Instrumentor: Easily Customizable Code Instrumentation for LLVM

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Instrumenting Code

- **Track runtime behavior** of apps
  - Debugging and sanitization
  - Logging of events
  - Monitor resource usage
  - Performance analysis for optimization

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  ret i32 %v
}
```

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Original code:

Let's instrument loads!

```
i32 myfunc(ptr %p) {

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  ret i32 %v
}
```

Instrumenting Code

- **Track runtime behavior** of apps
  - Debugging and sanitization
  - Logging of events
  - Monitor resource usage
  - Performance analysis for optimization

Original code:

```
i32 myfunc(ptr %p) {

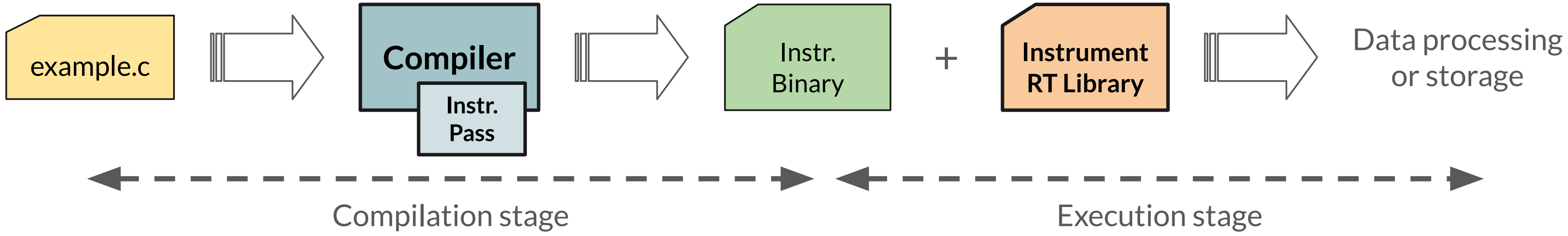
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

