An introduction to LLVM

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Quarkslab

LLVM is not (just) a Compiler!

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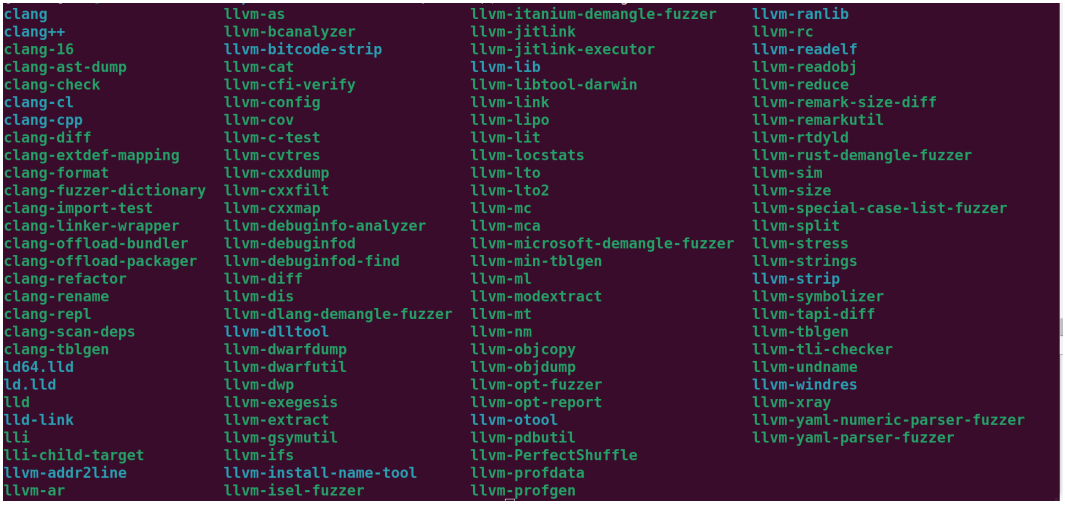
ls 'llvm/build/bin'



A *de facto* standard compiler infrastructure

The LLVM Project is a collection of **modular** *and* **reusable compiler** *and* **toolchain** *technologies.*

(llvm.org)

Main sub-projects:

- The **LLVM Core** library
- **Clang**
- **LLDB**
- **LLD**
- **libc**, **libc++** and **libc++ ABI**
- **compiler-rt**
- **MLIR**
- ...

Building compilers with LLVM

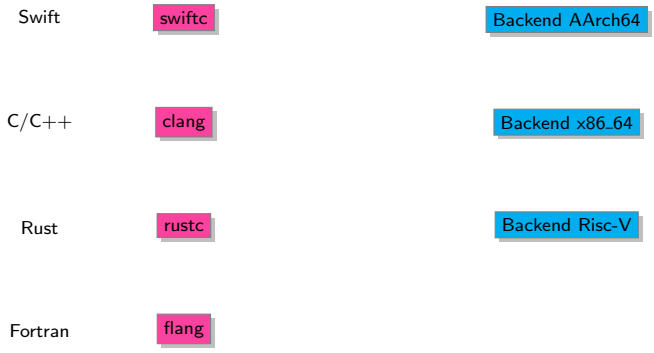
Swift

C/C++

Rust

Fortran

Building compilers with LLVM



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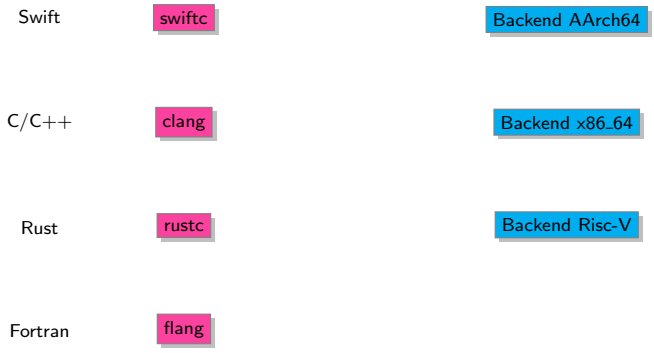

