Runtime Environments

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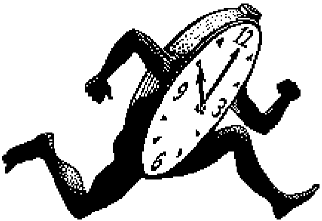


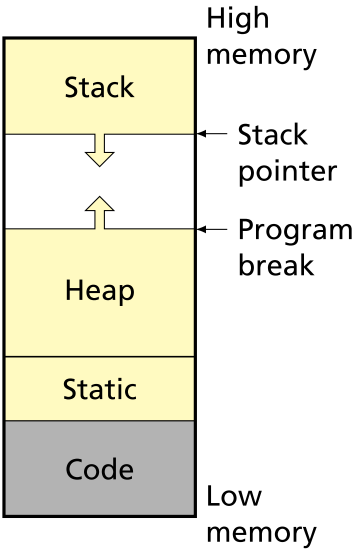
Storage Classes

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

Code for hello method

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 if sharing is possible

The Stack and Activation Records

Stack-Allocated Objects

Natural for supporting recursion.

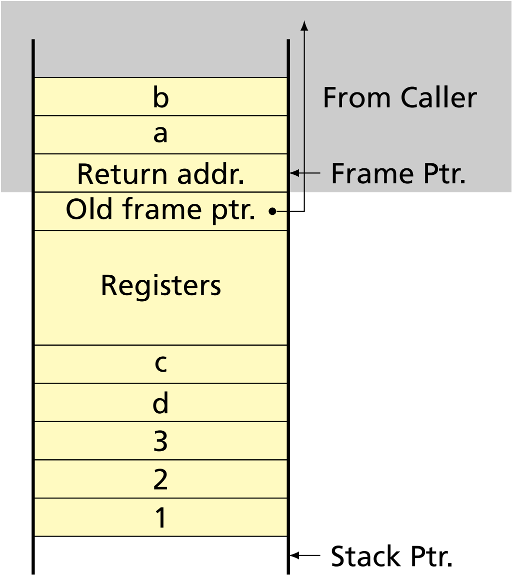
Idea: some objects persist from when a procedure is called to when it returns.

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

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);

