code analysis *and* transformation

Alias Analysis

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Memory alias analysis: the problem

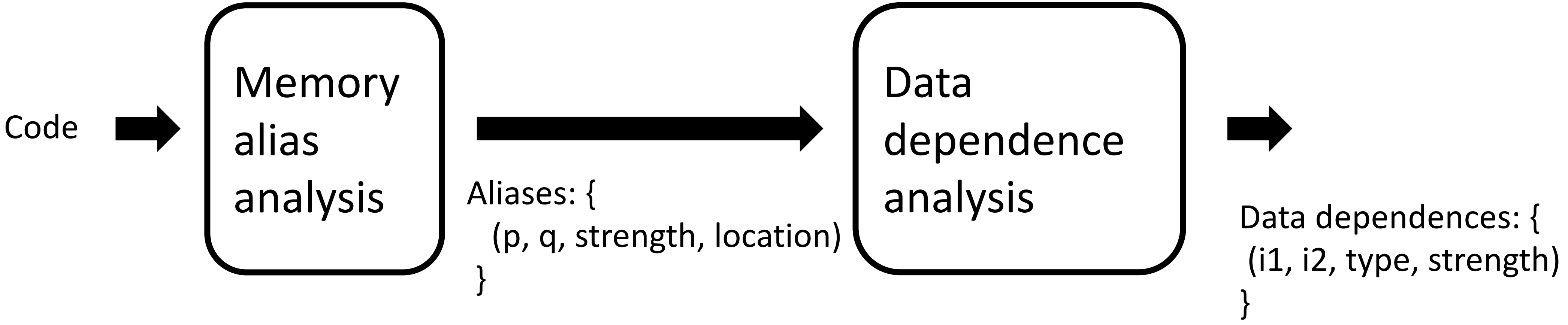
- Does *j* depend on *i* ?

```
i: (*p) = varA + 1
j: varB = (*q) * 2
```

```
i: obj1.f = varA + 1
j: varB= obj2.f * 2
```

- Do p and q point to the same memory location?
  - Does q alias p?

Memory alias/data dependence analysis



Outline

- Enhance CAT with alias analysis
- Simple alias analysis
- Alias analysis in LLVM

Let’s start looking at the interaction between

memory alias analysis

and

a code transformation you are familiar with:
constant propagation

Escape variables

```
int x, y;
int *p;
p = &x;
myF(p);
...
```

```
void myF (int *q){
   ...
}
```

Constant propagation revisited

```
int x, y;
int *p;
... = &x;
...
x = 5;
*p = 42;
y = x + 1;
```

We need to know which variables escape.
(think about how to do it in LLVM)

Is x constant here?

- If p **does not point** to x, then x = 5
- Yes, because x doesn't "escape" and therefore only one value of x reaches this last statement
- If p **definitely points** to x, then x = 42
- If p **might point** to x, then we have two reaching definitions that reach this last statement, so x is not constant

Goal of memory alias analysis: understanding

To exploit **memory alias analysis** in a code transformation

typically you extend the related code analyses

to use the information about pointer aliases

Do you remember liveness analysis?

- A variable v is live at a given point of a program p if
  - Exist a directed path from p to an use of v and
  - that path does not contain any definition of v
- Liveness analysis is backwards
- What is the most conservative output of the analysis?

GEN[i] = ?   KILL[i] = ?

$IN[i] = GEN[i] \cup (OUT[i] - KILL[i])$

$OUT[i] = \bigcup_{s \text{ a successor of } i} IN[s]$

Liveness analysis revisited

int x, y;

int *p;

... = &x;

x = 5;

...(no uses/definitions of x)

*p = 42;

y = x + 1;

How can we modify liveness analysis?

Is x alive here?

- If p **does not point** to x, then
  yes
  value of x stored there will be used later
- If p **definitely points** to x, then
  no
- If p **might point** to x, then
  yes

Liveness analysis revisited

mayAliasVar : variable -> set<variable>

mustAliasVar: variable -> set<variable>

How can we modify conventional liveness analysis?

