Pointer Analysis for C/C++ with cclyzer

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cclyzer

Static Analysis Framework for C/C++

- Analyzes C/C++ programs translated to LLVM Bitcode
- Declarative framework
  - Analyzes written in Datalog rules
- Uses the LogicBlox Datalog engine
  - Relations stored as database tables
  - Output relations computed using Datalog's least fixpoint model of the program

LLVM IR - Basic Instructions

❏ Stack allocations	(1)	`p = alloca [type]`
❏ Heap allocations	(2)	`p = malloc nbytes`
❏ Load from address	(3)	`v = load p`
❏ Store to address	(4)	`store v, p`
❏ Address-of-field	(5)	p_{offset} = &(p->f)
❏ Address-of-array-index	(6)	p_{offset} = &(p[i])
❏ Function call	(7)	v = call fn (arg_1, arg_2, ...)
❏ No-op cast	(8)	`v = bitcast p to [type]`

LLVM Bitcode vs Java Bytecode

I. Addresses of Fields

LLVM Bitcode

- As in C, an instance field can have its *address taken*
- ... and then *loaded* elsewhere.
- By elsewhere, we mean even in a different function
- Expression ‘`p->f`’ in fact translates to:

  p_{offset} `= &(p->f)`
  `v = load` p_{offset}

Java Bytecode*

- Impossible in Java
- May only allocate objects and then load from or store to some field
- Load/store instructions hence are ternary, containing an extra *field operand*

LLVM Bitcode vs Java Bytecode

II. Virtual registers

LLVM Bitcode

- All source-level variables become pointers … unless optimized away
- E.g., ‘`int p = 3;`’ becomes:

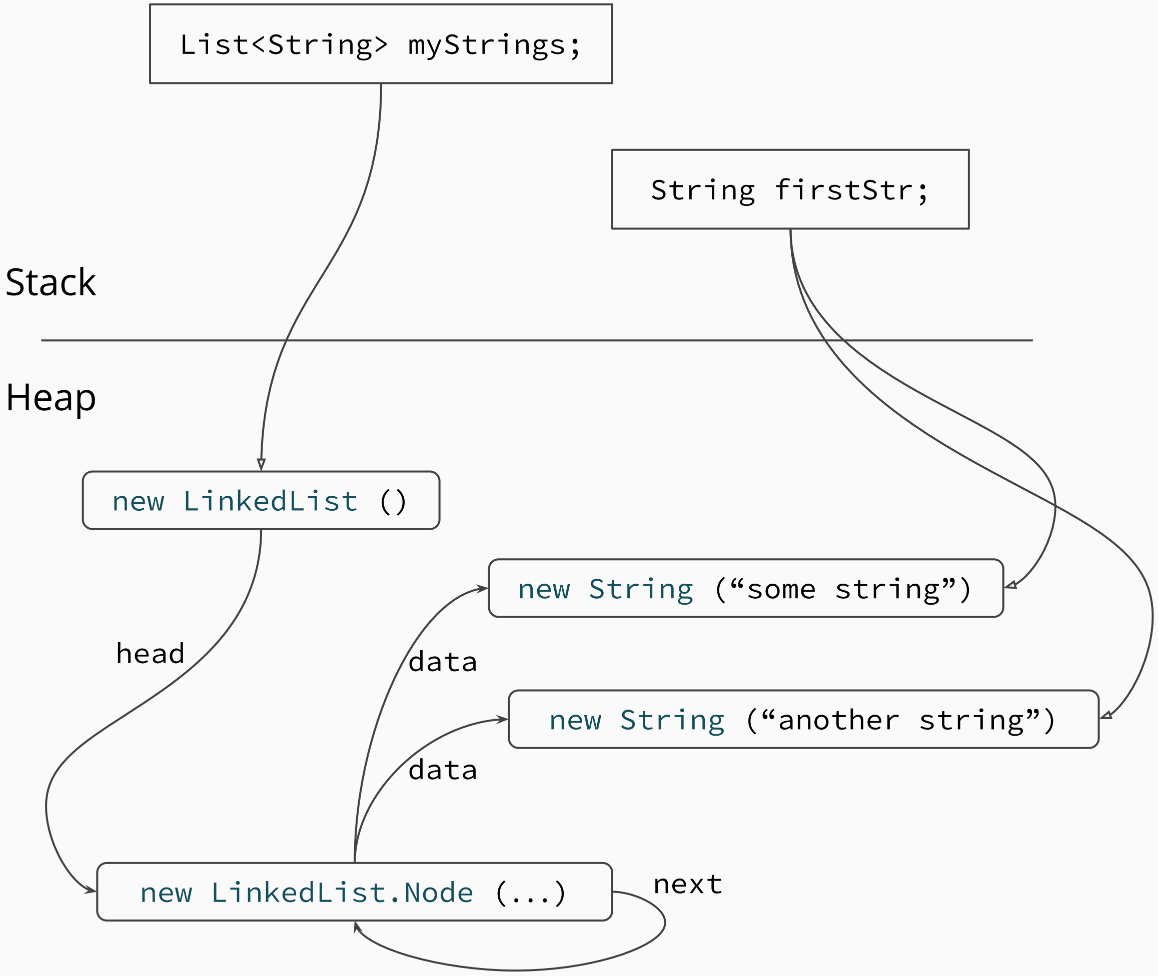
```
%p = alloca i32
store i32 3, i32* %p
```

