Lecture 5: Interpreter runtime structures

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601.428/628 Compilers and Interpreters

Today

- Scopes, environments, function calls
- Runtime data structures
- Reference counting

Scopes, environments, and function calls

Scope, lifetime

- Scope: in what region(s) of the program is a particular variable visible?
- Lifetime: *when* in the execution of the program does a variable exist?
- These are related but distinct concepts

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

Example program

```
var a, b, c;
a = 1;
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function add1(a) {
  var b;
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var d;
d = add1(c);

println(a);
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d;
```

scope of global variable a

Example program

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var a, b, c;
a = 1;
b = 2;
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function add1(a) {
  var b;
  b = 1;
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}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

scope of global variable a

global variable a not visible here: shadowed by parameter a

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

Scope of global variable b

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

Scope of global variable b

global variable b not visible here: shadowed by local variable

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

global variable c's scope is the entire program
- not shadowed by any identically-named parameters or local variables

Example program

```
var a, b, c;
a = 1;
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function add1(a) {
   var b;
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   c = 4;
   a + b;
}

var d;
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println(a);
println(b);
println(c);
d;
```

Assignment to global variable!

global variable c's scope is the entire program
- not shadowed by any identically-named parameters or local variables

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
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  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

scope of parameter a:
body of function

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b
  b = 1;
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  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

scope of local variable b:
from point of definition to
end of function body

Example program

```
var a, b, c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
  c = 4;
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```

scope of global variable d:
point of definition to end of module

Variable lifetime

- Global variables exist for the duration of the execution of the program
- Parameters and local variables exist for the duration of a function call
  - Call stack: each call pushes an *activation record*
  - A calls B, B calls C, C calls D, etc. — arbitrarily many calls can be in progress at any point
    - In practice, the call stack is usually limited in size
  - Recursion: A calls itself
    - Caller and callee always have distinct activation records

Environment

- We'll use the term *environment* for a data structure containing a collection of variables that have a common lifetime
- Global environment: has definitions of global variables
  - Global variables are visible throughout the program unless shadowed by a variable in an "inner" scope
- Function call environment: created to represent parameters of a called function
- Block (statement list) environment: created to accommodate local variables defined in a block (statement list enclosed by curly braces)

Nesting of environments

- Nesting: an "inner" environment can reference variables in an "outer" environment
  - But not vice versa!
- In a *block-structured* language, every "block" defines a new environment
  - Our interpreter language is block-structured (Assignment 2)
  - C, C++, Java are block-structured languages
- To implement nesting, each environment can have a pointer to its "parent" environment, i.e., the environment representing the enclosing scope

Example program

```
var a;
var b;
var c;
a = 1;
b = 2;
c = 3;

function add1(a) {
  var b;
  b = 1;
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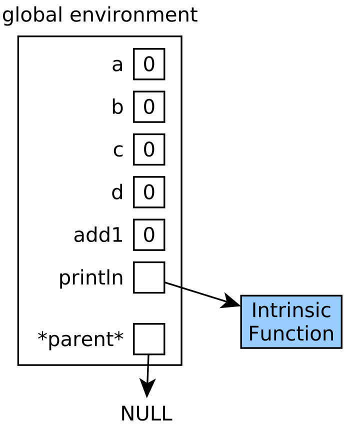
  a + b;
}

var d;
d = add1(c);

println(a);
println(b);
println(c);
d;
```



Example program

```
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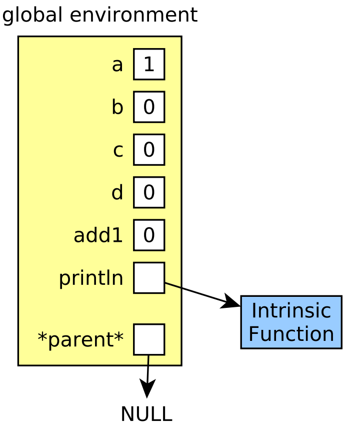

Example program

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var b;
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a = 1;
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function add1(a) {
  var b;
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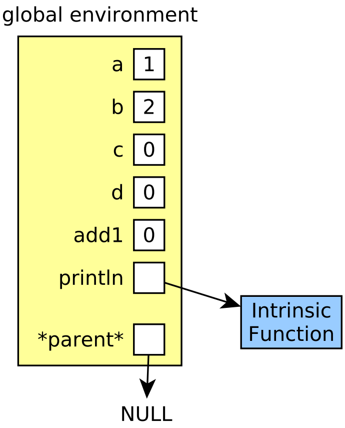

