5. Instruction Set Architecture – -from C to Assembly – function calls

EECS 370 – Introduction to Computer Organization - Winter 2016

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Announcements

- Due today
  - Project 1.a
  - Homework 1
- Reading assignments available in LECTURES tab of the website

- Correction: **C: a = b + names[i];**

~~mul r5, r3, #4~~ // calcu mov r5, r3, LSL #2 // r5 = r3 << 2

ldr r4, [r5, #1000] // load names[i]

add r1, r2, r4 // calculate b + names[i]

Recap

- ARM – branch instructions

- C –to assembly
  - Basic statements
  - Memory alignment
  - If-then-else

Loop – Example

```
// assume all variables are integers
// i is in r1, start of a is at address 500, sum is in r2
for (i=0 ; i < 100 ; i++) {
        if (a[i] > 0) {
                sum += a[i];
        }
}
```

```
          mov r1, #0
          mov r4, #400
Loop1:    cmp r1, r4
          bge  endLoop
          ldr  r5, [r1, #500]
          cmp r5, #0
          ble  endIf
          add  r2, r2, r5
endIf:    add  r1, r1, #4
          b    Loop1
endLoop:
```

# of branch instructions
= 3*100 + 1 = 301

a.k.a. while-do template

CTRL FLOW

Same Loop, Different Assembly

```
// assume all variables are integers
// i is in r1, start of a is at address 500, sum is in r2
for (i=0 ; i < 100 ; i++) {
        if (a[i] > 0) {
                sum += a[i];
        }
}
```

```
        mov r1, #0
        mov r4, #400
Loop1:  ldr   r5, [r1, #500]
        cmp r5, #0
        ble   endIf
        add  r2, r2, r5
endIf:  add  r1, r1, #4
        cmp r1, r4
        blt   Loop1
endLoop:
```

# of branch instructions
= 2*100 = 200

a.k.a. do-while template

CTRL FLOW

Class Problem 2

Write the ARM assembly code to implement the following C code:

```
// assume ptr is in r1
// struct {int val; struct node *next;} node;
// struct node *ptr;

if ((ptr != NULL) && (ptr->val > 0))
    ptr->val++;
```

ARM conditional assembly

- All ARM instructions can be executed conditionally, not just branches
- Conditional assembly programs may boost performance because execution penalty is < branch misprediction

Example:
```
while (r0 != r1) {
    if (r0>r1) r0 = r0 - r1;
    else r1 =r1 – r0;
}
```

standard assembly

```
TOP     cmp r0, r1
    beq END
    blt LESS
    sub r0, r0, r1
    b TOP
LESS    sub r1, r1, r0
    b TOP
END ….
```

conditional assembly

```
TOP     cmp r0, r1
    subgt r0, r0, r1
    sublt r1, r1, r0
    bne TOP
    …
```

Instruction Set Architecture (ISA) Design Lectures

- Lecture 2: Storage types and addressing modes
- Lecture 3 : LC-2K and ARM architecture
- Lecture 4 : Converting C to assembly – basic blocks
- **Lecture 5 : Converting C to assembly – functions**
- Lecture 6 : Translation software; libraries, memory layout

Converting function calls to assembly code

C: printf(“hello world\n”);

- Need to pass parameters to the called function (printf)
- Need to save return address of caller
- Need to save register values
- Need to jump to printf

Execute instructions for printf()
Jump to to return address

- Need to get return value (if used)
- Restore register values

FUNCTION CALLS

Task 1: Passing parameters

- Where should you put all of the parameters?
  - Registers?
    - Fast access but few in number and wrong size for some objects
  - Memory?
    - Good general solution but where?

- ARM answer:
  - Registers and memory
    - Put the first few parameters in registers (if they fit) (r0 – r3)
    - Put the rest in memory on the call stack
  - Example:
    mov   r0, #1000 // put address of char array “hello world” in r0

Call stack

- ARM conventions (and most other processors) allocate a region of memory for the call stack
  - This memory is used to manage all the storage requirements to simulate function call semantics
    - Parameters (that were not passed through registers)
    - Local variables
    - Temporary storage (when you run out of registers and need somewhere to save a value)
    - Return address
    - Etc.

- Sections of memory on the call stack [a.k.a. **stack frames**] are allocated when you make a function call, and de-allocated when you return from a function.

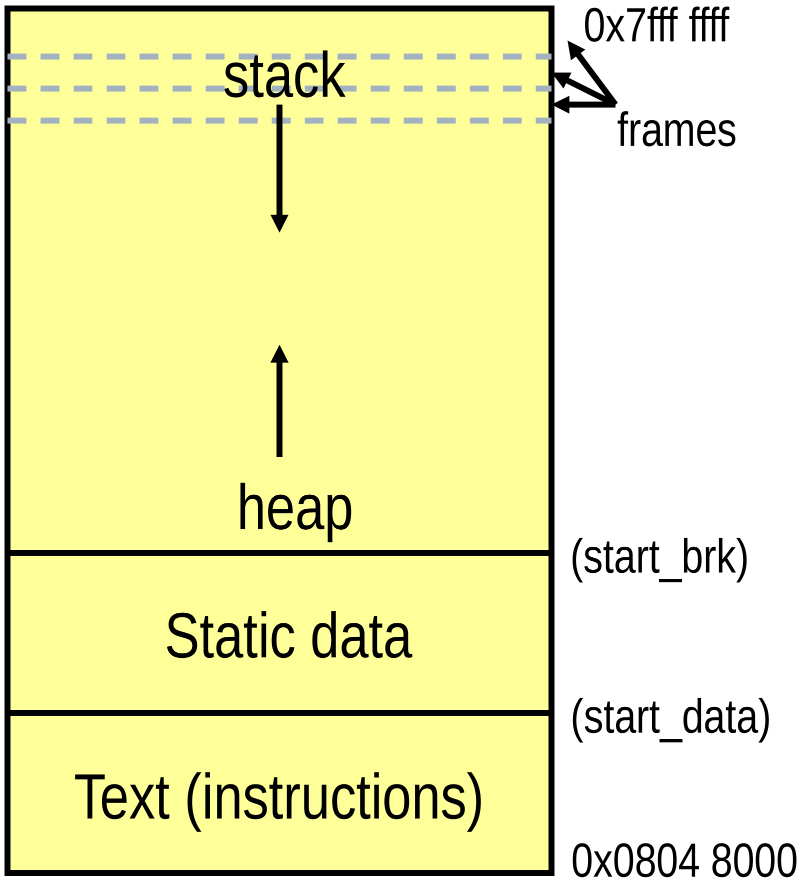
ARM (Linux) Memory Map

Stack: starts at 0x7fff ffff and grows down to lower addresses. Bottom of the stack resides in the SP register

