Programming Languages and Techniques (CIS120)

Lecture 14

February 11, 2013

Imperative Queues

Announcements

- Homework 4 due tonight at midnight
- Midterm 1 will be in class on Friday, February 15th
  - ROOMS:
    - Towne 100 (here) last names: A – K
    - Cohen G17 last names: L – Z
  - TIME: 11:00a.m. sharp, 50 mins
  - Covers up to Feb 6th
    - no Abstract Stack Machine

Mutable Records and the ASM

Abstract Stack Machine

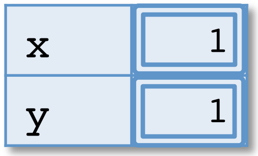
- Three “spaces”
  - workspace
    - contains the expression the computer is currently working with
    - Machine operation simplifies expression to value
  - stack
    - temporary storage for `let` bindings, function parameters and stored workspaces (function call)
    - maps variable names to values (primitive values or references to heap locations)
  - heap
    - storage area for large data structures (datatypes, tuples, first-class functions, records)

Mutable Records

- We had to go through all this abstract stack stuff to make the model of heap locations and sharing *explicit*.
  - Now we can say what it means to mutate a heap value in place.

```
type point = {mutable x:int; mutable y:int}

let p1 : point = {x=1; y=1;}
let p2 : point = p1
let ans : int = p2.x <- 17; p1.x
```

- We draw a record in the heap like this:
  - The doubled outlines indicate that those cells are mutable
  - Everything else is immutable
  - (field names don't actually take up space)



A point record in the heap.

Allocate a Record

Workspace

```
let p1 : point = {x=1; y=1;}
let p2 : point = p1
let ans : int =
    p2.x <- 17; p1.x
```

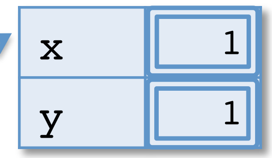
Stack

Heap

Allocate a Record

Workspace | Stack | Heap

```
let p1 : point =
let p2 : point = p1
let ans : int =
    p2.x <- 17; p1.x
```



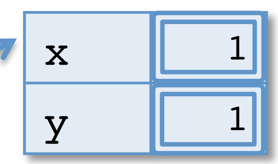
Let Expression

Workspace

```
let p1 : point =   .
let p2 : point = p1
let ans : int =
    p2.x <- 17; p1.x
```

Stack

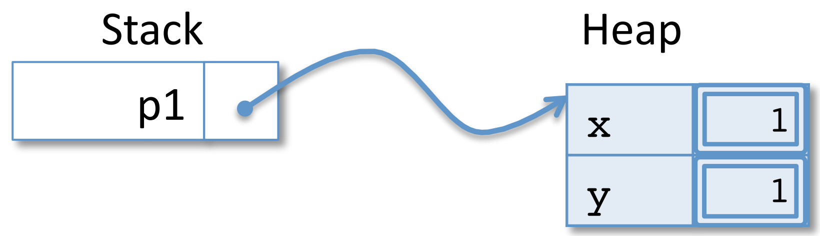
Heap



Push p1

Workspace

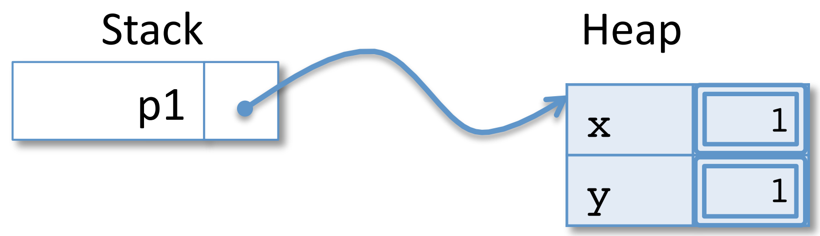
```
let p2 : point = p1
let ans : int =
    p2.x <- 17; p1.x
```



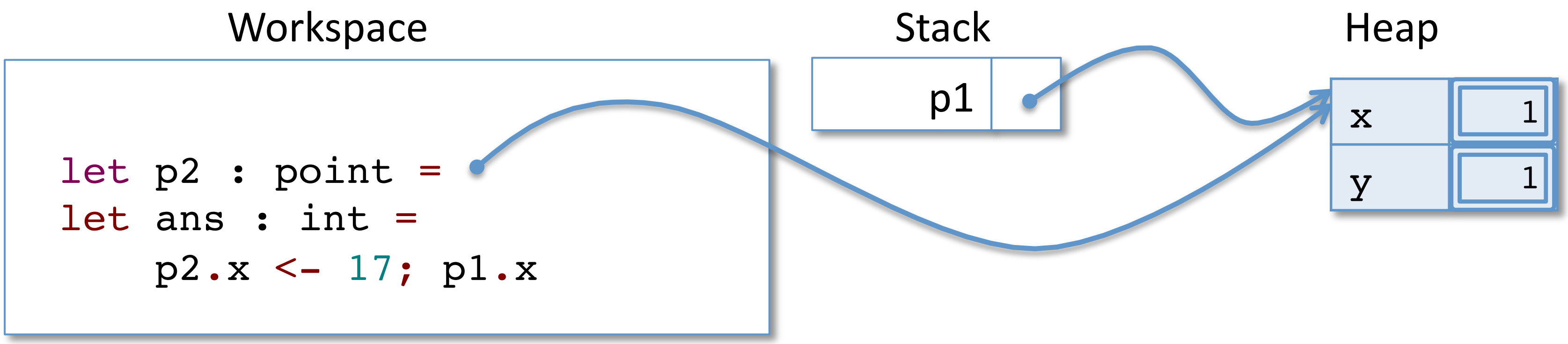
Lookup ‘p1’

