CSE 110A: Winter 2020

Fundamentals of Compiler Design I

Data on the Heap

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Data on the Heap

Next, lets add support for

- **Data Structures**

In the process of doing so, we will learn about

- **Heap Allocation**
- **Run-time Tags**

Creating Heap Data Structures

We have already support for *two* primitive data types

```
data Ty
  = TNumber     -- e.g. 0,1,2,3,...
  | TBoolean    -- e.g. true, false
```

we could add several more of course, e.g.

- `Char`
- `Double` or `Float`
- `Long` or `Short`

etc. (you should do it!)

However, for all of those, the same principle applies, more or less

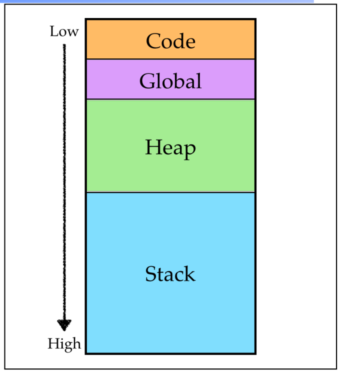
- As long as the data fits into a single word (4-bytes)

Creating Heap Data Structures

Instead, we're going to look at how to make **unbounded data structures**

- Lists
- Trees

which require us to put data on the **heap** (not just the *stack*) that we've used so far.



Pairs

While our *goal* is to get to lists and trees, but we will *begin* with the humble **pair**.

First, let's ponder what exactly we're trying to achieve. We want to enrich our language with *two* new constructs:

- **Constructing** pairs, with a new expression of the form `(e0, e1)` where `e0` and `e1` are expressions.
- **Accessing** pairs, with new expressions of the form `e[0]` and `e[1]` which evaluate to the first and second element of the tuple `e` respectively.

```
let t = (2, 3) in
  t[0] + t[1]
```

should evaluate to `5`.

Strategy

Next, lets informally develop a strategy for extending our language with pairs, implementing the above semantics. We need to work out strategies for:

- **Representing** pairs in the machine's memory,
- **Constructing** pairs (i.e. implementing `(e0, e1)` in assembly),
- **Accessing** pairs (i.e. implementing `e[0]` and `e[1]` in assembly).

1. Representation

Recall that we represent all values:

- `Number` like `0`, `1`, `2` ...
- `Boolean` like `true`, `false`

as a **single word** either

- 4 bytes on the stack, or
- a single register `eax`.

EXERCISE

What kinds of problems do you think might arise if we represent a pair `(2, 3)` on the *stack* as:

```
|     |
-------
|  3  |
-------
|  2  |
-------
| ... |
-------
```


QUIZ

How many words would we need to store the tuple

```
(3, (4, 5))
```

- `1` word
- `2` words
- `3` words
- `4` words
- `5` words

Pointers

Just about every problem in computing can be solved by adding a level of indirection.

We will **represent a pair** by a **pointer** to a block of **two adjacent words** of memory.

Pointers

This shows how the pair `(2, (3, (4, 5)))` and its sub-pairs can be stored in the **heap** using pointers.

`(4,5)` is stored by adjacent words storing

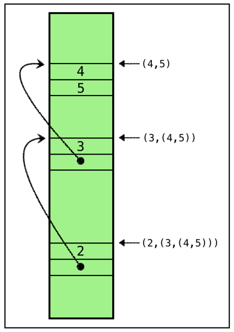
- `4` and
- `5`

`(3, (4, 5))` is stored by adjacent words storing

- `3` and
- a **pointer** to a heap location storing `(4, 5)`

`(2, (3, (4, 5)))` is stored by adjacent words storing

- `2` and
- a **pointer** to a heap location storing `(3, (4, 5))`.



A Problem: Numbers vs. Pointers?

How will we tell the difference between *numbers* and *pointers*?

That is, how can we tell the difference between

- the *number* 5 and
- a *pointer* to a block of memory (with address `5`)?

Each of the above corresponds to a *different* tuple

- `(4, 5)` or
- `(4, (…))`.

so it's crucial that we have a way of knowing *which* value it is.

Tagging Pointers

As you might have guessed, we can extend our **tagging mechanism** to account for *pointers*.

Type	LSB
`number`	xx0
`boolean`	111
`pointer`	1

That is, for

- `number` the **last bit** will be `0` (as before),
- `boolean` the **last 3 bits** will be `111` (as before), and
- `pointer` the **last 3 bits** will be `001`.

