

The LLVM compiler framework

Exploring LLVM

Daniele Cattaneo

Politecnico di Milano

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These slides were originally written by Michele Scandale, Ettore Speziale and Stefano Cherubin for the “Code Transformation and Optimization” course.

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LLVM official documentation

llvm.org/docs

A lot of documentation...

llvm.org/docs links to:

- ▶ 4 references about *Design & Overview*
- ▶ 6 references about *Getting Started / Tutorials*
- ▶ 35 references about *User Guides*
- ▶ 15 references about *Programming Documentation*
- ▶ 40 references about *Reference Documentation*
- ▶ 7 references about *Development Process Documentation*
- ▶ 5 Mailing Lists
- ▶ 4 IRC bots

Most of the above references are **outdated!**

You probably need documentation *about the documentation*.

Essential documentation

- | | |
|-----------------------------|--|
| Intro to LLVM | Quick and clear introduction to the compiler infrastructure. Mostly up-to-date.* |
| [1] | |
| Writing an LLVM pass | Explains step by step how to implement a Pass for those who never did anything like that. |
| [2] | (We will see this tutorial later in the course) |
| Doxygen | <i>The best code documentation is the code itself.</i> |
| [3] | Sometimes the generated doxygen documentation is enough. Updated to the latest development branch, refer to github branches for documentation about the stable versions. |
| llvm-dev | Mailing List. Last resource: ask other developers. |
| [3] | Warning: It has very high traffic. |

*At the time I am writing!

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Canonicalizing Pass Input

We will see the following passes:

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

They are **normalization** passes:

- ▶ they convert the code into a canonical form

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Variable Promotion

One of the most difficult things in compilers is
handling memory accesses.

Plain SAXPY (Scalar $ax + y$)

```
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

In the SAXPY kernel all the variables are **allocated** on the stack!

- ▶ Function arguments included!

They are allocated like that because the compiler follows a **conservative** approach:

- ▶ an instruction could take the address of one of the variables...

However, complex representations make optimizations more difficult:

- ▶ suppose you want to compute the $a*x+y$ expression using only **one** instruction (aka FMA4)
- ▶ hard to detect due to **load** and **store**

Variable Promotion

To limit the number of instructions accessing memory we need to eliminate **load** and **store**

- ▶ achieved by **promoting** variables from memory to registers

Inside the LLVM-IR:

memory Stack allocations

`%1 = alloca float, align 4`

register SSA variables

`%a`

The mem2reg pass focuses on:

- ▶ eliminating **allocas** used only by **load** and **store** instructions

Also available as a utility function:

- ▶ `llvm::PromoteMemToReg`

- ▶ see `llvm/Transforms/Utils/PromoteMemToReg.h`

Variable Promotion

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 is automatic:
replaceAllUsesWith
(RAUW) method

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
```

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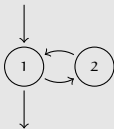
Loops

There are several kind of loops:

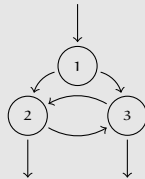
do-while Loops



while Loops



Irreducible Loops



LLVM focuses on one class of loop:

Natural Loops

Natural Loops

A natural loop:

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

Under this definition:

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

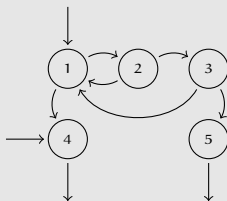
Loop Terminology

Loops are defined starting from the back-edges:

back-edge edge going back to the 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 are

- ▶ easy to **identify**
- ▶ not really analysis/optimization friendly!

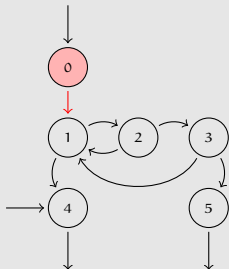
The loop-simplify pass normalizes natural loops:

pre-header ensures the **loop header** has a **single entry edge**

latch ensures the loop has a **single back-edge**

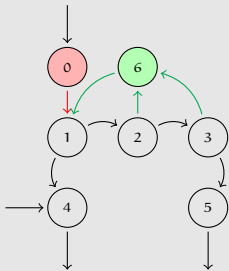
exit-block ensures **exits** **dominated** by loop **header**

Pre-header Insertion

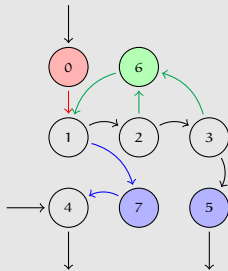


Loop Simplify

Latch Insertion



Exit-block Insertion



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

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Loop-closed SSA

Loop representation can be further normalized:

- ▶ `loop-simplify` normalizes the **shape** of the loop (*control flow*)
- ▶ it does not involve the instructions in the loop (*data flow*)

Keeping SSA form is expensive with loops:

- ▶ Any optimization involving an SSA variable **defined inside the loop**, and **used outside the loop**, causes a ripple effect!

