EECS 483: Compiler Construction

Lecture 11:
Dynamic Typing Continued, Heap Allocation

February 19
Winter Semester 2025

Announcements

- Assignment 3 released
- Monday's live code updated to include full interpreter

Representing Dynamically Typed Values

To implement our compiler, we need to specify

1. How each of our Snake values are represented at runtime
2. How to implement the primitive operations on these representations

Integers

Implement a snake integer as a 63-bit signed integer followed by a 0 bit to indicate that the value is an integer

Number	Representation
1	`0b00000000_0000.....0000_00000010`
6	`0b00000000_0000.....0000_00001100`
-1	`0b11111111_1111.....1111_11111110`

I.e., represent a 63-bit integer **n** as the 64-bit integer 2 * n

Booleans

The least significant bit must be 1 to distinguish from integers

Use least significant bits `0b01` to distinuish from integers and other datatypes

Use the remaining 62 bits to encode true and false as before as 1 and 0

Number	Representation
`true`	`0b00000000_0000.....0000_00000101`
`false`	`0b00000000_0000.....0000_00000001`

2^62 - 2 bit patterns are therefore "junk" in this format

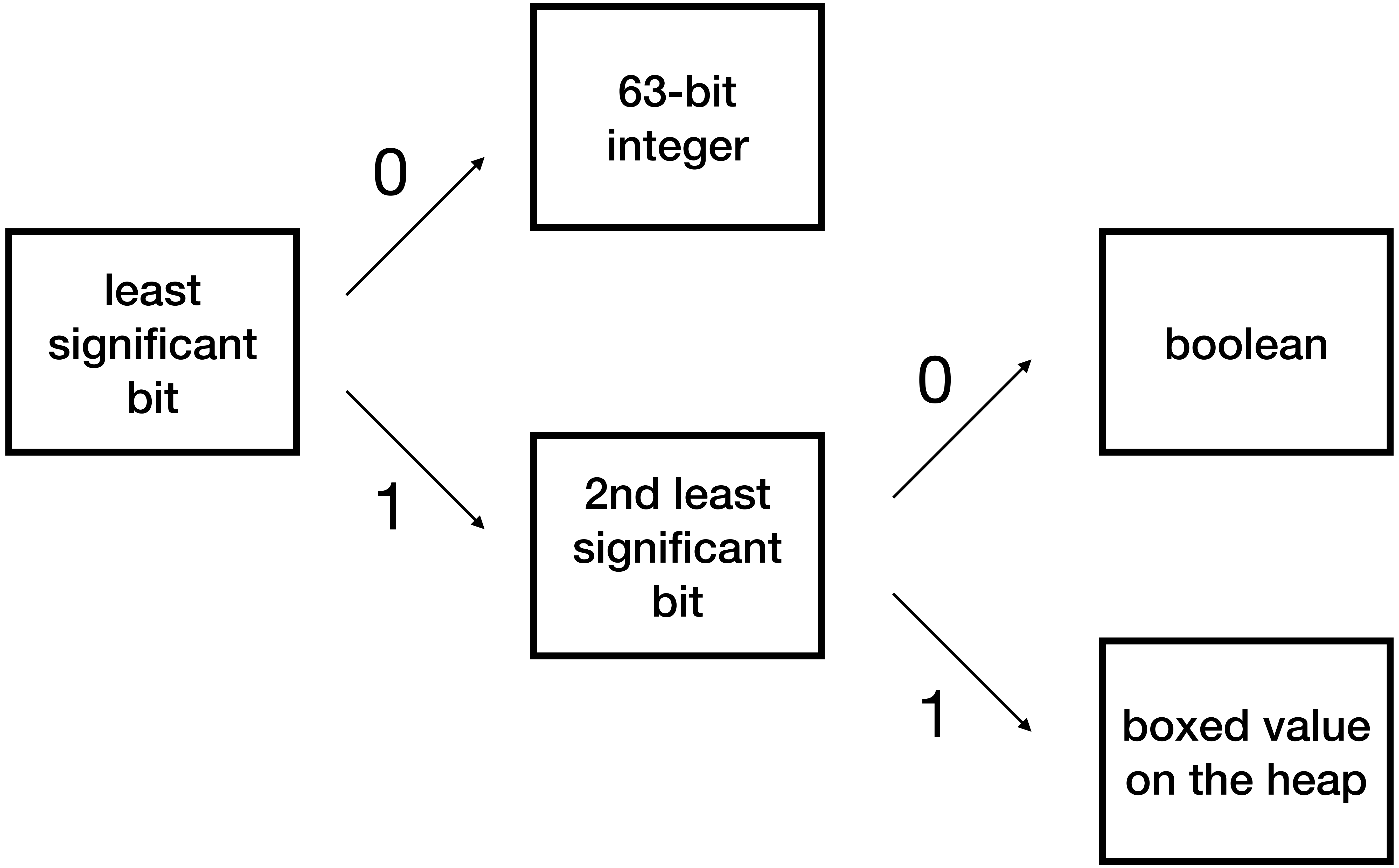
Boxed Data

The least significant bit must be 1 to distinguish from integers

Use least significant bits `0b11` to distinguish from booleans.

Use remaining 62-bits to encode a pointer to the data on the heap

Representing Dynamically Typed Values



Implementing Dynamically Typed Operations

We need to revisit our implementation of all primitives in assembly code to see how they should work with our new datatype representations.

1. Arithmetic operations (add, sub, mul)
2. Inequality operations (<=, <, >=, >)
3. Equality
4. Logical operations (&&, ||, !)

As well as supporting our new operations isInt and isBool

Implementing Dynamically Typed Operations

In dynamic typing, implementing a primitive operation has two parts:

1. How to check that the inputs have the correct type tag
2. How to actually perform the operation on the encoded data

Implementing Dynamically Typed Operations

Live code

Compiling Dynamic Typing

We know what the source semantics is and what kind of assembly code we want to generate.