(We have 3-bits worth for tags, so have wiggle room for other primitive types.)

Address Alignment

As we have a **3 bit tag**, leaving **32 - 3 = 29 bits** for the actual address. This means, our actual available addresses, written in binary are of the form

Binary	Decimal
0b00000000	0
0b00001000	8
0b00010000	16
0b00011000	24
0b00100000	32

That is, the addresses are **8-byte aligned**. Which is great because at each address, we have a pair, i.e. a **2-word = 8-byte block**, so the *next* allocated address will also fall on an 8-byte boundary.

2. Construction

To **construct** a pair `(e1, e2)` we

- **Allocate** a new 2-word block, and getting the starting address at `eax`,
- **Copy** the value of `e1` (resp. `e2`) into `[eax]` (resp. `[eax + 4]`).
- **Tag** the last bit of `eax` with `1`.

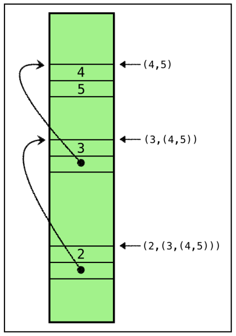
The resulting `eax` is the **value of the pair**

- The last step ensures that the value carries the proper tag.

ANF will ensure that `e1` and `e2` are both **immediate expressions** which will make the second step above straightforward.

EXERCISE

EXERCISE How will we do ANF conversion for `(e1, e2)`?



Allocating Addresses

We will use a **global** register `esi` to maintain the address of the **next free block** on the heap. Every time we need a new block, we will:

- **Copy** the current `esi` into `eax`
- set the last bit to `1` to ensure proper tagging.
- `eax` will be used to fill in the values
- **Increment** the value of `esi` by `8`
- thereby "allocating" 8 bytes (= 2 words) at the address in `eax`

Allocating Addresses

Note that *if*

- we *start* our blocks at an 8-byte boundary, and
- we *allocate* 8 bytes at a time,

then

- each address used to store a pair will fall on an 8-byte boundary (i.e. have last three bits set to `0`).

So we can safely turn the address in `eax` into a `pointer` + by setting the last bit to `1`.

NOTE: In your assignment, we will have blocks of varying sizes so you will have to take care to *maintain* the 8-byte alignment, by "padding".

Example: Allocation

In the figure below, we have

- a source program on the left,
- the ANF equivalent next to it.

Source

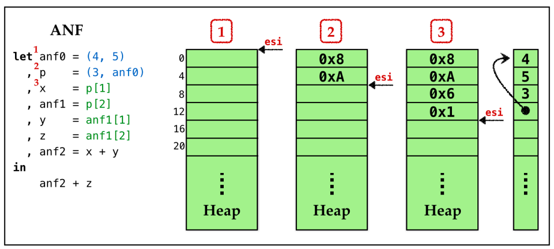
```
let p = (3, (4, 5))
  , x = p[1]
  , y = p[2][1]
  , z = p[2][2]
in
    x + y + z
```

ANF

```
let anf0 = (4, 5)
  , p    = (3, anf0)
  , x    = p[1]
  , anf1 = p[2]
  , y    = anf1[1]
  , z    = anf1[2]
  , anf2 = x + y
in
    anf2 + z
```


Example: Allocation

The figure below shows the how the heap and `esi` evolve at points 1, 2 and 3:



QUIZ

In the ANF version, `p` is the *second (local) variable* stored in the stack frame. What *value* gets moved into the *second stack slot* when evaluating the above program?

- `0x3`
- `(3, (4, 5))`
- `0x6`
- `0x9`
- `0x10`

3. Accessing

Finally, to **access** the elements of a pair, i.e. compiling expressions like `e[0]` (resp. `e[1]`)

- **Check** that immediate value `e` is a pointer
- **Load** `e` into `eax`
- **Remove** the tag bit from `eax`
- **Copy** the value in `[eax]` (resp. `[eax + 4]`) into `eax`.

Example: Access

Here is a snapshot of the heap after the pair(s) are allocated.

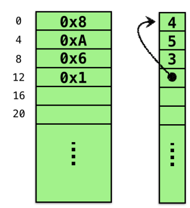
Source

```
let p = (3, (4, 5))
  , x = p[1]
  , y = p[2][1]
  , z = p[2][2]
in
    x + y + z
```

ANF

```
let anf0 = (4, 5)
  , p    = (3, anf0)
  , x    = p[1]
  , anf1 = p[2]
  , y    = anf1[1]
  , z    = anf1[2]
  , anf2 = x + y
in
    anf2 + z
```

Addr.



