ECE 220

Lecture x0008 - 02/08

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

Recap + reminders

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- Midterm 1 on 02/15, conflicts to be reported by 02/11

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    - Prototype vs. definition
  - Examples
  - Implementation in assembly & intro to RTS

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int inGlobal=2;
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int dummy(int in1, int in2);

int main(void){
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Symbol table

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inGlobal	int	0	Global
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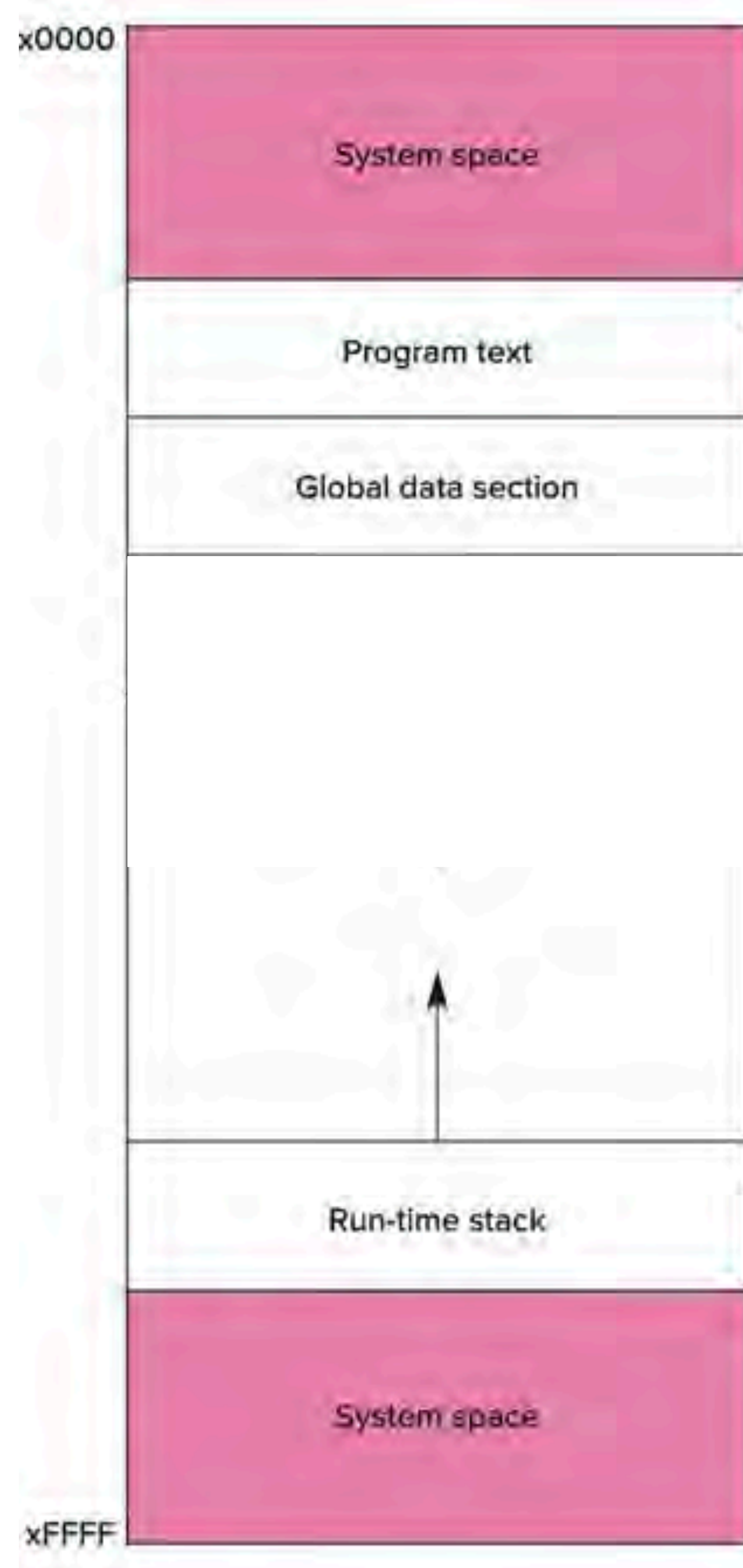
Why are some offsets negative and others positive?

Example: In LC3 memory map



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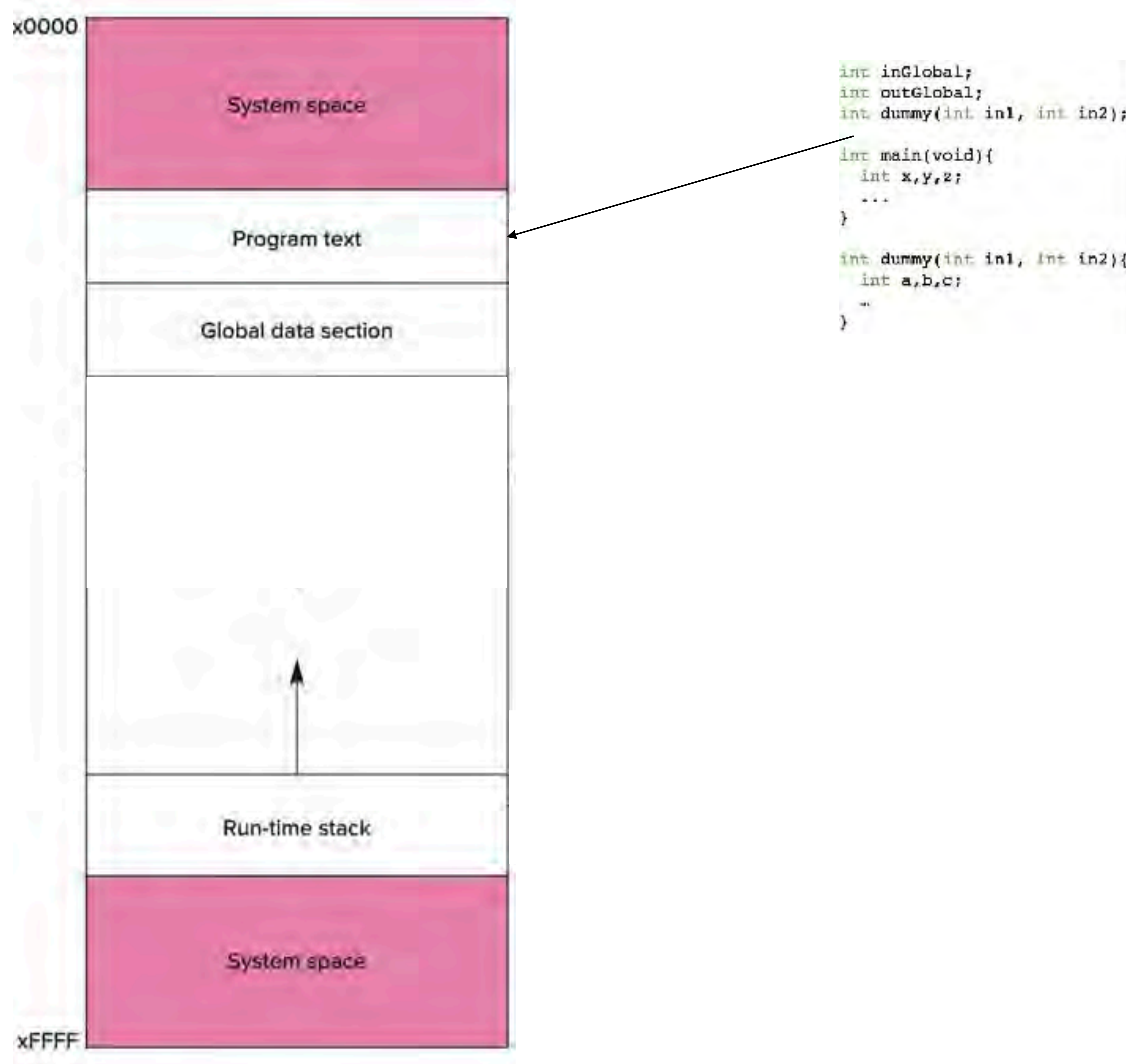

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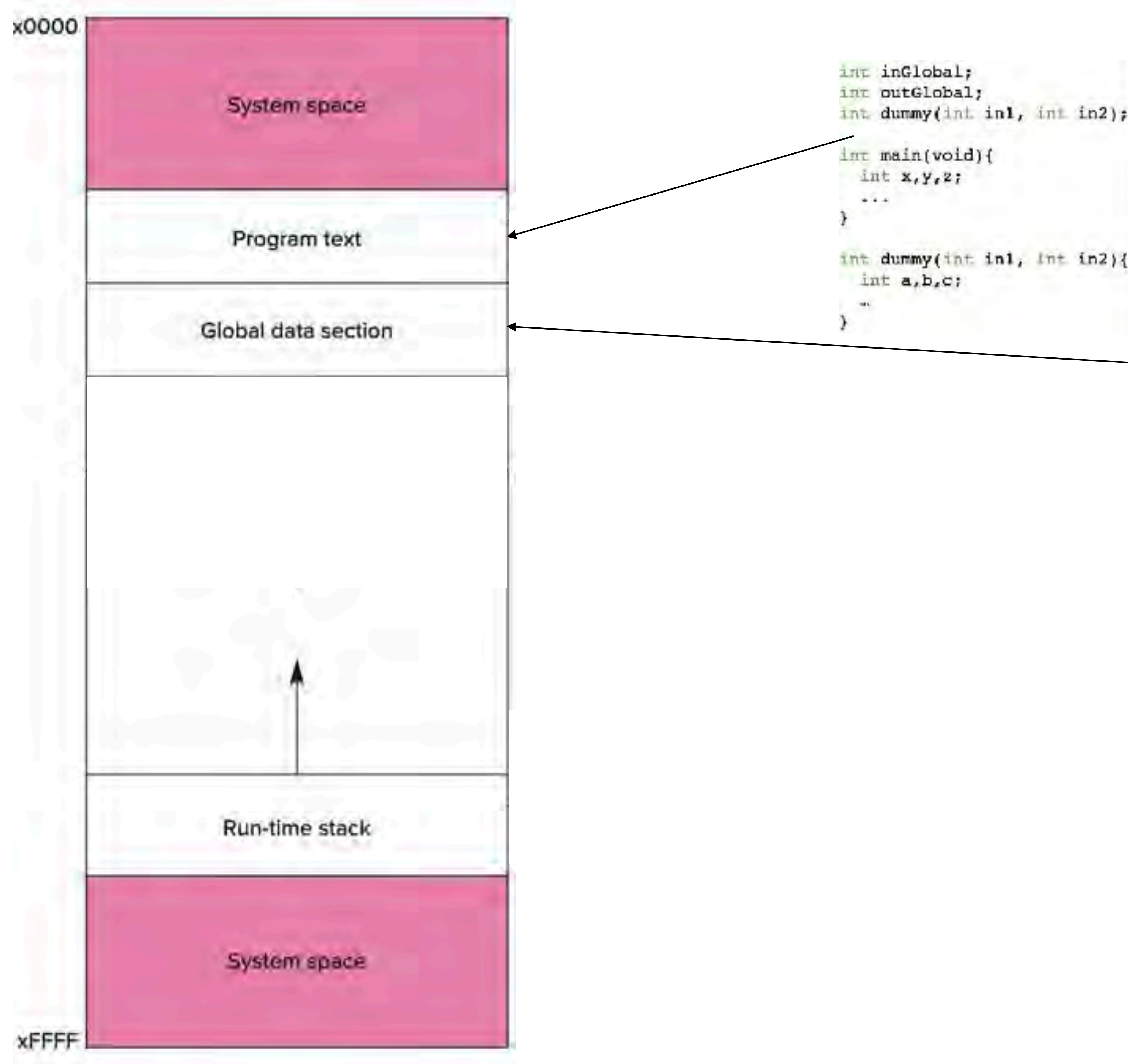

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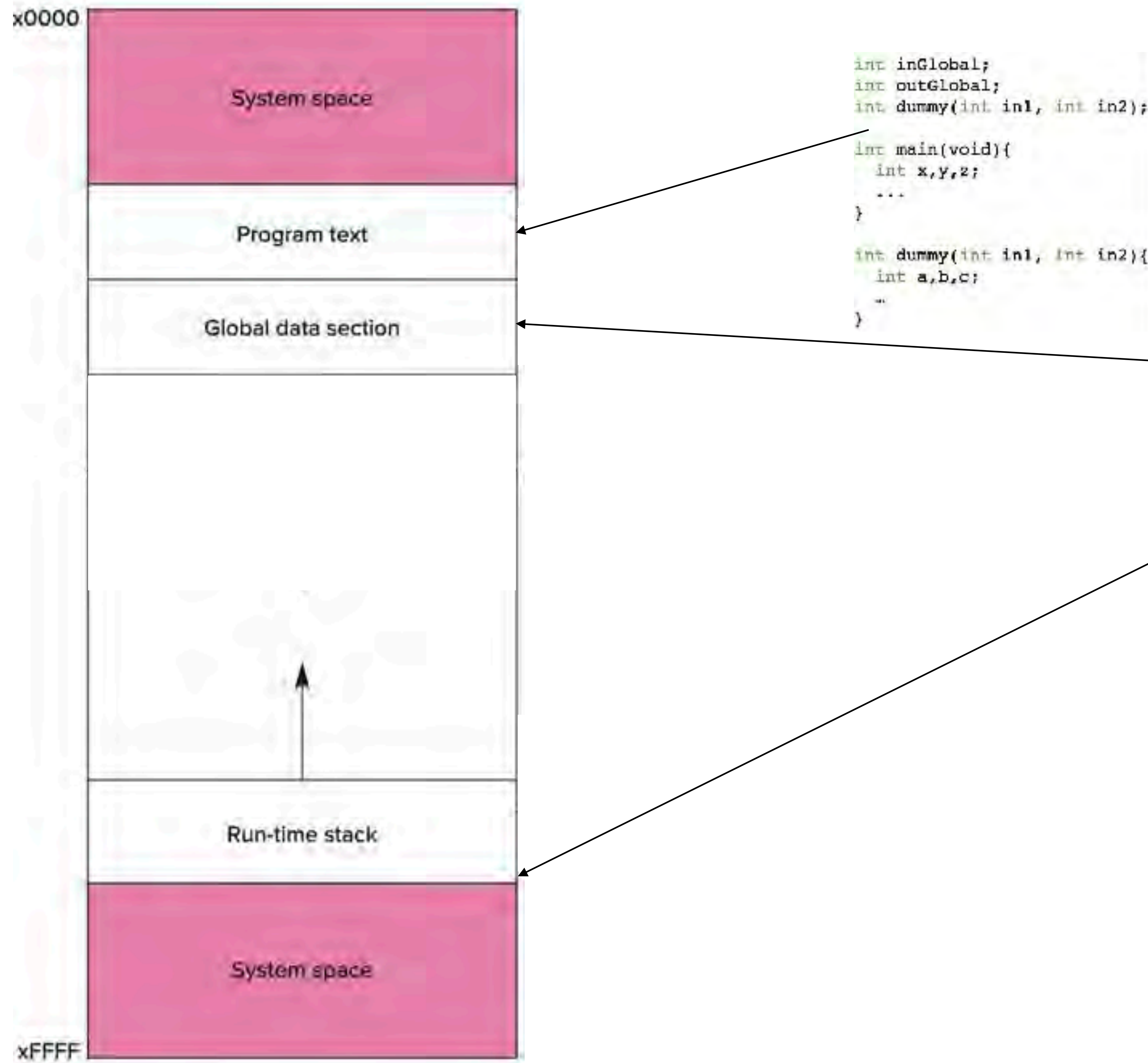


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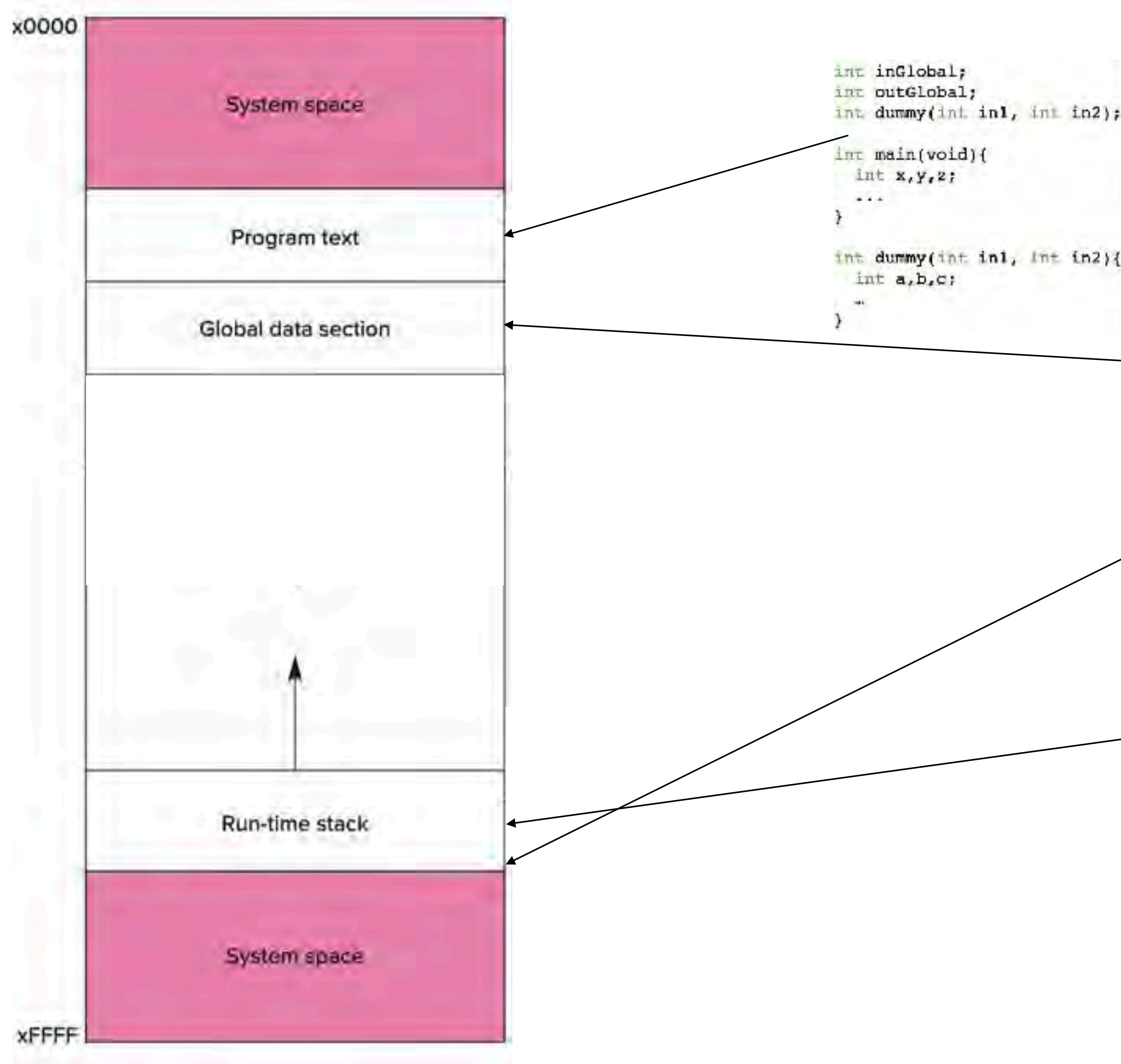

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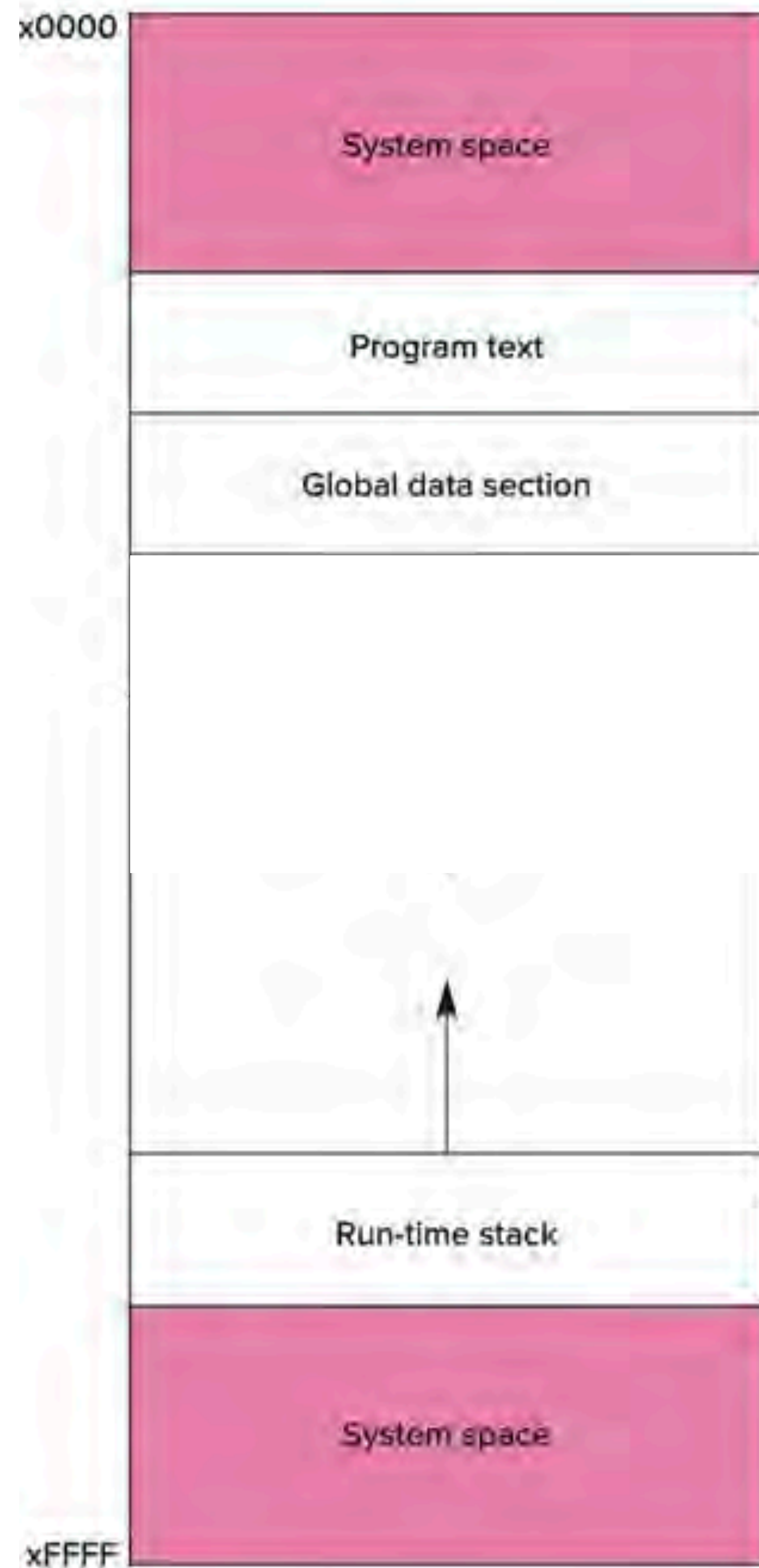


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Because function calls are implemented using a stack ADT.

Basic idea

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

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Example: function call

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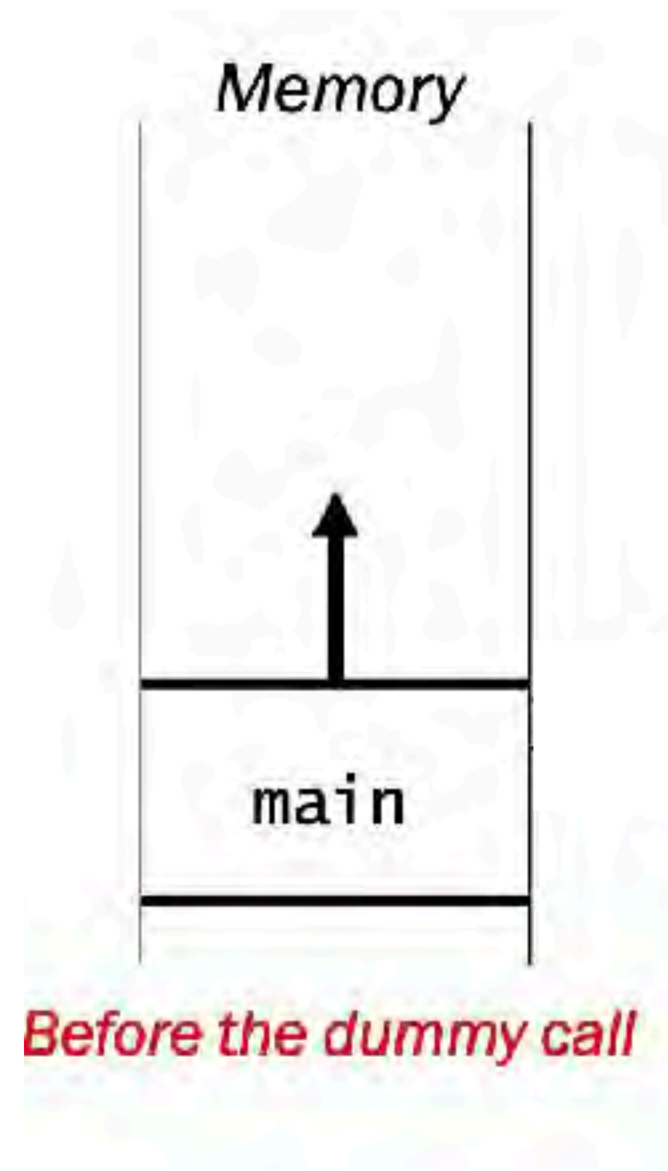

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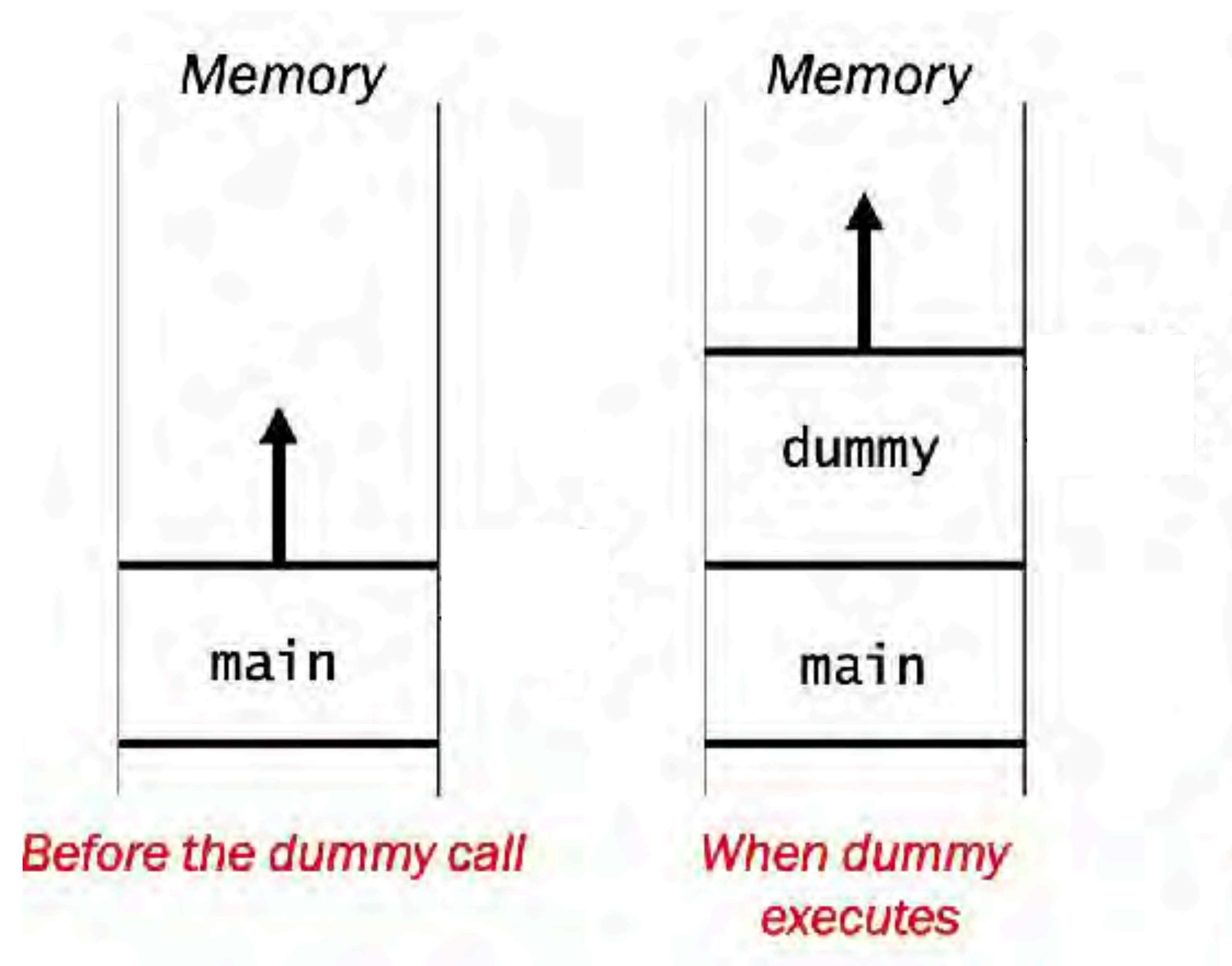

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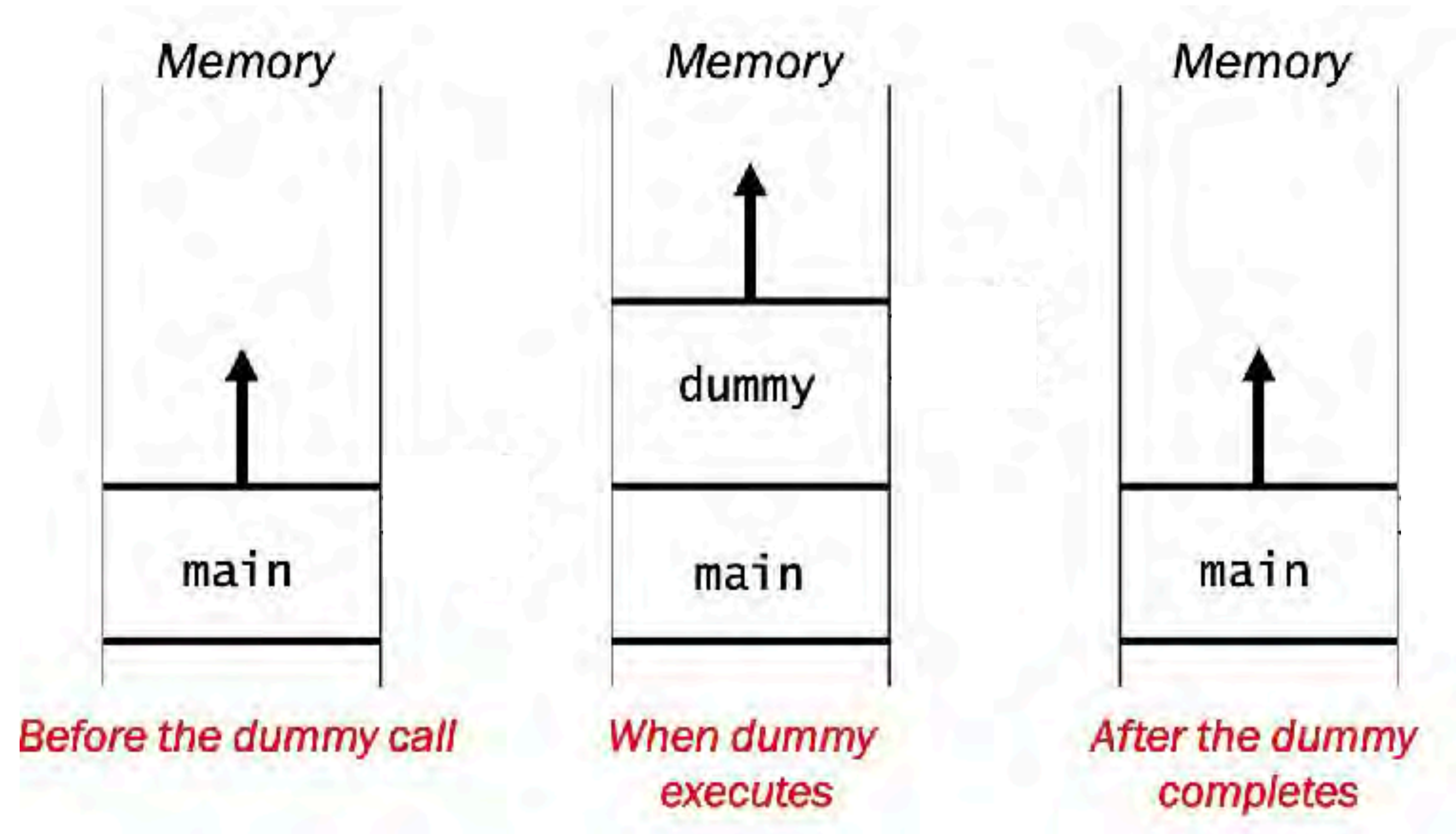
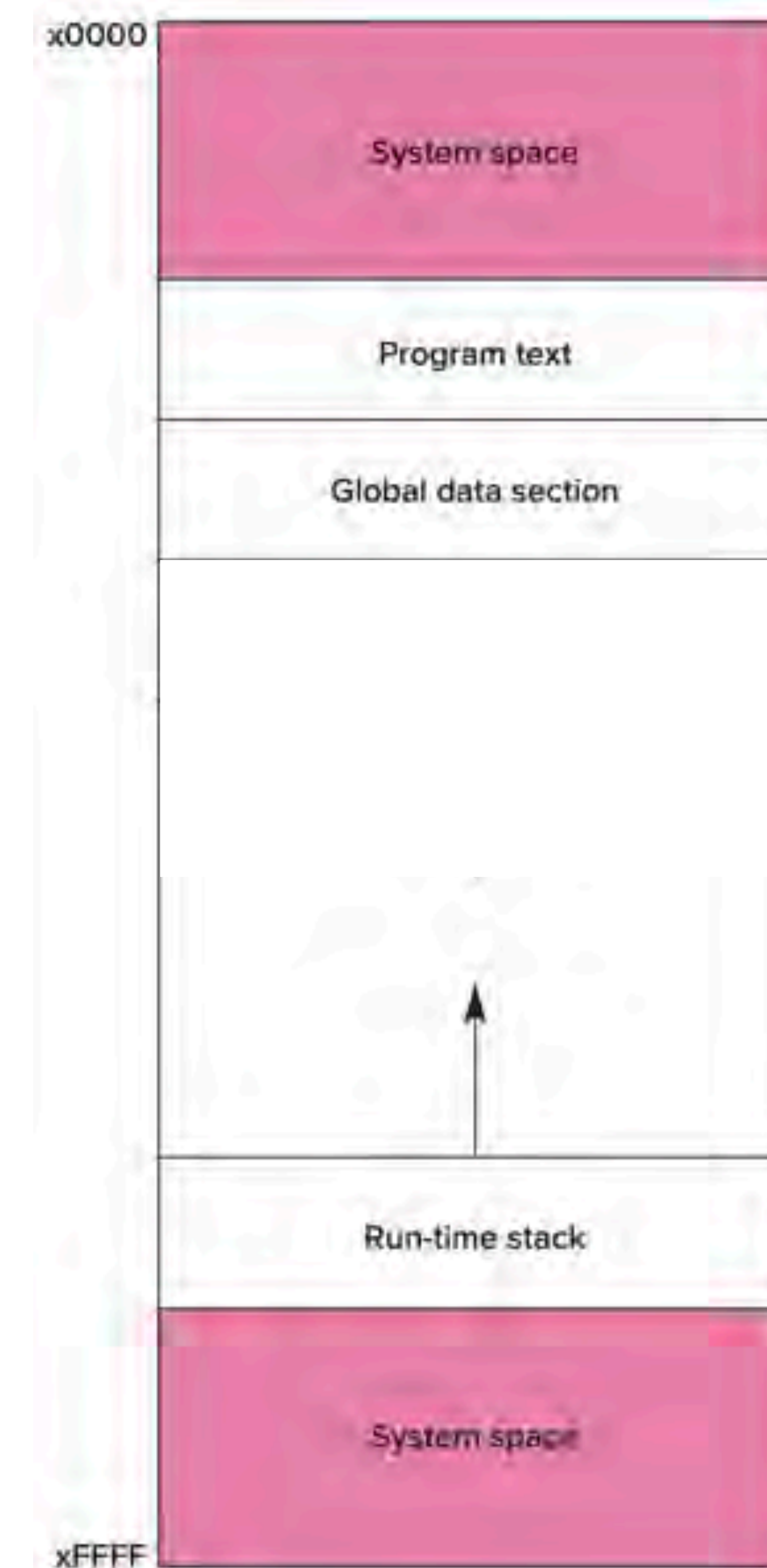


How to keep track?



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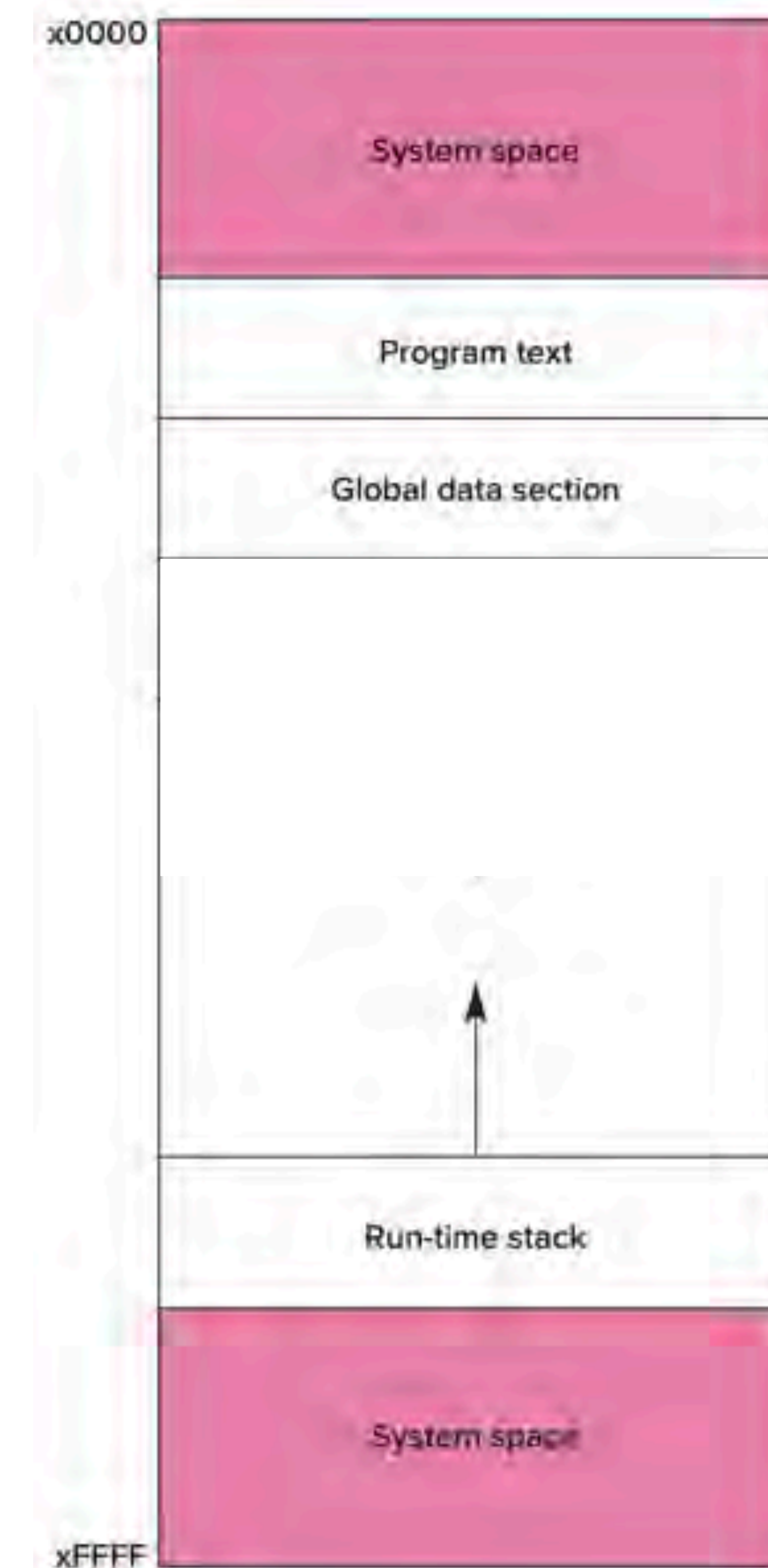
- Store pointers:



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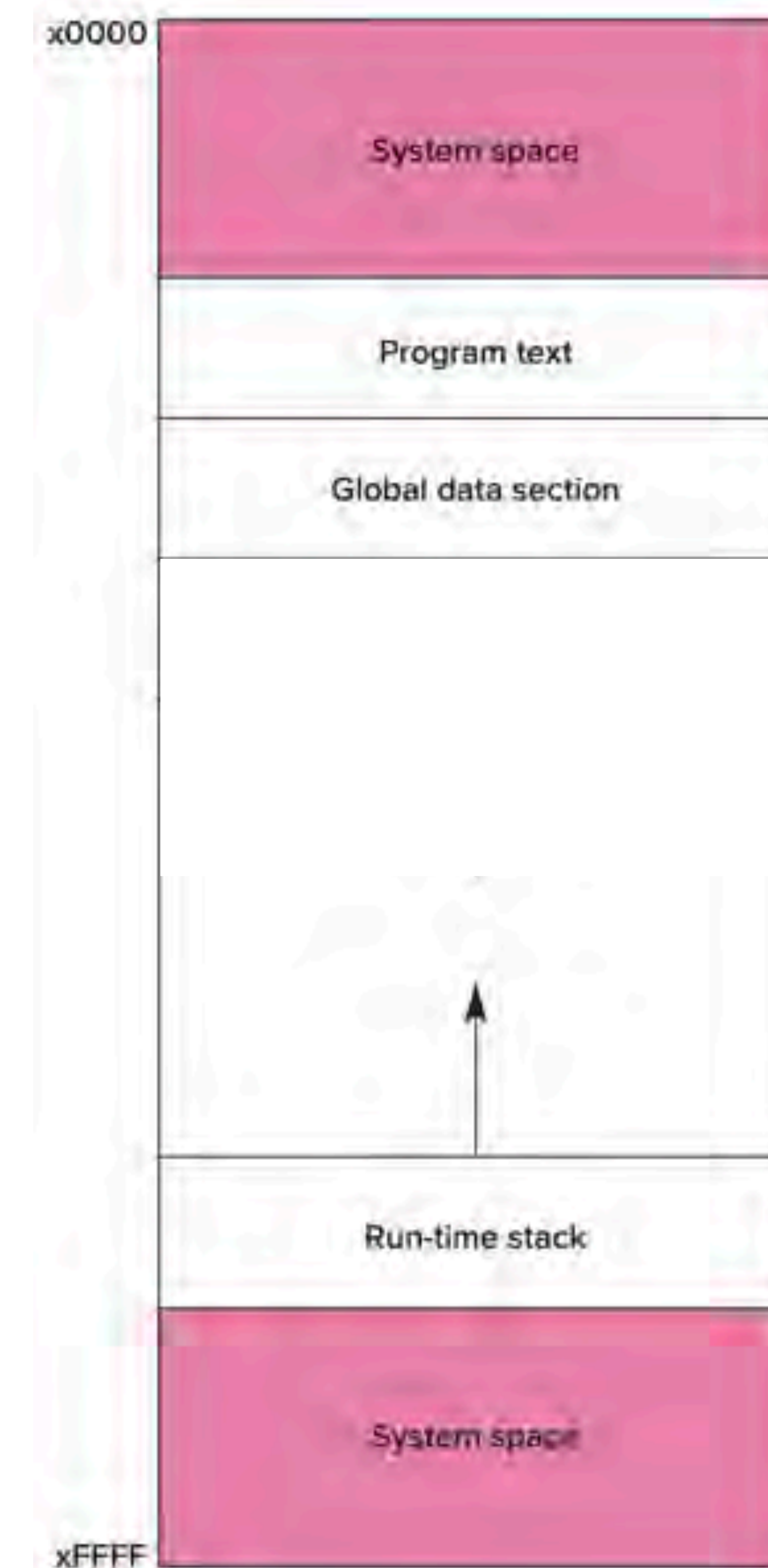

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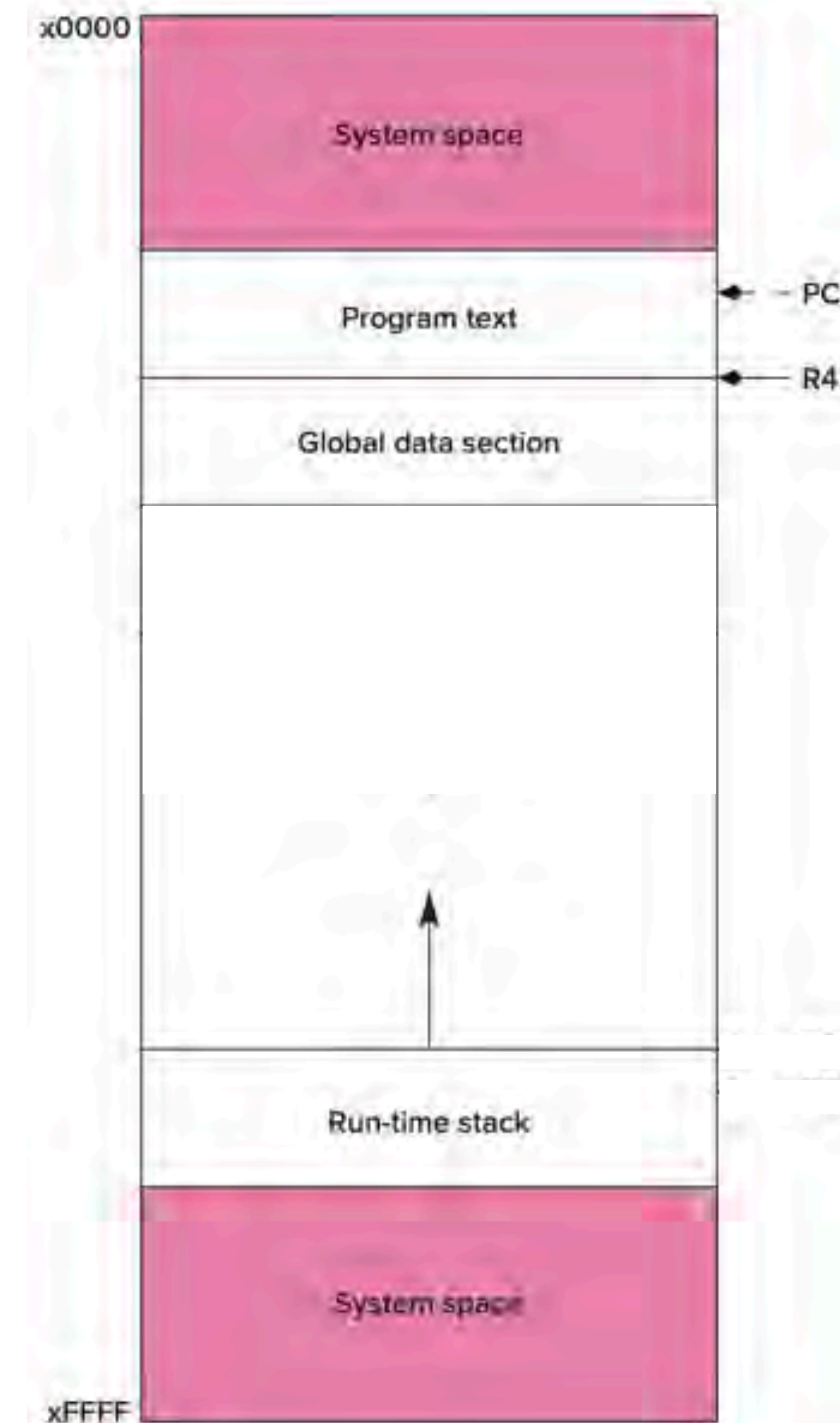