Instrumented code:

```
i32 myfunc(ptr %p) {
  call void @__before_load(ptr %p, i32 4)
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

Instrumentation Support

- Main actors
    a. **Compiler** augments the original code with extra code
    b. **Runtime component** receives that data during the execution



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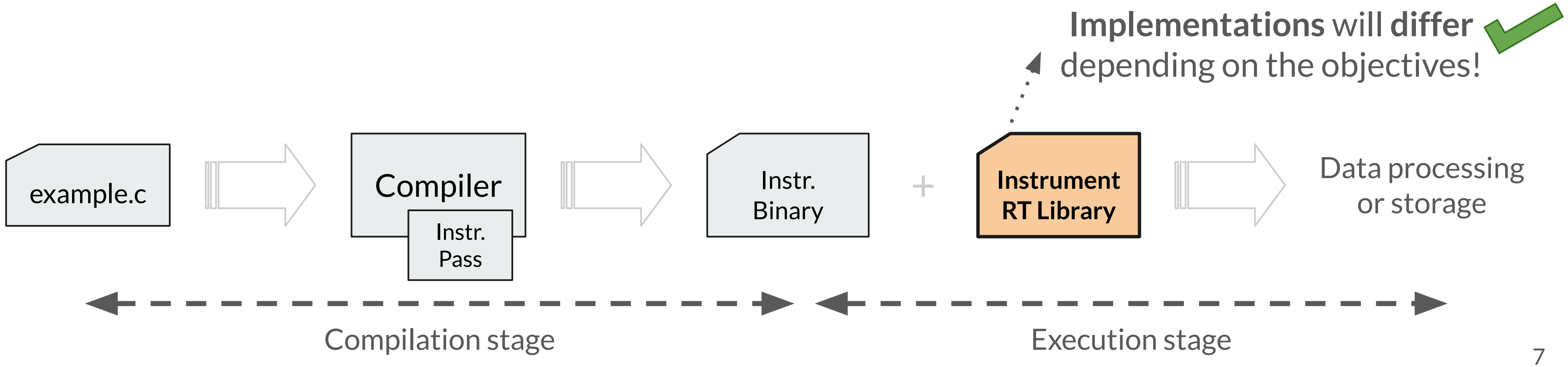

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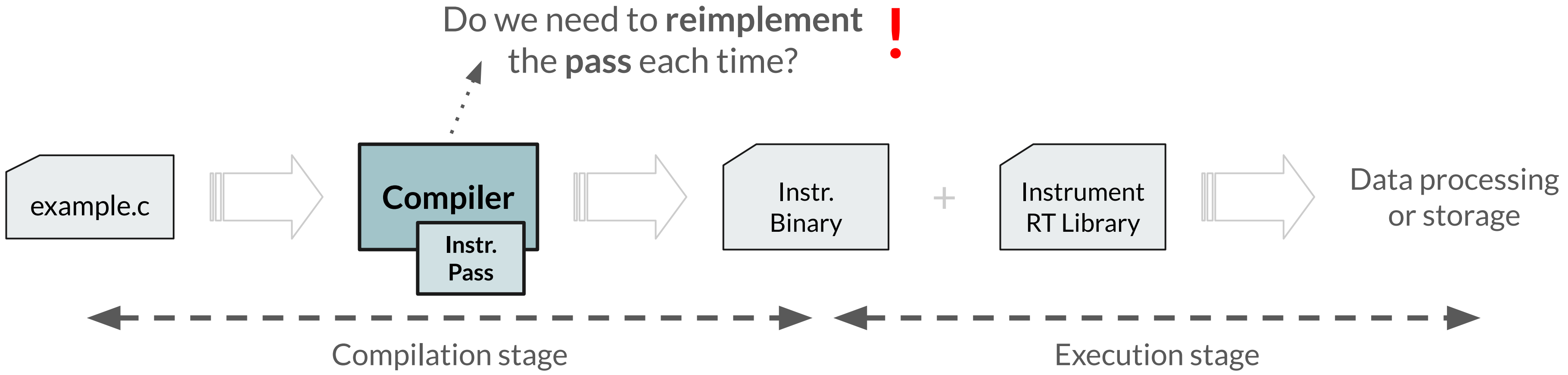

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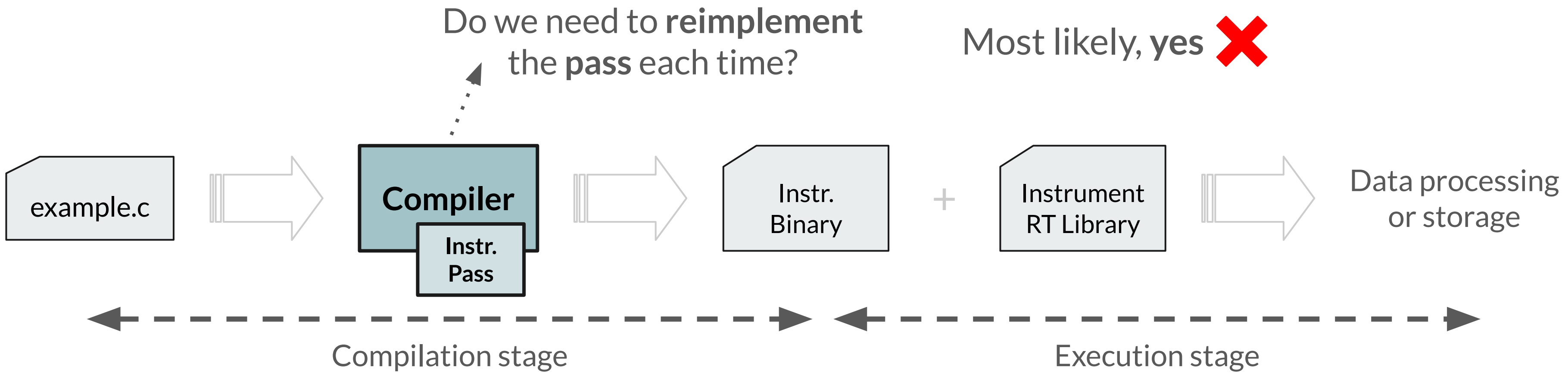
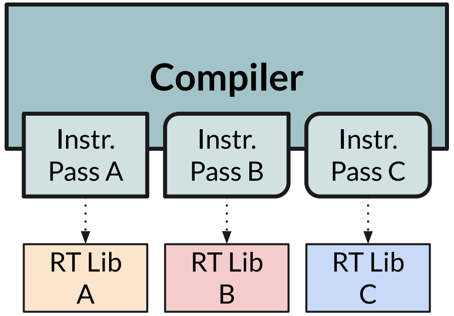


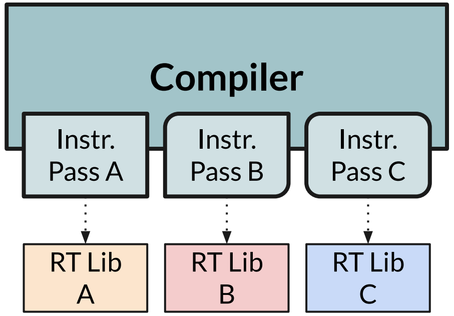
Instrumentation Support

- Compilers **lack generic mechanisms** for **instrumenting**



Instrumentation Support

- Compilers **lack generic mechanisms** for **instrumenting**
    - **Multiple passes** implement **custom** logic
    - Generally similar but quite different



Instrumentation Support

- Compilers **lack generic mechanisms** for **instrumenting**
