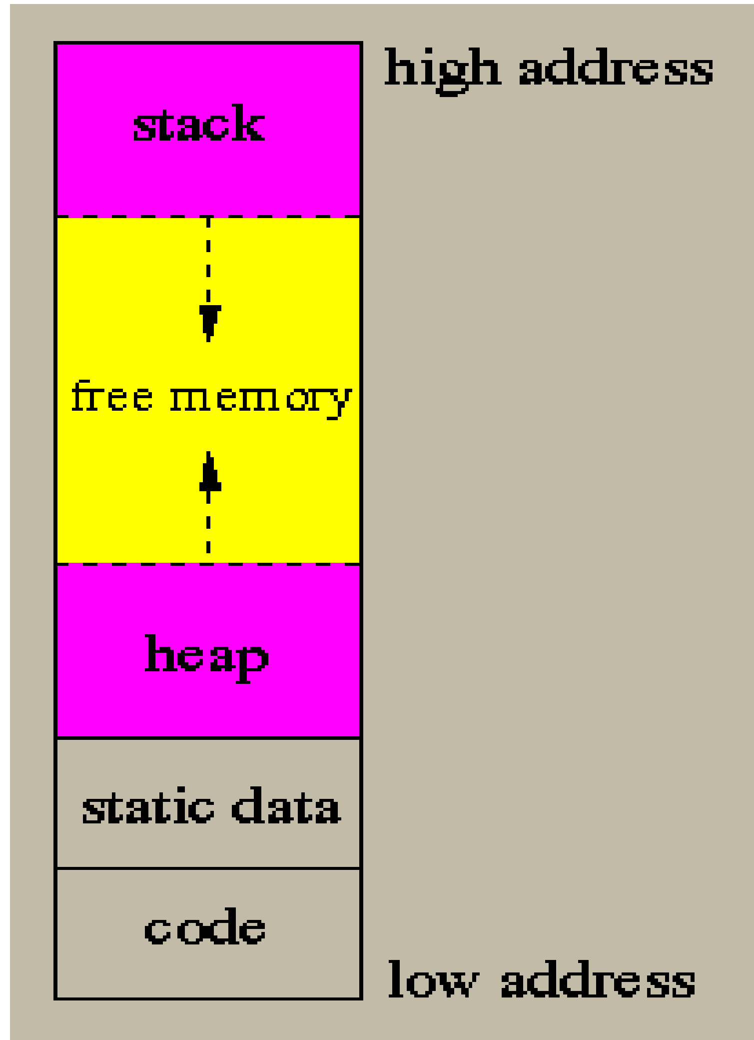
CSE@UTA

Run-Time Storage Organization

Leonidas Fegaras

Memory Layout

- Memory layout of an executable program:



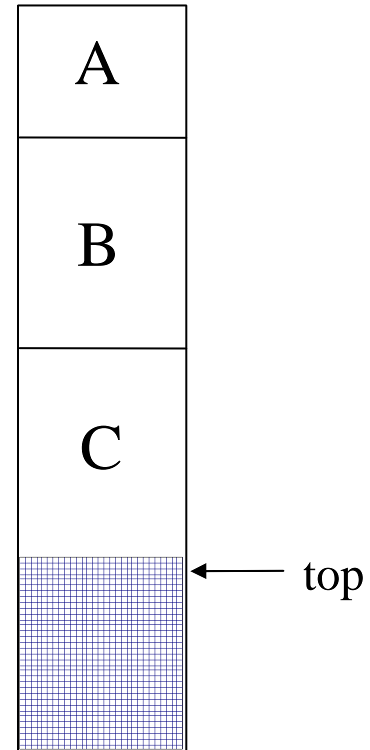
Run-Time Stack

- At run-time, function calls behave in a stack-like manner
  - when you call, you push the return address onto the run-time stack
  - when you return, you pop the return address from the stack
  - reason: a function may be recursive
- When you call a function, inside the function body, you want to be able to access
  - formal parameters
  - variables local to the function
  - variables belonging to an enclosing function (for nested functions)

