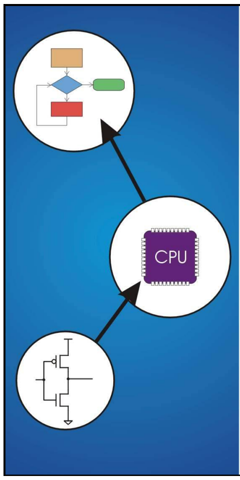


Chapter 10
Memory Model for Program Execution

Original slides by Chris Wilcox, Colorado State University

Problem

How do we allocate memory during the execution of a program written in C?

- Programs need memory for code and data such as instructions, global and local variables, etc.
- Modern programming practices encourage many (reusable) functions, callable from anywhere.
- Some memory can be statically allocated, since the size and type is known at compile time.
- Some memory must be allocated dynamically, size and type is unknown at compile time.

Motivation

Why is memory allocation important? Why not just use a memory manager?

- Allocation affects the performance and memory usage of every C, C++, Java program.
- Current systems do not have enough registers to store everything that is required.
- Memory management is too slow and cumbersome to solve the problem.
- Static allocation of memory resources is too inflexible and inefficient, as we will see.

Goals

- What do we care about?
  - Fast program execution
  - Efficient memory usage
  - Avoid memory fragmentation
  - Maintain data locality
  - Allow recursive calls
  - Support parallel execution
  - Minimize resource allocation
  - **Memory should never be allocated for functions that are not executed.**

Function Call

- Consider the following code:

```
// main program
int a = 10;
int b = 20
c = foo(a, b);
int foo(int x, int y)
{
  int z;
  z = x + y;
  return z;
}
```

- What needs to be stored?
  - Code, parameters, locals, globals, return values

Storage Requirements

- Code must be stored in memory so that we can execute the function.
- The return address must be stored so that control can be returned to the caller.
- Parameters must be sent from the caller to the callee so that the function receives them.
- Return values must be sent from the callee to the caller, that's how results are returned.
- Local variables for the function must be stored somewhere, is one copy enough?

Possible Solution: Mixed Code and Data

- Function implementation:

```
foo        JMP foo_begin   # skip over data
foo_rv     .BLKW 1         # return value
foo_ra     .BLKW 1         # return address
foo_paramx .BLKW 1         # 'x' parameter
foo_paramy .BLKW 1         # 'y' parameter
foo_localz .BLKW 1         # 'z' local
foo_begin  STR R7, foo_rv # save return
            …
           LDR R7, foo_ra # restore return
           RET
```

- Can construct data section by appending foo_

Possible Solution: Mixed Code and Data

- Calling sequence

```
ST R1, foo_paramx # R1 has 'x'
ST R2, foo_paramx # R2 has 'y'
JSR foo           # Function call
LDR R3, foo_rv    # R3 = return value
```

- Code generation is relatively simple.
- Few instructions are spent moving data.

Possible Solution: Mixed Code and Data

- Advantages:
  - Code and data are close together
  - Conceptually easy to understand
  - Minimizes register usage for variables
  - Data persists through life of program
- Disadvantages:
  - Cannot handle recursion or parallel execution
  - Code is vulnerable to self-modification
  - Consumes resource for inactive functions

Possible Solution: Separate Code and Data

- Memory allocation:

```
foo_rv     .BLKW 1   # foo return value
foo_ra     .BLKW 1   # foo return address
foo_paramx .BLKW 1   # foo 'x' parameter
foo_paramy .BLKW 1   # foo 'y' parameter
foo_localz .BLKW 1   # foo 'z' local
bar_rv     .BLKW 1   # bar return value
bar_ra     .BLKW 1   # bar return address
bar_paramw .BLKW 1   # bar 'w' parameter
```

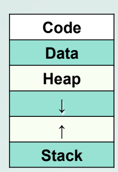
- Code for foo() and bar() are somewhere else
- Function code call is similar to mixed solution

