A Brief Introduction to LLVM

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  - Program analysis / optimization libraries
  - Machine code generation libraries
  - Tools that compose the libraries to perform tasks
- Easy to add / remove / change functionality

How will you be using it?

- Compiling programs to bitcode:

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clang -g -c -emit-llvm <sourcefile> -o <bitcode>.bc
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- Writing your own tools:

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./callcounter -static test.bc
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- Reporting properties of the program:

```
Function Counts
===============
b : 2
a : 1
printf : 3
```

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- A (relatively) simple
  intermediate representation (IR)
  - It captures the
    program dependence graph

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Code

```
#include<stdio.h>

void
foo(unsigned e) {
  for (unsigned i = 0; i < e; ++i) {
    printf("Hello\n");
  }
}

int
main(int argc, char **argv) {
  foo(argc);
  return 0;
}
```

```
clang -c -S -emit-llvm -O1 -g0
```

IR

```
@str = private constant [6 x i8] c"Hello\00"

define void @foo(i32) {
  %2 = icmp eq i32 %0, 0
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; <label>:3:                              ; preds = %4, %1
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  %5 = phi i32 [ %7, %4 ], [ 0, %1 ]
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  %7 = add nuw i32 %5, 1
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define i32 @main(i32, i8** nocapture readnone) {
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Functions

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Basic Blocks

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labels & predecessors

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}

define i32 @m                              ) {
  tail call void @foo(i32 %0)
  ret i32 0
}
```

branches & successors

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foo(unsigned e) {
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Instructions

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Inspecting Bitcode

- LLVM libraries help examine the bitcode
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  - Many helpers (e.g. CallBase, outs(), dyn_cast)

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```
Module& module = ...;
for (Function& fun : module) {
  for (BasicBlock& bb : fun) {
    for (Instruction& i : bb) {

...
```

Iterate over the:
- Functions in a Module
- BasicBlocks in a Function
- Instructions in a BasicBlock

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Module& module = ...;
for (Function& fun : module) {
  for (BasicBlock& bb : fun) {
    for (Instruction& i : bb) {
      CallBase* cb = dyn_cast<CallBase>(&i);
      if (!cb) {
        continue;
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```

`dyn_cast()` efficiently checks the runtime types of LLVM IR components.

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CallBase provides a common interface for different type of function calls

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      outs() << "Found a function call: " << i << "\n";
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```

`outs()` and other printing functions make inspecting components easy

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      outs() << "Found a function call: " << i << "\n";
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Working within the API allows you to ask questions about code.

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- Program dependence graphs help answer questions like:
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void foo()
  unsigned i = 0;
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What is the single definition of `i` at this point?

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  - Each variable has a single definition,
    so resolving dependencies is easier
- Phi instructions select which incoming value to use among options
  - Phi nodes must occur at the *beginning* of a basic block

Static Single Assignment (SSA)

```c
void foo() {
  unsigned i = 0;
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}
```

```llvm
define void @foo() {
  br label %1

; <label>:1                                ; preds = %1, %0
  %i.phi = phi i32 [ 0, %0 ], [ %2, %1 ]
  %2 = add i32 %i.phi, 1
  %exitcond = icmp eq i32 %2, 10
  br i1 %exitcond, label %3, label %1

; <label>:3                                ; preds = %1
  ret void
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Dependencies in General

- You can loop over the values an instruction uses

```
for (Use& u : inst->operands()) {
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Given %a = %b + %c:
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Dependencies in General

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for (Use& u : inst->operands()) {
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}
```

Given %a = %b + %c:
[%b, %c]

- You can loop over the instructions that use a particular value

```
Instruction* inst = ...;
for (User* user : inst->users())
  if (auto* i = dyn_cast<Instruction>(user)) {
    // inst is used by Instruction i
  }
```

Dealing with Types

- LLVM IR is strongly typed
  - Every value has a type → getType()
- A value must be explicitly cast to a new type

```
define i64 @trunc(i16 zeroext %a) {
  %1 = zext i16 %a to i64
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```

- Also types for pointers, arrays, structs, etc.
  - Strong typing means they take a bit more work

Dealing with Types: GEP

- We sometimes need to extract elements/fields from arrays/structs
  - Pointer arithmetic
  - Done using GetElementPointer (GEP)