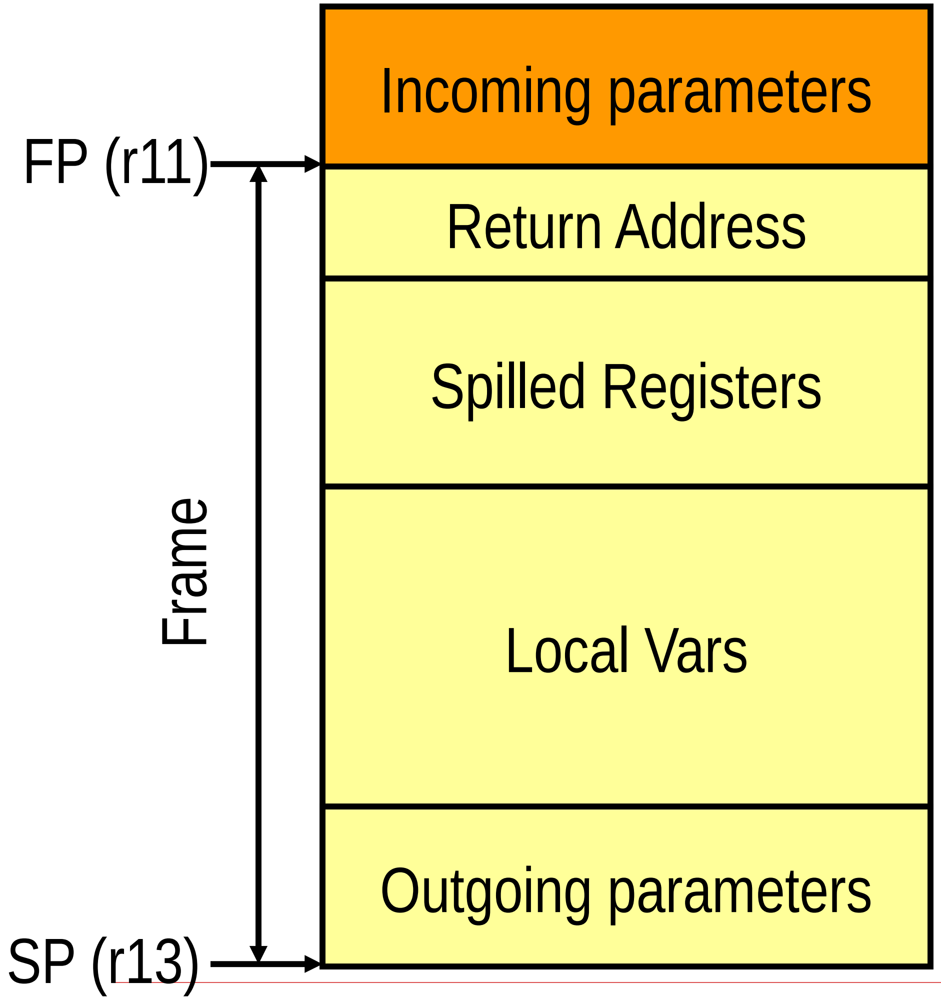
Heap: starts above static (page aligned) and grows up to higher addresses. Allocation done explicitly with malloc(). Deallocation with free(). Runtime error if no free memory before running into SP address.

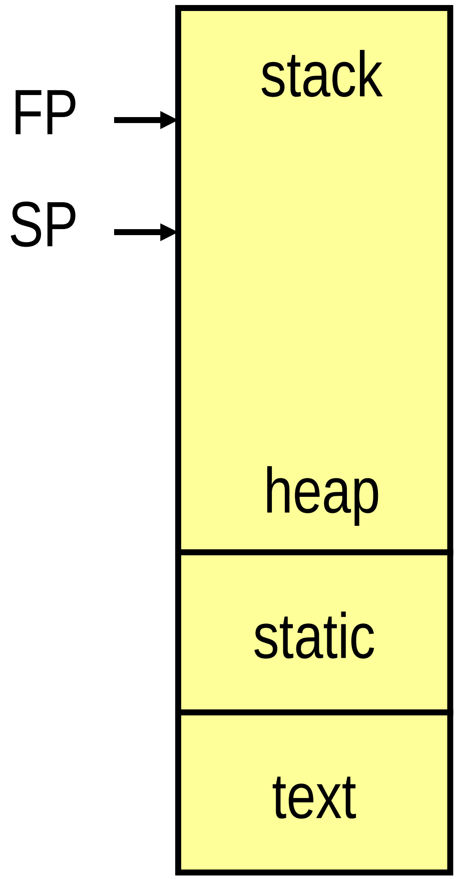
Static: starts above text (page aligned). Holds all global variables and those locals explicitly declared as "static".

Text: starts at 0x08048000. Holds all instructions in the program (except for Dynamically linked library routines DLLs)



The ARM Stack Frame





Allocating space to local variables

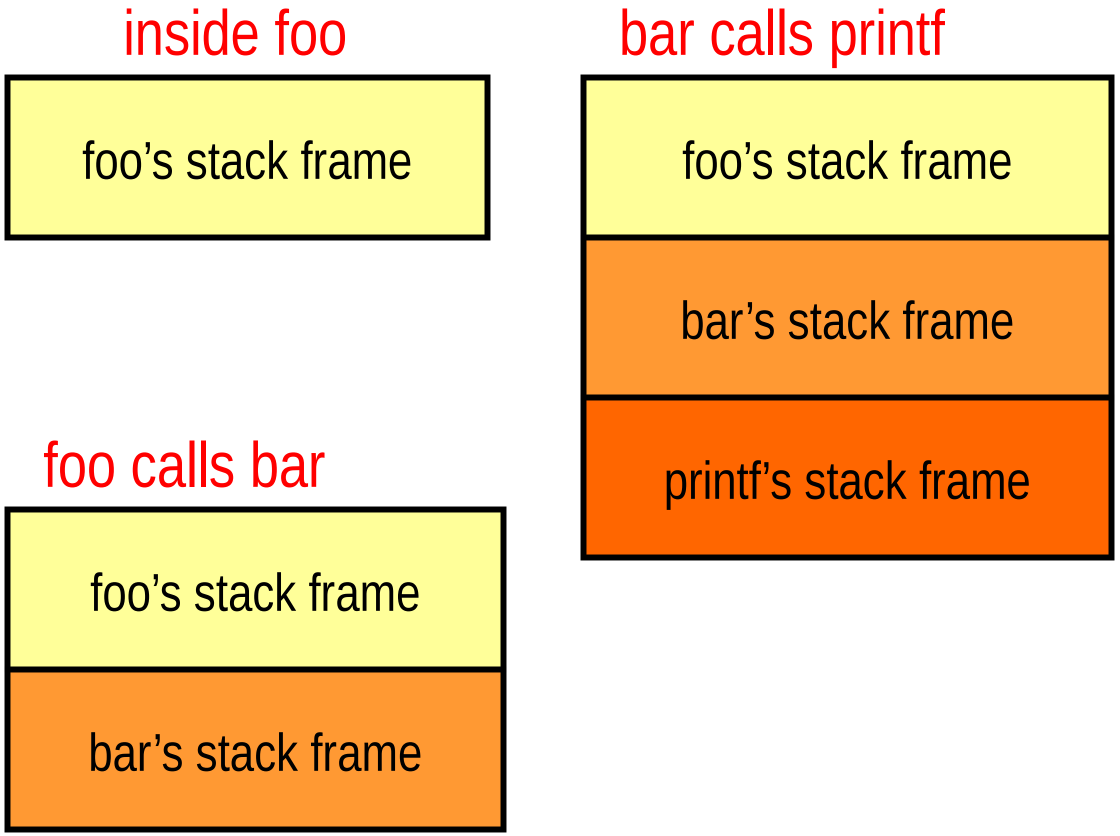
- Local variables (by default) are created when you enter a function, and disappear when you leave
  - Technical terminology: local variables are placed in the automatic storage class (as opposed to the static storage class used for globals).

