Finding Your Way Around the LLVM Dependence Analysis Zoo

MemorySSA and DependenceAnalysis Tutorial

Outline

- What is Dependence Analysis ? Why do we care ?
- Basic Theory
- MemorySSA, DependenceAnalysis:
    - What are they ?
    - Theoretical Foundation
    - Important Implementation Details
    - Understanding their Output

Why Do We Care About Dependence Analysis ?

In reordering transformations, preserve the dependences and you preserve the semantics!

What Is Dependence Analysis ?

Gathering information about the dependences of a program.

Example: Read-After-Write (RAW)

```
int x = 2;
int y = 3;
int c = x * y;
```

Example: Write-After-Read (WAR)

```
// x == 10
int y = x * 2;
x = 3;
```

Example: Write-After-Write (WAW)

```
int x = 10;
x = 20;
int c = x * 2;
```

What is a Dependence ?

- Dependence is an ordering between two operations that we have to preserve.
- This arises because if we don't, a *read* may break.
- A *data* dependence exists because the two operations access the same memory location.

MemorySSA

Why MemorySSA?

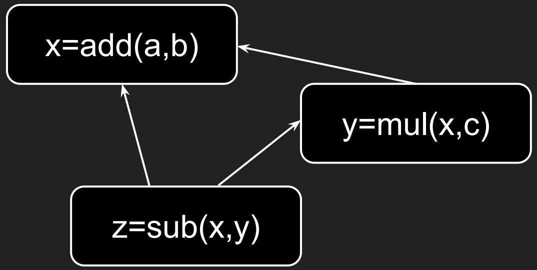
- Clean theory
- Minimalistic interface
- Actively used & maintained

The Idea

```
%x = add %a, %b
%y = mul %x, %c
%z = sub %x, %y
```

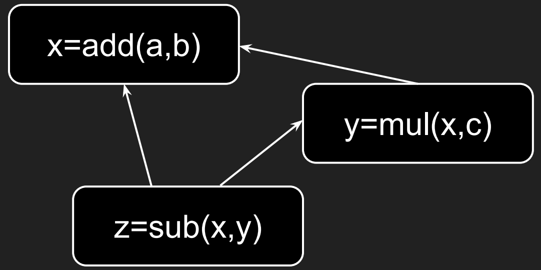
Def-Use Chains

```
%x = add %a, %b

%y = mul %x, %c

%z = sub %x, %y
```



Def-Use Chains

```
%x = add %a, %b
%y = mul %x, %c
%z = sub %x, %y
```




```
llvm::Value *X = /* %x */
for (auto *User : X->users()) {
  print(*User)
}

// %y, %z
```

```
llvm::Instruction *Z = /* %z */
for (auto *Op : Z->operands()) {
  print(*Op)
}

// %x, %y
```

Dependence

```
store %v, i32* %a

%y = load i32* %b

%z = load i32* %c
```

```
llvm::Instruction *Z = /* %z */
for (auto *Op : Z->operands()) {
  print(*Op)
}
```

// %c ~~%y, %z~~

Clobber & Alias

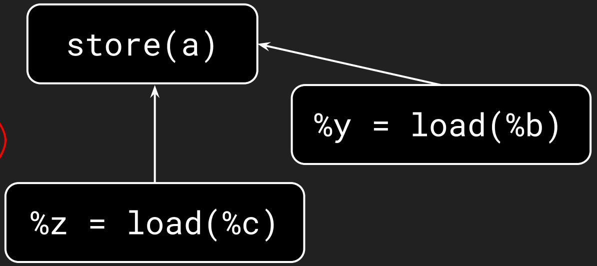
```
store %v, i32* %a

%y = load i32* %b

%z = load i32* %c
```

Alias: Can `%c` point to the same memory as `%a`?

Clobber:
If a `store` happens before a `load` and the pointers *alias*.
-> the `store` is a **clobber** of the `load`

Clobber & Alias

```
store %v, i32* %a

%y = load i32* %b

%z = load i32* %c
```



Alias: Can %c point to the same memory as %a?