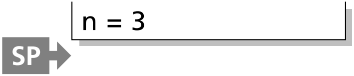
}
```

(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)

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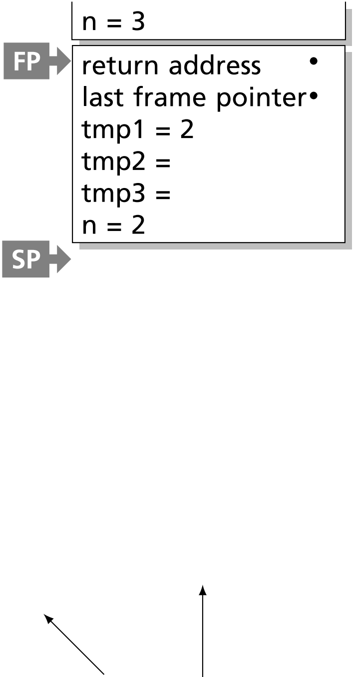


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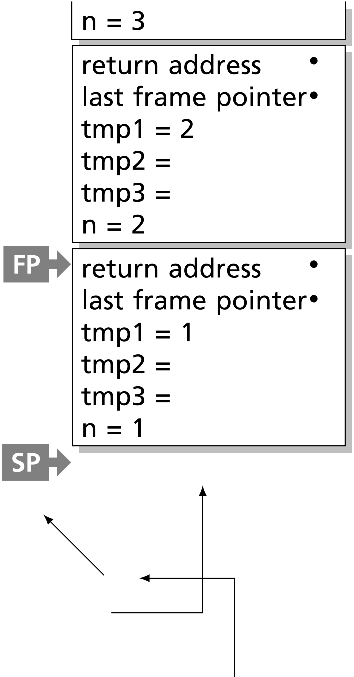

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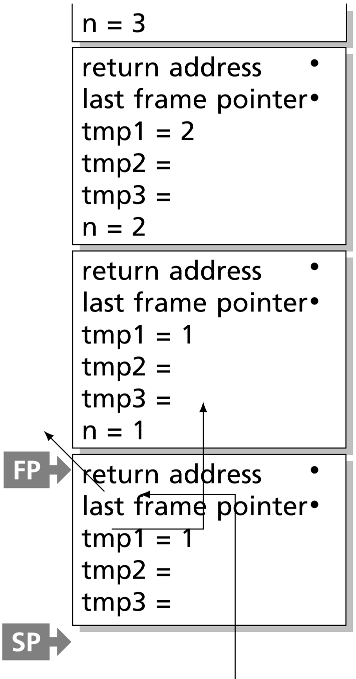

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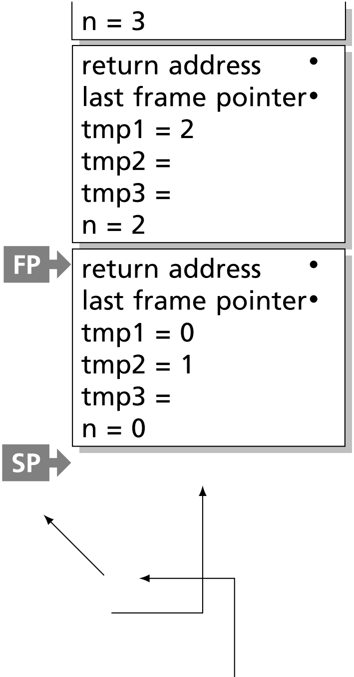

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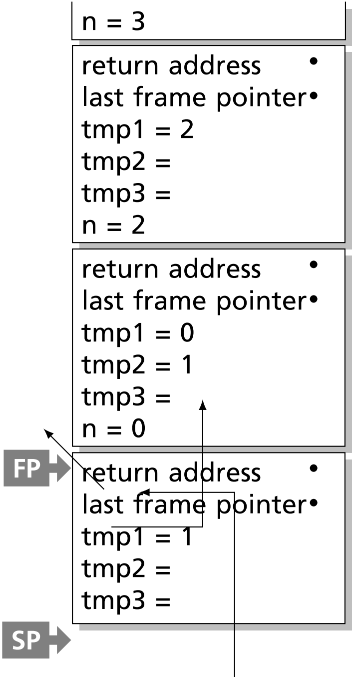

Executing fib(3)

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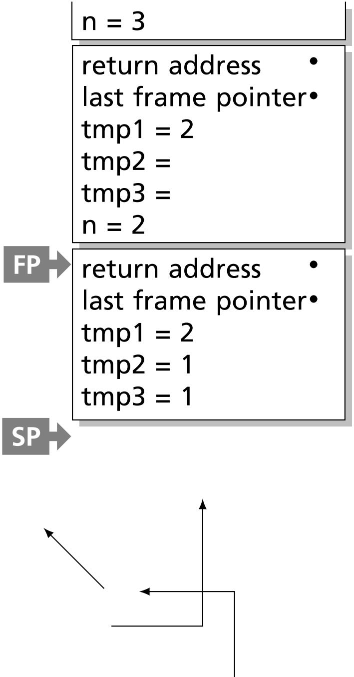

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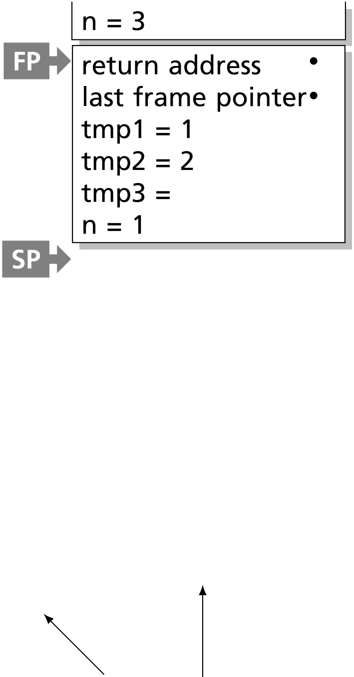


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Executing fib(3)

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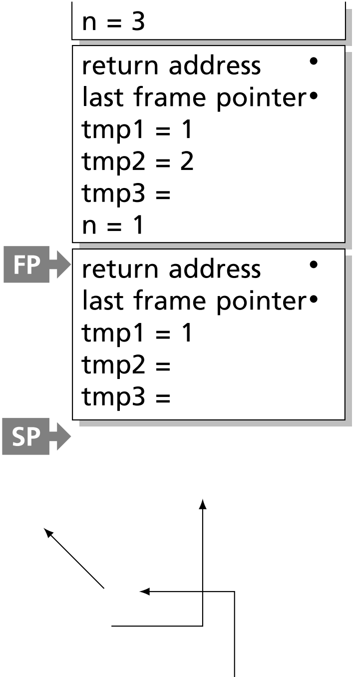

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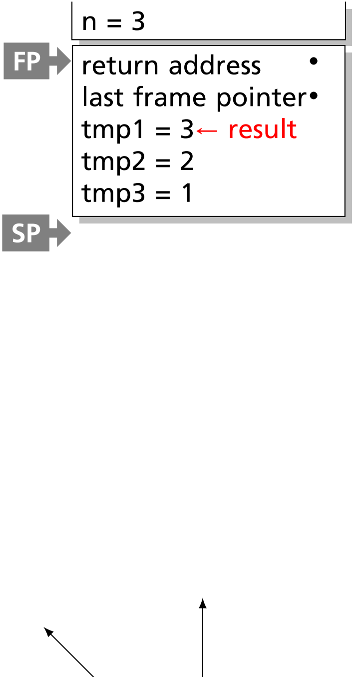


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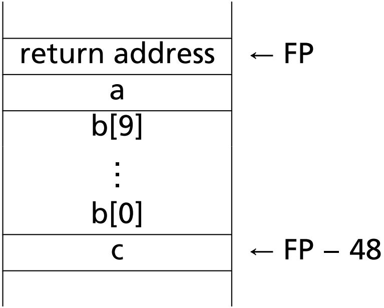
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```

Allocating Fixed-Size Arrays

Local arrays with fixed size are easy to stack.

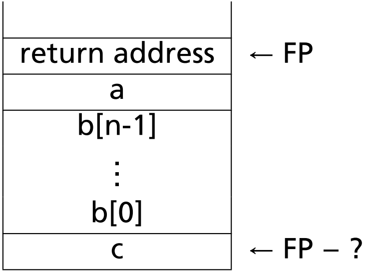
```
void foo()
{
  int a;
  int b[10];
  int c;
}
```



Allocating Variable-Sized Arrays

Variable-sized local arrays aren't as easy.

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

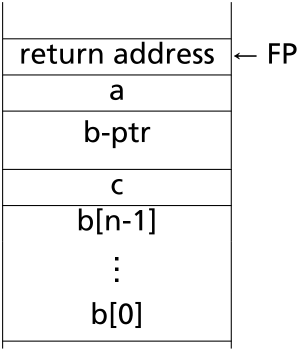


Doesn't work: generated code expects a fixed offset for c.
Even worse for multi-dimensional arrays.

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.

Nesting Function Definitions

