c⚙de analysis

and

transf⚙rmation

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?

Outline

- Enhance CAT with alias analysis

- Simple alias analysis

- Alias analysis in LLVM

Exploiting alias analysis in CATs

- Easiest: extending the transformation
- Midway: extending the analysis

This is what homework H5 is about!

- Hardest: writing a CAT-specific alias analysis

This is what homework H6 is about!

Let’s start looking at the interaction between

memory alias analysis

and

a code transformation you are familiar with:
constant propagation

… but first, let’s recall a term

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

(your H4)

Is x constant here?

- Yes, because x does not “escape” and therefore only one value of x reaches this last statement
- If p **does not point** to x, then x = 5 at the 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

Let's exploit alias analysis for making liveness analysis more powerful

- 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
- What is the most conservative output of the analysis? (the bottom of the lattice)

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

IN[i] = GEN[i] U(OUT[i] – KILL[i])

OUT[i] = $\cup_{s \text{ a successor of } i}$ 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
- Yes, because x = 5 doesn’t “escape” and the
  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

What is the most conservative output of the analysis?
(the bottom of the lattice)

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] U(OUT[i] – KILL[i])

OUT[*i*] = $U_{s \text{ a successor of } i}$ 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}

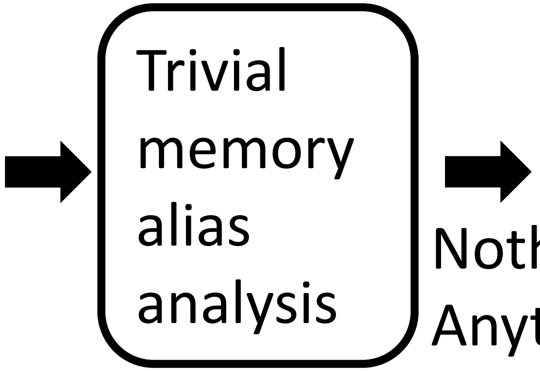
KILL[i] = {mustAliasVar(v) | variable v is defined by i}

IN[i] = GEN[i] U(OUT[i] – KILL[i])

OUT[*i*] = $\mathrm{U}_{s \text{ a successor of } i}$ 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] U(OUT[i] – KILL[i])

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

Great alias analysis impact

int x, y;

int *p;

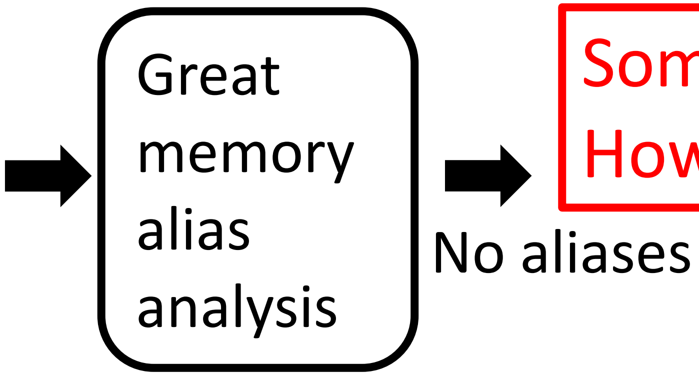
... = &x;

~~x = 5;~~

...(no uses/definitions of x)

*p = 42;

y = ~~x~~ + 1;
5



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] U(OUT[i] – KILL[i])

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

Outline

- Enhance CAT with alias analysis

- 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

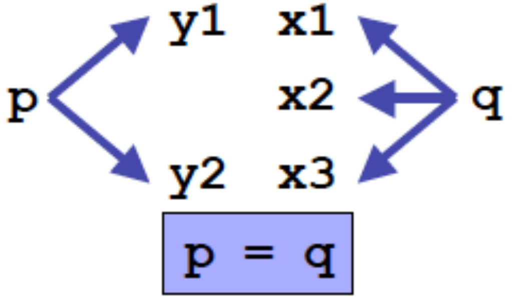
...

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] = {(p,x) | x escapes}

    OUT[i] = {(p, z) | (q, z) ∈ IN[i]} U (IN[i] – KILL[i])



Code example

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

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

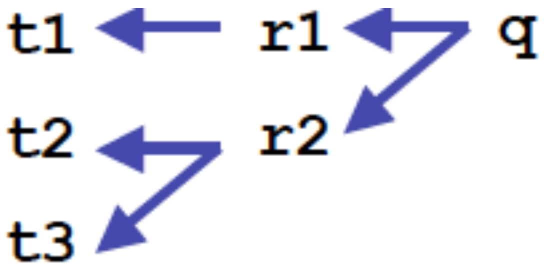
KILL[1] = {(p, x), (p, y), (p,v)}
KILL[2] = {(q, x), (q, y), (q,v)}
KILL[3] = { }
KILL[4] = {(z, x), (z, y), (z, v)}
KILL[5] = { }
KILL[6] = {(p, x), (p, y), (p, v)}

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

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

May points-to analysis

p = *q



- IN[i] = $U_{\text{p is a predecessor of i}}$ 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] = {(p,x) | x escapes}
    OUT[i] = {(p,z) | (q,z) ∈ IN[i]} U (IN[i] – KILL[i])
- i: p = *q
  - GEN[i] = { } KILL[i] = {(p,x) | x escapes}
    OUT[i] = {(p,t) | (q,r)∈IN[i] & (r,t)∈IN[i]} U (IN[i] – KILL[i])
- i: *q = p **?? (1 point)**

- This was a reasonable alias analysis for understanding pointers that could point only to variables

- How about pointers that could point to memory locations?
  (stack and heap)
  - Challenge: memory locations don’t have pre-defined symbols like variables

Memory alias analysis: dealing with dynamically allocated memory

- Each invocation of a memory allocator 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

```
for (i=0; i < 10; i++){
    v[i] = new malloc(100);
}
```

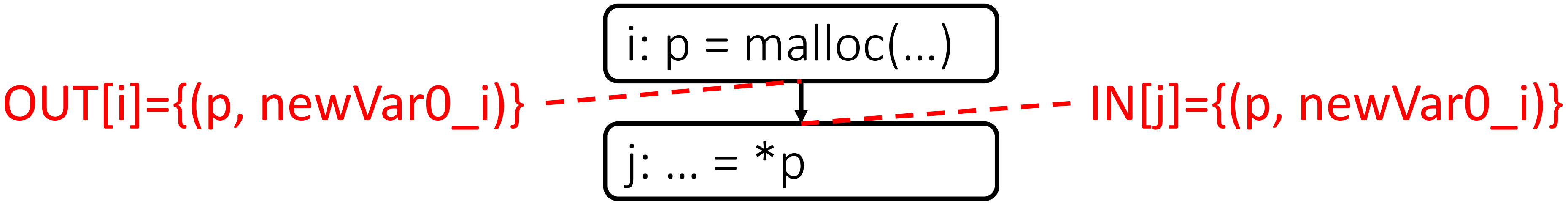
Memory alias analysis: dealing with dynamically allocated memory