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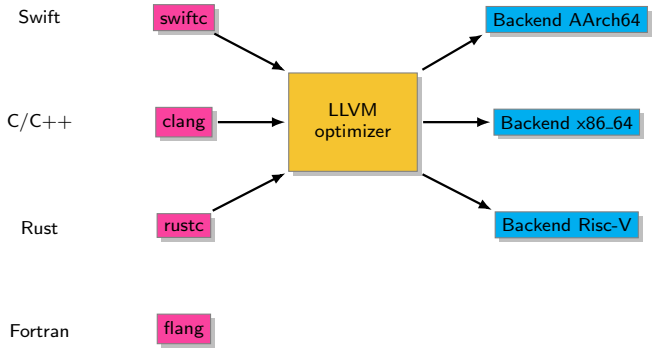
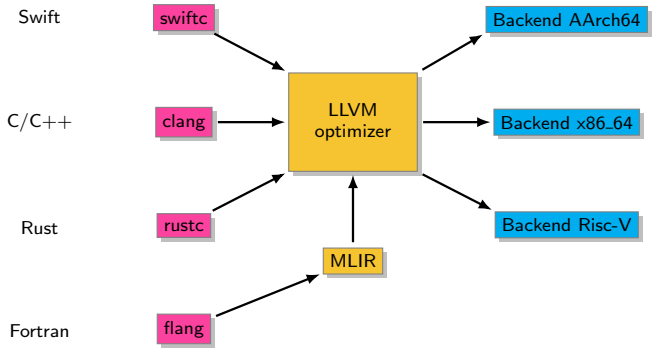
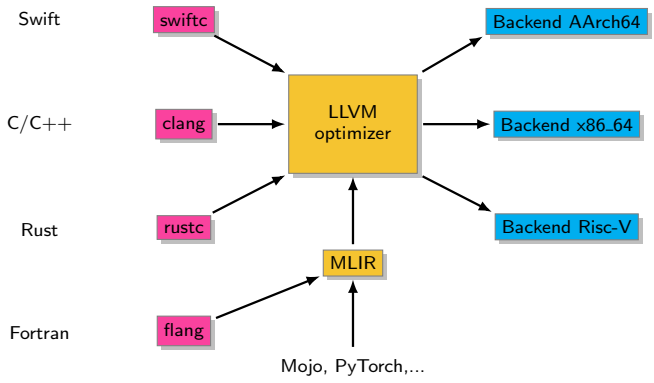


Building compilers with LLVM



Building compilers with LLVM



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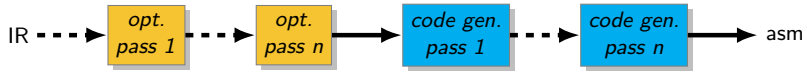
The LLVM Optimizer



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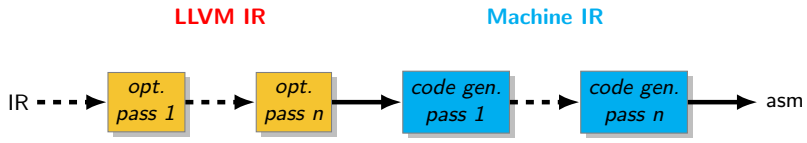

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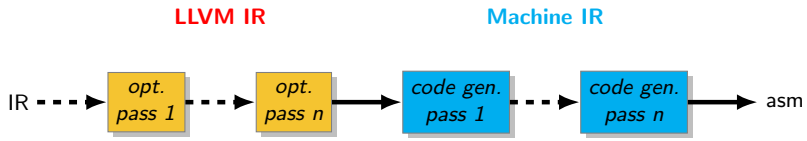

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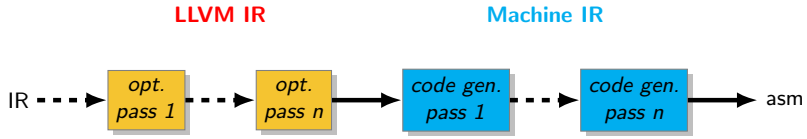