```
struct rec {
  int x;
  int y;
};

struct rec *buf;

void foo() {
  buf[5].y = 7;
}
```

```
%struct.rec = type { i32, i32 }

@buf = global %struct.rec* null

define void @foo() {
  %1 = load %struct.rec*, %struct.rec** @buf
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  store i32 7, i32* %2
  ret void
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- The header files!
  - All in llvm-12.x.src/include/llvm/

```
BasicBlock.h      InstrTypes.h
DerivedTypes.h    IRBuilder.h
Function.h        Support/InstVisitor.h
Instructions.h    Type.h
```

Creating a
Static Analysis

Making a new analysis

- Analyses are organized into individual passes
  - ModulePass
  - FunctionPass
  - LoopPass
  - …

Derive from the appropriate base class to make a Pass

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3 Steps

1) Declare your pass
2) Register your pass
3) Define your pass

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  - ...

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3 Steps

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3) Define your pass

Let's count the number of **static direct calls** to each function.

Making a ModulePass (1)

- Declare your ModulePass

```
struct StaticCallCounter : public llvm::ModulePass {

  static char ID;

  DenseMap<Function*, uint64_t> counts;

  StaticCallCounter()
    : ModulePass(ID)
      { }

  bool runOnModule(Module& m) override;

  void print(raw_ostream& out, const Module* m) const override;

  void handleInstruction(CallBase& cb);
};
```

Making a ModulePass (1)

- Declare your ModulePass

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struct StaticCallCounter : public llvm::ModulePass {

  static char ID;

  DenseMap<Function*, uint64_t> counts;

  StaticCallCounter()
    : ModulePass(ID)
      { }

  bool runOnModule(Module& m) override;

  void print(raw_ostream& out, const Module* m) const override;

  void handleInstruction(CallBase& cb);
};
```

Making a ModulePass (1)

- Declare your ModulePass

```
struct StaticCallCounter : public llvm::ModulePass {
  static char ID;
  DenseMap<Function*, uint64_t> counts;
  StaticCallCounter()
    : ModulePass(ID)
      { }
  bool runOnModule(Module& m) override;
  void print(raw_ostream& out, const Module* m) const override;
  void handleInstruction(CallBase& cb);
};
```

Making a ModulePass (2)

- Register your ModulePass
  - This allows it to even be dynamically loaded as a plugin
  - Depending on your use cases, it may not be necessary

```
char StaticCallCounter::ID = 0;

RegisterPass<StaticCallCounter> SCCReg("callcounter",
                      "Print the static count of direct calls");
```

Making a ModulePass (3)

- Define your ModulePass
  - Need to override **`runOnModule()`** and **`print()`**

```
bool
StaticCallCounter::runOnModule(Module& m) {
  for (auto& f : m)
    for (auto& bb : f)
      for (auto& i : bb)
        if (CallBase *cb = dyn_cast<CallBase>(&i)) {
          handleInstruction(CallSite{&i});
        }
  return false; // False because we didn't change the Module
}
```

Making a ModulePass (3)

- Define your ModulePass
  - Need to override **`runOnModule()`** and **`print()`**

```
bool
StaticCallCounter::runOnModule(Module& m) {
  for (auto& f : m)
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      for (auto& i : bb)
        if (CallBase *cb = dyn_cast<CallBase>(&i)) {
          handleInstruction(CallSite{&i});
        }
  return false; // False because we didn't change the Module
}
```

Making a ModulePass (3)

- Analysis continued…

```
void
StaticCallCounter::handleInstruction(CallBase* cb) {
  // Check whether the called function is directly invoked
  auto called = cb.getCalledOperand()->stripPointerCasts();
  auto fun    = dyn_cast<Function>(called);
  if (!fun) { return; }

  // Update the count for the particular call
  auto count = counts.find(fun);
  if (counts.end() == count) {
    count = counts.insert(std::make_pair(fun, 0)).first;
  }
  ++count->second;
}
```

Making a ModulePass (3)

- Analysis continued...