- Each invocation of a memory allocator 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})



i: p = malloc(…)

j: … = *p

OUT[i]={(p, newVar0_i)}

IN[j]={(p, newVar0_i)}

Memory alias analysis: dealing with dynamically allocated memory

- Each invocation of a memory allocator creates a new piece of memory

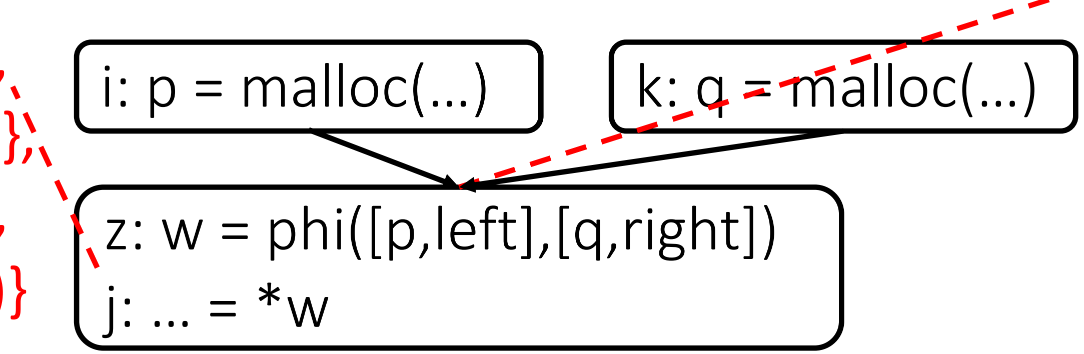
  p = new T();   p = malloc(10);

- 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})

IN[j]={ (p, newVar0_i),
(q, newVar0_k)},
(w, newVar0_i),
(w, newVar0_k)}



```
i: p = malloc(…)
```

```
k: q = malloc(…)
```

```
z: w = phi([p,left],[q,right])
j: … = *w
```

IN[z]={ (p, newVar0_i),
(q, newVar0_k)}

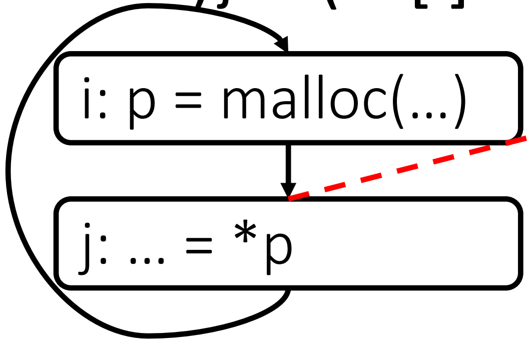
Memory alias analysis: dealing with dynamically allocated memory

- Each invocation of a memory allocator 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})



IN[j]={(p, newVar0_i),
(p, newVar1_i),
(p, newVar2_i),
…

Memory alias analysis: dealing with dynamically allocated memory

- Each invocation of a memory allocator 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
  - Iterative data-flow analysis may not converge

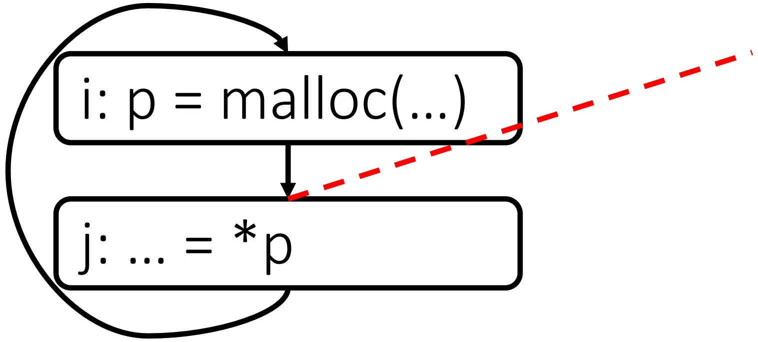
Memory alias analysis: dealing with dynamically allocated memory

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$_i$)} U (IN[i] – {(p,x) for all x})



IN[j]={(p, inst$_i$)}

Let us look at the implication of this design choice

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

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

```
for (i=0; i < 10; i++) v[i] = new malloc(100);
*(v[0]) = …
*(v[1]) = …
```

Alias analysis result:

v[i] and v[j] alias

Dependence analysis result:

These 2 instructions depend on each other

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$_i$)} U (IN[i] – {(p,x) for all x})

Alternatives

- Summary variable for odd iterations, summary variable for even iterations
- Summary variable for entire heap
- Summary node for each object type

Analysis time/precision tradeoff

Alias analysis common tradeoffs

- Field sensitivity

  obj->field1

  obj->field2

- Flow sensitivity

- Context sensitivity

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

How hard is the memory alias analysis problem?

- Undecidable
  - Landi 1992
  - Ramalingan 1994
- All solutions are conservative approximations
  - But all correct
- Is this problem solved?
  - Numerous papers in this area
  - Haven’t we solved this problem yet? [Hind 2001]

Alias analyses challenges

- So far we saw only one challenge: dynamic memory allocations

Let’s see the other challenges

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

The most accurate analyses are inter-procedural

Quality of memory alias analysis

- Quality decreases
  - Across functions
  - When indirect access pointers are used
  - When dynamically allocated memory is used
  - When pointer arithmetic is used
  - When pointer to/from integer casting 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

What is available in LLVM

- LLVM includes several alias analyses

- Each one is specialized to understand a different code pattern

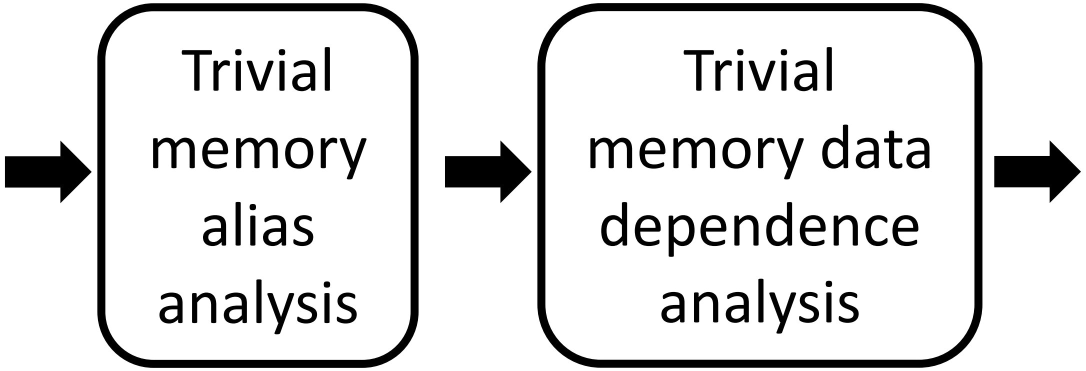
- Each one with its tradeoff between accuracy and analysis time

