Exploring LLVM

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This material is strongly based on material produced by Michele Scandale and Ettore Speziale for the course 'Code Optimizations and Transformations'.

Contents

LLVM official documentation

`llvm.org/docs`

A lot of documentation...

`llvm.org/docs` mentions:

- 5 references about *Design & Overview*
- 19 references about *User Guides*
- 13 references about *Programming Documentation*
- 32 references about *Subsystem Documentation*
- 7 references about *Development Process Documentation*
- 5 Mailing Lists
- 5 IRC bots

Most of the above references are OUT-OF-DATE.

You probably need documentation about the documentation itself.

Essential documentation

Intro to LLVM [1] gives a quick and clear introduction to the compiler infrastructure. It is mostly up-to-date.[1]

Writing an LLVM pass [2] explains step by step how to implement a Pass for those who never did anything like that. We will see this tutorial later in the course.

Doxygen [3] *The best code documentation is the code itself.* Sometimes the generated doxygen documentation is enough. It also contains links to the web version of the source code. It is always up-to-date.

llvm-dev Mailing List. Last resource: ask other developers. Warning: 24/7 many people are posting in this ML.

[1] at the time I am writing

Contents

Canonicalize Pass Input

We will see the following passes:

Pass	Switch
Variable promotion	`mem2reg`
Loop simplify	`loop-simplify`
Loop-closed SSA	`lcssa`
Induction variable simplification	`indvars`

They are normalization passes:

- put data into a canonical form

Variable Promotion

One of the most difficult things in compiler is:

- considering memory accesses

Plain SAXPY

```
define float @saxpy(float %a, float %x, float %y) {
entry:
  %a.addr = alloca float, align 4
  %x.addr = alloca float, align 4
  %y.addr = alloca float, align 4
  store float %a, float* %a.addr, align 4
  store float %x, float* %x.addr, align 4
  store float %y, float* %y.addr, align 4
  %0 = load float, float* %a.addr, align 4
  %1 = load float, float* %x.addr, align 4
  %mul = fmul float %0, %1
  %2 = load float, float* %y.addr, align 4
  %add = fadd float %mul, %2
  ret float %add
}
```

Variable Promotion
Simplifying Representation

In the SAXPY kernel some **`alloca`** are generated:

- represent local variables [2]

They are generated due to compiler conservative approach:

- maybe some instruction can take the addresses of such variables, hence a memory location is needed

Complex representations makes hard performing further actions:

- suppose you want to compute `a * x + y` using only one instruction [3]
- hard to detect due to **`load`** and **`store`**

[2] Arguments are local variables
[3] e.g. FMA4

Variable Promotion
Using Memory Only When Necessary

To limit the number of instruction accessing memory:

- we need to eliminate **`load`** and **`store`**
- achieved by promoting variables from memory to registers

Inside LLVM SSA-based representation:

memory Stack allocations – e.g `%1 = alloca float, align 4`

register SSA variables – e.g. `%a`

The **`mem2reg`** pass focus on:

- eliminating **`alloca`** with only **`load`** and **`store`** uses

Also available as utility:

- `llvm::PromoteMemToReg`[4]

[4] see lib/Transforms/Utils/PromoteMemoryToRegister.cpp

Variable Promotion

Example on simplified code

Starting Point

```
%1 = alloca float
%2 = alloca float
%3 = alloca float
store %a, %1
store %x, %2
store %y, %3
%4 = load %1
%5 = load %2
%6 = fmul %4, %5
%7 = load %3
%8 = fadd %6, %7
ret %8
```

Copy propagation performed transparently by the compiler

Promoting **alloca**

```
%1 = %a
%2 = %x
%3 = %y
%4 = %1
%5 = %2
%6 = fmul %4, %5
%7 = %3
%8 = fadd %6, %7
ret %8
```

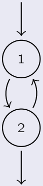
After Copy-propagation

```
%1 = fmul %a, %x
%2 = fadd %1, %y
ret %2
```

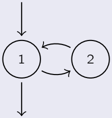
Loops

Different kind of loops:

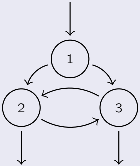
do-while Loops



while Loops



Irreducible Loops



In LLVM the focus is on one kind of loop:

- natural loops

Natural Loops

A natural loop:

- has only one entry node – *header*
- there is a back edge that enter the loop header

Under this definition:

- the irreducible loop is not a natural loop
- since LLVM consider only natural loops, the irreducible loop is not recognized as a loop

Loop Terminology

Loops defined starting from back-edges:

back-edge edge entering loop header: $(3, 1)$

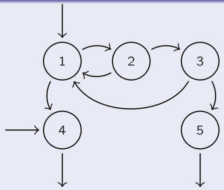
header loop entry node: 1

body nodes that can reach back-edge source node (3) without passing from back-edge target node (1) plus back-edge target node: $\{1, 2, 3\}$

exiting nodes with a successor outside the loop: $\{1, 3\}$

exit nodes with a predecessor inside the loop: $\{4, 5\}$

A loop



Loop Simplify

Natural loops finding is the base pass identify loops, but:

- some features are not analysis/optimization friendly

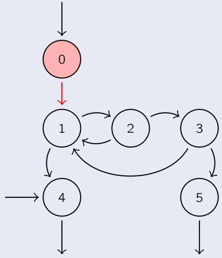
The **`loop-simplify`** pass normalize natural loops:

pre-header
: the only predecessor of header node

latch
: the starting node of the only back-edge

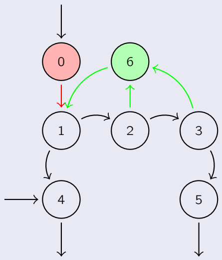
exit-block
: ensures exits dominated by loop header

Pre-header Insertion

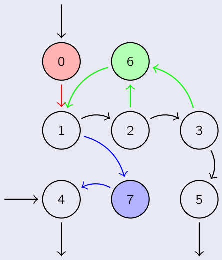


Loop Simplify
Example

Latch Insertion



Exit-block Insertion



- pre-header always executed before entering the loop
- latch always executed before starting a new iteration
- exit-blocks always executed after exiting the loop

Loop-closed SSA

Loop representation can be further normalized:

- `loop-simplify` normalize the shape of the loop
- nothing is said about loop definitions

Keeping SSA form is expensive with loops:

- `lcssa` insert **`phi`** instruction at loop boundaries for variables defined inside the loop body and used outside
- this guarantee isolation between optimization performed inside and outside the loop
- faster keeping IR into SSA form – propagation of code changes outside the loop blocked by **`phi`** instructions

Loop-closed SSA

Example

Linear Search

```
unsigned search(float *x, unsigned n, float y) {
  unsigned i, j = 0;
  for(i = 0; i != n; ++i)
    if(x[i] == y)
      j = i;
  return j;
}
```

The example is trivial:

- think about having large loop bodies
- transformation becomes useful

Loop-closed SSA

Example

Before LCSSA

```
for.cond:
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %j.0 = phi i32 [ 0, %entry ], [ %j.1, %for.inc ]
  %cmp = icmp ne i32 %i.0, %n
  br i1 %cmp, label %for.body, label %for.end

  ...

if.end:
  %j.1 = phi i32 [ %i.0, %if.then ], [ %j.0, %for.body ]
  br label %for.inc

for.inc:
  %inc = add i32 %i.0, 1
  br label %for.cond

for.end:
  ret i32 %j.0
```

Loop-closed SSA

Example

After LCSSA

```
for.cond:
  %i.0 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
  %j.0 = phi i32 [ 0, %entry ], [ %j.1, %for.inc ]
  %cmp = icmp ne i32 %i.0, %n
  br i1 %cmp, label %for.body, label %for.end

  ...

if.end:
  %j.1 = phi i32 [ %i.0, %if.then ], [ %j.0, %for.body ]
  br label %for.inc

for.inc:
  %inc = add i32 %i.0, 1
  br label %for.cond

for.end:
  %j.0.lcssa = phi i32 [ %j.0, %for.cond ]
  ret i32 %j.0.lcssa
```

Induction Variables

Some loop variables are *special*:

- e.g. counters

Generalization lead to induction variables:

