CSE401: Storage Layout (A)

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Run-time storage layout:

focus on compilation, not interpretation

- Play 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

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)

Data layout of aggregates

- Aggregate scalars together
- Different compilers make different decisions
- The decisions are sometimes machine dependent
  - Note that through the discussion of the front-end, we essentially never mentioned the target machine
  - We didn’t in interpretation, either
  - But now it’s going to start to come up constantly

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?

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

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;
```

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

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/0 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
- Arrays could change locations in memory and size quite easily

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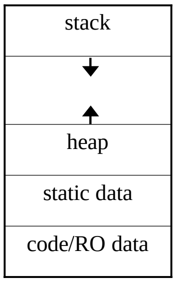
String representation

- A string is an array of characters
  - So, can use array layout rule for strings
- Pascal: strings have 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: use special end-of-string character (e.g., `\0`)

Storage allocation strategies

- Given layout of data structure, where in memory to allocate space for each variable/data structure?
- 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

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

Static allocation

- Statically allocate variables/data structures with global lifetime
  - Global variables
  - Compile-time constant strings, arrays, etc.
  - `static` local variables in C, all locals in FORTRAN
  - Machine code
- 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
- Procedure activation records allocated on a stack
  - A stack-allocated activation record called a *stack frame*
  - Frame includes formals, locals, static link of procedure
  - Dynamic link points to stack frame above
- Fast to allocate and deallocate storage
- Good memory locality

Constraints on stack allocation

- Stack allocation required no references to stack-allocated data 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);
```

Constraints on stack allocation

- 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;
```

Heap allocation

- For data with unknown lifetime
  - `new/malloc` to allocate space
  - `delete/free`/garbage collection to deallocate space
- 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

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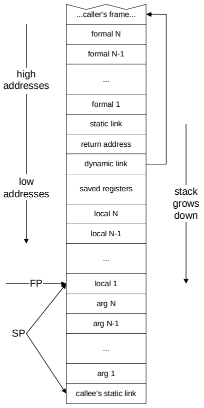
Stack frame layout

- Need space for
  - Formals
  - Locals
  - Dynamic link
  - Static link
  - Other run-time data (e.g., return address, saved registers)
- Assign dedicated registers to support access to stack frames
  - Frame pointer (FP): ptr to beginning of stack frame (fixed)
  - Stack pointer (SP): 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



...caller's frame...
formal N
formal N-1
...
formal 1
static link
return address
dynamic link
saved registers
local N
local N-1
...
local 1
arg N
arg N-1
...
arg 1
callee's static link

high addresses
low addresses
stack grows down
FP
SP