```
void
StaticCallCounter::handleInstruction(CallBase* cb) {
  // Check whether the called function is directly invoked
  auto called = cb.getCalledOperand()->stripPointerCasts();
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Making a ModulePass (3)

- Analysis continued…

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StaticCallCounter::handleInstruction(CallBase* cb) {
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  auto count = counts.find(fun);
  if (counts.end() == count) {
    count = counts.insert(std::make_pair(fun, 0)).first;
  }
  ++count->second;
}
```

Making a ModulePass (3)

- Printing out the results

```
void
CallCounterPass::print(raw_ostream& out, const Module* m) const {
  out << "Function Counts\n"
      << "===============\n";
  for (auto& kvPair : counts) {
    auto* function = kvPair.first;
    uint64_t count = kvPair.second;
    out << function->getName() << " : " << count << "\n";
  }
}
```

Creating a
Dynamic Analysis

Making a Dynamic Analysis

- We have counted the *static* direct calls to each function.
- How might we count all ***dynamic calls*** to each function?

Making a Dynamic Analysis

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- How might we count all ***dynamic calls*** to each function?
- Need to modify the original program!

Making a Dynamic Analysis

- We have counted the *static* direct calls to each function.
- How might we count all ***dynamic calls*** to each function?
- Need to modify the original program!
- Steps:
  1) ***Modify*** the program using passes
  2) ***Compile*** the modified version
  3) ***Run*** the new program

Modifying the Original Program

- **Goal**: Count the dynamic calls to each function in an execution.
  - So how do we want to modify the program?

```
void foo()
  bar();
}
```

⇒ ?

Keep a counter for each function!

2 Choices:

1) increment count for each function ***as it starts***
2) increment count for each function ***at its call site***

Does that even matter? Are there trade offs?

Modifying the Original Program

- **Goal**: Count the dynamic calls to each function in an execution.
  - So how do we want to modify the program?

```
void foo()
  bar();
}
```

```
void foo()
  count[foo]++;
  bar();
}
```

- We'll increment at the function entry.

  (the demo code shows both options)

Modifying the Original Program

- **Goal**: Count the dynamic calls to each function in an execution.
  - So how do we want to modify the program?

```
void foo()
  bar();
}
```

⇒

```
void foo()
  count[1]++;
  bar();
}
```

```
0 ↦ main
1 ↦ foo
2 ↦ bar
  …
```

- We'll increment at the function entry.
  - *Using numeric IDs* for functions is sometimes easier

Modifying the Original Program

- **Goal**: Count the dynamic calls to each function in an execution.
  - So how do we want to modify the program?

```
void foo()
  bar();
}
```

⇒

```
void foo()
  countCall(1);
  bar();
}
```

```
void
countCall(id)
  count[id]++;
}
```

- We'll increment at the function entry.
  - *Using numeric IDs* for functions is sometimes easier
  - *Inserting function calls* is easier than adding raw instructions

Modifying the Original Program

- **Goal**: Count the dynamic calls to each function in an execution.
  - So how do we want to modify the program?

```
void foo()
  bar();
}
```

⇒

```
void foo()
  countCall(1);
  bar();
}
```

```
void countCall(id)
  count[id]++;
}
```

- We'll increment at the function entry.
  - *Using numeric IDs* for functions is sometimes easier
  - ***Inserting function calls*** is easier than adding raw instructions
    - Add new definitions to the original code
    - Link against an ***instrumentation library***

Modifying the Original Program

- What might adding this call look like?

```
void
DynamicCallCounter::handleInstruction(CallBase& cb, Value* counter) {
  // Check whether the called function is directly invoked
  auto calledValue    = cb.getCalledOperation()->stripPointerCasts();
  auto calledFunction = dyn_cast<Function>(calledValue);
  if (!calledFunction) {
    return;
  }

  // Insert a call to the counting function.
  IRBuilder<> builder(&cb);
  builder.CreateCall(counter, builder.getInt64(ids[calledFunction]));
}
```

Modifying the Original Program

- What might adding this call look like?

```
void
DynamicCallCounter::handleInstruction(CallBase& cb, Value* counter) {
  // Check whether the called function is directly invoked
  auto calledValue    = cb.getCalledOperation()->stripPointerCasts();
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Modifying the Original Program

- What might adding this call look like?

