Runtime Environments

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Columbia University

* Course website: https://verigu.github.io/4115Fall2022/

** These slides are borrowed from Prof. Edwards.

Course Evaluation

2 extra credits: complete the course final evaluation and send proofs (such as a screenshot) to: Gu4115TA@lists.cs.columbia.edu

Please do not share the evaluation details with us.

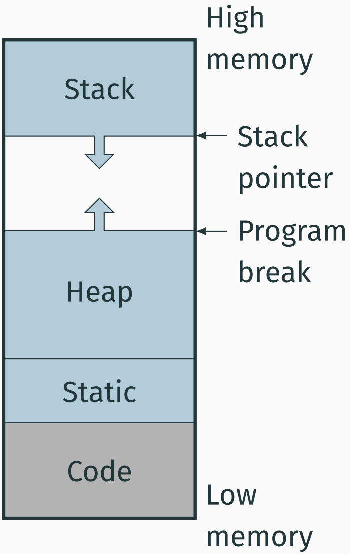
Storage Classes

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

```java
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.

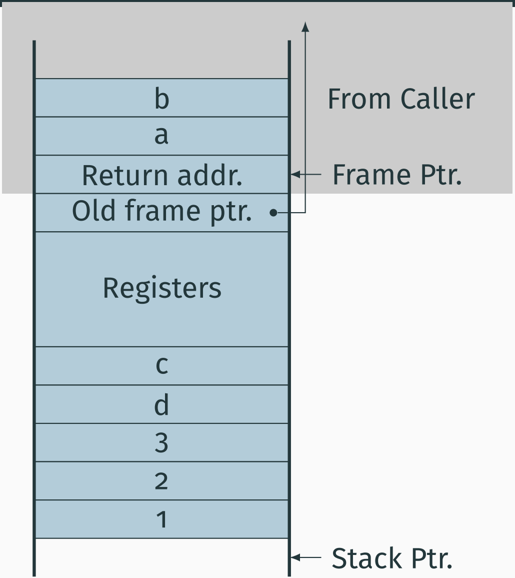
Naturally implemented with a stack: linear array of memory that grows and shrinks at only one boundary.

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)

```
int fib(int n) {

  if (n<2)