Workspace

```
let p2 : point = p1
let ans : int =
    p2.x <- 17; p1.x
```



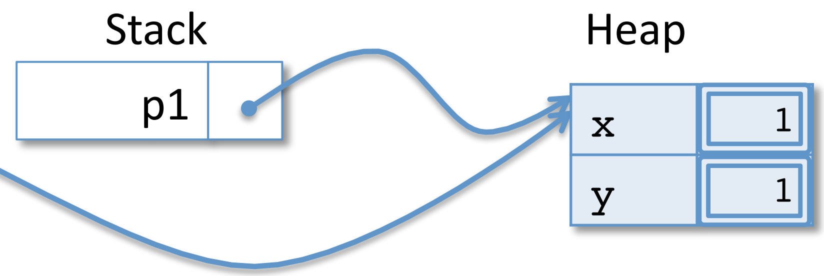
Lookup ‘p1’


Workspace
Stack
Heap
let p2 : point =
let ans : int =
p2.x <- 17; p1.x
p1
x
1
y
1

Let Expression

Workspace

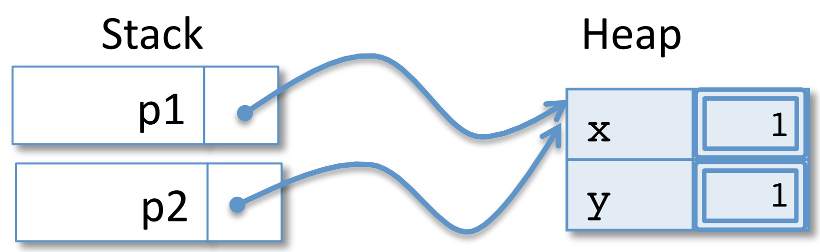
```
let p2 : point =  .
let ans : int =
    p2.x <- 17; p1.x
```



Push p2

Workspace

```
let ans : int =
    p2.x <- 17; p1.x
```

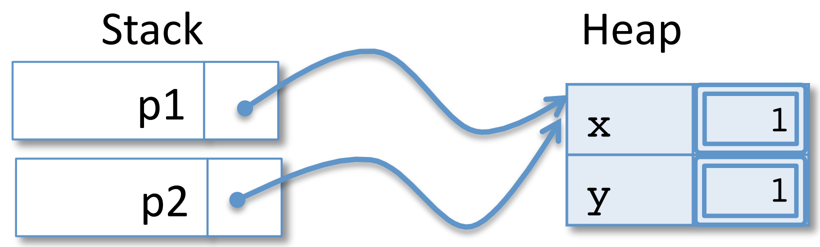


Note: p1 and p2 are references to the *same* heap record.
They are *aliases* – two different names for the *same* thing.

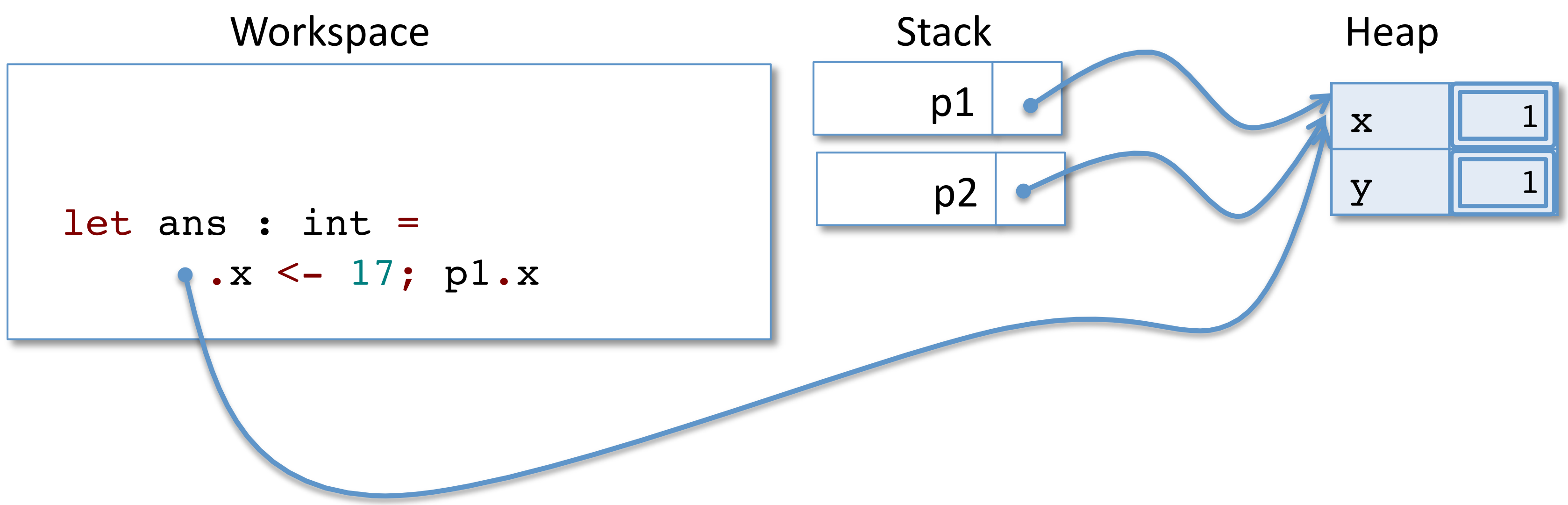
Lookup ‘p2’