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DynamicCallCounter::handleInstruction(CallBase& cb, Value* counter) {
  // Check whether the called function is directly invoked
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  auto calledFunction = dyn_cast<Function>(calledValue);
  if (!calledFunction) {
    return;
  }

  // Insert a call to the counting function.
  IRBuilder<> builder(&cb);
  builder.CreateCall(counter, builder.getInt64(ids[calledFunction]));
}
```

In practice, it is more complex.
You can find details in the demo code.

Using a Runtime Library

- Recall that the definition of **`countCall()`** needs to live somewhere
  1) Add directly to the modified code
  2) Implemented separately & linked in via a library

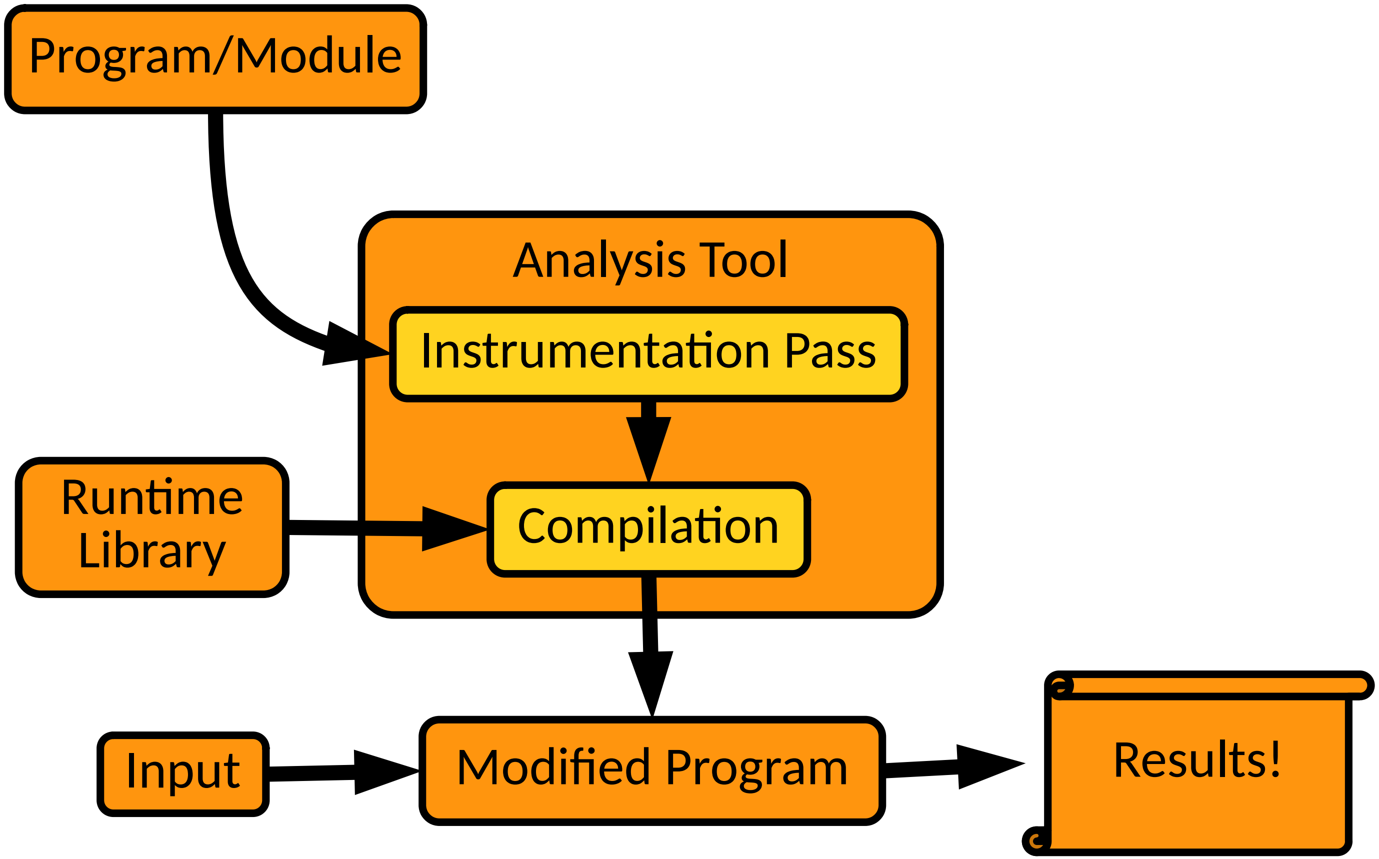
What trade offs do you see?

Using a Runtime Library

- Recall that the definition of `countCall()` needs to live somewhere
  1) Add directly to the modified code