- ‘`&p`’ becomes just ‘`%p`’
- Subsequent assignments to ‘`p`’ become store instructions to ‘`%p`’
- Additional temporary variables are introduced for intermediate expressions (e.g., ‘`%1`’, ‘`%2`’)
- Both ‘`%p`’ and ‘`%1`’, ‘`%2`’ are *virtual registers*.
- At register allocation:
  1. some will be replaced by *physical registers*
  2. some will be *spilled*.

Pointer Analysis on LLVM bitcode

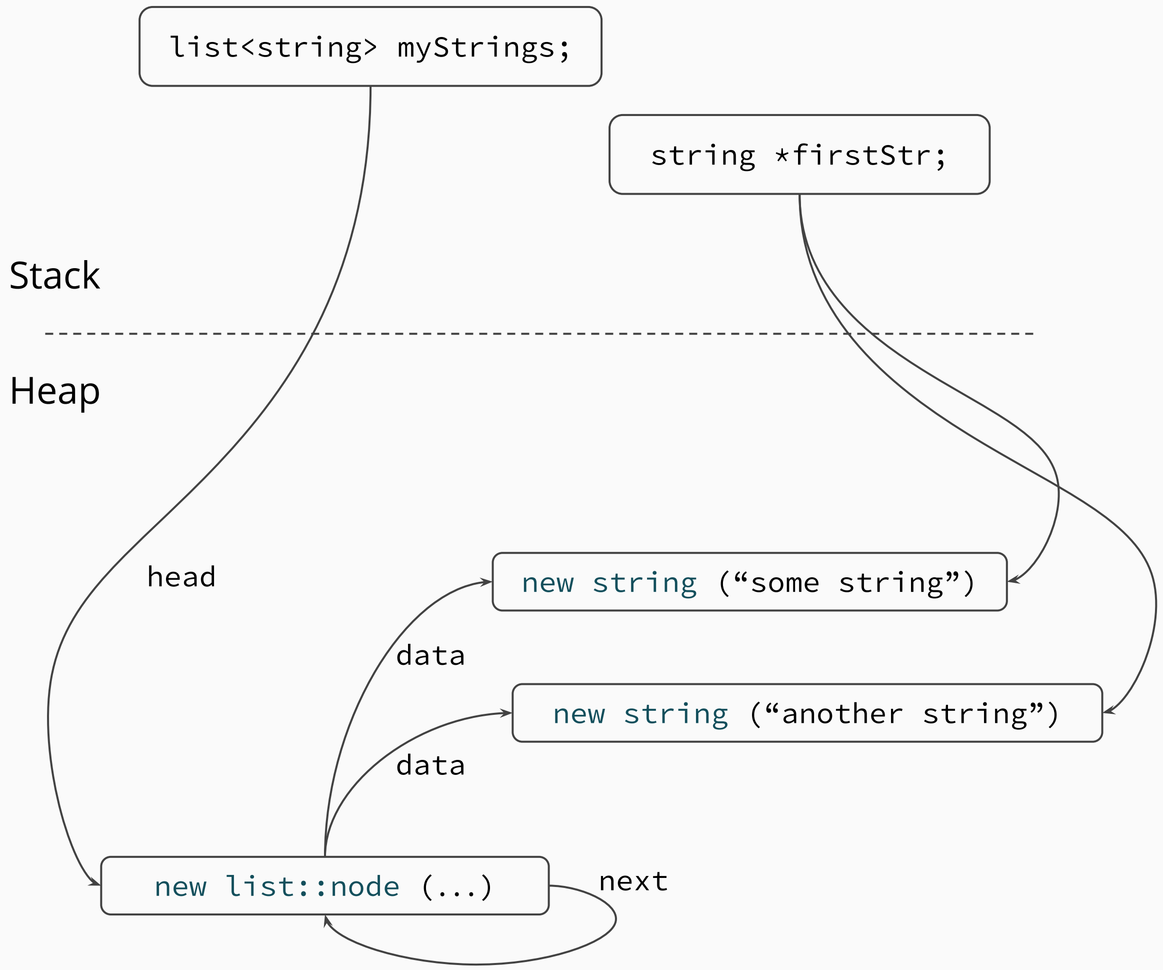
Java Memory Abstraction

- Clear distinction
  - variables reside on stack
  - allocated objects reside on heap
- Pointer analysis
  - variables *point-to* heap objects
  - heap objects *point-to* other heap objects through some field



