Run-time storage layout:
focus on compilation, not interpretation

- Plan how and where to keep data at run-time
- Representation of
  - int, bool, etc.
  - arrays, records, etc.
  - procedures
- Placement of
  - global variables
  - local variables
  - parameters
  - results

Data layout of scalars

Based on machine representation

<table>
<thead>
<tr>
<th>Type</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer</td>
<td>Use hardware representation (2, 4, and/or 8 bytes of memory, maybe aligned)</td>
</tr>
<tr>
<td>Bool</td>
<td>1 byte or word</td>
</tr>
<tr>
<td>Char</td>
<td>1-2 bytes or word</td>
</tr>
<tr>
<td>Pointer</td>
<td>Use hardware representation (2, 4, or 8 bytes, maybe two words if segmented machine)</td>
</tr>
</tbody>
</table>

Data layout of aggregates

- Aggregate scalars together
- Different compilers make different decisions
- Decisions are sometimes machine dependent
  - Note that through the discussion of the front-end, we never mentioned the target machine
  - We didn’t in interpretation, either
  - But now it’s going to start to come up constantly
  - Necessarily, some of what we will say will be “typical”, not universal.

Layout of records

- Concatenate layout of fields
  - Respect alignment restrictions
  - Respect field order, if required by language
  - Why might a language choose to do this or not do this?
  - Respect contiguity?

Layout of arrays

- Repeated layout of element type
  - Respect alignment of element type
  - How is the length of the array handled?

r : record
b : bool;
i : int;
m : record
b : bool;
c : char;
end
j : int;
end

s : array [5] of record;
i : int;
o : char;
end
## Layout of multi-dimensional arrays

- Recursively apply layout rule to subarray first
- This leads to row-major layout
- Alternative: column-major layout
  - Most famous example: FORTRAN

```
A[3][2] of record;  
I : int;     
C : char;  
end;
```

## Implications of Array Layout

- Which is better if row-major? col-major?

```plaintext
a: array [1000, 2000] of int;
for i:= 1 to 1000 do 
for j:= 1 to 2000 do 
a[i,j] := 0;
for j:= 1 to 2000 do 
for i:= 1 to 1000 do 
a[i,j] := 0;
```

## Dynamically sized arrays

- Arrays whose length is determined at run-time
  - Different values of the same array type can have different lengths
  - Can store length implicitly in array
  - Where? How much space?
- Dynamically sized arrays require pointer indirection
  - Each variable must have fixed, statically known size

```
a : array of record;  
i : int;     
c : char;  
end;
```

## Dope vectors

- PL/1 handled arrays differently, in particular storage of the length
- It used something called a dope vector, which was a record consisting of
  - A pointer to the array
  - The length of the array
  - Subscript bounds for each dimension
- Arrays could change locations in memory and size quite easily

## String representation

- A string = an array of characters
  - So, can use array layout rule for strings
- Pascal, C strings: statically determined length
  - Layout like array with statically determined length
- Other languages: strings have dynamically determined length
  - Layout like array with dynamically determined length
  - Alternative: special end-of-string char (e.g., `\0`)

## Storage allocation strategies

- Given layout of data structure, where in memory to allocate space for each instance?
- Key issue: what is the lifetime (dynamic extent) of a variable/data structure?
  - Whole execution of program (e.g., global variables)
  - Execution of a procedure activation (e.g., locals)
  - Variable (dynamically allocated data)
  - Heap allocation
Parts of run-time memory

- Code/Read-only data area
  - Shared across processes running same program
- Static data area
  - Can start out initialized or zeroed
- Heap
  - Can expand upwards through system call
- Stack
  - Expands/contracts downwards automatically

Static allocation

- Statically allocate variables/data structures with global lifetime
  - Machine code
    - Compile-time constant scalars, strings, arrays, etc.
    - Global variables
    - static locals in C, all variables in FORTRAN
  - Compiler uses symbolic addresses
  - Linker assigns exact address, patches compiled code

Stack allocation

- Stack-allocate variables/data structures with LIFO lifetime
  - Data doesn't outlive previously allocated data on the same stack
- Stack-allocate procedure activation records
  - A stack-allocated activation record = a stack frame
    - Frame includes formals, locals, temps
    - And housekeeping: static link, dynamic link, ...
- Fast to allocate and deallocate storage
- Good memory locality

Stack allocation II

- What about variables local to nested scopes within one procedure?

