ECE 220

Lecture x0008 - 09/19

Slides based on material originally by: Yuting Chen & Thomas Moon

Recap + reminders

- Midterm 1 on 09/26, conflicts to be reported by 09/22
- Material covered:
  - Lectures 1 - 6
  - Relevant textbook sections
  - See practice material
- HKN review session 09/22 from 1230 - 1500 hrs

- Last time
  - Functions in C
    - Prototype vs. definition
  - Examples
  - Implementation in assembly & intro to RTS

How do functions work at assembly level?

- When C-compiler compiles a program, it keeps track of variables in a program using a **symbol table**.
- For our purposes, the symbol table contains
  - Identifier
  - type of the variable,
  - memory location allocated (by offset - see next slide) and
  - scope

Getting this to work - example

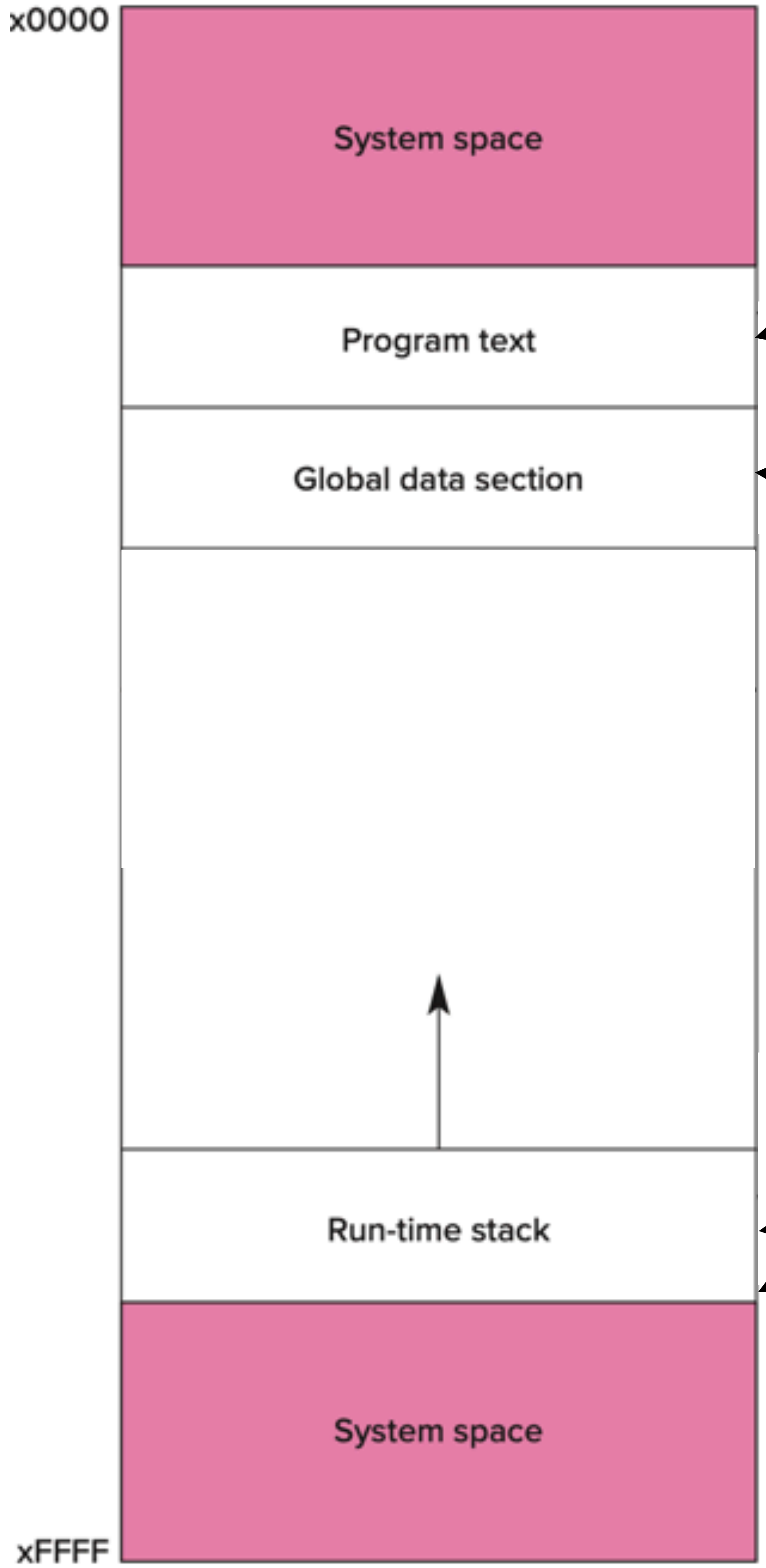
```
int inGlobal=2;
int outGlobal=3;
int dummy(int in1, int in2);

int main(void){
   int x,y,z;
   ...
}

int dummy(int in1, int in2){
   int a,b,c;
   …
}
```

Symbol table

Name	Type	Location	Scope
inGlobal	int	0	Global
outGlobal	int	1	Global
x	int	0	Main
y	int	-1	Main
z	int	-2	Main
a	int	0	Dummy
b	int	-1	Dummy
c	int	-2	Dummy

Why are some offsets negative and others positive?

Example: In LC3 memory map




```c
int inGlobal;
int outGlobal;
int dummy(int in1, int in2);

int main(void){
  int x,y,z;
  ...
}

int dummy(int in1, int in2){
  int a,b,c;
  …
}
```

Symbol table

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inGlobal	int	0	Global
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a	int	0	Dummy
b	int	-1	Dummy
c	int	-2	Dummy

Because function calls are implemented using a stack ADT.

Run-time stack: A place (actually a stack data structure) to hold *activation frames*

Basic idea

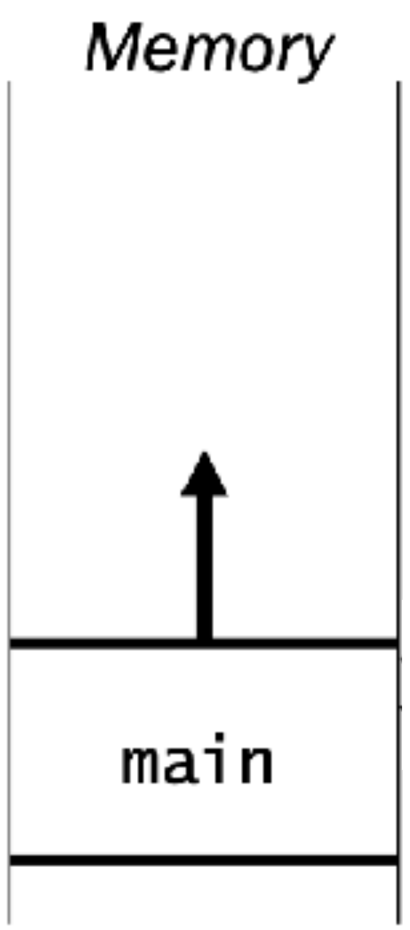
Activation record: Parts of a *stack* that holds information about *each function call* (sometimes called *stack frames*)

- ***Every*** function *call* creates an activation record (or stack frame) and pushes it onto the run-time stack.
- Whenever a function *completes* (returns), the activation record is popped off the run-time stack
- Whenever a function calls *another one* (nested, including itself), the run time stack grows (pushes another activation record onto the run-time stack).