GEN[i] = {v | variable v is used by i}

KILL[i] = {v' | variable v' is defined by i}

$$IN[i] = GEN[i] \cup (OUT[i] - KILL[i])$$

$$OUT[i] = \bigcup_{s \text{ a successor of } i} IN[s]$$

Liveness analysis revisited

mayAliasVar : variable -> set<variable>

mustAliasVar: variable -> set<variable>

GEN[i] = {mayAliasVar(v) U mustAliasVar(v) | variable v is used by i}

KILL[i] = {mustAliasVar(v) | variable v is defined by i}

$$\text{IN}[i] = \text{GEN}[i] \cup (\text{OUT}[i] - \text{KILL}[i])$$

$$\text{OUT}[i] = \bigcup_{s \text{ a successor of } i} \text{IN}[s]$$

Trivial analysis: no code analysis

```
int x, y;
int *p;
... = &x;
x = 5;
...(no uses/definitions of x)
*p = 42;
y = x + 1;
```

Trivial memory alias analysis

Nothing must alias
Anything may alias everything else

GEN[i] = {mayAliasVar(v) U mustAliasVar(v) | v is used by i}

KILL[i] = {mustAliasVar(v) | v is defined by i}

IN[i] = GEN[i] $\cup$ (OUT[i] – KILL[i])

OUT[i] = $\bigcup_{s \text{ a successor of } i}$ IN[s]

Great alias analysis impact

int x, y;

int *p;

... = &x;

~~x = 5;~~

...(no uses/definitions of x)

*p = 42;

y = $\cancel{x}_{5}$ + 1;

Great memory alias analysis

No aliases

Some compilers expose only data dependences.
How can we compute aliases for them?

GEN[i] = {mayAliasVar(v) U mustAliasVar(v) | v is used by i}

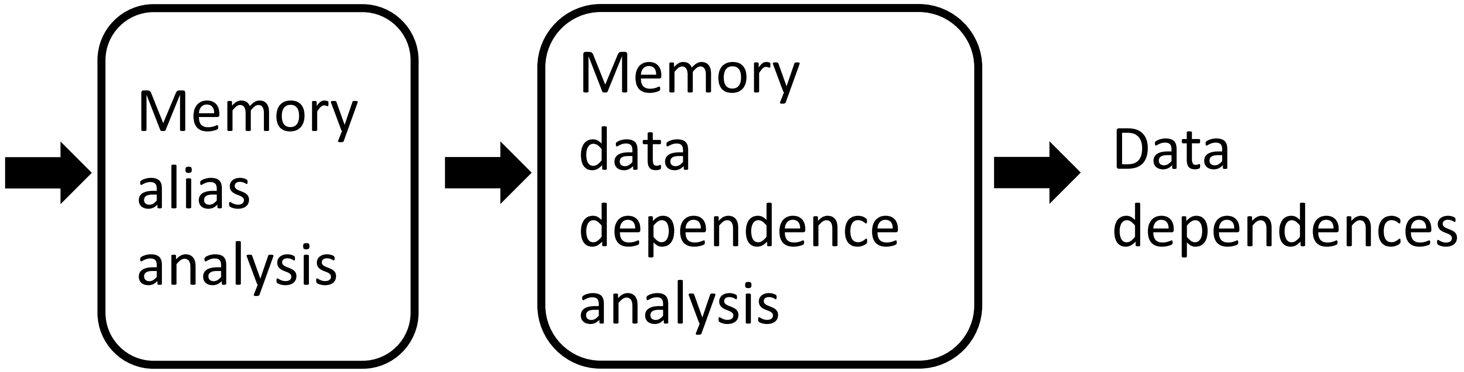
KILL[i] = {mustAliasVar(v) | v is defined by i}

IN[i] = GEN[i] $\cup$ (OUT[i] – KILL[i])

$\mathrm{OUT}[i] = \bigcup_{s \text{ a successor of } i} \mathrm{IN}[s]$

Data dependences and pointer aliases

```
int x, y;
int *p;
... = &x;
...
x = 5;
*p = 42;
y = x + 1;
```



Outline

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- Simple alias analysis

- Alias analysis in LLVM

Memory alias analysis

- **Assumption**:
  no dynamic memory, pointers can point only to variables

- **Goal**:
  at each program point, compute set of (p->x) pairs
  if p points to variable x

- **Approach**:
  - Based on data-flow analysis
  - May information

```
1: p = &x ;
2: q = &y;
3: if (...){
4:   z = &v;
   }
5: x++;
6: p = q;
7: print *p
```