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

}
```

(Assembly-like 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) {
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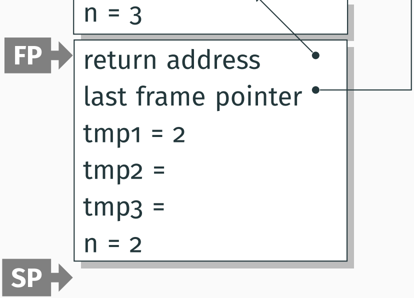

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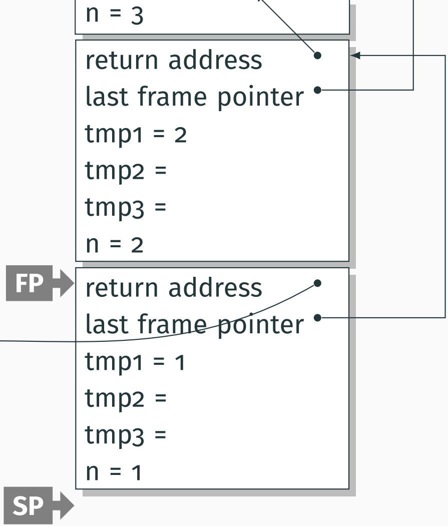

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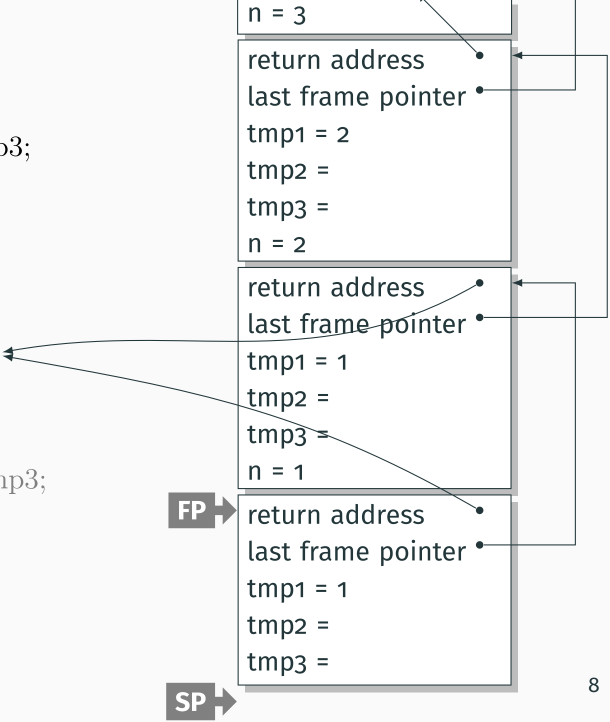

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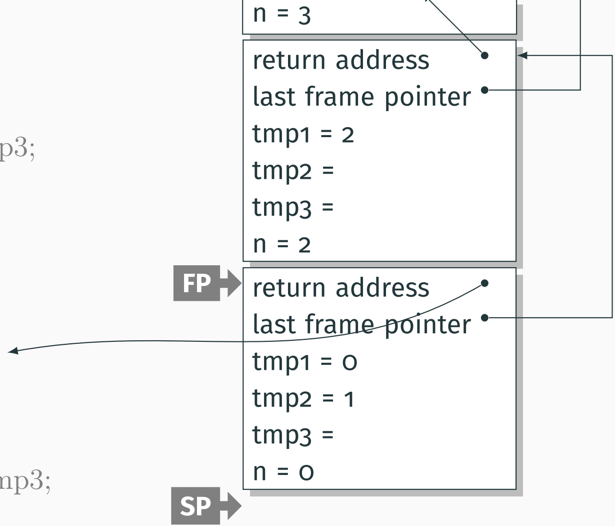

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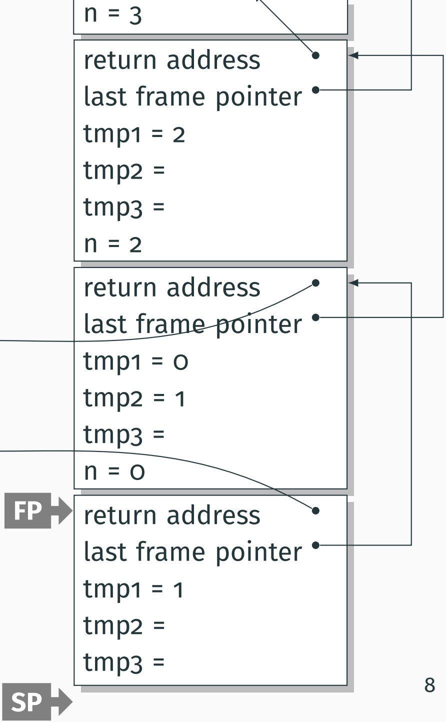

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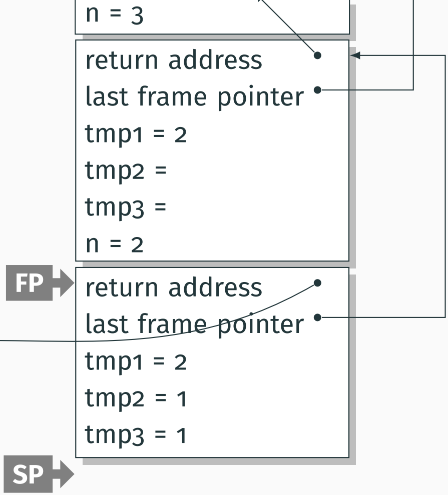

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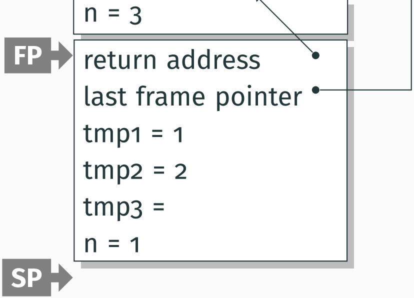