  - **Multiple passes** implement **custom** logic
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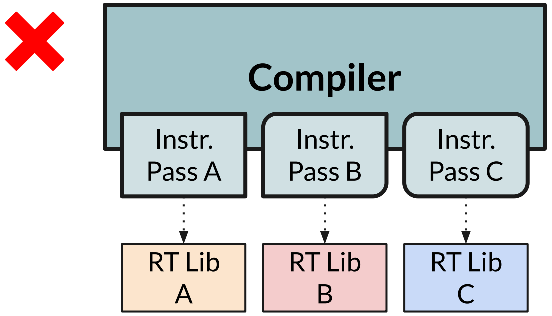
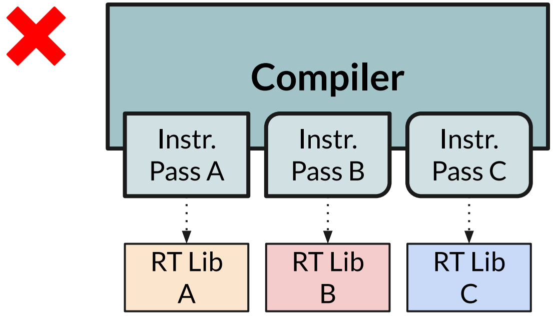
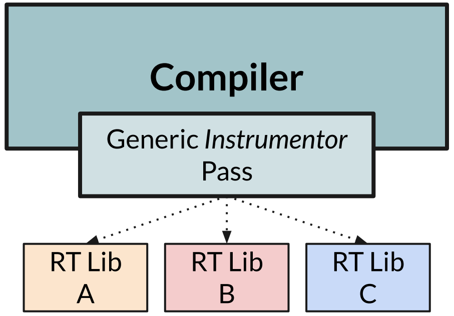
- **Missing** significant **opportunities** like
  - Improving code **maintainability**
  - Reducing code **replication**
  - **Simplifying development** of instrumentation tools



Why not a Generic Instrumentation Pass?

- New ***Instrumentor* pass** in LLVM
    - Generic, customizable and extendable
    - Enabling **multiple** uses and users

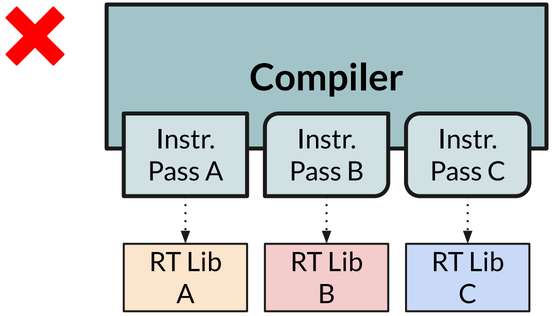


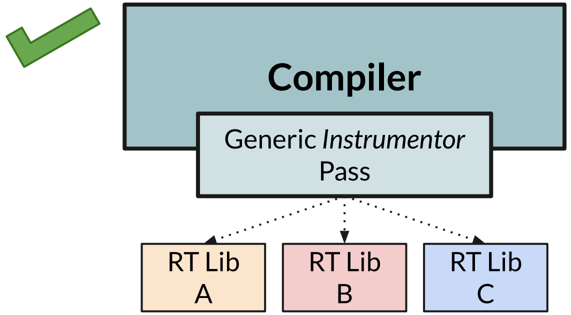


Why not a Generic Instrumentation Pass?

- New ***Instrumentor* pass** in LLVM
  - Generic, customizable and extendable
  - Enabling **multiple** uses and users

- **Exploiting** the **opportunities**
  - Improve code **maintainability**
  - Reduce code **replication**
  - **Simplify development** of instrumentation tools





Instrumentor

Instrumentor Pass

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
  },









}
```