May points-to analysis

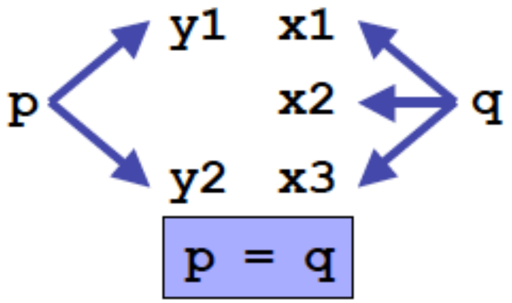
...
Which variable does p point to? → print *p

- Data flow values:

  {(v, x) | v is a pointer variable and x is a variable}

- Direction: forward
- i: p = &x
  - GEN[i] = {(p, x)}   KILL[i] = {(p, v) | v "escapes"}
  - OUT[i] = GEN[i] U (IN[i] – KILL[i])
- IN[i] = $U_{\text{p is a predecessor of i}}$ OUT[p]   Why?
- Different OUT[i] equation for different instructions
- i: p = q
  - GEN[i] = { }   KILL[i] = { }

    OUT[i] = {(p, z) | (q, z) $\in$ IN[i]} U (IN[i] – {(p,x) for all x})



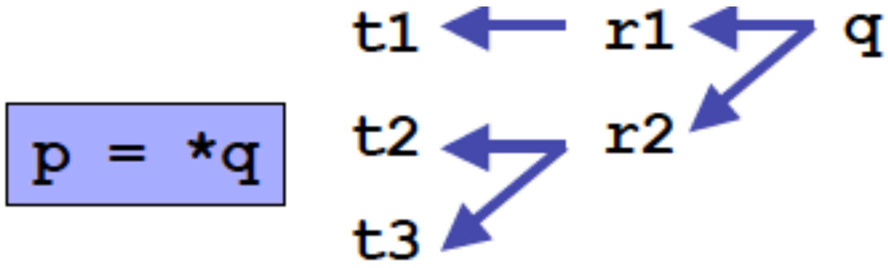
Code example

```
1: p = &x ;
2: q = &y;
3: if (…){
4:   z = &v;
   }
5: x++;
6: p = q;
```

GEN	KILL
GEN[1] = {(p, x)}	KILL[1] = {(p, x), (p, y), (p,v)}
GEN[2] = {(q, y)}	KILL[2] = {(q, x), (q, y), (q,v)}
GEN[3] = { }	KILL[3] = { }
GEN[4] = {(z, v)}	KILL[4] = {(z, x), (z, y), (z, v)}
GEN[5] = { }	KILL[5] = { }
GEN[6] = { }	KILL[6] = { }

IN	OUT
IN[1] = { }	OUT[1] = {(p,x)}
IN[2] = {(p,x)}	OUT[2] = {(q,y),(p,x)}
IN[3] = {(q,y),(p,x)}	OUT[3] = {(q,y),(p,x)}
IN[4] = {(q,y),(p,x)}	OUT[4] = {(z,v),(q,y),(p,x)}
IN[5] = {(z,v),(q,y),(p,x)}	OUT[5] = {(z,v),(q,y),(p,x)}
IN[6] = {(z,v),(q,y),(p,x)}	OUT[6] = {(p,y),(z,v),(q,y)}

May points-to analysis



- IN[i] = $\mathrm{U}_{\text{p is a predecessor of i}}$ OUT[p]
- i: p = &x
  - GEN[i] = {(p,x)} KILL[i] = {(p,v) | v “escapes”}
  - OUT[i] = GEN[i] U (IN[i] – KILL[i])
- i: p = q
  - GEN[i] = { } KILL[i] = { }
    OUT[i] = {(p,z) | (q,z) $\in$ IN[i]} U (IN[i] – {(p,x) for all x})
- i: p = *q
  - GEN[i] = { } KILL[i] = { }
    OUT[i] = {(p,t) | (q,r)$\in$IN[i] & (r,t)$\in$IN[i]} U (IN[i] – {(p,x) for all x})
- i: *q = p **?? (1 point)**

Memory alias analysis: dealing with dynamically allocated memory

- Issue: each allocation creates a new piece of memory

  p = new T(); p = malloc(10);

- Simple solution: generate a new "variable" for every DFA iteration to stand for new memory
- Extending our data-flow analysis

  OUT[i] = {(p, newVar)} U (IN[i] – {(p,x) for all x})

- Problem:
  - Domain is unbounded (why)?
  - Iterative data-flow analysis may not converge

Memory alias analysis: dealing with dynamically allocated memory

Simple solution

- Create a summary “variable” for each allocation statement
  - Domain is now bounded
- Data-flow equation

  i: p = new T

  $OUT[i] = \{(p, inst_i)\} \cup (IN[i] - \{(p,x) \text{ for all } x\})$

Alternatives

- Summary variable for entire heap
- Summary node for each type

$\boxed{\textbf{Analysis time/precision tradeoff}}$

Representations of aliasing

Alias pairs

- Pairs that refer to the same memory
- High memory requirements

Equivalence sets

- All memory references in the same set are aliases

Points-to pairs

- Pairs where the first member points to the second
- Specialized solution

How hard is the memory alias analysis problem?

