Functions (in C) & their implementation in Assembly

(Chapters 14,17)

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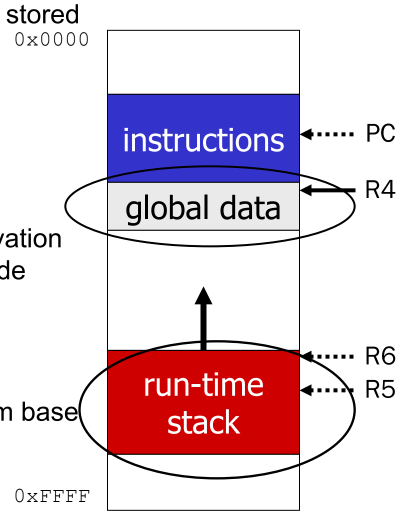
LC3 Memory Allocation & Activation Records

•Global data section: global variables stored here
  - •R4 points to beginning

•Run-time stack: for local variables
  - R6 points to top of stack
  - R5 points to top frame on stack
  - Local variables are stored in an activation record, i.e., stack frame, for each code block (function)
  - New frame for each block/function (goes away when block exited)

• symbol table "offset" gives distrance from base of frame (R5 for local var).
  - Address of local var = R5 + offset
  - •Address of global var = R4 + offset

• return address from subroutines in R7



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Implementing Functions (C to LC3)

- How to handle function calls ?
  - Where to store the data?
- implementation uses Run-time stack
  - Activation record for each function on stack
- recursion ? How is this implemented ?

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Example: Functions calling functions…

```
int mult(int a, int b) {
    int c=0 ;
    while (b > 0) {
      c=c+a ;
      b=b-1 ;
    }
    return c ;
}
int pow(int a, int p) {
     int c ;
     for (c = 1; p > 0; p--)
         c = mult(c, a) ; // performs: c=c*a
     return c ;
}
int main() {
     int a=2,b=3,c=0;
    c = pow (a, b) ; // performs: c=a^b
}
```

We'll trace these through the stack

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Passing Parameters "By Value"

```
int mult(int a, int b) {
    int c=0 ;
   while (b > 0) {
     c=c+a ;
     b=b-1 ;
   }
   return c ;
}
int pow(int a, int p) {
     int c ;
     for (c = 1; p > 0; p--)
         c = mult(c, a) ;
     return c ;
}
int main() {
     int a=2,b=3,c=0;
    c = pow (a, b) ; // performs: 2^3
}
```

pow passes 'c' and 'a' to mult by value

Value of 'a' from pow is "bound" to local name 'b' in mult

In mult, 'b' is a local variable and can be modified (b = b-1)

When pow returns, 'a' in main is unaffected

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Function calls.. What needs to be done?

- Caller can pass parameters to the function
- Function returns a value
- Function needs to return to caller
  - PC needs to be stored
  - "pointer" to variables used by caller needs to be restored
- Function uses local variables, so allocate space for these variables
  - New scope (i.e., new frame pointer)
- Function can be called from another function…

- capture all this information in an Activation Record

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Activation Record/Stack Frame

- Activation record: Place to keep
  - Parameters, Local (auto) variables, Register spillage
  - Return address
  - Return value
  - Old frame pointer
- Frame pointer R5 points to beginning of a region of activation record for the function

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Run-Time Stack

- local variables are stored on the run-time stack in an *activation record (i.e., stack frame)*

- Frame pointer (R5) points to the beginning of a region of activation record that stores local variables for the current function
  - new function called – its record pushed to stack
  - function returns – its record is popped from stack

- When a new function is called, its activation record is pushed on the stack;
- when it returns, its activation record is popped off of the stack
  - Allows recursion