- Automatics are allocated on the call stack
  - How?
    by incrementing (or decrementing) the pointer to the top of the call stack

  -
    ```
    sub   r13, r13, #12   //  SP = SP – 12, allocate space for 3 integer locals
    add   r13, r13, #12   // SP = SP + 12, de-allocate space for locals
    ```

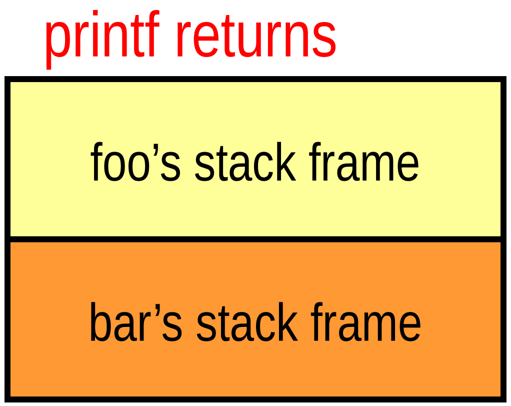
The stack grows as functions are called

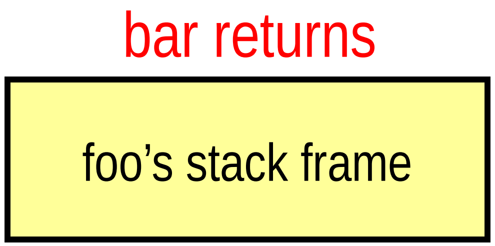
```
void foo()
{
    int x, y[2];
    bar(x);
}

void bar(int x)
{
    int a[3];
    printf();
}
```



The stack shrinks as functions return

```
void foo()
{
    int x, y[2];
    bar(x);
}

void bar(int x)
{
    int a[3];
    printf();
}
```

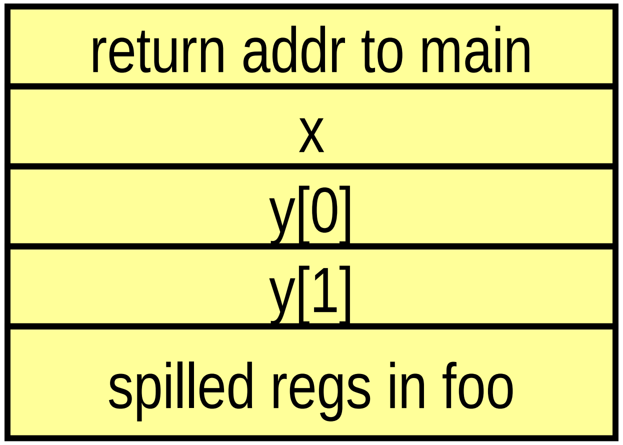




Stack frame contents

```
void foo()
{
    int x, y[2];
    bar(x);
}

void bar(int x)
{
    int a[3];
    printf();
}
```

inside foo – foo's stack frame

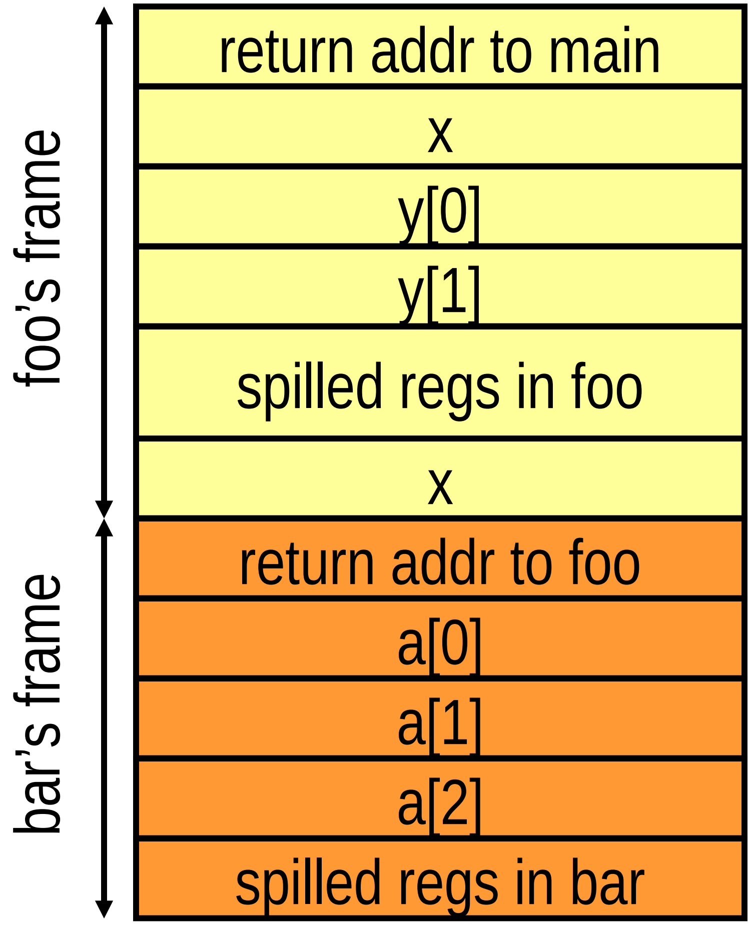


FUNCTION CALLS

Stack frame contents (2)

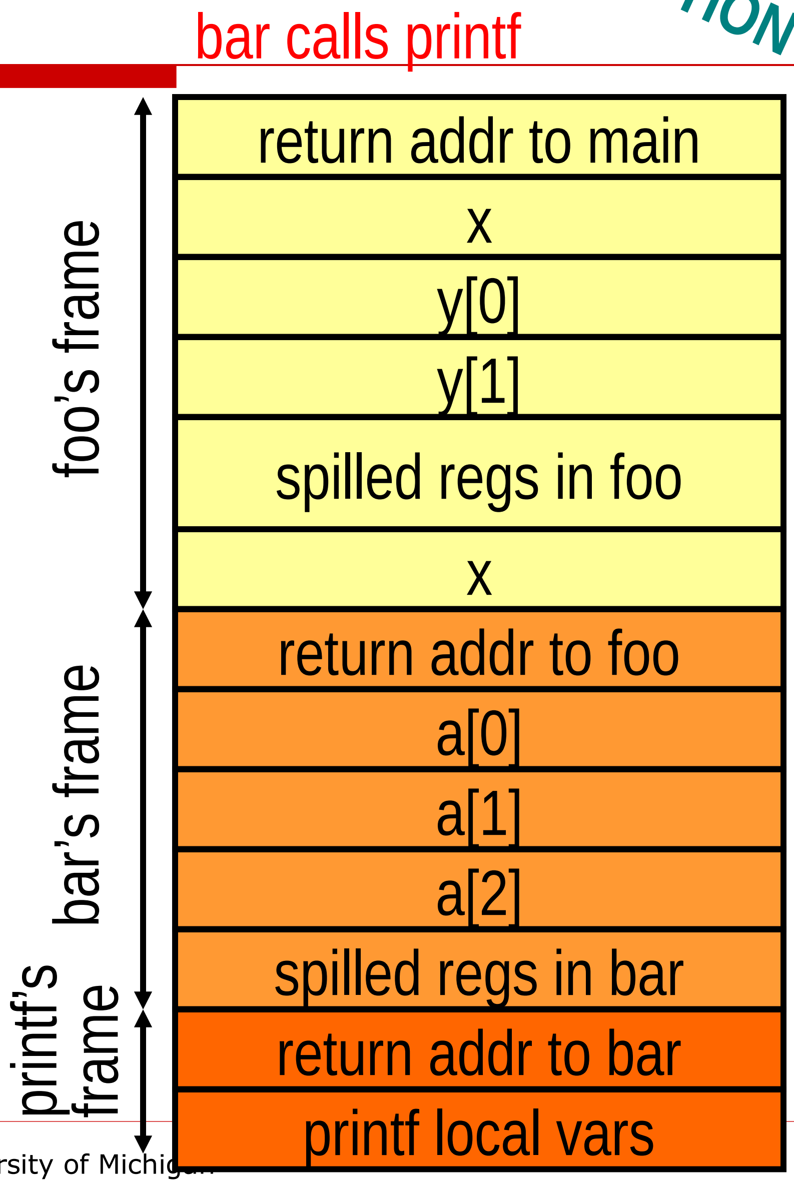
```
void foo()
{
    int x, y[2];
    bar(x);
}