Example: Access

Let's work out how the values corresponding to `x`, `y` and `z` in the example above get stored on the stack frame in the course of evaluation.

Variable	Hex Value	Value
`anf0`	`1`	`ptr 0`
`p`	`9`	`ptr 8`
`x`	`6`	`num 3`
`anf1`	`1`	`ptr 0`
`y`	`8`	`num 4`
`z`	`A`	`num 5`
`anf2`	`E`	`num 7`
result	`18`	`num 12`

Plan

Pretty pictures are well and good, time to build stuff!

As usual, lets continue with our recipe:

- Run-time
- Types
- Transforms

We've already built up intuition of the *strategy* for implementing tuples. Next, let's look at how to implement each of the above.

Run-Time

We need to extend the run-time (`c-bits/main.c`) in two ways.

- **Allocate** a chunk of space on the heap and pass in start address to `our_code`.
- **Print** pairs properly.

Allocation

The first step is quite easy we can use `calloc` as follows:

```
int main(int argc, char** argv) {
  int* HEAP = calloc(HEAP_SIZE, sizeof (int));
  int result = our_code_starts_here(HEAP);
  print(result);
  return 0;
}
```

The above code,

- **Allocates** a big block of contiguous memory (starting at `HEAP`),
- **Passes** this address in to `our_code`.

Now, `our_code` needs to start with instructions that will copy the parameter into `esi` and then bump it up at each allocation.

Printing

To print pairs, we must recursively traverse the pointers until we hit `number` or `boolean`.

We can check if a value is a pair by looking at its last 3 bits:

```
int isPair(int p) {
  return (p & 0x00000007) == 0x00000001;
}
```

Why is this sufficient?

Printing

```
void print(int val) {
  if(val & 0x00000001 ^ 0x00000001) { // val is a number
    printf("%d", val >> 1);
  }
  else if(val == 0xFFFFFFFF) {       // val is true
    printf("true");
  }
  else if(val == 0x7FFFFFFF) {       // val is false
    printf("false");
  }
  else if(isPair(val)) {
    int* valp = (int*) (val - 1);    // extract address
    printf("(");
    print(*valp);                  // print first element
    printf(", ");
    print(*(valp + 1));            // print second element
    printf(")");
  }
  else {
    printf("Unknown value: %#010x", val);
  }
}
```


Types

Next, lets move into our compiler, and see how the **core types** need to be extended.

We need to extend the *source* `Expr` with support for tuples

```
data Expr a
  = ...
  | Pair    (Expr a) (Expr a) a   -- ^ construct a pair
  | GetItem (Expr a) Field    a   -- ^ access a pair's element
```

In the above, `Field` is

```
data Field
  = First     -- ^ access first element of pair
  | Second    -- ^ access second element of pair
```

NOTE: Your assignment will generalize pairs to **n-ary tuples** using

- `Tuple [Expr a]` representing `(e1,...,en)`
- `GetItem (Expr a) (Expr a)` representing `e1[e2]`

Dynamic Types

Let us extend our **dynamic types** `Ty` see to include pairs:

```
data Ty = TNumber | TBoolean | TPair
```


Assembly

The assembly `Instruction` are changed minimally; we just need access to `esi` which will hold the value of the *next* available memory block:

```
data Register
  = ...
  | ESI
```


Transforms

Our code must take care of three things:

- **Initialize** `esi` to allow heap allocation,
- **Construct** pairs,
- **Access** pairs.

The latter two will be pointed out directly by GHC:

- They are new cases that must be handled in `anf` and `compileExpr`

Initialize

We need to **initialize** `esi` with the **start position** of the heap, that is passed in by the run-time.

How shall we get a hold of this position?

To do so, `our_code` starts off with a `prelude`

```
prelude :: [Instruction]
prelude =
  [ IMov (Reg ESI) (RegOffset 4 ESP)
          -- copy param (HEAP) off stack
  , IAdd (Reg ESI) (Const 8)
          -- adjust to ensure 8-byte aligned
  , IAnd (Reg ESI) (HexConst 0xFFFFFFF8)
          -- add 8 and set last 3 bits to 0
  ]
```

- **Copy** the value off the (parameter) stack, and
- **Adjust** the value to ensure the value is *8-byte aligned*.

QUIZ

Why add `8` to `esi`? What would happen if we *removed* that operation?