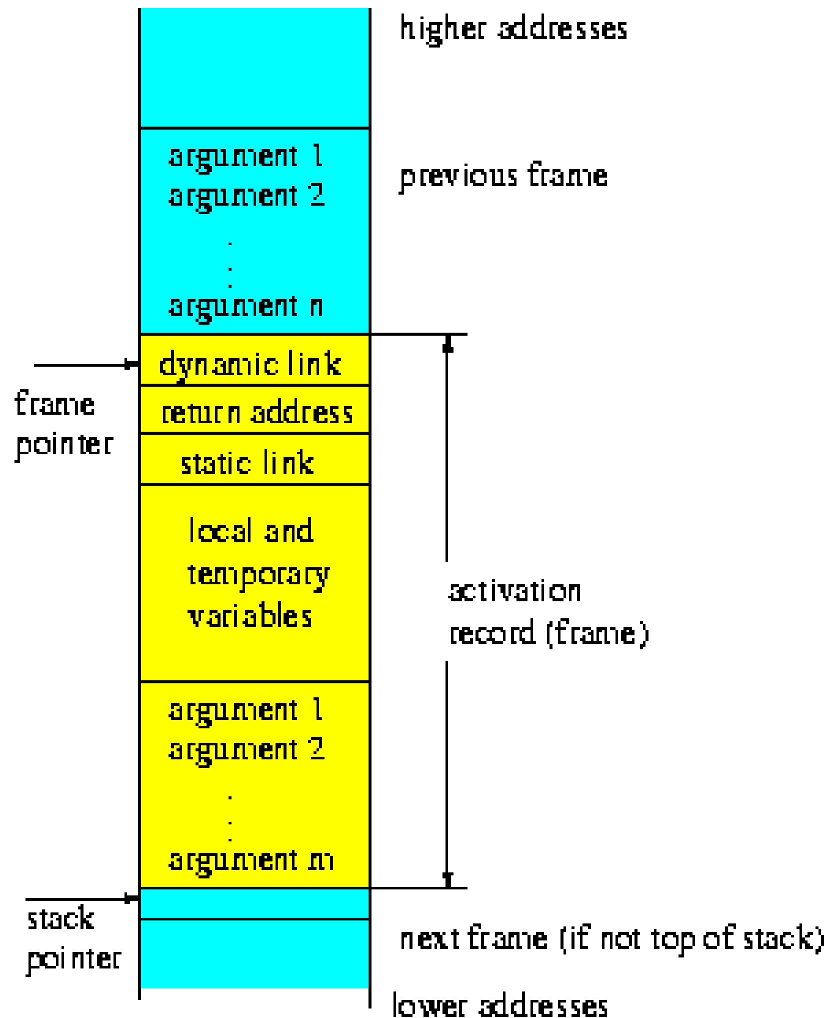
```
procedure P ( c: integer )
  x: integer;
  procedure Q ( a, b: integer )
  i, j: integer;
  begin
    x := x+a+j;
  end;
begin
  Q(x,c);
end;
```

Activation Records (Frames)

- When we call a function, we push an entire frame onto the stack
- The frame contains
  - the return address from the function
  - the values of the local variables
  - temporary workspace
  - ...
- The size of a frame is not fixed
  - need to chain together frames into a list (via dynamic link)
  - need to be able to access the variables of the enclosing functions *efficiently*



A Typical Frame Organization



Static Links

- The static link of a function f points to the latest frame in the stack of the function that statically contains f
  - If f is not lexically contained in any other function, its static link is null

```
procedure P ( c: integer )
  x: integer;
  procedure Q ( a, b: integer )
  i, j: integer;
  begin
    x := x+a+j;
  end;
begin
  Q(x,c);
end;
```

- If P called Q then the static link of Q will point to the latest frame of P in the stack
- Note that
  - we may have multiple frames of P in the stack; Q will point to the latest
  - there is no way to call Q if there is no P frame in the stack, since Q is hidden outside P in the program

The Code for Function Calls

- When a function (the caller) calls another function (the callee), it executes the following code:
  - *pre-call*: do before the function call
    - allocate the callee frame on top of the stack
    - evaluate and store function parameters in registers or in the stack
    - store the return address to the caller in a register or in the stack
  - *post-call*: do after the function call
    - copy the return value
    - deallocate (pop-out) the callee frame
    - restore parameters if they passed by reference

The Code for Function Calls (cont.)