Workspace

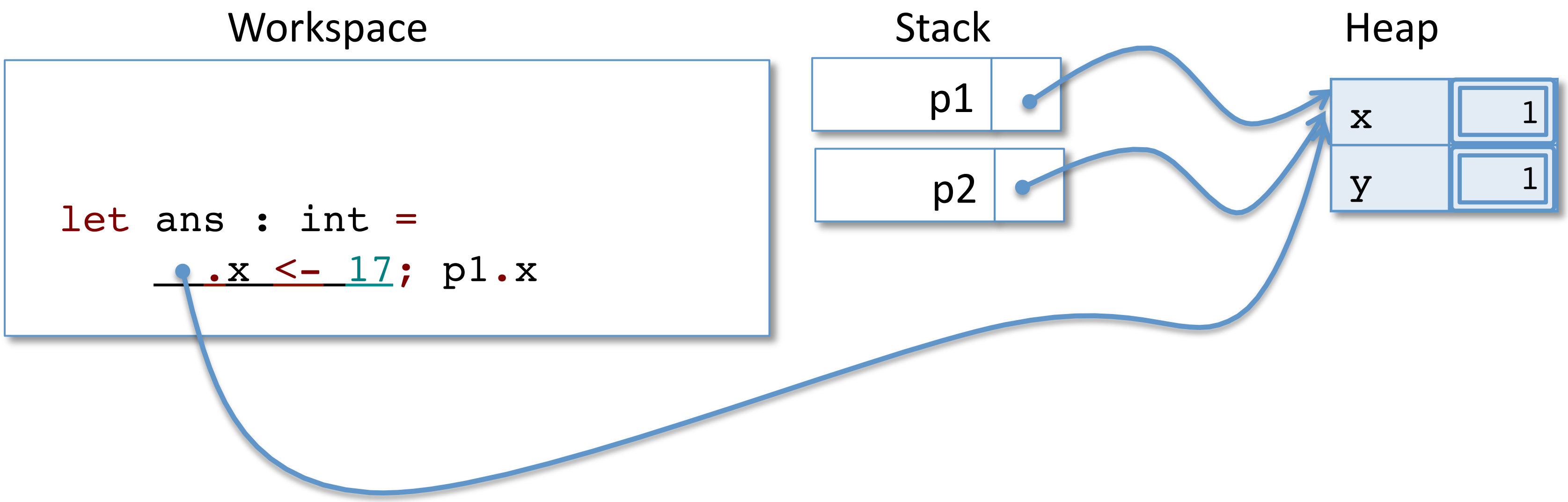
```
let ans : int =
    p2.x <- 17; p1.x
```



Lookup ‘p2’