  2) Implemented separately & linked in via a library
- In practice, linking against a library is common, easy, & powerful
  - Regardless of the language being analyzed

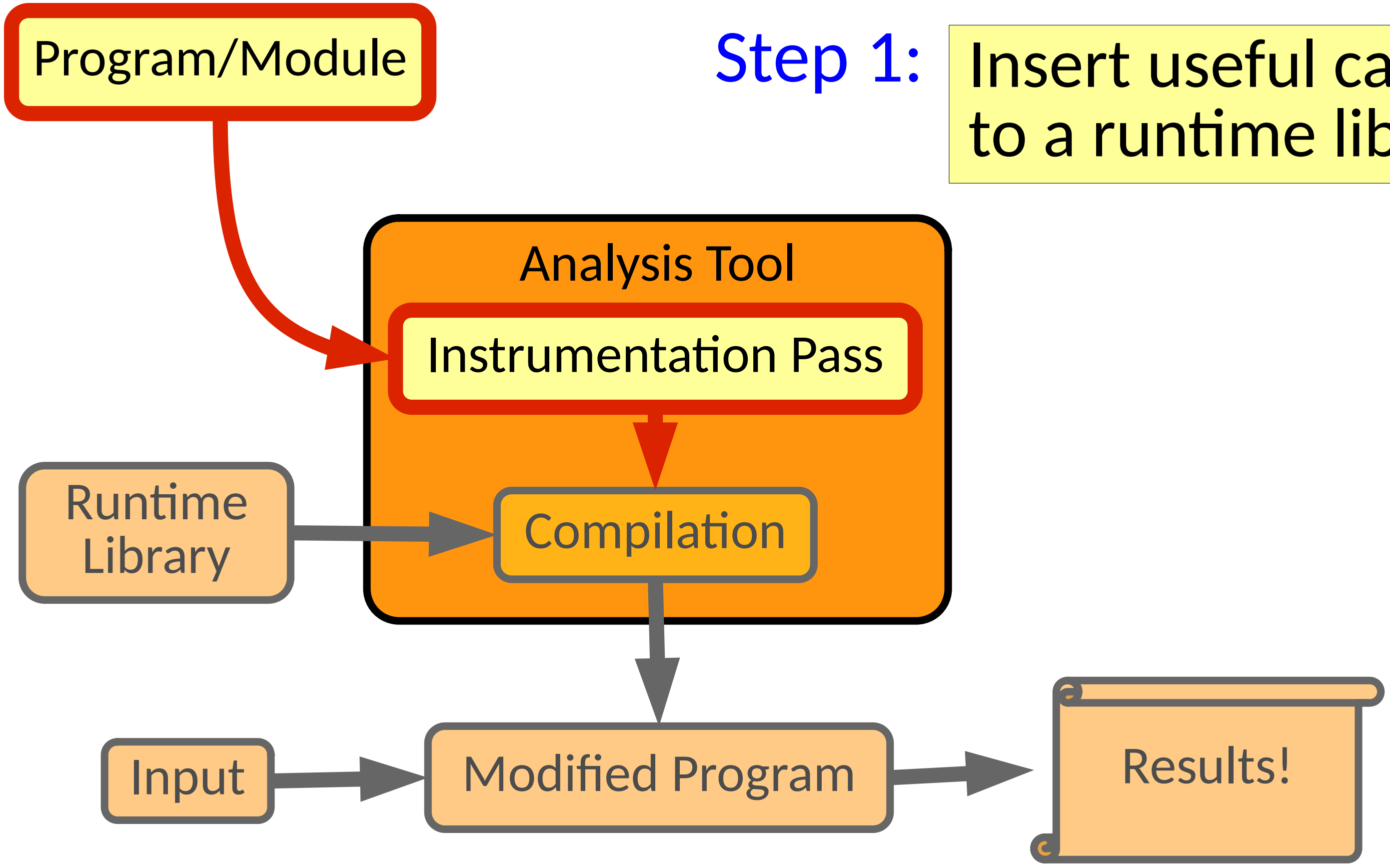
```
void
countCalled(uint64_t id) {
  ++functionInfo[id];
}
```

Revisiting the Big Picture of Dynamic Analysis



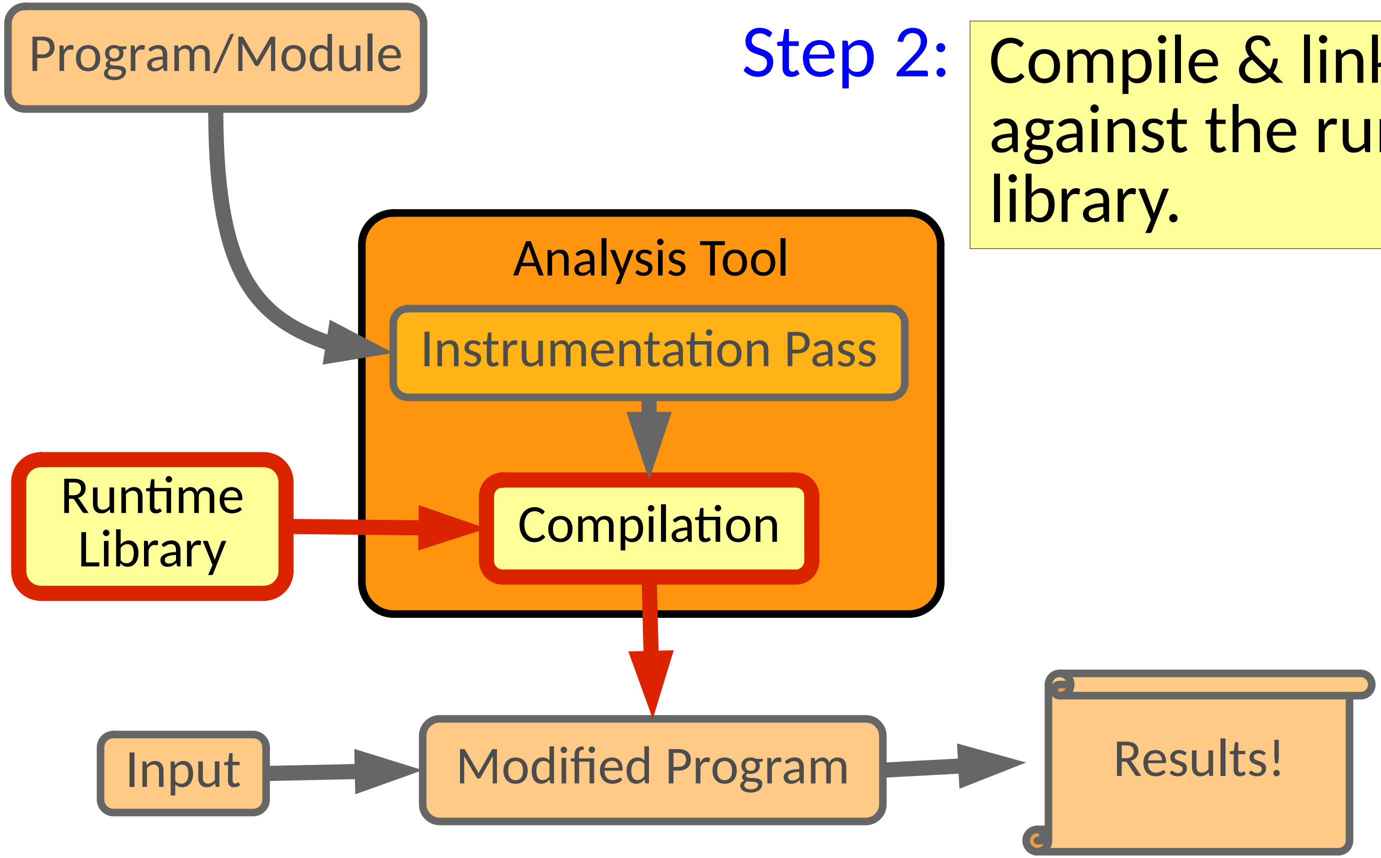
Revisiting the Big Picture of Dynamic Analysis

Step 1: Insert useful calls to a runtime library



