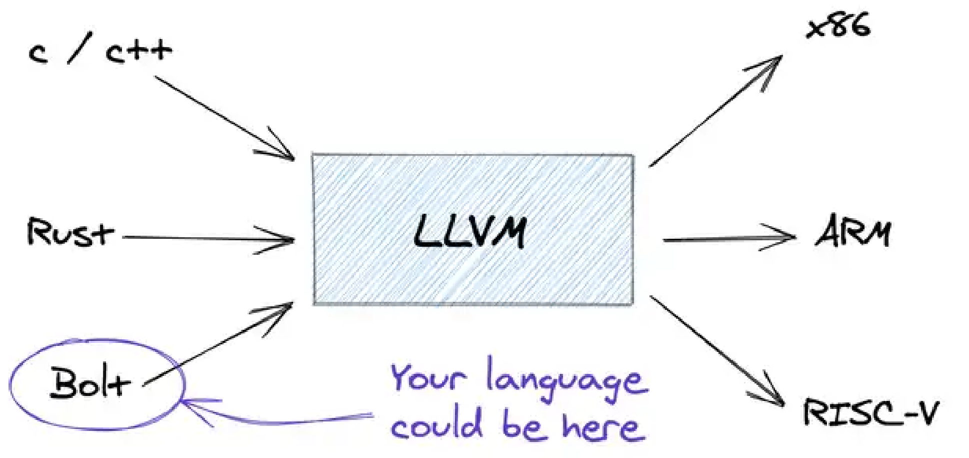
CREATING THE BOLT COMPILER: PART 8

A Complete Guide to LLVM for Programming Language Creators

DECEMBER 24, 2020 12 MIN READ



SERIES: CREATING THE BOLT COMPILER

Update: this post has now taken off on Hacker News and Reddit. Thank you all!

Who's this tutorial for?

This series of compiler tutorials is for people who don't just want to create a *toy* language. You want objects. You want polymorphism. You want concurrency. You want garbage collection. Wait you don't want GC? Okay, no worries, we won't do that :P

If you've just joined the series at this stage, here's a quick recap. We're designing a Java-esque concurrent object-oriented programming language *Bolt*. We've gone through the compiler frontend, where we've done the parsing, type-checking and dataflow analysis. We've desugared our language to get it ready for LLVM - the main takeaway is that objects have been desugared to structs, and their methods desugared to functions.

Learn about LLVM and you'll be the envy of your friends. Rust uses LLVM for its backend, so it must be cool. You'll beat them on all those performance benchmarks, without having to hand-optimise your code or write machine assembly code. Shhhh, I won't tell them.

Just give me the code!

All the code can be found in the Bolt compiler repository.

The C++ class definitions for our desugared representation (we call this *Bolt IR*) can be found in deserialise_ir folder. The code for this post (the LLVM IR generation) can be found in the llvm_ir_codegen folder. The repo uses the Visitor design pattern and ample use of `std::unique_ptr` to make memory management easier.

To cut through the boilerplate, to find out how to generate LLVM IR for a particular language expression, search for the `IRCodegenVisitor::codegen` method that takes in the corresponding `ExprIR` object. e.g. for if-else statements:

Copy

```
Value *IRCodegenVisitor::codegen(const ExprIfElseIR &expr) {
      ... // this is the LLVM IR generation
}
```

Understanding LLVM IR

LLVM sits in the **middle-end** of our compiler, *after* we've desugared our language features, but *before* the backends that target specific machine architectures (x86, ARM etc.)

LLVM's IR is pretty low-level, it can't contain language features present in some languages but not others (e.g. classes are present in C++ but not C). If you've come across instruction sets before, LLVM IR is a RISC instruction set.

The upshot of it is that LLVM IR looks like a more *readable* form of assembly. As LLVM IR is **machine independent**, we don't need to worry about the number of registers, size of datatypes, calling conventions or other machine-specific details.

So instead of a fixed number of physical registers, in LLVM IR we have an unlimited set of *virtual* registers (labelled `%0` , `%1` , `%2` , `%3` ... we can write and read from. It's the backend's job to map from virtual to physical registers.

And rather than allocating specific sizes of datatypes, we retain **types** in LLVM IR. Again, the backend will take this type information and map it to the size of the datatype. LLVM has types for different sizes of `int` s and floats, e.g. `int32` , `int8` , `int1` etc. It also has derived types: like **pointer** types, **array** types, **struct** types, **function** types. To find out more, check out the Type documentation.

Now, built into LLVM are a set of optimisations we can run over the LLVM IR e.g. dead-code elimination, function inlining, common subexpression elimination etc. The details of these algorithms are irrelevant: LLVM implements them for us.

Our side of the bargain is that we write LLVM IR in Static Single Assignment (SSA) form, as SSA form makes life easier for optimisation writers. SSA form sounds fancy, but it just means we define variables before use and assign to variables **only once**. In SSA form, we cannot reassign to a variable, e.g. `x = x+1` ; instead we assign to a fresh variable each time (`x2 = x1 + 1`).