Arguments passed in
Variables defined in function
Bookkeeping information

Example: function call

```
int dummy(int in1, int in2);

int main(void){
   int x,y,z;
   ...
   z = dummy(x, y);
}

int dummy(int in1, int in2){
   int a,b,c;
   …
}
```



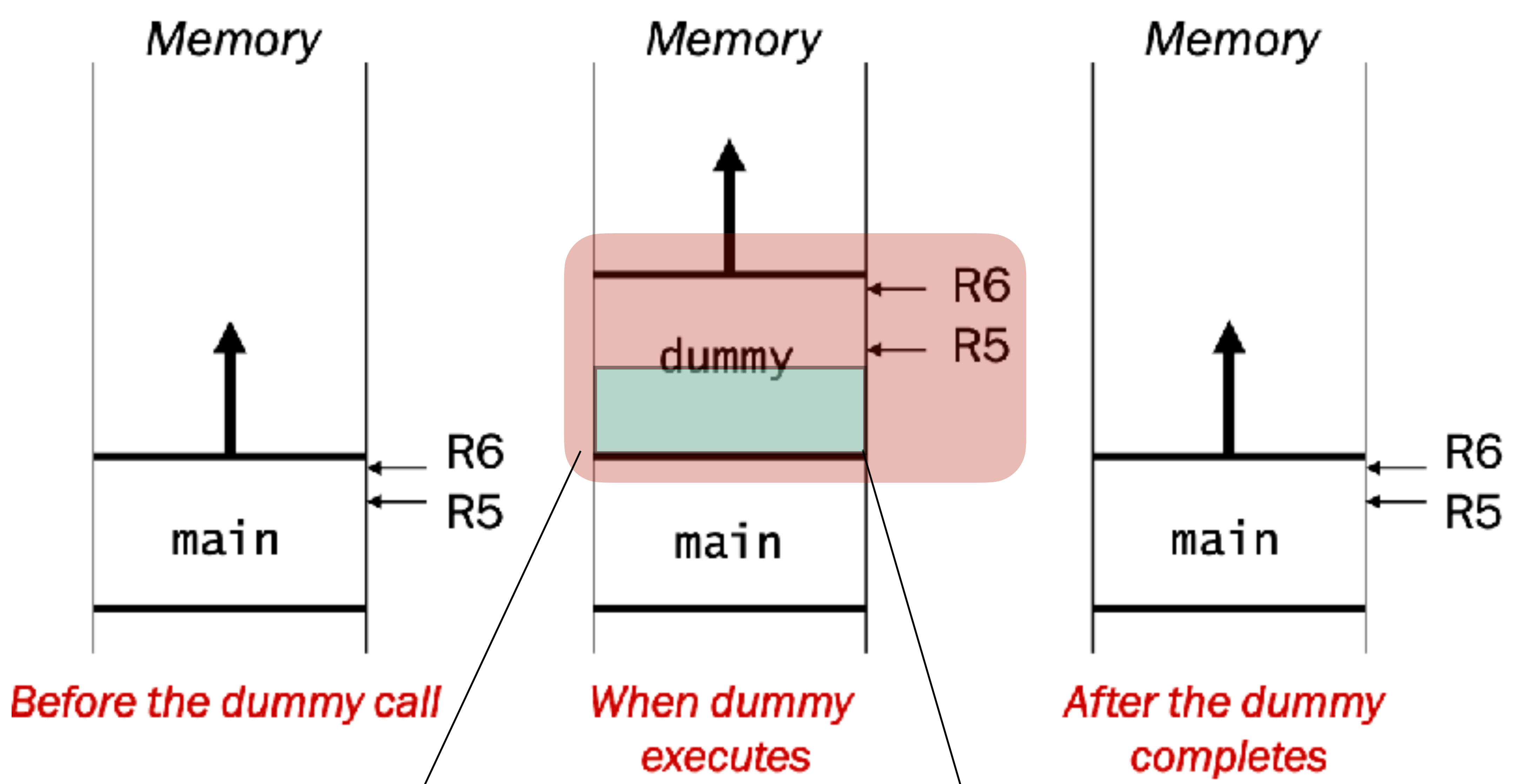
Before the dummy call

How to keep track?

- Store pointers:
  - Program counter - PC
  - **Global pointer** pointing to first global variable - `R4`
  - Top of stack, called **stack pointer** - `R6`
  - *Current* **frame pointer** - `R5`
    - Actually points to first local variable of *current* function

Example: function call

```
int dummy(int in1, int in2);

int main(void){
   int x,y,z;
   ...
   z = dummy(x, y);
}

int dummy(int in1, int in2){
   int a,b,c;
   …
}
```



Activation record for dummy

If `R5` is first local variable, what goes here?

Details of a function call

- To *successfully* transfer execution between the caller and callee a few things need to be taken care of:
  - Arguments need to be passed around
  - Bookkeeping has to be done:
    - **Return value**: Space for value returned by function according to type has to be allocated
    - **Return address**: Pointer to next instruction has to be saved so caller can resume
    - Caller's frame pointer saved
  - Callee local variables have to be stored

Activation record

Pushed before local variables

Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
2. Pass control to callee (`JSR/JSRR`)
3. *Callee* build-up: (push bookkeeping info and local variables onto stack)
4. Execute function
5. *Callee* tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)
6. Return to caller (`RET`)
7. *Caller* tear-down (pop callee's return value and arguments from stack)

Stack build up (steps 1–3)

Stack teardown (steps 5–7)

Caller (steps 1–2) | Callee (steps 3–6) | Caller (step 7)

Example function call

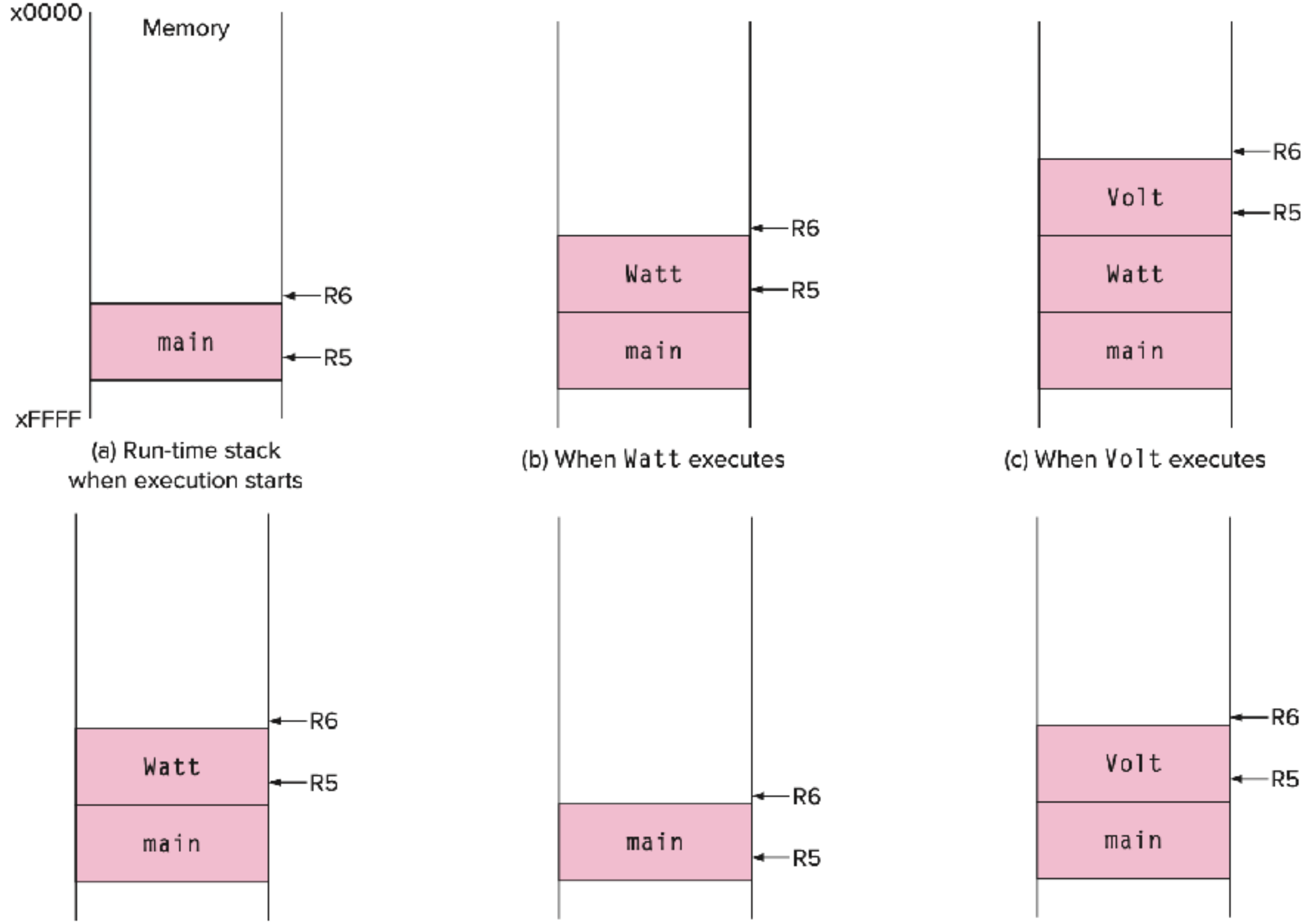
```
int main (void){
     int a;
     int b;
     …
     b = Watt(a);          // main calls Watt first
     b = Volt(a, b);       // then calls Volt
}

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

int Watt(int a) {
     int w;
     ...
     w = Volt(w,10);    // Watt also calls Volt
     …
     return w;
}
```