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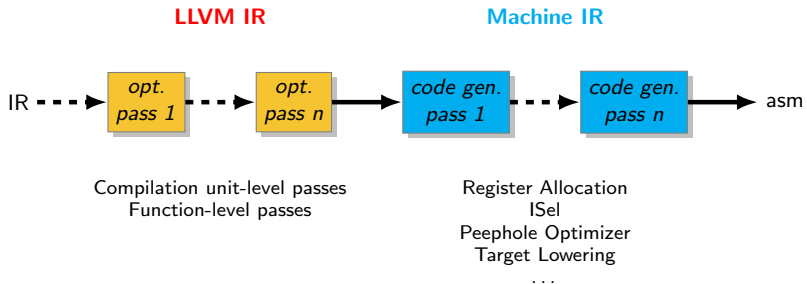

- Pre-defined pass pipelines: '-O0', '-O1', '-O2', '-O3', '-Os', '-Oz'
- Passes can be modified by options
- Passes can be added to the pipelines with options
- Pass scheduling handled by pass managers

https://llvm.org/docs/Passes.html
https://llvm.org/doxygen/PassBuilderPipelines_8cpp_source.html
https://llvm.org/docs/WritingAnLLVMBackend.html

PassBuilderPipelines.cpp: A perpetual WIP

```
1  // TODO: Investigate the cost/benefit of tail call elimination on debugging.
2  FunctionPassManager
3  PassBuilder::buildO1FunctionSimplificationPipeline(OptimizationLevel Level,
4                                                      ThinOrFullLTOPhase Phase) {
5
6    FunctionPassManager FPM;
7
8    ...
9
10   // TODO: Investigate promotion cap for O1.
11   LPM1.addPass(LICMPass(PTO.LicmMssaOptCap, PTO.LicmMssaNoAccForPromotionCap,
12                         /*AllowSpeculation=*/false));
13
14   // Sparse conditional constant propagation.
15   // FIXME: It isn't clear why we do this *after* loop passes rather than
16   // before...
17   FPM.addPass(SCCPPass());
18
19   ...
20
21   // Finally, do an expensive DCE pass to catch all the dead code exposed by
22   // the simplifications and basic cleanup after all the simplifications.
23   // TODO: Investigate if this is too expensive.
24   FPM.addPass(ADCEPass());
25
26   ...
```

Compilation unit-level transformations

Interprocedural transformations

- Call Graph modifications
- Inlining, outlining, cloning, merging functions, global dce,...

Global variable modifications

- GlobalOpt, ConstantMerge, GlobalDCE,...

Function-level transformations

- Constant propagation, Common subexpressions elimination, loop transformations, ...
- Requires instructions to be moved relative to one another
- respecting their dependencies :
  - **spatial**
    (am I referencing the same memory area or register?)
  - **temporal**
    (is this store executed before this load?)

```
1        a = ...;
2        ... = a;
3        a = ...;
```

LLVM provides this information in various ways:

- its **internal representation** (LLVM IR)
  - Basic blocks and CFG
  - SSA form
    transforms register dependencies into value chains (use-defs chains)
    beware: does not represent memory dependencies!
- **analyses** that transformation passes can request/query
  - AliasAnalysis (AA)
  - MemorySSA
  - ...