So in short: LLVM IR looks like assembly with **types**, minus the messy machine-specific details. LLVM IR must be in SSA form, which makes it easier to optimise.

Let’s look at an example!

An example: Factorial

Let’s look at a simple factorial function in our language Bolt:

factorial.bolt

Copy

```
function int factorial(int n){
  if (n==0) {
    1
  }
  else{
    n * factorial(n - 1)
  }
}
```

The corresponding LLVM IR is as follows:

factorial.ll

Copy

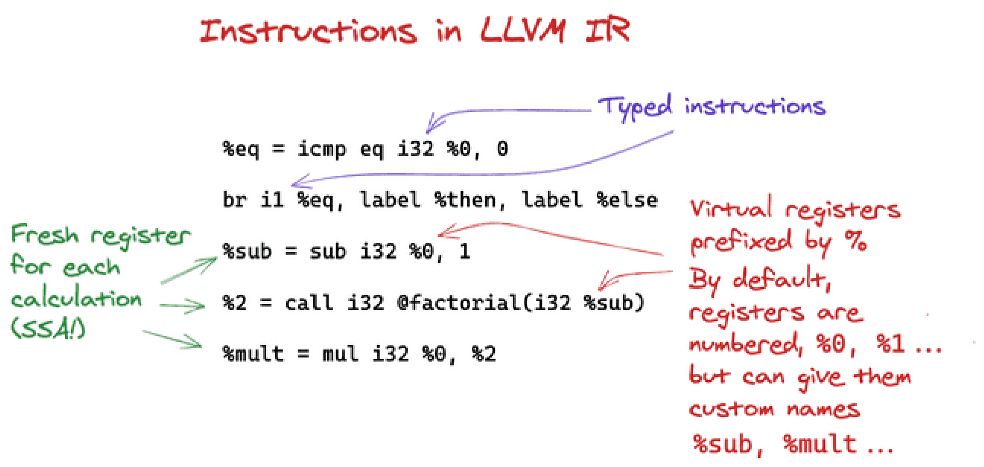
```
define i32 @factorial(i32) {
entry:
  %eq = icmp eq i32 %0, 0   // n == 0
  br i1 %eq, label %then, label %else

then:                                         ; preds = %en
  br label %ifcont

else:                                         ; preds = %en
  %sub = sub i32 %0, 1   // n - 1
  %2 = call i32 @factorial(i32 %sub) // factorial(n-1)
  %mult = mul i32 %0, %2  // n * factorial(n-1)
  br label %ifcont

ifcont:                                       ; preds = %el
  %iftmp = phi i32 [ 1, %then ], [ %mult, %else ]
  ret i32 %iftmp
}
```

> Note the `.ll` extension is for **human-readable** LLVM IR output. There's also `.bc` for bit-code, a more compact machine representation of LLVM IR.

We can walk through this IR in 4 levels of detail:

At the Instruction Level:

Notice how LLVM IR contains assembly instructions like `br` and `icmp`, but abstracts the machine-specific messy details of function calling conventions with a single `call` instruction.

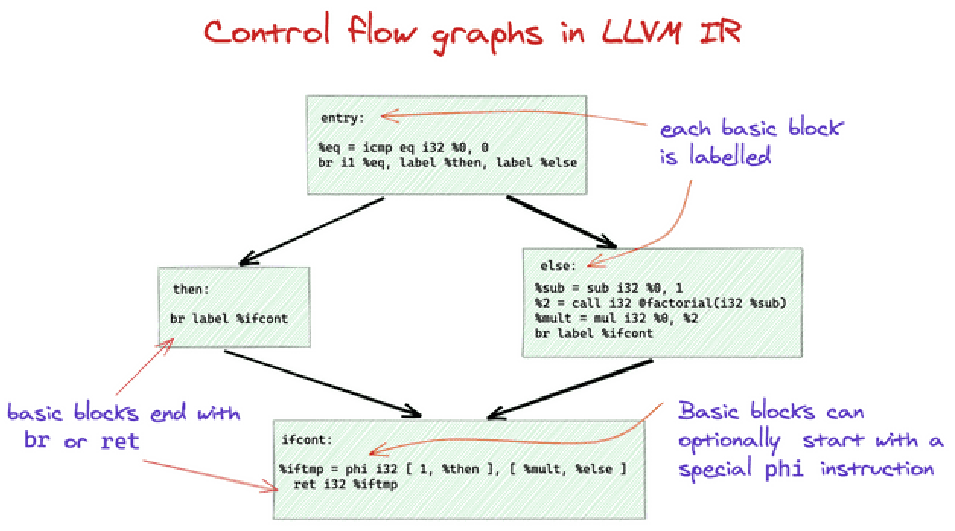

Instructions in LLVM IR
Typed instructions
Fresh register for each calculation (SSA!)
Virtual registers prefixed by %
By default, registers are numbered, %0, %1 ... but can give them custom names %sub, %mult ...

```
%eq = icmp eq i32 %0, 0
br i1 %eq, label %then, label %else
%sub = sub i32 %0, 1
%2 = call i32 @factorial(i32 %sub)
%mult = mul i32 %0, %2
```