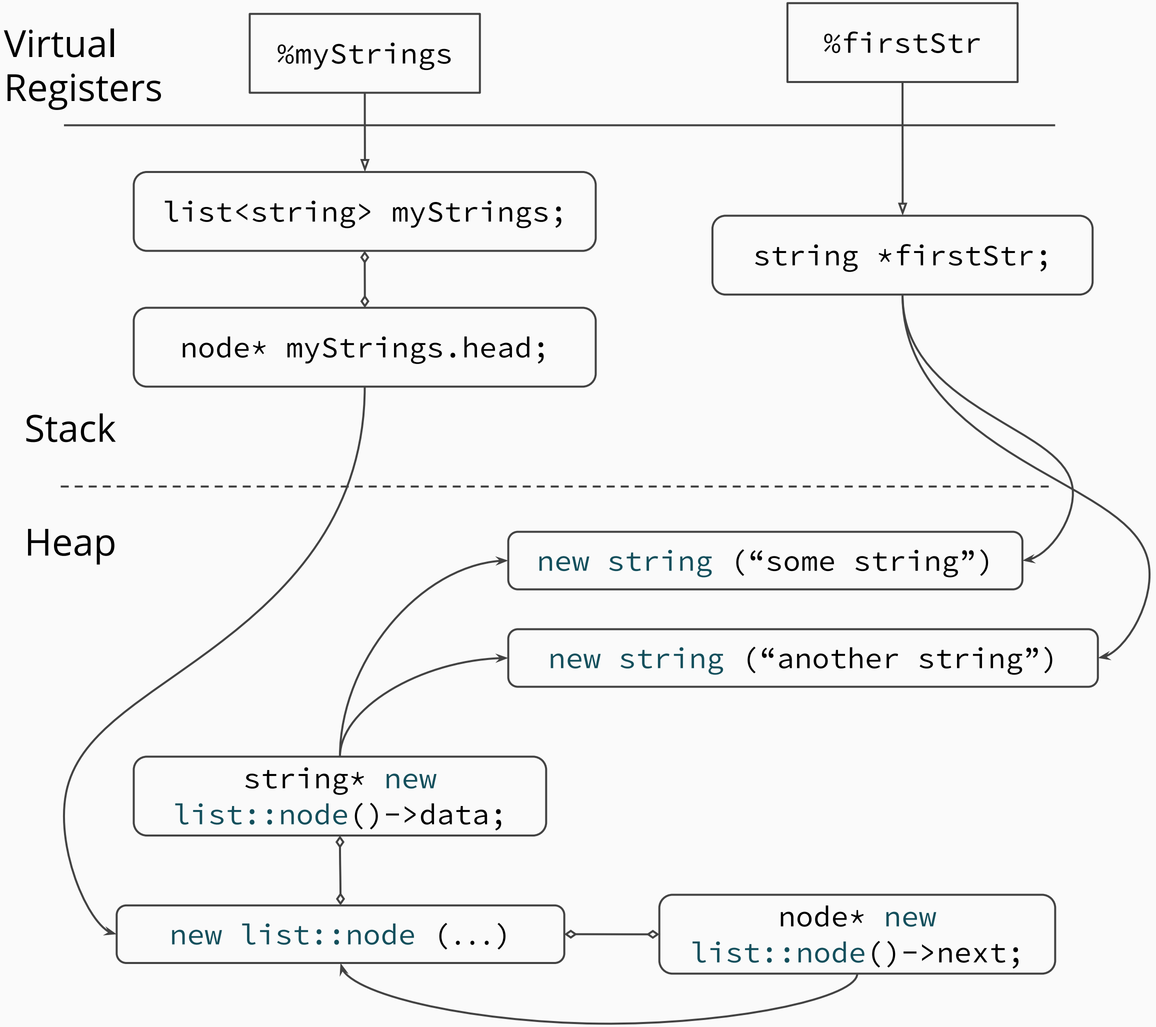
C/C++ Memory Abstraction

- Objects may be allocated:
  1. either on the heap
  2. or on the stack
- Pointer analysis
  - Dereference edges from abstract object to another abstract object
- What about field edges?
  - Objects contain other objects; unlike Java
  - Recall: we can take the address of a field



Our LLVM Memory Abstraction

- Decouple a variable from its stack allocation
- From now on, by *variable*, we mean virtual register
- Pointer analysis