Example program

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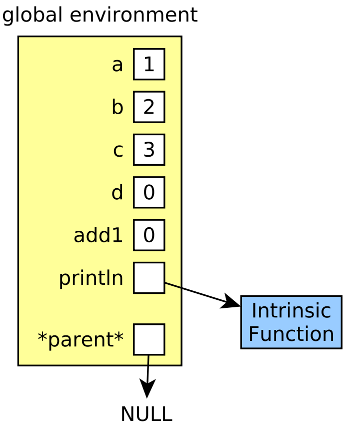

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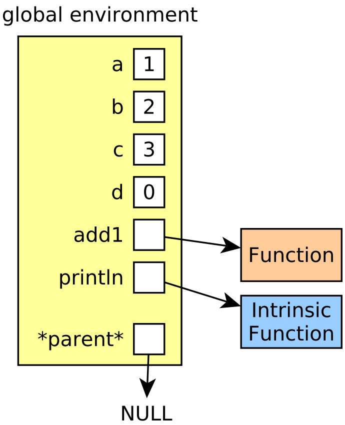

Example program

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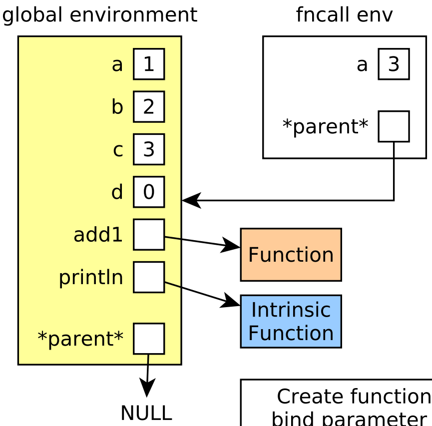

