Runtime Environments

Ronghui Gu

Spring 2019

Columbia University

* Course website: https://www.cs.columbia.edu/ rgu/courses/4115/spring2019

** These slides are borrowed from Prof. Edwards.

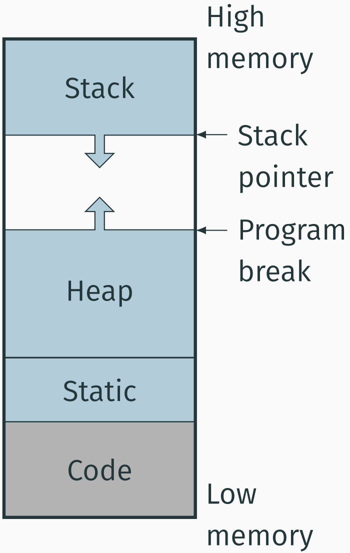
Storage Classes

Storage Classes and Memory Layout

Stack: objects created/destroyed in last-in, first-out order

Heap: objects created/destroyed in any order; automatic garbage collection optional

Static: objects allocated at compile time; persist throughout run



Static Objects

```
class Example {
  public static final int a = 3;

  public void hello() {
    System.out.println("Hello");
  }
}
```

Examples

Static class variable

String constant “Hello”

Information about the Example class

Advantages

Zero-cost memory management

Often faster access (address a constant)

No out-of-memory danger

Disadvantages

Size and number must be known beforehand

Wasteful

The Stack and Activation Records

Stack-Allocated Objects

Idea: some objects persist from when a procedure is called to when it returns.

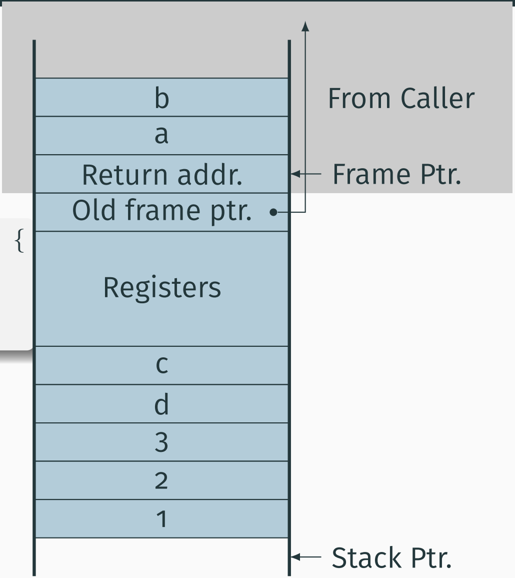
Naturally implemented with a stack: linear array of memory that grows and shrinks at only one boundary.

Natural for supporting recursion.

Each invocation of a procedure gets its own *frame* (*activation record*) where it stores its own local variables and bookkeeping information.

An Activation Record: The State Before Calling *bar*

```
int foo(int a, int b) {
  int c, d;
  bar(1, 2, 3);
}
```



Recursive Fibonacci

(Real C)

```c
int fib(int n) {

  if (n<2)

     return 1;
  else
     return
          fib(n-1)
          +
          fib(n-2);

}
```

(Assembly-like C)

```c
int fib(int n) {
      int tmp1, tmp2, tmp3;
      tmp1 = n < 2;
      if (!tmp1) goto L1;
      return 1;
L1:   tmp1 = n - 1;
      tmp2 = fib(tmp1);
L2:   tmp1 = n - 2;
      tmp3 = fib(tmp1);
L3:   tmp1 = tmp2 + tmp3;
      return tmp1;
}
```

```
          fib(3)
         /      \
     fib(2)    fib(1)
     /    \
fib(1)   fib(0)
```

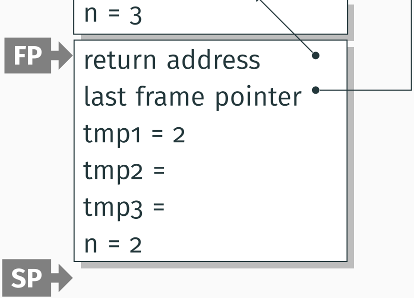
Executing fib(3)

