ECE 220

Lecture x0008 - 02/12

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

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Recap

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- Last time

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  - Functions in C

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  - Prototype vs. definition

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- Let’s quickly review!

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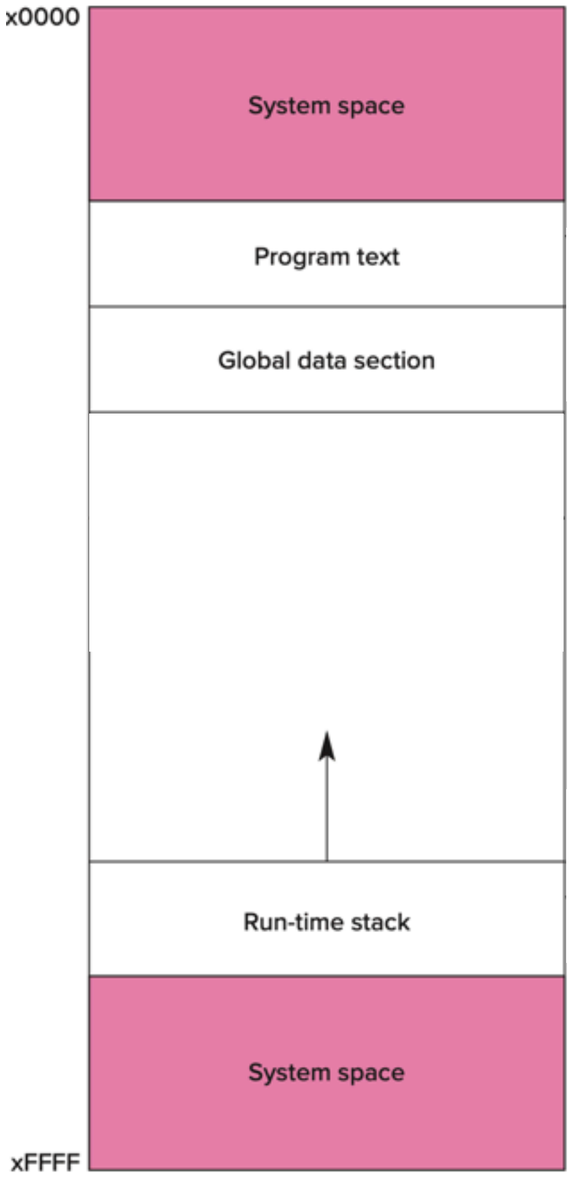
Why are some offsets negative and others positive?

Example: In LC3 memory map



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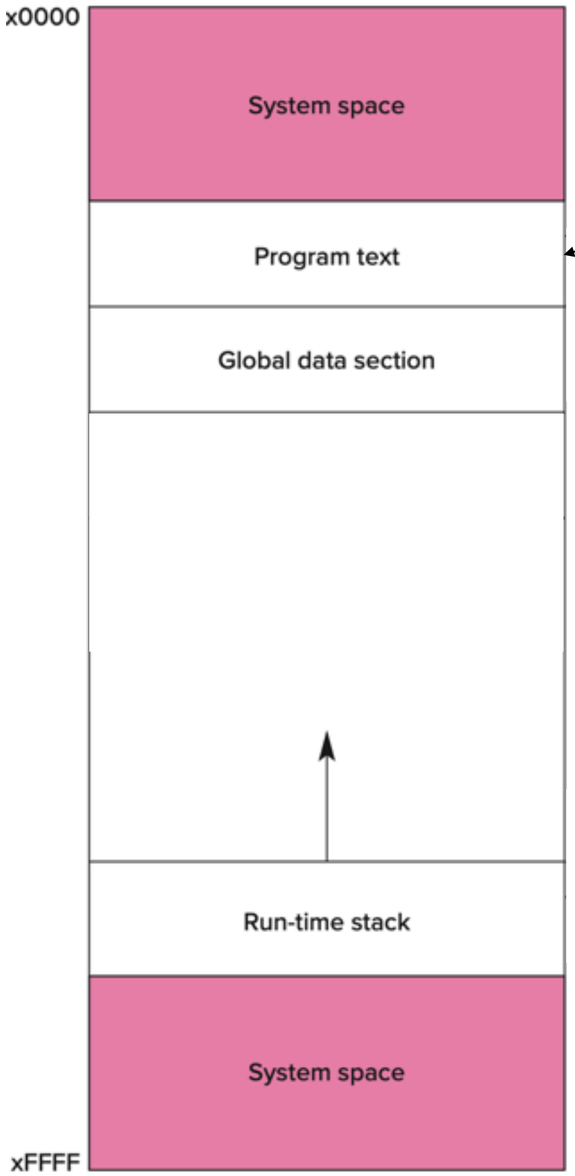


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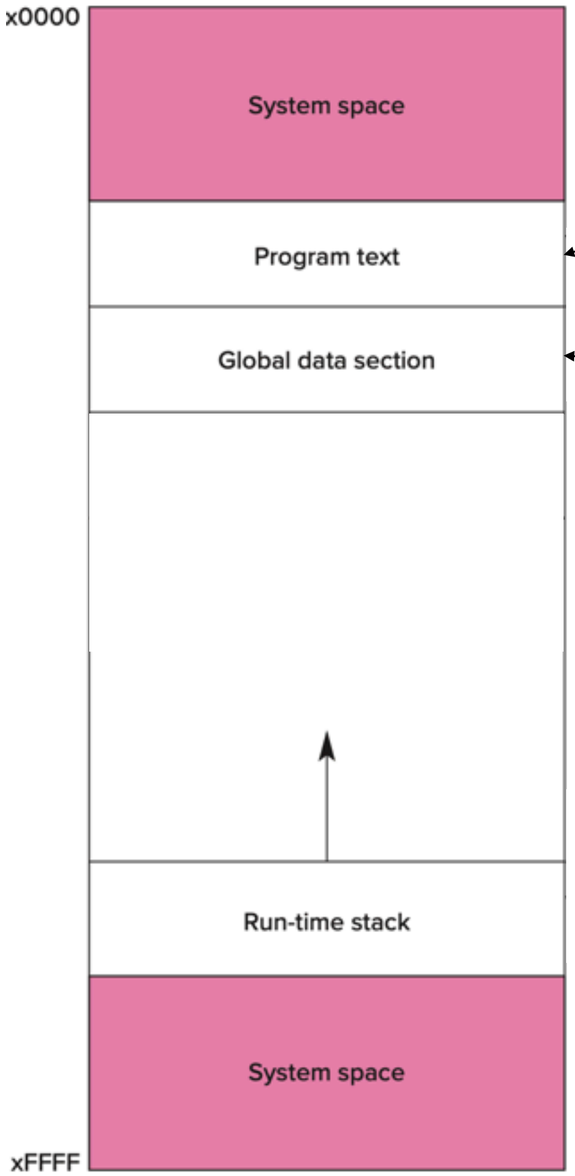


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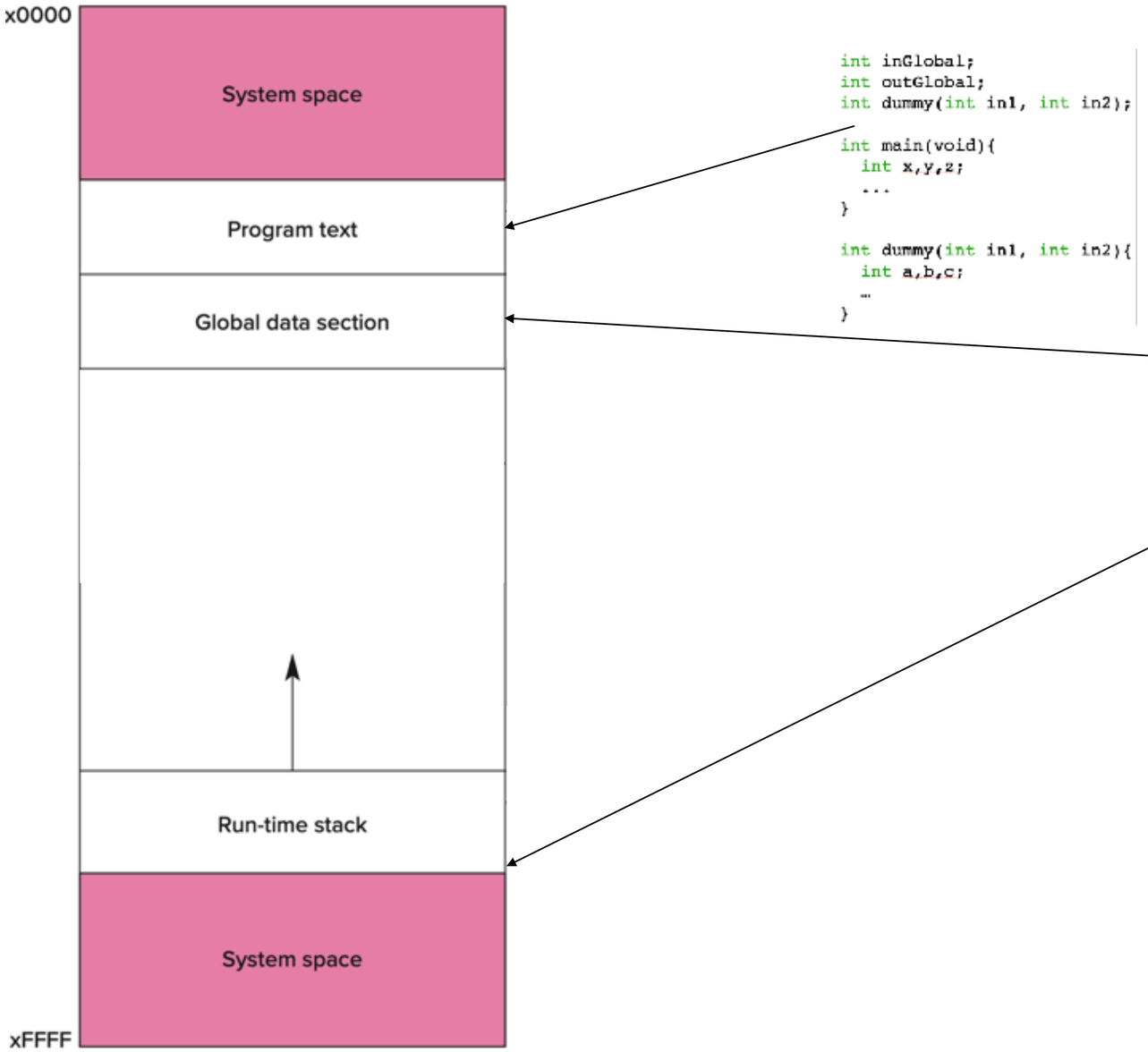


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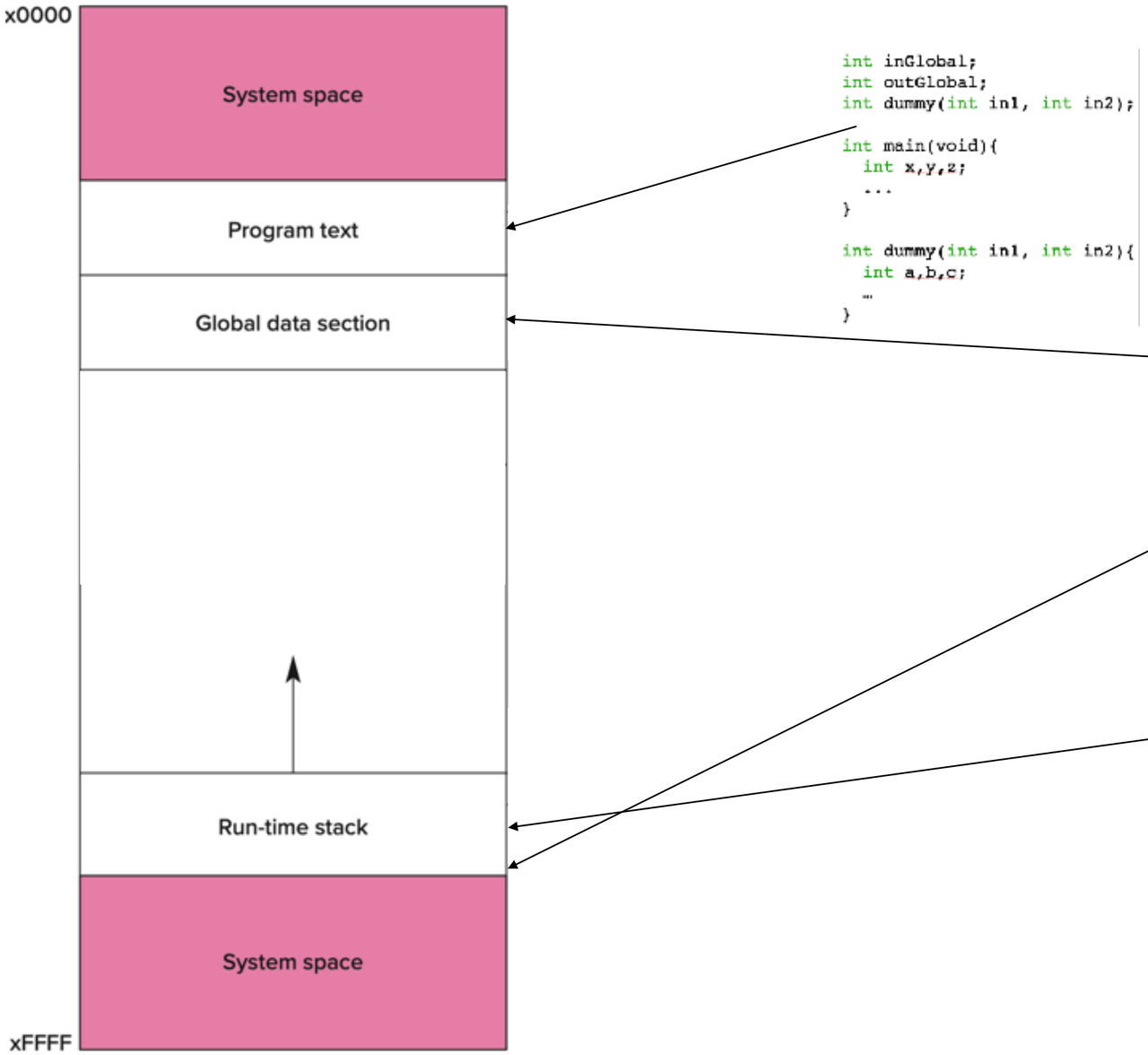


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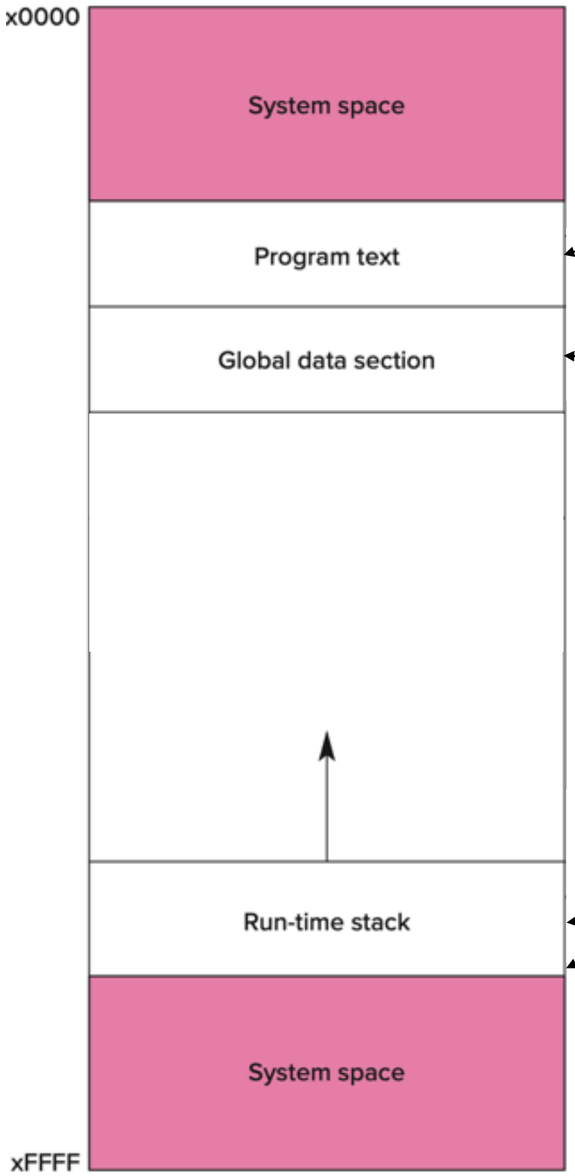


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Because function calls are implemented using a stack ADT.

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- Whenever a function calls *another one* (nested, including itself), the run time stack grows (pushes another activation record onto the run-time stack).

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Example: function call

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int dummy(int in1, int in2);

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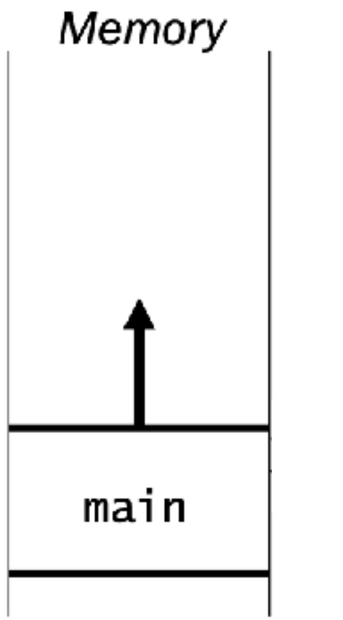

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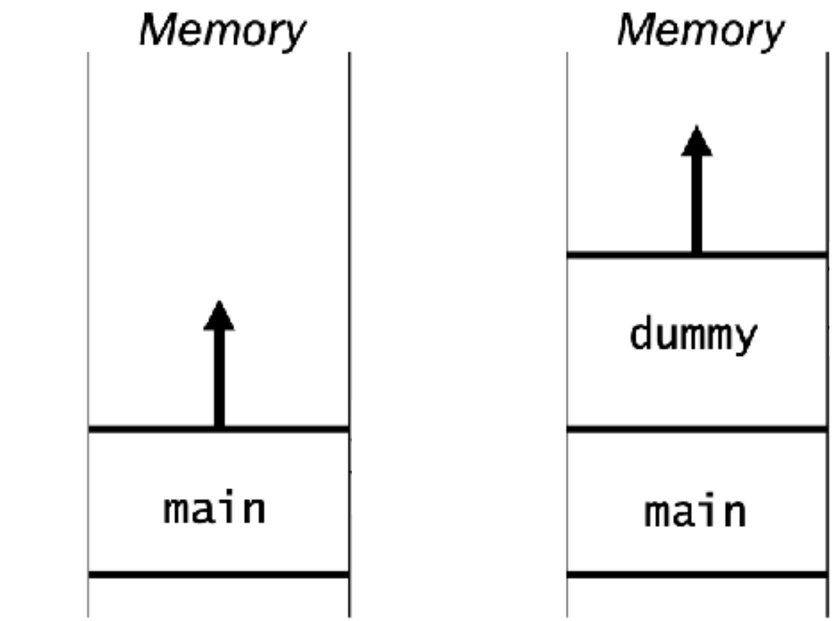

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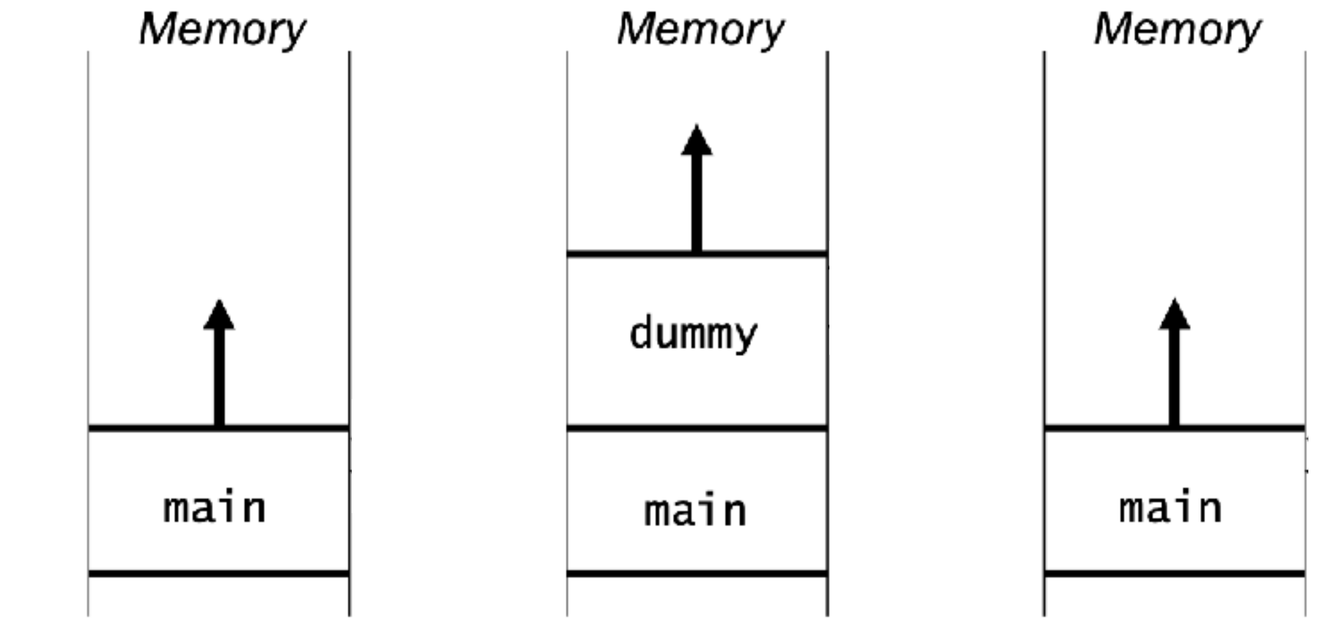

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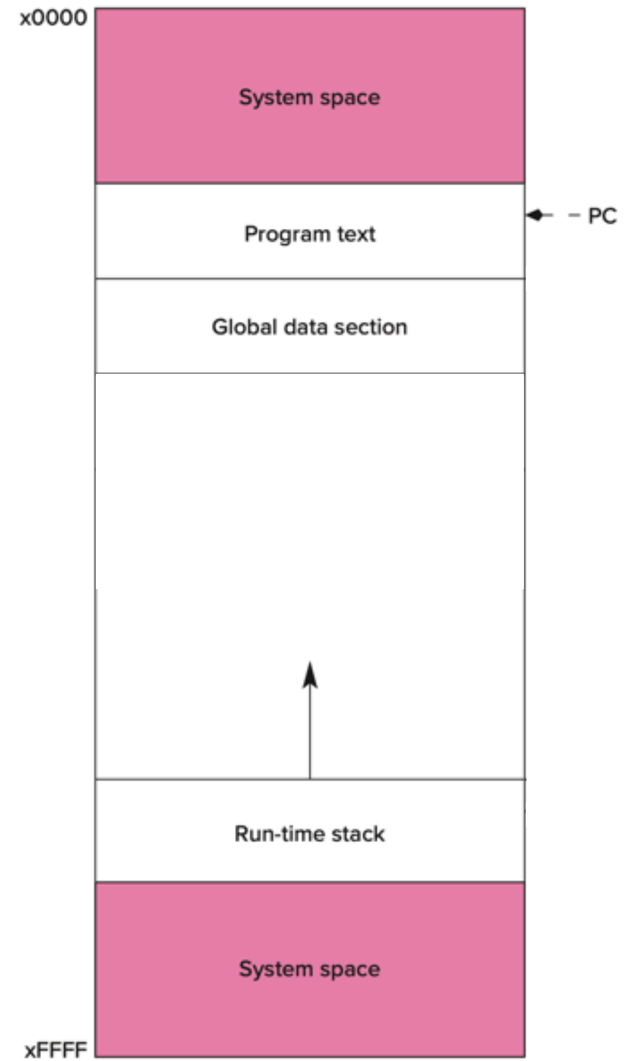

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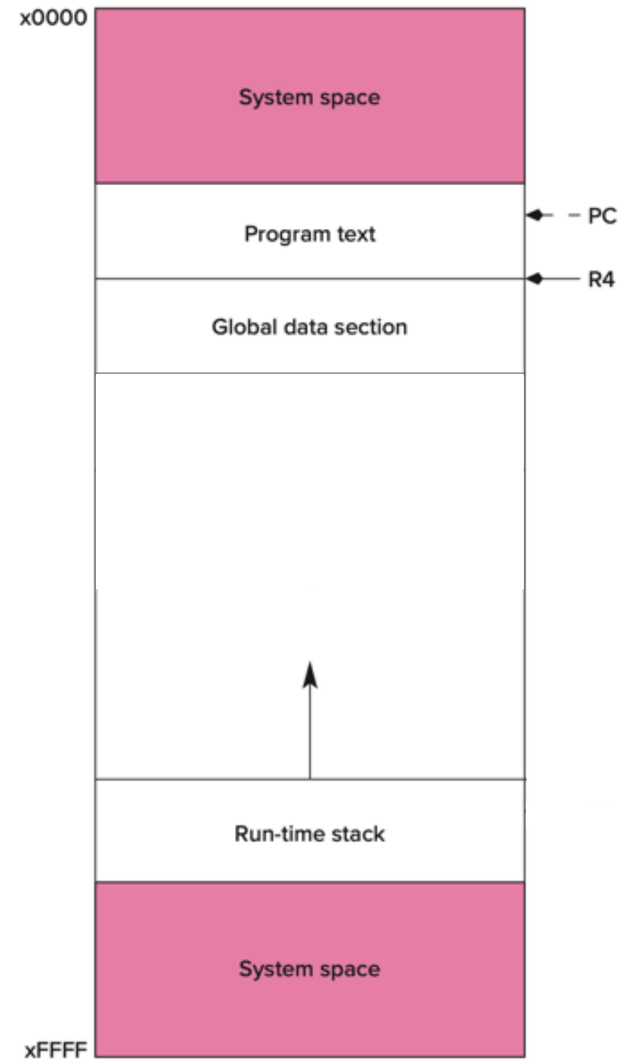

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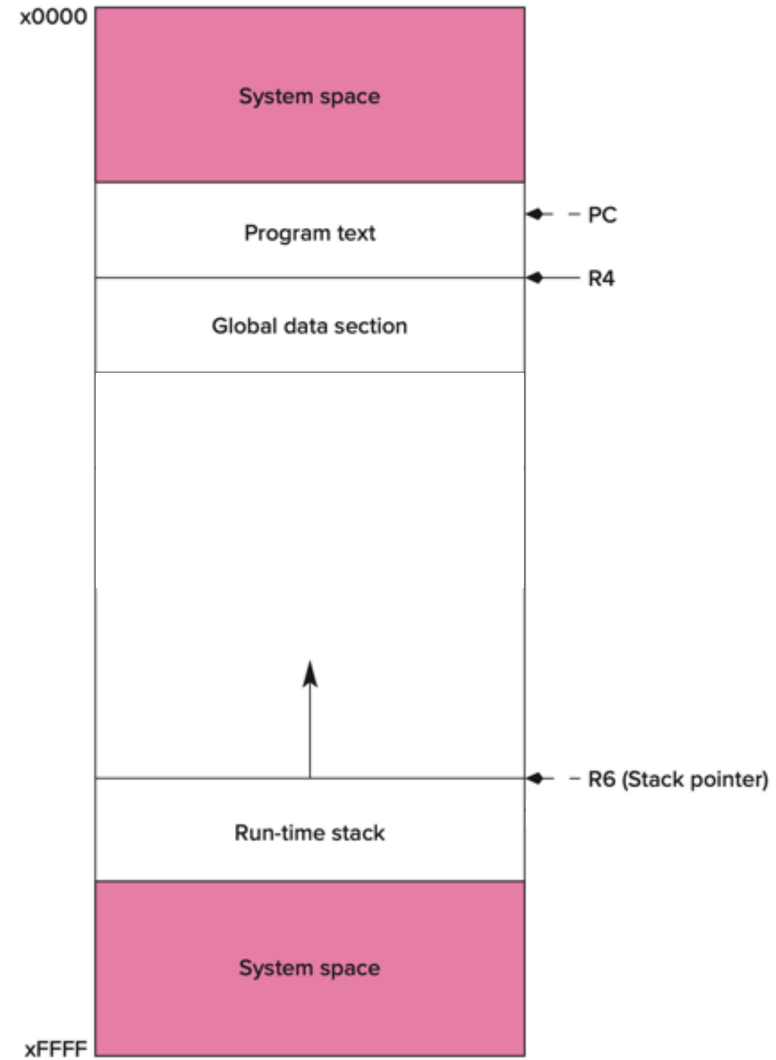

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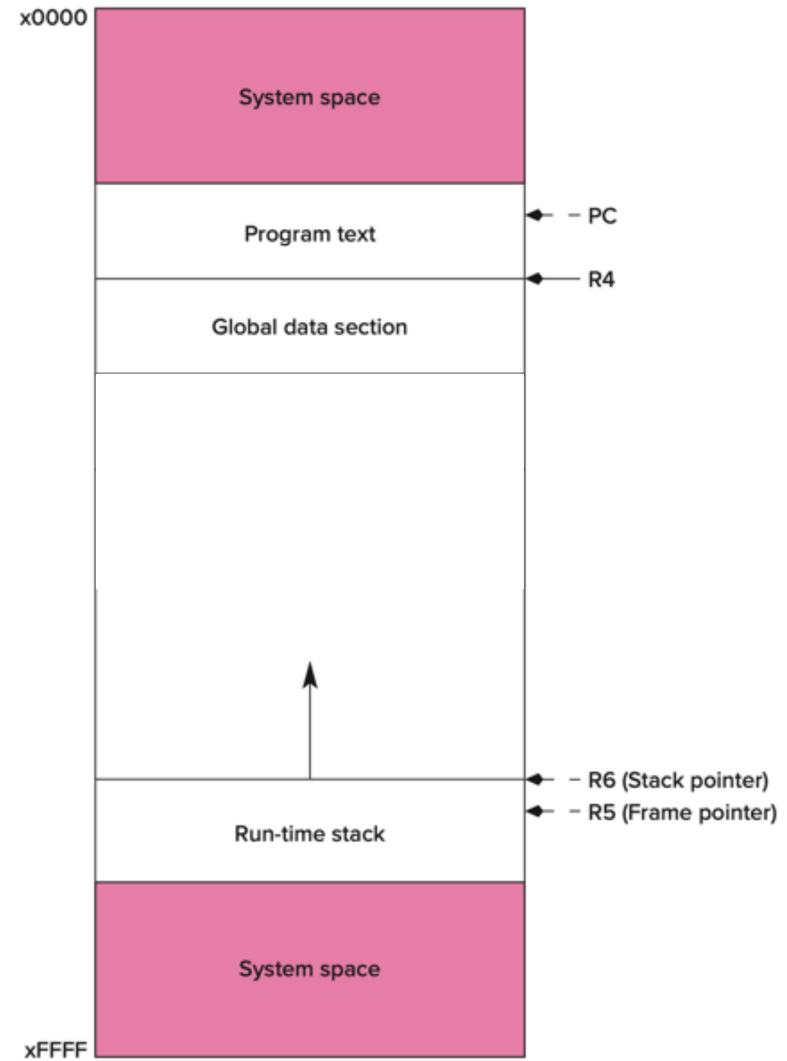

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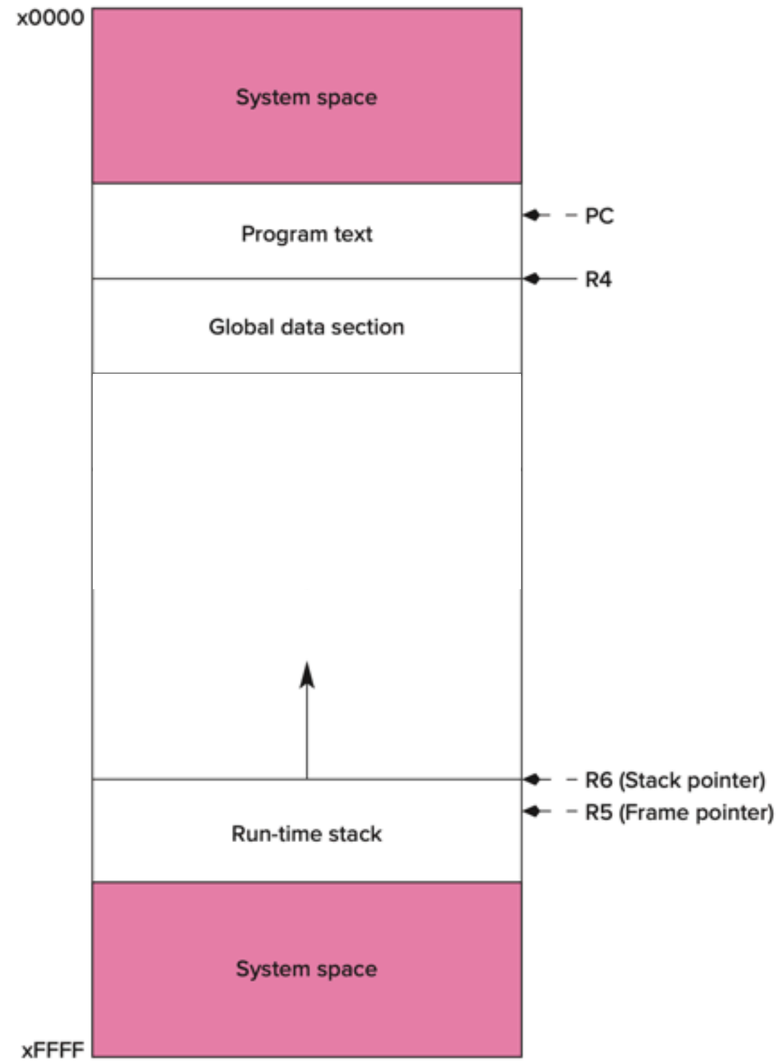

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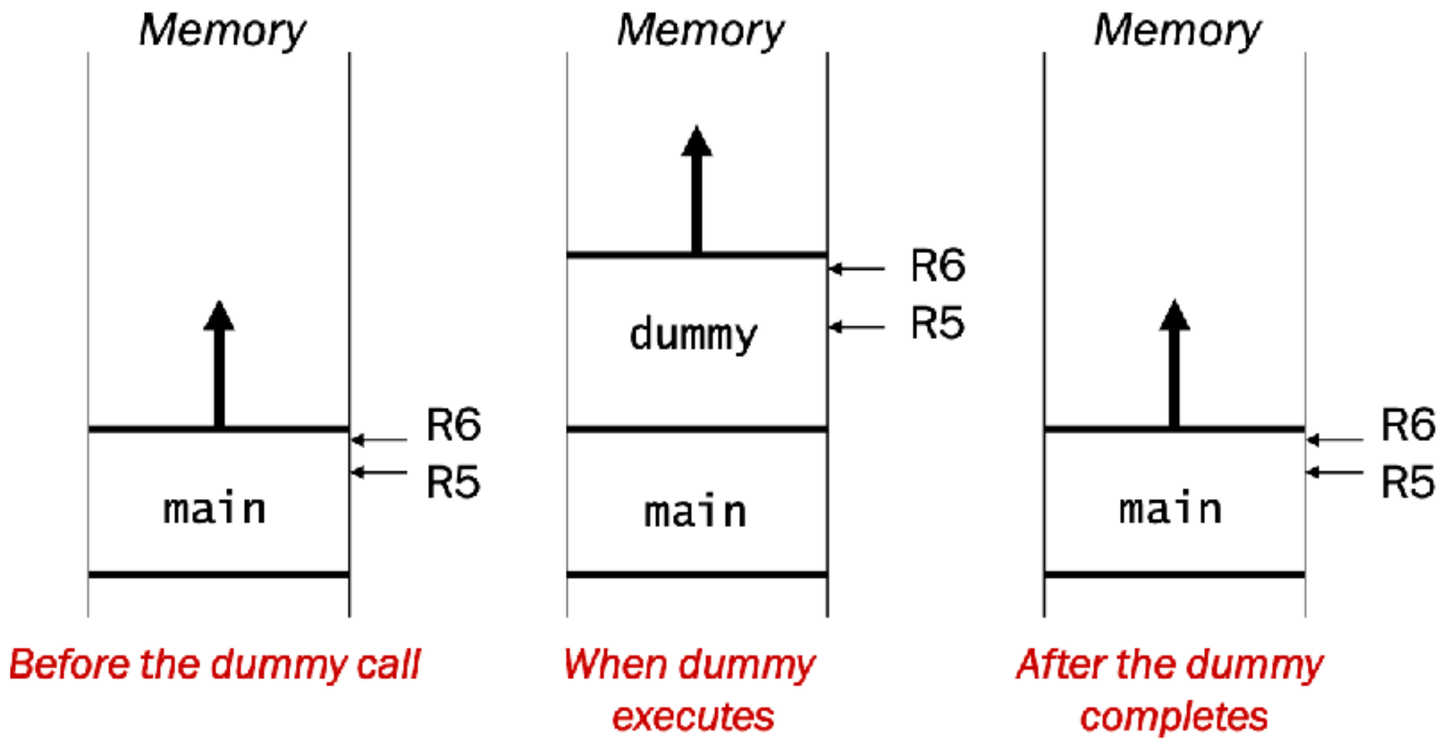

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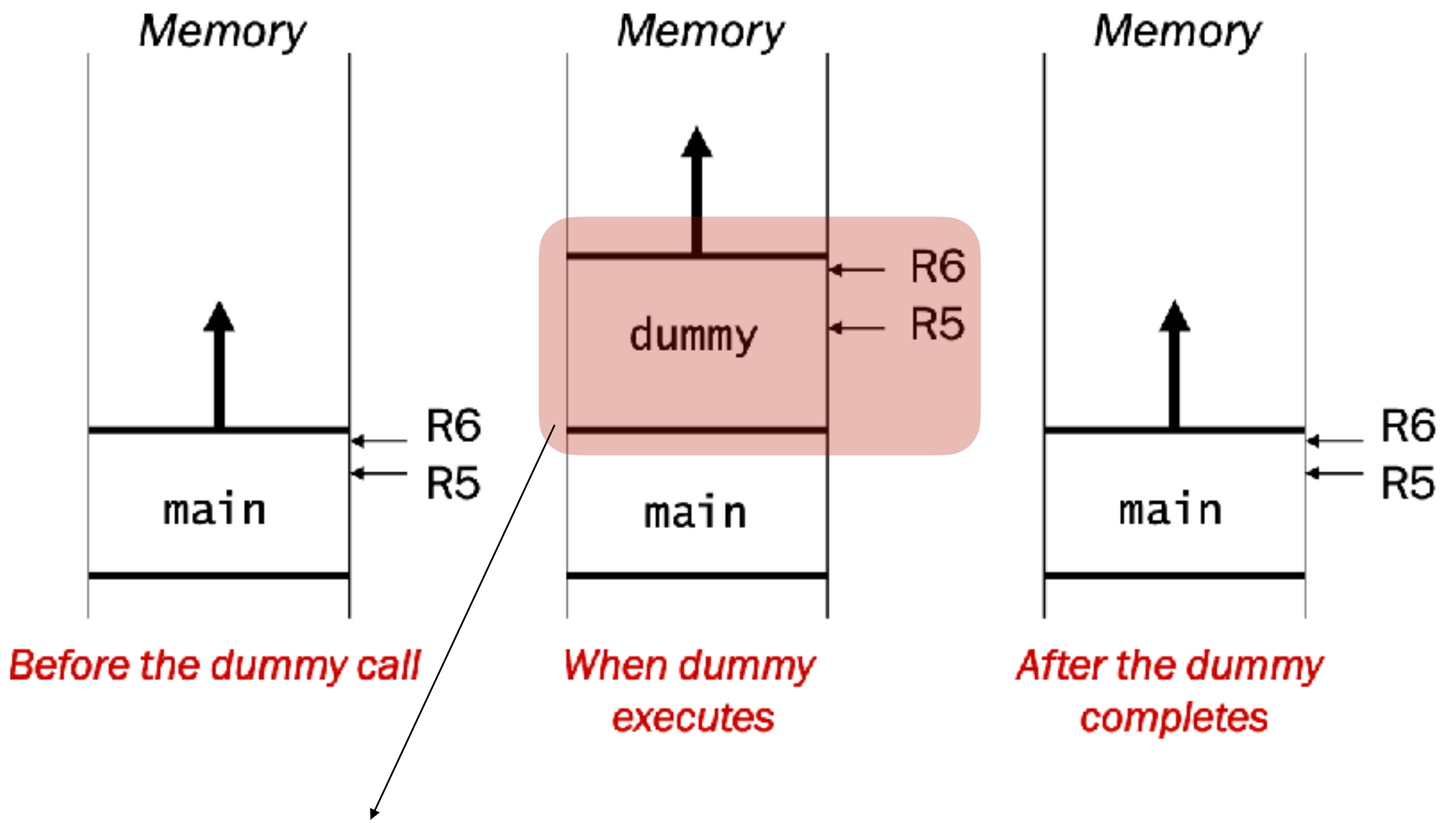

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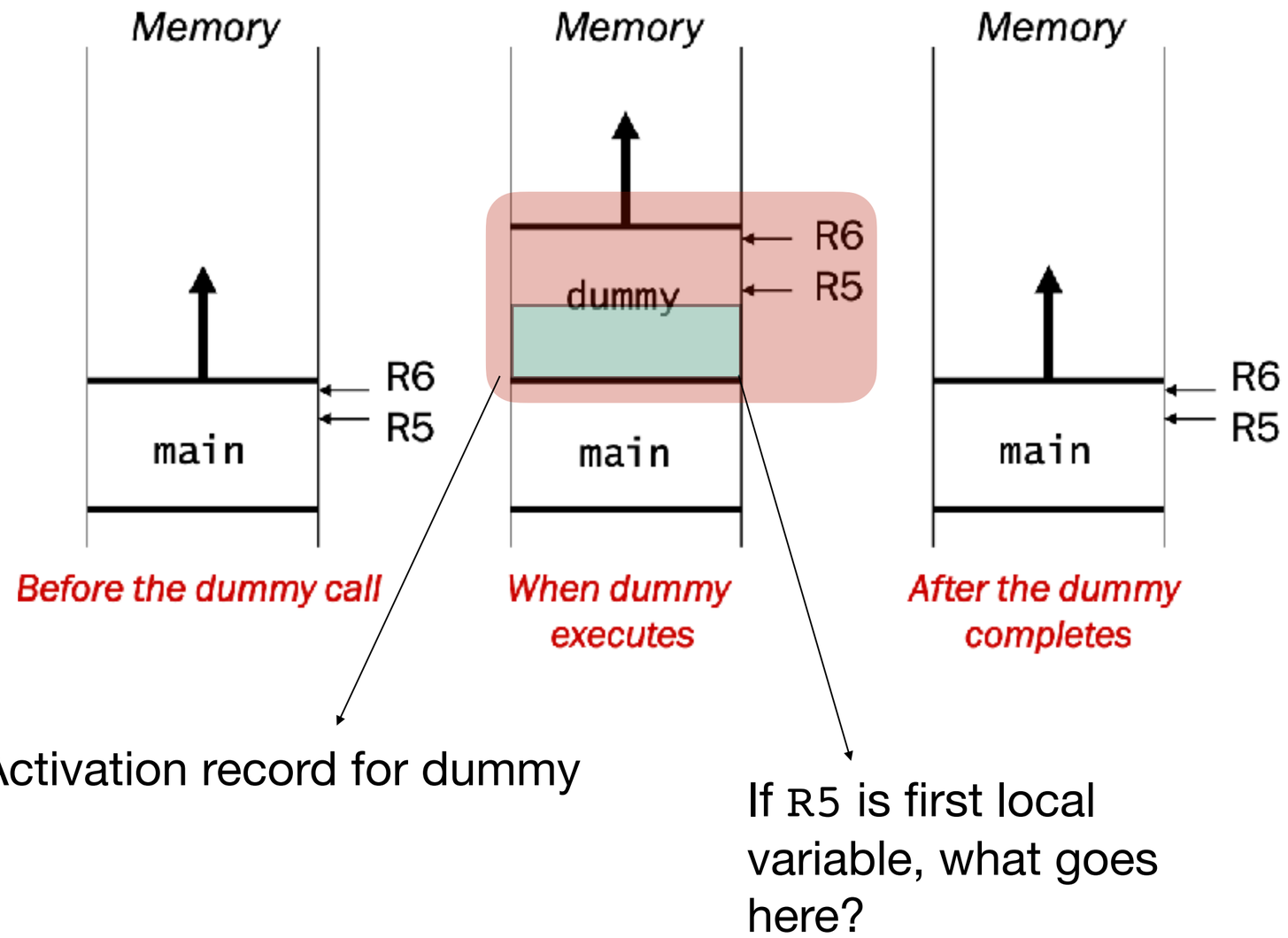

Activation record for dummy

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

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Activation record

Pushed before local variables

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Stack teardown

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Caller

Example function call

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```
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;
}
```

Run-time stack

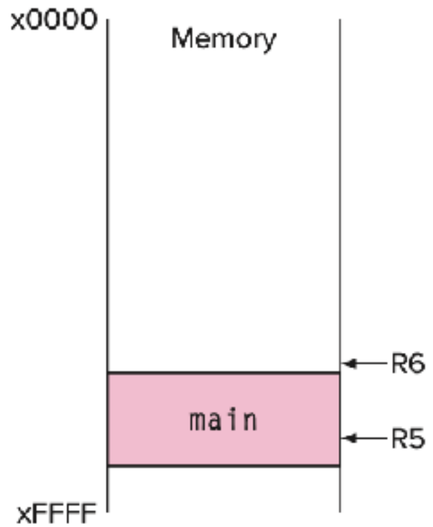
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

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

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;
}
```



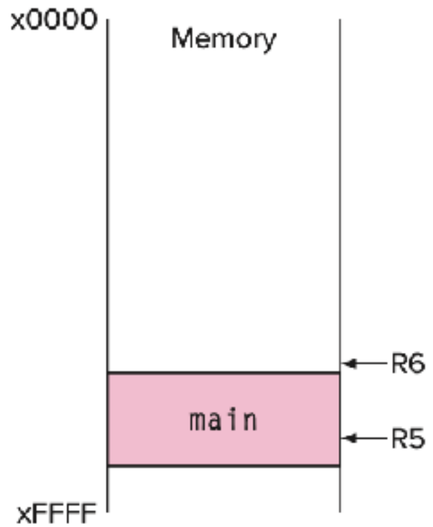
(a) Run-time stack when execution starts

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;
}
```



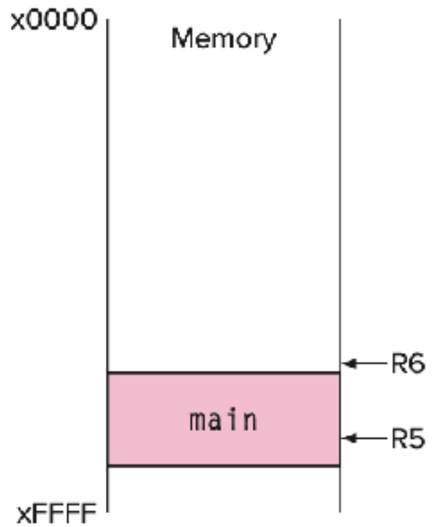
(a) Run-time stack when execution starts

Run-time stack

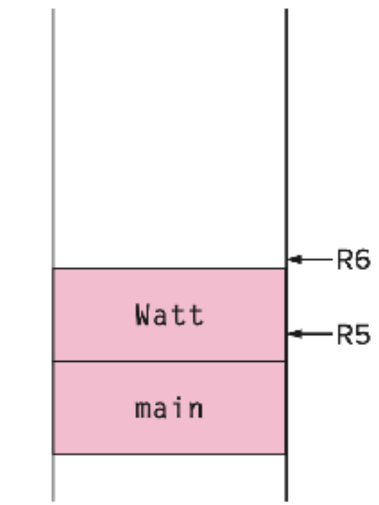
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

```
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



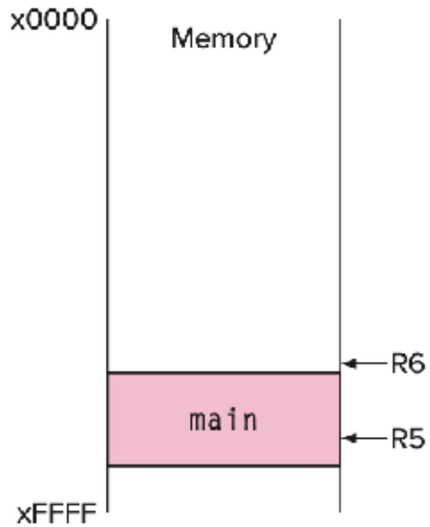
(b) When `Watt` executes

Run-time stack

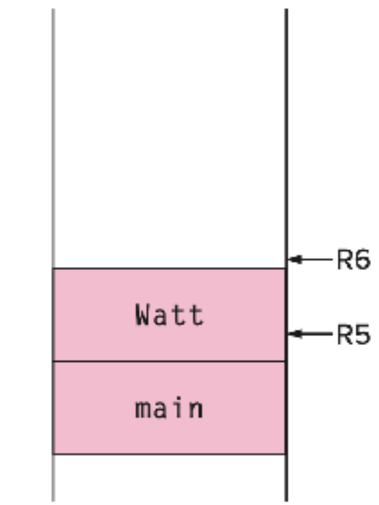
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

```
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



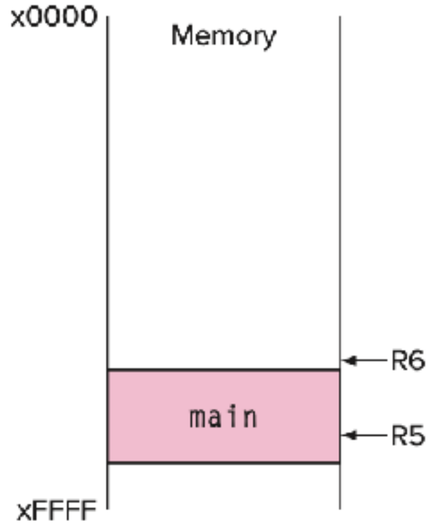
(b) When Watt executes

Run-time stack

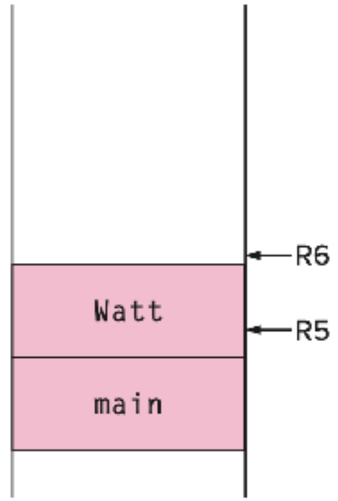
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

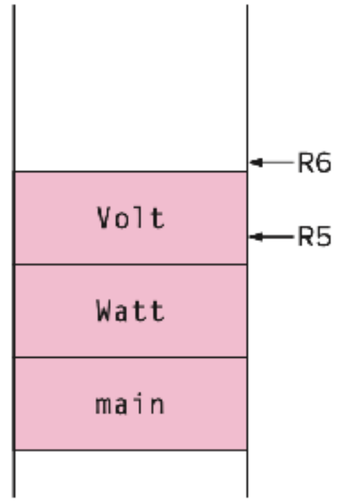
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



(a) Run-time stack when execution starts



(b) When `Watt` executes



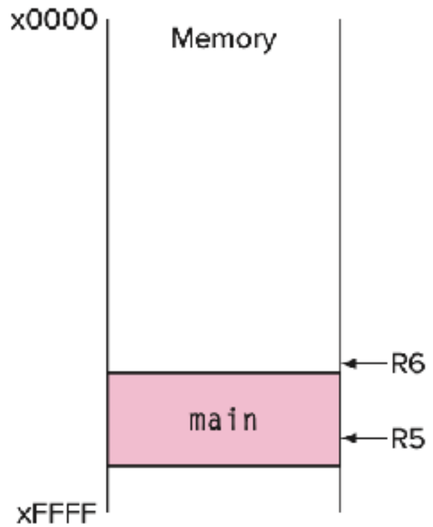
(c) When `Volt` executes

Run-time stack

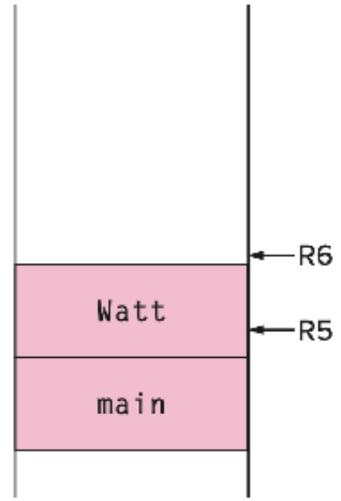
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

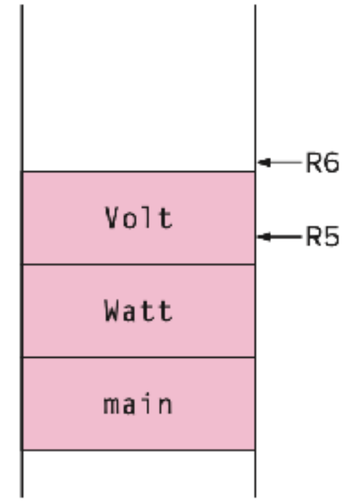
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



(a) Run-time stack when execution starts



(b) When `Watt` executes



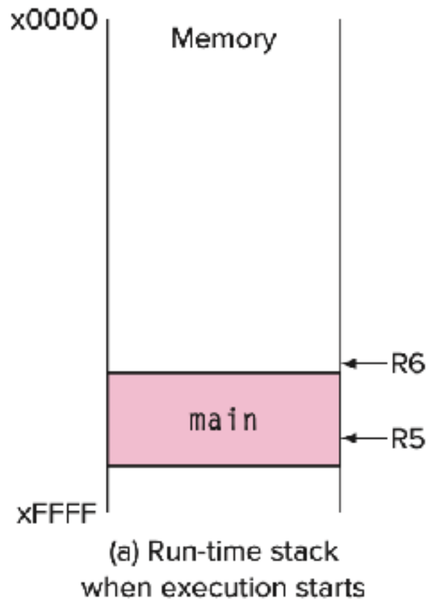
(c) When `Volt` executes

Run-time stack

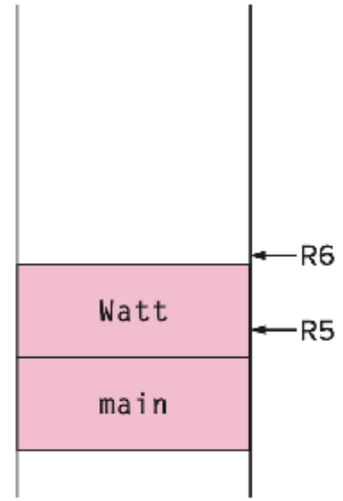
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

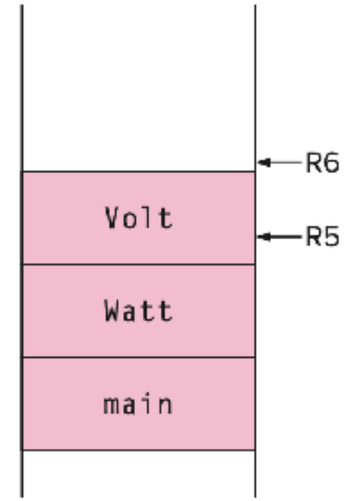
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



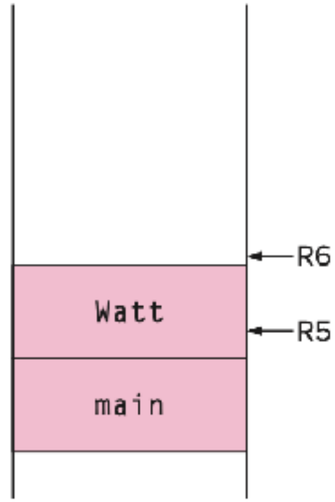
(a) Run-time stack when execution starts



(b) When `Watt` executes



(c) When `Volt` executes

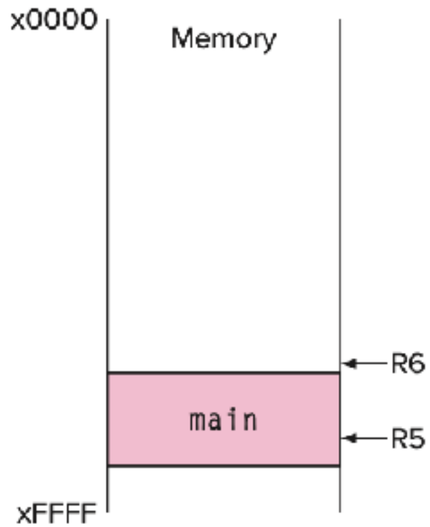


(d) After `Volt` completes

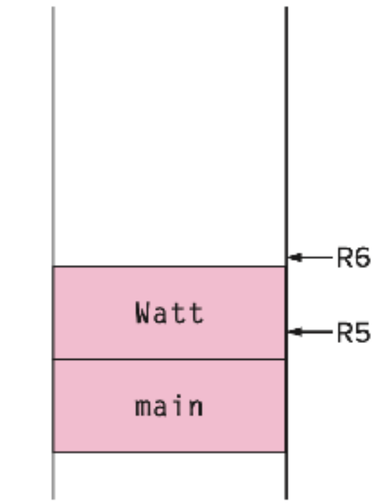
Run-time stack

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

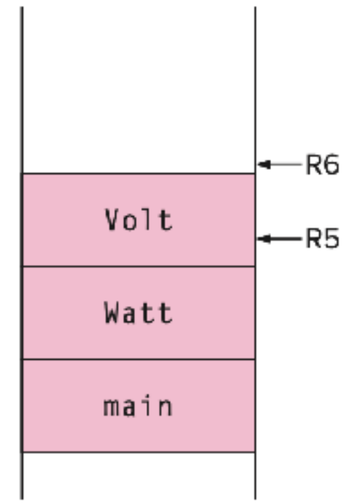
```
int Volt(int q, int r)
{
      int k;
      int m;
      ...
      return k;
}

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



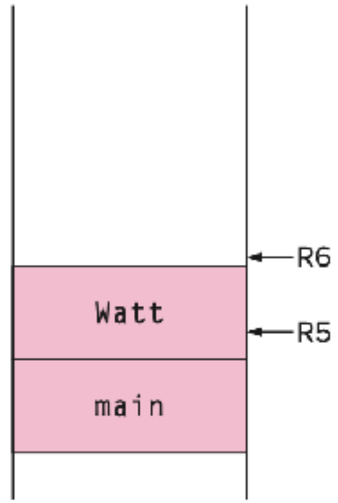
(a) Run-time stack when execution starts



