A Brief Introduction to Using LLVM

Nick Sumner

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  - Machine code generation libraries
  - Tools that compose the libraries to perform task

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  - A simple, typed IR (*bitcode*)
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  - Machine code generation libraries
  - Tools that compose the libraries to perform tasks
- Easy to add / remove / change functionality

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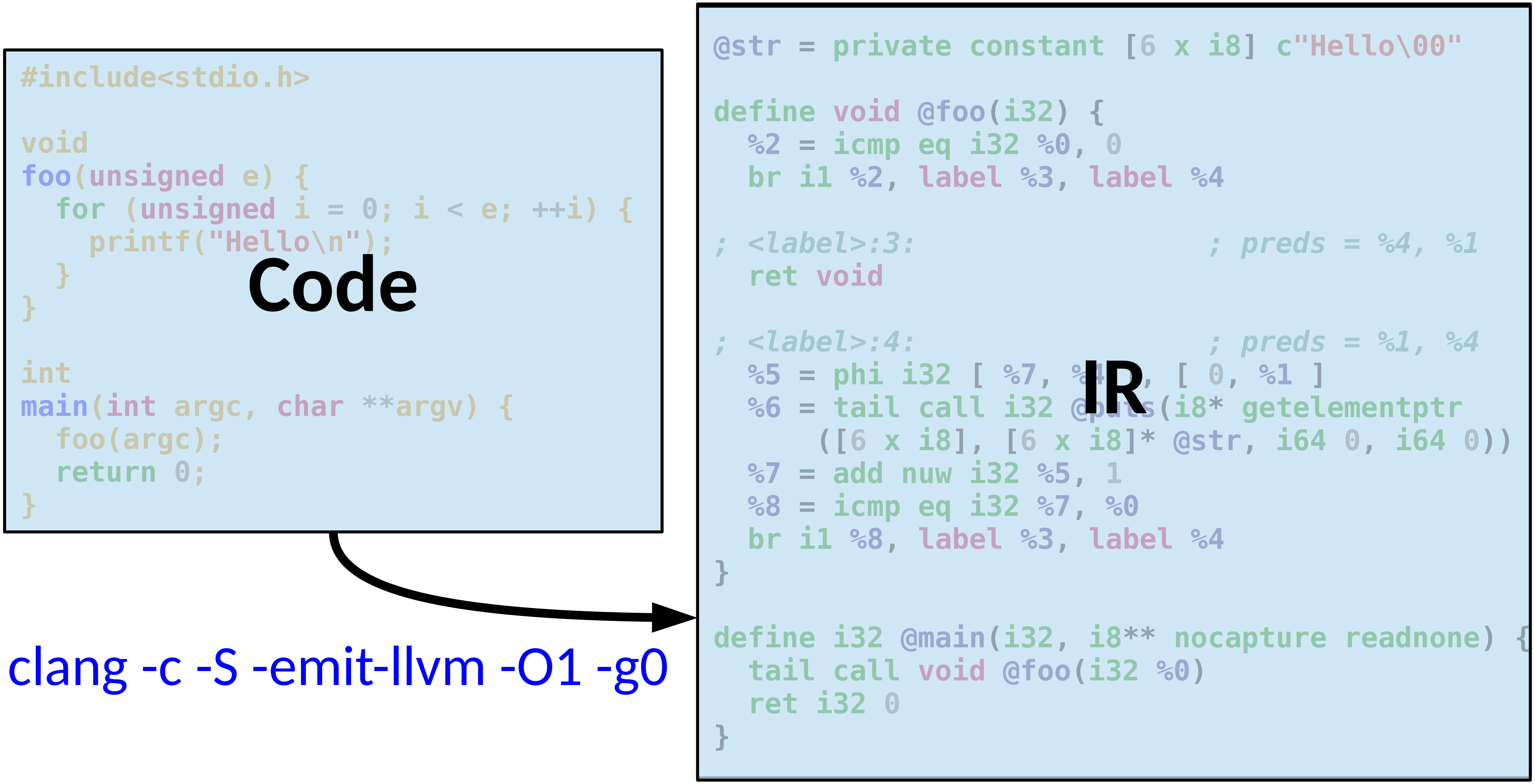

Code

```
#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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; <label>:4:                            ; preds = %1, %4
  %5 = phi i32 [ %7, %4 ], [ 0, %1 ]
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define i32 @main(i32, i8** nocapture readnone) {
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(and llvm-dis)

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}

define i32 @main(i32, i8** nocapture readnone) {
  tail call void @foo(i32 %0)
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}
```

Functions

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main(int argc, char **argv) {
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}
```

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Basic Blocks

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define i32 @main(i32, i8** nocapture readnone) {
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labels & predecessors

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branches & successors

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Instructions

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define i32 @main(i32, i8** nocapture readnone) {
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```

Inspecting Bitcode

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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

Inspecting Bitcode

- LLVM libraries help examine the bitcode
  - Easy to examine and/or manipulate
  - Many helpers (e.g. CallSite,)