```
let articles words =

  let report w =

    let count = List.length
      (List.filter ((=) w) words)
    in w ^ ": " ^
      string_of_int count

  in String.concat ", "
    (List.map report ["a"; "the"])

in articles
    ["the"; "plt"; "class"; "is";
     "a"; "pain"; "in";
     "the"; "butt"]
```

```
let count words w = List.length
  (List.filter ((=) w) words) in

let report words w = w ^ ": " ^
  string_of_int (count words w) in

let articles words =
  String.concat ", "
    (List.map (report words)
     ["a"; "the"]) in

articles
    ["the"; "plt"; "class"; "is";
     "a"; "pain"; "in";
     "the"; "butt"]
```

Produces “a: 1, the: 2”

Implementing Nested Functions with Access Links

a:

(access link) •
x = 5
s = 42

```
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

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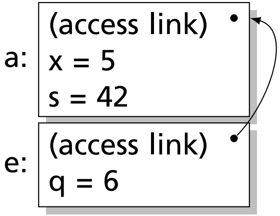

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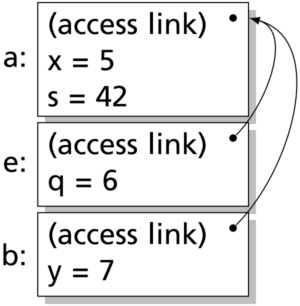

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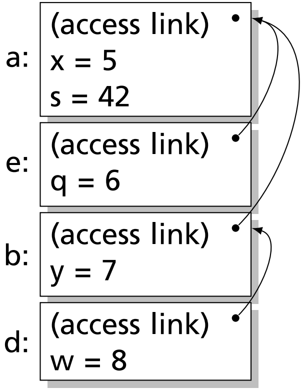

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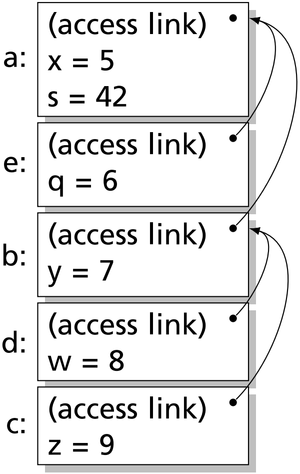
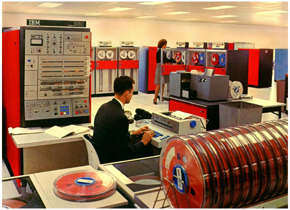


In-Memory Layout Issues

Layout of Records and Unions

Modern processors have byte-addressable memory.

0
1
2
3



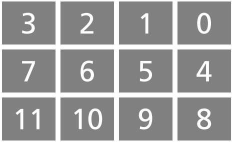
The IBM 360 (c. 1964) helped to popularize byte-addressable memory.

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

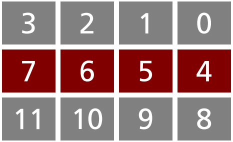
16-bit integer:			1	0
32-bit integer:	3	2	1	0

Layout of Records and Unions

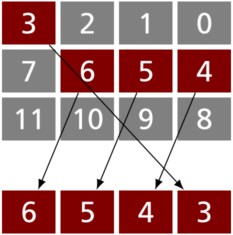
Modern memory systems read data in 32-, 64-, or 128-bit chunks:



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



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

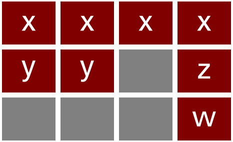
Padding

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

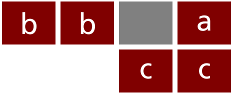
Rules:

- 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 */
};
```

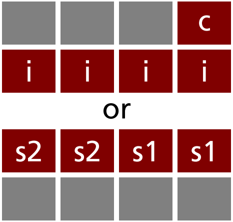


Unions

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  */
};
```

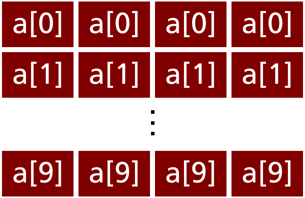

```
union twostructs {
  struct {
    char c;    /* 1 byte */
    int i;     /* 4 bytes */
  } a;
  struct {
    short s1; /* 2 bytes */
    short s2; /* 2 bytes */
  } b;
};
```



Arrays

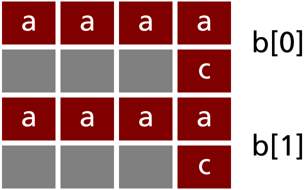
Basic policy in C: an array is just one object after another in memory.