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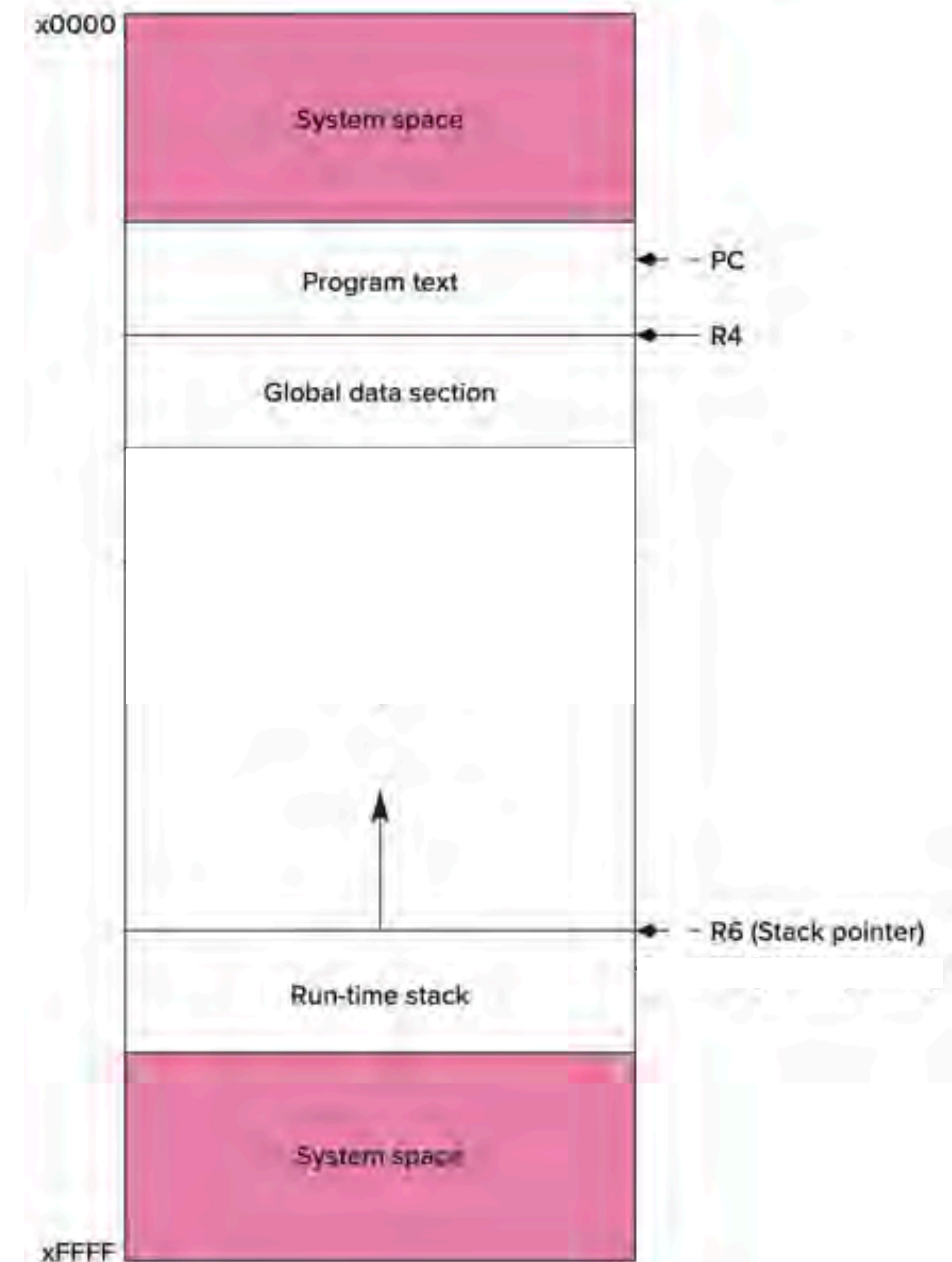

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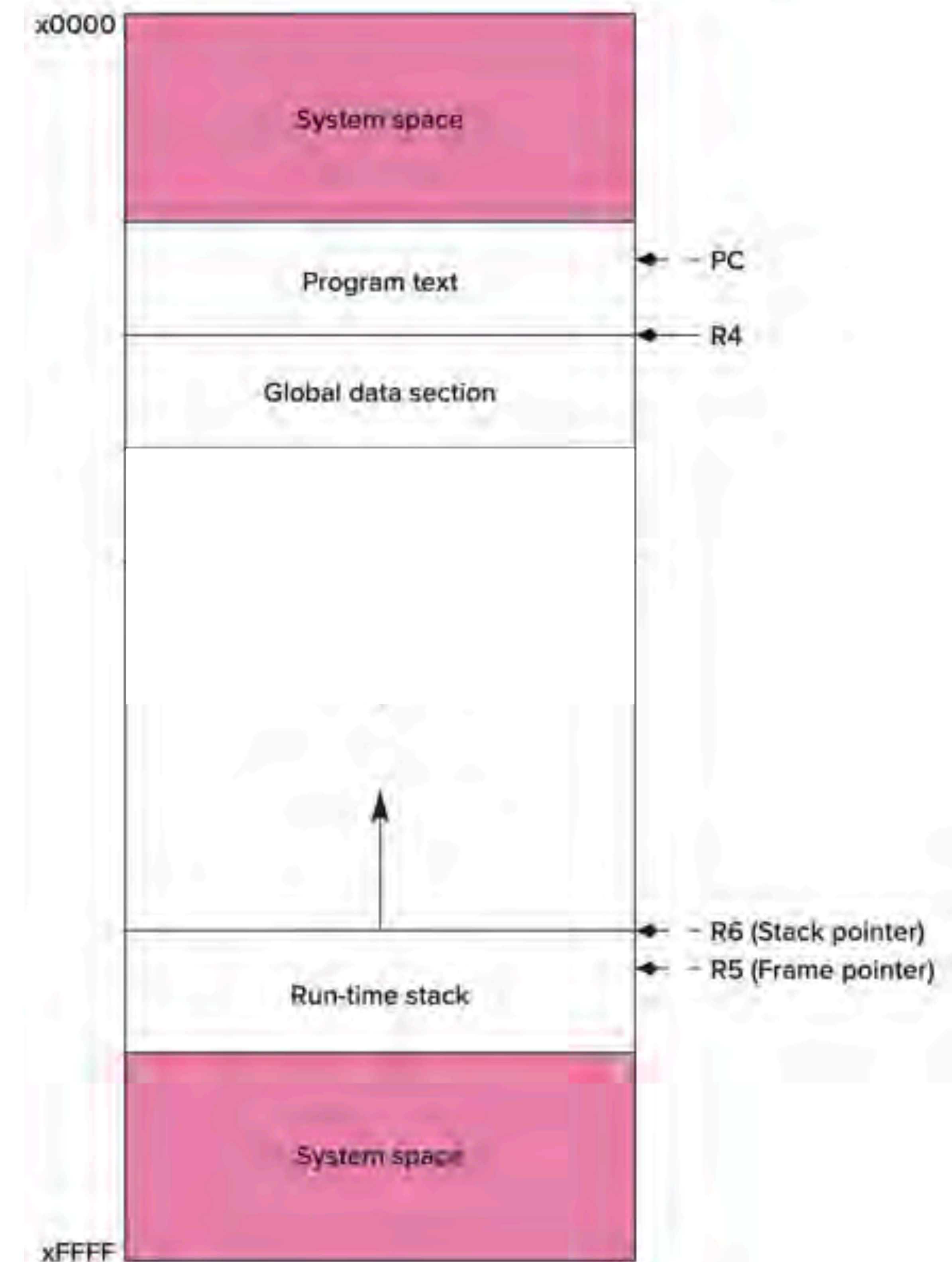

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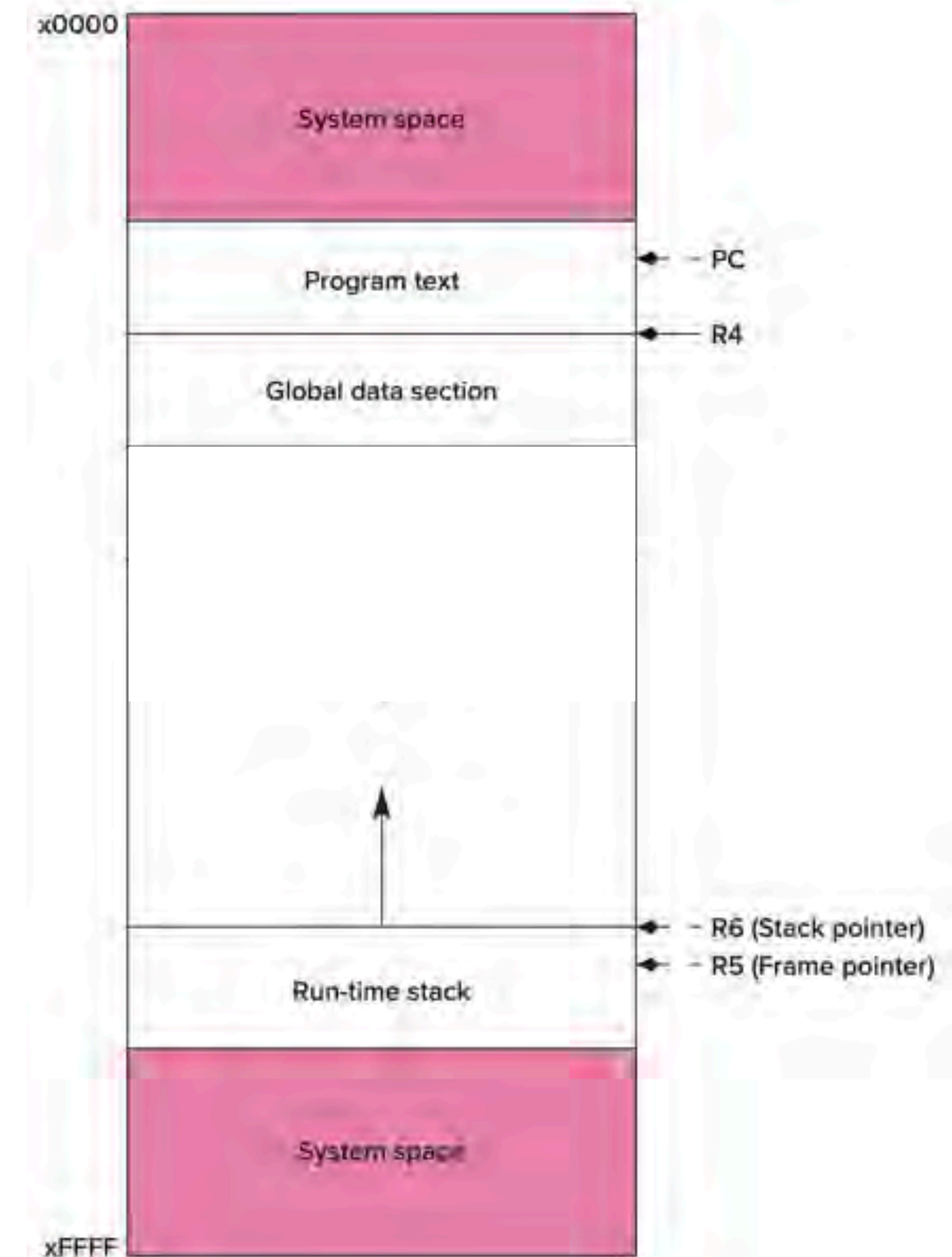
        - Actually points to first local variable of *current* function



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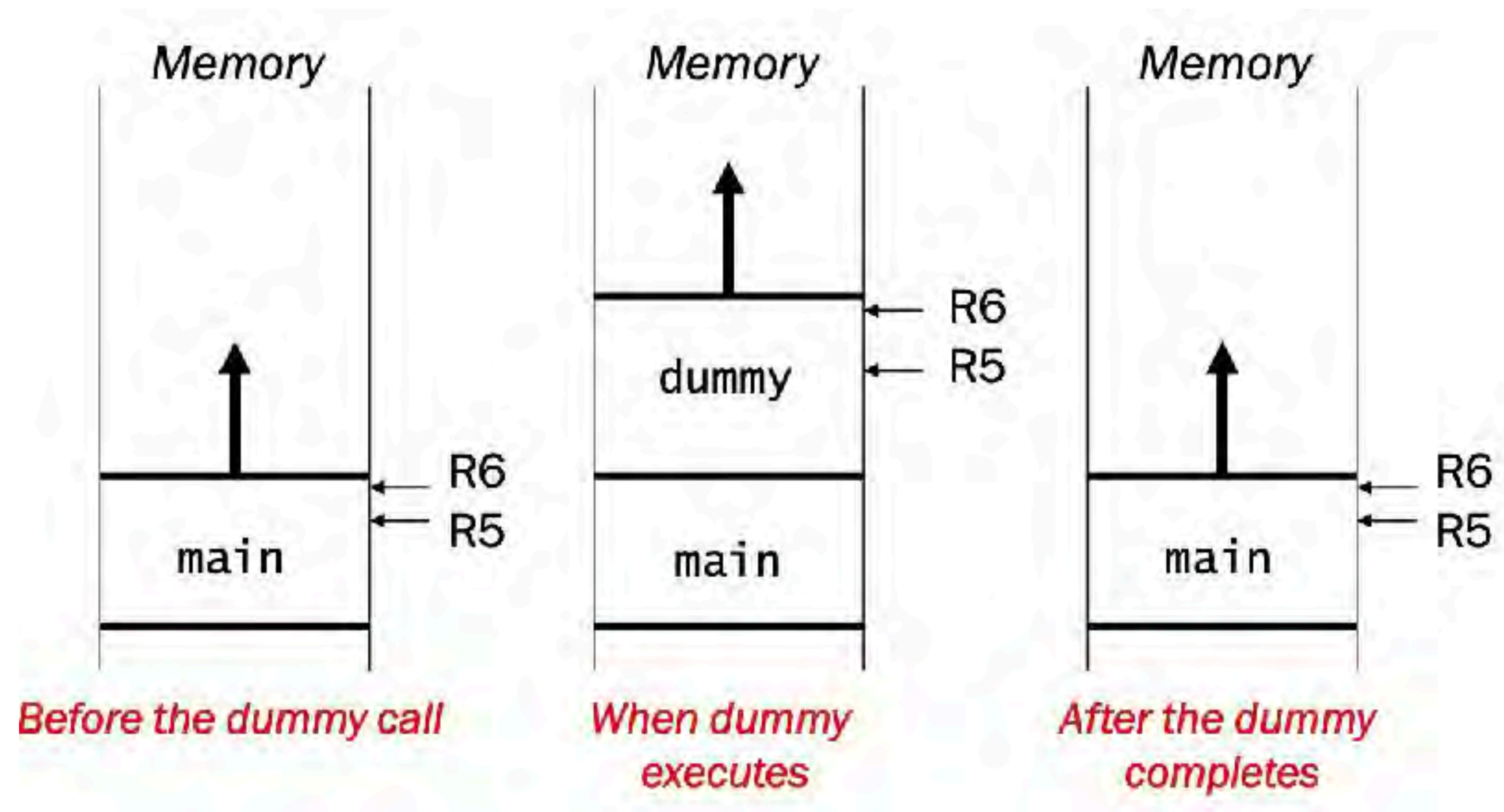

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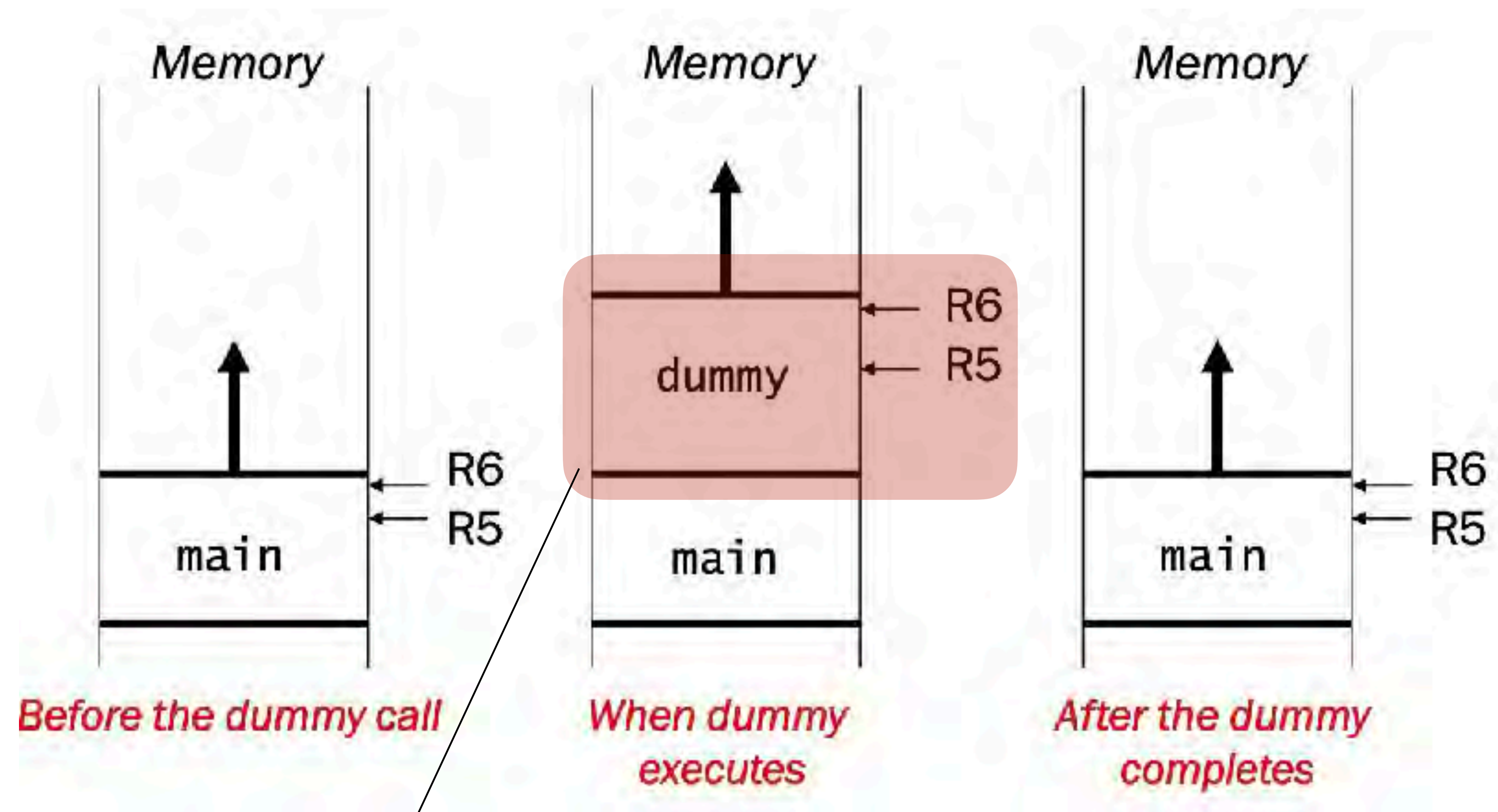

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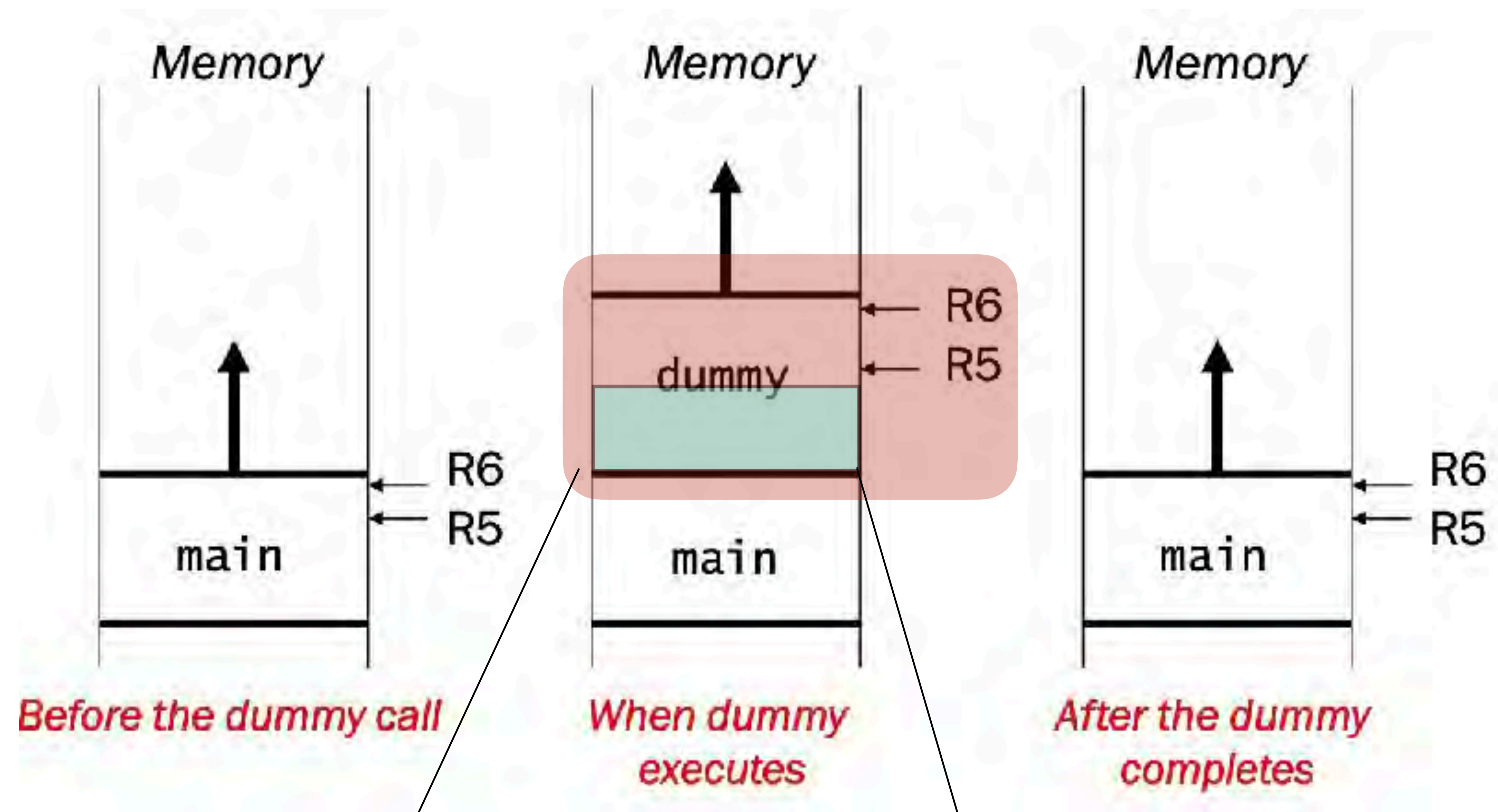

Activation record for dummy

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

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Pushed before local variables

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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

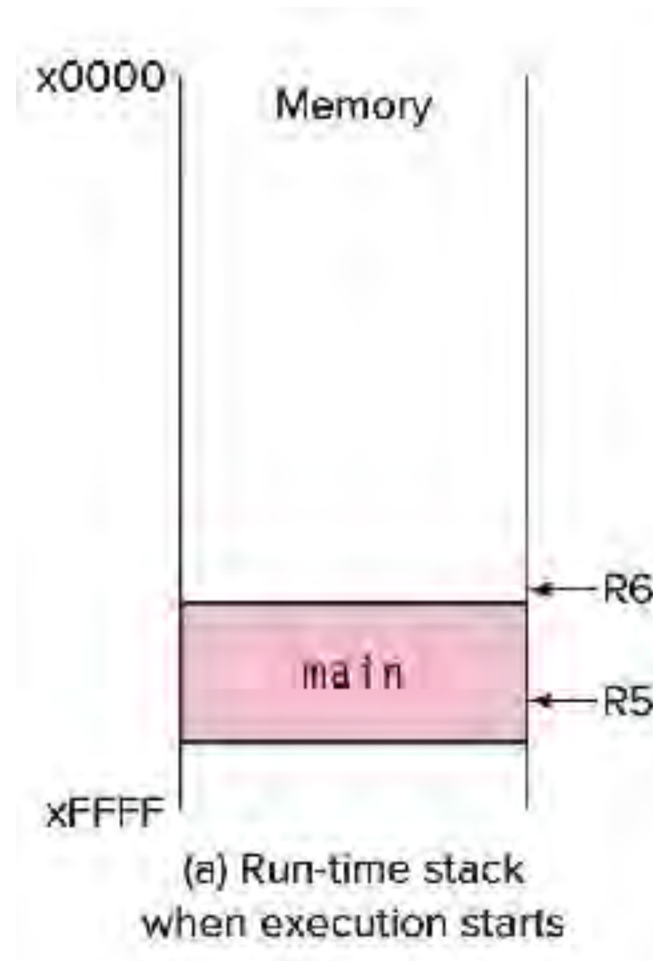
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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

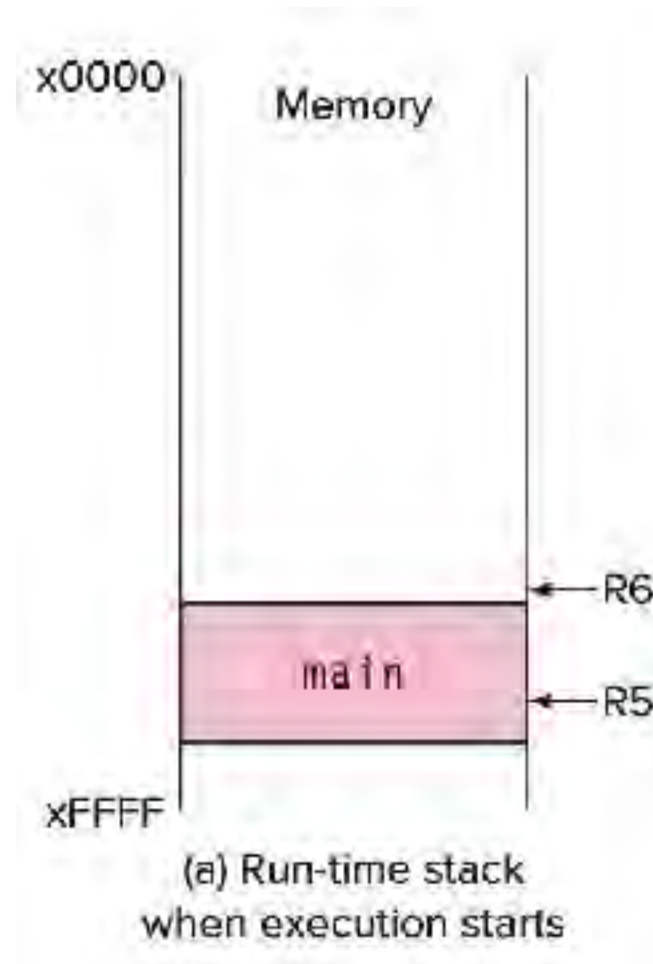
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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

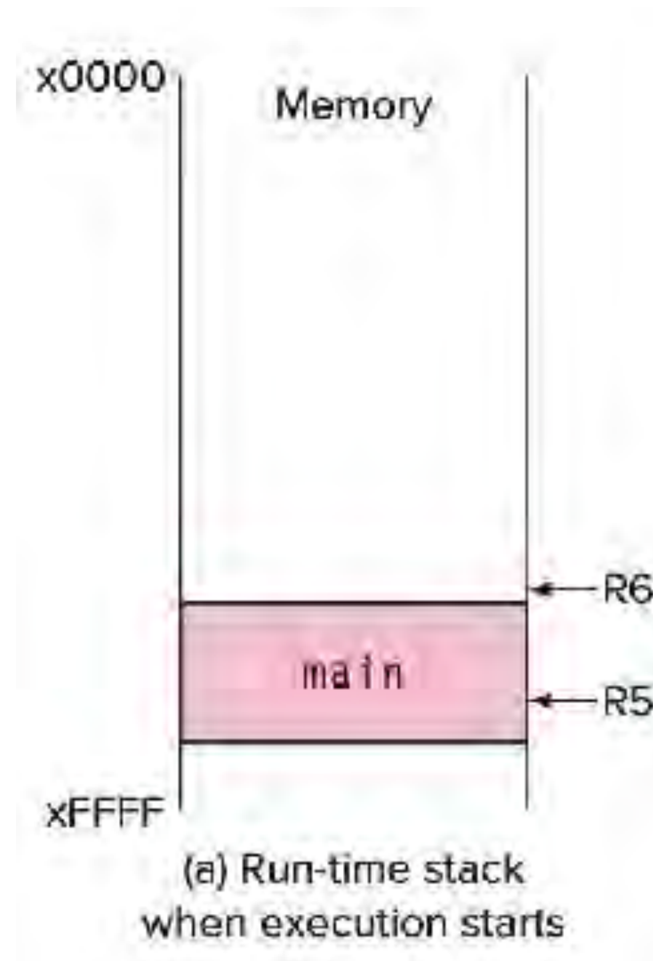
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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

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



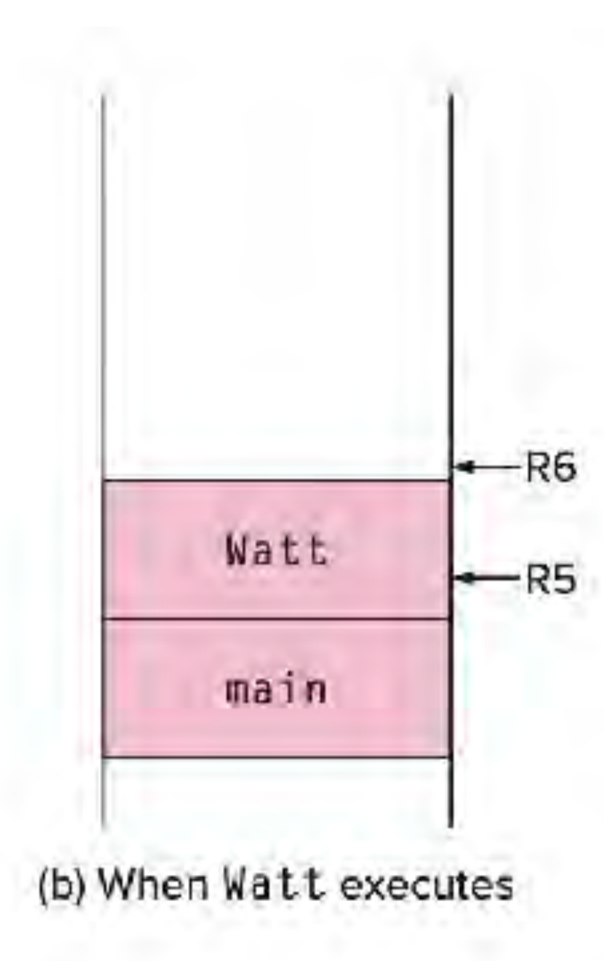
(a) Run-time stack when execution starts

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

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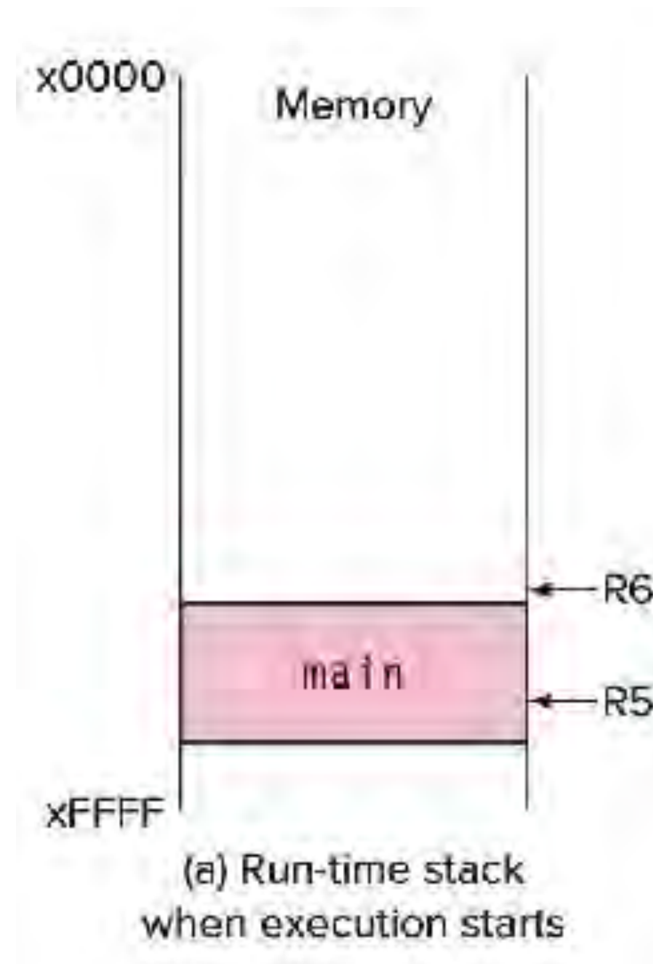
Run-time stack

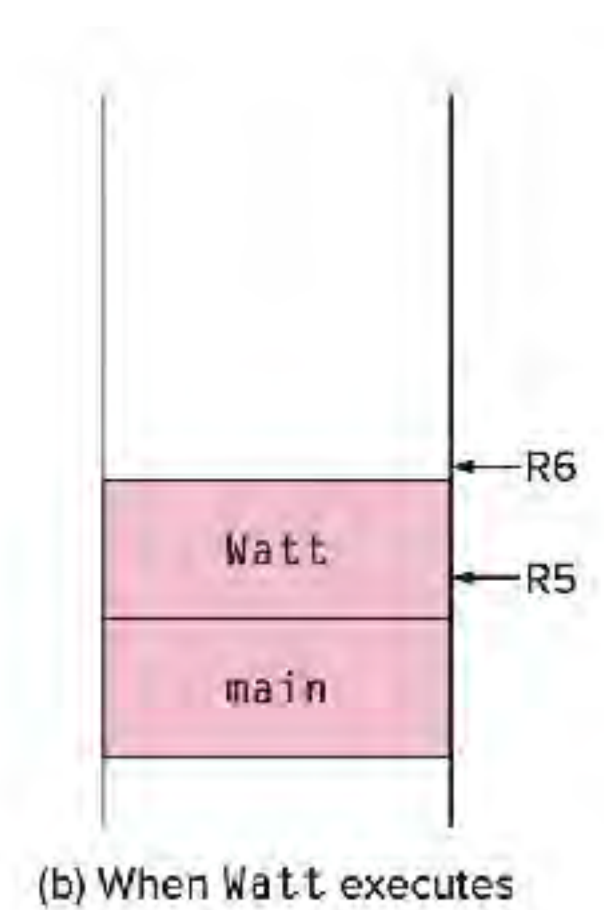
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

```
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

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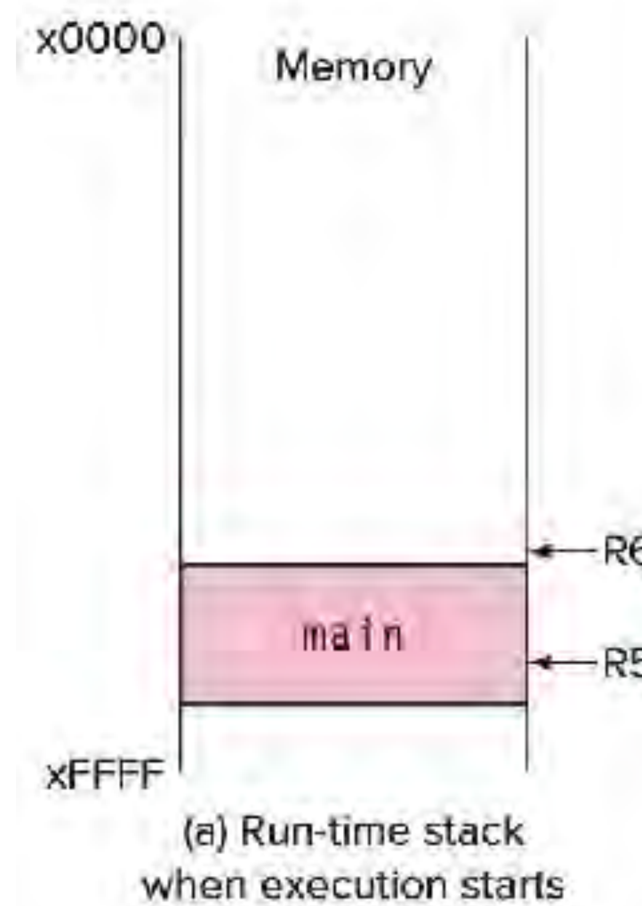
Run-time stack

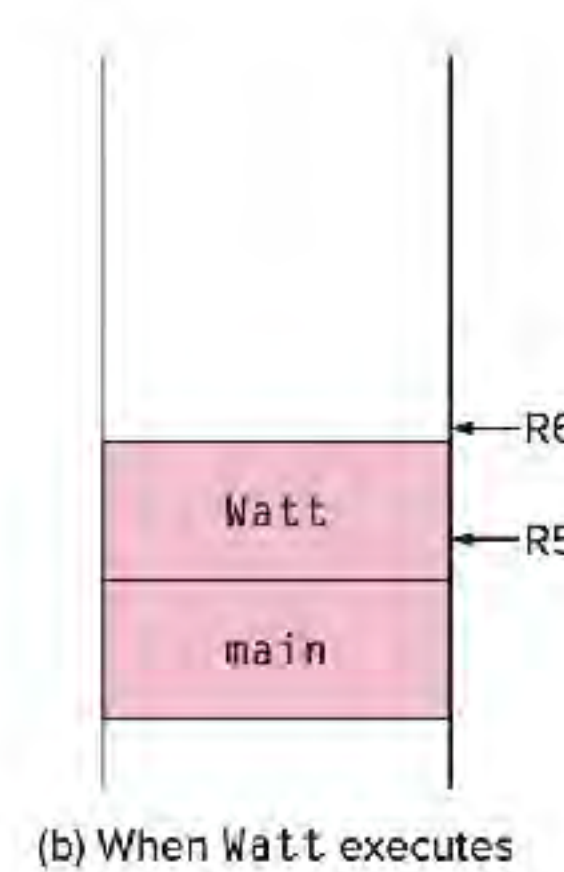
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

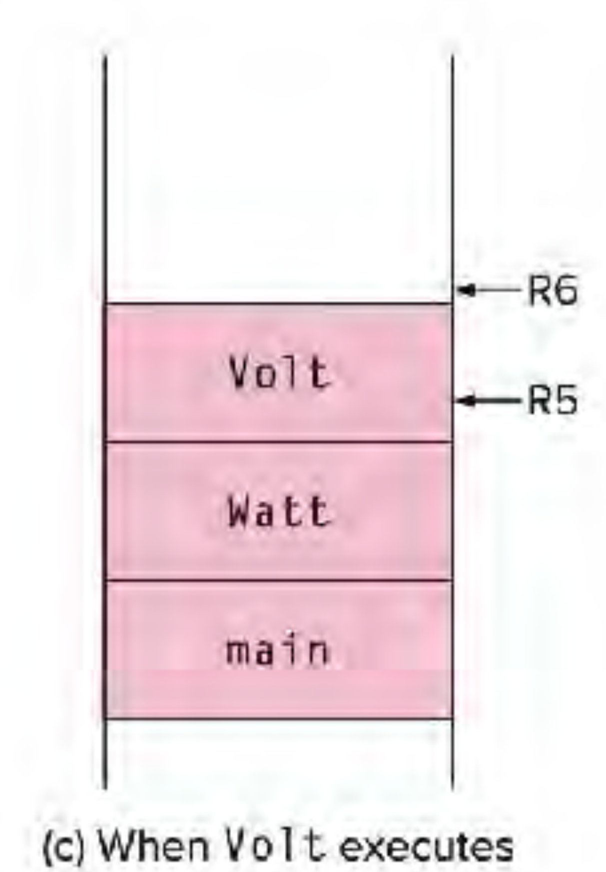
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



(a) Run-time stack when execution starts



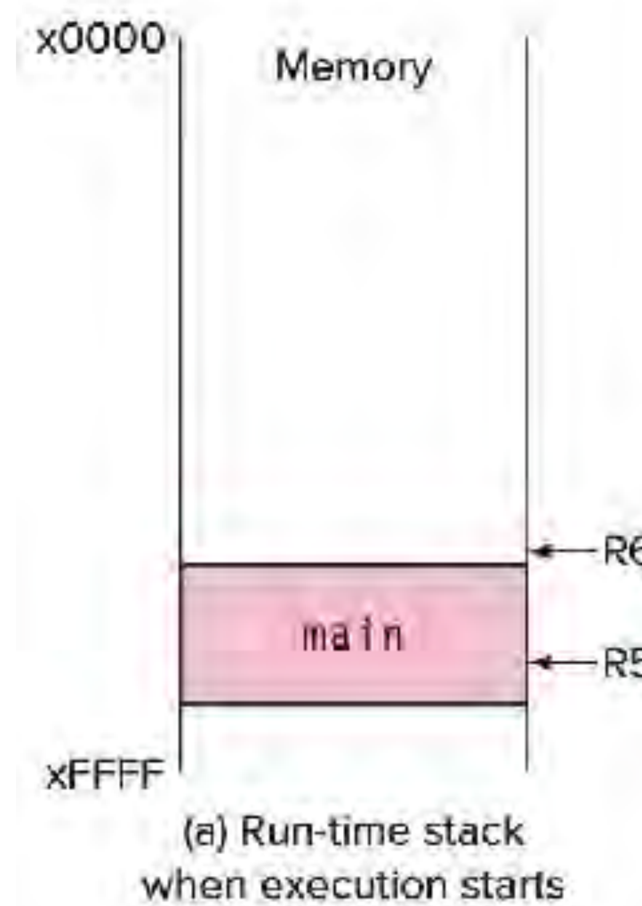
(b) When Watt executes



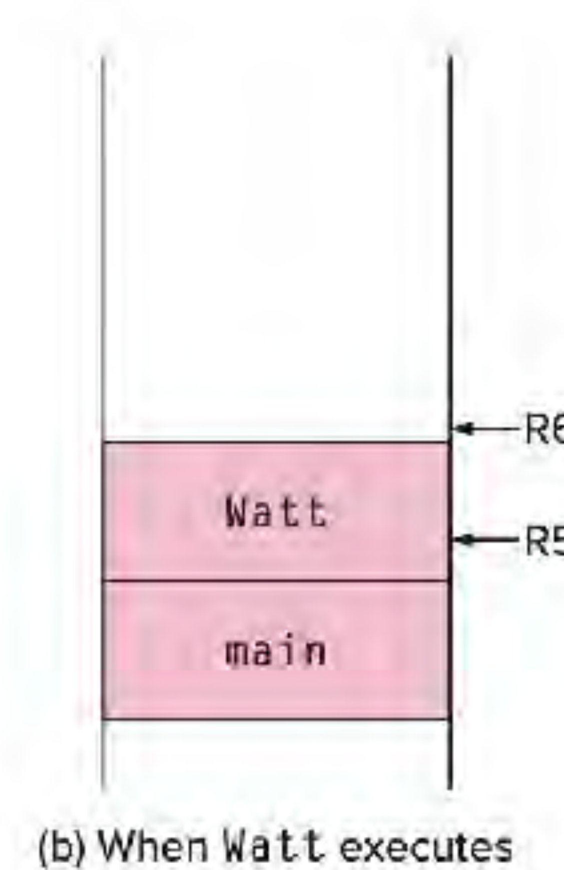
(c) When Volt executes

Run-time stack

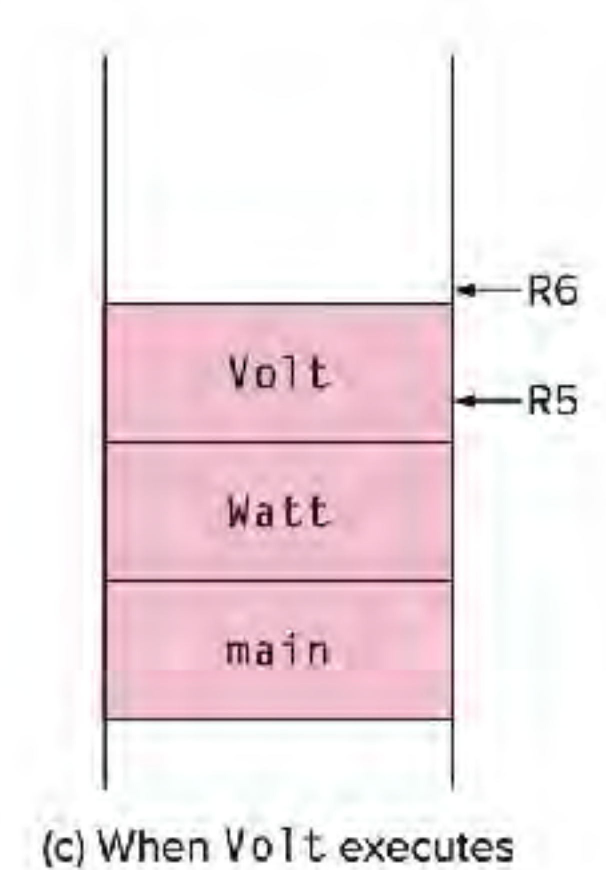
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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



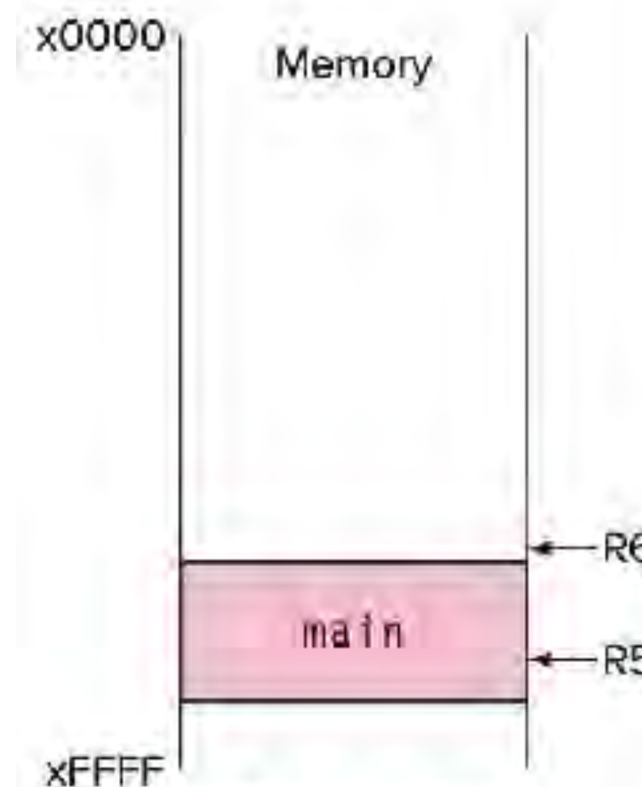
(b) When Watt executes



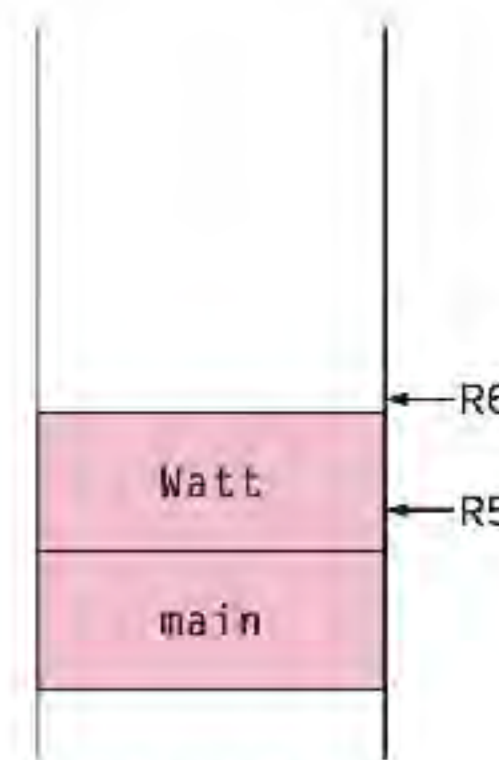
(c) When Volt executes

Run-time stack

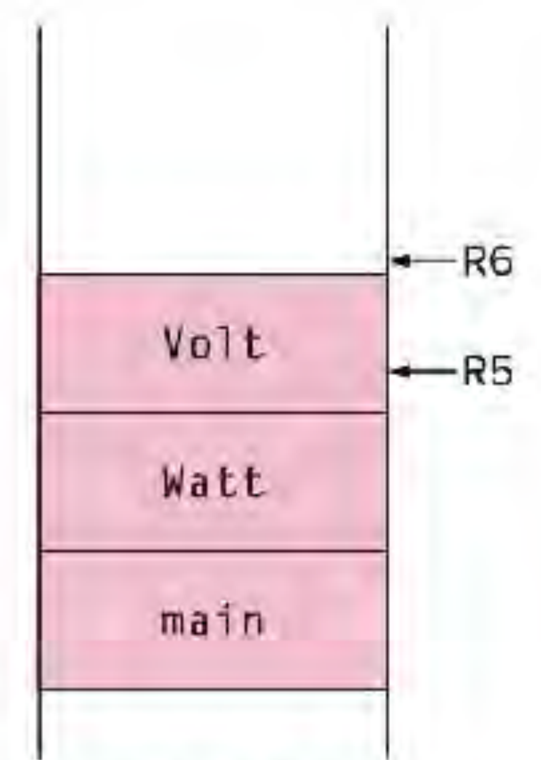
```
int main (void){
     int a;
     int b;
     …
     b = Watt(a);
     b = Volt(a, b);
}