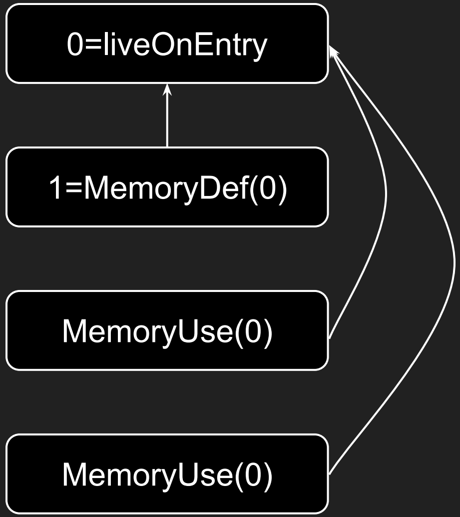
Clobber:
If a store happens before a load and the pointers *alias*.
-> the store is a **clobber** of the load

SSA on versioned Memory

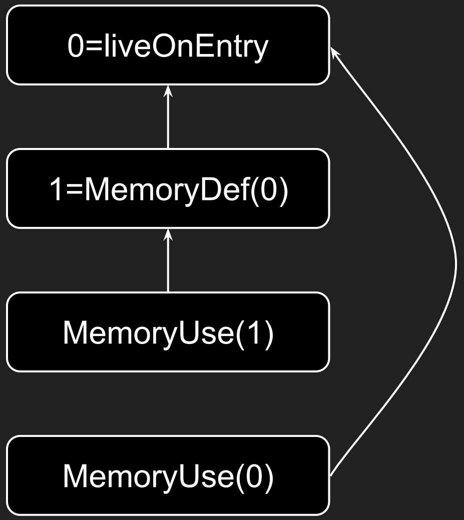
- `liveOnEntry` - memory state at function entry
- `x = MemoryDef(y)` - modify memory version `y` producing `x` (eg for a `store`)
- `MemoryUse(x)` - read memory version `x` (eg for a `load`)
- `MemoryPhi(x,y,..)` - merge incoming memory versions at block entry

	0=liveOnEntry
`store %v, i32* a`	MemoryDef
`%y = load i32* %b`	MemoryUse
`%z = load i32* %c`	MemoryUse

```
%a = alloca i32
%b = alloca i32
%c = alloca i32

store %v, i32* %a

%y = load i32* %b

%z = load i32* %c
```

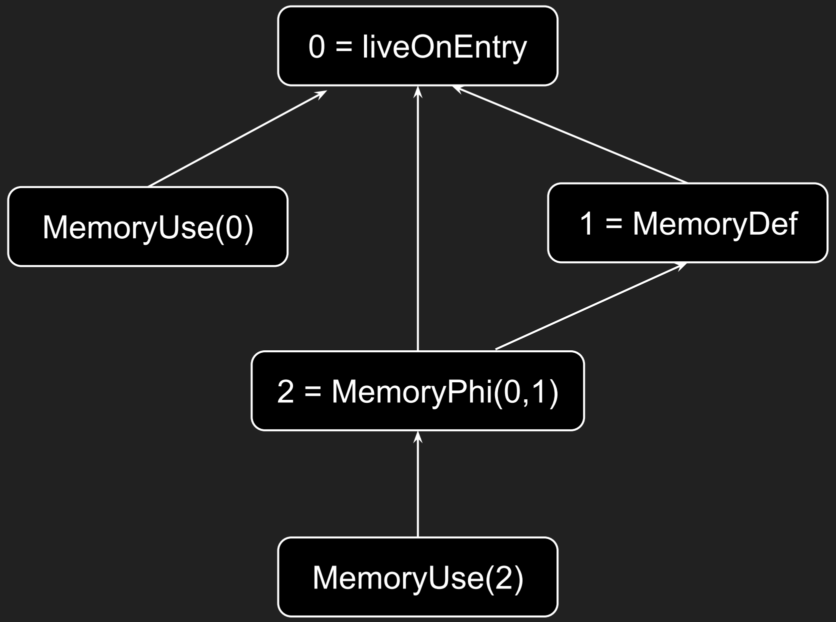


```
def @foo(i32* %a,i32 %i) {
  %b = getelementptr %a, %i
  %c = alloca i32

  store %v, i32* %a


  %y = load i32* %b


  %z = load i32* %c
}
```



Memory SSA

```
define void @f(i32* %p, i1 %cond) {
entry:
; MemoryUse(liveOnEntry)
  %0 = load i32, i32* %p, align 4
  br i1 %cond, label %if.then, label %if.end

if.then:
; 1 = MemoryDef(liveOnEntry)
  store i32 42, i32* %p, align 4
  br label %if.end

if.end:
; 2 = MemoryPhi({entry,liveOnEntry},{if.then,1})
; MemoryUse(2)
  %1 = load i32, i32* %p, align 4
  ret void
}
```