At the Control Flow Graph Level:

If we take a step back, you can see the IR defines the **control flow graph** of the program. IR instructions are grouped into labeled **basic blocks**, and the `preds` labels for each block represent incoming edges to that block. e.g. the `ifcont` basic block has predecessors `then` and `else`:

> At this point, I'm going to assume you have come across Control Flow Graphs and basic blocks. We introduced Control Flow Graphs in a previous post in the series, where we used them to perform different dataflow analyses on the program. I'd recommend you go and check the CFG section of that dataflow analysis post now. I'll wait here :)


Control flow graphs in LLVM IR
each basic block is labelled
basic blocks end with br or ret
Basic blocks can optionally start with a special phi instruction

```
entry:

%eq = icmp eq i32 %0, 0
br i1 %eq, label %then, label %else
```

```
then:

br label %ifcont
```

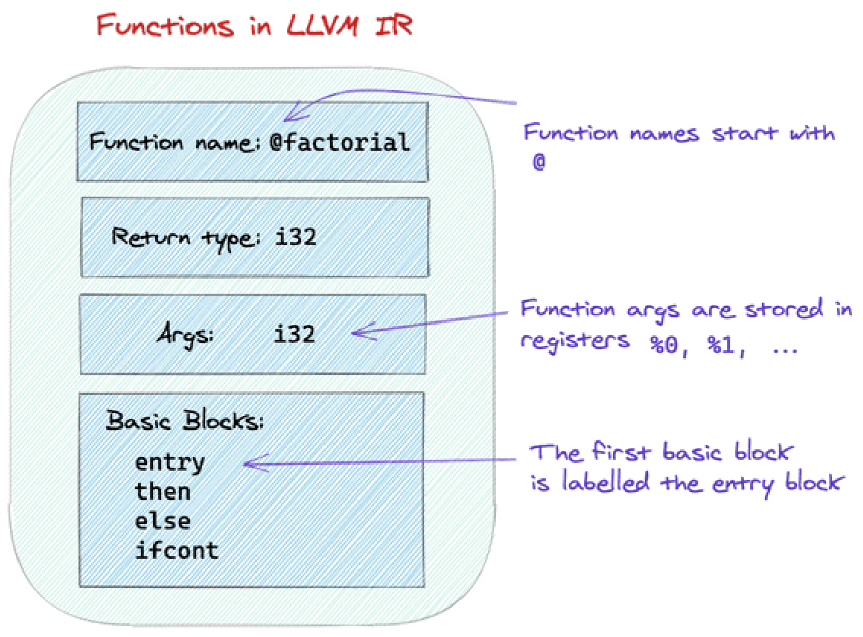
```
else:
%sub = sub i32 %0, 1
%2 = call i32 @factorial(i32 %sub)
%mult = mul i32 %0, %2
br label %ifcont
```

```
ifcont:

%iftmp = phi i32 [ 1, %then ], [ %mult, %else ]
  ret i32 %iftmp
```

The `phi` instruction represents **conditional assignment**: assigning different values depending on which preceding basic block we've just come from. It is of the form `phi type [val1, predecessor1], [val2, predecessor2], ...` In the example above, we set `%iftmp` to 1 if we've come from the `then` block, and `%mult` if we've come from the `else` block. Phi nodes must be at the **start** of a block, and include one entry for each predecessor.

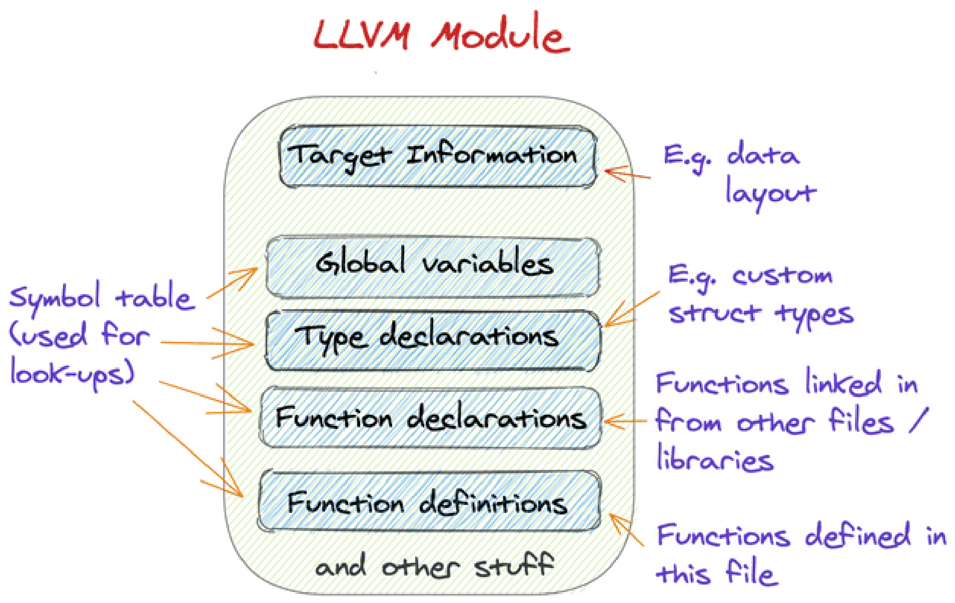
At the Function Level:

Taking another step back, the overall structure of a function in LLVM IR is as follows:


Functions in LLVM IR
Function name: @factorial
Return type: i32
Args: i32
Basic Blocks:
entry
then
else
ifcont
Function names start with @
Function args are stored in registers %0, %1, ...
The first basic block is labelled the entry block

At the Module Level:

An LLVM **module** contains all the information associated with a program file. (For multi-file programs, we'd link together their corresponding modules.)