In implementing the compiler, we now we have a design choice: in what phase of the compiler do we actually "implement" dynamic typing?

1. Implement everything in x86 code generation
2. Implement everything in lowering to SSA
3. Implement in multiple passes

Compiling Dynamic Typing

Approach 1: implement all dynamic typing semantics in code generation.

In this case, SSA values would be dynamically typed, like Diamondback

Compiling Dynamic Typing

Approach 1: implement all dynamic typing semantics in code generation.

Diamondback

```
x + y
```

SSA

```
r = x + y
ret r
```

x86

```
mov rax, [rsp - 8]
test rax, 1
jnz err_arith_exp_int
mov r10, [rsp - 8]
test r10, 1
jnz err_arith_exp_int
add rax, r10
ret
```

Compiling Dynamic Typing

Approach 1: implement all dynamic typing semantics in code generation.

In this case, SSA values would be dynamically typed, like Diamondback

Downside: goes against the philosophy that SSA should be thin wrapper around the assembly code.

Makes the semantics of SSA more complex and so the code generation more complex.

More complex code generation: missed opportunities for SSA-based optimization

Compiling Dynamic Typing

Approach 2: implement dynamic typing in the translation to SSA

In this approach, SSA values are as before always 64-bit integers, and SSA operations work on these 64-bit integers (as they do now)

Compiling Dynamic Typing

Approach 2: implement dynamic typing in the translation to SSA

Diamondback

```
x * y
```

SSA

```
check_y():
  y_bit = y & 1
  c = y_bit == 0
  cbr mult_xy() err()
mult_xy():
  tmp = x * y
  z = tmp >> 1
  ret z
x_bit = x & 1
b = x_bit == 0
cbr check_y() err()
...
```

Compiling Dynamic Typing

Approach 2: implement dynamic typing in the translation to SSA

Benefit: code generation is very simple, at cost of SSA lowering more complex

Downside: difficult to optimize unnecessary tag checks away

Compiling Dynamic Typing

Approach 3: implement dynamic typing in multiple passes

In lowering to SSA, make some aspects of dynamic typing explicit but leave the tag checking as primitive operations.

Implement the tag checking in the x86 code generation.