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



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

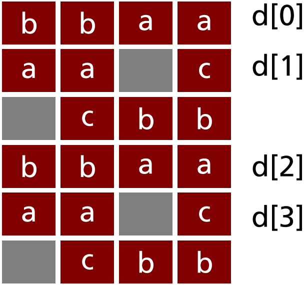
```
struct {
  int a;
  char c;
} b[2];
```



Arrays and Aggregate types

The largest primitive type dictates the alignment

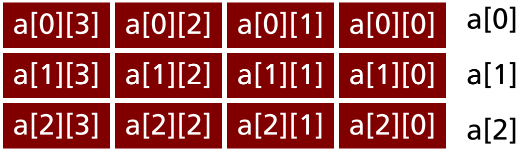
```
struct {
  short a;
  short b;
  char c;
} d[4];
```



Arrays of Arrays

`char a[4];`

`char a[3][4];`



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

```
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();
  }

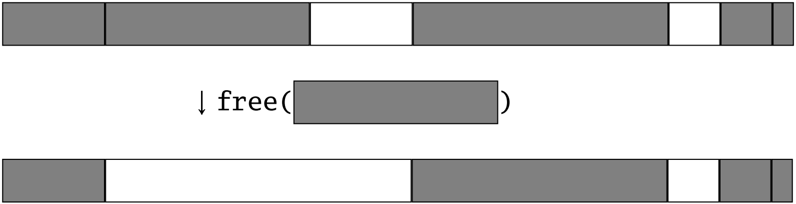
  /* do something with the array */

  free(points);
}
```

Dynamic Storage Allocation

Dynamic Storage Allocation

Dynamic Storage Allocation



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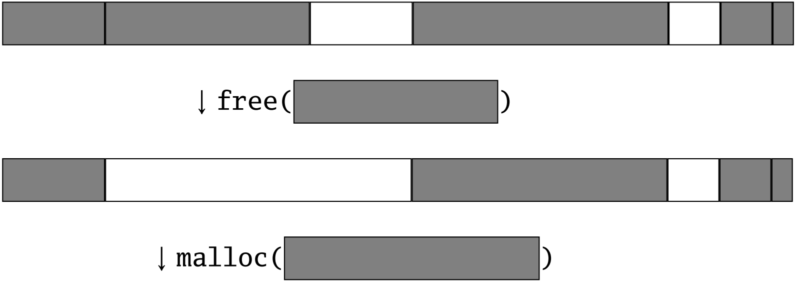

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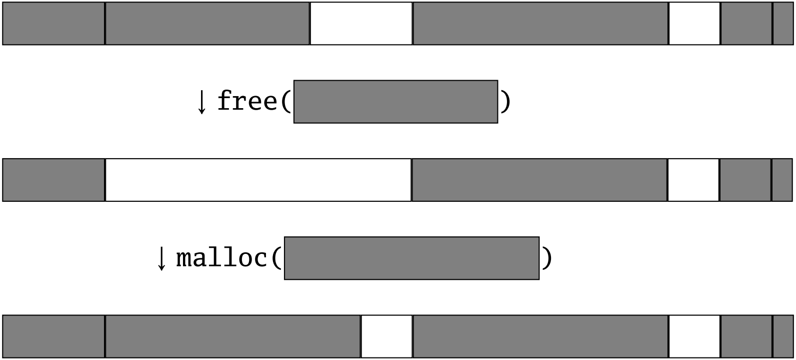


Dynamic Storage Allocation

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

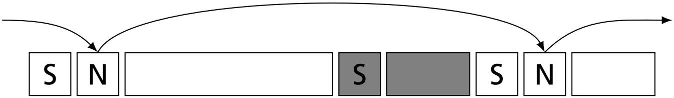
`free()`

- 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



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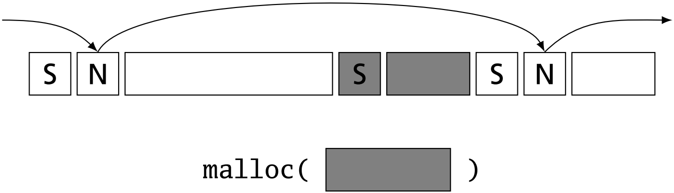