(b) When `Watt` executes



(c) When `Volt` executes

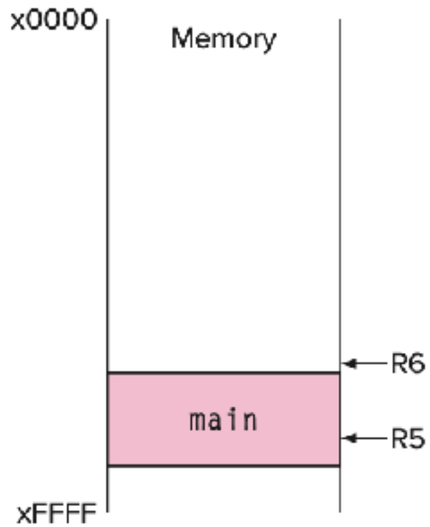


(d) After `Volt` completes

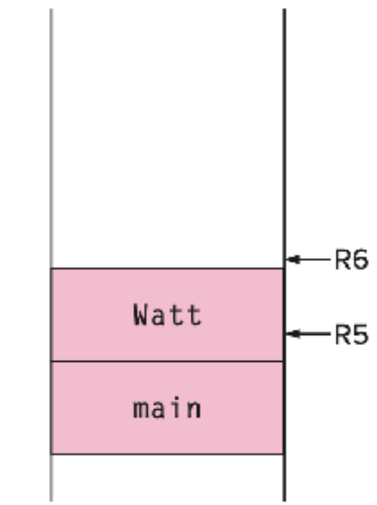
Run-time stack

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

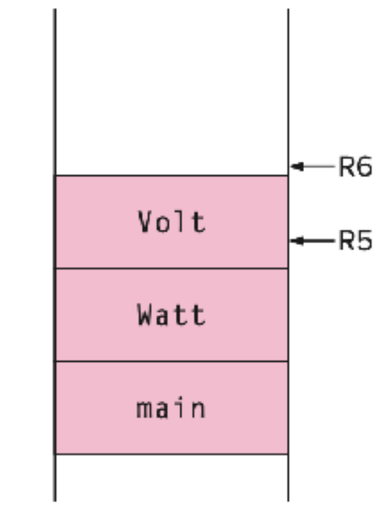
```
int Volt(int q, int r)
{
      int k;
      int m;
      ...
      return k;
}

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



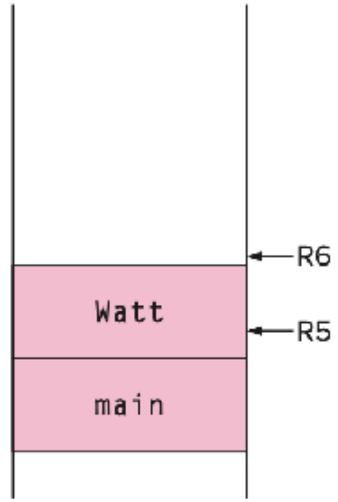
(a) Run-time stack when execution starts



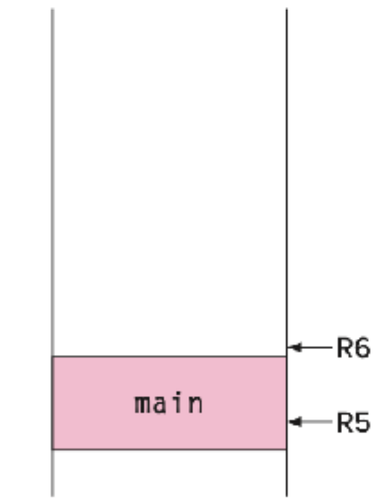
(b) When `Watt` executes



(c) When `Volt` executes



(d) After `Volt` completes



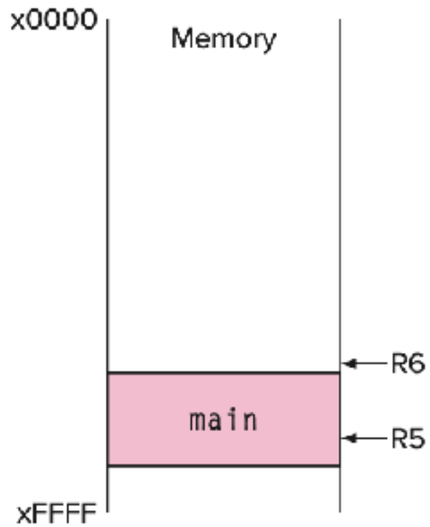
(e) After `Watt` completes

Run-time stack

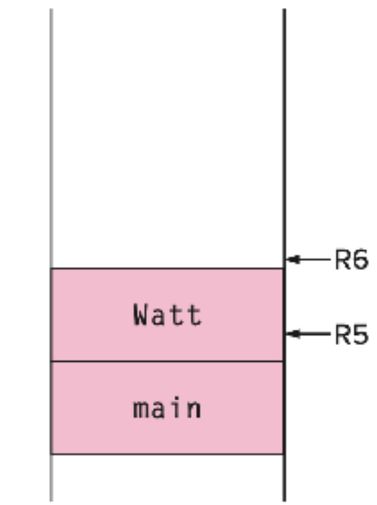
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

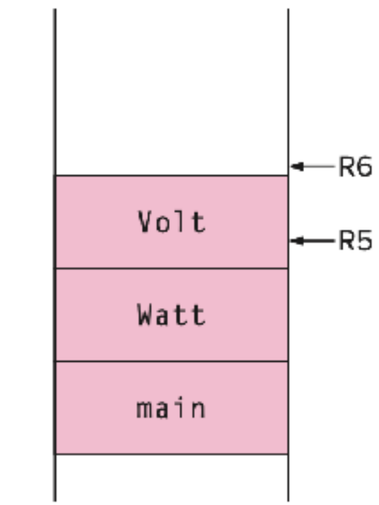
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



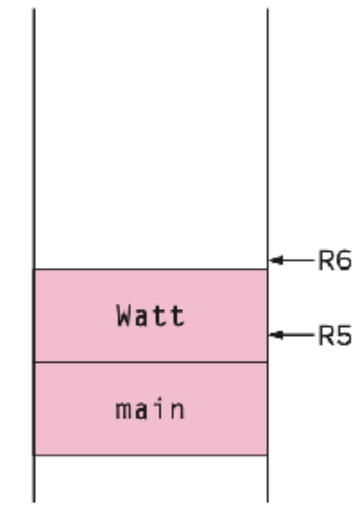
(a) Run-time stack when execution starts



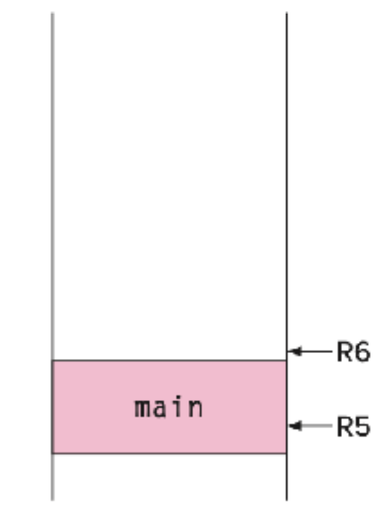
(b) When `Watt` executes



(c) When `Volt` executes



(d) After `Volt` completes



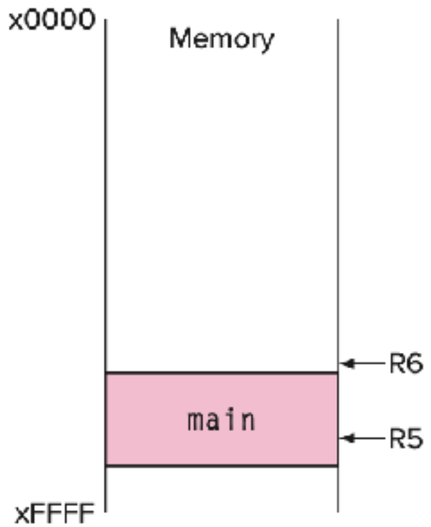
(e) After `Watt` completes

Run-time stack

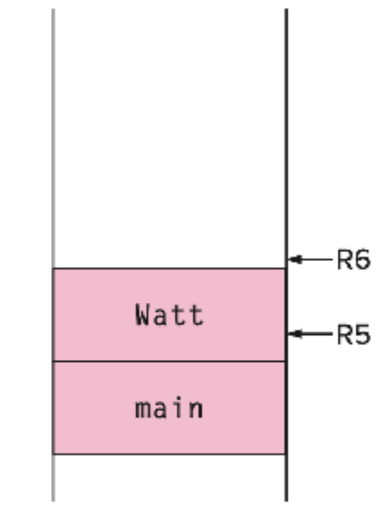
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

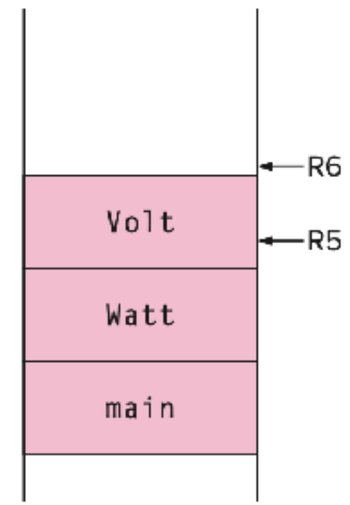
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



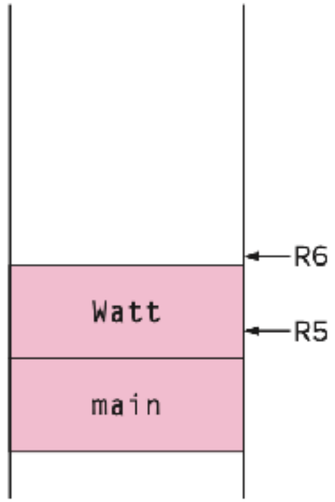
(a) Run-time stack when execution starts



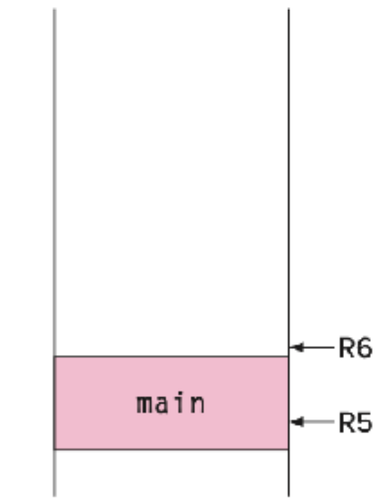
(b) When `Watt` executes



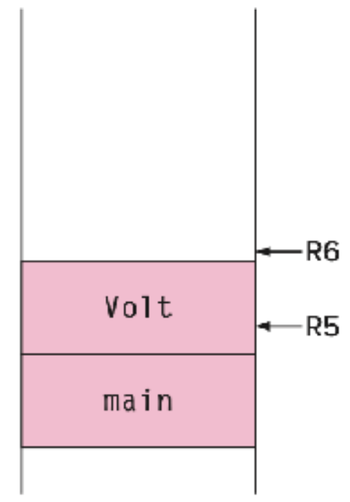
(c) When `Volt` executes



(d) After `Volt` completes



(e) After `Watt` completes



(f) When `Volt` executes

C Run-time stack protocol

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.

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.

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

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

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

C Run-time stack protocol

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

C Run-time stack protocol

- `Volt` called with two arguments

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

C Run-time stack protocol

- `Volt` called with two arguments
- Value *returned* by `Volt` is assigned to local integer variable `w`

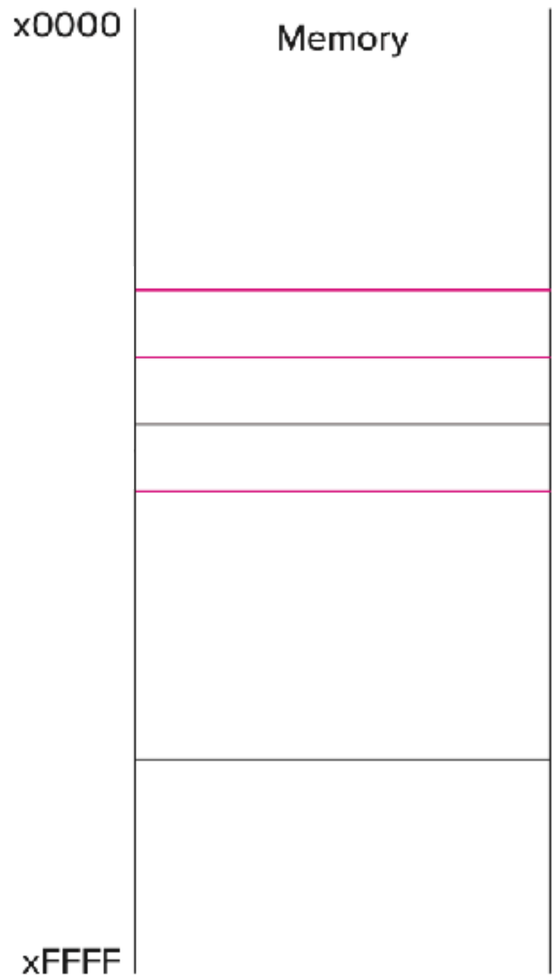
```
int Watt(int a)
{
     int w;
     ...
     w = Volt(w,10);
     …
     return w;
}
```

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

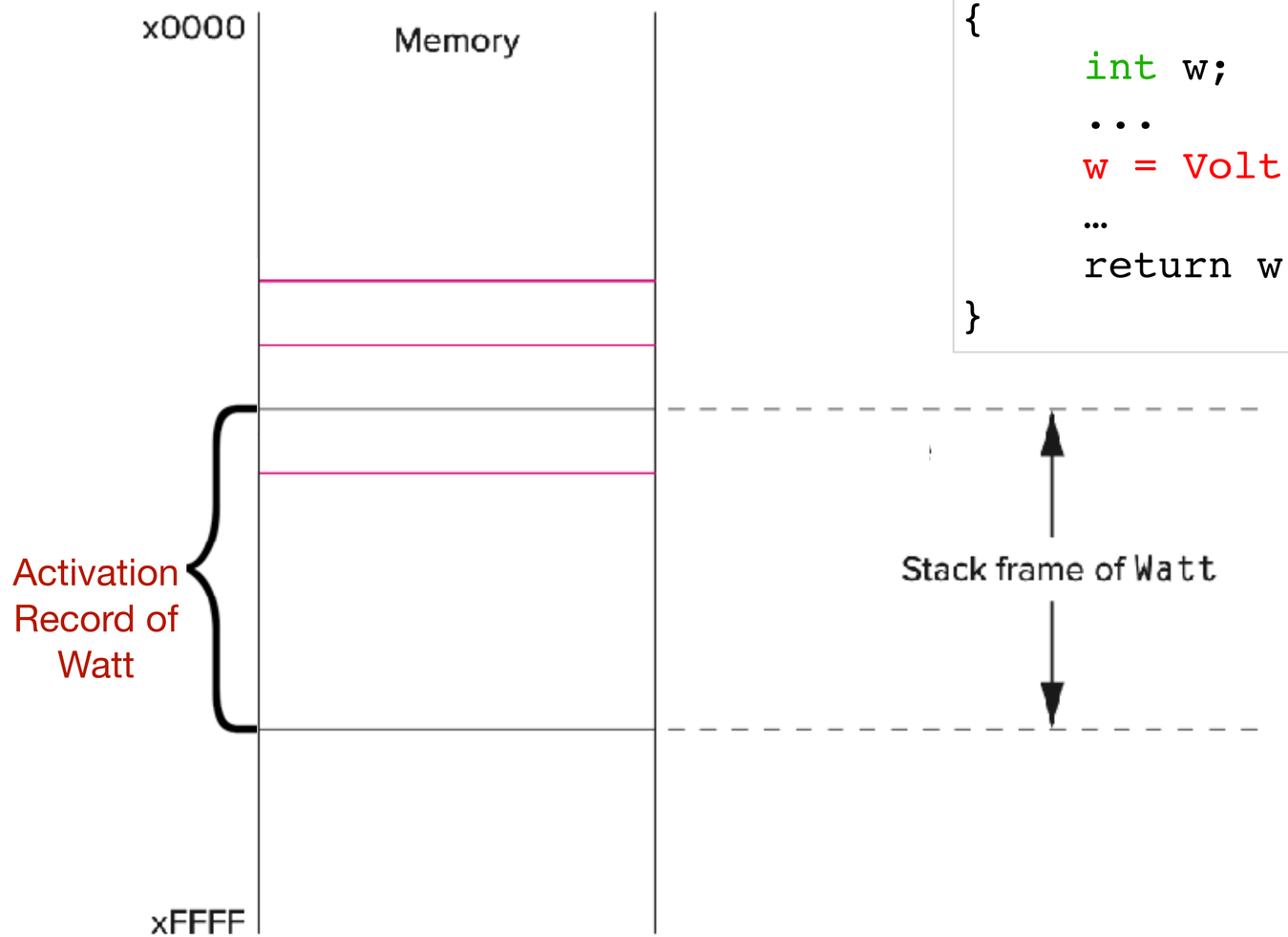
```
int Watt(int a)
{
     int w;
     ...
     w = Volt(w,10);
     …
     return w;
}
```

LC-3 Implementation



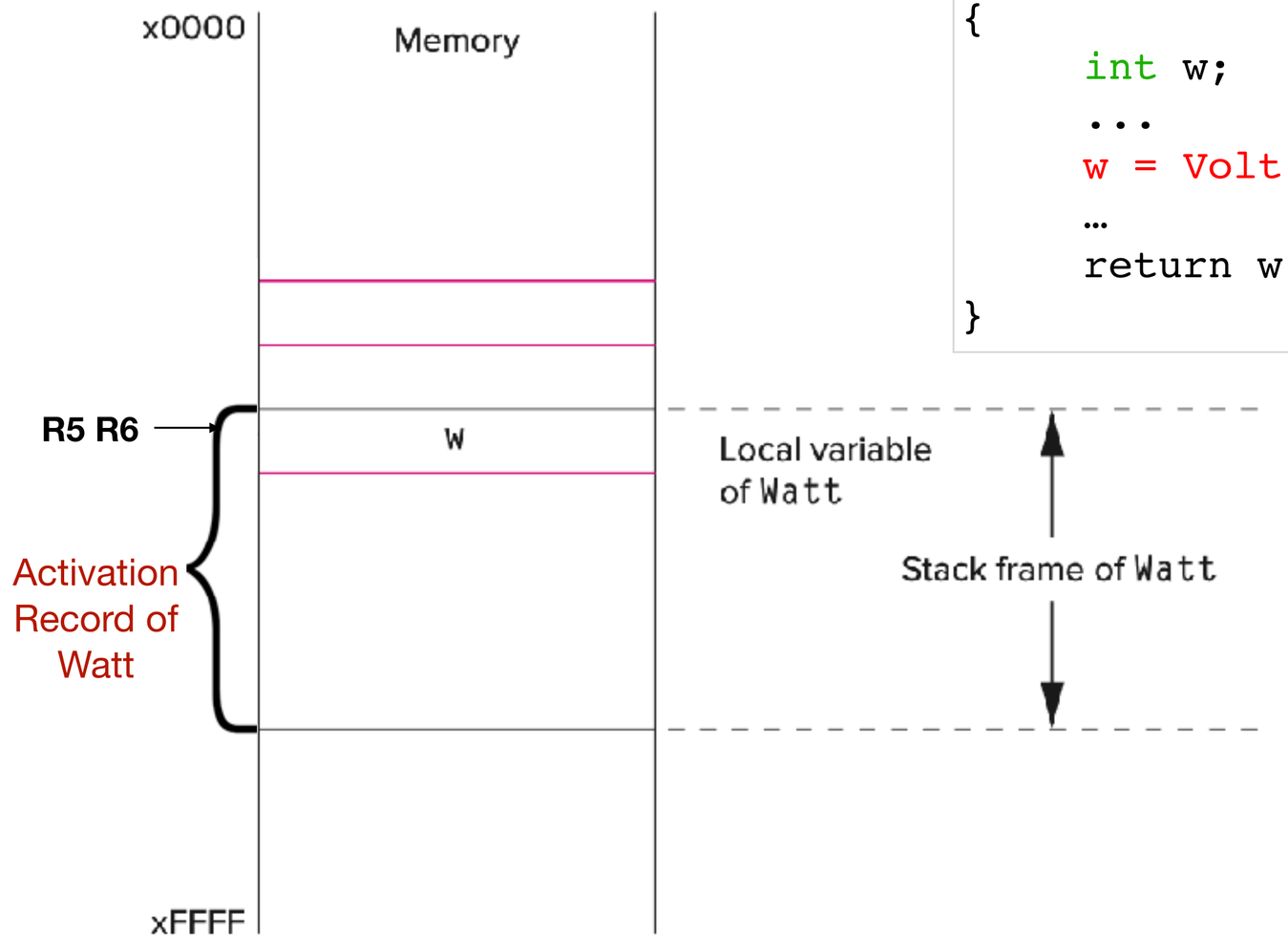

```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation




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

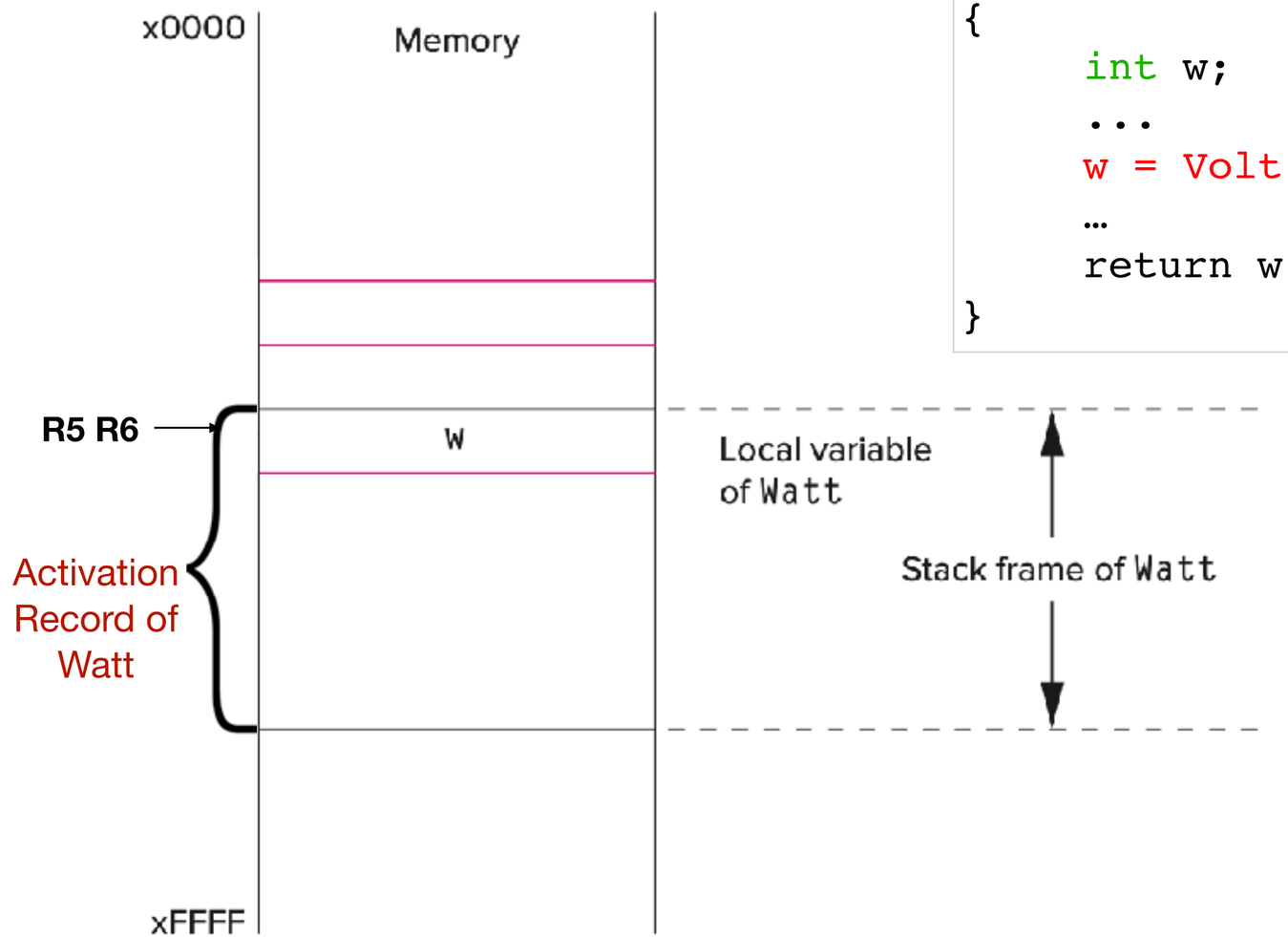
LC-3 Implementation




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

LC-3 Implementation

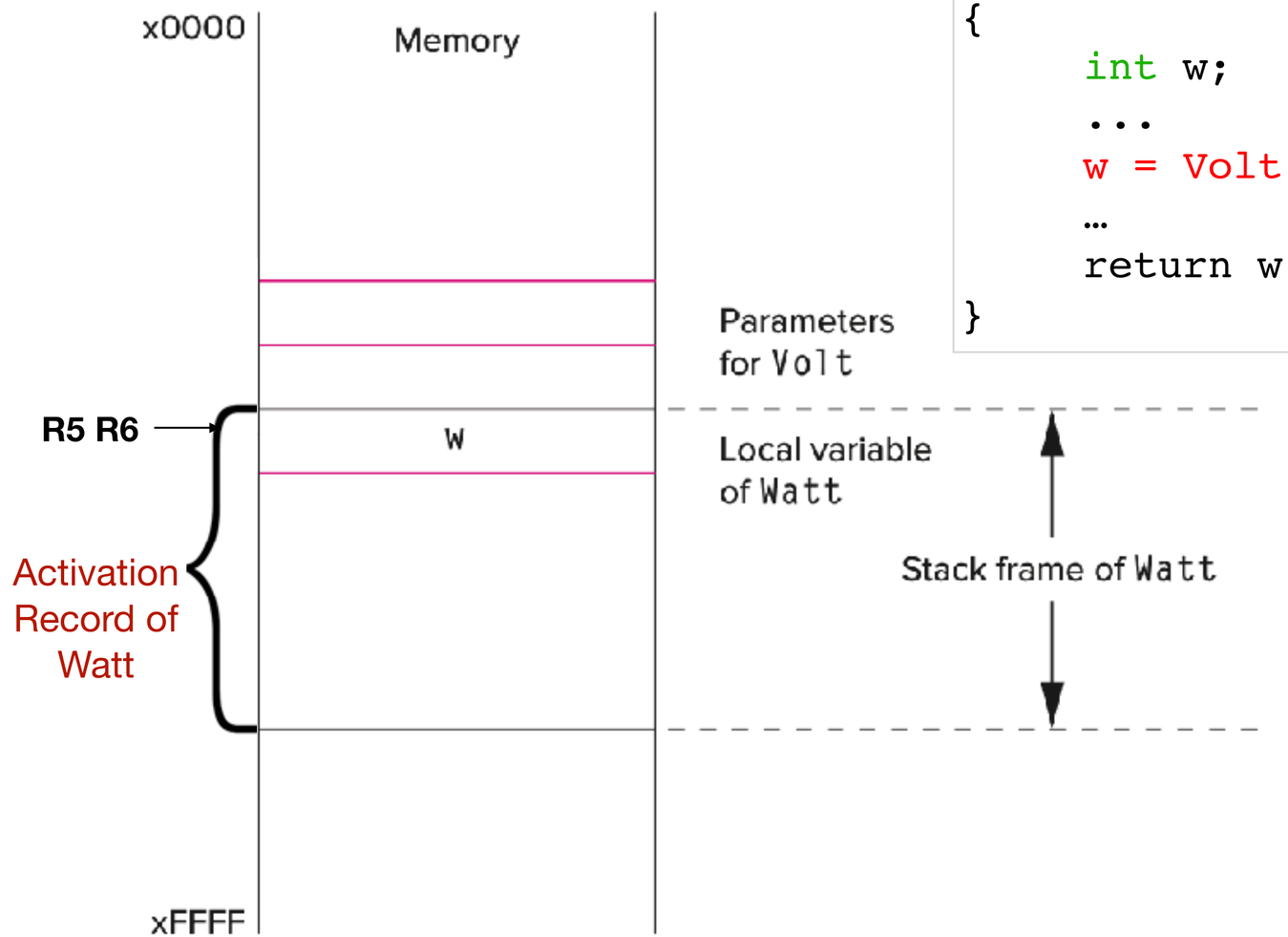
1. Caller setup (push callee's arguments onto stack)




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

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)

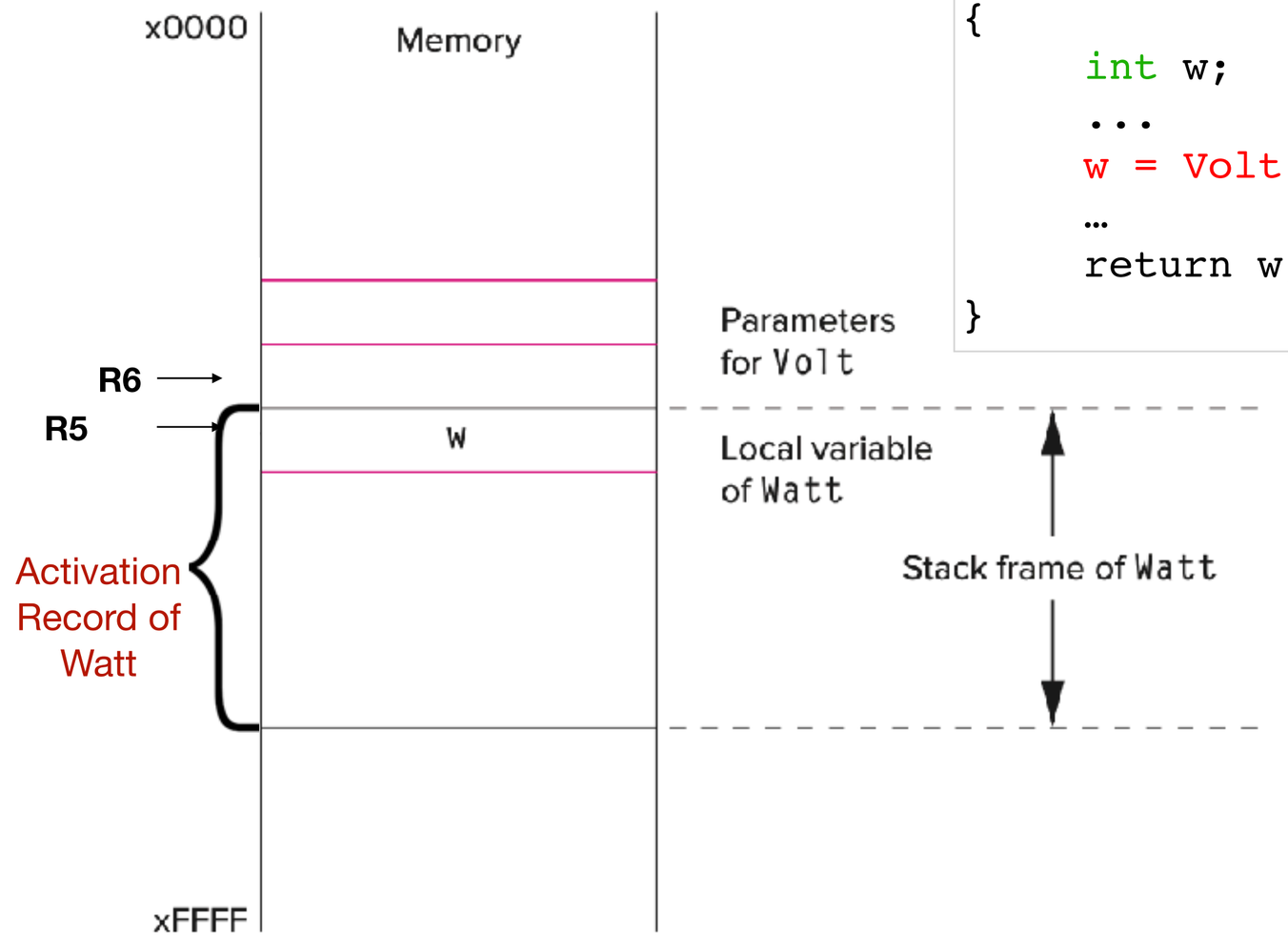



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)

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

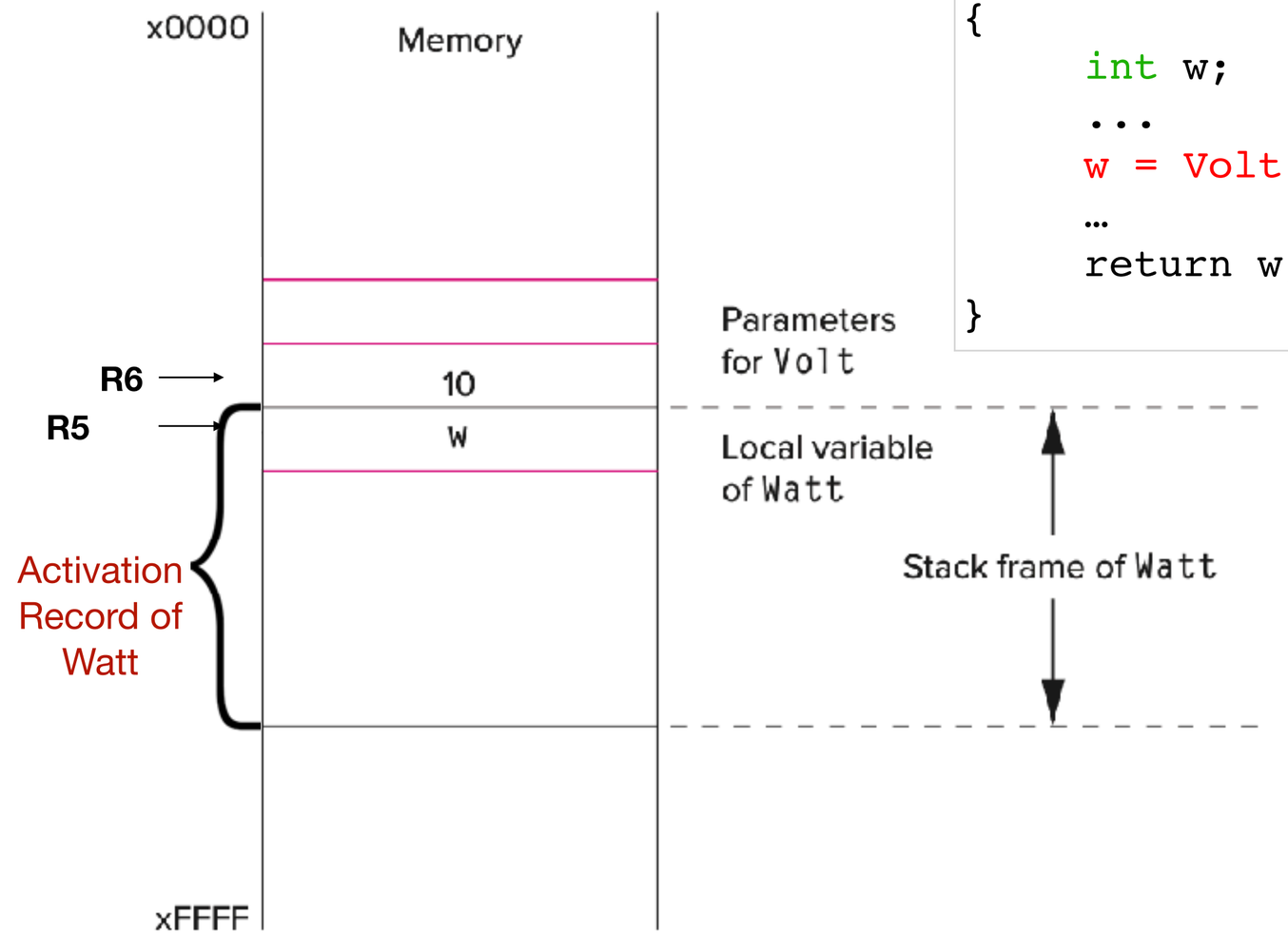



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)

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

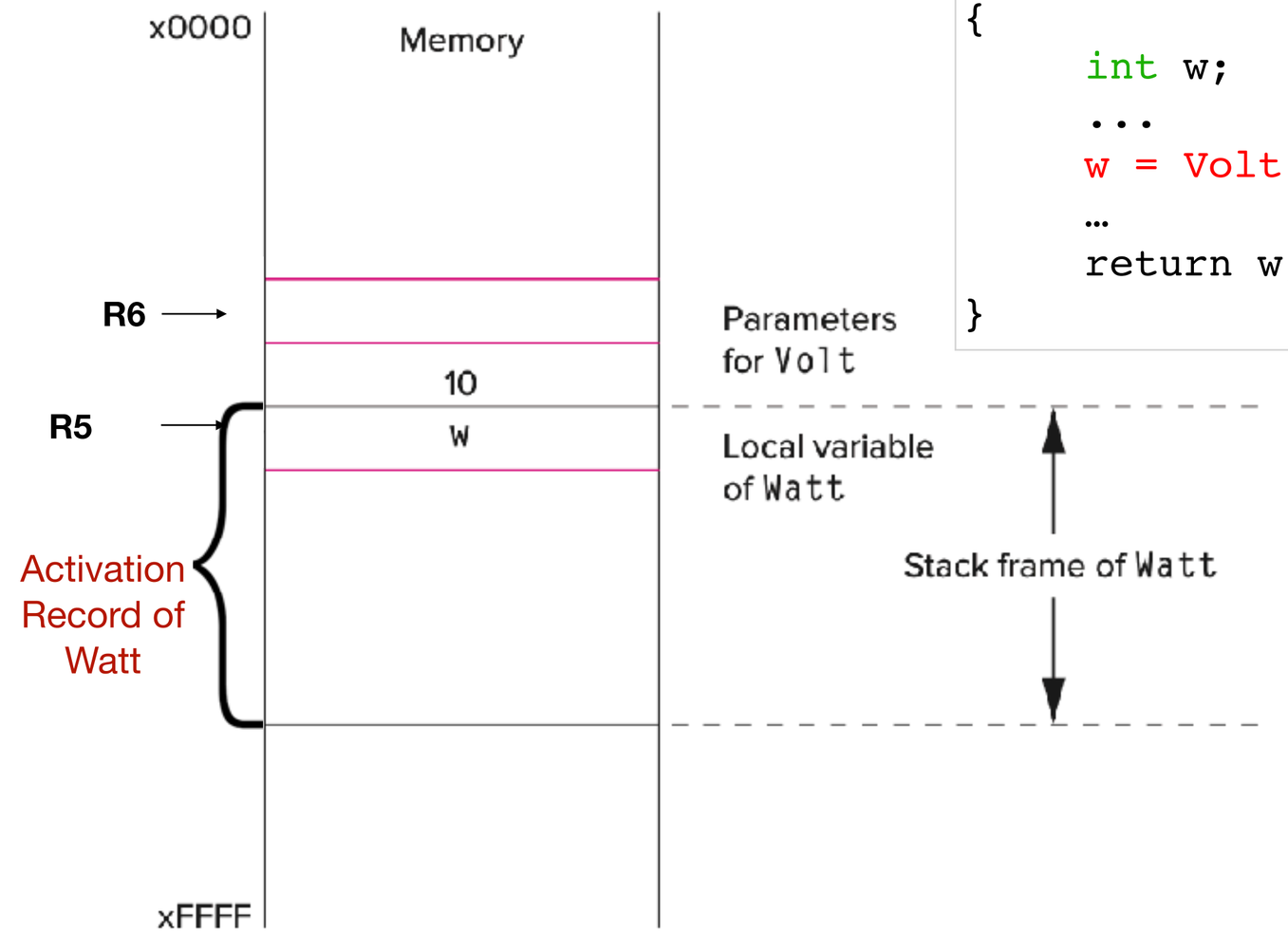



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)

```
; 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
```

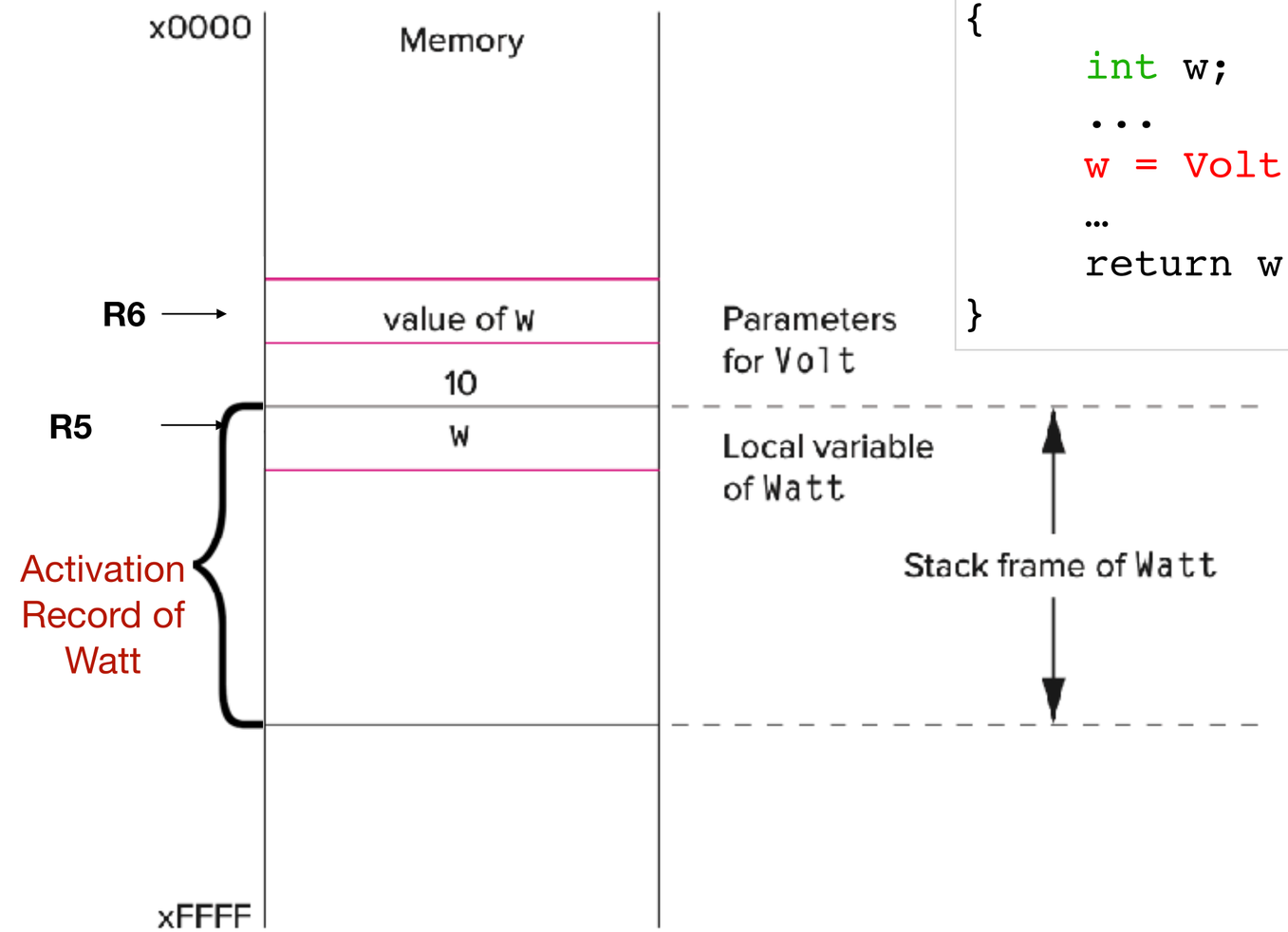



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

1. Caller setup (push callee's arguments onto stack)

```
; 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
```

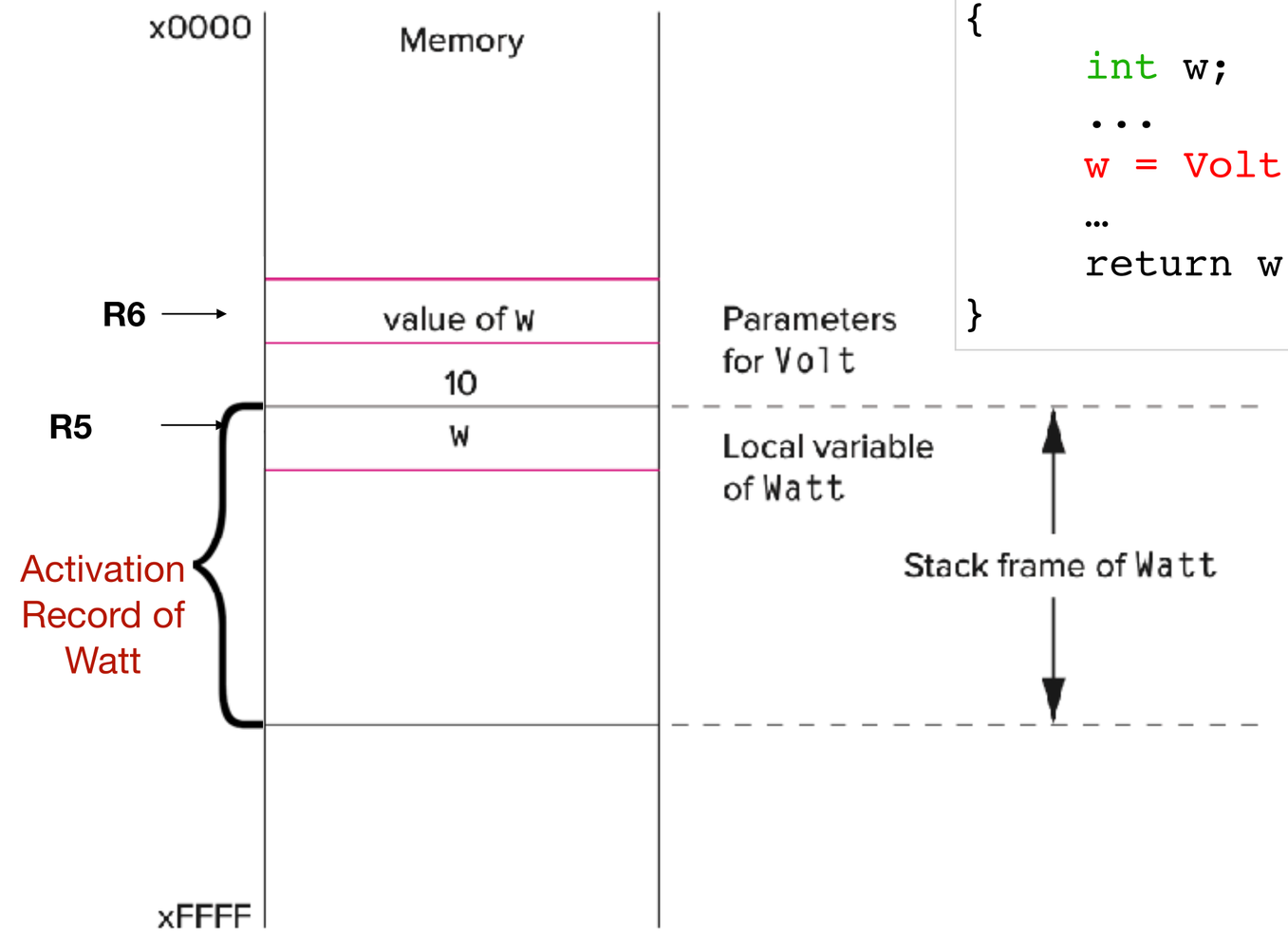



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

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
```

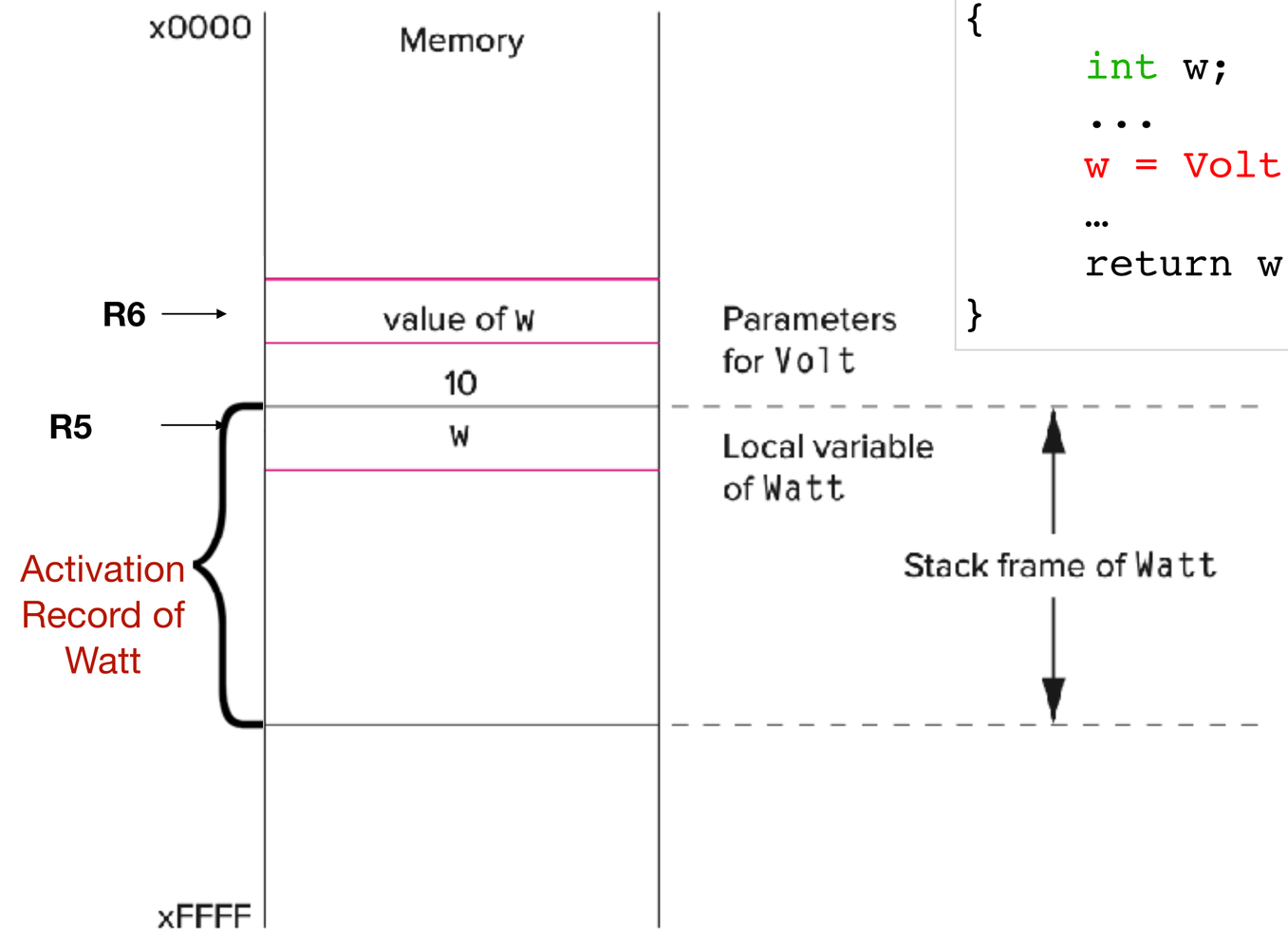



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

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

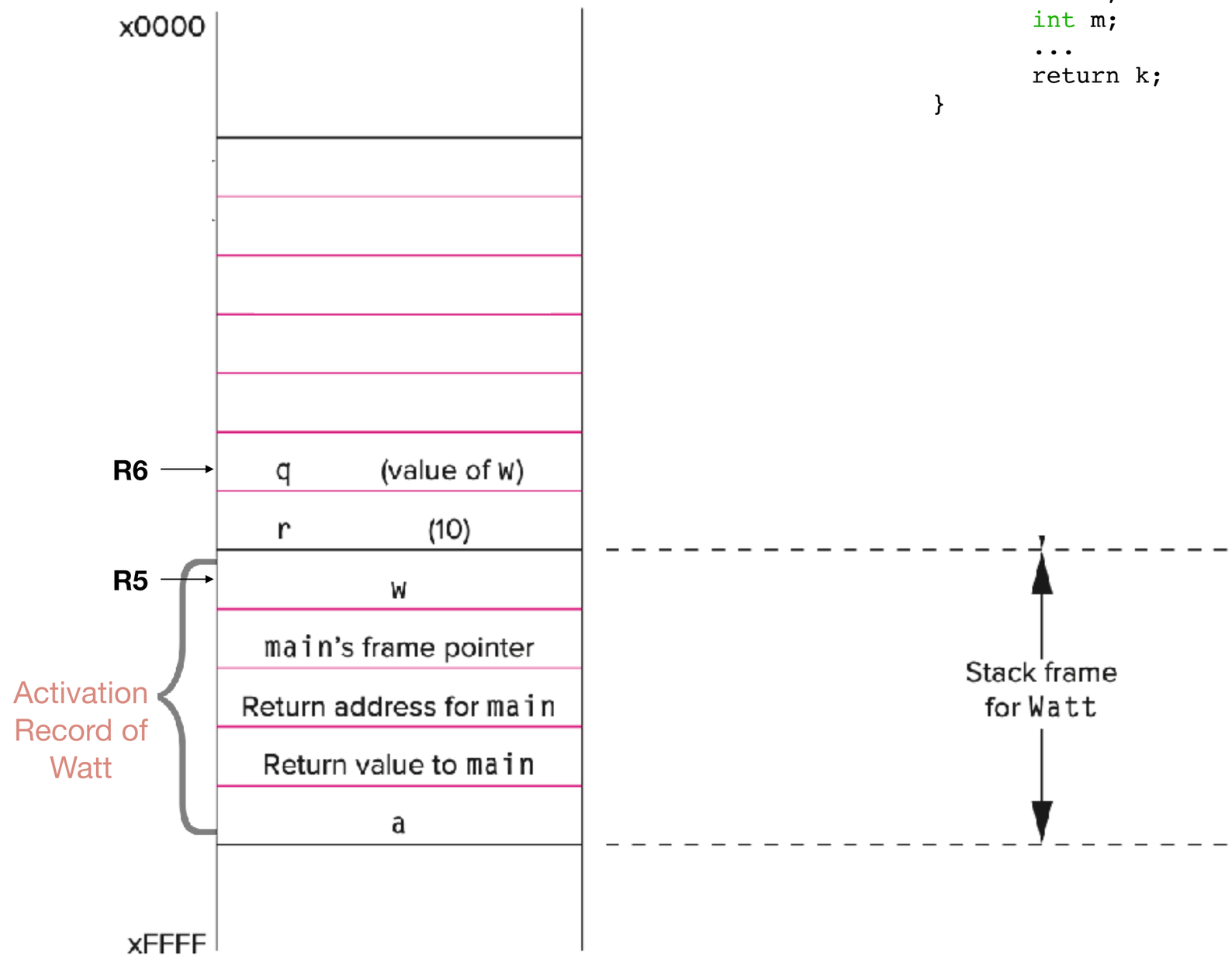
```
; push second arg
AND R0, R0, #0
ADD R0, R0, #10
ADD R6, R6, #-1
STR R0, R6, #0