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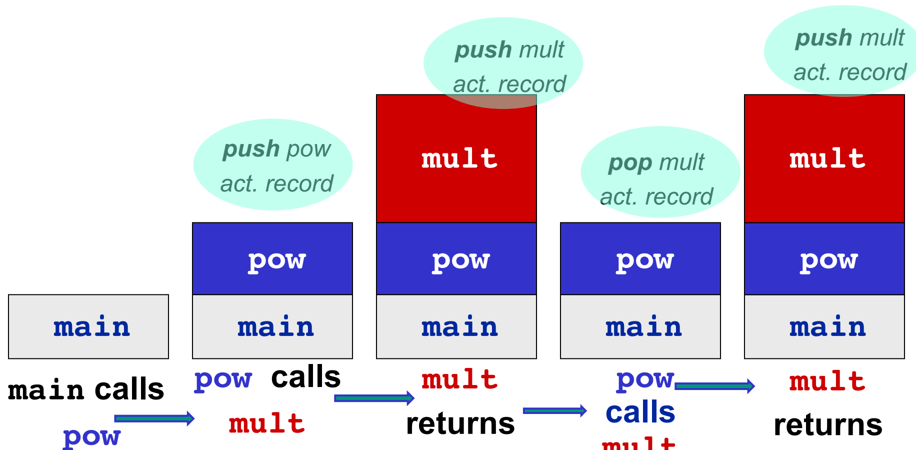
Function Calls & Stack Frames (Activation Records)

- Stack managed in function-sized chunks called frames or activation records
  - This all happens at run-time



In C, top-level user function is always 'main'

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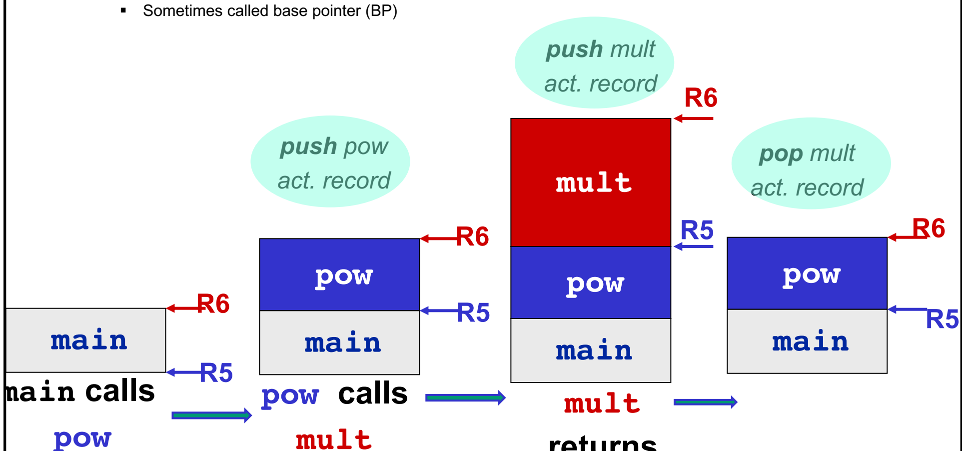
Frame Pointer (R5) and Stack Pointer (R6)

- LC3 uses two more registers as part of calling convention
  - R6 is the stack pointer (SP), "points to" current "top" of stack
  - R5 is the frame pointer (FP), "points to" bottom of current frame
    - Sometimes called base pointer (BP)



In x86, esp and ebp are the stack and base pointer registers

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So what other info to keep in Activation Record: Bookkeeping records

- Return value
  - space for value returned by function
  - allocated even if function does not return a value
- Return address
  - save pointer to next instruction in calling function
  - convenient location to store R7 in case another function (JSR) is called
- Dynamic link
  - caller's frame pointer
  - used to pop this activation record from stack

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The Stack Frame Layout (Activation Records)

- In caller's stack frame: addresses > R5
  - Caller's saved frame pointer
  - return address, return value
  - arguments
- In running function's stack frame: addresses <= R5
  - Local variables
  - temporaries
  - arguments to running function's callees

temporaries, arguments to callees	← R6
local variables	
caller's frame pointer	← R5; Bookkeeping & arguments
return address	Bookkeeping & arguments
return value	Bookkeeping & arguments
arguments	Bookkeeping & arguments