Our `factorial` function is just one function definition in our module. If we want to execute the program, e.g. to compute `factorial(10)` we need to define a `main` function, which will be the entrypoint for our program's execution. The `main` function's signature is a hangover from C (we return 0 to indicate successful execution):

example_program.c

Copy

```c
// a C main function
int main(){
  factorial(10);
  return 0;
}
```

We specify that we want to compile for an Intel Macbook Pro in the module target info:

example_module.ll

Copy

```
source_filename = "Module"
target triple = "x86_64-apple-darwin18.7.0"
```

```
...
define i32 @factorial(i32) {
  ...
}
define i32 @main() {
entry:
  %0 = call i32 @factorial(i32 10)
  ret i32 0
}
```

The LLVM API: Key Concepts

Now we've got the basics of LLVM IR down, let's introduce the LLVM API. We'll go through the key concepts, then introduce more of the API as we explore LLVM IR further.

LLVM defines a whole host of classes that map to the concepts we've talked about.

- `Value`
- `Module`
- `Type`
- `Function`
- `BasicBlock`
- `BranchInst` ...

> These are all in the namespace `llvm`. In the Bolt repo, I chose to make this namespacing explicit by referring to them as `llvm::Value`, `llvm::Module` etc.)

Most of the LLVM API is quite mechanical. Now you've seen the diagrams that define modules, functions and basic blocks, the relationship between their corresponding classes in the API falls out nicely. You can query a `Module` object to get a list of its `Function` objects, and query a `Function` to get the list of its `BasicBlock`s, and the other way round: you can query a `BasicBlock` to get its parent `Function` object.

`Value` is the base class for any value computed by the program. This could be a function (`Function` subclasses `Value`), a basic block (`BasicBlock` also subclasses `Value`), an instruction, or the result of an intermediate computation.

Each of the expression `codegen` methods returns a `Value *` : the result of executing that expression. You can think of these `codegen` methods as generating the IR for that expression and the `Value *` representing the virtual register containing the expression's result.

ir_codegen_visitor.h

Copy

```
virtual Value *codegen(const ExprIntegerIR &expr) override;
virtual Value *codegen(const ExprBooleanIR &expr) override;
virtual Value *codegen(const ExprIdentifierIR &expr) override;
virtual Value *codegen(const ExprConstructorIR &expr) override;
virtual Value *codegen(const ExprLetIR &expr) override;
virtual Value *codegen(const ExprAssignIR &expr) override;
```

How do we generate the IR for these expressions? We create a **unique** `Context` object to tie our whole code generation together. We use this `Context` to get access to core LLVM data structures e.g LLVM modules and `IRBuilder` objects.

We'll use the context to create just one module, which we'll imaginatively name `"Module"` .

ir_codegen_visitor.cc

Copy

```
context = make_unique<LLVMContext>();
builder = std::unique_ptr<IRBuilder<>>(new IRBuilder<>(*context
module = make_unique<Module>("Module", *context);
```

IRBuilder

We use the `IRBuilder` object to incrementally build up our IR. It is intuitively the equivalent of a file pointer when reading/writing a file - it carries around *implicit* state, e.g. the last instruction added, the basic block of that instruction etc. Like moving around a file pointer, you can set the `builder` object to insert instructions at the end of a particular Basic Block with the `SetInsertPoint(BasicBlock *TheBB)` method. Likewise you can get the current basic block with `GetInsertBlock()` .

The builder object has `Create___()` methods for each of the IR instructions. e.g. `CreateLoad` for a `load` instruction, `CreateSub`, `CreateFSub` for integer and floating point `sub` instructions respectively etc. Some `Create__()` instructions take an optional `Twine` argument: this is used to give the result's register a custom name. e.g. `iftmp` is the twine for the following instruction:

```
%iftmp = phi i32 [ 1, %then ], [ %mult, %else]
```

Use the IRBuilder docs to find the method corresponding to your instruction.

Types and Constants

We don't directly construct these, instead we `get__()` them from their corresponding classes. (LLVM keeps track of how a unique instance of each type / constant class is used).

