Computer Systems 1
Lecture 12

Procedures and the Call Stack

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Topics

Procedures: reusable code

- Often there is a sequence of instructions that comes up again and again
  - For example: sqrt (square root)
  - It takes a lot of instructions to calculate a square root
  - An application program may need a square root in many different places
- We don't want to keep repeating the code
  - It's tedious
  - It wastes space (all those instructions require memory!)
- The aim: write it once and reuse the same instructions many times

Procedure

- Write the code one time — the block of code is called a procedure (or subroutine, function)
- Put the instructions off by themselves somewhere, not in the main flow of instructions
- Give the block of code a label (e.g. work) that describes what it does
- Every time you need to perform this computation, **call** it: go to work
- When it finishes, the procedure needs to **return**: go back to the instruction **after** the one that jumped to it

Call and return

- One idea is just to use jump instructions for both call and return
- But that isn't actually sufficient — let's look in more detail at what happens

Returning to the instruction after the call

- Suppose a procedure named dowork is used in several places
- Each call jumps to the same place (the address of the first instruction of the procedure
- But the calls come from different places
- Therefore the procedure must finish by returning to different places

Calling and returning

Here is a main program that calls a procedure “dowork” several times. (It takes the value in R1 and doubles it, and the main program would use the result but we ignore that here.)

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        load      R1,x[R0]       ; R1 = x
        “goto”    dowork[R0]     ; call the procedure “dowork”
        load      R1,y[R0]       ; R1 = y
        “goto”    dowork[R0]     ; call dowork
        sub       R5,R6,R7       ; R5 = R6-R7


dowork  add       R1,R1,R1       ; R1 = R1+R1
        “return”                 ; return — go back to the caller
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The return must go to different points in the program—how can it do that?

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The return must go to different points in the program—how can it do that?

The jump-and-link instruction: jal

- When the main program calls the subroutine, it needs to remember where the call came from
- This is the purpose of the jal instruction — jump and link
- jal R5,dowork[R0]
  - A pointer to the next instruction after the jal — the return address — is loaded into the destination register (e.g. R5)
  - Then the machine jumps to the effective address

Jumping

All jump instructions (jump, jal, jumplt, etc.) refer to effective addresses

- jump loop[R0]
  goto loop
- jump 0[R14]
  goto instruction whose address is in R14
- jump const[R2]
  goto instruction whose address is const+R2

Implementing call and return

- To call a procedure `dowork`: jal R13,dowork[R0]
  - The address of the instruction *after* the jal is placed in R13
  - The program jumps to the effective address, and the procedure starts executing
- To return when the procedure has finished: jump 0[R13]
  - The effective address is 0 + the address of the instruction after the jal
  - The program jumps there and the main program resumes

Calling with jal and returning with jump

```
        load   R1,x[R0]          ; R1 = x
        jal    R13,dowork[R0]    ; call dowork
        load   R1,y[R0]          ; R1 = y
        jal    R13,dowork[R0]    ; call dowork
        sub    R5,R6,R7          ; R5 = R6-R7

dowork  add    R1,R1,R1          ; R1 = R1+R1
        jump   0[R13]            ; return
```

- call — jal puts a pointer to the next instruction into R13
- return — follow the pointer in R13

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Parameter passage

- There are several different conventions for passing argument to the function, and passing the result back
- What is important is that the caller and the procedure agree on how information is passed between them
- If there is a small number of arguments, the caller may put them in registers before calling the procedure
- If there are many arguments, the caller builds an array or vector (sequence of adjacent memory locations), puts the arguments into the vector, and passes the address of the vector in a register (typically R1)
- A simple convention: the argument and result are passed in R1

Functions

- A function is a procedure that
  - Receives a parameter (a word of data) from the caller
  - Calculates a result
  - Passes the result back to the caller when it returns
- A pure function is a function that doesn't do anything else — it doesn't change any global variables, or do any input/output

Example: Passing argument and result in R1

```
; Main program
       load   R1,x[R0]         ; arg = x
       jal    R13,work[R0]     ; result = work (x)
       ...
       load   R1,y[R0]         ; arg = y
       jal    R13,work[R0]     ; result = work (y)
       ...

; Function work (x) = 1 + 7*x
work   lea    R2,7[R0]         ; R7 = 2
       lea    R3,1[R0]         ; R3 = 1
       mul    R1,R1,R2         ; result = arg * 7
       add    R1,R3,R1         ; result = 1 + 7*arg
       jump   0[R13]           ; return
```

What if a procedure calls another procedure?