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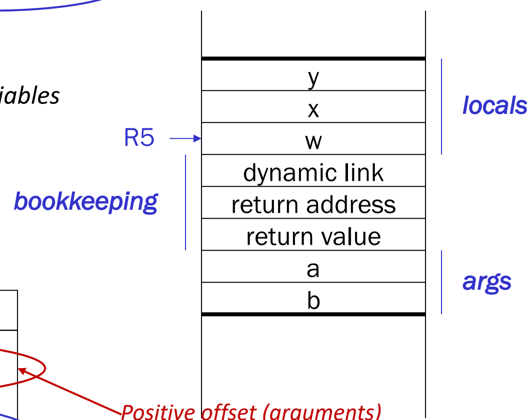
Activation Record Example

```
•int NoName(int a, int b)
{
   int w, x, y;
   .
   .
   .
   return y;
}
```

arguments

Local variables



Name	Type	Offset	Scope
a	int	4	NoName
b	int	5	NoName
w	int	0	NoName
x	int	-1	NoName
y	int	-2	NoName

Positive offset (arguments)

Local vars – 0 or negative offset

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Recursion

•A recursive function is one that solves its task by calling itself on smaller pieces of data.

- recurrence function in mathematics – use this to prove correctness of recurrence functions (induction !!)
- Like iteration -- can be used interchangeably; sometimes recursion results in a simpler solution.

• Example: Factorial(n) = n*(n-1)*(n-2)*..*2*1

```
 int factorial(n){
      if (n >1) return n*factorial(n-1)
        else return 1;
}
/* call from main */
 res=factorial(n);
```

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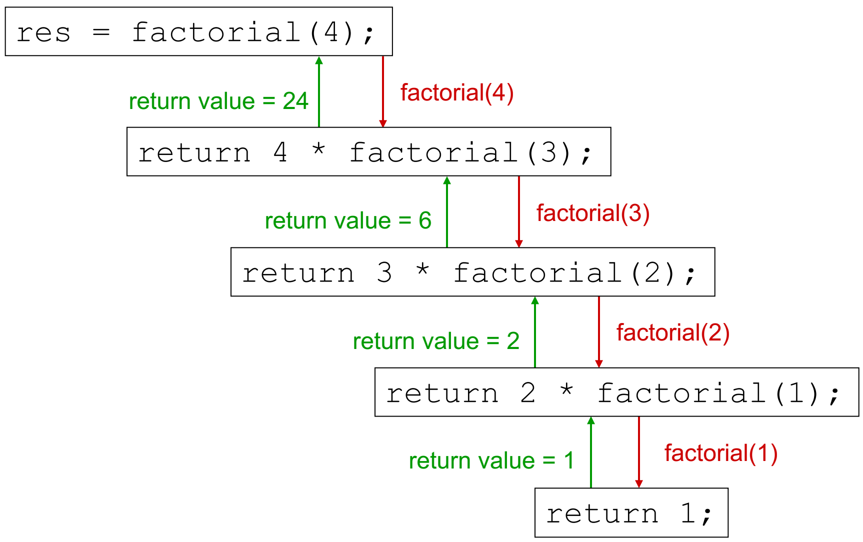
Executing Factorial



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How is recursion implemented ?

- Do we need to do anything different from how we handled function calls ?
- No!
  - Activation record for each instance/call of Fibonacci !

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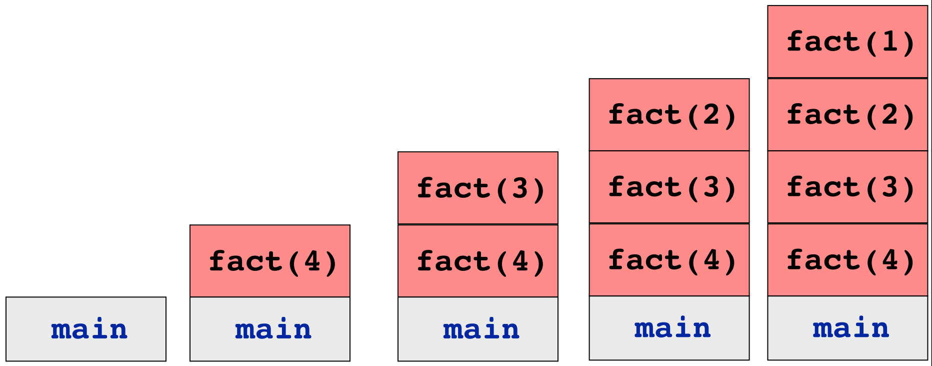
Sequence of stack frames during factorial(4) execution