For example, we `getSigned` to get a constant signed integer of a particular type and value, and `getInt32Ty` to get the `int32` type.

expr_codegen.cc

Copy

```
Value *IRCodegenVisitor::codegen(const ExprIntegerIR &expr) {
  return ConstantInt::getSigned((Type::getInt32Ty(*context)),
                                expr.val);
};
```

Function types are similar: we can use `FunctionType::get`. Function types consist of the return type, an array of the types of the params and whether the function is variadic:

function_codegen.cc

Copy

```
FunctionType::get(returnType, paramTypes, false /* doesn't have
```

Type declarations

We can declare our own custom struct types.

e.g. a Tree with a `int` value, and pointers to left and right subtrees:

Copy

```
%Tree = type {i32, Tree*, Tree* }
```

Defining a custom struct type is a two-stage process.

First we create the type with that name. This adds it to the module's **symbol table**. This type is **opaque**: we can now reference in other type declarations e.g. function types, or other struct types, but we can't create structs of that type (as we don't know what's in it).

Copy

```
StructType *treeType = StructType::create(*context, StringRef("
```

> LLVM boxes up strings and arrays using `StringRef` and `ArrayRef` .
> You can directly pass in a string where the docs require a StringRef, but I choose to make this `StringRef` explicit above.

The second step is to specify an array of types that go in the struct body. Note since we've defined the opaque `Tree` type, we can get a `Tree *` type using the `Tree` type's `getPointerTo()` method.

Copy

```
treeType->setBody(ArrayRef<Type *>({Type::getInt32Ty(*context);
```

So if you have custom struct types referring to other custom struct types in their bodies, the best approach is to declare all of the opaque custom struct types, *then* fill in each of the structs' bodies.

class_codegen.cc

Copy

```
void IRCodegenVisitor::codegenClasses(
    const std::vector<std::unique_ptr<ClassIR>> &classes) {
  // create (opaque) struct types for each of the classes
  for (auto &currClass : classes) {
    StructType::create(*context, StringRef(currClass->className
  }
  // fill in struct bodies
  for (auto &currClass : classes) {
    std::vector<Type *> bodyTypes;
    for (auto &field : currClass->fields) {
          // add field type
          bodyTypes.push_back(field->codegen(*this));
    }
    // get opaque class struct type from module symbol table
    StructType *classType =
        module->getTypeByName(StringRef(currClass->className));
    classType->setBody(ArrayRef<Type *>(bodyTypes));
  }
```

Functions

Functions operate in a similar two step process:

1. Define the function prototypes
2. Fill in their function bodies (skip this if you're linking in an external function!)

The function prototype consists of the function name, the function type, the "linkage" information and the module whose symbol table we want to add the function to. We choose External linkage - this means the function prototype is viewable externally. This means that we can link in an external function definition (e.g. if using a library function), or expose our function definition in another module. You can see the full enum of linkage options here.

function_codegen.cc

Copy

```
  Function::Create(functionType, Function::ExternalLinkage,
                              function->functionName, module.get()
```

To generate the function definition we just need to use the API to construct the control flow graph we discussed in our `factorial` example:

function_codegen.cc

Copy

```
void IRCodegenVisitor::codegenFunctionDefn(const FunctionIR &fu
  // look up function in module symbol definition
  Function *llvmFun =
      module->getFunction(function.functionName);
  BasicBlock *entryBasicBlock =
      BasicBlock::Create(*context, "entry", llvmFun);
  builder->SetInsertPoint(entryBasicBlock);
  ...
```

The official Kaleidoscope tutorial has an excellent explanation of how to construct a control flow graph for an if-else statement.

More LLVM IR Concepts

Now we've covered the basics of LLVM IR and the API, we're going to look at some more LLVM IR concepts and introduce the corresponding API function calls alongside them.

Stack allocation

There are two ways we can store values in local variables in LLVM IR. We've seen the first: **assignment to virtual registers**. The second is **dynamic memory allocation** to the stack using the `alloca` instruction. Whilst we can store ints, floats and pointers to either the stack or virtual registers, **aggregate** datatypes, like structs and arrays, don't fit in registers so have to be stored on the stack.

Yes, you read that right. Unlike most programming language memory models, where we use the heap for dynamic memory allocation, in LLVM we just have a stack.

> Heaps are not provided by LLVM - they are a *library* feature. For single-threaded applications, stack allocation is sufficient. We'll talk about the need for a global heap in multi-threaded programs in the next post (where we extend Bolt to support concurrency).

We've seen struct types e.g. `{i32, i1, i32}` . Array types are of the form `[num_elems x elem_type]` . Note `num_elems` is a constant - you need to provide this when generating the IR, not at runtime. So `[3 x int32]` is valid but `[n x int32]` is not.

We give `alloca` a type and it allocates a block of memory on the stack and returns a *pointer* to it, which we can store in a register. We can use this pointer to load and store values from/onto the stack.