  - Variables point-to (abstract) objects
  - Objects, when *dereferenced* point-to other objects
  - Fields of objects are objects themselves



Analyzing C/C++ code with cclyzer

https://github.com/plast-lab/cclyzer

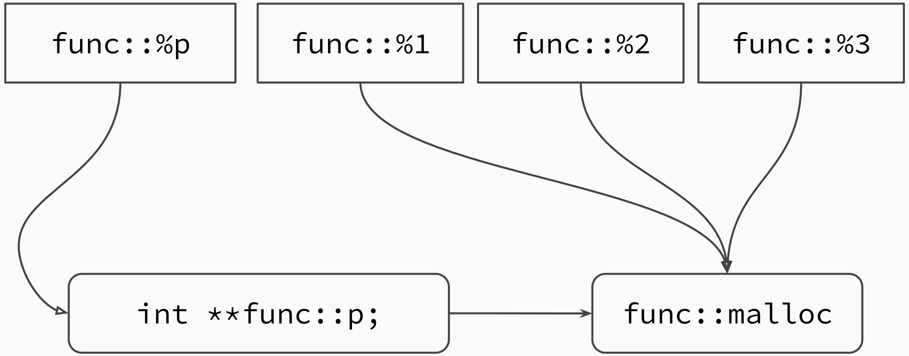
Simple Example: Computing Points-to

LLVM Bitcode

```
int func() {
    int*** %p = alloca [int **];
    void*  %1 = call @malloc(8);
    int**  %2 = bitcast %1 to int**;

    store %2, %p;
    int**  %3 = load %p;

    ret %3;
}
```