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

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



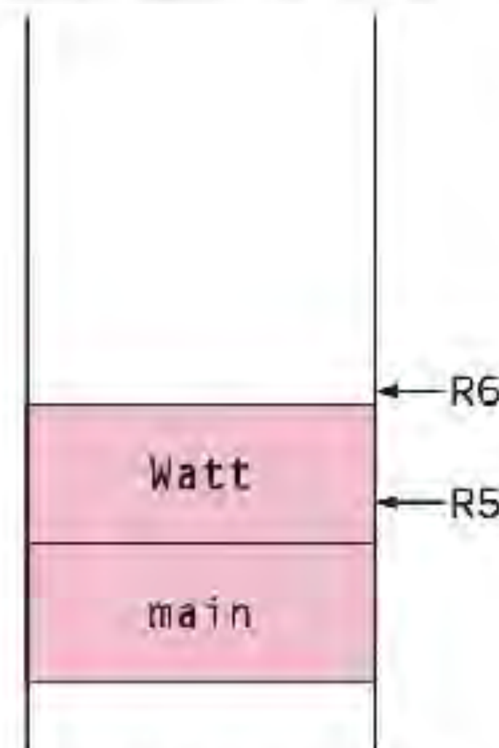
(a) Run-time stack when execution starts



(b) When Watt executes



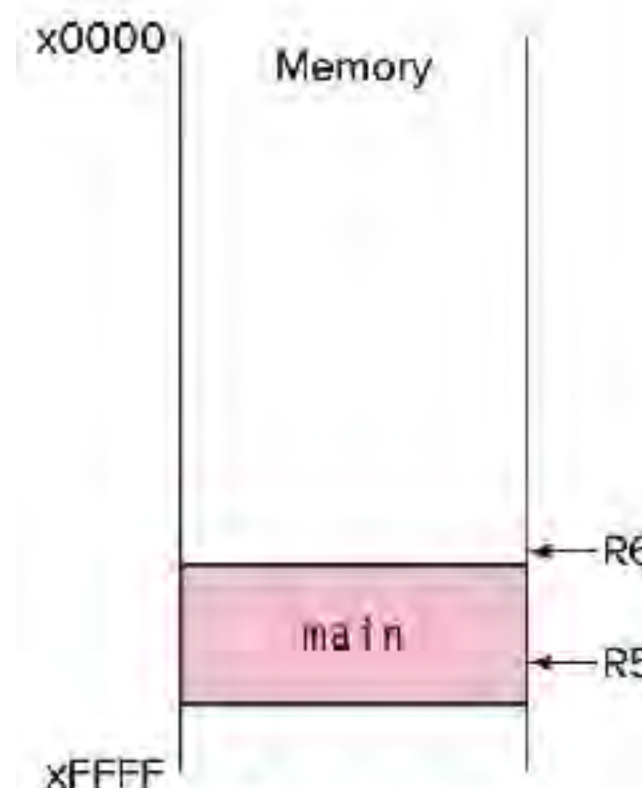
(c) When Volt executes



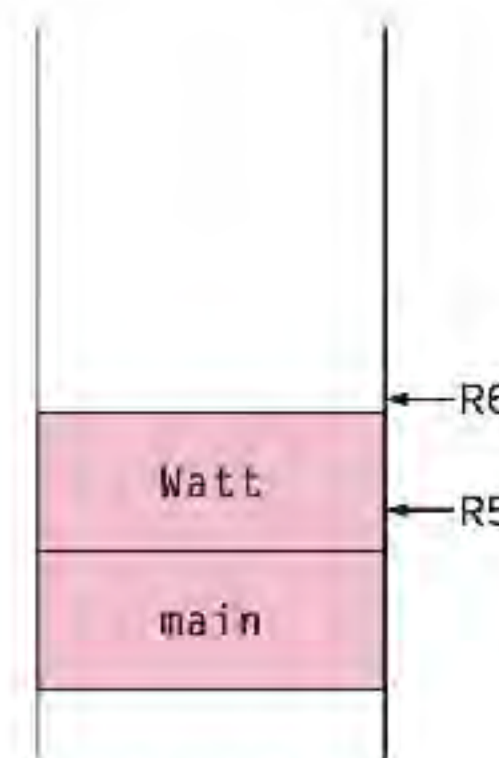
(d) After Volt completes

Run-time stack

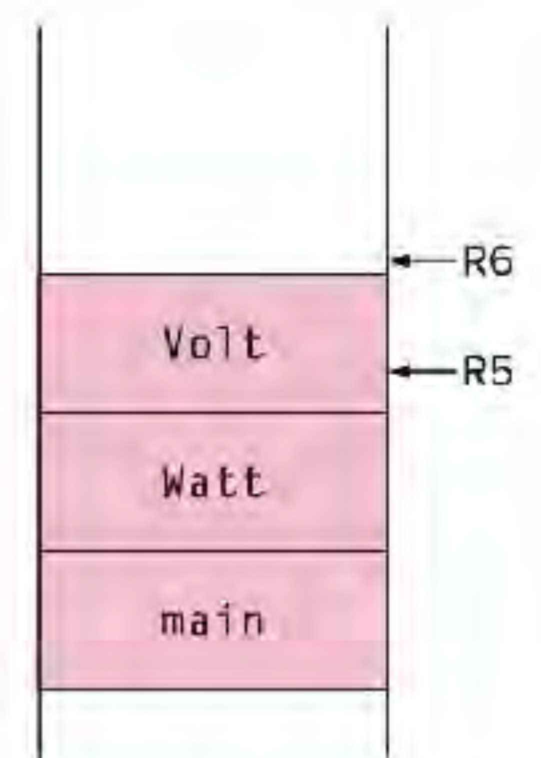
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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

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



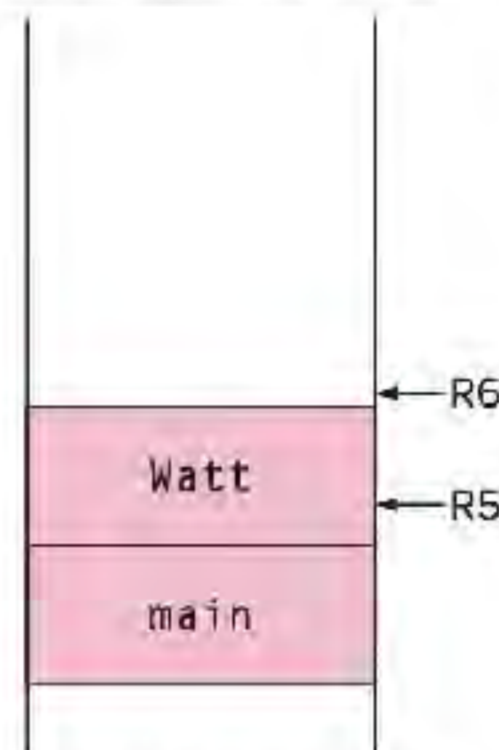
(a) Run-time stack when execution starts



(b) When Watt executes



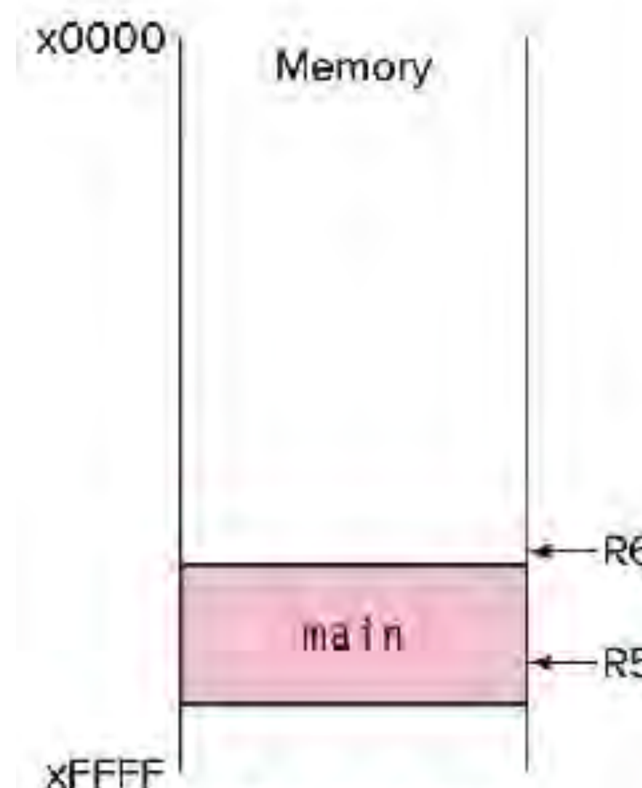
(c) When Volt executes



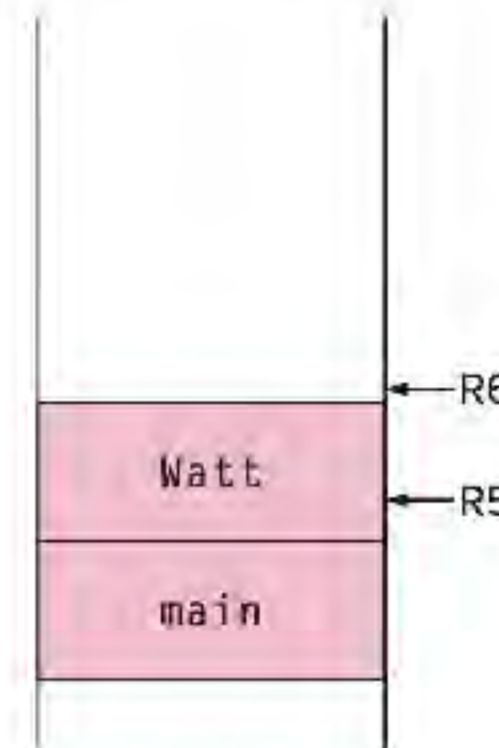
(d) After Volt completes

Run-time stack

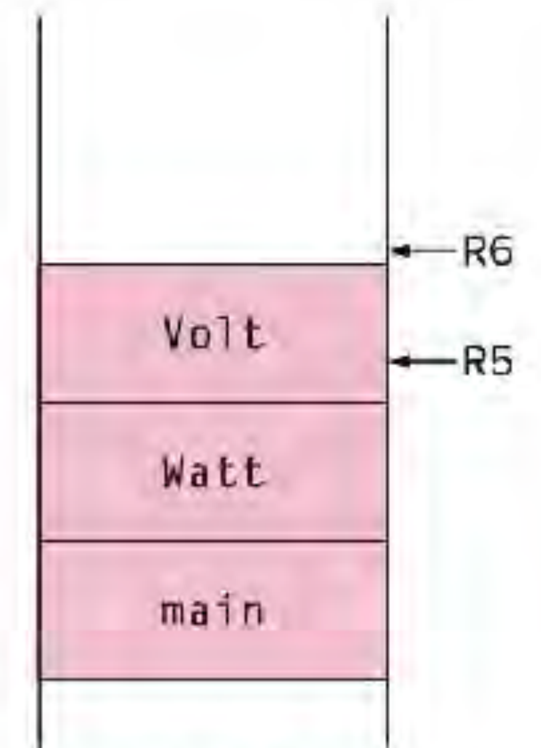
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}

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

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



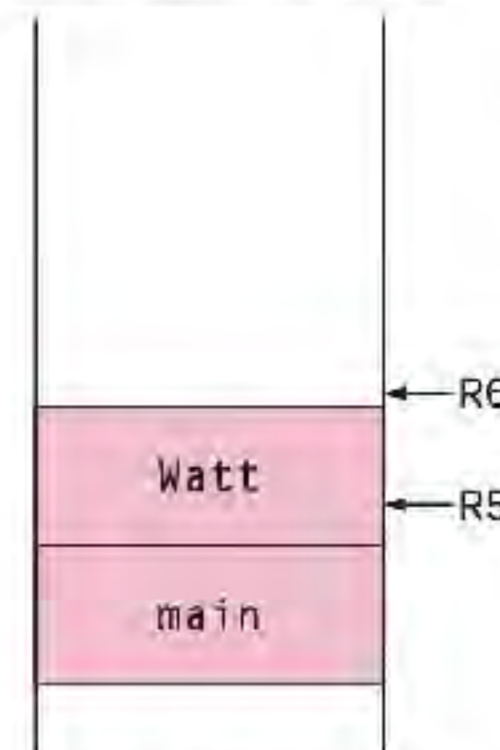
(a) Run-time stack when execution starts



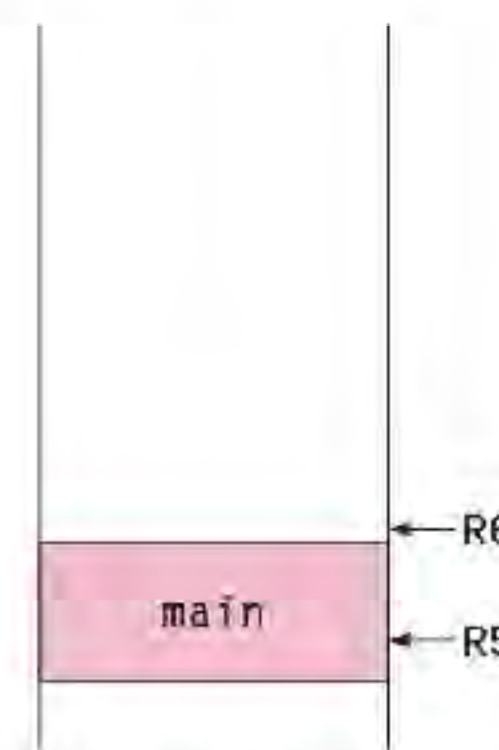
(b) When Watt executes



(c) When Volt executes



(d) After Volt completes



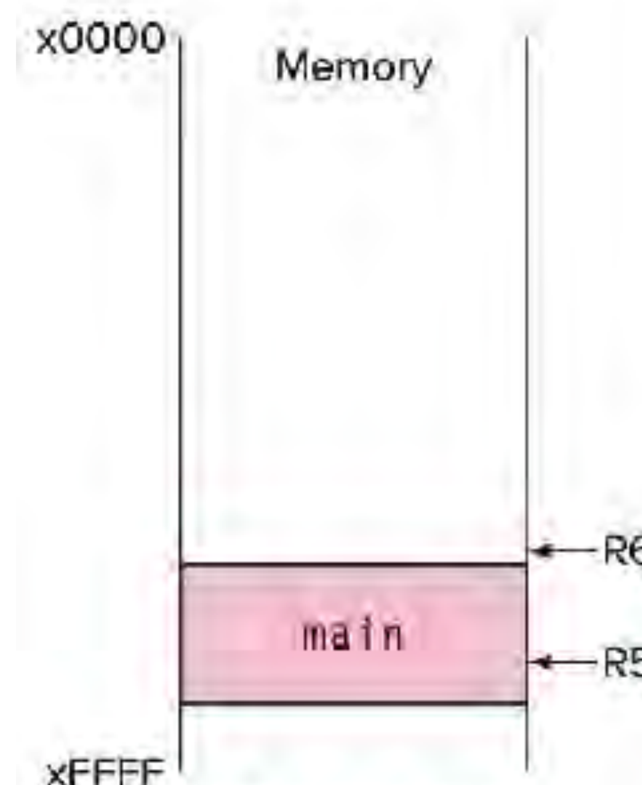
(e) After Watt completes

Run-time stack

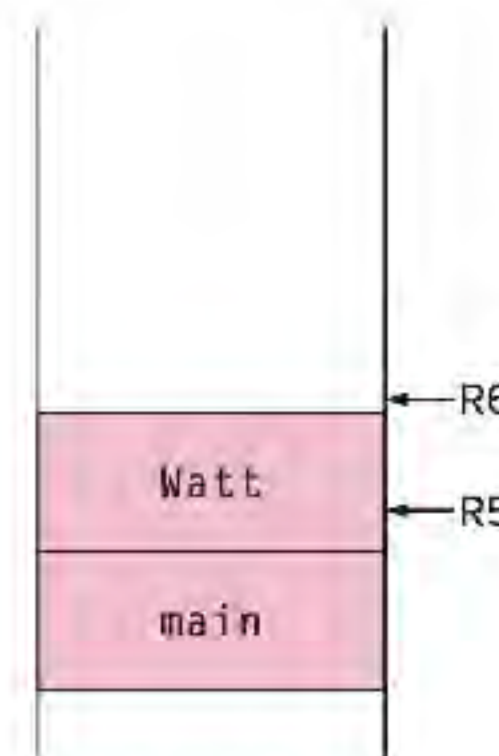
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

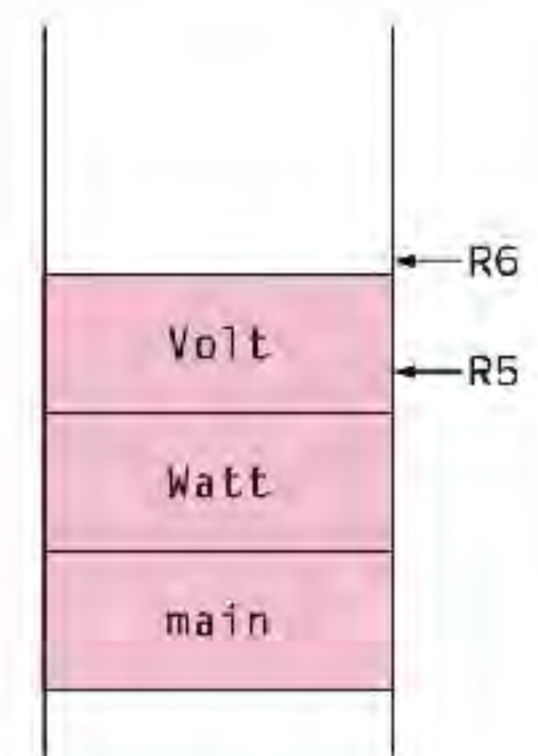
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



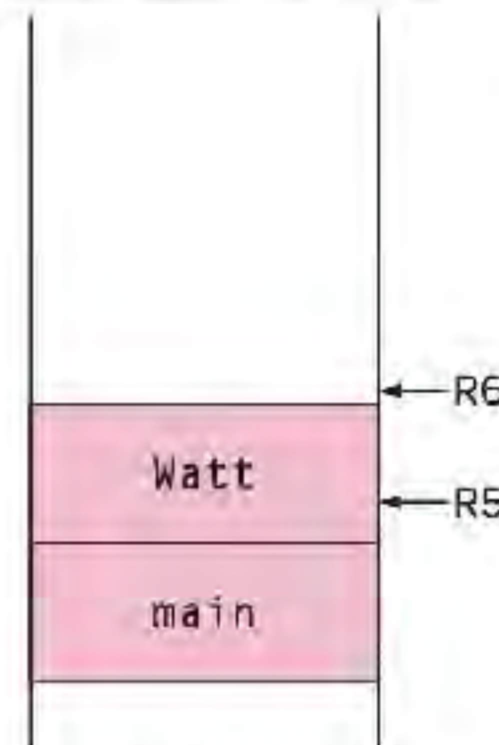
(a) Run-time stack when execution starts



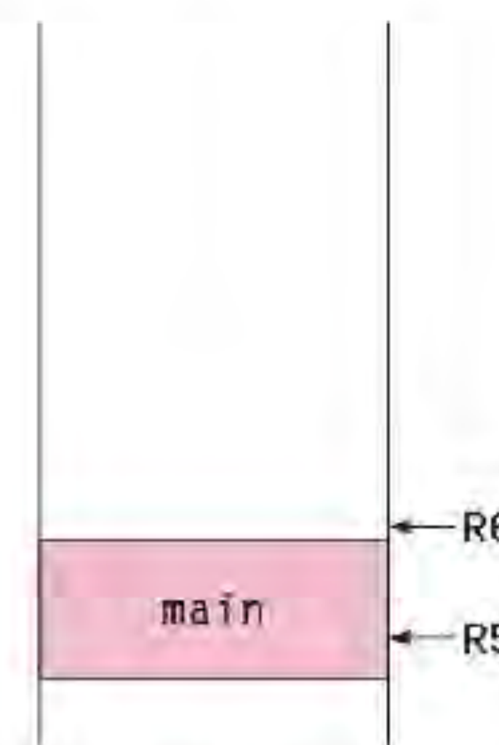
(b) When Watt executes



(c) When Volt executes



(d) After Volt completes



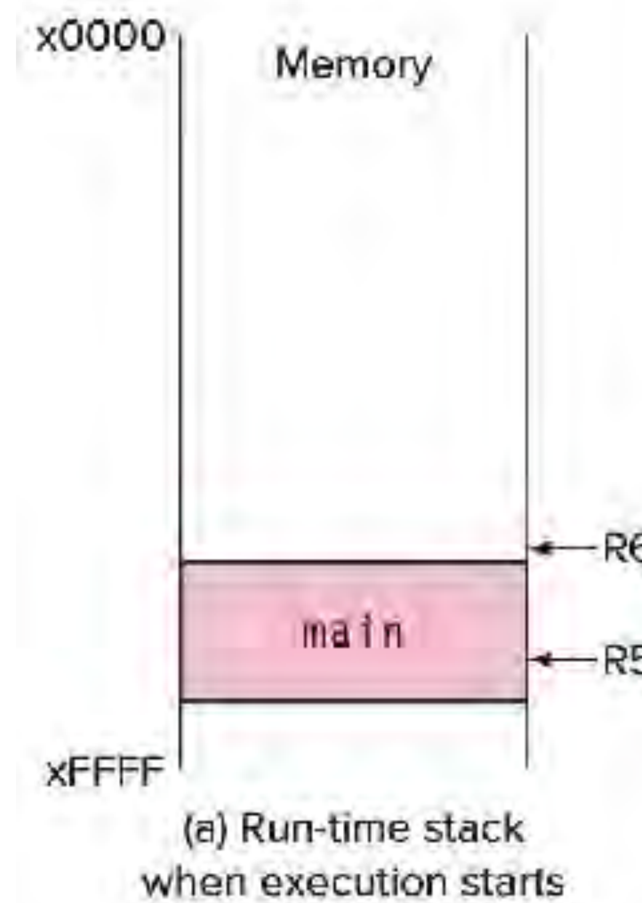
(e) After Watt completes

Run-time stack

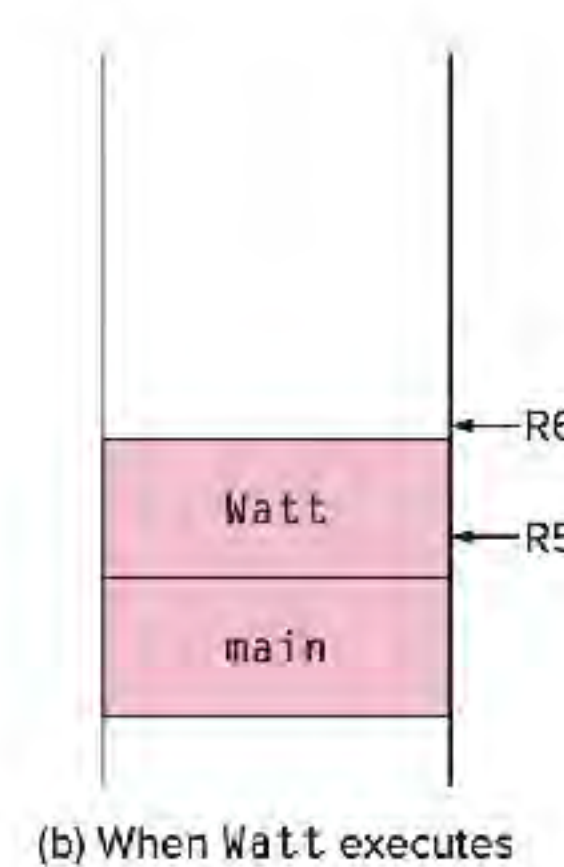
```
int main (void){
      int a;
      int b;
      …
      b = Watt(a);
      b = Volt(a, b);
}
```

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

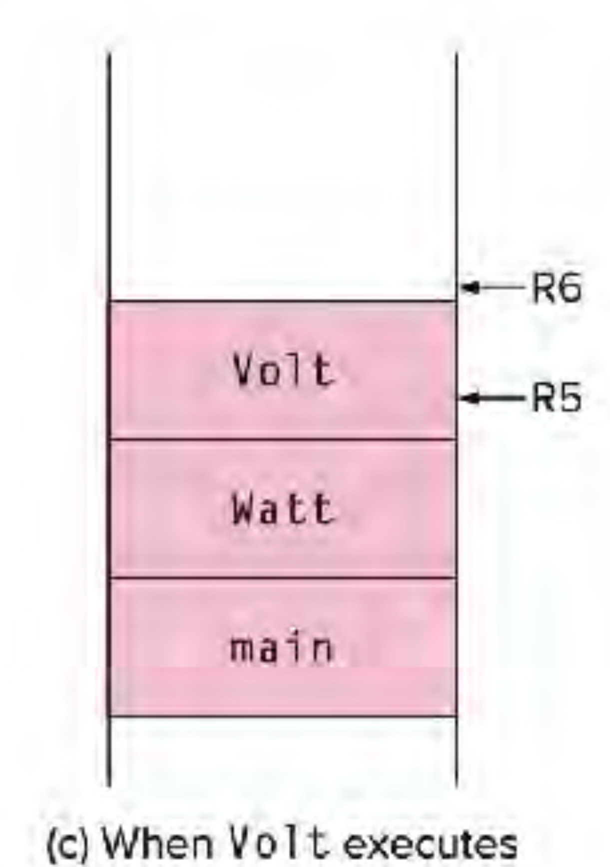
```
int Watt(int a) {
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



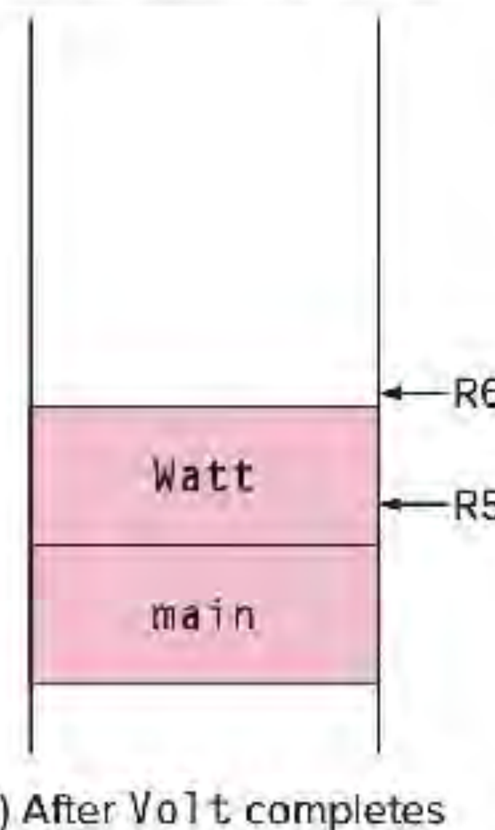
(a) Run-time stack when execution starts



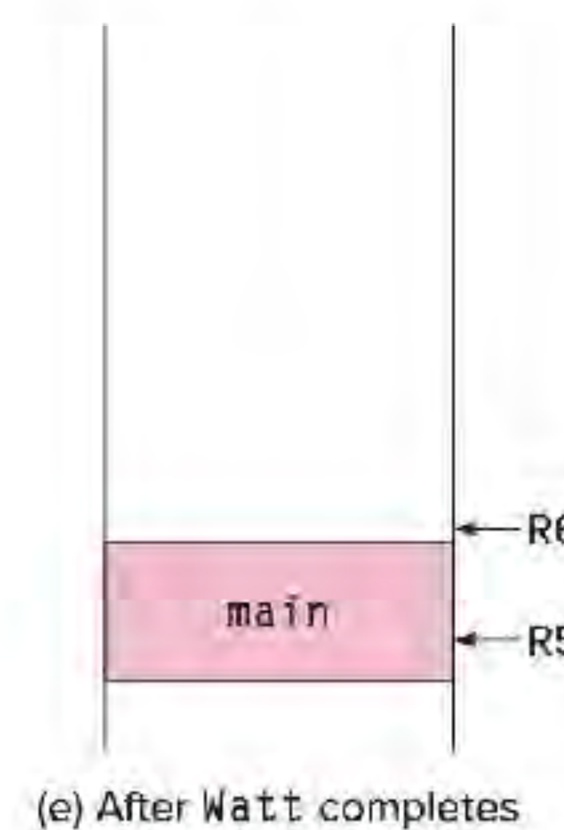
(b) When Watt executes



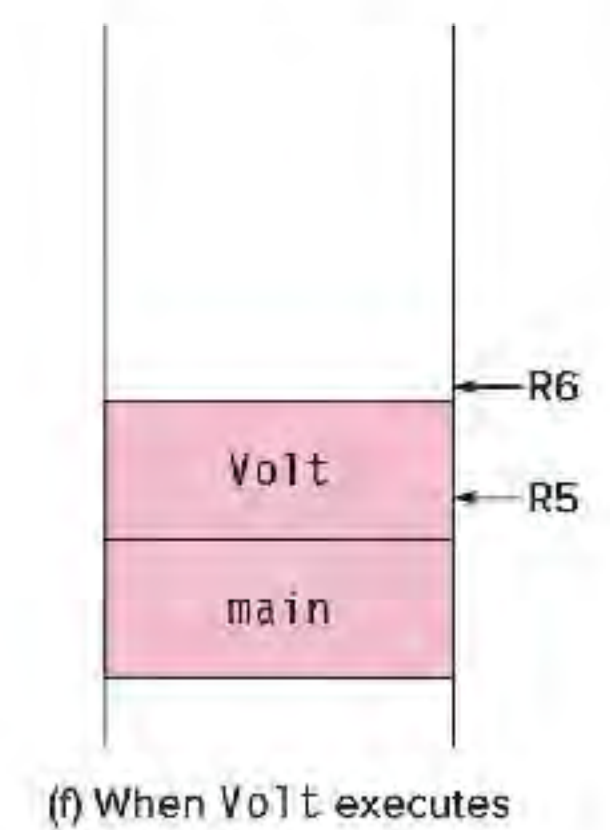
(c) When Volt executes



(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;
}
```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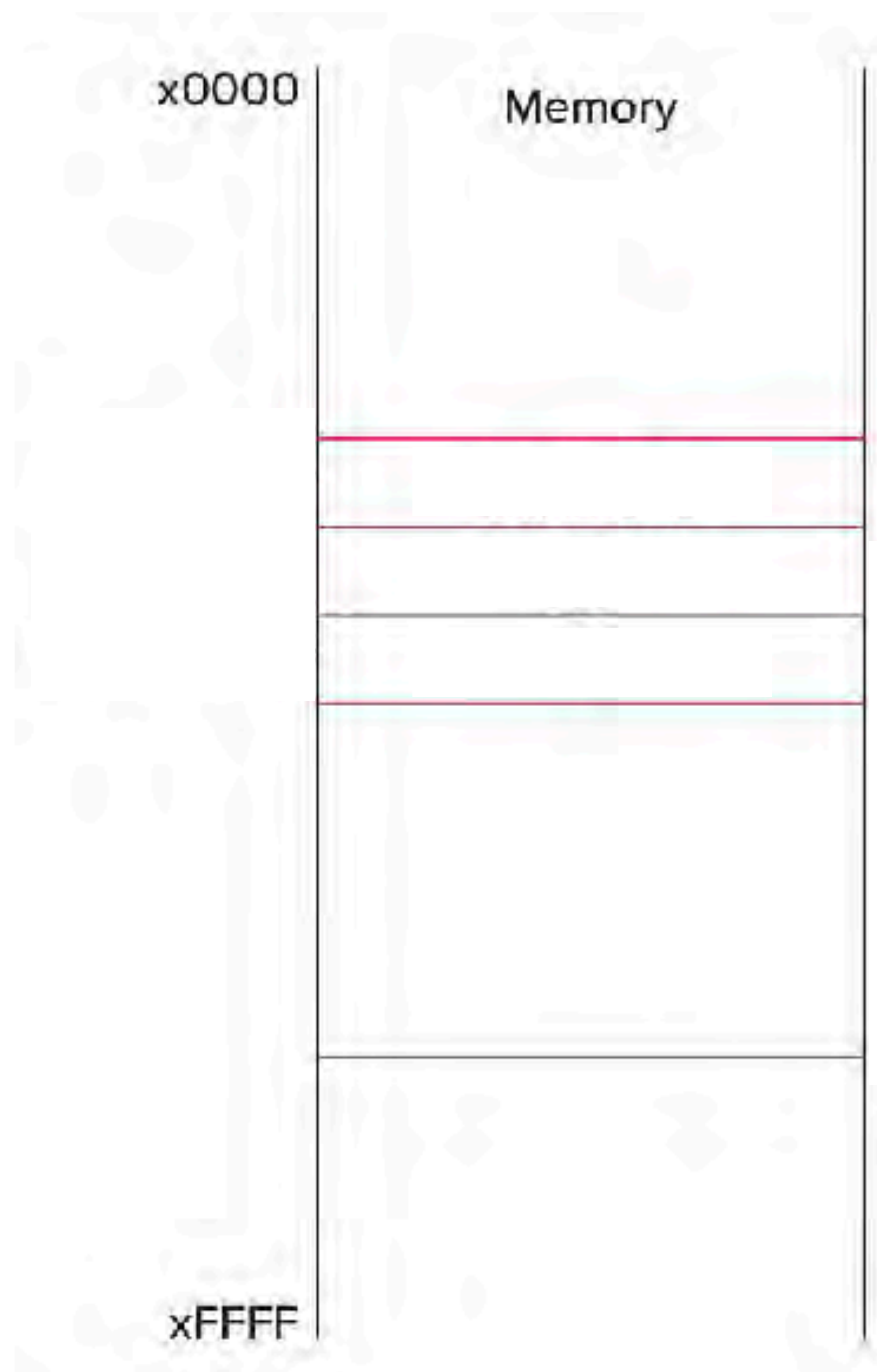
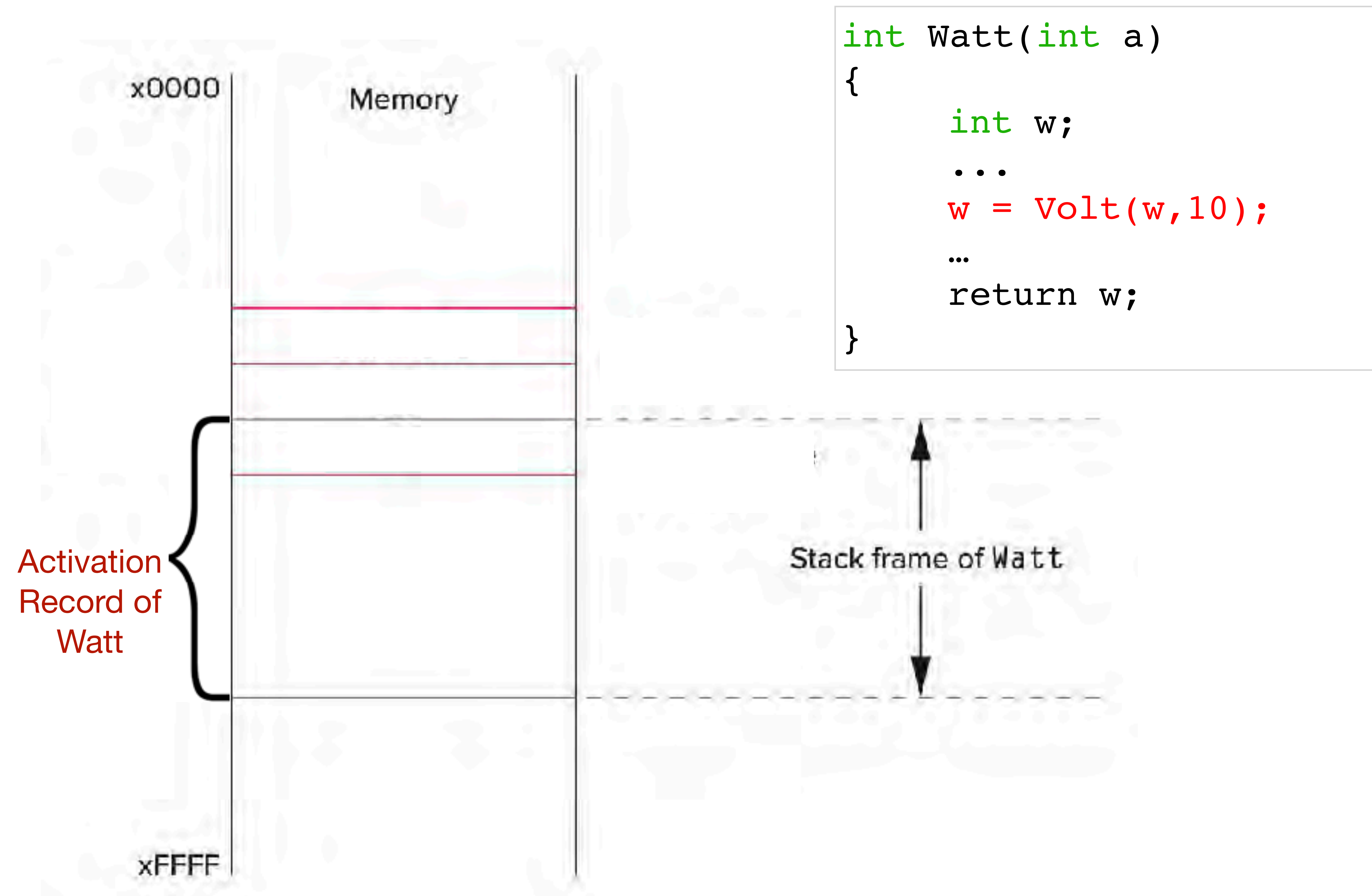
LC-3 Implementation




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

LC-3 Implementation



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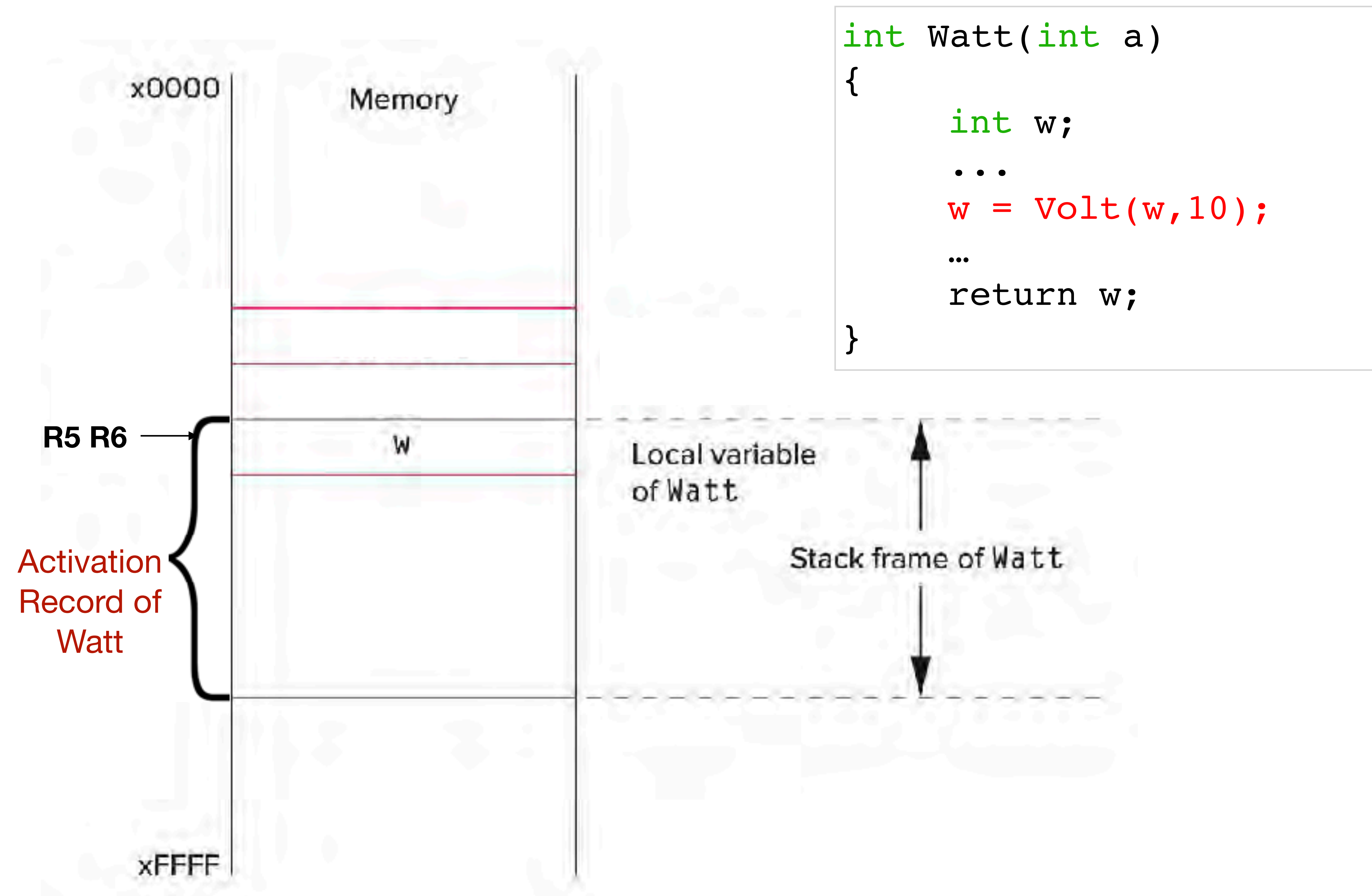
LC-3 Implementation