void bar(int x)
{
    int a[3];
    printf();
}
```

foo calls bar



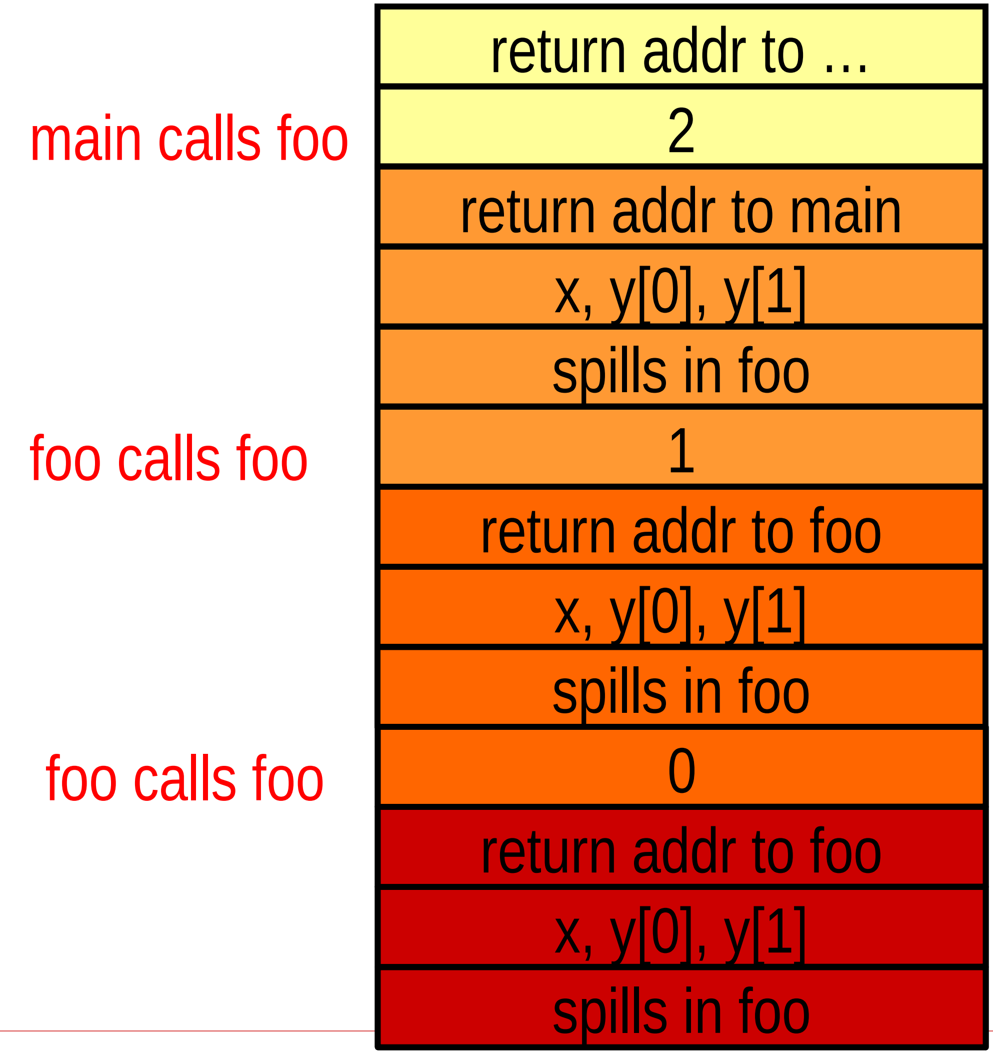
Stack frame contents (3)

```
void foo()
{
    int x, y[2];
    bar(x);
}

void bar(int x)
{
    int a[3];
    printf();
}
```



Recursive function example

```
main()
{
    foo(2);
}

void foo(int a)
{
    int x, y[2];
    if (a > 0)
        foo(a-1);
}
```



Virtual functions

- Call stack is <u>identical</u>
- key difference: call is implemented as table lookup (i.e., indirect call versus direct call)
  - "class->method()" is translated to:

```
"switch (class.type)
        case A:  r1 = &class.method_typeA
        case B:  r1 = &class.method_typeB
        etc.
call r1"
```

Assigning variables to memory spaces

```
int w;
void foo(int x)
{
    static int y[4];
    char *p;
    p = malloc(10);
    …
    printf("%s\n", p);
}
```

w goes in static, as it's a global

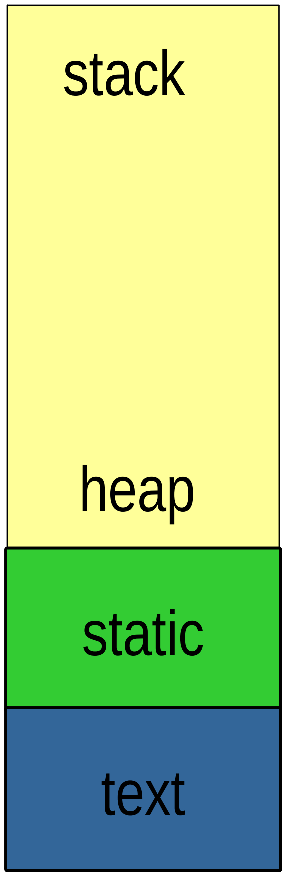
x goes on the stack, as it's a parameter

y goes in static, 1 copy of this!!

p goes on the stack

allocate 10 bytes on heap, ptr set to the address

string goes in static, pointer to string on stack, p goes on stack



Need for Saving registers during a call

CALLER-CALLEE

- What happens to the values we have in registers when we make a function call? Assume variables x in foo() and y in bar() happen to be allocated to the same register r1.