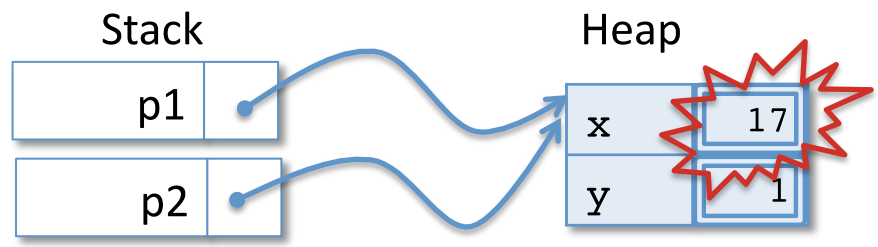
Assign to x field



Assign to x field

Workspace

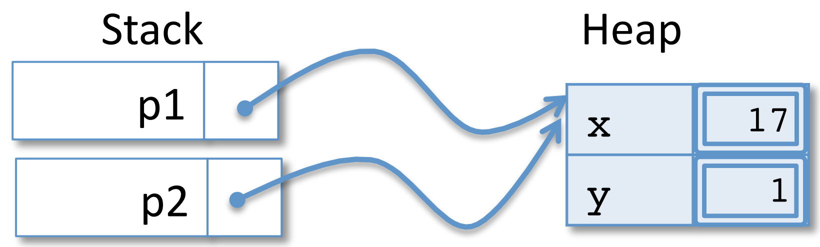
```
let ans : int =
    (); p1.x
```



Sequence ‘;’ Discards Unit

Workspace

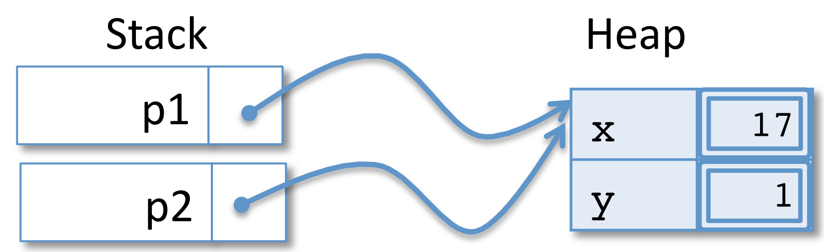
```
let ans : int =
    (); p1.x
```



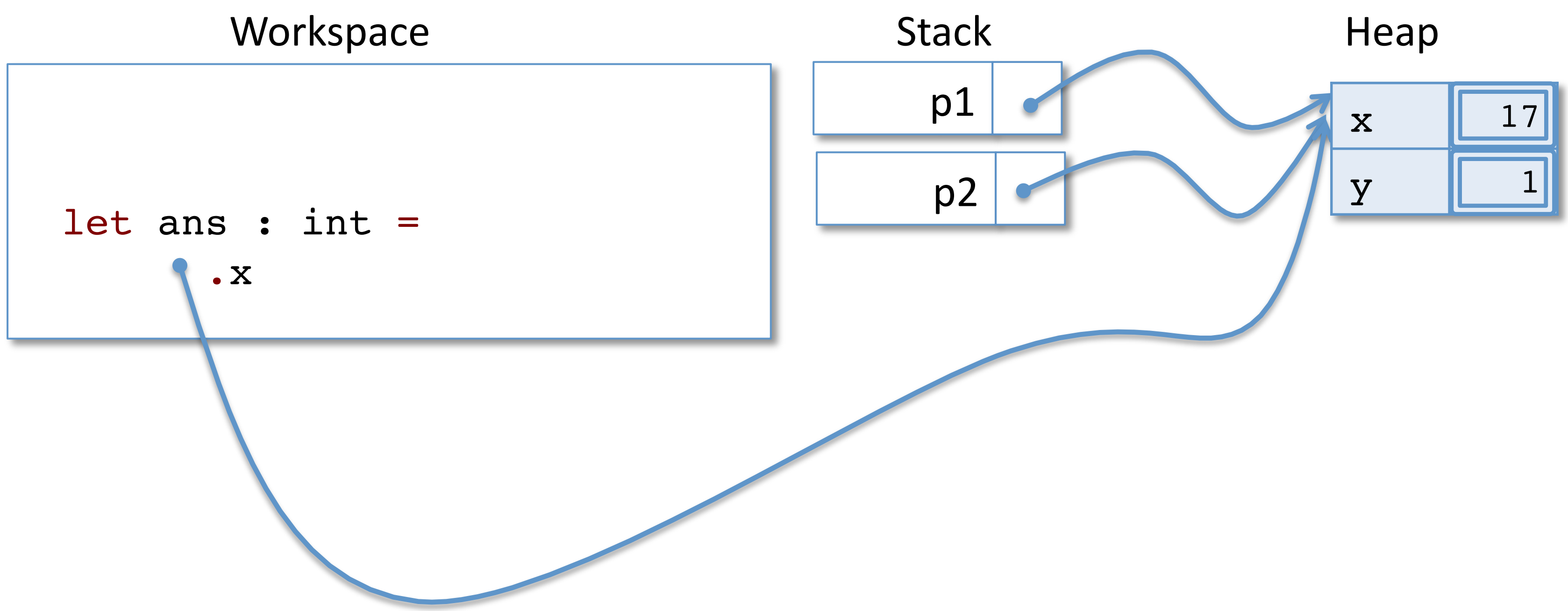
Lookup ‘p1’