n = 3

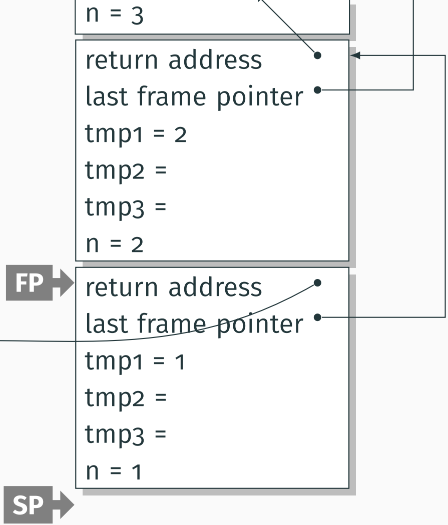
SP

```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```

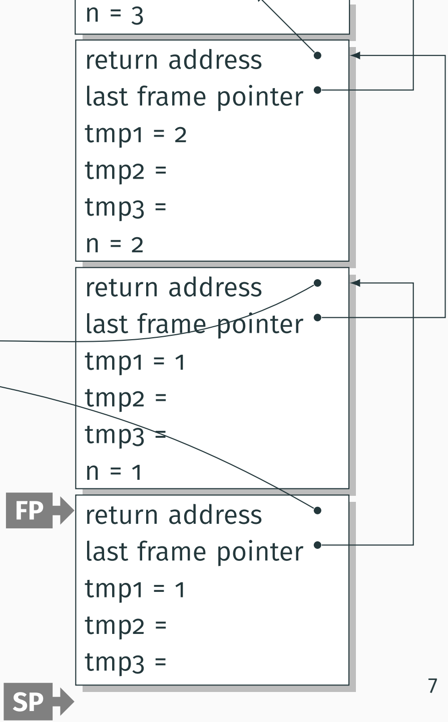
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



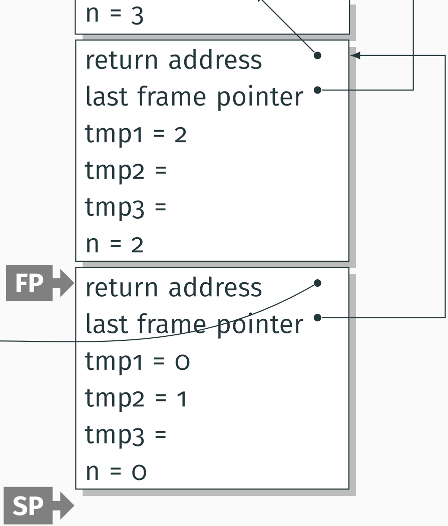
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



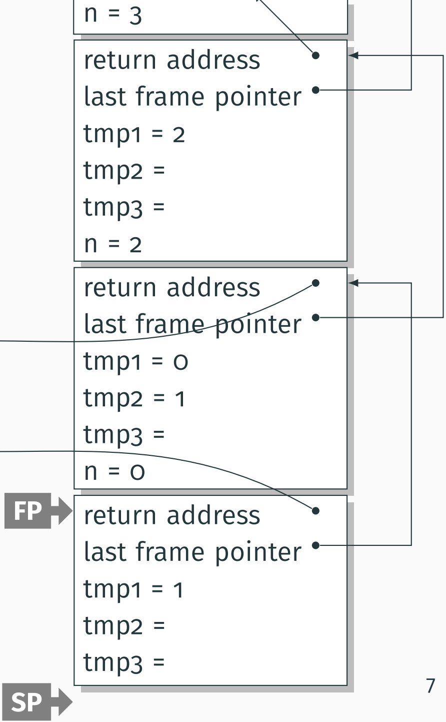
```c
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



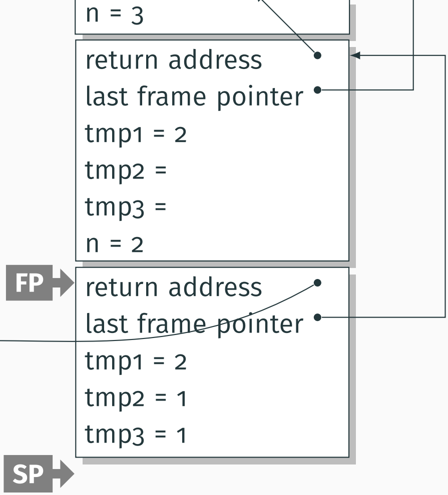
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



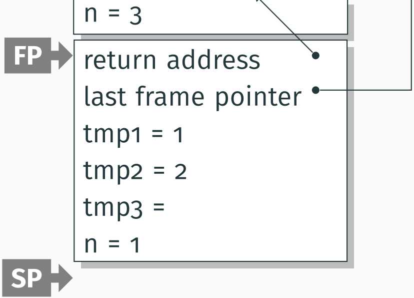
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



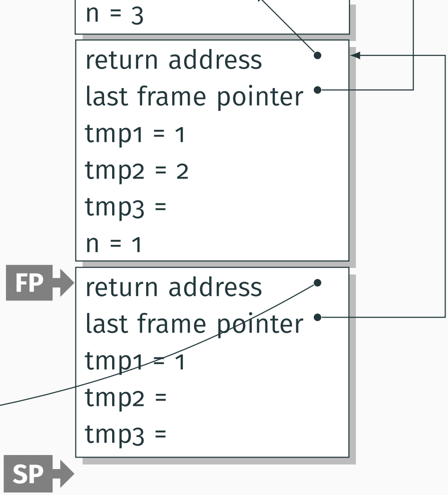
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