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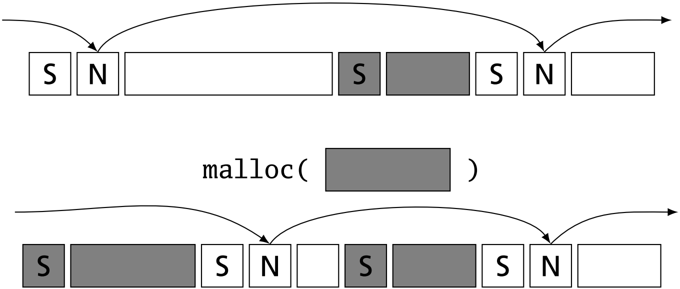

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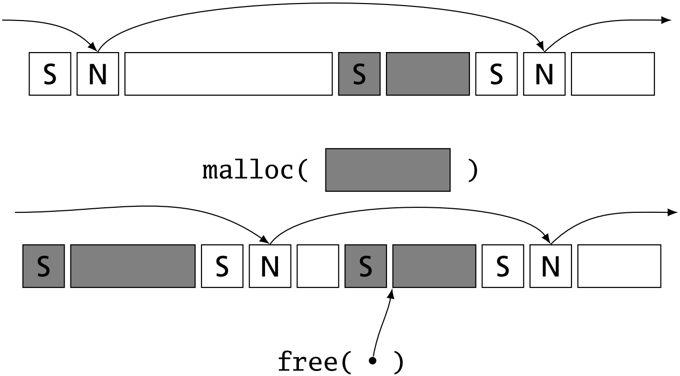
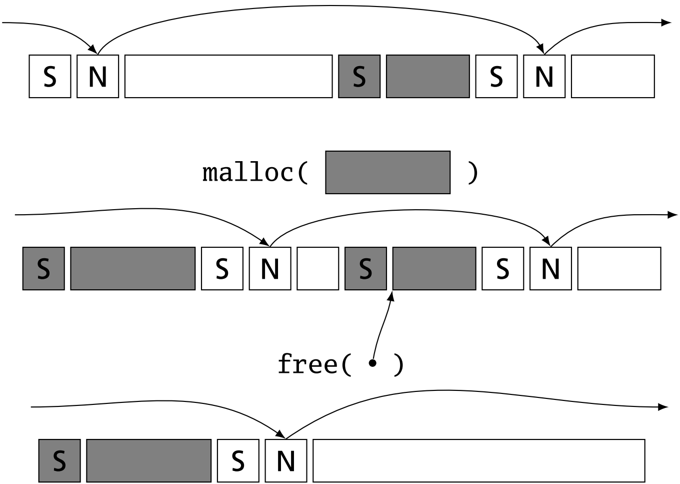


Simple Dynamic Storage Allocation



Dynamic Storage Allocation

Many, many other approaches.

Other “fit” algorithms

Segregation of objects by size

More clever data structures

Heap Variants

Memory pools: Differently-managed heap areas

Stack-based pool: only free whole pool at once

- Nice for build-once data structures

Single-size-object pool:

- Fit, allocation, etc. much faster
- Good for object-oriented programs

Fragmentation

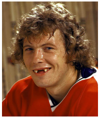
`malloc(`  `)` seven times give

`free()` four times gives

`malloc(`  `)` ?

Need more memory; can't use fragmented memory.

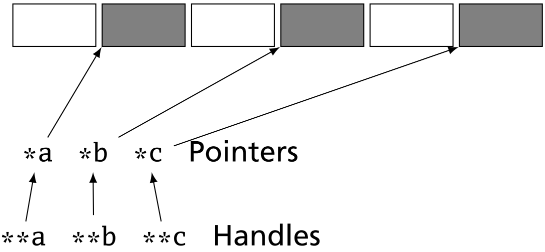
Hockey smile



Fragmentation and Handles

Standard CS solution: Add another layer of indirection.

Always reference memory through “handles.”



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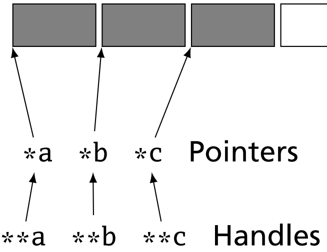

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Automatic Garbage Collection