Compiling Dynamic Typing

Approach 3: implement **some** dynamic typing in SSA lowering

Diamondback

```
x * y
```

SSA

```
assertInt(x)
assertInt(y)
r = x * y
s = r >> 1
ret s
```

Insert type tag assertions in SSA, implement bit-twiddling manually

Compiling Dynamic Typing

Approach 3: implement **some** dynamic typing in SSA lowering

SSA

```
assertInt(x)
```

x86

```
mov rax, [rsp - offset(x)]
test rax, 1
jnz assert_int_fail
...
assert_int_fail:
  sub rsp, 8
  call snake_assert_int_error
```

Compiling Dynamic Typing

Optimization opportunity

Diamondback

```
def fact(x):
  if x == 0:
    1
  else:
    x * fact(x - 1)
in
fact(7)
```

SSA

```
...
tmp1 = x - 1
tmp2 = call fact(tmp1)
assertInt(x)
assertInt(tmp2)
r = x * tmp2
ret r
```

will these **assertInt** ever fail?

Compiling Dynamic Typing

Optimization opportunity

Diamondback

```
def fact(x):
  if x == 0:
    1
  else:
    x * fact(x - 1)
in
fact(7)
```

SSA

```
...
tmp1 = x - 1
tmp2 = call fact(tmp1)
assertInt(x)
assertInt(tmp2)
r = x * tmp2
ret r
```

with a simple **static analysis** determine that x, tmp2 always have the correct tag for an Int. Remove unnecessary assertions

Compiling Dynamic Typing

Compare to approach 2:

Diamondback

```
x * y
```

how would we remove the checking from the code on the right?

SSA

```
check_y():
  y_bit = y & 1
  c = y_bit == 0
  cbr mult_xy() err()
mult_xy():
  tmp = x * y
  z = tmp >> 1
  ret z
x_bit = x & 1
b = x_bit == 0
cbr check_y() err()
...
```

Summary: Adding Dynamic typing

How does adding dynamic typing affect each pass of our compiler?

Changes to Frontend

New error: only 63-bit integers are supported, so need to reject 64-bit values in the parser/frontend

Changes to Middle End

Diamondback values: tagged data, either a 63-bit int, or true or false

SSA values: 64-bit integers

Add primitive assertions **assertInt** and **assertBool** to SSA

Use bitwise masking and left/right shift in SSA to encode the correct semantics of Diamondback values and operations

Changes to Back End

Implement **assertInt** and **assertBool** operations in x86, calling out to functions implemented in Rust to display appropriate errors

Changes to Runtime (stub.rs)

Parse input arguments into snake values.

Update printing to account for new representation

Implement functions that display runtime errors and exit the process

State of the Snake Language

Adder: Straightline Code (arithmetic circuits)

Boa: local control flow (finite automata)

Cobra: procedures, extern (pushdown automata)

Snake v4: **Diamondback**

1. Add new datatypes, use dynamic typing to distinguish them at runtime
2. **Include heap-allocated variable-sized arrays, allowing for unrestricted memory usage**

Computational power: Turing complete

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  [x , x + 1, x + 2]
```

allocate an array with a statically known size

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  newArray(x)
```

allocate an array with dynamically determined size (elements initialized to 0)

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let a = [x , -1 * x ] in
   a[0]
```

array indexing

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let a = [x , -1 * x ] in
   a[1] := a[1] + 1
   a[1]
```

arrays can be mutably updated

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let a = [x , -1 * x ] in
  length(a)
```

should be able to access the length of any array value

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let a = [x , -1 * x ] in
   a[3]
```

Out of bounds access/update should be runtime errors

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let a = [x , -1 * x ] in
   isArray(a)
```

support tag checking as with ints, bools

Extending the Snake Language

Diamondback: Arrays

```
def main(x):
  let list = [0, 1, false] in
  let _ = list[2] := list in
  ...
```

mutable updates allow for cyclic data

Concrete Syntax

‹expr›: ...

| ‹array›

| ‹expr› `[` ‹expr› `]`

| ‹expr› `[` ‹expr› `]` `:=` ‹expr›

| `newArray` `(` ‹expr› `)`

| `isBool` `(` ‹expr› `)`

| `isInt` `(` ‹expr› `)`

| `isArray` `(` ‹expr› `)`

| `length` `(` ‹expr› `)`

‹exprs›:

| ‹expr›

| ‹expr› `,` ‹exprs›

‹array›:

| `[` `]`

| `[` ‹exprs› `]`

Abstract Syntax

```
enum Prim {
  ...
  // Unary
  IsArray,
  IsBool,
  IsInt,
  NewArray,
  Length,