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The LLVM Internal Representation

A **language**:

- assembly-like
- generic though very C-oriented
  - goal: represent *all* high-level languages
- strongly typed
  - except for pointers...
- in SSA form
- 3 forms:
  - in-memory
  - human readable (`.ll` files)
  - on-disk bitcode (`.bc` files)

See https://llvm.org/docs/LangRef.html for full description

Main syntax elements

Module

- compilation unit
- contains global variables and functions
- metadata

Functions

- arguments
- list of Basic Blocks

Basic Blocks

- consecutive instructions
- a terminator (branch instruction, return, invoke,...)
- successors, predecessors

Instructions

- operators, calls, return, branching, select,...
- PHINode
- **!!! no assignment !!!**

My first function: types, instructions, values

```
1  int foo(int a, int b) {
2    return a + b;
3  }
```

Simplified llvm-ir:

```
1 define i32 @foo(i32 noundef %a, i32 noundef %b) {
2   %c = add nsw i32 %b, %a
3   ret i32 %c
4 }
```

```
$ clang-18 -O3 add.c -S -emit-llvm fno-discard-value-names -o -
```

```
; ModuleID = 'add.c'
source_filename = "add.c"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-i128:128-f80:128-n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"

; Function Attrs: mustprogress nofree norecurse nosync nounwind willreturn memory(none) uwtable
define dso_local i32 @foo(i32 noundef %0, i32 noundef %1) local_unnamed_addr #0 {
  %3 = add nsw i32 %1, %0
  ret i32 %3
}

attributes #0 = { mustprogress nofree norecurse nosync nounwind willreturn memory(none) uwtable "min-legal-vector-width"="0" "no-trapping-math"="true" "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3}
!llvm.ident = !{!4}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
!4 = !{!"Ubuntu clang version 18.1.3 (1ubuntu1)"}
```

```
$ clang-18 -O0 add.c -S -emit-llvm fno-discard-value-names -o -
```

```
; ModuleID = 'add.c'
source_filename = "add.c"
target datalayout = "e-m:e-p270:32:32-p271:32:32-p272:64:64-i64:64-i128:128-f80:128-n8:16:32:64-S128"
target triple = "x86_64-pc-linux-gnu"

; Function Attrs: noinline nounwind optnone uwtable
define dso_local i32 @foo(i32 noundef %0, i32 noundef %1) #0 {
  %3 = alloca i32, align 4
  %4 = alloca i32, align 4
  store i32 %0, ptr %3, align 4
  store i32 %1, ptr %4, align 4
  %5 = load i32, ptr %3, align 4
  %6 = load i32, ptr %4, align 4
  %7 = add nsw i32 %5, %6
  ret i32 %7
}

attributes #0 = { noinline nounwind optnone uwtable "frame-pointer"="all" "min-legal-vector-width"="0" "no-trapping-math"="true" "stack-protector-buffer-size"="8" "target-cpu"="x86-64" "target-features"="+cmov,+cx8,+fxsr,+mmx,+sse,+sse2,+x87" "tune-cpu"="generic" }

!llvm.module.flags = !{!0, !1, !2, !3, !4}
!llvm.ident = !{!5}

!0 = !{i32 1, !"wchar_size", i32 4}
!1 = !{i32 8, !"PIC Level", i32 2}
!2 = !{i32 7, !"PIE Level", i32 2}
!3 = !{i32 7, !"uwtable", i32 2}
```

Control flow: basic blocks, branches, predecessors, successors

```
1  extern void bar(int a);
2  extern void foo(int a);
3
4  void foobar(int a, int b,
5              int cond) {
6    if (a)
7      bar(a);
8    else
9      foo(b);
10 }
```

Control flow: basic blocks, branches, predecessors, successors

```c
extern void bar(int a);
extern void foo(int a);

void foobar(int a, int b,
            int cond) {
  if (a)
    bar(a);
  else
    foo(b);
}
```

```llvm
define void @foobar(i32 %a, i32 %b, i32 %cond) {

entry:
  %tobool.not = icmp eq i32 %a, 0
  br i1 %tobool.not, label %if.else, label %if.then

if.then:                ; preds = %entry

  tail call void @bar(i32 %a) #2
  br label %if.end

if.else:                ; preds = %entry

  tail call void @foo(i32 %b) #2
  br label %if.end

if.end:                 ; preds = %if.else, %if.then

  ret void
}
```

