Runtime Environments

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Storage Classes

The Stack and Activation Records

In-Memory Layout Issues

The Heap

Automatic Garbage Collection

Shared Libraries and Dynamic Linking

Objects and Inheritance

Exceptions
Storage Classes
Storage Classes and Memory Layout

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

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

Static: objects allocated at compile time; persist throughout run.

Diagram:
- Stack: High memory
- Program break
- Heap: Stack pointer
- Static: Low memory
- Code
Static Objects

```java
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*

```c
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)

```c
int fib(int n) {
    int tmp1, tmp2, tmp3;
    tmp1 = n < 2;
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    return 1;
L1:    tmp1 = n - 1;
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    return tmp1;
}

n = 3

return address

last frame pointer

tmp1 = 2

tmp2 =

tmp3 =

n = 2
Executing fib(3)

```c
int fib(int n) {
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    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}
```

n = 3
return address
last frame pointer
• tmp1 = 2
tmp2 =
tmp3 =
n = 2

FP

n = 2
return address
last frame pointer
• tmp1 = 0
tmp2 = 1
tmp3 =
n = 0

SP
```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;
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}
```
Executing fib(3)

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    tmp2 = fib(tmp1);
L2: tmp1 = n - 2;
    tmp3 = fib(tmp1);
L3: tmp1 = tmp2 + tmp3;
    return tmp1;
}

n = 3
return address
last frame pointer
return address
last frame pointer
tmp1 = 1
tmp2 = 2
tmp3 =
n = 1
return address
last frame pointer
return address
last frame pointer
tmp1 = 1
tmp2 =
tmp3 =
FP
SP
Executing fib(3)

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

FP

```
| n = 3
| return address
| last frame pointer
| tmp1 = 3 ← result
| tmp2 = 2
| tmp3 = 1
```

SP

```
n = 3
return address
last frame pointer
```
Local arrays with fixed size are easy to stack.

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

<table>
<thead>
<tr>
<th>return address</th>
<th>← FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
</tr>
<tr>
<td>b[9]</td>
<td></td>
</tr>
<tr>
<td>:</td>
<td></td>
</tr>
<tr>
<td>b[0]</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>← FP − 48</td>
</tr>
</tbody>
</table>
Allocating Variable-Sized Arrays

Variable-sized local arrays aren’t as easy.

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

<table>
<thead>
<tr>
<th>return address</th>
<th>← FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
</tr>
<tr>
<td>b[n-1]</td>
<td></td>
</tr>
<tr>
<td>:</td>
<td></td>
</tr>
<tr>
<td>:</td>
<td></td>
</tr>
<tr>
<td>b[0]</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>← FP – ?</td>
</tr>
</tbody>
</table>

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

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

Variables remain constant offset from frame pointer.
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"])

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

Produces “a: 1, the: 2”
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) (* b *)
  in
  let e q = b (q+1) in
  e (x+1) (* a *)
```

What does “a 5 42” give?

<table>
<thead>
<tr>
<th>(access link)</th>
<th>a:</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 5</td>
<td></td>
</tr>
<tr>
<td>s = 42</td>
<td></td>
</tr>
</tbody>
</table>
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)  (* b *)
    in
    let e q = b (q+1) in
    e (x+1)  (* a *)

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Implementing Nested Functions with Access Links

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  e (x+1) (* a *)
```

What does “a 5 42” give?

* a: (access link)
  * x = 5
  * s = 42

* b: (access link)
  * w = 8

* c: (access link)
  * z = 6

* d: (access link)
  * y = 7

* e: (access link)
  * q = 6
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?

- \( a: \) \( x = 5 \), \( s = 42 \)
- \( b: \) \( y = 7 \)
- \( c: \) \( z = 9 \)
- \( d: \) \( w = 8 \)
- \( e: \) \( q = 6 \)
In-Memory Layout Issues
Modern processors have byte-addressable memory.

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: \(\begin{array}{c}1 \ 0\end{array}\)

32-bit integer: \(\begin{array}{c}3 \ 2 \ 1 \ 0\end{array}\)
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).

```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 */
};
```
Unions

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

```c
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;
};
```

or

```c
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

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

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

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

```plaintext
```

```plaintext
a[0][0] a[0][1] a[0][2] a[0][3]
```

```plaintext
a[1][0] a[1][1] a[1][2] a[1][3]
```

```plaintext
```

```plaintext
a[0] a[1] 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

\[ \text{free( ... )} \]
Dynamic Storage Allocation

\[ \downarrow \text{free}() \]

\[ \text{malloc}() \]
Dynamic Storage Allocation

↓ free( )

↓ malloc( )
Dynamic Storage Allocation

↓ free(□)

↓ malloc(□)
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

malloc

free
Simple Dynamic Storage Allocation

malloc( )
Simple Dynamic Storage Allocation

```c
malloc()
```

```c
free()
```
Simple Dynamic Storage Allocation

malloc(  )

free(  )
Simple Dynamic Storage Allocation

malloc( )

free( )
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

[Diagram showing fragmented memory]

`free()` four times gives

[Diagram showing memory blocks after free calls]

`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.”

The original Macintosh did this to save memory.
Fragmentation and Handles

Standard CS solution: Add another layer of indirection.
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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

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

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```plaintext
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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

```latex
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
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```haskell
let a = (42, 17) in
let b = [a;a] in
let c = (1,2)::b in
b
```
Mark-and-Sweep

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```
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b
```
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```
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
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.

Address 0:

```
libXaw.a
libX11.a
xeyes
```

```
libXaw.a
libX11.a
xterm
```

```
libXaw.a
libX11.a
xclock
```
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.

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:

<table>
<thead>
<tr>
<th>Address 0:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>xeyes</td>
<td></td>
<td>xterm</td>
</tr>
<tr>
<td></td>
<td>libXaw.so</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>libX11.so</td>
<td></td>
</tr>
<tr>
<td></td>
<td>libX11.so</td>
<td>netscape</td>
</tr>
</tbody>
</table>

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.
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<th>libXaw.so</th>
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<th>libXm.so</th>
</tr>
</thead>
<tbody>
<tr>
<td>libX11.so</td>
<td>libX11.so</td>
<td>libX11.so</td>
</tr>
<tr>
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Address 0: xeyes

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

```plaintext
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

```plaintext
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
    Actually just a stub
call 10a24 ! strcpy
nop
ld [ %l7 + 0x20 ], %o0
call 10a3c ! baz
nop
ret
restore
```
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++

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

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

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

Equivalent C

```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.

```c
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
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
}
#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

```c
try {
    child();
}
} catch (Ex e) {
    foo();
}

void child() {
    child2();
}

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

```c
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

```
void foo() {
    try {
        bar();
    } catch (Ex1 e) {
        a();
    }
}

void bar() {
    baz();
}

void baz() {
    try {
        throw ex1;
    } catch (Ex2 e) {
        b();
    }
}
```

<table>
<thead>
<tr>
<th>Lines</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2</td>
<td>Pop stack</td>
</tr>
<tr>
<td>3–5</td>
<td>Handler @ 5 for Ex1</td>
</tr>
<tr>
<td>6–15</td>
<td>Pop stack</td>
</tr>
<tr>
<td>16–18</td>
<td>Handler @ 18 for Ex2</td>
</tr>
<tr>
<td>19–21</td>
<td>Pop stack</td>
</tr>
</tbody>
</table>