Revisiting points-to

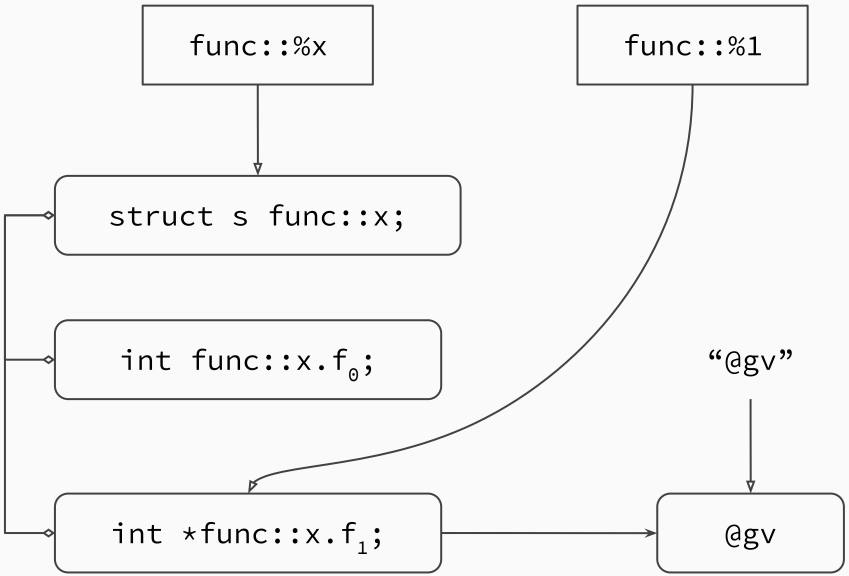
Field Sensitivity

LLVM Bitcode

```
int* @gv = global int 0;

%struct.s = type { int, int* }

void func() {
  %x = alloca [%struct.s];
  %1 = getelementptr %x, 0, 1; // &(x.
f1)
  store @gv, %1;
}
```



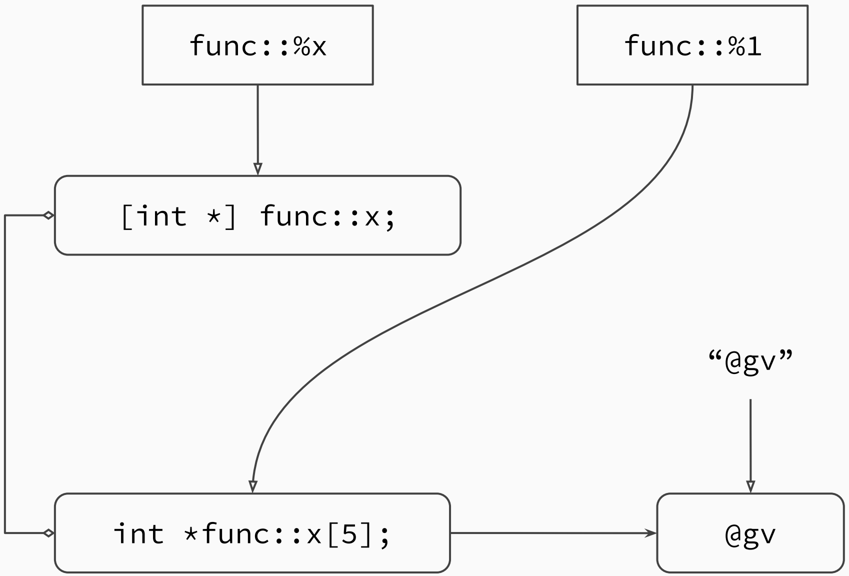
Revisiting points-to

Array Sensitivity

LLVM Bitcode

```
int* @gv = global int 0;


void func() {
  %x = alloca [100 x int*];
  %1 = getelementptr %x, 0, 5; // &(x
[5])
  store @gv, %1;
}
```



