

The LLVM compiler framework

Exploring LLVM

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Contents

- 1 Documentation**
- 2 Normalization Passes
- 3 Analysis Passes
- 4 Conclusions
- 5 Bibliography

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Most of the above references are **outdated!**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** [1] Quick and clear introduction to the compiler infrastructure. Mostly up-to-date.*
- 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. Updated to the latest development branch, refer to github branches for documentation about the stable versions.
- llvm-dev** [3] Mailing List. Last resource: ask other developers. Warning: It has very high traffic.

*At the time I am writing!

Contents

1 Documentation

2 Normalization Passes

Variable Promotion

Loop Simplification

Loop-closed SSA

Induction variable simplification

Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

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

Contents

1 Documentation

2 Normalization Passes

- Variable Promotion

- Loop Simplification

- Loop-closed SSA

- Induction variable simplification

- Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

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

Simplifying Representation

In the SAXPY kernel all the variables are **all** located 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

Using Memory Only When Necessary

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

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 is automatic:
replaceAllUsesWith (RAUW)
method

Promoting a `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
```

Contents

1 Documentation

2 Normalization Passes

Variable Promotion

Loop Simplification

Loop-closed SSA

Induction variable simplification

Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

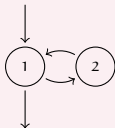
Loops

There are several kind of loops:

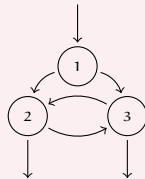
do-while Loops



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:

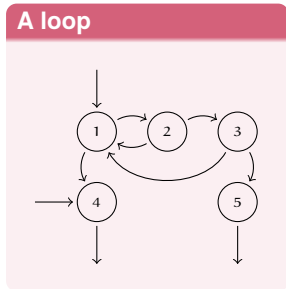
back-edge edge going back to the loop header: (3, 1)

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}



Loop Simplify

Natural loops are

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

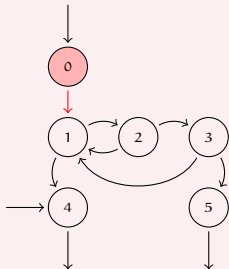
The loop-simplify pass normalizes natural loops:

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

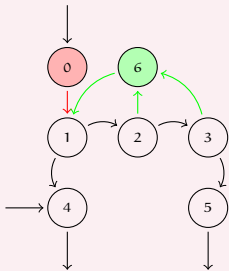
Pre-header Insertion



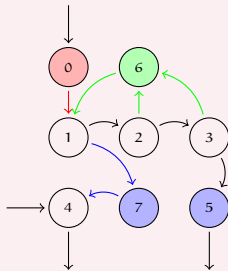
Loop Simplify

Example

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

Contents

1 Documentation

2 Normalization Passes

Variable Promotion

Loop Simplification

Loop-closed SSA

Induction variable simplification

Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

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

Example

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

Example

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

Example

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
```

Contents

1 Documentation

2 Normalization Passes

Variable Promotion

Loop Simplification

Loop-closed SSA

Induction variable simplification

Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

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

Contents

1 Documentation

2 Normalization Passes

Variable Promotion

Loop Simplification

Loop-closed SSA

Induction variable simplification

Recap

3 Analysis Passes

4 Conclusions

5 Bibliography

Normalization

Wrap-up

“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`

Contents

1 Documentation

2 Normalization Passes

3 Analysis Passes

Dominance Trees

Loop Information

Scalar Evolution

Alias Analysis

Memory SSA

4 Conclusions

5 Bibliography

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

Contents

- 1 Documentation
- 2 Normalization Passes
- 3 **Analysis Passes**
 - Dominance Trees
 - Loop Information
 - Scalar Evolution
 - Alias Analysis
 - Memory SSA
- 4 Conclusions
- 5 Bibliography

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`

Contents

1 Documentation

2 Normalization Passes

3 Analysis Passes

Dominance Trees

Loop Information

Scalar Evolution

Alias Analysis

Memory SSA

4 Conclusions

5 Bibliography

Loop Information

Loop information is represented using two classes:

11vm::LoopInfo The result of `11vm::LoopAnalysis`, performed on a given function.