; 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;
}
```

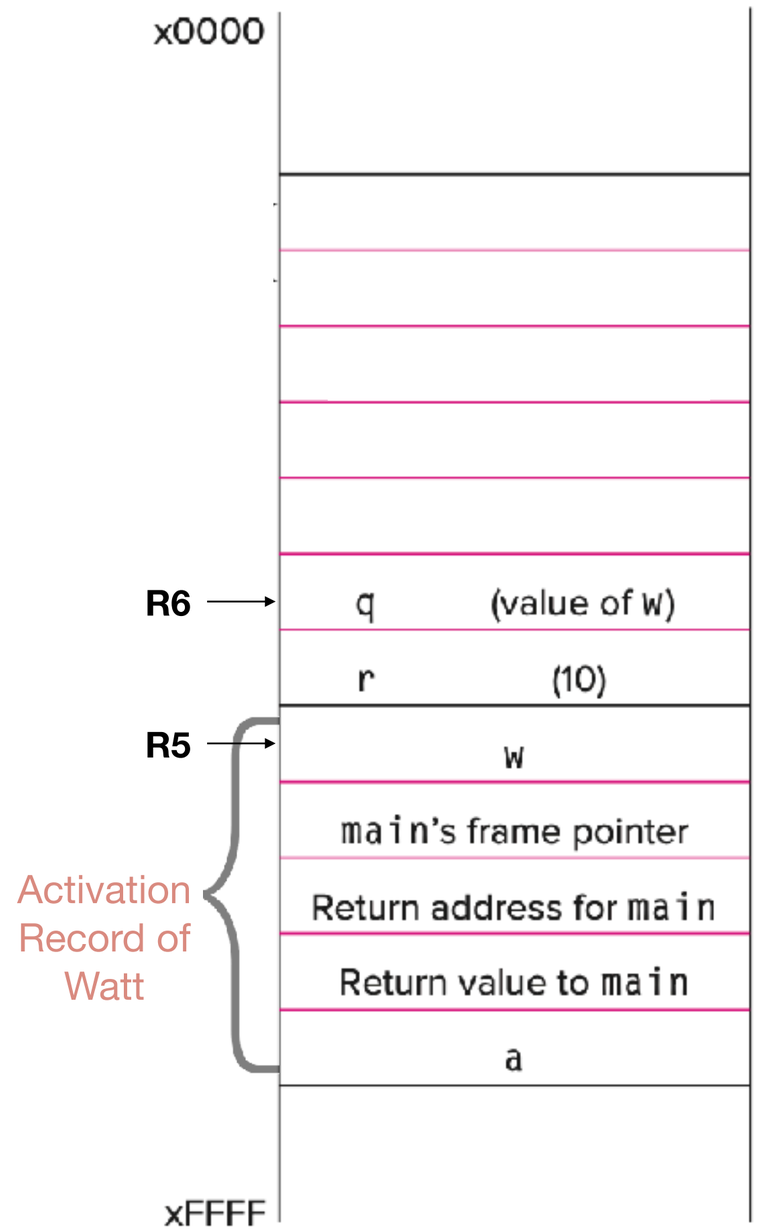
LC-3 Implementation

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



LC-3 Implementation

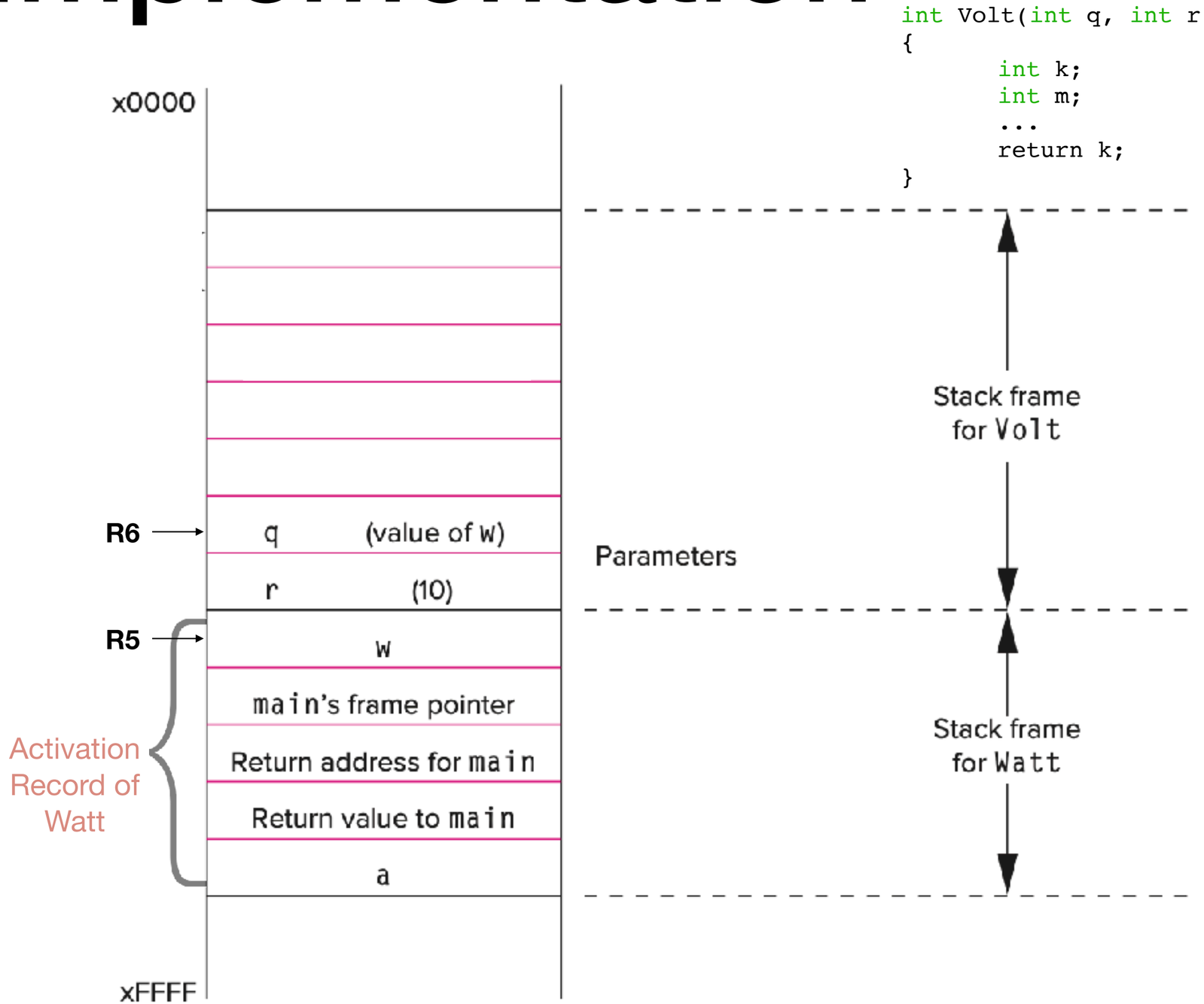
3. Callee setup (push bookkeeping info and local variables onto stack)




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

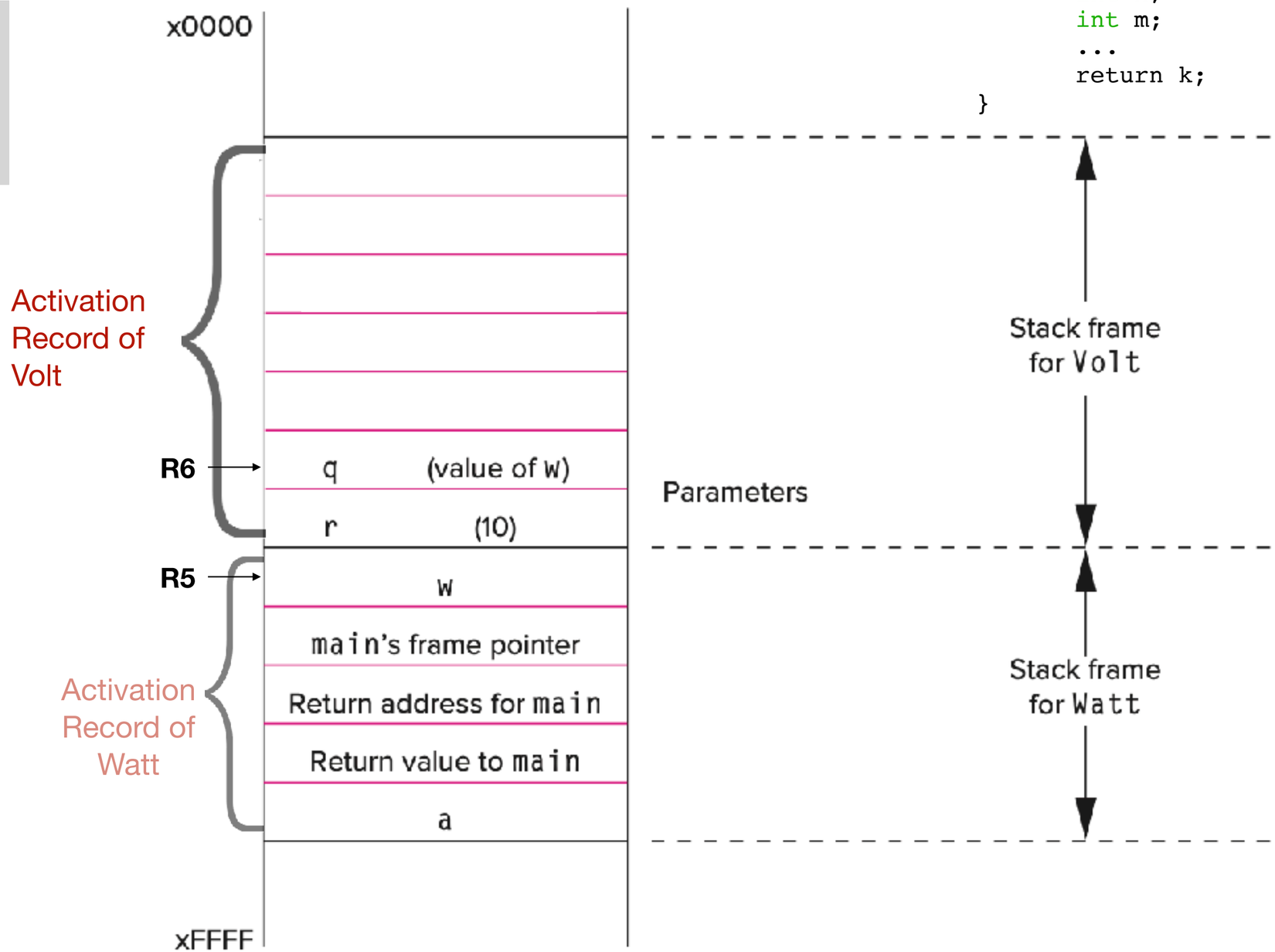
LC-3 Implementation

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



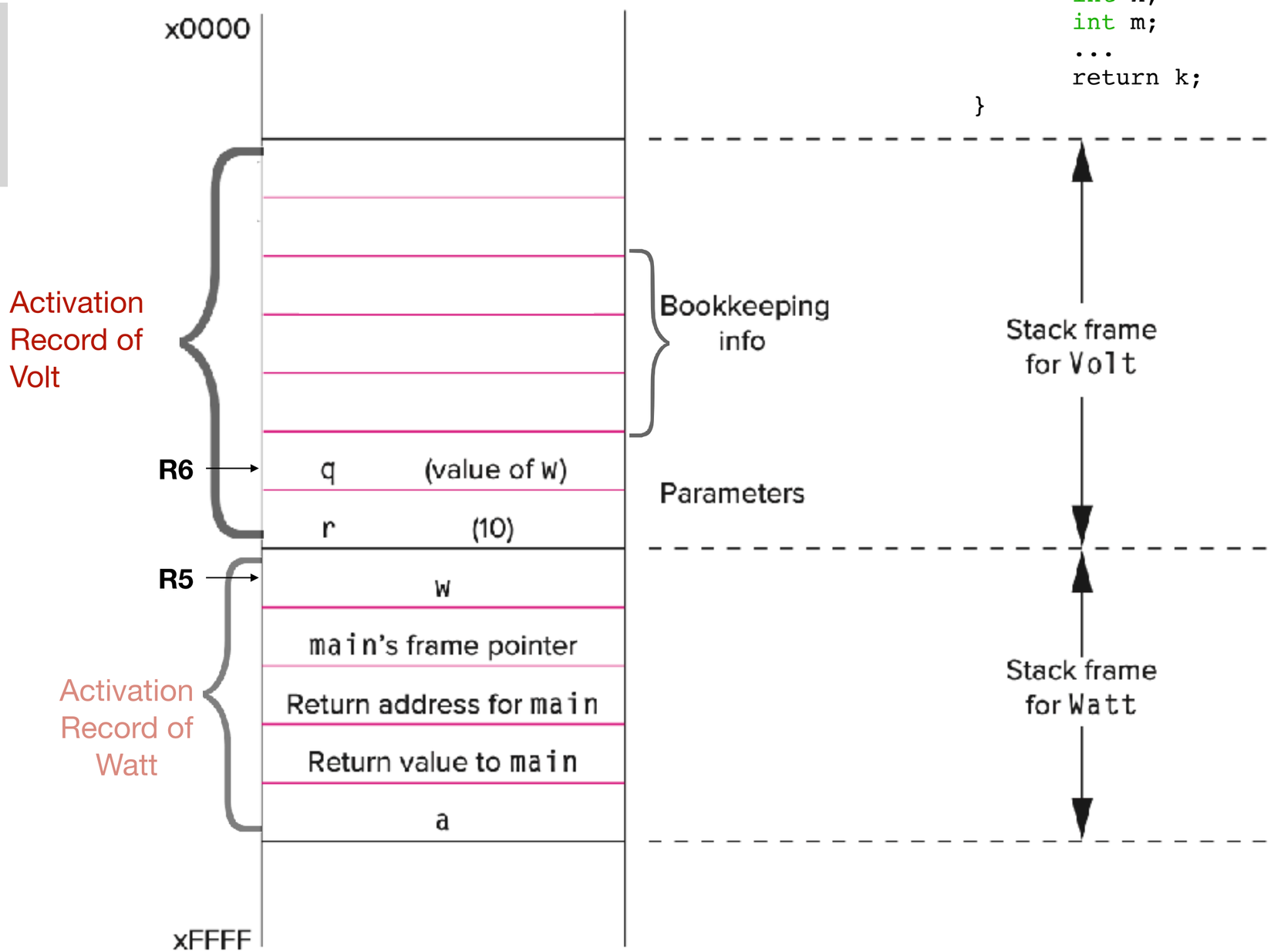
LC-3 Implementation

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



LC-3 Implementation

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

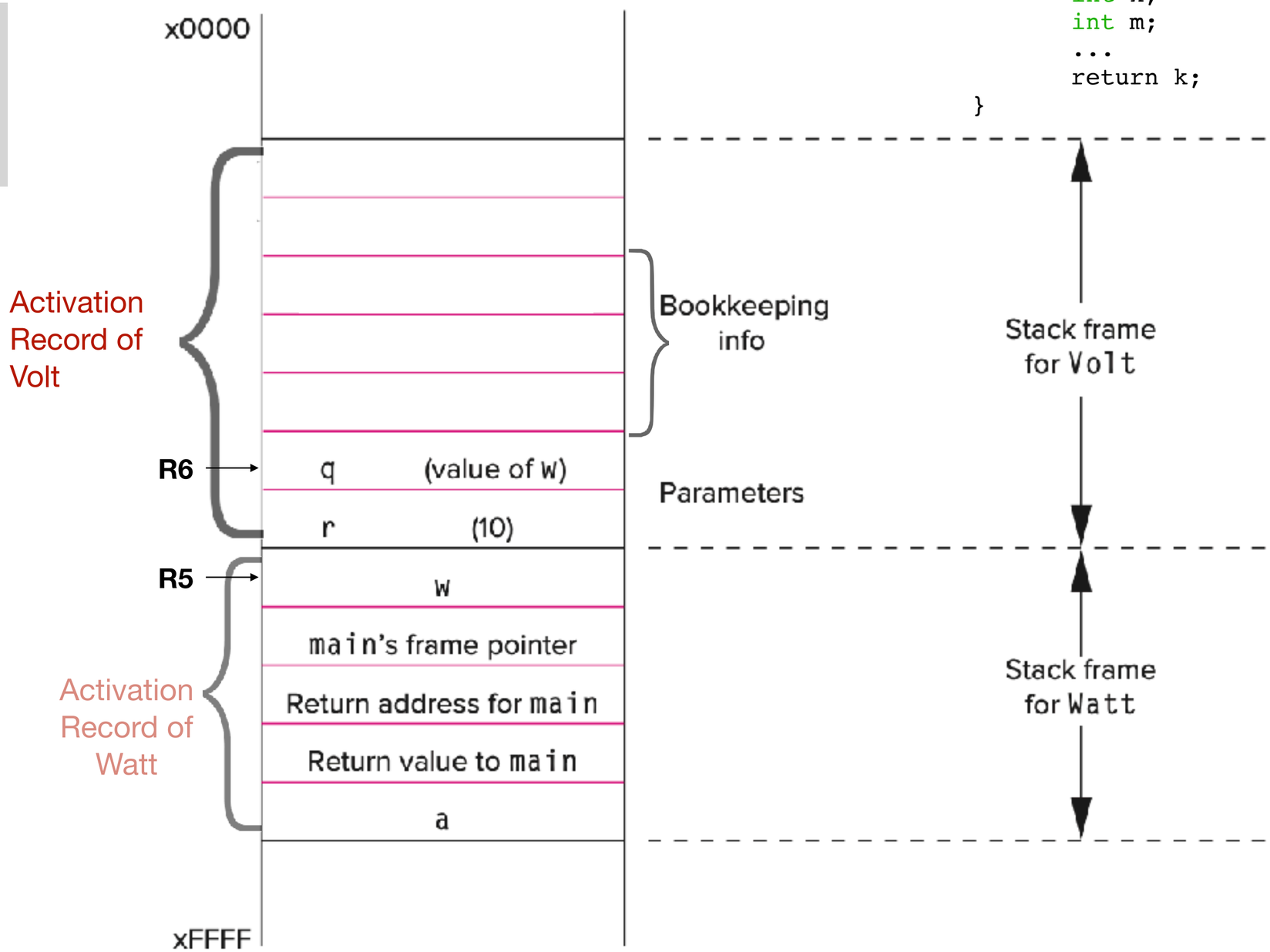


LC-3 Implementation

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

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

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

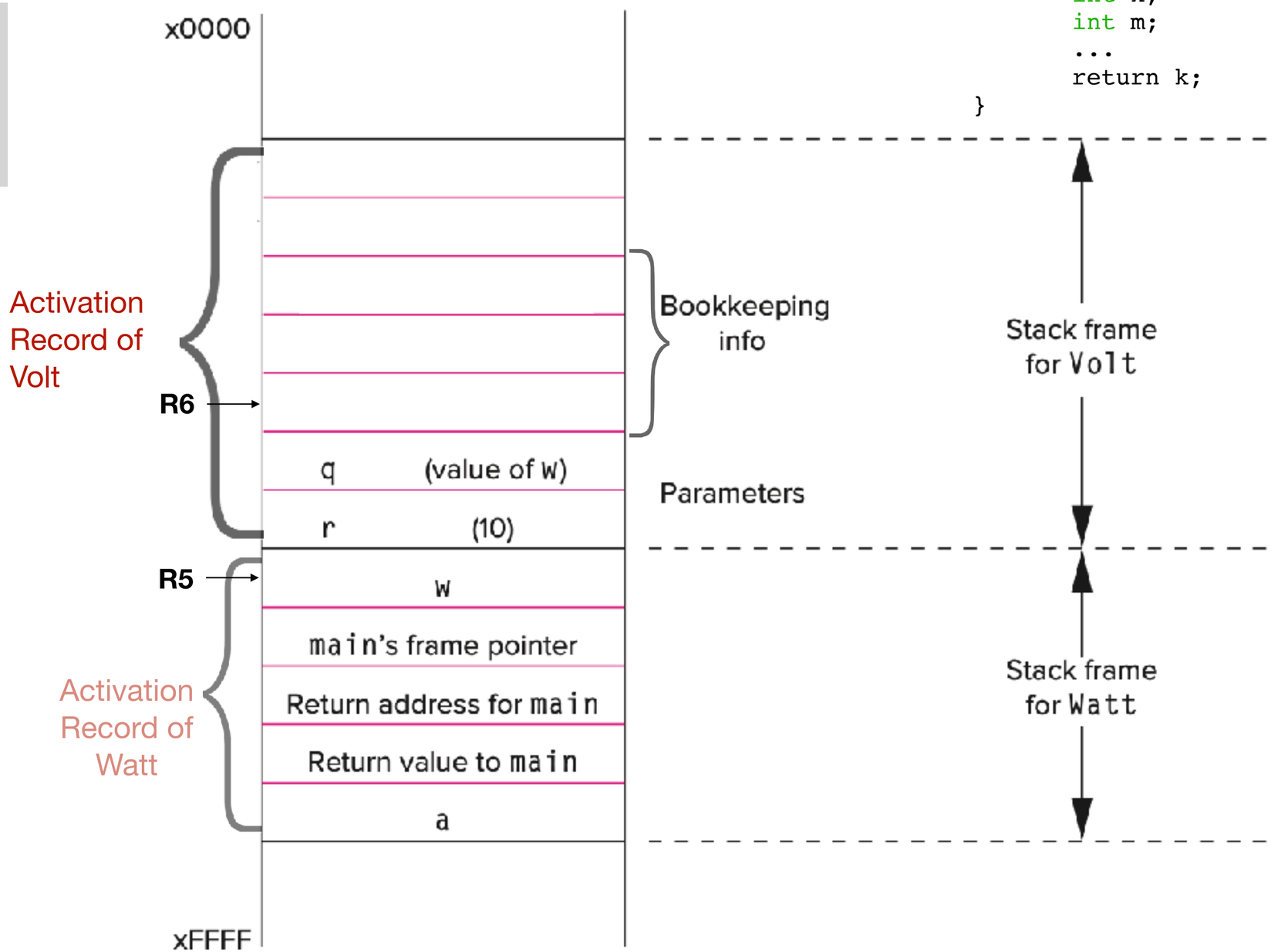


LC-3 Implementation

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

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

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

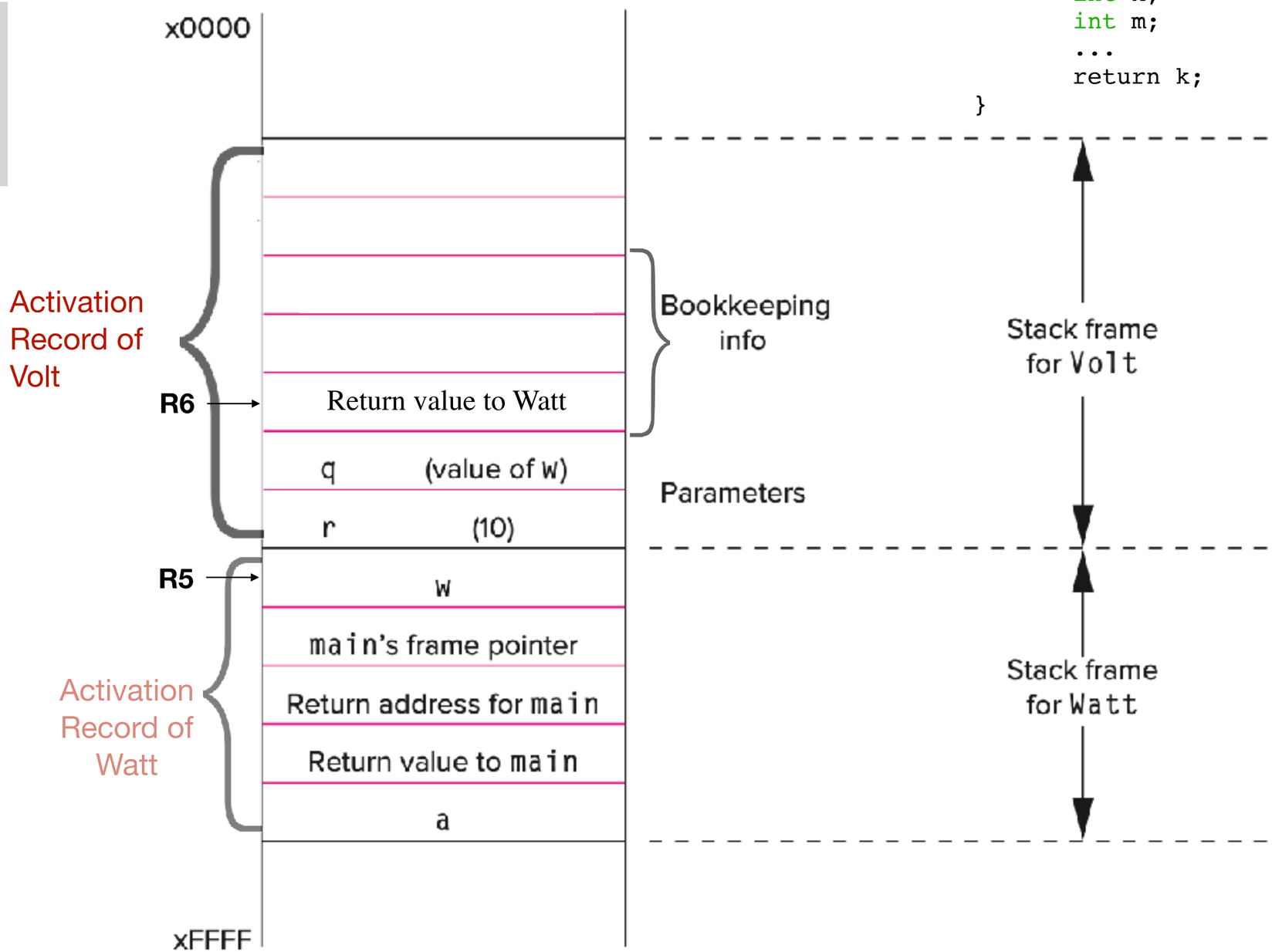


LC-3 Implementation

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

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

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

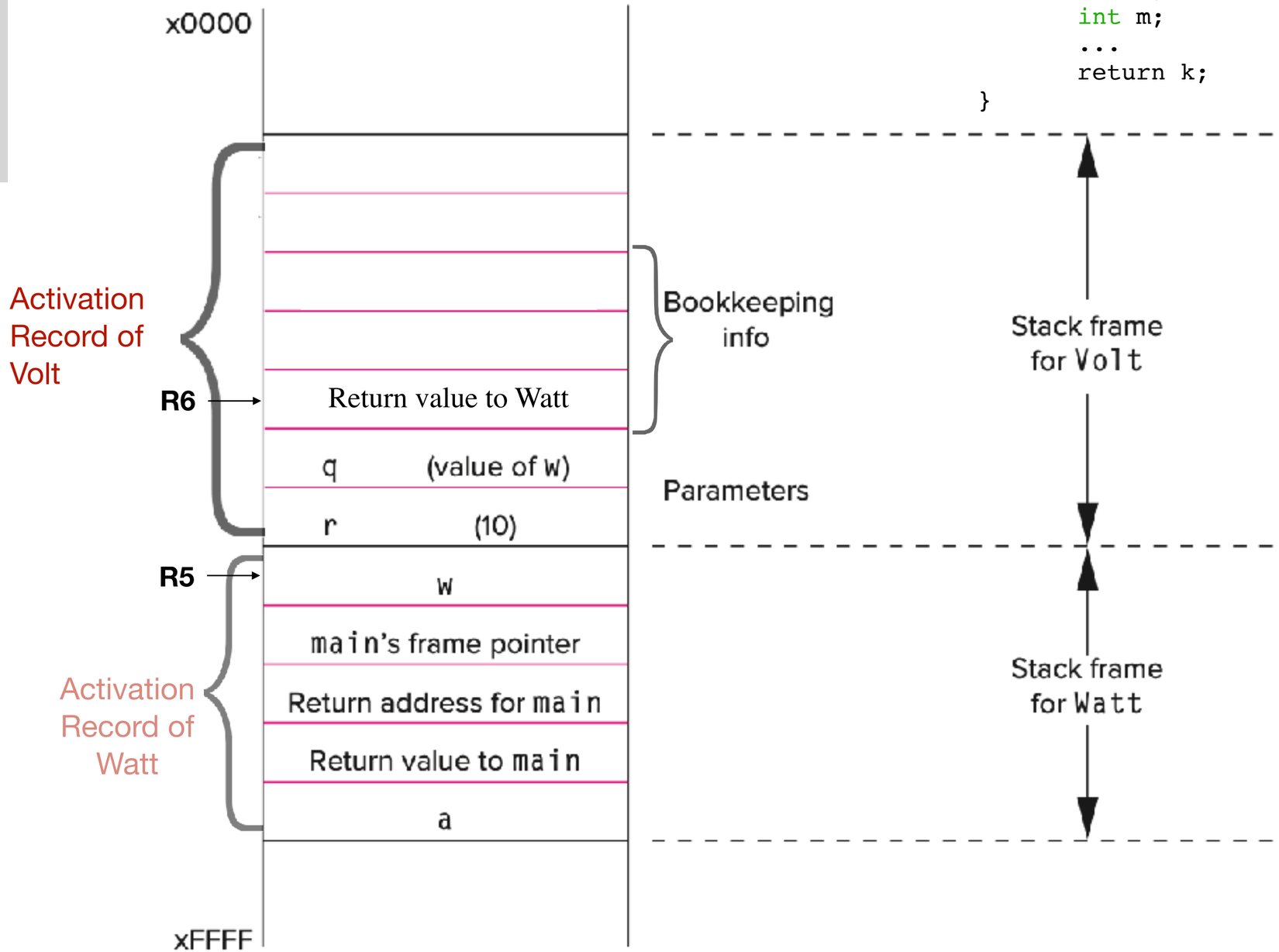


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
```

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

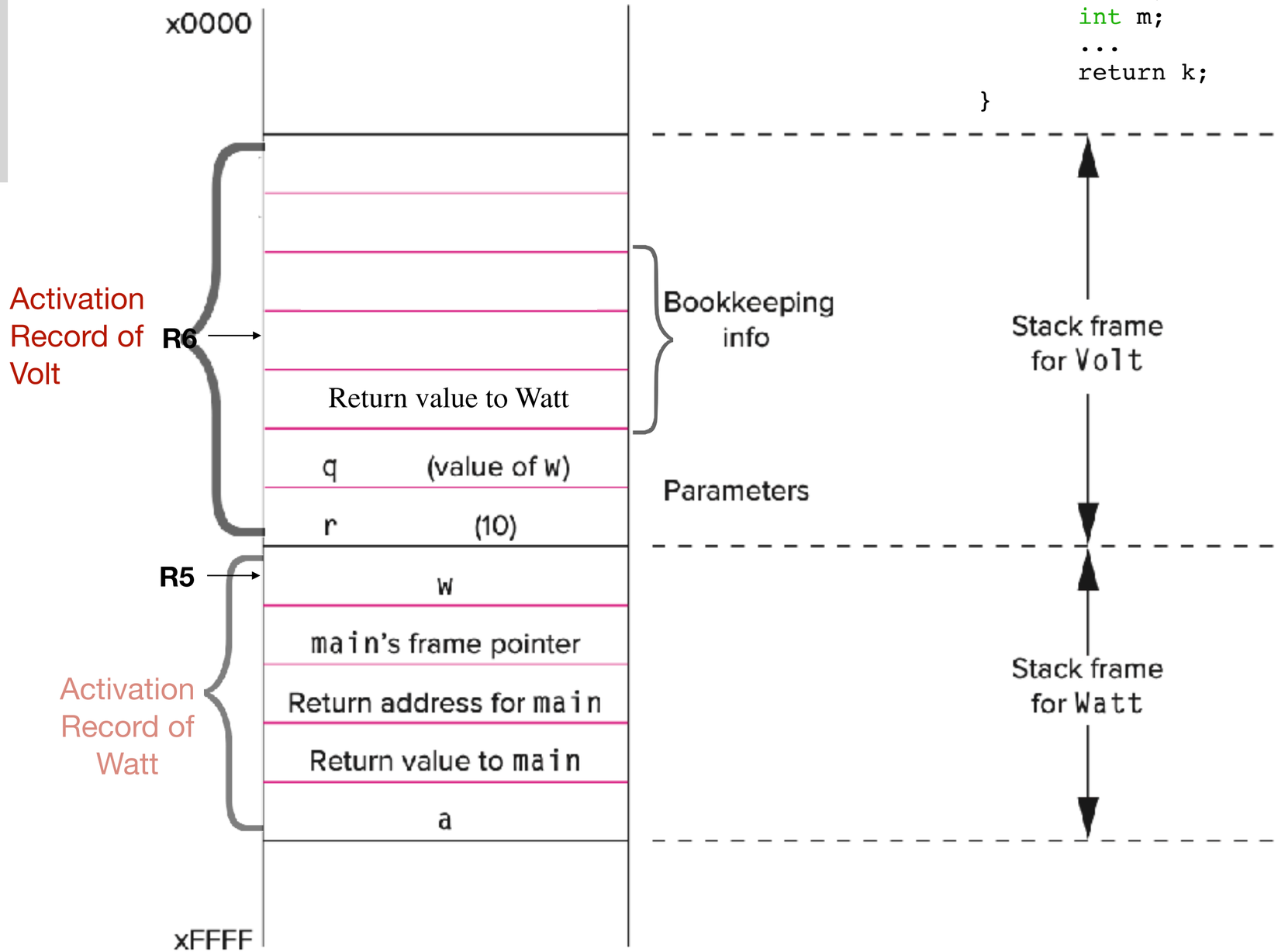


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
```

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

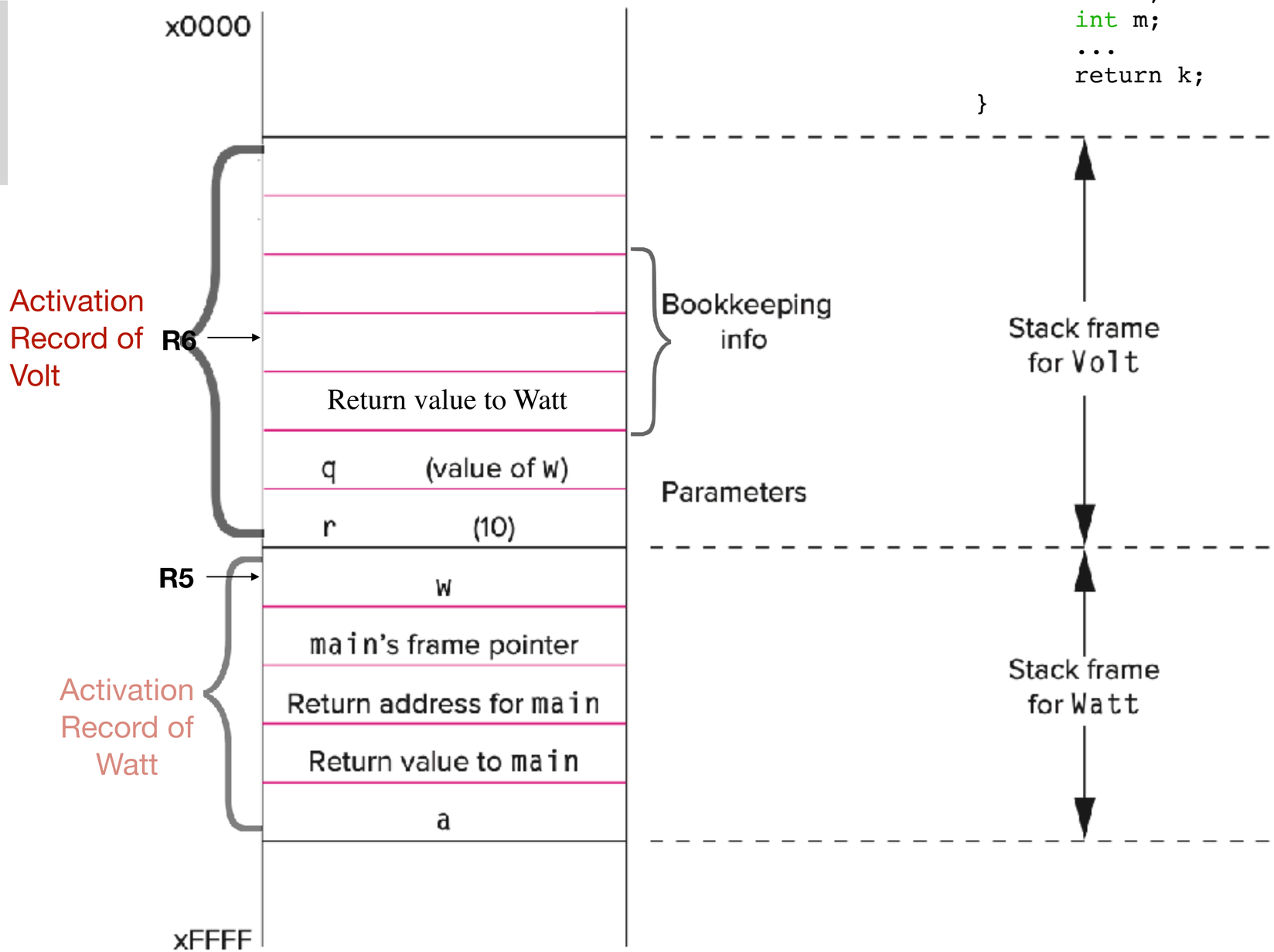


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0
```

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

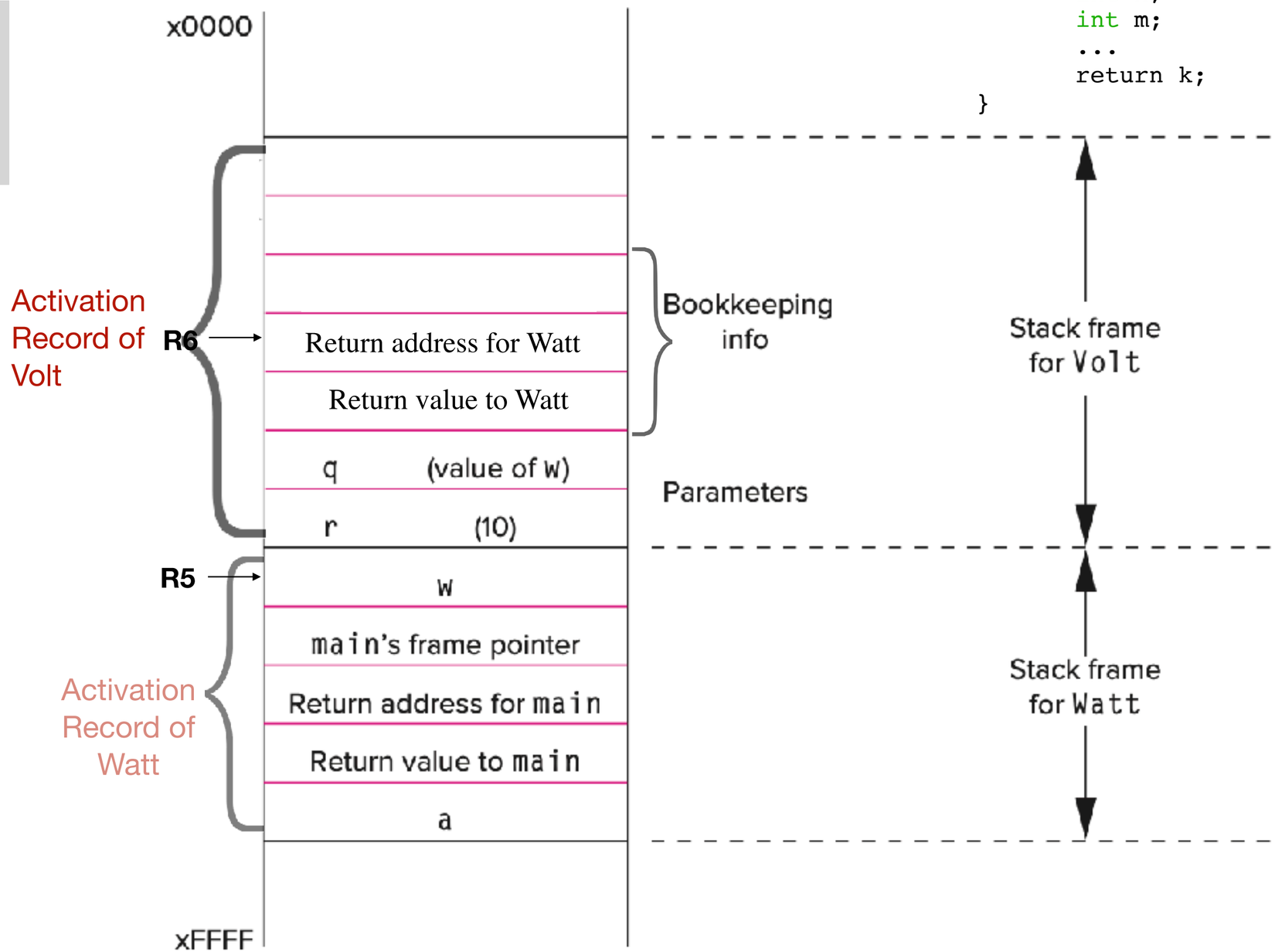


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0
```

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

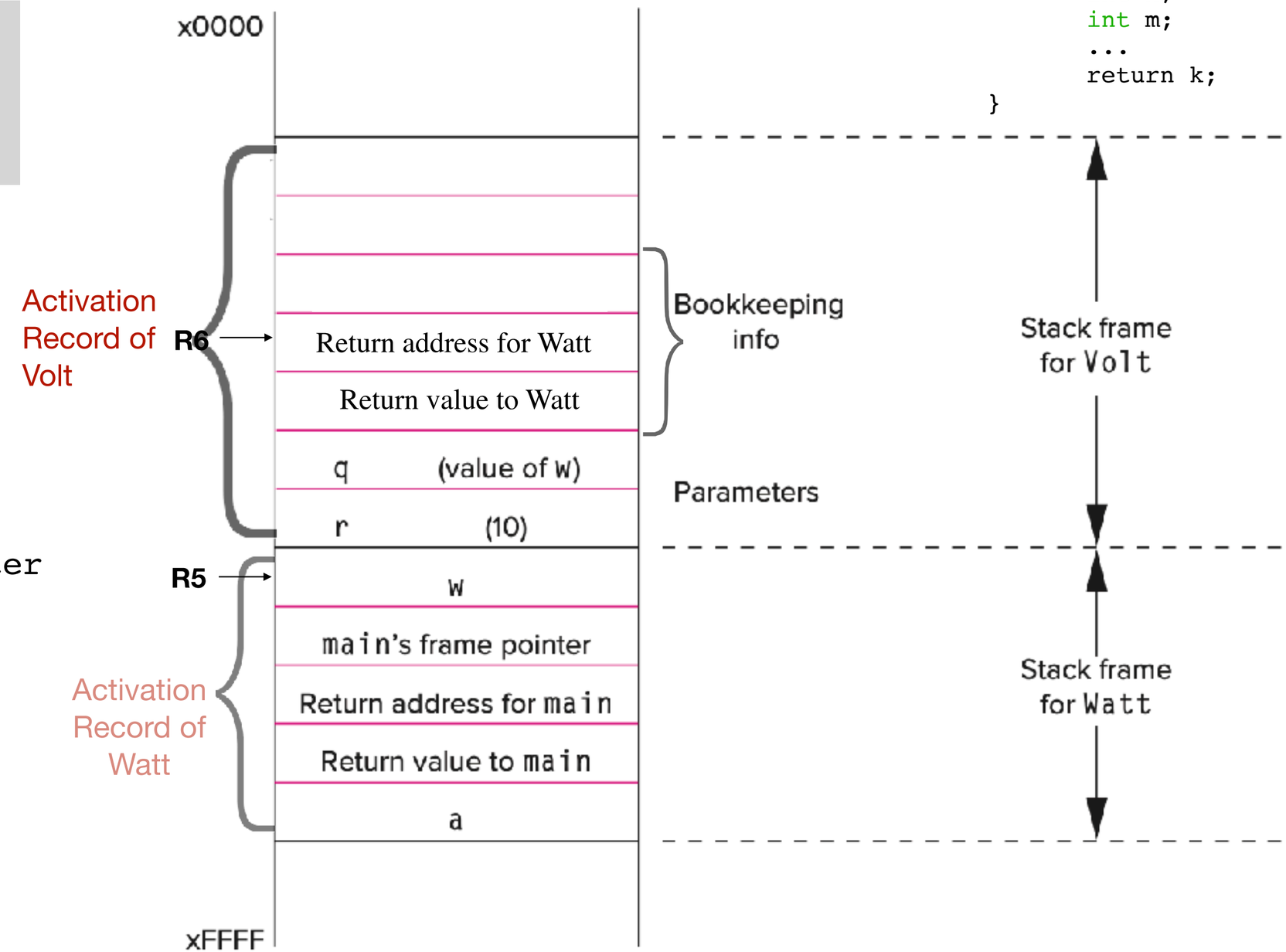


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
```

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

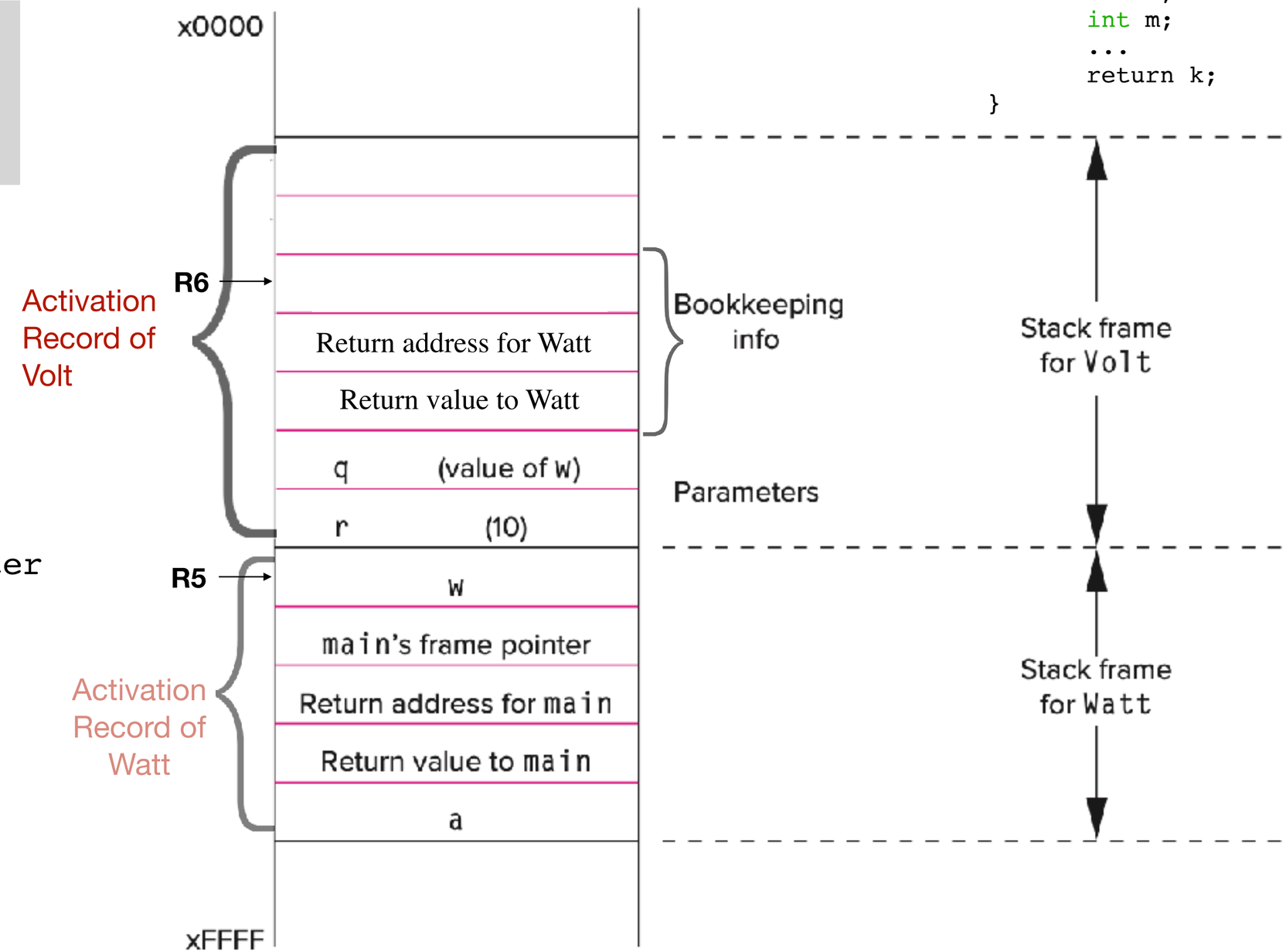


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
```

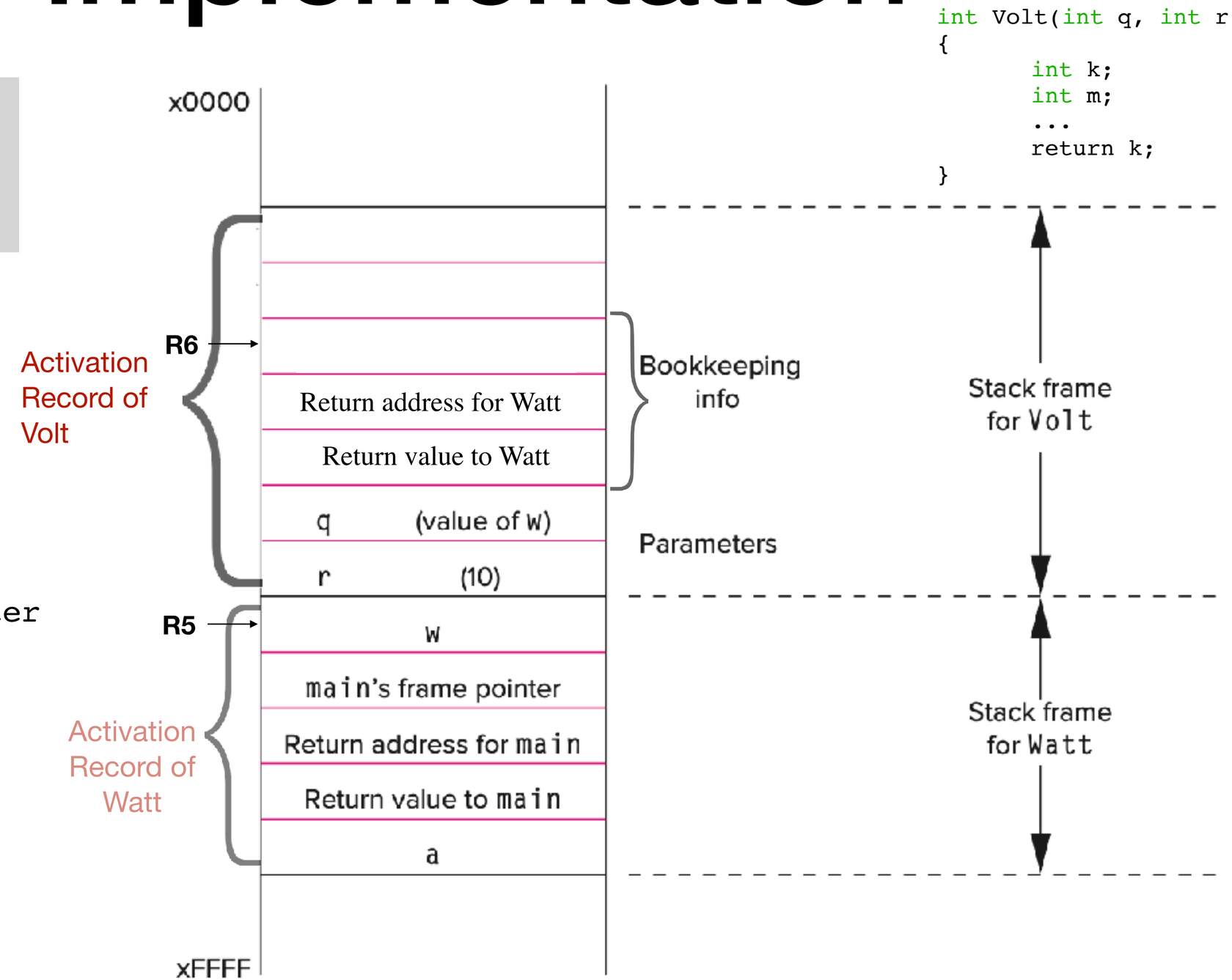
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

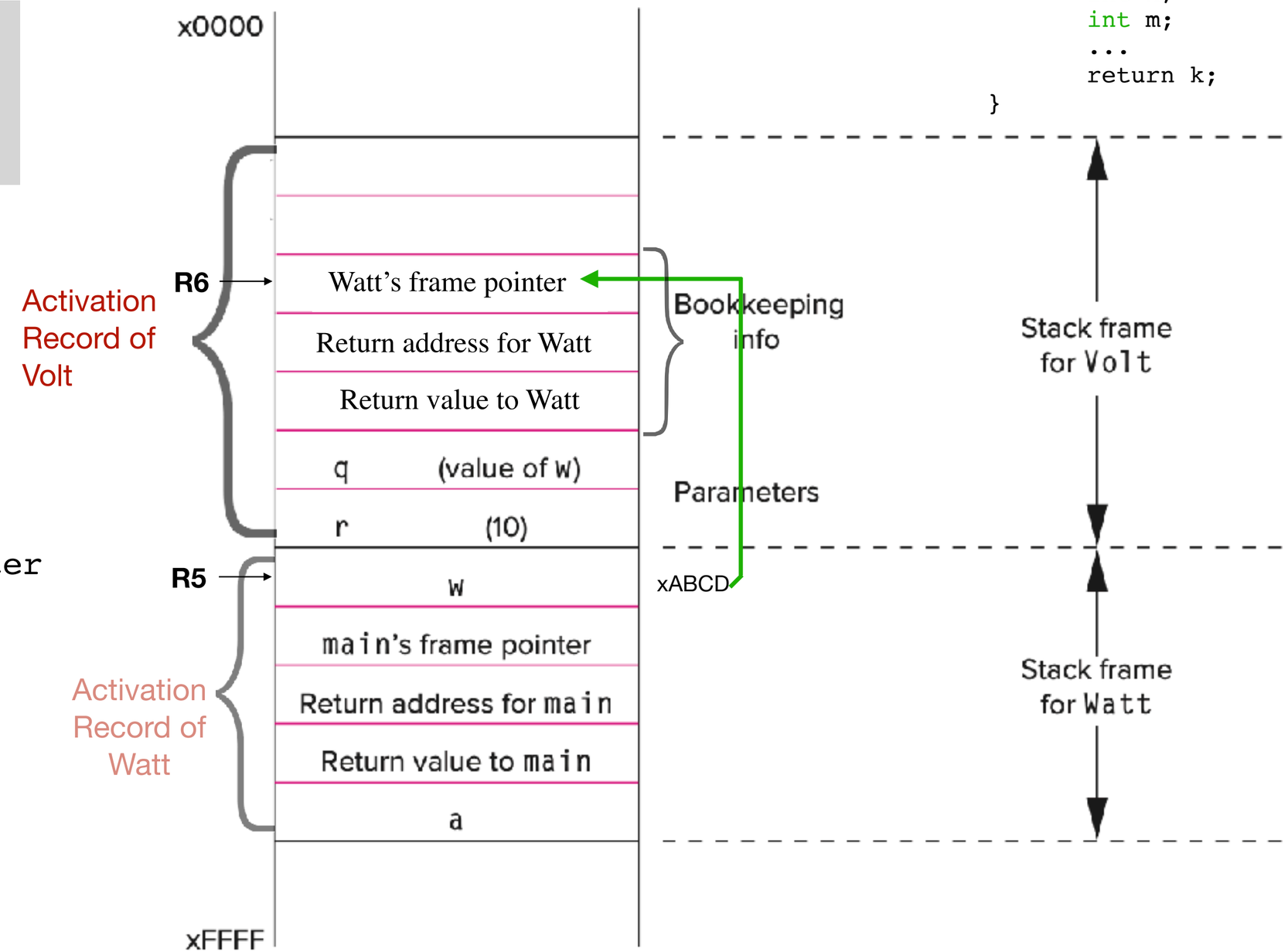
```
;space for return value
ADD R6, R6, #-1

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
```



LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0
```

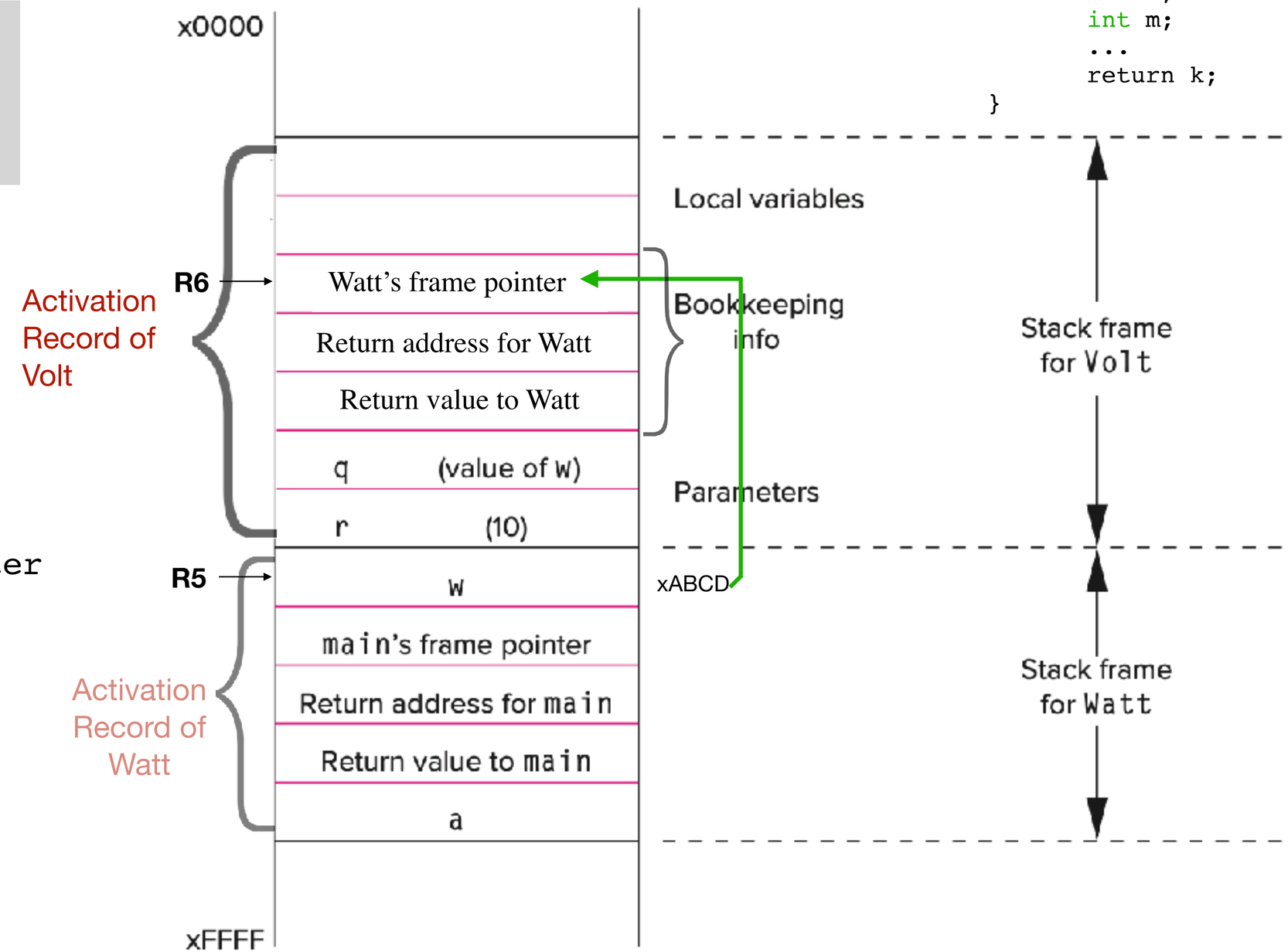


LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0
```

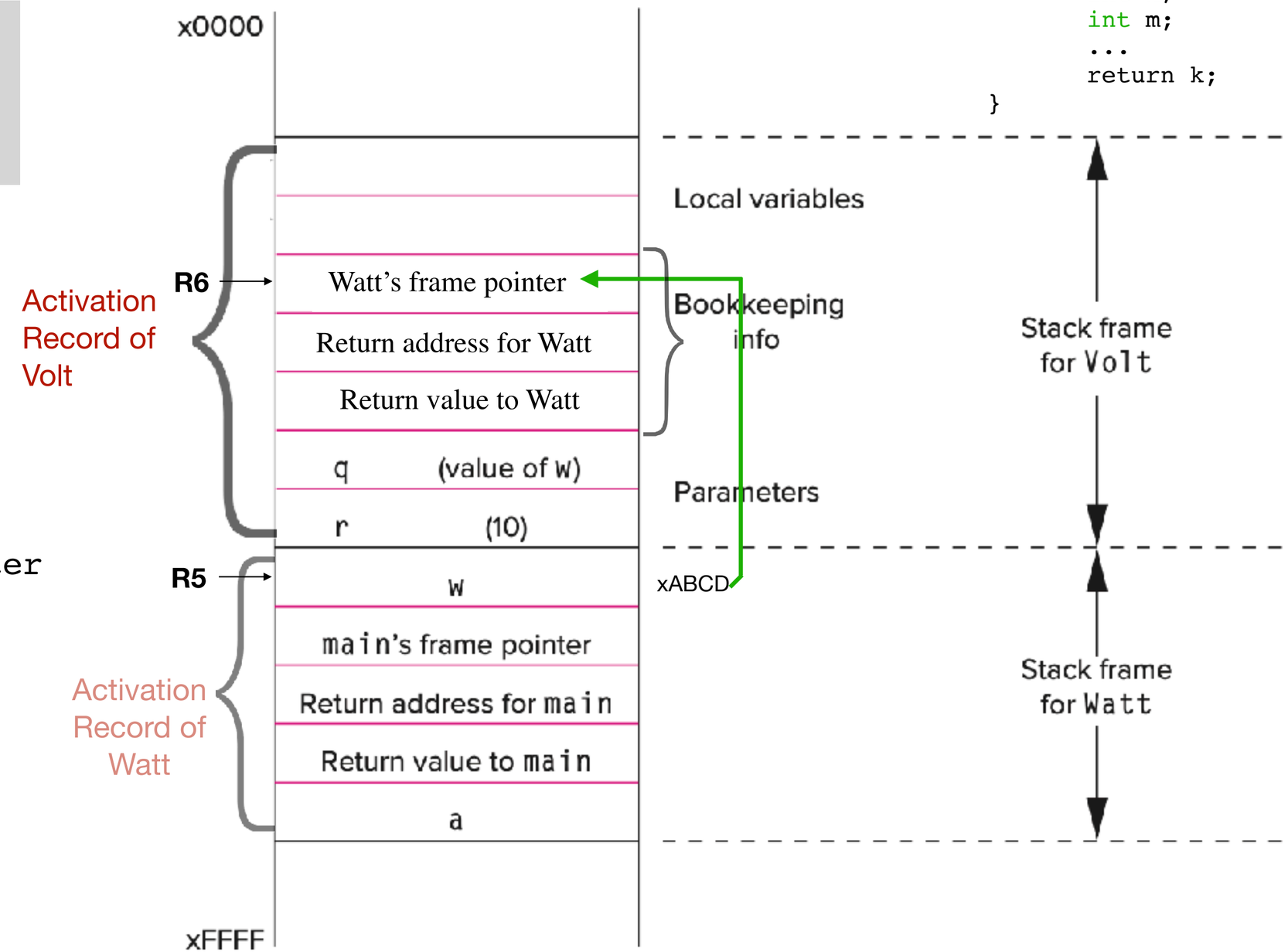
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

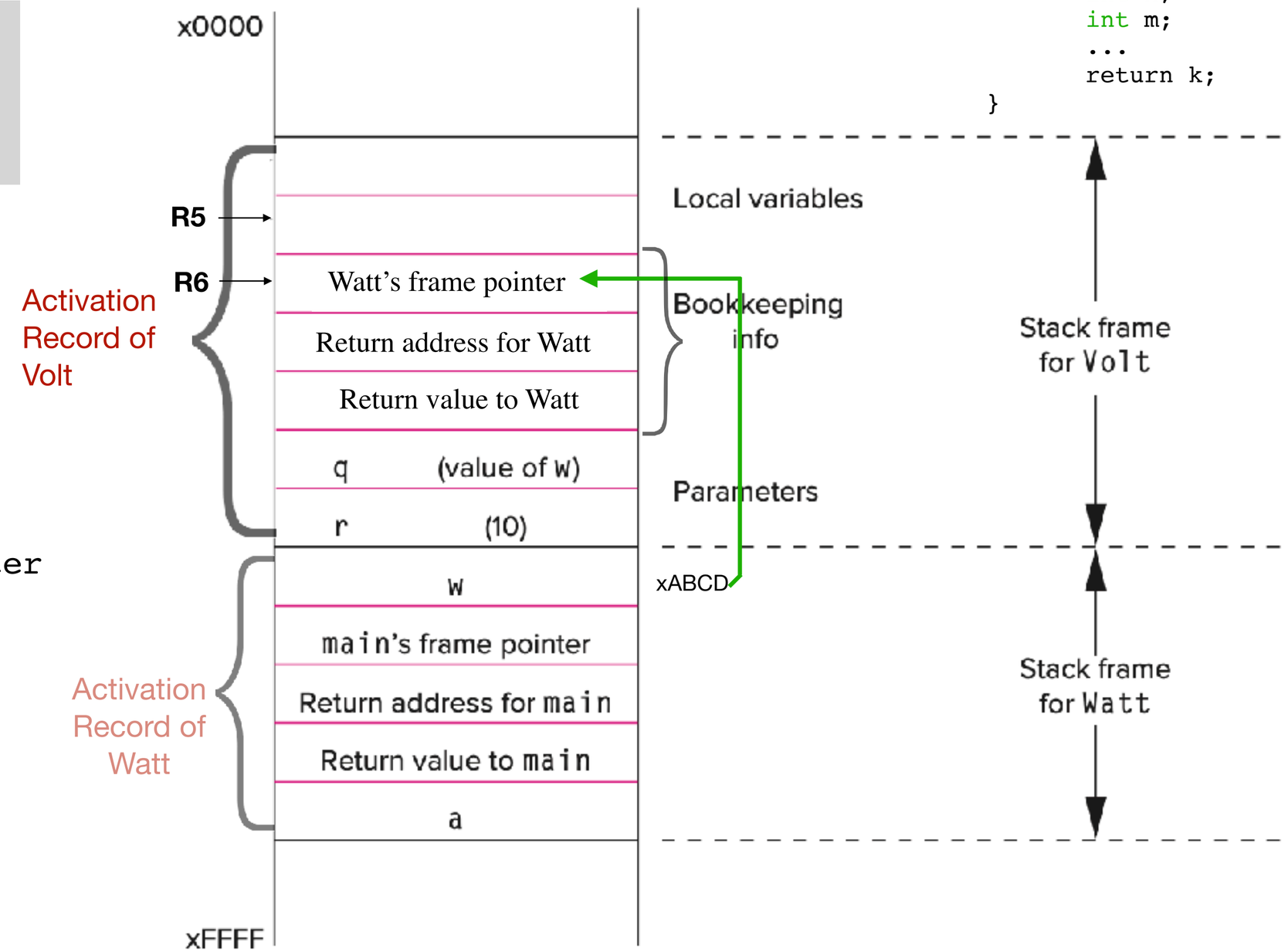
```
;space for return value
ADD R6, R6, #-1

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
```



LC-3 Implementation

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

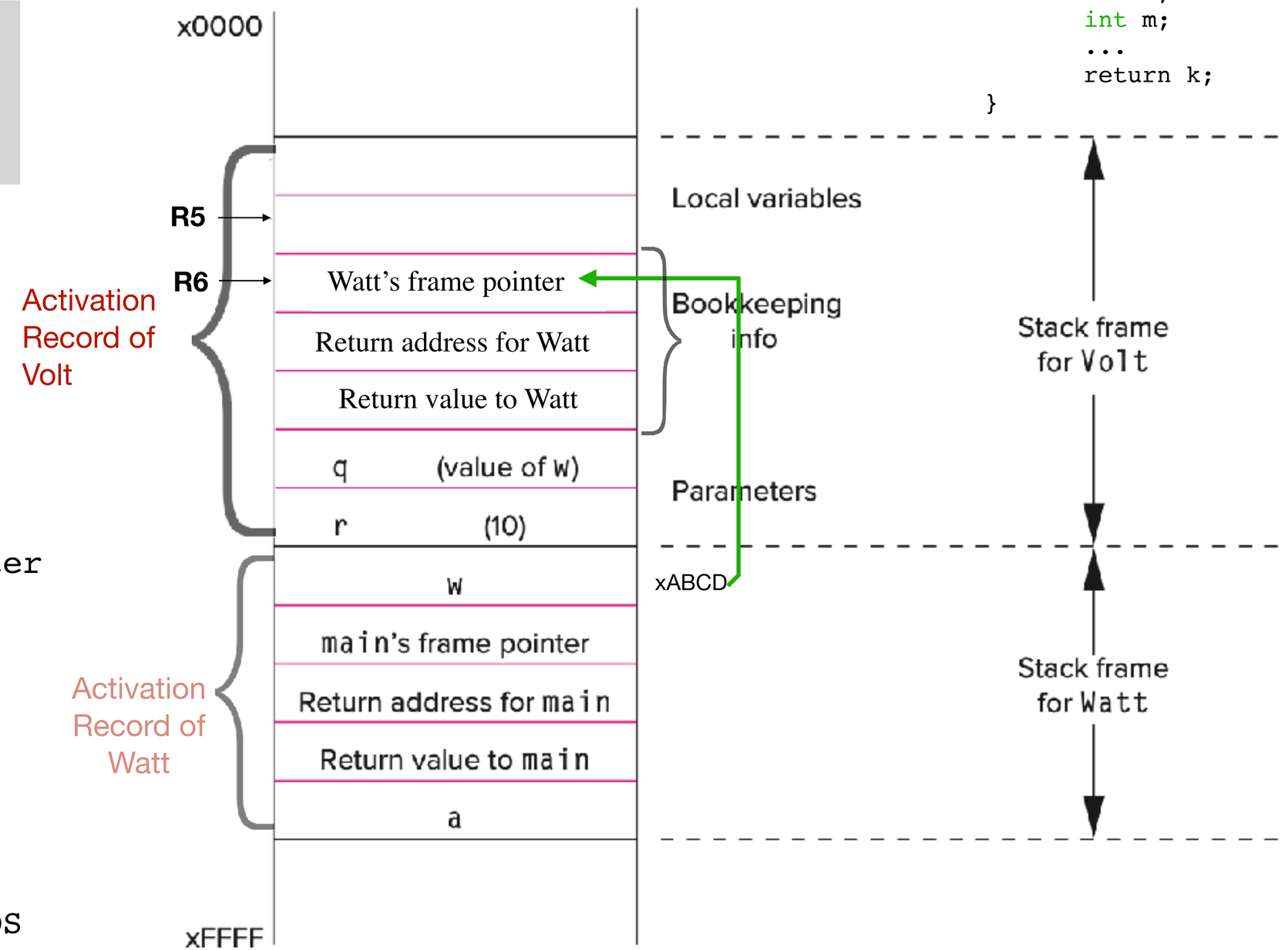
```
;space for return value
ADD R6, R6, #-1