```
Module& module = ...;
for (Function& fun : module) {
  for (BasicBlock& bb : fun) {
    for (Instruction& i : bb) {
      CallSite cs(&i);
      if (!cs.getInstruction()) {
        continue;
      }







...
```

CallSite helps you extract information from Call and Invoke instructions.

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      if (!cs.getInstruction()) {
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      }
      outs() << "Found a function call: " << i << "\n";



...
```

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- LLVM libraries help examine the bitcode
  - Easy to examine and/or manipulate
  - Many helpers (e.g. CallSite, outs(), dyn_cast)

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Module &module = ...;
for (Function& fun : module) {
  for (BasicBlock& bb : fun) {
    for (Instruction& i : bb) {
      CallSite cs(&i);
      if (!cs.getInstruction()) {
        continue;
      }
      outs() << "Found a function call: " << i << "\n";
      Value* called = cs.getCalledValue()->stripPointerCasts();
      if (Function* f = dyn_cast<Function>(called)) {
        outs() << "Direct call to function: " << f->getName() << "\n";
...
```

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

Dealing with SSA

- You may ask where certain values came from
  - Useful for tracking dependencies (PDG)
  - “Where was this variable defined?”

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void foo()
  unsigned i = 0;
  while (i < 10) {
    i = i + 1;
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```

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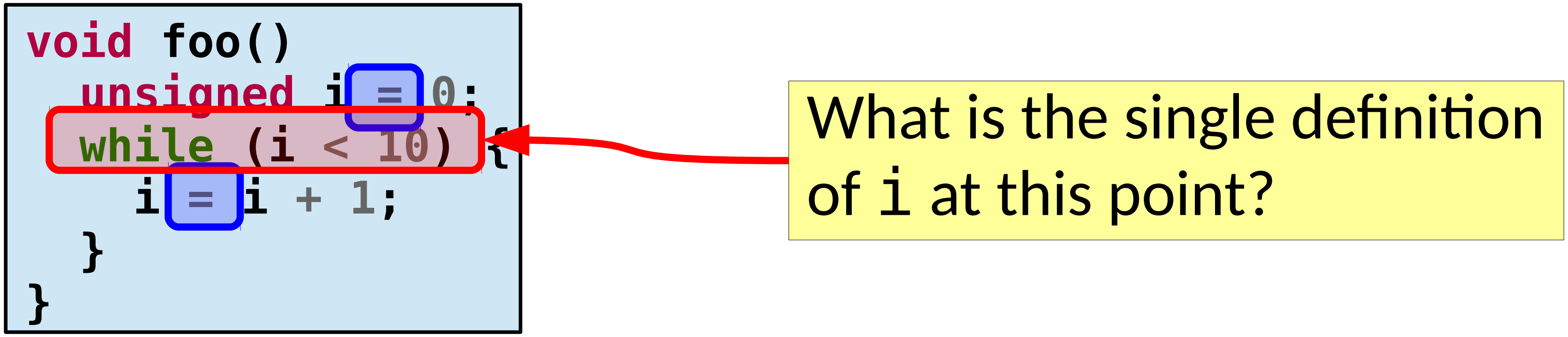

```
void foo()
  unsigned i = 0;
  while (i < 10) {
    i = i + 1;
  }
}
```

What is the single definition of `i` at this point?

Dealing with SSA

- Thus the phi (φ) instruction
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  }
}
```

```
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
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}
```