Instrumentor Pass

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
  },
  "instruction_pre": {
    "load": {
      "enabled": true,
      "pointer": true,
      "pointer.replace": false,
      "pointer_as": false,
      "value_size": true,
      "alignment": true,
      "is_volatile": true
    }
  }
}
```

Instrumentor Pass

Original IR:

```
i32 myfunc(ptr %p) {
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
  },
  "instruction_pre": {
    "load": {
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Instrumentor Pass

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```
i32 myfunc(ptr %p) {
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

After *Instrumentor* pass:

```
i32 myfunc(ptr %p) {
  call void @__instr_pre_load(
        ptr %p, i32 4, i32 8, i32 0)
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
  },
  "instruction_pre": {
    "load": {
      "enabled": true,
      "pointer": true,
      "pointer.replace": false,
      "pointer_as": false,
      "value_size": true,
      "alignment": true,
      "is_volatile": true
    }
  }
}
```

opt -passes=**instrumentor -instrumentor-read-config-file=file.json** prog.ll -S

Instrumentor Pass

Original IR:

```
i32 myfunc(ptr %p) {
  %v = load i32, ptr %p, align 8
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}
```

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
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    "load": {
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    }
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Instrumentor Pass

Original IR:

```
i32 myfunc(ptr %p) {
  %v = load i32, ptr %p, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

After *Instrumentor* pass:

```
i32 myfunc(ptr %p) {
  %np = call ptr @__instr_pre_load(
              ptr %p, i32 4, i32 8, i32 0)
  %v = load i32, ptr %np, align 8
  store i32 10, ptr %p, align 8
  ret i32 %v
}
```

```
{
  "configuration": {
    "runtime_prefix": "__instr_",
  },
  "instruction_pre": {
    "load": {
      "enabled": true,
      "pointer": true,
      "pointer.replace": true,
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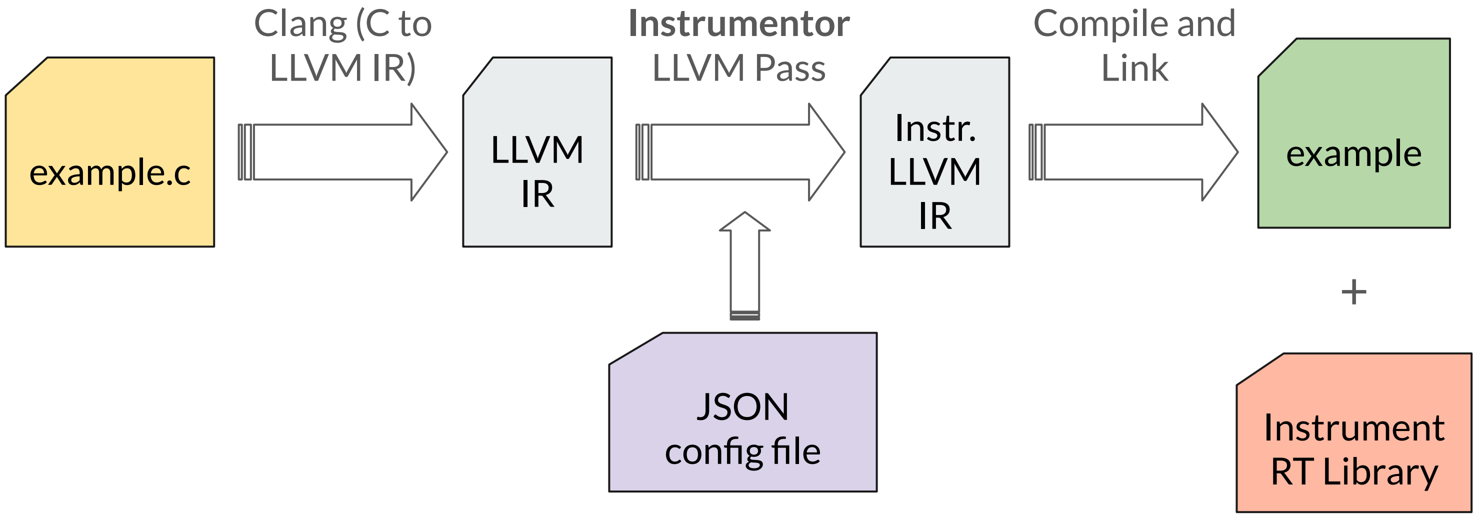
      "is_volatile": true
    }
  }
}
```

How does the Instrumentor work?



opt -passes=**instrumentor -instrumentor-read-config-file=file.json** example.ll -S

or

clang -Xclang **-finstrumentor -mllvm -instrumentor-read-config-file=file.json** example.c

Instrumentor

- Instrumentation **opportunities**
  - Instructions
  - Functions
  - Global variables
  - Module

- **Position** of the instrumentation
  - Before (*pre*) and/or after (*post*)