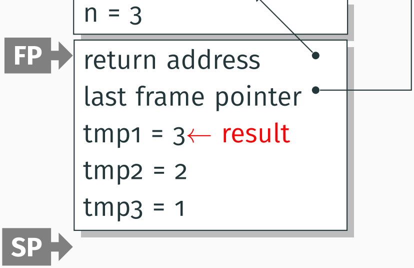
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



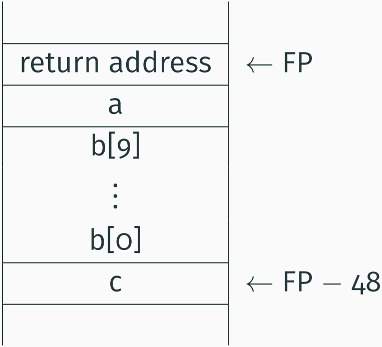
```
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
    if (!tmp1) goto L1;
    return 1;
L1: tmp1 = n - 1;
    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```



Allocating Fixed-Size Arrays

Local arrays with fixed size are easy to stack.

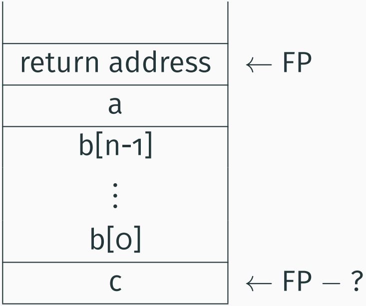
```c
void foo()
{
  int a;
  int b[10];
  int c;
}
```



Allocating Variable-Sized Arrays

Variable-sized local arrays aren’t as easy.

```
void foo(int n)
{
  int a;
  int b[n];
  int c;
}
```

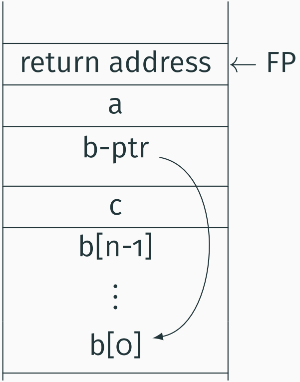


Doesn’t work: generated code expects a fixed offset for c. Even worse for multi-dimensional arrays.

Allocating Variable-Sized Arrays

As always:
add a level of indirection

```
void foo(int n)
{
  int a;
  int b[n];
  int c;
}
```



Variables remain constant offset from frame pointer.

Implementing Nested Functions with Access Links

```
let a x s =
  let b y =
    let c z = z + s in
    let d w = c (w+1) in
   d (y+1) in (* b *)
  let e q = b (q+1) in
e (x+1) (* a *)
```

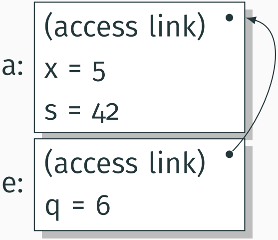
What does “a 5 42” give?

a:

(access link) •
x = 5
s = 42

Implementing Nested Functions with Access Links

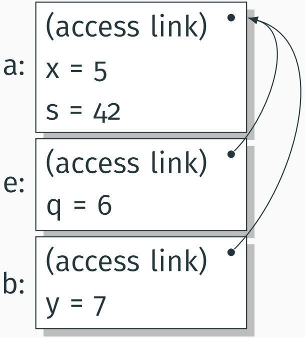
```
let a x s =
  let b y =
    let c z = z + s in
    let d w = c (w+1) in
    d (y+1) in (* b *)
  let e q = b (q+1) in
e (x+1) (* a *)
```



What does “a 5 42” give?

Implementing Nested Functions with Access Links

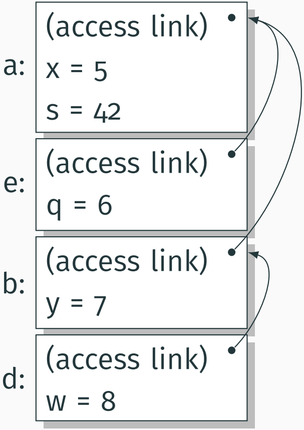
```
let a x s =
  let b y =
    let c z = z + s in
    let d w = c (w+1) in
   d (y+1) in (* b *)
  let e q = b (q+1) in
e (x+1) (* a *)
```



What does “a 5 42” give?

Implementing Nested Functions with Access Links