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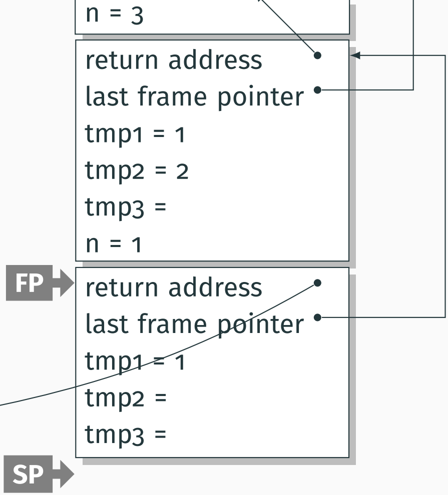

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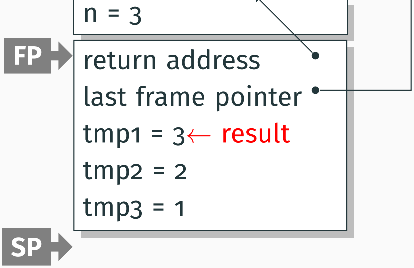
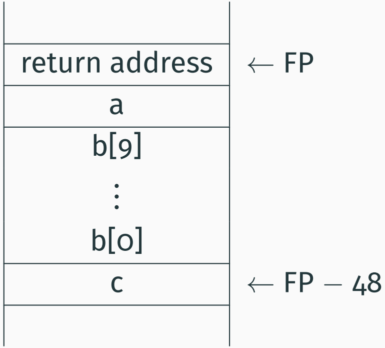


Allocating Fixed-Size Arrays

Local arrays with fixed size are easy to stack.

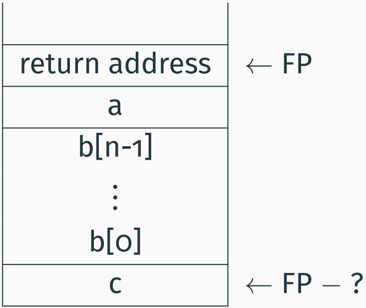
```
void foo()
{
  int a;
  int b[10];
  int c;
}
```



Allocating Variable-Sized Arrays

Variable-sized local arrays aren't as easy.

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



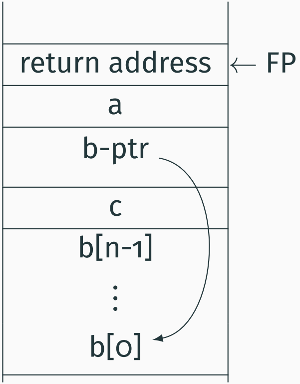
Doesn't work: generated code expects a fixed offset for c.

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 *)
```