Stack allocation: constraints I

- No references to stack-allocated data allowed after returns
- This is violated by general first-class functions

Stack allocation: constraints II

- Also violated if pointers to locals are allowed
Heap allocation
- For data with unknown lifetime
  - `new/malloc` to allocate space
  - `delete/free/garbage collection` to deallocate
- Heap-allocate activation records of first-class functions
- Relatively expensive to manage
- Can have dangling reference, storage leaks
  - Garbage collection reduces (but may not eliminate) these classes of errors

Stack frame layout
- Need space for
  - Formals
  - Locals
  - Various housekeeping data
    - Dynamic link (pointer to caller's stack frame)
    - Static link (pointer to lexically enclosing stack frame)
    - Return address, saved registers, ...
- Dedicated registers to support stack access
  - FP - frame pointer: ptr to start of stack frame (fixed)
  - SP - stack pointer: ptr to end of stack (can move)

Key property
- All data in stack frame is at a fixed, statically computed offset from the FP
- This makes it easy to generate fast code to access the data in the stack frame
  - And even lexically enclosing stack frames
- Can compute these offsets solely from the symbol tables
  - Based also on the chosen layout approach

Accessing locals
- If a local is in the same stack frame then
  \[ t := *(fp + local_offset) \]
- If in lexically-enclosing stack frame
  \[ t := *(fp + static_link_offset) \]
  \[ t := *(t + local_offset) \]
- If farther away
  \[ t := *(fp + static_link_offset) \]
  \[ t := *(t + static_link_offset) \]
  \[ t := *(t + local_offset) \]

At compile-time…
- …need to calculate
  - Difference in nesting depth of use and definition
  - Offset of local in defining stack frame
  - Offsets of static links in intervening frames
Calling conventions

- Define responsibilities of caller and callee
  - To make sure the stack frame is properly set up and torn down
- Some things can only be done by the caller
- Other things can only be done by the callee
- Some can be done by either
- So, we need a protocol

PL/0 calling sequence

- Caller
  - Evaluate actual args
    - Order?
  - Push onto stack
    - Order?
  - Alternative: First k args in registers
  - Push callee's static link
  - Or in register?
    - Before or after stack arguments?
  - Execute call instruction
    - Hardware puts return address in a register

- Callee
  - Save return address on stack
  - Save callee's frame pointer (dynamic link) on stack
  - Save any other registers that might be needed by callee
  - Allocates space for locals, other data
    - sp := sp - size_of_locals - other_data
  - Locals stored in what order?
  - Set up new frame pointer (fp := sp)
  - Start executing callee's code

PL/0 return sequence

- Callee
  - Deallocate space for local, other data
    - sp := sp + size_of_locals + other_data
  - Restore caller's frame pointer, return address & other regs, all without losing addresses of stuff still needed in stack
  - Execute return instruction

- Caller
  - Deallocate space for callee's static link, args
    - sp := fp
  - Continue execution in caller after call

Accessing callee procedures similar to accessing locals

- Call to procedure declared in same scope:
  - static_link := fp
call p

- Call to procedure in lexically-enclosing scope:
  - static_link := *(fp + static_link_offset)
call p

- If farther away
  - t := *(fp + static_link_offset)
t := *(t + static_link_offset)
  - static_link := *(t + static_link_offset)
call p

Some questions

- Return values?
- Local, variable-sized, arrays
  - proc P(int n) {
    var x array[1 .. n] of int;
    var y array[-5 .. 2*n] of array[1 .. n] int;
  }
- Max length of dynamic-link chain?
- Max length of static-link chain?

