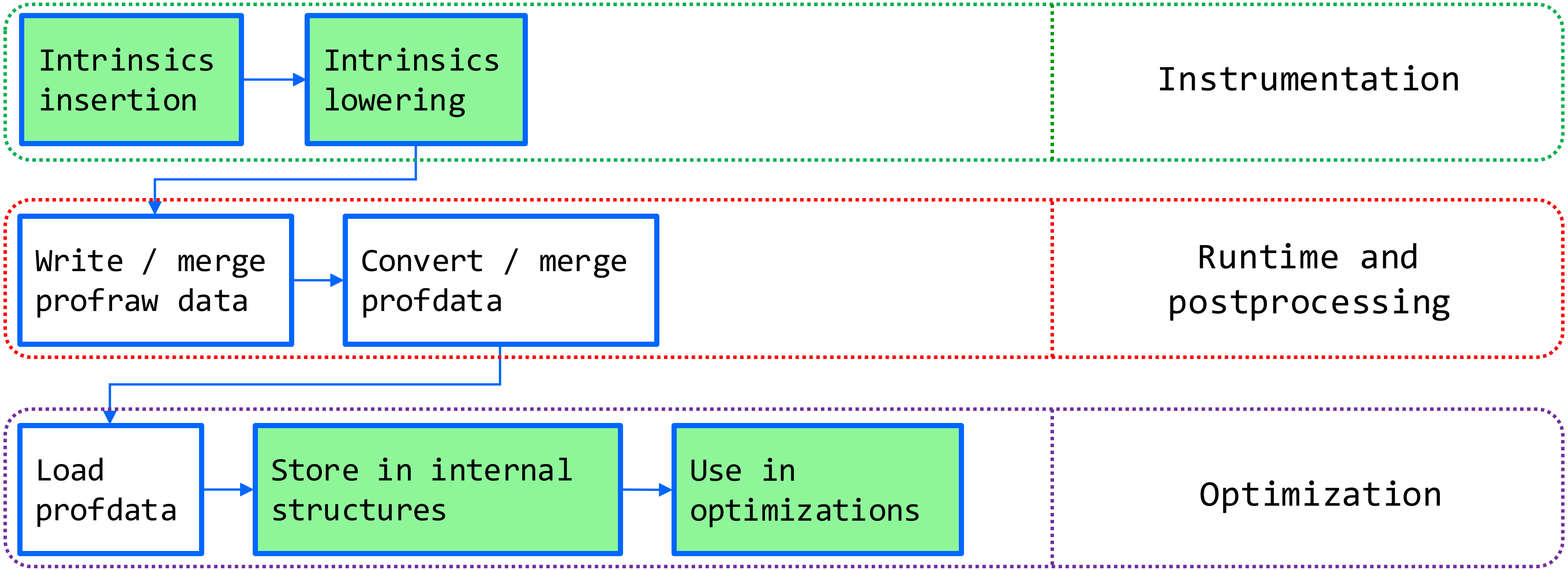
Overview of callsite-aware PGO Implementation

Pipeline



Overview of callsite-aware PGO Implementation

Pipeline



Implementation of callsite-aware PGO

- Right before every callsite we need to insert intrinsic which will provide pointer to necessary counters
- How to add this intrinsic:

include/llvm/IR/Intrinsics.td

```
// A call to provide a pointer to callsite counters
// 1st parameter – callee hash
// 2nd parameter – callsite id
def int_instrprof_callsite_counters :
   Intrinsic<[],                                   // Ret type(s)
             [llvm_i64_ty, llvm_i32_ty], // Parameters
             []>;                              // Properties
```

Implementation of callsite-aware PGO

- include/llvm/IR/IntrinsicInst.h

```
/// This represents the llvm.instrprof_callsite_counters intrinsic.
class InstrProfCallsiteCounters : public IntrinsicInst
{
public:
  static bool classof(const IntrinsicInst *I) {
    return I->getIntrinsicID() == Intrinsic::instrprof_callsite_counters;
  }

  ConstantInt *getCalleeHash() const {
    return cast<ConstantInt>(const_cast<Value *>(getArgOperand(0)));
  }

  ConstantInt *getCallsiteID() const {
    return cast<ConstantInt>(const_cast<Value *>(getArgOperand(1)));
  }
}
```

Implementation of callsite-aware PGO

- Insert intrinsic before each call (if callee is registered)

lib/Transforms/Instrumentation/PGOInstrumentation.cpp

```
const int32_t CallsiteID = getCallsiteId(CalleeHash, CallInstr);
If (CallsiteID > 0) {
  Builder.CreateCall(
          Intrinsic::getDeclaration(M, Intrinsic::instrprof_callsite_counters),
          { Builder.getInt64(CalleeHash),
            Builder.getInt32(CallsiteID) });
}
```

Implementation of callsite-aware PGO

- Example (IR Dump After PGOInstrumentationGenPass):

```
define dso_local void @bar() #0 {
entry:
  call void @llvm.instrprof.increment(i8* getelementptr inbounds ([3 x i8], [3 x i8]* @__profn_bar,
                                      i32 0, i32 0), i64 742261418966908927, i32 1, i32 0)
  call void @llvm.instrprof.callsite.counters(i64 6699318081062747564, i32 3)
  call void @foo()
  call void @llvm.instrprof.callsite.counters(i64 6699318081062747564, i32 0)
  ret void
}
```