- In addition, each function has the following code:
  - prologue: to do at the beginning of the function body
    - store frame pointer in the stack or in a display
    - set the frame pointer to be the top of the stack
    - store static link in the stack or in the display
    - initialize local variables
  - epilogue: to do at the end of the function body
    - store the return value in the stack
    - restore frame pointer
    - return to the caller

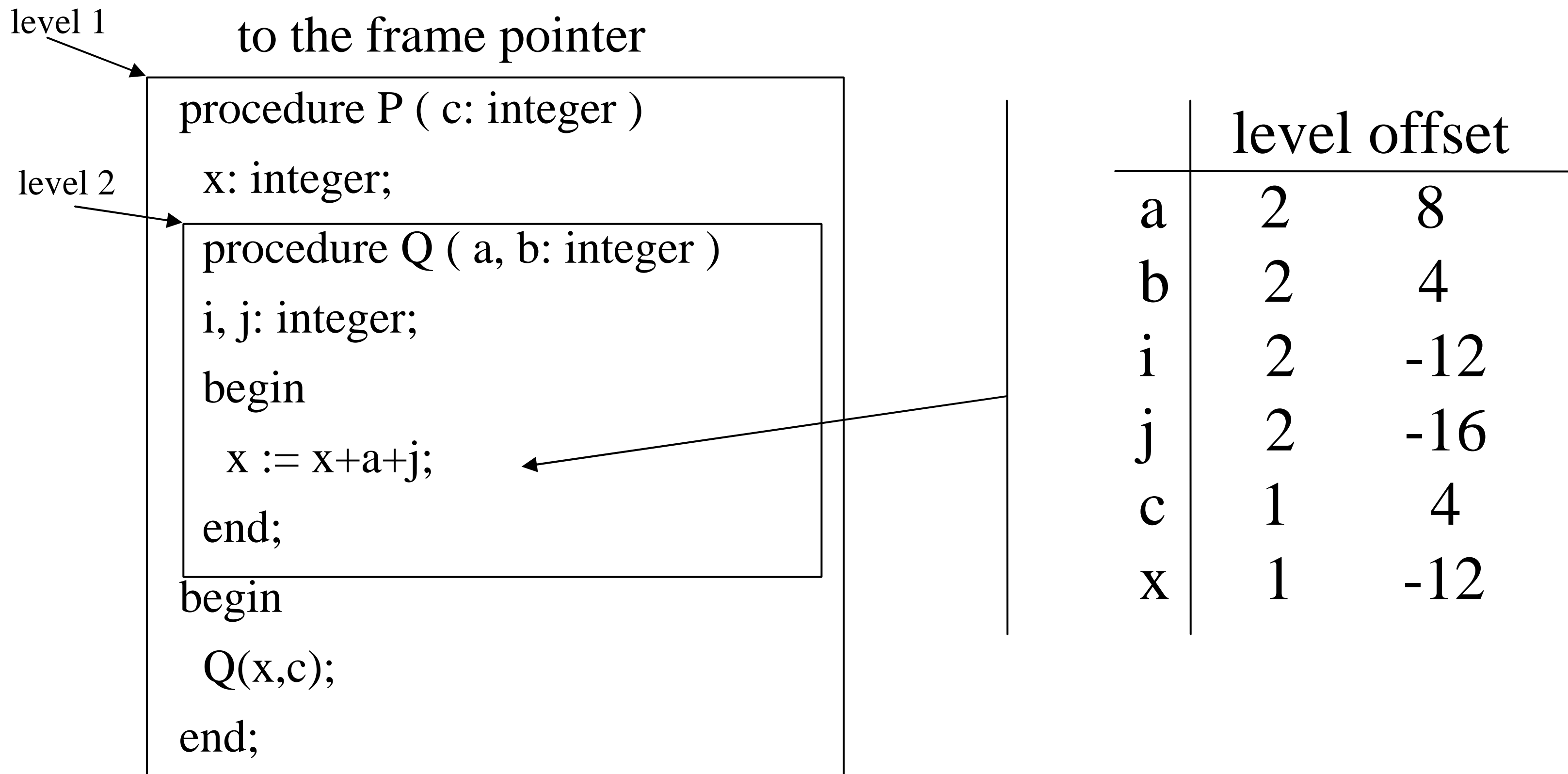
Storage Allocation

We can classify the variables in a program into four categories:

1) statically allocated data that reside in the static data part of the program
   - these are the global variables.
2) dynamically allocated data that reside in the heap
   - these are the data created by malloc in C
3) register allocated variables that reside in the CPU registers
   - these can be function arguments, function return values, or local variables
4) frame-resident variables that reside in the run-time stack
   - these can be function arguments, function return values, or local variables

Frame-Resident Variables

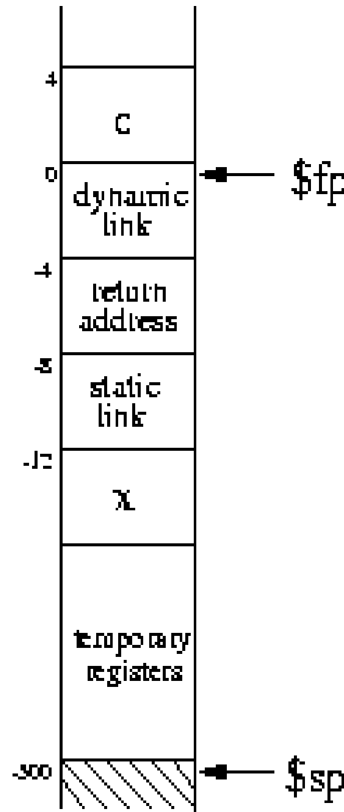
- Every frame-resident variable (ie. a local variable) can be viewed as a pair of (level,offset)
  - the variable level indicates the lexical level in which this variable is defined
  - the offset is the location of the variable value in the run-time stack relative to the frame pointer



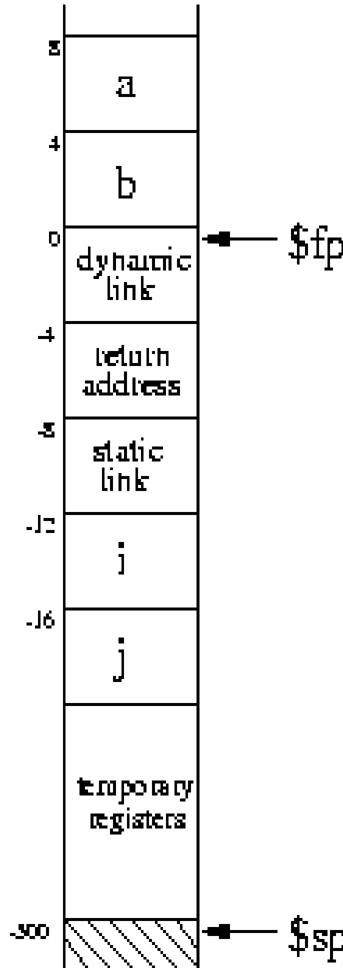
	level	offset
a	2	8
b	2	4
i	2	-12
j	2	-16
c	1	4
x	1	-12

Variable Offsets

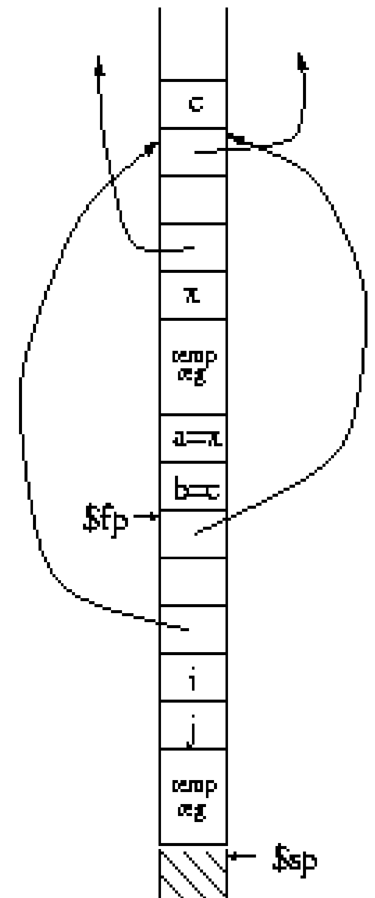
```
procedure P ( c: integer )
x: integer;
  procedure Q ( a, b: integer )
  i, j: integer;
  begin
    x := x+a+j;
  end;
begin
  Q(x,c);
end;
```



