Runtime Environments II

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Columbia University

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

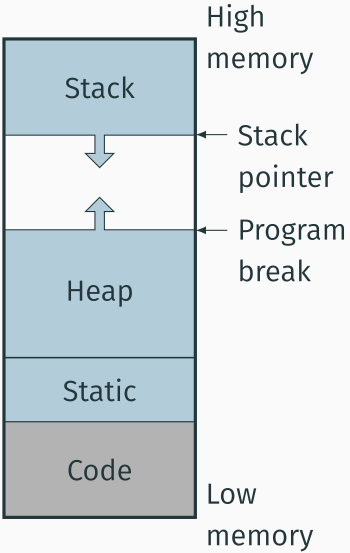
** These slides are borrowed from Prof. Edwards.

Storage Classes and Memory Layout

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

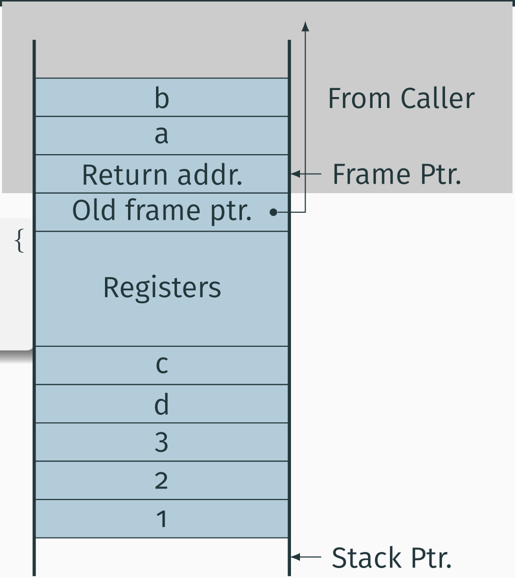
Heap: objects created/destroyed in any order; automatic garbage collection optional

Static: objects allocated at compile time; persist throughout run



Stack-Allocated Objects

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



Implementing Nested Functions with Access Links

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

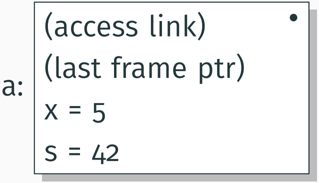

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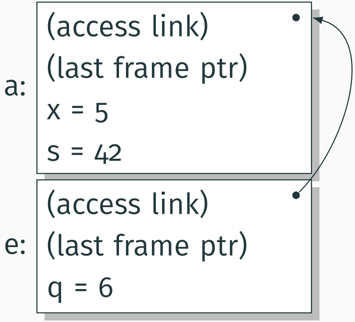

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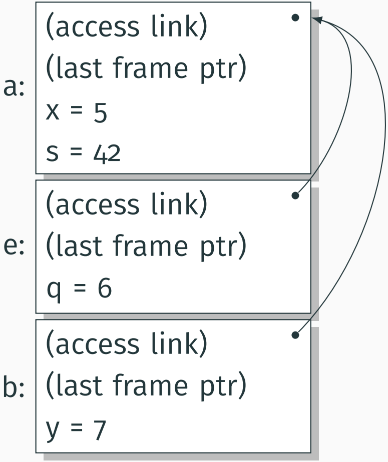

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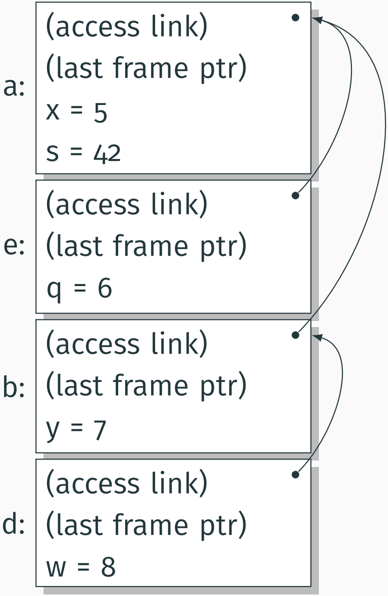
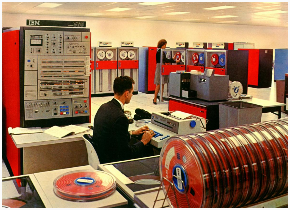


In-Memory Layout Issues

Layout of Records and Unions

Modern processors have byte-addressable memory.

0
1
2
3



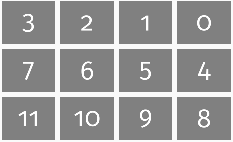
The IBM 360 (c. 1964) helped to popularize byte-addressable memory.