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
```



LC-3 Implementation

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

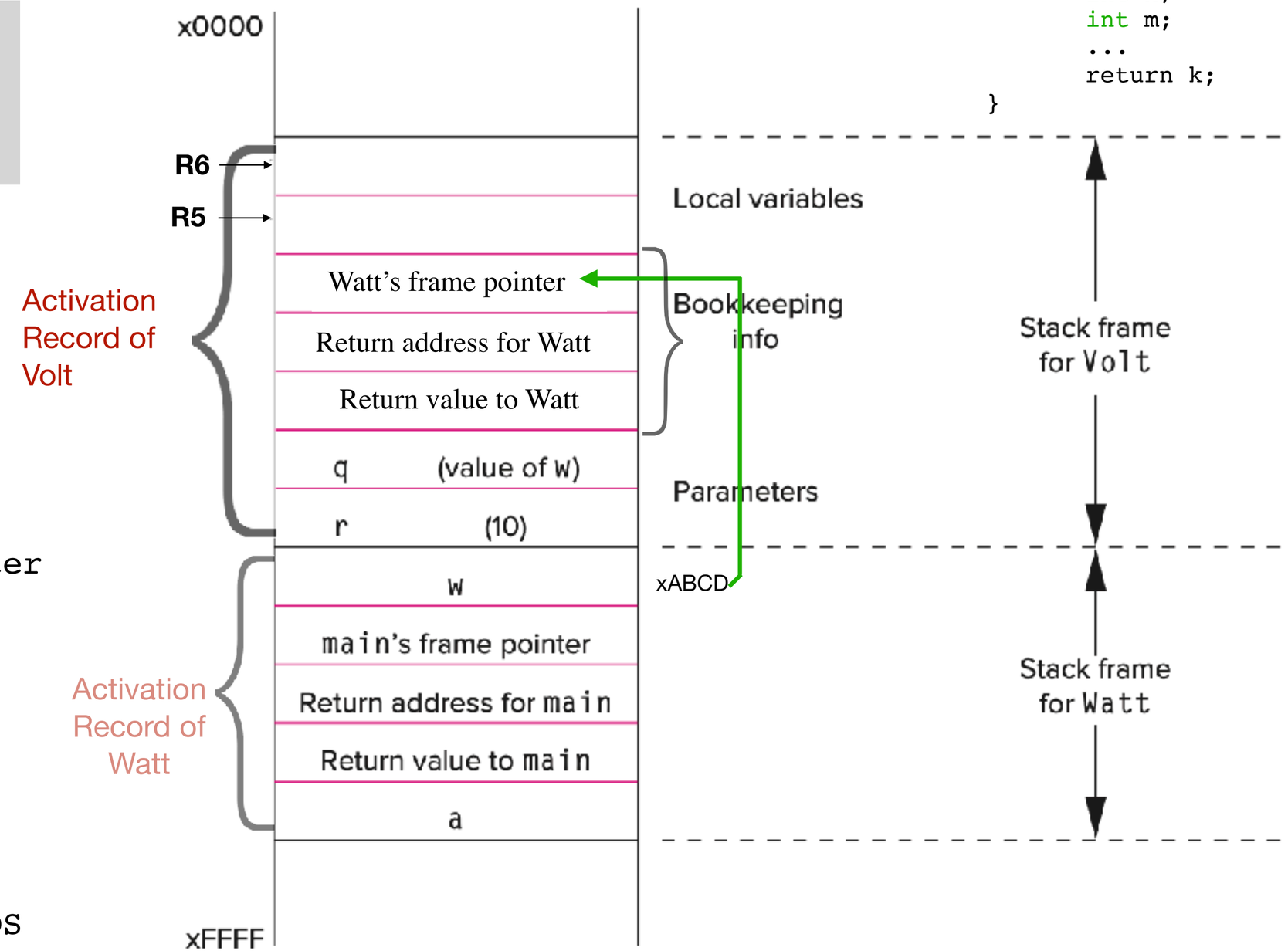
```
;space for return value
ADD R6, R6, #-1

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
;Space for local variables
ADD R6, R6, #-2  ; updates TOS
```



LC-3 Implementation

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

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
;Space for local variables
ADD R6, R6, #-2  ; updates TOS
```

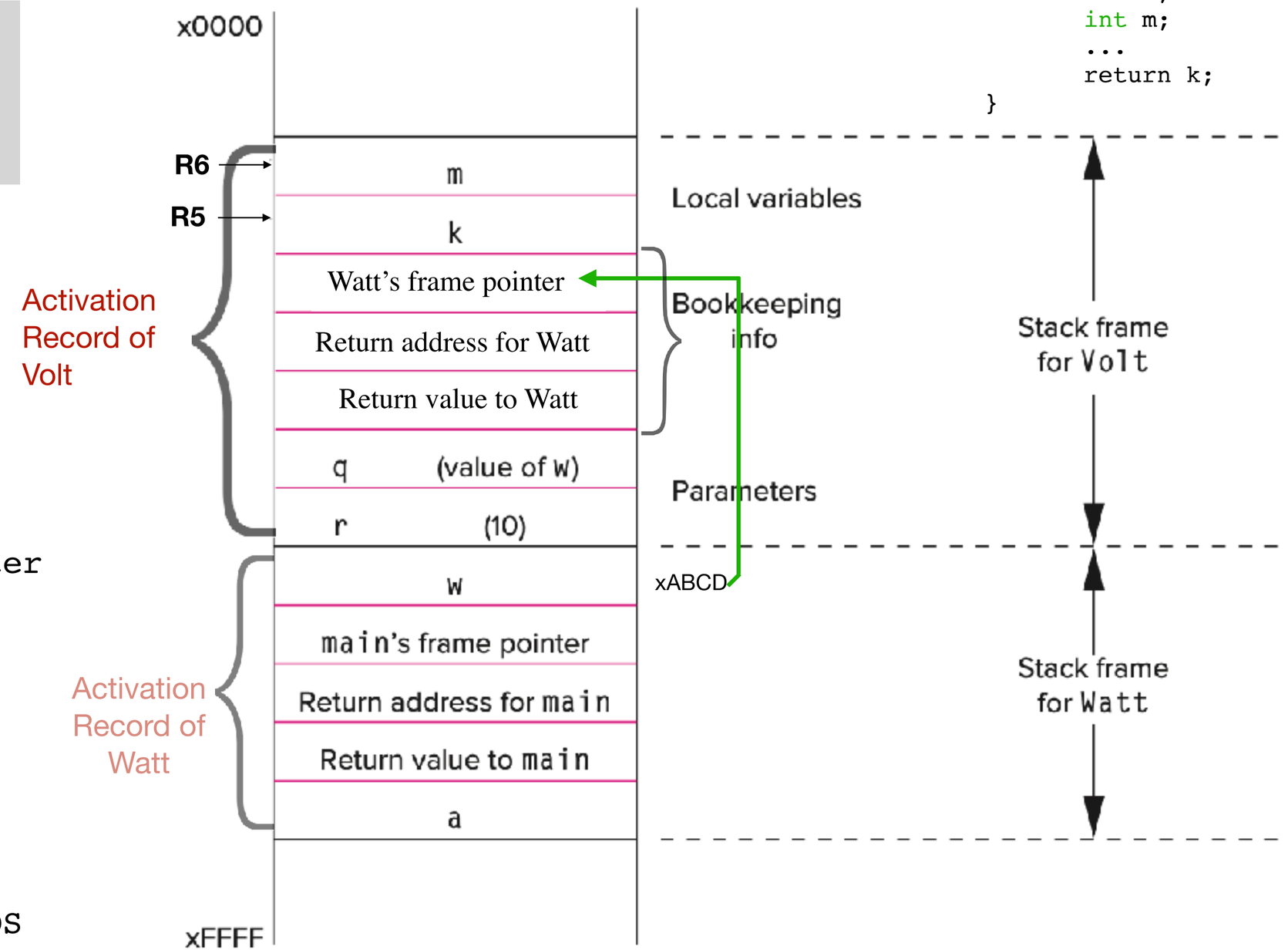



```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

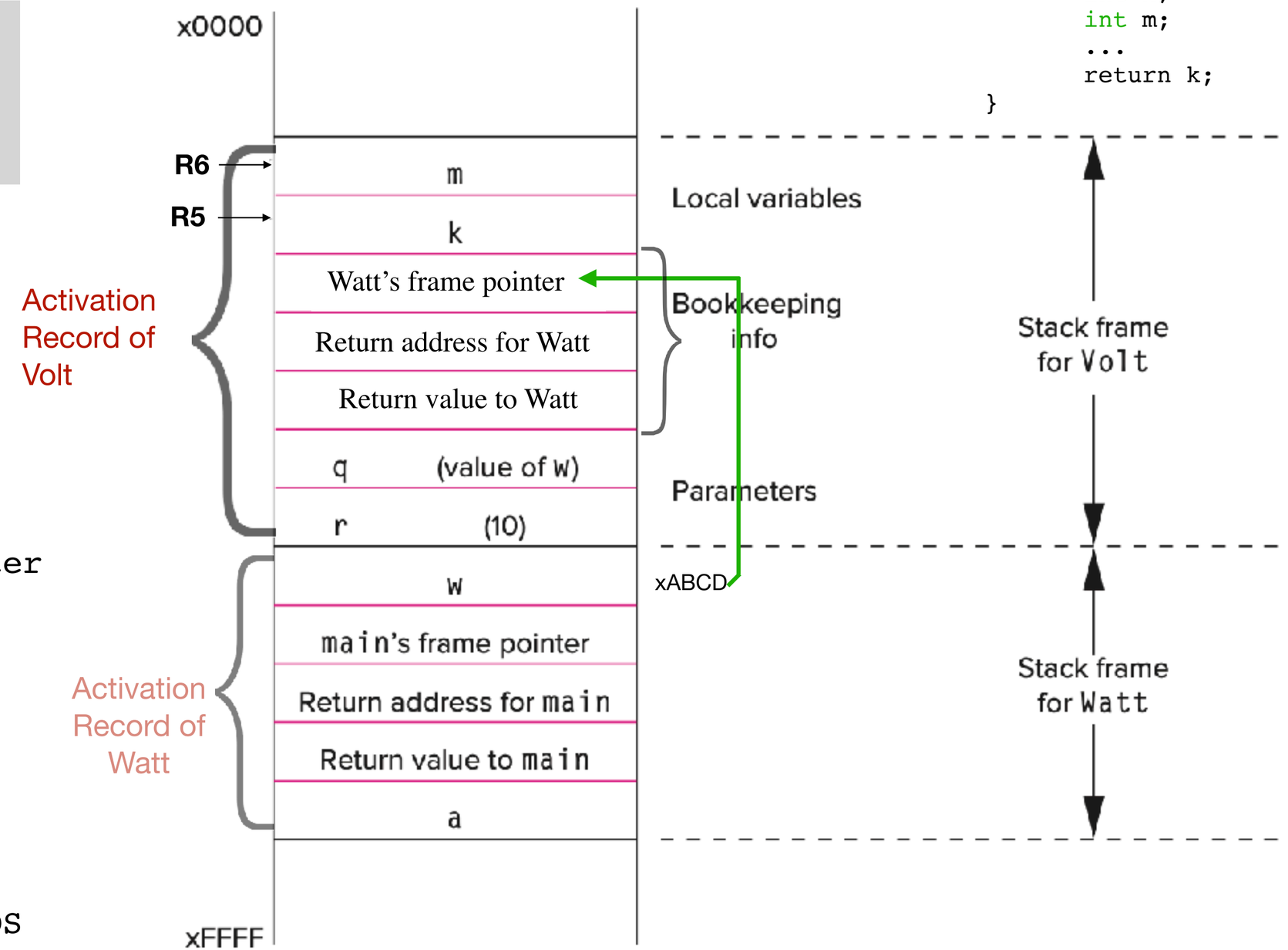
```
;space for return value
ADD R6, R6, #-1

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
;Space for local variables
ADD R6, R6, #-2  ; updates TOS
```



LC-3 Implementation

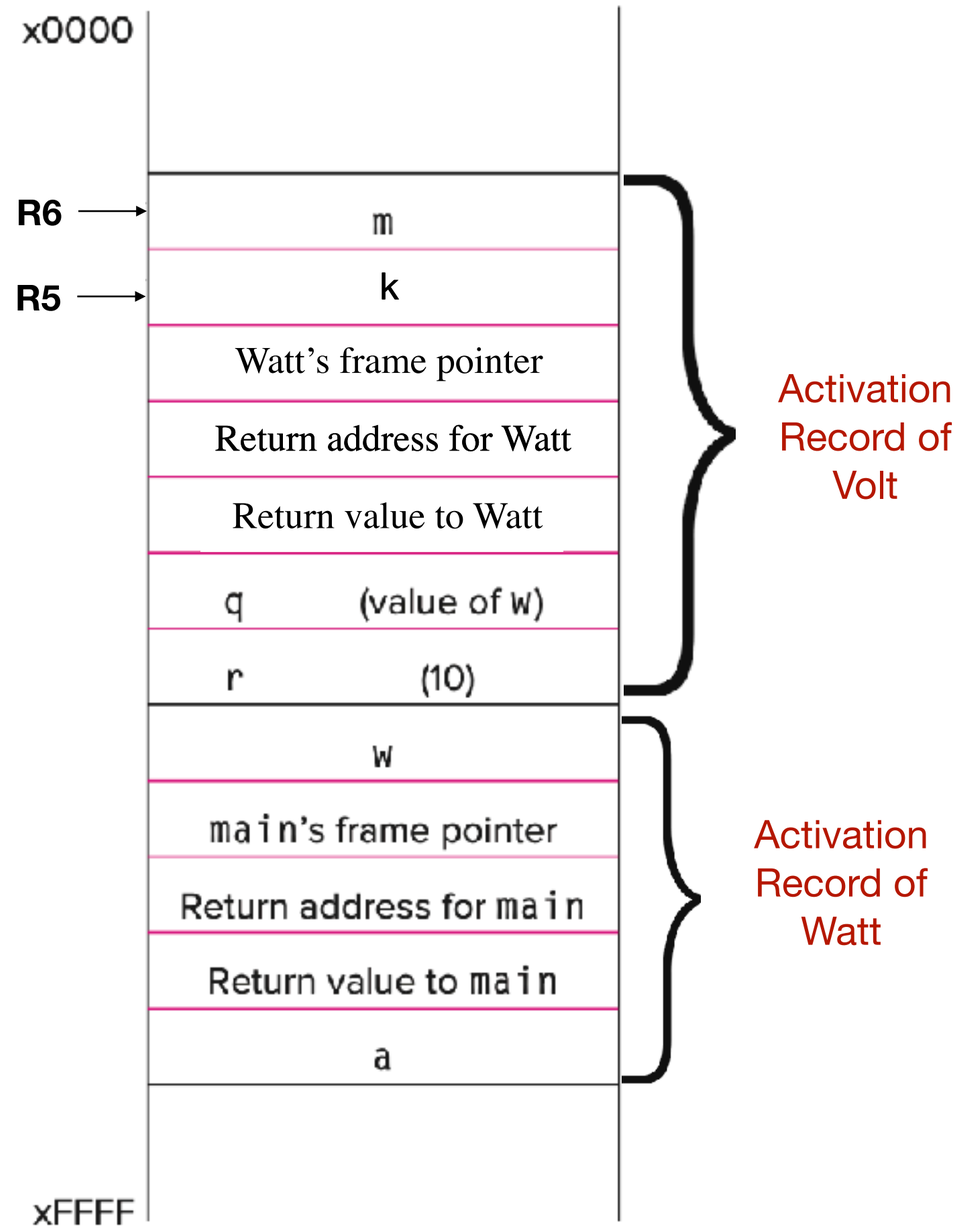
3. Callee setup (push bookkeeping info and local variables onto stack)
4. Execute function

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

;space for return address
ADD R6, R6, #-1
;Push R7 (Return Addr)
STR R7, R6, #0

;space for Caller Frame Pointer
ADD R6, R6, #-1
;Push R5 (CFP)
STR R5, R6, #0

;Set frame pointer for Volt
ADD R5, R6, #-1
;
;Space for local variables
ADD R6, R6, #-2  ; updates TOS
```



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

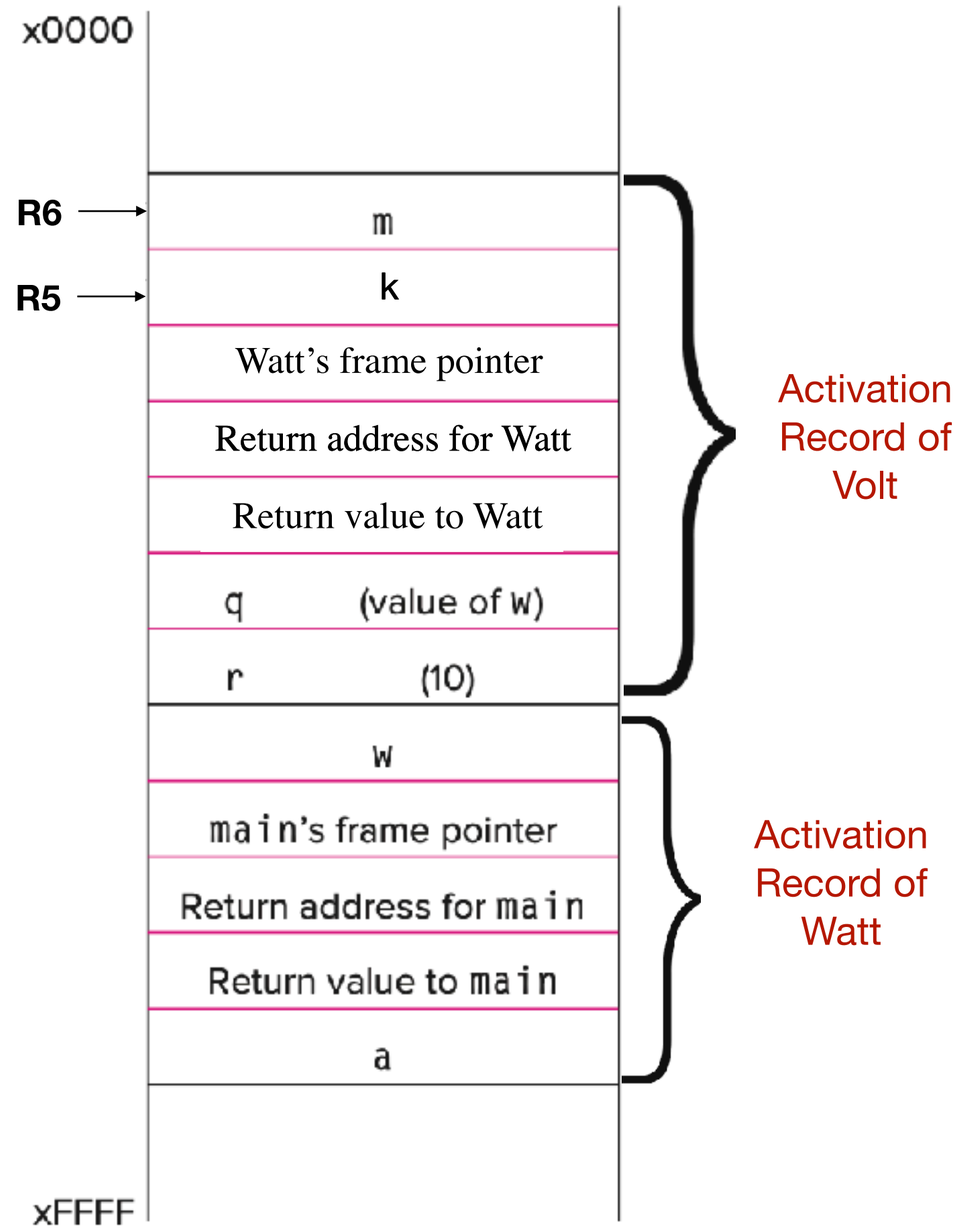
LC-3 Implementation



```
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)

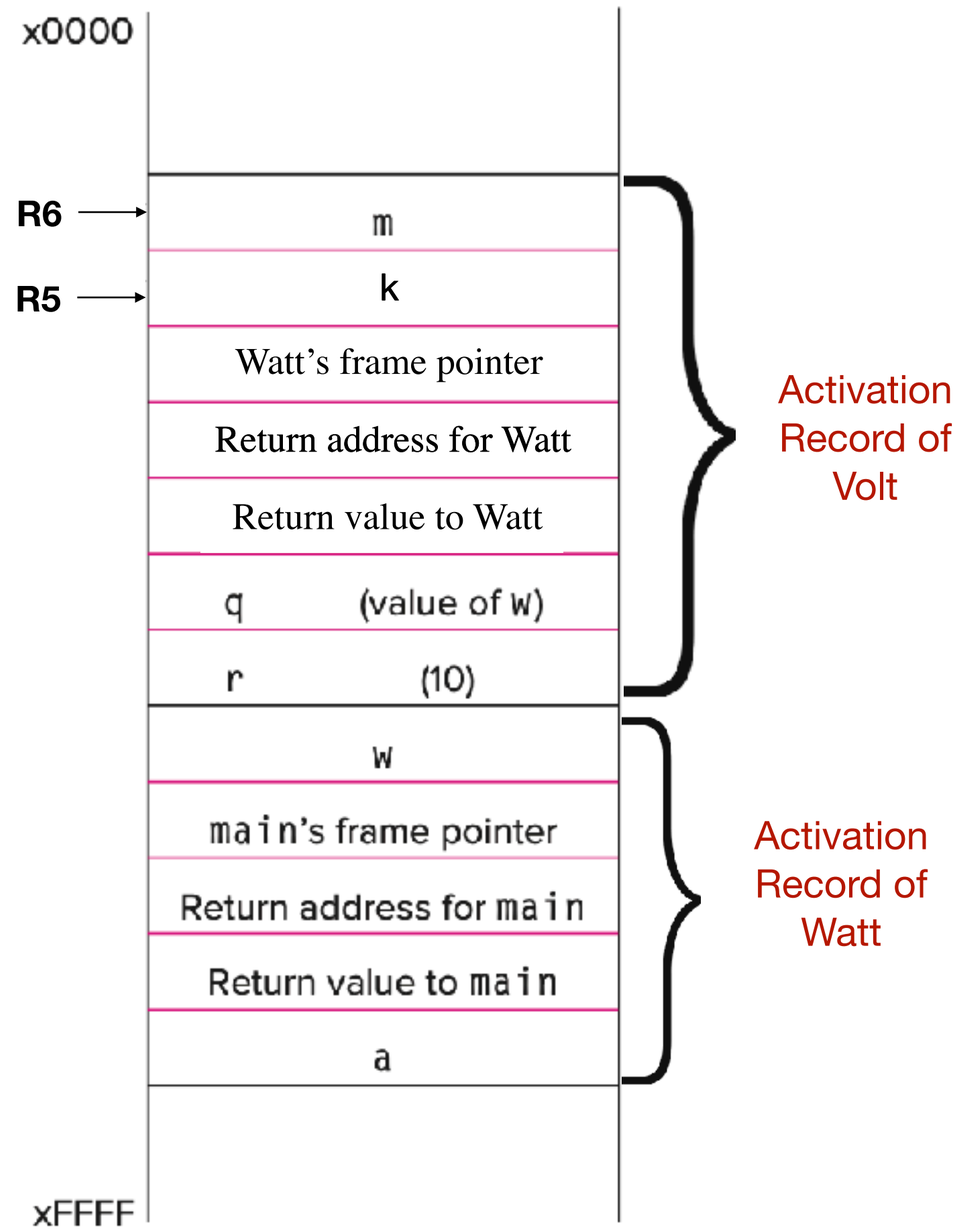


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; copy k into return value(R5+3)
```

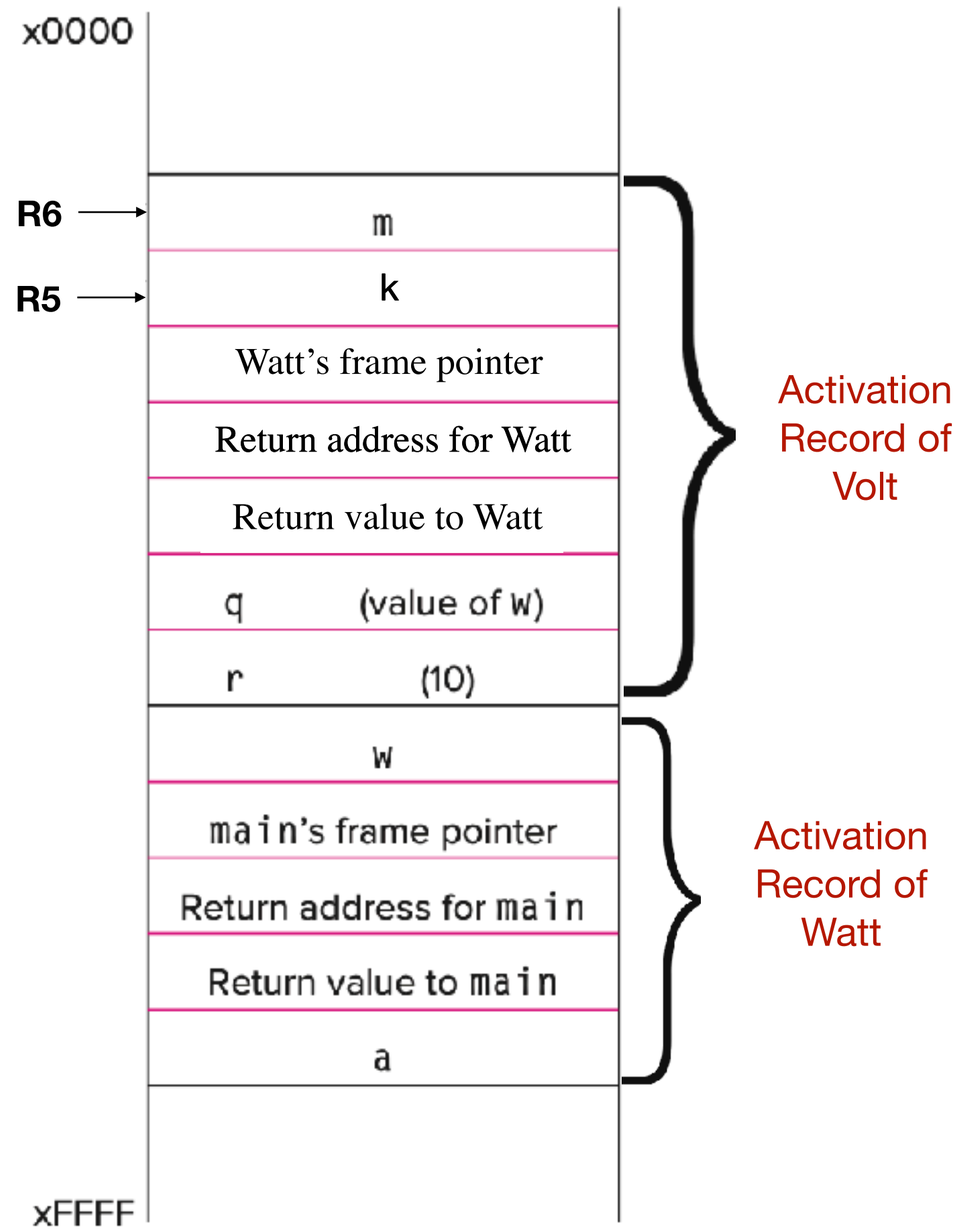


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

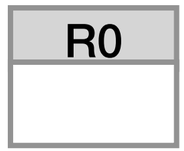


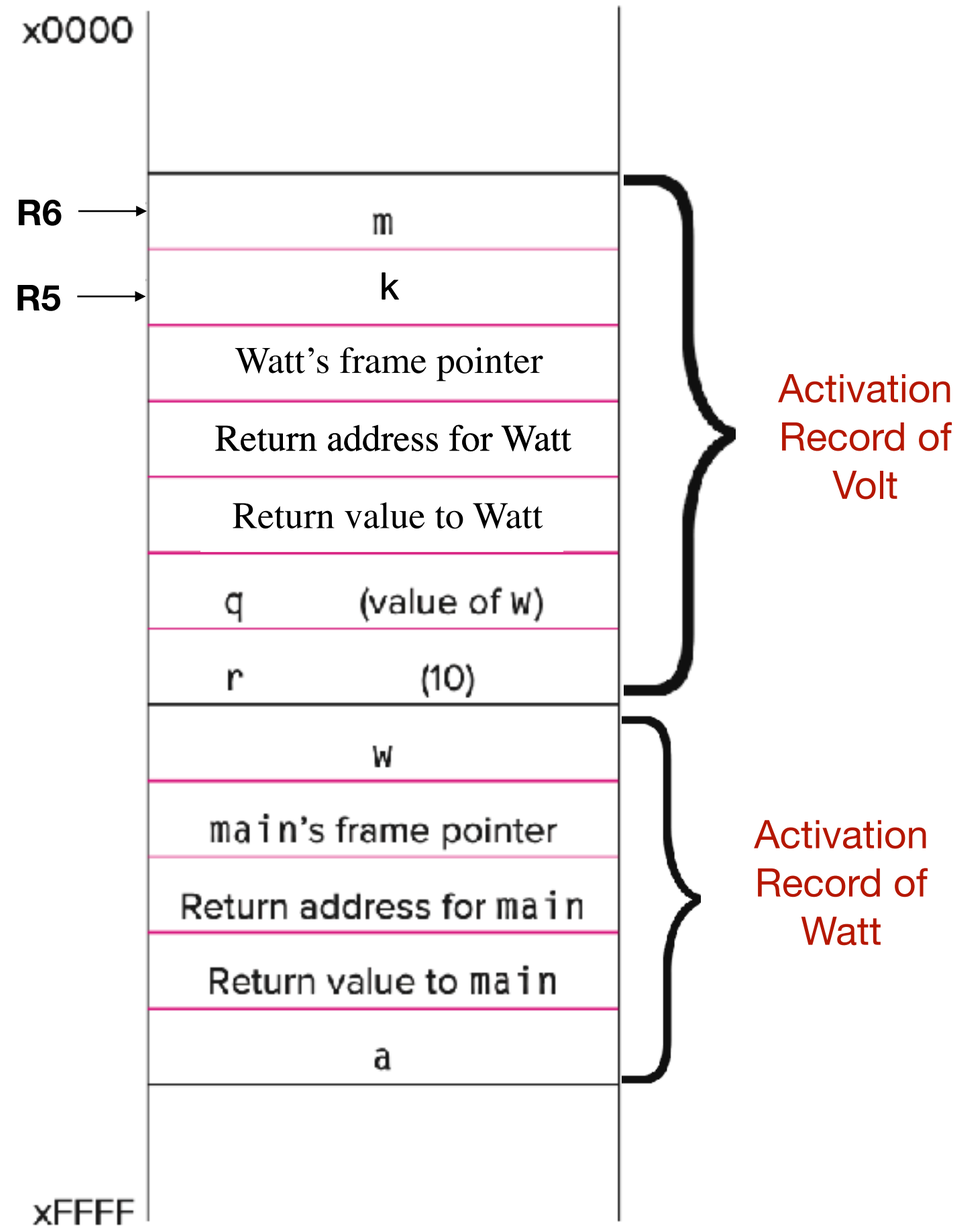
```c
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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





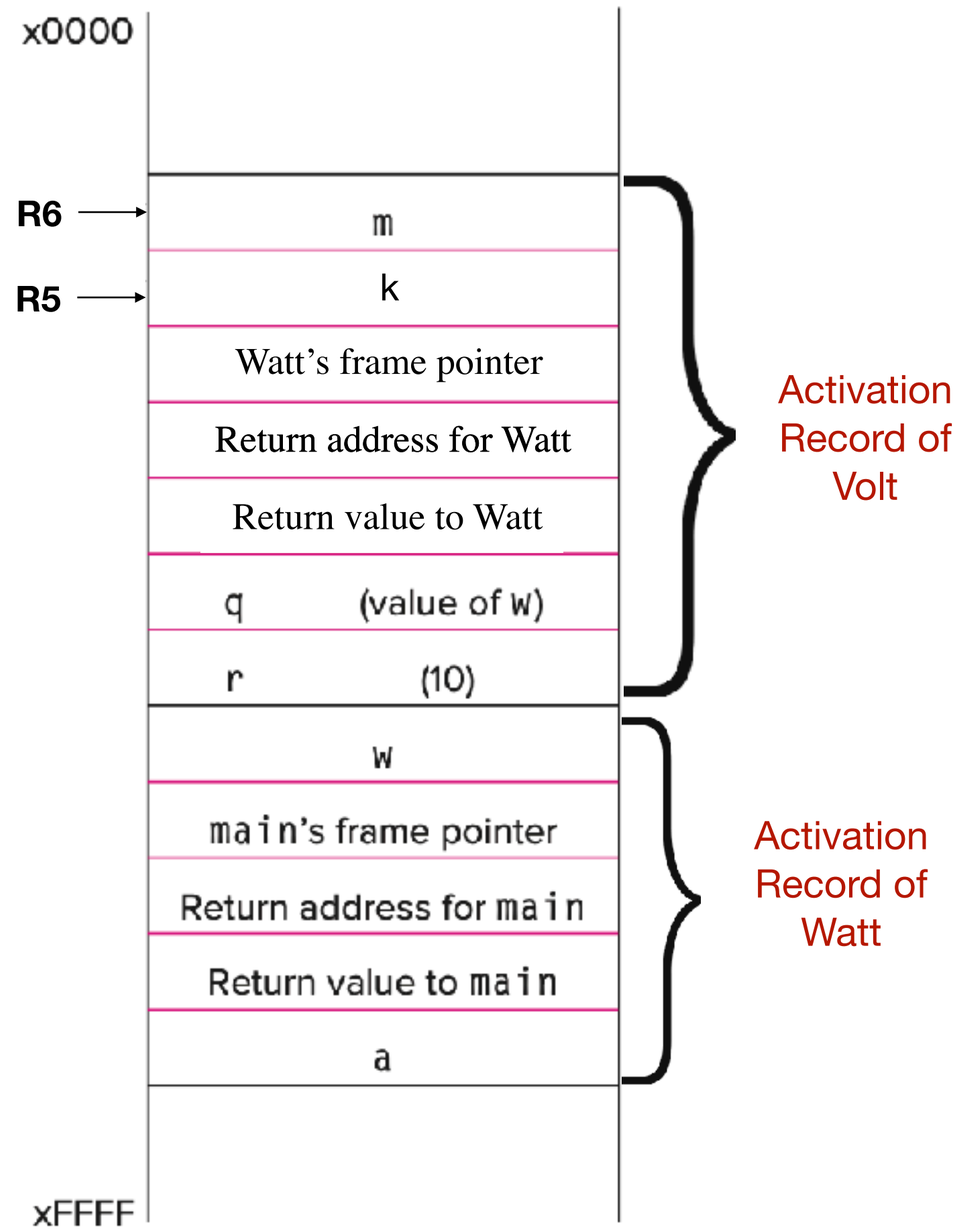
```c
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

R0
k



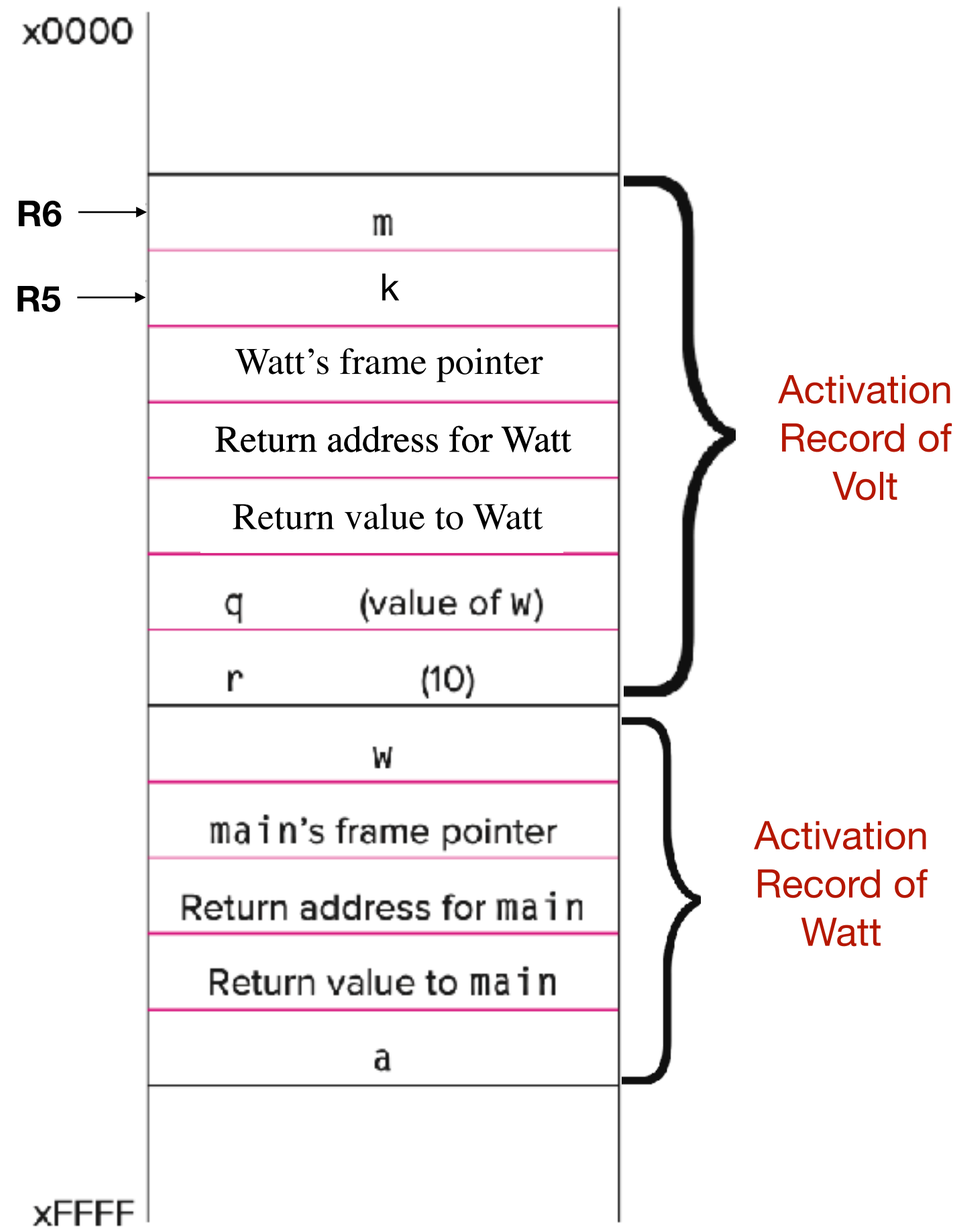
```c
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

R0
k



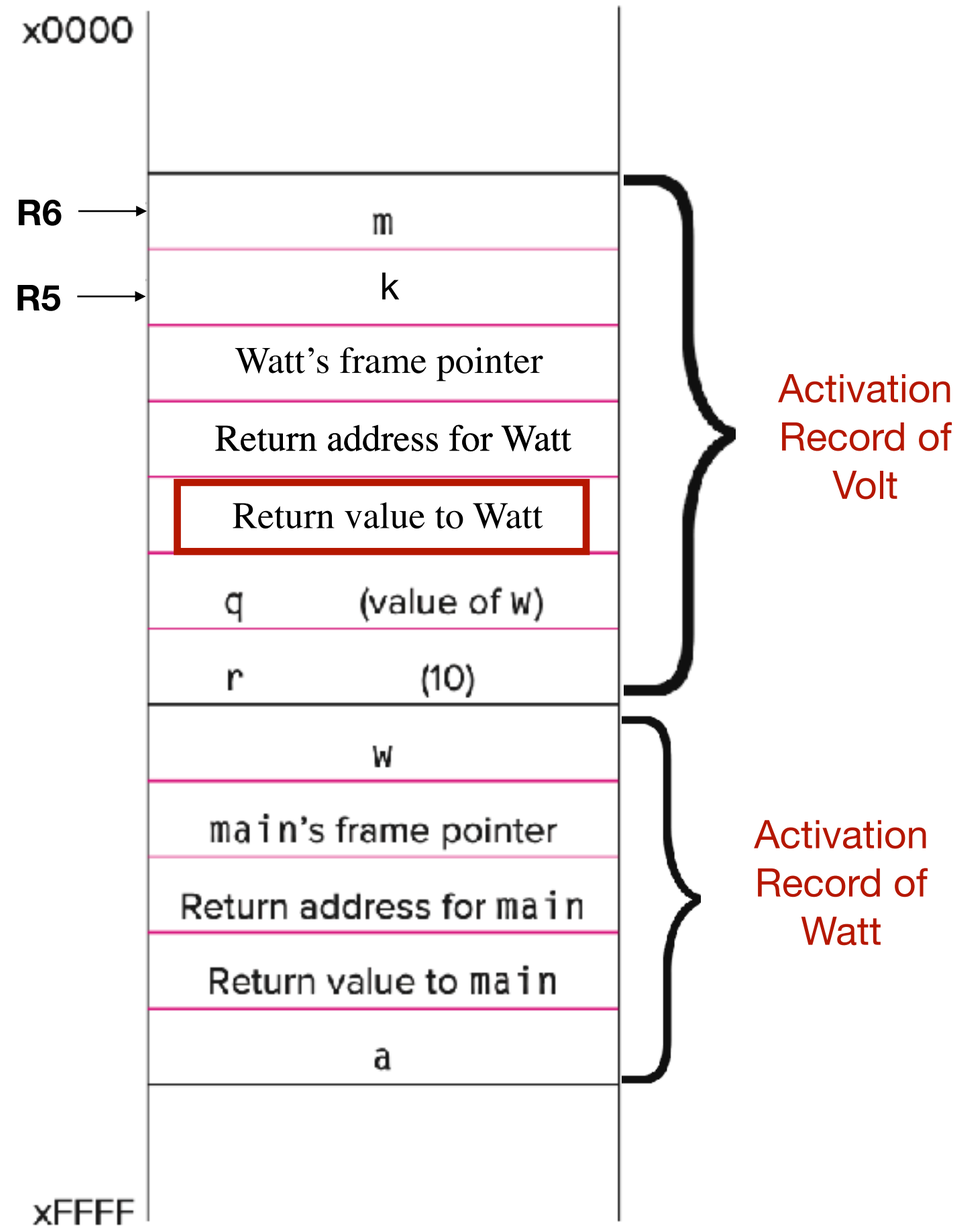
```c
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

R0
k



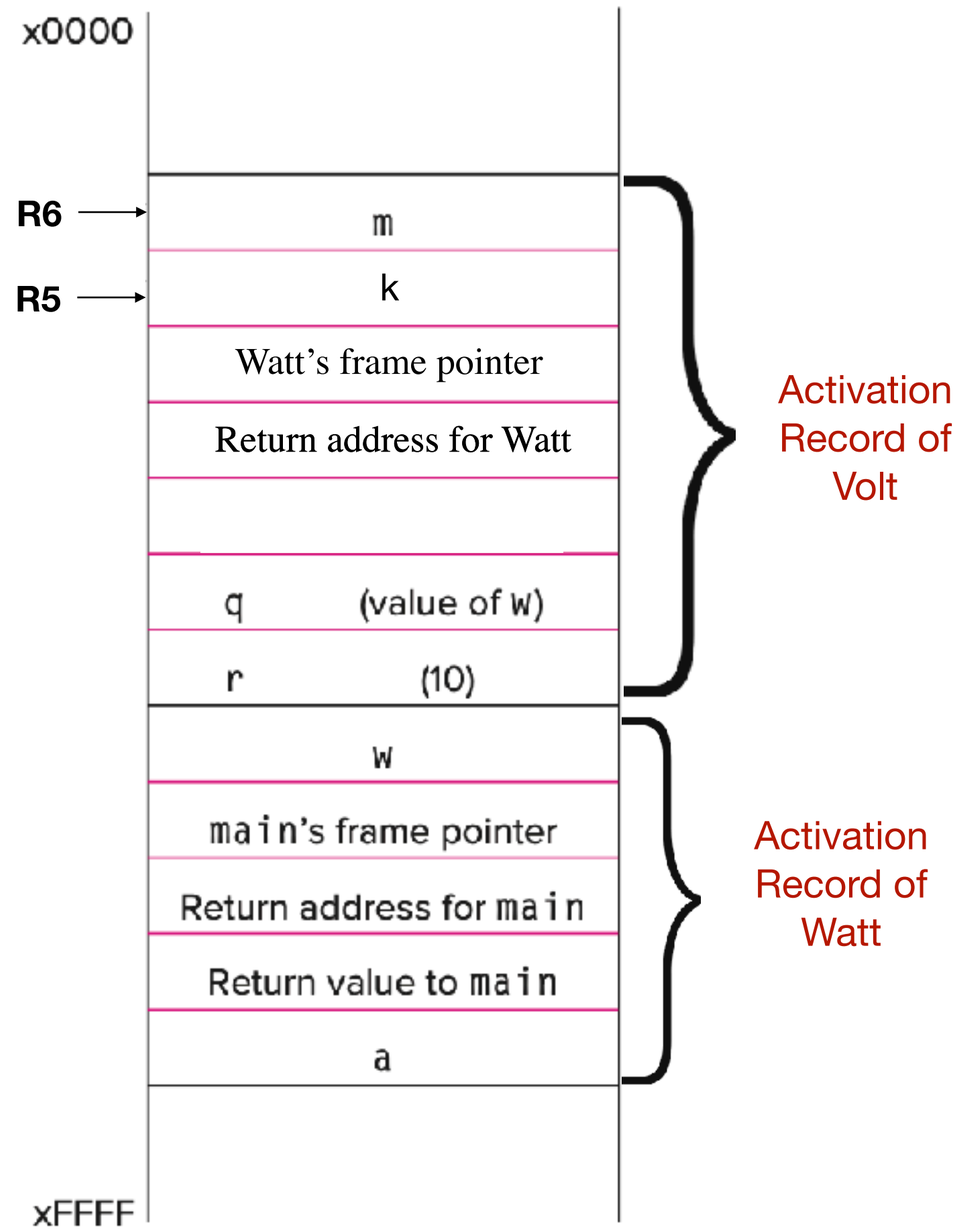
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

R0
k



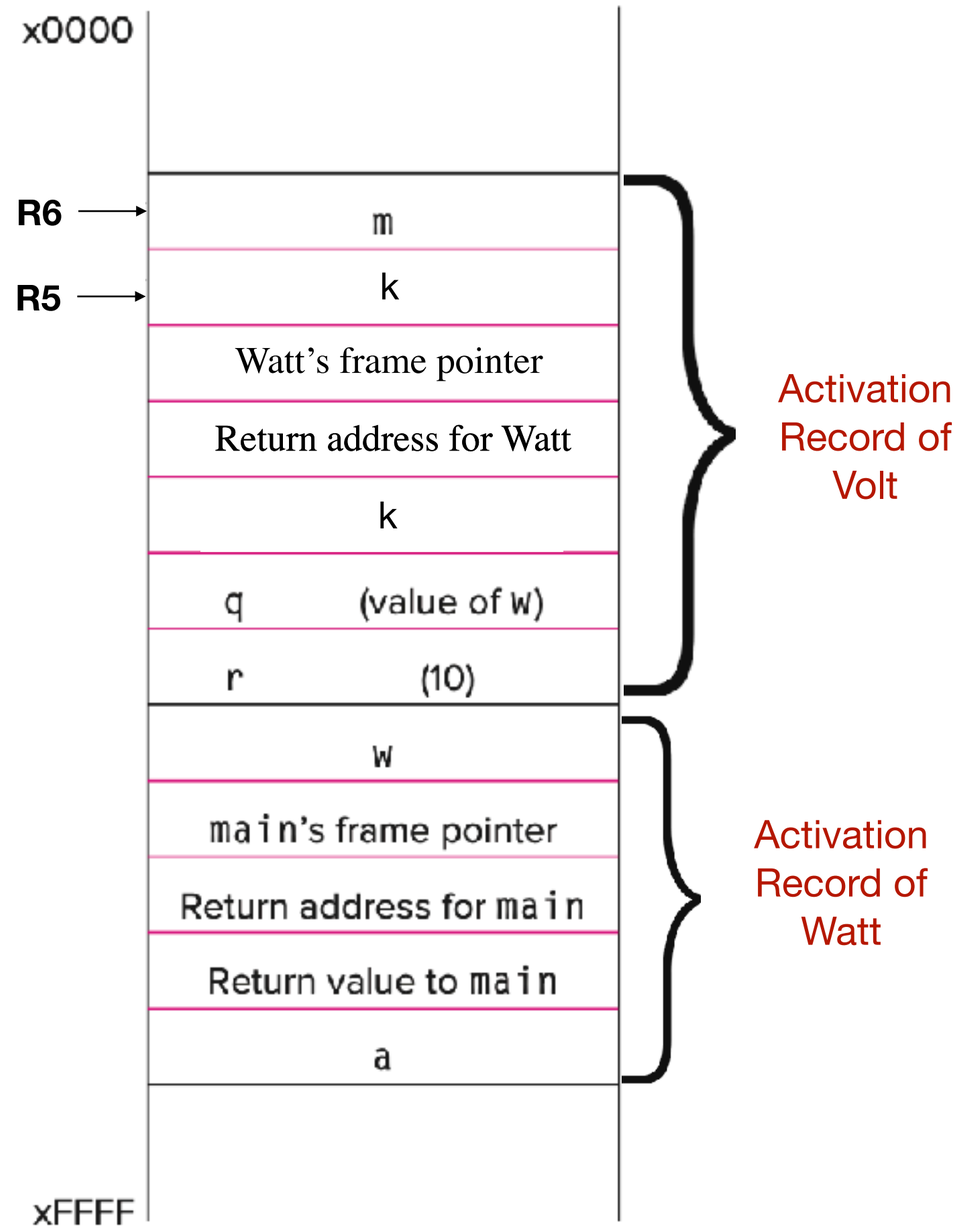
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

R0
k



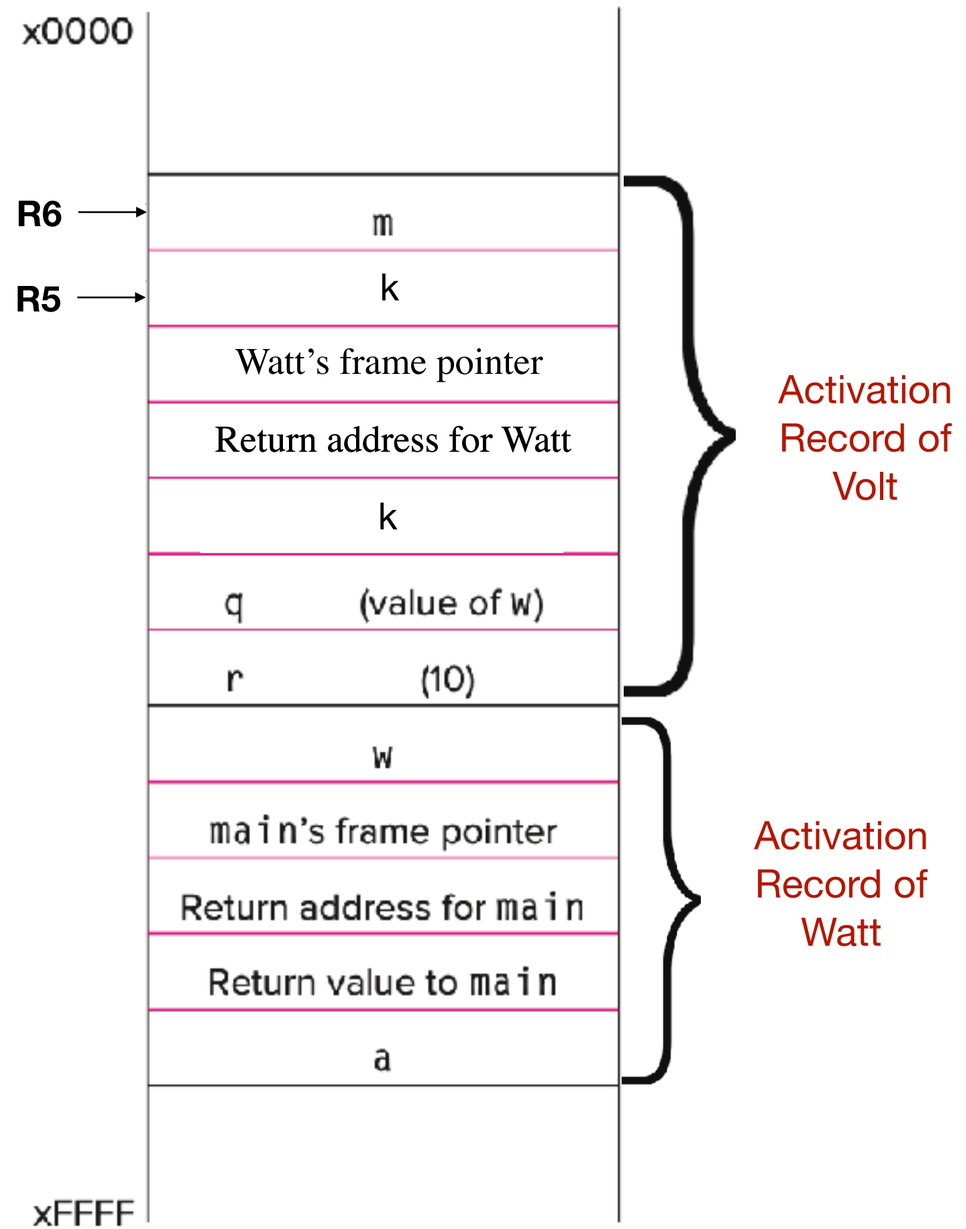
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

; pop local variables
```

R0
k



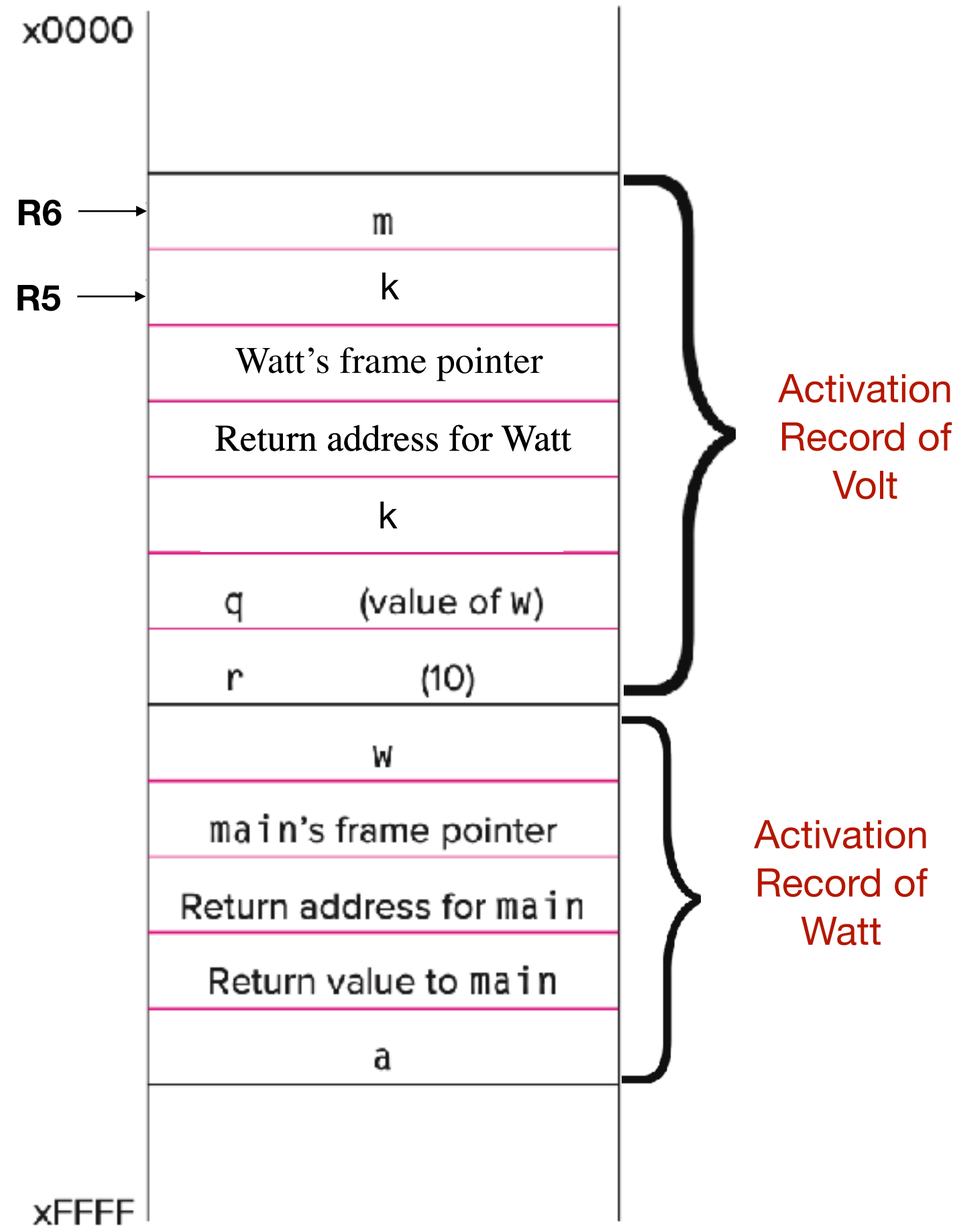
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

; pop local variables
ADD R6, R5, #1
```

R0
k



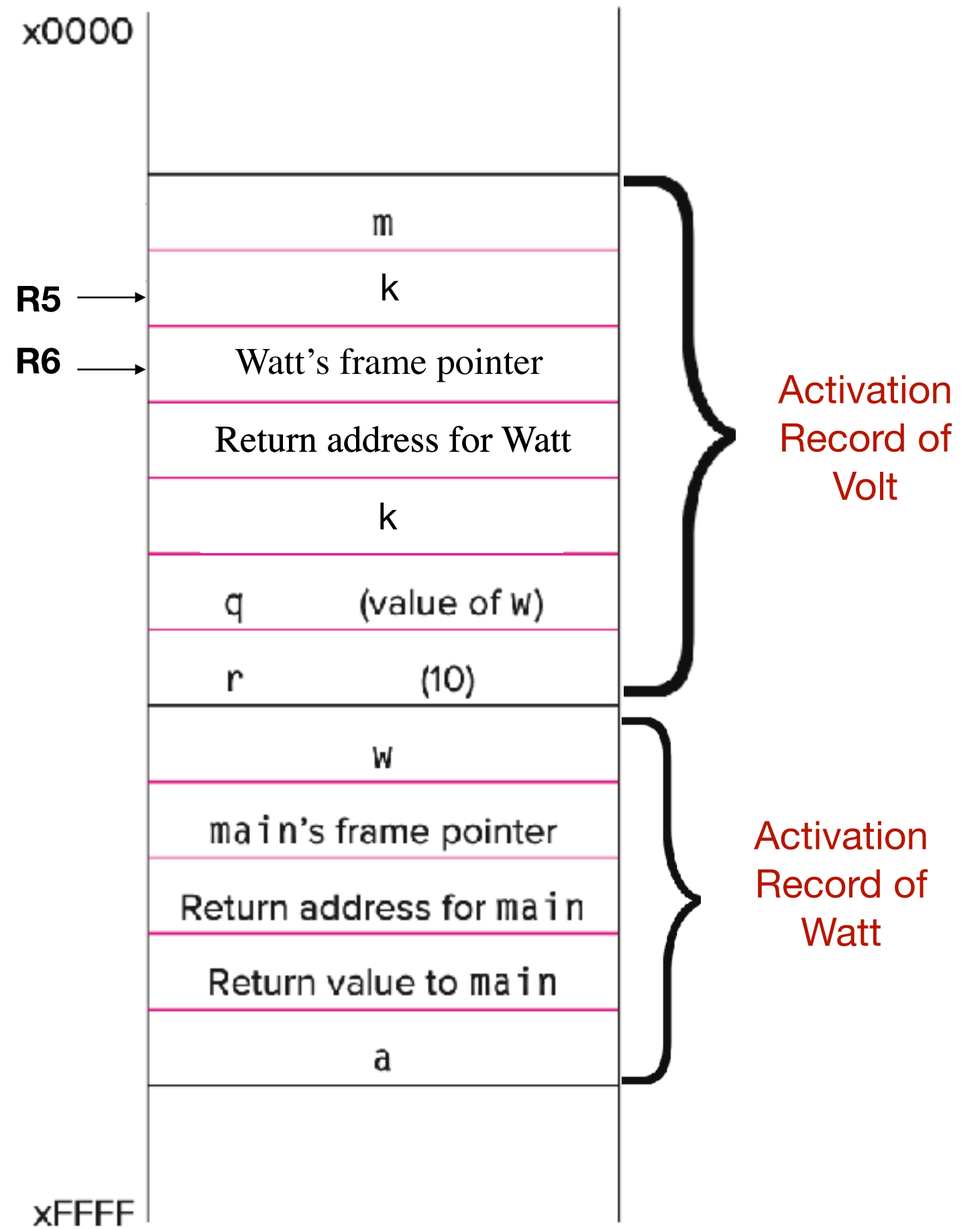
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

