COMP 3221

Microprocessors and Embedded Systems

Lectures 16 : Functions in C/ Assembly - II

http://www.cse.unsw.edu.au/~cs3221

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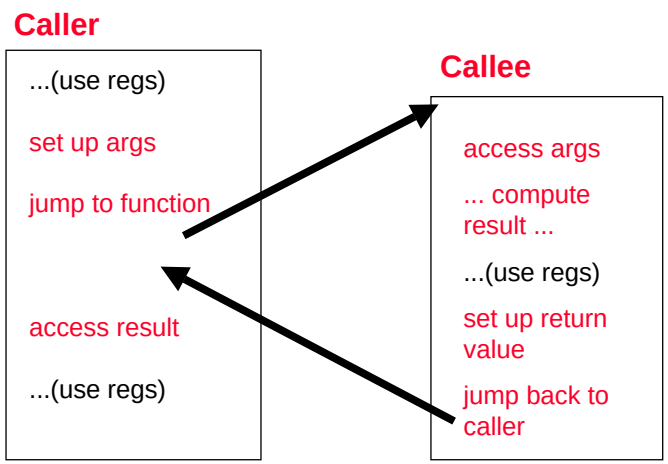
Overview

- Resolving Registers Conflicts
- Caller /Callee Responsibilities
- Frame/Stack pointer
- Conclusion

Review: Basics of Function Call



Review: Function Call Bookkeeping

- Procedure address
- Return address
- Arguments
- Return value
- Local variables
- Registers (conflicts)

Registers for functions

- → `lr = r14`
- → `a1, a2, a3, a4`
- → `a1`
- → `v1, v2, v3, v4, v5, v6, v7`

=>ARM Procedure Call Standards (APCS) conventions for use of registers simplify bookkeeping

Review: Instruction Support for Functions?

- Single instruction to branch and save return address: branch and link (`bl`):

```
1012 bl sum  ; lr = 1016,goto sum
```


Review: APCS Register Convention: Summary

register name	software name	use and linkage
r0 – r3	a1 – a4	first 4 integer args scratch registers integer function results
r4 – r11	v1- v8	local variables
r9	sb	static variable base
r10	sl	stack limit
r11	fp	frame pointer
r12	ip	intra procedure-call scratch pointer
r13	sp	stack pointer
r14	lr	return address
r15	pc	program counter

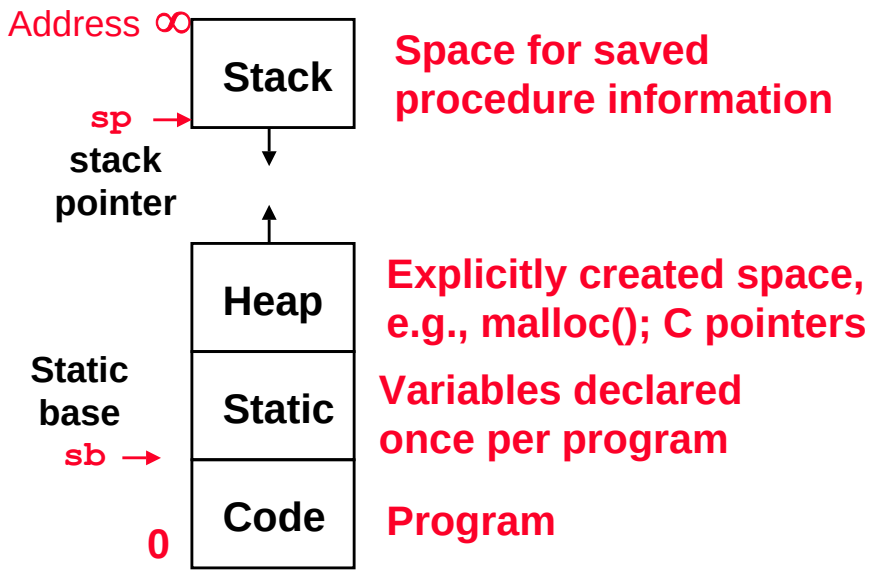
Red are SW conventions for compilation, blue are HW

ARM Procedure Call Standard (APCS)