```
"instruction_pre": {
  "load": {
    "enabled": true,
    "pointer": true,
    "pointer.replace": true,
    "pointer_as": true,
    "base_pointer_info": true,
    "value_size": true,
    "alignment": true,
    "value_type_id": true,
    "atomicity_ordering": true,
    "is_volatile": true
  },
  "store": {
    "enabled": true,
    "pointer": true,
    "pointer.replace": true,
    "pointer_as": true,
    "base_pointer_info": true,
    "value": true,
    "value_size": true,
    "alignment": true,
    "value_type_id": true,
    "atomicity_ordering": true,
    "is_volatile": true
  }
}
```

Instrumentor

```
"instruction_pre": {
  "store": {
    "enabled": true,
    "pointer": true,
    "pointer.replace": false,
    "pointer_as": true,
    "base_pointer_info": true,
    "value": true,
    "value_size": true,
    "alignment": true,
    "value_type_id": true,
    "atomicity_ordering": true,
    "is_volatile": true
  }
}
```

- Instrumentation **opportunities**
  - Instructions
    - **Loads, stores**

- **Position** of the instrumentation
  - Before (*pre*) and/or after (*post*)

```
%1 = load i32, ptr %p, align 8
%2 = add i32, %1, 128
call void @__instr_pre_store(ptr %p, ...)
store i32 %2, ptr %p, align 8
```

Instrumentor

- Instrumentation **opportunities**
  - Instructions
    - Loads, stores
    - **Function calls (+ inspection of args)**

```
"instruction_pre": {
  "call": {
    "enabled": true,
    "callee": true,
    "callee_name": true,
    "intrinsic_id": true,
    "allocation_info": true,
    "num_parameters": true,
    "parameters": true,
    "parameters.replace": true,
    "is_definition": true
  }
}
```

- **Position** of the instrumentation
  - Before (*pre*) and/or after (*post*)

```
%1 = load ptr, ptr @stdout
%2 = load ptr, ...
%3 = load i32, ...
call void @__instr_pre_call(ptr @fprintf, ...)
%4 = call i32 @fprintf(ptr %1, ptr %2, i32 %3)
```

Instrumentor

- Instrumentation **opportunities**
  - Instructions
    - Loads, stores
    - Function calls (+ inspection of args)
    - **Allocas**

```
"instruction_post": {
  "alloca": {
    "enabled": true,
    "address": true,
    "address.replace": true,
    "size": true,
    "alignment": true
  }
}
```

- **Position** of the instrumentation
  - Before (*pre*) and/or after (*post*)