```
void foo()
{
    int x = 1;
    bar(x);
    x = x + 1;
}

void bar(int k)
{
    int y = 2;
    y++
 }
```

```
void foo()
{
    r1 = 1;
    bar(r1);
    r1 = r1 + 1;
}

void bar(int k)
{
    r1 = 2;
    r1 = r1 + 1
 }
```

Saving registers during a call

CALLER-CALLEE

- What happens to the values we have in registers when we make a function call? **a = b * c + sqrt (d);**

Options:

1. You can save your registers **before** you make the function call and restore the registers when you return (**caller-save register**). Where?

   The stack frame is used to store anything required to support function calls

   What if the function you are calling doesn't use that register? No harm done, but wasted work!!!

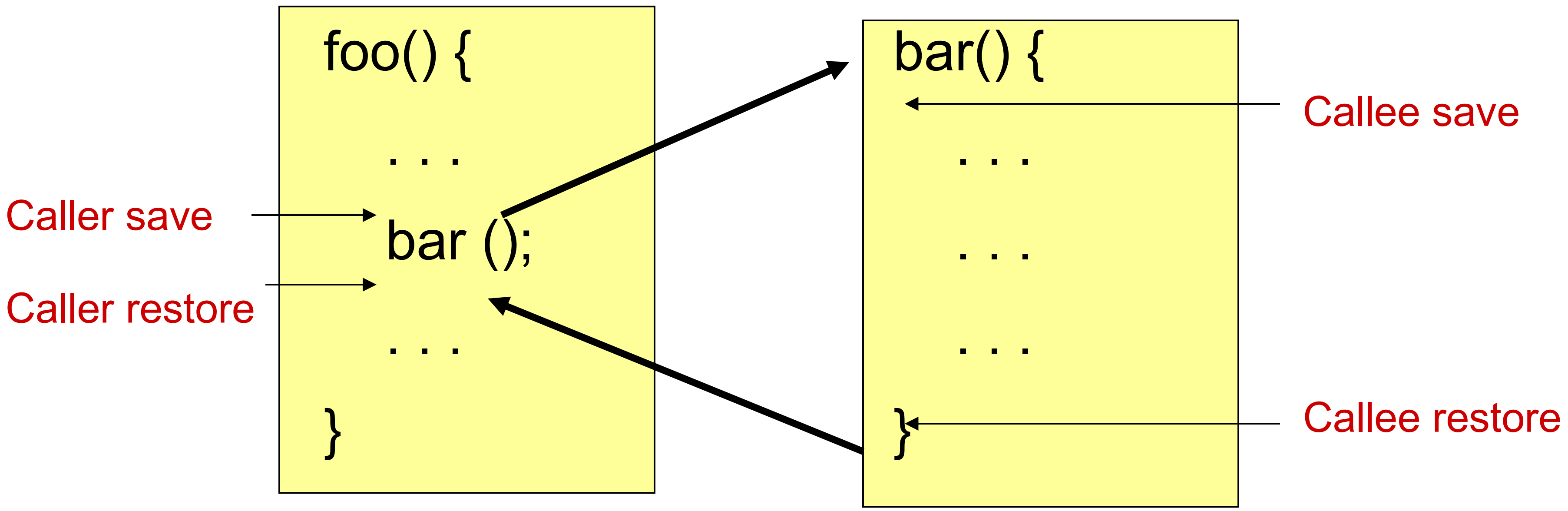
2. You can save your registers **after** you make the function call and restore the registers before you return (**callee-save register**). Where?

   What if the caller function doesn't use that register? No harm done, but wasted work!!!

Most assembly programming conventions use a mix of both

CALLER-CALLEE

Caller-Callee save/restore



Caller save: Callee may change, so caller responsible for saving immediately before call and restoring immediately after call

Callee save: Callee may not change, so callee (called function) must leave these unchanged. Can be ensured by inserting saves at the start of the function and restores at the end

Caller/callee example

CALLER-CALLEE

```
foo()
{
    r0 = 5;
    r4 = -1;
    bar();
    r3 = r0 + r4;
}
```

```
bar()
{
    r0 = 10;
    r4 = 5;
}
```

If r0 is caller-save and r4 is callee-save

```
foo()
{
    r0 = 5;
    r4 = -1;
    save r0; i.e., str r0, [r13, #20]
    bar();
    restore r0; i.e., ldr r0, [r13, #20]
    r3 = r0 + r4;
}
```