Run-time stack

```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



(a) Run-time stack when execution starts

(b) When Watt executes

(c) When Volt executes

(d) After Volt completes

(e) After Watt completes

(f) When Volt executes

C Run-time stack protocol

- **STEP 1**: The caller function copies arguments for the callee onto the run-time stack and passes control to the callee.
- **STEP 2**: The callee function pushes space for local variables and other information onto the run-time stack, essentially creating its stack frame on top of the stack.
- **STEP 3**: The callee executes
- **STEP 4**: Once it is ready to return, the callee pops its stack frame off the run-time stack, and gives the *return value* and control to the caller.

C Run-time stack protocol

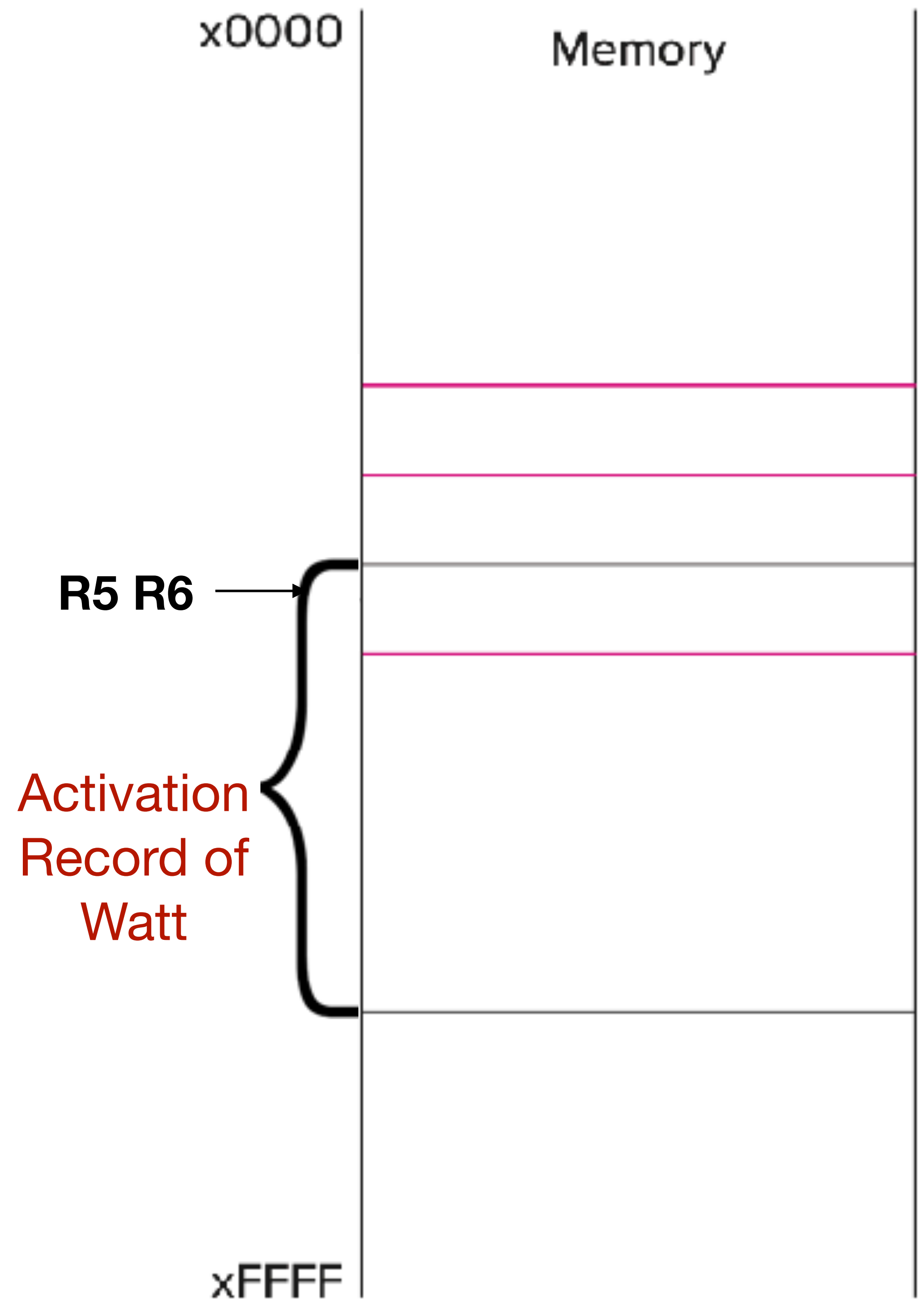
- `Volt` called with two arguments
- Value *returned* by `Volt` is assigned to local integer variable `w`.
- *Arguments* are pushed onto stack from **right to left** in the order in which they appear in the function call

```
int Watt(int a)
{
    int w;
    ...
    w = Volt(w,10);
    …
    return w;
}
```

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)
2. Pass control to callee

```
; push second arg
AND R0, R0, #0
ADD R0, R0, #10
ADD R6, R6, #-1
STR R0, R6, #0