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

; pop local variables
ADD R6, R5, #1
```

R0
k



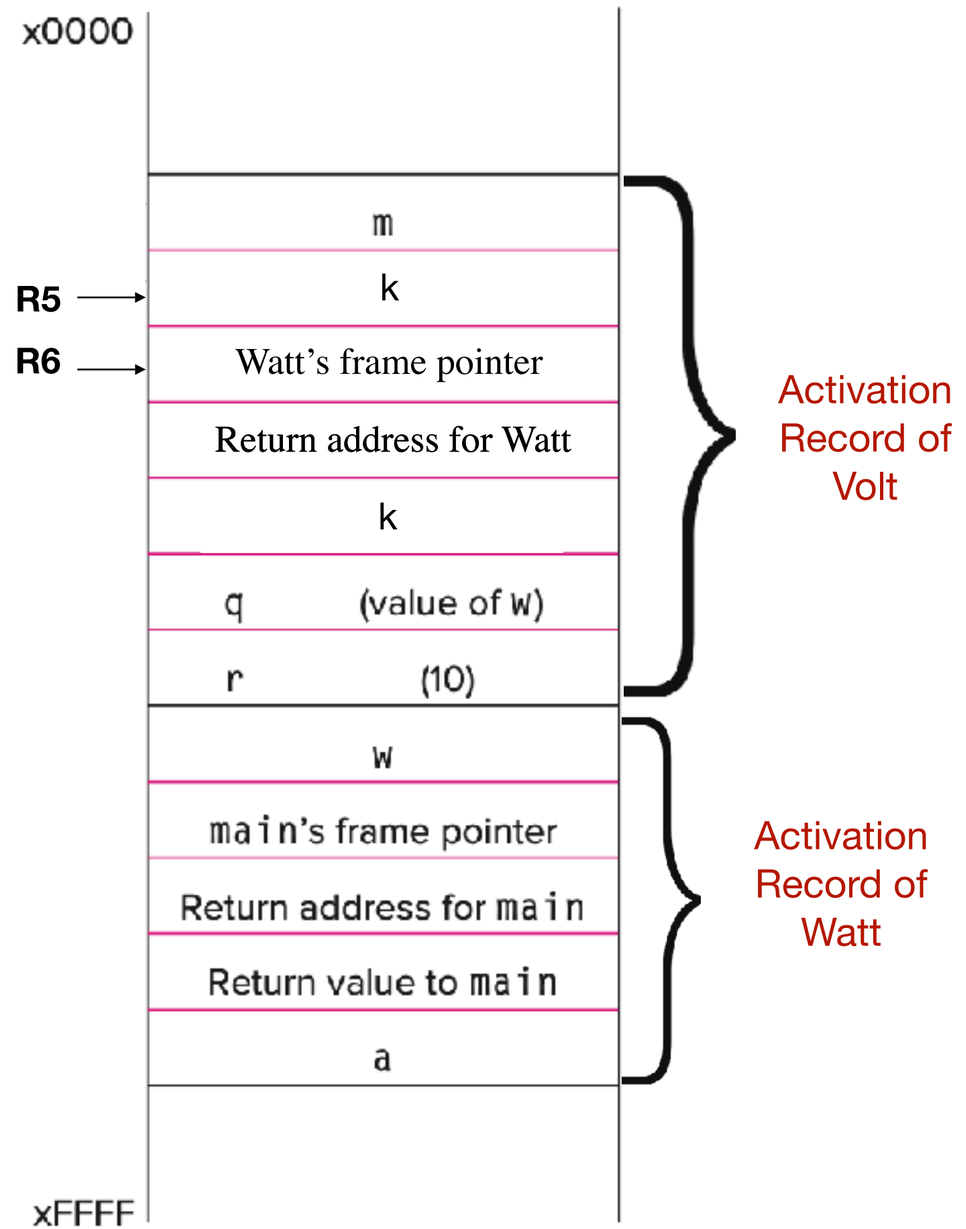
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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)
```

R0
k



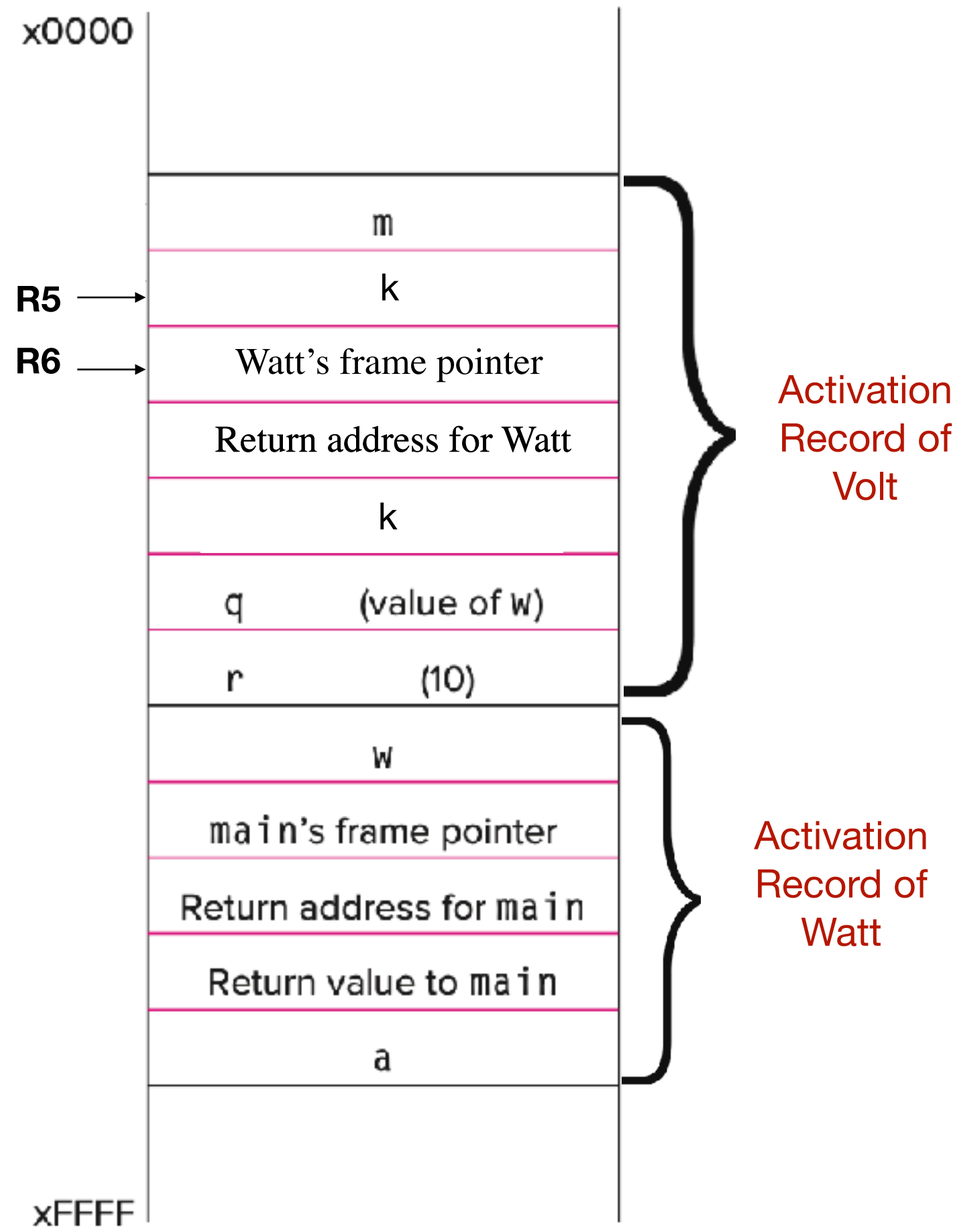
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k



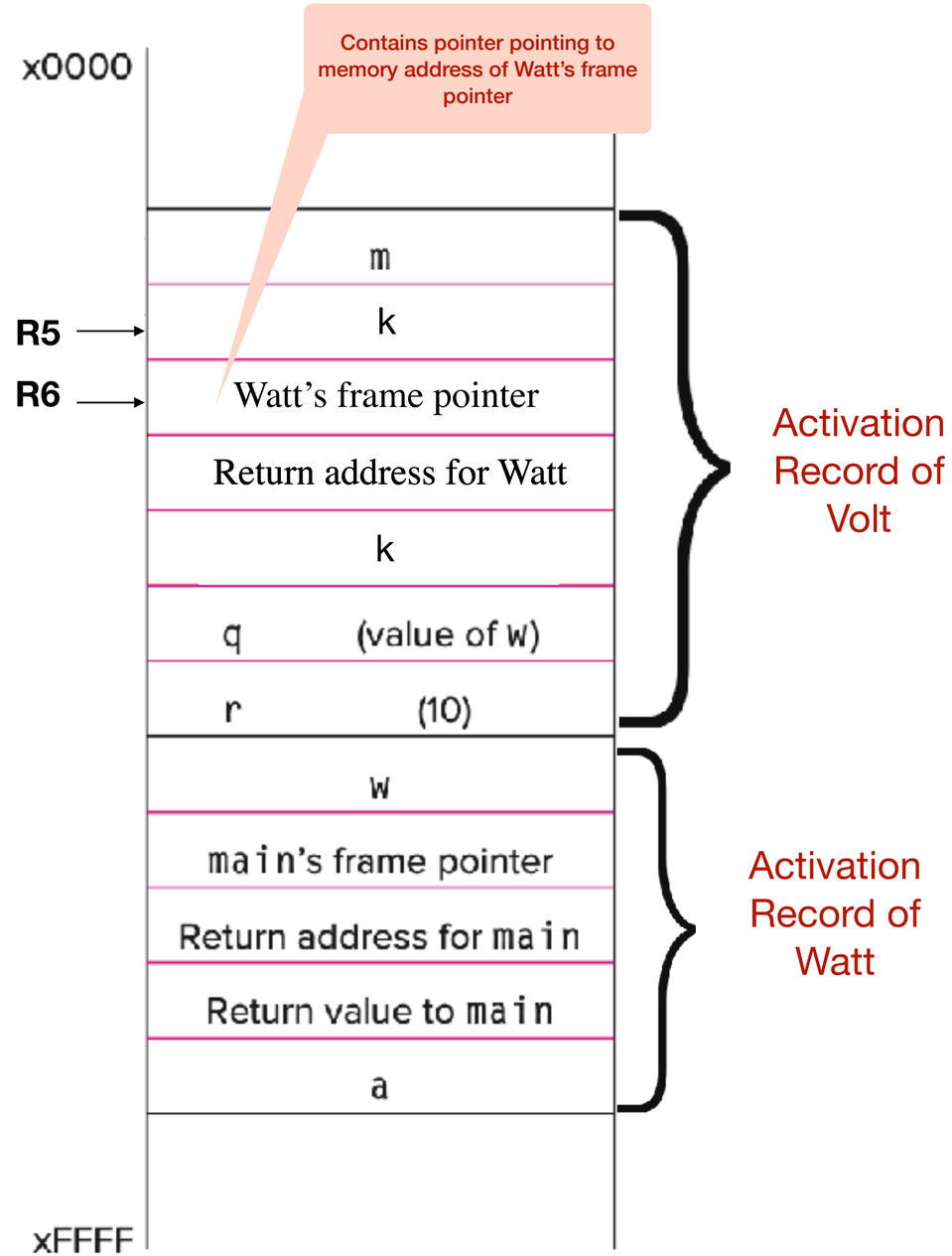
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k



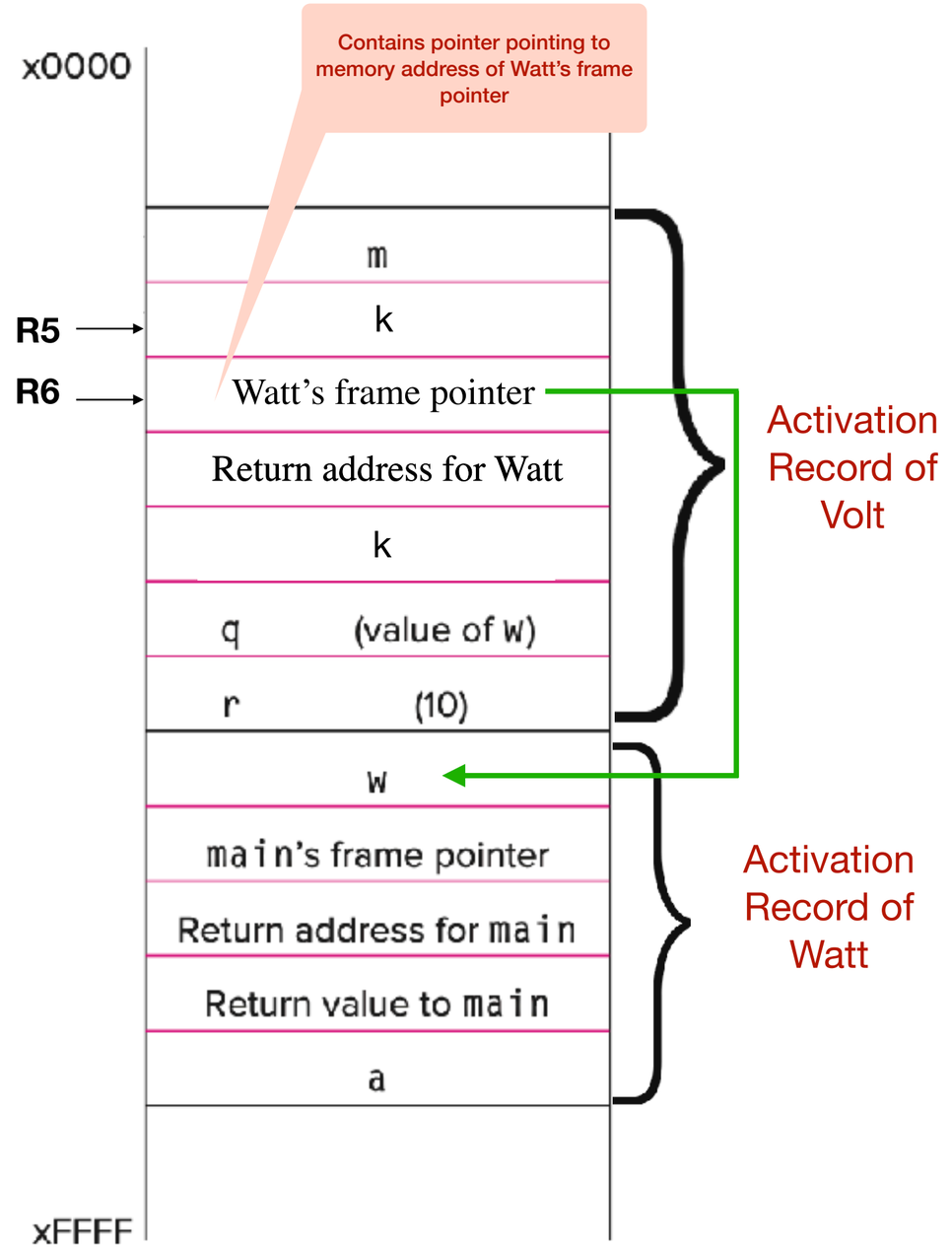
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k



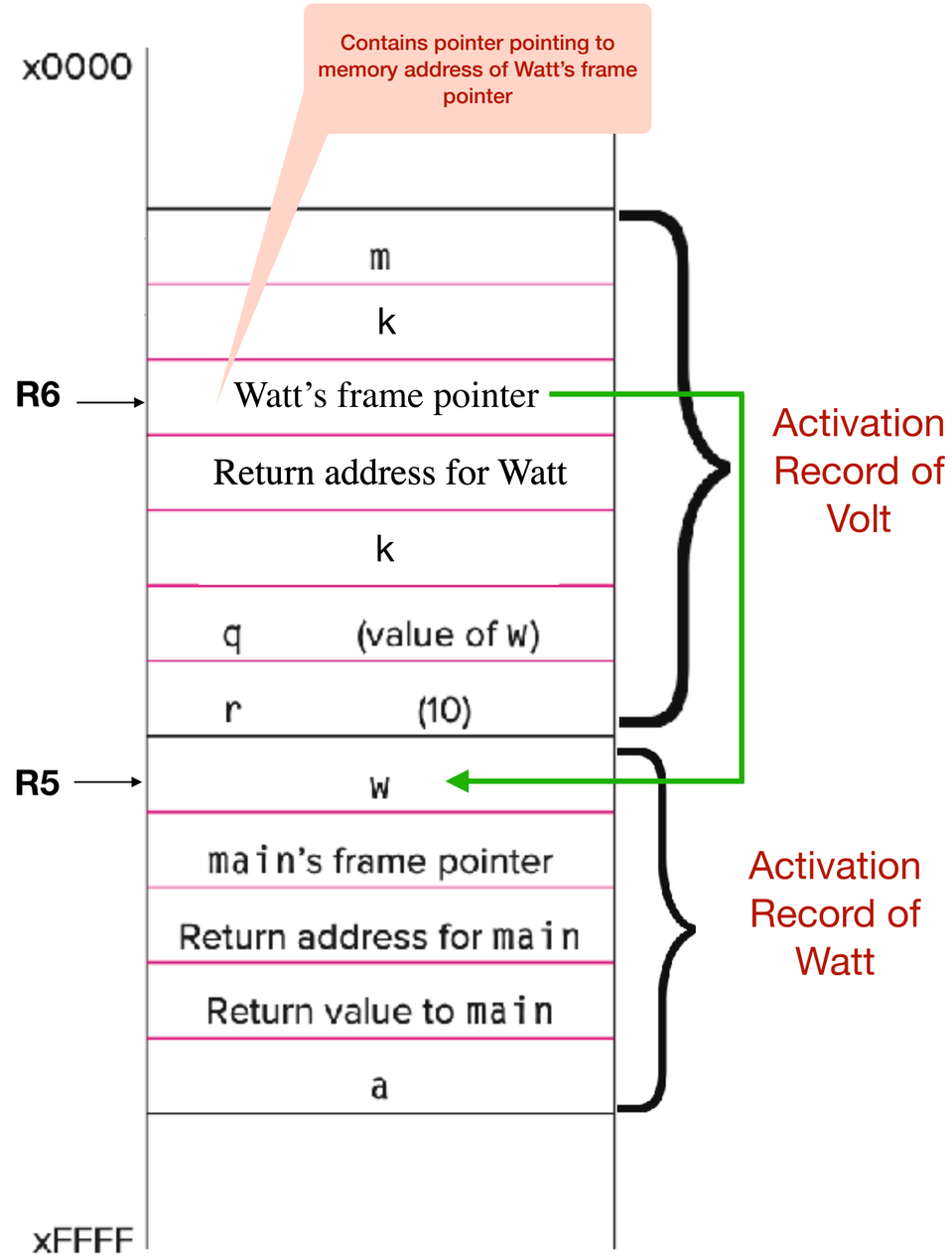
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k



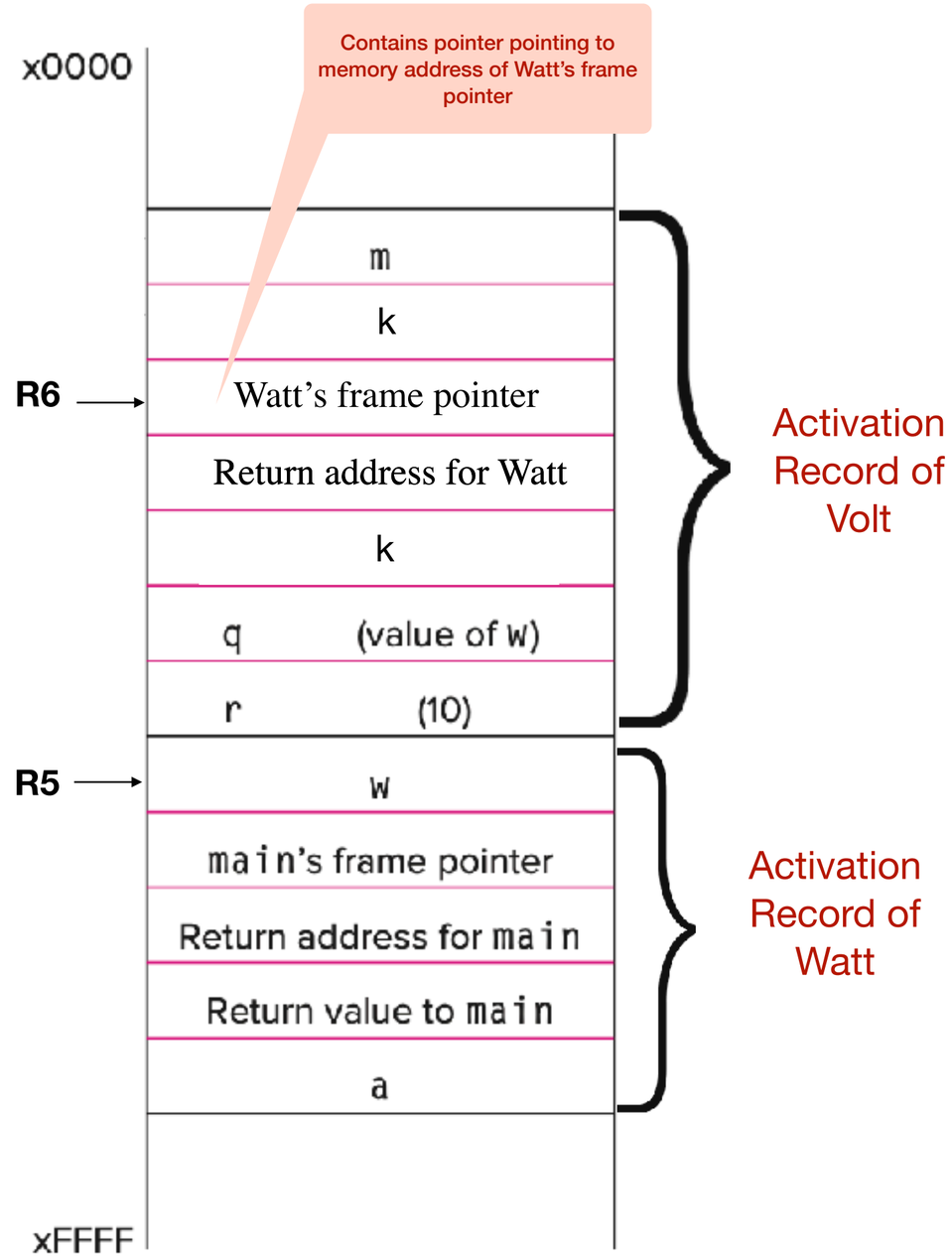
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k

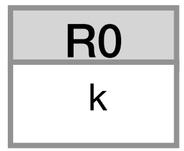


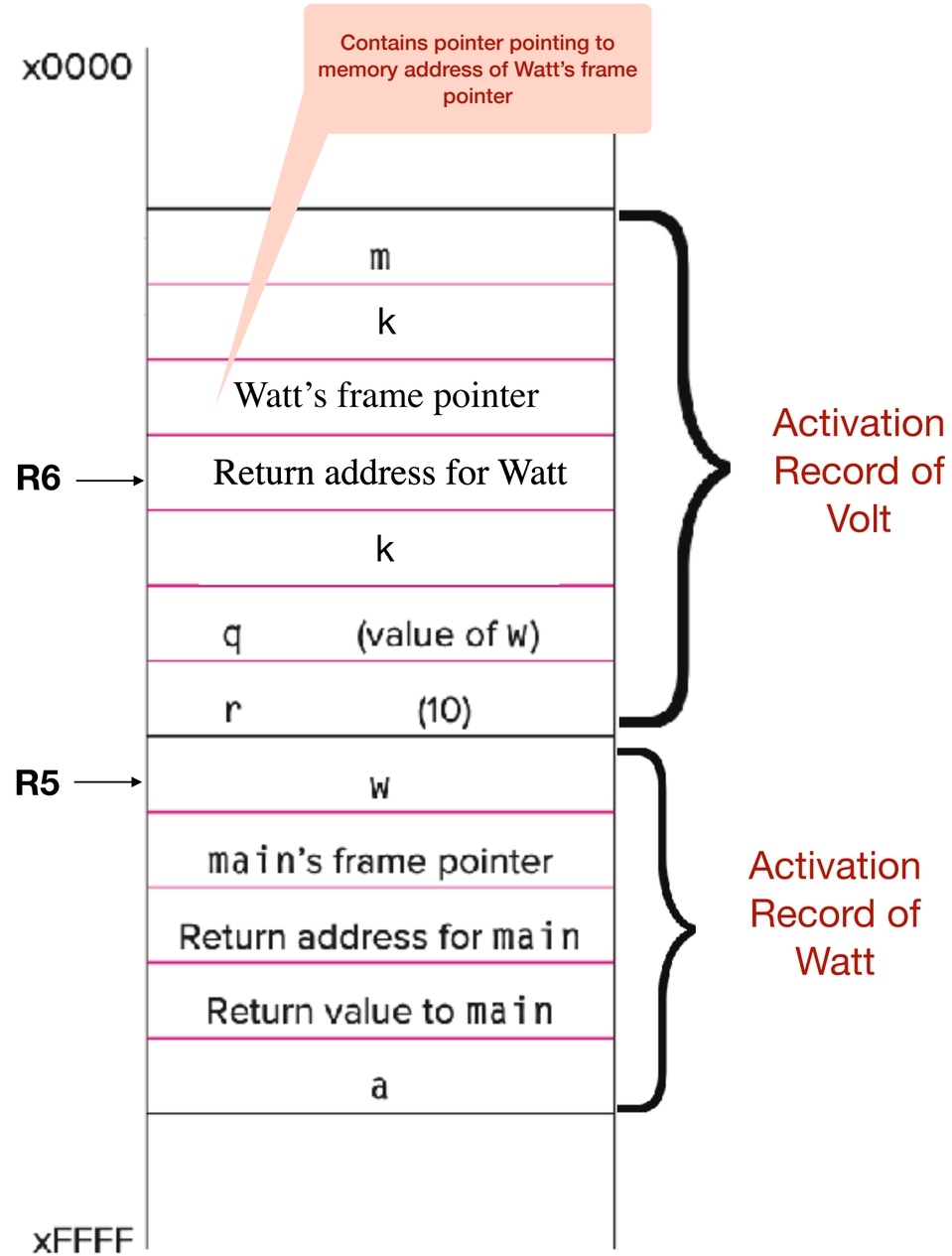
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```



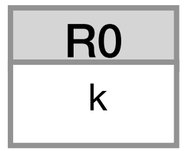


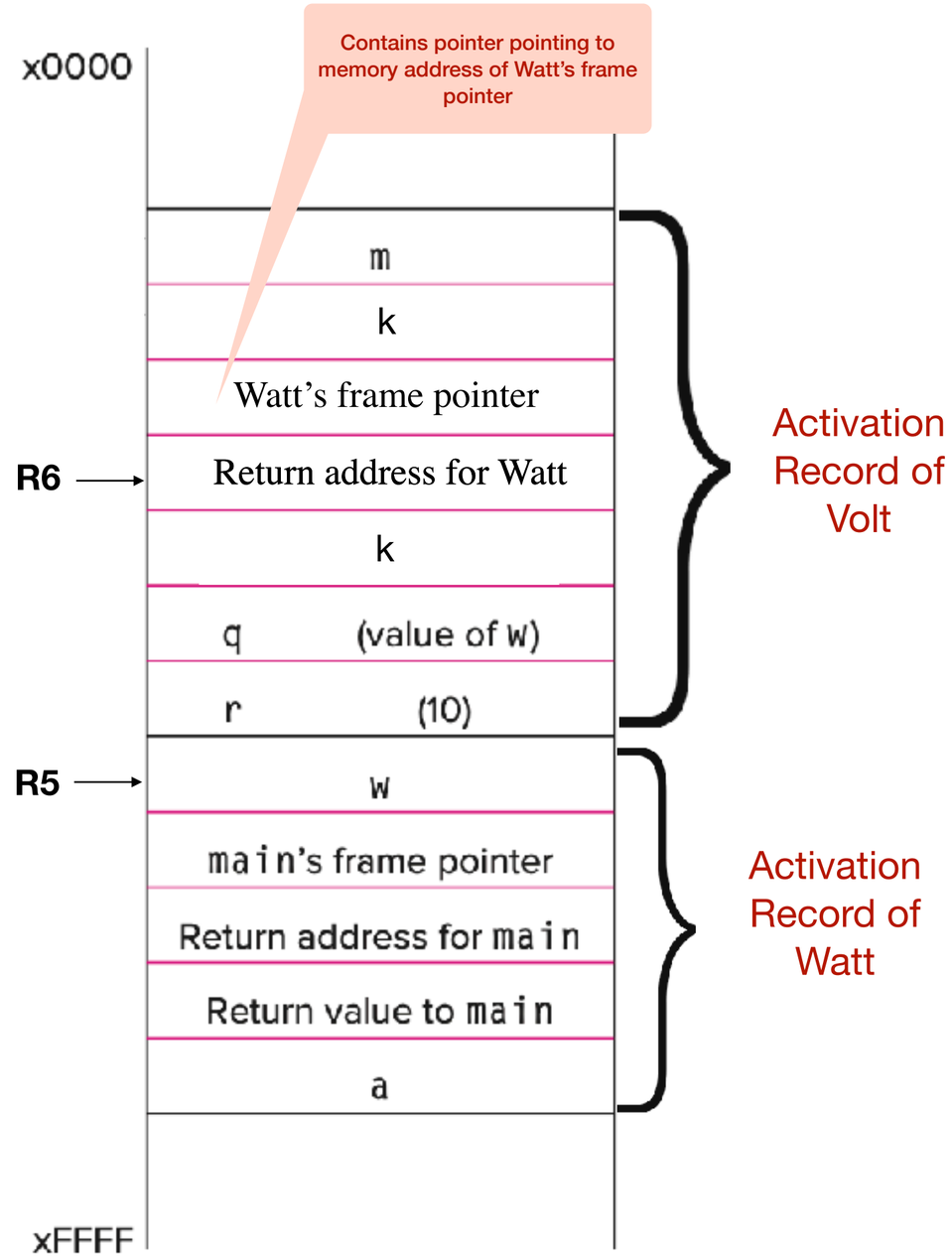
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```





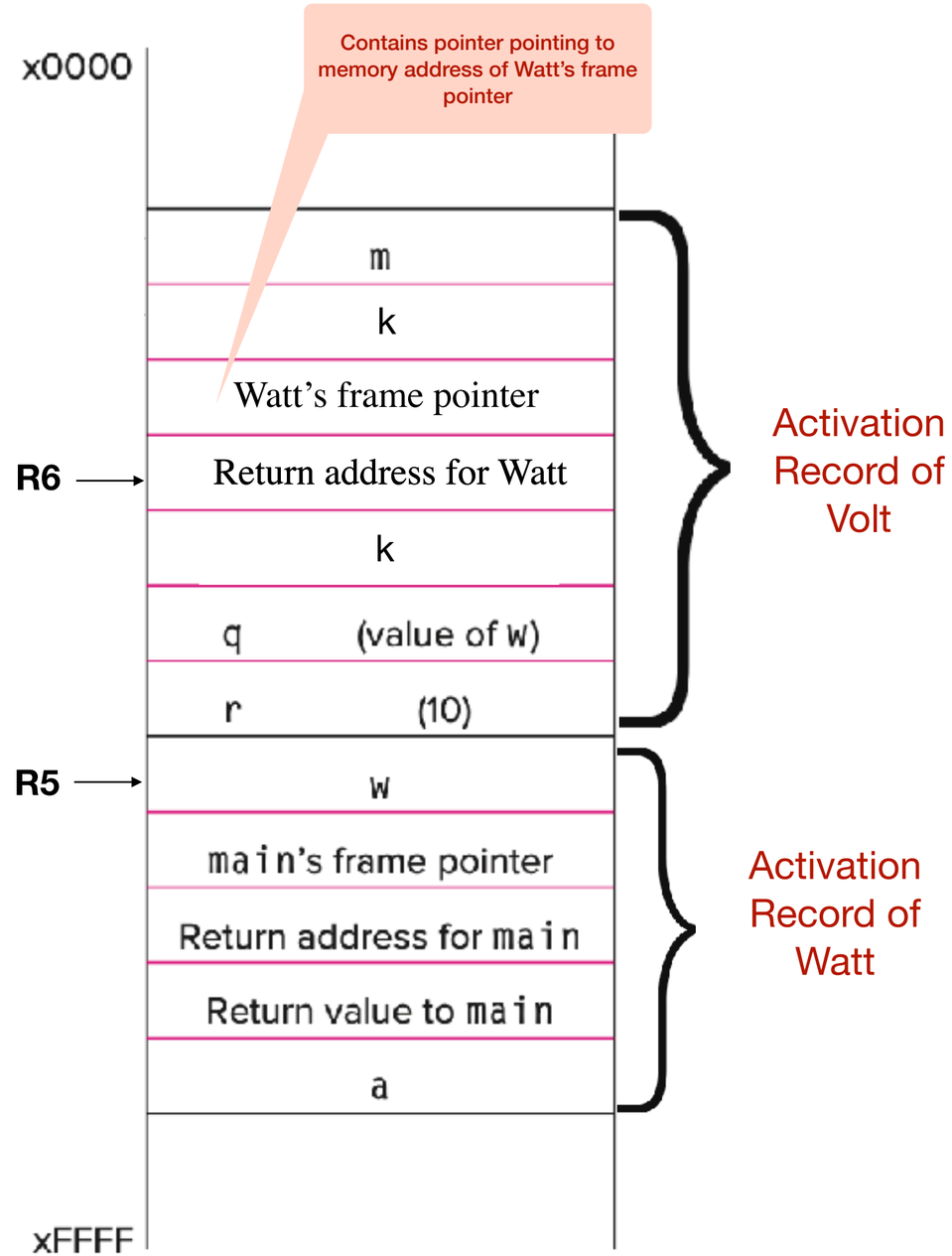
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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)
```

R0
k



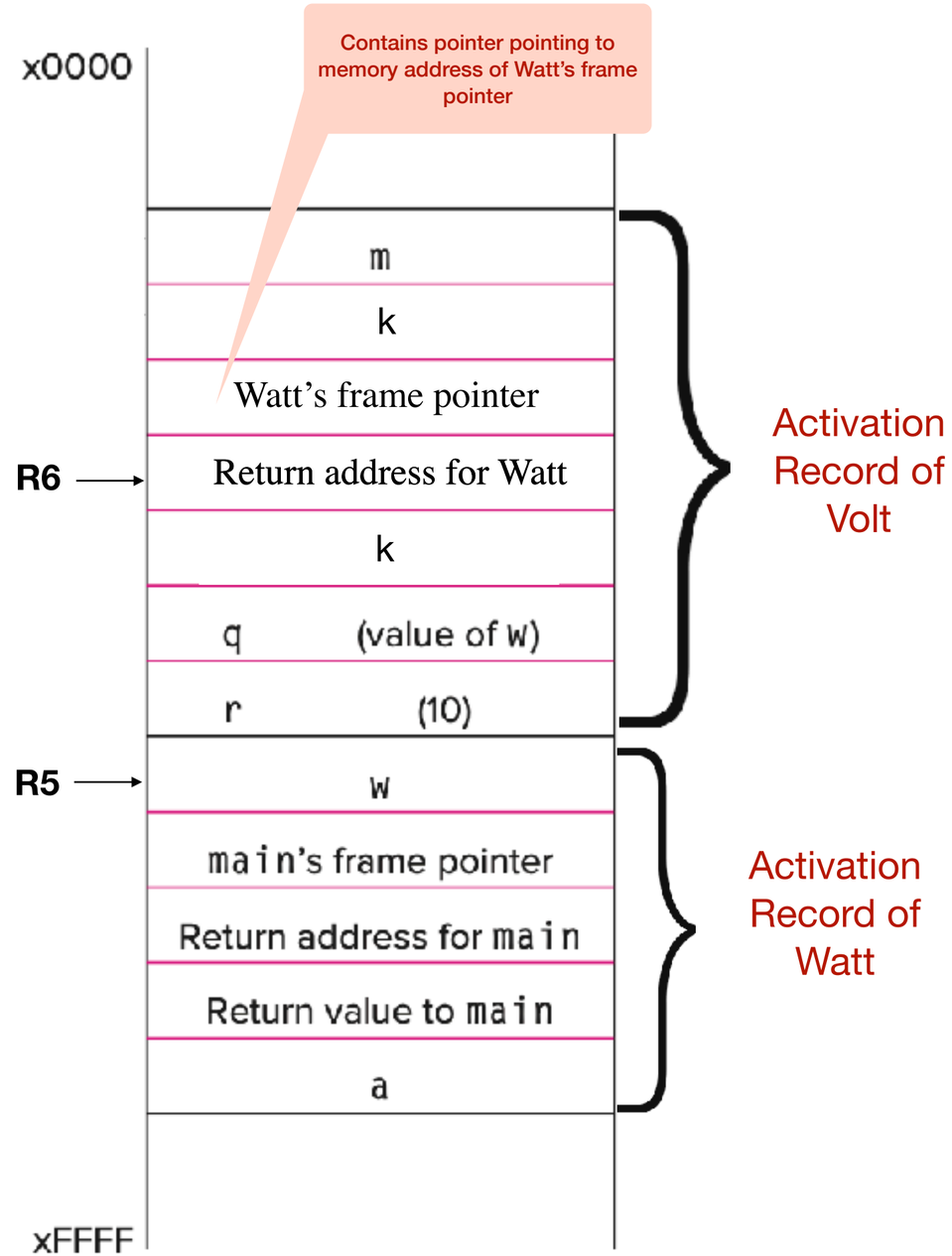
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

LC-3 Implementation

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

```
; 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
```

R0
k



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

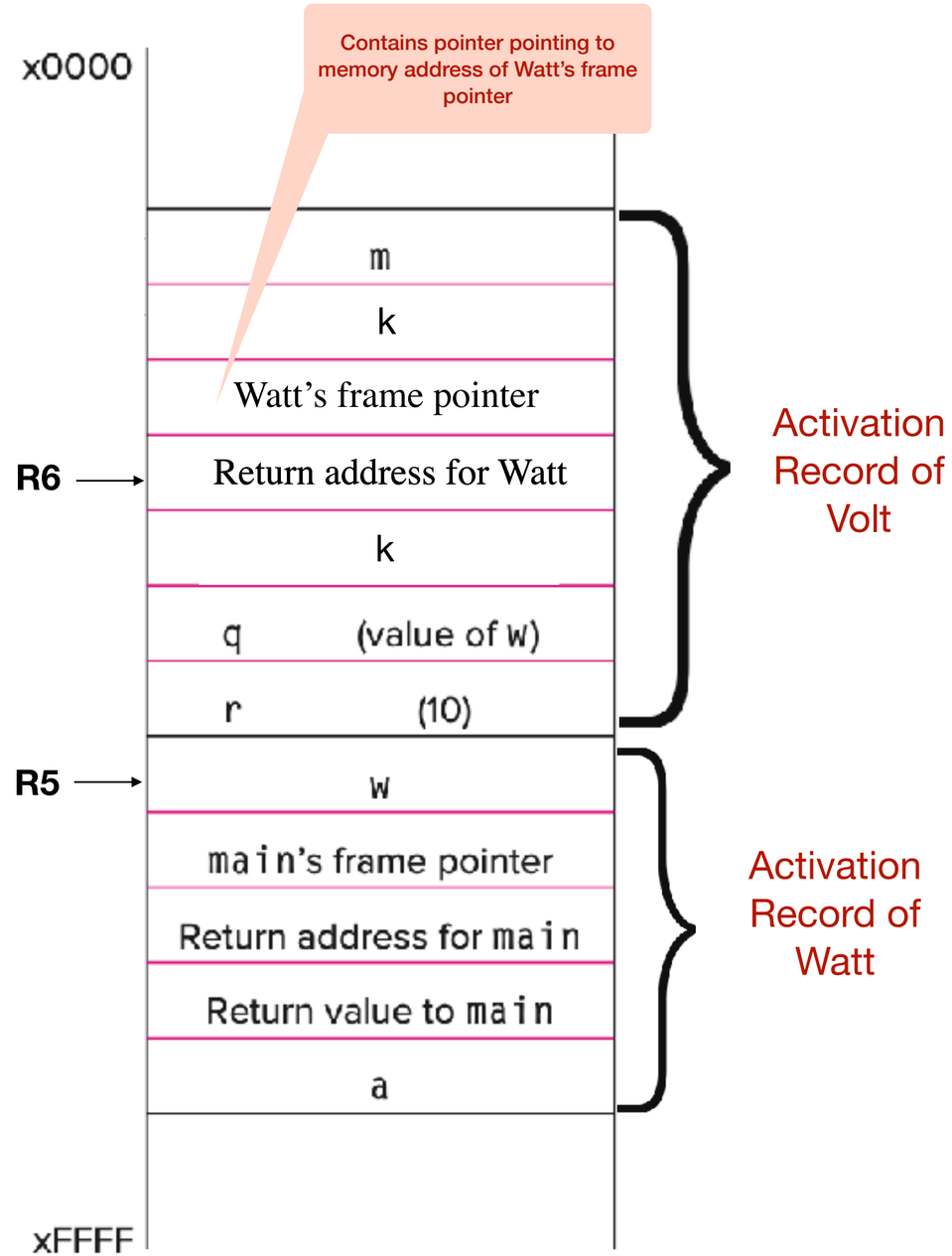
LC-3 Implementation

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

```
; 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
```

R0
k

R7



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

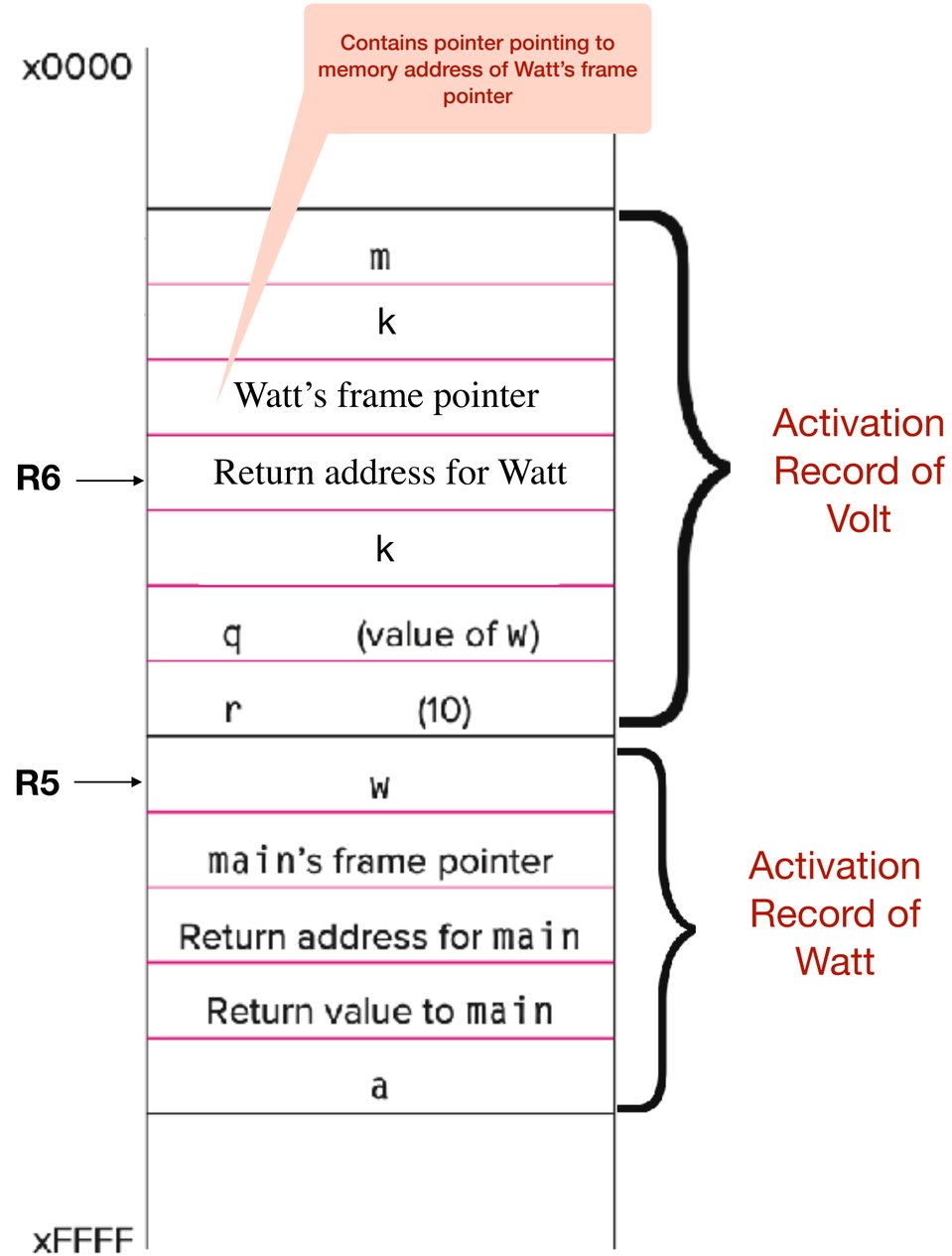
LC-3 Implementation

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

```
; 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
```

R0
k

R7
Return address for Watt



```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)

```
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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
```
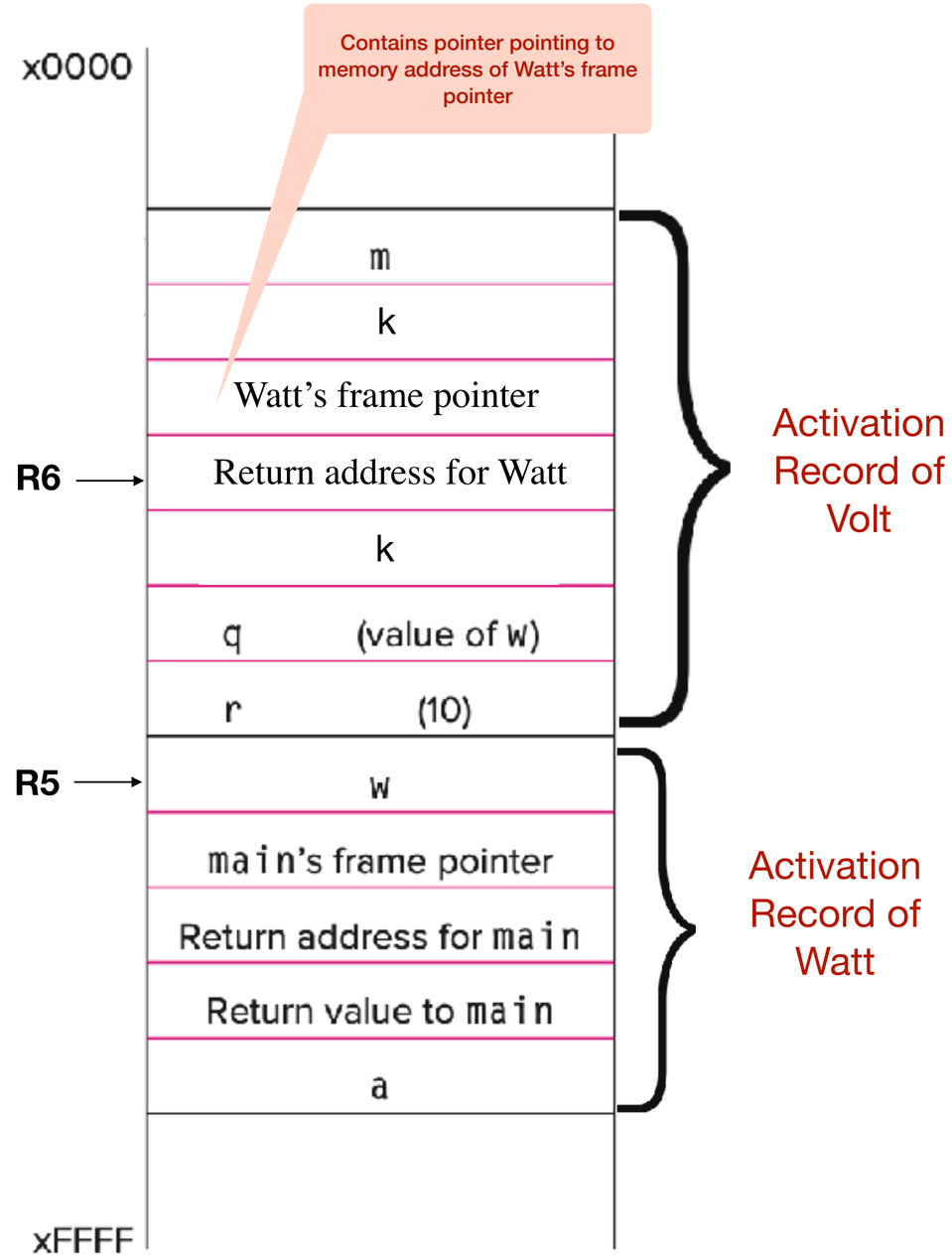

R0
k

R7
Return address for Watt



```
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{
        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)

```
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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
```
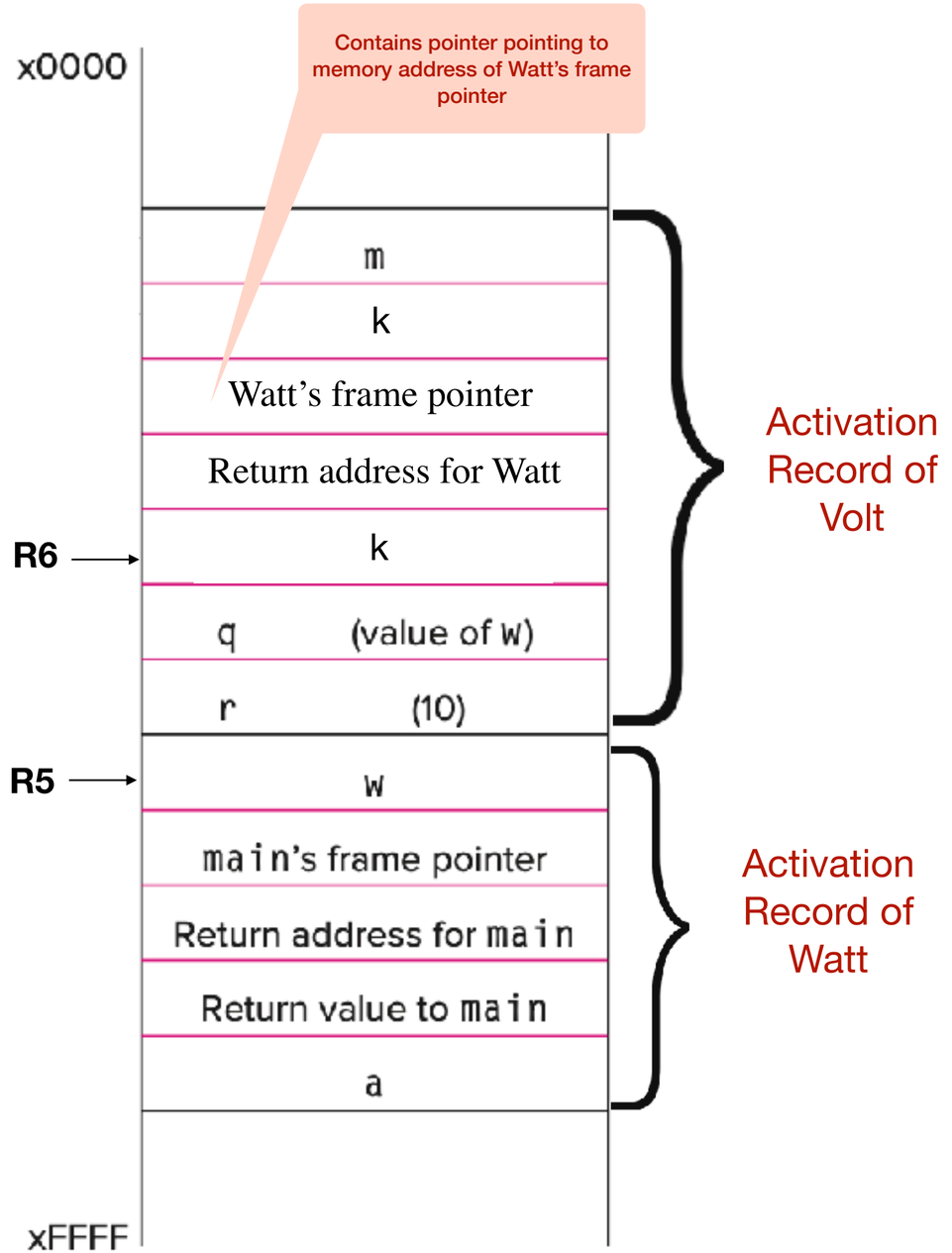

R0
k

R7
Return address for Watt



```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)

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LDR R0, R5, #0
STR R0, R5, #3

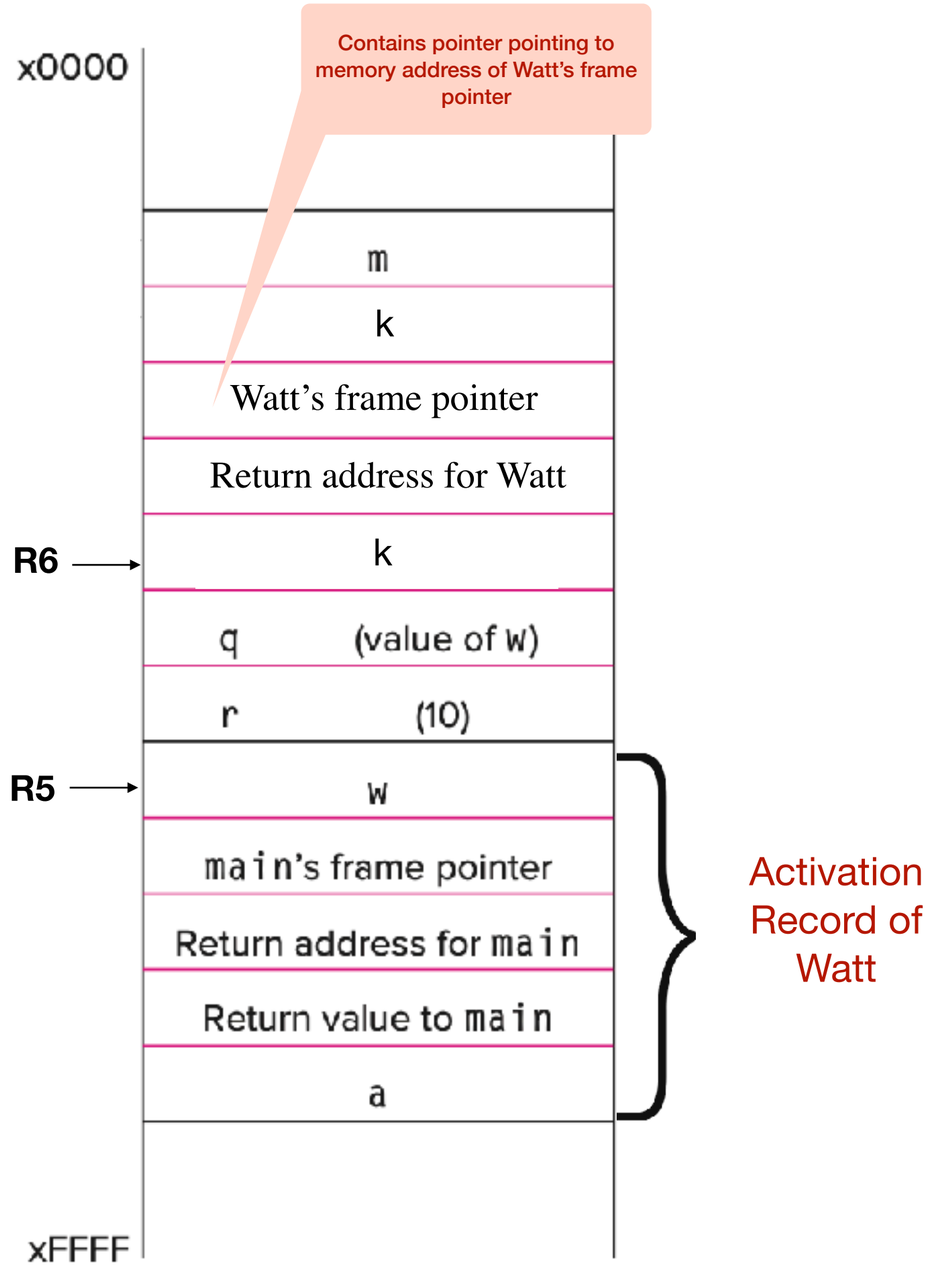
; pop local variables
ADD R6, R5, #1

; 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
```

R0
k

R7
Return address for Watt



```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)

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LDR R0, R5, #0
STR R0, R5, #3

; pop local variables
ADD R6, R5, #1

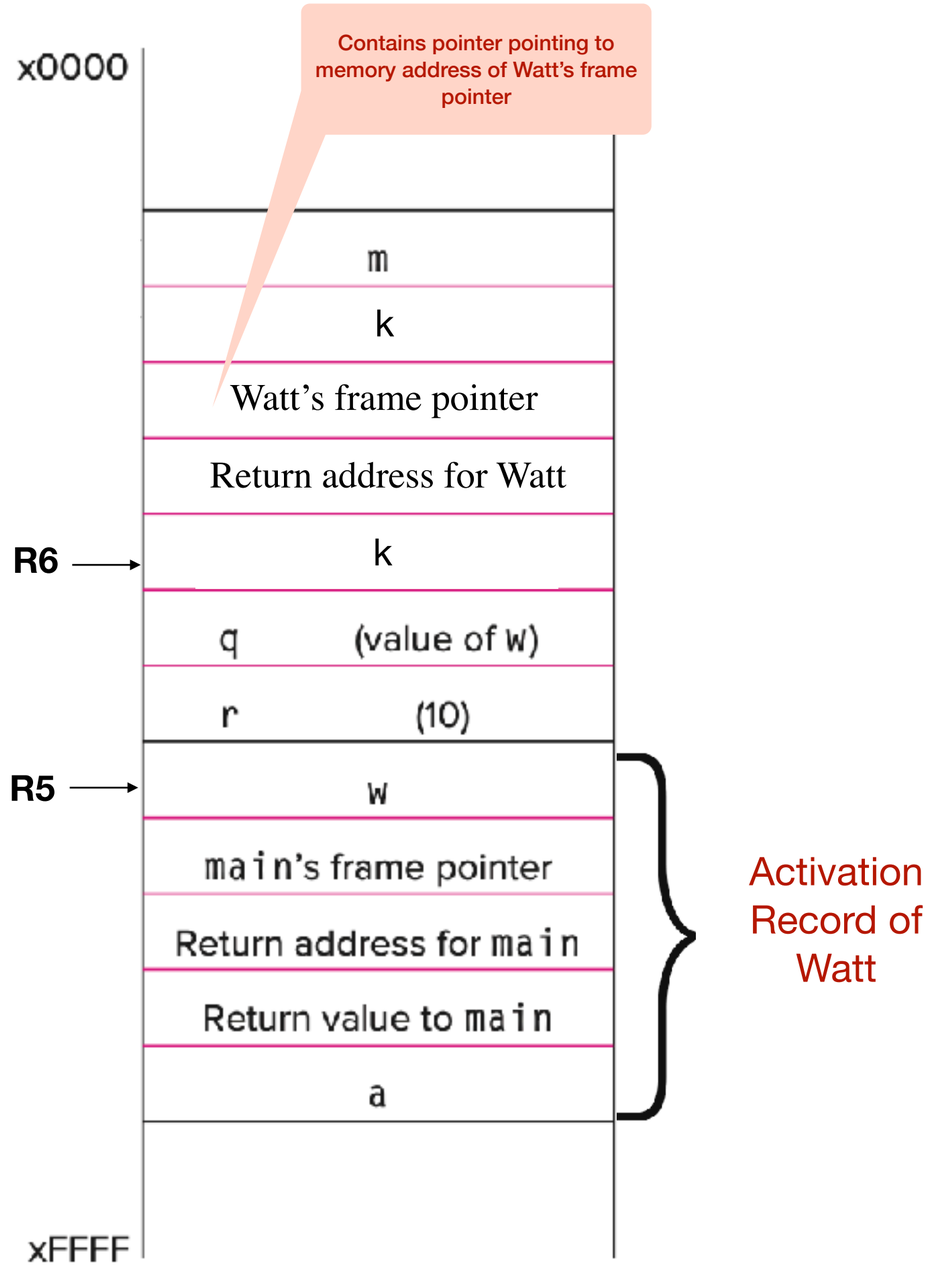
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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

; return control to caller
```

R0
k

R7
Return address for Watt



```c
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        ...
        return k;
}
```

LC-3 Implementation

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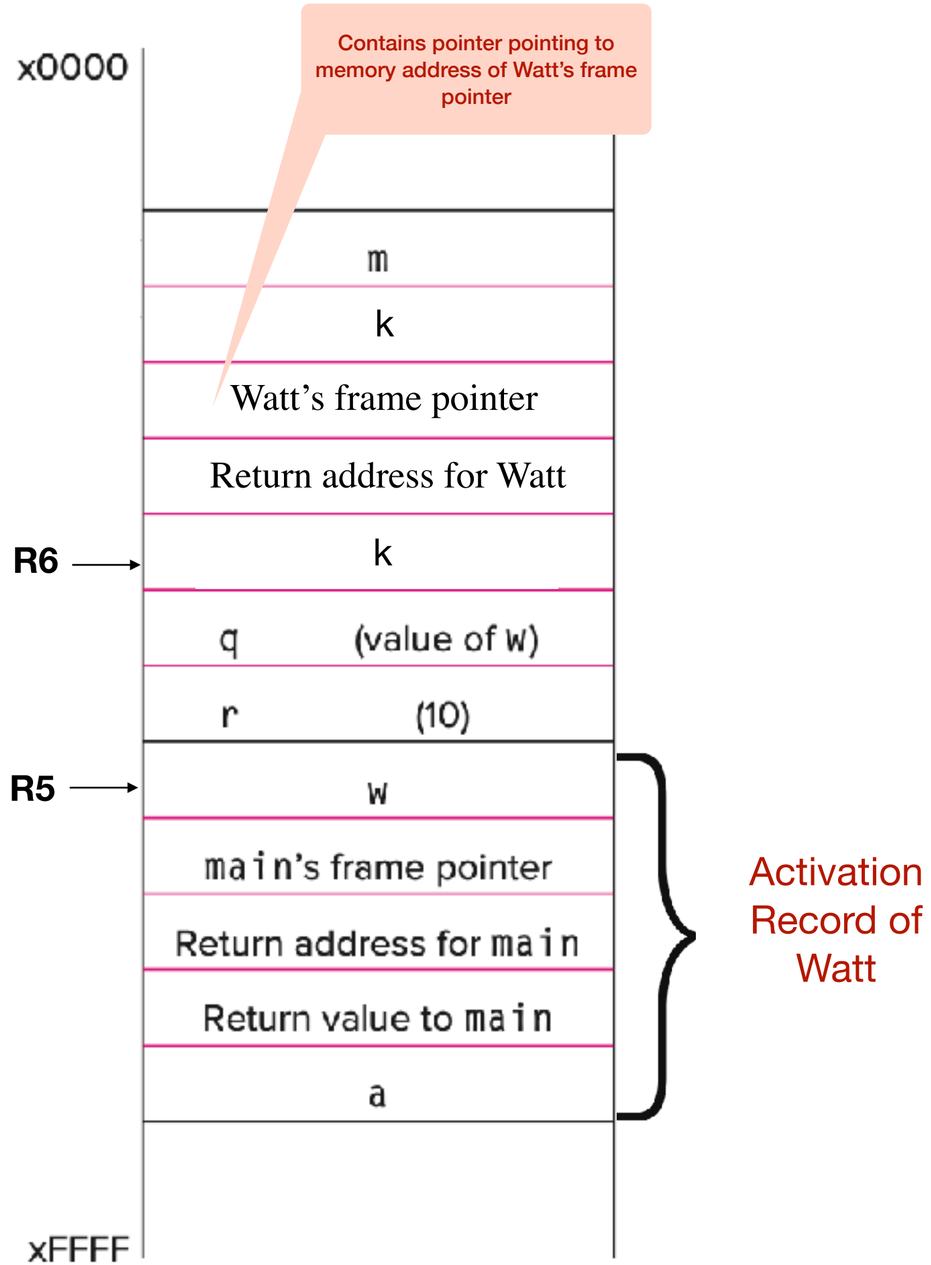
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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

; return control to caller
RET
```