- `foo` is a loop induction variable if its successive values form an arithmetic progression:

  ```
  foo = bar * baz + biz
  ```

  where `bar`, `biz` are loop-invariant [5], and `baz` is an induction variable
- `foo` is a canonical induction variable if it is always incremented by a constant amount:

  ```
  foo = foo + biz
  ```

  where `biz` is loop-invariant

[5] Constants inside the loop

Induction Variable Simplification

Canonical induction variables are used to drive loop execution:

- given a loop, the **`indvars`** pass tries to find its canonical induction variable

With respect to theory, LLVM canonical induction variable is:

- initialized to `0`
- incremented by `1` at each loop iteration

Normalization

Wrap-up

Normalization passes running order:

1. `mem2reg`: limit use of memory, increasing the effectiveness of subsequent passes
2. `loop-simplify`: canonicalize loop shape, lower burden of writing passes
3. `lcssa`: keep effects of subsequent loop optimizations local, limiting overhead of maintaining SSA form
4. **`indvars`**: normalize induction variables, highlighting the canonical induction variable

Other normalization passes available:

- try running **`opt -help`**

Contents

Checking Input Properties

Analysis basically allows to:

- derive information and properties of the input
- verify properties of input

Keeping analysis information is expensive:

- tuned algorithms updates analysis information when an optimization invalidates them
- incrementally updating analysis is cheaper than recomputing them

Many LLVM analysis supports incremental updates:

- this is an optimization
- focus on information provided by analysis

Useful Analysis

We will see the following passes:

Analysis

Pass	Switch	Transitive
Control flow graph	`none`	No
Dominator tree	`domtree`	No
Post-dominator tree	`postdomtree`	No
Loop information	`loops`	Yes
Scalar evolution	`scalar-evolution`	Yes
Alias analysis	`special`	Yes
Memory dependence	`memdep`	Yes

Require Analysis

Ask the pass manager to schedule a specific pass before running the current one.

Requiring analysis by transitivity:

yes `llvm::AnalysisUsage::addRequiredTransitive<T>()`

no `llvm::AnalysisUsage::addRequired<T>()`

In cases where analyses chain,the addRequiredTransitive method should be used instead of the addRequired method.
This informs the PassManager that the transitively required pass should be alive as long as the requiring pass is.

Control Flow Graph

The Control Flow Graph is implicitly maintained by LLVM:

- no specific pass to build it

Recap:

- CFG for a function is a set of basic blocks
- a basic block is a set of instructions

Functions and basic blocks acts like containers:

- STL-like accessors: `front()`, `back()`, `size()`, ...
- STL-like iterators: `begin()`, `end()`

Each contained element is aware of its container:

- `getParent()`

Control Flow Graph
Walking

Every CFG has an entry basic block:

- the first executed basic block
- it is the root/source of the graph
- get it with `llvm::Function::getEntryBlock()`

More than one exit blocks can be generated:

- their terminator instructions are **`ret`**s
- they are the leaves/sinks of the graph
- use `llvm::BasicBlock::getTerminator()` to get the terminator ...
- ...then check its real class

Side Note
Casting Framework

For performance reasons, a custom casting framework is used:

- you cannot use **`static_cast`** and **`dynamic_cast`** with types/classes provided by LLVM

LLVM Casting Functions

Meaning	Function
Static cast of `Y *` to `X *`	`X * llvm::cast<X>(Y *)`
Dynamic cast of `Y *` to `X *`	`X * llvm::dyn_cast<X>(Y *)`
Is `Y` an `X`?	`bool llvm::isa<X>(Y *)`

Example:

- is `BB` a sink?

```
llvm::isa<llvm::ReturnInst>(BB.getTerminator())
```

Control Flow Graph
Basic Blocks

Every basic block `BB` has one or more:

predecessors from `pred_begin(BB)` to `pred_end(BB)` [6]

successors from `succ_begin(BB)` to `succ_end(BB)`

Convenience accessors directly available in `llvm::BasicBlock`:

- e.g. `llvm::BasicBlock::getUniquePredecessor()`

Other convenience member functions:

- moving a basic block: `llvm::BasicBlock::moveBefore(llvm::BasicBlock *)` or `llvm::BasicBlock::moveAfter(llvm::BasicBlock *)`
- split a basic block: `llvm::BasicBlock::splitBasicBlock(llvm::BasicBlock::iterator)`
- ...