```
bar()
{
    save r4; i.e., str r4, [r13, #8]
    r0 = 10;
    r4 = 5;
    restore r4; i.e., ldr r4, r13, #8]
}
```

Saving/Restoring Optimizations

CALLER-CALLEE

- Caller-saved
  - Only needs saving if it is "live" across a function call
  - Live = contains a useful value: Assign value before function call, use that value after the function call
  - In a leaf function, caller saves can be used without saving/restoring

- Callee-saved
  - Only needs saving at beginning of function (generally infrequent as outside of loops) and restoring at end of function
  - Only save/restore it if function overwrites the register

- Each has its advantages. Neither is always better.

CALLER-CALLEE

ARM caller-callee convention

- Have some registers that are caller-saved, and some that are callee-saved
  - Example: ARM
    - 5 caller saved
    - 10 callee saved

ARM register conventions

r0	parameter, return value, caller saved
r1-r3	parameters, caller saved
r4-r10	callee saved
r11	frame pointer, callee saved
r12	caller saved
r13	stack pointer, callee saved
r14	link register, callee saved
r15	program counter, not saved

- **Choose registers for variables so to minimize the number of dynamic saves/restores**

Calling convention

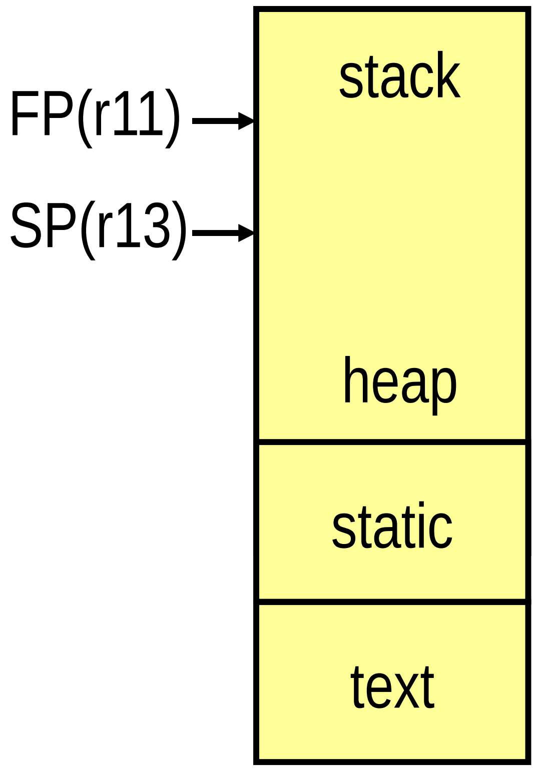
- This is a **convention**: calling convention
  - There is no difference in H/W between caller and callee save registers

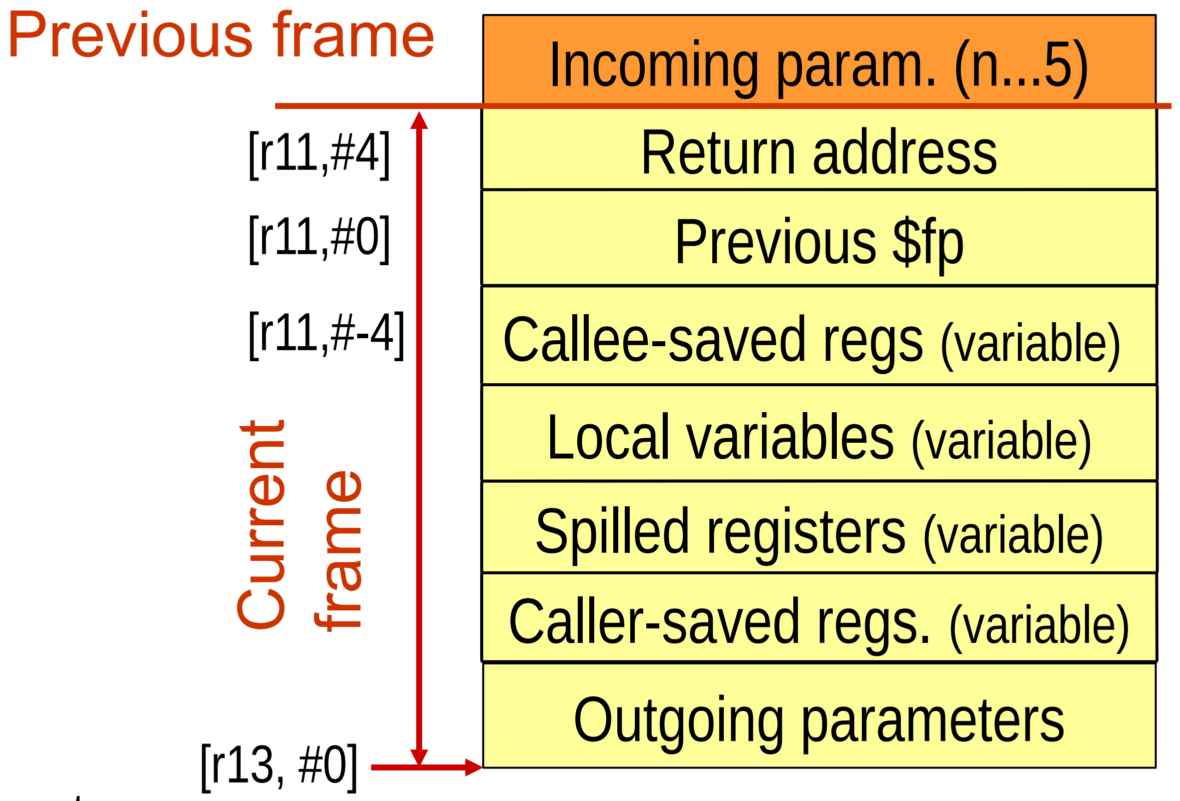
- Passing parameters in registers is also a convention
- Allows assembly code written by different people to work together
  - Need conventions about who saves regs and where args are passed.
- These conventions collectively make up the ABI or "application binary interface"

- Why are these conventions important?
  - What happens if a programmer/compiler violates them?

ARM Stack Frame (typical organization)

CALLER-CALLEE





Note 1: in ARM, the first 4 parameters are passed via registers. Other ISAs have ≠ conventions

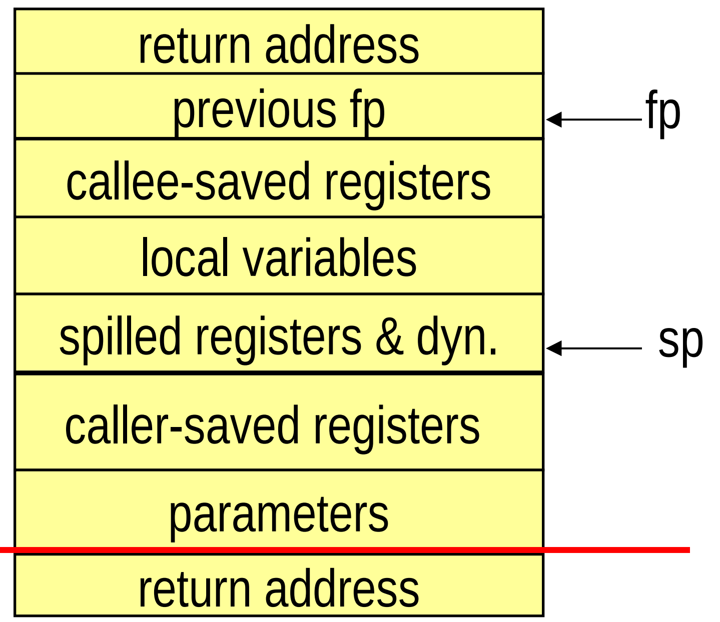
Note 2: why is the last parameter first on the stack ?

CALLER-CALLEE

The stack during program execution…

foo() is in execution…

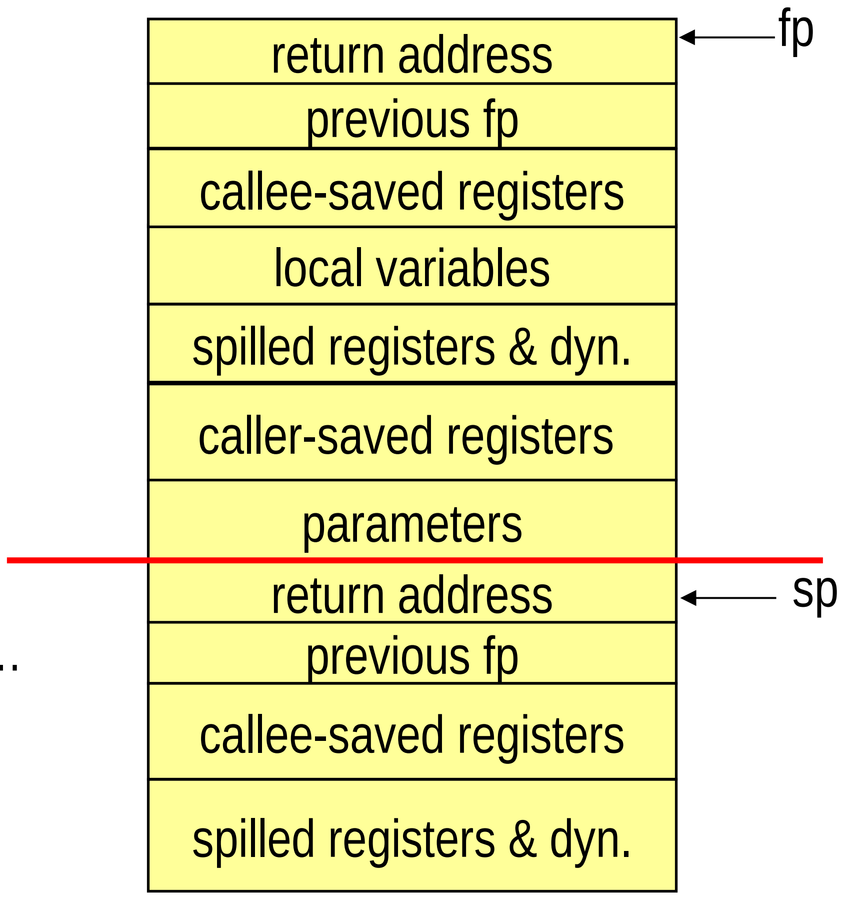
…foo() calls bar…



The stack

CALLER-CALLEE

bar() in execution…

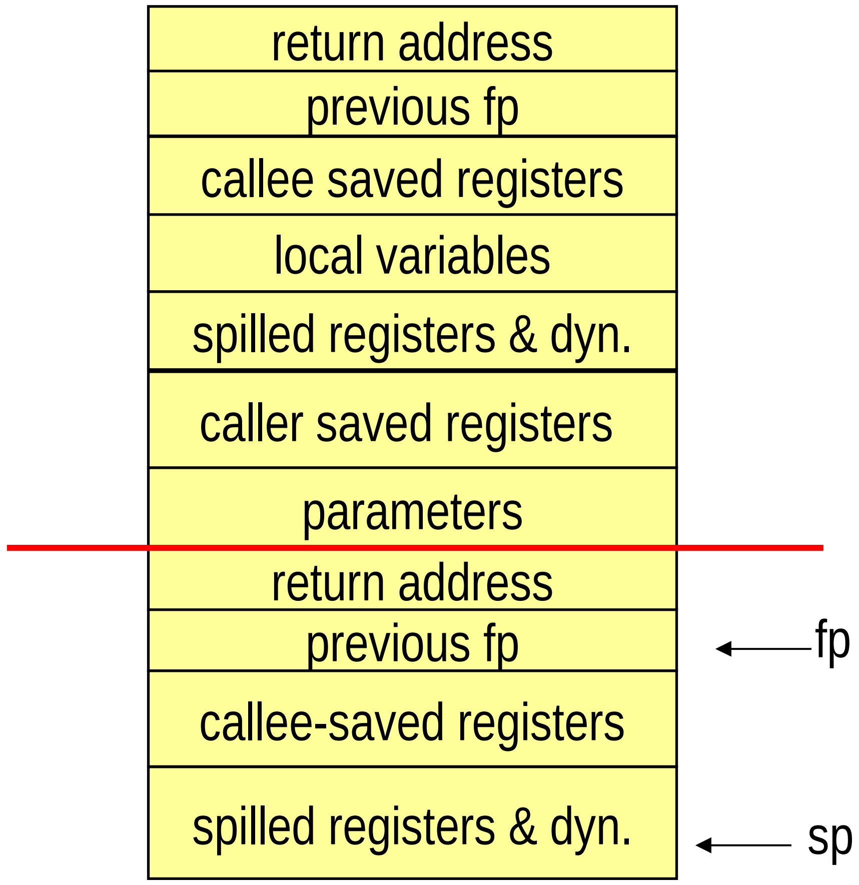


The stack

CALLER-CALLEE

foo() continues…

bar() returns…



Putting it all together (using activation records)