Automatic Garbage Collection

Entrust the runtime system with freeing heap objects

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

Advantages

Much easier for the programmer

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

Disadvantages

Slower, sometimes unpredictably so

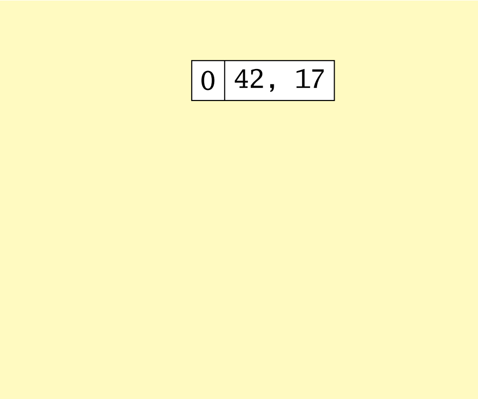
May consume more memory

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
```



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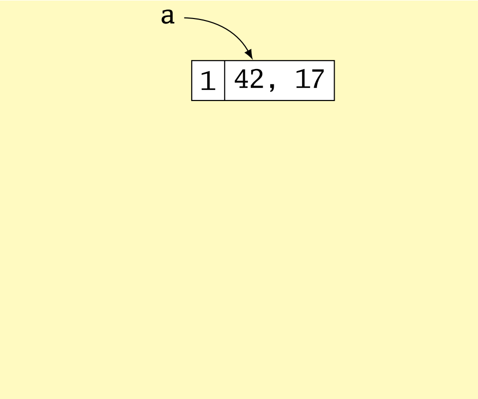

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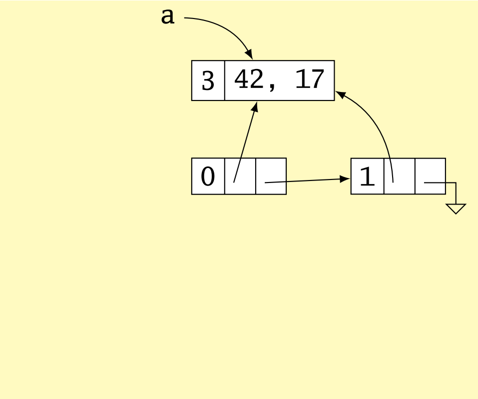

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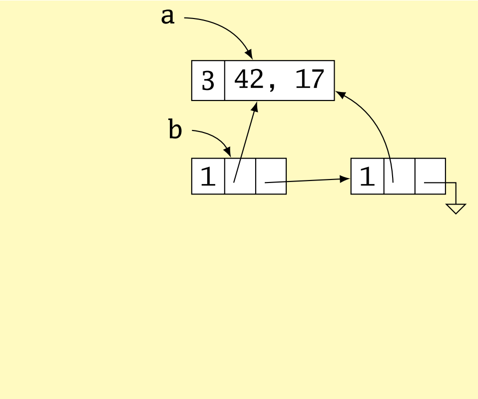

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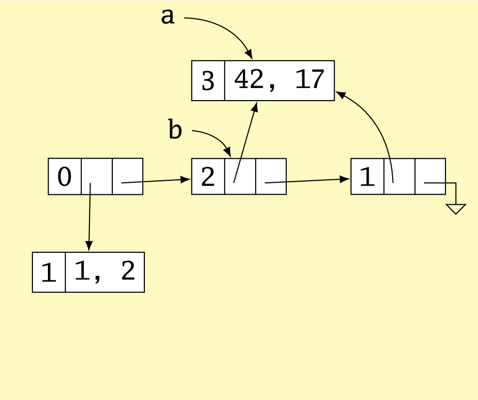

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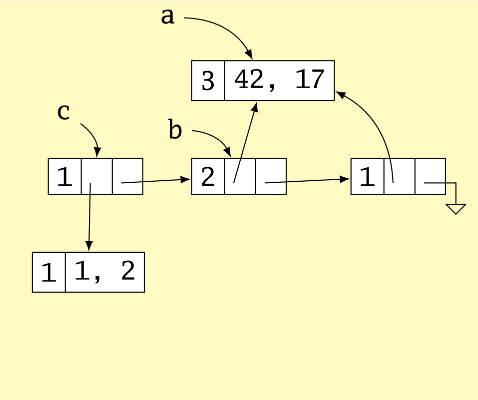

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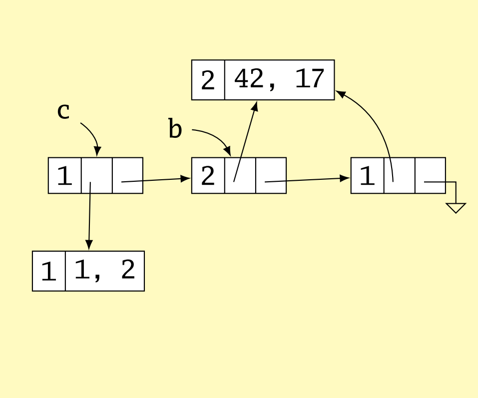

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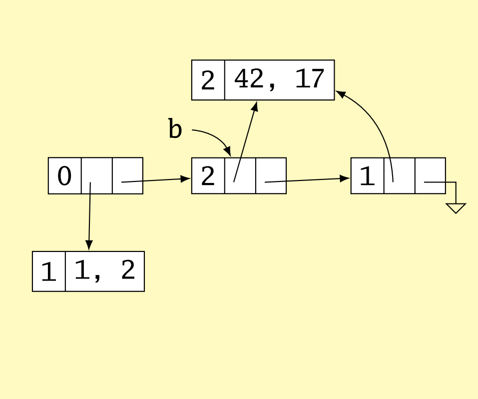

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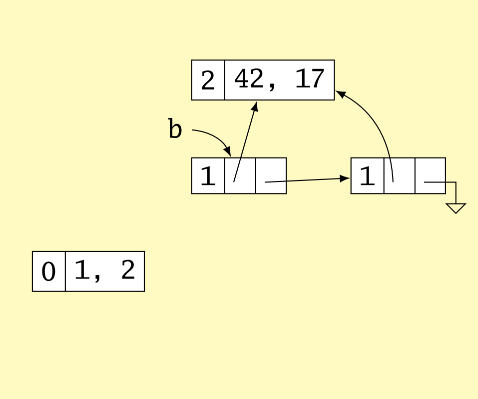

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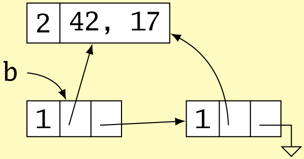
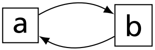


Issues with Reference Counting

Circular structures defy reference counting:



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

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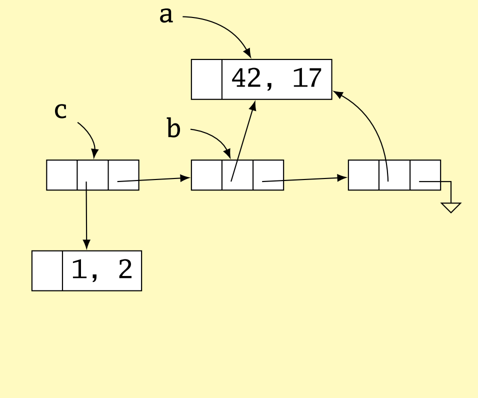

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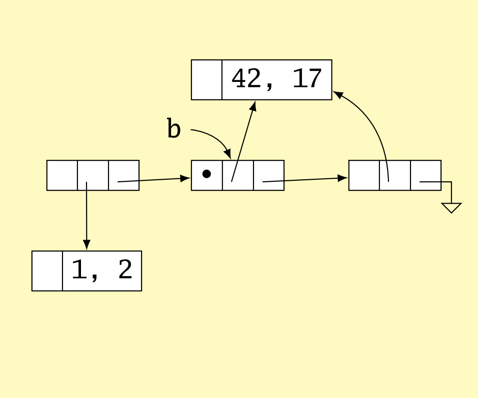

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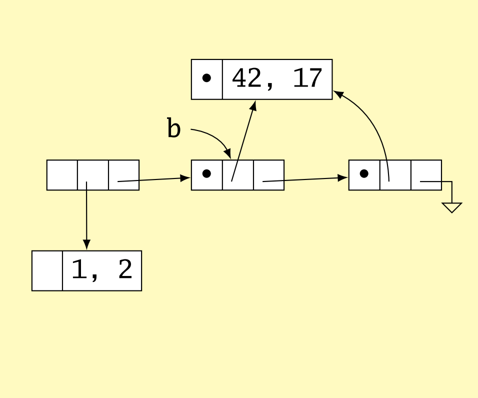

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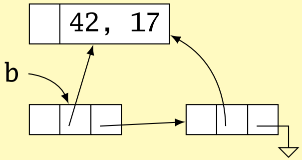