Exercise: apply to this example

module M;
var x:int;
proc P(y:int); proc Q(y:int);
var q:int;
beg Q(x+y); end Q;
proc R(z:int);
var r,z,y:int;
beg R(x+y+z); end R;
beg Q(x+y); R(42); P(0); end P;
beg
x := 1;
P(2);
end M.
Exercise: symbol table

<table>
<thead>
<tr>
<th>x</th>
<th>int</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>proc</td>
<td></td>
</tr>
<tr>
<td>al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>y</td>
<td>int</td>
<td></td>
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Exercise: stack frames

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What do these mean?

```
proc P(int a);
beg
    i := i + 5;
    output := a;
    a := a + 1;
    output := a;
    end;
int i=2;
P(i); output i;
P(2); output 2;
```

```
proc Q(int a, int b);
beg
    c := a;
    a := b;
    b := c;
    end;
int i=2; j=3;
Q(i, j);
```

Parameter passing

- When passing args, need to support right semantics
- Issue #1: when is argument expression evaluated?
  - Before call?
  - When first used by callee?
  - At every use by callee?
- Issue #2: what happens if callee assigns to formal?
  - Is this visible to the caller? If so, when?
  - What happens with aliasing among arguments and lexically visible variables?
- Different choices lead to
  - Different representations for passed arguments and
  - Different code to access forms

Parameter passing modes

- call-by-value
- call-by-sharing
- call-by-reference
- call-by-value-result
- call-by-name
- call-by-need
- ...

Call-by-value

```
var a : int;
proc foo(x:int, y:int);
beg
    x := x + 1;
    y := y + a;
    end foo;
    a := 2;
    foo(a, a);
    output := a;
```
Call-by-reference

- Assignment to formal changes actual value in caller
  - Immediately
  - Actual must be value
- Implementation: pass pointer to actual
  - Efficient for big data structures?
  - References to formal must do extra dereference

```
var a : int;
proc foo(x:int,y:int);
begin
  x := x + 1;
  y := y + a;
end foo;

a := 2;
foo(a,a);
output := a;
```

Big immutable data
for example, a constant string

- Suppose language has call-by-value semantics
- But, it's expensive to pass by-value
- Could implement as call-by-reference
  - Since you can't assign to the data, you don't care
  - Let the compiler decide?

Call-by-value-result

- Assignment to formal copies final value back to caller on return
  - "copy-in, copy-out"
- Implement as call-by-value with copy back when procedure returns
  - More efficient than call-by-reference
  - For scalars?
  - For arrays?

```
var a : int;
proc foo(x:int,y:int);
begin
  x := x + 1;
  y := y + a;
end foo;

a := 2;
foo(a,a);
output := a;
```

Call-by-result

```
var a : int;
proc foo(x:int,y:int);
begin
  x := x + 1;
  y := y + a;
end foo;

a := 2;
foo(a,a);
output := a;
```

Ada: in, out, in out

- Programmer selects intent
- Compiler decides which mechanism is more efficient
- Program's meaning "shouldn't" depend on which is chosen

Call-by-name, call-by-need

- Variations on lazy evaluation
  - Only evaluate argument expression if and when needed by callee
- Supports very cool programming tricks
- Somewhat hard to implement efficiently in traditional compilers
  - Thunks
- Largely incompatible with side-effects
  - So more common in purely functional languages like Haskell and Miranda
  - But did appear first in Algol-60
Call-by-name

- Replace each use of a parameter in the callee, by the text of the actual parameter, but in the caller's context
- This implies reevaluation of the actual every time the formal parameter is used
- And evaluation of the actual might return different values each time

Jensen’s device

- How to implement the equivalent of a math formula like $\sum_{i=0}^{n} A_{2i}$
  $\text{sum}(i, 0, n, A[2*i])$?
- Pass by-reference or by-value do not work, since they can only pass one element of A
- So: Jensen’s device