- Undecidable
  - Landi 1992
  - Ramalingan 1994

- All solutions are conservative approximations

- Is this problem solved?
  - Numerous papers in this area
  - Haven’t we solved this problem yet? [Hind 2001]

Limits of intra-procedural analysis

```
foo() {
int x, y, a;
int *p;
x = 5;
p = foo(&x);
…
}
```

```
foo(int *p){
   return p;
}
```

Does the function call modify x? where does p point to?

- With our intra-procedural analysis, we don't know
- Make worst case assumptions
  - Assume that any reachable pointer may be changed
  - Pointers can be "reached" via globals and parameters
  - Pointers can be passed through objects in the heap
  - p may point to anything that might escape foo

Quality of memory alias analysis

- Quality decreases
  - Across functions
  - When indirect access pointers are used
  - When dynamically allocated memory is used

- Partial solutions to mitigate them
  - Inter-procedural analysis
  - Shape analysis

Outline

- Enhance CAT with alias analysis
- Simple alias analysis
- Alias analysis in LLVM

Using dependence analysis in LLVM

```
int x, y;
int *p;
... = &x;
x = 5;
...(no uses/definitions of x)
*p = 42;
y = x + 1;
```

→ Trivial memory alias analysis → Trivial memory data dependence analysis → Every memory instruction depends on every instruction that might access memory

Nothing must alias
Anything may alias everything else

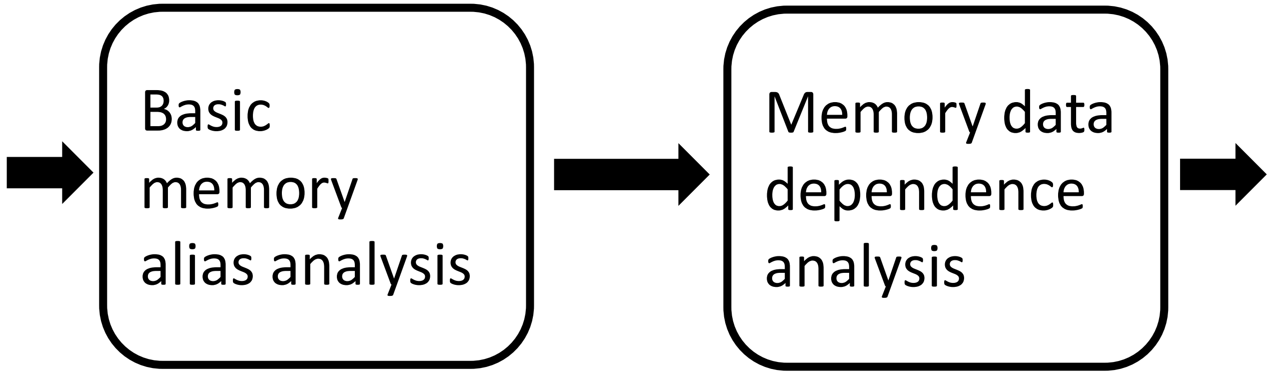
```
opt -no-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

LLVM alias analysis: basicaa

- Distinct globals, stack allocations, and heap allocations can never alias
  - p = &g1 ; q = &g2;
  - p = alloca(…); q = alloca(…);
  - p = malloc(…); q = malloc(…);
- They also never alias nullptr
- Different fields of a structure do not alias
- Baked in information about common standard C library functions
- … a few more …

Using basicaa

```
int x, y;
int *p;
... = &x;
x = 5;
...(no uses/definitions of x)
*p = 42;
y = x + 1;
```