R0
k

R7
Return address for Watt



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

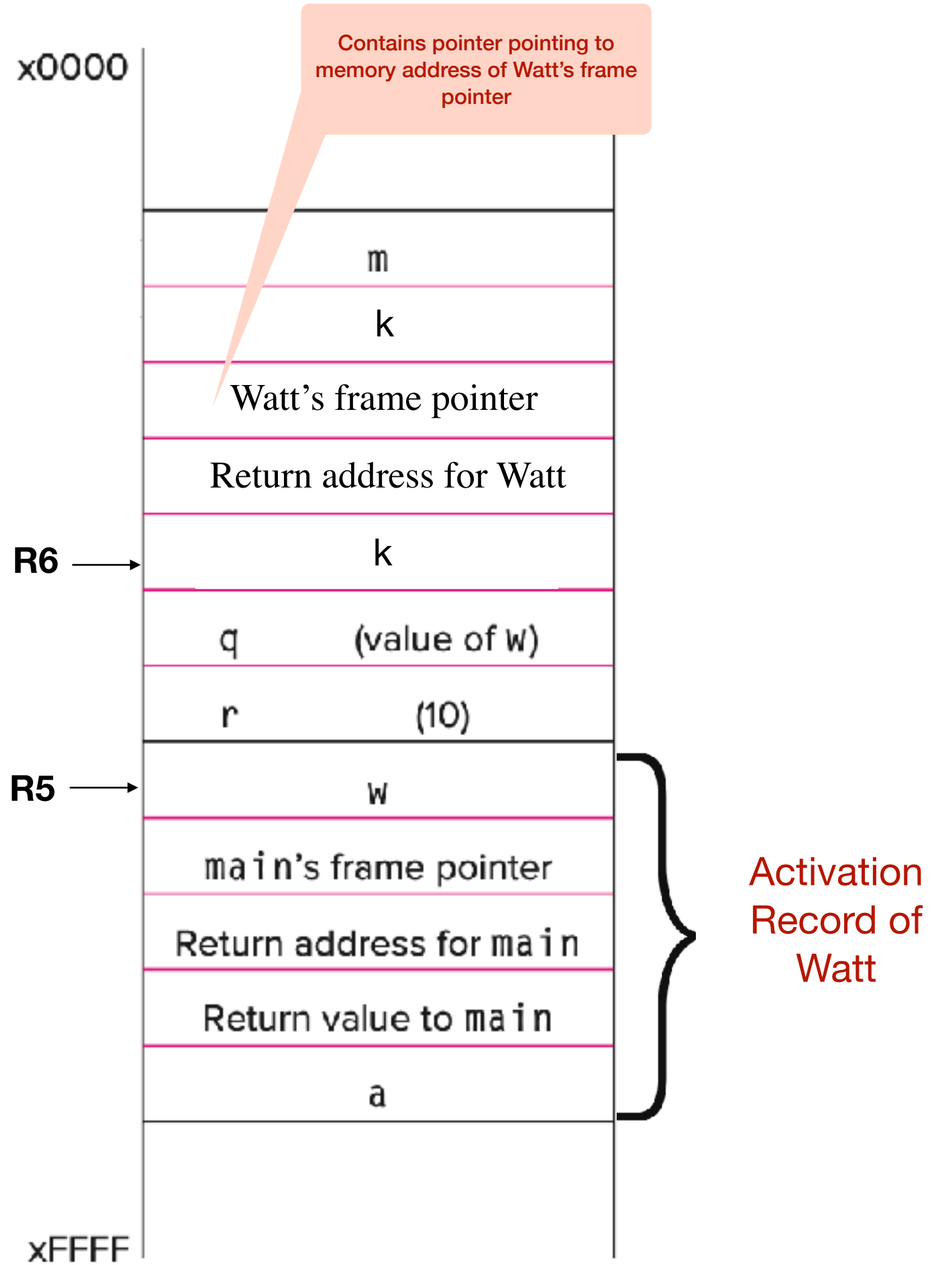
LC-3 Implementation

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
Return address for Watt



```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

```
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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
```
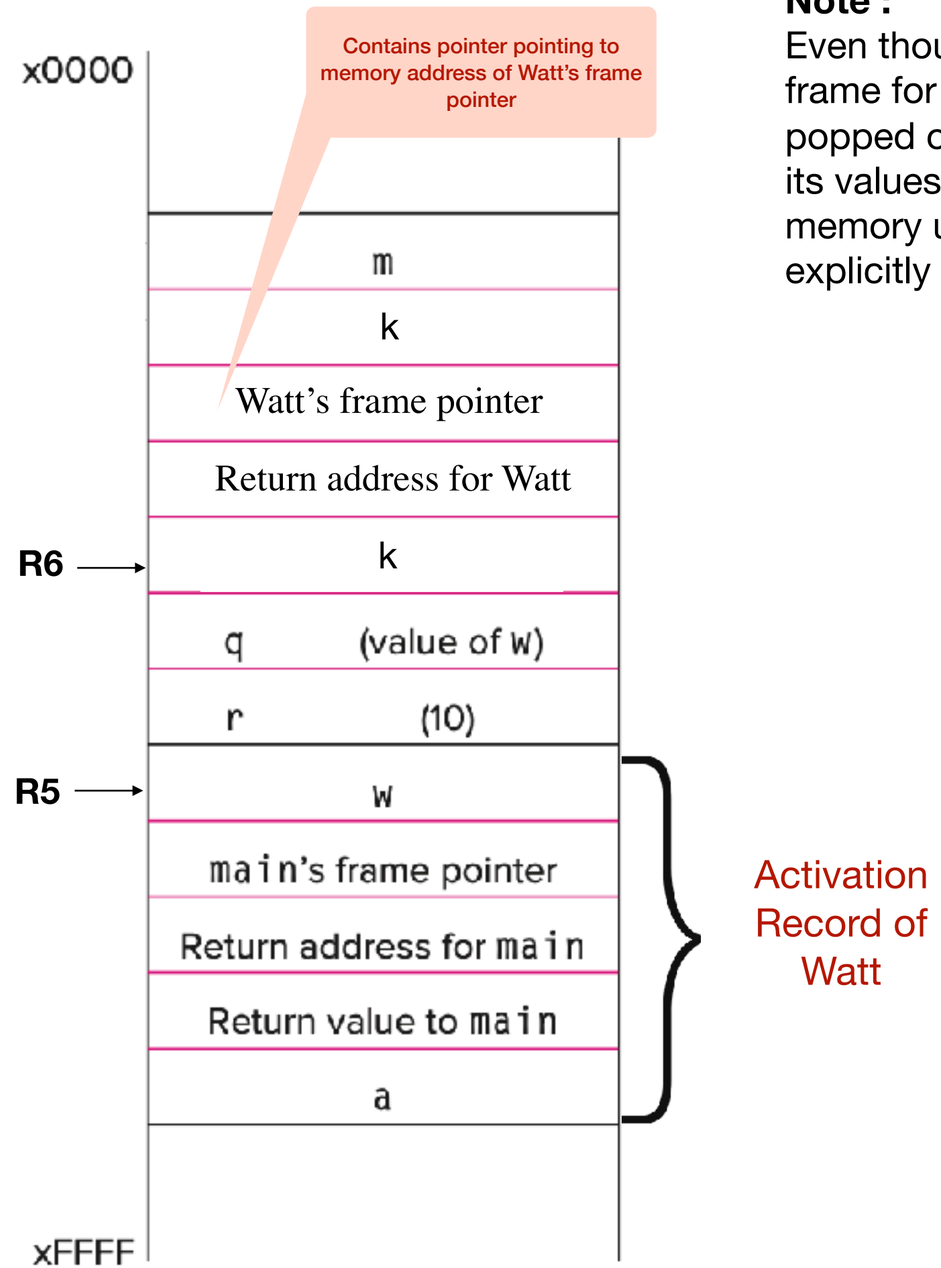

R0
k

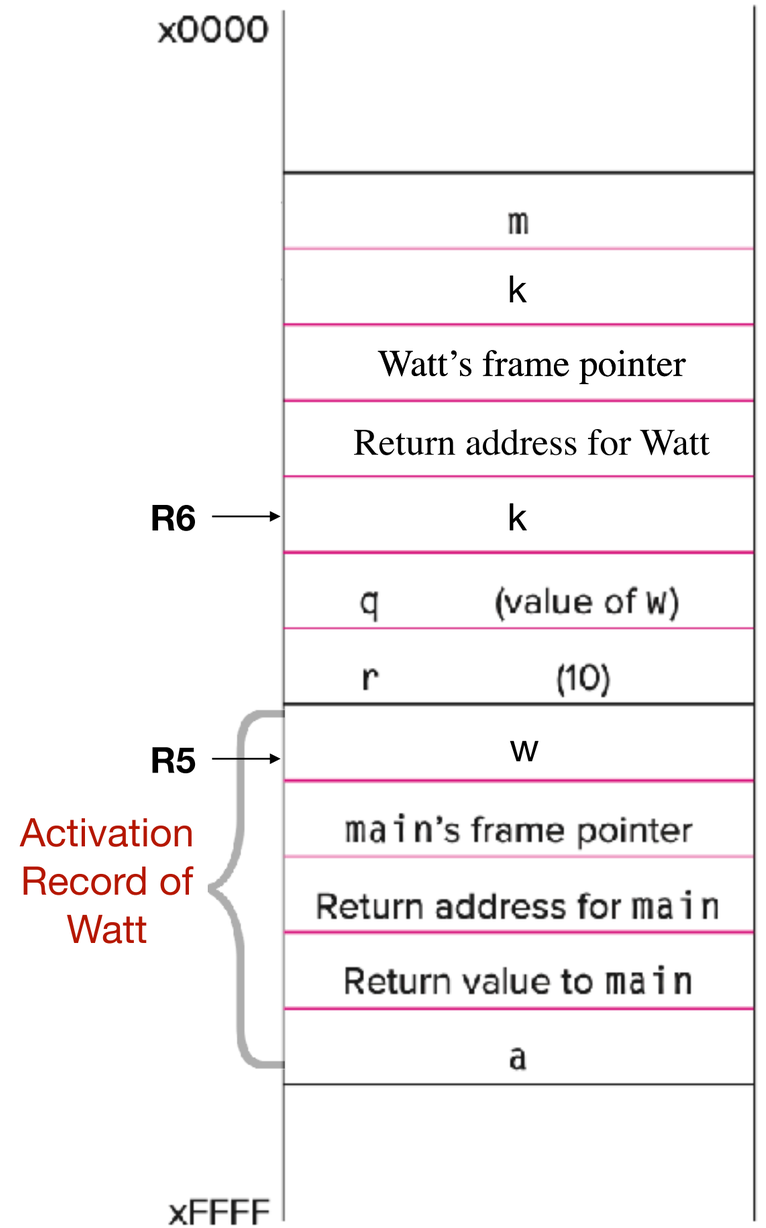
R7
Return address for Watt



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;
}
```

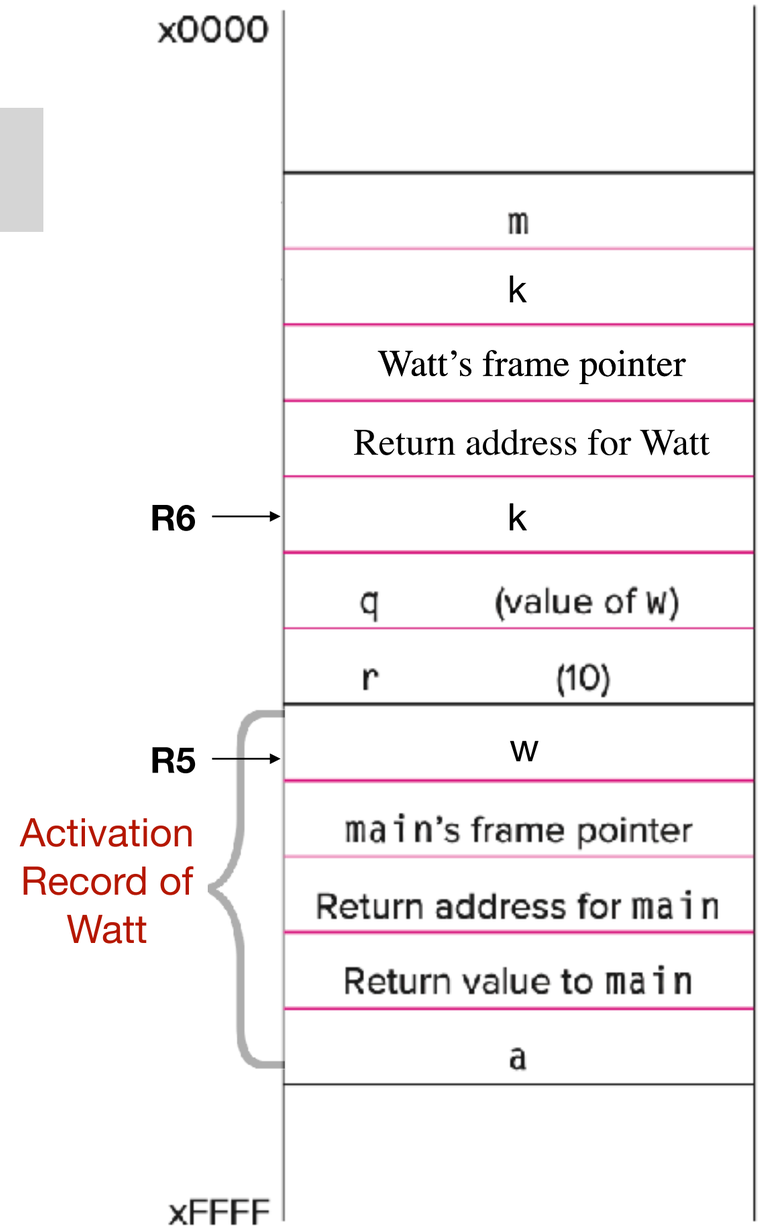
LC-3 Implementation



```
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)

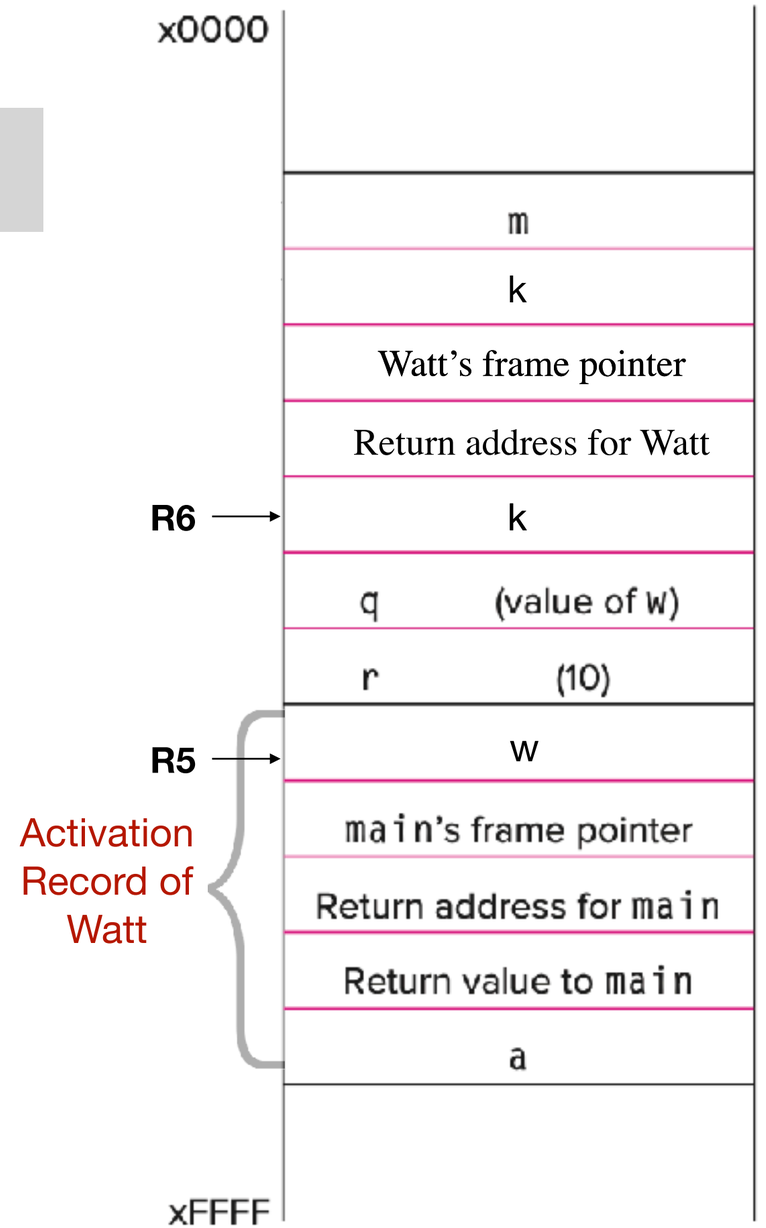


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

LC-3 Implementation

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

```
JSR VOLT
```

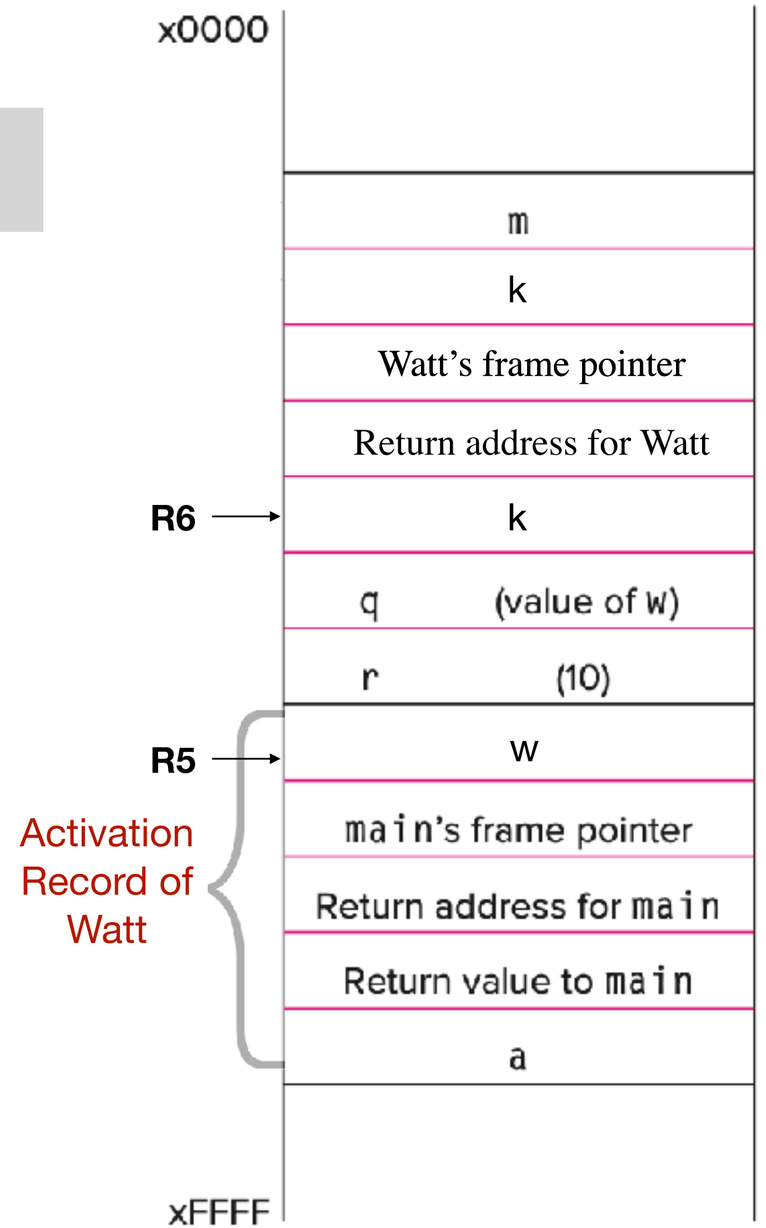


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

LC-3 Implementation

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

```
JSR VOLT
; load return value (top of stack)
```

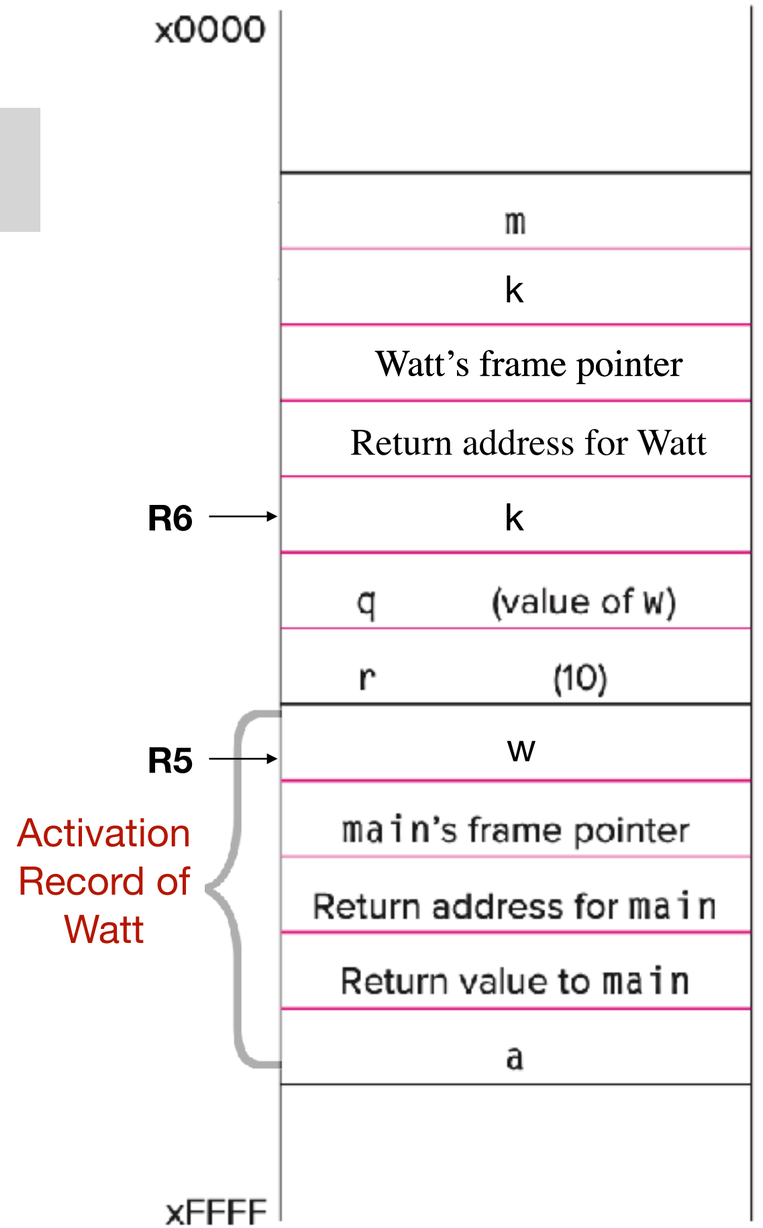


```c
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```

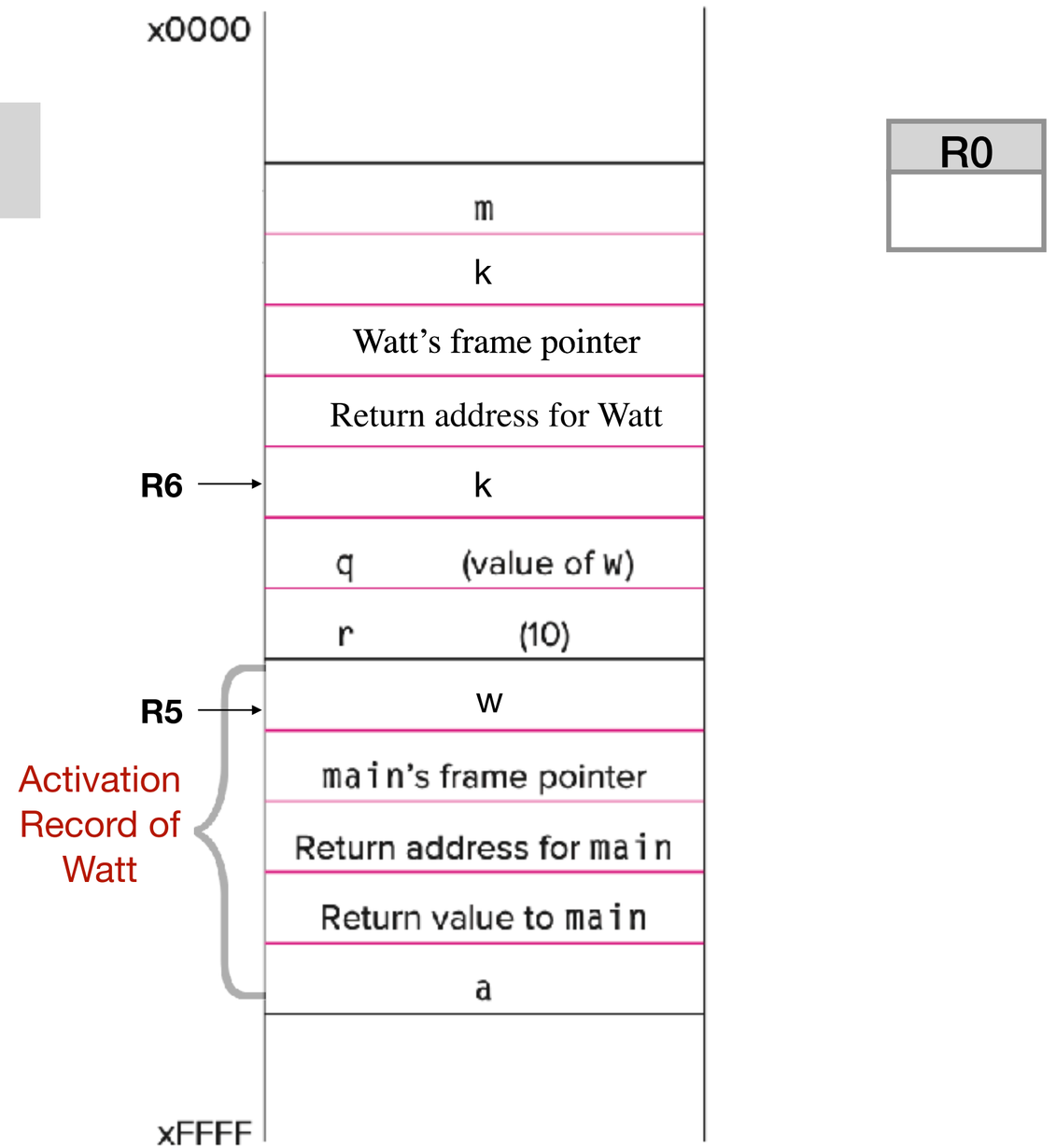


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```

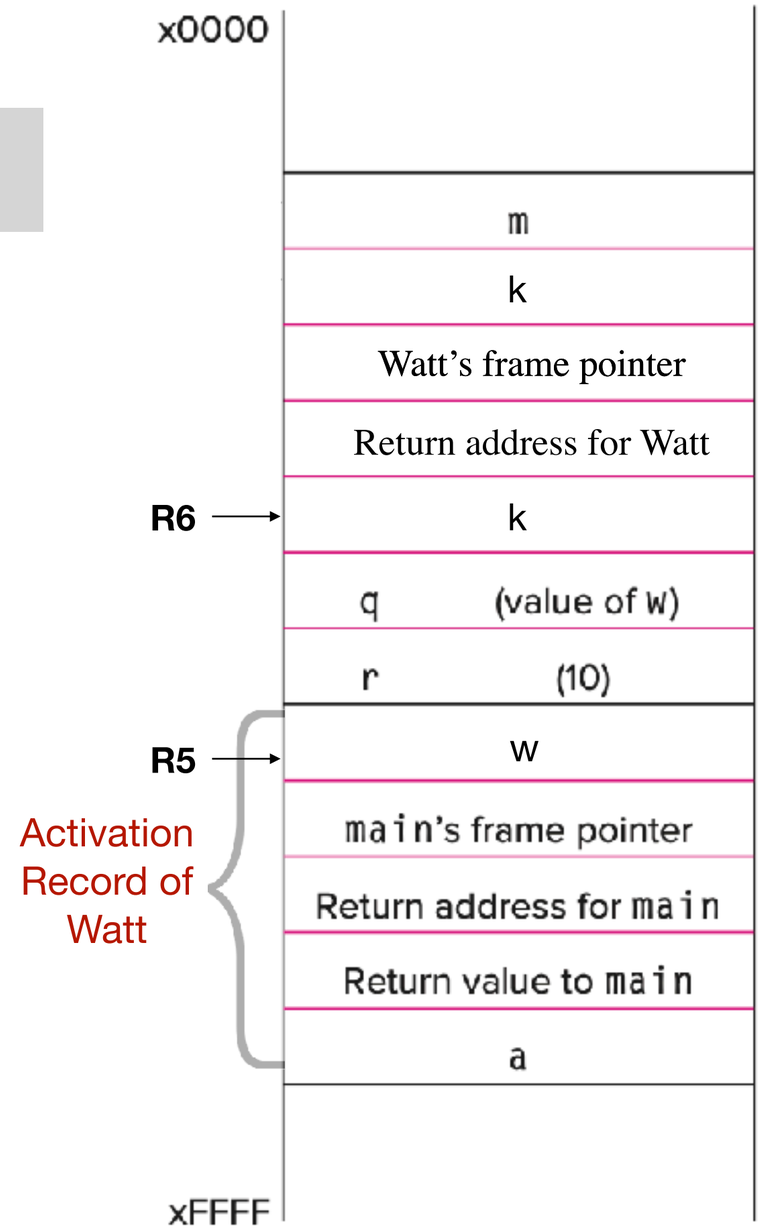


```c
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



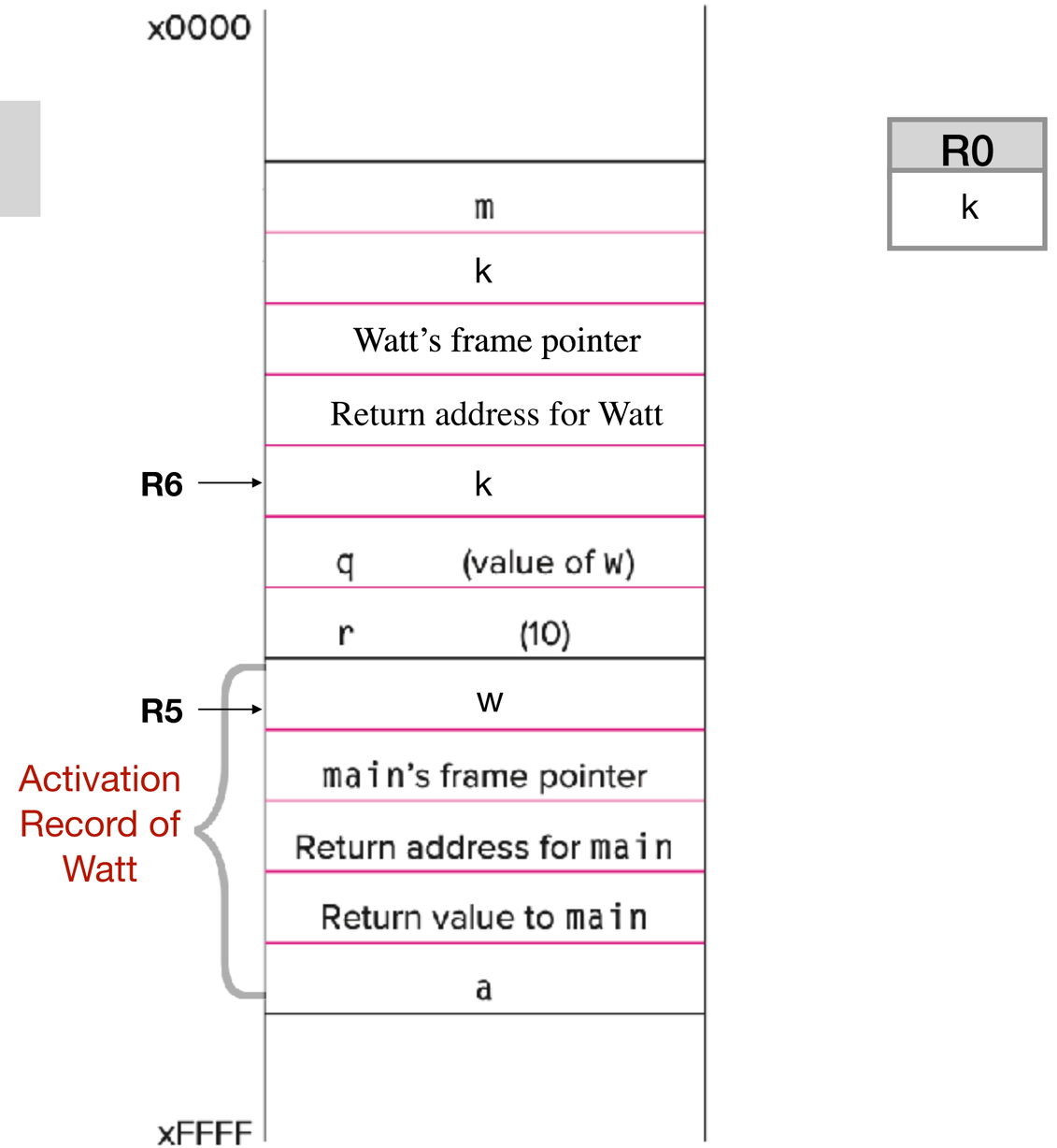
R0
k

```c
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
```



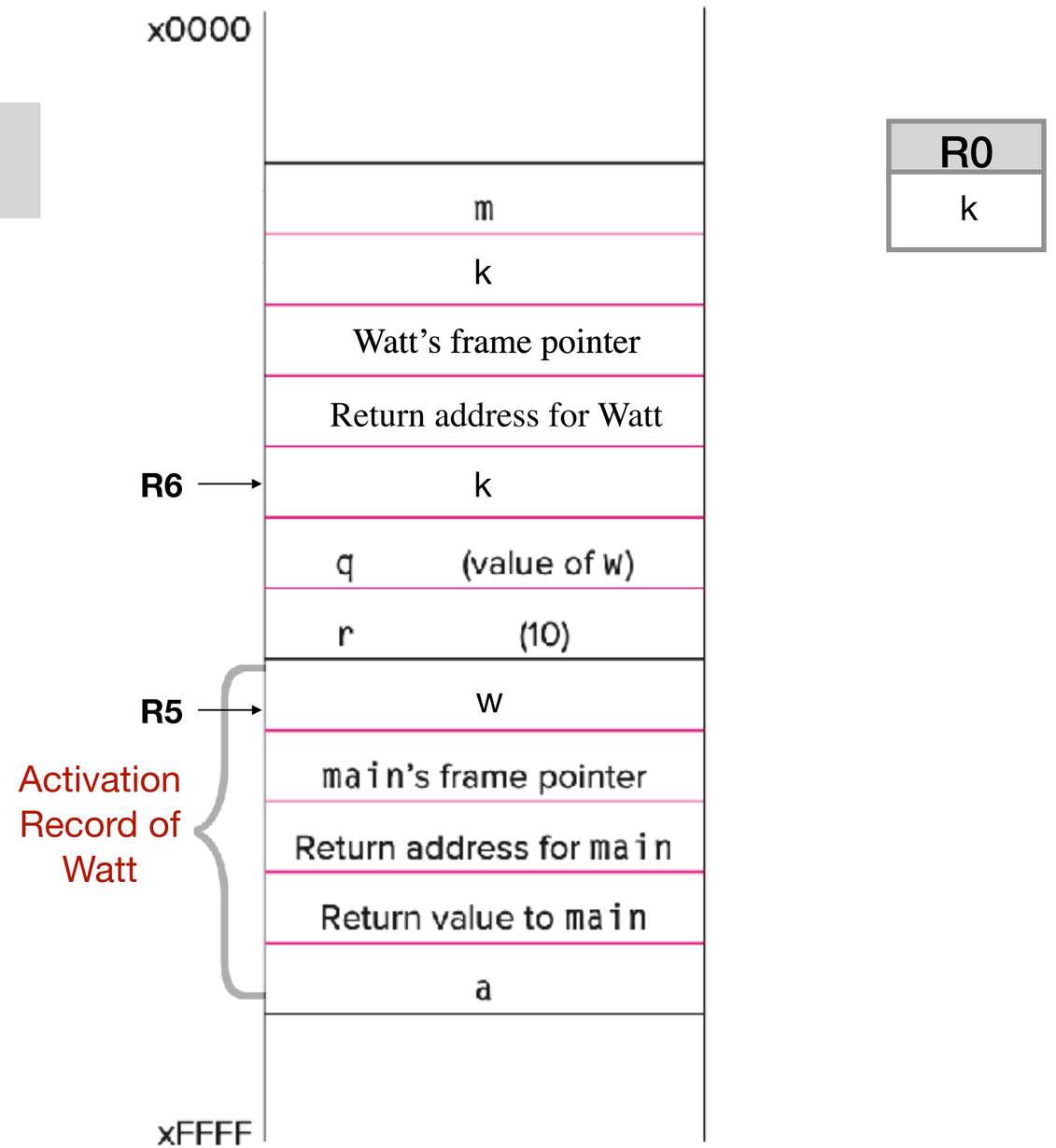
```c
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



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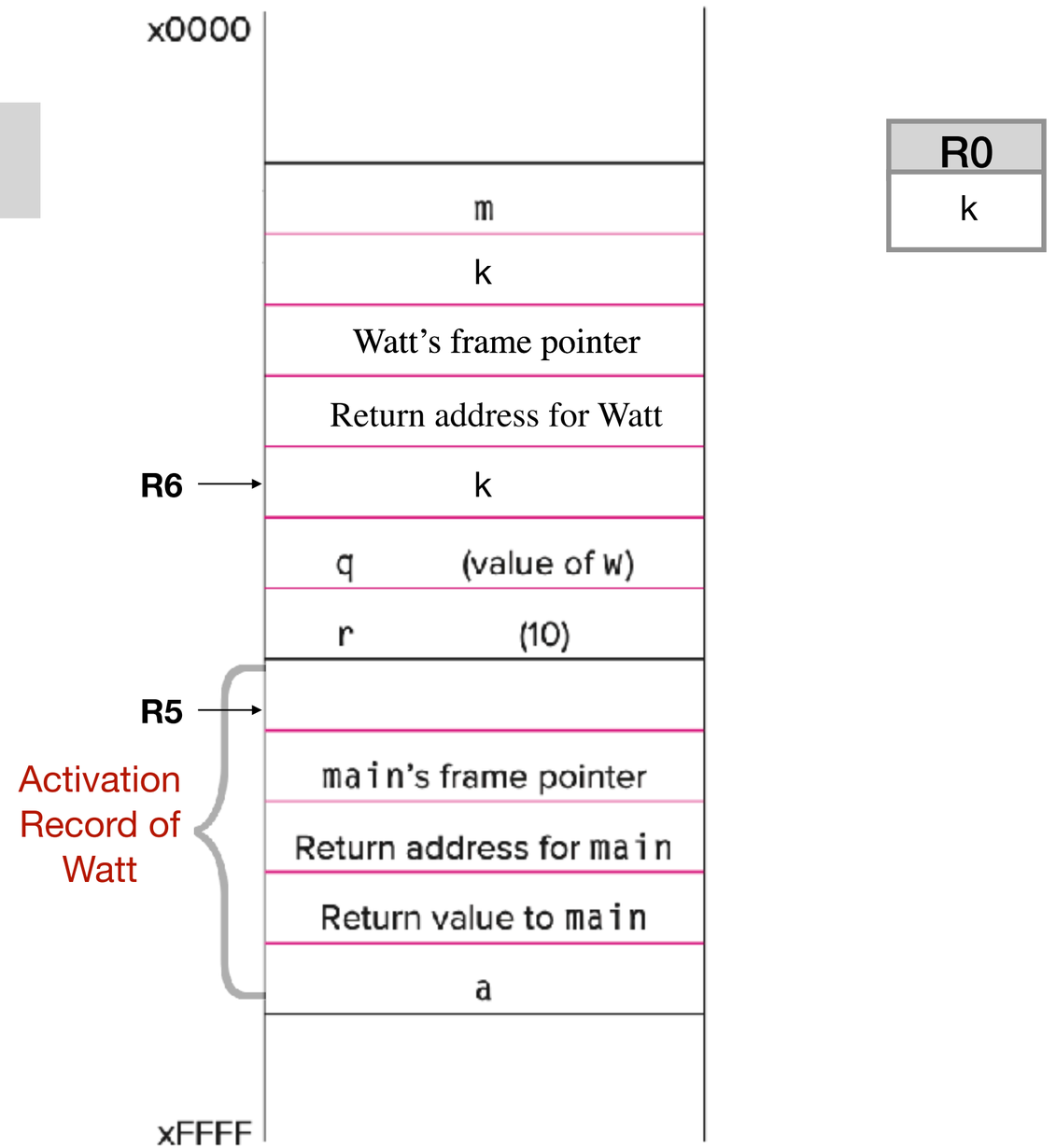
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



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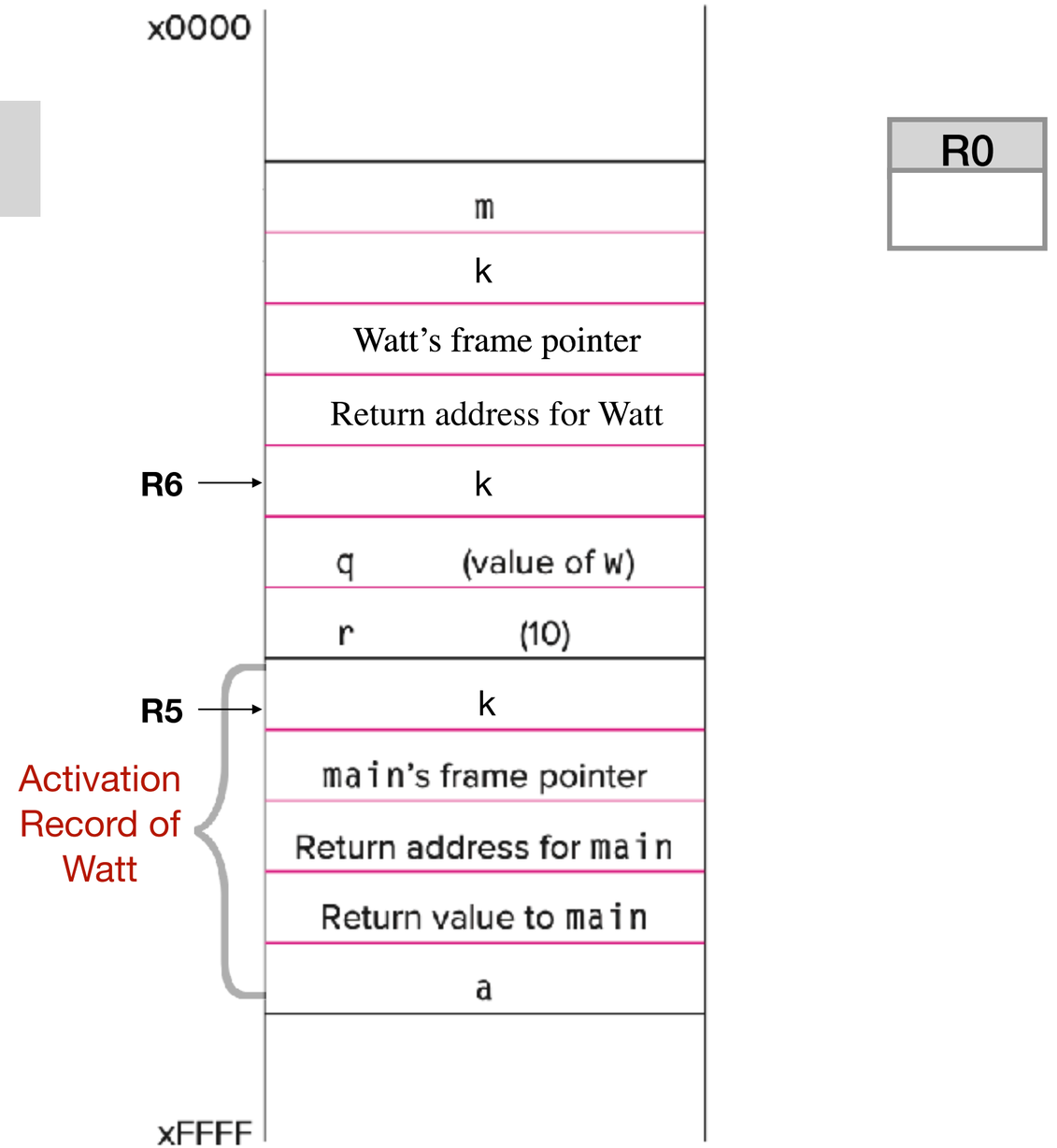

LC-3 Implementation

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
```



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

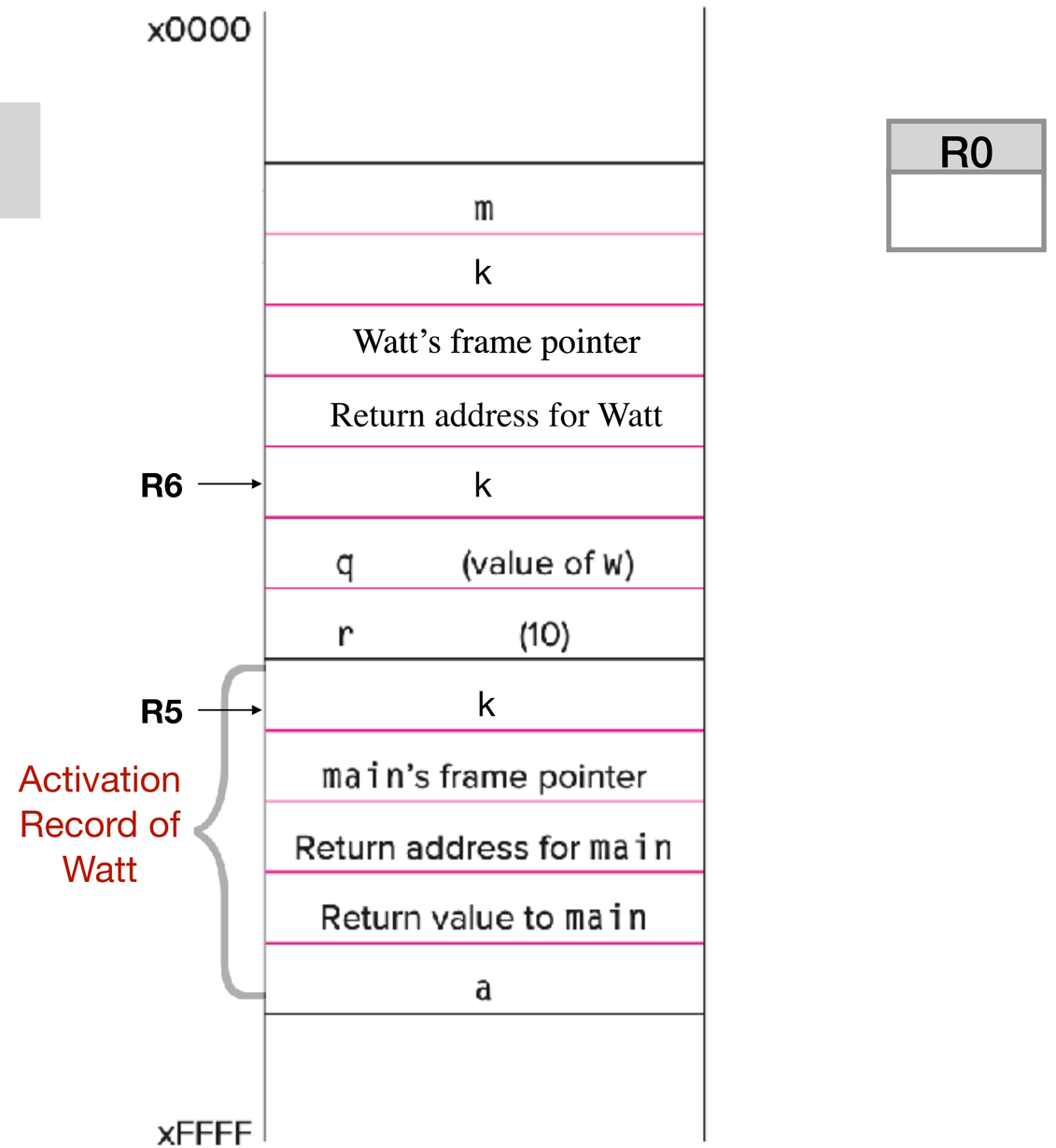
LC-3 Implementation

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
```



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

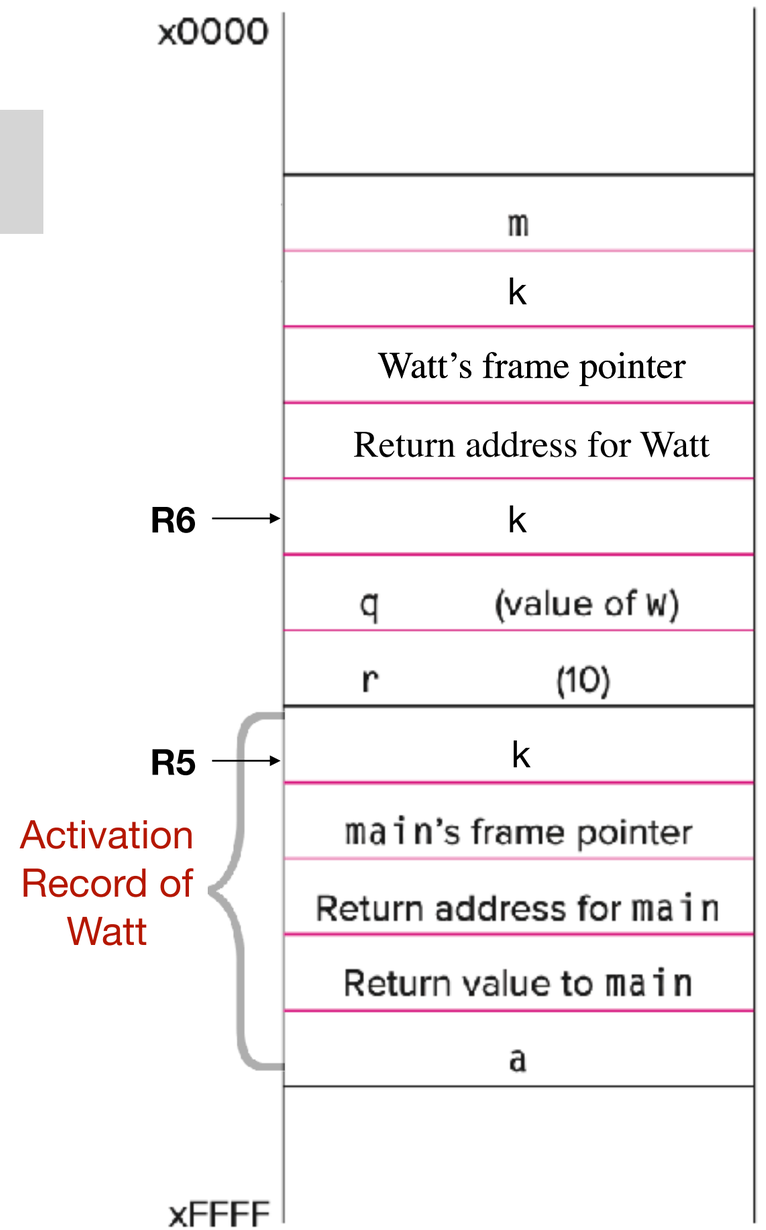
LC-3 Implementation

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
```



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

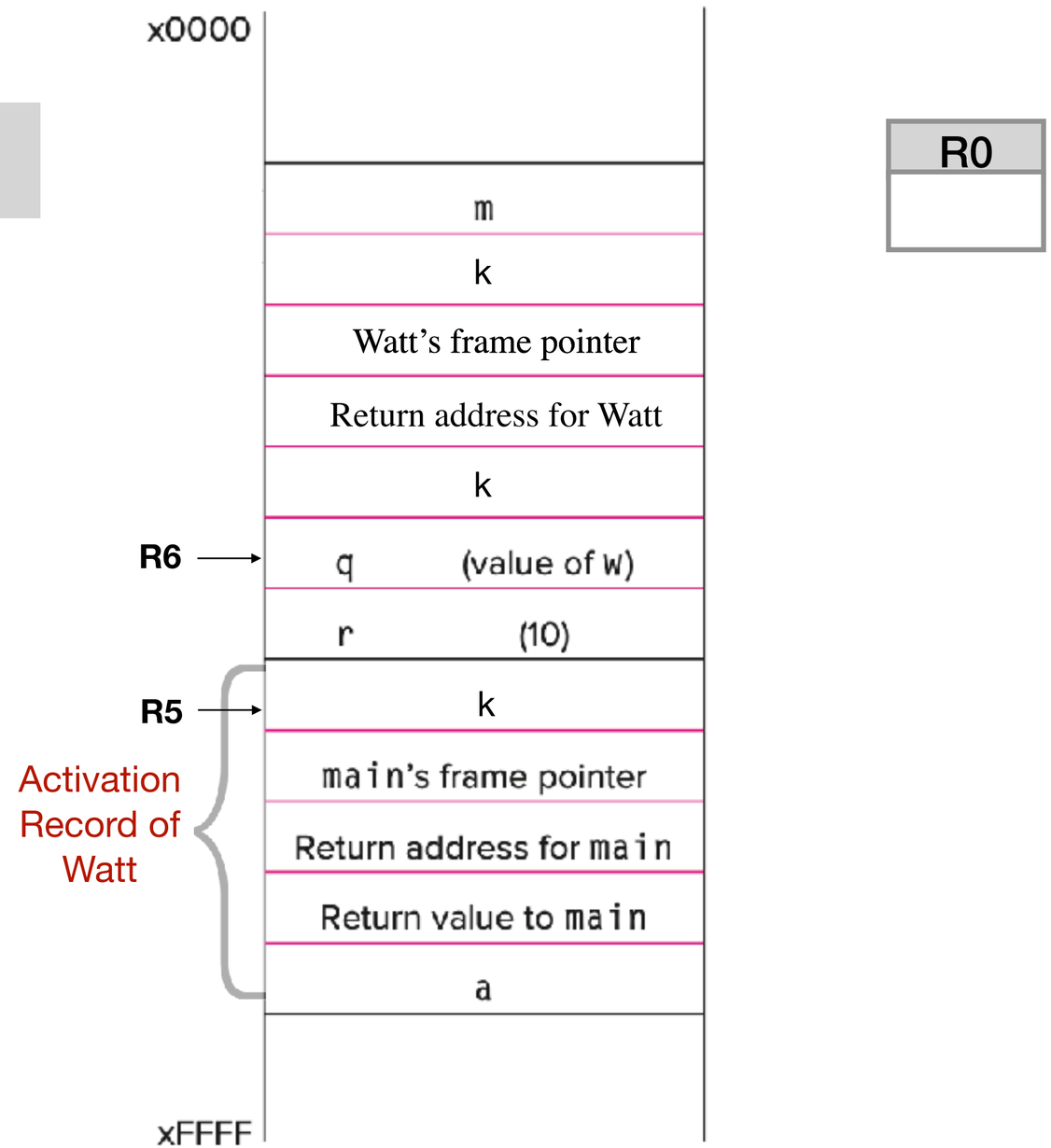
LC-3 Implementation

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
```



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

LC-3 Implementation

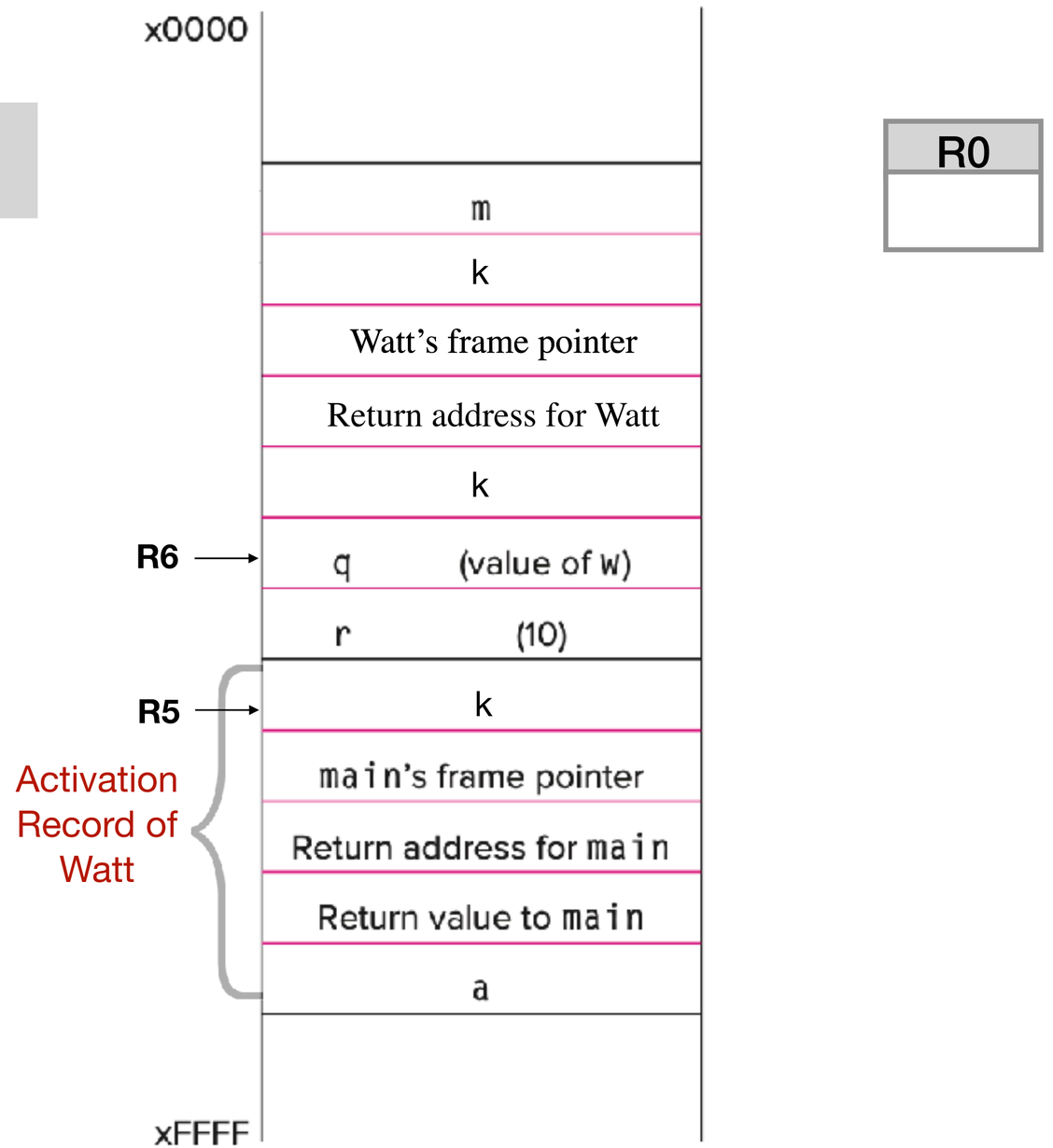
7. Caller tear-down (pop callee's return value and arguments from stack)

```
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
```



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

LC-3 Implementation

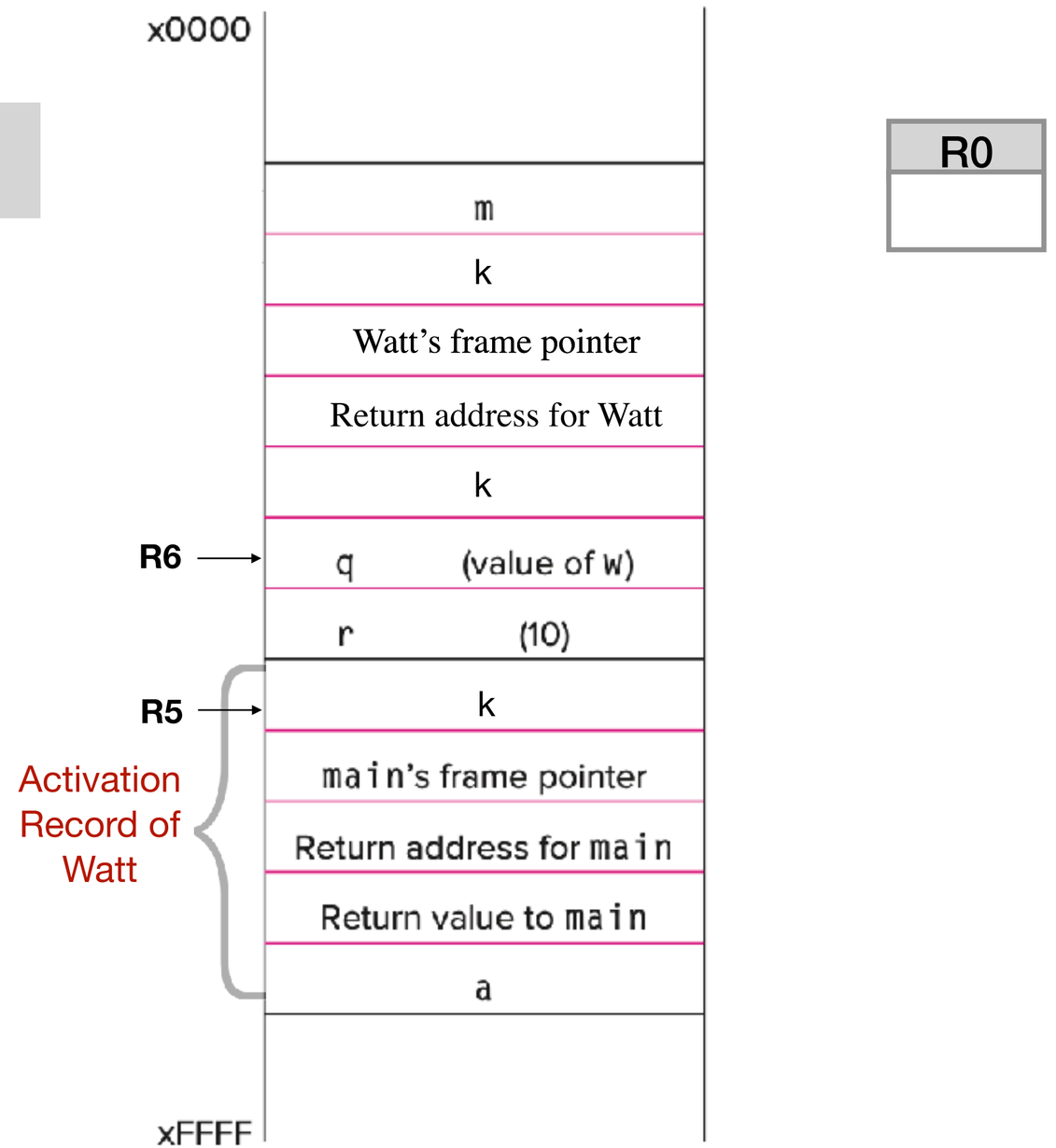
7. Caller tear-down (pop callee's return value and arguments from stack)

```
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
```



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

LC-3 Implementation

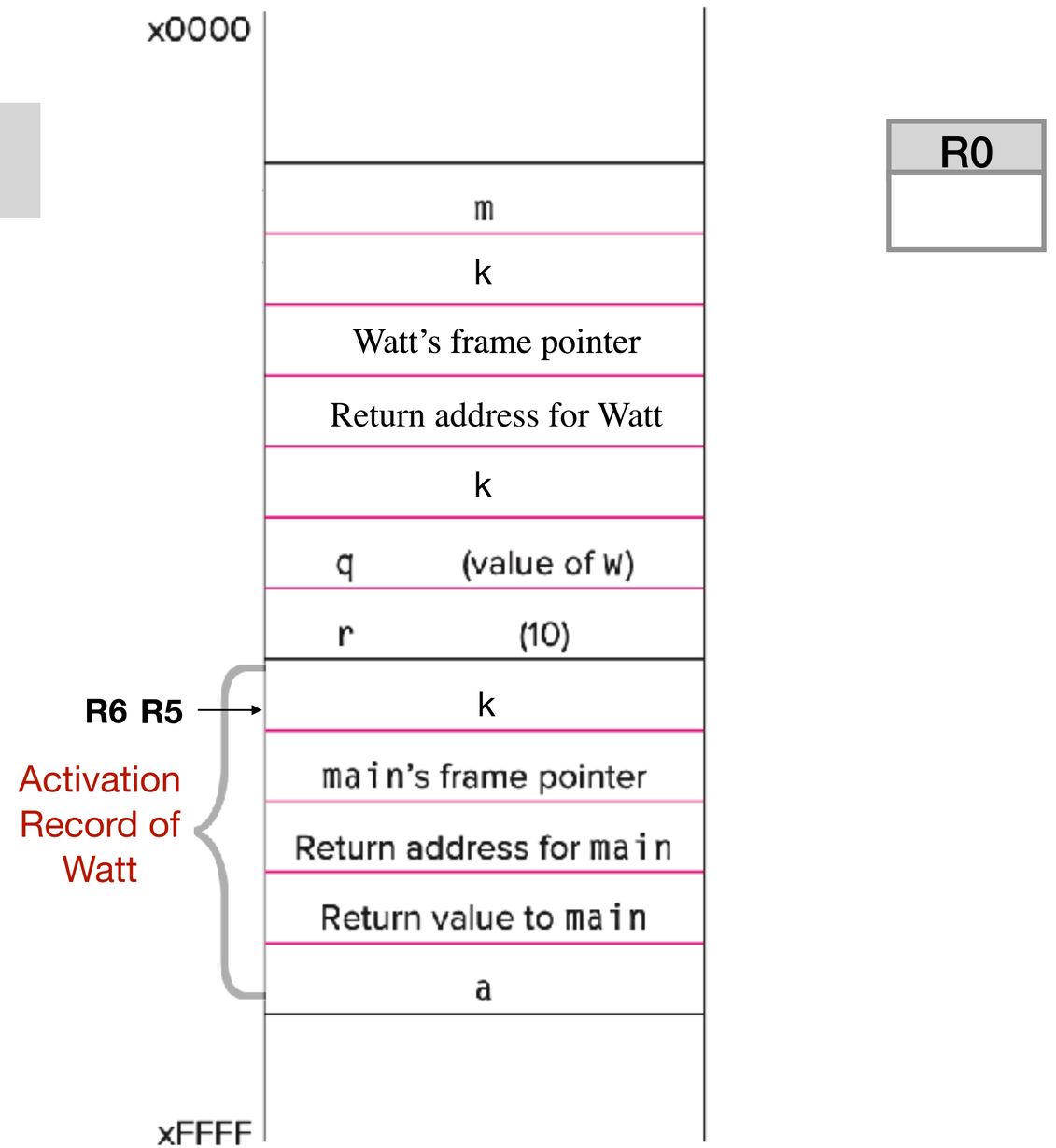
7. Caller tear-down (pop callee's return value and arguments from stack)

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

; perform assignment
STR R0, R5, #0

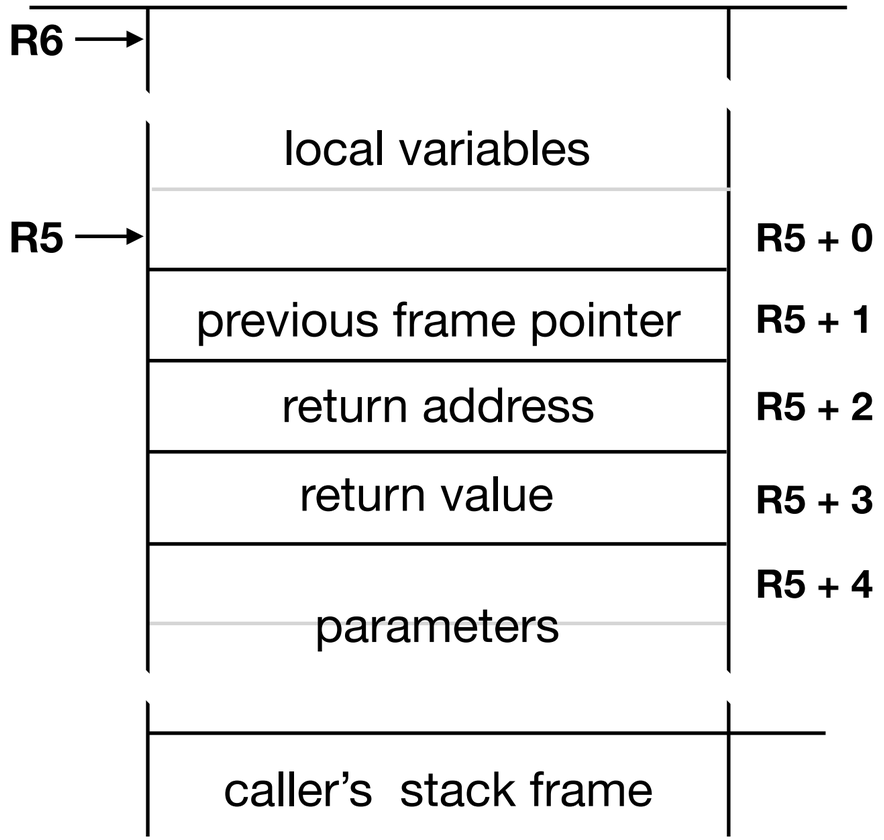
; pop return value
ADD R6, R6, #1

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



General principles

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



Exercise: build the activation frame

```
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;
}
```

Goal:

Swap valueA and valueB in main.