Using dependence analysis in LLVM

Nothing must alias

Anything may alias everything else

```
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

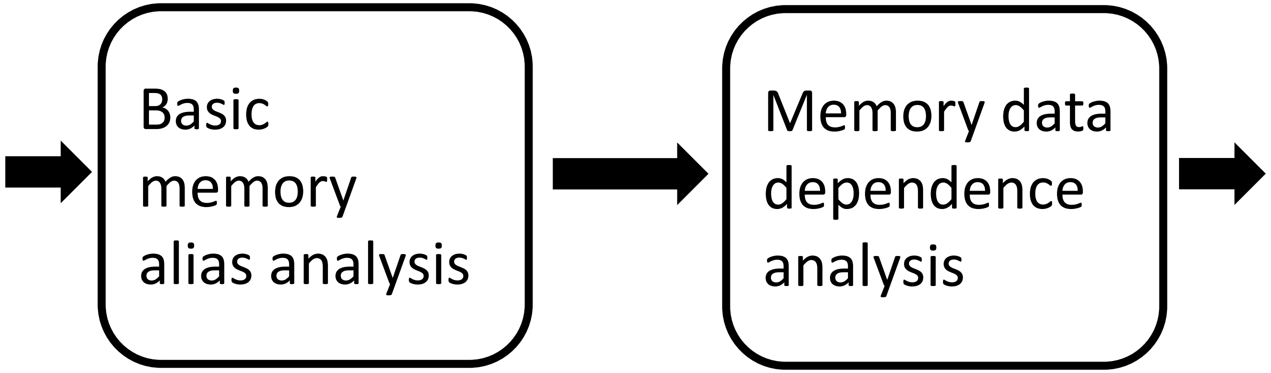
```
opt -no-aa -CAT bitcode.bc -o optimized_bitcode.bc
```

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

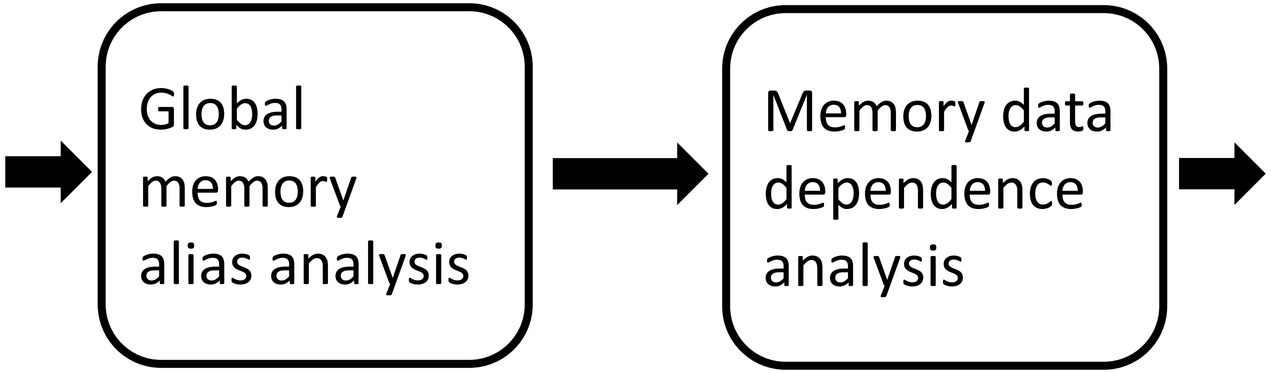
- Specialized for understanding reads/writes of globals
  - Analyze only globals that don’t have their address taken

- Context-sensitive
- 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
```

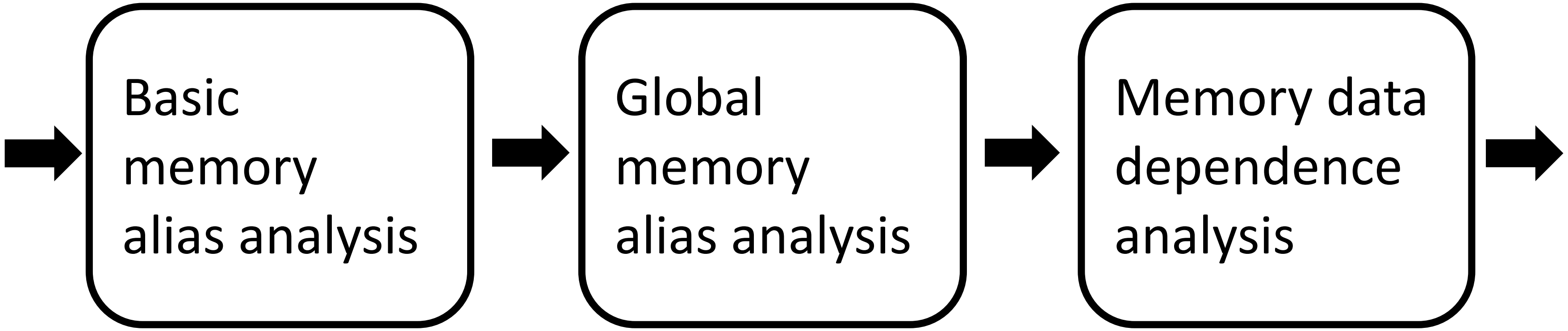
- basicaa, globals-aa have their strengths and weaknesses

- We would like to use both of them!

