Building, Testing and Debugging a Simple out-of-tree LLVM Pass

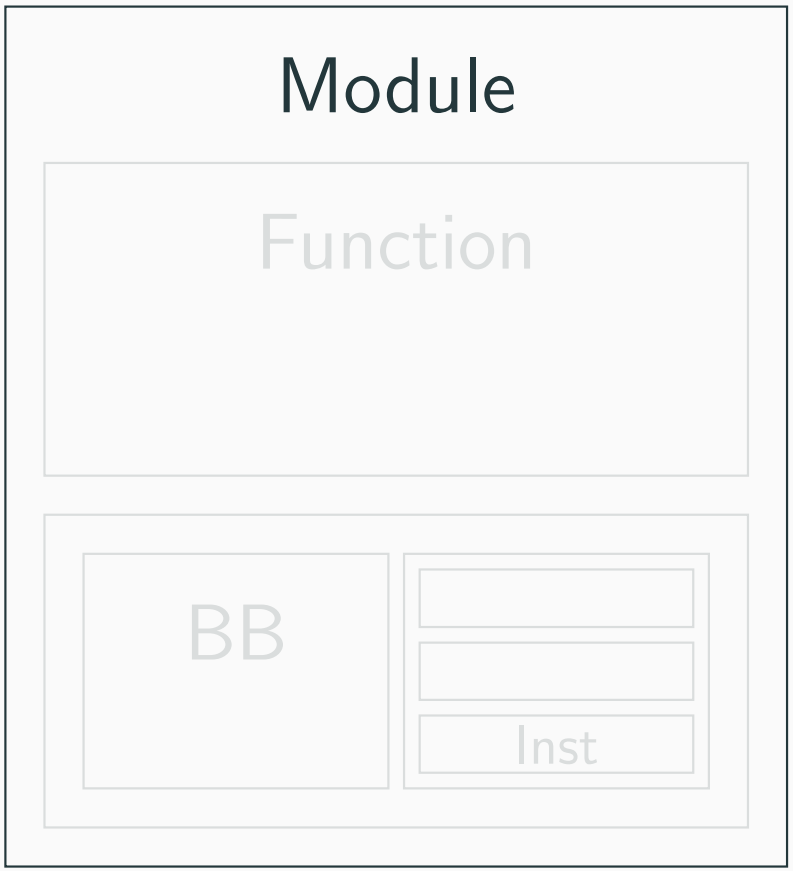
March 17, 2016, LLVM Developers' Meeting

LLVM 3.8 — Resources

`https://github.com/quarkslab/llvm-dev-meeting-tutorial-2015`

the repo actually got updated for this talk, ft. LLVM 3.8

Instruction Booklet



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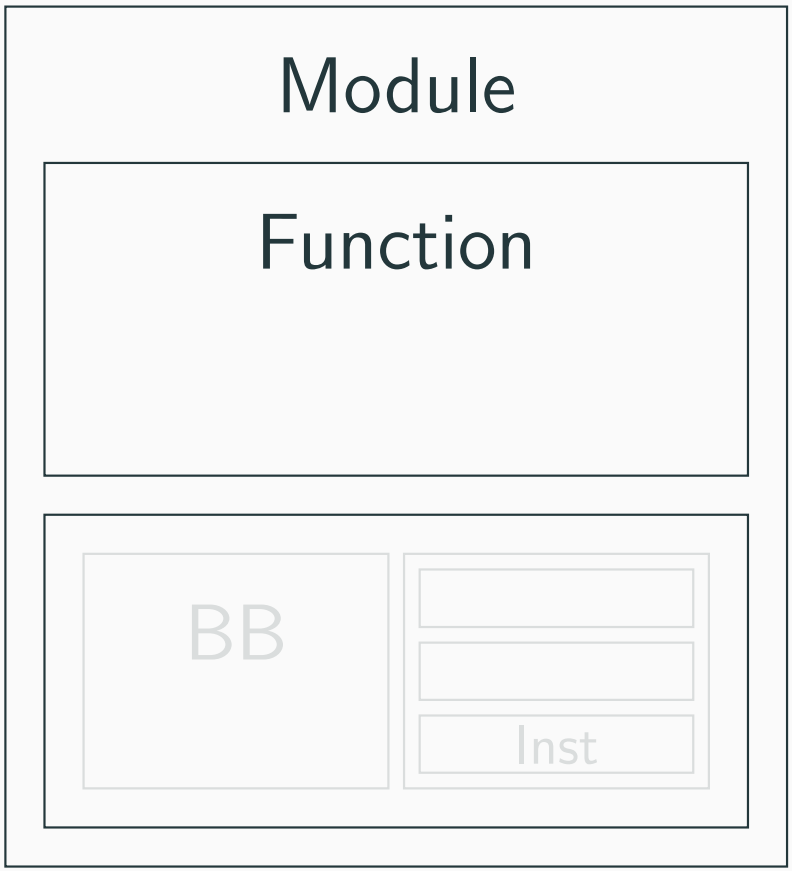

