

A Brief Introduction to Using LLVM

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- A set of formats, libraries and tools.
 - A simple, typed IR (*bitcode*)
 - 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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- Analyzing the bitcode:

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- Reporting properties of the program:

[**main**] : [A], [C], [F]

[A] : [B]

[C] : [E], [D]

What is LLVM Bitcode?

- A (Relatively) Simple IR

```
#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;
}
```

Code

**clang -c -emit-llvm
(and llvm-dis)**

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

define void @foo(i32 %e) {
    %1 = icmp eq i32 %e, 0
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    .lr.ph:                                ; preds = %.lr.ph, %0
        %i = phi i32 [ %2, %.lr.ph ], [ 0, %0 ]
        %str1 = getelementptr
                                         [6 x i8]* @str, i64 0, i64 0
        %puts = tail call i32 @puts(i8* %str1)
        %2 = add i32 %i, 1
        %cond = icmp eq i32 %2, %e
        br il %cond, label %.exit, label %.lr.ph

    .exit:                                ; preds = %.lr.ph, %0
        ret void
}

define i32 @main(i32 %argc, i8** %argv) {
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IR

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Functions

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        %puts = tail call i32 @puts(i8* %str1)
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Basic Blocks

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Basic Blocks

labels & predecessors

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Basic Blocks

branches & successors

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        call i32 @puts(i8* %str1)

        %2 = add i32 %i, 1
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Instructions

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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

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

...

Inspecting Bitcode

- 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
 - “Where was this variable defined?”

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- LLVM IR is in SSA form
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 - What does this mean?
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void foo()
  unsigned i = 0;
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    i = i + 1;
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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?

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- Thus the phi instruction
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```
void foo()
  unsigned i = 0;
  while (i < 10) {
    i = i + 1;
  }
```

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

; <label>:1
%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
ret void
}
```

Dealing with SSA

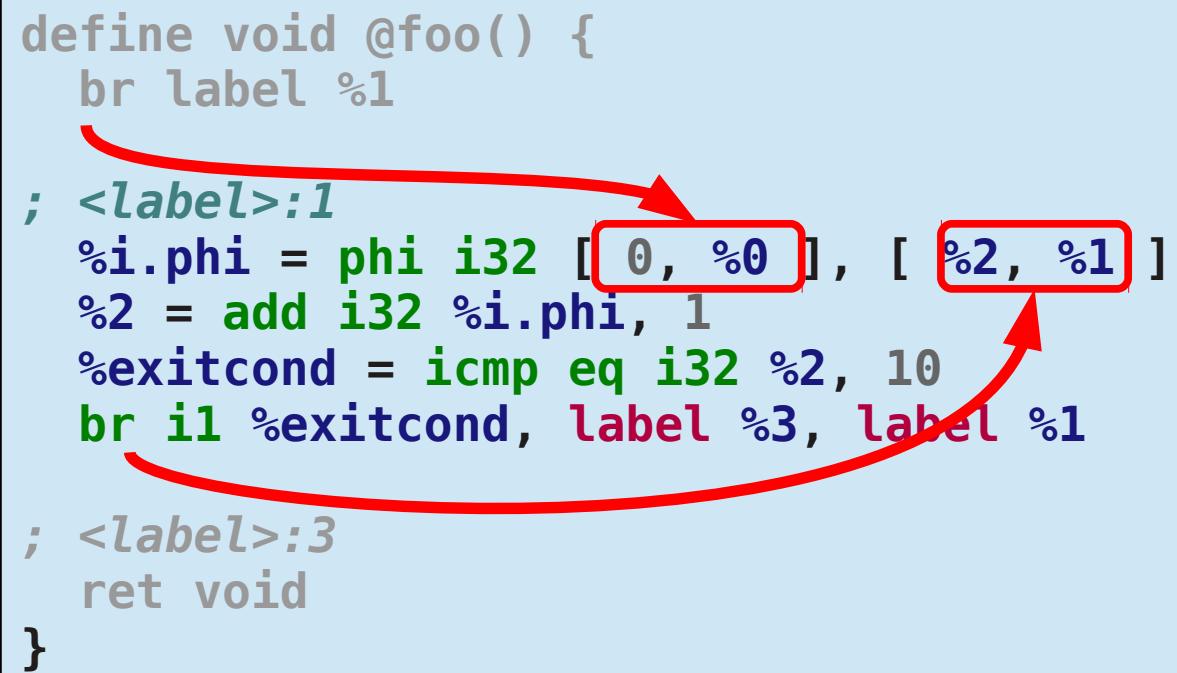
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```