Mark-and-Sweep

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

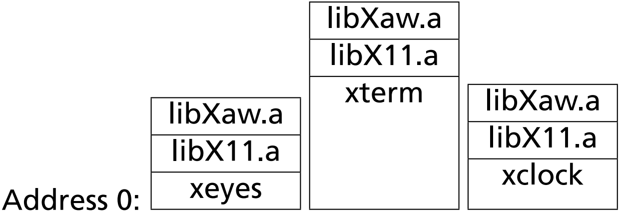
Real-time garbage collection tricky

Shared Libraries and Dynamic Linking

Shared Libraries and Dynamic Linking

The 1980s GUI/WIMP revolution required many large libraries (the Athena widgets, Motif, etc.)

Under a *static linking* model, each executable using a library gets a copy of that library's code.



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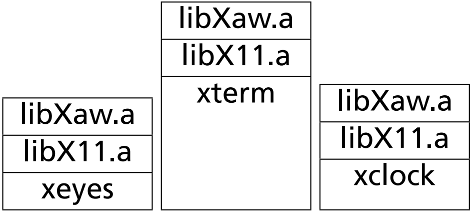


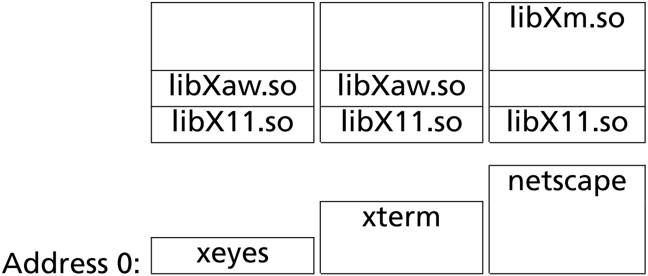
Wasteful: running many GUI programs at once fills memory with nearly identical copies of each library.

Something had to be done: another level of indirection.

Shared Libraries: First Attempt

Most code makes assumptions about its location.

First solution (early Unix System V R3) required each shared library to be located at a unique address:



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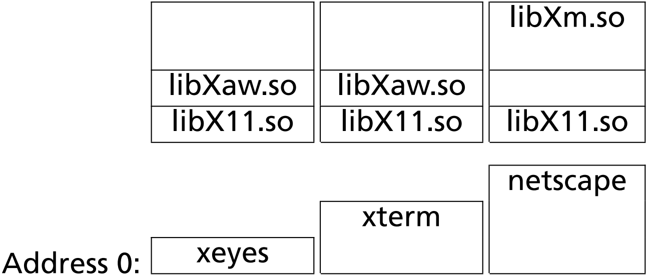
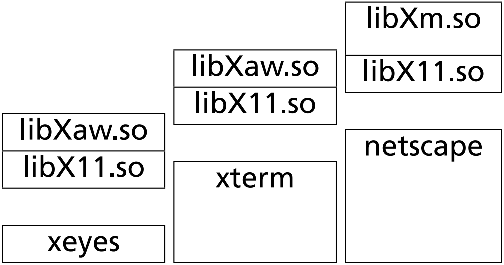


Obvious disadvantage: must ensure each new shared library located at a new address.

Works fine if there are only a few libraries; tended to discourage their use.

Shared Libraries

Problem fundamentally is that each program may need to see different libraries each at a different address.



Position-Independent Code

Solution: Require the code for libraries to be position-independent. Make it so they can run anywhere in memory.

As always, add another level of indirection:

- All branching is PC-relative
- All data must be addressed relative to a base register.
- All branching to and from this code must go through a jump table.

Position-Independent Code for bar()

Normal unlinked code