The `lcssa` transformation is the solution:

- ▶ inserts **phi** instructions at loop boundaries
- ▶ now, optimizations performed inside the loop do not affect the code outside of it

Loop-closed SSA

Linear Search

```
int *search(int *x, int n, int y)
{
    int j = -1;
    for (int i = 0; i < n; i++)
        if (x[i] == y)
            j = i;
    return j;
}
```

The example is trivial, this transformation is mostly useful for *large loop bodies*.

Loop-closed SSA

Before LCSSA

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

for.body:
    [...]

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

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

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

Loop-closed SSA

After LCSSA

for.cond:

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

for.body:

[...]

if.end:

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

for.inc:

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

for.end:

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

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Induction Variables

Some loop variables are *special*:

- ▶ e.g. counters

The generalization of this intuition are **induction variables**:

- ▶ `foo` is a **loop induction variable**

if its successive values form an arithmetic progression:

$$\text{foo} = \text{bar} * \text{baz} + \text{biz}$$

where: `bar`, `biz` are loop-invariant *,
`baz` is an induction variable

- ▶ `foo` is a **canonical induction variable**

if it is always incremented by a constant amount:

$$\text{foo} = \text{foo} + \text{biz}$$

where `biz` is loop-invariant

*Constants inside the loop

Induction Variable Simplification

Canonical induction variables are often used to **drive** loop execution.

Given a loop, the `indvars` pass tries to transform its induction variables into **canonical** induction variables.

- ▶ It also transforms loop exit conditions in simple inequalities
- ▶ Definition of other variables derived from the induction variables are moved outside the loop if used there

LLVM defines canonical induction variables as:

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

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Normalization

“Standard” running order:

1. `mem2reg`: limits use of memory
2. `loop-simplify`: canonicalizes loops
 - ▶ Improved detection of a lot of standard patterns!
3. `lcssa`: keeps effects of subsequent loop optimizations local
limits overhead of maintaining SSA form
4. `indvars`: normalizes induction variables
simplifies and highlights the loop condition

For more normalization passes:

- ▶ try running `opt -help`

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Checking Input Properties

Analyses basically allow to:

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

Keeping analyzed information updated is expensive:

- ▶ tuned algorithms update information when an optimization invalidates it
- ▶ incrementally updating analyses are cheaper than recomputing them

As an **optimization**, many LLVM analysis supports incremental updates.

Useful Analyses

We will see the following passes:

| Pass | Switch | Transitive |
|---------------------|------------------|------------|
| Dominator tree | domtree | No |
| Post-dominator tree | postdomtree | No |
| Loop information | loops | Yes |
| Scalar evolution | scalar-evolution | Yes |
| Alias analysis | — | Yes |
| Memory SSA | memoryssa | Yes |

Requesting an Analysis

Your pass needs to tell the pass manager which analyses it needs!

Transitive analyses:

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

Non-transitive analyses:

```
llvm::AnalysisUsage::addRequired<T>()
```

For **chained analyses***, 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.

*Analyses that use the result of another analysis

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Dominance Trees

Dominance trees answer to control-related queries:

is A executed **before** B?



`llvm::DominatorTree`

is A executed **after** B?



`llvm::PostDominatorTree`

The interfaces of these two trees is mostly the same:

- ▶ **bool** `dominates(A, B)`
- ▶ **bool** `properlyDominates(A, B)`

A and B are either `llvm::BasicBlocks` or `llvm::Instructions`

By using `opt`, it is possible to show the trees:

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

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Loop Information

Loop information is represented using two classes:

llvm::LoopInfo The result of `llvm::LoopAnalysis`, performed on a given function.

llvm::Loop Represents a single loop in a function. Contained inside a `llvm::LoopInfo`.

Using `llvm::LoopInfo` it is possible to:

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

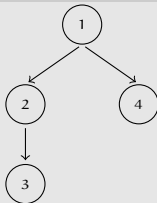
Loop Information

Loops are represented as a **tree**:

Source

```
while(i < 10) {           // loop 1
  while(j < 10)           // loop 2
    while(k < 10)         // loop 3
    ...
  while(h < 10)           // loop 4
  ...
}
```

Loop Hierarchy



children loops `llvm::Loop::begin(), end()`

parent loop `llvm::Loop::getParentLoop()`

Loop Information

Accessors for important nodes:

```
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(...)
```

The list of all BBs in the loop is accessible via:

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

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Scalar Evolution

The **SC**alar **EV**olution pass analyzes scalar expressions inside loops.

- ▶ all expressions are categorized and represented uniformly
- ▶ is capable of handling **general induction variables**
- ▶ also useful outside of loops
- ▶ opt flags: `-analyze -scalar-evolution`

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

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 starting value
- ▶ B operator
- ▶ C stride
- ▶ D loop head BB

{0,+,1}=0+1+1+1+...