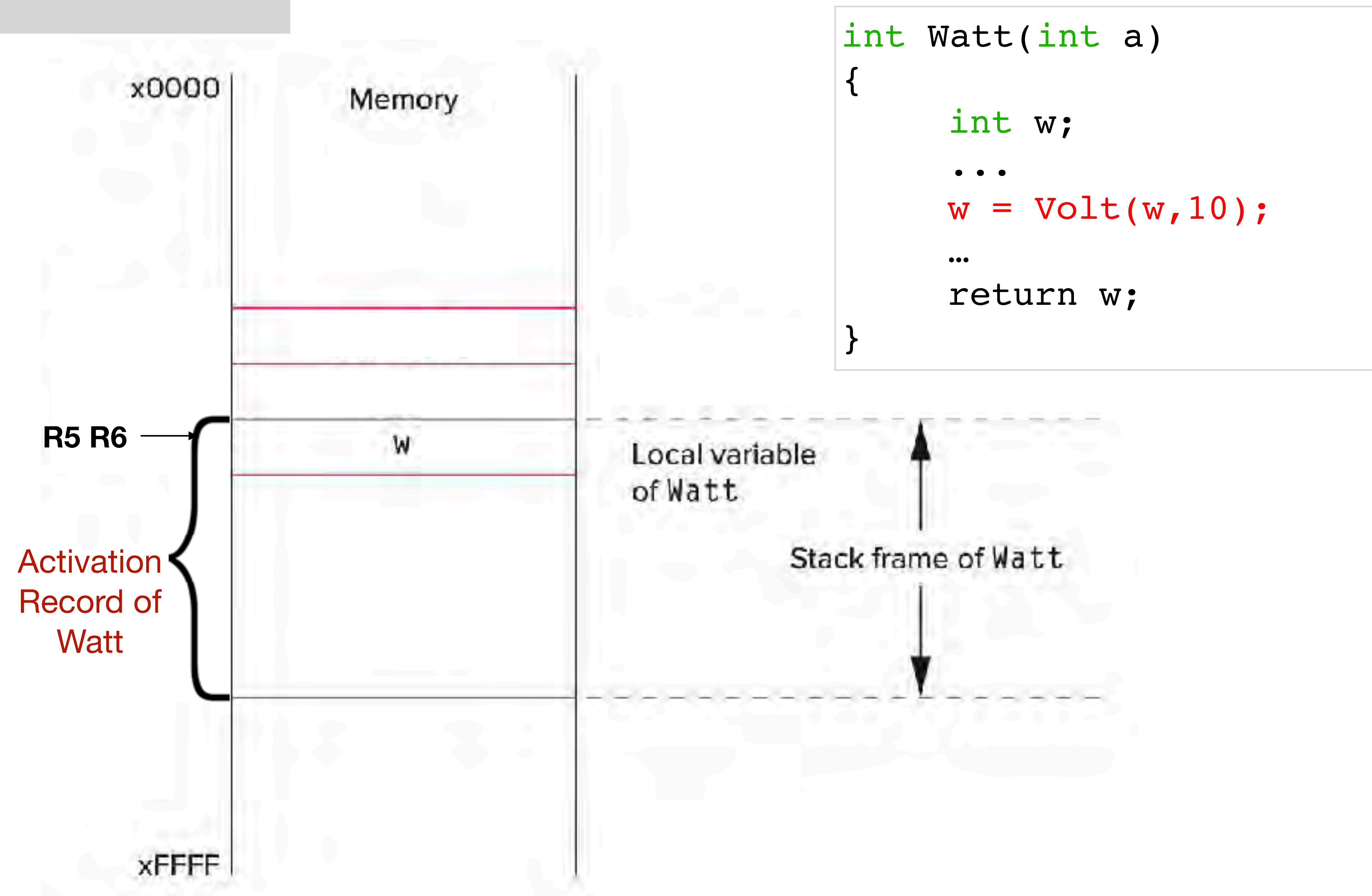



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

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

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



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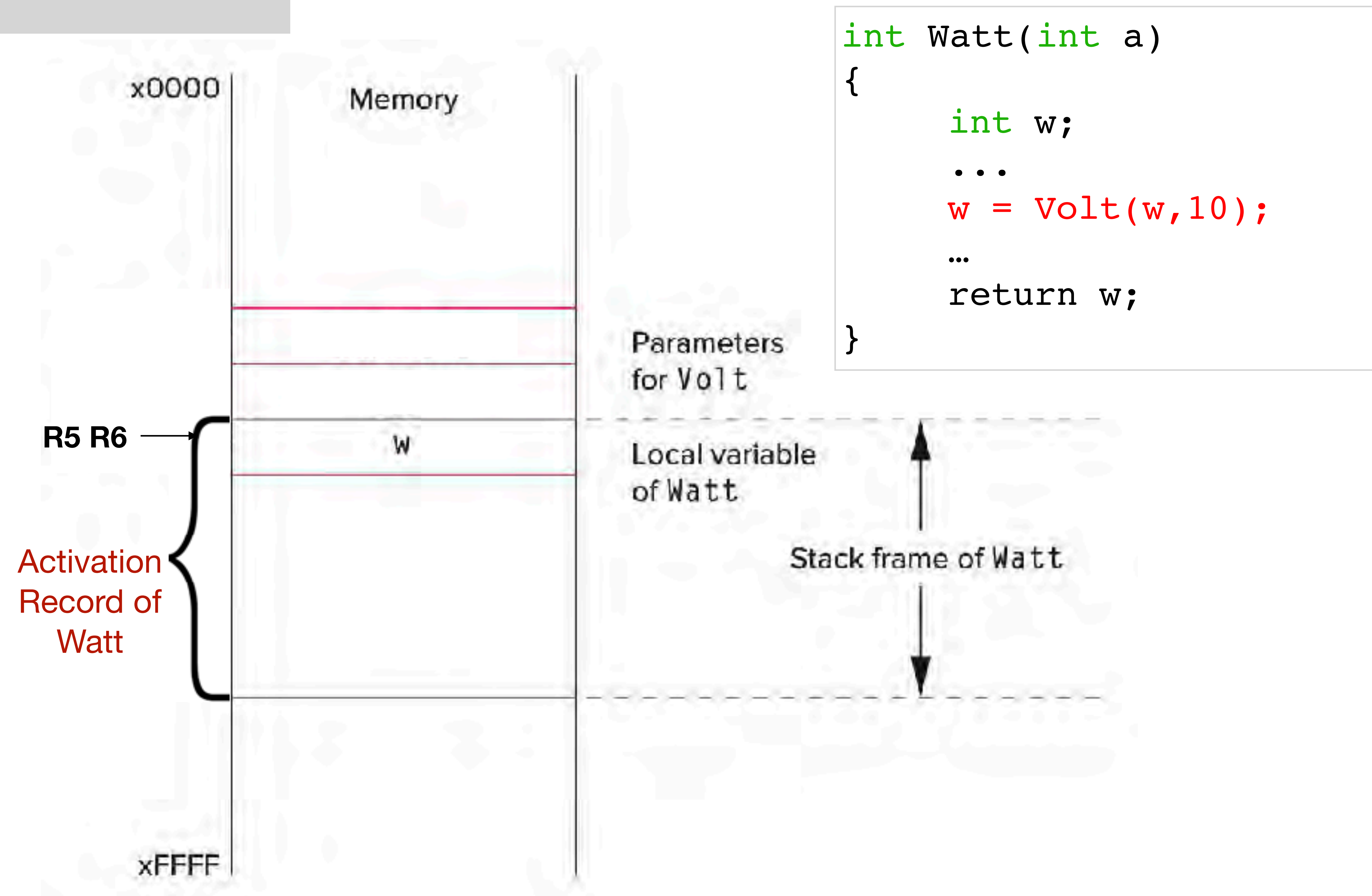
LC-3 Implementation

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

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



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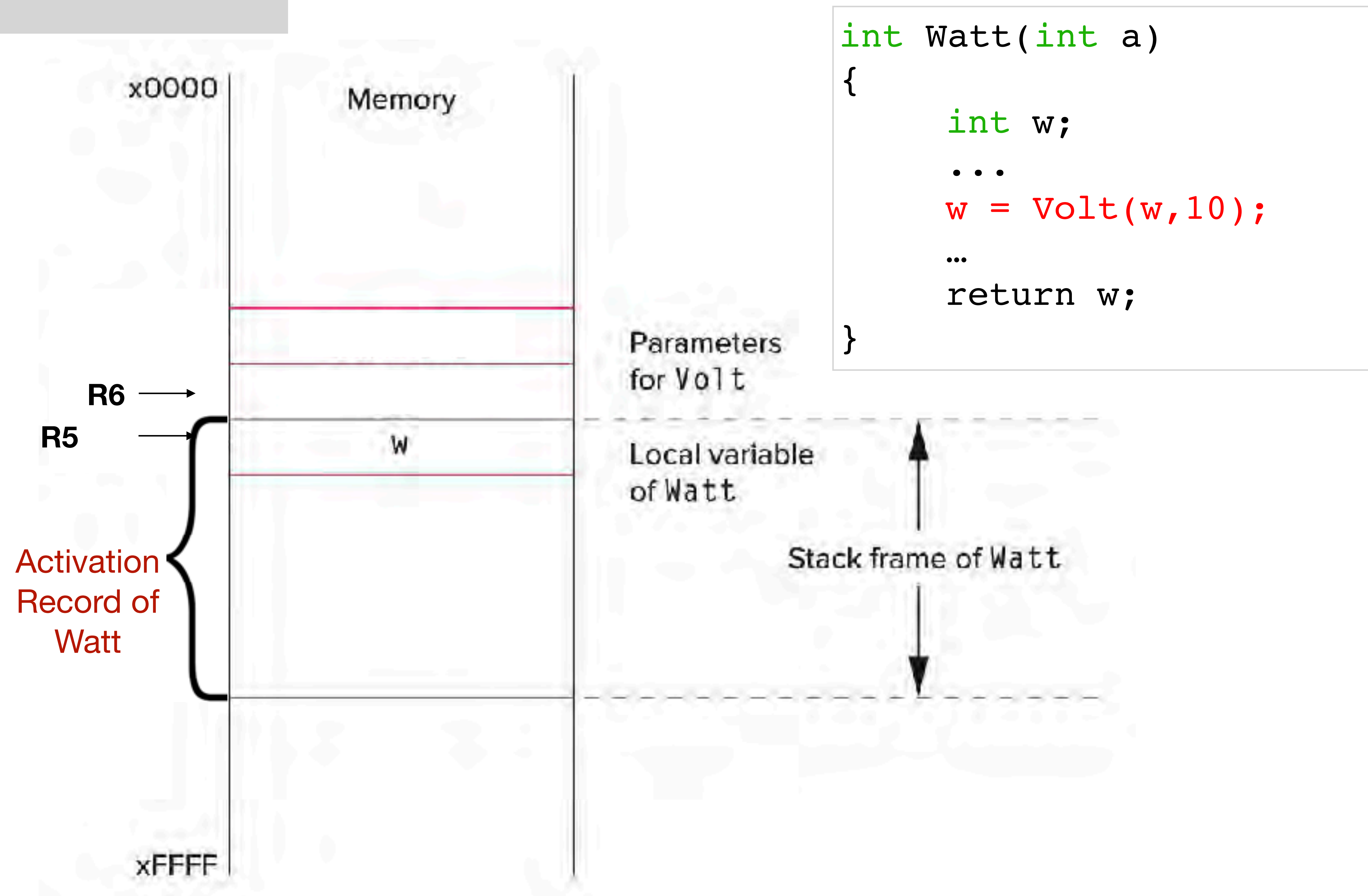
LC-3 Implementation

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;
}
```



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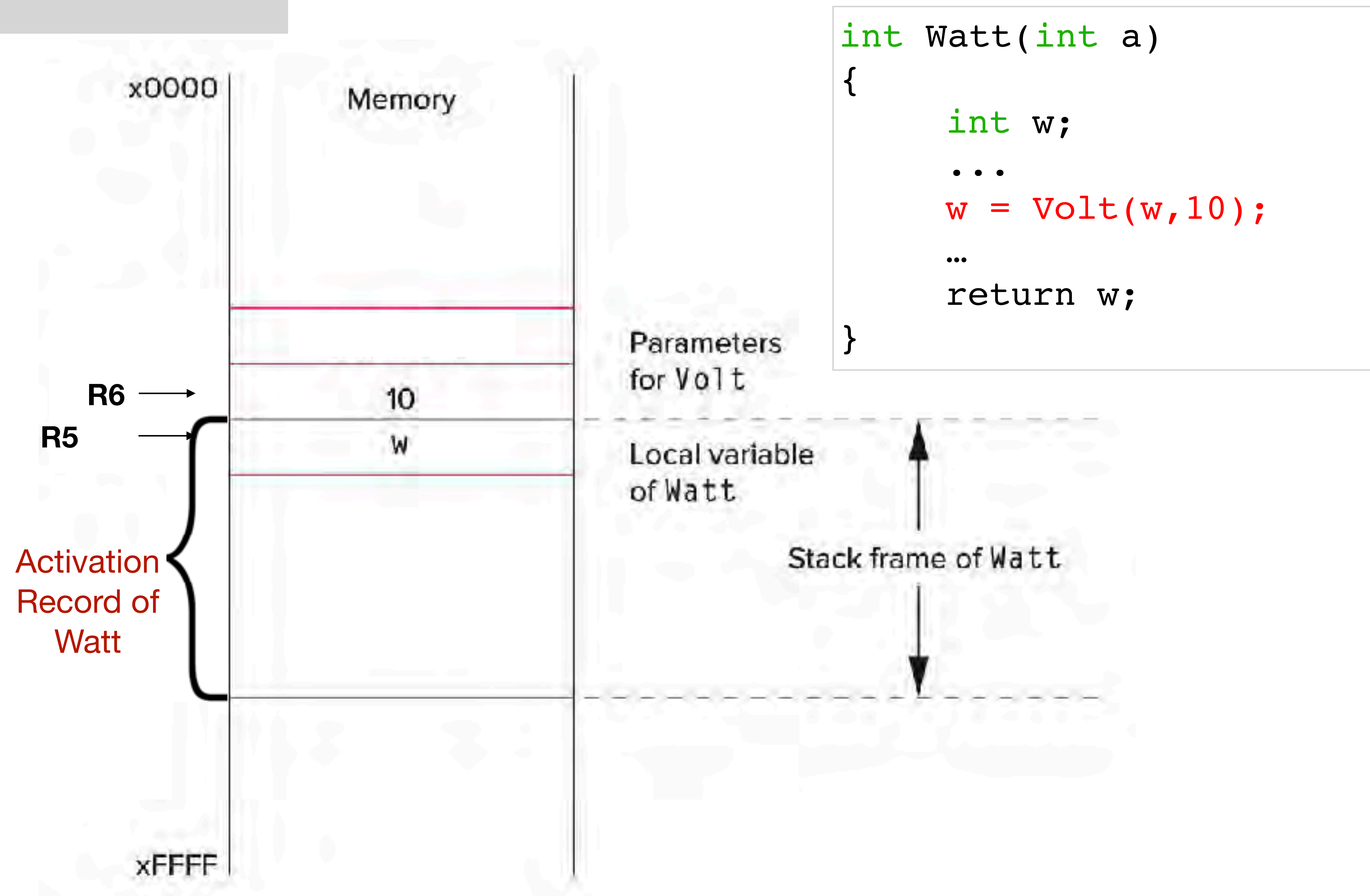
LC-3 Implementation

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
```



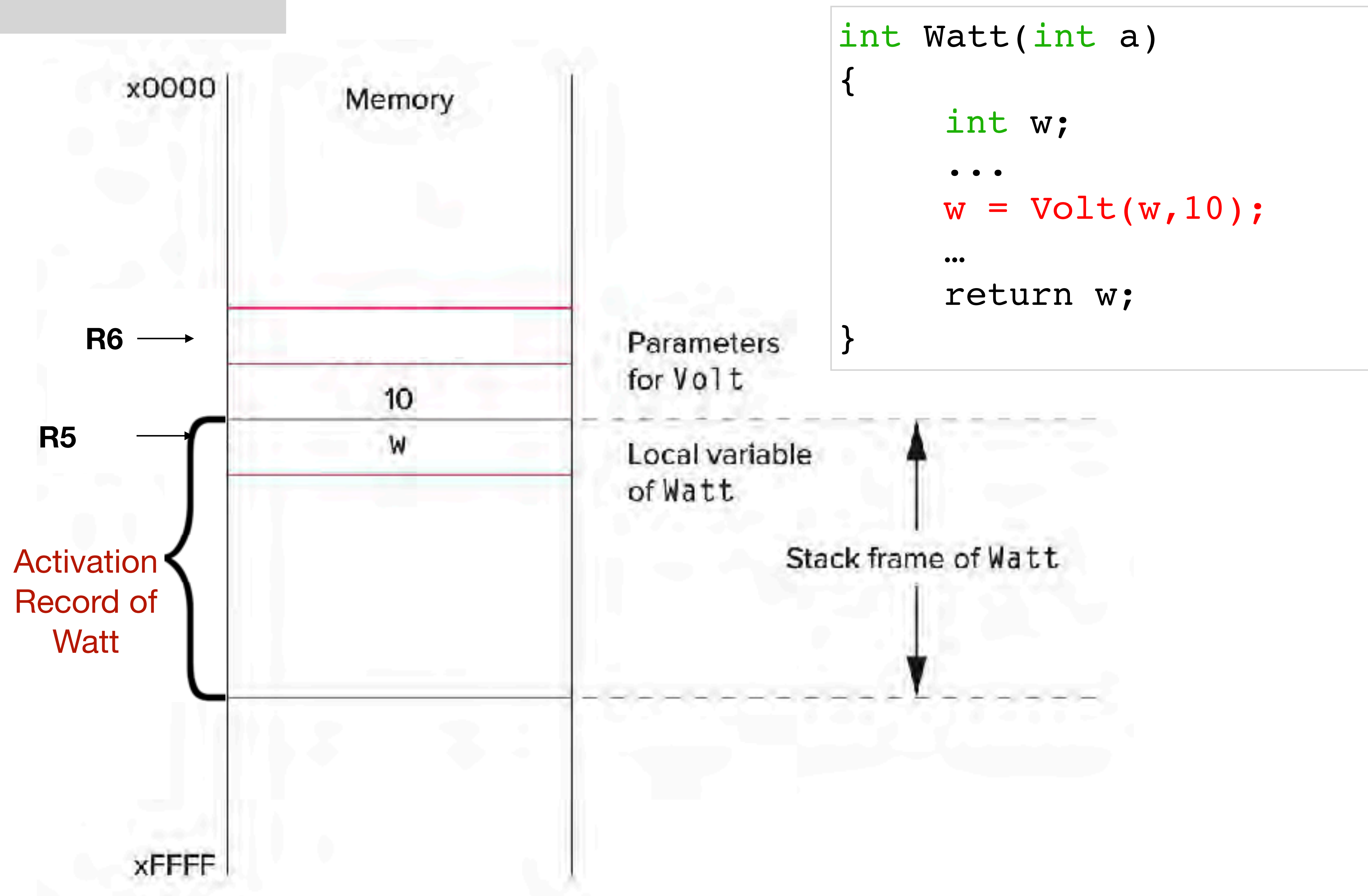

```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

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
```

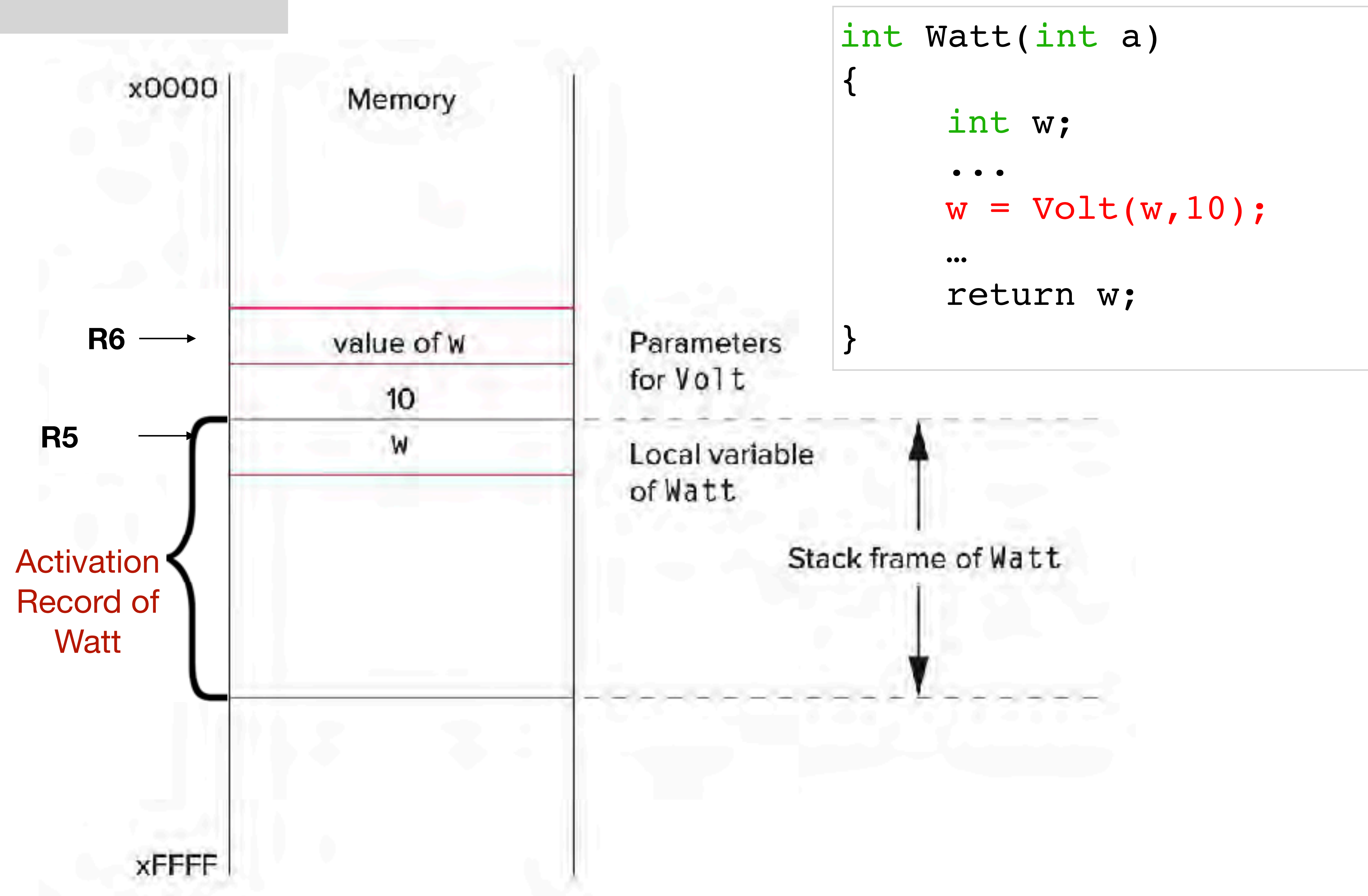
```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



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
```

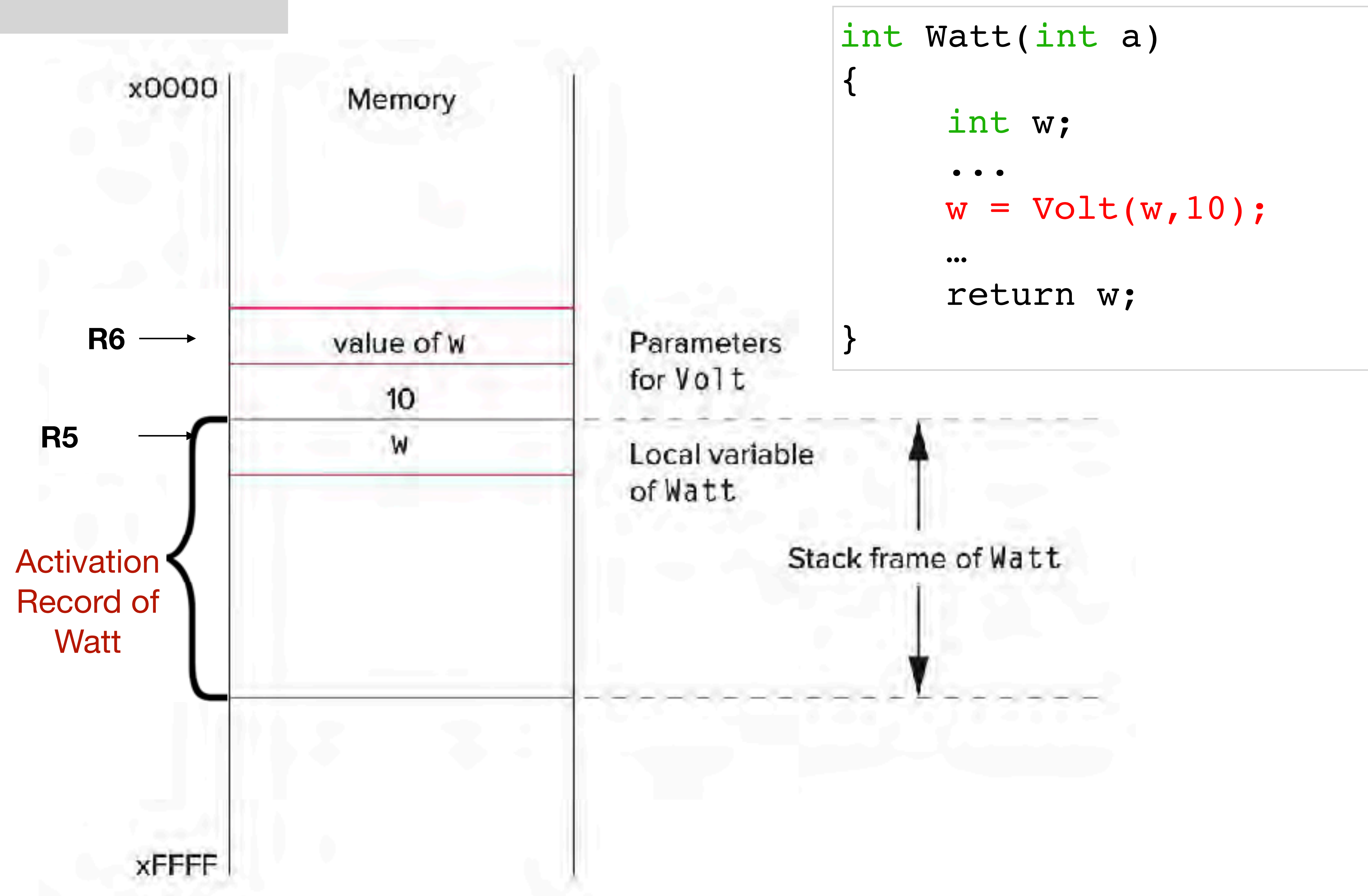



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

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
```

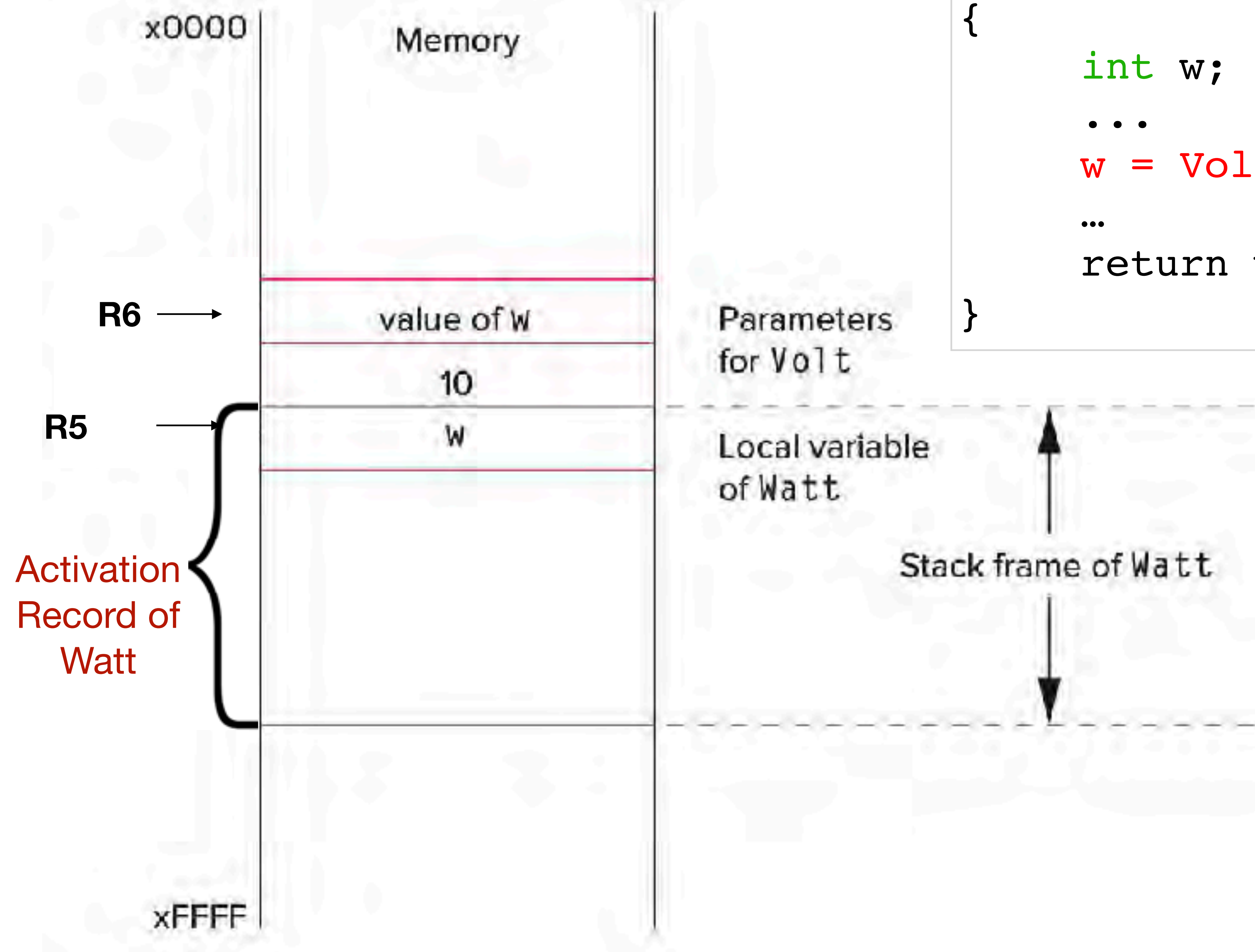



```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

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

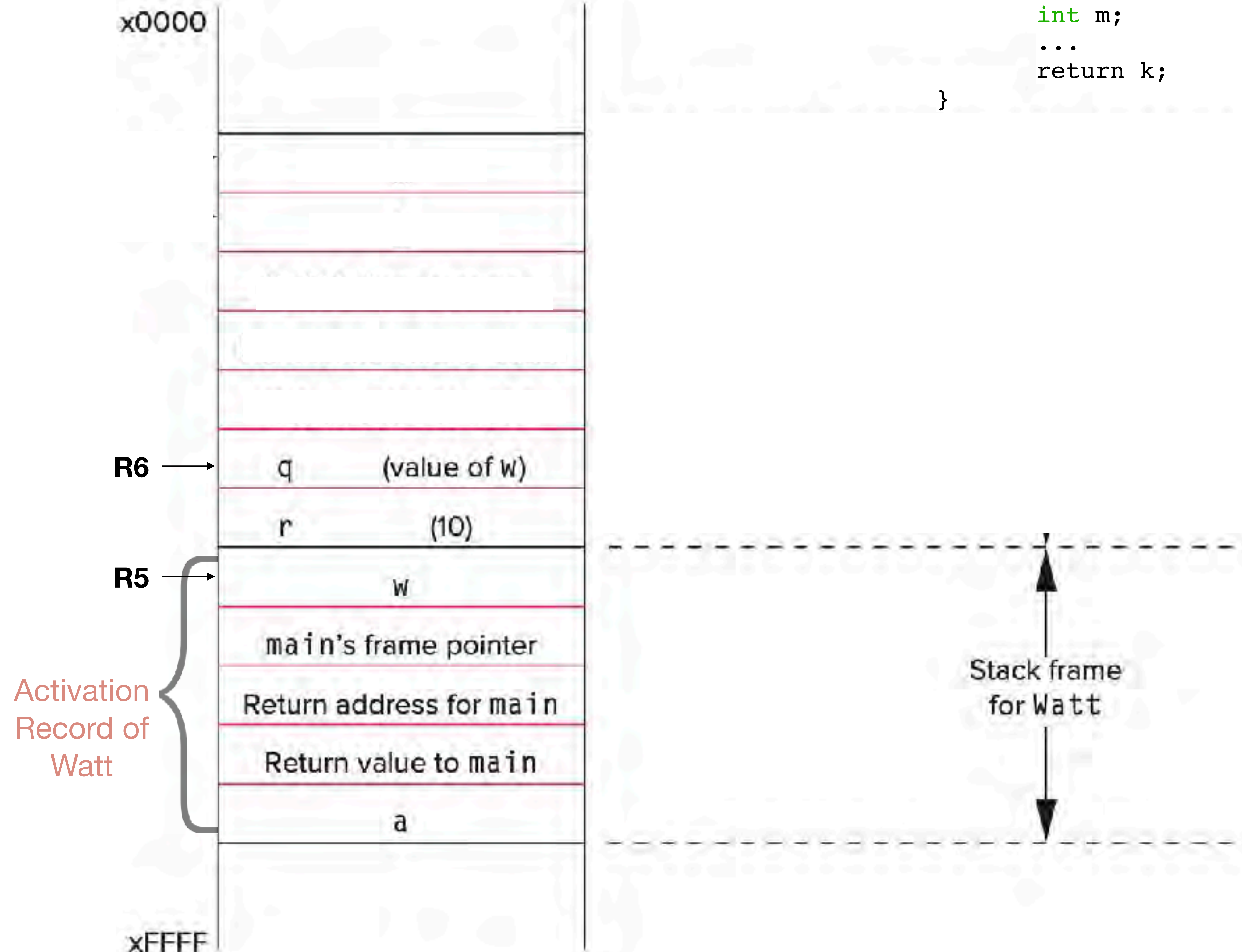
```
; push second arg
AND R0, R0, #0
ADD R0, R0, #10
ADD R6, R6, #-1
STR R0, R6, #0

; 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;
}
```



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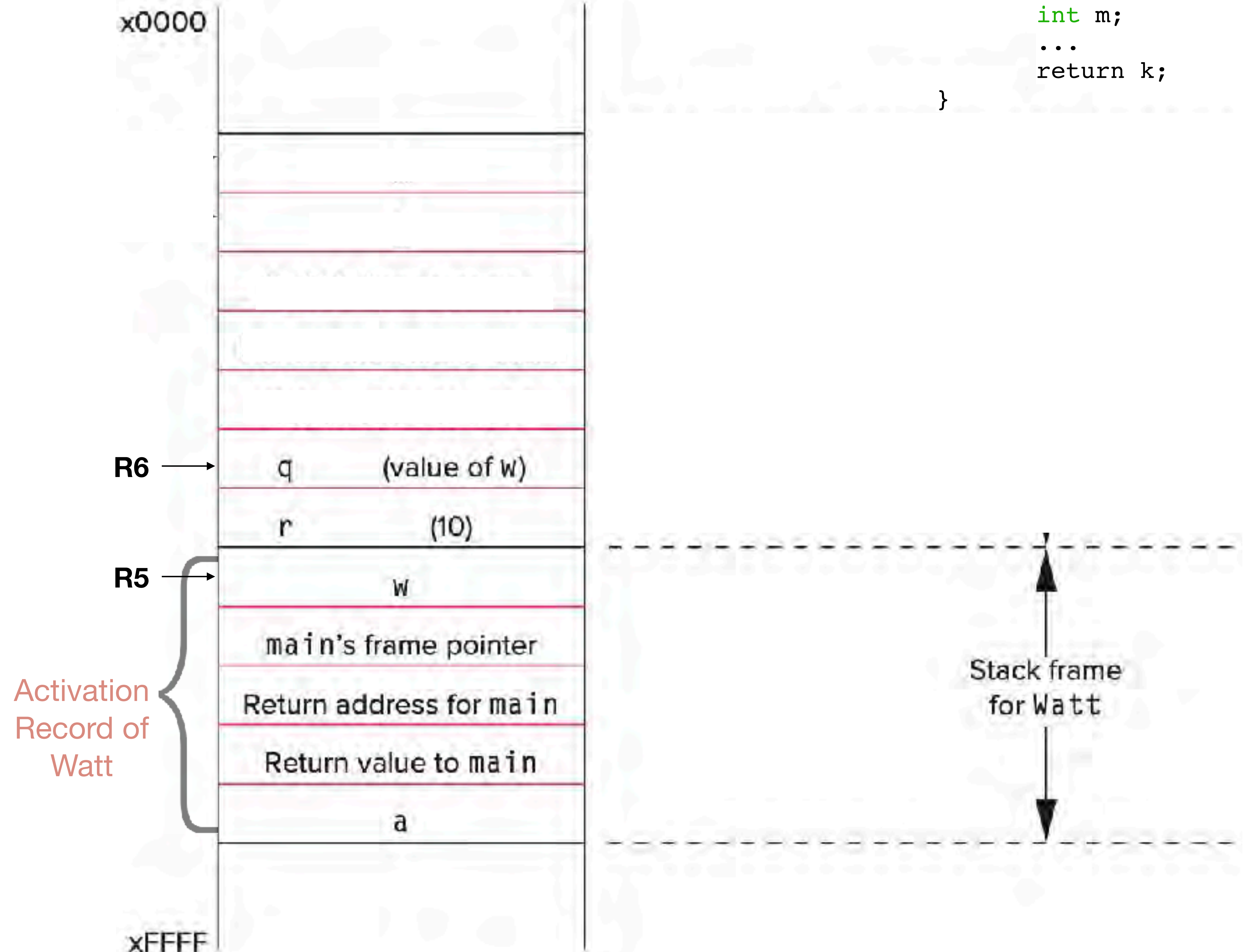
LC-3 Implementation

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

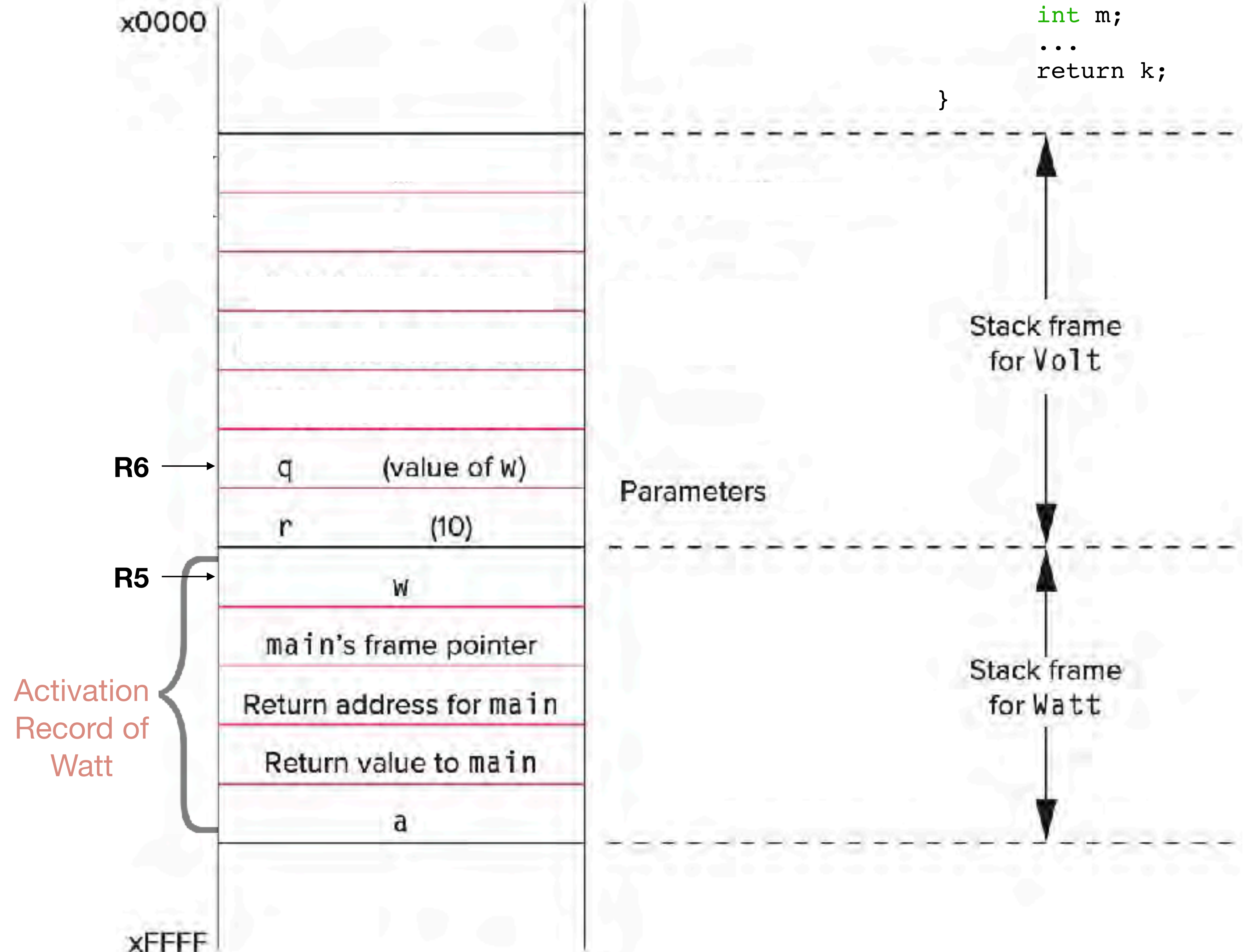
3. Callee setup (push bookkeeping info and local variables onto stack)