a:

(access link) •
x = 5
s = 42

What does “a 5 42” give?

Implementing Nested Functions with Access Links

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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 *)
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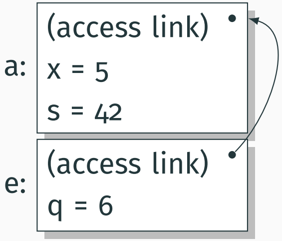

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Implementing Nested Functions with Access Links

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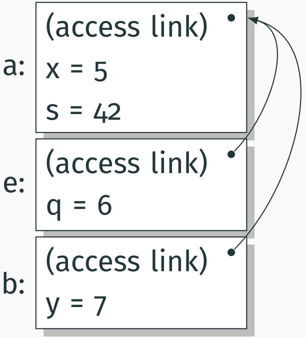

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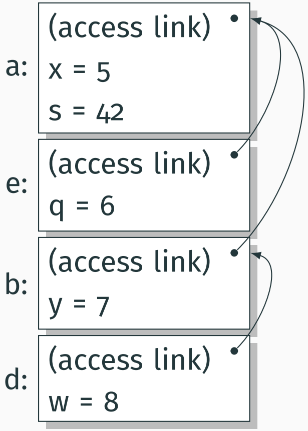

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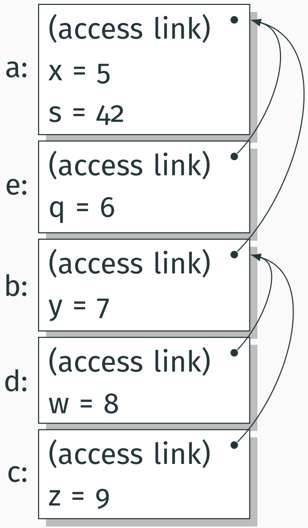
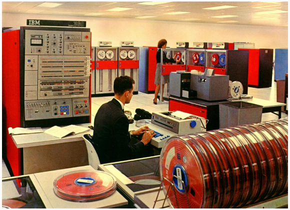


In-Memory Layout Issues

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

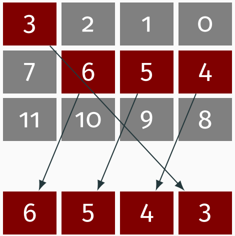
Modern memory systems read data in 32-, 64-, or 128-bit chunks:

3	2	1	0
7	6	5	4
11	10	9	8

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

3	2	1	0
7	6	5	4
11	10	9	8

How about reading an unaligned value?

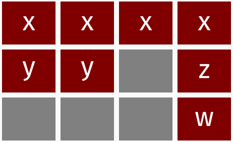


Padding

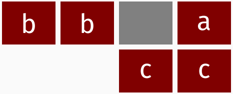
To avoid unaligned accesses, the C compiler pads the layout of unions and records. Rules:

- Each n-byte-aligned object must start on a multiple of n bytes (no unaligned accesses).
- Any object containing an n-byte-aligned 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  */
  short y;  /* 2 bytes */
  char w;   /* 1 byte  */
};
```




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



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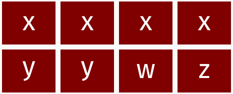


```
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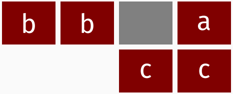
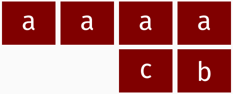
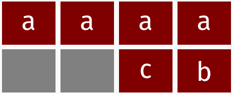


Padding: (1) or (2)?

```
struct padded {
  int a;   /* 4 bytes  */
  char b; /* 1 byte */
  char c; /* 1 byte */
};
```



(1)



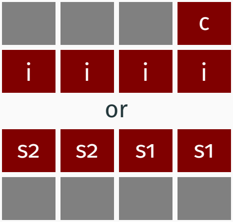
(2)

Unions

A C *union* shares one space among all fields

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

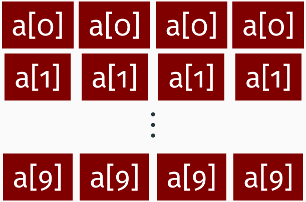

```
union twostructs {
  struct {
    char c;    /* 1 byte */
    int i;     /* 4 bytes */
  } a;
  struct {
    short s1; /* 2 bytes */
    short s2; /* 2 bytes */
  } b;
};
```



Arrays

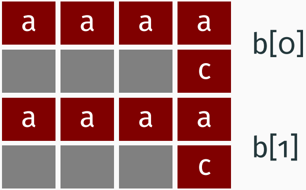
Basic policy in C: an array is just one object after another in memory.

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



What if we remove rule 2 of padding?

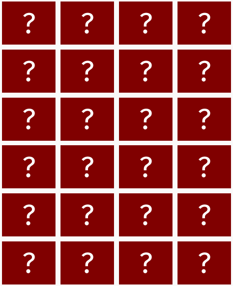
```
struct {
  int a;
  char c;
} b[2];
```



Arrays and Aggregate types

The largest primitive type dictates the alignment

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



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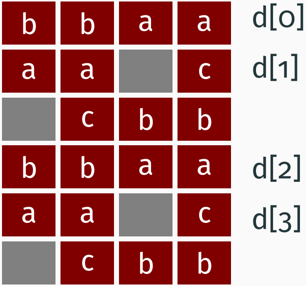
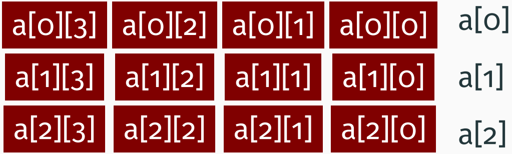