- LLVM can chain alias analyses ☺
  - Best of N

Using basicaa and globals-aa

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



Basic memory alias analysis

Global memory alias analysis

Memory data dependence analysis

```
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?

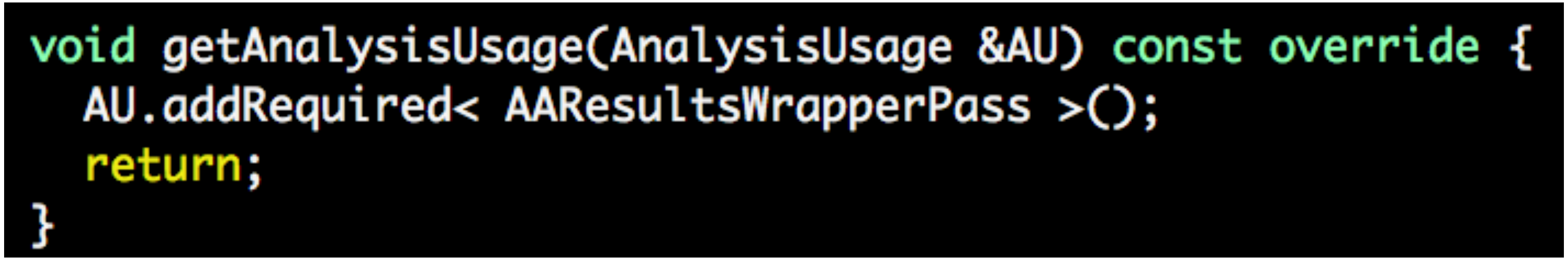
- What does ”alias” mean in LLVM exactly?
  What is the memory model adopted by LLVM?

- We have seen how to invoke alias analyses

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

- What does ”alias” mean in LLVM exactly?
  What is the memory model adopted by LLVM?

Asking LLVM to run an AA before our pass



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

Which AA will run?

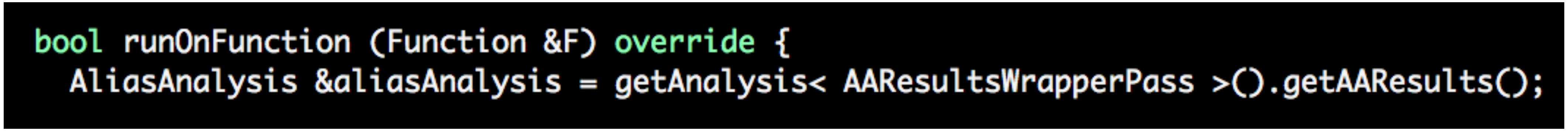
```
opt -basicaa -CAT bitcode.bc -o optimized_bitcode.bc
```

```
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
  - You cannot use the AA results to check aliases of other functions

AliasAnalysis LLVM class: queries

You can ask to AliasAnalysis the following common queries:

- *Do these two memory pointers alias?* alias(…)

```
(*p1) = …
…       = *p2
```

- Can this instruction read/write a given memory location? getModRefInfo(…)
  - Can this function call read/write a given memory location?
- Does this function reads/modifies memory at all?
- Does this function call read/write memory at all?

AliasAnalysis LLVM class: the memory location

- Memory location representation:
  - Starting address (Value *)
  - Static size (e.g., 10 bytes)

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

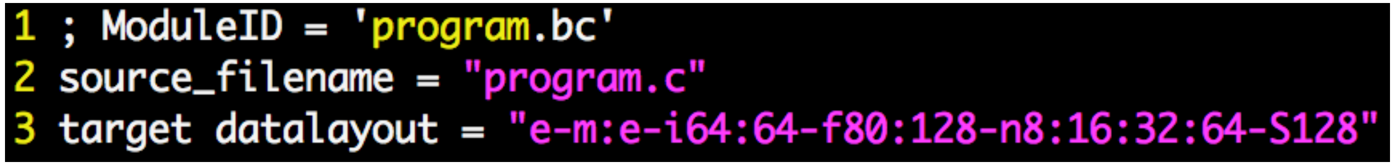
- From instruction/pointer to the memory location accessed
  - MemoryLocation::get(memInst)

AliasAnalysis LLVM class: the alias method

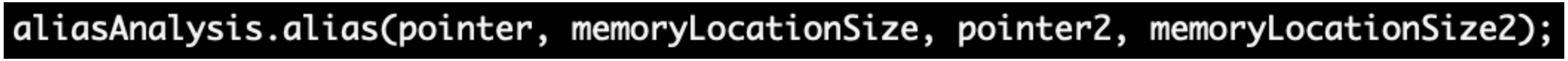
- Query: the alias method

  aliasAnalysis.alias(…)

  Input: 2 memory locations

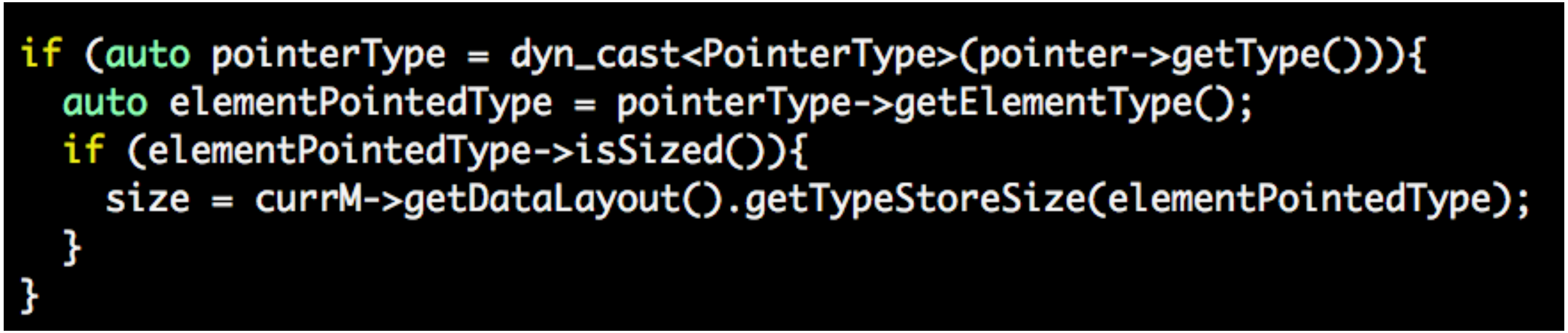


```
; ModuleID = 'program.bc'
source_filename = "program.c"
target datalayout = "e-m:e-i64:64-f80:128-n8:16:32:64-S128"
```



```
aliasAnalysis.alias(pointer, memoryLocationSize, pointer2, memoryLocationSize2);
```

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



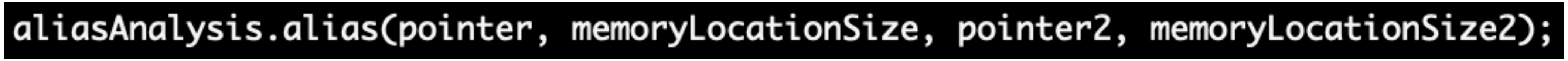
```
if (auto pointerType = dyn_cast<PointerType>(pointer->getType())){
  auto elementPointedType = pointerType->getElementType();
  if (elementPointedType->isSized()){
    size = currM->getDataLayout().getTypeStoreSize(elementPointedType);
  }
}
```