[6] see include/llvm/IR/CFG.h

Control Flow Graph
Instructions

The `llvm::Instruction` class define common operations:

- e.g. getting an operand: `llvm::Instruction::getOperand(unsigned)`

Subclasses provide specialized accessors:

- e.g the **`load`** instruction takes an operand that is a pointer: `llvm::LoadInst::getPointerOperand()`

The value produced by the instruction is the instruction itself:

Example

Consider:

```
%6 = load i32, i32* %1, align 4
```

the **`load`** is described by an instance of `llvm::LoadInst`. That instance also models the `%6` variable

Instructions

Creating New Instructions

Instructions built using:

- constructors – e.g. `llvm::LoadInst::LoadInst(...)`
- factory methods – e.g. `llvm::GetElementPtrInst::Create(...)`

Interface is not homogeneous:

- some instructions support both methods
- others support only one

At build-time, instructions can be:

- appended to a basic block
- inserted after/before a given instruction

Insertion point usually specified as builder last argument

Side Note

Definitions and Uses

LLVM class hierarchy is built around two simple concepts:

value something that can be used: `llvm::Value`

user something that can use: `llvm::User`

A value is a definition:

- `llvm::Value::use_begin()`, `llvm::Value::use_end()` to visit uses [7]

An user access definitions:

- `llvm::User::op_begin()`, `llvm::User::op_end()` to visit used values [8]

Functions:

- used by call sites
- uses formal parameters

Instructions:

- define an SSA value
- uses operands

[7] `llvm::Instruction` derives from `llvm::Value`

[8] `llvm::Value` derives from `llvm::User`

Side Note
Value Typing

Every `llvm::Value` is typed:

- use `llvm::Value::getType()` to get the type

Since every instructions is/define a value:

- instructions are typed

Example

Consider:

```
%6 = load i32, i32* %1, align 4
```

the `%6` variable actually is the instruction itself. Its type is the type of **`load`** return value, `i32`

Dominance Trees

Dominance trees answer to control-related queries:

- is this basic block executed before that?
- `llvm::DominatorTree`

- is this basic block executed after that?
- `llvm::PostDominatorTree`

The two trees interface is similar:

- `bool dominates(X *, X *)`
- `bool properlyDominates(X *, X *)`

Where `X` is an `llvm::BasicBlock` or an `llvm::Instruction`

Using **opt** is possible printing them:

- `-view-dom`, `-dot-dom`
- `-view-postdom`, `-dot-postdom`

Loop Information

Loop information are represented using two classes:

- `llvm::LoopInfo` analysis detects natural loops
- `llvm::Loop` represents a single loop

Using `llvm::LoopInfo` it is possible:

- navigate through top-level loops:
  `llvm::LoopInfo::begin()`, `llvm::LoopInfo::end()`
- get the loop for a given basic block:
  `llvm::LoopInfo::operator[](llvm::BasicBlock *)`

Loop Information
Nesting Tree

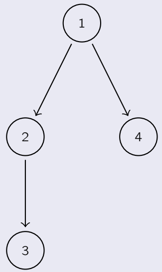
Loops are represented in a nesting tree:

Source

```
while(i < 10) {        // loop 1
  while(j < 10)        // loop 2
    while(k < 10)      // loop 3
      ...

  while(h < 10)        // loop 4
    ...
}
```

Loop Nest



Nest navigation:

- children loops: `llvm::Loop::begin()`, `llvm::Loop::end()`
- parent loop: `llvm::Loop::getParentLoop()`

Loop Information

Query Loops

Accessors for relevant nodes also available:

pre-header	`llvm::Loop::getLoopPreheader()`
header	`llvm::Loop::getHeader()`
latch	`llvm::Loop::getLoopLatch()`
exiting	`llvm::Loop::getExitingBlock()`, `llvm::Loop::getExitingBlocks(...)`
exit	`llvm::Loop::getExitBlock()` `llvm::Loop::getExitBlocks(...)`