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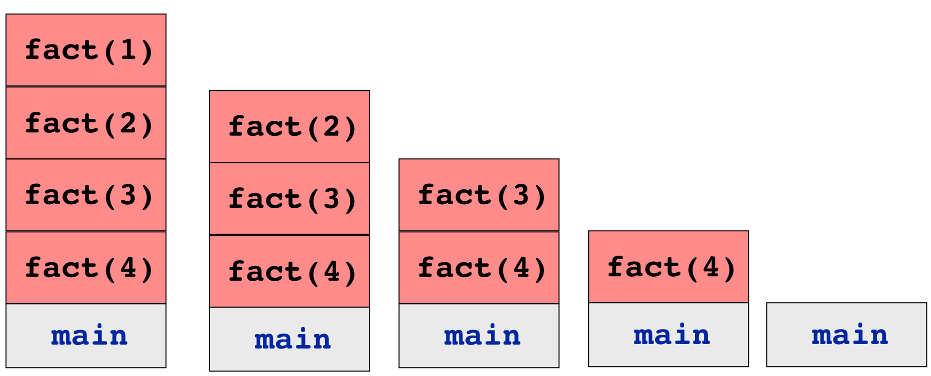
Returning from each instance of factorial



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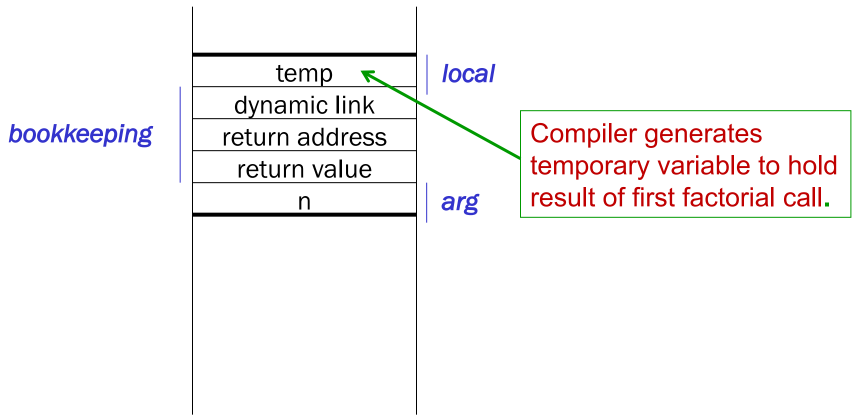
Factorial: LC-3 Code

- Activation Record
-



Questions ?

Functions in C & Translation to Assembly: Part 2 – Memory Layout during Function Call and Return

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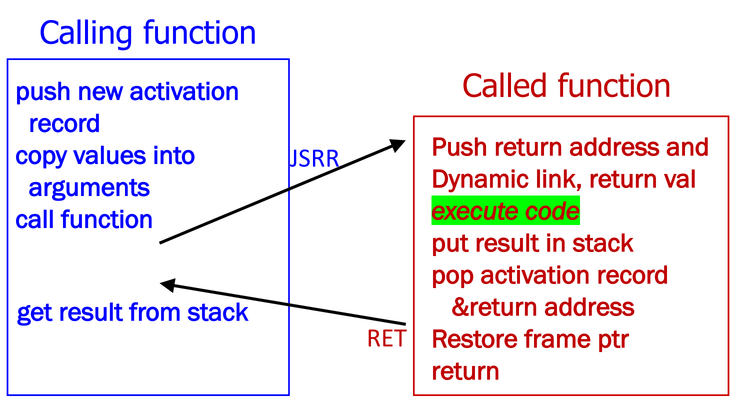
Implementing Functions: Overview

- Activation record
  - information about each function, including arguments and local variables
  - stored on run-time stack



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Caller and Callee: Who does what?

- Caller
  - Puts arguments onto stack (R→L)
  - Does a JSR (or JSRR) to function
- Callee
  - Makes space for Return Value and Return Address (and saves Return address. i.e., R7)
  - makes space for and saves old FP (Frame Pointer)
    - Why ?
  - Makes FP point to next space
  - Moves SP enough for all local variables
  - Starts execution of "work" of function

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Who does what?