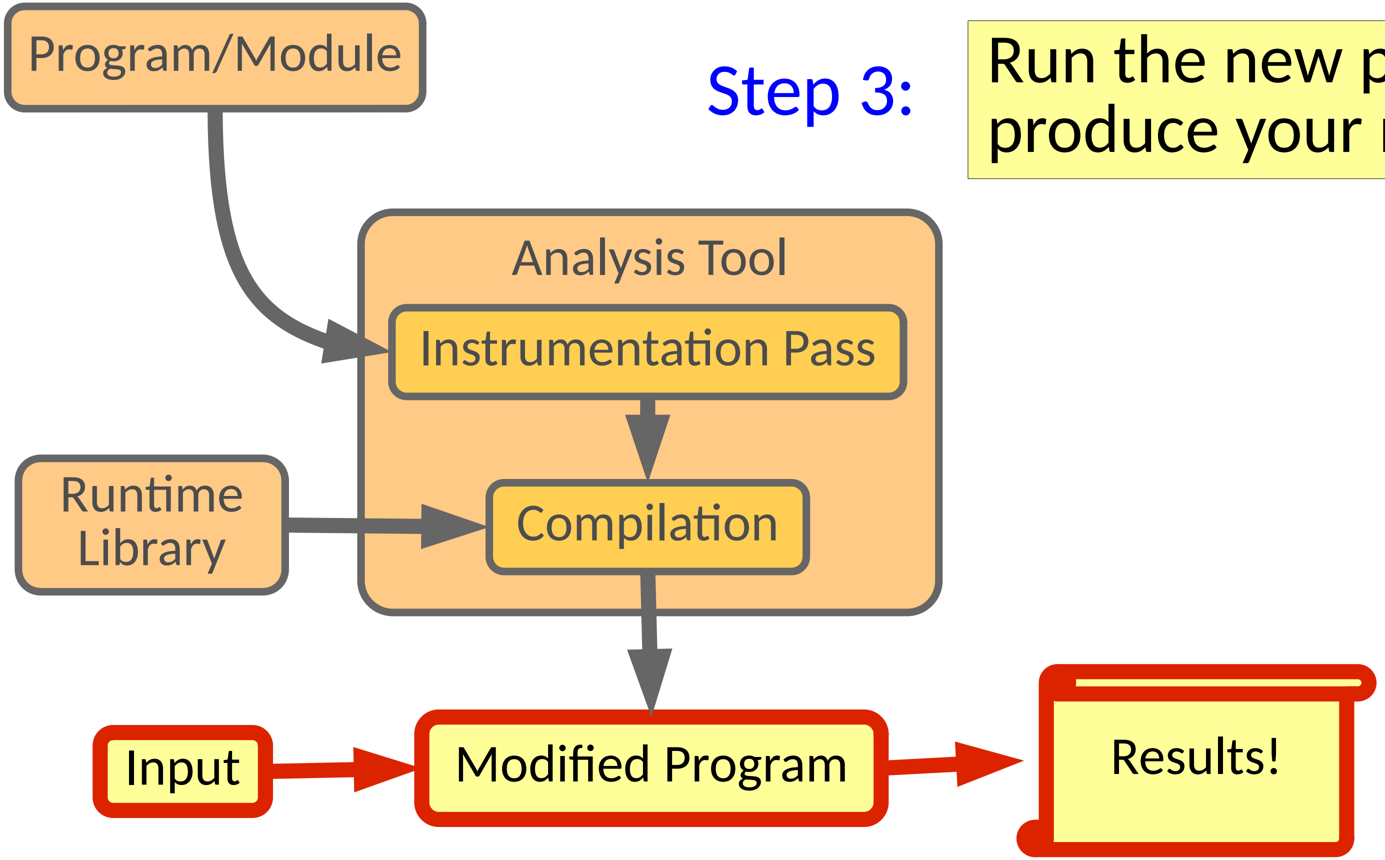
Revisiting the Big Picture of Dynamic Analysis

Step 2: Compile & link against the runtime library.



Revisiting the Big Picture of Dynamic Analysis

Step 3: Run the new program to produce your results



Summary

- LLVM organizes groups of passes and tools into projects
- Easiest way to start is by using the demo on the course page
- For the most part, you can follow the directions online
  & in the project description