AliasAnalysis LLVM class: the alias method

- Query: the alias method

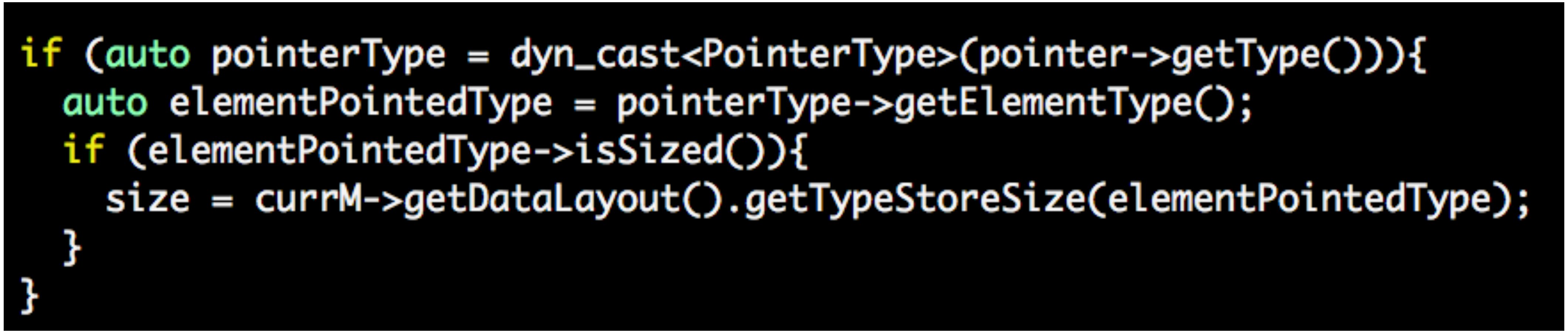
  aliasAnalysis.alias(…)

  Input: 2 memory locations



```
aliasAnalysis.alias(pointer, memoryLocationSize, pointer2, memoryLocationSize2);
```

- What if you don’t know the size of the memory location?



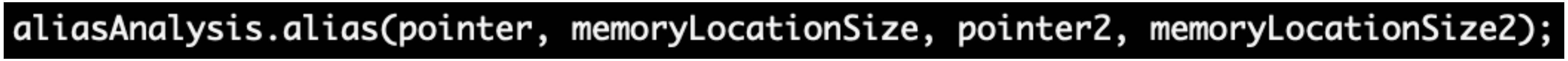
```
if (auto pointerType = dyn_cast<PointerType>(pointer->getType())){
  auto elementPointedType = pointerType->getElementType();
  if (elementPointedType->isSized()){
    size = currM->getDataLayout().getTypeStoreSize(elementPointedType);
  }
}
```

AliasAnalysis LLVM class: the alias method

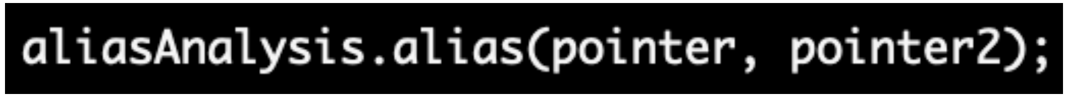
- Query: the alias method

  aliasAnalysis.alias(…)

  Input: 2 memory locations



```
aliasAnalysis.alias(pointer, memoryLocationSize, pointer2, memoryLocationSize2);
```

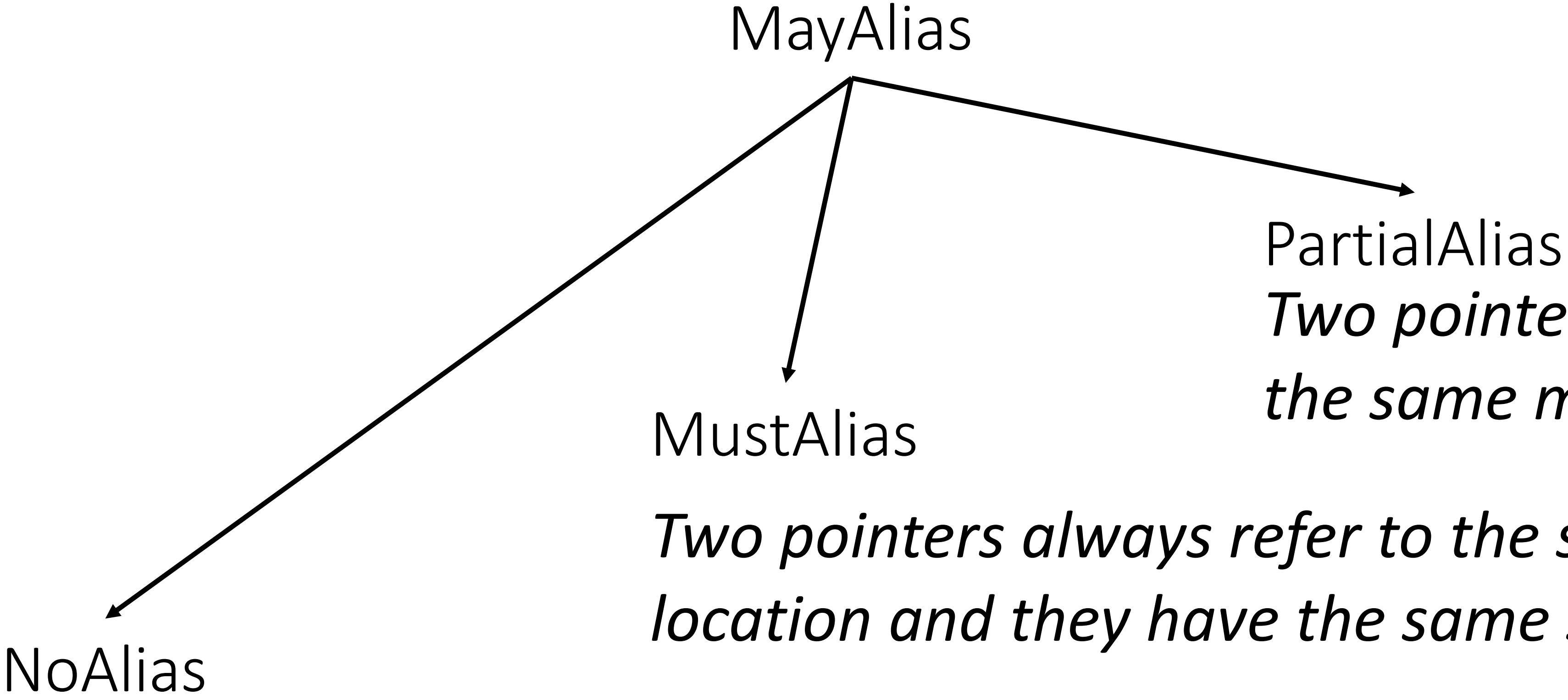


```
aliasAnalysis.alias(pointer, pointer2);
```

Constraint:
Value(s) used in the APIs that are not constant
must have been defined in the same function

Output: AliasResult (this is an enum)