11vm::Loop Represents a single loop in a function. Contained inside a `11vm::LoopInfo`.

Using `11vm::LoopInfo` it is possible to:

- navigate through top-level loops:
 - `11vm::LoopInfo::begin()`
 - `11vm::LoopInfo::end()`
- get the loop for a given basic block:
 - `11vm::LoopInfo::operator[](11vm::BasicBlock *)`

Loop Information

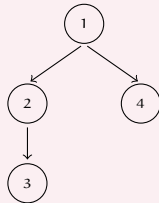
Nesting Tree

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

Query Loops

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()`

Contents

1 Documentation

2 Normalization Passes

3 Analysis Passes

Dominance Trees

Loop Information

Scalar Evolution

Alias Analysis

Memory SSA

4 Conclusions

5 Bibliography

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

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 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

More than Induction Variables

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

SCEV tree explorable through the visitor pattern:

- `llvm::SCEVVisitor`

*Not further splittable

Scalar Evolution

Analysis Interface

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 *)`
 - ...

Contents

1 Documentation

2 Normalization Passes

3 Analysis Passes

Dominance Trees

Loop Information

Scalar Evolution

Alias Analysis

Memory SSA

4 Conclusions

5 Bibliography

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

Interface of the system: `llvm::AAResults`

Requiring Alias Analysis

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

Chained Analysis

AA is actually a chain of multiple analyses, executed in sequence:

1. Basic Alias Analysis (bas icaa)

...

nth. Type Based Alias Analysis (tbaa)*

...

last. Dummy Alias Analysis (noaa)

Every analysis in the chain *fills the gap* left by the previous analyses.

*AKA the evil 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
```

Basic building block:
`llvm::MemoryLocation`

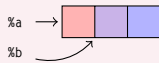
Encapsulates a tuple:
(**address**, **size**)

Can be computed from a
`llvm::Value`

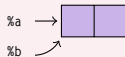
Distinct Locations



Overlapping Locations



Same Location



Alias Analysis

Basic Interface

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 yet – 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

Basic Interface

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

Mid-level Interface

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 Set Memory Accesses

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

Mid-level Interface

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()
```

Contents

1 Documentation

2 Normalization Passes

3 Analysis Passes

Dominance Trees

Loop Information

Scalar Evolution

Alias Analysis

Memory SSA

4 Conclusions

5 Bibliography

Memory SSA

Alias Analyzer High-level Interface

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

APIs

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.

Contents

- 1 Documentation
- 2 Normalization Passes
- 3 Analysis Passes
- 4 Conclusions**
- 5 Bibliography

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?

Contents

- 1 Documentation
- 2 Normalization Passes
- 3 Analysis Passes
- 4 Conclusions
- 5 Bibliography**

Bibliography I



Chris Lattner.

Intro to LLVM.

<http://www.aosabook.org/en/llvm.html>.



Chris Lattner and Jim Laskey.

Writing an LLVM Pass.

<http://llvm.org/docs/WritingAnLLVMPass.html>.



LLVM Community.

Doxygen annotations.

<http://llvm.org/doxygen/annotated.html>.



Chris Lattner and Vikram Adve.

LLVM Language Reference Manual.

<http://llvm.org/docs/LangRef.html>.



LLVM Community.

LLVM Coding Standards.

<http://llvm.org/docs/CodingStandards.html>.

Bibliography II



LLVM Community.

LLVM Passes.

<http://llvm.org/docs/Passes.html>.



LLVM Community.

Autovectorization in LLVM.

<http://llvm.org/docs/Vectorizers.html>.



LLVM Community.

LLVM Programmer's Manual.

<http://llvm.org/docs/ProgrammersManual.html>.