The view of the stack inside procedure P



The view of the stack inside procedure Q



Run-time stack at the point of x := x+a+j

Accessing a Variable

- Let $fp be the frame pointer
- You are generating code for the body of a function at the level L1
- For a variable with (level,offset)=(L2,O) you generate code:
  1) you traverse the static link (at offset -8) L1-L2 times to get the containing frame
  2) you accesss the location at the offset O in the containing frame
- eg, for L1=5, L2=2, and O=-16, we have
  - Mem[Mem[Mem[Mem[$fp-8]-8]-8]-16]
- eg:

a: Mem[$fp+8]
b: Mem[$fp+4]
i: Mem[$fp-12]
j: Mem[$fp-16]
c: Mem[Mem[$fp-8]+4]
x: Mem[Mem[$fp-8]-12]

	level	offset
a	2	8
b	2	4
i	2	-12
j	2	-16
c	1	4
x	1	-12

The Code for the Call Q(x,c)

```
Mem[$sp] = Mem[$fp-12]        ; push x
$sp = $sp-4
Mem[$sp] = Mem[$fp+4]         ; push c
$sp = $sp-4
static_link = $fp
call Q
$sp = $sp+8                   ; pop arguments
```

The Code for a Function Body

- Prologue:

  Mem[$sp] = $fp ; store $fp

  $fp = $sp ; new beginning of frame

  $sp = $sp+frame_size ; create frame

  save return_address

  save static_link

- Epilogue:

  restore return_address

  $sp = $fp ; pop frame

  $fp = Mem[$fp] ; follow dynamic link

  return using the return_address

Finding Static Link

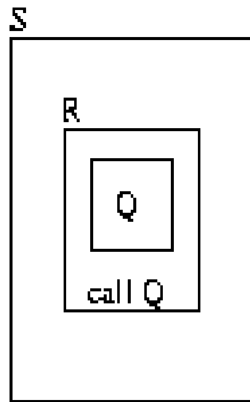
- The caller set the static_link of the callee before the call
  - this is because the caller knows both the caller and callee
  - the callee doesn't know the caller
- Suppose that L1 and L2 are the nesting levels of the caller and the callee procedures
  - When the callee is lexically inside the caller's body, that is, when L2=L1+1, we have:

    static_link = $fp
  - Otherwise, we follow the static link of the caller L1-L2+1 times
- For L1=L2, that is, when both caller and callee are at the same level, we have

  static_link = Mem[$fp-8]
- For L1=L2+2 we have

  static_link = Mem[Mem[Mem[$fp-8]-8]-8]

Finding Static Link (cont.)

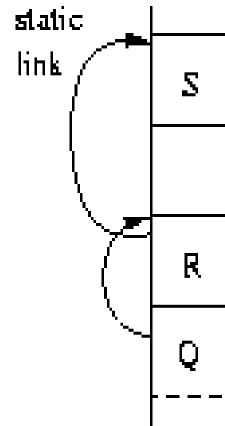


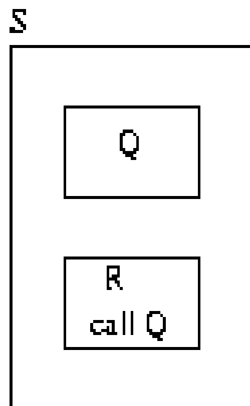
1) R calls Q

level(R)=level(Q)−1

the static link of Q is set to the beginning of R

move \$vo, \$fp



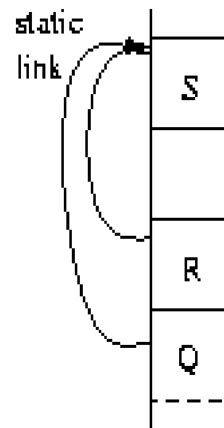


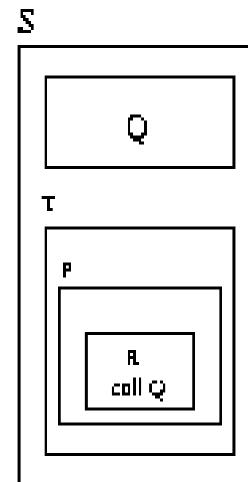
2) R calls Q

level(R)=level(Q)

the static link of Q is set to the static link of R

lw \$v0, −8(\$fp)





3) R calls Q

level(R)=level(Q)+n

the static link of Q is set by following the static link of R n+1 times

lw \$t0, −8(\$fp)

lw \$t0, −8(\$t0)

lw \$v0, −8(\$t0)