```
opt -no-aa -CAT bitcode.bc -o optimized_bitcode.bc
opt -basicaa -CAT bitcode.bc -o optimized_bitcode.bc
```

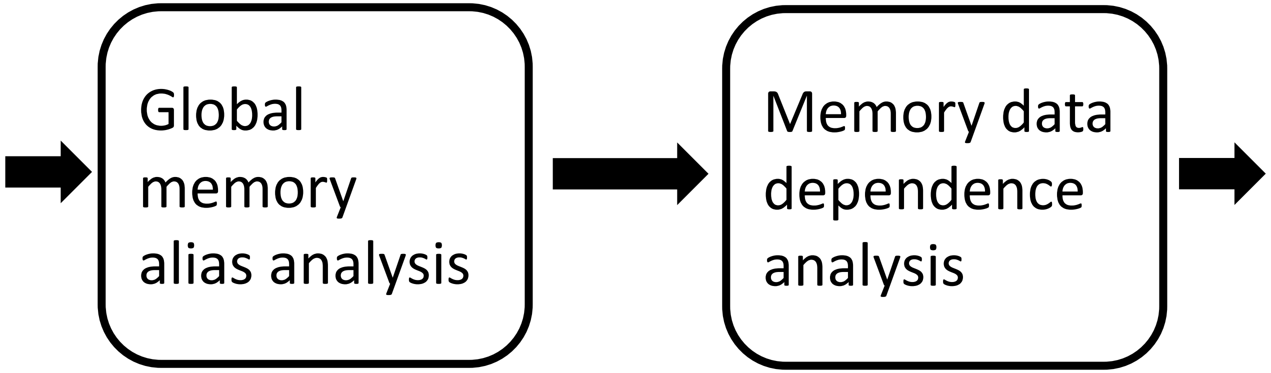
LLVM alias analysis: globals-aa

- Specialized for understanding reads/writes of globals
  - Analyze only globals that don't have their address taken
- Context-sensitive
- Mod/ref
- Provide information for call instructions
  - e.g., does call i read/write global g1?

```
int g1;
int g2;
void f (void *p1){
    … = &g2;
    g(p1);
    …
}
```

Using globals-aa

```
int x, y;
int *p;
... = &x;
x = 5;
...(no uses/definitions of x)
*p = 42;
y = x + 1;
```




```
opt -globals-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

- basicaa, globals-aa have their strengths and weaknesses

- We would like to use both of them!

- LLVM can chain alias analyses ☺

Using basicaa and globals-aa

```
int x, y;
int *p;
... = &x;
x = 5;
...(no uses/definitions of x)
*p = 42;
y = x + 1;
```


```
opt -basicaa -globals-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

Other LLVM alias analyses

- tbaa
- cfl-steens-aa
- scev-aa
- cfl-anders-aa

- + others not included in the official LLVM codebase

Alias analyses used

- How can we find out what AA is used in O0/O1/O2/O3?
  - opt –O3 -disable-output -debug-pass=Arguments bitcode.bc

- -O0:
- -O1: -basicaa -globals-aa –tbaa
- -O2: -basicaa -globals-aa -tbaa
- -O3: -basicaa -globals-aa –tbaa

- You can always extend O3 adding other AA

- We have seen how to invoke alias analyses

- How can we access alias information and/or dependences in a pass?

- How can we identify which variables might escape?

Identify escaped variables in LLVM

```
int main (int argc, char *argv[]){
  CATData d1  = CAT_create_signed_value(5);

  function_that_complicates_everything(&d1);

  int64_t value = CAT_get_signed_value(d1);

  printf("Values: %lld\n", value);

  return 0;
}
```

Identify escaped variables in LLVM

```
; Function Attrs: nounwind uwtable
define i32 @main(i32 %argc, i8** %argv) #0 {
  %d1 = alloca i8*, align 8
  %1 = call i8* @CAT_create_signed_value(i64 5)
  store i8* %1, i8** %d1, align 8
  call void @function_that_complicates_everything(i8** %d1)
  %2 = load i8*, i8** %d1, align 8
  %3 = call i64 @CAT_get_signed_value(i8* %2)
  %4 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
  ret i32 0
}
```

Identify escaped variables in LLVM

… and if variable references are passed to other functions …

Asking LLVM to run an AA before our pass

```
void getAnalysisUsage(AnalysisUsage &AU) const override {
  AU.addRequired< AAResultsWrapperPass >();
  return;
}
```

Which AA will run?