Create function call environment, bind parameter to argument value

Example program

```
var a;
var b;
var c;
a = 1;
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function add1(a) {
  var b;
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}

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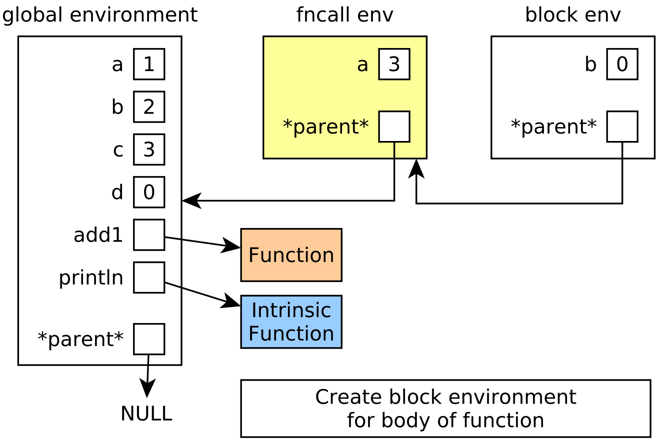

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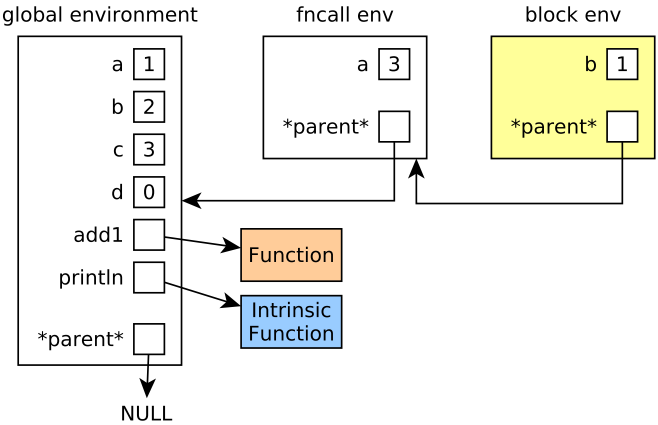

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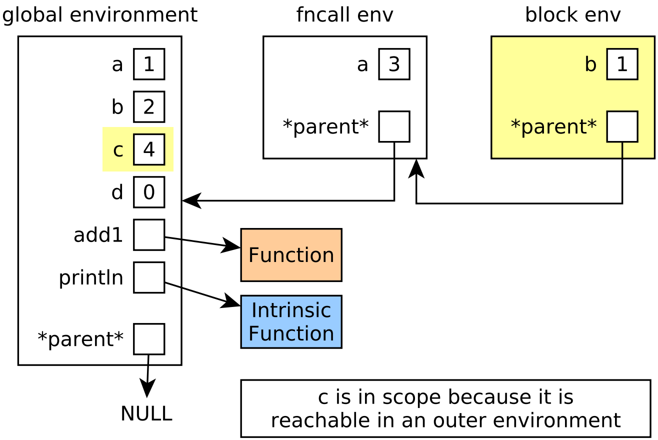

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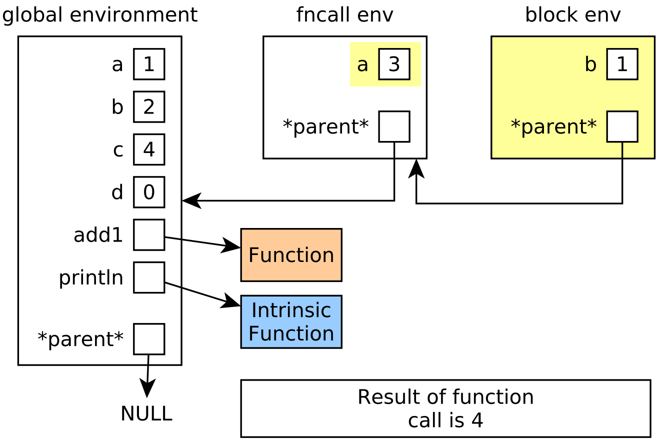

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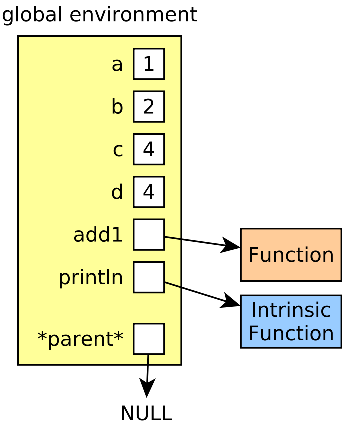

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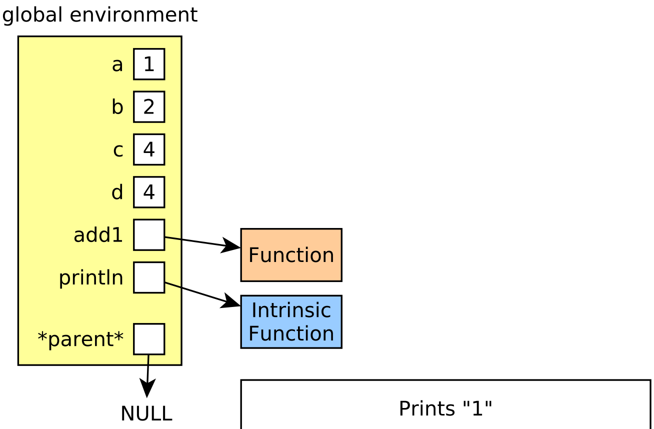

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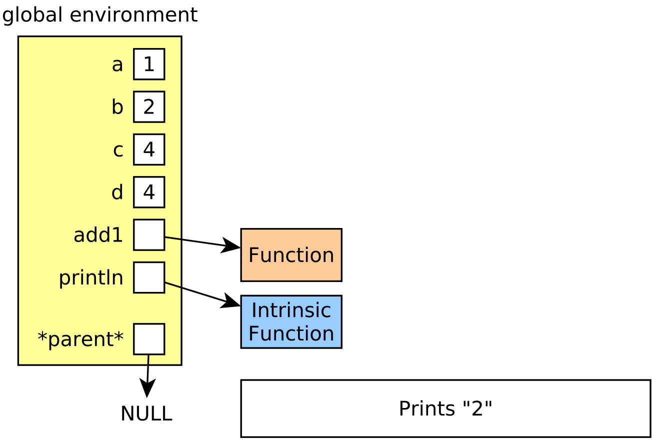

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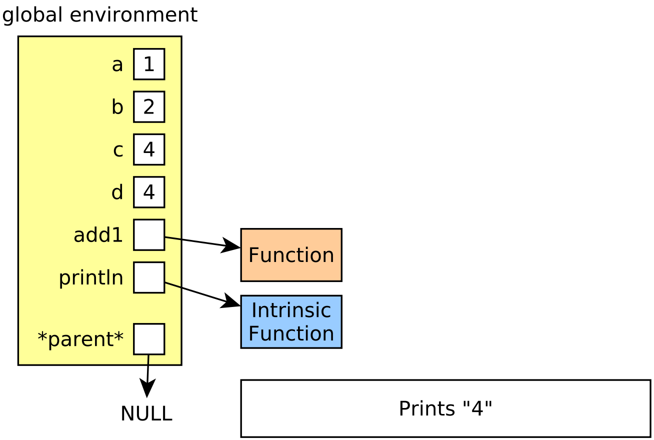

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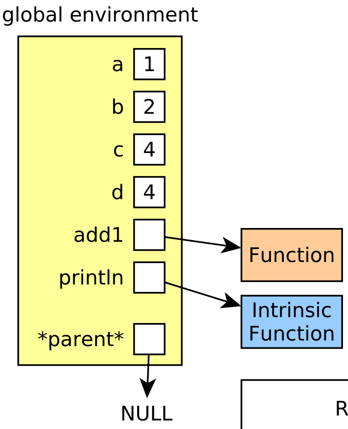

Result of program is 4

Lexical addresses