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;
}
```

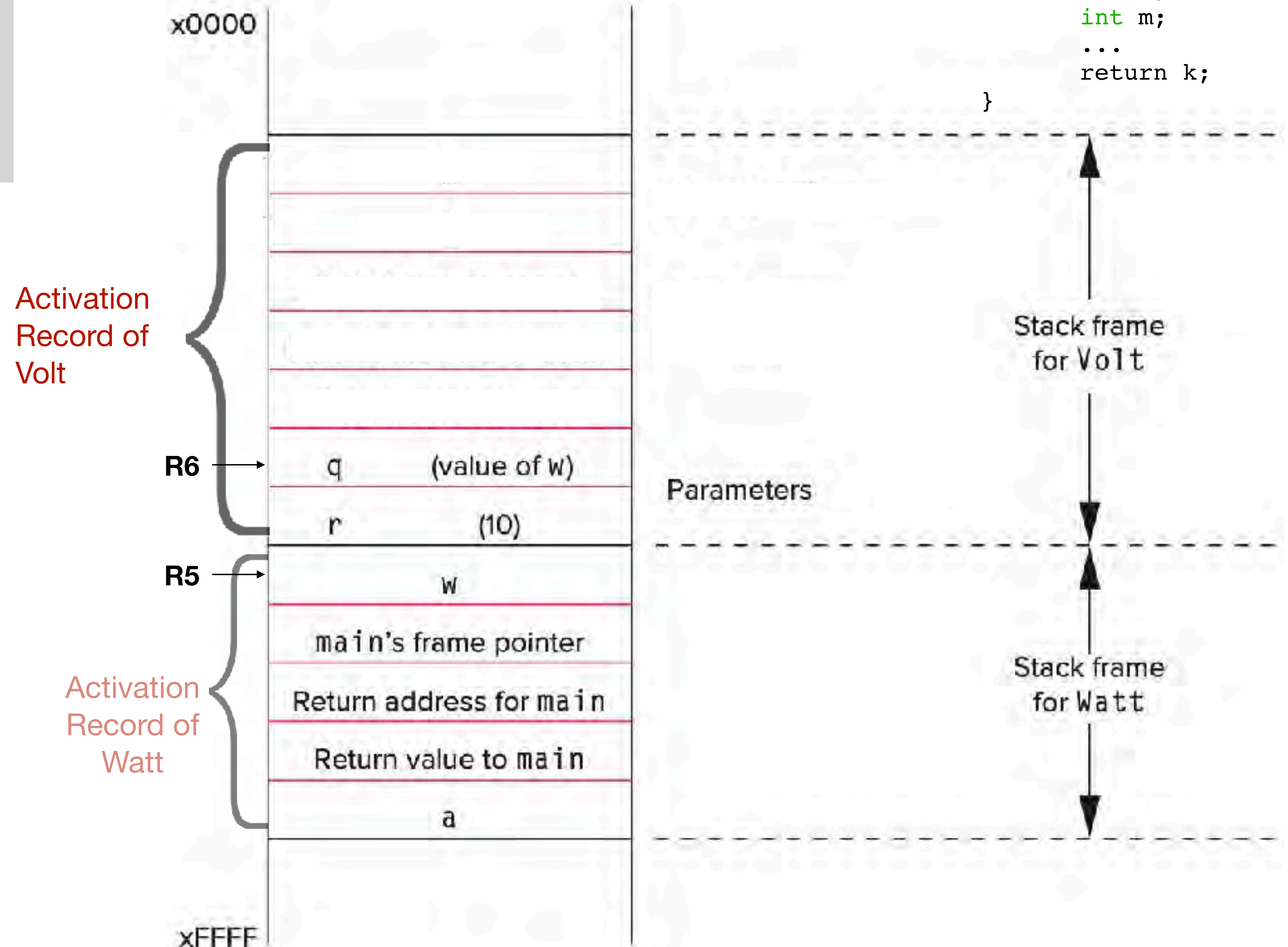


UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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

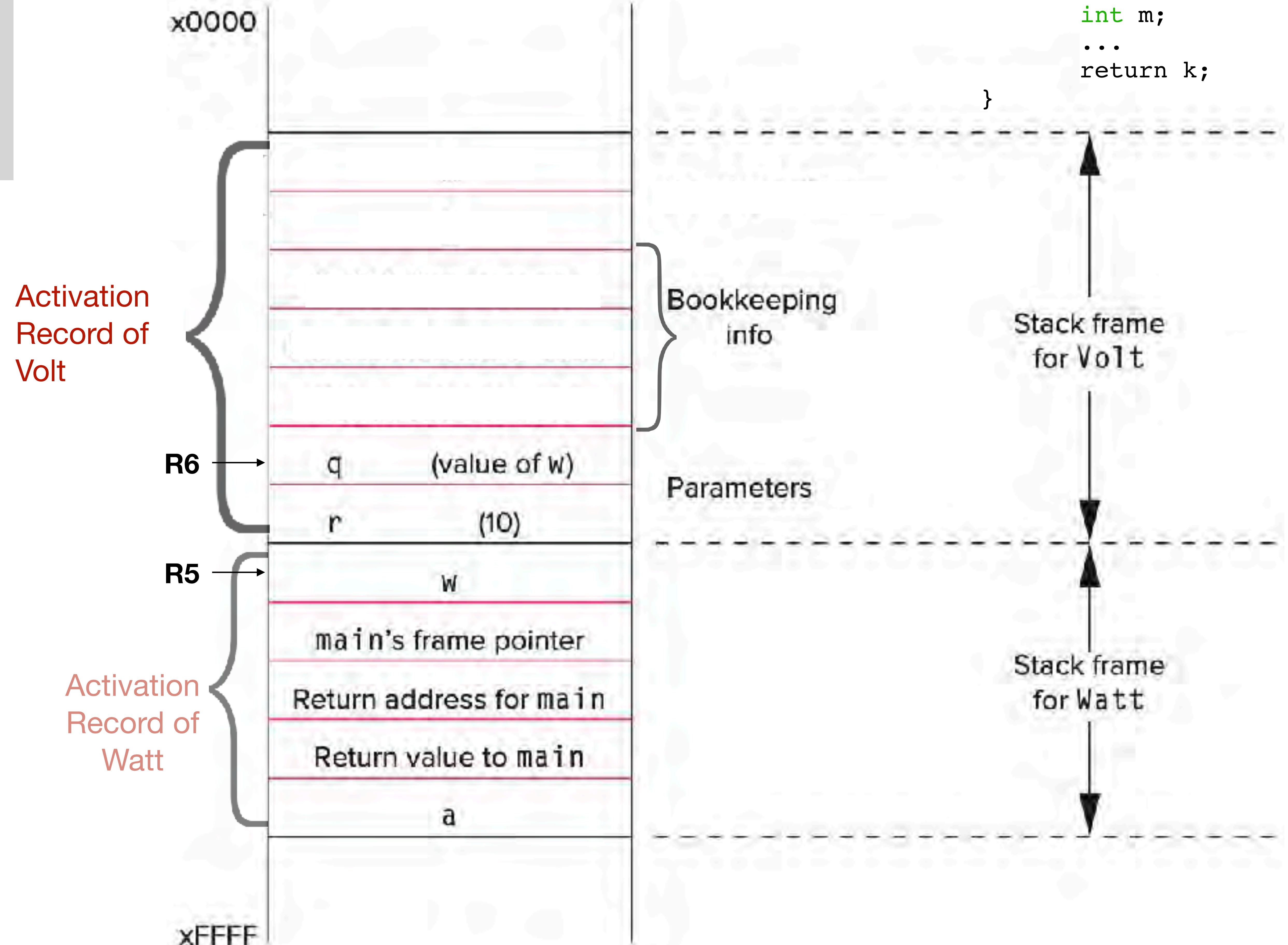
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

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

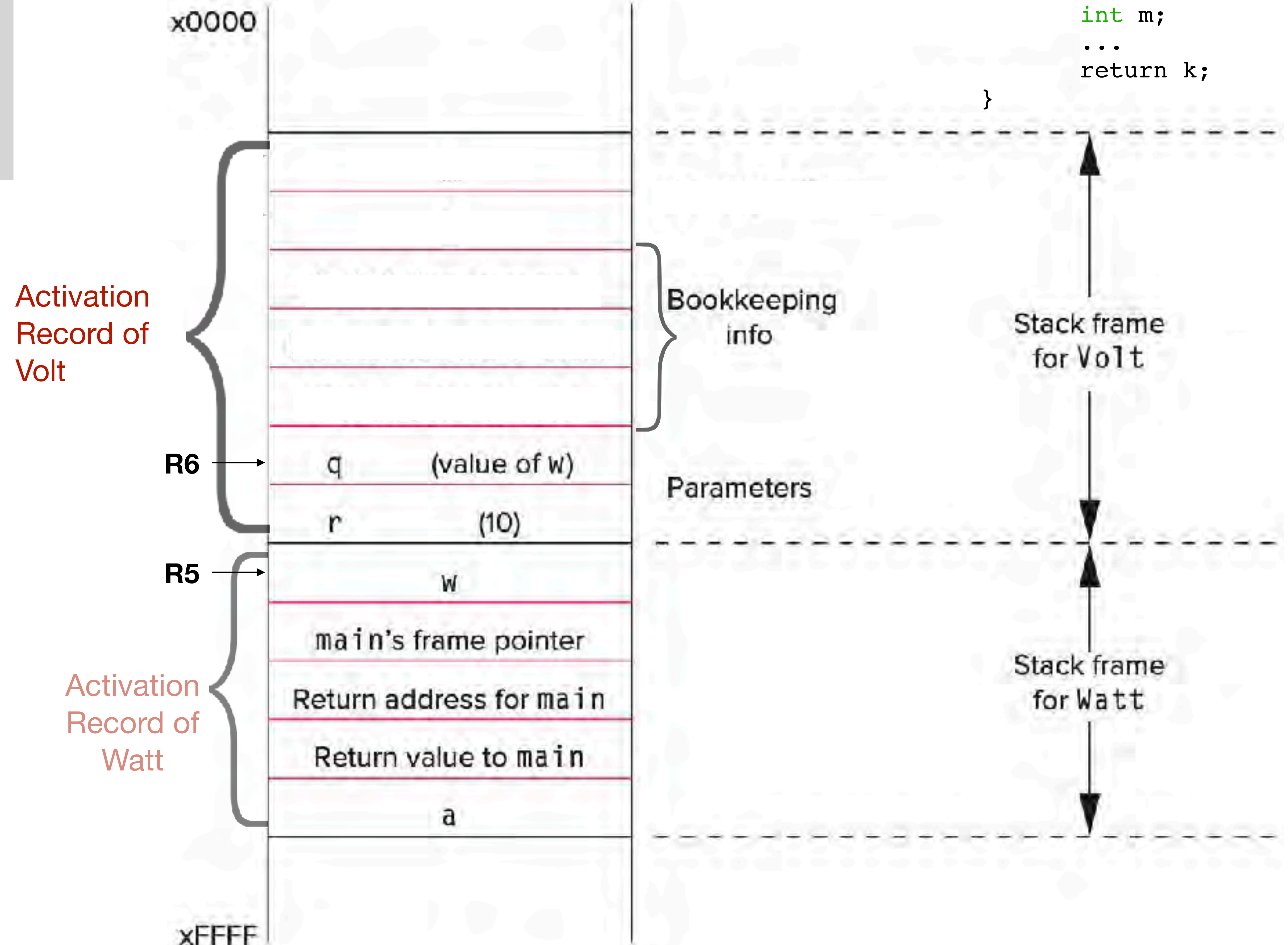


LC-3 Implementation

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

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

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



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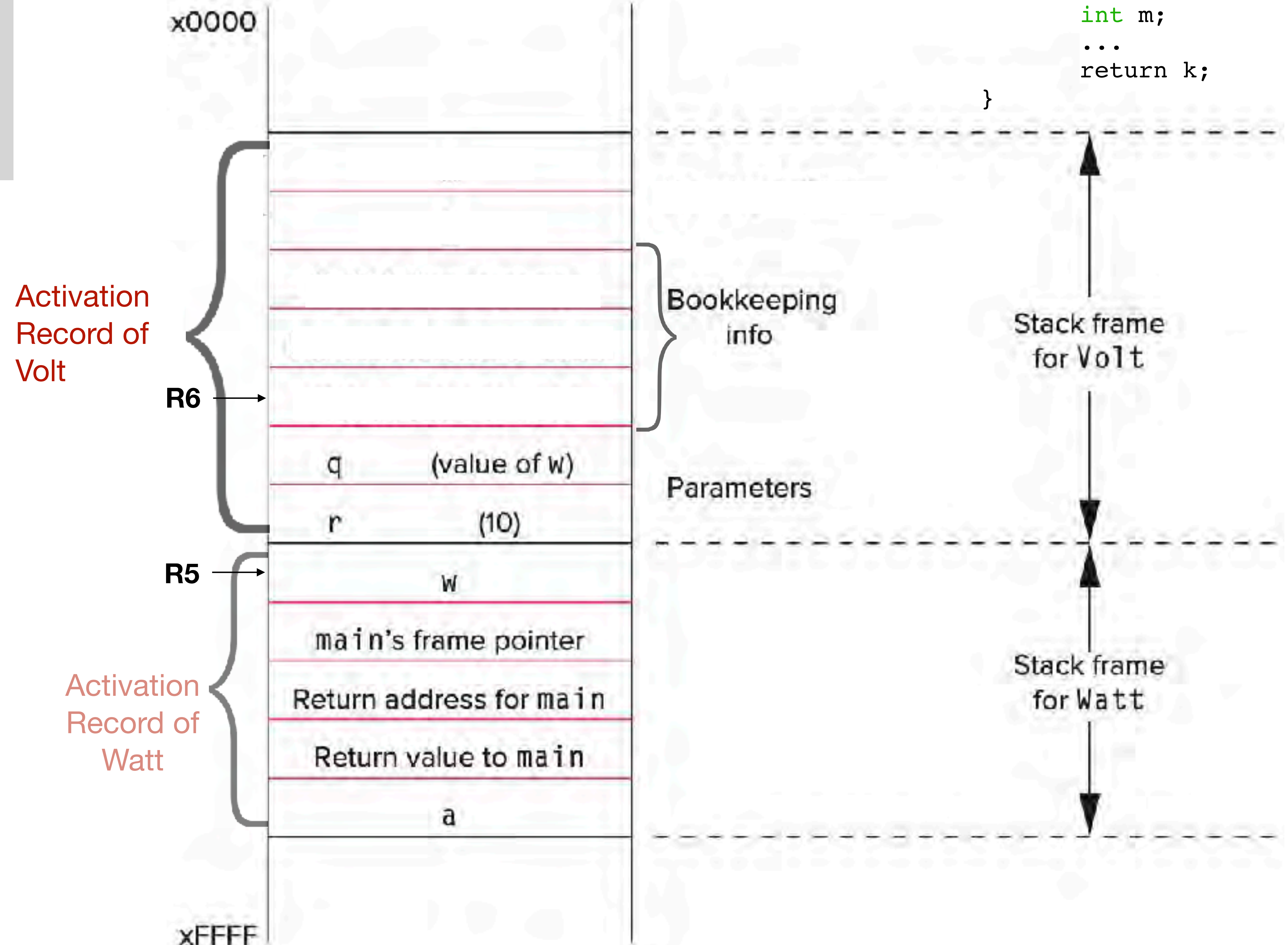
LC-3 Implementation

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

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

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

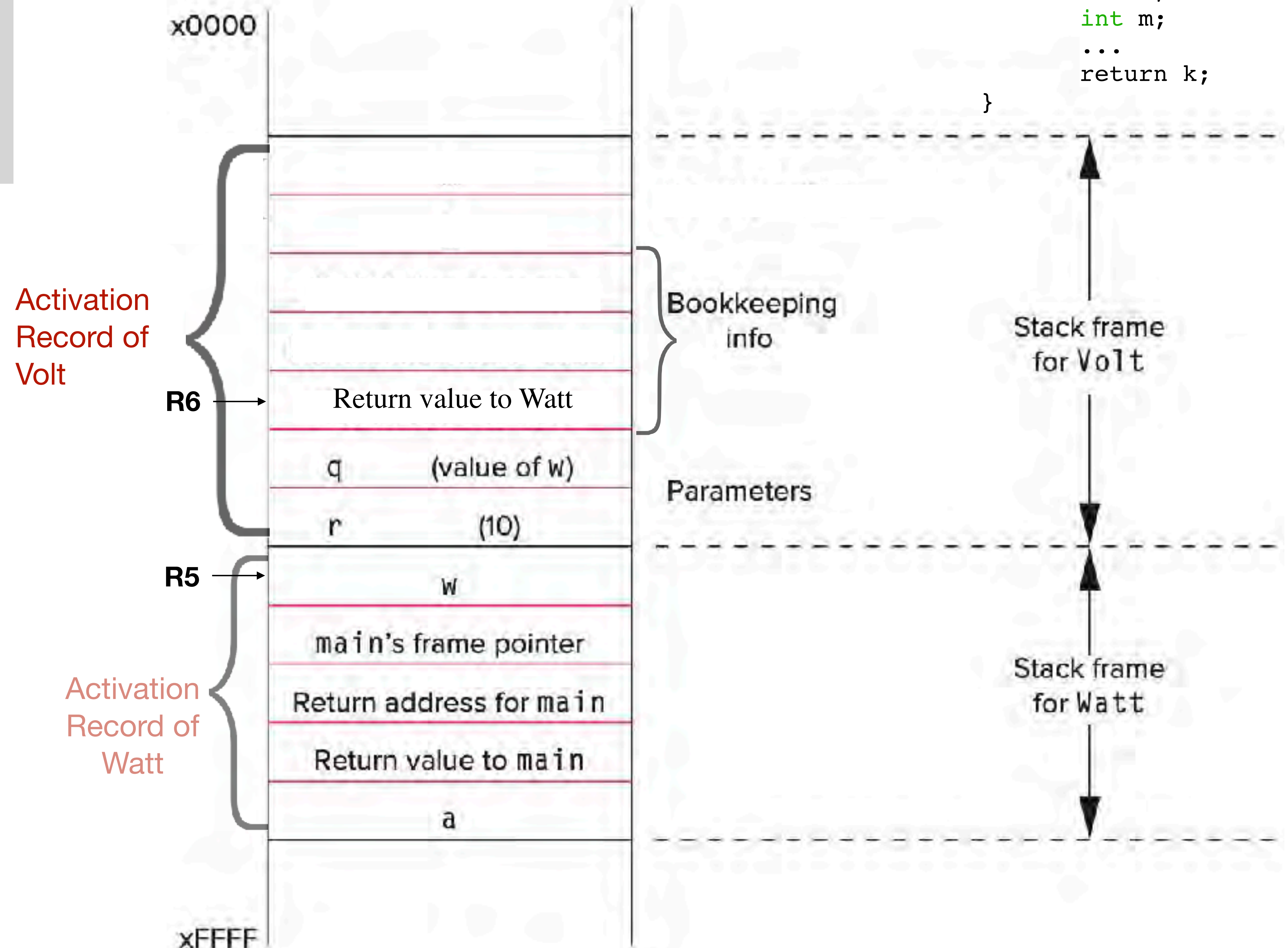


LC-3 Implementation

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

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

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



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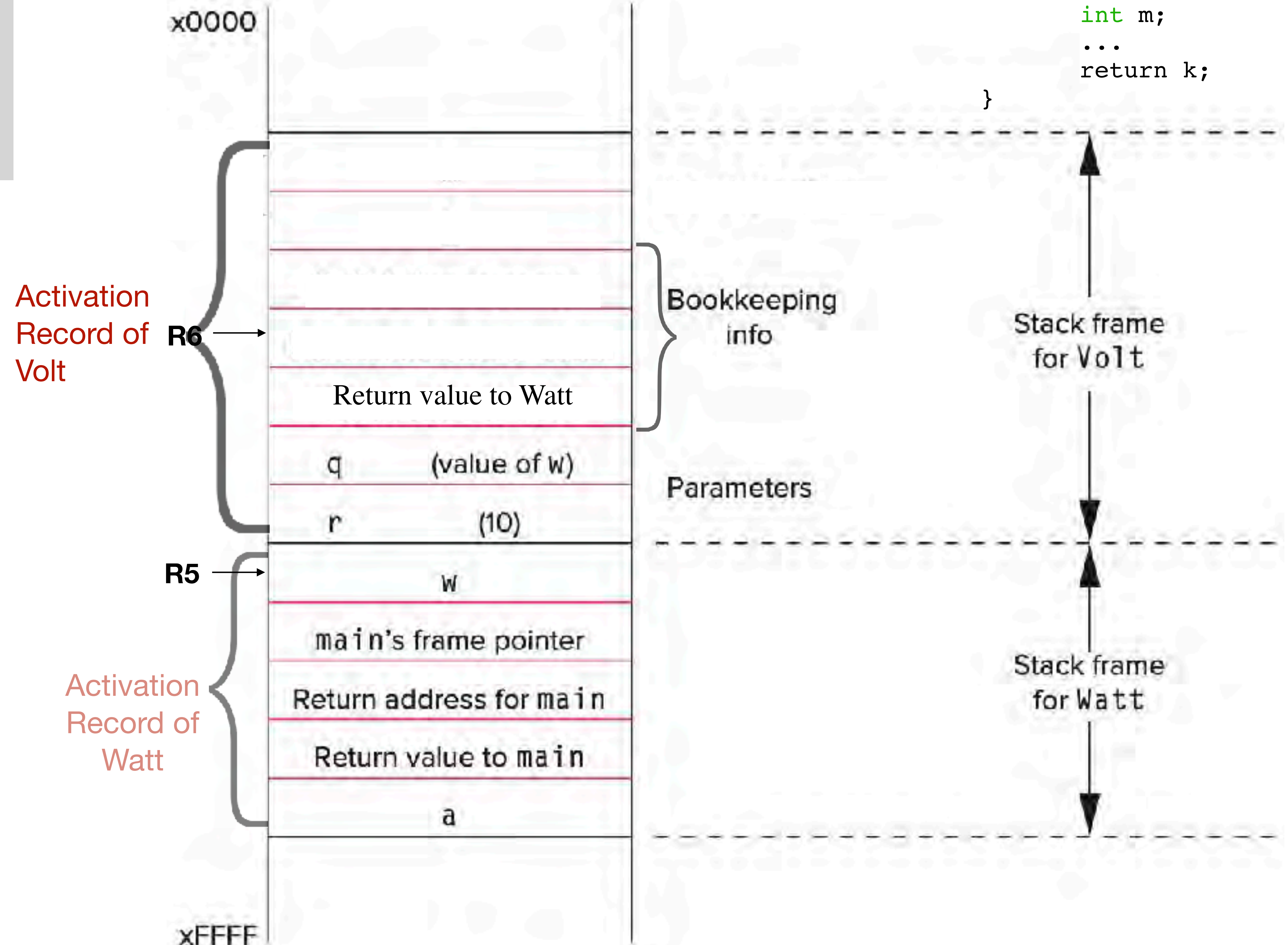
LC-3 Implementation

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

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

ADD R6, R6, #-1
```

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



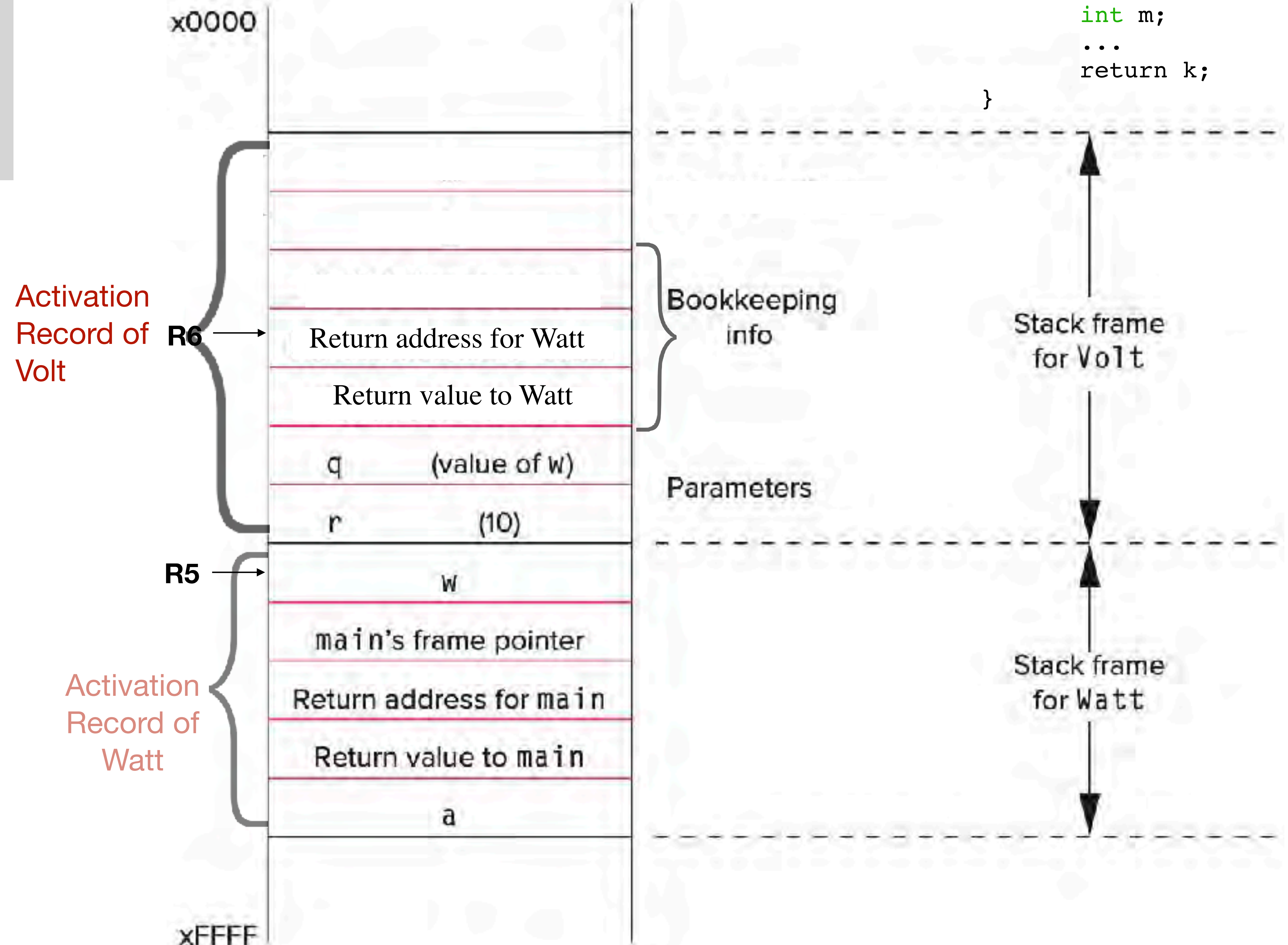
LC-3 Implementation

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

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

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

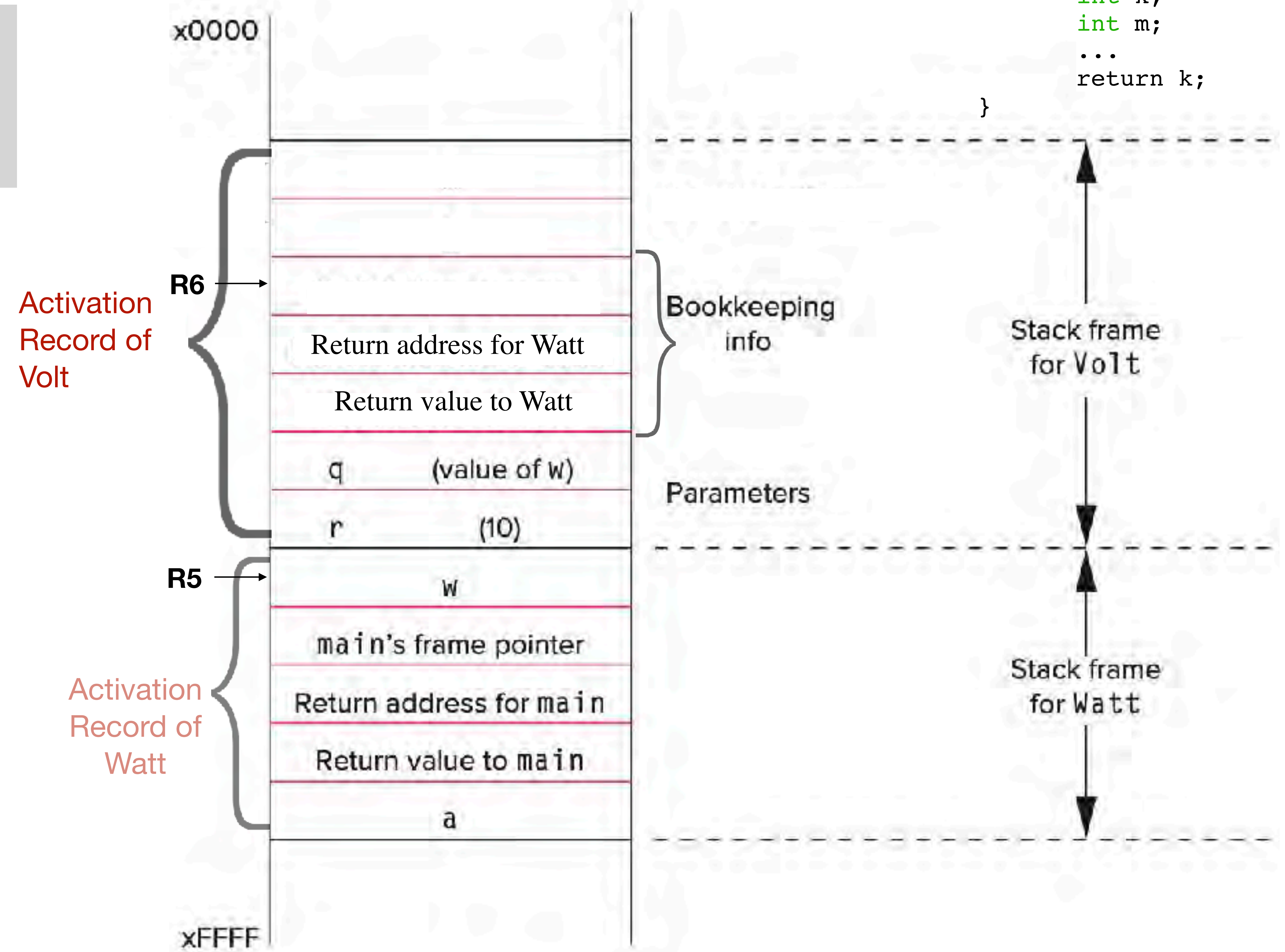
3. Callee setup (push bookkeeping info and local variables onto stack)

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

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

ADD R6, R6, #-1
```

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



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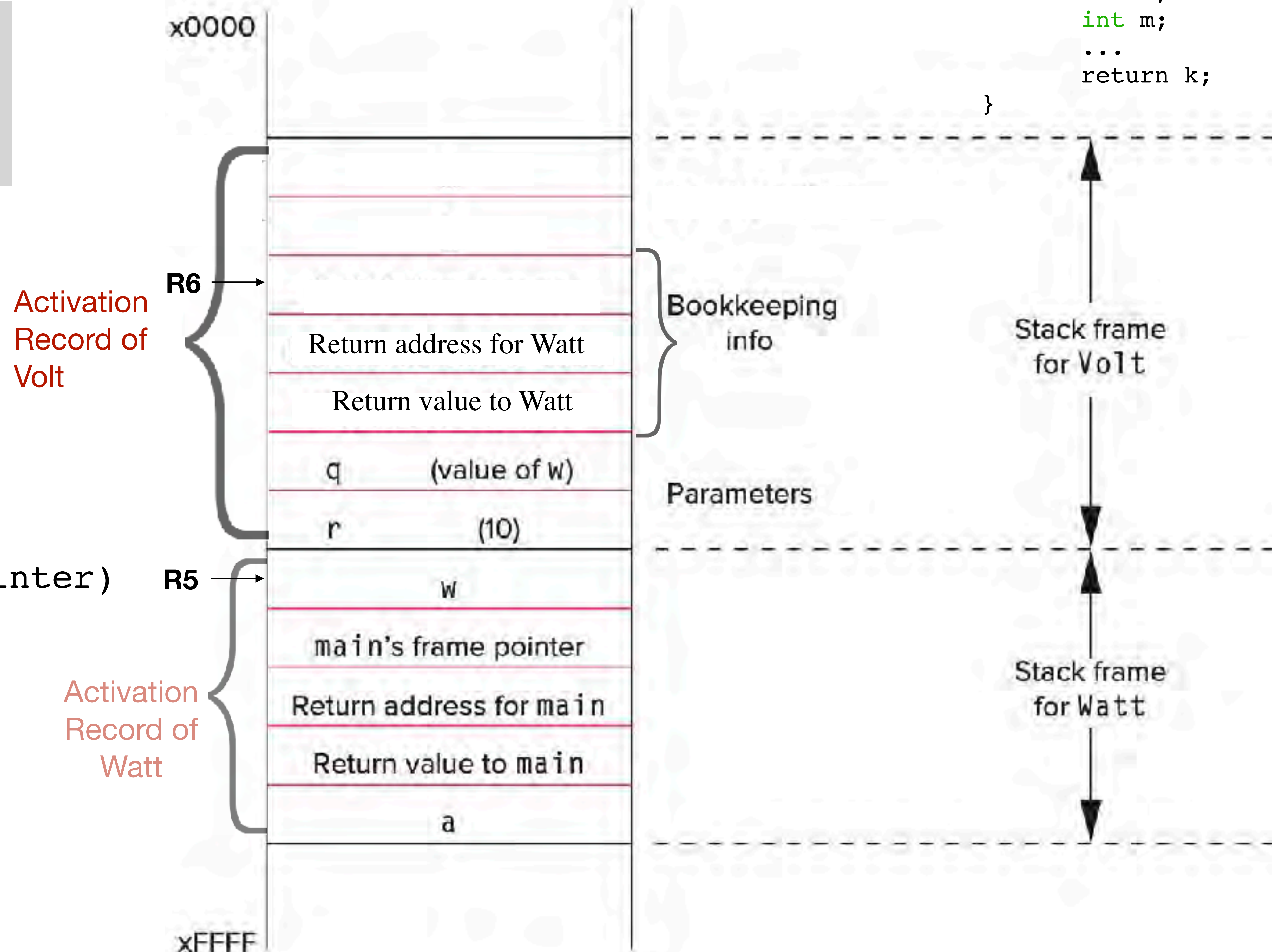
LC-3 Implementation

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

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

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

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



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LC-3 Implementation

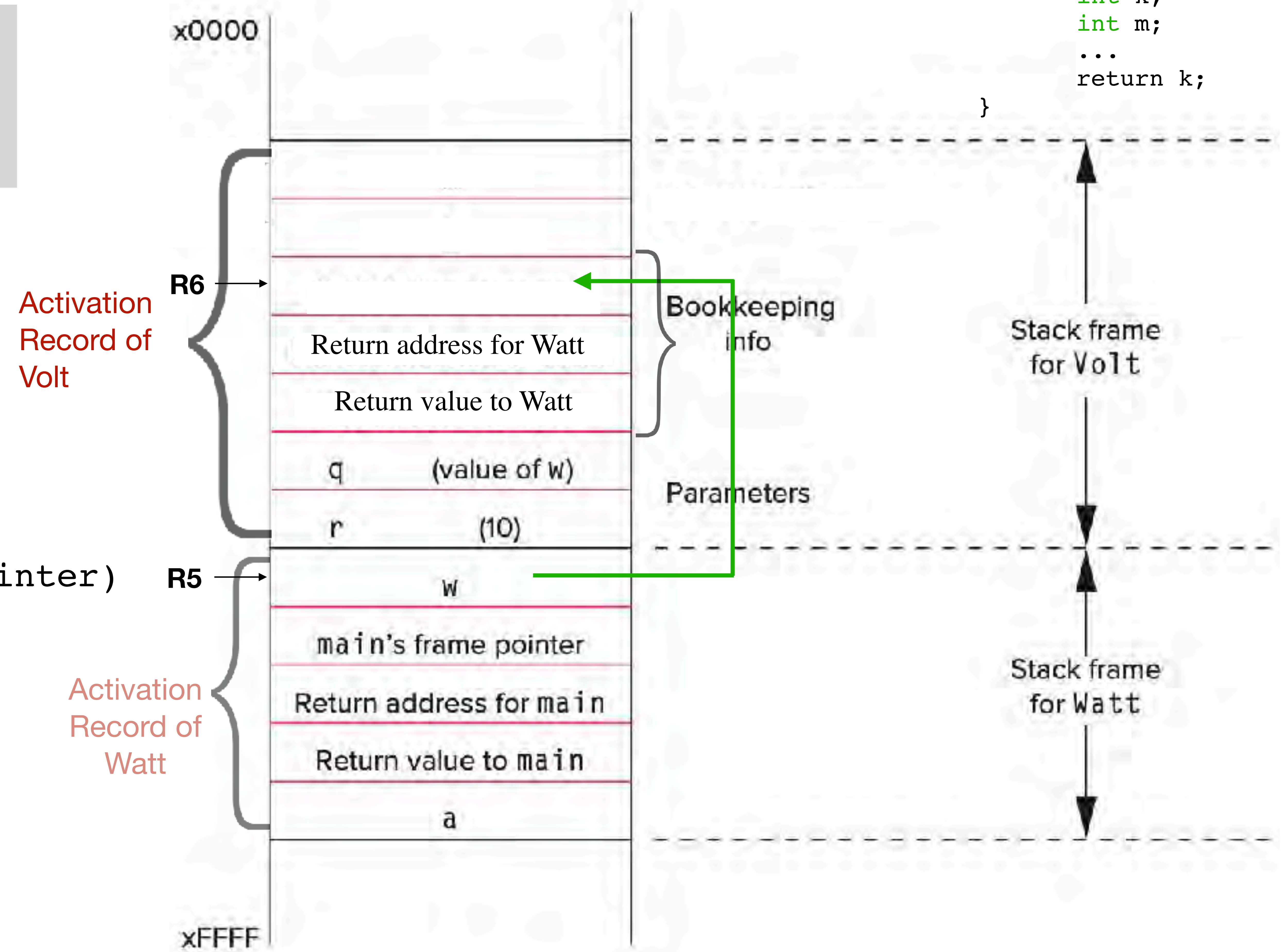
3. Callee setup (push bookkeeping info and local variables onto stack)

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

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

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

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



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LC-3 Implementation

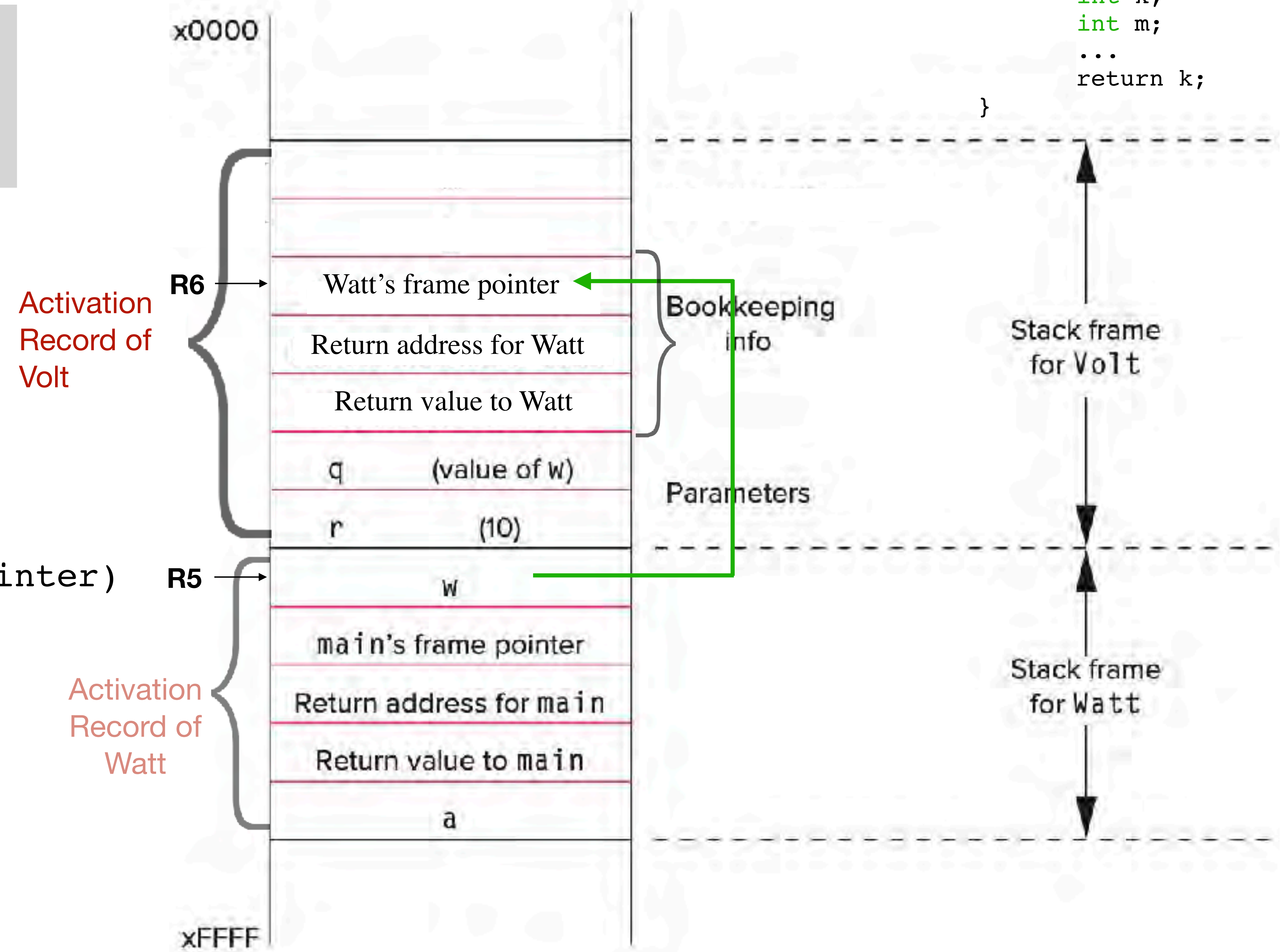
3. Callee setup (push bookkeeping info and local variables onto stack)

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

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

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

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



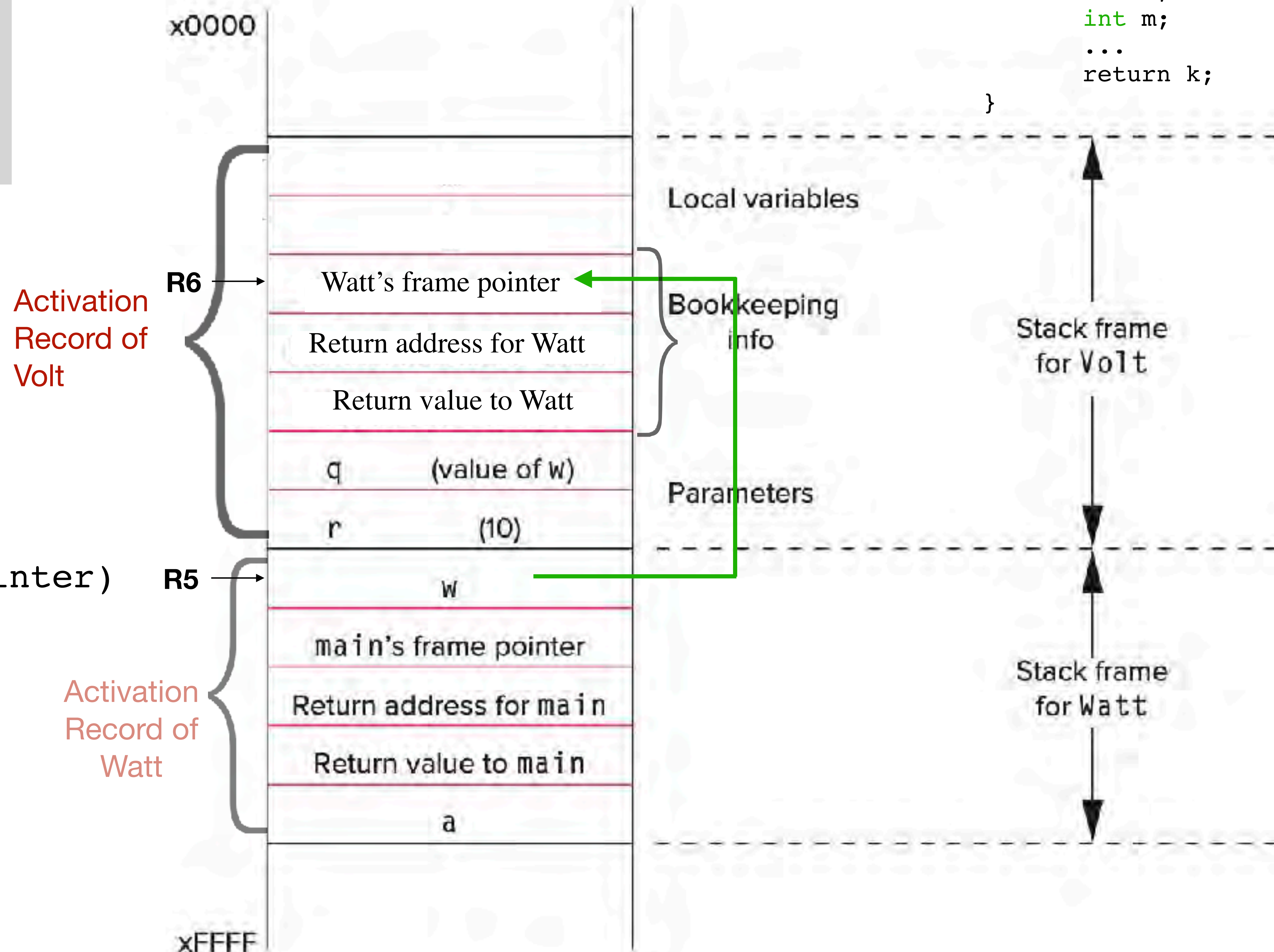
LC-3 Implementation

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

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

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

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



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LC-3 Implementation

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

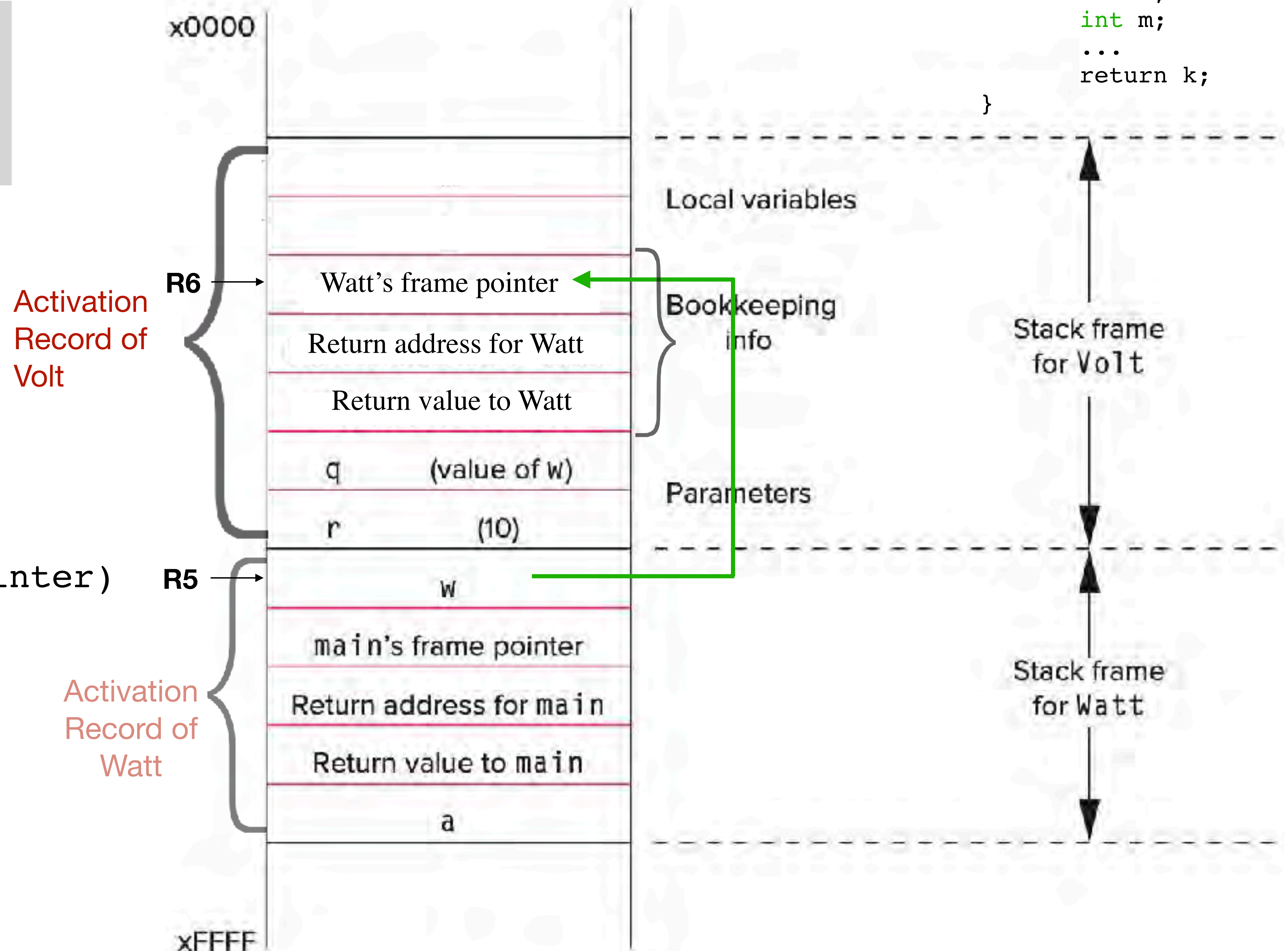
```
;return value
ADD R6, R6, #-1