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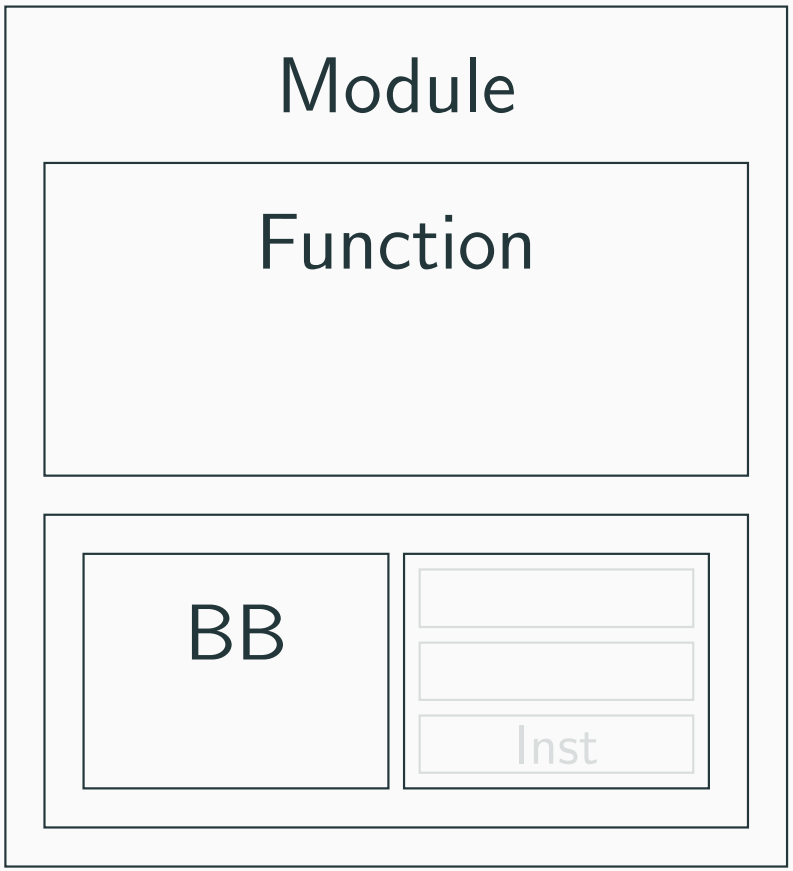

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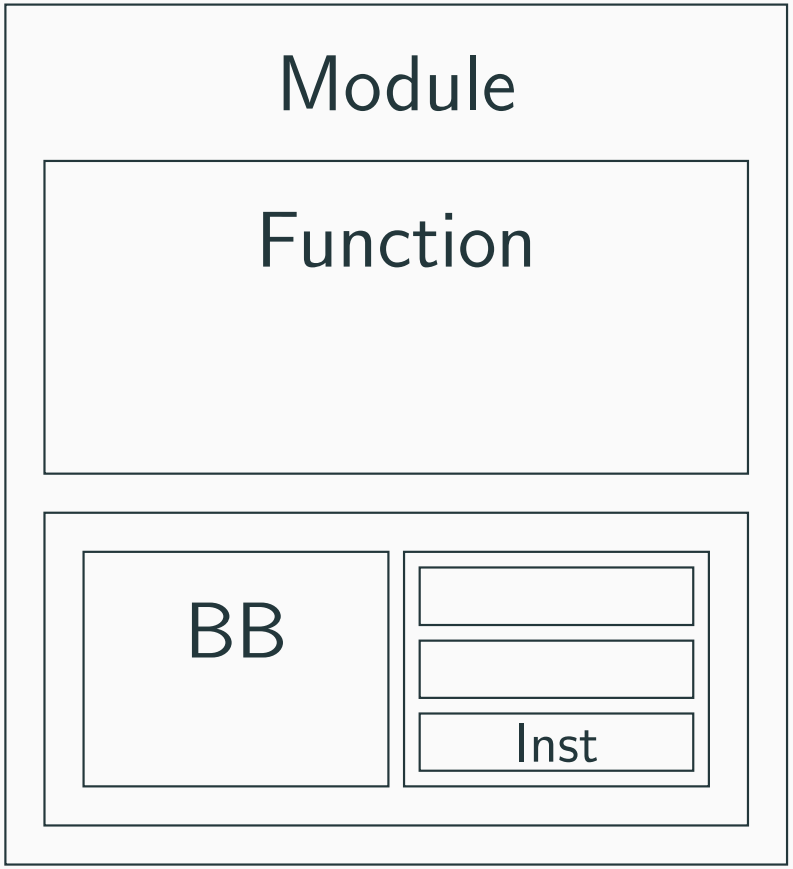