```
void myfunc() {
  %p = alloca i64, align 8
  %np = call void @__instr_post_alloca(
              ptr %p, i64 8, i64 8)
  %1 = load i64, ptr %np
  ...
}
```

Instrumentor

- Instrumentation **opportunities**
  - Instructions
    - Loads, stores
    - Function calls (+ inspection of args)
    - Allocas
    - Branches, compares
    - …

- **Position** of the instrumentation
  - Before (*pre*) and/or after (*post*)

Instrumentor

- Instrumentation **opportunities**
    - Instructions
        - Loads, stores
        - Function calls (+ inspection of args)
        - Allocas
        - Branches, compares
        - ...
    - Function enter/exit (+ inspect of args)
    - Global variables
    - Module constructor/dtor

- **Position** of the instrumentation
    - Before (*pre*) and/or after (*post*)

Instrumentor

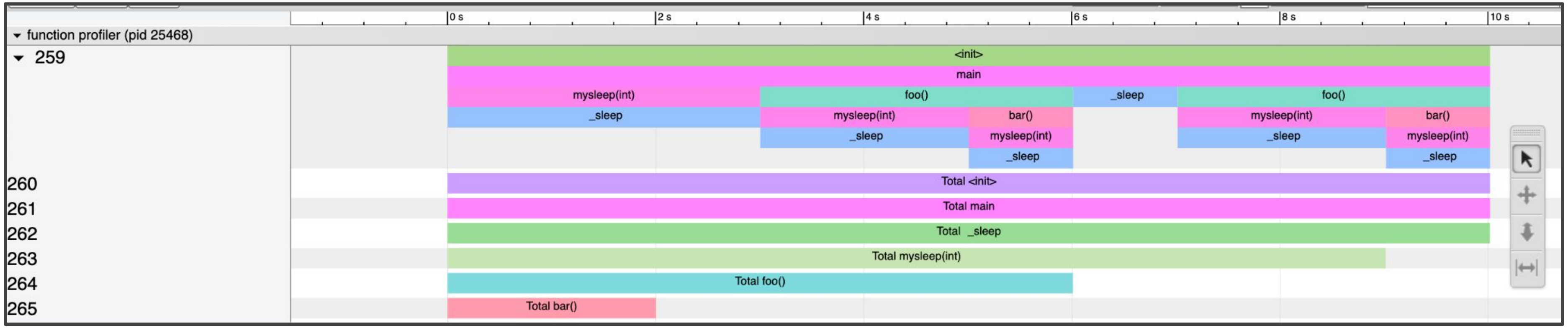
- Instrumentation **opportunities**
  - Instructions
  - Function enter/exit (+ inspect of args)
  - Global variables
  - Module constructor/dtor

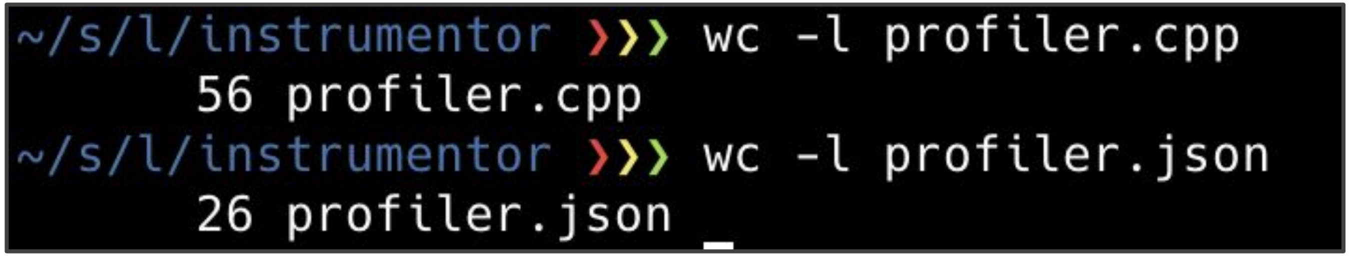
- Other opportunities for **optimization**
  - Loop range info (e.g., hoisting checks)
  - Base pointer info

Use cases

Example Use: Profiler

The final result (visualized):





```
~/s/l/instrumentor ❯❯❯ wc -l profiler.cpp
      56 profiler.cpp
~/s/l/instrumentor ❯❯❯ wc -l profiler.json
      26 profiler.json
```

Example Use: Profiler

```json
{
  "configuration": {
    "runtime_prefix": "__profiler_"
  },
  "function_pre": {
    "function": {
      "enabled": true,
      "address": true,
      "name": true
    }
  },
  "instruction_pre": {
    "call": {
      "enabled": true,
      "callee": true,
      "callee_name": true
    }
  },
  "instruction_post": {
    "call": {
      "enabled": true,
      "callee": true,
      "callee_name": true
    }
  }
}
```

Example Use: Profiler

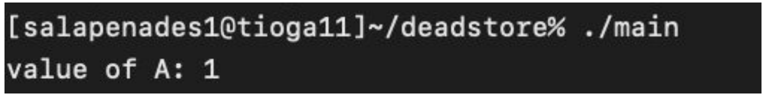
```
#include <stdio.h>
#include "llvm/Demangle/Demangle.h"
#include "llvm/Support/Error.h"
#include "llvm/Support/TimeProfiler.h"

using namespace llvm;

extern "C" {
struct __init_ty {
    __init_ty() {
      timeTraceProfilerInitialize(10, "function profiler", true);
      timeTraceProfilerBegin("<init>", "");
    }

    ~__init_ty() {
      if (has_main)
        timeTraceProfilerEnd();
      timeTraceProfilerEnd();
      if (auto Err = timeTraceProfilerWrite("prof.json", "prof.alt.json"))
        printf("Error writing out the time trace: %s\n",
               toString(std::move(Err)).c_str());
      timeTraceProfilerCleanup();
    }
  };

  void *callee = nullptr;
  bool callee_found = false;
  bool has_main = false;
} __state;
```