Dealing with SSA

- Thus the phi (φ) instruction
  - It selects which of the definitions to use
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  unsigned i = 0;
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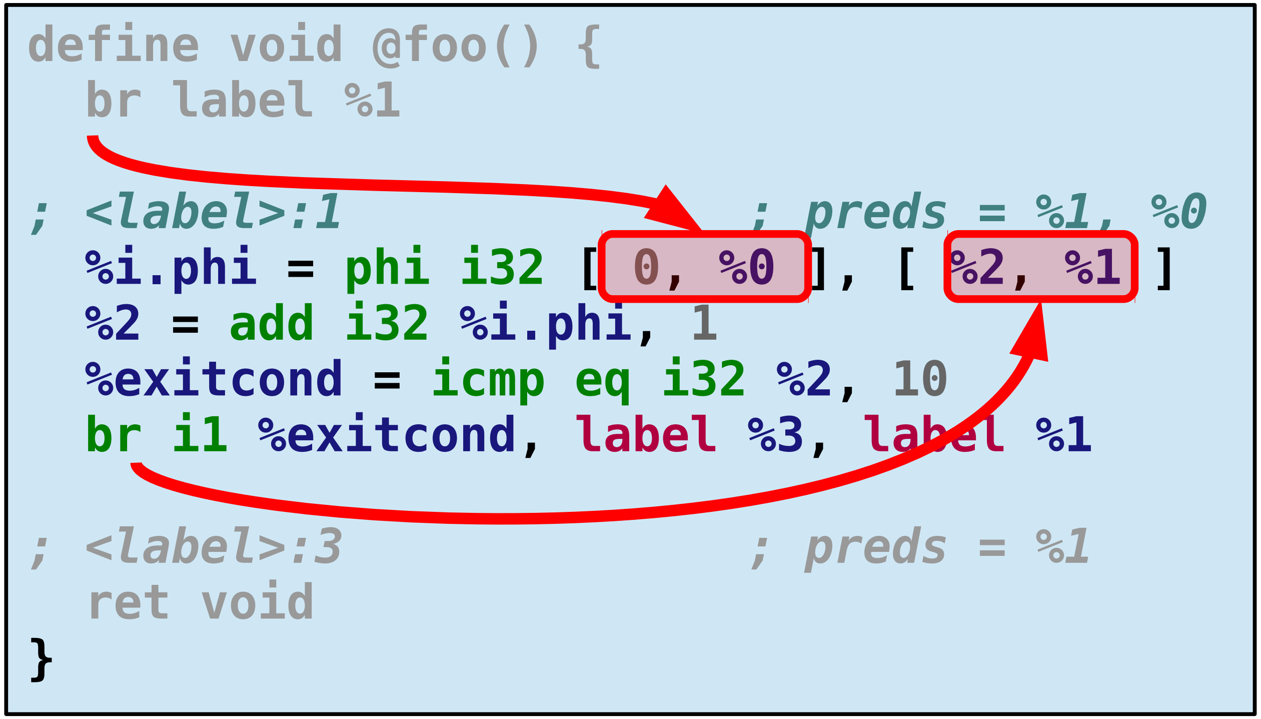

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Dependencies in General

- You can loop over the values an instruction uses

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

```
for %a = %b + %c:
    [%b, %c]
```

Dependencies in General

- You can loop over the values an instruction uses

```
for (Use& u : inst->operands()) {
  // inst uses the Value* u
}
```

- 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
  }
```

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- LLVM IR is *strongly typed*
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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)

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  int x;
  int y;
};

struct rec *buf;

void foo() {
  buf[5].y = 7;
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```
%struct.rec = type { i32, i32 }

@buf = global %struct.rec* null

define void @foo() {
  %1 = load %struct.rec*, %struct.rec** @buf
  %2 = getelementptr %struct.rec, %struct.rec* %1, i64 5, i32 1
  store i32 7, i32* %2
  ret void
}
```

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- The header files!
  - All in llvm-3.x.src/include/llvm/

```
BasicBlock.h
CallSite.h
DerivedTypes.h
Function.h
Instructions.h
InstrTypes.h
IRBuilder.h
Support/InstVisitor.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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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(CallSite cs);
};
```

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

  void handleInstruction(CallSite cs);
};
```

Making a ModulePass (2)

- Register your ModulePass
  - This allows it to by dynamically loaded as a plugin

```
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)
        handleInstruction(CallSite(&i));
  return false; // False because we didn't change the Module
}
```

Making a ModulePass (3)

- analysis continued…

```cpp
void
StaticCallCounter::handleInstruction(CallSite cs) {
  // Check whether the instruction is actually a call
  if (!cs.getInstruction()) { return; }

  // Check whether the called function is directly invoked
  auto called = cs.getCalledValue()->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…

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}
```

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";
  }
}
```

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- How might we compute the ***dynamic* calls** to each function?

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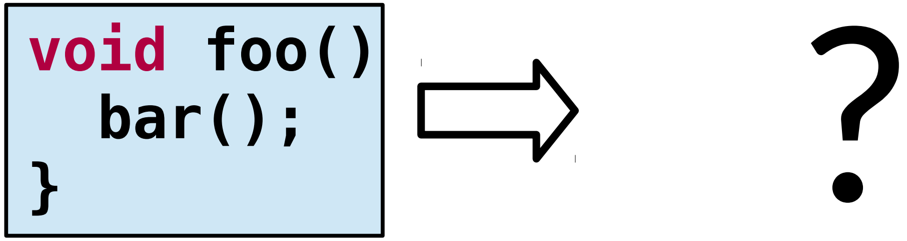
- How might we compute the ***dynamic* calls** to each function?
- Need to *modify* the original program!
- Steps:
  1) ***Modify*** the program using passes
  2) ***Compile*** the modified version
  3) ***Run*** the new program

Modifying the Original Program

Goal: Count the dynamic calls to each function in an execution.

So how do we want to modify the program?



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

?

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Goal: Count the dynamic calls to each function in an execution.