; push first arg
LDR R0, R5, #0    ;R ← w
ADD R6, R6, #-1
STR R0, R6, #0

; call subroutine
JSR VOLT
```



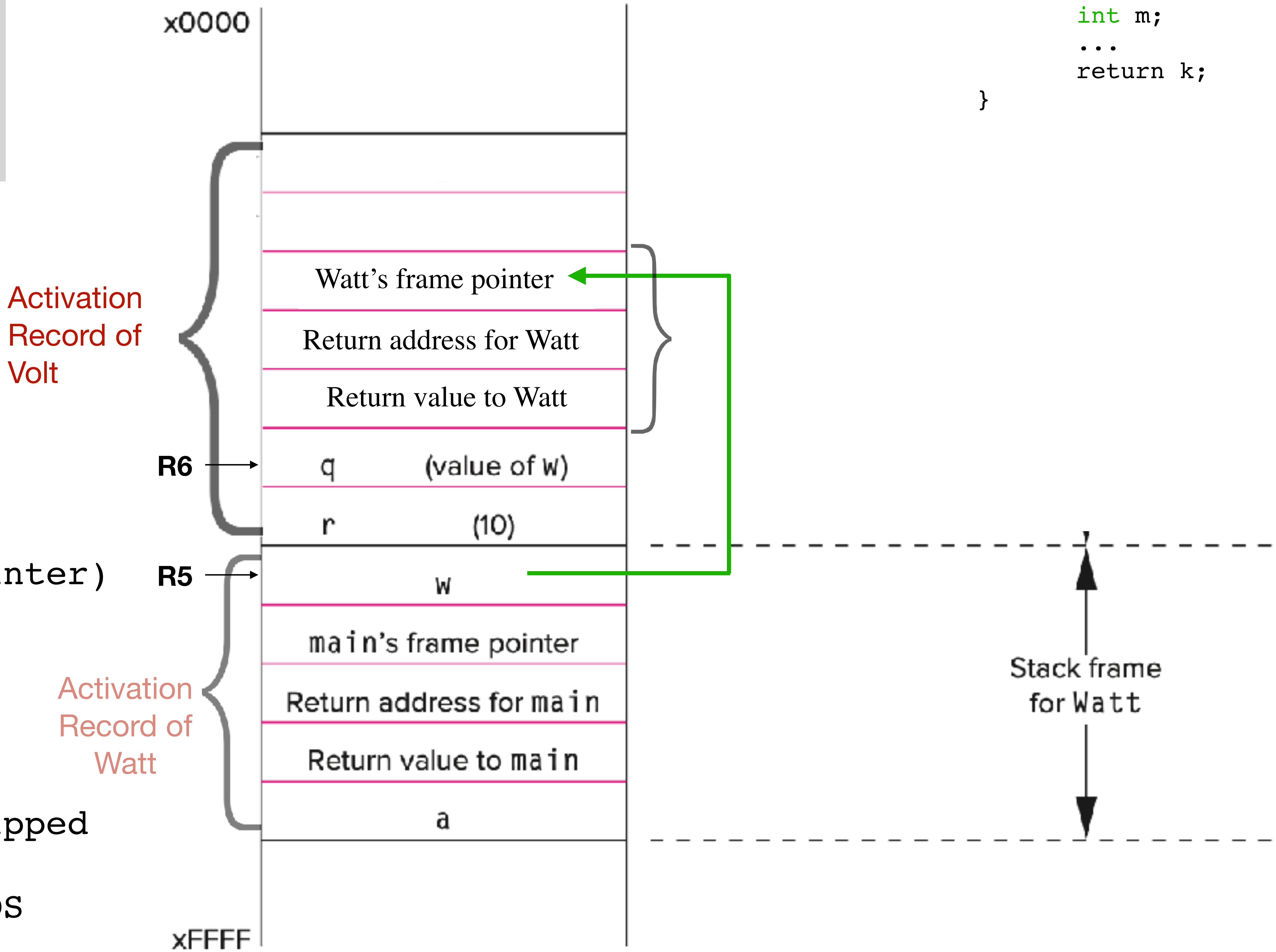

```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

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

3. Callee setup (push bookkeeping info and local variables onto stack)
4. Execute function

```
;return value
ADD R6, R6, #-1

ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

ADD R6, R6, #-1
;Push R5 (Caller's frame pointer)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
; Push local variables - skipped
;
ADD R6, R6, #-2   ; update TOS
```



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

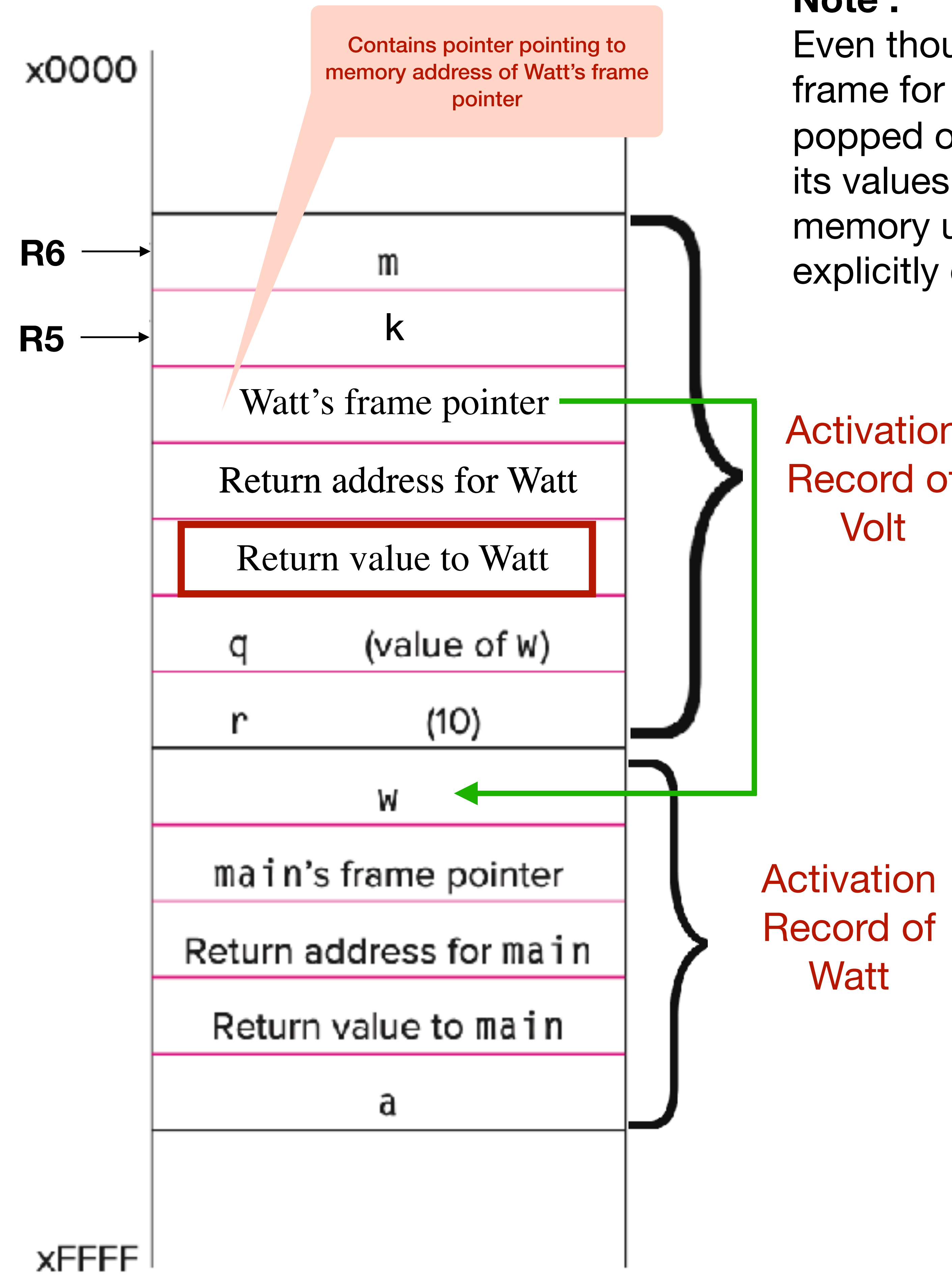
LC-3 Implementation

5. Callee tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)
6. Return to caller

```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

; pop local variables
ADD R6, R5, #1

; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

; pop return addr (to R7)
LDR R7, R6, #0
ADD R6, R6, #1

; return control to caller
RET
```