```
void __profiler_pre_function(void *address, char *name) {
  if (__state.callee == address && !__state.callee_found) {
    timeTraceProfilerBegin(demangle(name), "");
    __state.callee_found = true;
  }

  if (!memcmp(name, "main", 4)) {
    __state.has_main = true;
    timeTraceProfilerBegin("main", "");
  }
}

void __profiler_pre_call(void *callee, char *callee_name) {
  timeTraceProfilerBegin(
      callee_name ? demangle(callee_name) : "<indirect>", "");
  if (!callee_name)
    __state.callee = callee;
}

void __profiler_post_call(void *callee, char *callee_name) {
  if (__state.callee_found) {
    __state.callee = nullptr;
    __state.callee_found = false;
    timeTraceProfilerEnd();
  }
  timeTraceProfilerEnd();
}

}
```

Example Use: Detect dead and redundant stores

OK

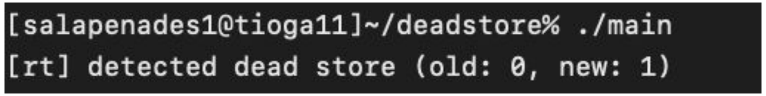
```c
int A;

int main() {
  A = 0;
  A++;
  printf("value of A: %d\n", A);
}
```



```
[salapenades1@tioga11]~/deadstore% ./main
value of A: 1
```

Dead Store

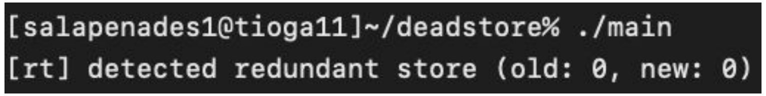
```c
int A;

int main() {
  A = 0;
  A = 1;
}
```



```
[salapenades1@tioga11]~/deadstore% ./main
[rt] detected dead store (old: 0, new: 1)
```

Redundant Store

```c
int A;

int main() {
  A = 0;
  printf("value of A: %d\n", A);
  A = 0;
}
```



```
[salapenades1@tioga11]~/deadstore% ./main
[rt] detected redundant store (old: 0, new: 0)
```

Example Use: Detect dead and redundant stores

Runtime code:

```
$ wc -l rt.cpp
38 rt.cpp
```

Instrumentor config:

```
{
  "configuration": {
    "runtime_prefix": "__rt_",
  },
  "instruction_pre": {
    "load": {
      "enabled": true,
      "pointer": true,
      "value_size": true
    },
    "store": {
      "enabled": true,
      "pointer": true,
      "value": true,
      "value_size": true
    }
  }
}
```

Some extras

Extras: Use Instrumentor within LLVM

- Use **Instrumentor** programmatically **w/o JSON** file
  - **Fine-grained control** of what is instrumented
  - Pass **custom data** to RT calls
- Using class inheritance and callbacks

```
LoadIO::ConfigTy LICConfig;
LICConfig.PassPointerAs = false;
LICConfig.PassValue = false;
LICConfig.ReplaceValue = false;
LICConfig.PassAlignment = false;
LICConfig.PassValueTypeId = false;
LICConfig.PassIsVolatile = false;

auto *LIC =
InstrumentationConfig::allocate<LoadIO>(/*IsPRE=*/true);
LIC->HoistKind = HOIST_MAXIMALLY;
LIC->CB = [&](Value &V) {
  return LSI.shouldInstrumentLoad(cast<LoadInst>(V), IIRB);
};
LIC->init(*this, IIRB, &LICConfig);
```

Extras: Auto Generate RT Stub

```
{
  "configuration": {
    "runtime_prefix": "__rt_",
    "runtime_stubs_file": "rt.c"
  },
  "module_pre": {
    "module": {
      "enabled": true,
      "module_name": true,
      "name": true
    }
  },
  ...
}
```

Extras: Auto Generate RT Stub

```
$ opt -passes=instrumentor -instrumentor-read-config-file=file.json t.ll
```

```
{
  "configuration": {
    "runtime_prefix": "__rt_",
    "runtime_stubs_file": "rt.c"
  },
  "module_pre": {
    "module": {
      "enabled": true,
      "module_name": true,
      "name": true
    }
  },
  ...
}
```

Extras: Auto Generate RT Stub