Arrays of Arrays

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


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



The Heap

Heap-Allocated Storage

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

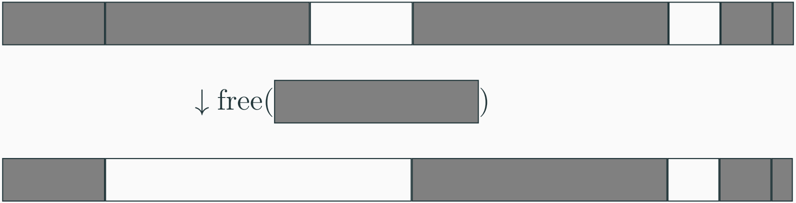
Dynamic Storage Allocation in C

```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);
}
```

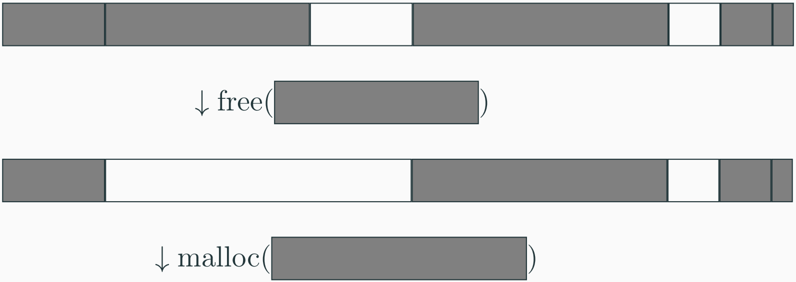
Dynamic Storage Allocation

Dynamic Storage Allocation

Dynamic Storage Allocation



Dynamic Storage Allocation



Dynamic Storage Allocation

Dynamic Storage Allocation

Rules:

- Each allocated block contiguous
- Blocks stay fixed once allocated

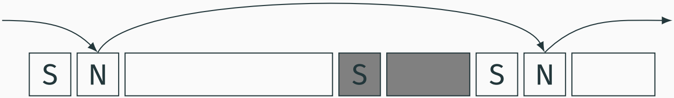
malloc()

free()

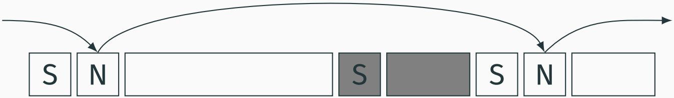
Simple Dynamic Storage Allocation

- 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



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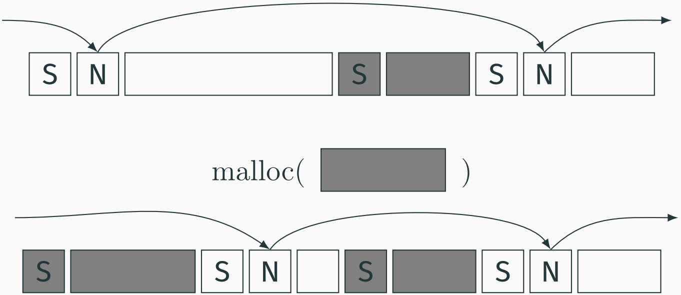