```
let a x s =
  let b y =
    let c z = z + s in
    let d w = c (w+1) in
    d (y+1) in (* b *)
  let e q = b (q+1) in
e (x+1) (* a *)
```

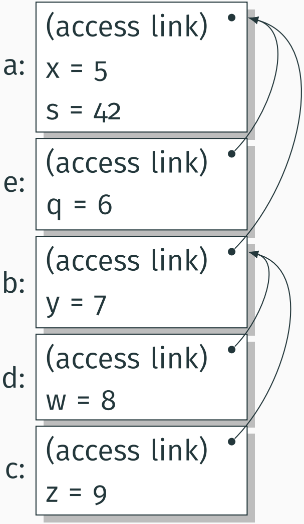


What does “a 5 42” give?

Implementing Nested Functions with Access Links

```
let a x s =
  let b y =
    let c z = z + s in
    let d w = c (w+1) in
    d (y+1) in (* b *)
  let e q = b (q+1) in
e (x+1) (* a *)
```

What does “a 5 42” give?

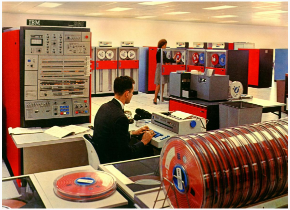


In-Memory Layout Issues

Layout of Records and Unions

Modern processors have byte-addressable memory.

0
1
2
3



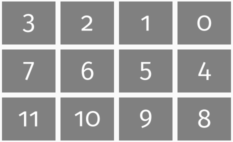
The IBM 360 (c. 1964) helped to popularize byte-addressable memory.

Many data types (integers, addresses, floating-point numbers) are wider than a byte.

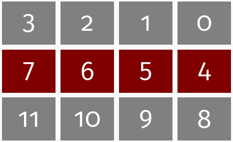
16-bit integer:			1	0
32-bit integer:	3	2	1	0

Layout of Records and Unions

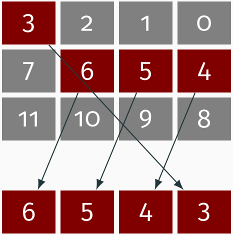
Modern memory systems read data in 32-, 64-, or 128-bit chunks:



Reading an aligned 32-bit value is fast: a single operation.



It is harder to read an unaligned value: two reads plus shifting



SPARC and ARM prohibit unaligned accesses

MIPS has special unaligned load/store instructions

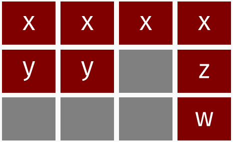
x86, 68k run more slowly with unaligned accesses

Padding

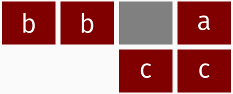
To avoid unaligned accesses, the C compiler pads the layout of unions and records. Rules:

- Each n-byte object must start on a multiple of n bytes (no unaligned accesses).
- Any object containing an n-byte object must be of size mn for some integer m (aligned even when arrayed).

```
struct padded {
  int x;    /* 4 bytes */
  char z;   /* 1 byte  */
  short y;  /* 2 bytes */
  char w;   /* 1 byte  */
};
```




```
struct padded {
  char a;   /* 1 byte  */
  short b;  /* 2 bytes */
  short c;  /* 2 bytes */
};
```



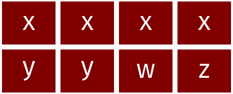
Padding

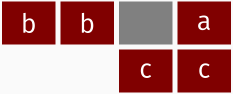
To avoid unaligned accesses, the C compiler pads the layout of unions and records. Rules:

- Each n-byte object must start on a multiple of n bytes (no unaligned accesses).
- Any object containing an n-byte object must be of size mn for some integer m (aligned even when arrayed).

```c
struct padded {
  int x;    /* 4 bytes */
  char z;   /* 1 byte  */
  char w;   /* 1 byte  */
  short y;  /* 2 bytes */
};
```

```c
struct padded {
  char a;   /* 1 byte  */
  short b;  /* 2 bytes */
  short c;  /* 2 bytes */
};
```



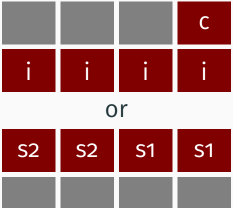


Unions

A C *struct* has a separate space for each field; a C *union* shares one space among all fields

```
union intchar {
  int i;     /* 4 bytes */
  char c;    /* 1 byte  */
};
```


```
union twostructs {
  struct {
    char c;     /* 1 byte */
    int i;      /* 4 bytes */
  } a;
  struct {
    short s1;  /* 2 bytes */
    short s2;  /* 2 bytes */
  } b;
};
```



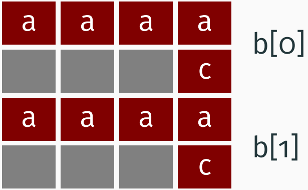
Arrays

Basic policy in C: an array is just one object after another in memory.