- The simplest kind of procedure
  - Call it with `jal R13,procname[R0]`
  - It returns by executing `jump 0[R13]`

Limitations of basic call

- If the procedure modifies any registers, it may destroy data belonging to the caller
- If the procedure calls another procedure, it can't use R13 again. Each procedure would need a dedicated register for its return address, limiting the program to a small number of procedures
- The basic call mechanism doesn't allow a procedure to call itself (this is called recursion)

R13 overwritten: proc1 returns to the wrong place!

```
        load    R1,x[R0]          ; R1 := x
        jal     R13,proc1[R0]     ; call proc1
        load    R1,y[R0]          ; R1 := y

        store   R1,result[R0]     ; result := 2 × (2x)^2
proc1   lea     R2,1[R0]          ; R2 := 1
proc1   add     R1,R1,R1          ; R1 := R1+1
        jal     R13,proc2[R0]     ; R1 := square (R1)
        add     R1,R1,R1          ; R1 := R1+1
        jump    0[R13]            ; return

square  mul     R1,R1,R1          ; R1 = R1*R1
        jump    0[R13]            ; return
```

$\boxed{\text{R13}}$

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R13

Saving state

- Calling a procedure creates new information
  - The return address
  - Whatever values the procedure loads into the registers
- But this new information could overwrite essential information belonging to the caller
- We need to save the caller's state so the procedure won't destroy it

The wrong way to save state

- Suppose we just have a variable saveRetAdr
- Store R13 into it in the procedure, load that when we return
- Now it's ok for proc1 to call proc2
- But if proc2 calls proc3 we are back to the same problem: it doesn't work!
- The solution: a stack

Saving registers

- Most procedures need to use several registers
- It's nearly impossible to do *anything* without using some registers!
- The first thing a procedure should do is to *save the registers* it will use by copying them into memory (with store instructions).
- The last thing it should do before returning is to *restore the registers* by copying their values back from memory (with load instructions).

Where can the registers be saved?

- It won't work to copy data from some of the registers to other registers!
- It's essential to save the data into memory
- Two approaches
  - Allocate fixed variables in memory to save the registers into — simple but doesn't allow recursion
  - Maintain a stack in memory, and push the data onto the stack — this is the best approach and is used by most programming languages

Who saves the state: the caller or the procedure?

- Two approaches:
- Caller saves (used occasionally)
  - Before calling a procedure, the caller saves the registers, so all its essential data is in memory
  - After the procedure returns, the caller does whatever loads are needed
- Callee saves (usually the preferred solution)
  - The caller keeps data in registers, and assumes that the procedure won't disturb it
  - The first thing the procedure does is to save the registers it needs to use into memory
  - Just before returning, the procedure restores the registers by loading the data from memory

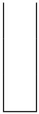
Stack of return addresses

- To allow a large number of procedures, we can't dedicate a specific register to each one for its return address
- Therefore we
  - Always use the same register for the return address in a jal instruction (we will use R13)
  - The first thing a procedure does is to store its return address into memory
  - The last thing the procedure does is to load its return address and jump to it
  - The return addresses are pushed onto a *stack*, rather than being stored at a fixed address

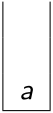
Stacks

- A stack is a container
- Initially it is empty
- You can push a value onto the stack; this is now sitting on the top of the stack
- You can pop the stack; this removes the most recently pushed value and returns it
- A stack allows access only to the top value; you cannot access anything below the top
- We can save procedure return addresses on a stack because return always needs the most recently saved return address

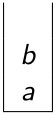
Initially the stack is empty



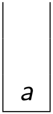
Call procedure, push return address a



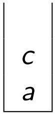
Call another procedure, push return address b



Return: pop produces return address b



Call some procedure, push return address c



Call a procedure, push return address d

d
c
a

The call stack

- Central technique for
  - Preserving data during a procedure call
  - Holding most of your variables
- It goes by several names; these are all the same thing
  - call stack
  - execution stack
  - "The stack"
- It's important!
  - Most programming languages use it
  - Computers are designed to support it
  - Often referred to (Stack Overflow web site, etc.)

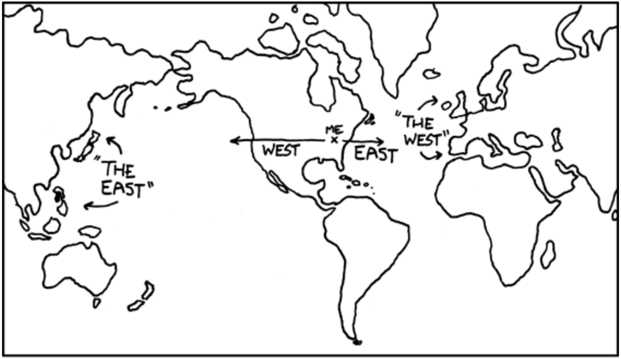
Stack frames

- There is a call stack or execution stack that maintains complete information about all procedure calls and returns
- Every "activation" of a procedure pushes a stack frame
- When the procedure returns, its stack frame is popped (removed) from the stack
- R14 contains the address of the current (top) stack frame
- The stack frame contains:
  - A pointer to the previous stack frame (this is required to make the pop work)
  - The return address (saved value of R13)
  - The saved registers (so the procedure can use the registers without destroying information)
  - Local variables (so the procedure can have some memory of its own to use)

Implementing the call stack

- Dedicate R14 to the stack pointer
- This is a programming convention, not a hardware feature
- When the program is started, R14 will be set to point to an empty stack
- When a procedure is called, the saved state will be pushed onto the stack: store a word at 0[R14] and add 1
- When a procedure returns, it pops the stack and restores the state: subtract 1, load from 0[R14]
- The program should never modify R14 apart from the push and pop

terminology



THIS ALWAYS BUGGED ME.

https://xkcd.com/503/