SSA: Static Single Assignment form

```
1  extern int foo(int in);
2  extern int bar(int in);
3
4  int foo_or_bar(int a,
5                 int cond){
6    if (cond) {
7      a = foo(a);
8    } else {
9      a = bar(a);
10   }
11   return a;
12 }
```

SSA: Static Single Assignment form

```
1  extern int foo(int in);
2  extern int bar(int in);
3
4  int foo_or_bar(int a,
5                 int cond){
6    if (cond) {
7      a = foo(a);
8    } else {
9      a = bar(a);
10   }
11   return a;
12 }
```

```
1  define i32 @foo_or_bar(i32 %a, i32 %cond) {
2  entry:
3    %res_cond = icmp eq i32 %cond, 0
4    br i1 %res_cond, label %then, label %else
5
6  then:                             ; preds = %entry
7
8    %a  = tail call i32 @foo(i32 %a) #2
9    br label %return
10
11 else:                             ; preds = %entry
12
13   %a  = tail call i32 @bar(i32 %a) #2
14   br label %return
15
16 return:                           ; preds = %then, %else
17
18
19   ret i32 %a
20 }
```

SSA: Static Single Assignment form

```
1  extern int foo(int in);
2  extern int bar(int in);
3
4  int foo_or_bar(int a,
5                 int cond){
6    if (cond) {
7      a = foo(a);
8    } else {
9      a = bar(a);
10   }
11   return a;
12 }
```

```
1  define i32 @foo_or_bar(i32 %a, i32 %cond) {
2  entry:
3    %res_cond = icmp eq i32 %cond, 0
4    br i1 %res_cond, label %then, label %else
5
6  then:                                ; preds = %entry
7
8    %a1 = tail call i32 @foo(i32 %a) #2
9    br label %return
10
11 else:                                ; preds = %entry
12
13   %a2 = tail call i32 @bar(i32 %a) #2
14   br label %return
15
16 return:                              ; preds = %then, %else
17
18   %a3 = phi i32 [ %a1, %then ], [ %a2, %else ]
19   ret i32 %a3
20 }
```

for loops

```
1  void loop(int* a, unsigned int n) {
2    for (int i = 0; i<n; ++i) {
3      a[i] = i;
4    }
5  }
```

for loops

```
$ clang-18 -O1 loop.c -S -emit-llvm -o - -fno-discard-value-names
```

```
define void @loop(ptr %a, i32 %n) {
entry:
  %cmp4.not = icmp eq i32 %n, 0
  br i1 %cmp4.not, label %for.cond.cleanup, label %for.body.preheader

for.body.preheader:                               ; preds = %entry
  %wide.trip.count = zext i32 %n to i64
  br label %for.body

for.cond.cleanup:                                 ; preds = %for.body, %entry
  ret void

for.body:                                         ; preds = %for.body.preheader, %for.body
  %indvars.iv = phi i64 [ 0, %for.body.preheader ],
                        [ %indvars.iv.next, %for.body ]
  %arrayidx = getelementptr inbounds i32, ptr %a, i64 %indvars.iv
  %0 = trunc i64 %indvars.iv to i32
  store i32 %0, ptr %arrayidx, align 4, !tbaa !5
  %indvars.iv.next = add nuw nsw i64 %indvars.iv, 1
  %exitcond.not = icmp eq i64 %indvars.iv.next, %wide.trip.count
  br i1 %exitcond.not, label %for.cond.cleanup, label %for.body, !llvm.loop !9
}
```

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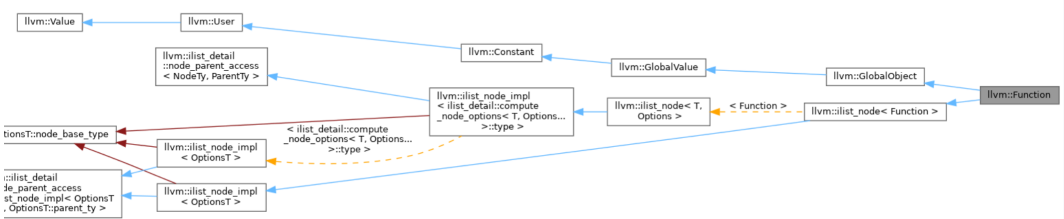
In memory LLVM Intermediate Representation (IR)