  MakeArray, // 0 or more arguments
  ArrayGet, // first arg is array, second is index
  ArraySet, // first arg is array, second is index, third is new value
}
```

Extending the Snake Language

Diamondback: Arrays

Semantics:

1. Each time we allocate an array should be a new memory location, so that updates don't overwrite previous allocations

2. What value does `e1[e2] := e3` produce?
   options: a constant, the value of e1 or e3, the old value of `e1[e2]`

3. Is equality of arrays by value or by reference?

   [0, 1, 2] == [0 , 1, 2]

Allocating Arrays

Where should the contents of our arrays be stored?

- Stack?

- Heap?

Stack Allocation

Can we allocate our arrays on the stack?

```
def main(x):
  let a = [x , -1 * x ] in
   a[1] := 0
```

Stack Allocation

Can we allocate our arrays on the stack?

```
def main(x):
  let a = [0, 1] in
  def f(n):
    a[n] + a[n + 1]
  in
  x + f(n)
```

Stack Allocation

Can we allocate our arrays on the stack?

```
def main(x):
 def f():
    [0, 1, 2, 3, 4]
  in
  def g(arr, i, j, k):
    arr[i] * arr[j] * arr[k]
  in
  let arr = f(x) in
  g(arr, 0, 2, 4)
```

If f allocates in its stack frame and returns a pointer,

The memory will be overwritten by any future calls

Doing this safely would require **copying** any returned data into the caller's stack frame. Not feasible for dynamically sized values.

Stack Allocation

Dynamically sized data can only feasibly be stack allocated if it is **local** to the function, i.e., only used in call stacks that contain the current function's stack frame.

If the dynamically sized data is **returned** from the function that allocates it, we instead allocate it in a separate memory region, the **heap**, and return a pointer to it.

Heap Allocation

The heap contains data whose lifetime is not tied to a local stack frame.

This makes the usage of the data more flexible, but complicates the question of when the data is **deallocated**.

For today, let's assume we do not deallocate memory.
  A strategy used in some specialized applications (missiles)

Today's simple heap model: the heap is a large region of memory, disjoint from the stack, some of it is used, and we have a pointer to the next available portion of memory.

Heap Allocation

The heap contains data whose lifetime is not tied to a local stack frame.

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  A strategy used in some specialized applications (missiles)

The Heap

Let's take a particularly simple view of the heap for now: the heap is a large region of memory, disjoint from the stack. Some amount of this space is used, and we have a **heap pointer** that points to the next available region.

If memory is never deallocated (but also in copying gc), the structure is similar to the stack: we have a region of used space and a region of free space and the **heap pointer**, like the stack pointer, points to the beginning of the free space.

While the stack grows downward in memory, the heap grows upward.

Memory Management

Need our assembly programs to have access to the heap pointer at all times.

We will implement management of the heap in our **runtime system**, i.e., in Rust. Our assembly code programs will interface with the runtime system by calling functions the runtime system provides.

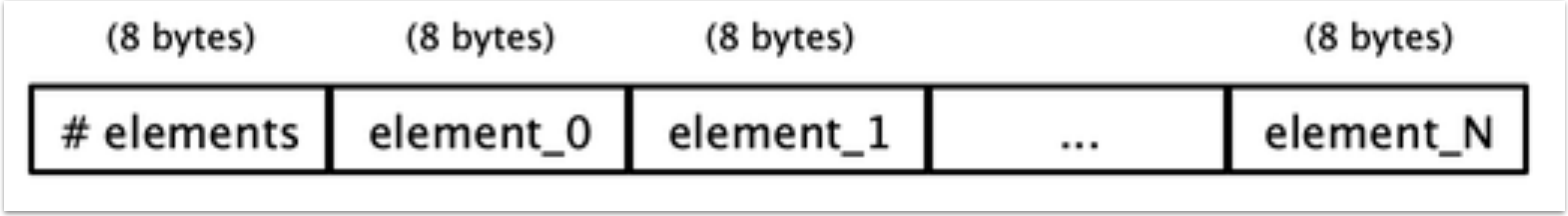
Implementing Arrays

When we implement arrays, we have two different representations to define:
1. How they are stored as "objects" in the heap
2. How they are represented as Snake values

Arrays as Objects

What data does an array need to store?

1. Need to layout the values sequentially so we can implement get/set
2. Need to store the **length** of the array to implement length as well as bounds checking for get/set.



Arrays as Values

The Snake value we store on the stack for an array is a **tagged** pointer to the array stored on the heap.

We overwrite the 2 least significant bits of the pointer with the tag 0b11.

This is safe, as long as those 2 least significant bits of the pointer contain no information, i.e., if they are always 0.

2 least significant bits of a pointer are 0 means the address is a multiple of 4, meaning the address is at a 4-byte alignment.

All arrays on our heap take up size that is a multiple of 8 bytes, so as long as the base of the heap is 4-byte aligned, we maintain this invariant.

Heap/Runtime Demo

Live code: runtime system

Heap/Runtime Demo

Summary:

Pre-allocate a large chunk of memory for our Snake program to use as its heap.

Allocation is managed by the runtime system, i.e., the stub.rs code.

Implementing Array Operations

Like with dynamically typed booleans, implementing array operations involves a combination of

1. Checking tags to ensure that the inputs are valid
2. Removing tags to get access to the underlying pointers
3. "Actual" loads and stores to memory
4. Adding tags to outputs

Implementing Array Operations

Like with dynamically typed booleans, implementing array operations involves a combination of

1. Checking tags to ensure that the inputs are valid

2. Removing tags to get access to the underlying pointers

3. "Actual" loads and stores to memory

4. Adding tags to outputs

As with booleans, we will add **assertions** as primitives to SSA, but implement the rest using new SSA operations for load/store.

SSA Extensions

1. **assertArray(x)**

   fail if x is not tagged as an array

2. **assertInBounds(n, m)**

   fail if m is an out of bounds index into a length n array, i.e., assert m < n

2. **load(p, off)**

   load 8 bytes of memory at [p + off * 8]

3. **store(p, off, v)**

   store the 8-byte value v at [p + off * 8]

4. **allocateArray(n)**

   allocate an array of length n from the runtime system

Implementing New Operations

1. **assertArray(x):** similar to assertInt, assertBool

2. **assertInBounds(n, m)**
```
cmp n, m
jle oob_error
```

3. **load(p, off, amt)**
```
mov dest, [p + off * 8]
```

4. **store(p, off, amt, v)**
```
mov [p + off * 8], v
```

5. **allocateArray(n):** call into the RTSs

Translation to SSA

1. newArray
2. array literals
3. array access
4. array update
5. isArray

Translation to SSA

Array allocation

Diamondback