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```
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}
```

?

Keep a counter for each function!

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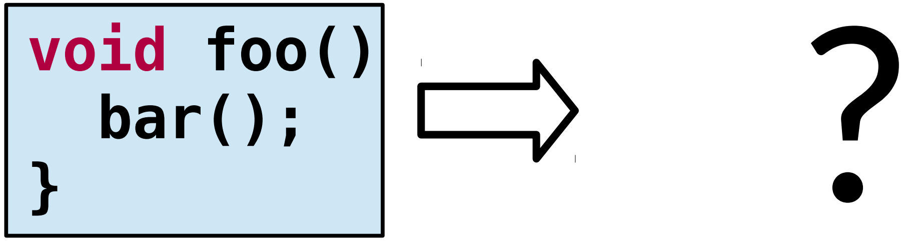
Goal: Count the dynamic calls to each function in an execution.

So how do we want to modify the program?



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

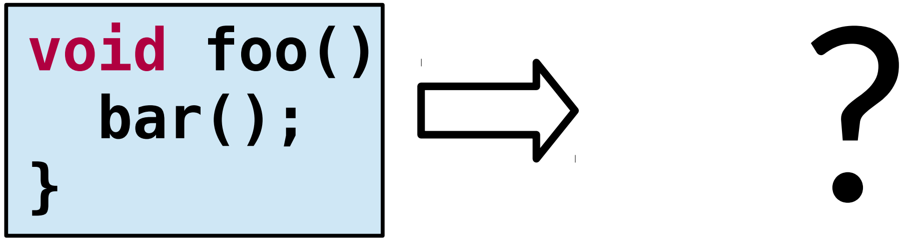
Keep a counter for each function!

2 Choices:

Modifying the Original Program

Goal: Count the dynamic calls to each function in an execution.

So how do we want to modify the program?



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?

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*

Modifying the Original Program

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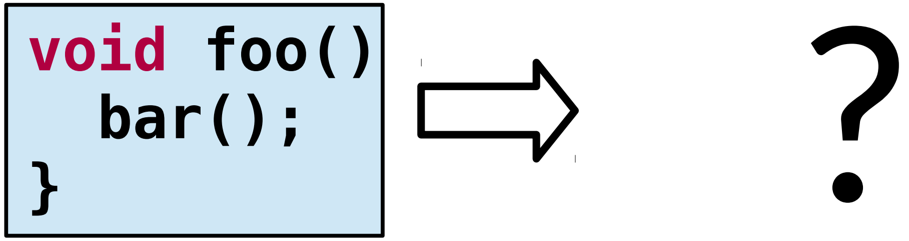

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?

Keep a counter for each function!

2 Choices:
1) increment count for each function *as it starts*
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Does that even matter? Are there trade offs?

Modifying the Original Program

Goal: Count the dynamic calls to each function in an execution.

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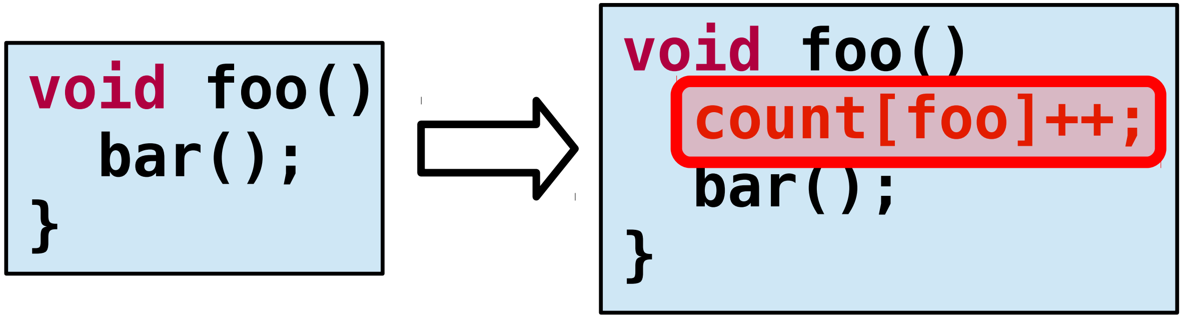


```
void foo()
  bar();
}
```

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

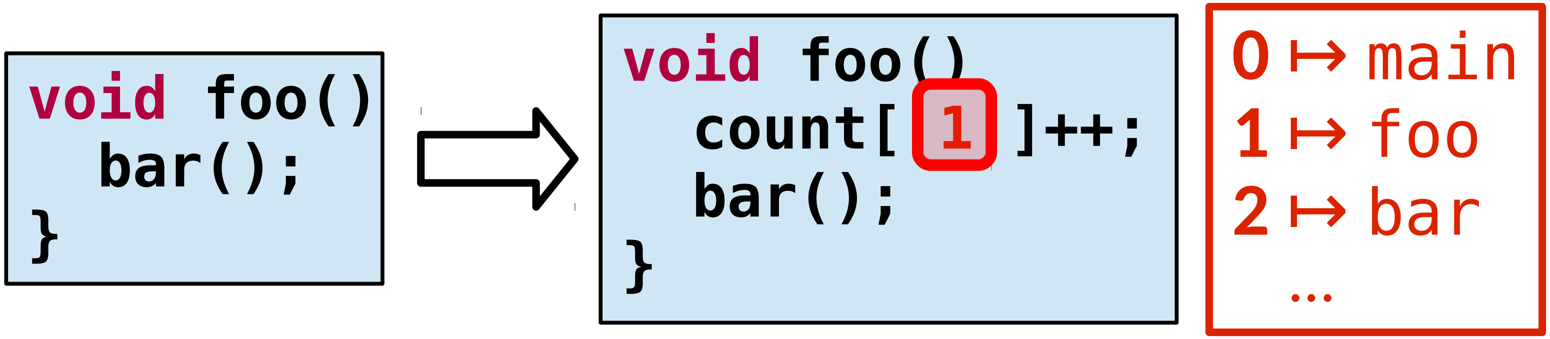
We'll increment at the function entry.

(The demo code has both)

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
  …
```