```
opt -basicaa -CAT bitcode.bc -o optimized_bitcode.bc
```

```
opt -globals-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

```
opt -basicaa -globals-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

AliasAnalysis LLVM class

- Interface between
  passes that use the information about pointer aliases and
  passes that compute them (i.e., alias analyses)
- To access the result of alias analyses:

```
bool runOnFunction (Function &F) override {
  AliasAnalysis &aliasAnalysis = getAnalysis< AAResultsWrapperPass >().getAAResults();
```

  - AliasAnalysis provides information about pointers used by F

```
bool runOnModule (Module &M) override {
  for (auto &F : M){
    if (F.empty()){
      continue ;
    }
    errs() << "Function \"" << F.getName() << "\"\n";

    AliasAnalysis &aliasAnalysis = getAnalysis< AAResultsWrapperPass >(F).getAAResults();
    checkFunction(M, F, aliasAnalysis);
  }
```

AliasAnalysis LLVM class: queries

- You can ask to AliasAnalysis the following common queries:
  - *Do these two memory objects alias?*

```
(*p1) = …
…      = *p2
```

  - Can this function call read/write a given memory object?
- Memory object representation:
  - Starting address (Value *)
  - Static size (e.g., 10 bytes)

```
p1 = malloc(sizeof(T1));
```

Why size is used to represent memory objects?

```
int i;
char C[2];
char A[10];
/* ... */
for (i = 0; i != 10; ++i) {
  ((short*)C)[0] = A[i];  /* Two byte store! */
  C[1] = A[9-i];          /* One byte store */
}
```

AliasAnalysis LLVM class: the alias method

- Query: the alias method

  aliasAnalysis.alias(…)

  Input: 2 memory objects

```
; ModuleID = 'program.bc'
source_filename = "program.c"
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
```

- The size can be platform dependent: … = malloc(sizeof(long int))

```
if (auto pointerType = dyn_cast<PointerType>(pointer->getType())){
  auto elementPointedType = pointerType->getElementType();
  if (elementPointedType->isSized()){
    size = currM->getDataLayout().getTypeStoreSize(elementPointedType);
  }
}
```

AliasAnalysis LLVM class: query results

- Constrain to use AliasAnalysis:
  - Value(s) used in the APIs that are not constant must have been defined in the same function
  - Make sure you are asking a valid question

- AliasAnalysis exports two enums used to answer alias queries:
  - AliasResult : NoAlias, MayAlias, PartialAlias, MustAlias
  - ModRefResult: MRI_NoModRef, MRI_Mod, MRI_Ref, MRI_ModRef

AliasResult

- MayAlias
  - Two pointers might refer to the same object
- NoAlias
  - Two pointers cannot refer to the same object
- MustAlias
  - Two pointers always refer to the same object
- PartialAlias
  - Two pointers always point to two objects that partially overlap

Alias query example

```
switch (aliasAnalysis.alias(pointer, sizePointer, pointer2, sizePointer2)){
  case NoAlias:
    errs() << "     No alias\n" ;
    break ;
  case MayAlias:
    errs() << "     May alias\n" ;
    break ;
  case PartialAlias:
    errs() << "     Partial alias\n" ;
    break ;
  case MustAlias:
    errs() << "     Must alias\n" ;
    break ;
  default:
    abort();
}
```

Memory instructions

- What if we want to use memory instructions directly?
  - e.g., can this load access the same memory object of this store?

```
switch (aliasAnalysis.alias(MemoryLocation::get(memInst), MemoryLocation::get(memInst2))){
  case NoAlias:
    errs() << "     No alias\n" ;
    break ;
  case MayAlias:
    errs() << "     May alias\n" ;
    break ;
  case PartialAlias:
    errs() << "     Partial alias\n" ;
    break ;
  case MustAlias:
    errs() << "     Must alias\n" ;
    break ;
  default:
    abort();
}
```

Mod/ref queries

- Information about whether the execution of an instruction can modify (mod) or read (ref) a memory location
- It is always conservative (like alias queries)
- API: getModRefInfo
- This API is often used
  to understand dependences between function calls

Mod/ref query example

... call inst, fence inst, ...

```
switch (aliasAnalysis.getModRefInfo(memInst, pointer, sizePointer)){
  case MRI_NoModRef:
    break ;
  case MRI_Mod:
    break ;
  case MRI_Ref:
    break ;
  case MRI_ModRef:
    break ;
  default:
    abort();
}
```

MemoryLocation

Other alias queries

The AliasAnalysis and ModRef API includes other functions

- pointsToConstantMemory
- doesNotAccessMemory
- onlyReadsMemory
- onlyAccessesArgPointees
- …