```
newArray(e)
```

```
Continuation:
```

result stored in `res`
body of cont: **b**

SSA

```
...
n = ... compile e
assertInt(n)
l = n >> 1
arr = allocateArray(n)
res = arr | 0b11
b
```

Translation to SSA

Array literals

Diamondback

```
[e0 , ... , e(n-1)]
```

```
Continuation:
```
result stored in `res`
body of cont: **b**

SSA

```
...
x0 = ... compile e0
...
arr = allocateArray(n)
store(arr, 1, x0)
...
store(arr, n, x(n-1))
res = arr | 0b11
b
```

Translation to SSA

Array access

Diamondback

```
e1[e2]
```

```
Continuation:
```

result stored in `res`

body of cont: **b**

SSA

```
...
x1 = ... compile e1
...
x2 = ... compile e2
assertArray(x1)
assertInt(x2)
arr = x1 ^ 0b11
len = load(arr, 0)
ix = x2 >> 1
assertInBounds(len, ix)
res = load(arr, ix)
b
```

Translation to SSA

Array update

Diamondback

```
e1[e2] := e3
```

`Continuation:`
result stored in `res`
body of cont: **b**

SSA

```
...
x1 = ... compile e1
...
x2 = ... compile e2
...
x3 = ... compile e3
assertArray(x1)
assertInt(x2)
arr = x1 ^ 0b11
len = load(arr, 0)
ix = x2 >> 1
assertInBounds(len, ix)
store(arr, ix)
res = x3
b
```

Translation to SSA

Array tag check

Diamondback

```
isArray(e)
```

`Continuation:`

result stored in `res`

body of cont: **b**

SSA

```
...
x = ... compile e
tag = x & 0b11
isArr = tag == 0b11
shifted = isArr << 2
res = shifted | 0b01
b
```