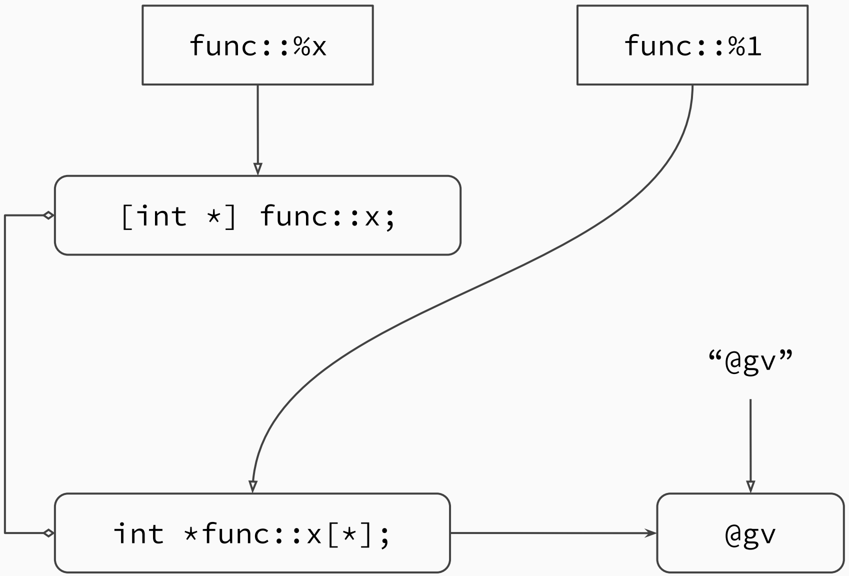
Revisiting points-to

Array Sensitivity

LLVM Bitcode

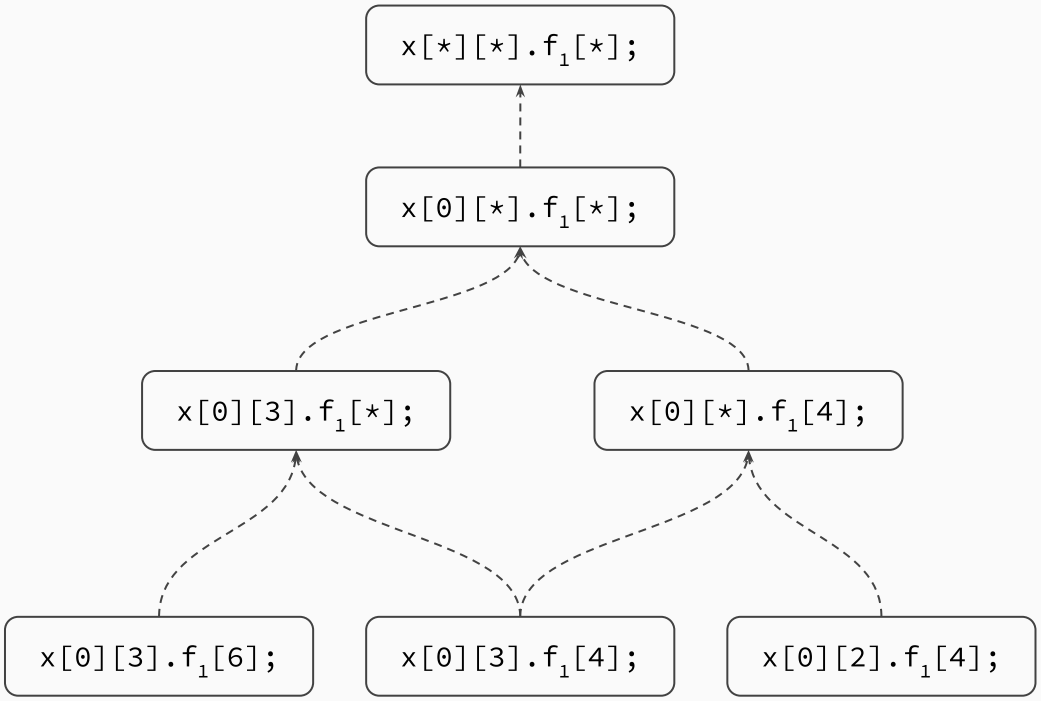
```
int* @gv = global int 0;


void func() {
  %x = alloca [100 x int*];
  %i = ...
  %1 = getelementptr %x, 0, %i; // &(x
[i])
  store @gv, %1;
}
```