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

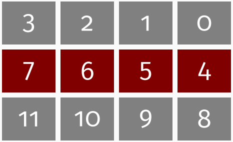
16-bit integer:			1	0
32-bit integer:	3	2	1	0

Layout of Records and Unions

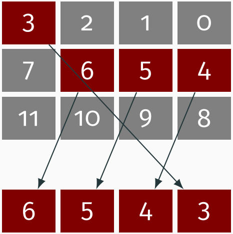
Modern memory systems read data in 32-, 64-, or 128-bit chunks:



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



How about reading an unaligned value?

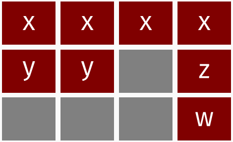


Padding

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

- Each n-byte 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  */
  short y;  /* 2 bytes */
  char w;   /* 1 byte  */
};
```

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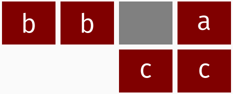

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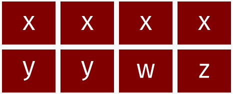


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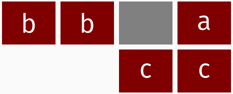

Padding: (1) or (2)?

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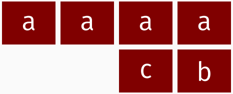
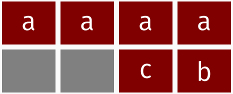


(1)



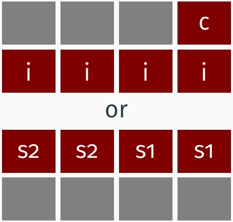
(2)

Unions

A C *union* shares one space among all fields

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


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



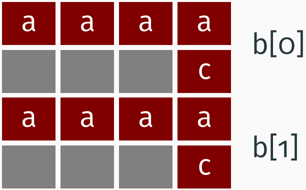
Arrays

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

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

What if we remove rule 2 of padding?

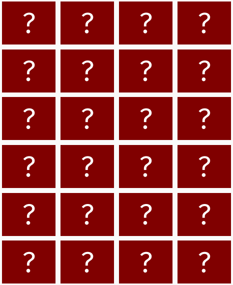
```c
struct {
  int a;
  char c;
} b[2];
```



Arrays and Aggregate types

The largest primitive type dictates the alignment

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



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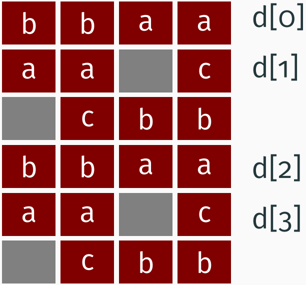
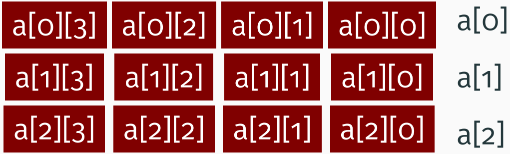


Arrays of Arrays