Workspace

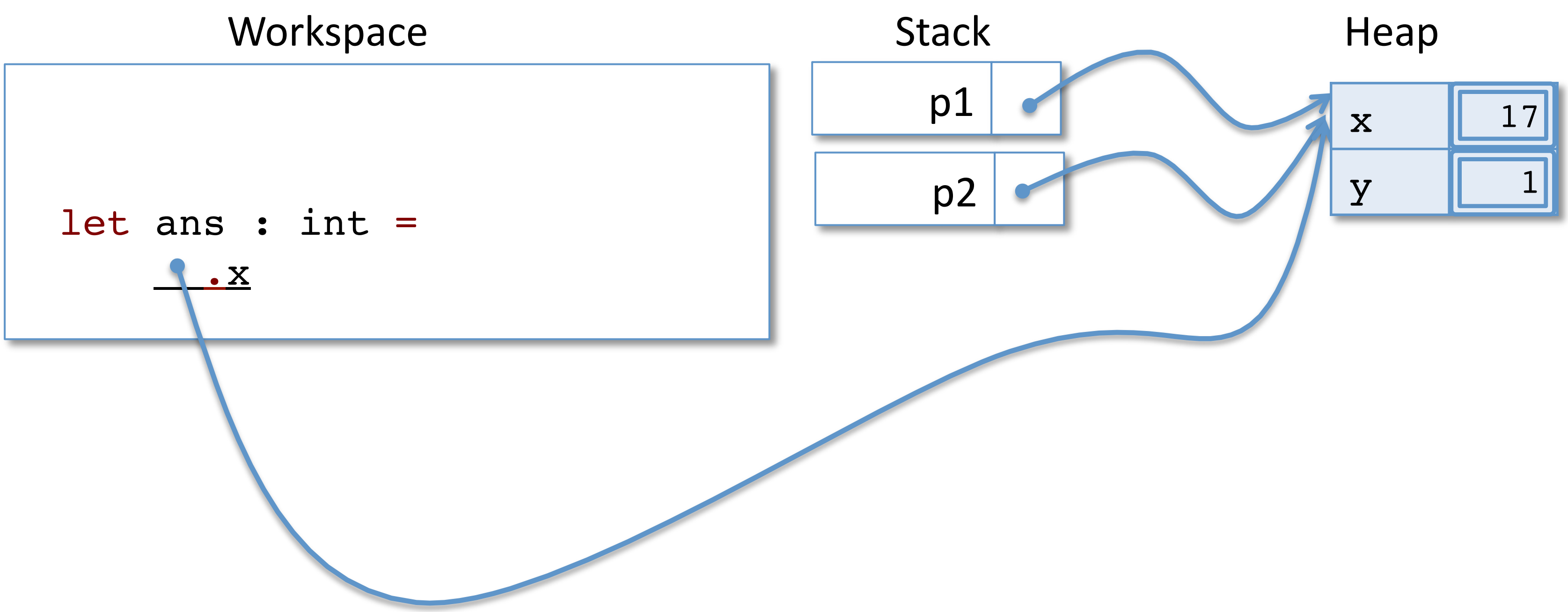
```
let ans : int =
    p1.x
```



Lookup ‘p1’