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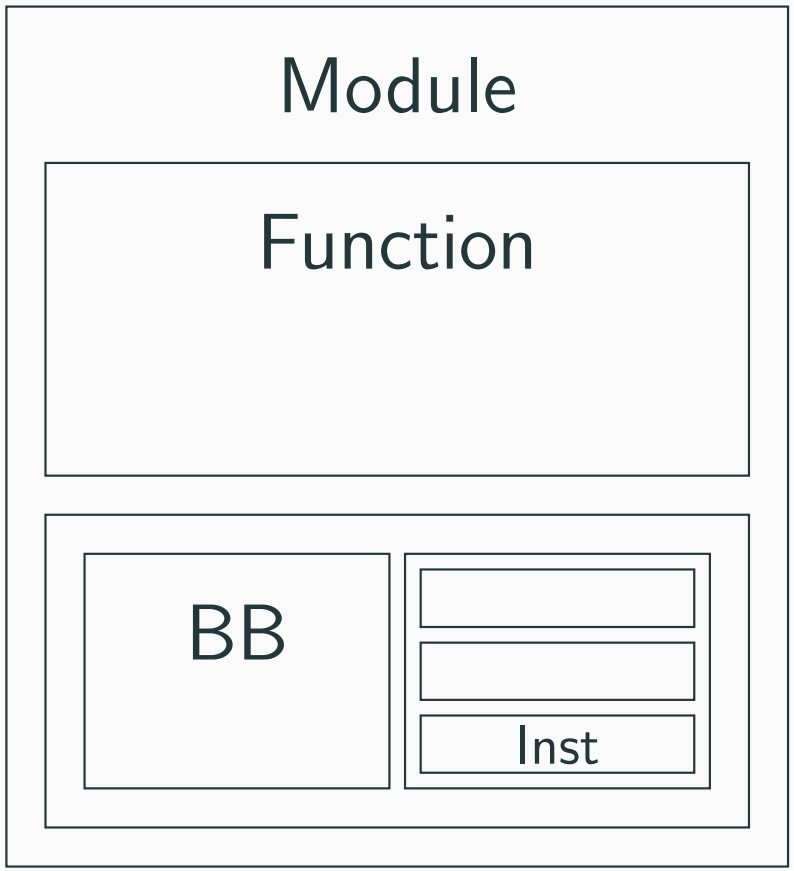

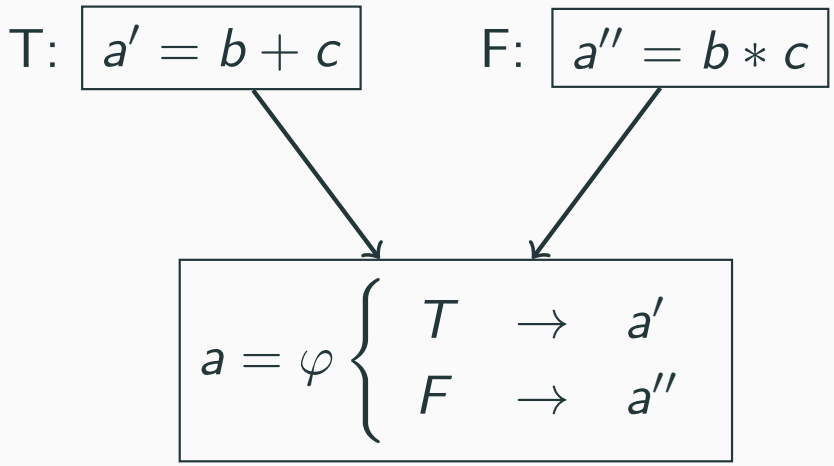

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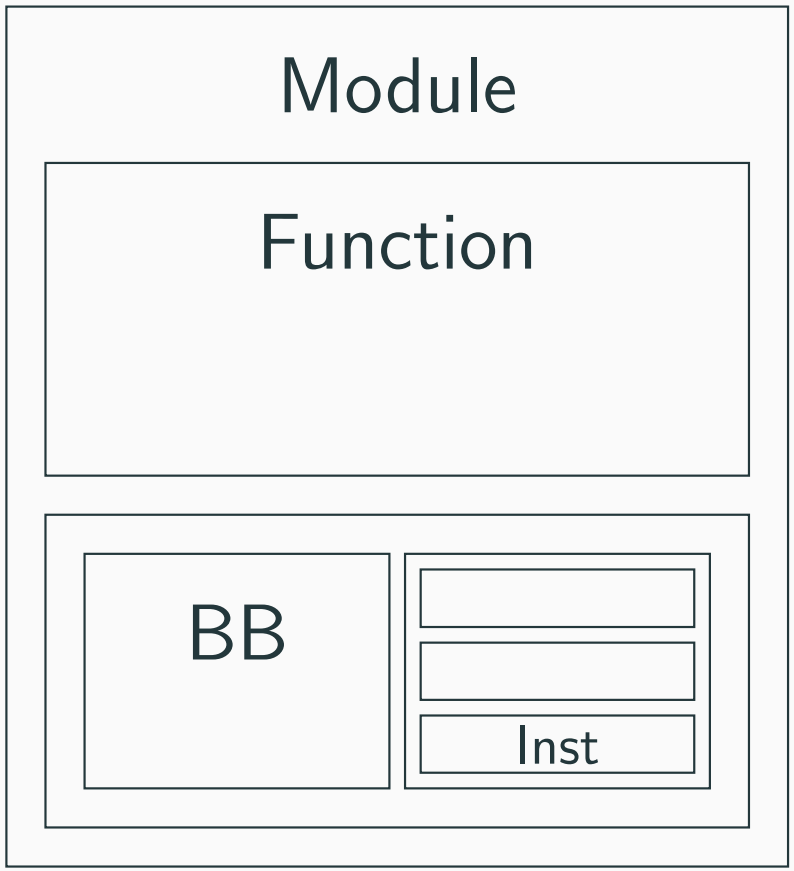
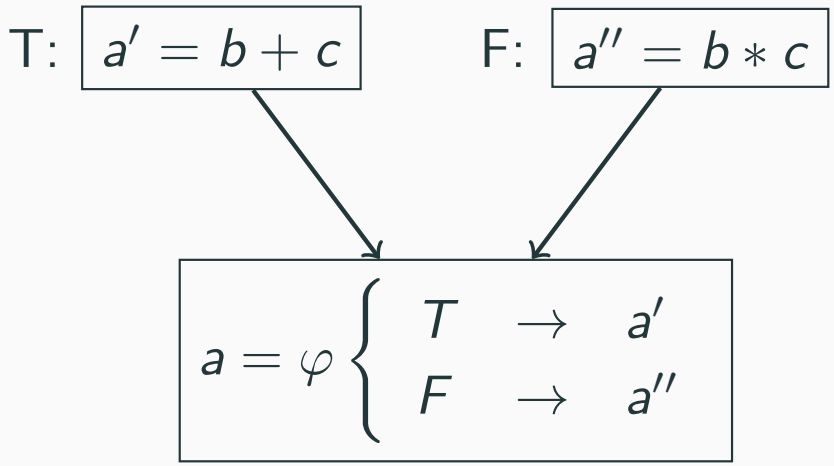