1. `esi` would not be 8-byte aligned?
2. `esi` would point into the stack?
3. `esi` would not point into the heap?
4. `esi` would not have enough space to write 2 bytes?

Construct

To *construct* a pair `(v1, v2)` we directly implement the **above strategy**:

```
compileExpr env (Pair v1 v2)
    -- 1. allocate pair, resulting addr in `eax`
  = pairAlloc
    -- 2. copy values into slots
    ++ pairCopy First  (immArg env v1)
    ++ pairCopy Second (immArg env v2)
    -- 3. set the tag-bits of `eax`
    ++ setTag   EAX     TPair
```

Let's look at each step in turn.

Allocate

To allocate, we just copy the current pointer `esi` and increment by `8` bytes,

- accounting for two 4-byte (word) blocks for each pair element.

```
pairAlloc :: Asm
pairAlloc
    -- copy current "free address" `esi` into `eax`
  = [ IMov (Reg EAX) (Reg ESI)
    -- increment `esi` by 8
    , IAdd (Reg ESI) (Const 8)
    ]
```


Copy

We copy an `Arg` into a `Field` by saving the `Arg` into a helper register `ebx`, and copying `ebx` into the field's slot on the heap.

```
pairCopy :: Field -> Arg -> Asm
pairCopy fld a
  = [ IMov (Reg EBX)    a
    , IMov (pairAddr f) (Reg EBX)
    ]
```

The field's slot is either `[eax]` or `[eax + 4]` depending on whether the field is `First` or `Second`.

```
pairAddr :: Field -> Arg
pairAddr fld = Sized DWordPtr
                 (RegOffset (4 * fieldOffset fld) EAX)

fieldOffset :: Field -> Int
fieldOffset First  = 0
fieldOffset Second = 1
```


Tag

Finally, we set the tag bits of `eax` by using `typeTag TPair` which is defined

```
setTag :: Register -> Ty -> Asm
setTag r ty = [ IAdd (Reg r) (typeTag ty) ]

typeTag :: Ty -> Arg
-- last 1 bit  is  0
typeTag TNumber  = HexConst 0x00000000
-- last 3 bits are 111
typeTag TBoolean = HexConst 0x00000007
 -- last 1 bits is  1
typeTag TPair    = HexConst 0x00000001
```

Access

To access tuples, lets update `compileExpr` with our **strategy**:

```
compileExpr env (GetItem e fld)
    -- 1. check that e is a (pair) pointer
  = assertType env e TPair
    -- 2. load pointer into eax
 ++ [ IMov (Reg EAX) (immArg env e) ]
    – 3. remove tag bit to get address
 ++ unsetTag EAX TPair
 ++ [ IMov (Reg EAX) (pairAddr fld) ]   -- 4. copy value from
resp. slot to eax
```

we remove the tag bits by doing the opposite of `setTag` namely:

```
unsetTag :: Register -> Ty -> Asm
unsetTag r ty = ISub (Reg EAX) (typeTag ty)
```


N-ary Tuples

Thats it! Let's take our compiler out for a spin, by using it to write some interesting programs!

First, lets see how to generalize pairs to allow for

- triples `(e1,e2,e3)`, —> (e1, (e2, e3))
- quadruples `(e1,e2,e3,e4)`, -> (e1, (e2, (e3, e4)))
- pentuples `(e1,e2,e3,e4,e5)`

...and so on.

We just need a library of functions in our new `egg` language to

- **Construct** such tuples, and
- **Access** their fields.

Constructing Tuples

We can write a small set of functions to **construct** tuples (up to some given size):

```
def tup3(x1, x2, x3):
  (x1, (x2, x3))

def tup4(x1, x2, x3, x4):
  (x1, (x2, (x3, x4)))

def tup5(x1, x2, x3, x4, x5):
  (x1, (x2, (x3, (x4, x5))))
```

Accessing Tuples

We can write a single function to access tuples of any size.

```
let yuple = (10, (20, (30, (40, (50, false))))) in

$> get(yuple, 0)
10
$> get(yuple, 1)
20
$> get(yuple, 2)
30
```


Accessing Tuples

We can write a single function to access tuples of any size.

```
def tup3(x1, x2, x3):
  (x1, (x2, x3))

def tup5(x1, x2, x3, x4,
x5):
  (x1, (x2, (x3, (x4, x5))))

let t  = tup5(1, 2, 3, 4, 5)
in
  , x0 = print(get(t, 0))
  , x1 = print(get(t, 1))
  , x2 = print(get(t, 2))
  , x3 = print(get(t, 3))
  , x4 = print(get(t, 4))
in
  99
```

should print out:

```
0
1
2
3
4
99
```


Accessing Tuples

How shall we write it?

```
def get(t, i):
  TODO-IN-CLASS
```

QUIZ

Using the above "library" we can write code like:

```
let quad = tup4(1, 2, 3, 4) in
  get(quad, 0) + get(quad, 1)
   + get(quad, 2) + get(quad, 3)
```

What will be the result of compiling the above?