```
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

```
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

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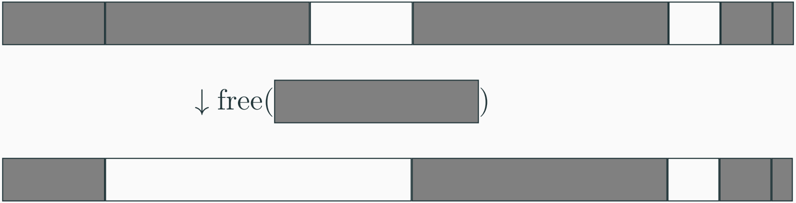

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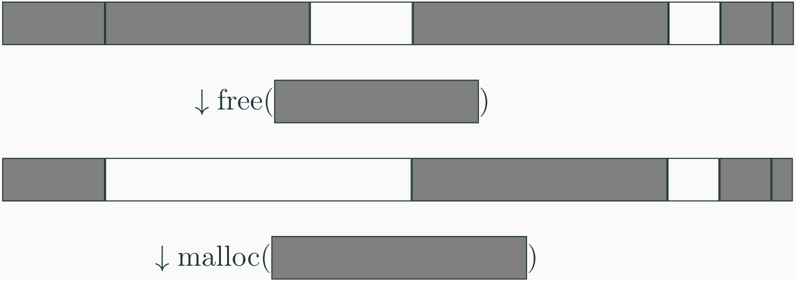

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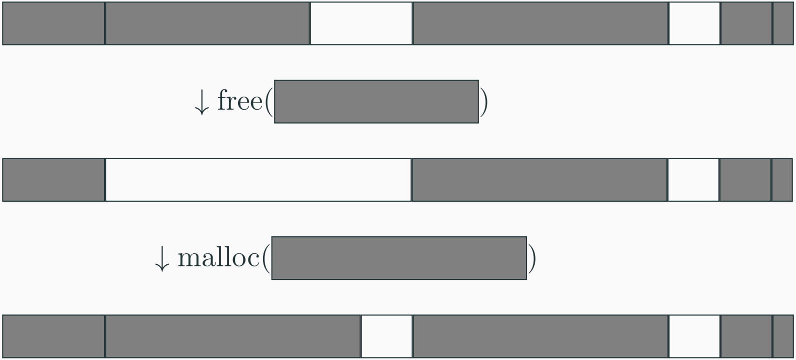


Dynamic Storage Allocation

Rules:

- Each allocated block contiguous
- Blocks stay fixed once allocated

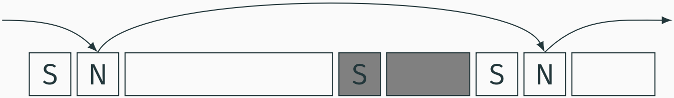
malloc()

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



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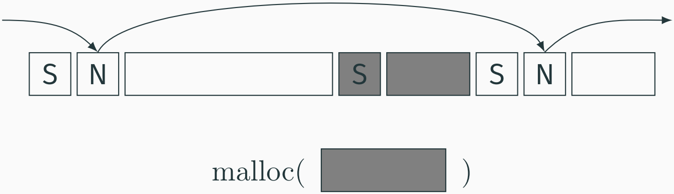

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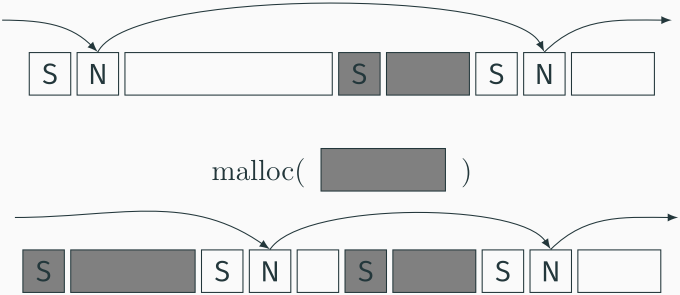

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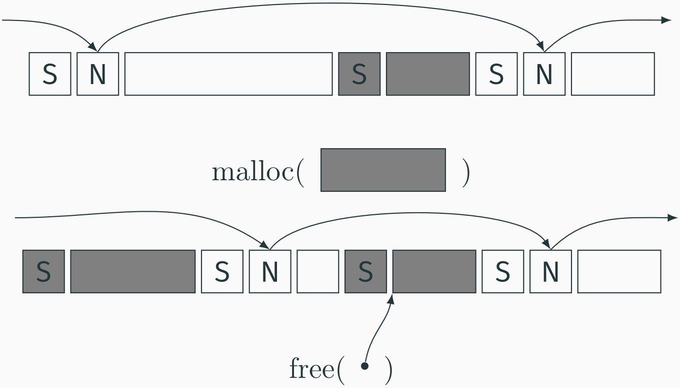

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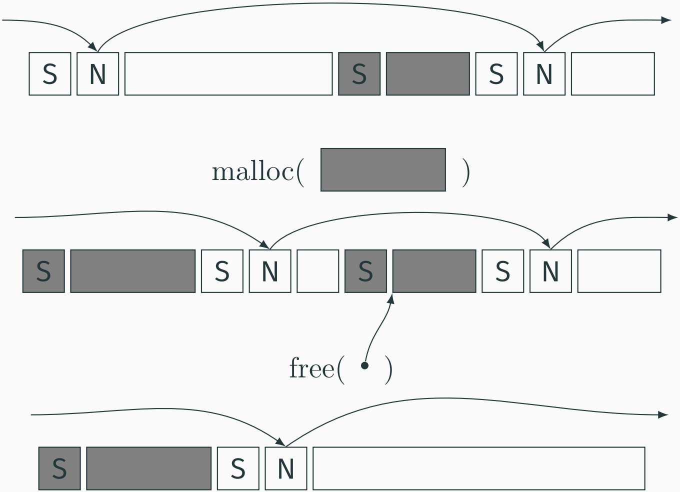


Fragmentation

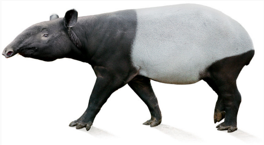
malloc( ) seven times give

free() four times gives