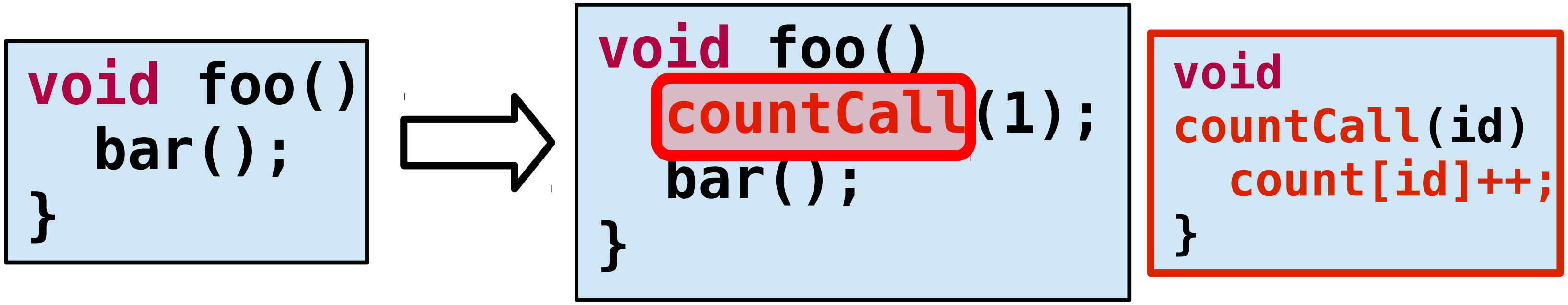
We'll increment at the function entry

- *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 sometimes easier

Modifying the Original Program

What might adding this call look like?

```
void
DynamicCallCounter::handleInstruction(CallSite cs, Value* counter) {
  // Check whether the instruction is actually a call
  if (!cs.getInstruction()) {
    return;
  }

  // Check whether the called function is directly invoked
  auto calledValue    = cs.getCalledValue()->stripPointerCasts();
  auto calledFunction = dyn_cast<Function>(calledValue);
  if (!calledFunction) {
    return;
  }

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

Modifying the Original Program

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Modifying the Original Program

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  builder.CreateCall(counter, builder.getInt64(ids[calledFunction]));
}
```