A classic problem: a procedure to swap two elements

- Textual substitution is a simple, clear semantic model
- There are some useful applications, like Jensen’s device
- Argument expressions are evaluated lazily

Call-by-name advantages

- Call-by-name arguments are compiled to thunks, special parameter-less procedures
  - One gives value of actual, appropriately evaluated in caller’s environment
  - Other gives l-value, again in caller’s environment
- Thunks are passed into the called procedure and called to evaluate the argument whenever necessary

Call-by-name disadvantages

- Call-by-name arguments are compiled to thunks, special parameter-less procedures
  - One gives value of actual, appropriately evaluated in caller’s environment
  - Other gives l-value, again in caller’s environment
- Thunks are passed into the called procedure and called to evaluate the argument whenever necessary

Call-by-name

```plaintext
proc square(x);
    int x;
    begin
        x := x * x
    end;
    square(A[i]);
```

Jensen’s device

```plaintext
int proc sum(j, lo, hi, A[]);
    int j, lo, hi, A[], s;
    begin
        s := 0;
        for j := lo to hi do
            s := s + A[j];
    end;
    return s;
end;
```

A classic problem: a procedure to swap two elements

```plaintext
proc swap(int a, int b);
    int temp;
    begin
        temp := a;
        a := b;
        b := temp;
    end;
```

Call-by-name advantages

```plaintext
int proc sum(j, lo, hi, A[]);
    int j, lo, hi, A[], s;
    begin
        s := 0;
        for j := lo to hi do
            s := s + A[j];
    end;
    return s;
end;
```

Call-by-name disadvantages

```plaintext
int proc sum(j, lo, hi, A[]);
    int j, lo, hi, A[], s;
    begin
        s := 0;
        for j := lo to hi do
            s := s + A[j];
    end;
    return s;
end;
```
Parameters and compiling

- There is an intimate link between the semantics of a programming language and the mechanisms used for parameter passing
- Maybe more than other programming language constructs, the connection is extremely strong between implementation and language semantics in this area

PL/0 storage allocation

- How and when it is decided how big a stack frame will be?
  - It's necessary that the frame always be the same size for every invocation of a given procedure
- Also, how and when is it decided exactly where in a stack frame specific data will be?
  - Some pieces are decided a priori (such as the return address)
  - Others must be decided during compile-time, such as local variables (since the number and size can't be known beforehand)
- This is all done during the storage allocation phase

PL/0 storage allocation

```c
void SymTabScope::allocateSpace() {
  _localsSize = 0;
  _formalsSize = 0;
  for (int i = 0; i < _symbols->length(); i++)
    _symbols->fetch(i)->allocateSpace(this);
  for (int j = 0; j < _children->length(); j++)
    _children->fetch(j)->allocateSpace();
}
```

```c
int SymTabScope::allocateFormal(int size) {
  int offset = _formalsSize;
  _formalsSize += size;
  return offset;
}
```

```c
int SymTabScope::allocateLocal(int size) {
  int offset = _localsSize;
  _localsSize += size;
  return offset;
}
```

```c
void VarSTE::allocateSpace(SymTabScope* s) {
  int size = _type->size();
  _offset = s->allocateLocal(size);
}
```

```c
void FormalSTE::allocateSpace(SymTabScope* s) {
  int size = _type->size();
  _offset = s->allocateFormal(size);
}
```

Call-by-sharing

- If implicitly reference aggregate data via pointer (e.g., Java, Lisp, Smalltalk, ML, …) then call-by-sharing is call-by-value applied to implicit pointer
  - “call-by-pointer-value”
  - Efficient, even for big aggregates
  - Assignments of formal to a different aggregate don’t affect caller (e.g., f := x)
  - Updates to contents of aggregate visible to caller immediately (e.g., f[i] := x)
  - Aliasing/sharing relationships are preserved