R0
k

R7



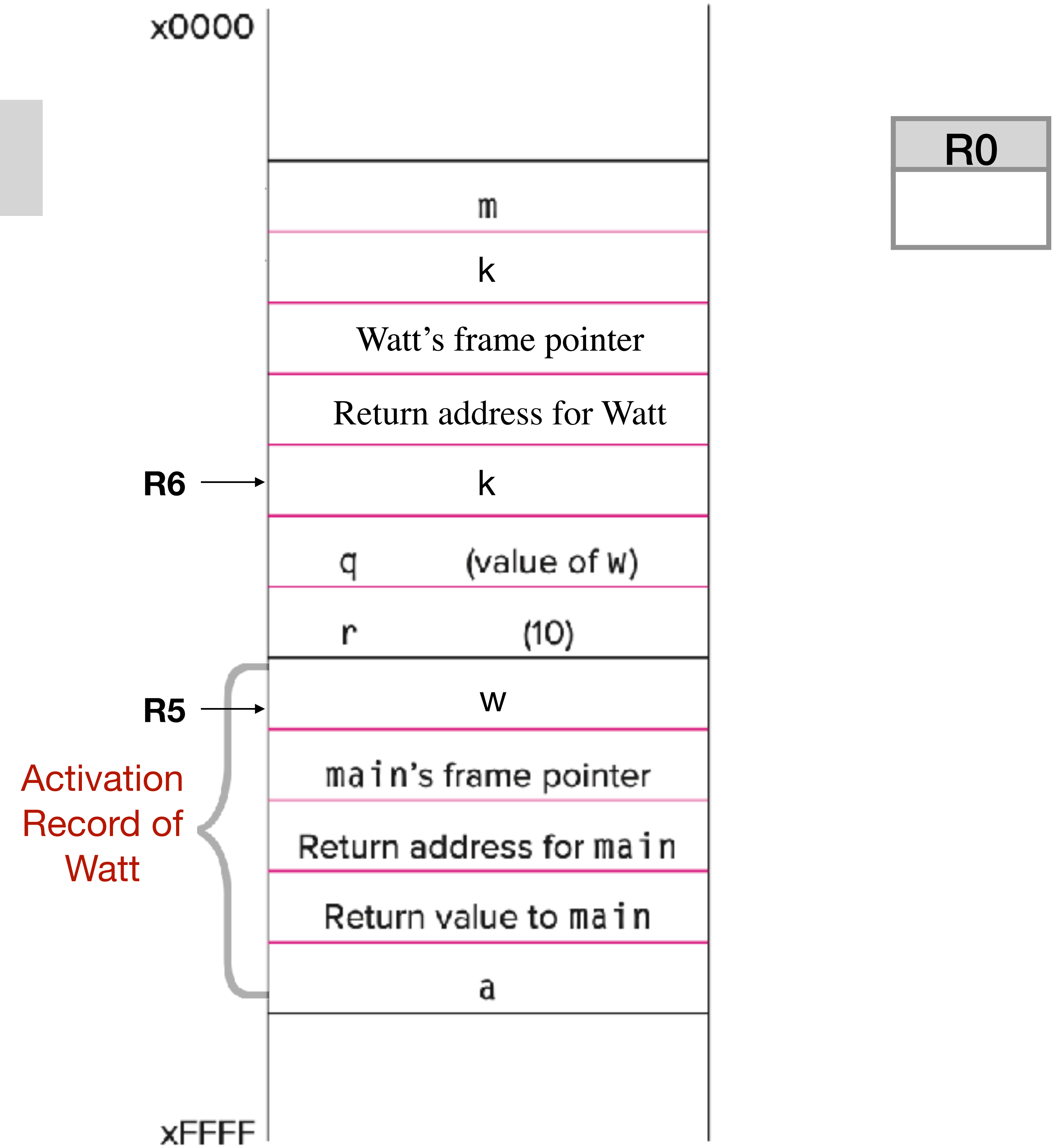
Note :
Even though the stack frame for `Volt` is popped off the stack, its values remain in memory until they are explicitly overwritten

```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

LC-3 Implementation

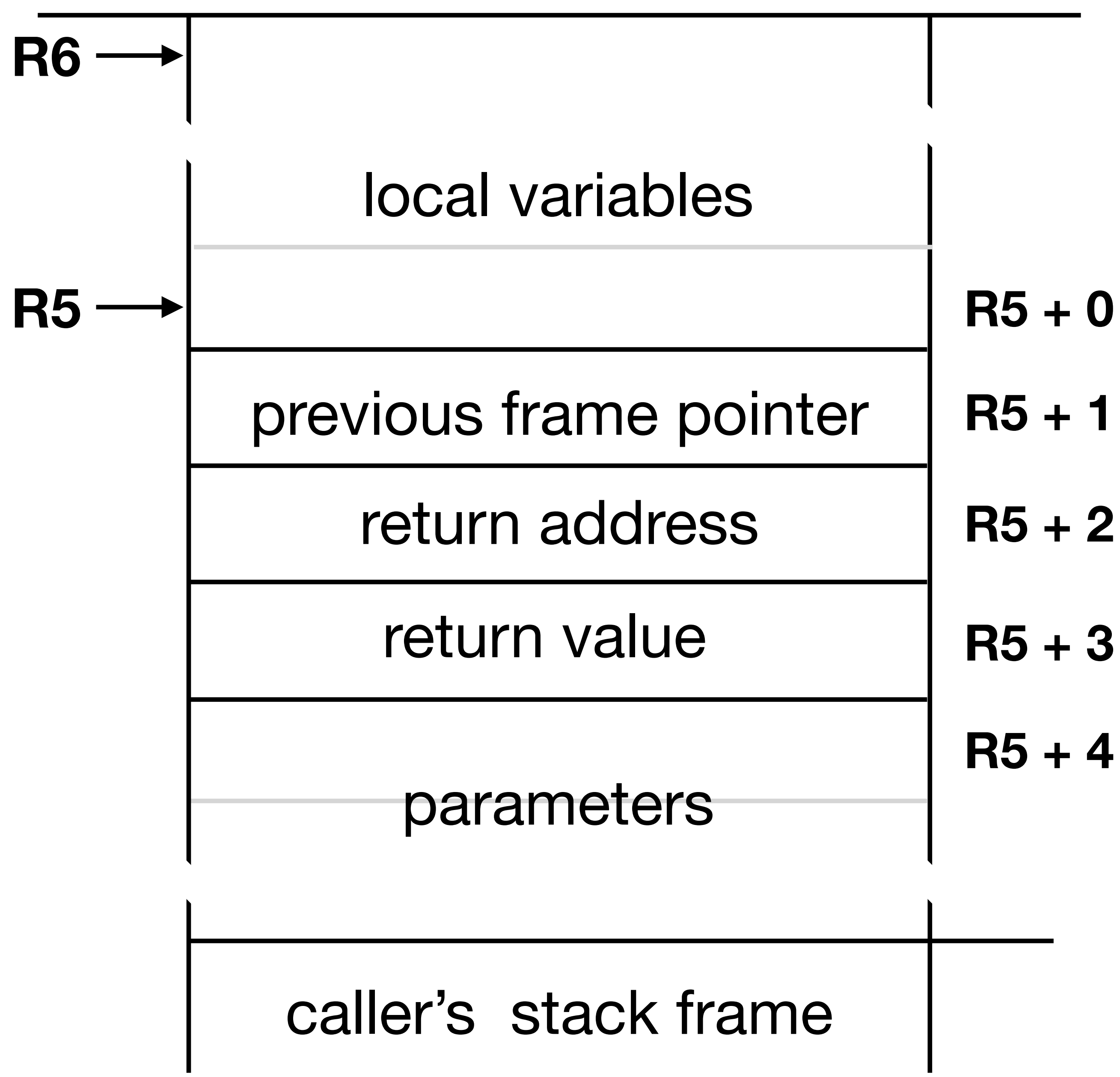
7. Caller tear-down (pop callee's return value and arguments from stack)