For example, storing a 32-bit int on the stack:

Copy

```
%p = alloca i32 // store i32* pointer in %p
 store i32 1, i32* %p
 %1 = load i32, i32* %p
```

The corresponding builder instructions are... you guessed it `CreateAlloca` , `CreateLoad` , `CreateStore` . `CreateAlloca` returns a special subclass of `Value *` : an `AllocaInst *` :

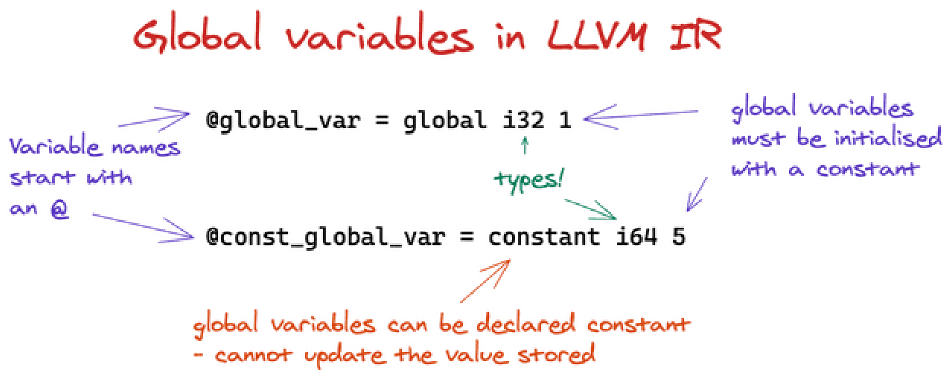
Copy

```
AllocaInst *ptr = builder->CreateAlloca(Type::getInt32Ty(*conte
                                        /* Twine */ "p");
// AllocaInst has additional methods e.g. to query type
ptr->getAllocatedType(); // returns i32
builder->CreateLoad(ptr);
builder->CreateStore(someVal, ptr);
```

Global variables

Just as we `alloca` local variables on a stack, we can create global variables and `load` from them and `store` to them.

Global variables are declared at the start of a module, and are part of the module symbol table.


Global variables in LLVM IR
@global_var = global i32 1
@const_global_var = constant i64 5
Variable names start with an @
global variables must be initialised with a constant
types!
global variables can be declared constant - cannot update the value stored

We can use the `module` object to create named global variables, and to query them.

Copy

```
module->getOrInsertGlobal(globalVarName, globalVarType);
...
GlobalVariable *globalVar = module->getNamedGlobal(globalVarNam
```

Global variables **must** be initialised with a constant value (not a variable):

Copy

```
globalVar->setInitializer(initValue);
```

Alternatively we can do this in one command using the `GlobalVariable` constructor:

Copy

```
GlobalVariable *globalVar = new GlobalVariable(module, globalVa
              GlobalValue::ExternalLinkage, initValue, globalVa
```

As before we can `load` and `store` :

Copy

```
builder->CreateLoad(globalVar);
```

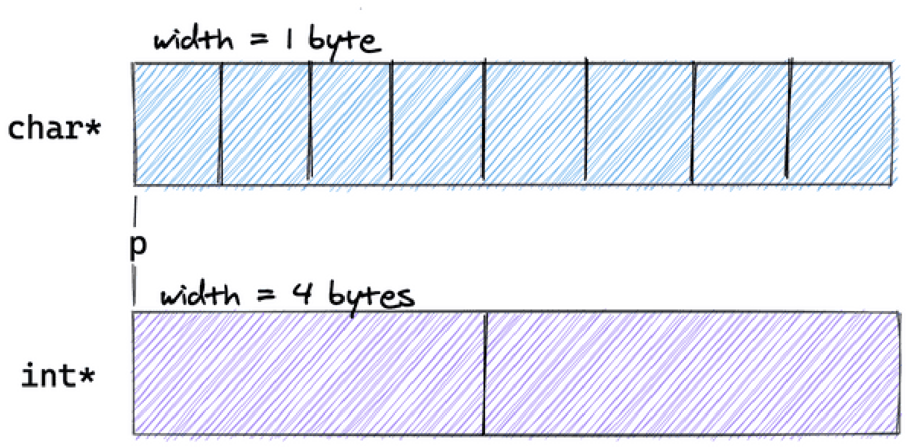
```
builder->CreateStore(someVal, globalVar); // not for consts!
```

GEPs

We get a **base pointer** to the aggregate type (array / struct) on the stack or in global memory, but what if we want a pointer to a **specific element**? We'd need to find the **pointer offset** of that element within the aggregate, and then add this to the base pointer to get the address of that element. Calculating the pointer offset is machine-specific e.g. depends on the size of the datatypes, the struct padding etc.

The Get Element Pointer (GEP) instruction is an instruction to apply the pointer offset to the base pointer and return the resultant **pointer**.

Consider two arrays starting at `p`. Following C convention, we can represent a pointer to that array as `char*` or `int*`.