malloc( ) ?

Need more memory; can’t use fragmented memory.

Zebra

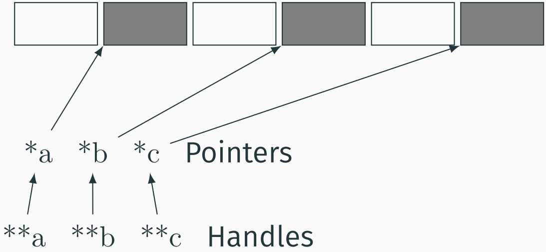


Tapir

Fragmentation and Handles

Standard CS solution: Add another layer of indirection.

Always reference memory through “handles.”



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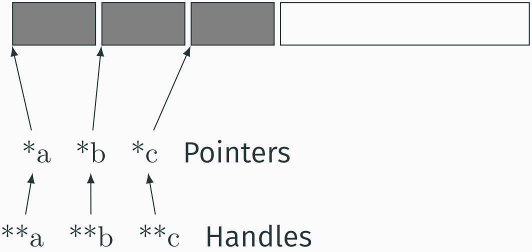

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Automatic Garbage Collection

Automatic Garbage Collection

Entrust the runtime system with freeing heap objects

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

Advantages?

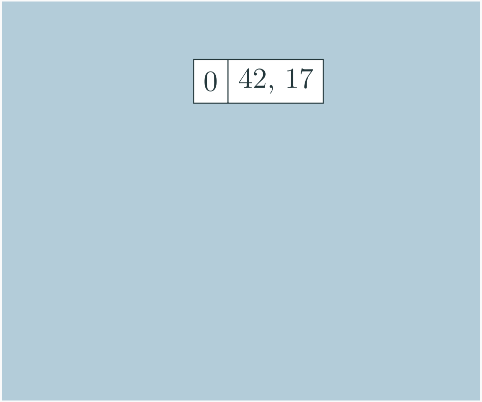
Disadvantages?

Reference Counting

What and when to free?

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

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



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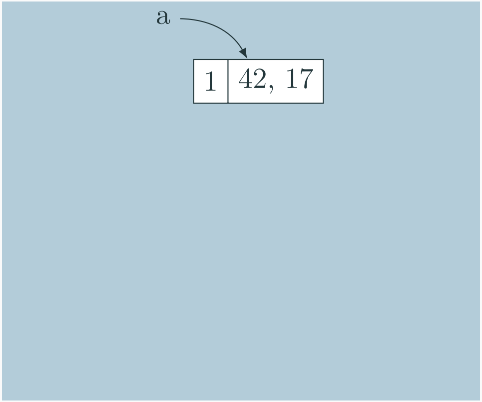

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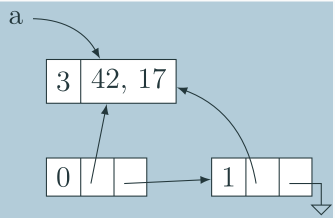

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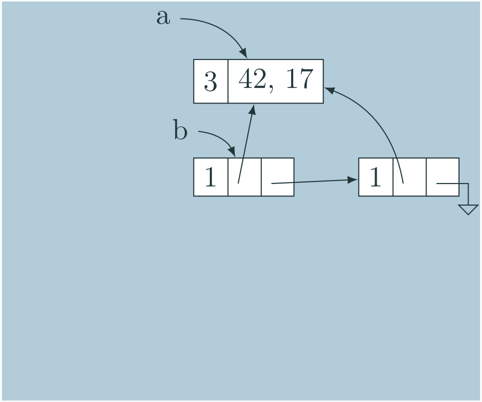