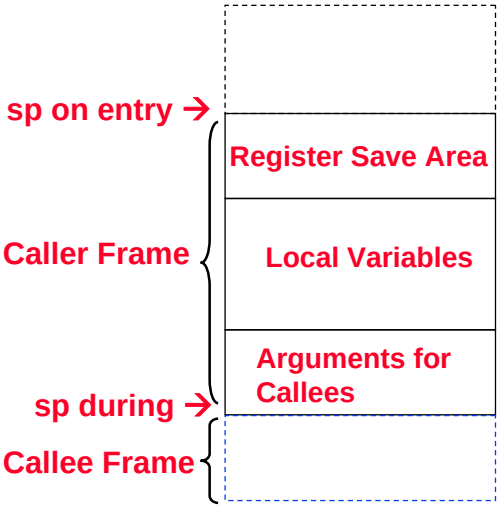
Review: Nested Procedures

- A caller function is itself called from another function.
- We need to store `lr` for the caller before it can call another function.
- In general, may need to save some other info in addition to `lr`.
- But; Where do we save these info?

Review: C memory allocation map



Review: Typical Structure of a Stack Frame



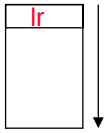
- compiler calculates total frame size (F)
- at start of call, subtract F from SP
- at end, add F to SP
- where are args from caller?
- where are args for callee

Basic Structure of a Function

Prologue

```
entry_label:
    sub sp,sp, #fsize      ; create space on stack
    str lr,[sp, #fsize-4]; save lr
                           ; save other regs
```

Body . .



Epilogue

```
                           ;restore other regs
    ldr lr, [sp,#fsize-4];restore lr
    add sp, sp,  #fsize   ;reclaim space on stack
    mov pc, lr
```


Compiling nested C func into ARM

C

```
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
}
```

ARM

```
sumSquare:
Prologue  sub sp,sp,#8      ; space on stack
          str lr,[sp,#4]    ; save ret addr
          str a2,[sp,#0]    ; save y
          mov a2,a1         ; mult(x,x)
          bl mult           ; call mult
Body      ldr a2,[sp,#0]    ; restore y
          add a1,a1,a2      ; mult()+y
          ldr lr,[sp,#4]    ; get ret addr
Epilogue  add sp,sp,#8      ; => stack space
          mov pc, lr
```


Compiling nested C func into ARM (Better way)

C

```
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
}
```

ARM

```
sumSquare:
Prologue  str lr,[sp,#-4]!; save ret addr
          str a2,[sp,#-4]!; save y
          mov a2,a1       ; mult(x,x)
          bl mult         ; call mult
Body      ldr a2,[sp,#4]! ; restore y
          add a1,a1,a2    ; mult()+y
          ldr lr,[sp,#4]! ; get ret addr
                          ; => stack space
Epilogue  mov pc, lr
```

Function Call Bookkeeping: thus far

° Procedure address	x	
° Return address	x	lr
° Arguments	x	a1 – a4
° Return values	x	a1 – a4
° Local variables	x	v1 – v8

° Registers
- what if they are reused?
- what if there aren't enough?

Readings for Week #6

° Steve Furber: ARM System On-Chip; 2nd Ed, Addison-Wesley, 2000, ISBN: 0-201-67519-6. Chapters 6

° Experiment 3 Documentation

Exceeding limits of registers

° Recall: assembly language has fixed number of operands, HLL doesn't

° Local variables: `v1, ..., v8`
- What if more than 8 words of local variables?

° Arguments; `a1, ..., a4`
- What if more than 4 words of arguments?

° Place extra variables and extra arguments onto stack (`sp`)

° Use scratch registers and data transfers to access these variables

Register Conflicts

° Procedure A calls Procedure B
- A referred to as is "calling procedure" or "caller"
- B referred to as is "called procedure" or "callee"

° Both A and B want to use the 15 registers

=> must cooperate

Register Conflicts: 2 options (A calls B)

1) Called procedure/callee (B) leaves registers the way it found them (except `lr`); its B's job to save it before using it and then restore it: "callee saves"
   - Since B only saves what it changes, more accurate is "callee saves (what it uses)"

° 2) B can use any register it wants; Calling procedure/caller A must save any register it wants to use after call of B: "caller saves"
   - Since A knows what it needs after call, more accurate is "caller saves (if it wants to)"

° Is either optimal?