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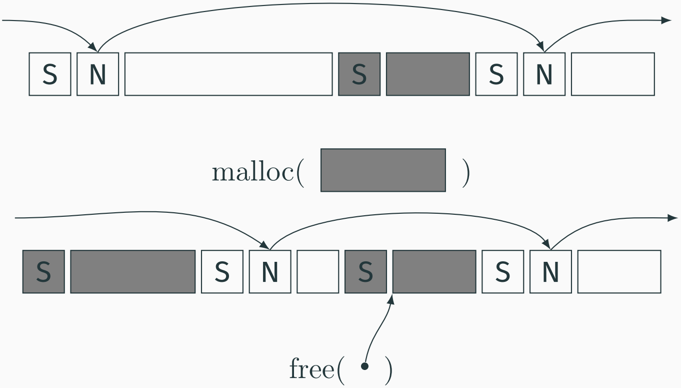
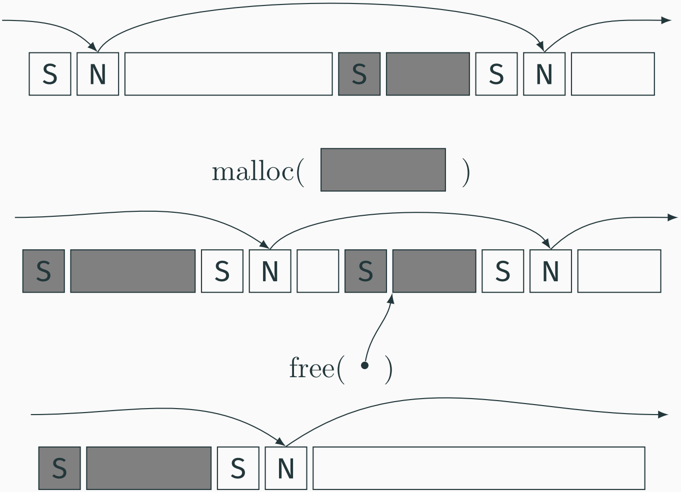


Simple Dynamic Storage Allocation



Fragmentation

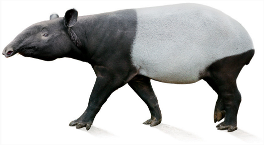
malloc( ) seven times give

free() four times gives

malloc( ) ?

Need more memory; can't use fragmented memory.

Zebra

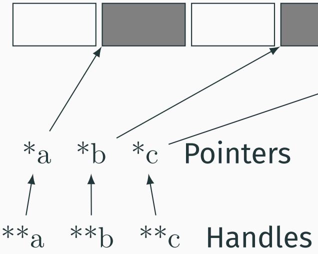


Tapir

Fragmentation and Handles

Standard CS solution: Add another layer of indirection.

Always reference memory through “handles.”



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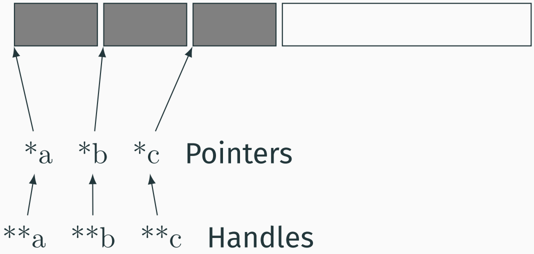

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Automatic Garbage Collection

Automatic Garbage Collection

Entrust the runtime system with freeing heap objects

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

Advantages?

Disadvantages?

Reference Counting

What and when to free?

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

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let b = [a;a] in
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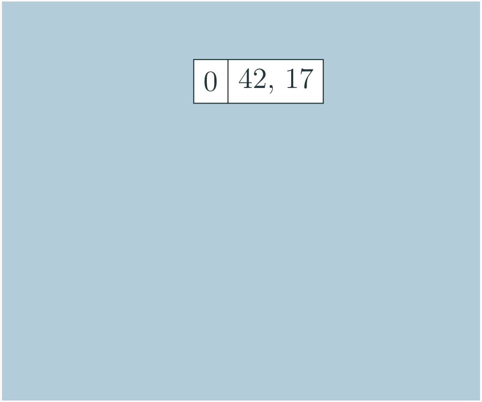

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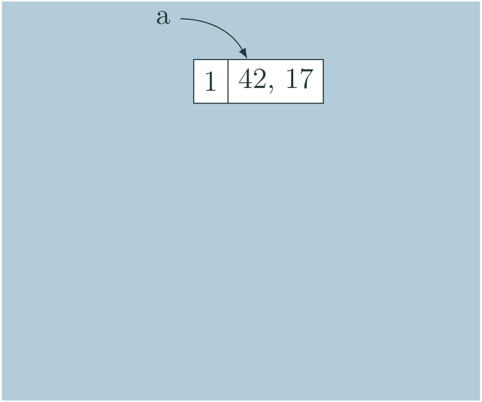