In a language where every variable's scope is known statically, we can use *lexical addresses* to associate variable references with their definitions

Each variable has an integer position

Lexical address is pair (*depth*, *position*)

- *depth*: 0 if referenced variable is in current environment, 1 if in parent, 2 if in grandparent, etc.

Example program

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var c;
a = 1;
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c = 3;

function add1(a) {
  var b;
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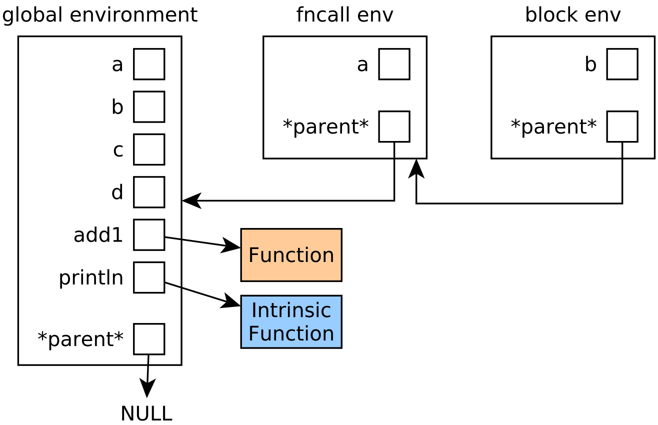

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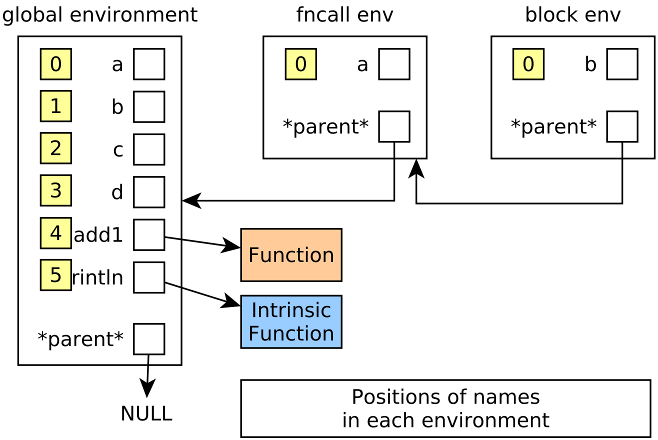

Example program

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function add1(a) {
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var d;
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```
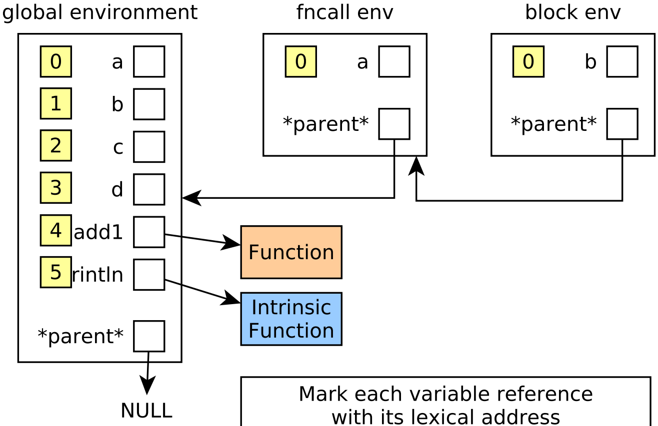

(0,0)



Mark each variable reference with its lexical address

Example program

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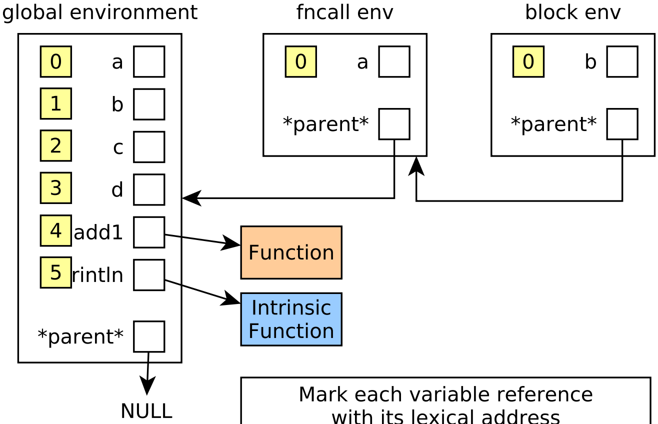
d;
```