- *kind of* enriched Abstract Syntax Tree
- Implemented in C++
- Full doxygen documentation online
- ex: class `Function` (https://llvm.org/doxygen/classllvm_1_1Function.html)

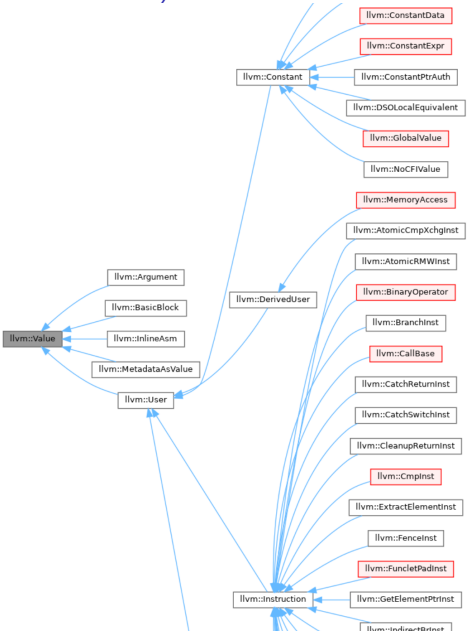


The `Value` class (https://llvm.org/doxygen/classllvm_1_1Value.html)

Almost everything is a Value!

base class of all values computed by a program that may be used as operands to other values.

- functions, global variables
- constants
- basic blocks
- instructions . . .



The `Value` class (https://llvm.org/doxygen/classllvm_1_1Value.html)

Almost everything is a Value!

base class of all values computed by a program that may be used as operands to other values.

- functions, global variables
- constants
- basic blocks
- instructions ...

A Value has Uses

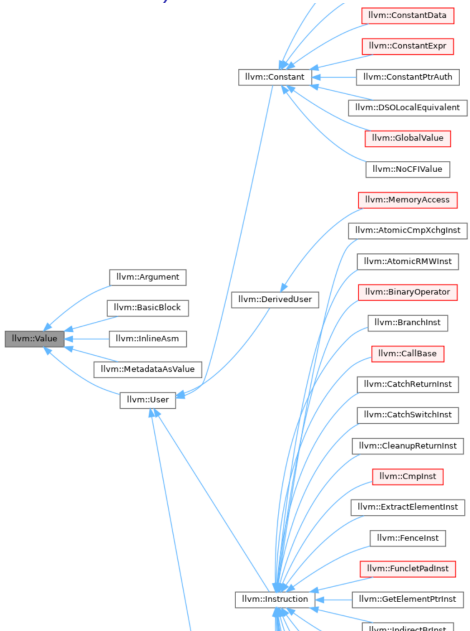
- implements a data flow graph
- can be iterated

  `iterator_range< use_iterator > uses ();`

  ex: `for (auto VUses: V.uses()){...}`
- can be replaced

  `void replaceAllUsesWith(Value *OtherValue);`

  ex: `myValue.replaceAllUsesWith(myNewValue);`



Adding a new function to a Module

```
1 define i32 @my_new_function(i32 %0, i32 %1) {
2 myBB:
3   %2 = add i32 %0, %1
4   ret i32 %2
5 }
```

Adding a new function to a Module

```
define i32 @my_new_function(i32 %0, i32 %1) {
myBB:
  %2 = add i32 %0, %1
  ret i32 %2
}
```

```
Function *createMyNewFunction(Module *M) {

  LLVMContext &Ctx = M.getContext();

  FunctionType *myNewFunctionTy
      = FunctionType::get(IntegerType::get(Ctx, 32),
                          {IntegerType::get(Ctx, 32), IntegerType::get(Ctx, 32)},
                               false);

  Function *myNewFunction = Function::Create(
      myNewFunctionTy, GlobalValue::InternalLinkage, "my_new_function", M);

  myNewFunction->addFnAttr(llvm::Attribute::NoInline);
  return myNewFunction;
}
```