- Callee (continued)
  - As registers are needed their current contents can be spilled onto stack
  - When computation done...
  - Bring Stack Pointer SP back to base
  - Restore Frame Pointer FP (adjust SP)
  - Restore Return Address RA (adjust SP)
  - Leave SP pointing at return value
  - RET
- Caller (after RET)
  - Grabs return value and uses it

- Observe the steps needed to support function call and return
  - These steps do not do any of the function's work

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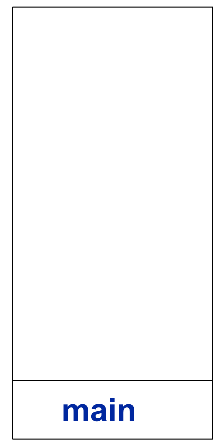
Example : Function Call

Show contents of stack/memory at each time:

```
int main{
        int a,b;
                                ← Time 1
        a=5
        b=foo(a);   /* assume b=foo(a) is at address 2100 */
                                ← Time 5
        …}
int bar(int q, int r){
        int k, m;
                                ← Time 3
        k=q+r;
        return k;
}                               ← Time 4a
int foo(int a){
        int w;
        w=8;
        w = bar(w,10);          ← Time 2
                    /* w=bar(w,10) is at address 2200 */
        return w;               ← Time 4b
}
```

R5=#3000
(for main)



First construct Symbol Table

Identifier	Type	Offset	Scope
a	int	0	main
b	int	-1	main
w	int	0	foo
a	int	4	foo
k	int	0	bar
m	Int	-1	bar
q	int	4	bar
r	int	5	bar

main (a, b) **foo** (w, a) **bar** (k, m, q, r)

arguments to function:
positive offset

Remember: 3 places in Activation record
for Ret.Addr, old FP, Return value => arguments start at offset 4+

Memory Contents at Time 1 (Run time stack): when main starts

```
int main {
     int a,b; /*time 1 */
     a=5;
     b=foo(a); @2100
     ..} /*time 5*/
int bar(int q, int r){
     int k,m;
     /*Time 3 */
     k=q+r;
     return k; /*time 4a */
     }
int foo(int a){
     int w; /*Time 2*/
     w=8;
     w=bar(w,10);/*time 4b*/
     return w;}
```

Address	Content/Identifier	Value
2996		
2997		
2998		
2999	b (local var)	?(not initialized)
3000	a (local var)	?(not initialized)

R6:2999 TOS → 2999

R5=3000 frame pointer → 3000

main: 2999–3000

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Memory contents at Time 2: after foo is called and just before foo executes its first instruction

```
int main {
     int a,b; /*time 1 */
     a=5;
     b=foo(a);
     ..} /*time 5*/
int bar(int q, int r){
     int k,m;
     /*Time 3 */
     k=q+r;
     return k; /*time 4a */
     }
int foo(int a){
     int w; /*Time 2*/
     w=8;
     w=bar(w,10);/*time 4b*/
     return w;}
```

Address	Content	Value
2989		
2990		
2991		
2992		
2993		
2994	w (local var)	?
2995	dynamic link (for main)	3000
2996	return addr (to main)	2101
2997	return value	
2998	argument: a	5
2999	b (local var)	?
3000	a (local var)	5

R6:2994 → 2994

R5=2994 frame pointer → 2994

foo: 2994–2998

main: 2999–3000

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Memory Contents at Time 3: when foo calls bar, just before bar executes first instruction.

R6:2987 → 2987

R5=2988 → 2988
frame ptr

Address	Content	Value
2987	m (local var)	?
2988	k (local var)	?
2989	dyn.link (to foo)	2994
2990	ret. addr. (to foo)	2201
2991	ret.value	
2992	q (argument)	8
2993	r (argument)	10
2994	w (local var)	8
2995	dynamic link	3000
2996	return addr	2101
2997	return value	
2998	argument: a	5
2999	b (local var)	?
3000	a (local var)	5

bar (2987–2993)
foo (2994–2998)
main (2999–3000)

```
int main {
      int a,b; /*time 1 */
      a=5;
      b=foo(a);
      ..} /*time 5*/
int bar(int q, int r){
      int k,m;
      /*Time 3 */
      k=q+r;
      return k; /*time 4a */
      }
int foo(int a){
      int w; /*Time 2*/
      w=8;
      w=bar(w,10);/*time 4b*/
      return w;}
```