LLVM 3.8 — Tutorial

Press Start Button

LLVM 3.8 — Prerequisite

Please Load LLVM3.8

LLVM 3.8

Select difficulty

> **Easy** <

Hard

Nightmare

Stage Selection

Adding a new Front-End

In-Tree Pass Development

> **Out-of-Tree Pass Development** <

Adding a new Back-End

LLVM 3.8

OS Selection

> **Linux** <

OSX

Windows

Level Up

Stage 1 — Build Setup

Stage 2

Stage 3

Stage 4

stage 1

Goals

- Use LLVM CMake support
- Build a minimal pass

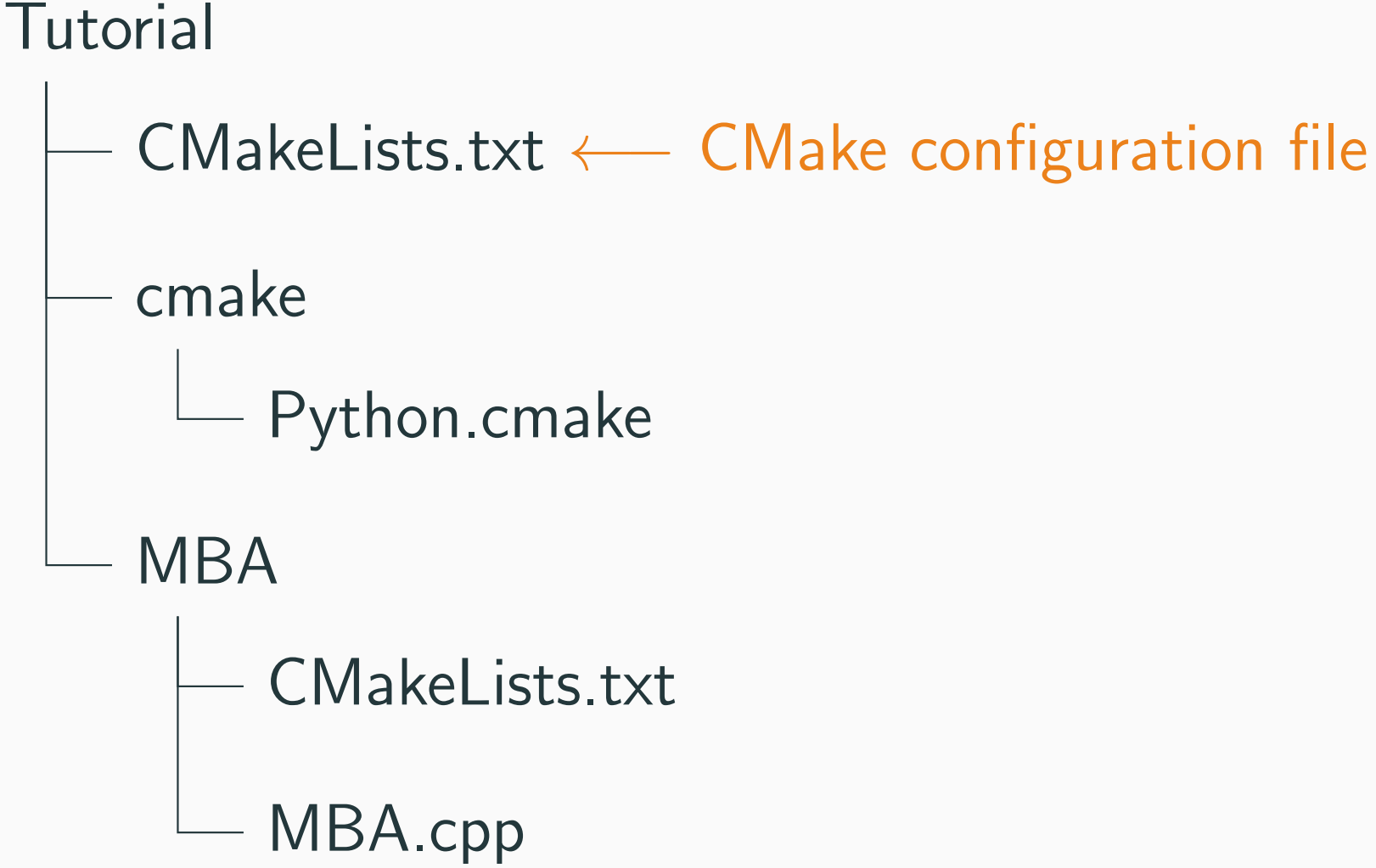
Bonus

- Setup a minimal test driver
- Make the pass compatible with `clang`

stage 1 — Directory Layout

Tutorial
- CMakeLists.txt
- cmake
  - Python.cmake
- MBA
  - CMakeLists.txt
  - MBA.cpp