Note: you can also use `Module::getOrInsertFunction(...)` or its variants

Adding a Basic Block to a function

```
1 define i32 @my_new_function(i32 %0, i32 %1) {
2 myBB:
3   %2 = add i32 %0, %1
4   ret i32 %2
5 }
```

Adding a Basic Block to a function

```
define i32 @my_new_function(i32 %0, i32 %1) {
myBB:
  %2 = add i32 %0, %1
  ret i32 %2
}
```

```
void populateMyNewFunction(Function *myNewFunction) {
  LLVMContext &Ctx = myNewFunction->getContext();
  BasicBlock *myBB = BasicBlock::Create(Ctx, "myBB", myNewFunction);

  IRBuilder<> Builder(myBB);

  Argument *arg0 = myNewFunction->getArg(0);
  Argument *arg1 = myNewFunction->getArg(1);

  Value *result = Builder.CreateAdd(arg0, arg1);
  Builder.CreateRet(result);
}
```

Creating control flow

```
define i32 @foobar(i32 %0, i32 %1, i32 %2) {

header:
  br i1 %cond, label %then, label %else

then:                ; preds = %header

  %3 = add i32 %0, %1
  br label %footer

else:                ; preds = %header

  %4 = sub i32 %0, %1
  br label %footer

footer:              ; preds = %else, %then

  %5 = phi i32 [%3, %then], [%4, %else]
  ret %5
}
```

Creating control flow

```
1  Function *functionWithCF(Function *F) {
2    Context &Ctx = myNewFunction.getContext();
3    auto *headerBB = BasicBlock::Create(Ctx, "header", F);
4    auto *thenBB = BasicBlock::Create(Ctx, "then", F);
5    auto *elseBB = BasicBlock::Create(Ctx, "else", F);
6    auto *footerBB = BasicBlock::Create(Ctx, "footer", F);
7
8    Argument *arg0 = F->getArg(0);
9    Argument *arg1 = F->getArg(1);
10   Argument *cond = F->getArg(2);
11
12   IRBuilder<> B(headerBB);
13   B.createCondBr(cond, thenBB, elseBB);
14
15   B.setInsertPoint(thenBB);
16   Value *add = B.createAdd(arg0, arg1);
17   B.createBr(footerBB);
18
19   B.setInsertPoint(elseBB);
20   Value *sub = B.createSub(arg0, arg1);
21   B.createBr(footerBB);
22
23   B.setInsertPoint(footer);
24   PHINode *phi = B.createPHI(arg0.getType(), 2);
25   phi->addIncoming(add, thenBB); phi->addIncoming(sub, elseBB);
26   B.CreateRet(phi);
27 }
```

Creating a new LLVM transformation pass

Where?

- **in tree**
  - clone the LLVM code base
  - put your code deep inside
  - compile everything (might be looong :( )
  - use `clang`, `opt`,... as usual
  - fear LLVM upgrades...
- **out of tree, using pass plugins**
  - install LLVM on your laptop
  - put the code of your pass in a specific directory
  - with a appropriate `CMakeLists.txt` file
  - compile everything into a dynamic library (fast :))
  - use `opt` with `-load-pass-plugin` and `load` options