Possible Solution: Separate Code and Data

- Advantages:
  - Code can be marked 'read only'
  - Conceptually easy to understand
  - Early Fortran used this scheme
  - Data persists through life of program
- Disadvantages:
  - Cannot handle recursion or parallel execution
  - Consumes resource for inactive functions

Real Solution: Execution Stack

- Instructions are stored in code segment
- Global data is stored in data segment
- Statically allocated memory uses stack
- Dynamically allocated memory uses heap



- Code segment is write protected
- Initialized and uninitialized globals
- Heap can be fragmented
- Stack size is usually limited
- Stack can grow either direction (usual convention is **down**)

Execution Stack

- What is a stack?
  - First In, Last Out (FILO) data structure
  - PUSH adds data, POP removes data
  - Overflow condition: push when stack full
  - Underflow condition: pop when stack empty
  - Stack grows and shrinks as data is added and removed
  - Stack grows downward from the end of memory space
  - Function calls allocate a stack frame
  - Return cleans up by freeing the stack frame
  - Corresponds nicely to nested function calls
  - **Stack Trace** shows current execution (Java/Eclipse)

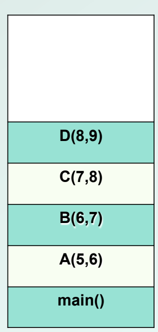
Stack Trace

- Example stack trace from gdb: main() calls A() calls B() calls C() calls D().
- Breakpoint is set in function D(), note that main() is at the bottom, D() is at the top.

```
(gdb) info stack
#0  D (a=8, b=9) at stacktest.c:23
#1  0x00400531 in C (a=7, b=8) at stacktest.c:19
#2  0x0040050c in B (a=6, b=7) at stacktest.c:15
#3  0x004004e7 in A (a=5, b=6) at stacktest.c:11
#4  0x00400566 in main () at stacktest.c:29
```


Execution Stack

- Picture of stack during program execution, same call stack as previous slide:
  - main() calls A(5,6)
  - A(5,6) calls B(6,7)
  - B(6,7) calls C(7,8)
  - C(7,8) calls D(8,9)

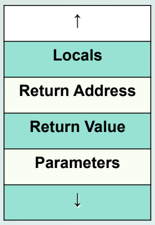


Stack Requirements

- Consider what has to happen in a function call:
  - Caller must allocate space for the return value.
  - Caller must pass parameters to the callee.
  - Caller must save the return address.
  - Caller must transfer control to the callee.
  - Callee requires space for local variables.
  - Callee must return control to the caller.
- Parameters, return value, return address, and locals are stored on the stack.
- The order above determines the responsibility and order of stack operations.

Execution Stack

- Definition: A stack frame or activation record is the memory required for a function call:



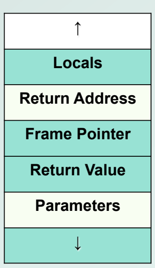
  - Stack frame below contains the function that called this function.
  - Stack frame above contains the functions called from this function.
  - Caller allocates return value, pushes parameters and return address.
  - Callee allocates and frees local variables, stores the return value.

Stack Pointers

- Clearly we need a variable to store the **stack pointer** (SP), LC3 assembly uses R6.
- Stack execution is ubiquitous, so hardware has a stack pointer, sometimes even instructions.
- Problem: stack pointer is difficult to use to access data, since it moves around constantly.
- Solution: allocate another variable called a **frame pointer** (FP), for stack frame, uses R5.
- Where should frame pointer point? Convention sets it between caller and callee data.

Execution Stack

- Definition: A stack frame or activation record is the memory required for a function call:



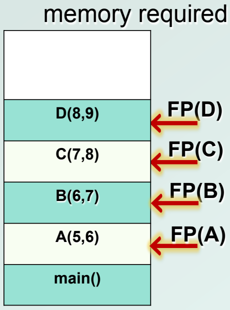
  - Locals are accessed by negative offsets from frame pointer.
  - Parameters and return value are accessed by positive offsets.
  - Most offsets are small, this explains LDR/STR implementation.
  - Base register stores pointer, signed offset accesses both directions.