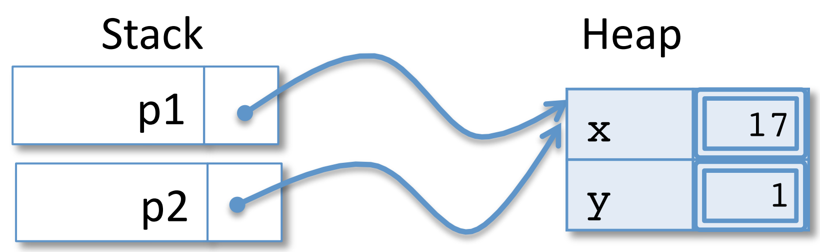
Project the 'x' field



Project the ‘x’ field

Workspace

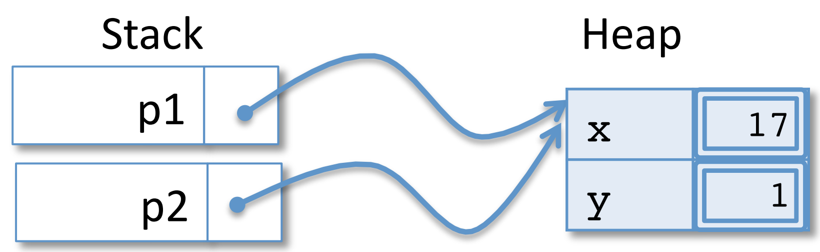
```
let ans : int =
    17
```



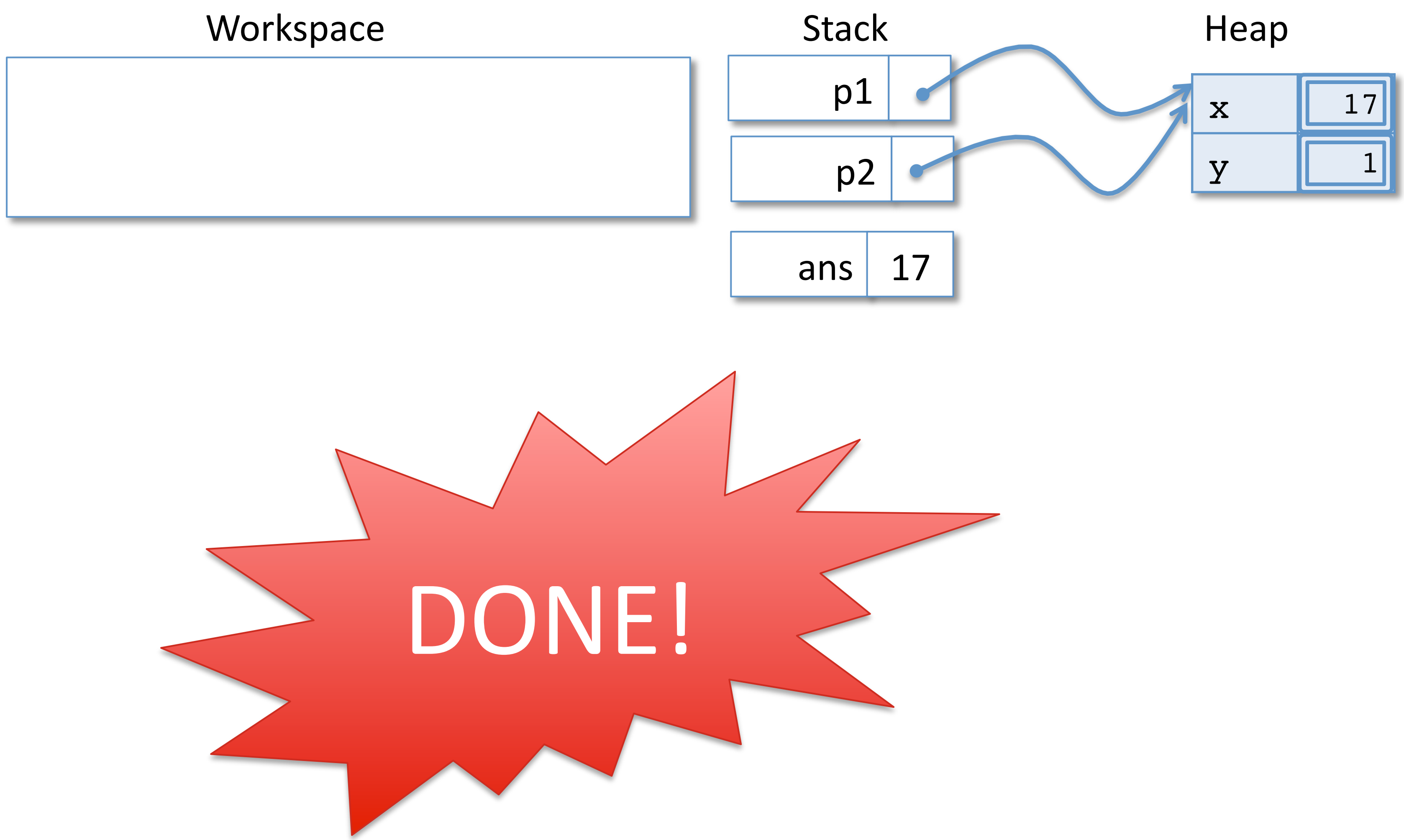
Let Expression

Workspace

```
let ans : int =
      17
```



Push ans



Reference and Equality

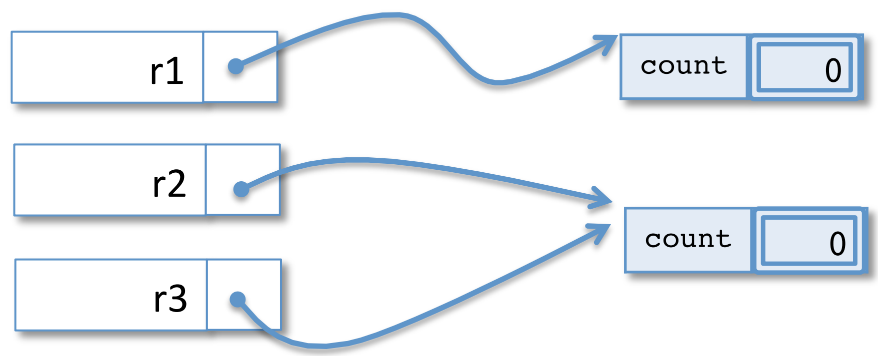
= vs. ==

Reference Equality

- Suppose we have two counters. How do we know whether they share the same internal state?
  - `type counter = { mutable count : int }`
  - We could increment one and see whether the other's value changes.
  - But we could also just test whether the references alias directly.

- Ocaml uses '==' to mean *reference* equality:
  - two reference values are '==' if they point to the same data in the heap:

```
r2 == r3

not (r1 == r2)

r1 = r2
```



Structural vs. Reference Equality

- Structural (in)equality: `v1 = v2`   `v1 <> v2`
  - recursively traverses over the *structure* of the data, comparing the two values' components for structural equality
  - function values are never structurally equivalent to anything
  - structural equality can go into an infinite loop (on cyclic structures)
  - use this for comparing *immutable* datatypes

- Reference equality: v1 == v2   v1 != v2
  - Only looks at where the two references point into the heap
  - function values are only equal to themselves
  - equates strictly fewer things than structural equality
  - use this for comparing *mutable* datatypes

Putting State to Work

Queues

A design problem

Suppose you are implementing a website to sell tickets to a very popular music event. To be fair, you would like to allow people to select seats first come, first served. How would you do it?