(0,0)
(2,2)
(1,0)
(0,0)



Mark each variable reference
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Example program

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var b;
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var d;
d = add1(a);

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println(b);
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```

(0,0)
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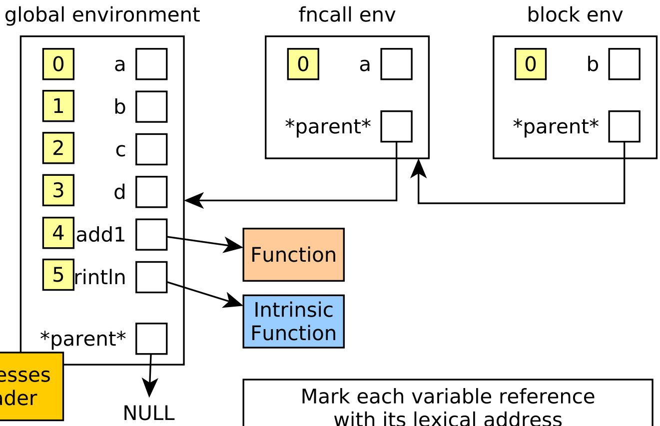
Remaining lexical addresses left as exercise for reader



Mark each variable reference with its lexical address

Determining lexical addresses

Analyze source:

- Keep track of current (static) environment, initially the global environment
- Enter a nested scope $\rightarrow$ enter a nested environment (with previous environment as its parent)
- Leave a nested scope $\rightarrow$ return to parent environment
- Keep track of names defined (variables, functions)
- As long as definitions precede uses, we can associate each reference to a name with an entry in a static environment
- Static (pre-execution) environments are also called *symbol tables*
  - Much more about these when we move on to compilers!

Runtime data structures

Runtime data structures

Important runtime data structures to support the execution of the program being interpreted:

- Values
- Environments
- Functions

Values

How to represent a runtime value? Assuming a dynamically-typed language, where a value's data type can't (necessarily) be predicted until the program runs, we need:

- The value's type
- A representation of the value

Value representation

- Different data types require different representations
- Some values are fixed size (e.g., fixed-precision integers, floating point values, pointer or reference to an object)
- Some values require arbitrary storage (e.g., arrays, objects, etc.)
- Typical approach: allow the representation to be either an "atomic" (fixed-size) value, or a pointer to a "dynamic" representation object

Kinds of values

```
enum ValueKind {
  // "atomic" values
  VALUE_INT,
  VALUE_DOUBLE,
  VALUE_INTRINSIC_FN,
  // other kinds of atomic values...

  // "dynamic" values
  VALUE_FUNCTION,
  VALUE_ARRAY,
  VALUE_STRING,
  // other kinds of dynamic values
};
```

Atomic values

```
union Atomic {
  int ival;
  double dval;
  IntrinsicFn intrinsic_fn;
  // etc.
};
```

`IntrinsicFn` is a pointer to an "intrinsic" function, i.e., one implemented directly by the interpreter

Value

```
class Value {
private:
  ValueKind m_kind;
  union {
    Atomic m_atomic;
    ValRep *m_valrep;
  };

public:
  // various constructors...
  Value(const Value &other);
  ~Value();

  Value &operator=(const Value &rhs);

  // member functions...
};
```