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

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

;Set frame pointer for Volt
```

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



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LC-3 Implementation

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

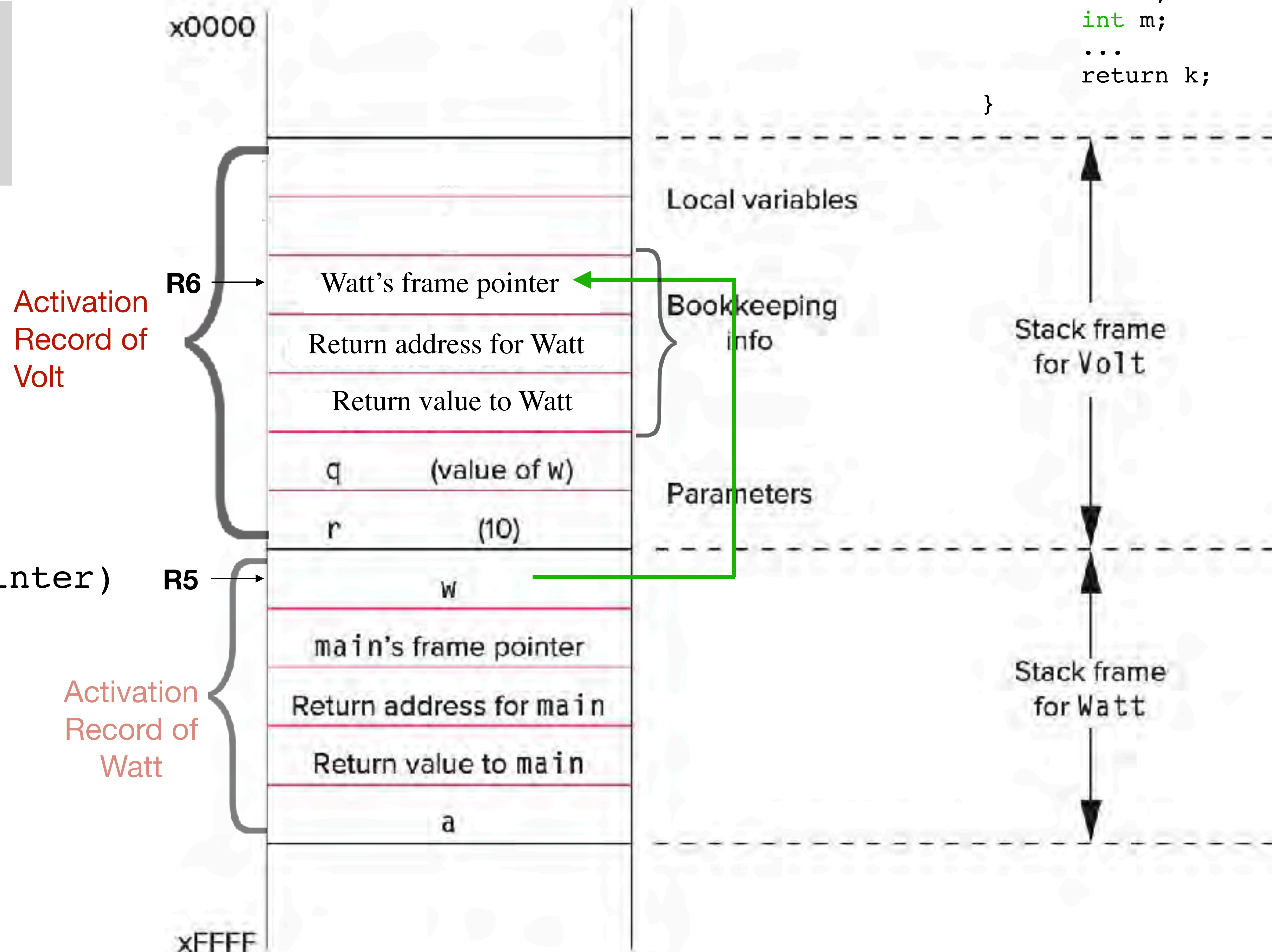
3. Callee setup (push bookkeeping info and local variables onto stack)

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

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

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

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



LC-3 Implementation

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

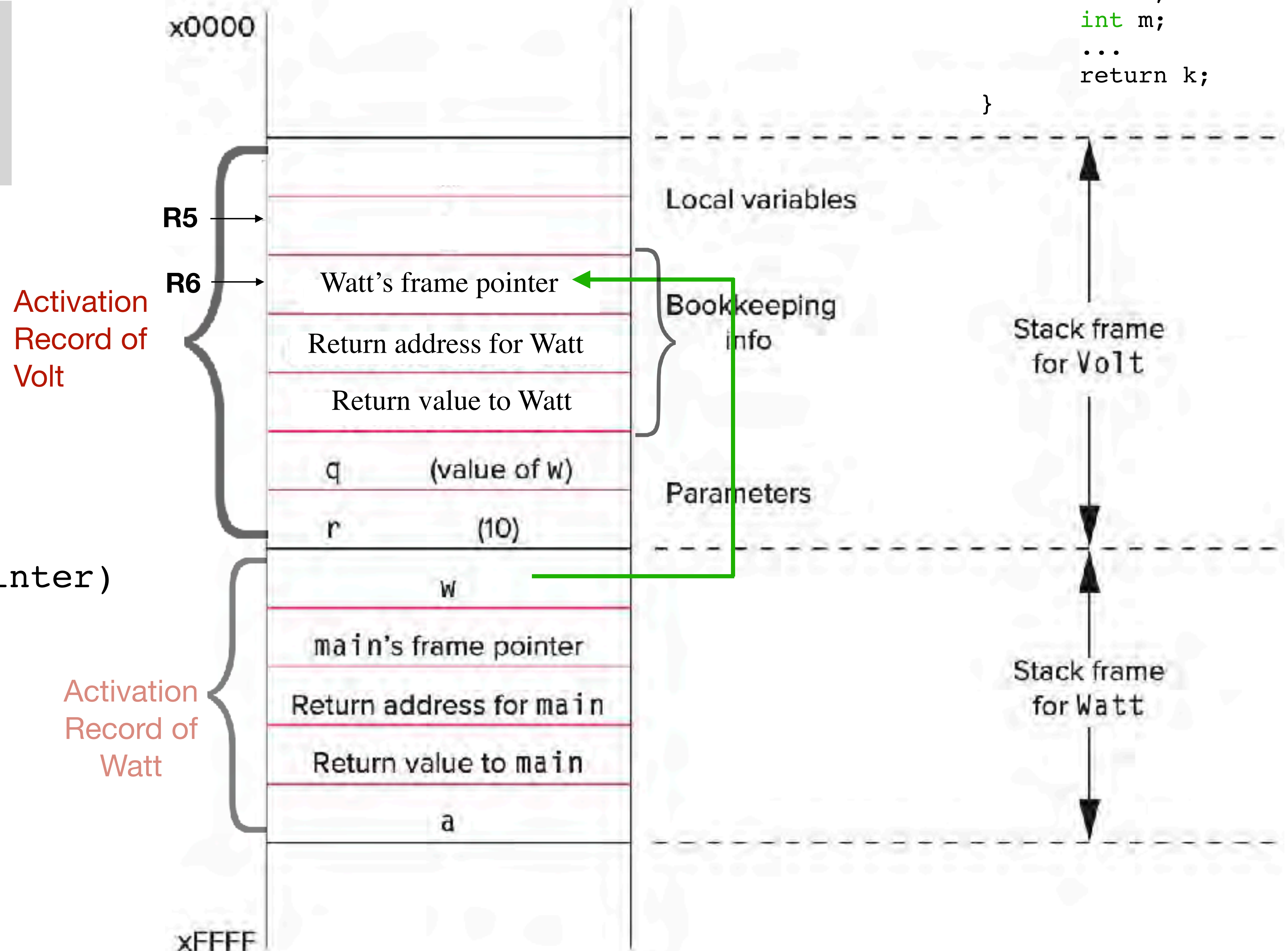
3. Callee setup (push bookkeeping info and local variables onto stack)

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

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

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

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



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LC-3 Implementation

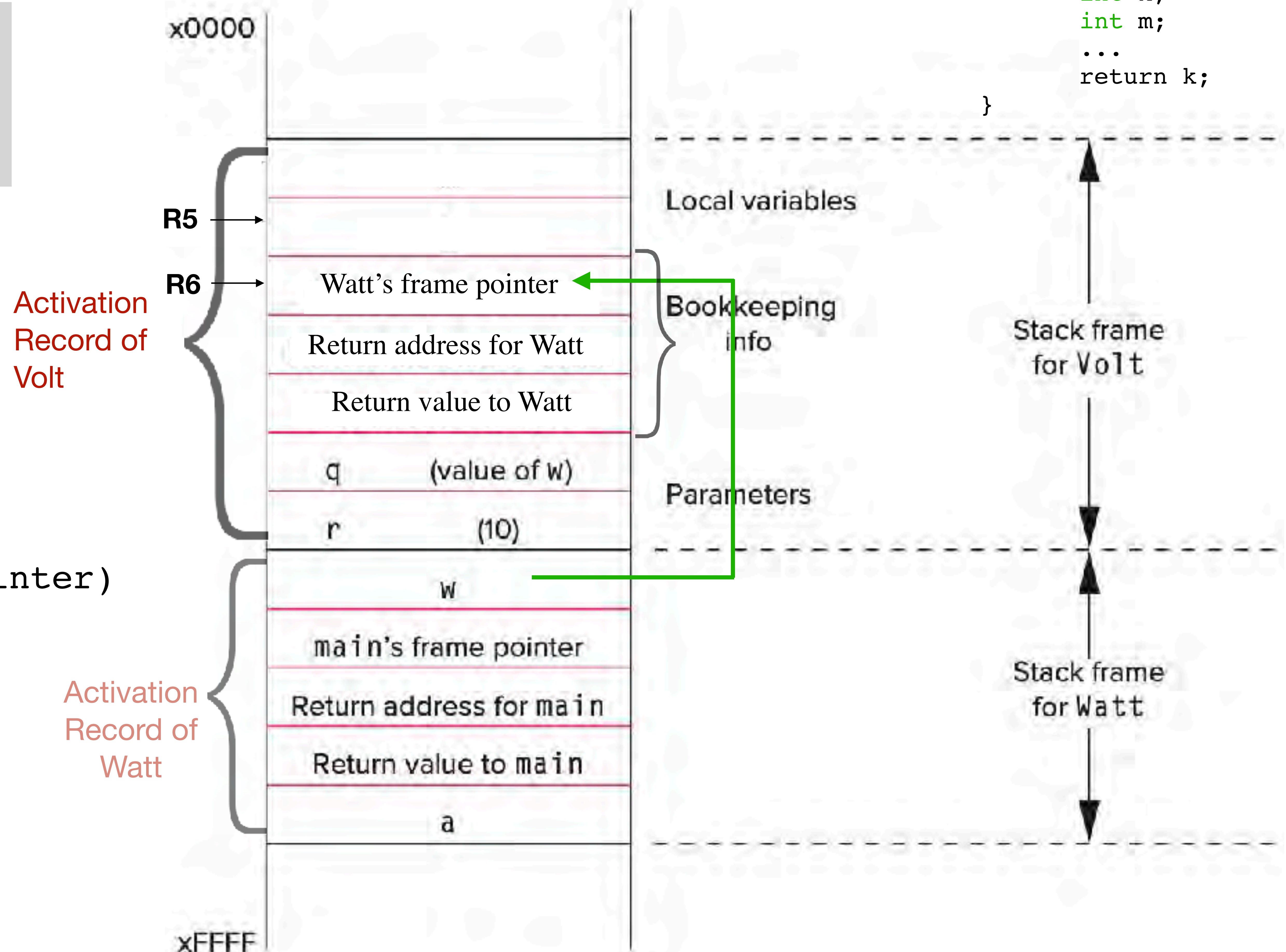
3. Callee setup (push bookkeeping info and local variables onto stack)
4. Execute function

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

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

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

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



UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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

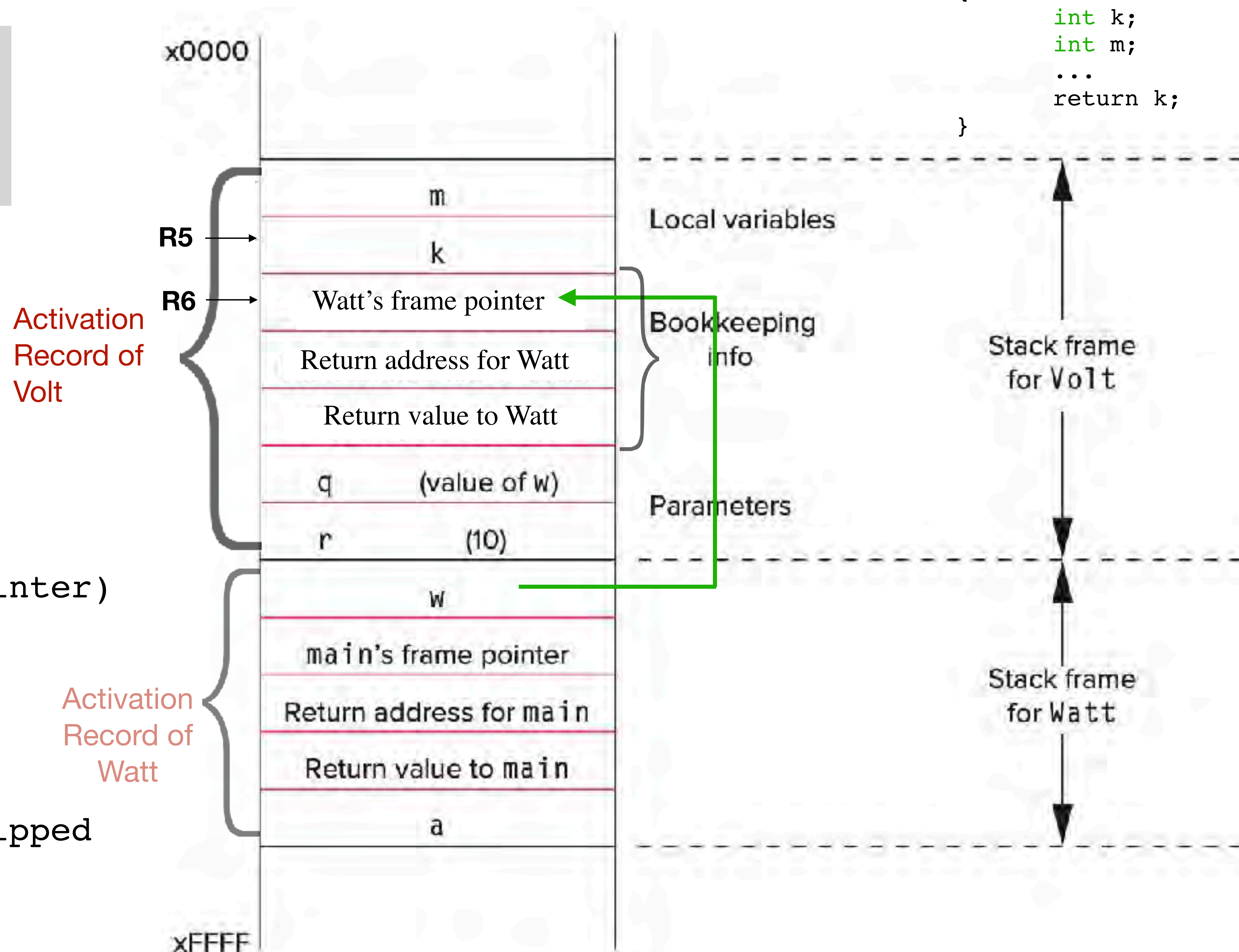
```
;return value
ADD R6, R6, #-1

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

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

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

```
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)
4. Execute function

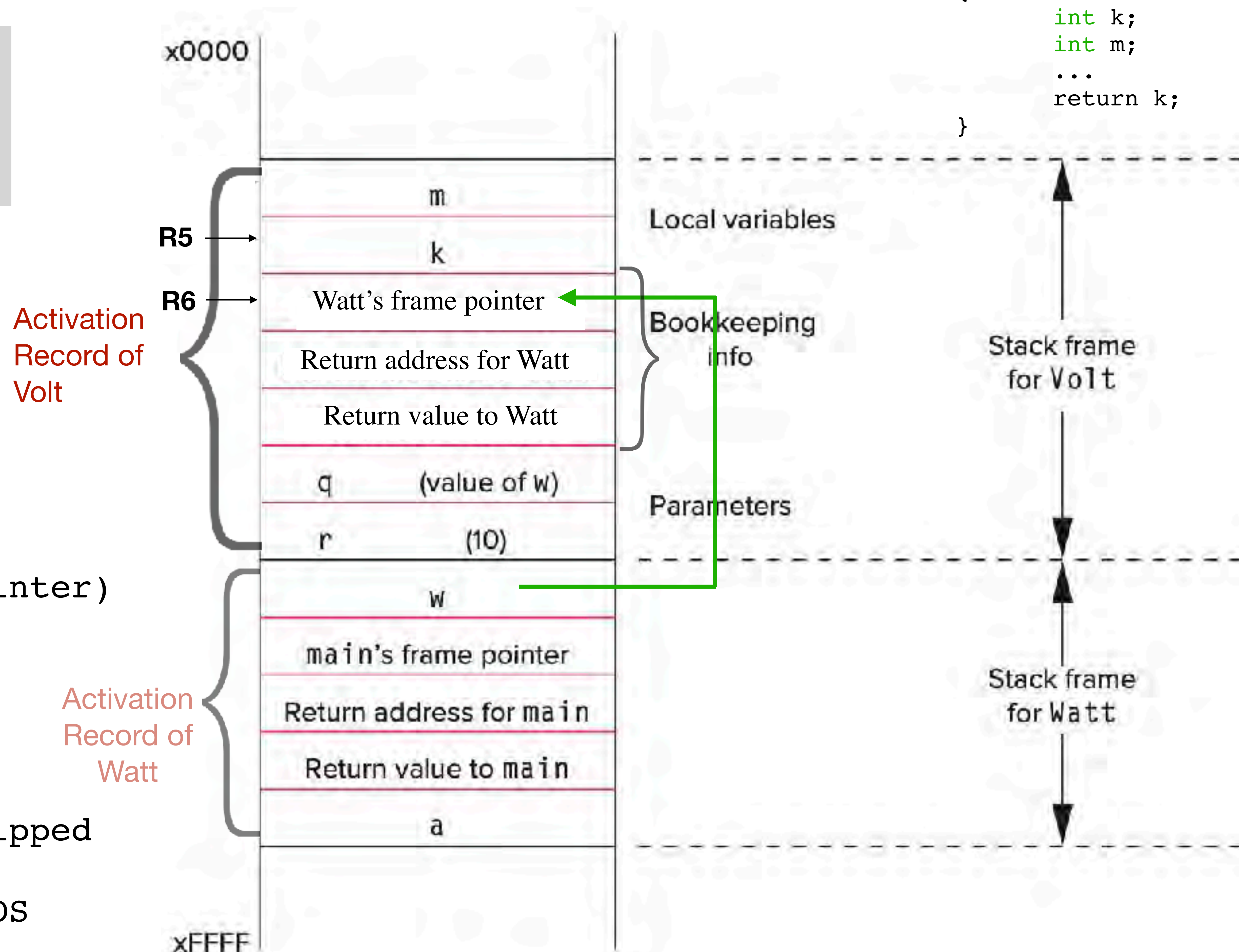
```
;return value
ADD R6, R6, #-1

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

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

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

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



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LC-3 Implementation

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

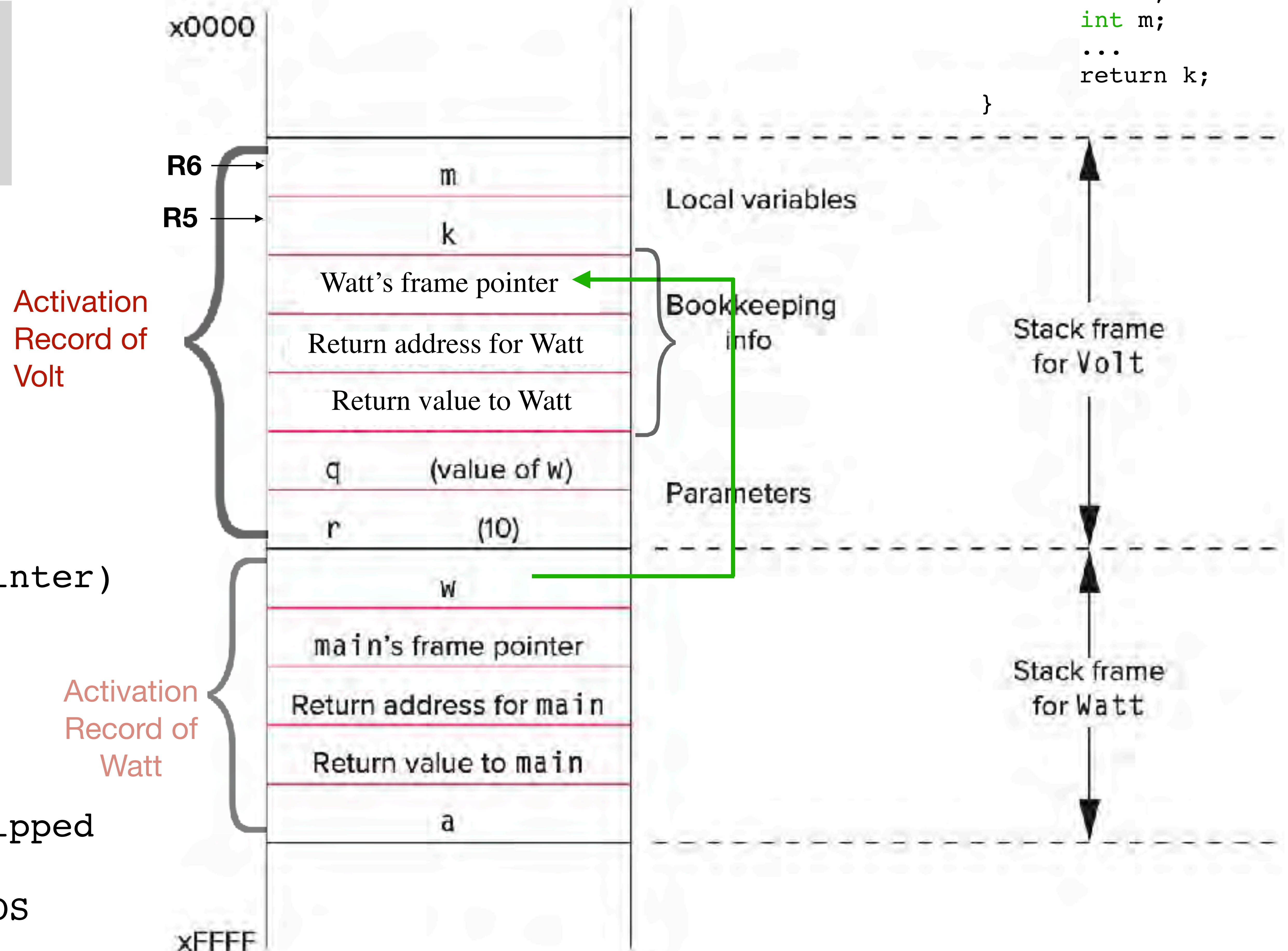
```
;return value
ADD R6, R6, #-1

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

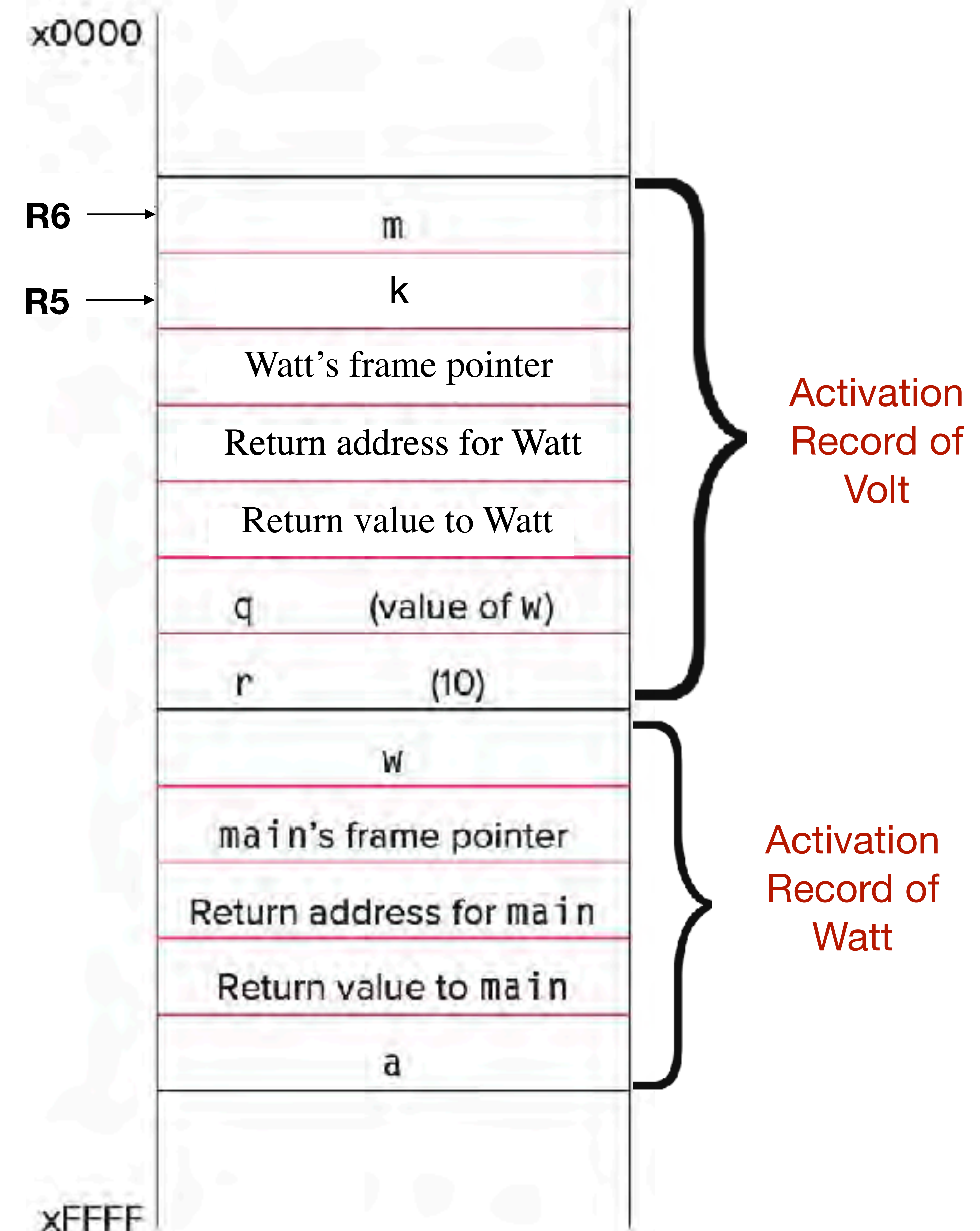
ADD R6, R6, #-1
;Push R5 (Caller's frame pointer)
STR R5, R6, #0

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

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

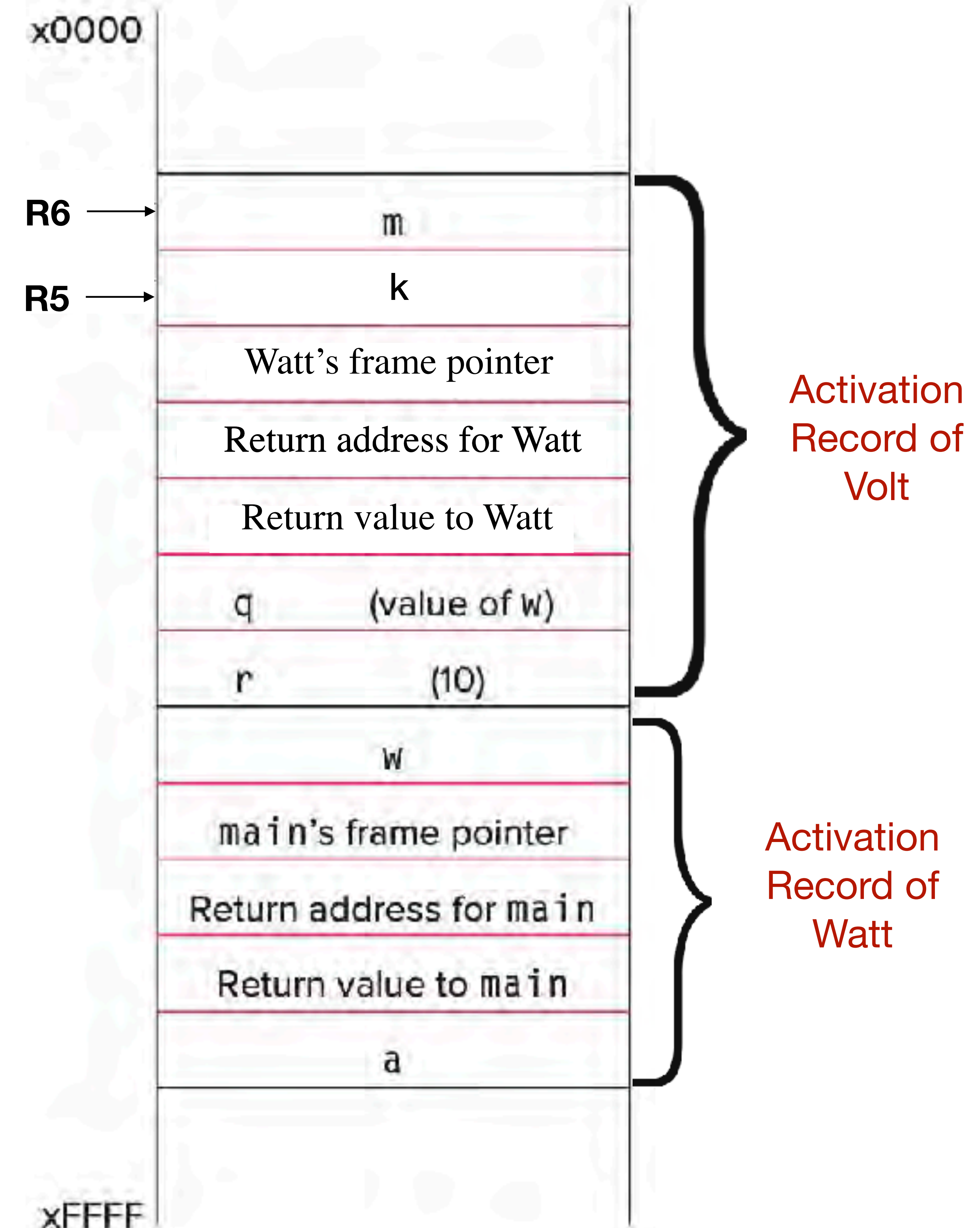


LC-3 Implementation



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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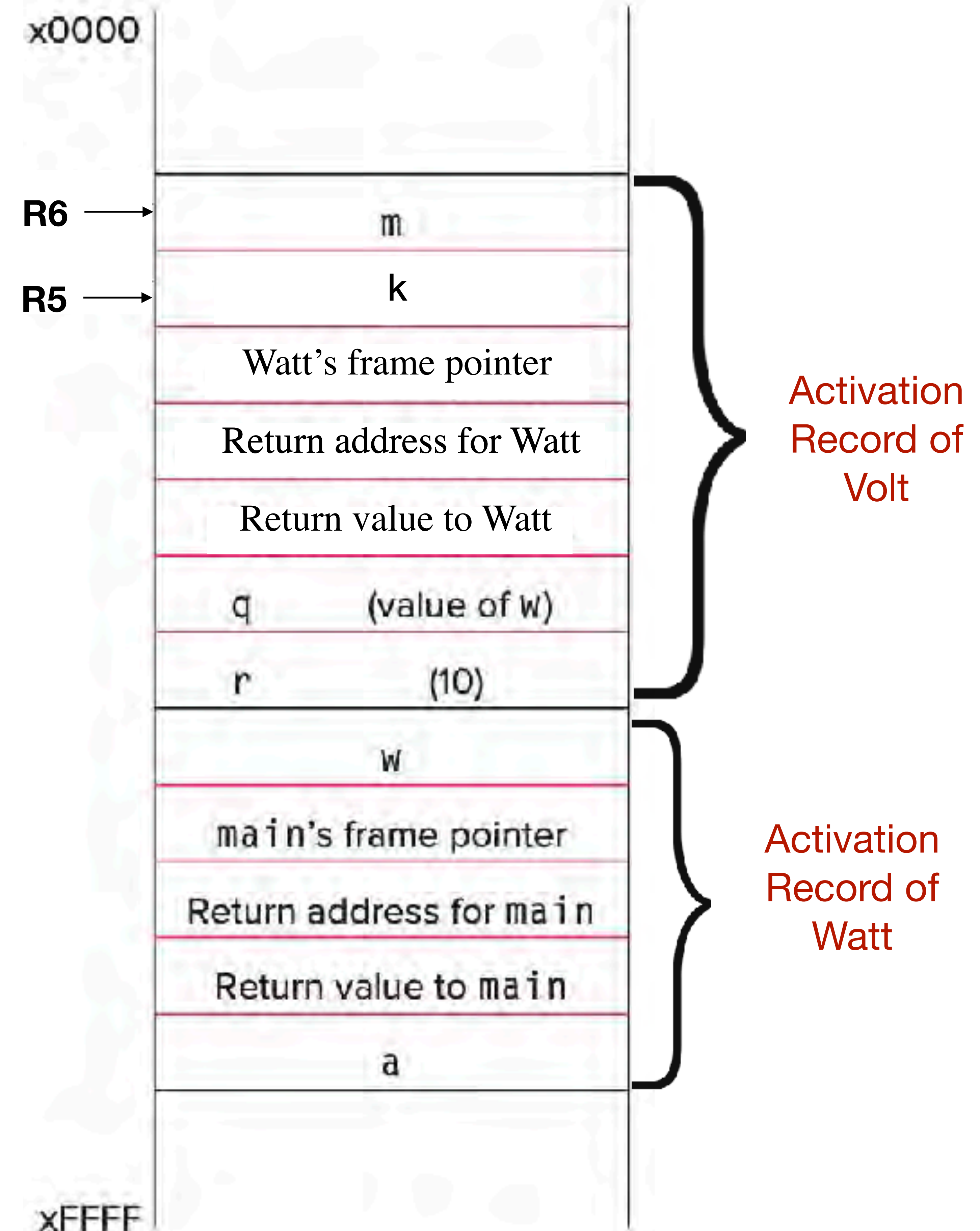
LC-3 Implementation

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)
```



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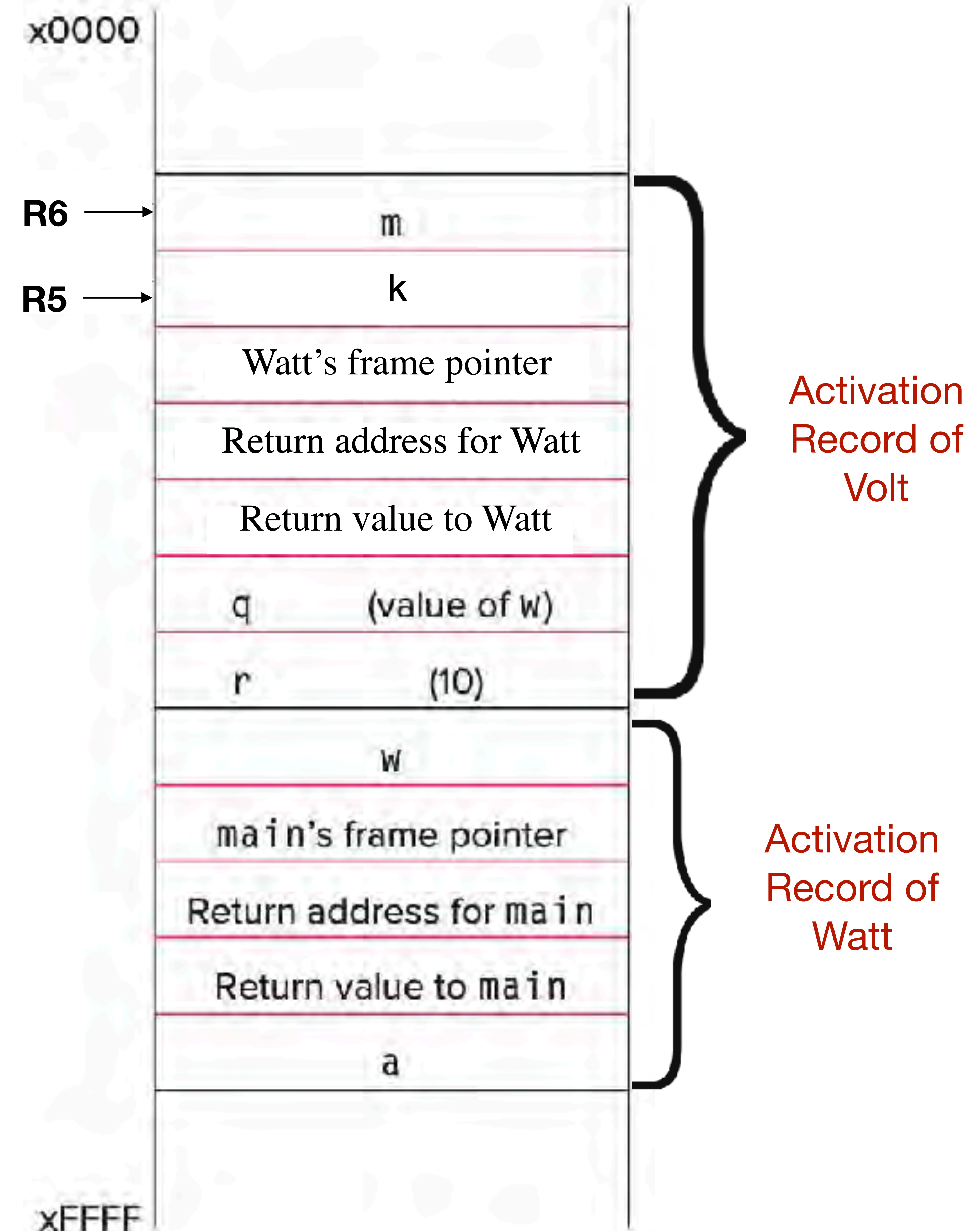
LC-3 Implementation

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

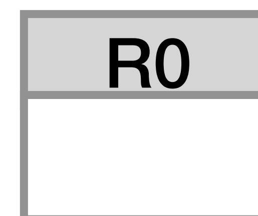
```
; copy k into return value(R5+3)
LDR R0, R5, #0
```

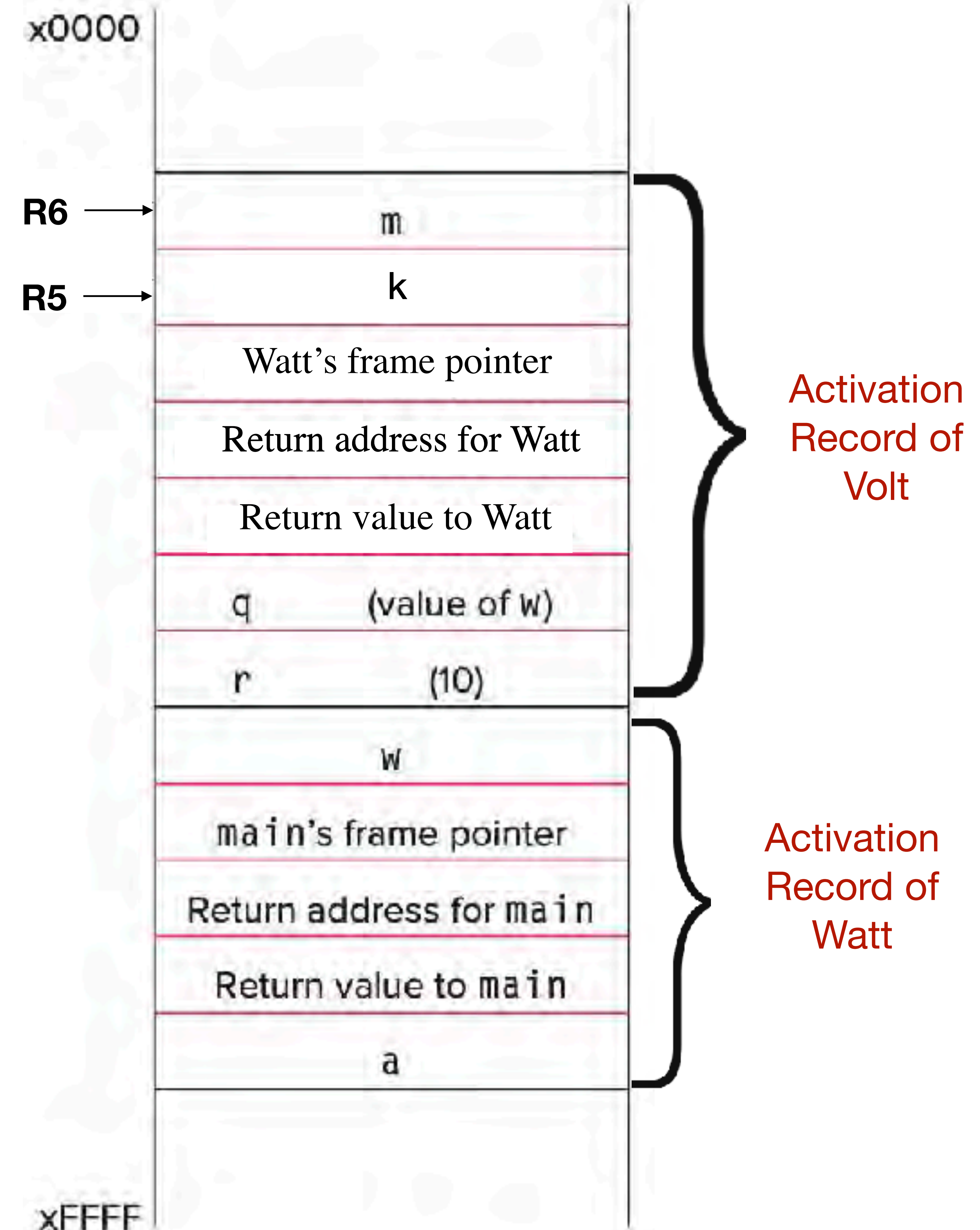


LC-3 Implementation

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
```





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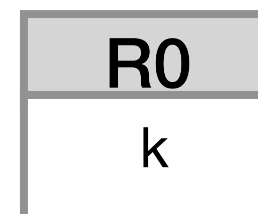
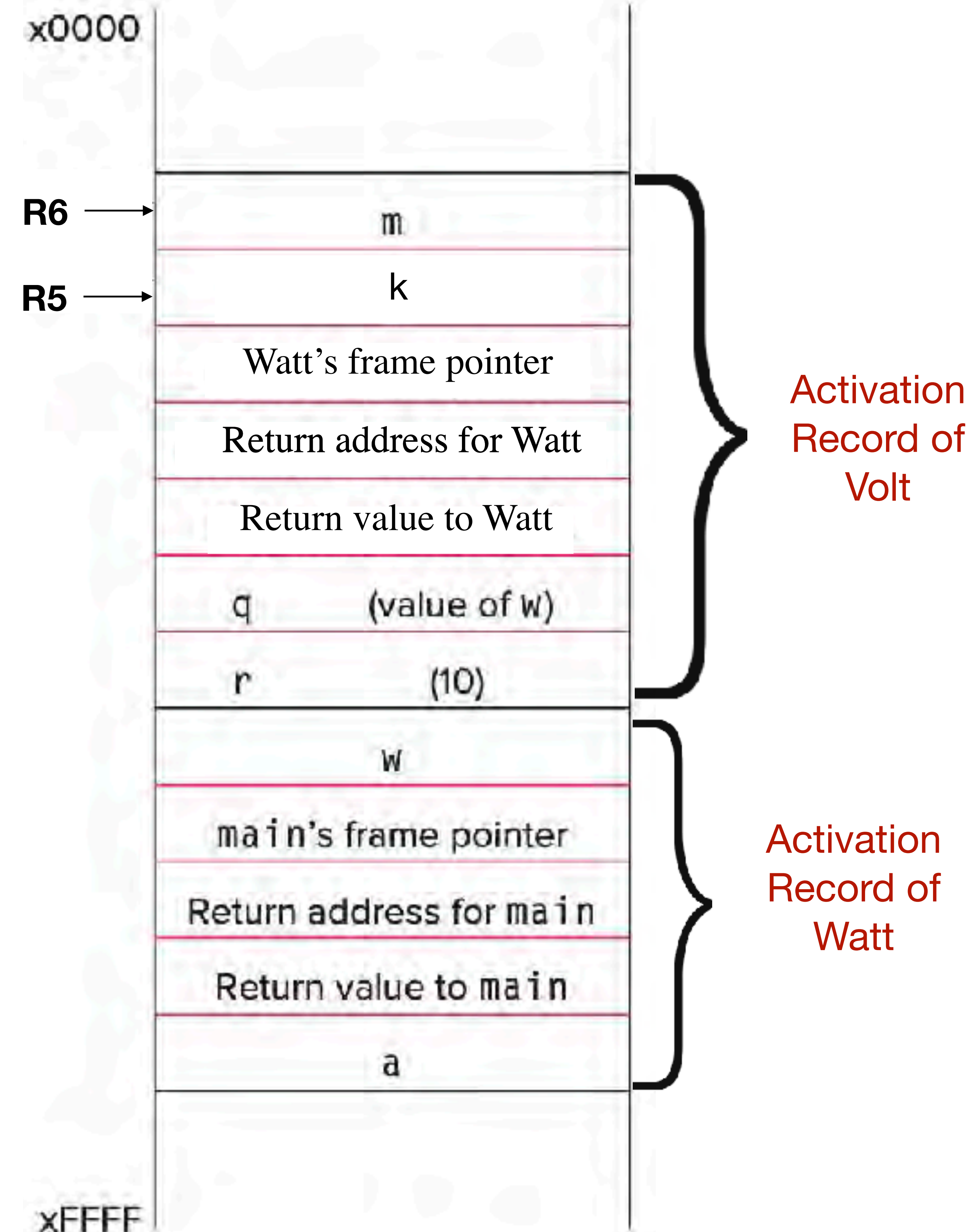
LC-3 Implementation

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
```





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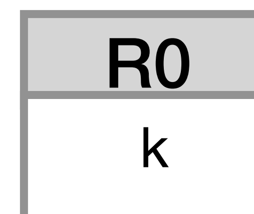
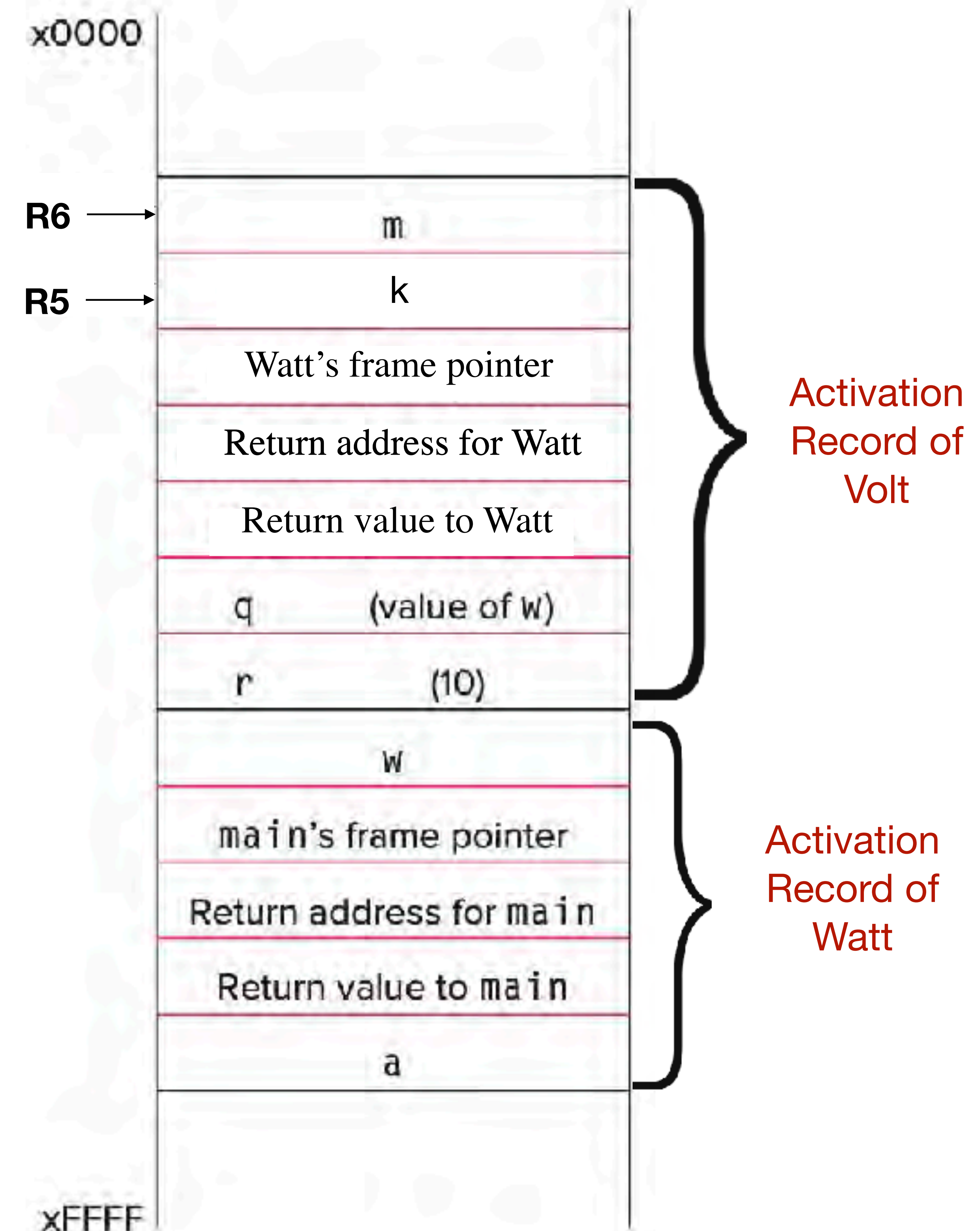
LC-3 Implementation