Implementation of callsite-aware PGO

- Lowering of the intrinsic
  lib/Transforms/Instrumentation/InstrProfiling.cpp

```
bool InstrProfiling::lowerIntrinsics(Function *F) {
  ...
  } else if (auto *CSCounters = dyn_cast<InstrProfCallsiteCounters>(Instr)) {
        lowerCSCounters(CSCounters);
        MadeChange = true;
  }
  ...

lowerCSCounters – record callsite id to a memory location (every function has its own)
```

Implementation of callsite-aware PGO

- Example (IR Dump After Frontend instrumentation-based coverage lowering)

```
define dso_local void @bar() #0 {
entry:
  %pgocount = load i64, i64* getelementptr inbounds ([1 x i64],
                                [1 x i64]* @__profc_bar, i64 0, i64 0), align 8
  %0 = add i64 %pgocount, 1
  store i64 %0, i64* getelementptr inbounds ([1 x i64],
                                [1 x i64]* @__profc_bar, i64 0, i64 0), align 8
  store i32 3, i32* @__llvm_prof_foo_csid, align 4
  call void @foo()
  store i32 0, i32* @__llvm_prof_foo_csid, align 4
  ret void
}
```

Implementation of callsite-aware PGO

- Example (IR Dump After Frontend instrumentation-based coverage lowering)

```
define dso_local void @foo() #0 {
entry:
  %load_csid = load i32, i32* @__llvm_prof_foo_csid, align 4
  %0 = mul i32 %load_csid, 1
  %1 = add i32 %0, 0
  %2 = getelementptr inbounds [5 x i64], [5 x i64]* @__profc_foo, i32 0, i32 %1
  %pgocount = load i64, i64* %2, align 8
  %3 = add i64 %pgocount, 1
  store i64 %3, i64* %2, align 8
  ret void
}
```

Implementation of callsite-aware PGO

- Example (IR Dump After Frontend instrumentation-based coverage lowering)

```
define dso_local void @foo() #0 {
entry:
  %load_csid = load i32, i32* @__llvm_prof_foo_csid, align 4
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  %1 = add i32 %0, 0
  %2 = getelementptr inbounds [5 x i64], [5 x i64]* @__profc_foo, i32 0, i32 %1
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Implementation of callsite-aware PGO

- Example (IR Dump After Frontend instrumentation-based coverage lowering)

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Implementation of callsite-aware PGO

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Implementation of callsite-aware PGO

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  %1 = add i32 %0, 0
  %2 = getelementptr inbounds [5 x i64], [5 x i64]* @__profc_foo, i32 0, i32 %1
  %pgocount = load i64, i64* %2, align 8
  %3 = add i64 %pgocount, 1
  store i64 %3, i64* %2, align 8
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Implementation of callsite-aware PGO

- Example (IR Dump After Frontend instrumentation-based coverage lowering)

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  %pgocount = load i64, i64* %2, align 8
  %3 = add i64 %pgocount, 1
  store i64 %3, i64* %2, align 8
  ret void
}
```

llvm-profdata

- Overview of this tool
- What possibilities does it have
  - show
  - merge
  - overlap
- How to add an extension to it
  - llvm/tools/llvm-profdata/llvm-profdata.cpp
    - mergeInstrProfile
    - lib/ProfileData/InstrProfReader.cpp
    - lib/ProfileData/InstrProfWriter.cpp

Clang and profdata

- How to load profdata from file
  - -fprofile-use=/path/to/merged/profdata
  - lib/ProfileData/InstrProf.cpp
    - readNextRecord
    - readHeader
    - readRawCounts
    - ReadData
    - createSymtab

Clang and profdata

- Where to store it
- lib/Transforms/Instrumentation/PGOInstrumentation.cpp
  - FuncPGOInstrumentation
  - MST
  - Assign branch-probabilities to BBs
- How this data can be used by optimizations?
  - different inline strategy for different callsites

Summary

- PGO is important optimization approach
- LLVM PGO can be easily extend
- Still it has a lot of work to do
- Now you are able to enhance PGO in LLVM
  - Add something new or
  - Fix existing features. There is a pair (of dozens) of TODOs and FIXMEs in PGO-related files (e.g. need to add support for instrument select instructions, which uses condition with vector type)

Thank you!

Q&A

Links

Patch:
- https://github.com/kpdev/llvm-project/tree/llvm-dev-mtg/callsite

Docs:
- PGO Docs: https://clang.llvm.org/docs/UsersManual.html#profile-guided-optimization
- MST: https://llvm.org/pubs/2010-04-NeustifterProfiling.pdf

Presentations:
- LLVM Dev Mtg 2013 Presentation: http://llvm.org/devmtg/2013-11/slides/Carruth-PGO.pdf
- MSVC team talk: https://channel9.msdn.com/Shows/C9-GoingNative/C9GoingNative-12-C-at-BUILD-2012-Inside-Profile-Guided-Optimization