Dynamic values

All classes implementing representations of dynamic values (functions, arrays, strings, etc.) derive from `ValRep`. I.e.:

```
class Function : public ValRep {
  // ...
};

class Array : public ValRep {
  // ...
};

class String : public ValRep {
  // ...
};
```

The type of representation object is indicated by the `Value`'s `m_kind` value: e.g., if it's `VALUE_FUNCTION` then `m_valrep` points to a `Function` object

Managing dynamic representations

- The `Value` class has (and needs) *value semantics* (copy constructor and assignment)
- Runtime values are frequently copied from one variable to another, passed to a function, returned from a function, etc.
- How do we ensure that dynamic representation objects are deallocated when no longer needed?
  - Issue: multiple `Value` instances might have pointers to the same dynamic representation object
  - More on this in a bit

Functions are values

```
function add1(x) {
  x + 1;
}
function apply(f, v) {
  f(v);
}

var g;
g = add1;

apply(g, 4);
```

The above program computes the value 5. Many dynamic languages and all functional languages treat functions as values.

Environment

An environment is

- A map of names to values
- A reference (pointer) to the parent environment (representing the enclosing scope)
  - The environment representing the global scope does not have a parent

Environment

```
class Environment {
private:
  Environment *m_parent;
  std::map<std::string, Value> m_varmap;

public:
  Environment(Environment *parent);
  ~Environment();

  // member functions...
};
```

Environment operations

Operations an environment should support:

- Creating a new variable (setting it to some initial default value)
  - It should be an error to define a variable that already exists
- Determining whether a variable is defined locally in the environment
- Looking up the value of a locally-defined variable
- Looking up the value of a variable, including searching outer scope(s) if necessary

Functions

A function is

- A list of 0 or more parameters
- A pointer to the environment representing the scope enclosing the function (for top-level functions, the global scope)
- An AST representing the body of the function

Since a function is a dynamic value, its representation is derived from `ValRep`.

Function representation

```
class Function : public ValRep {
private:
  std::vector<std::string> m_params;
  Environment *m_parent_env;
  Node *m_body;

public:
  Function(const std::vector<std::string> &params,
           Environment *parent_env,
           Node *body);
  ~Function();

  // member functions...
};
```

Executing a function call

- As we've seen, executing a function call means:
  - Creating a new environment for it (with global environment as parent)
  - Evaluating argument expressions
  - Binding function parameters to argument values in the new function call environment
  - Evaluating the body of the function in the new function call environment
    - Because the body of a function is a block, it will have its own environment whose parent is the function call environment
  - Result of evaluating body is result of function
    - Becomes value of function call expression at call site

Reference counting

Reference counting

Reference counting is a simple and mostly-effective way of keeping track of uses of dynamically allocated objects, and deleting them when they are no longer needed.

The idea is to maintain an integer *reference count* within each dynamic object:

- If the reference count is > 0, it is still in use
- If the reference count is $= 0$, it is no longer in use, and should be deleted

Maintaining reference counts

C++ makes it easy to track reference counts using "smart pointer" objects.

Rather than the interpreter keeping direct pointers to dynamic objects (`ValRep *`), it wraps them in an object with value semantics that

- increments and decrements reference counts as needed
- frees dynamic objects when the reference count reaches 0

In Assignment 2, the `Value` class serves as the smart pointer type for dynamic objects. (Which makes sense, because `Value` represents a runtime value.)

Attach and detach

The important operations for the smart pointer type are *attach* and *detach*:

- Attach: increment the dynamic object's reference count and store a pointer to it
- Detach: decrement current dynamic object's reference count, delete it if the reference count is 0
    - For safety, it's not a bad idea to store null in the pointer so that there isn't a dangling pointer to the dynamic object

Smart pointer operations

- Constructor from pointer to dynamic object: attach to the dynamic object
- Copy constructor: attach to the other smart pointer's dynamic object (if there is one)
- Destructor: detach from current dynamic object (if there is one)
- Assignment operator: detach from current dynamic object (if there is one), attach to other smart pointer's dynamic object (if there is one)

Limitation of reference counting

- Reference counting has trouble reclaiming dynamic objects if there are *reference cycles*
  - E.g., object A has a pointer to object B, and object B has a pointer to object A
  - Both A's and B's reference counts stay at 1 even though they are not reachable
- Various solutions exist: for example, periodically run a garbage collector