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
```



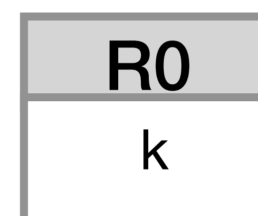


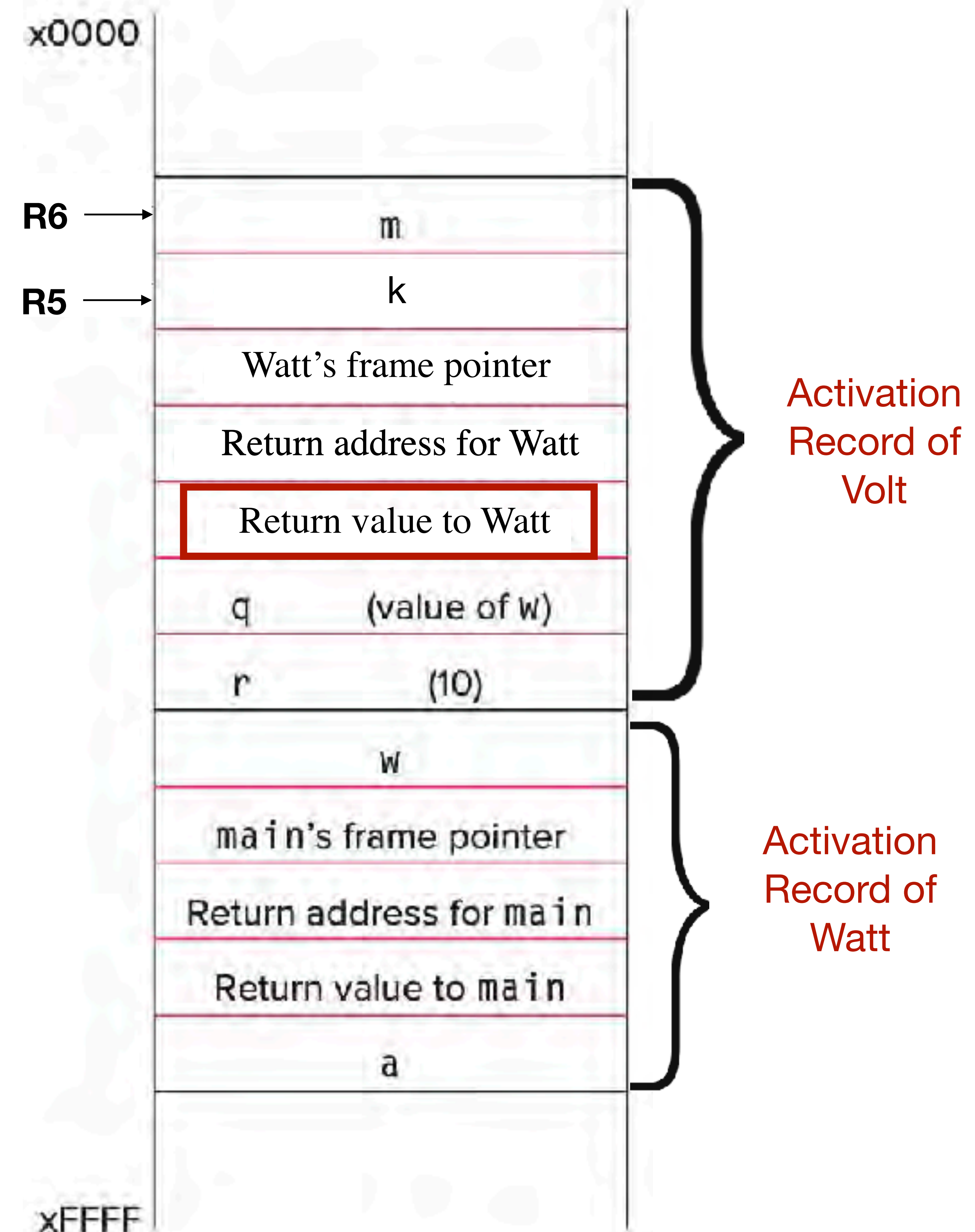
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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
```

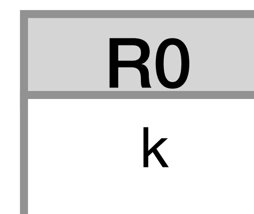


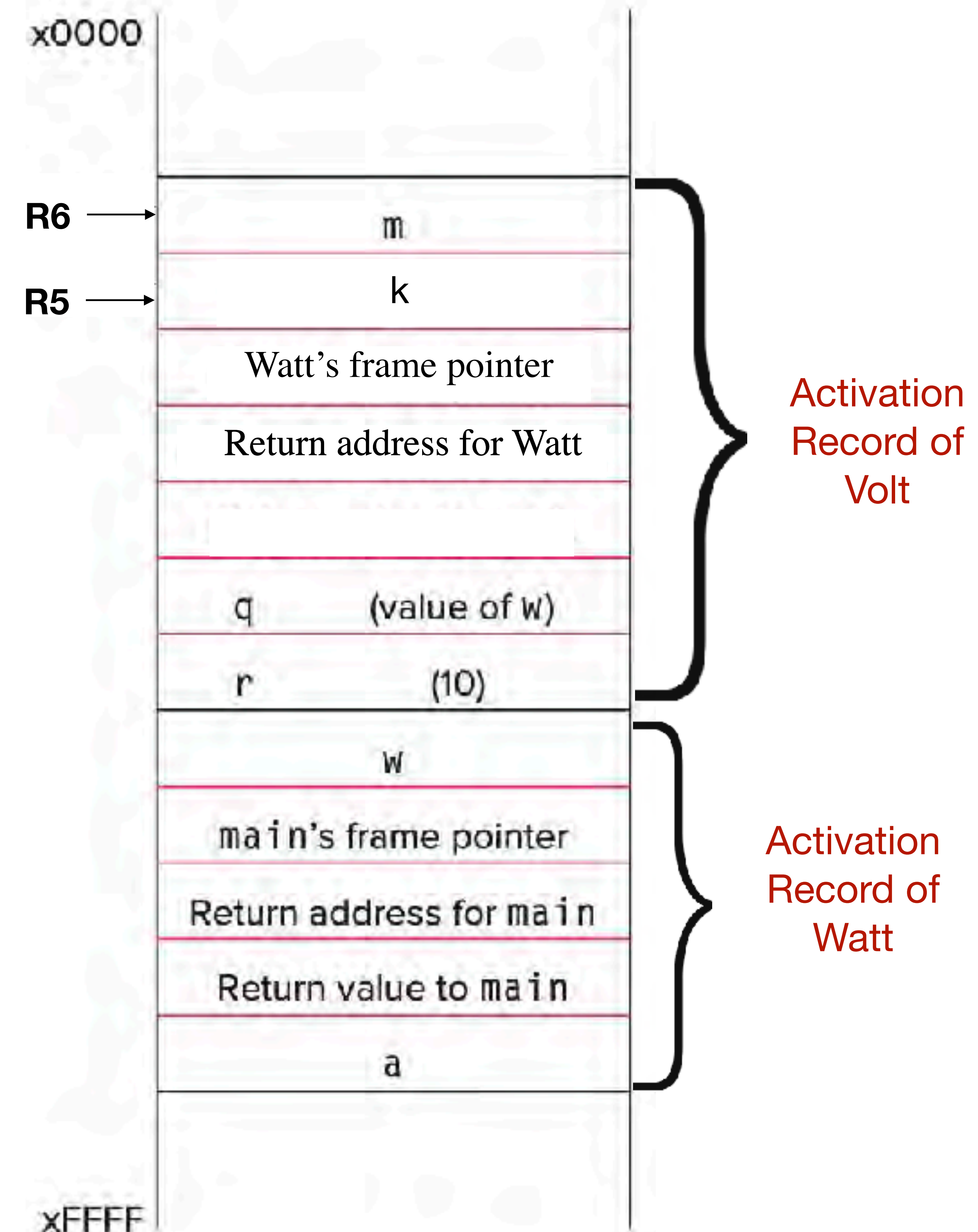


LC-3 Implementation

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
```





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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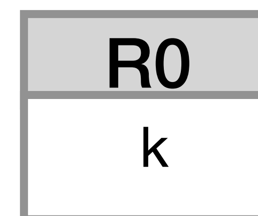
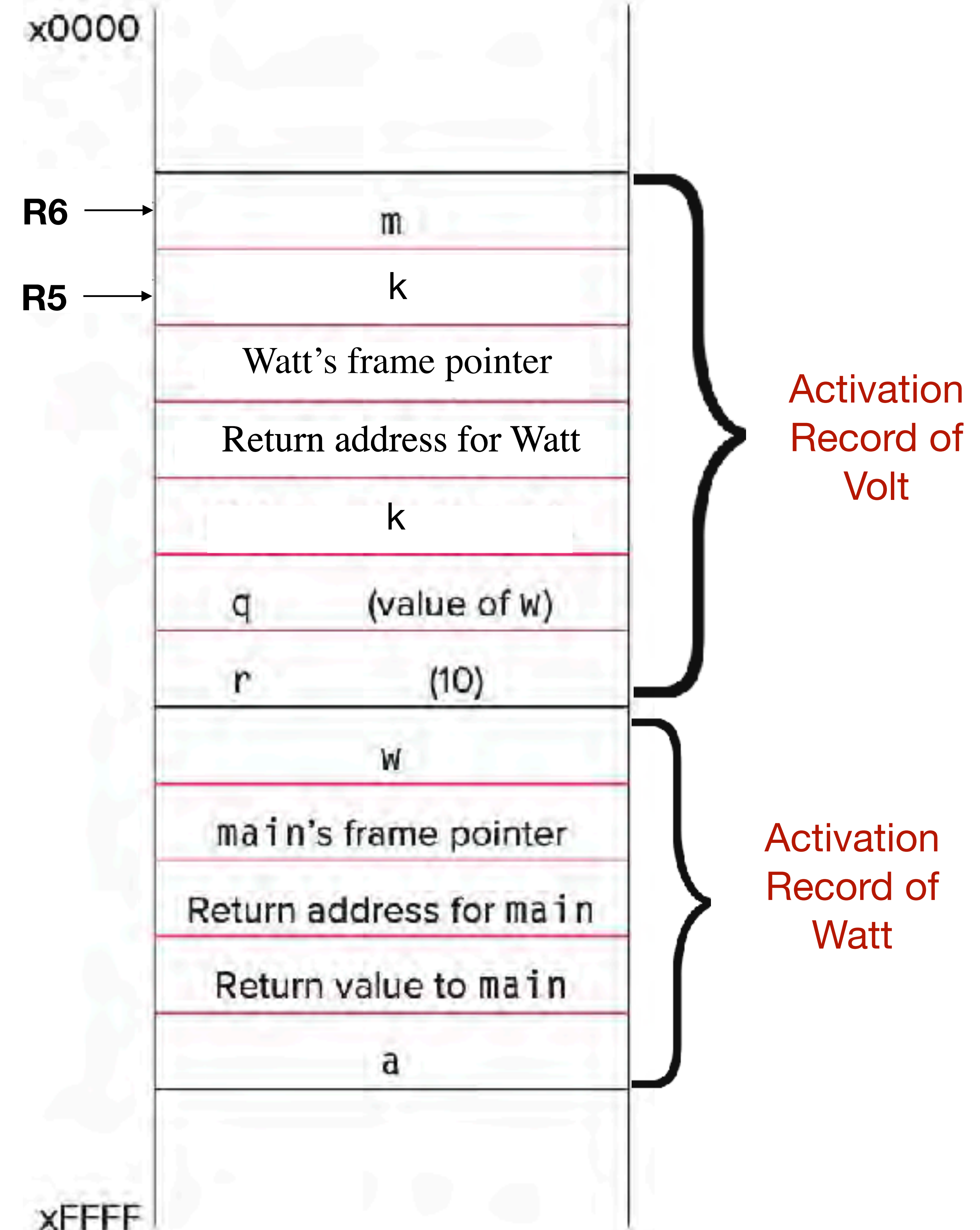


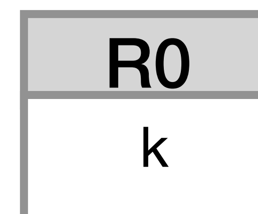


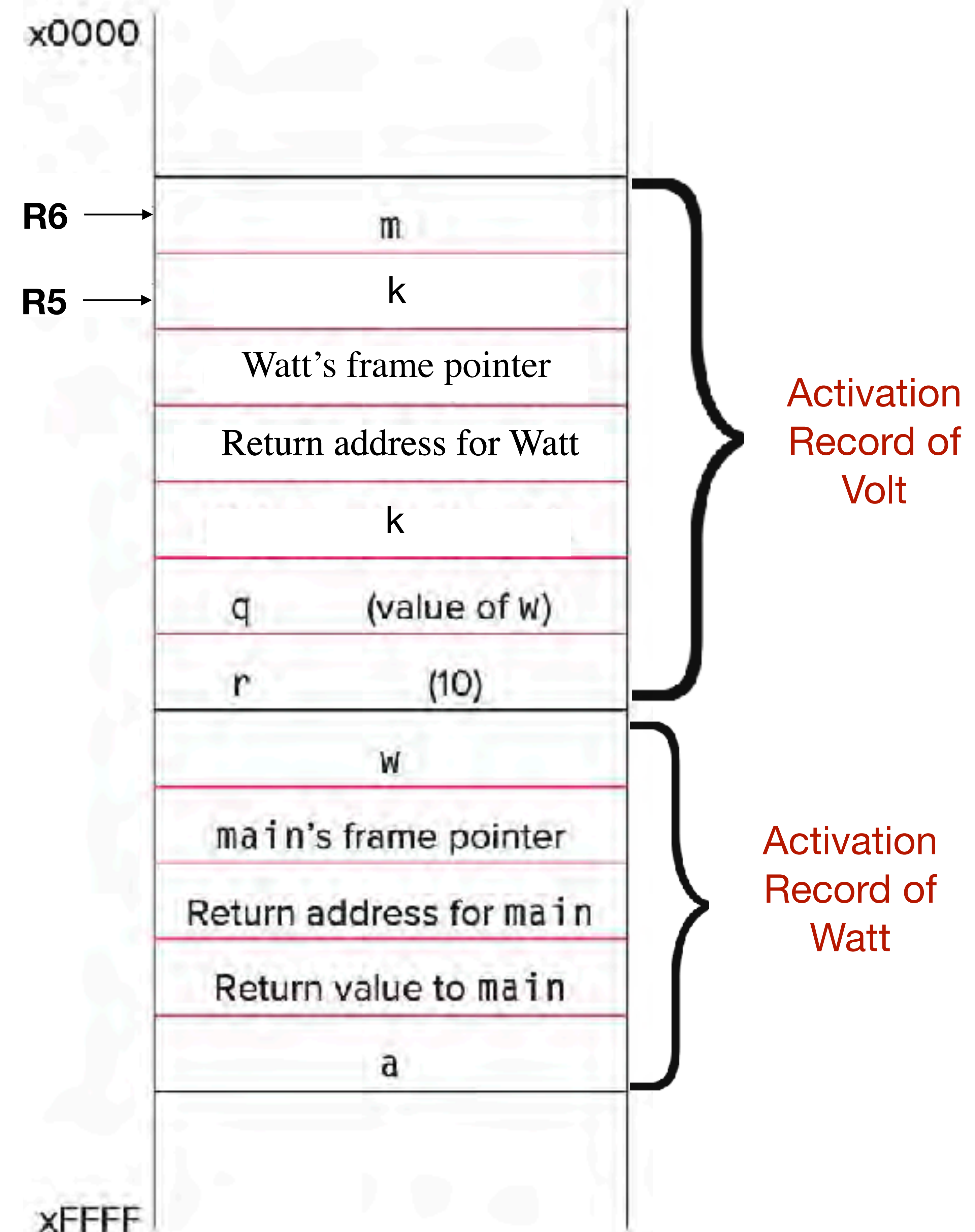
LC-3 Implementation

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
```



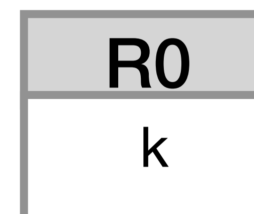


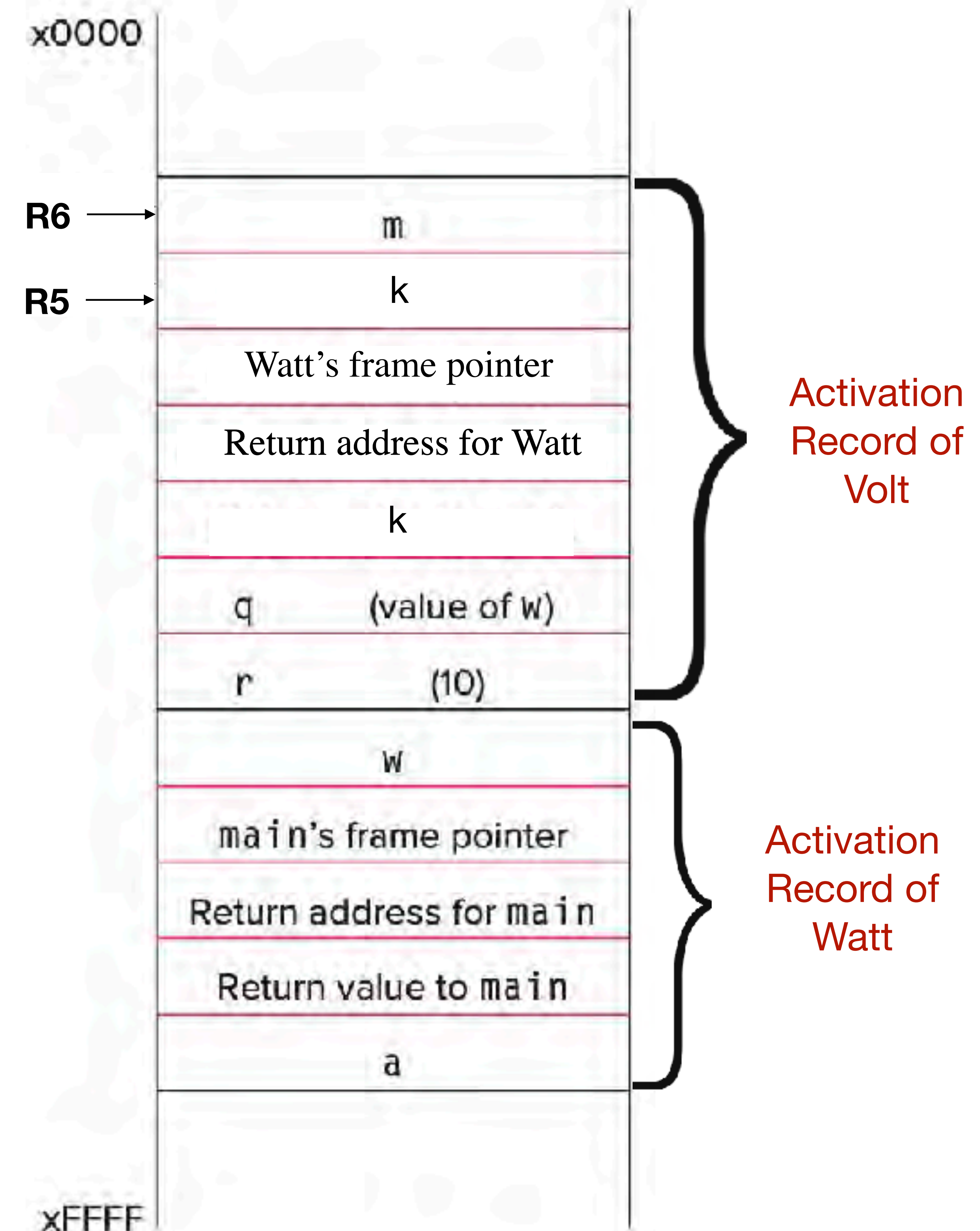
LC-3 Implementation

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
```





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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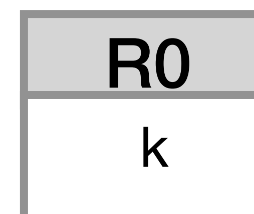
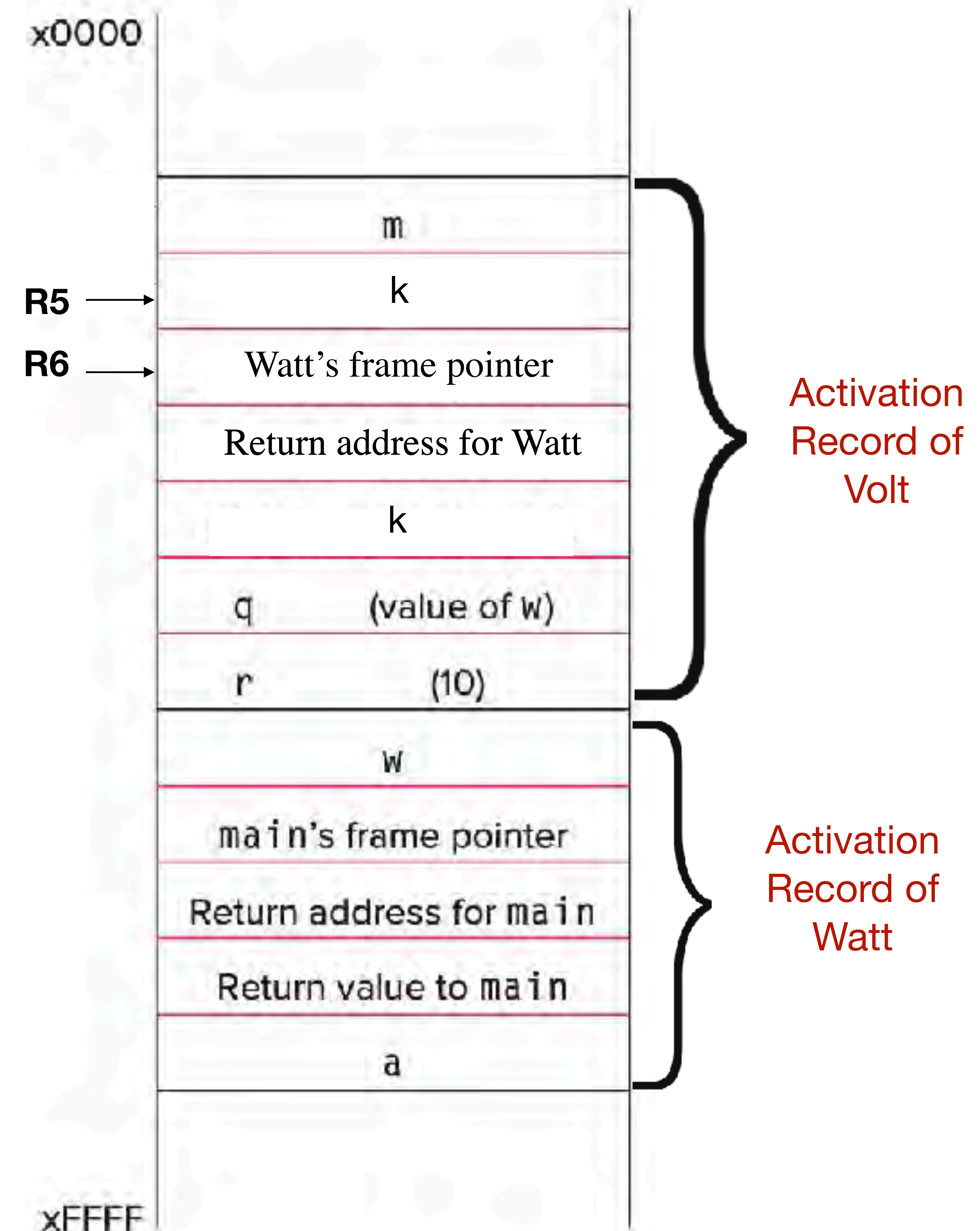
```





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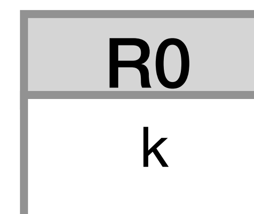
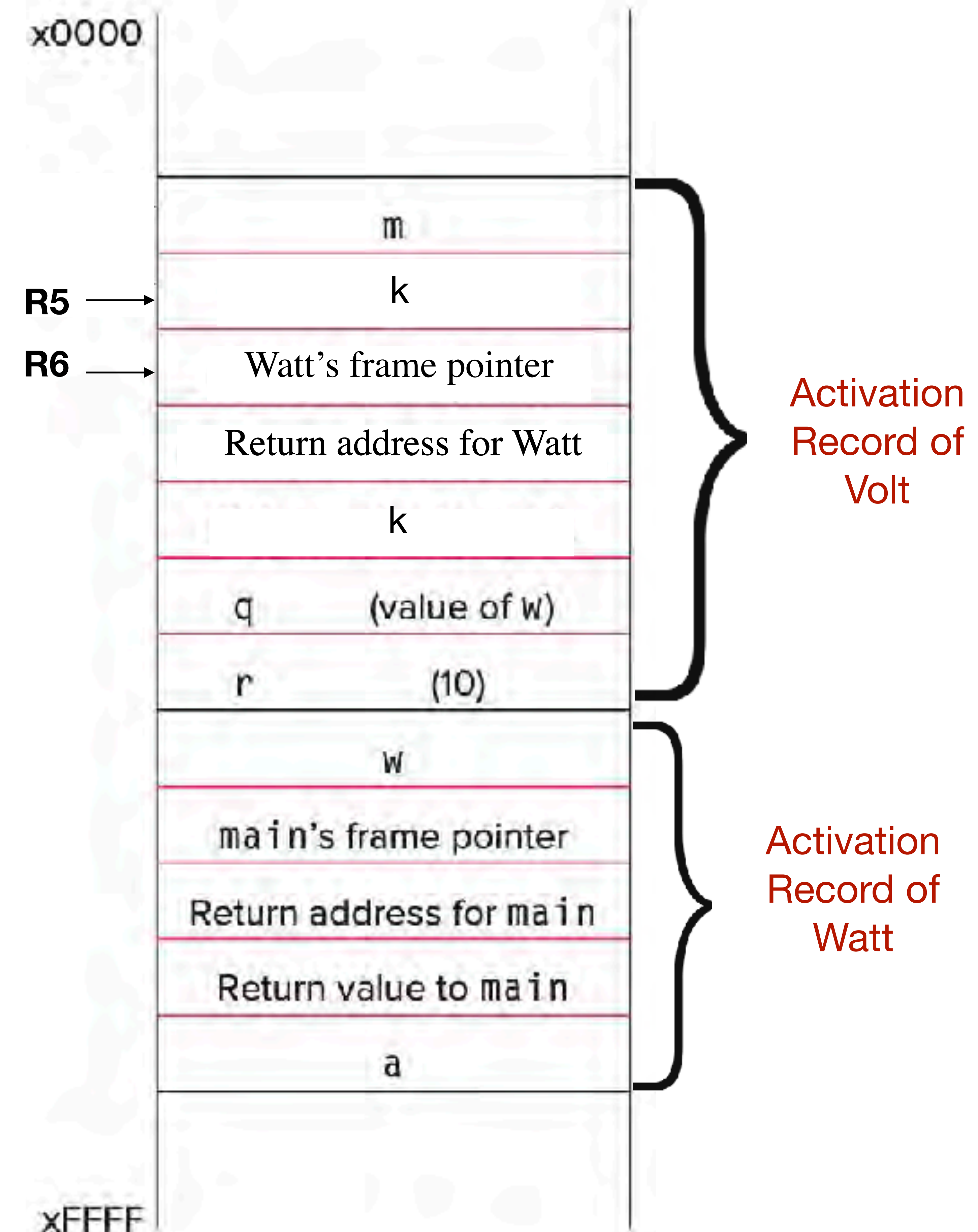
STR R0, R5, #3

; pop local variables
ADD R6, R5, #1

; pop Watt's frame pointer (to R5)
```





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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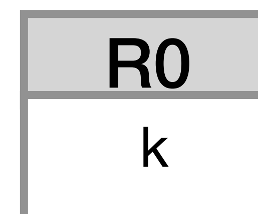
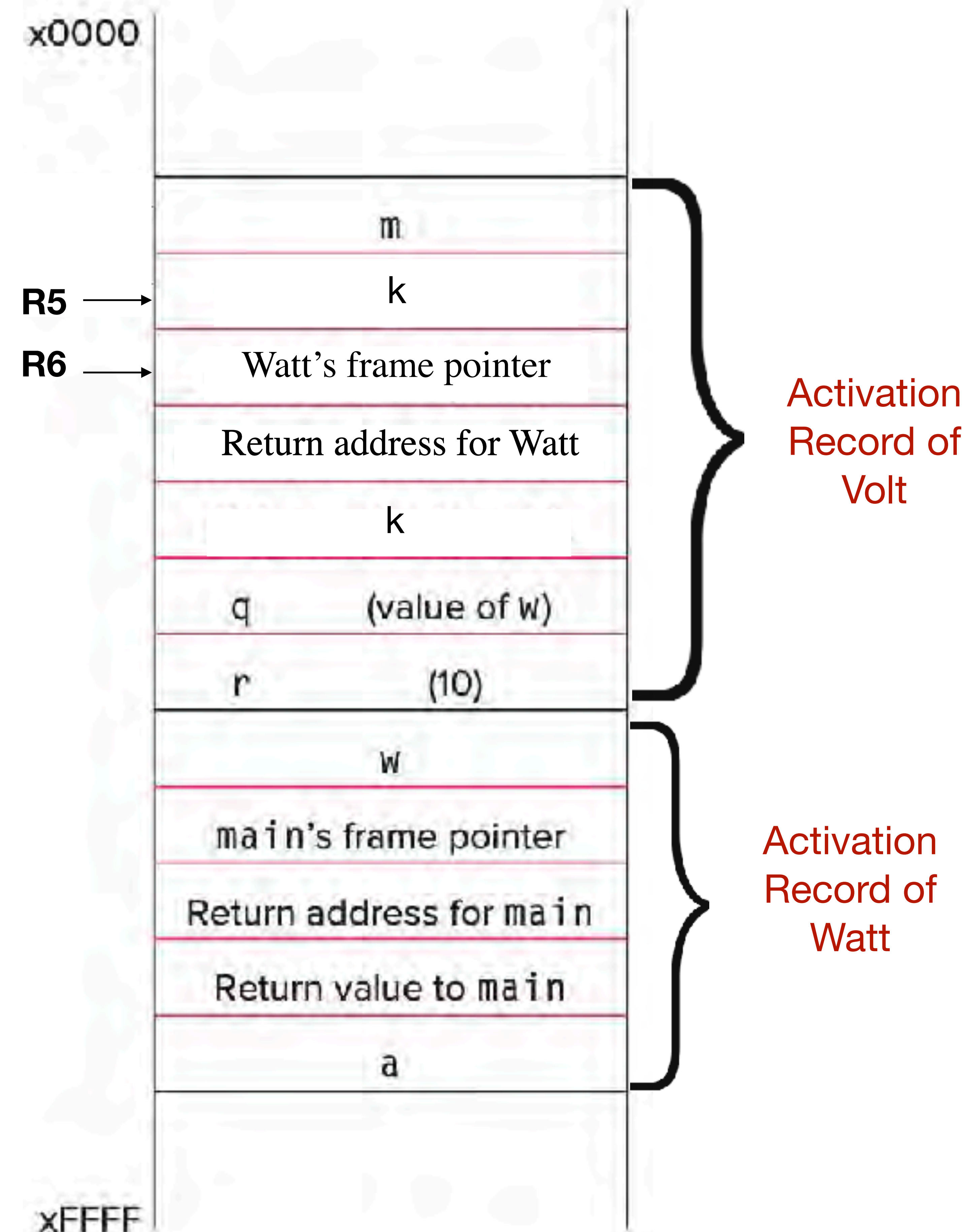
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
```





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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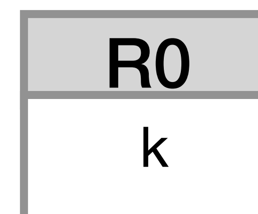
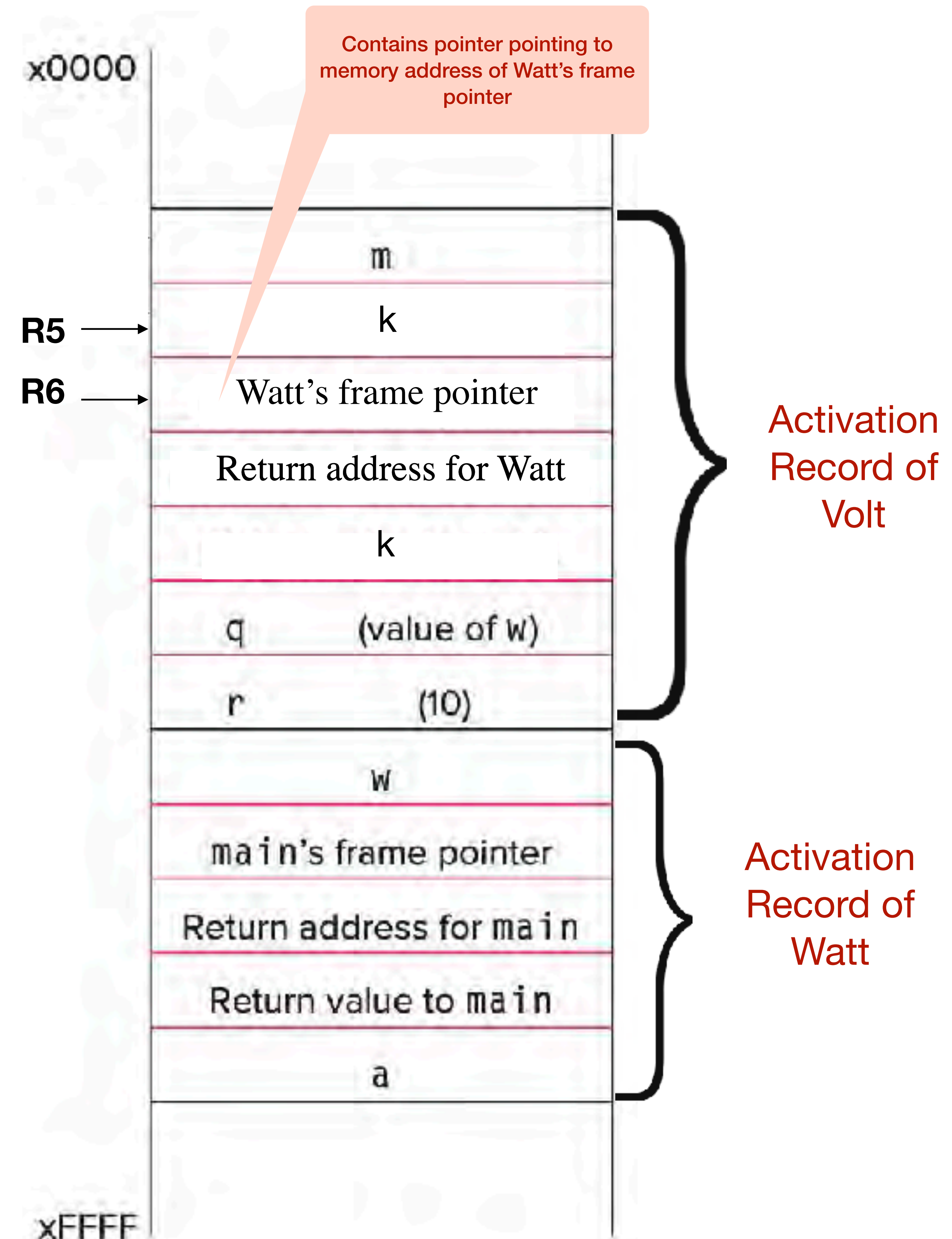
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
```





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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STR R0, R5, #3

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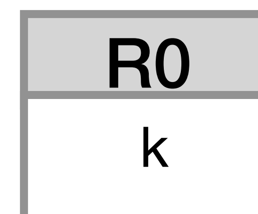
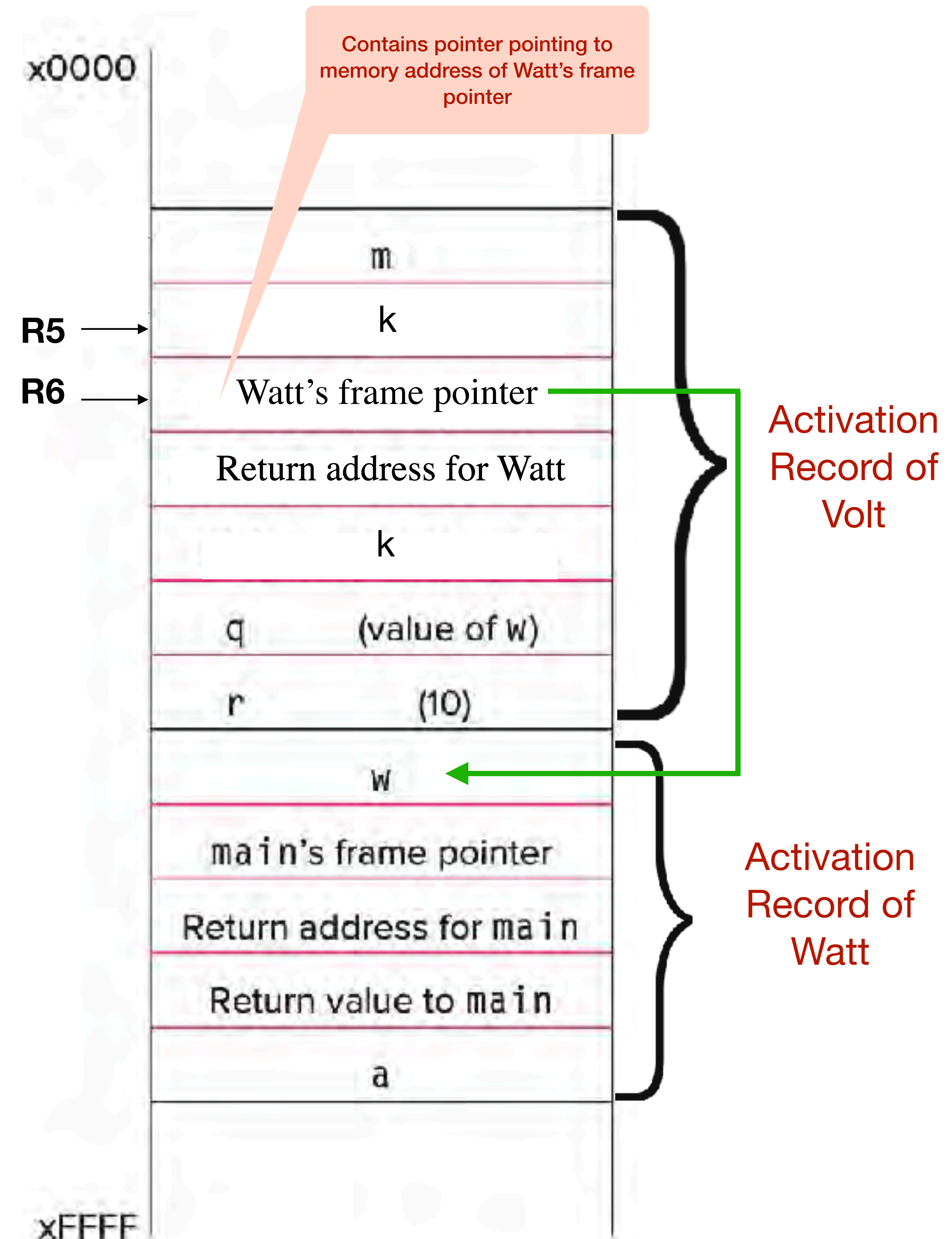
ADD R6, R5, #1

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





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LDR R0, R5, #0
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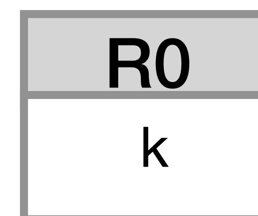
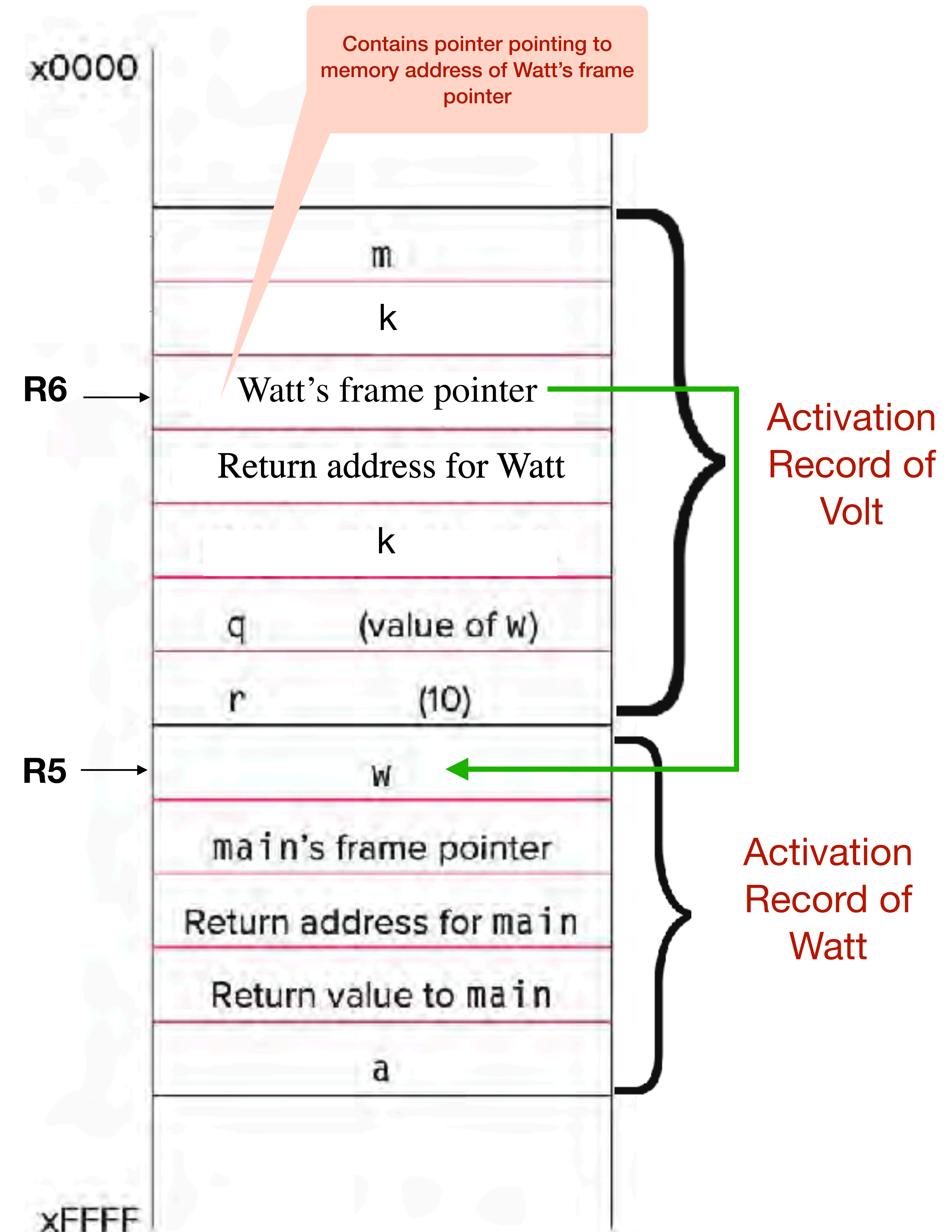
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
```





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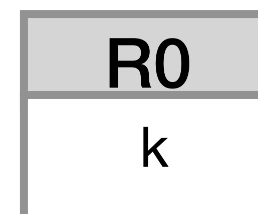
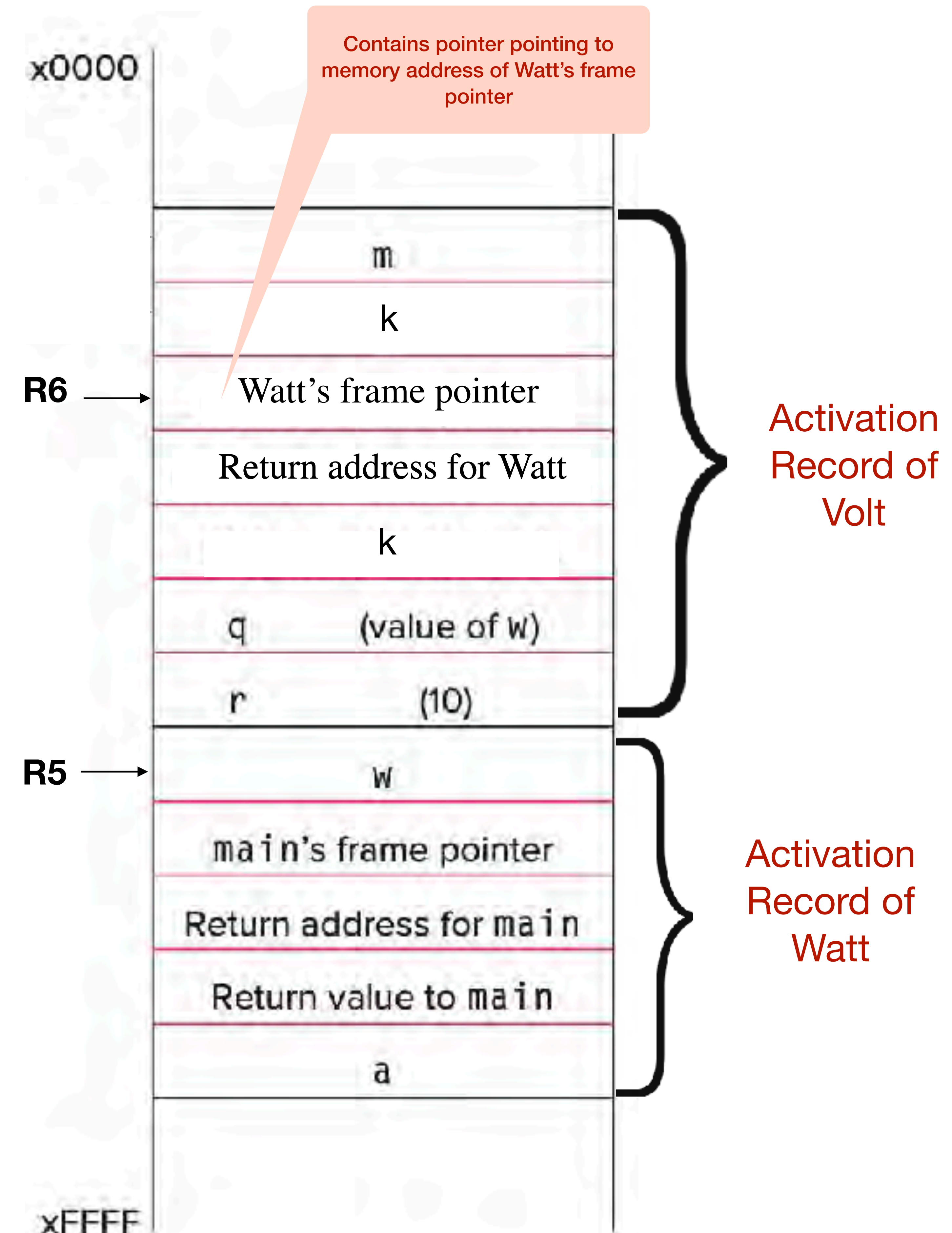
ADD R6, R5, #1