Exercise: build the activation frame

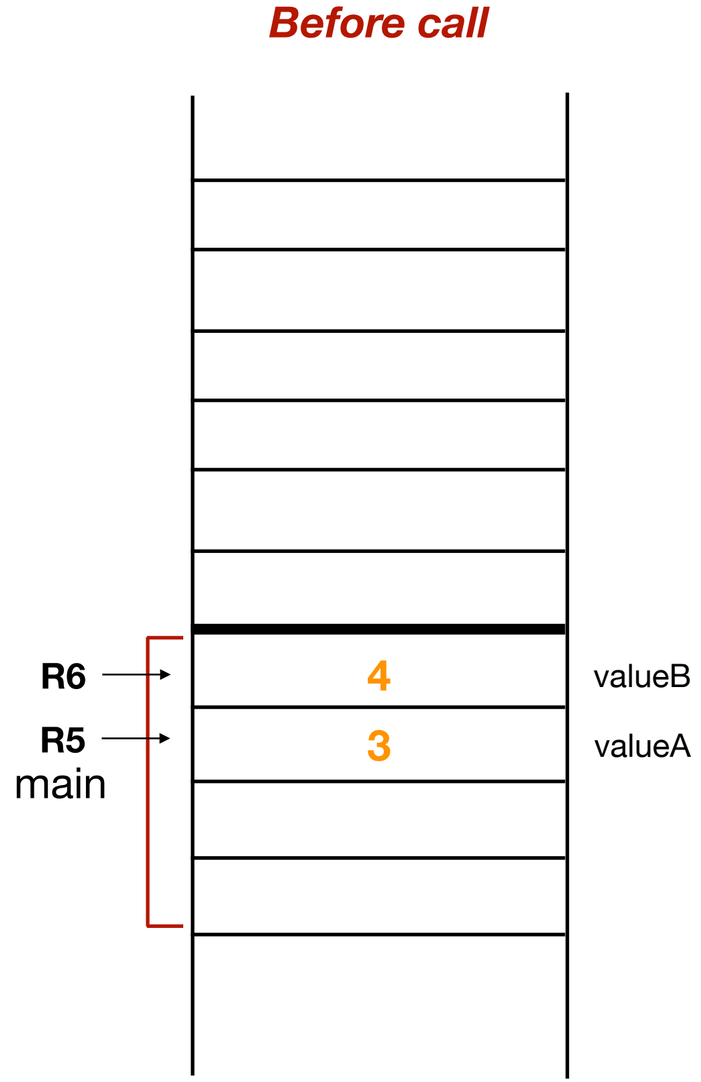
```
void Swap(int first, int second);

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;
}
```

Goal:

Swap valueA and valueB in main.



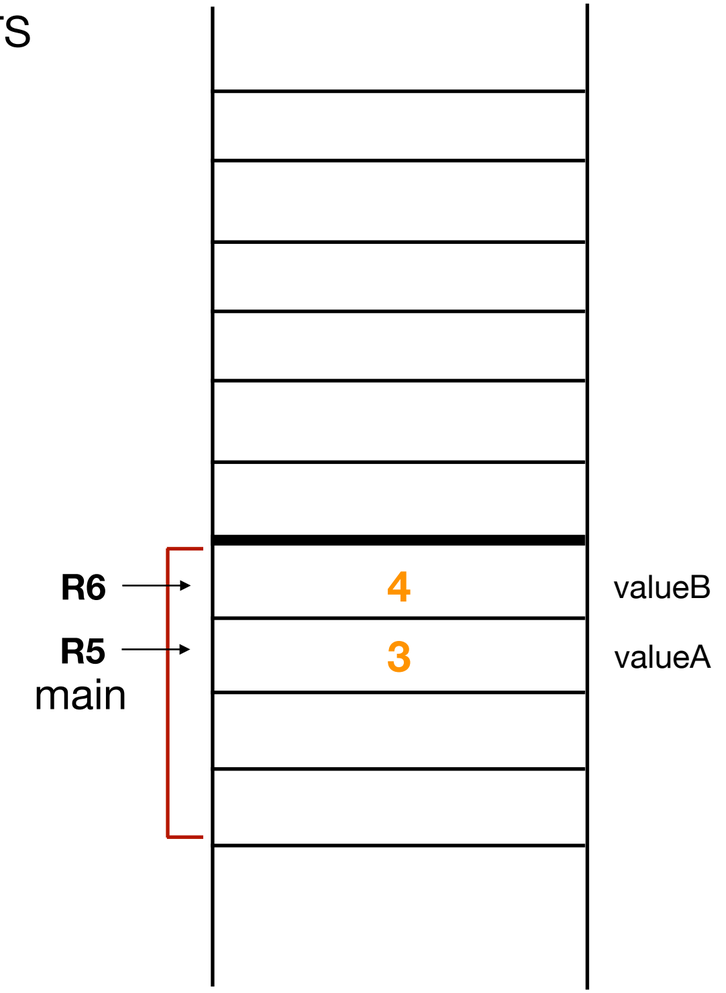
Exercise: build the activation frame

```
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



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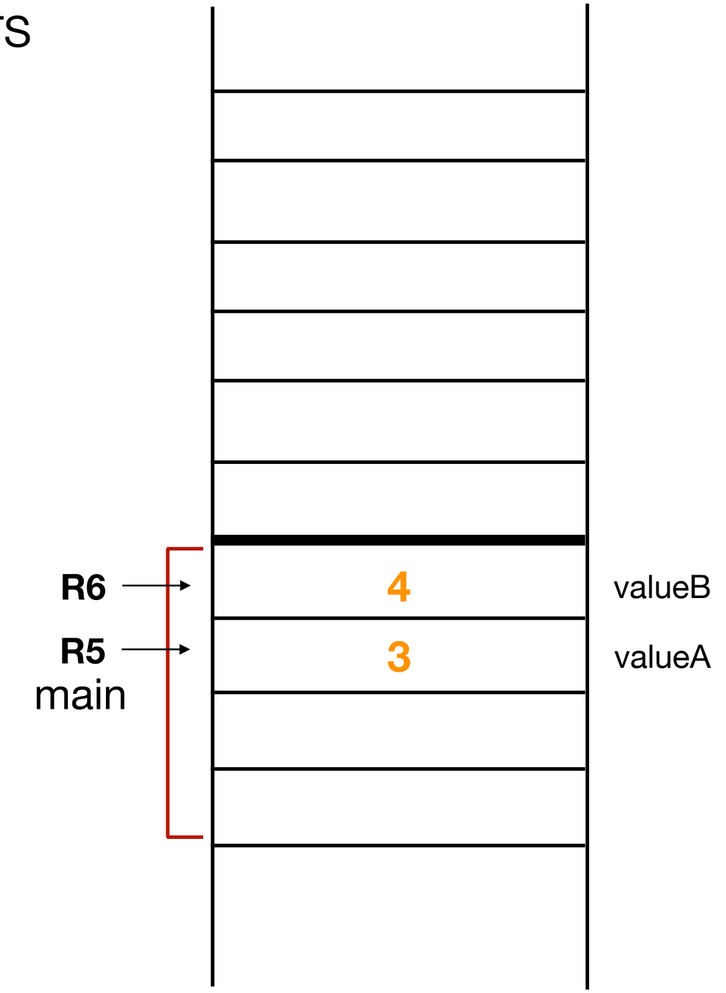
```

1. Push arguments (R-to-L) onto RTS
2. JSR



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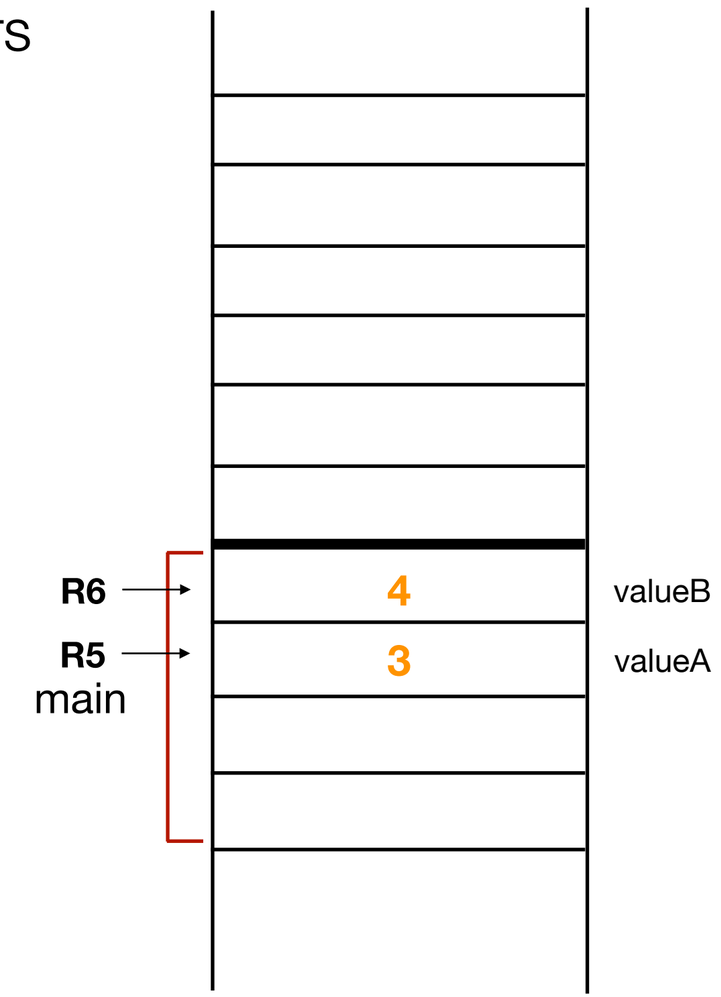
1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up
    A. Return value
    B. Return address
    C. Caller frame pointer (CFP)
    D. Push local variables



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3. Callee build up
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   B. Return address
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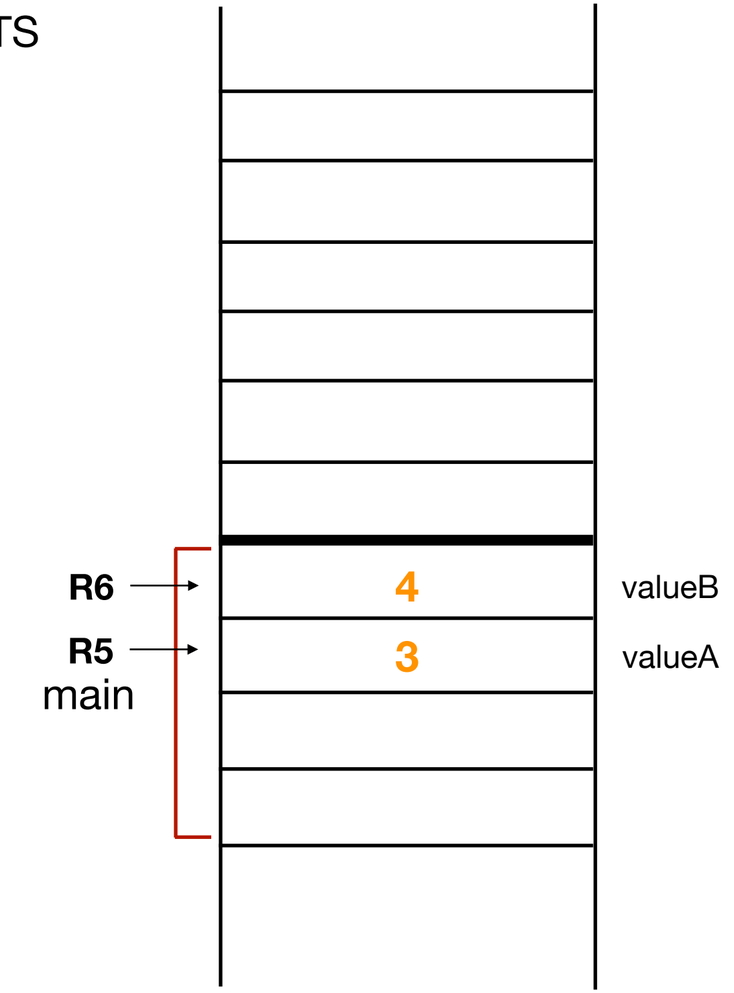
   D. Push local variables
4. Execute



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Exercise: build the activation frame

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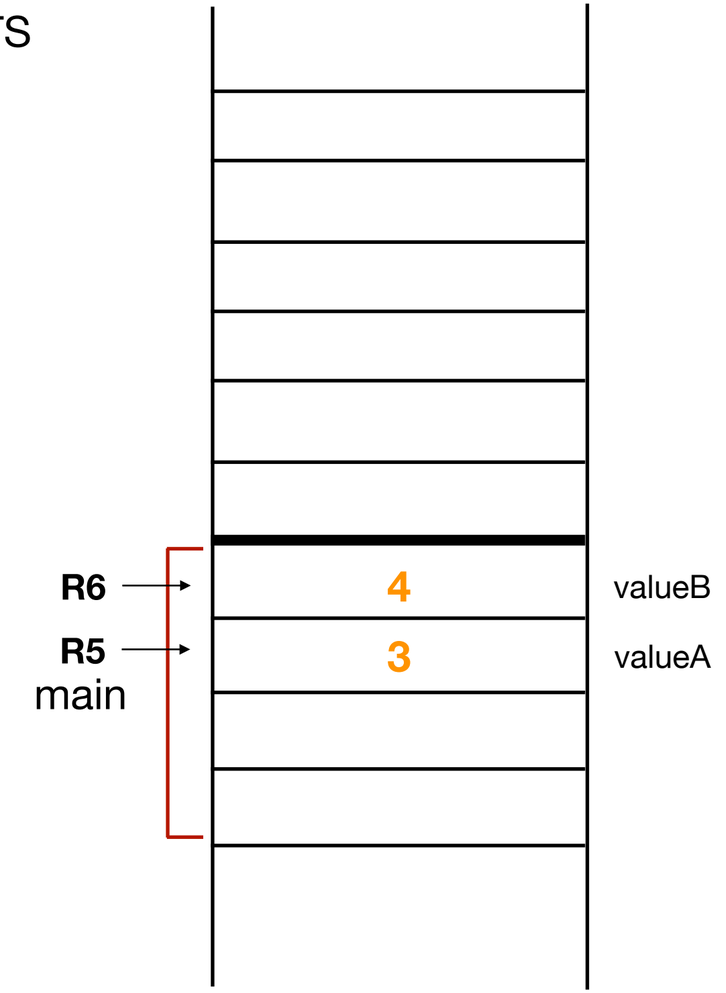
4. Execute
5. Callee tear down
   E. Update return value
   F. Pop local variables
   G. Pop CFP
   H. Pop return address



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Exercise: build the activation frame

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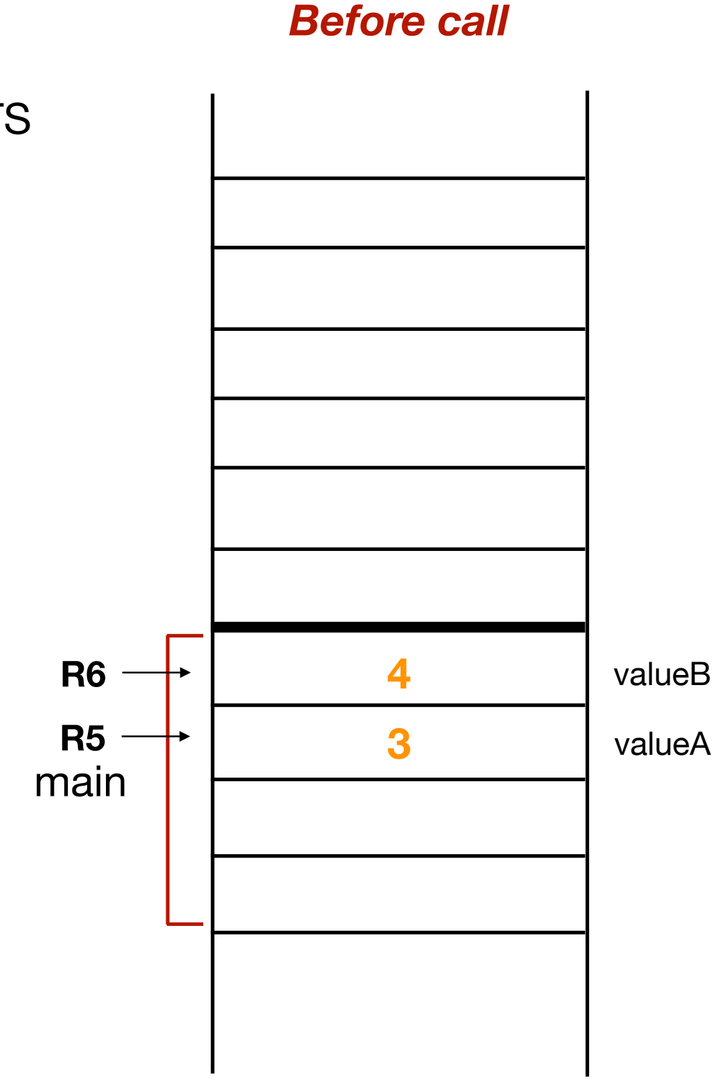

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Exercise: build the activation frame

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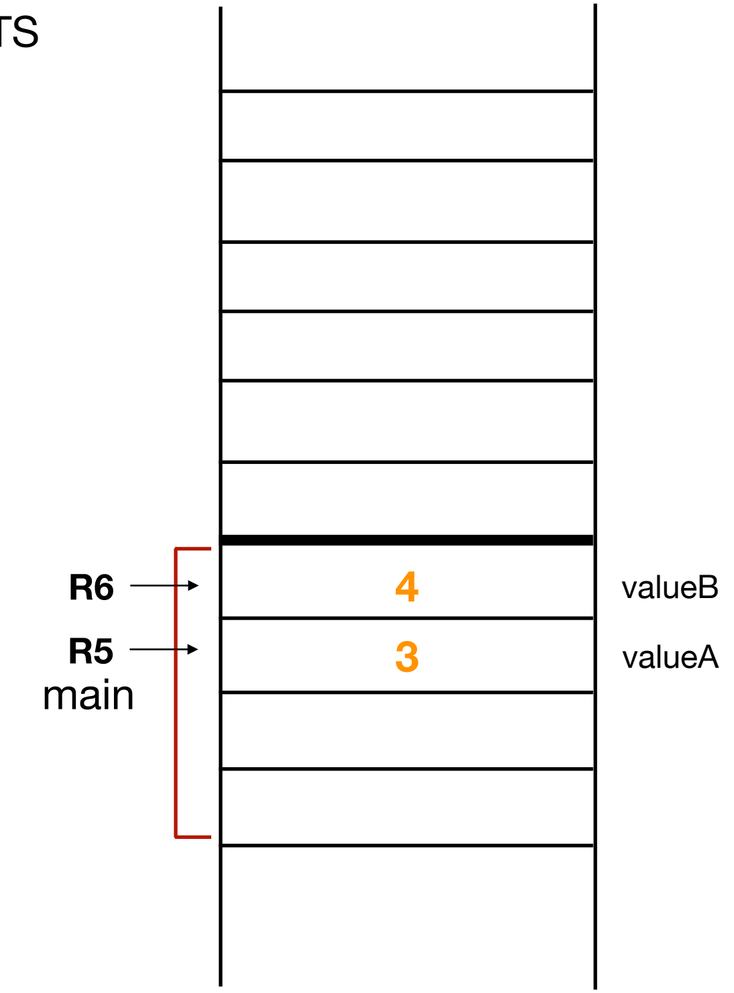
   G. Pop CFP
   H. Pop return address
6. RET
7. Caller tear down
   I. Pop return value
   J. Pop arguments



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

```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;
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}
```

`swap` function - build up

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3. Callee build up (push onto RTS)
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    D. Local variables
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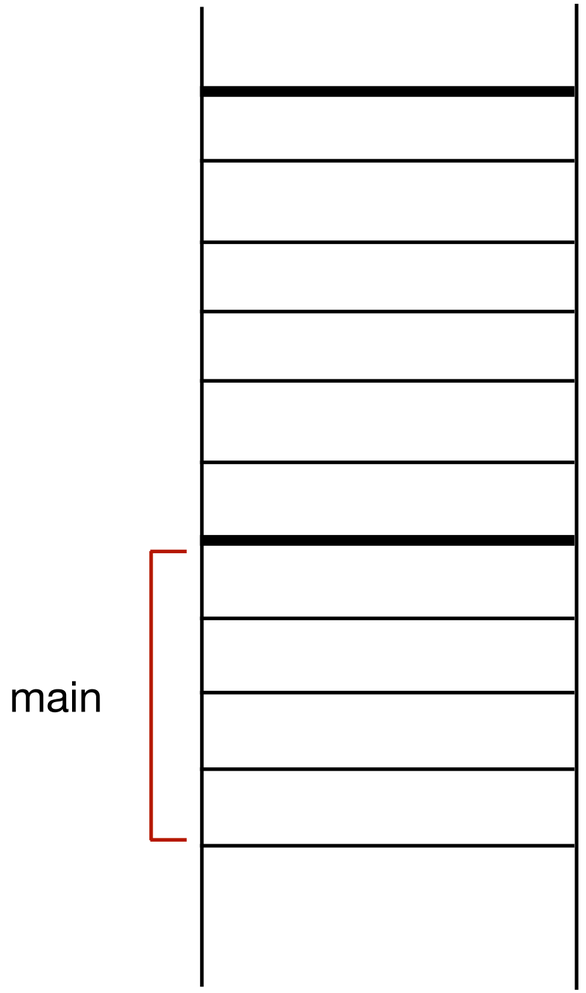
5. Callee tear down
    E. Update return value
    F. Pop local variables
    G. Pop CFP (into R5)
    H. Pop return address (into R7)
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Build up

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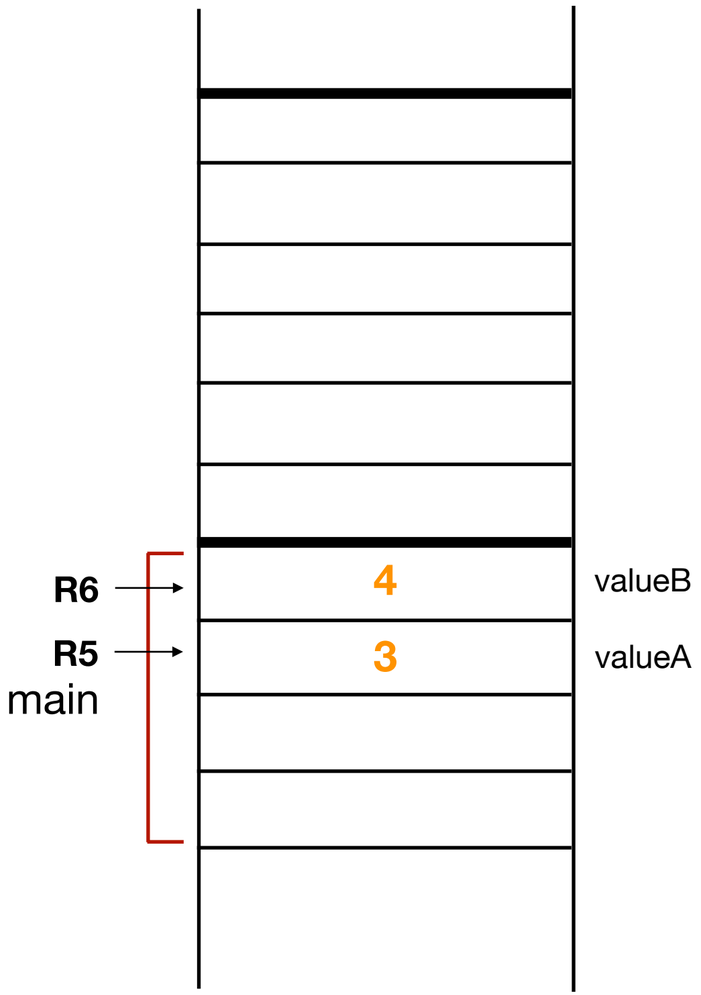
    I. Pop return value
    J. Pop arguments

Build up

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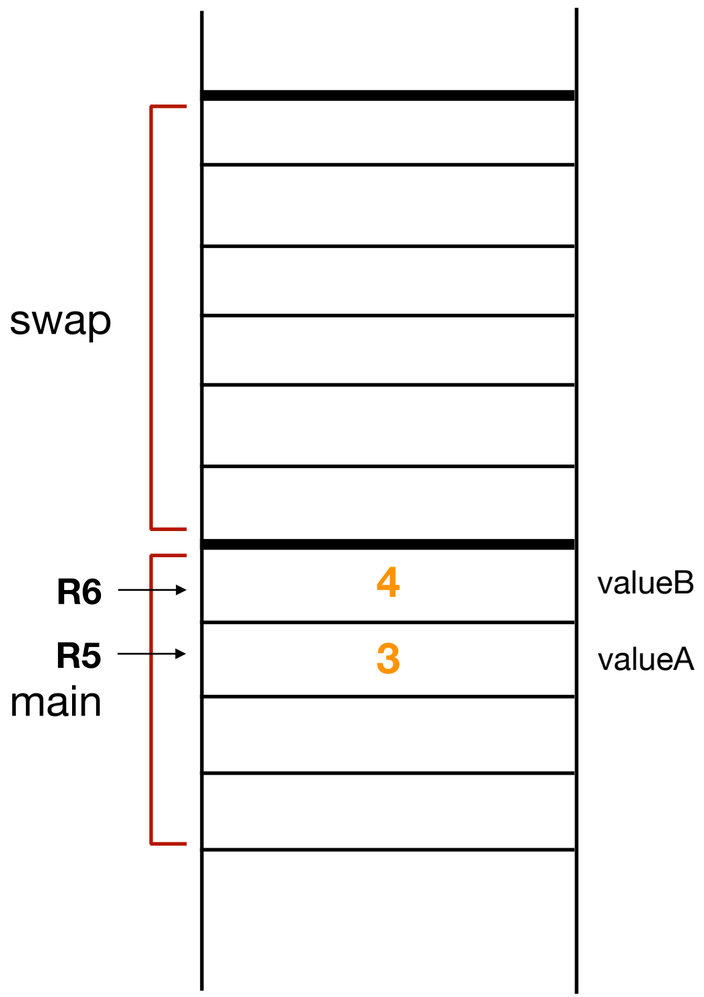


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6. RET
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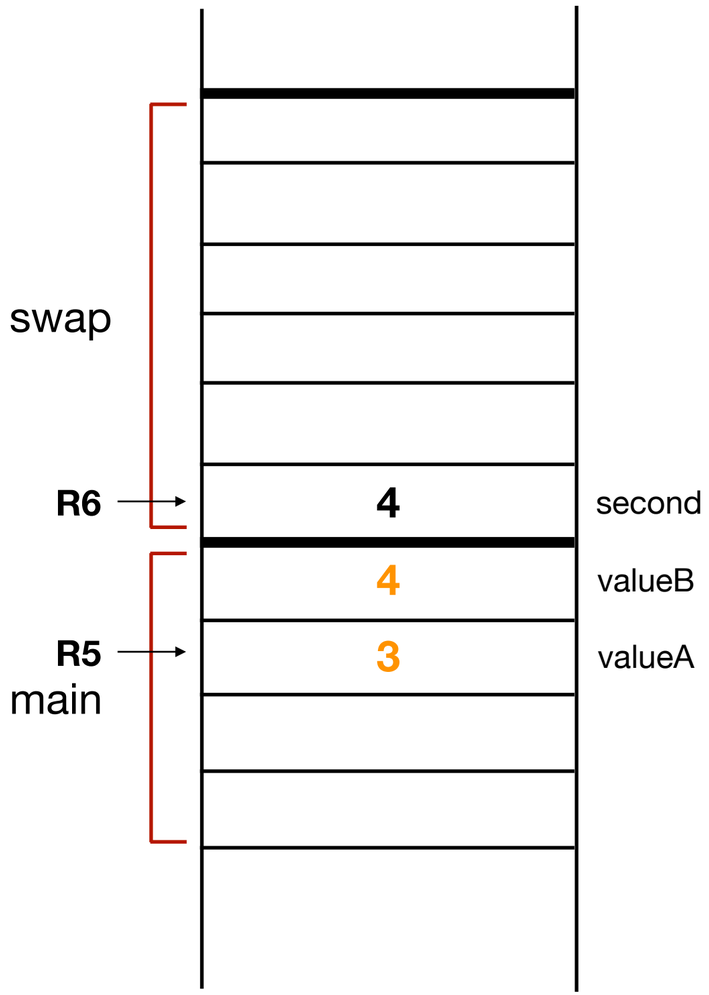
    I. Pop return value
    J. Pop arguments

Build up

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   second = temp;
}
```

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

`swap` function - build up

1. Push arguments (R-to-L) onto RTS
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6. RET
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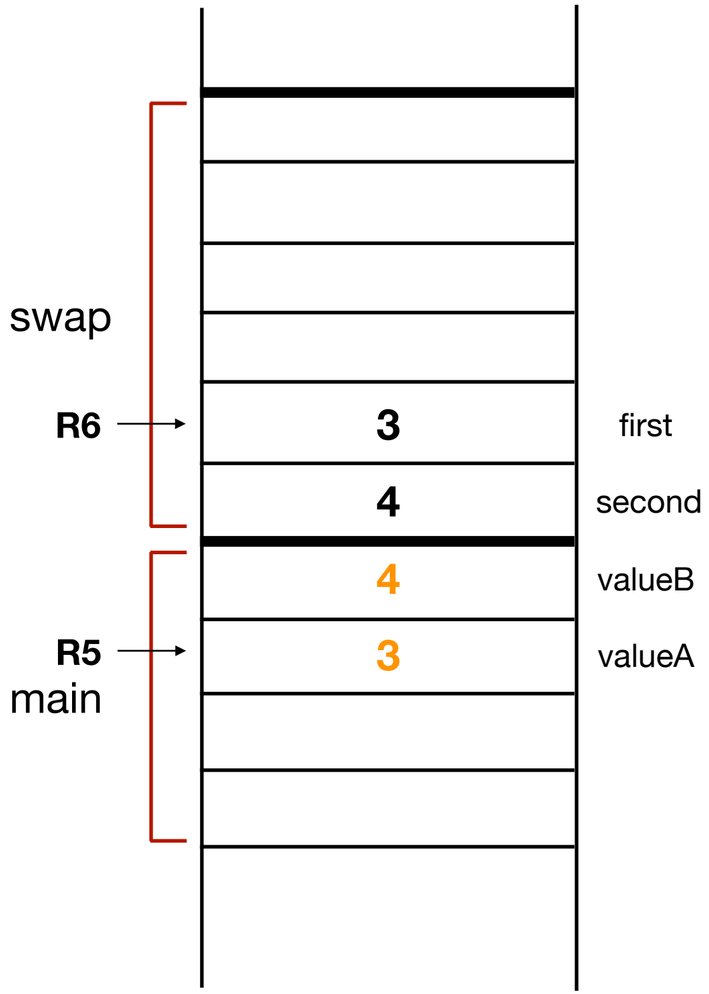
    I. Pop return value
    J. Pop arguments

Build up

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   temp = first;
   first = second;
   second = temp;
}
```

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

`swap` function - build up

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3. Callee build up (push onto RTS)
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6. RET
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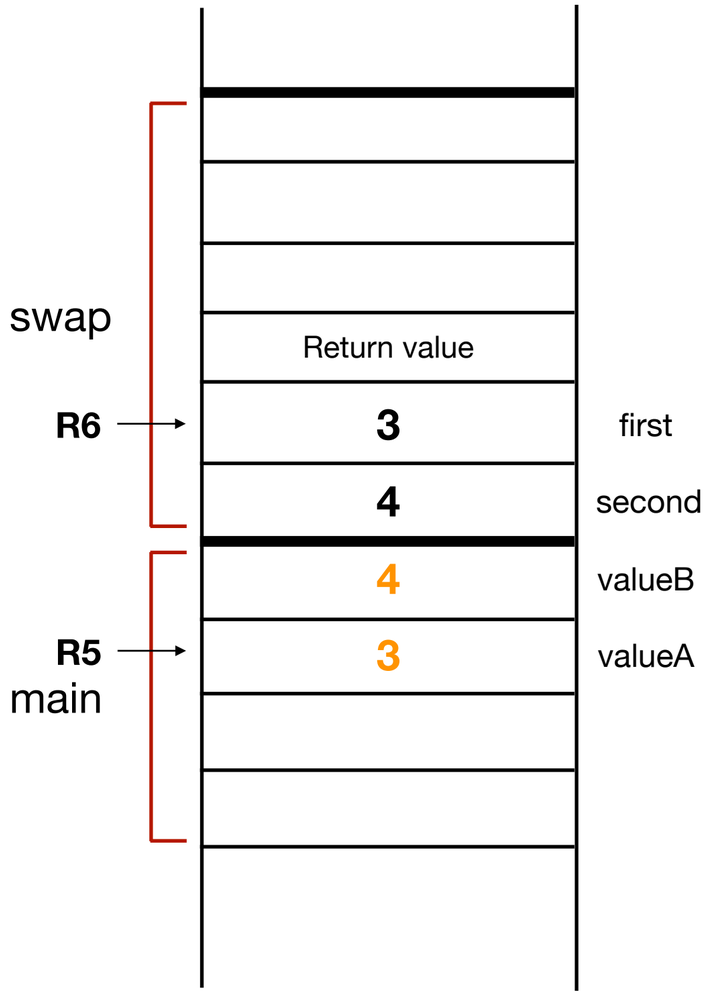
   I. Pop return value
   J. Pop arguments

Build up

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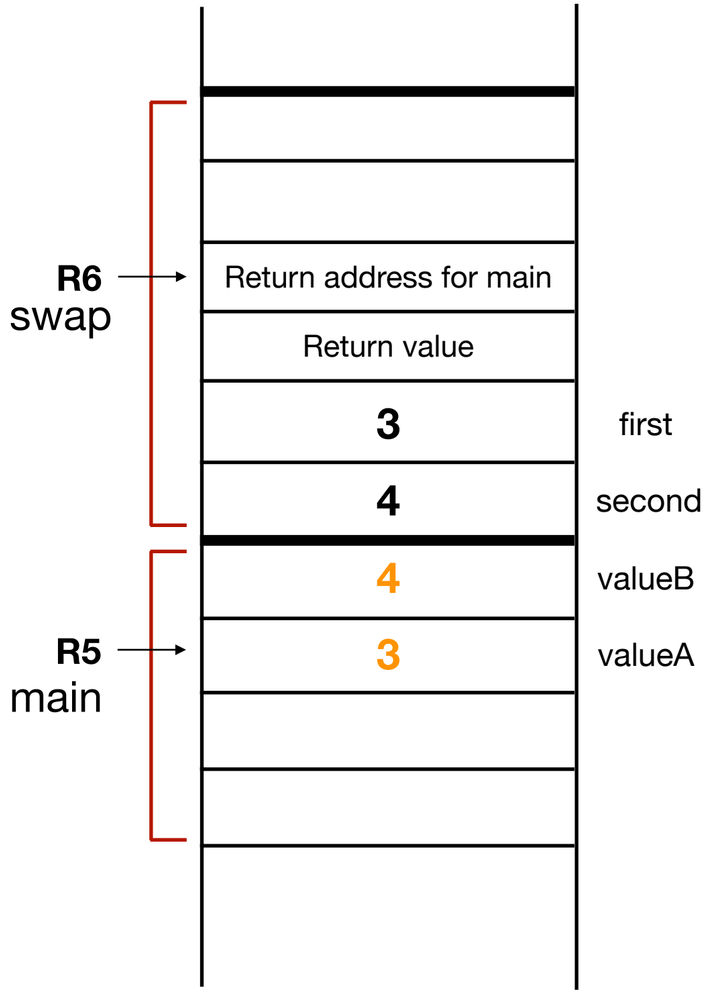
Build up

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}

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

```
ADD R6, R6, #-2
STR R7, R6, #0
```

`swap` function - 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
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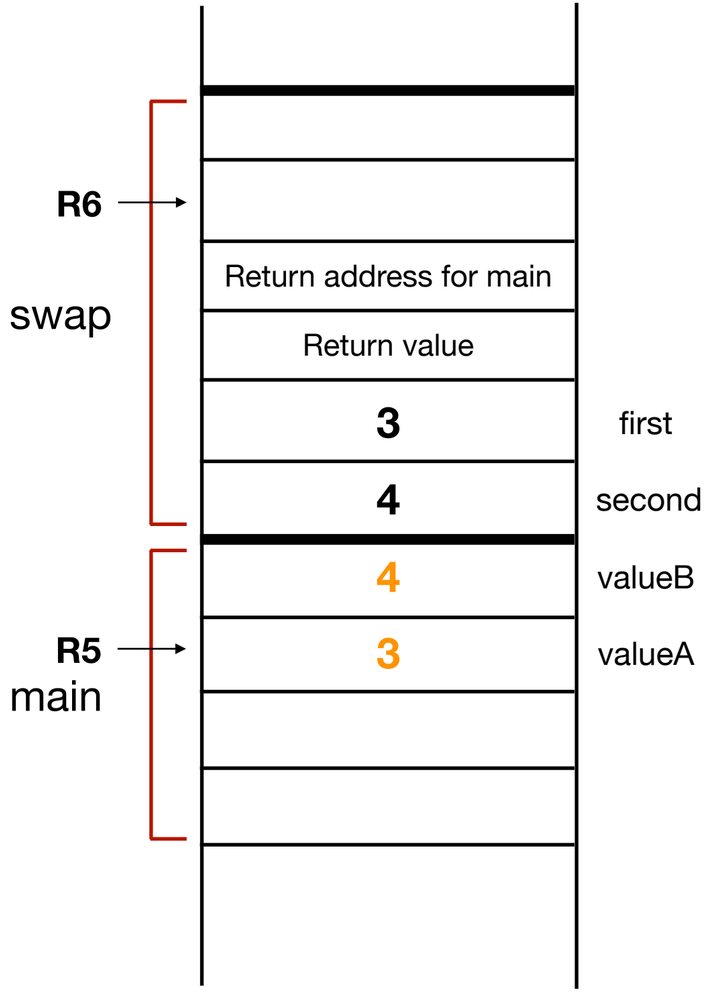
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Build up

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   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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

`swap` function - build up

1. Push arguments (R-to-L) onto RTS
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3. Callee build up (push onto RTS)
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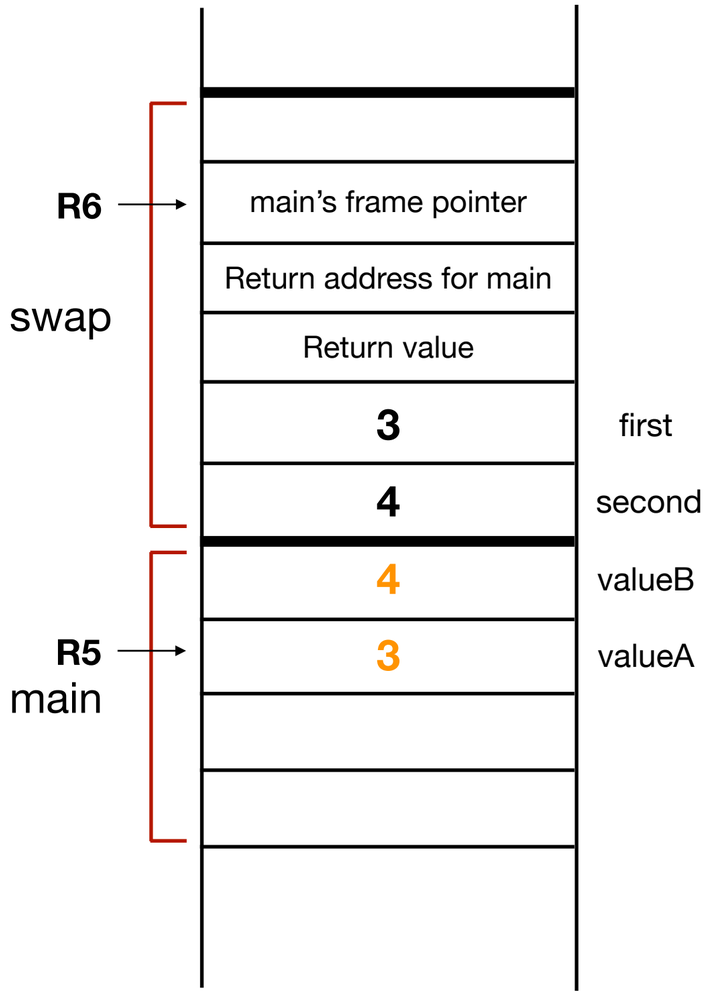
Build up

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```

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

`swap` function - build up

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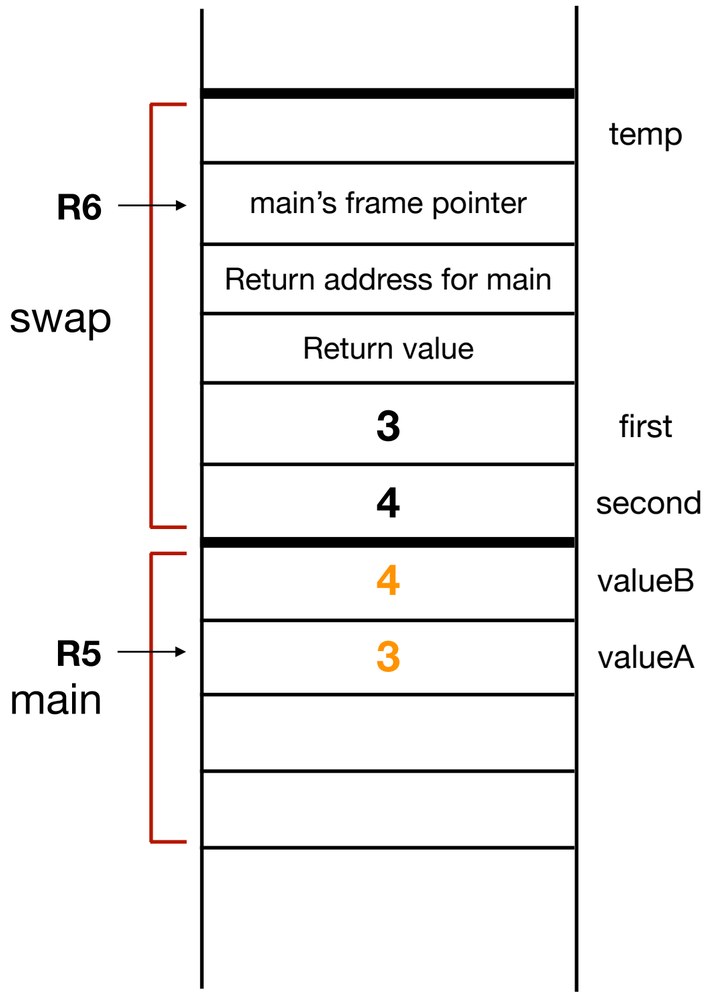
Build up

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`swap` function - build up

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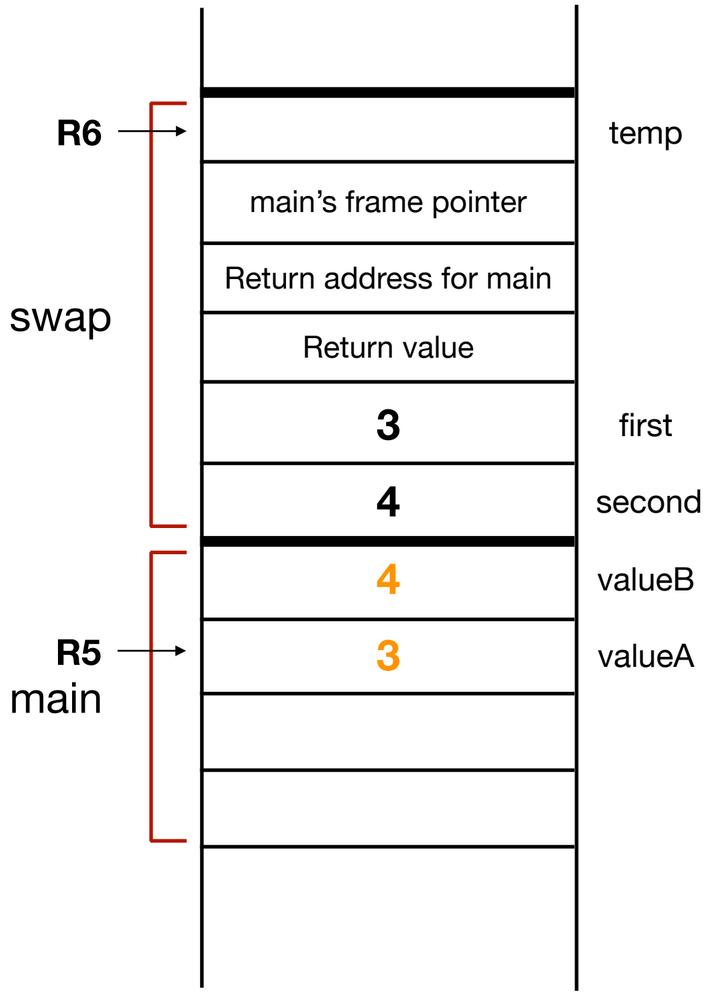
Build up

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}

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

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

`swap` function - 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)
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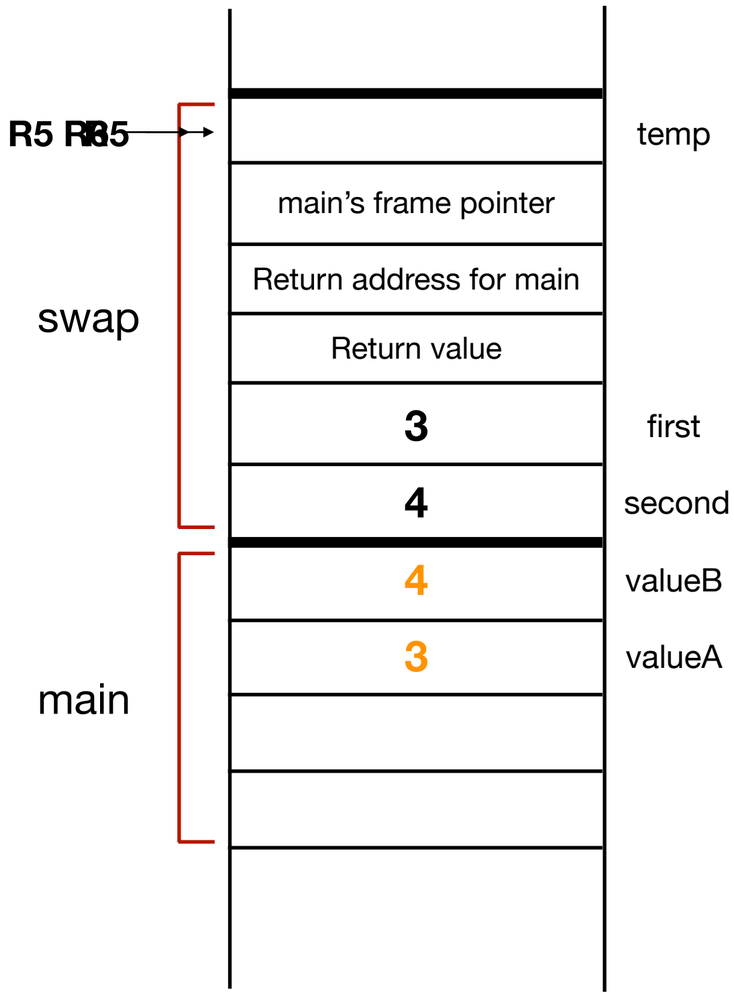
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Build up

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}

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

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

`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)
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    E. Update return value
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6. RET
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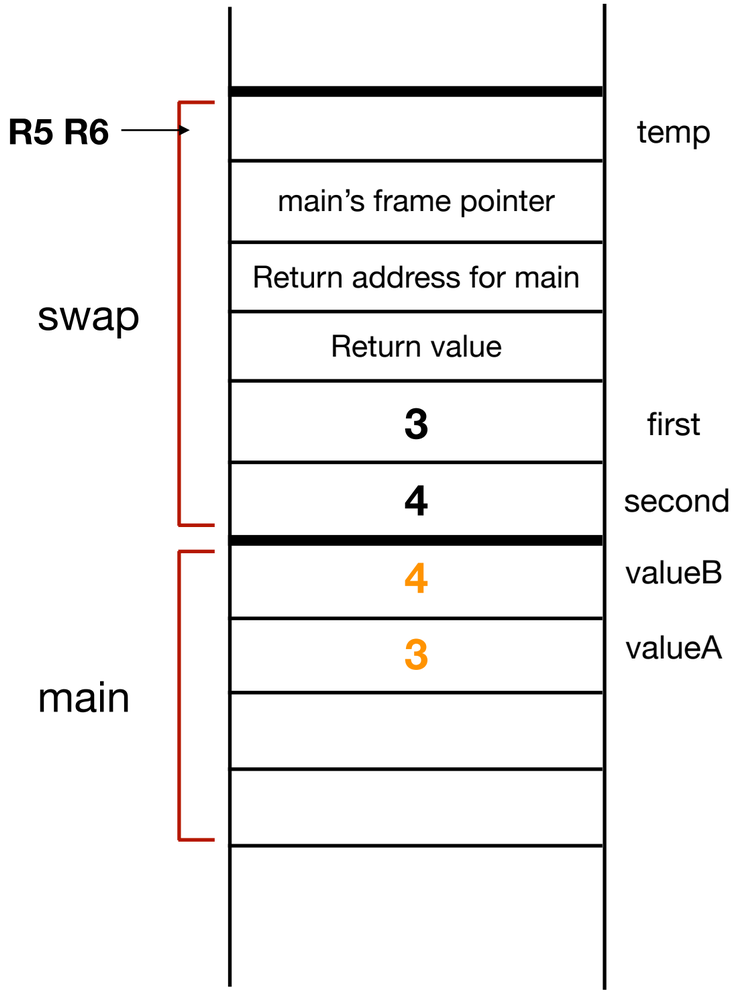
Execution

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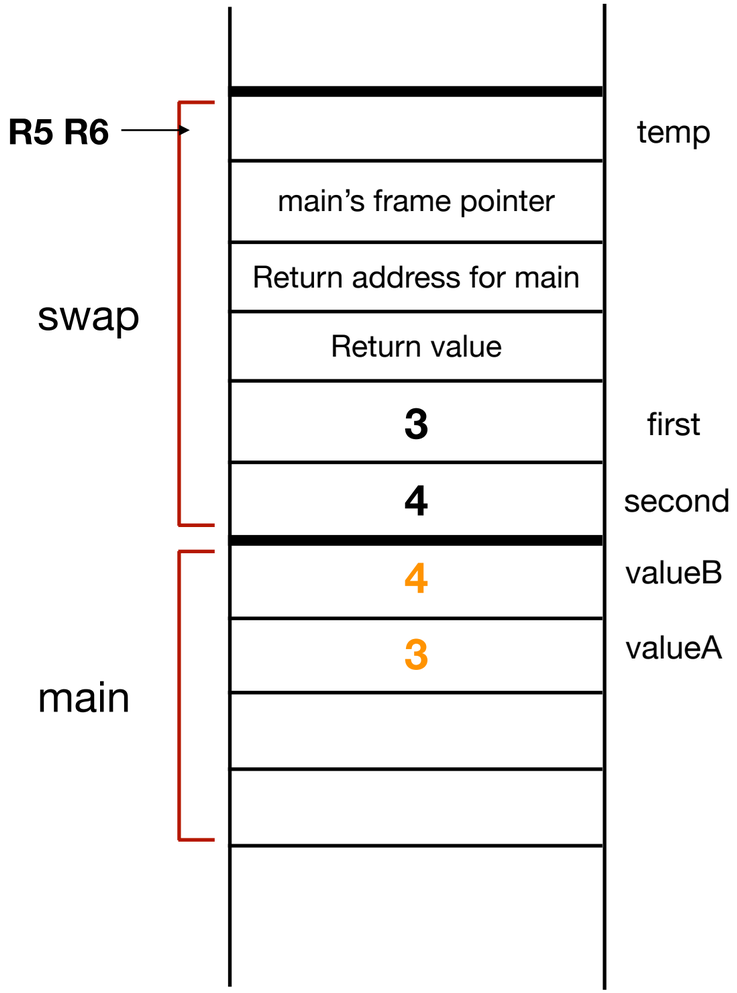