For more information: https://llvm.org/docs/WritingAnLLVMNewPMPass.html

```cpp
#include "llvm/IR/PassManager.h"
#include "llvm/IR/Function.h"
#include "llvm/Passes/PassBuilder.h"
#include "llvm/Passes/PassPlugin.h"
using namespace llvm;

struct MBA : public llvm::PassInfoMixin<MBA> {
  llvm::PreservedAnalyses run(Function &F, FunctionAnalysisManager &AM);
};

namespace {
  bool addPassToFPM(StringRef Name, FunctionPassManager &FPM,
                    ArrayRef<PassBuilder::PipelineElement>) {
    if (Name == "mypass") {
      FPM.addPass(MyPass());
      return true;
    }
    return false;
  }
}

PassPluginLibraryInfo getMyPassPluginInfo() {
  return {LLVM_PLUGIN_API_VERSION, "MyPass", LLVM_VERSION_STRING,
    [](PassBuilder &PB) { PB.registerPipelineParsingCallback(addPassToFPM); }};
}

extern "C" LLVM_ATTRIBUTE_WEAK ::llvm::PassPluginLibraryInfo
llvmGetPassPluginInfo() {
  return getMyPassPluginPluginInfo();
}
```

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Obfuscate = Transform = Compile

Obfuscate = Complexify but **Compile = Optimize**

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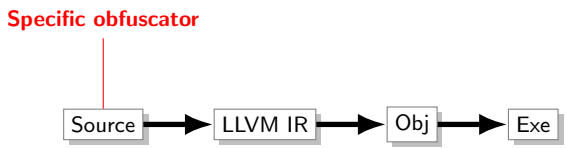

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Obfuscate = Transform = Compile

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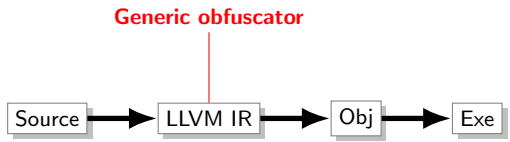

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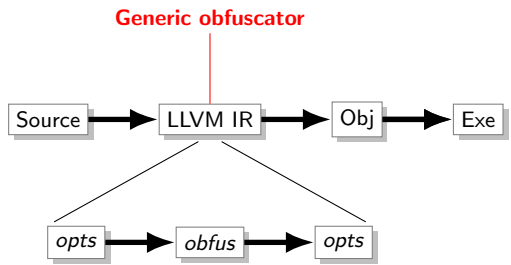

Protecting operations with MBAs

M

B

A

expressions

Information Hiding in Software with Mixed Boolean-Arithmetic Transforms, Zhou *et al.*, 2007

Protecting operations with MBAs

M

B

A rithmetic $+, -, \times$ $x + y$

expressions

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Protecting operations with MBAs

M

Boolean	$\wedge$, $\vee$, $\oplus$, $\neg$	$a \vee b$
Arithmetic	$+$, $-$, $\times$	$x + y$

expressions

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Protecting operations with MBAs

Mixed		$(x + y) \vee z$
Boolean	$\wedge$, $\vee$, $\oplus$, $\neg$	$a \vee b$
Arithmetic	$+$, $-$, $\times$	$x + y$

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Protecting operations with MBAs

Mixed		$(x + y) \vee z$
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expressions over $Z/2^nZ$

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Protecting operations with MBAs

Mixed		$(x + y) \vee z$	$(x \oplus y) + 2 \times (x \wedge y)$	$=$	$x + y$
Boolean	$\wedge$, $\vee$, $\oplus$, $\neg$	$a \vee b$	$(x \oplus y) + 2 \times (x \wedge y) - (x + y)$	$=$	0
Arithmetic	$+$, $-$, $\times$	$x + y$	$(x \oplus y) + 2 \times (x \wedge y) - (x + y) + 1$	$=$	1

expressions over $Z/2^nZ$

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Protecting operations with MBAs

Mixed		$(x + y) \vee z$	$(x \oplus y) + 2 \times (x \wedge y)$	$=$	$x + y$
Boolean	$\wedge$, $\vee$, $\oplus$, $\neg$	$a \vee b$	$(x \oplus y) + 2 \times (x \wedge y) - (x + y)$	$=$	0
Arithmetic	$+$, $-$, $\times$	$x + y$	$(x \oplus y) + 2 \times (x \wedge y) - (x + y) + 1$	$=$	1

expressions over $Z/2^nZ$

Very hard to **prove** and/or **simplify** by *solvers*

$\longrightarrow$ Let's use them to **obfuscate** programs!

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