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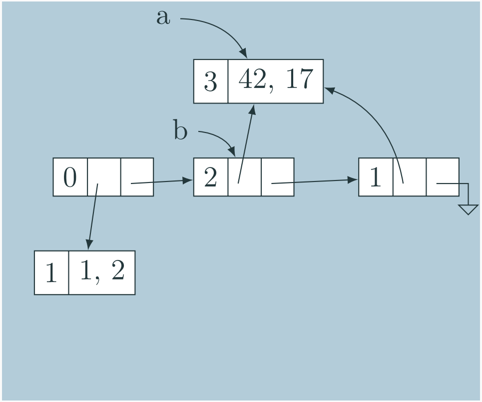

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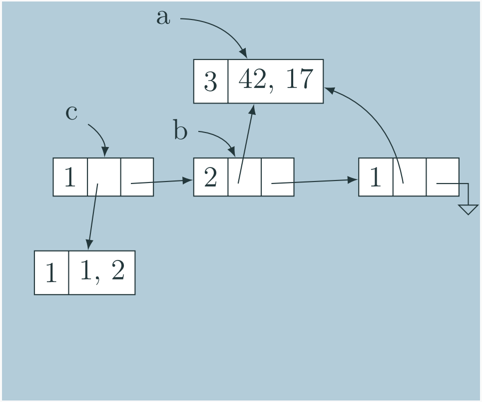

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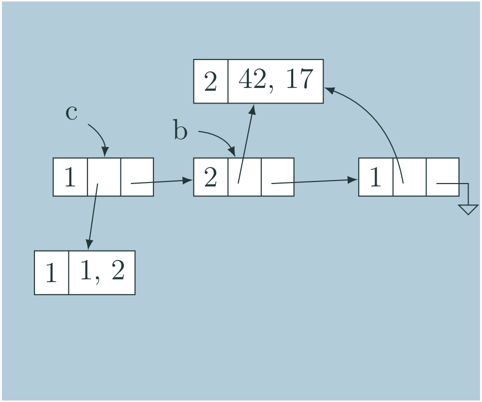

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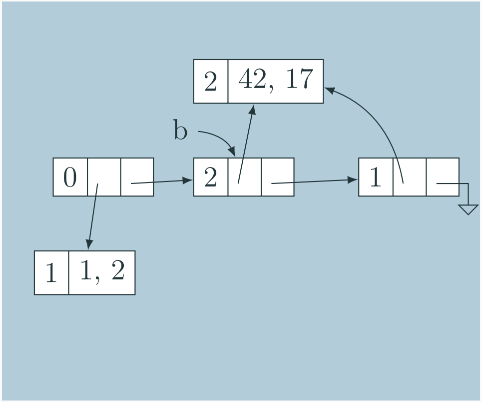

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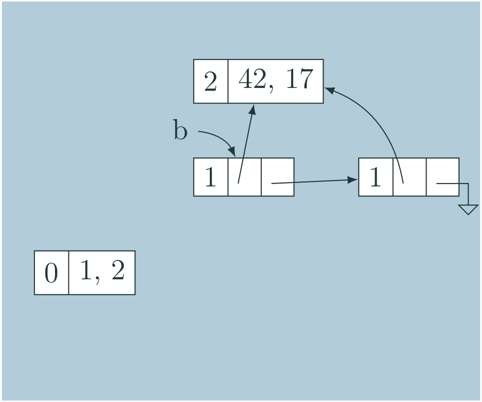

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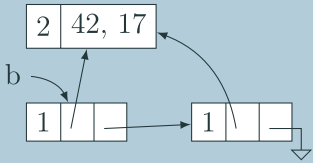

Issues with Reference Counting

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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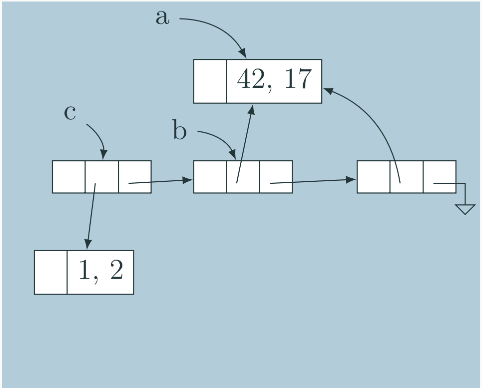

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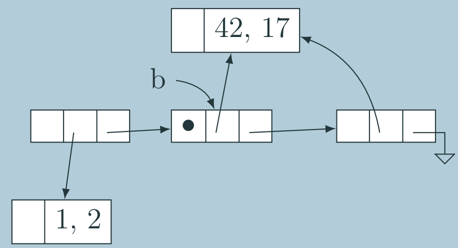

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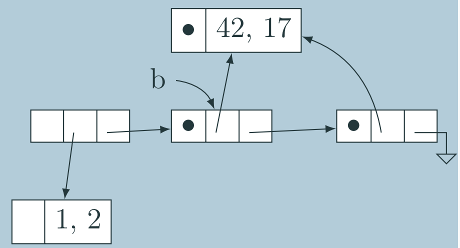

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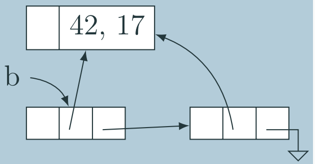

Mark-and-Sweep

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