CSE401: Storage Layout

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Autumn 2002

Slides by Chambers, Eggers, Notkin, Ruzzo, and others

1

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

2

Data layout of scalars
Based on machine representation

Integer	Use hardware representation (2, 4, and/or 8 bytes of memory, maybe aligned)
Bool	1 byte or word
Char	1-2 bytes or word
Pointer	Use hardware representation (2, 4, or 8 bytes, maybe two words if segmented machine)

3

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.

4

Layout of records

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

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

5

Layout of arrays

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

```
s : array [5] of
  record;
    i : int;
    c : char;
  end;
```

6

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 : array [3] of
      array [2] of
        record;
          i : int;
          c : char;
        end;
```

a[1][1]
a[1][2]
a[2][1]
a[2][2]
a[3][1]
a[3][2]

7

Implications of Array Layout

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

```
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 ;
```

8

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;
```

9

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

10

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`)

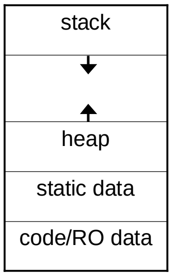
11

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)
    - ⇒ Static allocation
  - Execution of a procedure activation (e.g., locals)
    - ⇒ Stack allocation
  - Variable (dynamically allocated data)
    - ⇒ Heap allocation

12

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 (e.g. `sbrk`) system call
- Stack
  - Expands/contracts downwards automatically

13

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

14

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

15

Stack allocation II

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

```
procedure P() {
  int x;
  for(int i=0; i<10; i++){
      double x;
      …
  }
  for(int j=0; j<10; j++){
      double y;
      …
  }
}
```

16

Stack allocation: constraints I

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

```
proc foo(x:int): proctype(int):int;
  proc bar(y:int):int;
  begin
    return x + y;
  end bar;
begin
  return bar;
end foo;

var f:proctype(int):int;
var g:proctype(int):int;

f := foo(3);    g := foo(4);
output := f(5); output := g(6);
```

17

Stack allocation: constraints II

- Also violated if pointers to locals are allowed

```
proc foo (x:int): *int;
  var y:int;
begin
  y := x * 2;
  return &y;
end foo;

var w,z:*int;

z := foo(3);
w := foo(4);

output := *z;
output := *w;
```

18

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

19

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, …
- Dedicate 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)

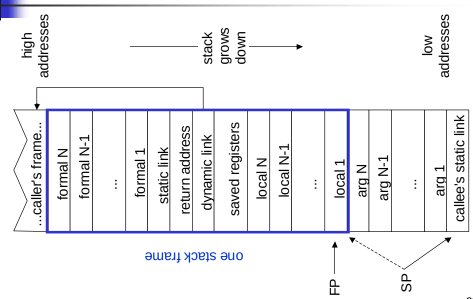
20

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

21

Stack Layout



22

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)
```

23

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

24

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

25

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 caller's frame pointer (dynamic link) on stack
  - Save any other registers that might be needed by caller
  - 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

26

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

27

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
  ```

28

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?

29

Exercise: apply to this example

```
module M;
  var x:int;
  proc P(y:int);
    proc Q(y:int);
      var qx:int;
      begin R(x+y);end Q;
    proc R(z:int);
      var rx,ry:int;
      begin P(x+y+z);end R;
    begin Q(x+y); R(42); P(0); end P;
begin
  x := 1;
  P(2);
end M.
```

30

Exercise: symbol table

M

x	int	0
P	proc	-
sl		
dl		

P

y	int	
Q	proc	-
R	proc	-
sl		
dl		

Q

y	int	
qx	int	
sl		
dl		

R

z	int	
rx	int	
ry	int	
sl		
dl		

31

Exercise: stack frames

M

x	int	0
P	proc	
sl		
dl		

P

y	int	
Q	proc	
R	proc	
sl		
dl		

Q

y	int	
qx	int	
sl		
dl		

R

z	int	
rx	int	
ry	int	
sl		
dl		

M frame	P frame	Q frame	R frame
			z
		y	static link
static link	y	static link	return address
return address	static link	return address	dynamic link
dynamic link	return address	dynamic link	saved registers
saved registers	dynamic link	saved registers	ry
x	saved registers	qx	rx

32

What do these mean?

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

int  i=2;
P(i); output i;
P(2); output 2;
```

```
proc Q(int a,int b);
  int c;
begin
  c := a;
  a := b;
  b := c;
end;

int i=2; j=3;
Q(i,j);
```

33

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 formals

34

Parameter passing modes

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

35

Call-by-value

- Assignment to formal doesn't affect caller's value
- Implementation: pass copy of argument value
  - Trivial for scalars
  - Inefficient for aggregates(?)

```
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;
```

36

Call-by-reference

- Assignment to formal changes actual value in caller
  - Immediately
  - Actual must be lvalue
- 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;
```

37

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?

38

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;
```

39

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;
```

40

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

41

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

42

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

```
proc square(x);
int x;
begin
  x := x * x
end;

square(A[i]);
```

43

Jensen's device

- How to implement the equivalent of a math formula like $\Sigma_{0 \le i \le n} A_{2i}$

  `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

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

44

A classic problem:
a procedure to swap two elements

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

- ```
  int x, y;
  x = 2;
  y = 5;
  swap(x, y);
  ```
- ```
  int j, z[10];
  j = 2;
  z[2] = 5;
  swap(j, z[j]);
  ```

45

Call-by-name advantages

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

46

Call-by-name disadvantages

- Repeatedly evaluating arguments can be inefficient
- Pass-by-name precludes some standard procedures from being implemented
- Pass-by-name is difficult to implement

47

thunks

- 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

48

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

49

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

50

PL/0 storage allocation

```
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();
    }
}
```

51

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

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

53