Loop basic blocks accessible via:

iterators	`llvm::Loop::block_begin()`, `llvm::Loop::block_end()`
vector	`std::vector<llvm::BasicBlock *> &llvm::Loop::getBlocks()`

Scalar Evolution

The SCalar EVolution framework:

- represents scalar expressions
- supports recursive updates
- lower burden of explicitly handling expressions composition
- is designed to support general induction variables

Example

```
for.cond:
  %i.0 = phi [ 0, %entry ], [ %i.inc, %for.inc ]
  %cond = icmp ne %i.0, 10
  br %cond, label %for.body, label %for.end
for.inc:
  %i.inc = add nsw %i.0, 1
  br label %for.cond
for.end:
  ...
```

SCEV for `%i.0`:

- initial value 0
- incremented
- by 1 at each iteration
- final value 10

Scalar Evolution

Example

Source

```
void foo() {
  int bar[10][20];

  for(int i = 0; i < 10; ++i)
    for(int j = 0; j < 20; ++j)
      bar[i][j] = 0;
}
```

SCEV `{A,B,C}<%D>`:

- A initial
- B operator
- C operand
- D defining BB

Induction Variables

```
%i.0 = phi i32 [ 0, %entry ], [ %inc6, %for.inc5 ]
-->  {0,+,1}<nuw><nsw><%for.cond>   Exits: 10
%j.0 = phi i32 [ 0, %for.body ], [ %inc, %for.inc ]
-->  {0,+,1}<nuw><nsw><%for.cond1>    Exits: 20
```

Scalar Evolution
More than Induction Variables

The scalar evolution framework manages any scalar expression:

Pointer SCEVs

```
  %arrayidx = getelementptr {...} %bar, i32 0, i32 %i.0
  -->  {%bar,+,80}<nsw><%for.cond>
Exits: {%bar,+,80}<nsw><%for.cond>

  %arrayidx4 = getelementptr {...} %arrayidx, i32 0, i32 %j.0
  -->  {{%bar,+,80}<nsw><%for.cond>,+,4}<nsw><%for.cond1>
Exits: {(80 + %bar),+,80}<nsw><%for.cond>
```

SCEV is an analysis used for common optimizations:

- induction variable substitution
- strength reduction
- vectorization
- ...

Scalar Evolution
SCEVs Design

SCEVs are modeled by the `llvm::SCEV` class:

- a subclass for each kind of SCEV: e.g. `llvm::SCEVAddExpr`
- instantiation disabled

A SCEV actually is a tree of SCEVs:

- `{(80 + %bar),+,80}` = `{%1,+,80}, %1 = 80 + %bar`

Tree leaves:

constant `llvm::SCEVConstant`: e.g. `80`

unknown [9] `llvm::SCEVUnknown`: e.g. `%bar`

SCEV tree explorable through the visitor pattern:

- `llvm::SCEVVisitor`

[9] Not further splittable

Scalar Evolution

Analysis Interface

The `llvm::ScalarEvolution` class:

- analyzes SCEVs for a `llvm::Function`
- builds SCEVs for values:

  `llvm::ScalarEvolution::getSCEV(llvm::Value *)`
- creates new SCEVs:

  `llvm::ScalarEvolution::getConstant(llvm::ConstantInt *)`

  `llvm::ScalarEvolution::getAddExpr(llvm::SCEV *, llvm::SCEV *)`

  ...
- gets important SCEVs:

  `llvm::ScalarEvolution::getBackedgeTakenCount(llvm::Loop *)`

  `llvm::ScalarEvolution::getPointerBase(llvm::SCEV *)`

  ...

Alias Analysis

Let X be an instruction accessing a memory location:

- is there another instruction accessing the same location?