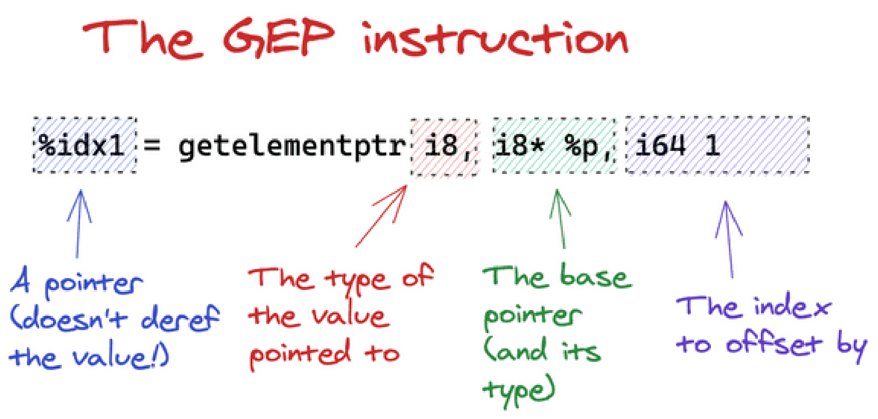


Below we show the GEP instruction to calculate the pointer `p+1` in each of the arrays:

Copy

```
// char = 8 bit integer = i8
%idx1 = getelementptr i8, i8* %p, i64 1 // p + 1 for char*
%idx2 = getelementptr i32, i32* %p, i64 1 // p + 1 for int*
```

This GEP instruction is a bit of a mouthful so here's a breakdown:


The GEP instruction
%idx1 = getelementptr i8, i8* %p, i64 1
A pointer (doesn't deref the value!)
The type of the value pointed to
The base pointer (and its type)
The index to offset by

This `i64 1` index adds **multiples** of the base type to the base pointer. `p+1` for `i8` would add 1 byte, whereas as `p+1` for `i32` would add 4 bytes to `p`. If the index was `i64 0` we'd return `p` itself.

The LLVM API instruction for creating a GEP is… `CreateGEP`.

Copy

```
Value *ptr = builder->CreateGEP(baseType, basePtr, arrayofIndic
```

Wait? *Array* of indices? Yes, the GEP instruction can have multiple indices passed to it. We've looked at a simple example where we only needed one index.

Before we look at the case where we pass multiple indices, I want to reiterate the purpose of this first index:

A pointer of type `Foo *` can represent in C the base pointer of an array of type `Foo`. The first index adds multiples of this base type Foo to traverse this array.

GEPS with Structs

Okay, now let's look at structs. So take a struct of type `Foo`:

Copy

```
%Foo = type { i32, [4 x i32], i32}
```

We want to index **specific** fields in the struct. The natural way would be to label them field `0`, `1` and `2`. We can access field `2` by passing this into the GEP instruction as **another index**.

Copy

```
%ThirdFieldPtr = getelementptr  %Foo, %Foo* %ptr, i64 0, i64 2
```

The returned pointer is then calculated as: `ptr + 0 * (size of Foo) + offset 2 * (fields of Foo)` .

For structs, you'll likely always pass the first index as `0` . The biggest confusion with GEPs is that this `0` can seem redundant, as we want the field `2` , so why are we passing a `0` index first? Hopefully you can see from the first example why we need that `0` . Think of it as passing to GEP the base pointer of an implicit `Foo` array of size 1.

To avoid the confusion, LLVM has a special `CreateStructGEP` instruction that asks only for field index (this is the `CreateGEP` instruction with a `0` added for you):

Copy

```
Value *thirdFieldPtr = builder->CreateStructGEP(baseStructType,
```

The more nested our aggregate structure, the more indices we can provide. E.g. for element index `2` of Foo's second field (the 4 element int array):

Copy

```
getelementptr  %Foo, %Foo* %ptr, i64 0, i64 1, i64 2
```

The pointer returned is: `ptr + 0 * (size of Foo) + offset 1 * (field of Foo) + offset 2 * (elems of array)` .

(In terms of the corresponding API, we'd use `CreateGEP` and pass the array `{0,1,2}` .)

A Good talk that explains GEP well.

mem2reg

If you remember, LLVM IR must be written in SSA form. But what happens if the Bolt source program we're trying to map to LLVM IR is not in SSA form?

For example, if we're reassigning `x` :

reassign_var.bolt

Copy

```
let x = 1
x = x + 1
```

One option would be for us to rewrite the program in SSA form in an earlier compiler stage. Every time we reassign a variable, we'd have to create a fresh variable. We'd also have to introduce `phi` nodes for conditional statements. For our example, this is straightforward, but in general this extra rewrite is a pain we would rather not deal with.

assign_fresh_vars.bolt

Copy

```
// Valid SSA: assign fresh variables
let x1 = 1
x2 = x1 + 1
```

We can use **pointers** to avoid assigning fresh variables. Note here we **aren't reassigning** the pointer `x` , just updating **the value it pointed to**. So this is valid SSA.

Copy

```
// valid SSA: use a pointer and update the value it points to
let x = &1;
*x = *x + 1
```

This switch to pointers is a much easier transformation than variable renaming. It also has a really nice LLVM IR equivalent: allocating *stack memory* (and manipulating the pointers to the stack) instead of reading from *registers*.