Execution Stack

- In the previous solutions, the compiler allocated parameters and locals in fixed memory locations.
- Using an execution stack means parameters and locals are constantly moving around.
- The frame pointer solves this problem by using fixed offsets instead of addresses.
- The compiler can generate code using offsets, without knowing where the stack frame will reside.
- Frame pointer needs to be saved and restored around function calls. How about the stack pointer?

Nested Calls

- Definition: A stack frame or activation record is the memory required for a function call:



  - Locals are accessed by negative offsets from frame pointer.
  - Parameters and return value are accessed by positive offsets.
  - Most offsets are small, this explains LDR/STR implementation.
  - Base register stores pointer, signed offset accesses both directions.

Execution Stack

- Advantages:
  - Code can be marked 'read only'
  - Conceptually easy to understand
  - Supports recursion and parallel execution
  - No resources for inactive functions
  - Good data locality, no fragmenting
  - Minimizes register usage
- Disadvantages:
  - More memory than static allocation

Detailed Example

- Assume POP and PUSH code as follows:

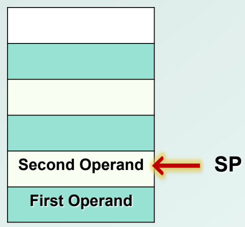
```
MACRO PUSH(reg)
        ADD R6,R6,#-1   ; Decrement SP
        STR reg,R6,#0   ; Store value
END

MACRO POP(reg)
        LDR reg,R6,#0    ; Load value
        ADD R6,R6,#1    ; Increment SP
END
```


Detailed Example

- Main program to illustrate stack convention:

```
       .ORIG x3000
MAIN    LD R6,STACK     ; init stack pointer
        LD R0,OPERAND0  ; load first operand
        PUSH R0         ; PUSH first operand
        LD R1,OPERAND1  ; load second operand
        PUSH R1         ; PUSH second operand
        JSR FUNCTION    ; call function
        LDR R0,R6,#0    ; POP return value
        ADD R6,R6,#3    ; unwind stack
        ST  R0,RESULT   ; store result
        HALT
```

Detailed Example



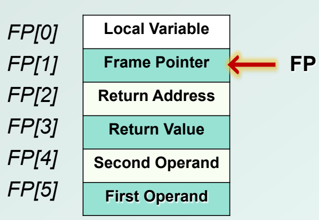
Stack before JSR instruction

Detailed Example

- Function code to illustrate stack convention:

```
FUNCTION
        ADD R6,R6,#-1   ; alloc return value
        PUSH R7         ; PUSH return address
        PUSH R5         ; PUSH frame pointer
        ADD R5,R6,#-1   ; FP = SP-1

        ADD R6,R6,#-1   ; alloc local variable
        LDR R2,R5,#4    ; load first operand
        LDR R3,R5,#5    ; load second operand
        ADD R4,R3,R2    ; add operands
        STR R4,R5,#0    ; store local variable
```


Detailed Example



Stack during body of FUNCTION

Detailed Example

- Function code to illustrate stack convention:

```
FUNCTION ; stack exit code
        STR R4,R5,#3    ; store return value
        ADD R6,R5,#1    ; SP = FP+1
        POP R5          ; POP frame pointer
        POP R7          ; POP return address
        RET             ; return

OPERAND0  .FILL x1234   ; first operand
OPERAND1  .FILL x2345   ; second operand
RESULT    .BLKW 1       ; result
STACK     .FILL x4000   ; stack address
```

Stack Execution

- Summary of memory model:
  - We have discussed the stack model for execution of C programs, and along the way we have shown how a compiler might generate code for function calls.
- Future programming assignment:
  - Write a recursive function in C, then implement the same function in assembly code, managing memory using the stack model.