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

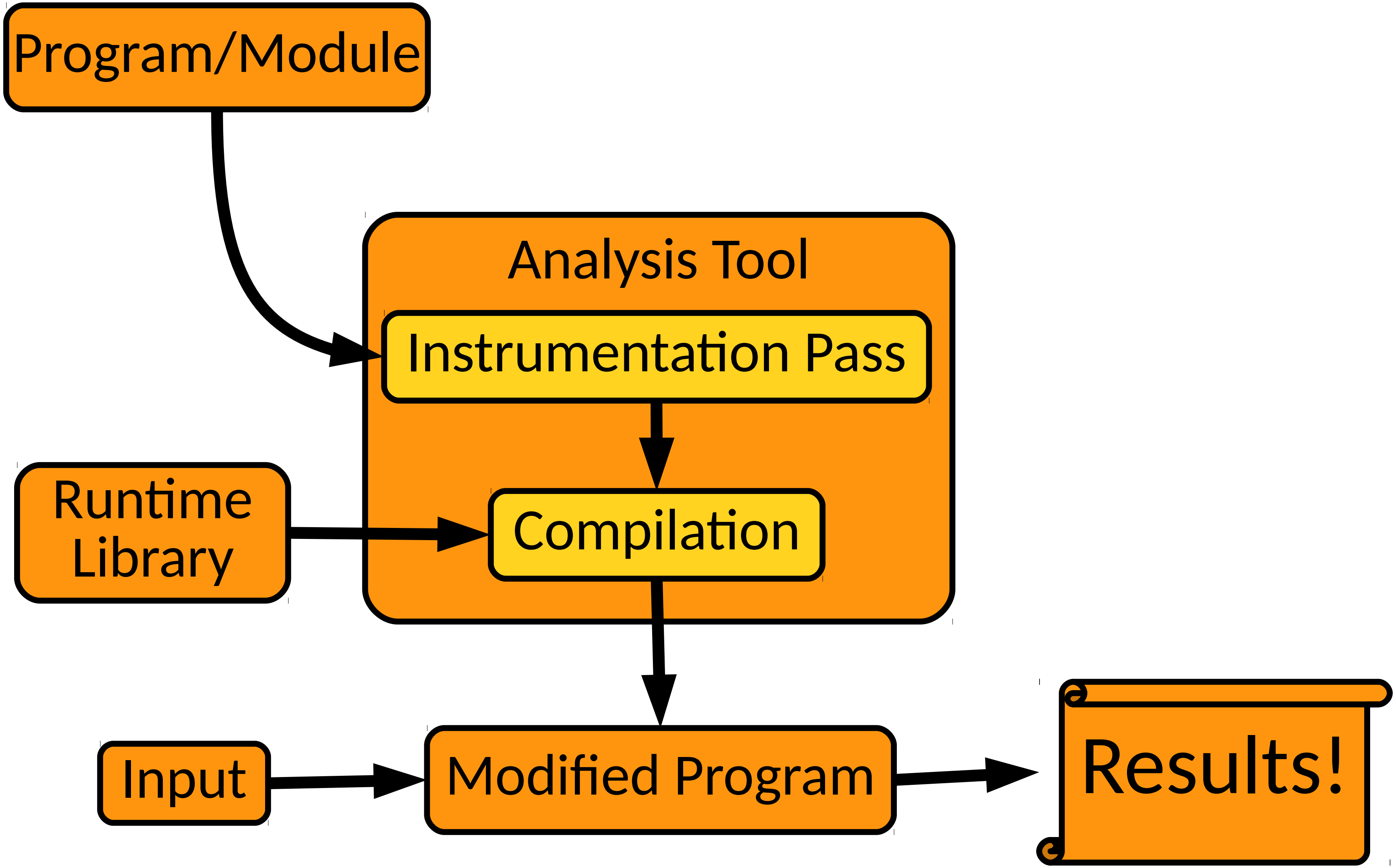
Using a Runtime Library

Don't forget that we need to put `countCall()` somewhere!

- Placed in a library linked with the main executable

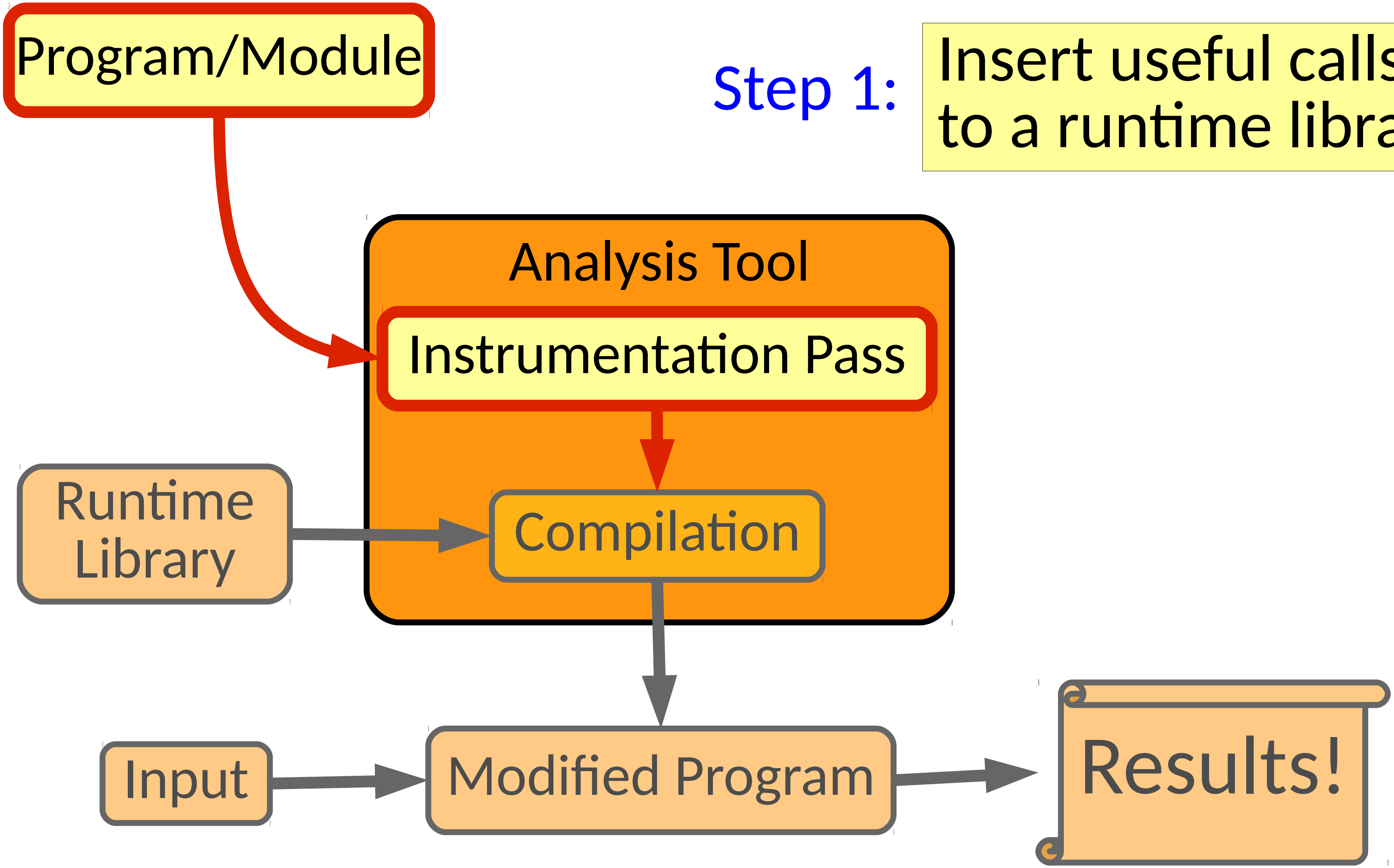
```
void
countCalled(uint64_t id) {
  ++functionInfo[id];
}
```