- Understand the problem
  - Some people may visit the website to buy tickets while others are still selecting their seats
  - Need to remember the order in which people purchase tickets
- Define the interface
  - Need a datastructure to store ticket purchasers
  - Need to add purchasers to the end of the line
  - Need to allow purchasers at the beginning of the line to select seats
  - Needs to be mutable so the state can be shared across web sessions

(Mutable) Queue Interface

```
module type QUEUE =
sig
  (* type of the data structure *)
  type 'a queue

  (* Make a new, empty queue *)
  val create : unit -> 'a queue

  (* Determine if the queue is empty *)
  val is_empty : 'a queue -> bool

  (* Add a value to the tail of the queue *)
  val enq : 'a -> 'a queue -> unit

  (* Remove the head value and return it (if any) *)
  val deq : 'a queue -> 'a

end
```

Define test cases

```
(* Some test cases for the queue *)
let test () : bool =
  let q : int queue = create () in
  enq 1 q;
  enq 2 q;
  1 = deq q
;; run_test "queue test 1" test

let test () : bool =
  let q : int queue = create () in
  enq 1 q;
  enq 2 q;
  let _ = deq q in
  2 = deq q
;; run_test "queue test 2" test
```

Implement the behavior

```
module ListQ : QUEUE  = struct

  type 'a queue = { mutable contents : ‘a list }

  let create () : 'a queue =
    { contents = [] }

  let is_empty (q:'a queue) : bool =
    q.contents = []

  let enq (x:'a) (q:'a queue) : unit =
    q.contents <- (q.contents @ [x])

  let deq (q:'a queue) : 'a =
    begin match q.contents with
      | [] -> failwith "deq called on empty queue"
      | x::tl -> q.contents <- tl; x
    end
  end
```

Here we are using type abstraction to protect the state. Outside of the module, no one knows that queues are implemented with a mutable structure. So, only these functions can modify this structure.

A Better Implementation

- Implementation is slow because of append:
  - `q.contents @ [x]` copies the entire list each time
  - As the queue gets longer, it takes longer to add data
  - Only has a *single* reference to the beginning of the list
- Let's do it again with TWO references, one to the beginning (head) and one to the end (tail).
  - Dequeue by updating the head reference (as before)
  - Enqueue by updating the tail of the list
- The list itself must be mutable
  - because we add to one end and remove from the other
- Step 1: *Understand the problem*

Data Structure for Mutable Queues

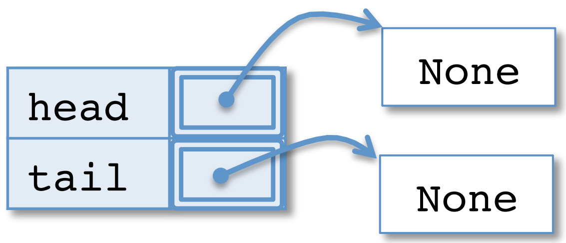
```
type 'a qnode = {
     v: 'a;
     mutable next : 'a qnode option
}

type 'a queue = { mutable head : 'a qnode option;
                  mutable tail : 'a qnode option }
```

There are two parts to a mutable queue:

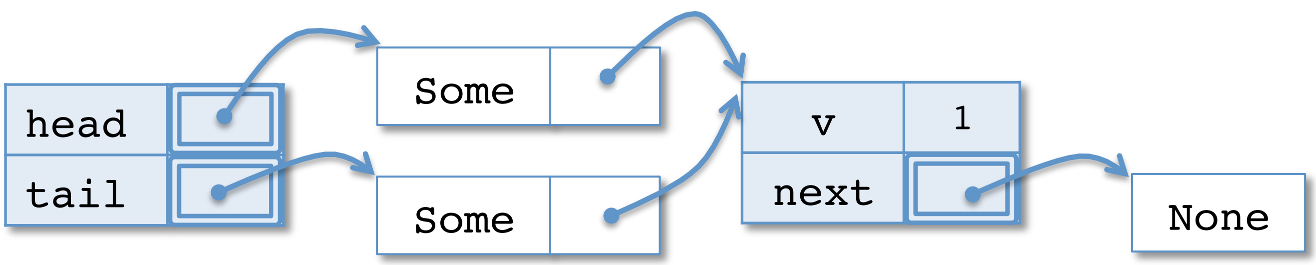
- the "internal nodes" of the queue with links from one to the next
- the head and tail references themselves

All of the references are options so that the queue can be empty.