```c
int a[10];
```

This is why you need padding at the end of *structs*.

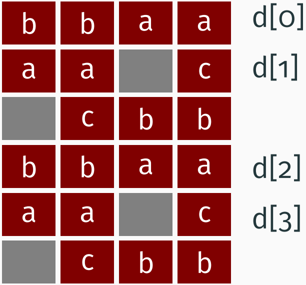
```c
struct {
  int a;
  char c;
} b[2];
```



Arrays and Aggregate types

The largest primitive type dictates the alignment

```
struct {
  short a;
  short b;
  char c;
} d[4];
```



Arrays of Arrays

```
char a[4];
```

a[3]	a[2]	a[1]	a[0]

```
char a[3][4];
```

a[0][3]	a[0][2]	a[0][1]	a[0][0]	a[0]
a[1][3]	a[1][2]	a[1][1]	a[1][0]	a[1]
a[2][3]	a[2][2]	a[2][1]	a[2][0]	a[2]

The Heap

Heap-Allocated Storage

Static works when you know everything beforehand and always need it.

Stack enables, but also requires, recursive behavior.

A *heap* is a region of memory where blocks can be allocated and deallocated in any order.

(These heaps are different than those in, e.g., heapsort)

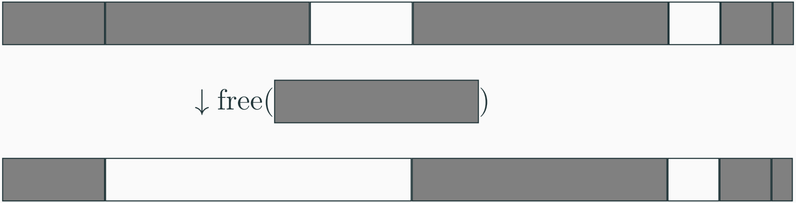
Dynamic Storage Allocation in C

```c
struct point {
   int x, y;
};

int play_with_points(int n)
{
  int i;
  struct point *points;

  points = malloc(n * sizeof(struct point));

  for ( i = 0 ; i < n ; i++ ) {
    points[i].x = random();
    points[i].y = random();
  }