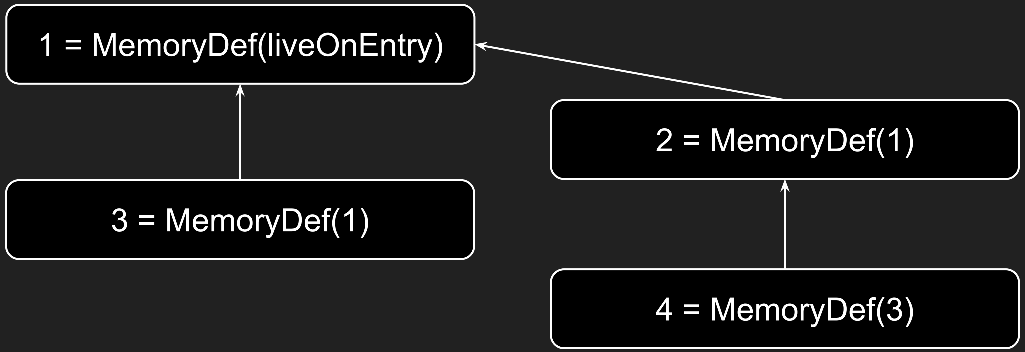


Limitations

..and how to walk past them

```
def @foo(i32* noalias A, i32* noalias B) {
  ...
  store i32 1, i32* %A
  ...
  store i32 2, i32* %B
  ...
  store i32 3, i32* %A
  ...
  store i32 4, i32* %B
  ...
}
```

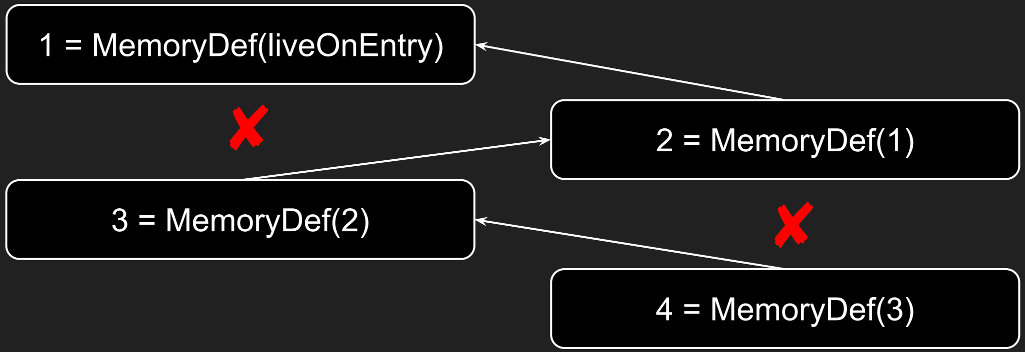
```
def @foo(i32* noalias A, i32* noalias B) {
  ...
  store i32 1, i32* %A
  ...
  store i32 2, i32* %B
  ...
  store i32 3, i32* %A
  ...
  store i32 4, i32* %B
  ...
}
```



(not actually the Memory SSA graph)

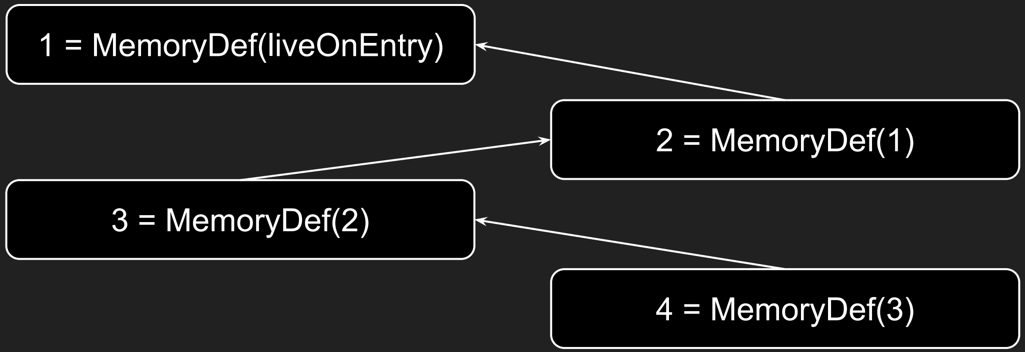
Unique Memory State

```
def @foo(i32* noalias A, i32* noalias B) {
   ...
   store i32 1, i32* %A
   ...
   store i32 2, i32* %B
   ...
   store i32 3, i32* %A
   ...
   store i32 4, i32* %B
   ...
}
```