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; <label>:3
  ret void
}
```



Dependencies in General

- You can loop over the values an instruction uses

```
for (auto i = inst->op_begin(), e = inst->op_end(); i != e; ++i) {  
    // inst uses the Value i  
}
```

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for (auto i = inst->op_begin(), e = inst->op_end(); i != e; ++i) {  
    // inst uses the Value i  
}
```

for %a = %b + %c:

[%b, %c]

Dependencies in General

- You can loop over the values an instruction uses

```
for (auto i = inst->op_begin(), e = inst->op_end(); i != e; ++i) {  
    // inst uses the Value i  
}
```

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

```
Instruction *inst = ...;  
for (auto i = inst->use_begin(), e = inst->use_end(); i != e; ++i)  
    if (auto *user = dyn_cast<Instruction>(*i)) {  
        // inst is used by Instruction user  
    }
```

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- LLVM IR is *strongly typed*
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define i64 @trunc(i16 zeroext %a) {  
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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
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```
struct rec {  
    int x;  
    int y;  
};  
  
struct rec *buf;  
  
void foo() {  
    buffer[5].y = 7;  
}
```

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

Dealing with Types: GEP

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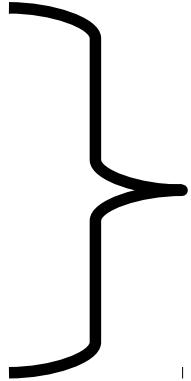
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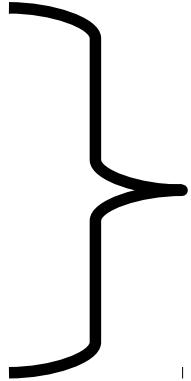
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- The online documentation is extensive:
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- The header files!
 - All in `llvm-3.x.src/include/llvm/`
 - `Function.h`
 - `BasicBlock.h`
 - `Instructions.h`
 - `InstrTypes.h`
 - `Support/CallSite.h`
 - `Support/InstVisitor.h`
 - `Type.h`
 - `DerivedTypes.h`

Making a New Analysis

- Analyses are organized into individual *passes*
 - ModulePass
 - FunctionPass
 - LoopPass
 - ...
- 
- Derive from the appropriate base class to make a Pass

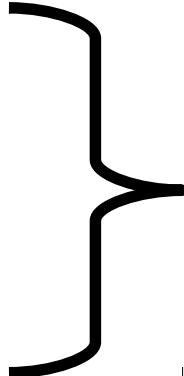
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3 Steps

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

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

Making a ModulePass (1)

- Declare your ModulePass

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

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```

Making a ModulePass (2)

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

```
char CallPrinterPass::ID = 0;  
  
RegisterPass<CallPrinterPass> CallPrinterPassReg("callprinter",  
                                                 "Print the static count of direct calls");
```

Making a ModulePass (3)

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

```
bool  
CallPrinterPass::runOnModule(Module &m) {  
    for (auto &f : m)  
        for (auto &bb : f)  
            for (auto &i : bb)  
                handleInstruction(&i);  
    return false; // False because we didn't change the Module  
}
```

Making a ModulePass (3)

- analysis continued...

```
void
CallPrinterPass::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)

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Making a ModulePass (3)

- Printing out the results

```
void
CallPrinterPass::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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- Easiest way to start is by using their sample project
 - `llvmsrc/projects/sample`
- For the most part, you can follow the directions online & in project description

Notes on Creating Projects

- Posted online, read on your own time:
 - Building
 - Copy the sample project to a new directory <proj>
 - Make another directory for building <projbuild>
 - <proj>/configure --disable-optimized --enable-debugging
–with-clang=/path/to/clang
 - Customizing
 - You build your entire project in <proj>/lib/sample/
 - Delete the existing source and write your module there instead
 - Add these lines to the Makefile in the library directory:

```
LOADABLE_MODULE=1
CPPFLAGS += -std=c++11
```

Extra Tips

- I have a pointer to something. What is it?
 - The getName() method works on most things.
 - You can usually: outs() << X
- How do I see the C++ API calls for constructing a module?
 - llc -march=cpp <bitcode>.bc -o <cppapi>.cpp