Dynamic Analysis Big Picture



Dynamic Analysis Big Picture

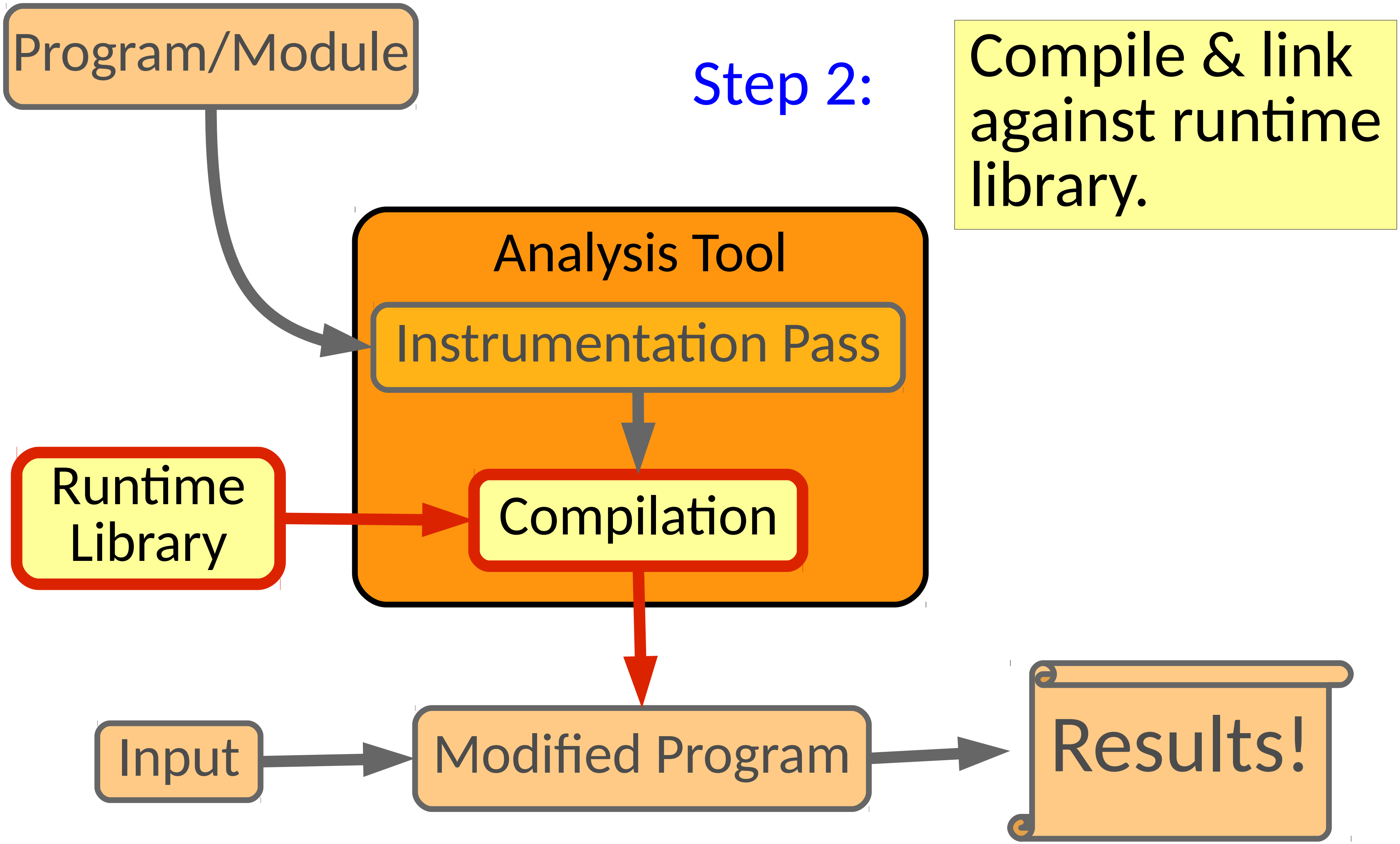
Step 1: Insert useful calls to a runtime library