stage 1 — Directory Layout



stage 1 — Directory Layout

Tutorial
- CMakeLists.txt
- cmake ⟵ CMake auxiliary files
  - Python.cmake
- MBA
  - CMakeLists.txt
  - MBA.cpp

stage 1 — Directory Layout

Tutorial
- CMakeLists.txt
- cmake
  - Python.cmake
- MBA ⟵ Our first pass
  - CMakeLists.txt
  - MBA.cpp

stage 1 — CMakeLists.txt

LLVM Detection

```
set(LLVM_ROOT "" CACHE PATH "Root of LLVM install.")

# A bit of a sanity check:
if(NOT EXISTS ${LLVM_ROOT}/include/llvm )
     message(FATAL_ERROR
               "LLVM_ROOT (${LLVM_ROOT}) is invalid")
endif()
```

stage 1 — CMakeLists.txt

Load LLVM Config

```
list(APPEND CMAKE_PREFIX_PATH
     "${LLVM_ROOT}/share/llvm/cmake")
find_package(LLVM REQUIRED CONFIG)
```

And more LLVM Stuff

```
list(APPEND CMAKE_MODULE_PATH "${LLVM_CMAKE_DIR}")
include(HandleLLVMOptions) # load additional config
include(AddLLVM) # used to add our own modules
```

stage 1 — CMakeLists.txt

Propagate LLVM setup to our project

```
add_definitions(${LLVM_DEFINITIONS})
include_directories(${LLVM_INCLUDE_DIRS})
# See commit r197394, needed by add_llvm_module in llvm
    /CMakeLists.txt *FIXED in 3.8*
#set(LLVM_RUNTIME_OUTPUT_INTDIR "${CMAKE_BINARY_DIR}/
    bin/${CMAKE_CFG_INT_DIR}")
#set(LLVM_LIBRARY_OUTPUT_INTDIR "${CMAKE_BINARY_DIR}/
    lib/${CMAKE_CFG_INT_DIR}")
```

Get Ready!

```
add_subdirectory(MBA)
```

stage 1 — MBA/CMakeLists.txt

Declare a Pass

```
add_llvm_loadable_module(LLVMMBA MBA.cpp)
```

1 Pass = 1 Dynamically Loaded Library

- Passes are loaded by a pass driver: opt

```
% opt -load LLVMMBA.so -mba foo.ll -S
```

- Or by clang (provided an extra setup)

```
% clang -Xclang -load -Xclang LLVMMBA.so foo.c -c
```

stage 1 — MBA.cpp

```
#include "llvm/Pass.h"
#include "llvm/IR/Function.h"
using namespace llvm;
class MBA : public BasicBlockPass {
  MBA() : BasicBlockPass(ID)
  {}
  bool runOnBasicBlock(BasicBlock &BB) override {
    bool modified = false;
    return modified;
  }
};
```

stage 1 — MBA.cpp

Registration Stuff

- Only performs registration for opt use!
- Uses a static constructor...

```
static RegisterPass<MBA>
    X("mba",  // the option name -> -mba
      "Mixed Boolean Arithmetic Substitution", //
         option description
      true, // true as we don't modify the CFG
      false // true if we're writing an analysis
      );
```

stage 1 — Bonus Level

Setup test infrastructure

- Rely on `lit`, LLVM's Integrated Tester
- `% pip install --user lit`

`CMakeLists.txt` update

```
list(APPEND CMAKE_MODULE_PATH "${CMAKE_CURRENT_SOURCE_DIR}/cmake")
include(Python)
find_python_module(lit REQUIRED)
add_custom_target(check
    COMMAND ${PYTHON_EXECUTABLE} -m lit.main
            "${CMAKE_CURRENT_BINARY_DIR}/Tests" -v
    DEPENDS LLVMMBA LLVMReachableIntegerValues LLVMDuplicateBB
)
```

stage 1 — Bonus Level

Make the pass usable from `clang`

- Automatically loaded in `clang`'s optimization flow:

  `clang -Xclang -load -Xclang`

- Several extension points exist

```
#include "llvm/IR/LegacyPassManager.h"
#include "llvm/Transforms/IPO/PassManagerBuilder.h"

static void registerClangPass(const PassManagerBuilder &,
                              legacy::PassManagerBase &PM)
{ PM.add(new MBA()); }
static RegisterStandardPasses RegisterClangPass
    (PassManagerBuilder::EP_EarlyAsPossible, registerClangPass);
```

Level Up

Stage 1

Stage 2 — Simple Pass

Stage 3

Stage 4

stage 2

Goals

- Learn basic LLVM IR manipulations
- Write a simple test case

Bonus

- Collect statistics on your pass
- Collect debug informations on your pass

stage 2 — MBA

Simple Instruction Substitution

Turns: $a + b$

Into: $(a \oplus b) + 2 \times (a \wedge b)$

Context

$\Rightarrow$ Useful for code obfuscation

stage 2 — runOnBasicBlock++

- Iterate over a BasicBlock
- Use LLVM's dyn_cast to check the instruction kind

```
for (auto IIT = BB.begin(), IE = BB.end(); IIT !=
    IE; ++IIT) {
  Instruction &Inst = *IIT;
  auto *BinOp = dyn_cast<BinaryOperator>(&Inst);
  if (!BinOp)
    continue;
  unsigned Opcode = BinOp->getOpcode();
  if (Opcode != Instruction::Add || !BinOp->getType
      ()->isIntegerTy())
```

stage 2 — `runOnBasicBlock++`

LLVM Instruction creation/insertion:

- Use `IRBuilder` from `llvm/IR/IRBuilder.h`
- Creates $(a \oplus b) + 2 \times (a \wedge b)$

```
IRBuilder<> Builder(BinOp);
Value *NewValue = Builder.CreateAdd(
  Builder.CreateXor(BinOp->getOperand(0),
                    BinOp->getOperand(1)),
  Builder.CreateMul(
    ConstantInt::get(BinOp->getType(), 2),
    Builder.CreateAnd(
      BinOp->getOperand(0),
      BinOp->getOperand(1)))
);
```

stage 2 — `runOnBasicBlock++`

Instruction substitution:

- Use `llvm::ReplaceInstWithValue` that does the job for you (need to be careful on iterator validity)

```
ReplaceInstWithValue(BB.getInstList(),
                     IIT, NewValue);
```

stage 2 — Write a simple test

`lit` principles

- One source file (say `.c` or `.ll`) per test case
- Use comments to describe the test
- Use substitution for test configuration

`FileCheck` — `grep` **on steroids!**

- Compares `argv[1]` and `stdin`
- Reads check**s** from comments in `argv[1]`

$\Rightarrow$ Requires LLVM with `-DLLVM_INSTALL_UTILS`

stage 2 — Tests

```
// RUN: clang %s -O2 -S -emit-llvm -o %t.ll
// RUN: opt -load %bindir/MBA/LLVMMBA${MOD_EXT} -mba %t
    .ll -S -o %t0.ll
// RUN: FileCheck %s < %t0.ll
// RUN: clang %t0.ll -o %t0
// RUN: %t0 -42 42
#include <stdio.h>
#include <stdlib.h>
int main(int argc, char * argv[]) {
  if(argc != 3)
    return 1;
  int a = atoi(argv[1]),
      b = atoi(argv[2]);
// CHECK: and
  return a + b;
}
```

stage 2 — More tests

```
; RUN: opt -load %bindir/MBA/LLVMMBA${MOD_EXT} -mba -mba-ratio=1 %s
    -S | FileCheck -check-prefix=CHECK-ON %s
; RUN: opt -load %bindir/MBA/LLVMMBA${MOD_EXT} -mba -mba-ratio=0 %s
    -S | FileCheck -check-prefix=CHECK-OFF %s

; CHECK-LABEL: @foo(
define i32 @foo(i32 %i, i32 %j) {

...

; CHECK-ON: mul
; CHECK-OFF-NOT: mul
  %add = add i32 %i.addr.0, %j

...

}
```

stage 2 — Bonus

How many substitutions have we done?

```
#include "llvm/ADT/Statistic.h"
STATISTIC(MBACount, "The # of substituted instructions"
    );

...

 ++MBACount;
```

Collect them!

```
% opt -load LLVMMBA.so -mba -stats ...
```

stage 2 — Bonus

DEBUG() and DEBUG_TYPE

Setup a guard:

```
#define DEBUG_TYPE "mba"
#include "llvm/Support/Debug.h"
```

Add a trace:

```
DEBUG(dbgs() << *BinOp << " -> " << *NewValue << "\n");
```

Collect the trace

```
% opt -O2 -mba -debug ... # verbose
% opt -O2 -mba -debug-only=mba ... # selective
```

Level Up

Stage 1

Stage 2

Stage 3 — Analyse

Stage 4

stage 3

Goals

- Use Dominator trees
- Write a `llvm::FunctionPass`
- Describe dependencies

Bonus

- Follow LLVM's guidelines

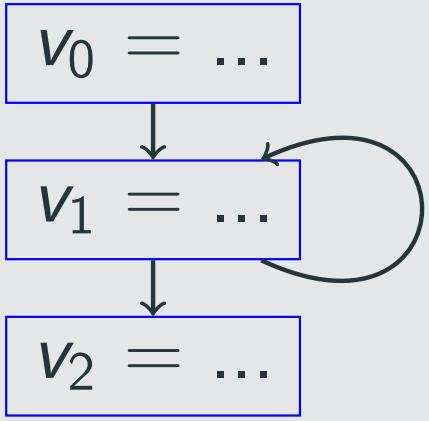
stage 3 — ReachableIntegerValues

Simple Module Analyse

Create a mapping between a `BasicBlock` and a set of `Values` that can be used in this block.

Algorithm

V = Visible values, D = Defined Values



$$V = \varnothing, D = \{v_0\}$$

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stage 3 — ReachableIntegerValues

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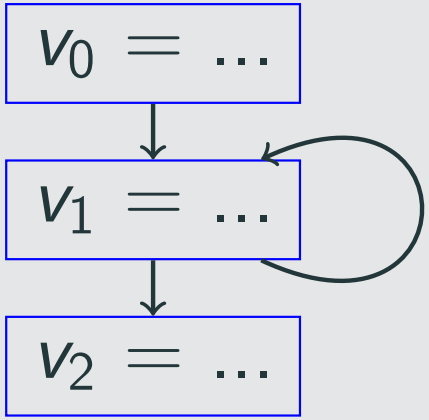