```
JSR VOLT
; load return value (top of stack)
LDR R0, R6, #0

; perform assignment
STR R0, R5, #0

; pop return value
ADD R6, R6, #1

; pop arguments
ADD R6, R6, #2
```



General principles

- R4 points first global variable
- R5 points to first local variable of currently executing function
- R6 is top of stack
- R7 is reserved for RET
- R0-R3 are caller saved

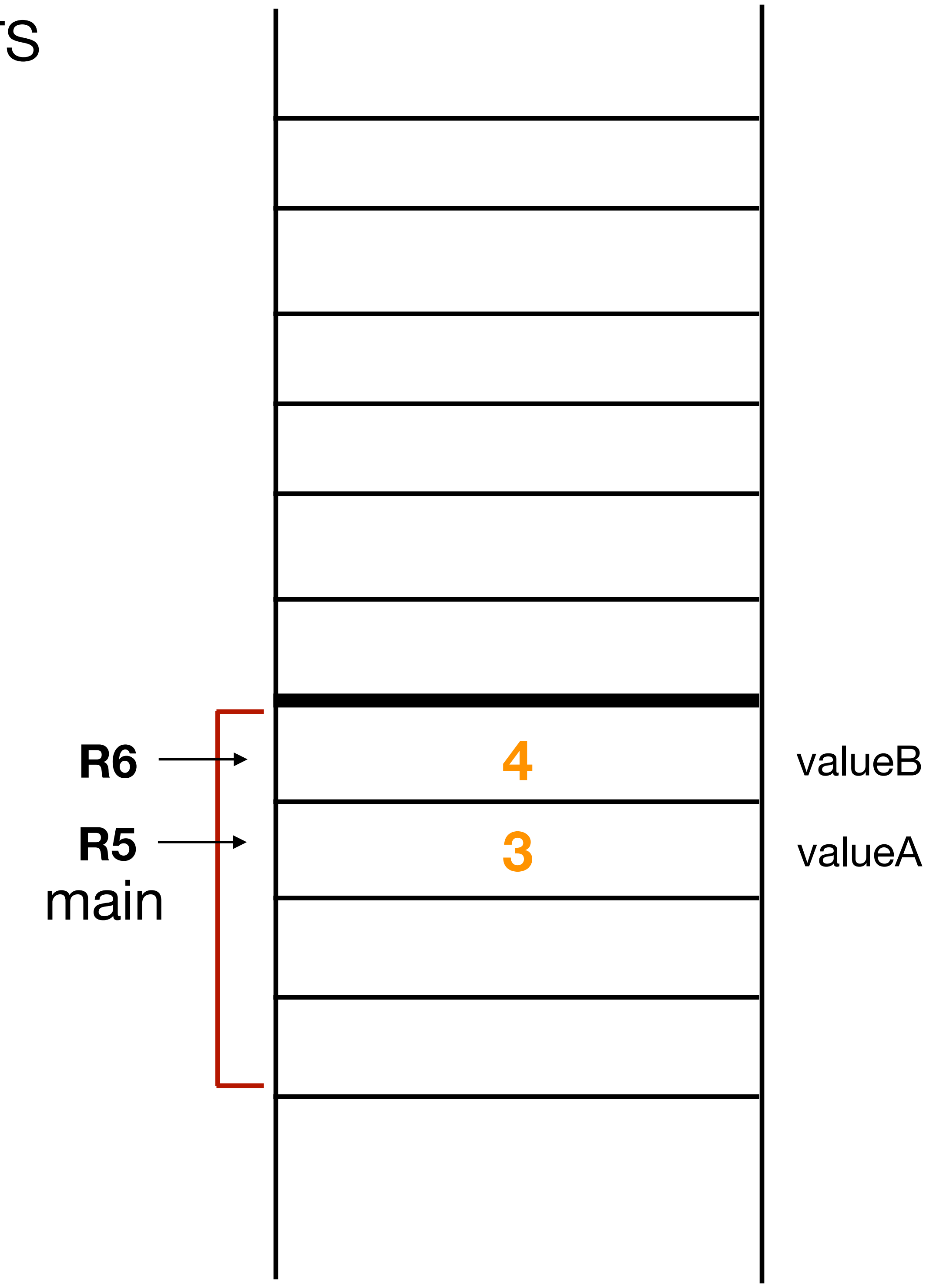


Exercise: build the activation frame

```c
void Swap(int first, int second);

int main(){
   int valueA = 3;
   int valueB = 4;
   Swap(valueA, valueB);
}

void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up
   - A. Return value
   - B. Return address
   - C. Caller frame pointer (CFP)
   - D. Push local variables
4. Execute
5. Callee tear down
   - E. Update return value
   - F. Pop local variables
   - G. Pop CFP
   - H. Pop return address
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Before call

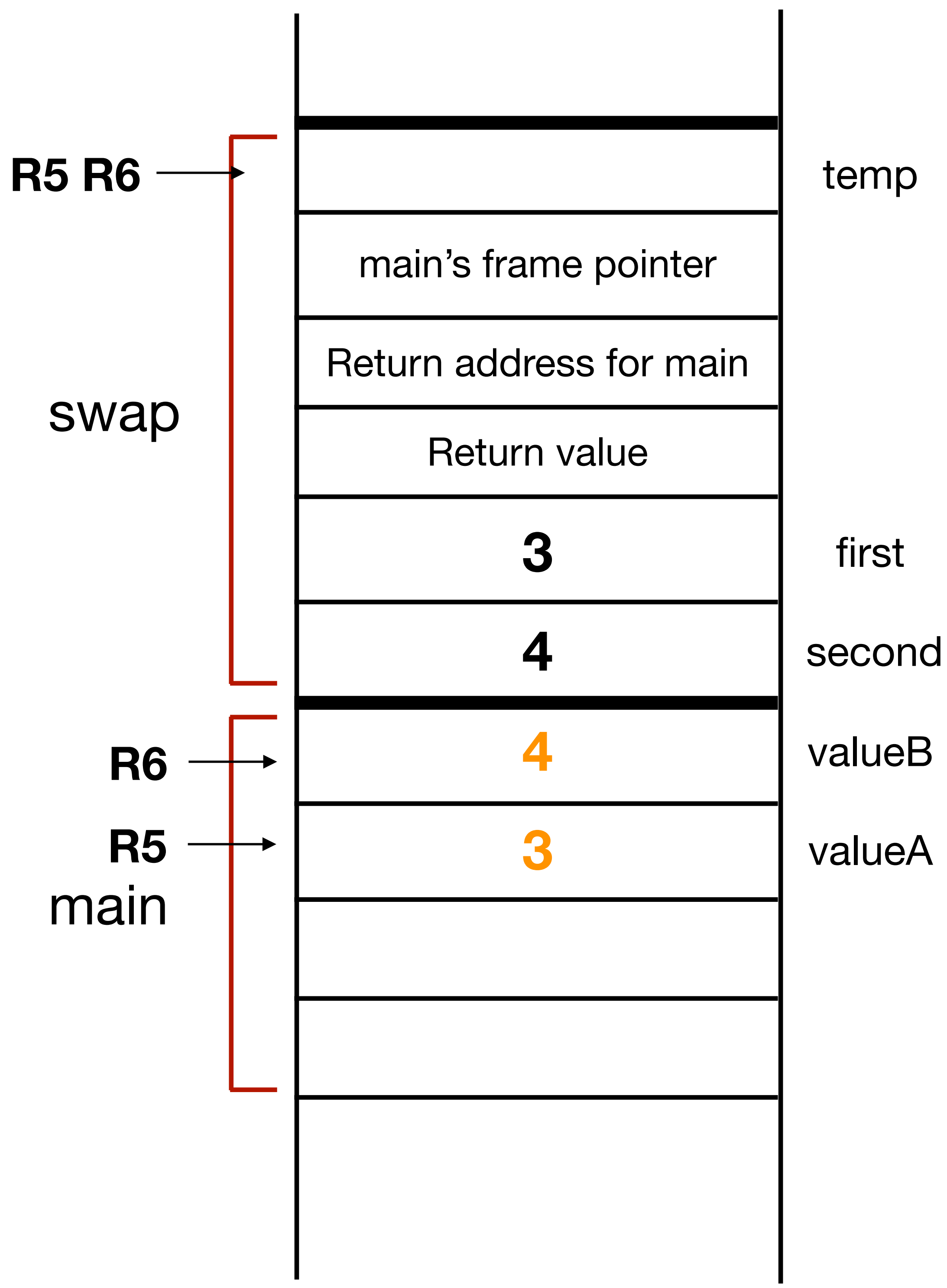


Goal:
Swap valueA and valueB in main.