AliasResult



Two pointers might refer to the same memory location

MayAlias

PartialAlias

Two pointers always refer to the same memory location

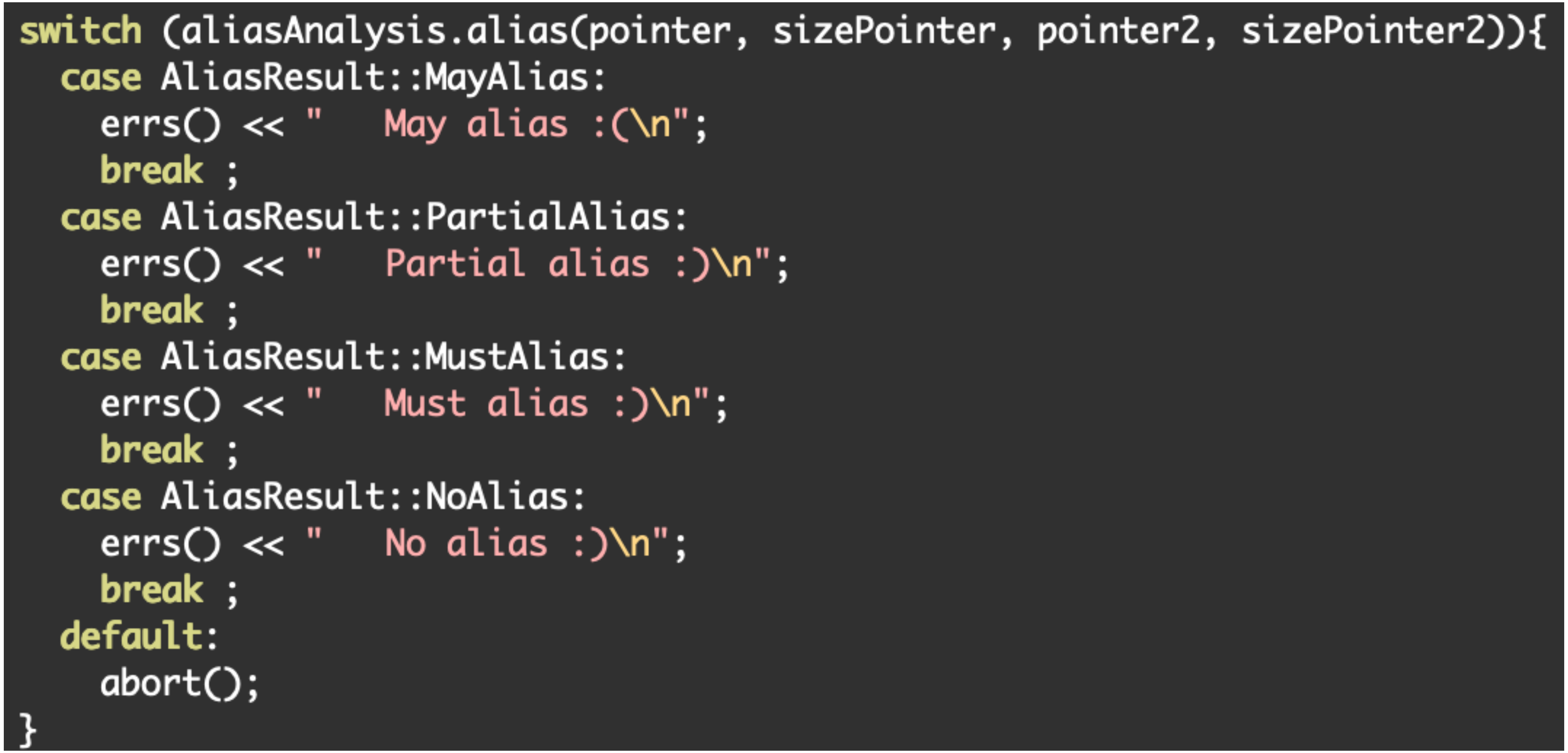
MustAlias

Two pointers always refer to the same memory location and they have the same start address