ARM Solution to Register Conflicts

° Divide registers into groups
   - Local variables / Callee Saved registers (`v1 – v8`)
   - Scratch registers / Argument / Caller Save registers (`a1 – a3`)
   - Some caller saved (if wants) and some callee saved (if used)

° Caller (A) save/restore scratch / argument (`a1 – a4`) if needs them after the call; also `lr` ➔ callee can use (`a1 – a4`) and `lr`

° Callee (B) must save/restore local variables / callee saved registers (`v1 – v8`) if it uses them ➔ caller can leave them unsaved
   - Procedure that doesn't call another tries to use only scratch / argument registers (`a1 – a4`)

Register Conventions (#1/5)

° Caller: the calling function

° Callee: the function being called

° When callee returns from executing, the caller needs to know which registers may have changed and which are guaranteed to be unchanged.

° Register Conventions: A set of generally accepted rules as to which registers will be unchanged after a procedure call (`bl`) and which may be changed.

Register Conventions (#2/5)

° Three views of registers `a1 – a4`

° `a1 – a4` : Change. These are expected to contain new return values.

Or

° `a1 – a4` : Change. These are volatile argument registers.

Or

° `a1 – a4` : Change. They're called scratch: any procedure may change them at any time.

Register Conventions (#3/5)

- `v1 – v8` : No Change. Very important, that's why they're called callee saved registers / local variable. If the callee changes these in any way, it must restore the original values before returning.
- `sp`: No Change. The stack pointer must point to the same place before and after the `bl` call, or else the caller won't be able to restore values from the stack.
  - Grows downward, sp points to last full location
- `lr`: Change. The `bl` call itself will change this register.
- `ip`: Change. In most variants of APCS `ip` is an scratch register.

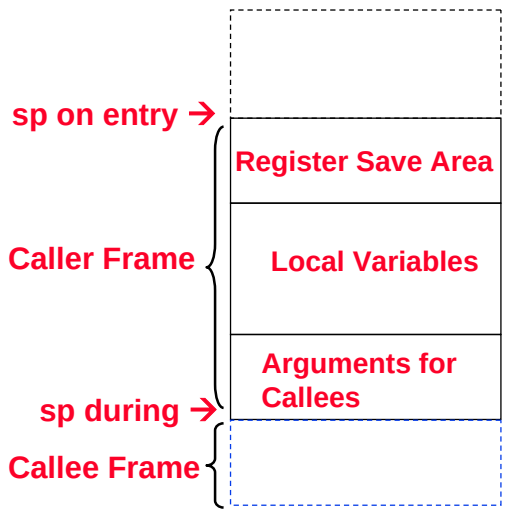
Register Conventions (#4/5)

- What do these conventions mean?
  - If function A calls function B, then function A must save any scratch registers `a1 – a4` that it may be using onto the stack before making a `bl` call.
  - Remember: Caller needs to save only registers it is using, not all scratch registers.
  - It also needs to store `lr` if A is in turn is called by another function.

Register Conventions (#5/5)

- Note that, even though the callee may not return with different values in the callee saved registers `v1 – v8`, it can use them by :
  - save `v1 – v8` on the stack
  - use these eight registers
  - restore `v1 – v8` from the stack
- The difference is that, with the scratch registers `a1 – a4`, the callee doesn't need to save them onto the stack.

Recall: Typical Structure of a Stack Frame



- compiler calculates total frame size (F) for the caller
- at start of procedure, subtract F from SP
- at end, add F to SP
- where are args from caller?
- where are the args for callee?

Callees' & Callers' Rights (Summary)

- Callees' Right
  - Right to use `a1 – a4` registers freely
  - Right to assume args are passed correctly in `a1 – a4`
- Callers' Rights
  - Right to use v1 – v8 registers without fear of being overwritten by Callee
  - Right to assume return values will be returned correctly in `a1 – a4`

Keep this slide in mind for exam

Callee's Responsibilities (Summary)

1. If using `v1 – v8` or big local structs, slide `sp` down to reserve memory:
   e.g. `sub sp, sp, #32`
2. If using `v1 – v8`, save before using:
   e.g. `str v1, [sp, #28]`
3. Receive args in `a1 – a4`, additional args on stack
4. Run the procedure body
5. If not `void`, put return values in `a1 – a4`
6. If applicable, undo steps 2-1
   e.g. `ldr v1, [sp,#28]`
   `add sp, sp, #32`
7. `mov pc, lr`