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Memory Contents at Time 4 (a): at RET instruction in bar

R6:2991 → 2991
Points to return val

R5=2994 → 2994
frame pointer

Address	Content	Value
2987		
2988		
2989		
2990		
2991	ret.value	[k]value of k **18**
2992	q (argument)	8
2993	r (argument)	10
2994	w (local var)	8
2995	dynamic link	3000
2996	return addr	2101
2997	return value	
2998	argument: a	5
2999	b (local var)	?
3000	a (local var)	5

foo (2994–2998)
main (2999–3000)

```
int main {
      int a,b; /*time 1 */
      a=5;
      b=foo(a);
      ..} /*time 5*/
int bar(int q, int r){
      int k,m;
      /*Time 3 */
      k=q+r;
      return k; /*time 4a */
      }
int foo(int a){
      int w; /*Time 2*/
      w=8;
      w=bar(w,10);/*time 4b*/
      return w;}
```

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Memory Contents at Time 4 (b) (after foo resumes)

Address	Content	Value
2987		
2988		
2989		
2990		
2991		
2992		
2993		
2994	w (local var)	[k] **18**
2995	dynamic link	3000
2996	return addr	2101
2997	return value	
2998	argument: a	5
2999	b (local var)	?
3000	a (local var)	5

R6:2994 → 2994

R5=2994 frame ptr → 2994

foo: 2994–2998

main: 2999–3000

```
int main {
      int a,b; /*time 1 */
      a=5;
      b=foo(a);
      ..} /*time 5*/
int bar(int q, int r){
      int k,m;
      /*Time 3 */
      return k; /*time 4a */
      }
int foo(int a){
      int w; /*Time 2*/
      w=8;
      w=bar(w,10);/*time 4b*/
      return w;}
```

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Time 5: Memory contents after foo returns and before main completes

Address	Content/Identifier	Value
2996		
2997		
2998		
2999	b (local var)	5 **18**
3000	a (local var)	[foo(5)] **5**

R6:2999 → 2999

R5=3000 frame ptr → 3000

main: 2999–3000

```
int main {
      int a,b; /*time 1 */
      a=5;
      b=foo(a);
      ..} /*time 5*/
int bar(int q, int r){
      int k,m;
      /*Time 3 */
      return k; /*time 4a */
      }
int foo(int a){
      int w; /*Time 2*/
      w=8;
      w=bar(w,10);/*time 4b*/
      return w;}
```

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Functions in C : Part 3 – LC3 Instructions to implement function call and return

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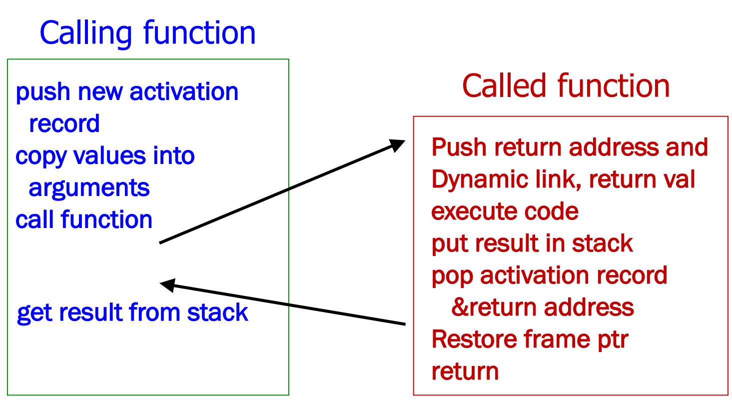
Implementing Functions: Overview

- Activation record
  - information about each function, including arguments and local variables
  - stored on run-time stack



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Example: Calling the Function

```
int main()
 {int a,b;
       a=5;
       b=foo(a);
}
int bar(int q, int r)
{
  int k;
  int m;
  ...
       return k;
}
int foo(int a)
{
  int w;
       w=8;
       ...
       w = bar(w,10);
       ...
       return w;
}
```