NoAlias

Two pointers cannot refer to the same memory location

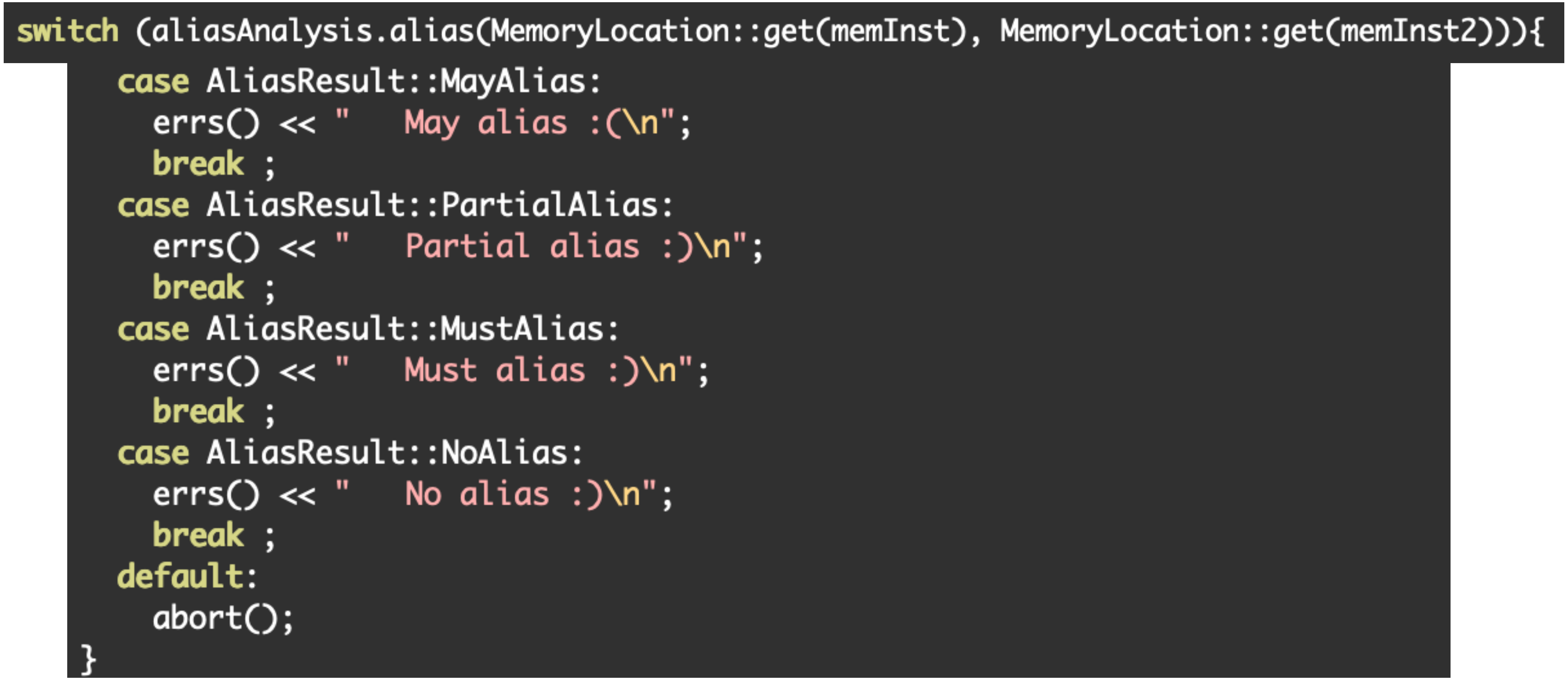
Alias query example



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

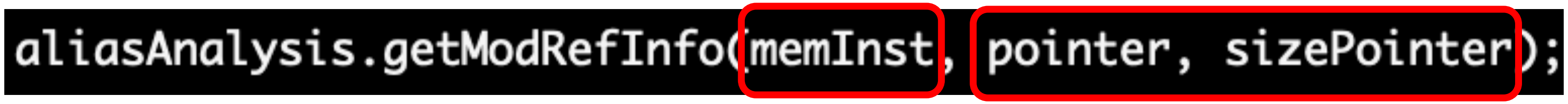
Mod/ref queries

- 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
  or between a memory instruction and a function call

Mod/ref query example

Input:

- An instruction
- A memory location



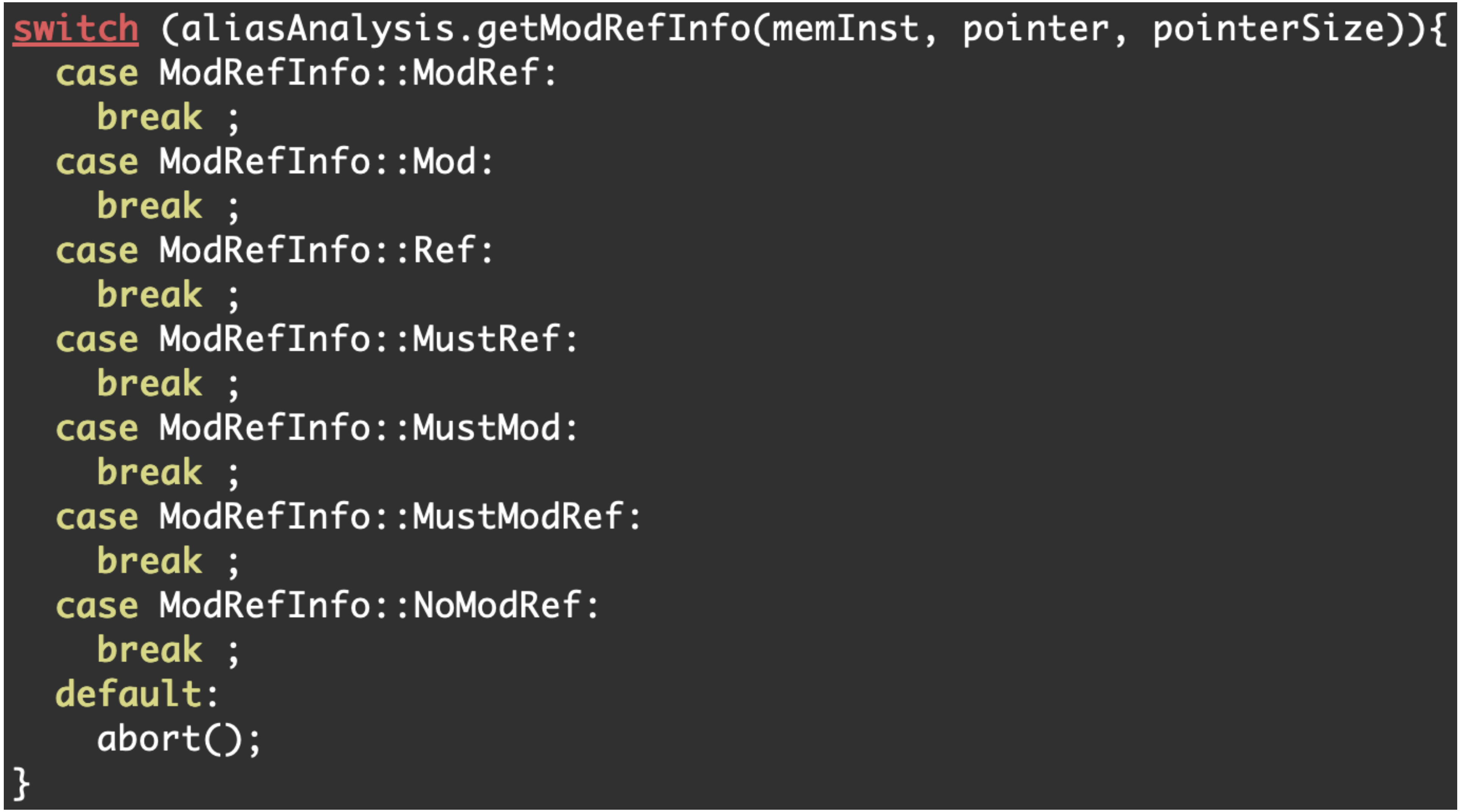
```
aliasAnalysis.getModRefInfo(memInst, pointer, sizePointer);
```

… call inst, fence inst, …

MemoryLocation

Output:

- Whether the memory location **may** be modified and/or **may** be read (the negation of may means cannot)
- ModRefInfo (this is an enum)