Dynamic Analysis Big Picture

Step 2:

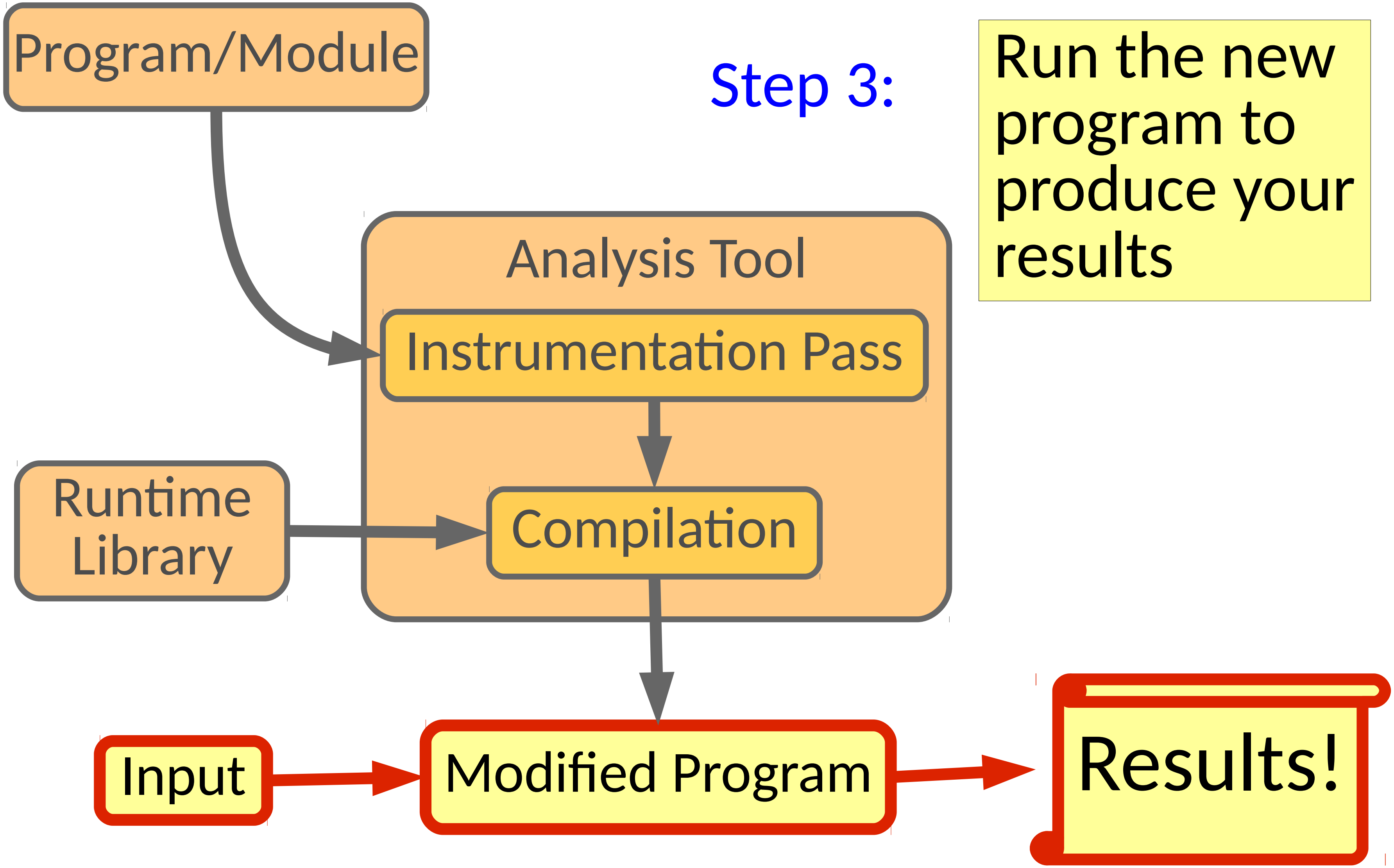
Compile & link against runtime library.



Dynamic Analysis Big Picture

Step 3:

Run the new program to produce your results



Bringing It All Together

LLVM Projects

- LLVM organizes groups of passes and tools into *projects*

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- 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 project description

Extra Tips

- I have a pointer to something. What is it?
  - The getName() method works on most things.
  - You can usually: outs() << x

Extra Tips

- I have a pointer to something. What is it?
  - The getName() method works on most things.
  - You can usually: outs() << x
- Sadly no longer true:

  How do I see the C++ API calls for constructing a module?

  - `llc -march=cpp <bitcode>.bc -o <cppapi>.cpp`