  /* do something with the array */

  free(points);
}
```

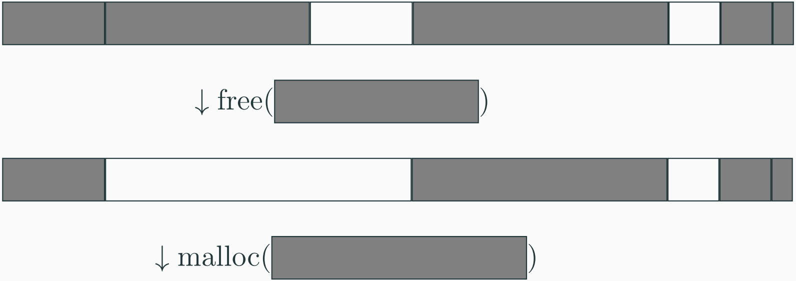
Dynamic Storage Allocation

Dynamic Storage Allocation

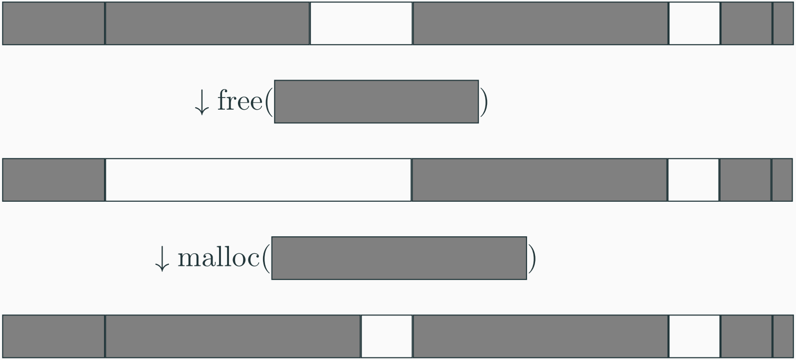
Dynamic Storage Allocation



Dynamic Storage Allocation



Dynamic Storage Allocation



Dynamic Storage Allocation

Rules:

- Each allocated block contiguous (no holes)
- Blocks stay fixed once allocated

malloc()

- Find an area large enough for requested block
- Mark memory as allocated

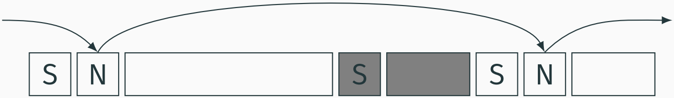
free()

- Mark the block as unallocated

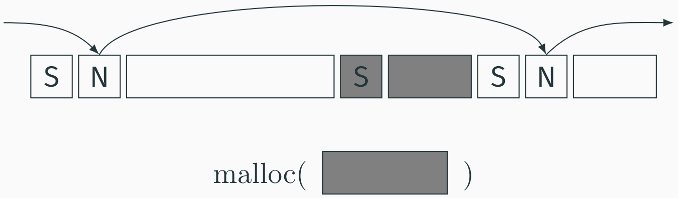
Simple Dynamic Storage Allocation

- Maintaining information about free memory
  - Simplest: Linked list
- The algorithm for locating a suitable block
  - Simplest: First-fit
- The algorithm for freeing an allocated block
  - Simplest: Coalesce adjacent free blocks

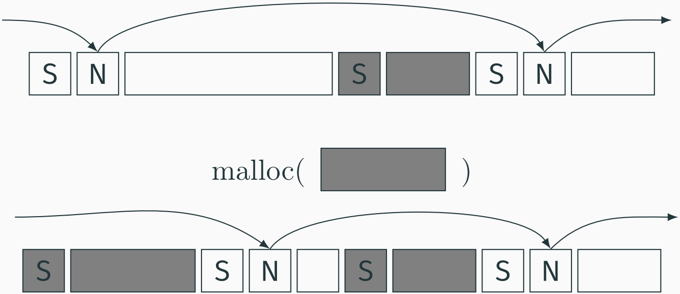
Simple Dynamic Storage Allocation



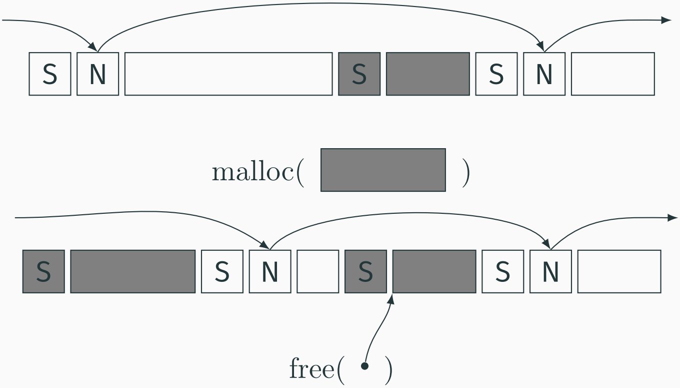
Simple Dynamic Storage Allocation



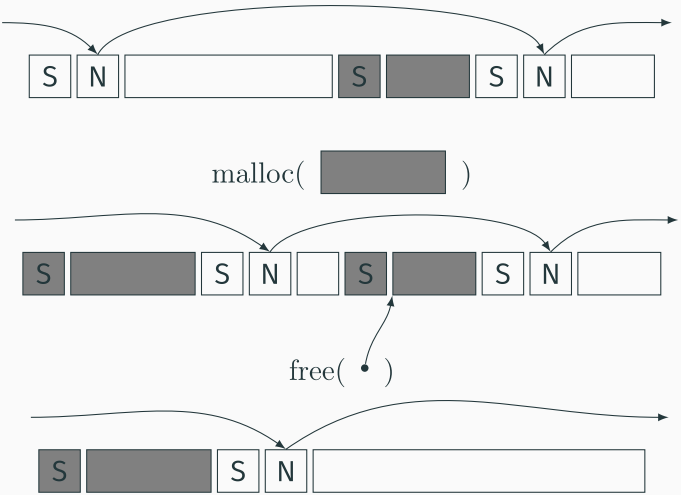
Simple Dynamic Storage Allocation



Simple Dynamic Storage Allocation



Simple Dynamic Storage Allocation



Dynamic Storage Allocation

Many, many other approaches.

Other “fit” algorithms

Segregation of objects by size

More clever data structures

Fragmentation

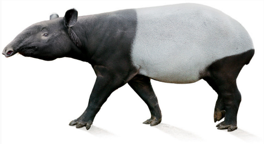
malloc() seven times give

free() four times gives

malloc() ?

Need more memory; can't use fragmented memory.

Zebra

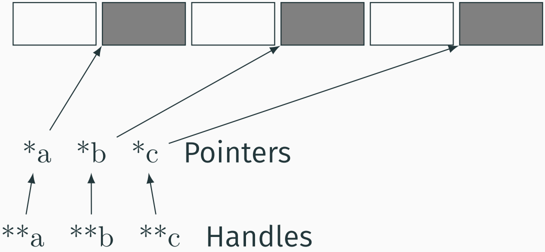


Tapir

Fragmentation and Handles

Standard CS solution: Add another layer of indirection.

Always reference memory through “handles.”

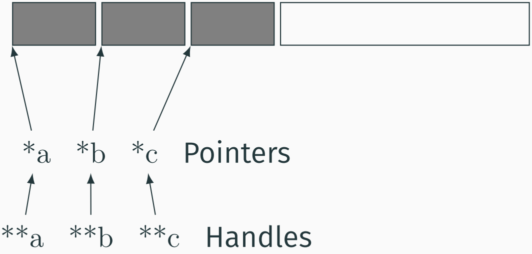