The Walker

```
def @foo(i32* noalias A, i32* noalias B) {
   ...
   store i32 1, i32* %A
   ...
   store i32 2, i32* %B
   ...
   store i32 3, i32* %A
   ...
   store i32 4, i32* %B
   ...
}
```




```
auto *Walker = MemorySSA->getWalker();
Walker->getClobberingMemoryAccess(/* 4 */)
// 2 = MemoryDef(1)
```

Conclusion

- MemorySSA: SSA on memory versions.
- Better results with The Walker.
- Use it! Clean, maintained, actively used, evolving

Stuff I didn't talk about

- How does MemorySSA know what aliases what?
  - -> AliasAnalysis
- Custom Walkers
- MayAlias, MustAlias, ModRef, ..

DependenceAnalysis

DependenceAnalysis analyzes dependences between pairs of memory accesses. Currently, it is an (incomplete) implementation of the approach described in:

Practical Dependence Testing
Goff, Kennedy, Tseng
PLDI 1991

```
std::unique_ptr<Dependence>
DependenceInfo::depends(Instruction *Src,
                        Instruction *Dst,
                        bool PossiblyLoopIndependent) {
```

Loops Are Especially Interesting

Loop-Specific Dependences:

- Loop-Independent
- Loop-Carried

Example: Loop-Independent Dependence

```
for (int i = 0; i < ...; ++i) {
  A[i] *= 2;
  y += A[i] + C;
}
```

Any single iteration of the loop has this dependence.

Example: Loop-Carried Dependence

```
for (int i = 0; i < ...; ++i) {
  int temp = A[i];
  A[i + 2] = temp;
}
```

Exists exactly because of the loop.

One iteration depends on another.

Example: Loop-Carried Dependence (Unrolled)

```
1 ---------------------------- i = 0;
2 temp = A[0];
3 A[2] = temp;
4 ---------------------------- i = 1;
5 temp = A[1];
6 A[3] = temp;
7 ---------------------------- i = 2;
8 temp = A[2];
9 A[4] = temp;
10 ...
```

Statements in lines 3 and 8 are dependent.

Distance / Direction Vectors

```
for (int i = 0; i < ...; ++i) {
  int temp = A[i];
  A[i + 2] = temp;
}
```

How many iterations from one access to another (on the same memory location) ?

Example: Dependence Distance

```
------------------------------ i = 0;
temp = A[0];
A[2] = temp;
------------------------------ i = 1;
temp = A[1];
A[3] = temp;
------------------------------ i = 2;
temp = A[2];
A[4] = temp;
------------------------------ i = 3;
temp = A[3];
A[5] = temp;
------------------------------ i = 4;
temp = A[4];
A[6] = temp;
...
```

The distance is (usually) constant.

Multi-Dimensional Distance / Direction Vectors

```
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    for (int k = 0; k < ...; ++k)
      A[i+1][j][k-1] = A[i][j][k] + C

Distance Vector: (1, 0, -1)
Direction Vector: (<, =, >)
```

Dependence Tests

How can the compiler deduce (in)dependences in some automatic, yet precise way ?

Indices and Subscripts

```
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    for (int k = 0; k < ...; ++k)
      A[i][j] = A[i][k];
```

Indices of the loop nest: $i,\ j,\ k$

Subscripts of the access pair:

$(i,\ i),\ (j,\ k)$

Subscript Classification

1) Complexity
2) Separability

Subscript Complexity

```
// Assume that `N` is loop-invariant.
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    for (int k = 0; k < ...; ++k)
      A[5][i+1][j] = A[N][i][k] + C;

```

How many indices each subscript uses ?

Subscript Separability

```
// Assume that `N` is loop-invariant.
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    for (int k = 0; k < ...; ++k)
      A[i][j][j] = A[i][j][k] + C;

```

How many subscripts use the same index ?

This is all good but...

LLVM IR does not have indices, subscripts or C-style multi-dimensional array accesses.

Quick answer: SCEV everywhere.