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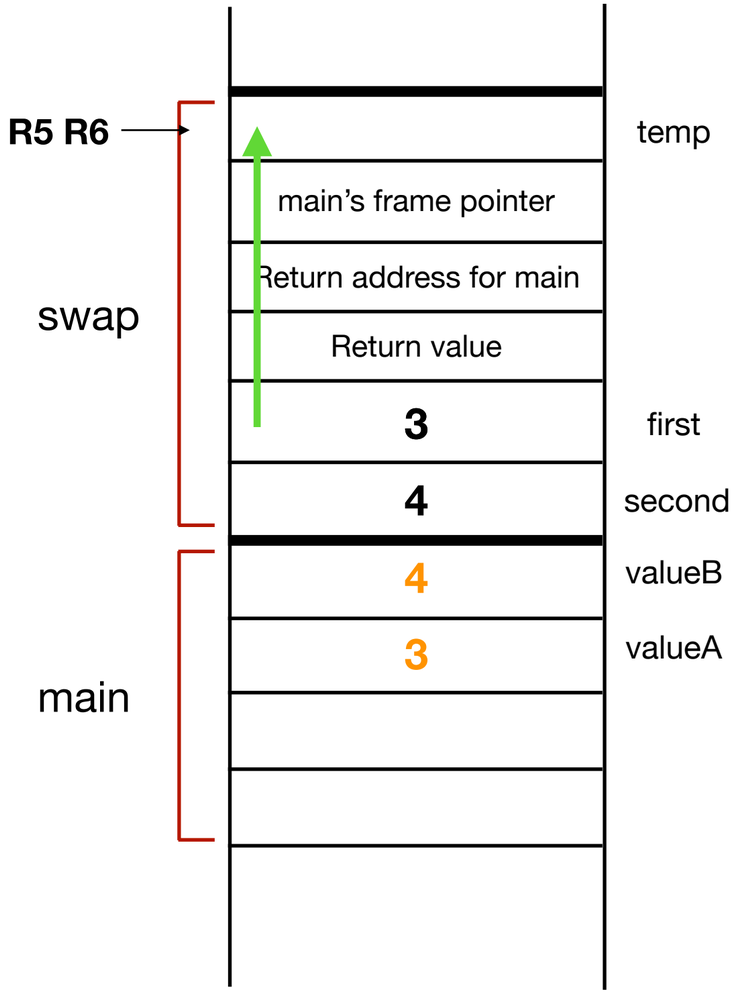


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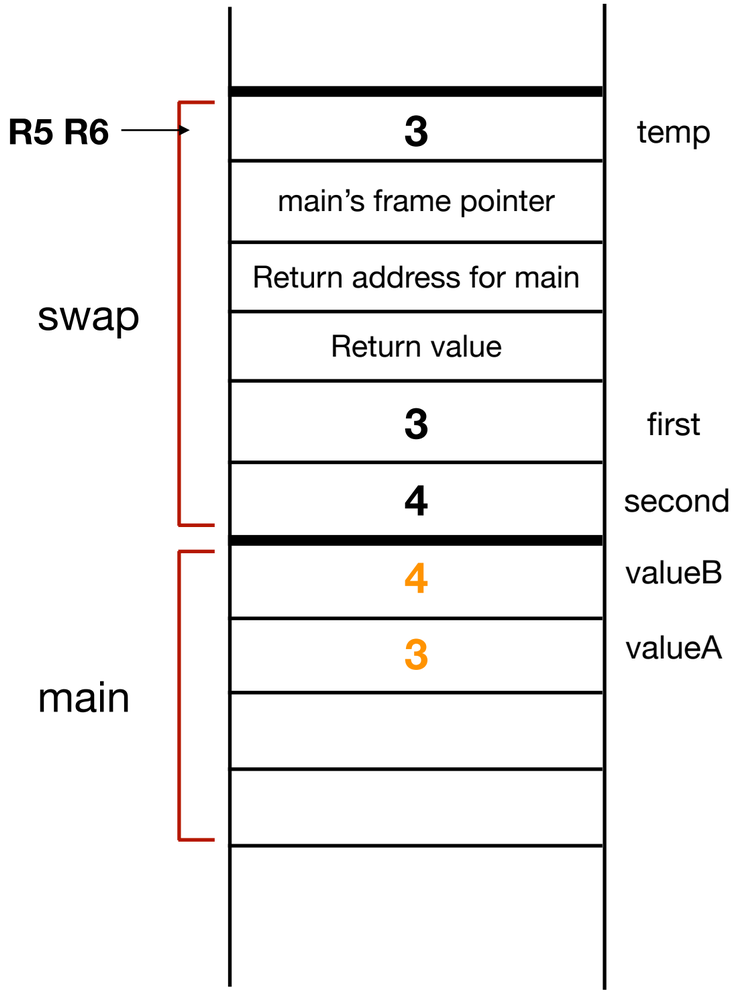


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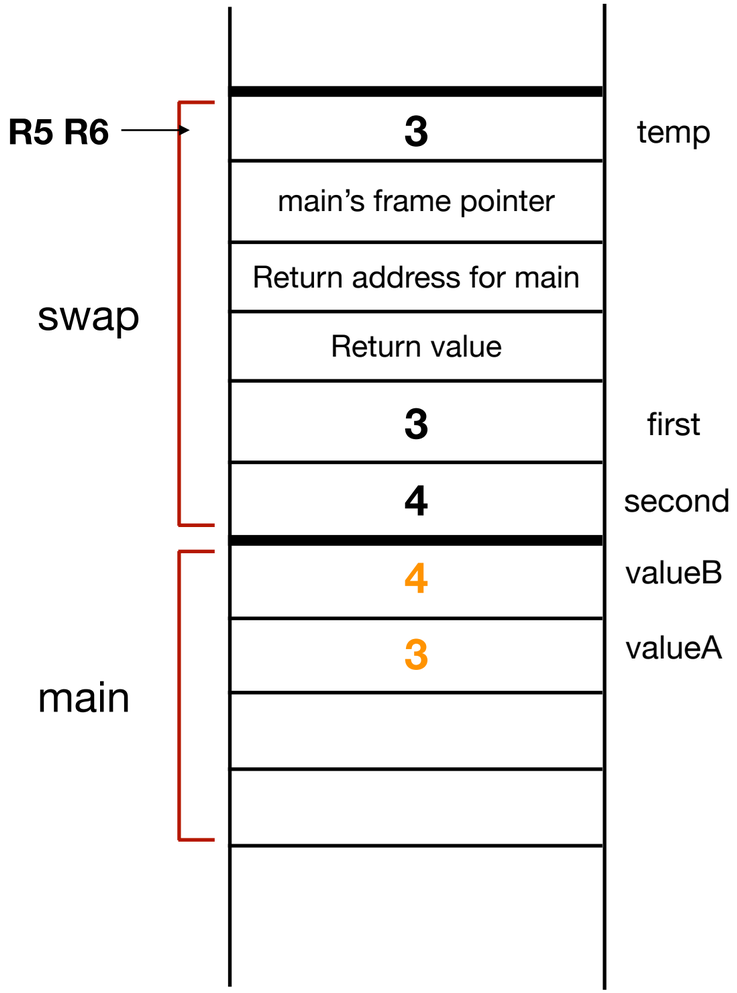


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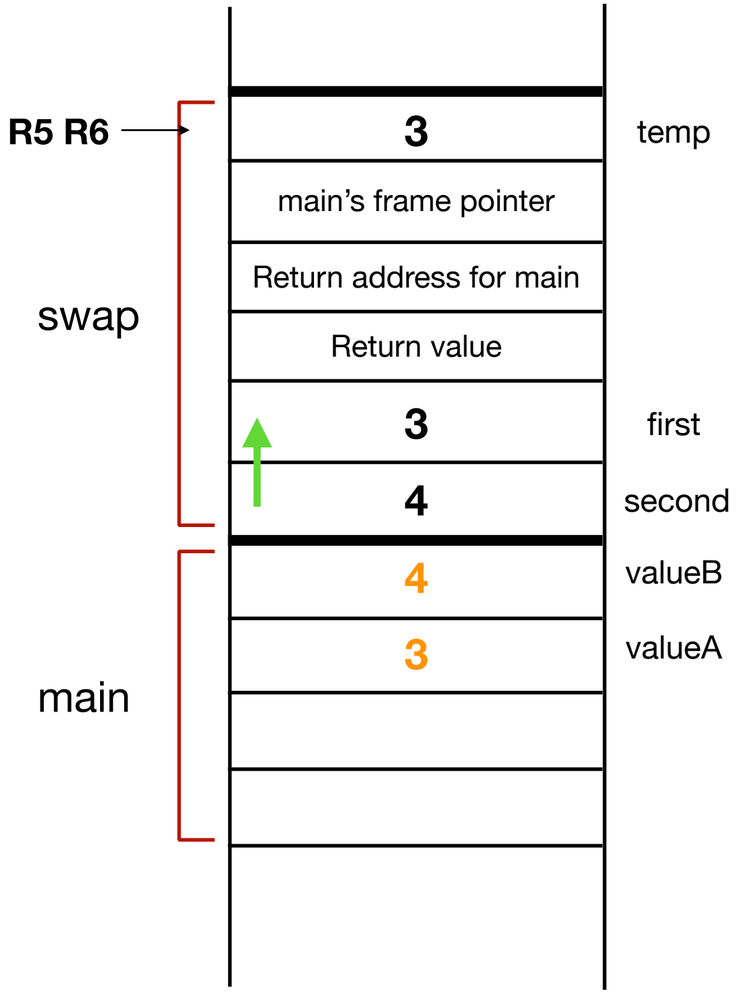


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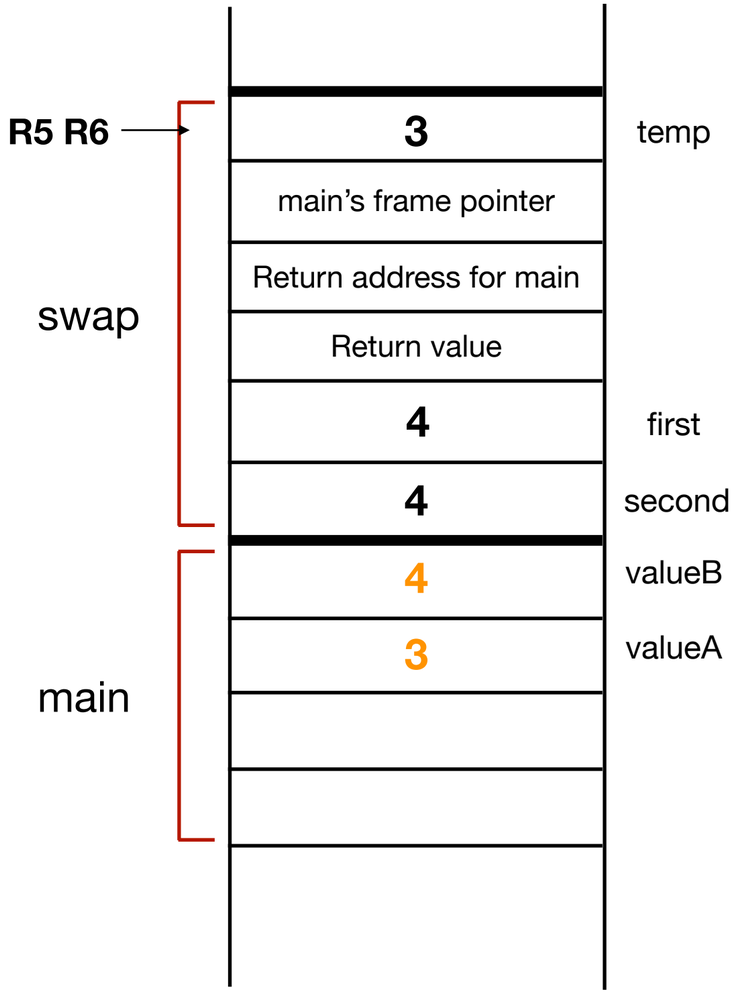


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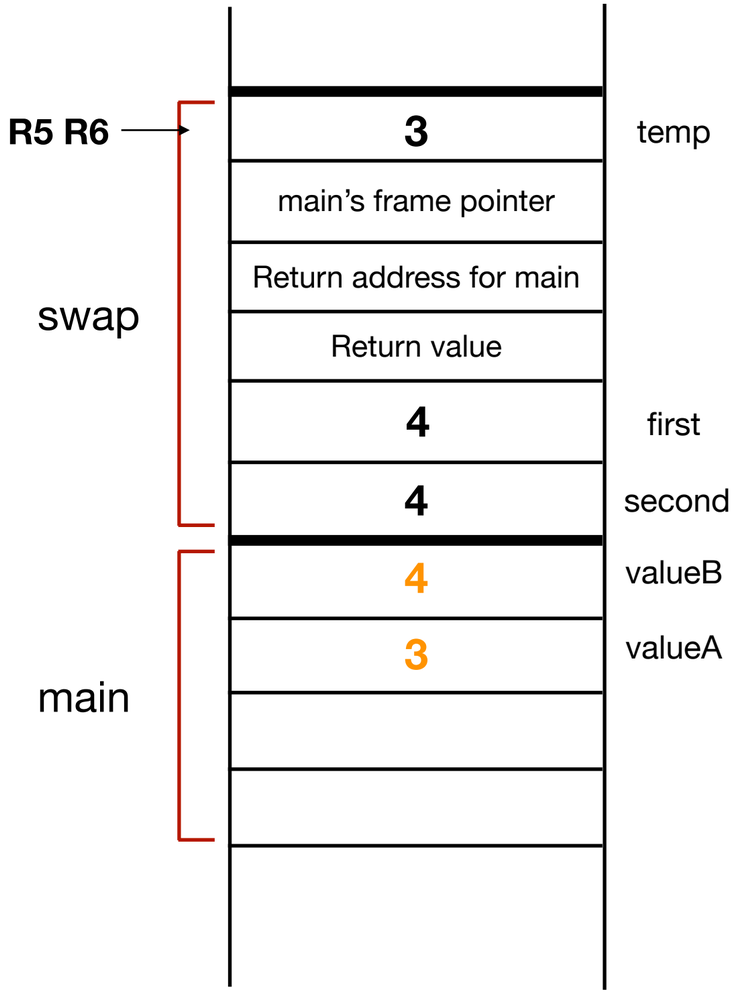


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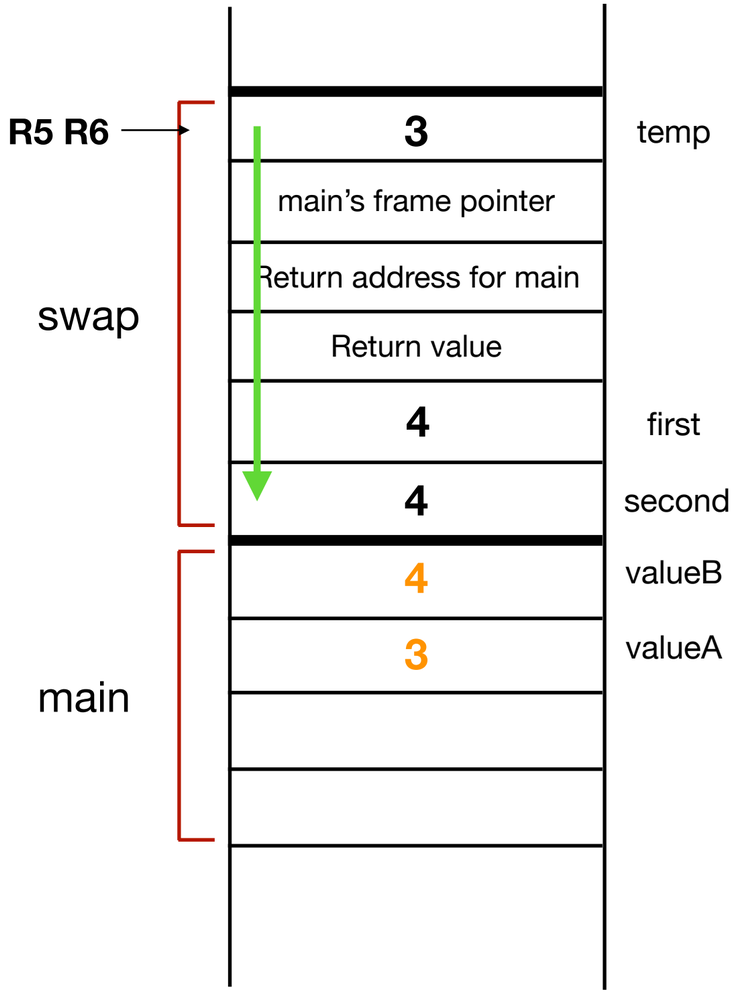


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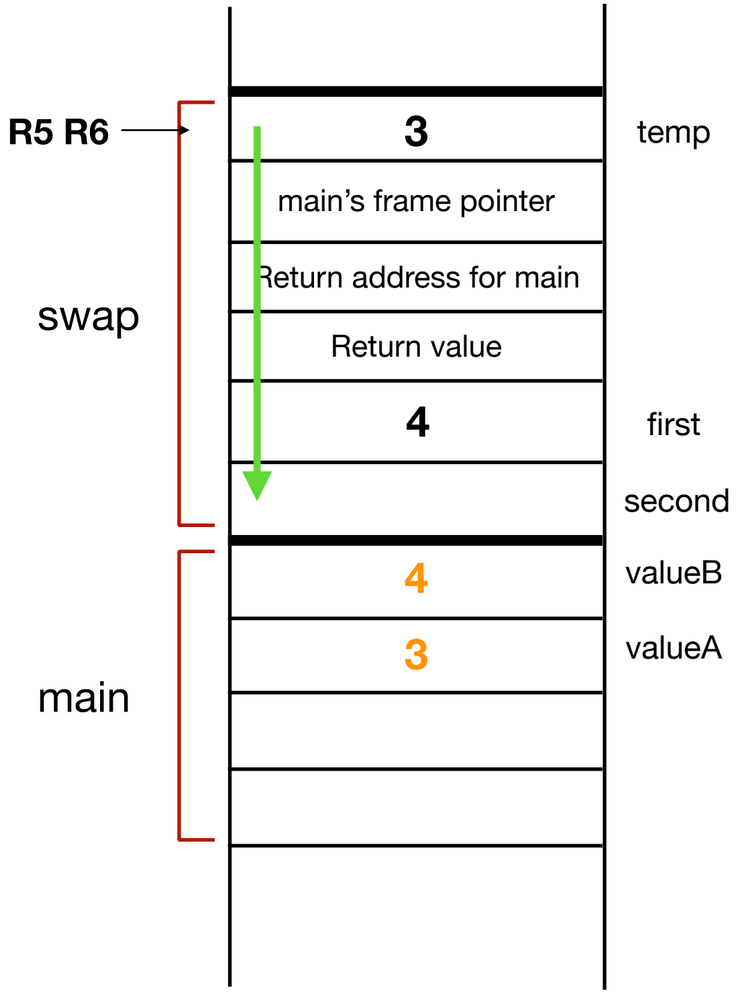


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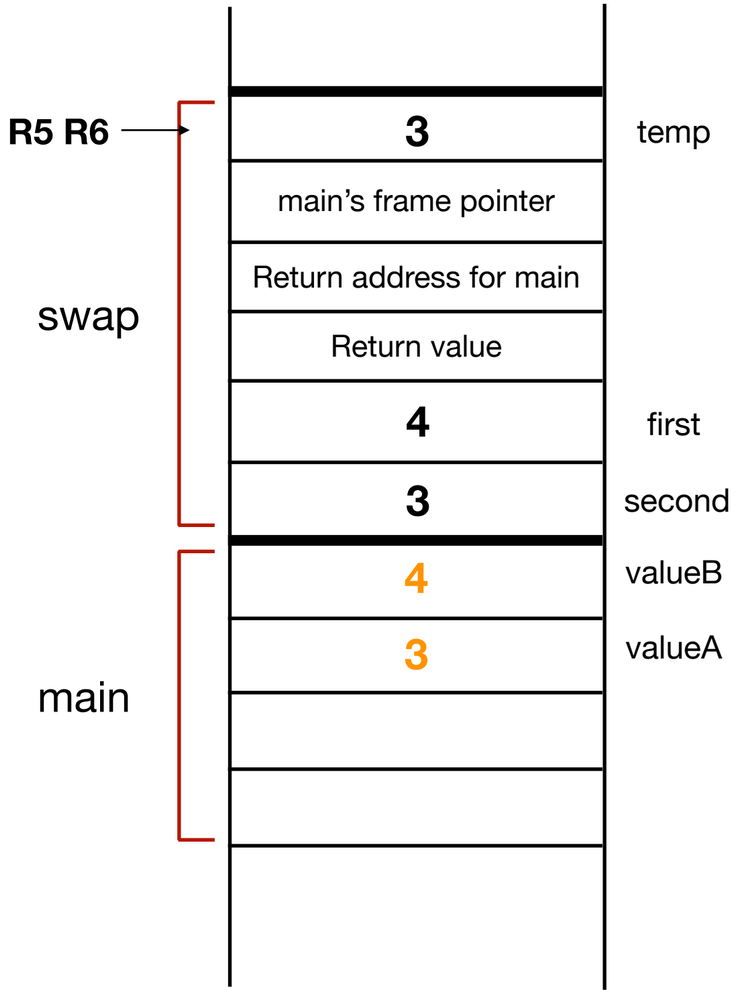


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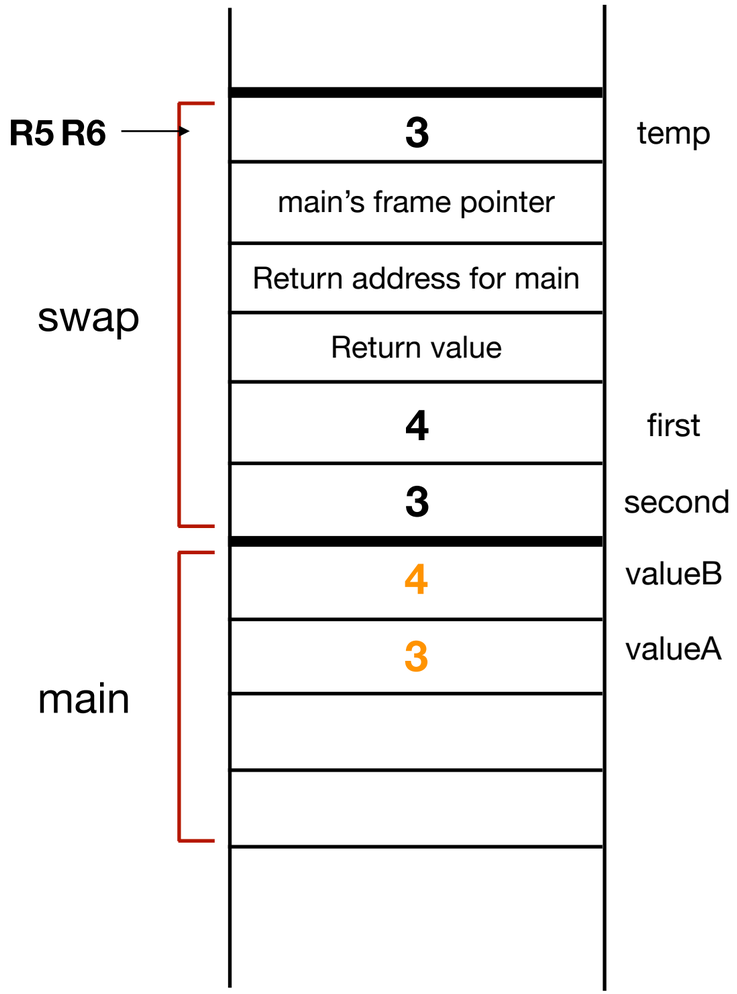


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LC3 commands left as an exercise

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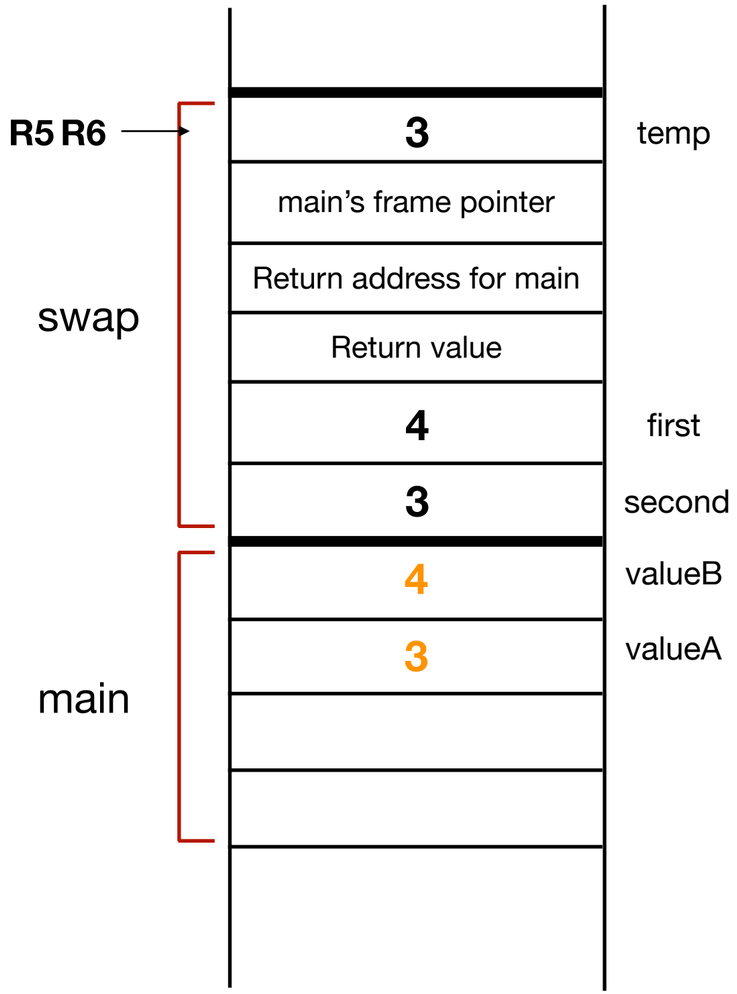


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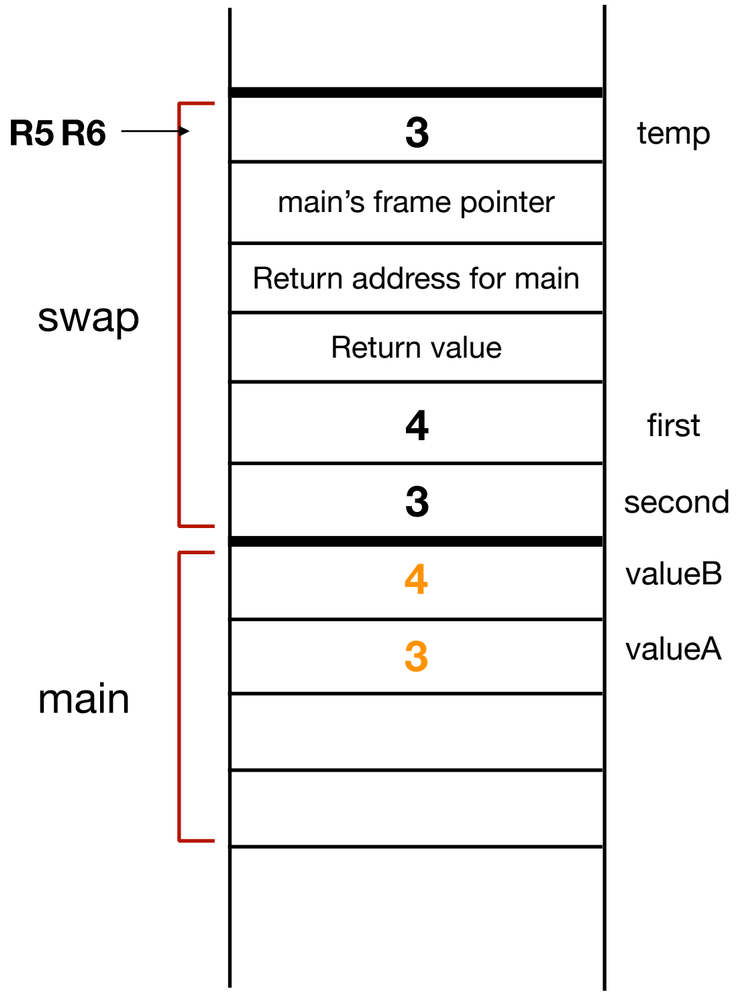


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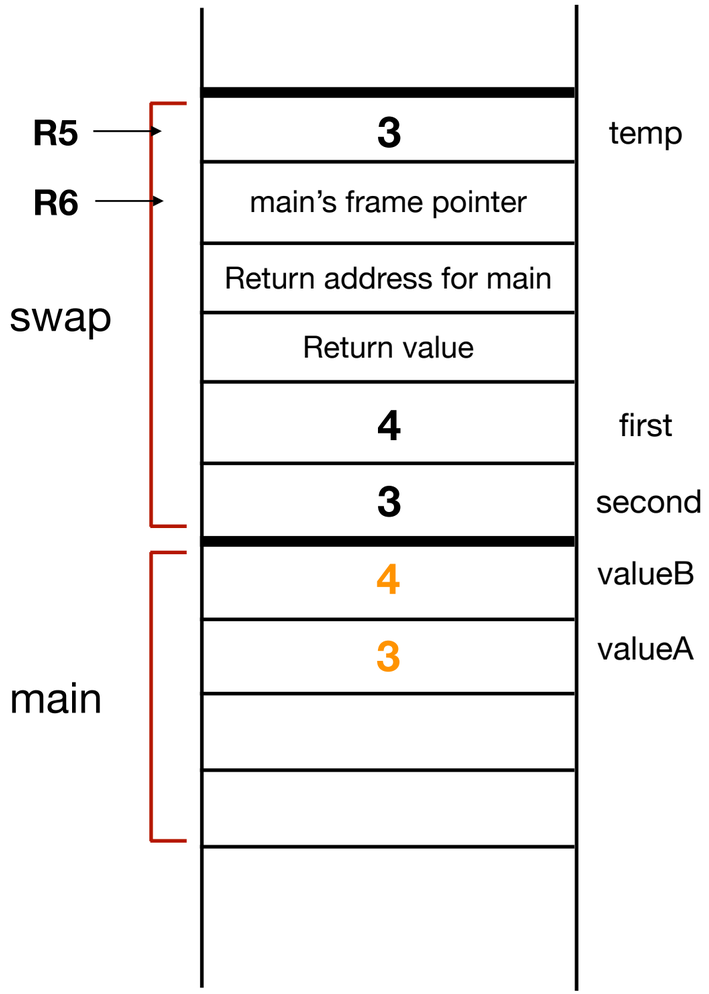


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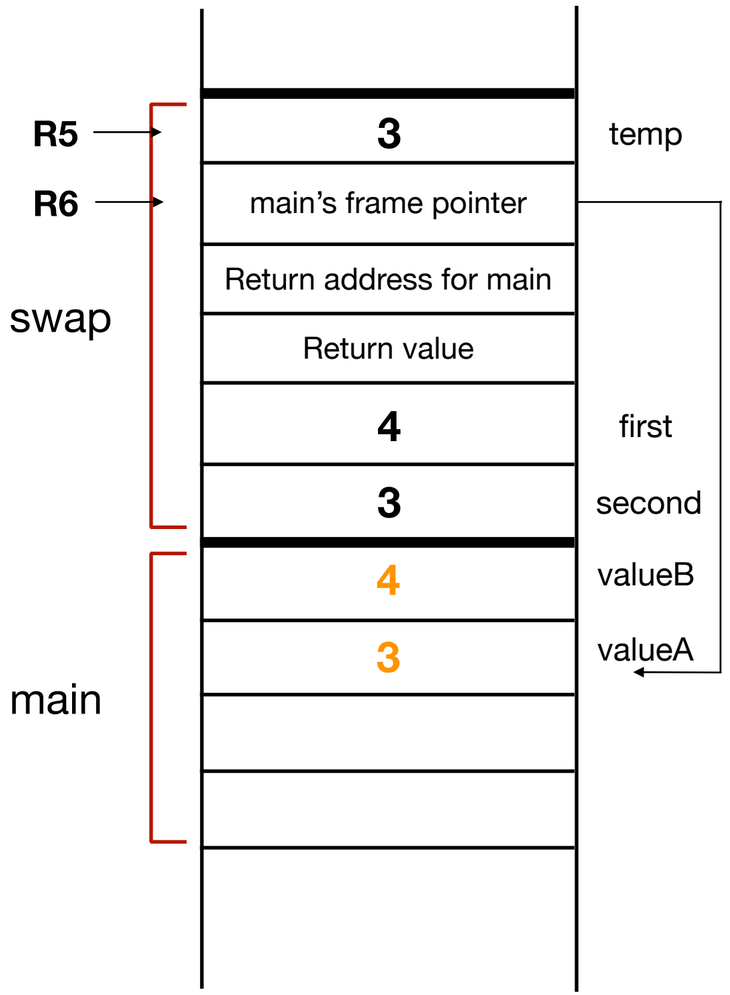


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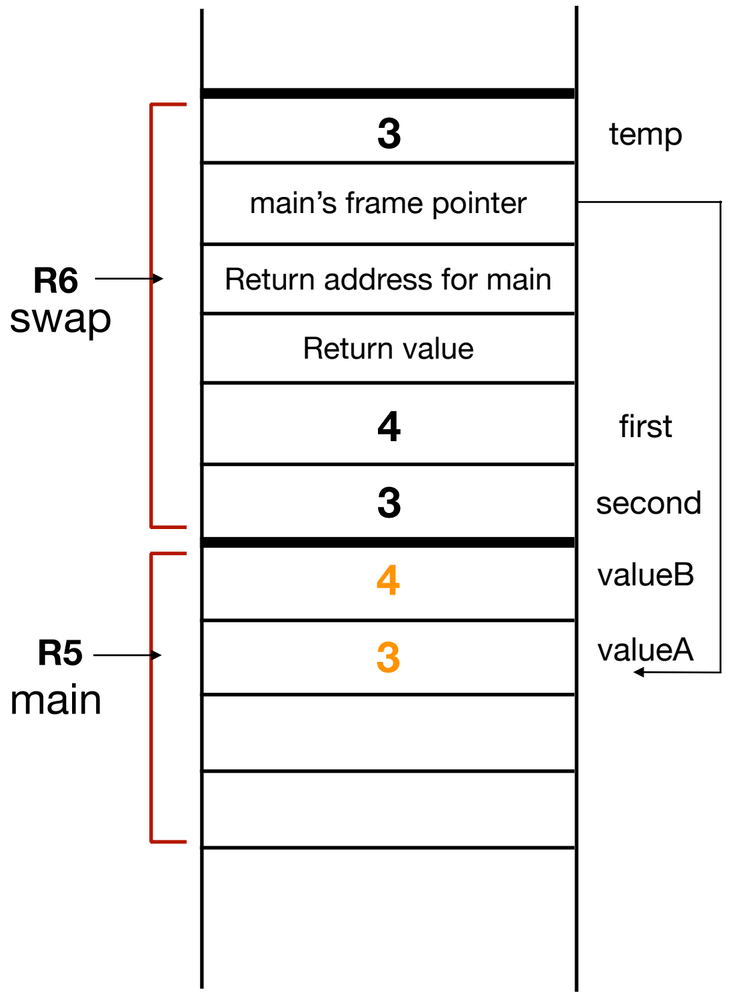


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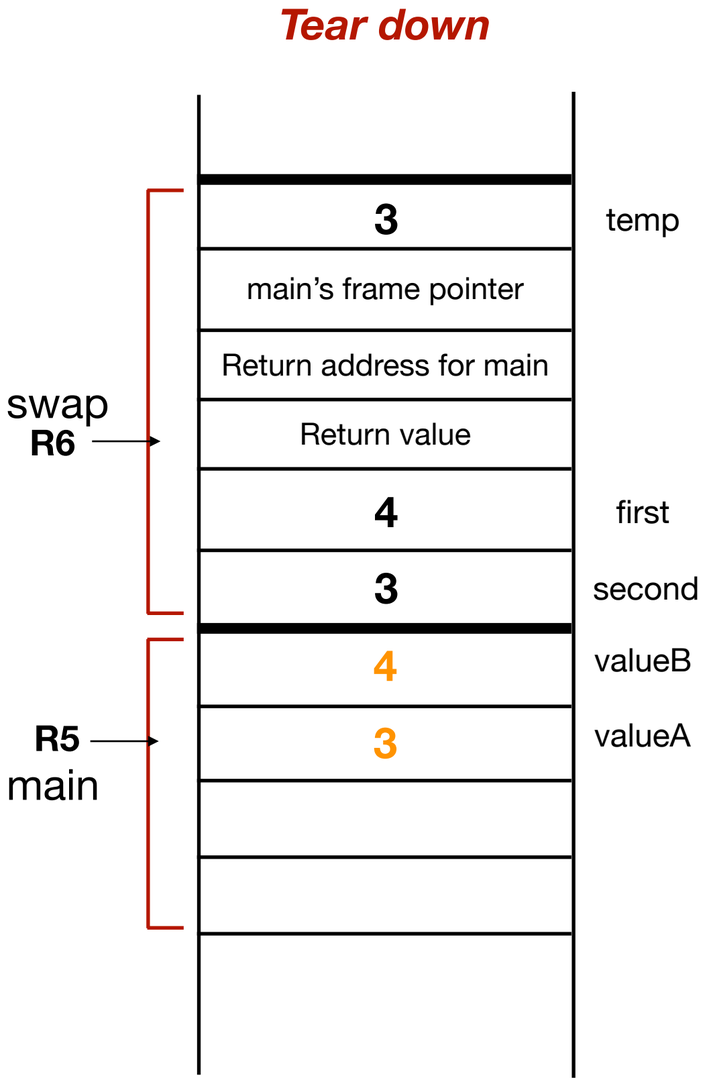

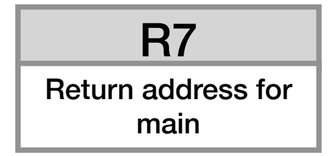


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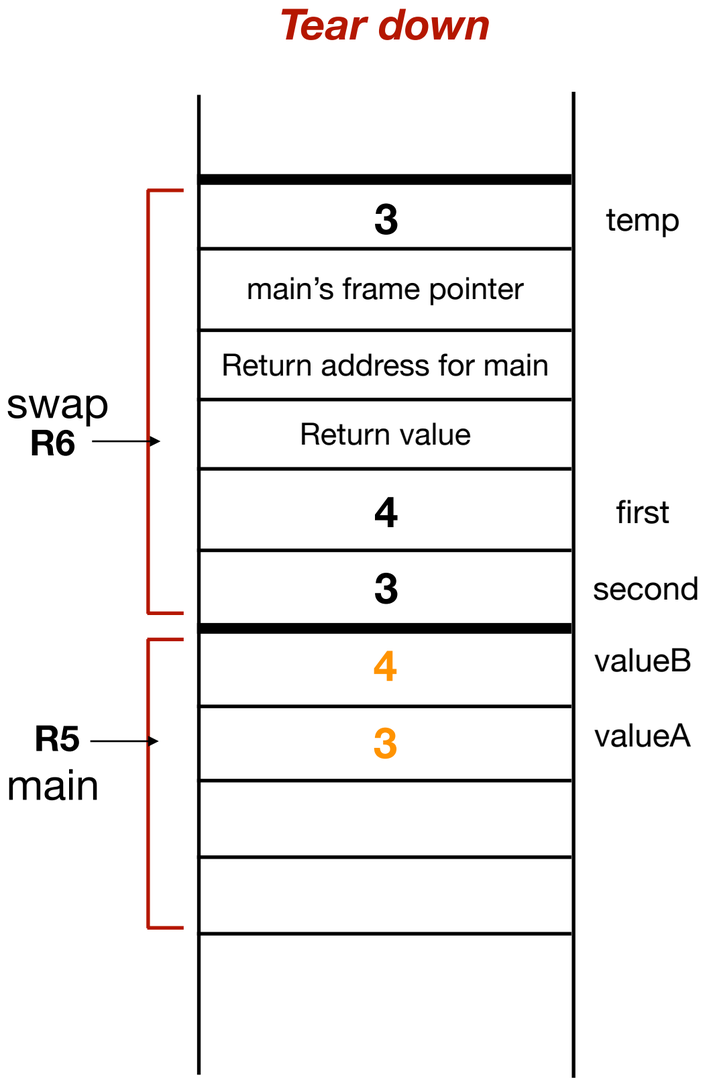

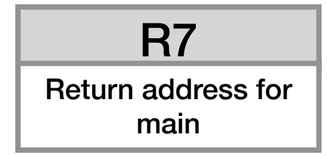


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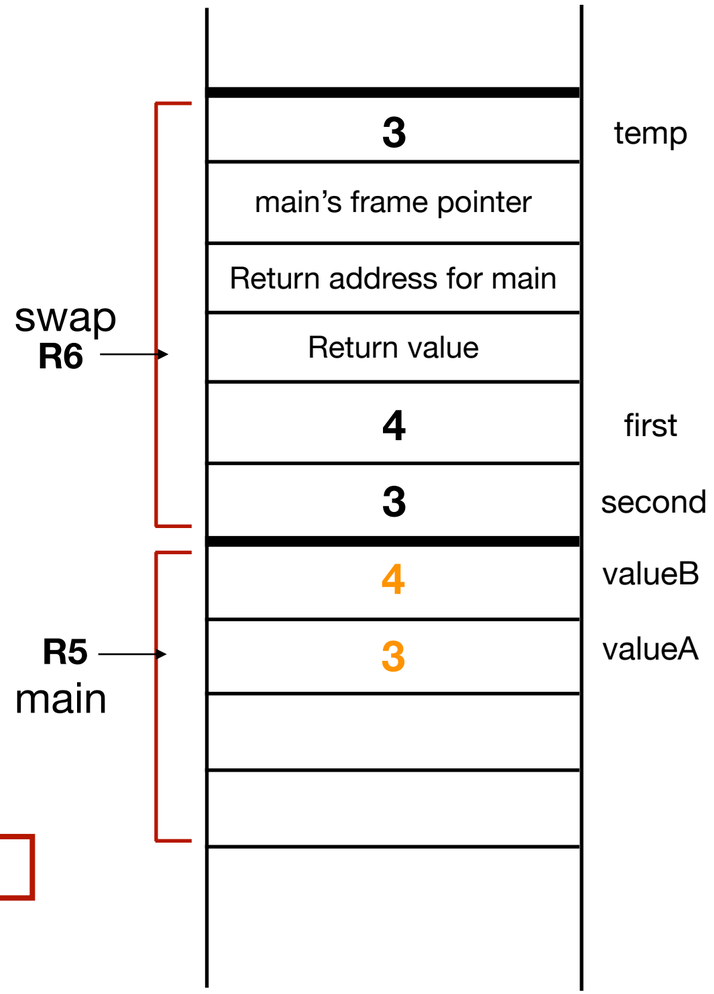
Tear down

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LC3 commands left as an exercise

`swap` function - tear down

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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
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    F. Pop local variables
    G. Pop CFP (into R5)
    H. Pop return address (into R7)
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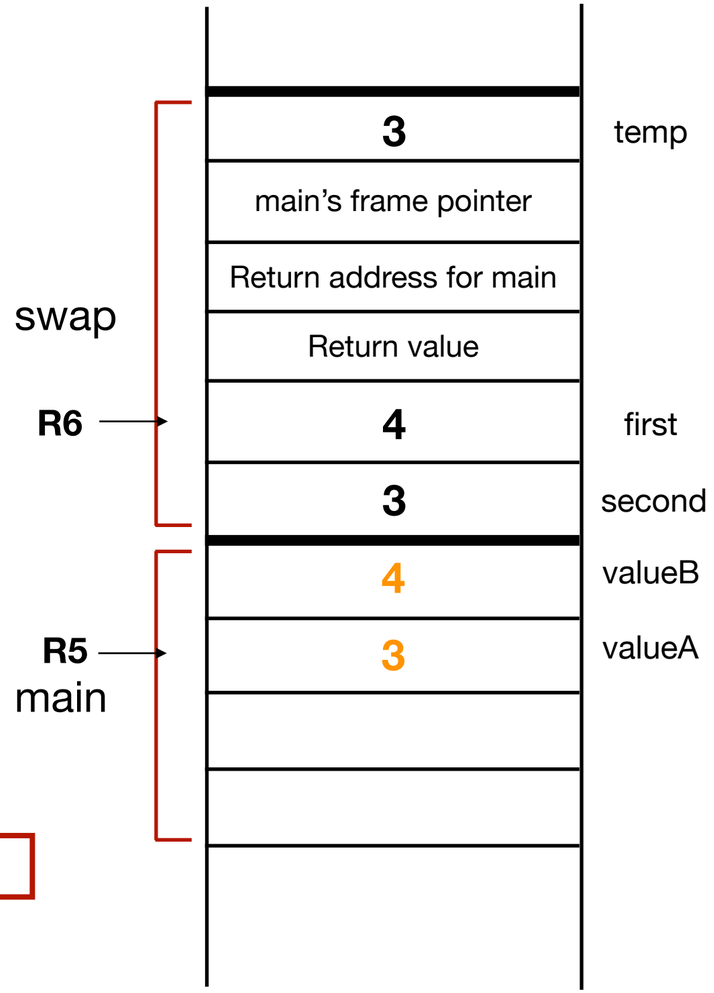


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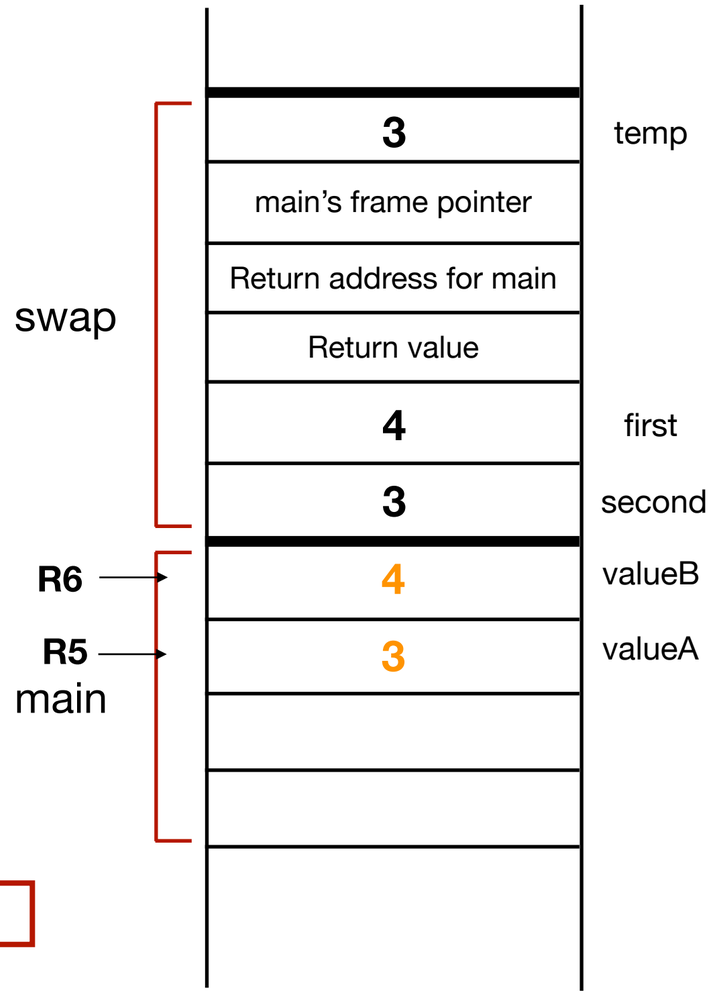


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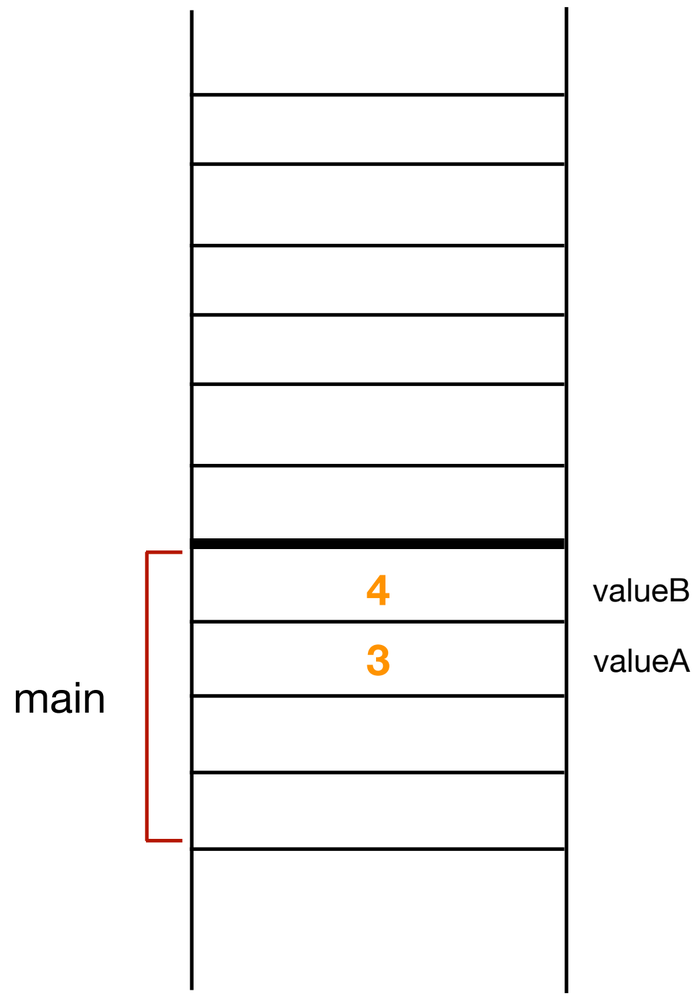
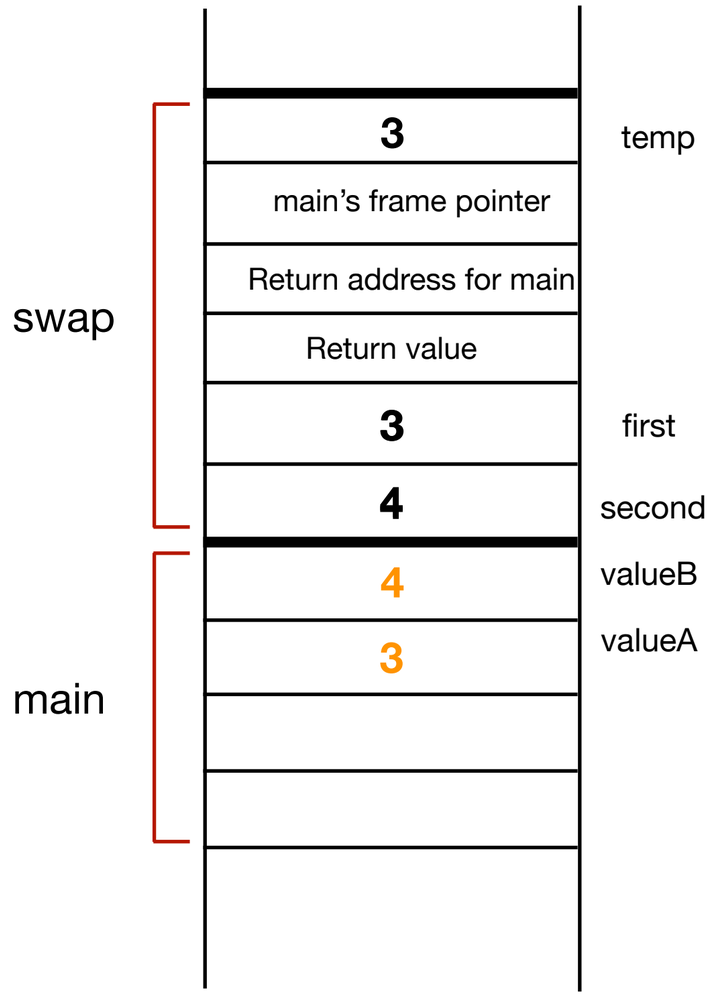
Before call



After call



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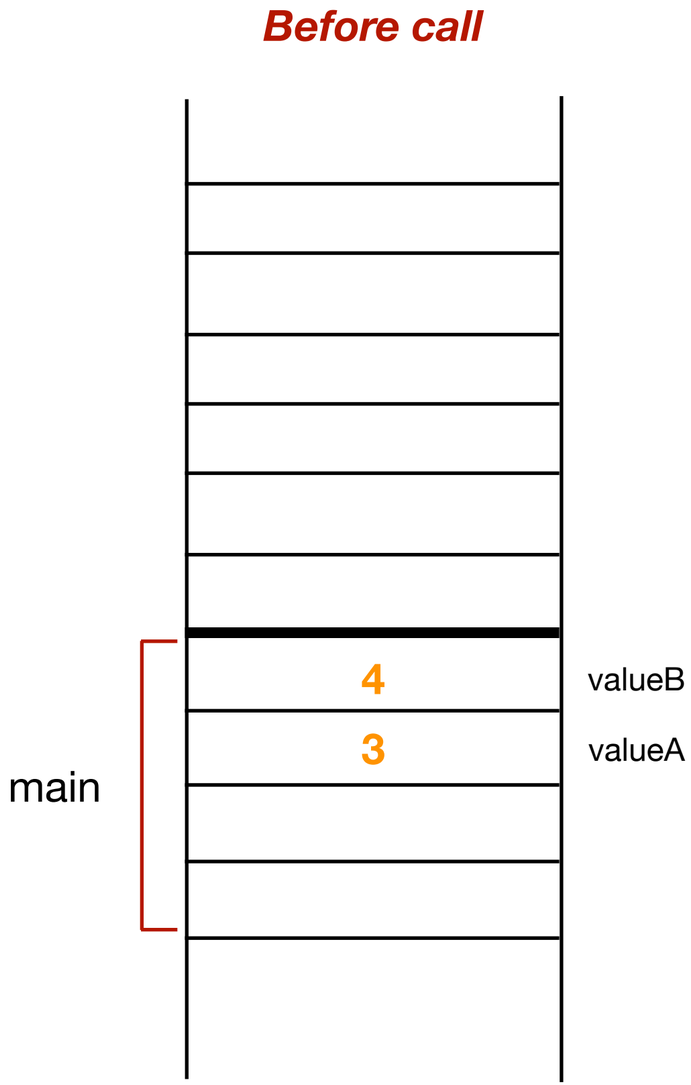

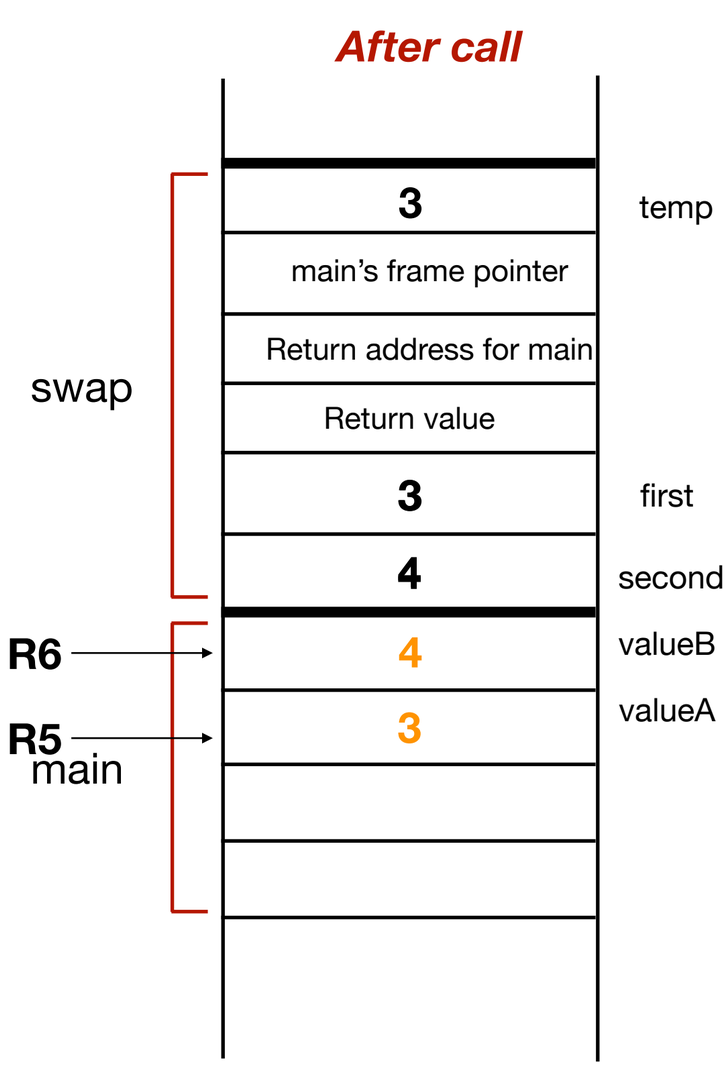

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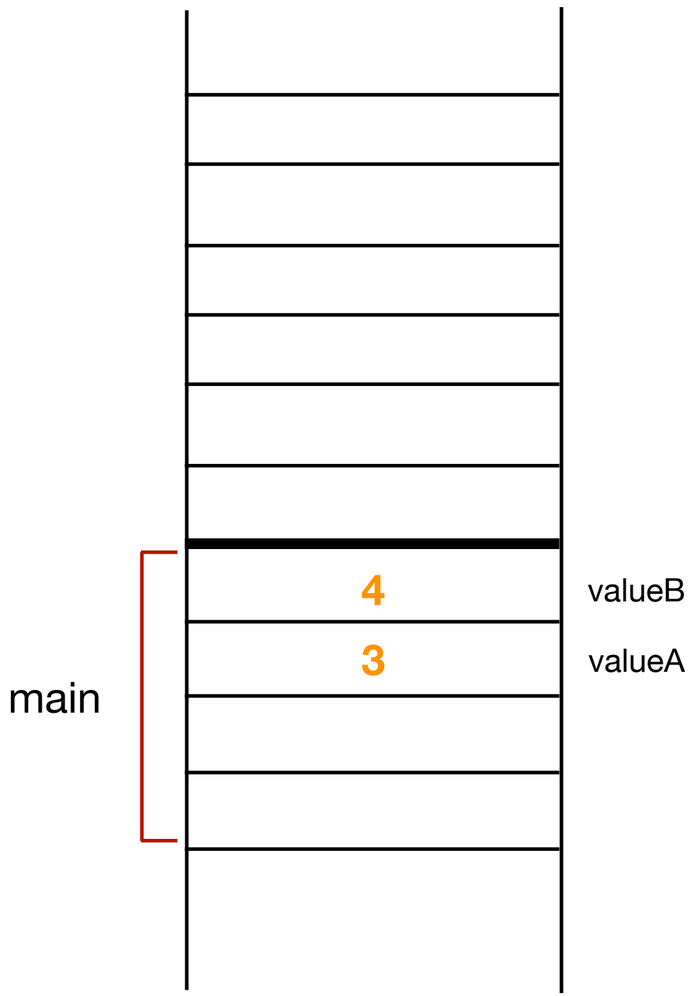

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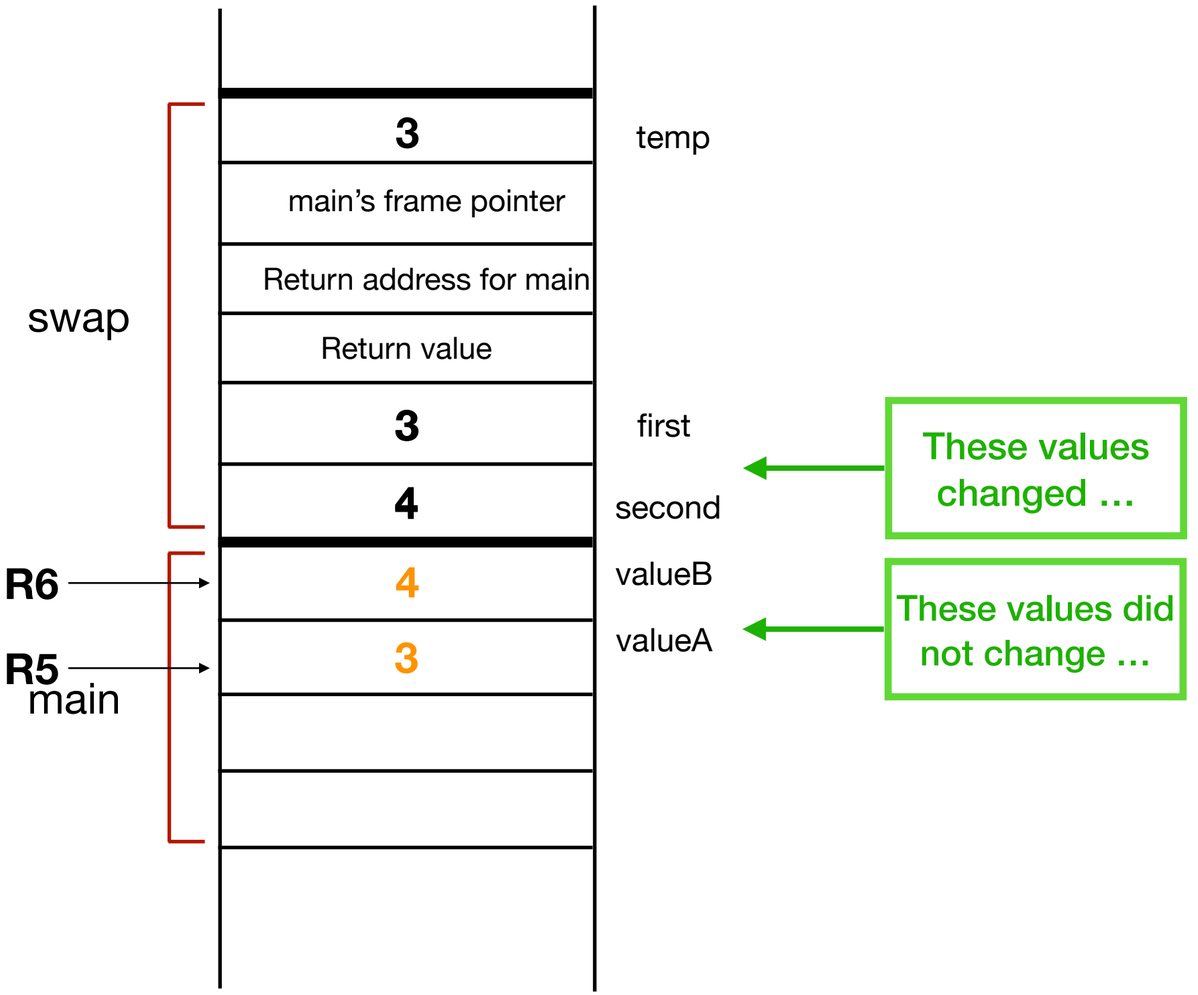

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- Enter **pointers.**

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Too fast?

Don’t miss next class! We will cover it again.