```
mov   r0, #1000       //  param “hello world\n”
str   r12, [r13, #24]       //  caller save r12
bl    _printf         //  call printf()
                  // r0 holds return value (ignored)
ldr   r12, [r13, #24]       // restore caller-saved r12 value
```

```
sub  r13, r13, #16   // allocate space for 2 locals +
str  r4, [r13, #8]   // callee save r4
str  r14, [r13, #12] // save return address
…                 // function body
mov r0, #0           // return value 0
ldr  r4, [r13,#8]    // restore callee-saved r4
ldr  r14, [r13, #12] // restore return address
add  r13, r13, #16   // deallocate call frame
mov r15, r14         // return to calling function
```

Calculating Caller/Callee Costs

Consider the cost of placing each variable **v** from function **f** in a callee register and a caller register:

Cost = number of store/load instructions required to accomplish the required saving/restoring

Callee_cost ▭ save at the start of the function, restore at end
= 2 * number of invocations of f

Caller_cost ▭ potentially save/restore across each funct. call in f
Caller cost = 0
For each function call in f, call_i
  if (v is live) caller_cost += 2 * number of times call_i is executed

Caller/Callee Selection

- Select assignment of variables to registers such that the sum of caller/callee costs is minimized
  - Execute fewest save/restores
- Each function greedily picks its own assignment ignoring the assignments in other functions
  - Calling convention assures all necessary registers will be saved
- 2 types of problems
  1. Given a single function ▭ Assume it is called 1 time
  2. Set of functions or program ▭ Compute number of times each function is called if it is obvious (i.e., loops with known trip counts or you are told)

Assumptions

CALLER-CALLEE

- A function can be invoked by many different call sites in different functions.
- Assume no inter-procedural analysis (hard problem)
  - A function has no knowledge about which registers are used in either its caller or callee
  - Assume main() is not invoked by another function
- Implication
  - Any register allocation optimization is done using function local information

Class Problem 3

```
foo() {
    a = …
    b = …
    bar();
    … = a;
    … = b;
    for (1 to 15) {
              c =  …
              d =  …
              … = c;
              printf();
              … = d;
    }
}
```

Assume that you have 2 caller and 2 callee save registers. Pick the best assignment for a, b, c, d. Assume each requires its own register.

Caller-saved vs. callee saved – Multiple function case

```
void main(){
  int a,b,c,d;
  .
  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;
  .
  .
  .
}
```

```
void foo(){
  int a,b;
  .
  .
  a = 2; b = 3;
  bar();
  a = a + b;
  .
  .
  .
}
```

```
void bar(){
  int a,b,c,d;
  .
  c = 0; d = 1;
  a = 2; b = 3;
  final();
  a = a+b+c+d;
  .
  .
  .
}
```