```
$ opt -passes=instrumentor -instrumentor-read-config-file=file.json t.ll

$ cat rt.c
```

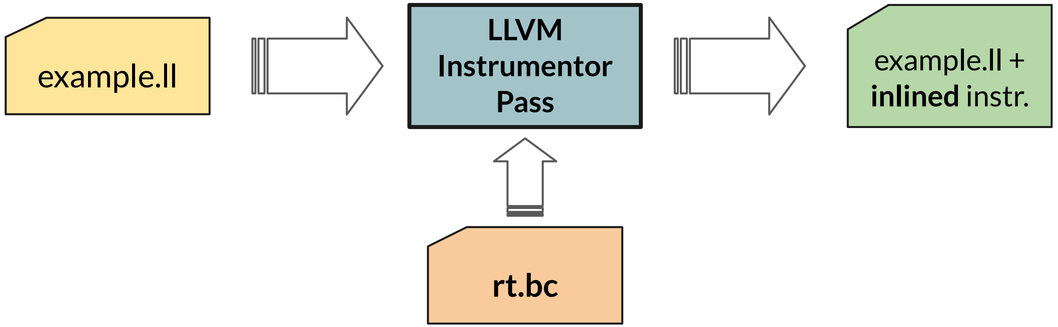
```
{
  "configuration": {
    "runtime_prefix": "__rt_",
    "runtime_stubs_file": "rt.c"
  },
  "module_pre": {
    "module": {
      "enabled": true,
      "module_name": true,
      "name": true
    }
  },
  ...
}
```

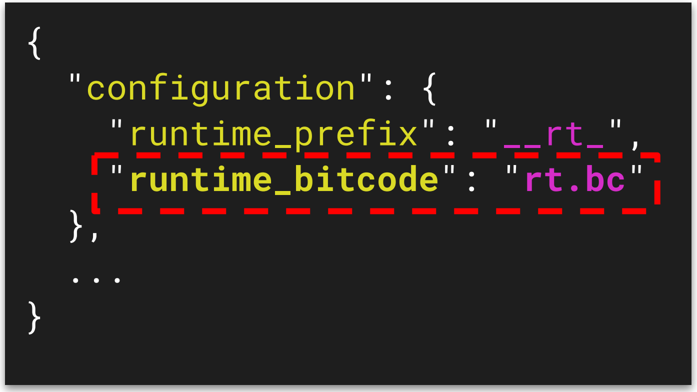
Extras: Auto Generate RT Stub

```c
#include <stdint.h>
#include <stdio.h>

void __rt_pre_module(char *module_name, char *name) {
  printf("module pre -- module_name: %s, name: %s\n",
         module_name, name);
}

void *__rt_pre_load(void *pointer, int32_t pointer_as,
                    int32_t value_size, int64_t alignment,
                    int32_t value_type_id, int32_t atomicity_ordering,
                    int8_t is_volatile) {
  printf("load pre -- pointer: %p, pointer_as: %i, value_size: %i, "
         "alignment: %lli, value_type_id: %i, atomicity_ordering: %i, "
         "is_volatile: %i\n",
         pointer, pointer_as, value_size, alignment,
         value_type_id, atomicity_ordering, is_volatile);
  return pointer;
}

void __rt_pre_alloca(int64_t size, int64_t alignment) {
  printf("alloca pre -- size: %lli, alignment: %lli\n",
         size, alignment);
}
```

```json
{
  "configuration": {
    "runtime_prefix": "__rt_",
    "runtime_stubs_file": "rt.c"
  },
  "module_pre": {
    "module": {
      "enabled": true,
      "module_name": true,
      "name": true
    }
  },
  ...
}
```

Extras: Inline RT Bitcode





```
{
  "configuration": {
    "runtime_prefix": "__rt_",
    "runtime_bitcode": "rt.bc"
  },
  ...
}
```

- Avoid cost of instrumentation RT calls
- Better optimization of RT code within user code

Conclusions

- **Instrumentor**: a customizable instrumentation based on LLVM
  - **Unified** way to **instrument** programs
  - Easy to **customize** as a user, easy to **extend** as a developer!
  - Paving the path for **future instrumentation-based tools**
- Many common use cases
  - Time profiling
  - Gather runtime information
  - etc.
- More complex use cases
  - InputGen [1]
  - Object (mem) sanitizer for CPU and GPU code [2]

[1] Ivanov, I. R., Meyer, J., Grossman, A., Moses, W. S., & Doerfert, J. (2024). **Input-Gen: Guided Generation of Stateful Inputs for Testing, Tuning, and Training**. *arXiv preprint arXiv:2406.08843*
[2] Doerfert, J., McDonough, E., & Singhal, V. (2024). **(Offload) ASAN via Software Managed Virtual Memory**. 2024 LLVM Developers' Meeting.

Thank you!

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