Alias analysis tries to answer the question:

application memory operation scheduling

problem often fails

Different algorithms for alias analysis:

- common interface – `llvm::AliasAnalysis` – for all algorithms
- by default, basic alias analyzer – **`basicaa`** – is used

Requiring Alias Analysis

```
AU.addRequiredTransitive<llvm::AliasAnalysis>();
```

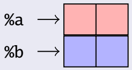
Alias Analysis

Memory Representation

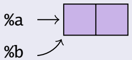
Source

```
%1 = load i16, i16* %a
%2 = load i16, i16* %b
store i16 %2, i32* %a
store i16 %1, i32* %b
```

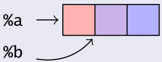
Distinct Locations



Same Location



Overlapping Locations



Basic building block is `llvm::AliasAnalysis::Location`:

- address: e.g. `%a`
- size: e.g. 2 bytes

Alias Analyzer
Basic Interface

Given two locations X, Y, the alias analyzer classifies them:

- `llvm::AliasAnalyzer::NoAlias`: X and Y are different memory locations
- `llvm::AliasAnalyzer::MustAlias`: X and Y are equal – i.e. they points to the same address
- `llvm::AliasAnalyzer::PartialAlias`: X and Y partially overlap – i.e. they points to different addresses, but the pointed memory areas partially overlap
- `llvm::AliasAnalyzer::MayAlias`: unable to compute aliasing information – i.e. X and Y can be different locations, or X can be a complete/partial alias of Y

Queries performed using:

- `llvm::AliasAnalyzer::alias(X, Y)`

Alias Analyzer
Mid-level Interface

Basic alias analyzer interface is low-level – we would like expressing queries about a single pointer X:

- how referenced memory location is accessed?
- which other instructions reference the same location?

What we need is a set, to classify memory locations:

- construct a `llvm::AliasSetTracker` starting from a `llvm::AliasAnalyer *`
- it builds (one or more) `llvm::AliasSet`

For a given location X, a `llvm::AliasSet`:

- contains all locations aliasing with X

Alias Analyzer
Alias Set Memory Accesses

Each alias set references the memory:

- `llvm::AliasSet::NoModRef`: no memory reference – i.e. the set is empty
- `llvm::AliasSet::Mod`: memory accessed in write-mode – e.g. a **`store`** is inside the set
- `llvm::AliasSet::Ref`: memory accessed in read-mode – e.g. a **`load`** is inside the set
- `llvm::AliasSet::ModRef`: memory accessed in read-write mode – e.g. a **`load`** and a **`store`** inside the set

Alias Analyzer
Mid-level Interface

Entry point is `llvm::AliasSetTracker::getAliasSetForPointer(...)`:

- `llvm::Value *`: location address
- `uint64_t`: location size
- `llvm::MDNode *`: used for type-based alias analysis [10]
- **bool** `*`: whether a new `llvm::AliasSet` has been created to hold the location – location does not alias up to now

Having the `llvm::AliasSet`:

- STL container-like interface: `size()`, `begin()`, `end()`, ...
- check reference type: `llvm::AliasSet::isRef()`, ...
- check aliasing type: `llvm::AliasSet::isMustAlias()`, ...

[10] set to `NULL`

Memory Dependence Analysis

Alias Analyzer High-level Interface

The `llvm::MemoryDependenceAnalysis` wraps alias analysis to answer queries in the following form:

- let `%foo` be an instruction accessing memory. Which preceding instructions does `%foo` depends on?

Reads:

- `store`s writing memory locations aliases with the one references by `%foo`

Writes:

- `load`s reading memory locations aliased with the one referenced by `%foo`

Memory Dependence Analysis

APIs

Let `%foo` be a `llvm::Instruction` accessing memory:

- call `llvm::MemoryDependenceAnalysis::getDependency(...)`
- you get a `llvm::MemDepResult`

Dependencies are classified:

- `llvm::MemDepResult::isClobber()`: an instruction clobbering – i.e. potentially modifying – location referenced by `%foo` has been found
- `llvm::MemDepResult::isDef()`: an instruction defining – e.g. writing – the exact location referenced by `%foo` has been found
- `llvm::MemDepResult::isNonLocal()`: no dependency found on `%foo` basic block
- `llvm::MemDepResult::isNonFuncLocal()`: no dependency found on `%foo` function

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Conclusions

Inside LLVM there a lot of passes:

normalization put program into a canonical form

analysis get info about program

Please remember that

- a good compiler writer re-uses code
- check LLVM sources before re-implementing a pass

Contents

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