So whenever we declare a local variable, we use `alloca` to get a pointer to freshly allocated stack space. We use the `load` and `store` instructions to read and update the value pointed to by the pointer:

TABLE OF CONTENTS

reassign_var.ll

Copy

```
%x = alloca i32
store i32 1, i32* %x

%1 = load i32, i32* %x
%2 = add i32 %1, 1
store i32 %2, i32* %x
```

Let's revisit the LLVM IR if we were to rewrite the Bolt program to use fresh variables. It's only *2* instructions, compared to the *5* instructions needed if using the stack. Moreover, we avoid the expensive `load` and `store` memory access instructions.

assign_fresh_vars.ll

Copy

```
%x1 = 1
%x2 = add i32 %x1, 1   // let x2 = x1 + 1
```

So while we've made our lives easier as compiler writers by avoiding a rewrite-to-SSA pass, this has come at the expense of performance.

Happily, LLVM lets us have our cake and eat it.

LLVM provides a `mem2reg` optimisation that optimises stack memory accesses into register accesses. We just need to ensure we declare all our `alloca` s for local variables in the **entry basic block** for the function.

How do we do this if the local variable declaration occurs midway through the function, in another block? Let's look at an example:

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```
// BOLT variable declaration
let x : int = someVal;

// translated to LLVM IR
%x = alloca i32
store i32 someVal, i32* %x
```

We can actually move the `alloca`. It doesn't matter where we allocate the stack space so long as it is allocated before use. So let's write the `alloca` at the very start of the parent function this local variable declaration occurs.

How do we do this in the API? Well, remember the analogy of the builder being like a file pointer? We can have multiple file pointers pointing to different places in the file. Likewise, we instantiate a new `IRBuilder` to point to the start of the `entry` basic block of the parent function, and insert the `alloca` instructions using that builder.

expr_codegen.cc

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```
Function *parentFunction = builder->GetInsertBlock()
                                ->getParent();
// create temp builder to point to start of function
IRBuilder<> TmpBuilder(&(parentFunction->getEntryBlock()),
                        parentFunction->getEntryBlock().begin()
// .begin() inserts this alloca at beginning of block
AllocaInst *var = TmpBuilder.CreateAlloca(boundVal->getType());
// resume our current position by using orig. builder
builder->CreateStore(someVal, var);
```

LLVM Optimisations

The API makes it really easy to add passes. We create a `functionPassManager`, add the optimisation passes we'd like, and then initialise the manager.

ir_codegen_visitor.cc

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```
std::unique_ptr<legacy::FunctionPassManager> functionPassManage
      make_unique<legacy::FunctionPassManager>(module.get());

  // Promote allocas to registers.
  functionPassManager->add(createPromoteMemoryToRegisterPass())
  // Do simple "peephole" optimizations
  functionPassManager->add(createInstructionCombiningPass());
  // Reassociate expressions.
  functionPassManager->add(createReassociatePass());
  // Eliminate Common SubExpressions.
  functionPassManager->add(createGVNPass());
  // Simplify the control flow graph (deleting unreachable bloc
  functionPassManager->add(createCFGSimplificationPass());

  functionPassManager->doInitialization();
```

We run this on each of the program's functions:

ir_codegen_visitor.cc

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```
for (auto &function : functions) {
    Function *llvmFun =
        module->getFunction(StringRef(function->functionName));
    functionPassManager->run(*llvmFun);
  }

  Function *llvmMainFun = module->getFunction(StringRef("main")
  functionPassManager->run(*llvmMainFun);
```

In particular, let's look at the the `factorial` LLVM IR output by our Bolt compiler before and after. You can find them in the repo:

factorial-unoptimised.ll

Copy

```
define i32 @factorial(i32) {
entry:
  %n = alloca i32
  store i32 %0, i32* %n
  %1 = load i32, i32* %n
  %eq = icmp eq i32 %1, 0
  br i1 %eq, label %then, label %else

then:                                             ; preds = %en
  br label %ifcont

else:                                 ; preds = %entry
  %2 = load i32, i32* %n
  %3 = load i32, i32* %n
  %sub = sub i32 %3, 1
  %4 = call i32 @factorial(i32 %sub)
  %mult = mul i32 %2, %4
  br label %ifcont

ifcont:                          ; preds = %else, %then
  %iftmp = phi i32 [ 1, %then ], [ %mult, %else ]
  ret i32 %iftmp
}
```

And the optimised version:

factorial-optimised.ll

Copy

```
define i32 @factorial(i32) {
entry:
  %eq = icmp eq i32 %0, 0
  br i1 %eq, label %ifcont, label %else

else:                                             ; preds = %en
  %sub = add i32 %0, -1
  %1 = call i32 @factorial(i32 %sub)
  %mult = mul i32 %1, %0
  br label %ifcont
ifcont:                                           ; preds = %en
  %iftmp = phi i32 [ %mult, %else ], [ 1, %entry ]
  ret i32 %iftmp
}
```

Notice how we've actually got rid of the `alloca` and the associated `load` and `store` instructions, and also removed the `then` basic block!

Wrap up

This last example shows you the power of LLVM and its optimisations. You can find the top-level code that runs the LLVM code generation and optimisation in the main.cc file in the Bolt repository.

In the next few posts we'll be looked at some more advanced language features: generics, inheritance and method overriding and concurrency! Stay tuned for when they come out!

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