Array Sensitivity

- Define partial order
- (n_1, n_2) when n_1 can be turned to n_2 by substituting constant indices with '*'
- points-to set of a node is a *superset* of the points-to set of its parent
- At *load* instructions, merge with the points-to sets of *all* children nodes



Strong Type Information

Type back-propagation

- Analysis only creates **typed** abstract subobjects
  - Must determine the type of their base object
  - What about objects of unknown type (e.g., `malloc()`)?
- Type back-propagation:
  - track *cast instructions* (resp. types) that an object of unknown type flows to
  - create a *new* abstract object per possible type, for a single allocation site
  - In turn, more abstract subobjects can now be created

Analyzing C++ code

compiled to LLVM IR

Challenges

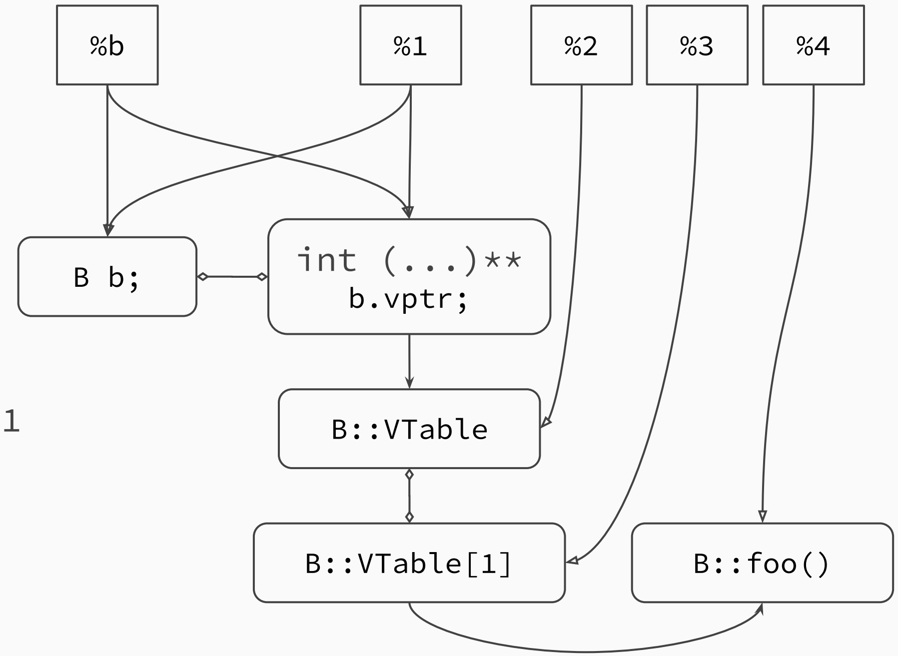
- LLVM bitcode is a representation that is well-suited for C code
- Too low-level for C++
- C++ features like classes, v-tables, references, and so on are translated to low-level constructs

Dynamic Dispatch Example

LLVM Bitcode

```
%class.B = type { int (...)**, ...}

void func() {
  %b = alloca [%class.B];
  ...
  %1 = bitcast %b to int (%class.B*)***
  %2 = load int (%class.B*)** %1
  %3 = getelementptr int (%class.B*)** %2, 1
  %4 = load int (%class.B*)* %3
  call int %4 (%class.B* %b)
}
```



Upcoming SAS '16 paper:

Structure-Sensitive Points-To Analysis for C and C++

George Balatsouras and Yannis Smaragdakis