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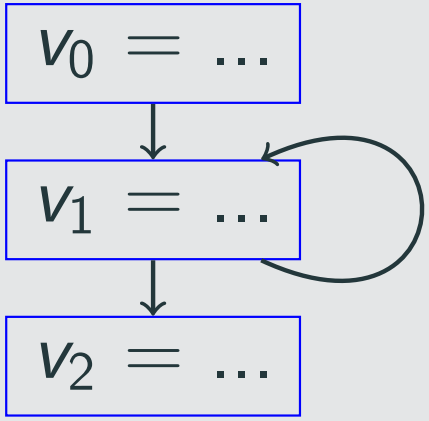

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stage 3 — ReachableIntegerValues

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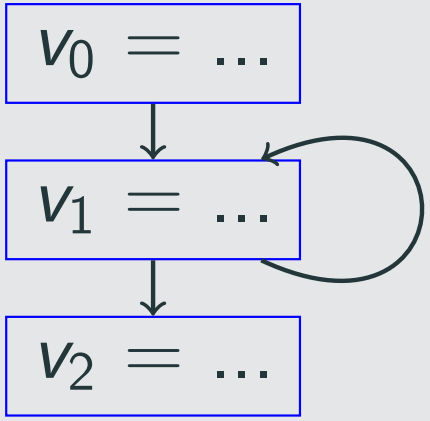

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stage 3 — Building an Analysis

Pass Registration

```
static RegisterPass<ReachableIntegerValuesPass>
    X("reachable-integer-values",          // pass option
      "Compute Reachable Integer values", // pass description
      true, // does not modify the CFG
      true  // and it's an analysis
      );
```

CMakeLists.txt

```
add_llvm_loadable_module(LLVMReachableIntegerValues
   ReachableIntegerValues.cpp)
```

stage 3 — Analysis

- Need to export the class declaration in a header
- Need to load the analysis in opt explicitly
- Result of the analysis stored as a member variable

API

```
void getAnalysisUsage(llvm::AnalysisUsage &Info)
    const override;
bool runOnFunction(llvm::Function &) override;
ReachableIntegerValuesMapTy const &
    getReachableIntegerValuesMap() const;
void print(llvm::raw_ostream &O, llvm::Module const
    *) const override;
```

stage 3 — Make Result Available

Dependency Processing

1. PM runs each required analysis (if not cached)
2. PM runs the Pass entry point
3. The Pass calls `getAnalysis<...>` to access the instance

stage 3 — Declare Dependencies

Dependency on DominatorTree

```
void ReachableIntegerValuesPass::getAnalysisUsage(
    AnalysisUsage &Info) const {
  Info.addRequired<DominatorTreeWrapperPass>();
  Info.setPreservesAll();
}
```

stage 3 — runOnFunction

Entry Point

```
bool ReachableIntegerValuesPass::runOnFunction(Function
    &F) {
  ReachableIntegerValuesMap.clear();

  //...init stuff

  auto *Root =
      getAnalysis<DominatorTreeWrapperPass>().
          getDomTree().getRootNode();

  //...fill the map

  return false;
}
```

stage 3 — print

Usage

```
> opt test.ll -load lib/LLVMReachableIntegerValues.so \
    -analyze -reachable-integer-values
```

Implementation

```
void ReachableIntegerValuesPass::print(raw_ostream &O,
    Module const*) const {
  for(auto const& KV: ReachableIntegerValuesMap) {
    O << "BB " << KV.first << '\n';
    for(auto const& IntegerValue : KV.second)
      O << "    " << *IntegerValue << '\n';
  }
}
```

stage 3 — Bonus

Optional: You're working out-of-tree.

But...

- Provides a common reference
- Helps for visual consistency

```
% find . \( -name '*.cpp' -o -name '*.h' \) \
    -exec clang-format-3.8 -i {} \;
```

http://llvm.org/docs/CodingStandards.html

Level Up

Stage 1

Stage 2

Stage 3

Stage 4 — Complex Pass

stage 4

Goals

- Use φ nodes
- Modify the Control Flow Graph (CFG)

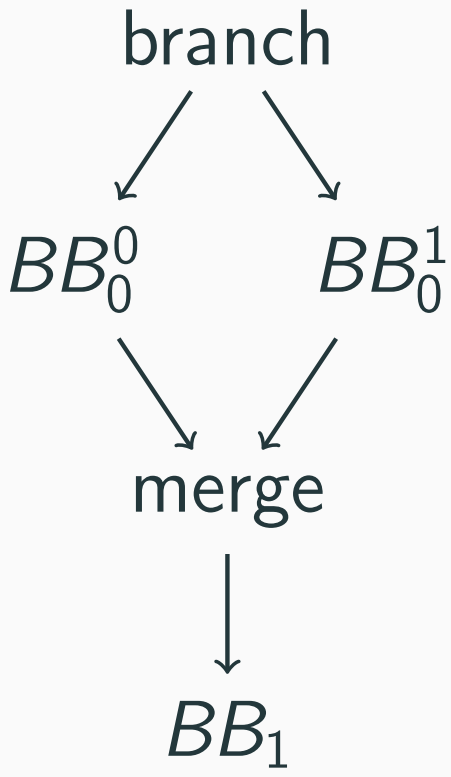
Bonus

- Declare extra options
- Fuzz your passes
- Add a support library

stage 4 — Duplicate Basic Blocks

Before

After



stage 4 — Problems

- Cloning `BasicBlocks` and iterating over a function loops
- Cloning an instruction creates a new `Value`
- Cloning several instructions requires a remapping

stage 4 — Forge a Random Branch

Get analysis result

```
auto const &RIV = getAnalysis<ReachableIntegerValuesPass>()
                      .getReachableIntegerValuesMap();
```

