

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'.

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- 1 Documentation
- 2 Normalization Passes
- 3 Analysis Passes
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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Most of the above references are OUT-OF-DATE.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.

¹at the time I am writing

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Canonicalize Pass Input

We will see the following passes:

Pass	Switch
Variable promotion	<code>mem2reg</code>
Loop simplify	<code>loop-simplify</code>
Loop-closed SSA	<code>lcssa</code>
Induction variable simplification	<code>indvars</code>

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 instruction³
- hard to detect due to **load** and **store**

²Arguments are local variables

³e.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

⁴see `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
```

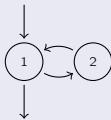
Loops

Different kind of loops:

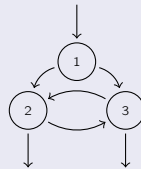
do-while Loops



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:

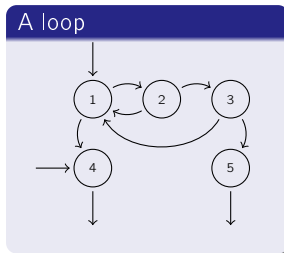
back-edge edge entering loop header: (3, 1)

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}



Loop Simplify

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

- some features are not analysis/optimization friendly

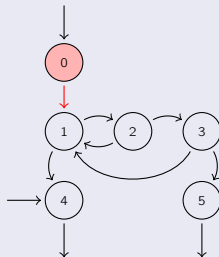
The **loop-simplify** pass normalize natural loops:

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**

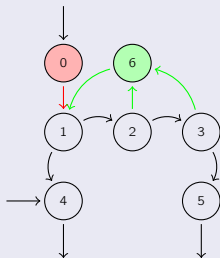
Pre-header Insertion



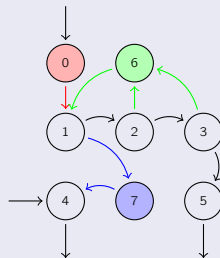
Loop Simplify

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 guarantees 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:

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

where `bar`, `biz` are loop-invariant⁵, and `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

⁵Constants 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**

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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	<code>none</code>	No
Dominator tree	<code>domtree</code>	No
Post-dominator tree	<code>postdomtree</code>	No
Loop information	<code>loops</code>	Yes
Scalar evolution	<code>scalar-evolution</code>	Yes
Alias analysis	<code>special</code>	Yes
Memory dependence	<code>memdep</code>	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 **rets**
- 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 <code>y *</code> to <code>x *</code>	<code>x * llvm::cast<X>(Y *)</code>
Dynamic cast of <code>y *</code> to <code>x *</code>	<code>x * llvm::dyn_cast<X>(Y *)</code>
Is <code>y</code> an <code>x</code> ?	<code>bool llvm::isa<X>(Y *)</code>

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)`
- ...

⁶see `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()`

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`

by using `opt`, it is possible print 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

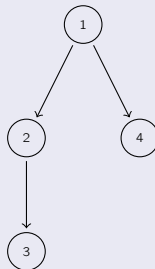
Nesting Tree

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 **SC**alar **EV**olution 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`

⁹Not 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

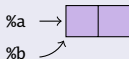
Source

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

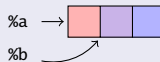
Distinct Locations



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::AliasAnalyzer *`
- 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 analysis¹⁰
- `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()`, ...

¹⁰set 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** instructions writing memory locations aliases with the one references by `%foo`

Writes:

- **load** instructions 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

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