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

The scalar evolution framework manages **any scalar expression**:

Pointer SCEVs in two nested loops

```
%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 by many common optimizations

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

Scalar Evolution

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* `llvm::SCEVUnknown`: e.g. `%bar`

SCEV tree explorable through the visitor pattern:

- ▶ `llvm::SCEVVisitor`

*Not further splittable

Scalar Evolution

The `llvm::ScalarEvolutionAnalysis` pass computes all the SCEVs for a given `llvm::Function`.

The `llvm::ScalarEvolution` instance produced by the pass provides the following services:

- ▶ get the SCEV representing a value:
 - ▶ `getSCEV(llvm::Value *)`
- ▶ get important SCEVs from other structures or SCEVs:
 - ▶ `getBackedgeTakenCount(llvm::Loop *)`
 - ▶ `getPointerBase(llvm::SCEV *)`
 - ▶ ...
- ▶ create new SCEVs explicitly:
 - ▶ `getConstant(llvm::ConstantInt *)`
 - ▶ `getAddExpr(llvm::SCEV *, llvm::SCEV *)`
 - ▶ ...

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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 optimization of memory operations

problem often fails

Different algorithms are available for alias analysis:

- ▶ common interface: `llvm::AAResults`
- ▶ base implementation: basic alias analysis (`basicaa`)

Requiring Alias Analysis

```
AU.addRequiredTransitive<AAResultsWrapperPass>();
```

Alias Analysis

Source

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

Basic building block:
`llvm::MemoryLocation`

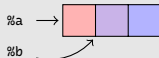
Encapsulates a tuple:
(**address**, **size**)

Can be computed from a
`llvm::Value`

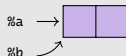
Distinct Locations



Overlapping Locations



Same Location



Alias Analysis

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

- ▶ **llvm::AliasResult::NoAlias**
X and Y **are different** memory locations
- ▶ **llvm::AliasResult::MustAlias**
X and Y **are equal** – i.e. they points to the same address
- ▶ **llvm::AliasResult::PartialAlias**
X and Y **partially overlap** – i.e. they points to different addresses, but the pointed memory areas partially overlap
- ▶ **llvm::AliasResult::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::AAResults::alias(X, Y)**

Alias Analysis

A different categorization involves whether an instruction **I** **reads and/or modifies** a memory location **X**:

- ▶ **llvm::ModRefInfo::NoModRef**

The access neither references nor modifies the value stored in **X**

- ▶ **llvm::ModRefInfo::Ref**

The access may reference the value stored in **X**

- ▶ **llvm::ModRefInfo::Mod**

The access may modify the value stored in **X**

- ▶ **llvm::ModRefInfo::ModRef**

The access may reference and may modify the value stored in **X**

Queries performed using:

- ▶ **llvm::AAResults::getModRefInfo(I, X)**

Alias Analysis

This interface is very low-level!

What if we wanted to compute all aliases of a single value X?

To do this, LLVM provides the `llvm::AliasSet` class:

1. instantiate a new `llvm::AliasSetTracker` starting from `llvm::AAResults*`
2. it builds (one or more) `llvm::AliasSet`

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

- contains all locations aliasing with X

```
*using llvm::AliasAnalysis = llvm::AAResults;
```

Alias Analysis

Alias sets return memory reference and aliasing information just like the low-level interface.

Warning: This information is **less precise**, as it is derived by **conservatively aggregating** more detailed data!

- ▶ **bool llvm::AliasSet::isRef()**
memory accessed in read-mode – e.g. a **load** is inside the set
- ▶ **bool llvm::AliasSet::isMod()**
memory accessed in write-mode – e.g. a **store** is inside the set
- ▶ **bool llvm::AliasSet::isMustAlias()**
all pointers in the set MustAlias with each other
- ▶ **bool llvm::AliasSet::isMayAlias()**
at least one pair of pointer is not a MustAlias pair

Alias Analysis

Entry point is

```
llvm::AliasSetTracker::getAliasSetFor(...)
```

Only argument is a reference to

```
llvm::MemoryLocation
```

Once you have the `llvm::AliasSet` you can inspect the list of memory locations in it with the standard C++ iterator pattern:

```
size(), begin(), end()
```

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Memory SSA

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

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

This is done by representing all memory accesses in a **SSA-like form**:

- ▶ **store**-like instructions become **definitions** (`MemoryDef`)
- ▶ **load**-like instructions become **uses** (`MemoryUse`)
- ▶ **stores** to the same location in parallel CFG branches become **phis** (`MemoryPhi`)

Memory Dependence Analysis

MemorySSA “instructions” are owned by `llvm::MemorySSA` objects.

They are **overlaid** on top of the normal CFG.

- ▶ `AccessList *getBlockAccesses(BasicBlock *)`
- ▶ `DefsList *getBlockDefs(BasicBlock *)`

This basic interface is very **hard to use**:

- ▶ `llvm::MemorySSAWalker` provides support for the most common query
- ▶ `MemoryAccess *getClobberingMemoryAccess(...)`
 - ▶ Returns the nearest dominating memory access that clobbers the same memory location given.

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Conclusions

Inside LLVM there a lot of passes:

normalization put program into a canonical form

analysis get info about the program

Please remember that:

- ▶ a good compiler engineer **re-uses** code
- ▶ check LLVM sources before re-implementing a pass

Thank You!

Questions?

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