Pick a random reachable value

```
std::uniform_int_distribution<size_t> Dist(0, ReachableValuesCount-1)
auto Iter = ReachableValues.begin();
std::advance(Iter, Dist(RNG));
```

Random condition

```
Value *Cond = Builder.CreateIsNull(
    ReMapper.count(ContextValue) ?
    ReMapper[ContextValue] :
    ContextValue);
```

stage 4 — Messing with Clones

Cloning an instruction

```
Instruction *ThenClone = Instr.clone(),
            *ElseClone = Instr.clone();
```

Remap operands

```
RemapInstruction(ThenClone, ThenVMap, RF_IgnoreMissingEntries);
```

Manual φ creation

```
PHINode *Phi = PHINode::Create(ThenClone->getType(), 2);
Phi->addIncoming(ThenClone, ThenTerm->getParent());
Phi->addIncoming(ElseClone, ElseTerm->getParent());
```

stage 4 — Bonus

Using `csmith`

1. Pick `http://embed.cs.utah.edu/csmith/`
2. Write a configuration file, e.g. `fuzz.cfg`:

```
clang -O2
clang -O2 -Xclang -load -Xclang LLVMDuplicateBB.so
```

3. Run generation!

```
% CSMITH_HOME=$PWD ./scripts/compiler_test.pl 1000 fuzz.cfg
```

stage 4 — Bonus

Control the obfuscation ratio

```
static llvm::cl::opt<Ratio> DuplicateBBRatio{
    "duplicate-bb-ratio",
    llvm::cl::desc("Only apply the duplicate basic block "
                   "pass on <ratio> of the basic blocks"),
    llvm::cl::value_desc("ratio"),
    llvm::cl::init(1.),
    llvm::cl::Optional
};
```

⇒ Need to specialize `llvm:cl` for the `Ratio` class.

stage 4 — Bonus

CMakeLists.txt

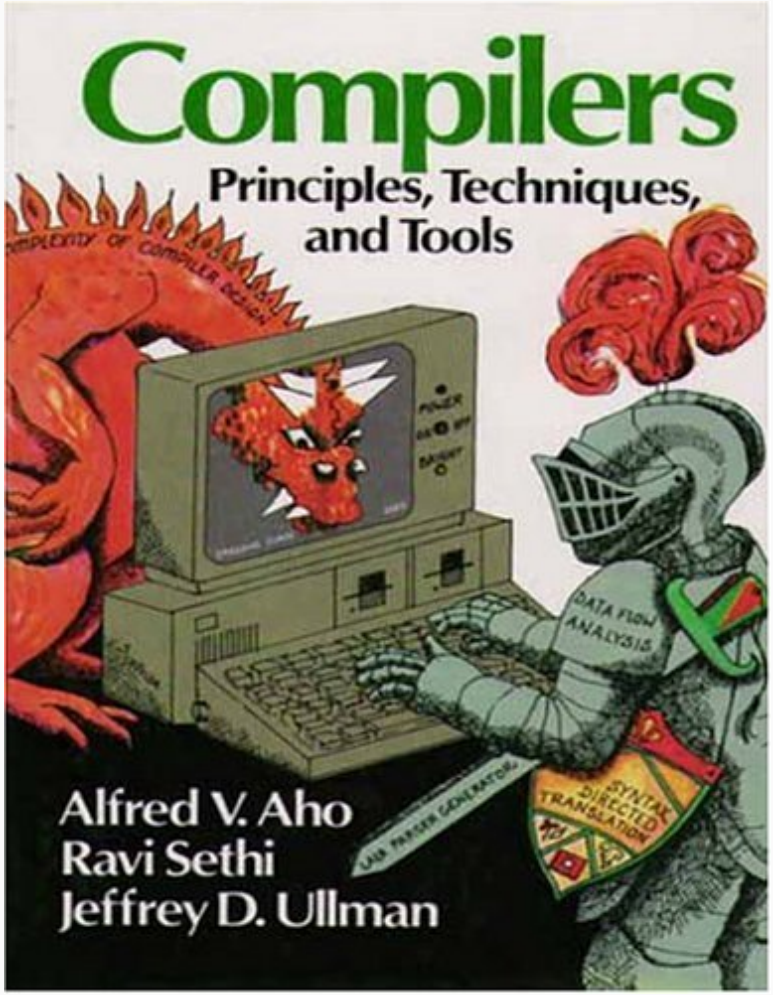
```
target_link_libraries(LLVMDuplicateBB Utils)
```

Specialize `llvm::cl::parser`

```
namespace llvm {
namespace cl {

template <> class parser<Ratio> : public basic_parser<Ratio> {
```

Final Boss


Compilers
Principles, Techniques, and Tools
DATA FLOW ANALYSIS
SYNTAX DIRECTED TRANSLATION
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Final Boss


DRAGON PUNCH
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GAME OVER

Creditz

Serge Guelton <sguelton@quarkslab.com>

Adrien Guinet <aguinet@quarkslab.com>

https://github.com/quarkslab/
llvm-dev-meeting-tutorial-2015

Insert Coins

Exit

> Play Again <