Multi-dimensional accesses in C: Multi-Indirection Pointers

```c
int ***A;
...
A[i][j][k];
```

Difficult to deal with because of no aliasing guarantees.

Multi-dimensional accesses in C: “Multi-Dimensional” Arrays

```
int A[][M];
...
A[i][j] is really A[i*M + j]
```

A multi-dimensional access is just syntactic sugar for a linear access.

Multi-dimensional accesses in C: “Multi-Dimensional” Arrays

We have to use *SCEV Delinearization* to turn `A[i*M + j]` back to `A[i][j]`, which is not always perfect.

Multi-dimensional accesses in C: “Multi-Dimensional” Arrays

```
int A[][M];
...
A[i][j] is really A[i*M + j]
```

Because it’s actually a linear access, there are no in-bounds guarantees for each dimension.

Returning to our question: How do we come up with automatic dependence tests ?

Quick answer: Look at the subscripts.

ZIV (Zero Index Variable) Test

No indices used in the subscript. Two cases: They’re either equal or they’re not.

ZIV (Zero Index Variable) Test

```
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    A[i][0] = A[i+1][0];
```

They *are* equal. We can *squash* their dimension.

ZIV (Zero Index Variable) Test

```
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    A[i] = A[i+1];
```

Equivalent subscripts.

ZIV (Zero Index Variable) Test

```
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    A[i][0] = A[i][1];
```

They're *not* equal. We always access different columns, so no dependence.

ZIV (Zero Index Variable) Test

```
// Assume x, y, N, T
// are loop-invariant
for (int i = 0; i < ...; ++i)
  for (int j = 0; j < ...; ++j)
    A[i][x+y] = A[i][N-T];
```

The ZIV subscripts can be complex as long as they’re loop-nest-invariant.

SIV (Single Index Variable) Subscript Test

Exactly one index used in the subscript. Hard to solve in full generality. We show 2 common subcases.

Strong SIV Test:

(ai + c1, ai + c2)

```
for (int i = 0; i < 2*N; i += 2)
  A[i+3] = A[i];

-->

for (int i = 0; i < N; ++i)
  A[2*i+3] = A[2*i];

Subscript: (2*i + 3, 2*i)
a = 2, c1 = 3, c2 = 0
```

a is usually the step.

Strong SIV Test:

(ai + c1, ai + c2)

Dependence Distance: $d = \frac{c1 - c2}{a}$

You have to cover `c1 - c2` distance by moving in steps of `a`.

Strong SIV Test:

(ai + c1, ai + c2)

Dependence Distance: $d = \frac{c1 - c2}{a}$

A dependence exists if and only if d is an integer and |d| <= U - L, where U and L are the loop upper and lower bounds.

Weak SIV Subscripts:

`(a1*i + c1, a2*i + c2)`

Now a1 != a2 ! Again, it’s hard to solve it in full generality but we show 2 common subcases.

Weak-Zero SIV Subscripts:

`(a1*i + c1, a2*i + c2)`

Subcases:

- (Weak-Zero) a1 = 0 or a2 = 0
- (Weak-Crossing) a1 = -a2

Weak-Zero SIV Test:

*(a1*i + c1, a2*i + c2)*

a1 = 0 or a2 = 0. Assume a2 = 0.

It finds dependences caused by a particular iteration `i` = $\frac{c2 - c1}{a1}$

Again, `i` needs to be an integer and within loop bounds for a dependence to exist.

Weak-Zero SIV Test:

*(a1*i + c1, a2*i + c2)*

```
for (int i = 1; i <= N; ++i)
  A[i][N] = A[1][N] + A[N][N];
```

`A[1][N]` causes a dependence from the first iteration to all others. Similarly, `A[N][N]` causes a dependence from all iterations to the last. We can peel those two!

Peel the first and last iterations

```
A[1][N] = A[1][N] + A[N][N];
for (int i = 2; i <= N-1; ++i)
  A[i][N] = A[i][N] + A[N][N];
A[N][N] = A[1][N] + A[N][N];
```

Weak-Crossing SIV Test: *(a1*i + c1, a2*i + c2)*

a1 = -a2. It finds dependences meeting at a particular iteration:

$$i = \frac{c2 - c1}{2*a1}$$

Why 2 is there ? And what the condition for a dependence is ?

Weak SIV Subscripts:

*(a1*i + c1, a2*i + c2)*

In general, we can view the SIV tests as line tests.

Geometric View of SIV Tests