The original Macintosh did this to save memory.

Fragmentation and Handles

Standard CS solution: Add another layer of indirection.

Always reference memory through “handles.”



The original Macintosh did this to save memory.

Automatic Garbage Collection

Automatic Garbage Collection

Entrust the runtime system with freeing heap objects

Now common: Java, C#, Javascript, Python, Ruby, OCaml and most functional languages

Advantages

Much easier for the programmer

Greatly improves reliability: no memory leaks, double-freeing, or other memory management errors

Disadvantages

Slower, sometimes unpredictably so

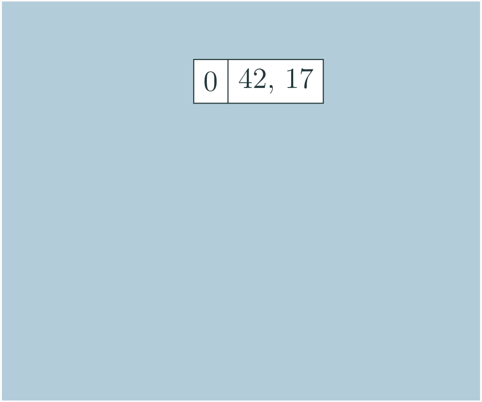
May consume more memory

Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

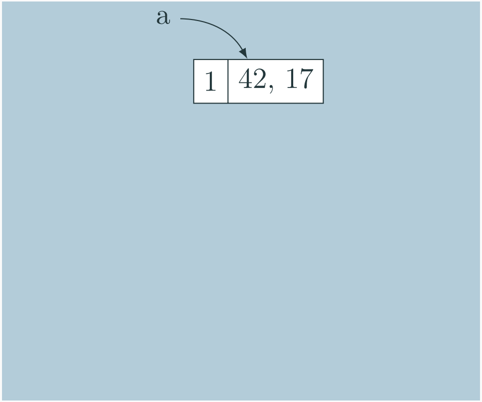


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

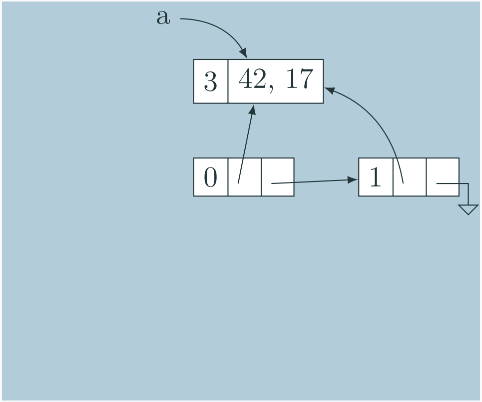


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

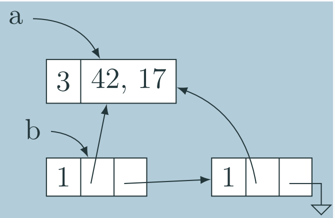


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

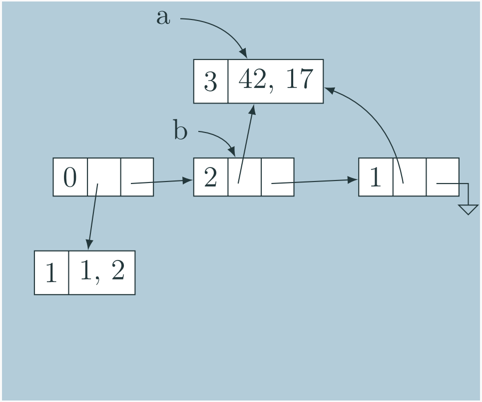


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

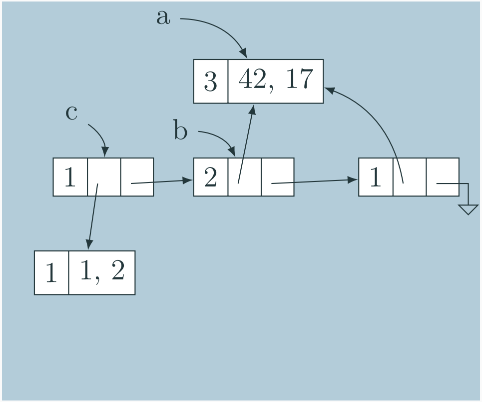


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b

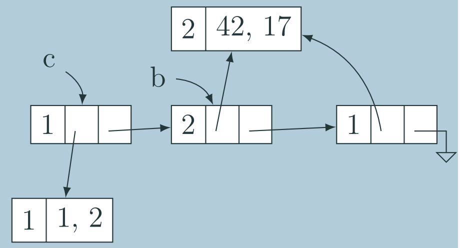


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

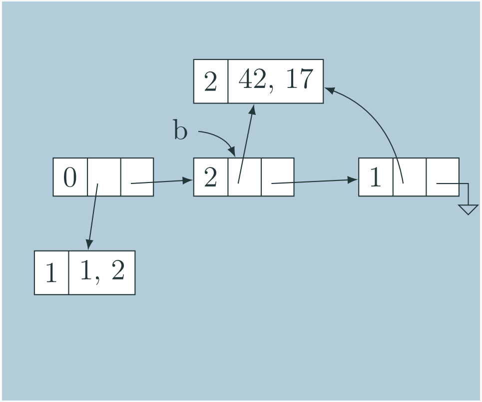


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

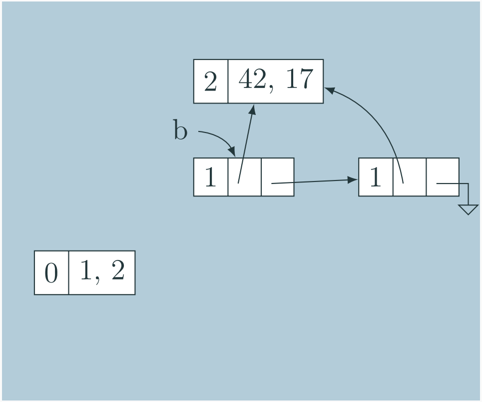


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```

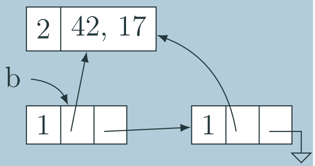


Reference Counting

What and when to free?

- Maintain count of references to each object
- Free when count reaches zero