swap function - build up

Build up

1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up (push onto RTS)
   A. Return value (allocate)
   B. Return address (from R7)
   C. Caller frame pointer (CFP)
   D. Local variables
4. Execute
5. Callee tear down
   E. Update return value
   F. Pop local variables
   G. Pop CFP (into R5)
   H. Pop return address (into R7)
6. RET
7. Caller tear down
   I. Pop return value
   J. Pop arguments



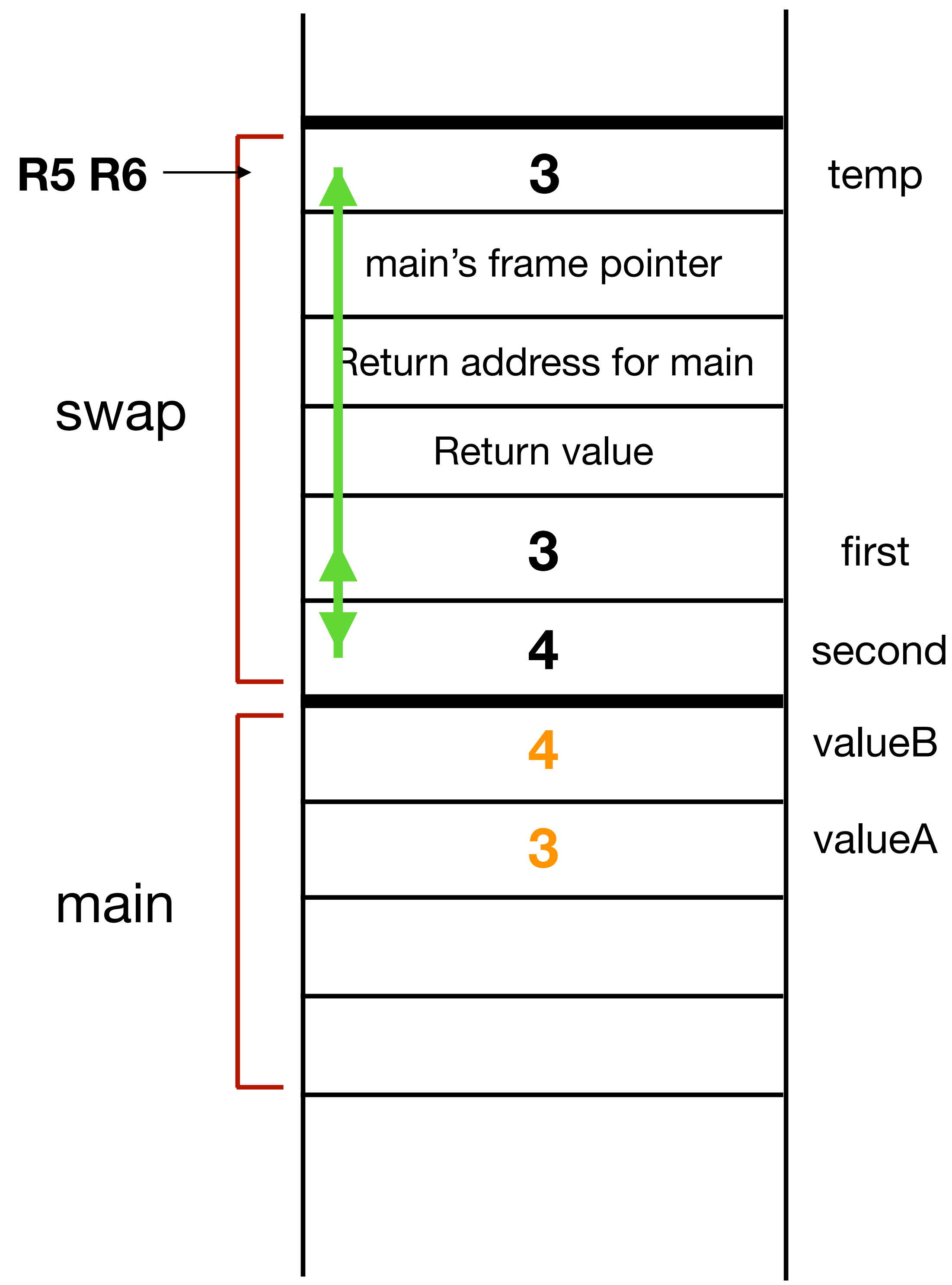

```
void Swap(int first, int second);

int main(){
   int valueA = 3;
   int valueB = 4;
   Swap(valueA, valueB);
}

void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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

swap function - execute

1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up (push onto RTS)
   - A. Return value (allocate)
   - B. Return address (from R7)
   - C. Caller frame pointer (CFP)
   - D. Local variables
4. Execute
5. Callee tear down
   - E. Update return value
   - F. Pop local variables
   - G. Pop CFP (into R5)
   - H. Pop return address (into R7)
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

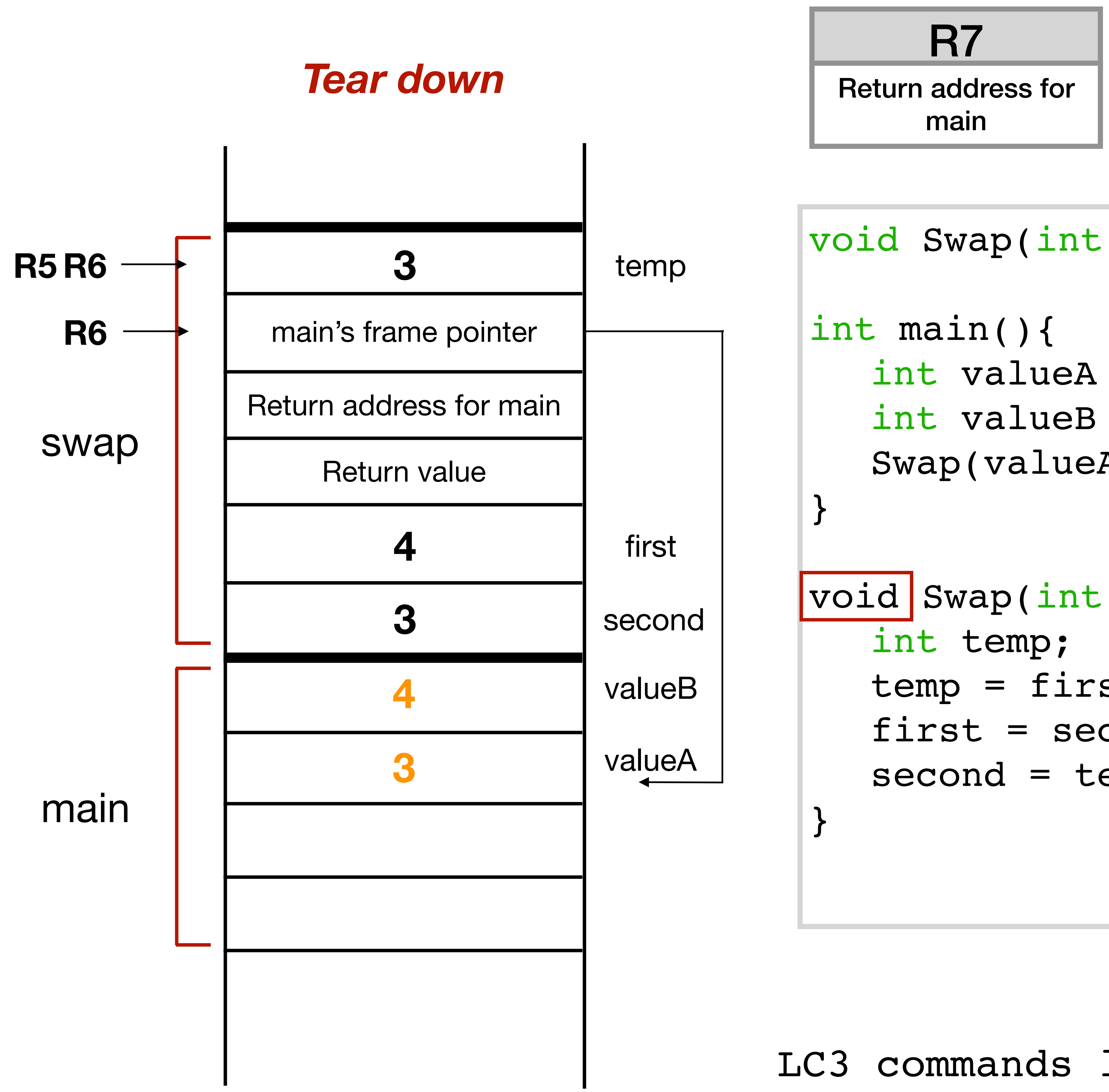
Execution