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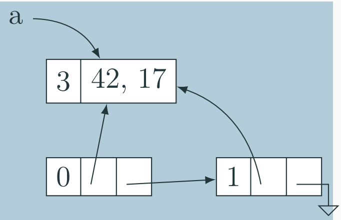

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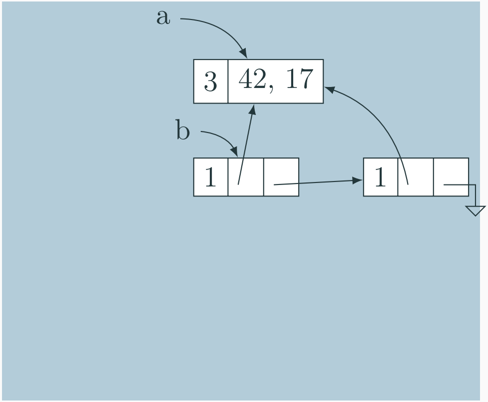

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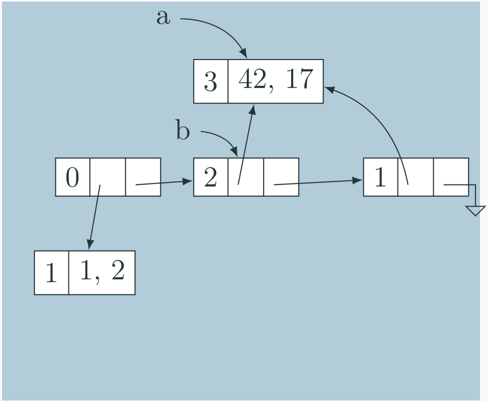

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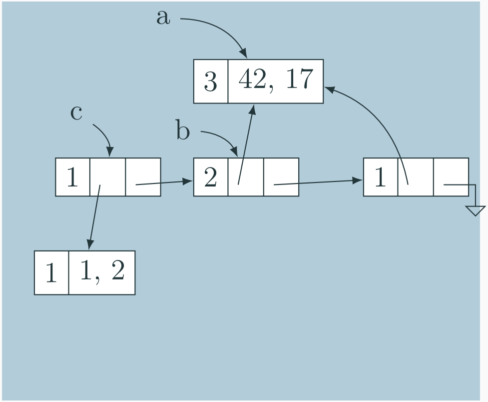

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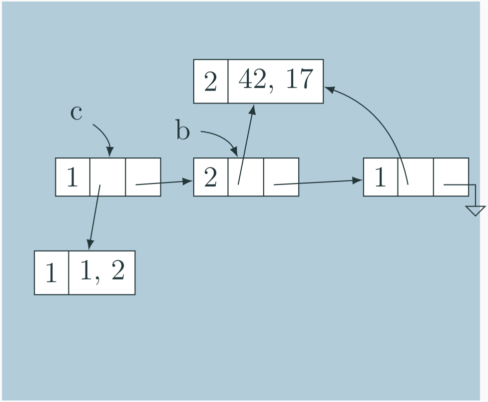

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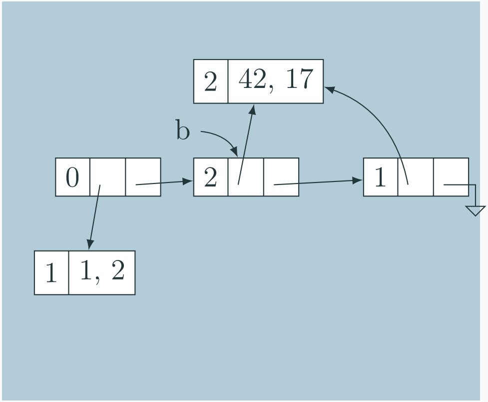