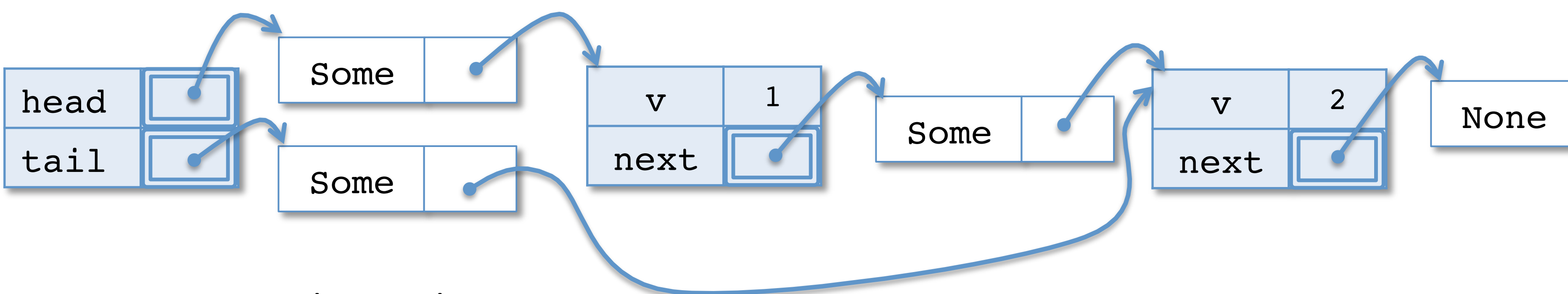
Queues in the Heap



An empty queue

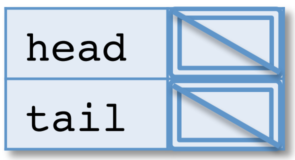


A queue with one element

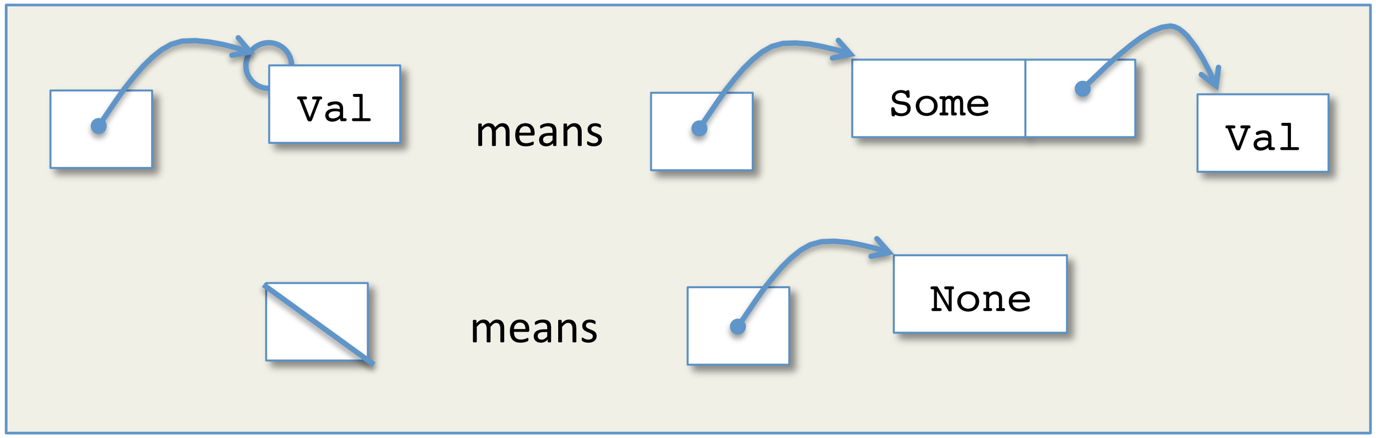


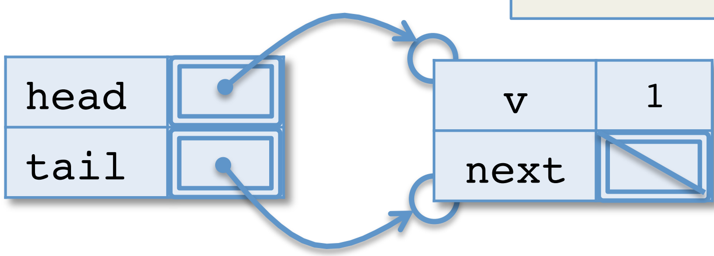
A queue with two elements

Visual Shorthand: Abbreviating Options

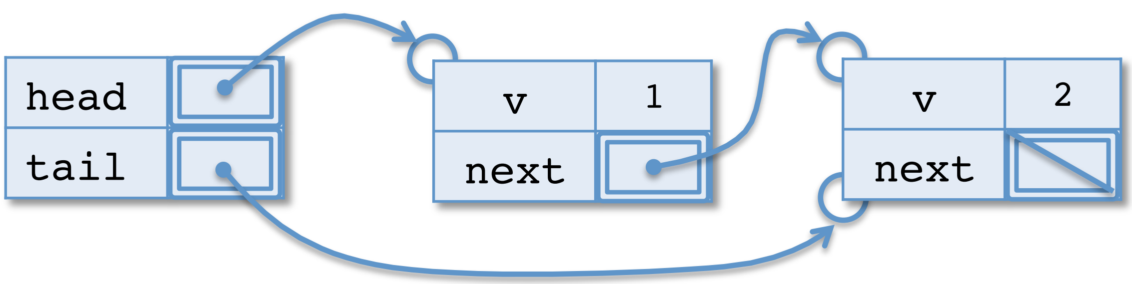


An empty queue





A queue with one element



A queue with two elements