Step 1: Calling the Function

- w = bar(w, 10);
- ; push second arg

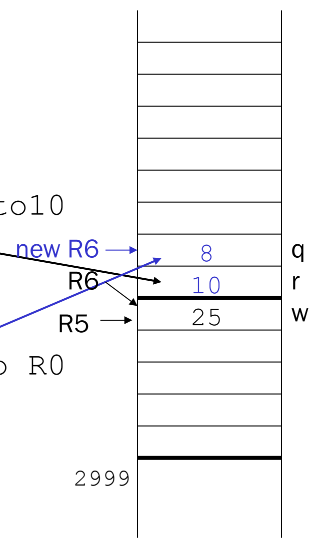
```
AND   R0, R0, #0
ADD   R0, R0, #10  ; set R0 to10
ADD   R6, R6, #-1
STR   R0, R6, #0;  push R0
```

- ; push first argument

```
LDR   R0, R5, #0   ;read w to R0
ADD   R6, R6, #-1  ;
STR   R0, R6, #0   ;push R0
```

- ; call subroutine

```
JSR   bar ; or JSRR
```



Note: Caller needs to know number and type of arguments, doesn't know about local variables. It needs to push the arguments and then JSR

Next steps: starting Callee function

- Create space for return value
- Store return address
- Store frame pointer
- Set new frame pointer
- Set space for local variables

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Starting the Callee Function

- ; leave space for return value

```
ADD  R6, R6, #-1
```

- ; push return address

```
ADD  R6, R6, #-1
STR  R7, R6, #0
```

- ; push dyn link (caller's frame ptr)

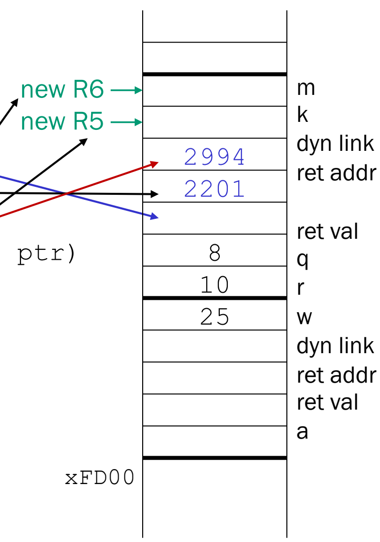
```
ADD  R6, R6, #-1
STR  R5, R6, #0
```

- ; set new frame pointer

```
ADD  R5, R6, #-1
```

- ; allocate space for locals

```
ADD  R6, R6, #-2
```




```
int bar(int q, int r)
{
  int k;
  int m;
  ...
  return k;
}
```

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Returning from function…steps

- •Write return value
- •return address into R7
- •Restore old frame pointer
- •Pop local variables
- •Where should top of stack point to after RET?
  - To the return value

- Go through the notes/textbook for remaining steps….

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Prologue, Body, Epilogue

- •Steps at start of function that we saw are called function prologue
  - Setup code compiler generates automatically
    - One of the (few) abstractions C provides over assembly
  - More sophisticated compilers can generate tighter prologues

- •Code that follows is translation of function body
  - lcc does this statement-by-statement
    - Results in many inefficiencies
  - More sophisticated compilers view entire function (at least)
    - Gives us opportunity to *optimize* the code

- •When explicit body finishes, need function epilogue
  - Cleanup code compiler generates automatically
  - epilogue (unwinding/popping of the stack)
- •Observation: a lot of extra instruction involved in function call
  - If we inline the function we can eliminate the call overhead…..
  - Remember this when we get to our last topic of code optimization

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Things to notice

- 1) Arguments are pushed onto stack right-to-left
  - So that first argument from left is closest to callee
  - This is called C convention (left-to-right is called PASCAL)
  - Needed for functions with *variable* argument counts (e.g., `printf`)
- 2) C is pass-by-value (not pass-by-reference)

  Functions receive "copies" of local variables

  Recall, arguments to functions were copies of local vars

  Protects local variables from being modified accidentally

3) We see why variables must be declared at start of function

Size of static/automatic variables are known at compile time:

```
ADD R6, R6, #-1  ; allocate space for local vars
```

Also, compiler may compile line-by-line, hence right up front!

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Function Calls -- Summary

- Activation records keep track of caller and callee variables
  - Stack structure
- What happens if we "accidentally" overwrite the return address ?
- Next: Pointers, Arrays, Dynamic data structures and the heap

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