1. Compile error
2. Segmentation fault
3. Other run-time error
4. 4
5. 10

QUIZ

Using the above "library" we can write code like:

```
def tup3(x1, x2, x3):
  (x1, (x2, (x3, false)))

let quad = tup3(1, 2, 3) in
  get(quad, 0) + get(quad, 1)
   + get(quad, 2) + get(quad, 3)
```

What will be the result of compiling the above?

1. Compile error
2. Segmentation fault
3. Other run-time error
4. 4
5. 10

QUIZ

```
def get(t, i):
  if i == 0:
    t[0]
  else:
    get(t[1],i-1)

-- get(t, 2) ===> get(t[1], 1) ===> get(t[1][1], 0)


def tup3(x1, x2, x3):
  (x1, (x2, (x3, false)))

let quad = tup3(1, 2, 3) in
--  quad = (1, (2, 3))
--  quad[1] = (2, 3)
--  quad[1][1] = (3, false)
--  quad[1][1][1] = false
```

Constructing Lists

Once we have pairs, we can start encoding **unbounded lists.**

To build a list, we need two constructor functions:

```
def empty(): false
def cons(h, t): (h, t)
```

We can now encode lists as:

```
cons(1, cons(2, cons(3, cons(4, empty()))))
```


Accessing Lists

To **access** a list, we need to know

1. Whether the list `isEmpty`, and
2. A way to access the `head` and the `tail` of a non-empty list.

```
def isEmpty(l):
  l == empty()

def head(l):
  l[0]

def tail(l):
  l[1]
```


Examples

We can now write various functions that build and operate on lists, for example, a function to generate the list of numbers between `i` and `j`

```
def range(i, j):
  if (i < j):
    cons(i, range(i+1, j))
  else:
    empty()

range(1, 5)
```

which should produce the result

```
(1,(2,(3,(4,false))))
```

Examples

and a function to sum up the elements of a list:

```
def sum(xs):
  if (isEmpty(xs)):
    0
  else:
    head(xs) + sum(tail(xs))

sum(range(1, 5))
```

which should produce the result `10`.

Recap

We have a pretty serious language now, with:

- **Data Structures**

which are implemented using

- **Heap Allocation**
- **Run-time Tags**

which required a bunch of small but subtle changes in the

- runtime and compiler

Recap

In your assignment, you will add *native* support for n-ary tuples, letting the programmer write code like:

```
# constructing tuples of arbitrary arity
(e1, e2, e3, ..., en)

# allowing expressions to be used as fields
e1[e2]
```

Next, we'll see how to

- use the "pair" mechanism to add **higher-order functions** and
- reclaim unused memory via **garbage collection**.

Recap

In your assignment, you will add *native* support for n-ary tuples, letting the programmer write code like:

```
# constructing tuples of arbitrary arity
(e1, e2, e3, ..., en)

# allowing expressions to be used as fields
e1[e2]
```

Next, we'll see how to

- use the "pair" mechanism to add **higher-order functions** and
- reclaim unused memory via **garbage collection**.

Haskell vs Egg-eater

```
data List = Node Int List         -- (Int, List)
          | Empty                 -- false

1:2:3:4:5:6:7:8:[]
(1,(2,(3,(4,(5,(6,(7,(8,false))))))))

def isEmpty(l):
  l == false

def cons(h, t):
  (h, t)

def head(e):
  e[0]

def tail(e):
  e[1]
```


Haskell vs Egg-eater

```
def length(l):
  if isEmpty(l):
    0
  else:
    1 + length(tail(l))
```

Haskell vs Egg-eater

```
data Tree = Node Int Tree Tree    -- (Int, Tree, Tree)
          | Leaf                  -- False

def node(n, l, r):
  return (n, l, r)

def isLeaf(t):
  t == false

def nodeVal(t)::
  t[0]

def nodeLeft(t)::
  t[1]

def nodeRight(t)::
  t[2]
```