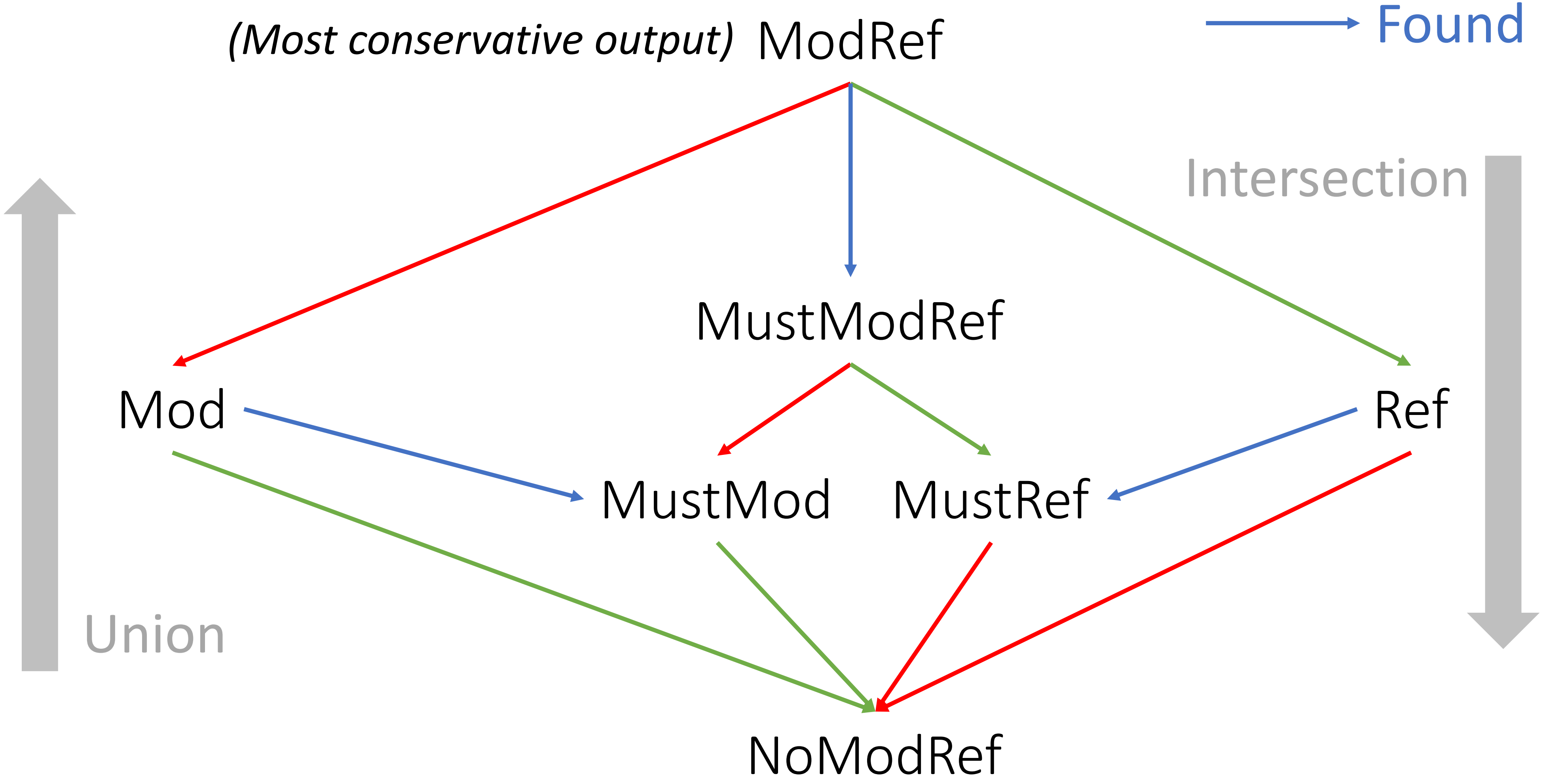
```
switch (aliasAnalysis.getModRefInfo(memInst, pointer, pointerSize)){
  case ModRefInfo::ModRef:
    break ;
  case ModRefInfo::Mod:
    break ;
  case ModRefInfo::Ref:
    break ;
  case ModRefInfo::MustRef:
    break ;
  case ModRefInfo::MustMod:
    break ;
  case ModRefInfo::MustModRef:
    break ;
  case ModRefInfo::NoModRef:
    break ;
  default:
    abort();
}
```

ModRefInfo

→ Found no ref

→ Found no mod

→ Found must alias



(Most conservative output) ModRef

MustModRef

Mod

Ref

MustMod

MustRef

NoModRef

Intersection

Union

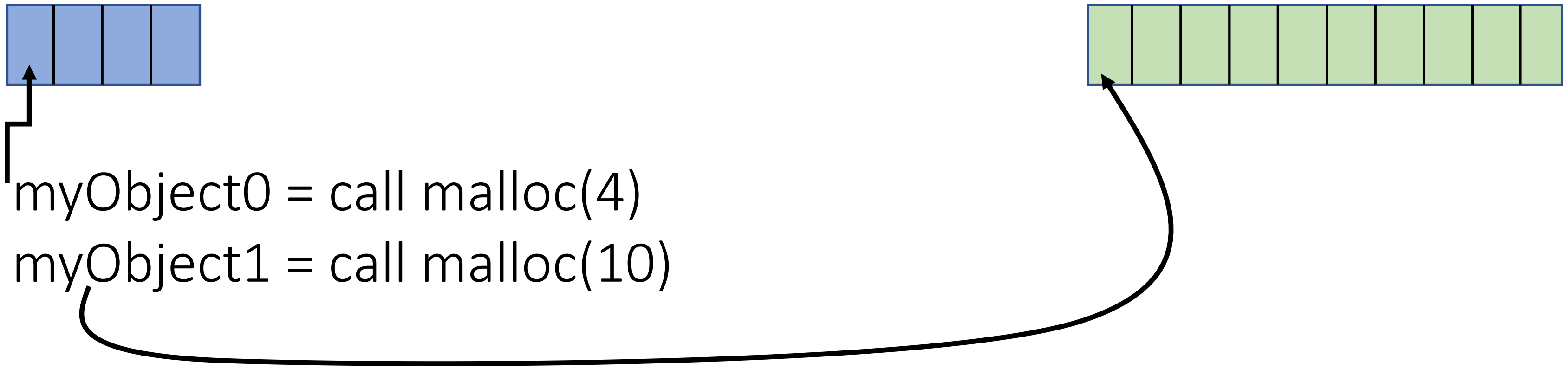
Other alias queries

The AliasAnalysis and ModRef API includes other functions

- pointsToConstantMemory
- doesNotAccessMemory
- onlyReadsMemory
- onlyAccessesArgPointees
- …

- We have seen how to invoke alias analyses
- How can we access alias information and/or dependences in a pass?
- What does ”alias” mean in LLVM exactly?
  What is the memory model adopted by LLVM?

The LLVM memory model

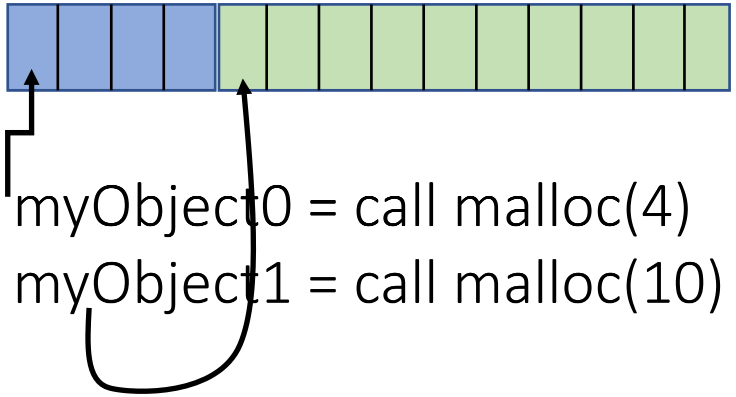


```
myObject0 = call malloc(4)
myObject1 = call malloc(10)

p = myObject0 + 4
```

Can p alias myObject1?

The LLVM memory model



myObject0 = call malloc(4)
myObject1 = call malloc(10)

p = myObject0 + 4

Can p alias myObject1?