```
void Swap(int first, int second);

int main(){
   int valueA = 3;
   int valueB = 4;
   Swap(valueA, valueB);
}

void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

`swap` function - tear down

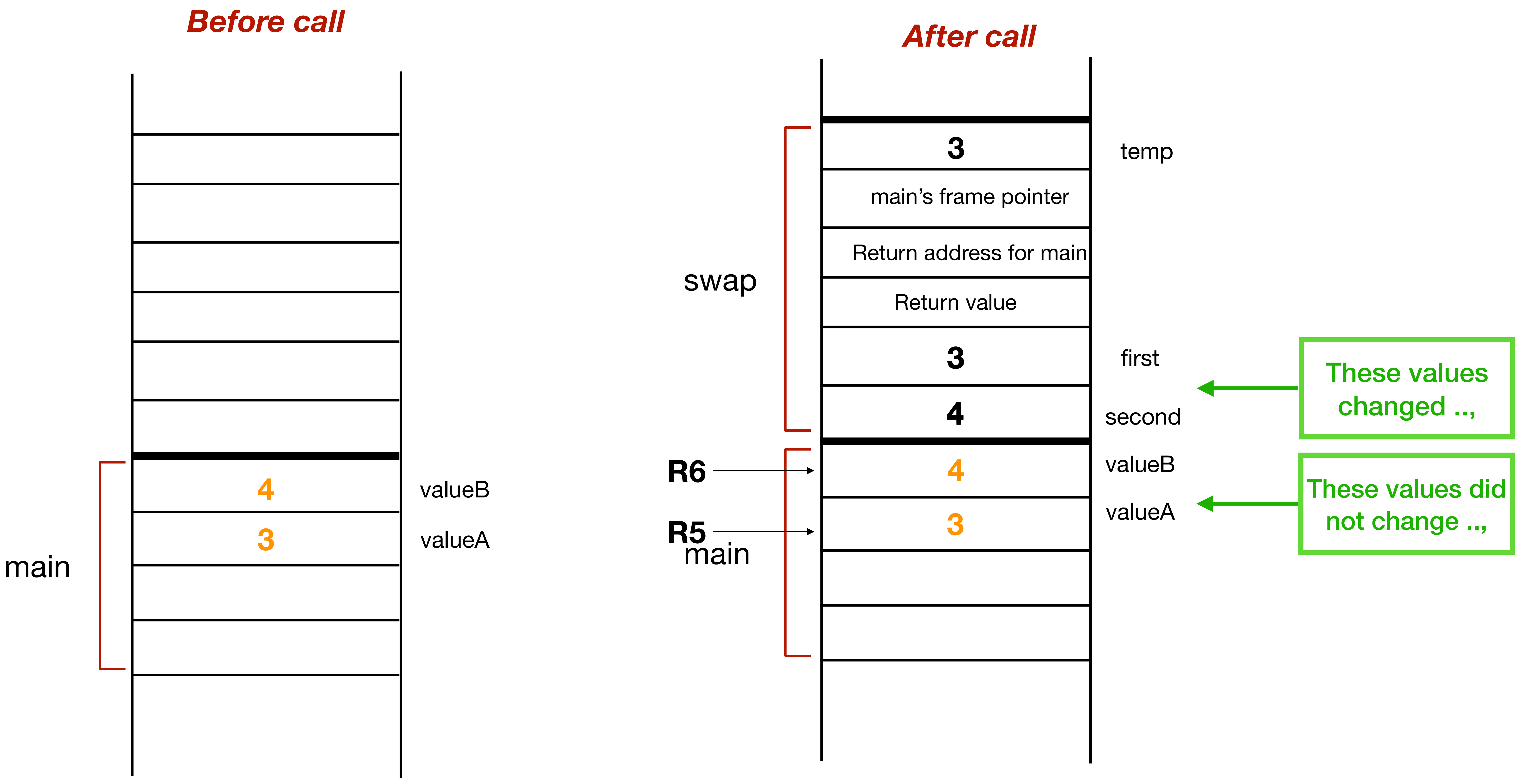
1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up (push onto RTS)
   - A. Return value (allocate)
   - B. Return address (from R7)
   - C. Caller frame pointer (CFP)
   - D. Local variables
4. Execute
5. Callee tear down
   - E. Update return value
   - F. Pop local variables
   - G. Pop CFP (into R5)
   - H. Pop return address (into R7)
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments




```c
void Swap(int first, int second);

int main(){
   int valueA = 3;
   int valueB = 4;
   Swap(valueA, valueB);
}

void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

LC3 commands left as an exercise

Swap function - did it work?



Argument passing

- Argument passing in C is what we call **pass-by-value**:
  - The functions get their own copies of the arguments
  - Changes made to these local copies are not reflected back
- Contrast with **pass-by-reference**.

- What needs to be changed for the `swap` function to work?
  - Somehow the `swap` function needs to know the *memory locations* of the variables that `main` needs swapped
  - Enter **pointers.**

Introduction to pointers

Working version

```
#include <stdio.h>
void Swap(int *first, int *second);

int main(){
  int valueA = 3;
  int valueB = 4;
  Swap(&valueA, &valueB);
}

void Swap(int *first, int *second){
int temp;
temp = *first;
*first = *second;
*second = temp;
}
```

Recall from `scanf`: what does `&var` do to `var`?

How do we tell the compiler some variables are supposed to hold memory addresses a.ka *pointers* and not usual values?

If you have pointer, how do you tell the compiler you want to refer to its contents?

Pointers *take time …*

Don't miss next class!

Time permitting

- `gcc` compilation arguments
  - `-Wall`
  - `-std=c99`
  - `-o`
  - `-O0`
  - `-Werror`
  - `-g`
- Compiling multiple source files

```
gcc -Wall main.c src1.c -o main
```

- Debugging
  - Preview of MP4
  - Demo