```
save  %sp, -112, %sp
sethi  %hi(0), %o0
  R_SPARC_HI22 .bss
mov  %o0, %o0
  R_SPARC_LO10 .bss
sethi  %hi(0), %o1
  R_SPARC_HI22 a
mov  %o1, %o1
  R_SPARC_LO10 a
call  14
  R_SPARC_WDISP30 strcpy
nop
sethi  %hi(0), %o0
  R_SPARC_HI22 .bss
mov  %o0, %o0
  R_SPARC_LO10 .bss
call  24
  R_SPARC_WDISP30 baz
nop
ret
restore
```

gcc -fpic -shared

```
save  %sp, -112, %sp
sethi  %hi(0x10000), %l7
call  8e0   ! add PC to %l7
add  %l7, 0x198, %l7
ld  [ %l7 + 0x20 ], %o0
ld  [ %l7 + 0x24 ], %o1
call  10a24 ! strcpy
nop
ld  [ %l7 + 0x20 ], %o0
call  10a3c ! baz
nop
ret
restore
```

Actually just a stub

call is PC-relative

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

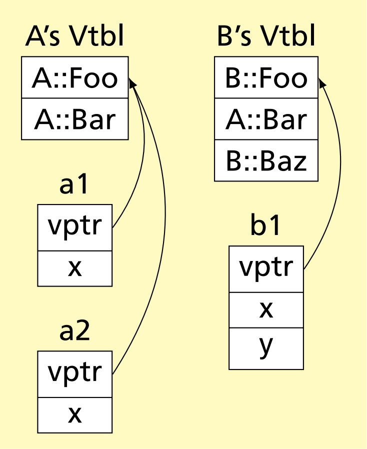
Trick: add to each object a pointer to the virtual table for its type, filled with pointers to the virtual functions.

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;
```



Exceptions

C++'s Exceptions

```
struct Except {} ex;  // This struct functions as an exception

void top(void) {
  try {
    child();
  } catch (Except e) { // throw sends control here
    printf("oops\n");
  }
}

void child() {
  child2();
}

void child2() {
  throw ex; // Pass control up to the catch block
}
```

C’s setjmp/longjmp: Idiosyncratic Exceptions

```
#include <setjmp.h>

jmp_buf closure;            /* return address, stack & frame ptrs. */

void top(void) {
  switch ( setjmp(closure) ) { /* normal: store closure, return 0 */
                               /* longjmp jumps here, returns 1 */


  case 0: child();             /* unexceptional case */
          break;

  case 1: break;               /* longjmp( ,1) called */
  }
}

void child() {
  child2();
}

void child2() {
  longjmp(closure, 1);
}
```

Implementing Exceptions

One way: maintain a stack of exception handlers

```
try {

  child();


} catch (Ex e) {
  foo();
}

void child() {
  child2();
}

void child2() {
  throw ex;
}
```

```
  push(Ex, Handler); // Push handler on stack

  child();
  pop();             // Normal termination
  goto Exit;         // Jump over "catch"
Handler:
  foo();             // Body of "catch"
Exit:

void child() {
  child2();
}

void child2() {
  throw(ex);       // Unroll stack; find handler
}
```

Incurs overhead, even when no exceptions thrown

Implementing Exceptions with Tables

Q: When an exception is *thrown*, where was the last *try*?

A: Consult a table: relevant handler or "pop" for every PC

```
1  void foo() {
2
3    try {
4      bar();
5    } catch (Ex1 e) {
6      a();
7    }
8  }
9
10 void bar() {
11   baz();
12 }
13
14 void baz() {
15
16   try {
17     throw ex1;
18   } catch (Ex2 e) {
19     b();
20   }
21 }
```

Lines	Action
1–2	Pop stack
3–5	Handler @ 5 for Ex1
6–15	Pop stack
16–18	Handler @ 18 for Ex2
19–21	Pop stack

4 6: handle