```
void final(){
  int a,b,c;
  .
  .
  a = 2; b = 3;
  .
  c = a+b;
  .
  .
  .
}
```

Note: assume main does not have to save any callee reg. (that is really the case for start)

Caller-saved vs. callee saved – Multiple function case

Questions:

1. In assembly code, how many regs. need to be stored/loaded in total if we use a **caller-save** convention ?
2. In assembly code, how many regs. need to be stored/loaded in total if we use a **callee-save** convention ?
3. In assembly code, how many regs. need to be stored/loaded in total if we use a mixed **caller/callee**-save convention with 3 callee-s. and 3 caller-s. registers ?

4. Assume bar() is in a loop inside foo() and the loop is iterated 10 times ? When the program is executed, how many regs. need to be stored/loaded in total for each of the above three scenarios?

Question 1: Caller-save

```
void main(){
   .
   .
   .
   [4 str]
   foo();
   [4 ldr]
   .
   .
   .
}
```

```
void foo(){
   .
   .
   .
   [2 str]
   bar();
   [2 ldr]
   .
   .
   .
}
```

```
void bar(){
   .
   .
   .
   [4 str]
   final();
   [4 ldr]
   .
   .
   .
}
```

```
void final(){
   .
   .
   .
   .
   .
   .
   .
   .
   .
}
```

Total: 10 str / 10 ldr

Question 2: Callee-save

```
void main(){
   .
   .
   .
   .
   foo();
   .
   .
   .
   .
}
```

```
void foo(){
   [2 str]
   .
   .
   .
   bar();
   .
   .
   .
   [2 ldr]
}
```

```
void bar(){
   [4 str]
   .
   .
   .
   final();
   .
   .
   .
   [4 ldr]
}
```

```
void final(){
   [3 str]
   .
   .
   .
   .
   .
   .
   .
   [3 ldr]
}
```

Total: 9 str / 9 ldr

Question 3: Mixed 3 caller / 3 callee

```
void main(){
   .
   .
   .
   [1 str]
   foo();
   [1 ldr]
   .
   .
   .
}
```

```
void foo(){
   [2 str]
   .
   .
   .
   bar();
   .
   .
   .
   [2 ldr]
}
```

```
void bar(){
   [4 str]
   .
   .
   .
   final();
   .
   .
   .
   [4 ldr]
}
```

```
void final(){
   .
   .
   .
   .
   .
   .
   .
   .
   .
}
```

1 caller r.
3 callee r.

3 caller r.

Total: 7 str / 7 ldr

Caller-saved vs. callee saved – Question 4

- Mixed 3 caller / 3 callee

```
void main(){
   .
   .
   .
   [1 str]
   foo();
   [1 ldr]
   .
   .
   .
}
```

1 caller r.
3 callee r.

```
void foo(){
   [2 str]
   .
   .
   .
   bar();
   .
   .
   .
   [2 ldr]
}
```

loop x10

2 callee r.

```
void bar(){
   [4 str]
   .
   .
   .
   final();
   .
   .
   .
   [4 ldr]
}
```

x10

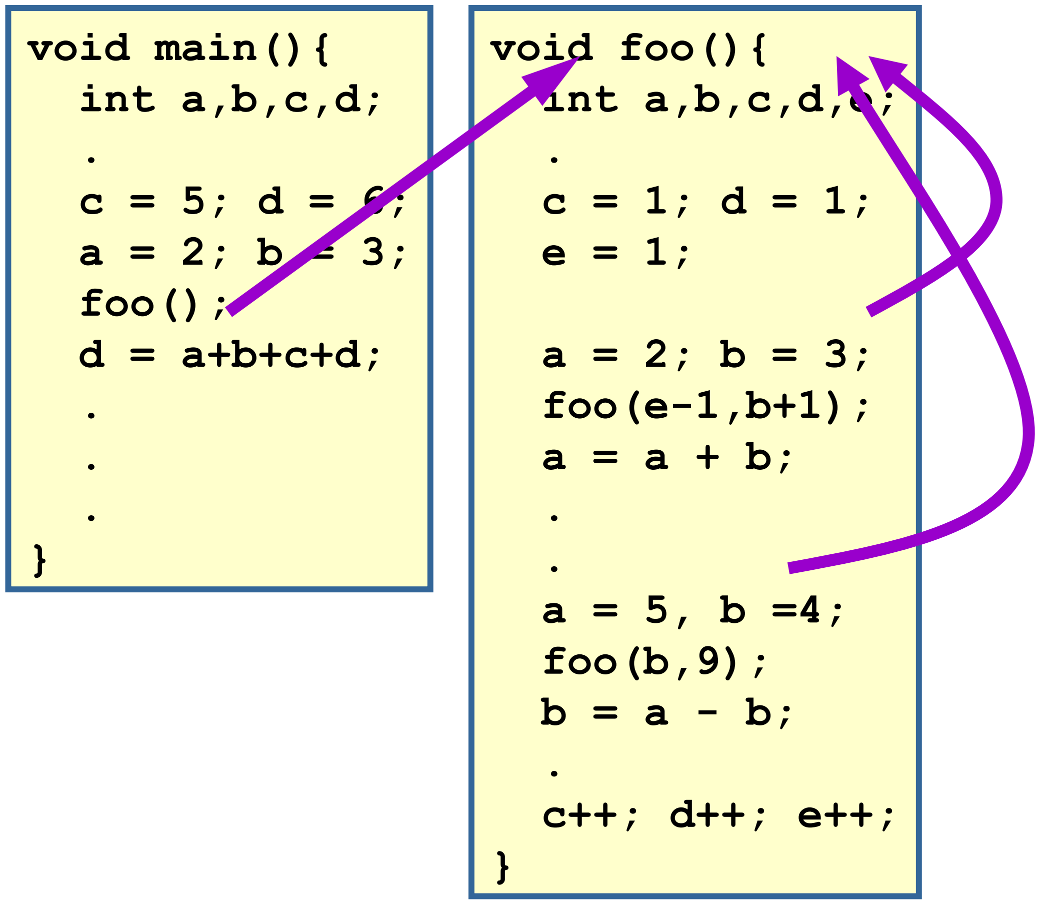
```
void final(){
   .
   .
   .
   .
   .
   .
   .
   .
   .
}
```

3 caller r.

x10

Total: 43 str / 43 ldr *Pure caller: (4+20+40+0) str / ldr - Pure callee (0+2+40+30) str / ldr*

Caller-saved vs. callee saved – A more interesting case



```
void main(){
    int a,b,c,d;
    .
    c = 5; d = 6;
    a = 2; b = 3;
    foo();
    d = a+b+c+d;
    .
    .
    .
}
```

```
void foo(){
    int a,b,c,d,e;
    .
    c = 1; d = 1;
    e = 1;

    a = 2; b = 3;
    foo(e-1,b+1);
    a = a + b;
    .
    .
    a = 5, b =4;
    foo(b,9);
    b = a - b;
    .
    c++; d++; e++;
}
```

Caller-saved vs. callee saved – the interesting case

- Assume the function foo() is called recursively 15 times in total
- When the program is executed, how many regs need to be stored/loaded in total for the following scenarios:
  - Use a **caller-save** convention ?
  - Use a **callee-save** convention ?
  - Use a mixed **caller/callee**-save convention with 3 callee-s. and 3 caller-s. registers ?