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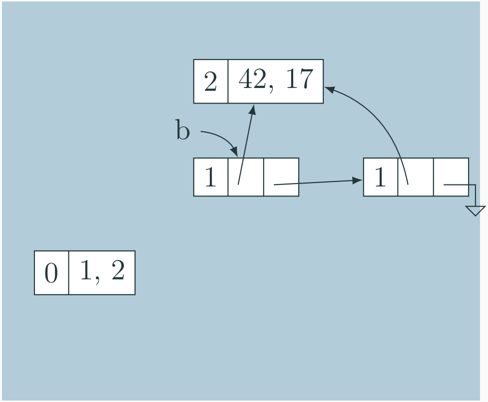

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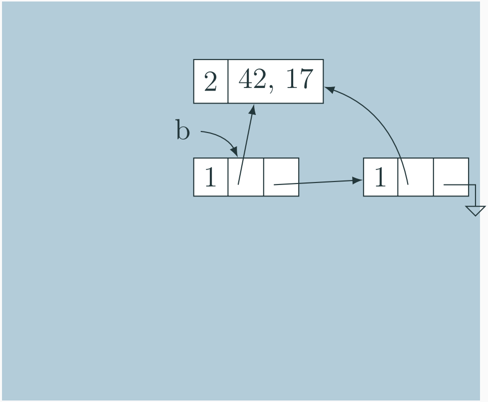

Issues with Reference Counting

Circular structures defy reference counting?

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

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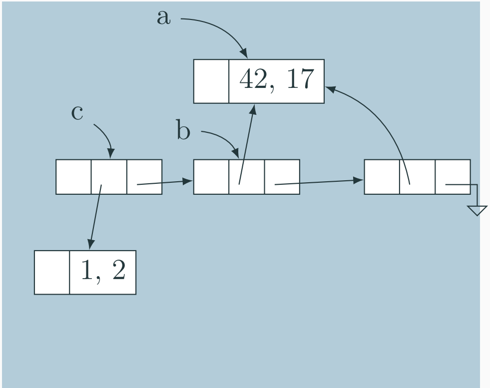

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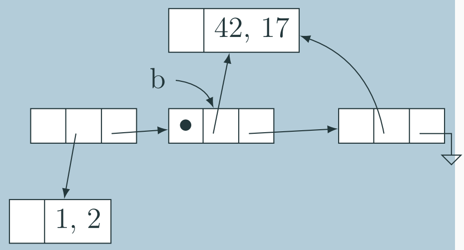

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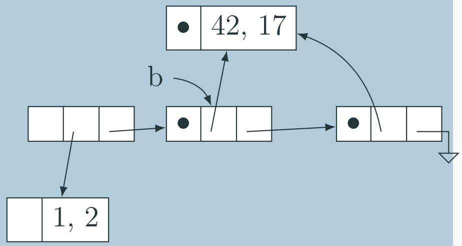

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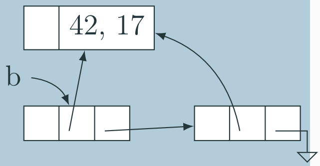

Mark-and-Sweep

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

Objects and Inheritance

Single Inheritance

Simple: Add new fields to end of the object

Fields in base class always at same offset in derived class (compiler never reorders)

Consequence: Derived classes can never remove fields

C++

```
class Shape {
  double x, y;
};

class Box : Shape {
  double h, w;
};


class Circle : Shape {
  double r;
};
```

Equivalent C

```
struct Shape {
  double x, y;
};

struct Box {
  double x, y;
  double h, w;
};

struct Circle {
  double x, y;
  double r;
};
```

Virtual Functions

```
class Shape {
  virtual void draw(); // Invoked by object's run-time class
};                     // not its compile-time type.

class Line : public Shape {
  void draw();
}

class Arc : public Shape {
  void draw();
};

Shape *s[10];
s[0] = new Line;
s[1] = new Arc;
s[0]->draw();   // Invoke Line::draw()
s[1]->draw();   // Invoke Arc::draw()
```

Virtual Functions

Trick: add to each object a pointer to the virtual table for its type, filled with pointers to the virtual functions.

Like the objects themselves, the virtual table for each derived type begins identically.

```
struct A {
  int x;
  virtual void Foo();
  virtual void Bar();
};

struct B : A {
  int y;
  virtual void Foo();
  virtual void Baz();
};

A a1;
A a2;
B b1;
```