Keep this slide in mind for exam

Caller's Responsibilities (Summary)

1. Slide `sp` down to reserve memory:
   e.g. `sub sp, sp, #28`
2. Save `lr` on stack before `bl` to callee clobbers it:
   e.g. `str lr, [sp, #24]`
3. If you'll still need their values after the function call, save `a1 – a4` on stack or copy to `v1 – v8` registers. Callee can overwrite "a" registers, but not "v" registers. e.g. `str a1, [sp, #20]`
4. Put first 4 words of args in `a1 – a4`, at most 1 arg per word, additional args go on stack: "arg 5" is `[sp, #0]`
5. `bl` to the desired function
6. Receive return values in `a1 – a4`
7. Undo steps 3-1: e.g. `ldr a1, [sp, #20]`, `ldr lr, [sp, #24]`, `add sp, sp, #28`

Keep this slide in mind for exam

Compile using pencil and paper Example 1 (#1/2)

```
int Doh(int i, int j, int k, int l){
  return i+j+l;
}
```

```
Doh:
_____________________
    add a1,
_____________________
_____________________
```

Compile using pencil and paper Example 1 (#2/2)

```
int Doh(int i, int j, int k, int l){
  return i+j+l;
}
```

```
Doh: add a1, a2, a1
     add a1, a4, a1
     mov pc lr
```

"a" Regs Safe For Callee

Compile using pencil and paper Example 2 (#1/2)

```
int Doh(int i, int j, int k, int m,
 char c, int n){
  return i+j+n;
}
```

```
Doh:
     add a1, _____
```


Compile using pencil and paper Example 2 (#2/2)

```
int Doh(int i, int j, int k, int m,
 char c, int n){
  return i+j+n;
}
```

6th argument

```
Doh: ldr ip, [sp,#4]
     add a1, a1, ip
     add a1, a1, a2
     mov pc lr
```

"a" & ip Regs Safe For Callee

Hard Compilation Problem (#1/2)

```
int Doh(int i, int j, int k, int m, char c,
 int n){return mult(i,j)+n;}
```

```
int mult(int m, int n);/* returns m × n */
```

Doh: _____	add _____
_____	_____
_____	_____
_____	_____
bl _____	_____

Slow-motion Replay (#1/2)

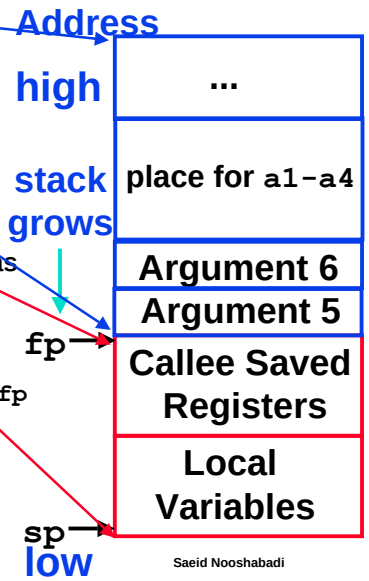
```
int Doh(int i, int j, int k, int m, char c,
  int n){ return sum(i,j)+n;}
int mult(int m, int n);/* returns m × n */
```

```
Doh: sub sp, sp,#4
     str lr, [sp]

     ldr v1,[sp,#8]
     bl mult

     add a1, a1, v1

     ldr lr, [sp]
     add sp, sp, #4
     mov pc, lr
```

1.Calling Sum => save lr, a Regs	2.Saving lr => must move sp	3.Need n after funccall => v1

Stack Memory Allocation Revisited

- Caller frame
  - Save caller-saved regs
  - Pass arguments (4 regs)
  - bl
- Callee frame
  - set fp@first word of frame
    fp = Caller's sp – 4 (fixed point)
  - Save registers on stack and update sp as needed
  - Accessing the local variables is always with reference to fp
  - Return saved register from stack using fp
- GCC uses frame pointer, ARM compilers by default don't
  - (allocate extra temporary register (ip), less bookkeeping on procedure call)



"And in Conclusion …"

- ARM SW convention divides registers into those calling procedure save/restore and those called procedure save/restore
  - Assigns registers to arguments, return address, return value, stack pointer
- Optional Frame pointer fp reduces bookkeeping on procedure call