```
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```



Issues with Reference Counting

Circular structures defy reference counting:

Neither is reachable, yet both have non-zero reference counts.

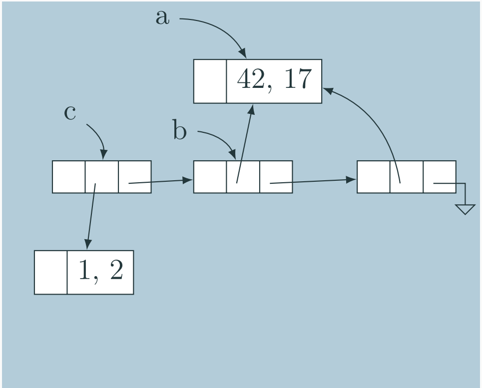
High overhead (must update counts constantly), although incremental

Mark-and-Sweep

What and when to free?

- Stop-the-world algorithm invoked when memory full
- Breadth-first-search marks all reachable memory
- All unmarked items freed

let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b

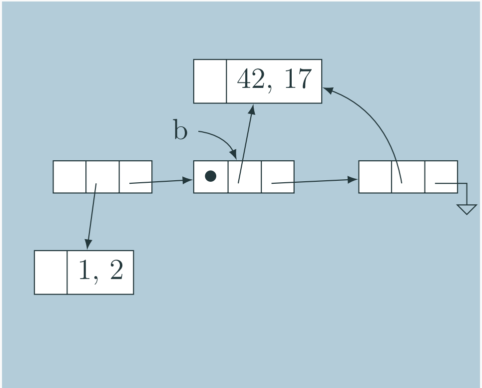


Mark-and-Sweep

What and when to free?

- Stop-the-world algorithm invoked when memory full
- Breadth-first-search marks all reachable memory
- All unmarked items freed

let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b

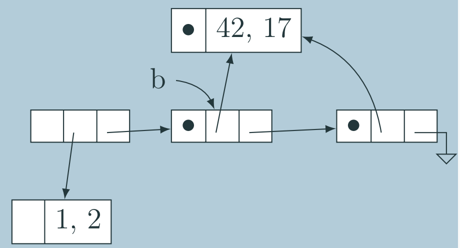


Mark-and-Sweep

What and when to free?

- Stop-the-world algorithm invoked when memory full
- Breadth-first-search marks all reachable memory
- All unmarked items freed

let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b

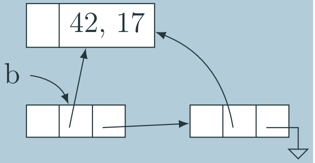


Mark-and-Sweep

What and when to free?

- Stop-the-world algorithm invoked when memory full
- Breadth-first-search marks all reachable memory
- All unmarked items freed

let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b



Mark-and-Sweep

Mark-and-sweep is faster overall; may induce big pauses

Mark-and-compact variant also moves or copies reachable objects to eliminate fragmentation

Incremental garbage collectors try to avoid doing everything at once

Most objects die young; generational garbage collectors segregate heap objects by age

Parallel garbage collection tricky

Real-time garbage collection tricky