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





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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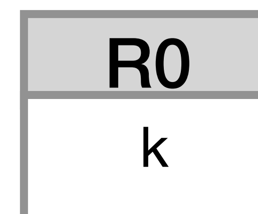
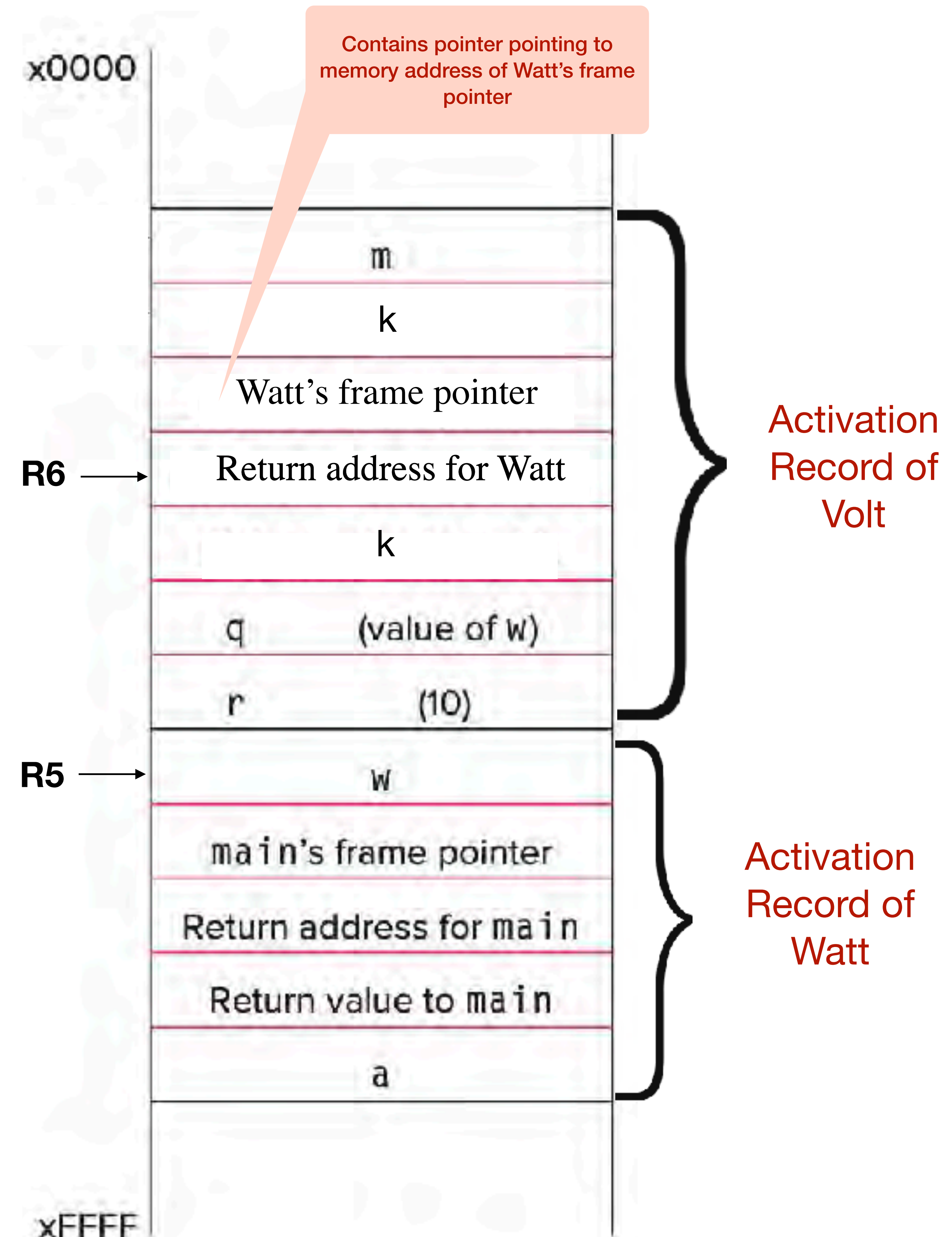
; pop local variables
ADD R6, R5, #1

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





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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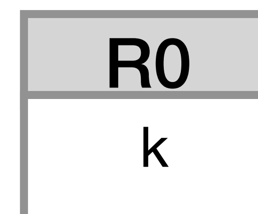
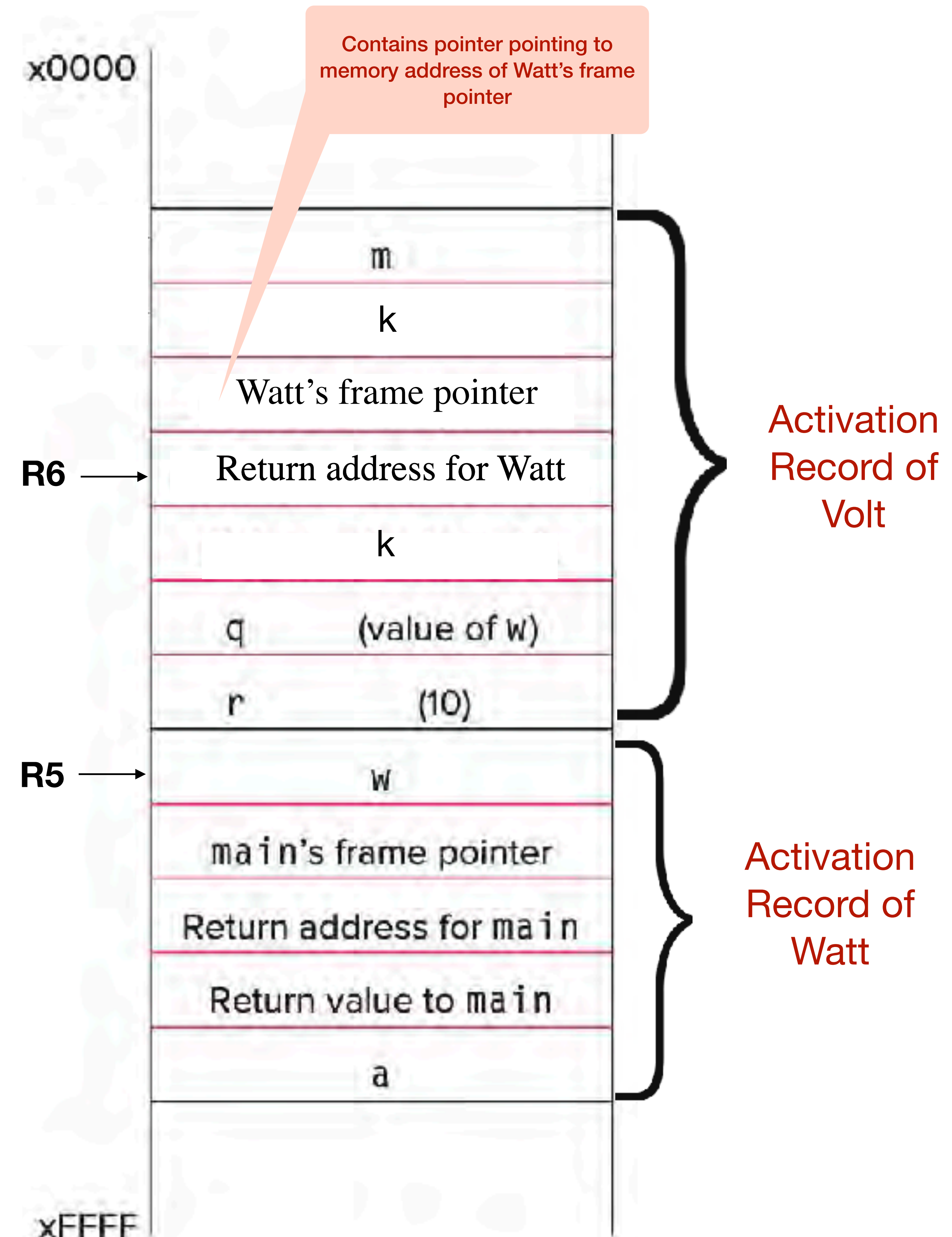
STR R0, R5, #3

; pop local variables
ADD R6, R5, #1

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





UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

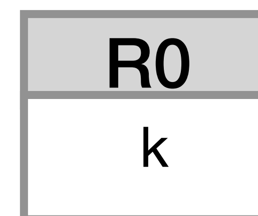
5. Callee tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)

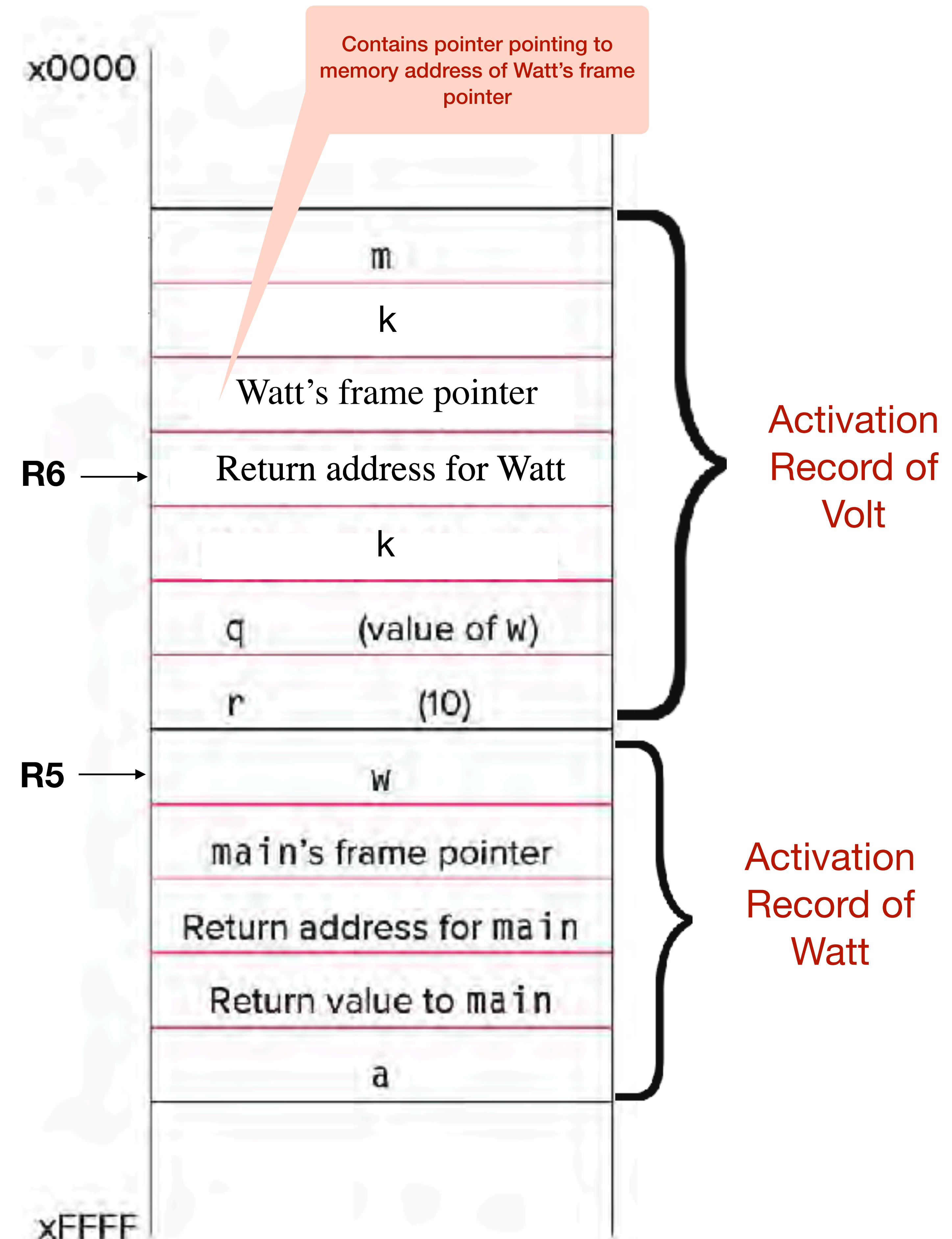
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

; 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)
```





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LC-3 Implementation

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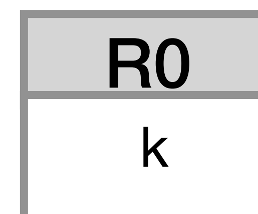
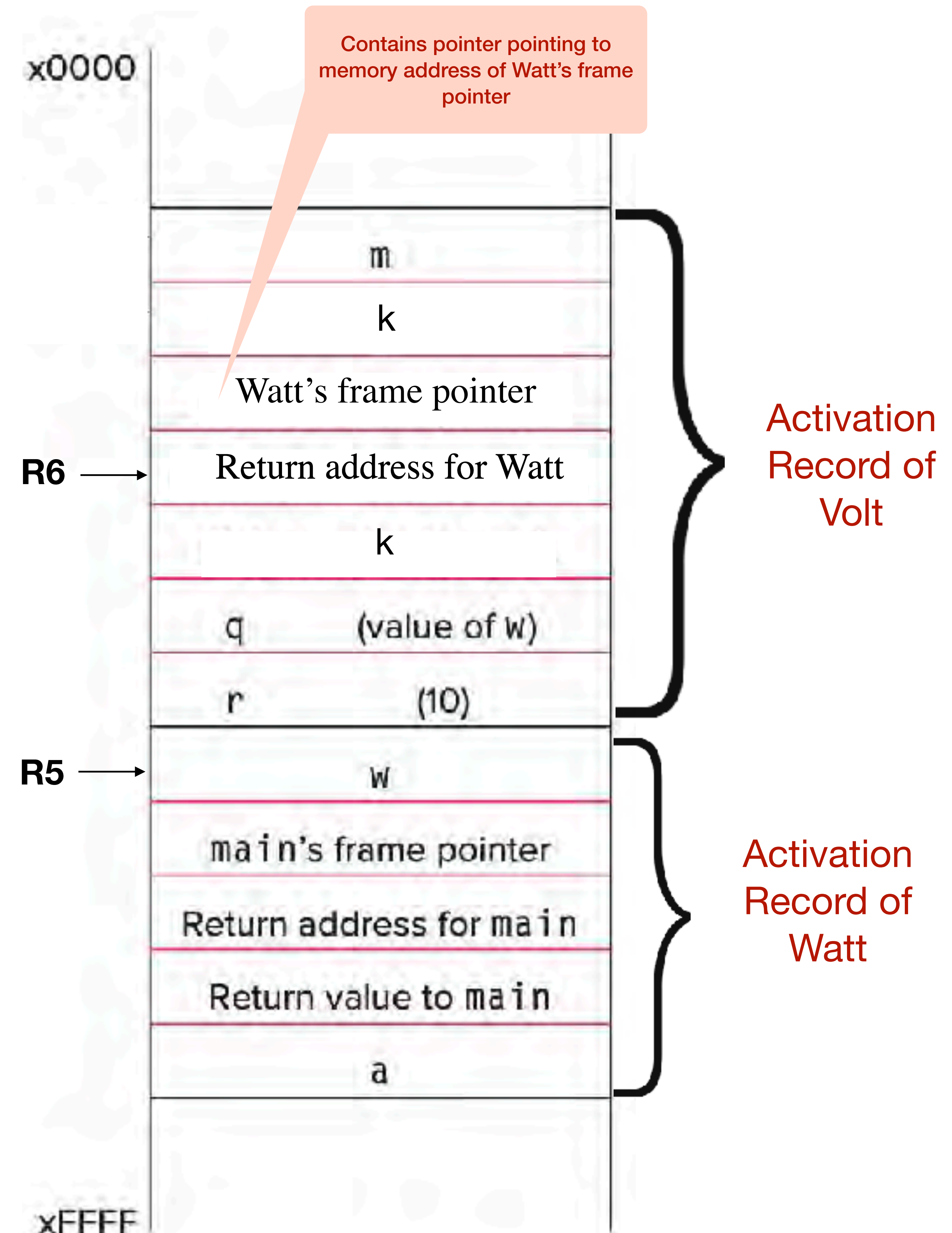
; pop local variables
ADD R6, R5, #1

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

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





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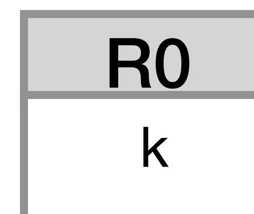
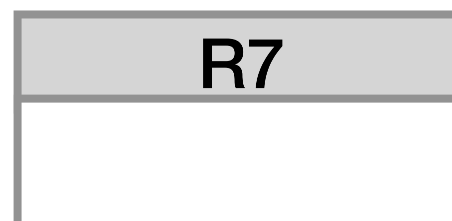
LDR R0, R5, #0
STR R0, R5, #3

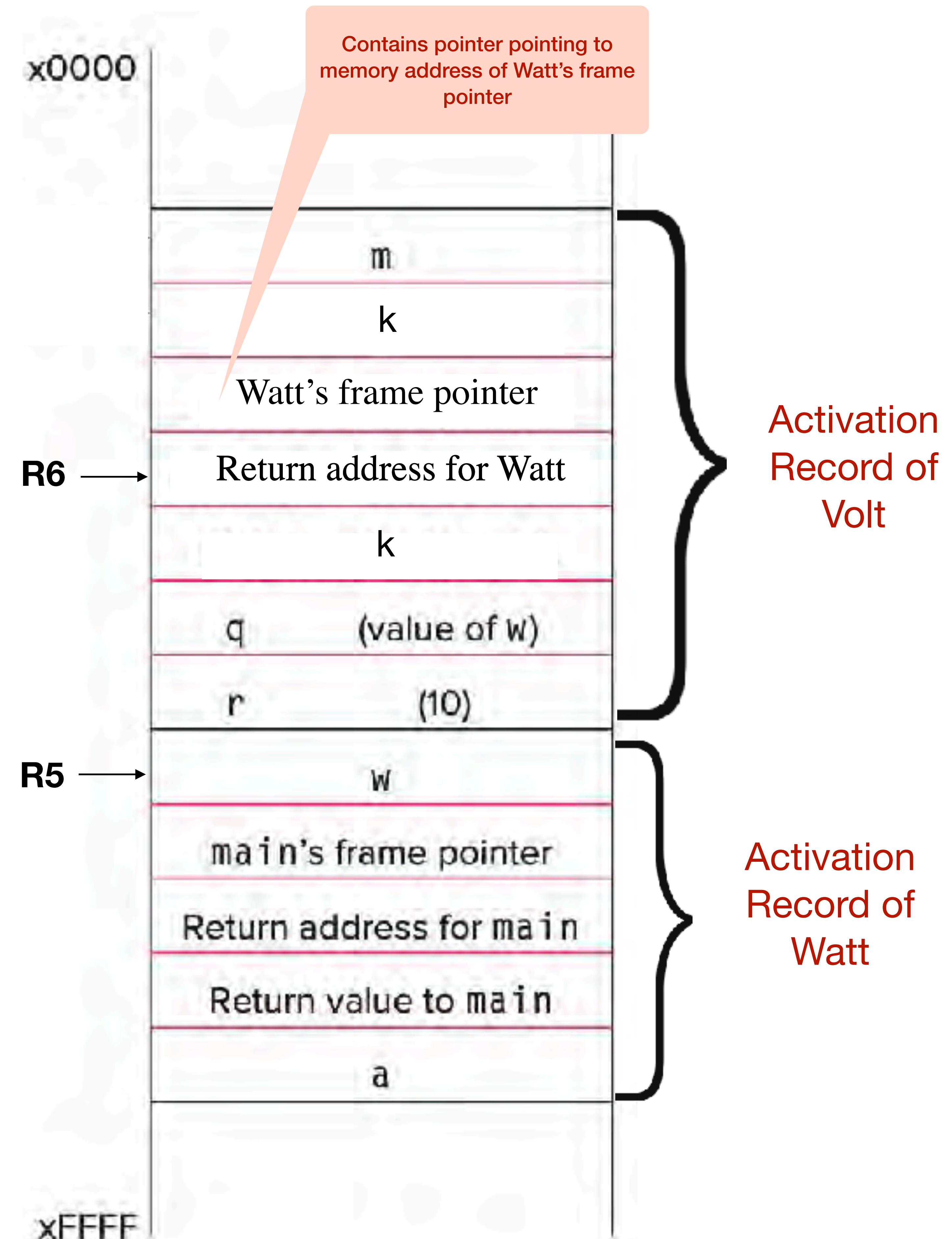
; pop local variables
ADD R6, R5, #1

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

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







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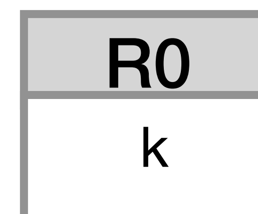
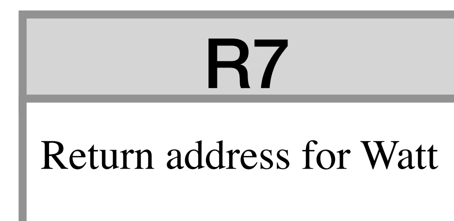
STR R0, R5, #3

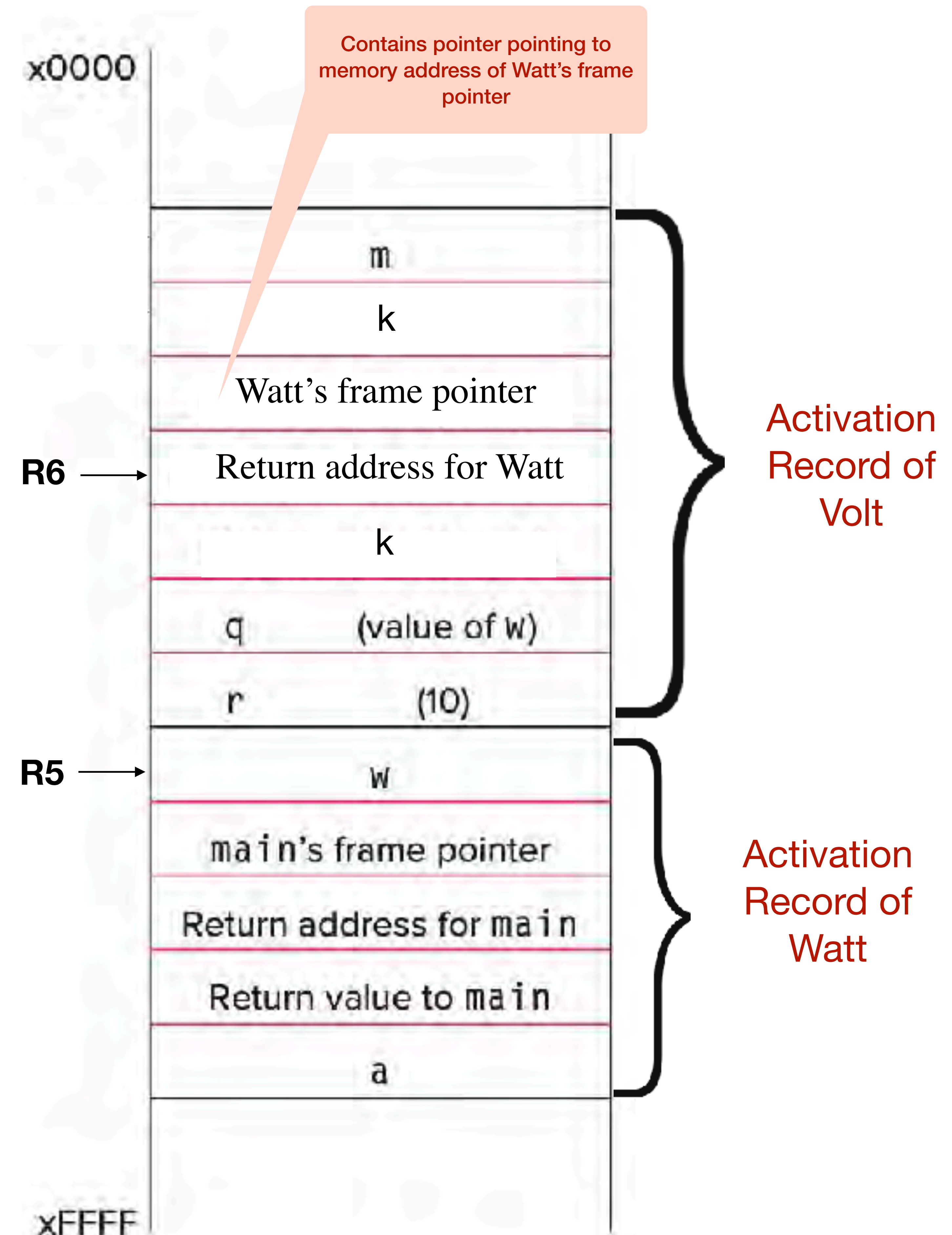
; pop local variables
ADD R6, R5, #1

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

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







LC-3 Implementation

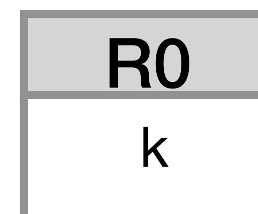
5. Callee tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)

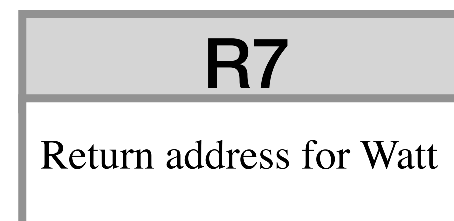
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

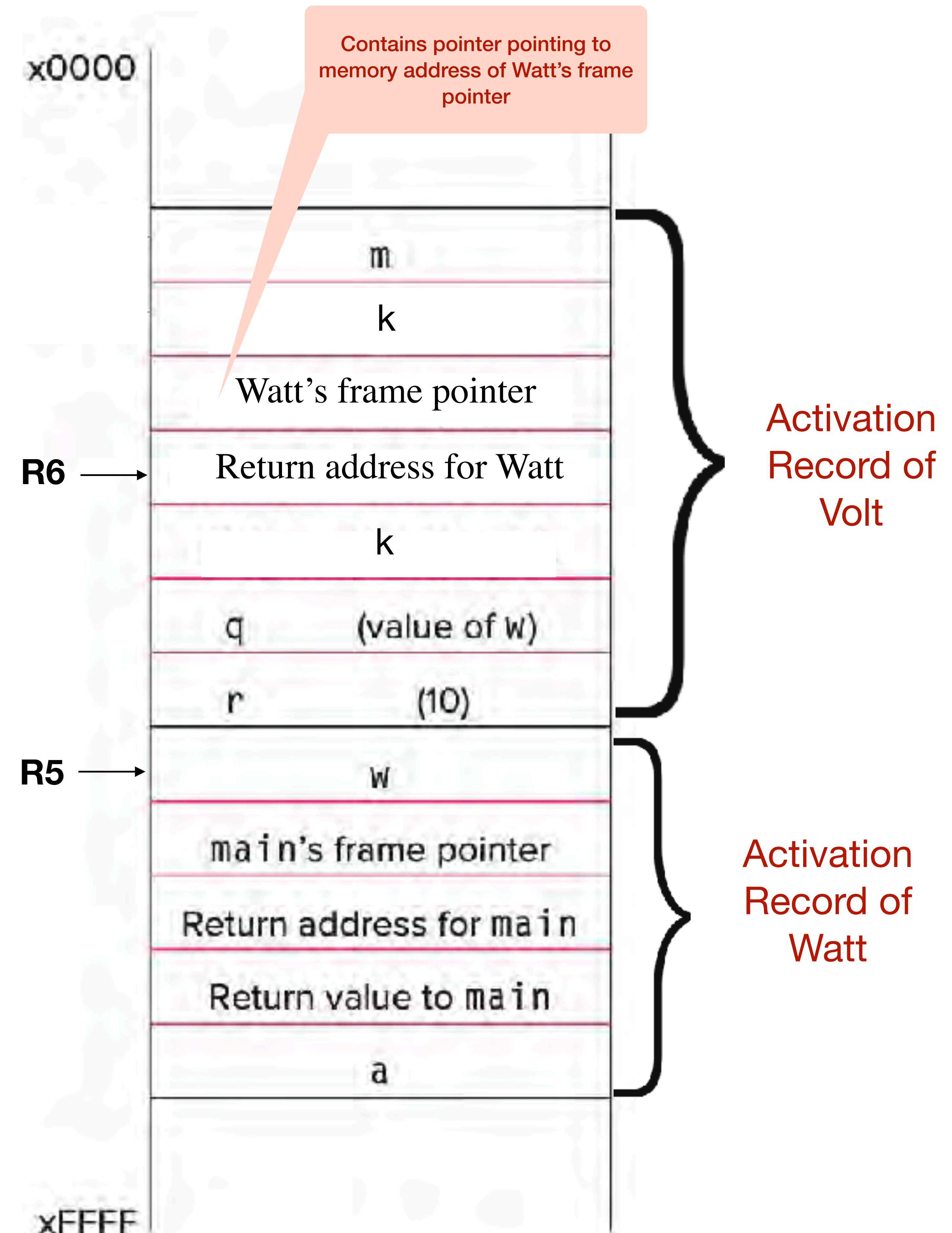
; pop local variables
ADD R6, R5, #1

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

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







UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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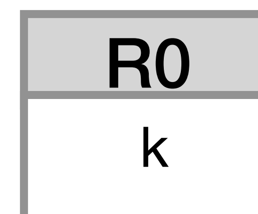
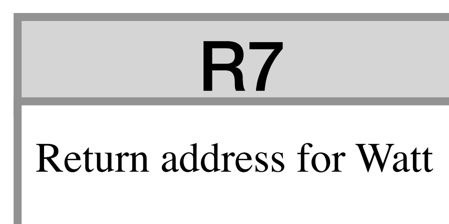
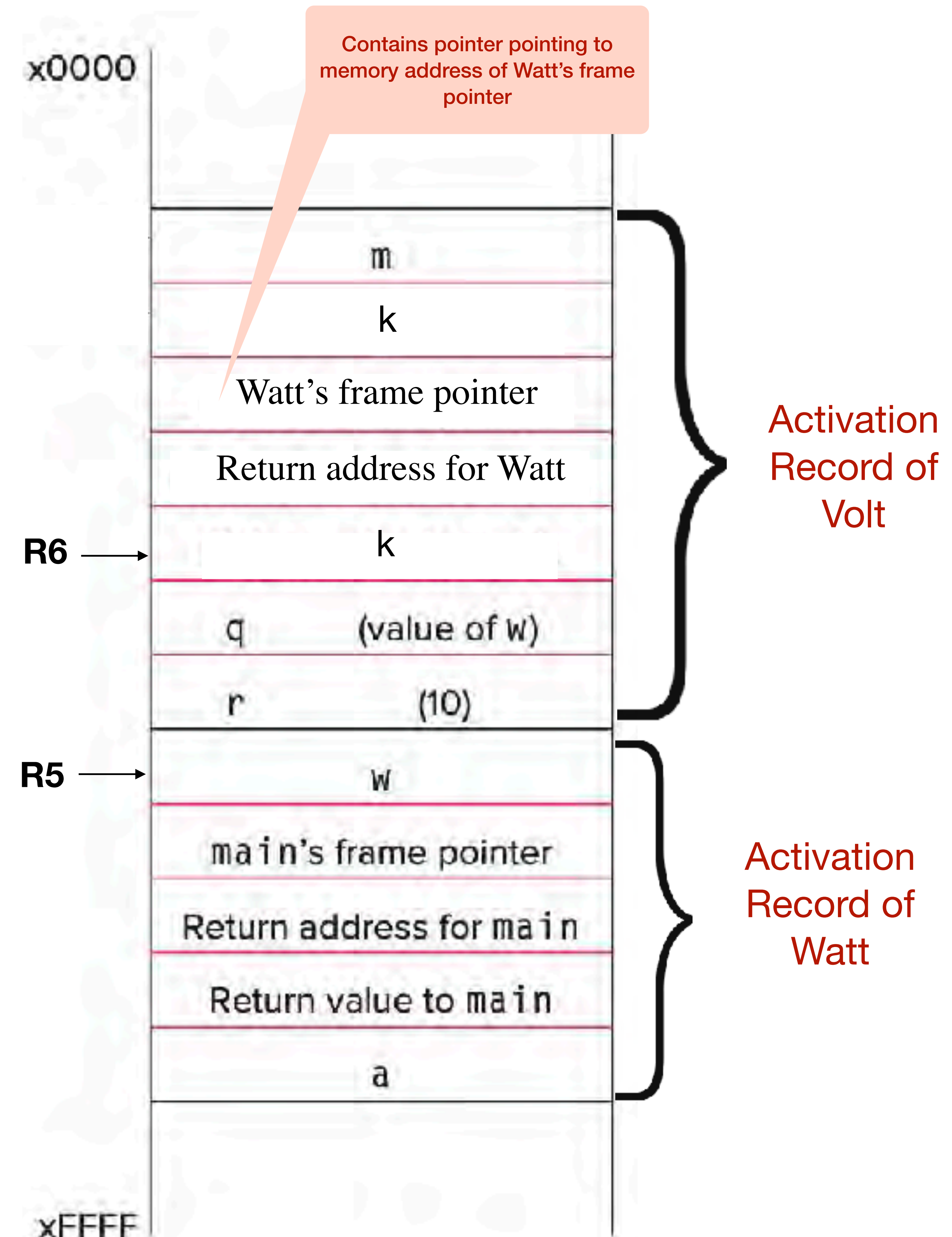
; pop local variables
ADD R6, R5, #1

; 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
```







UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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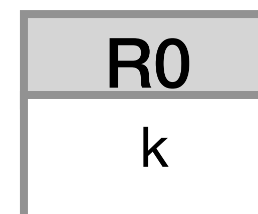
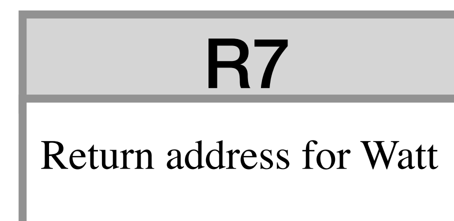
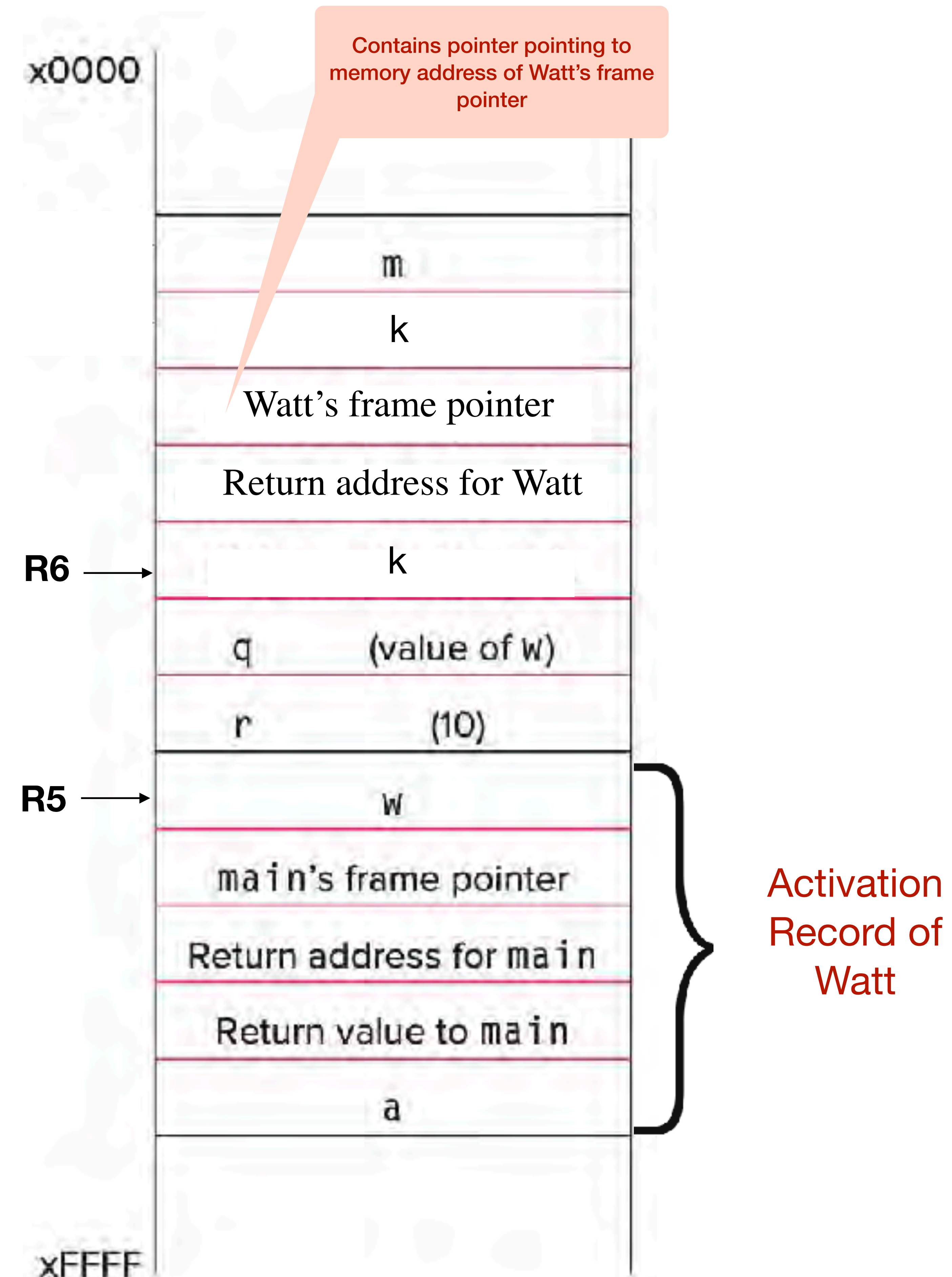
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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







UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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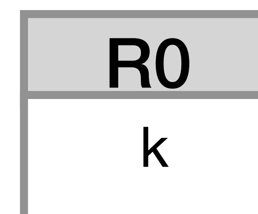
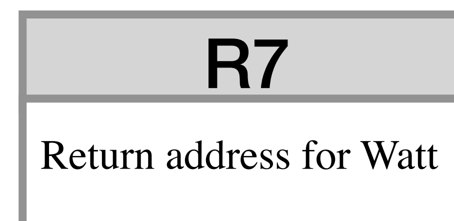
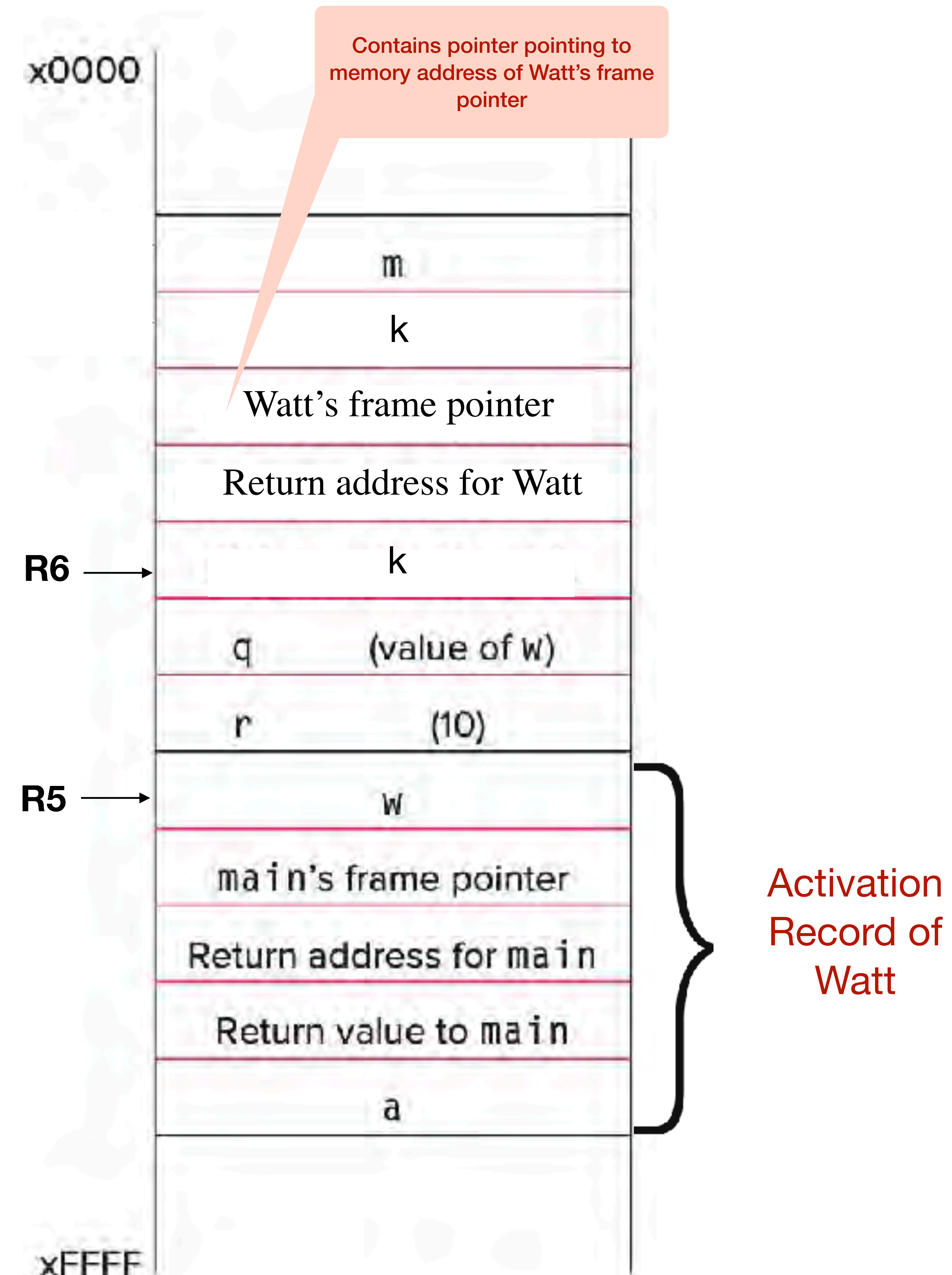
ADD R6, R6, #1

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

; return control to caller
```







UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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

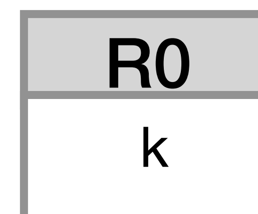
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

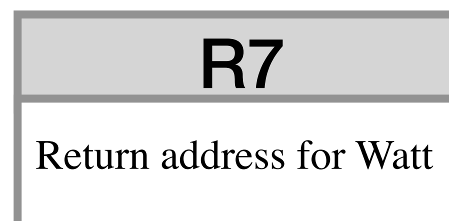
; pop local variables
ADD R6, R5, #1

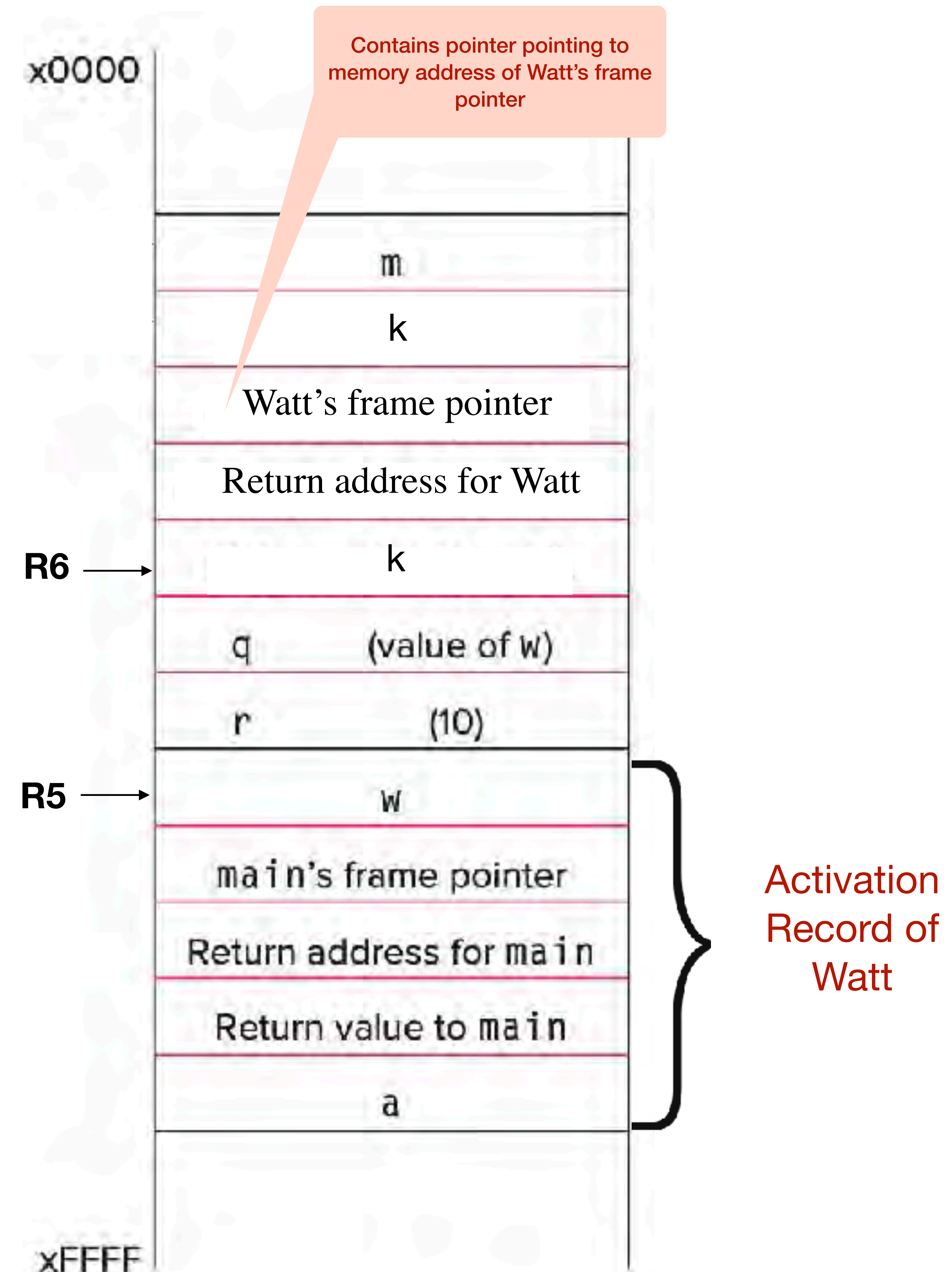
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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

; return control to caller
RET
```







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

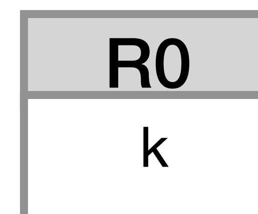
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

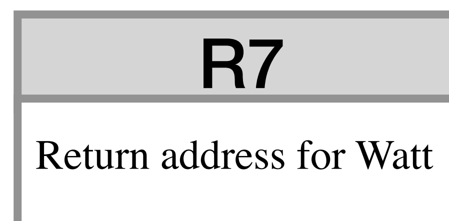
; pop local variables
ADD R6, R5, #1

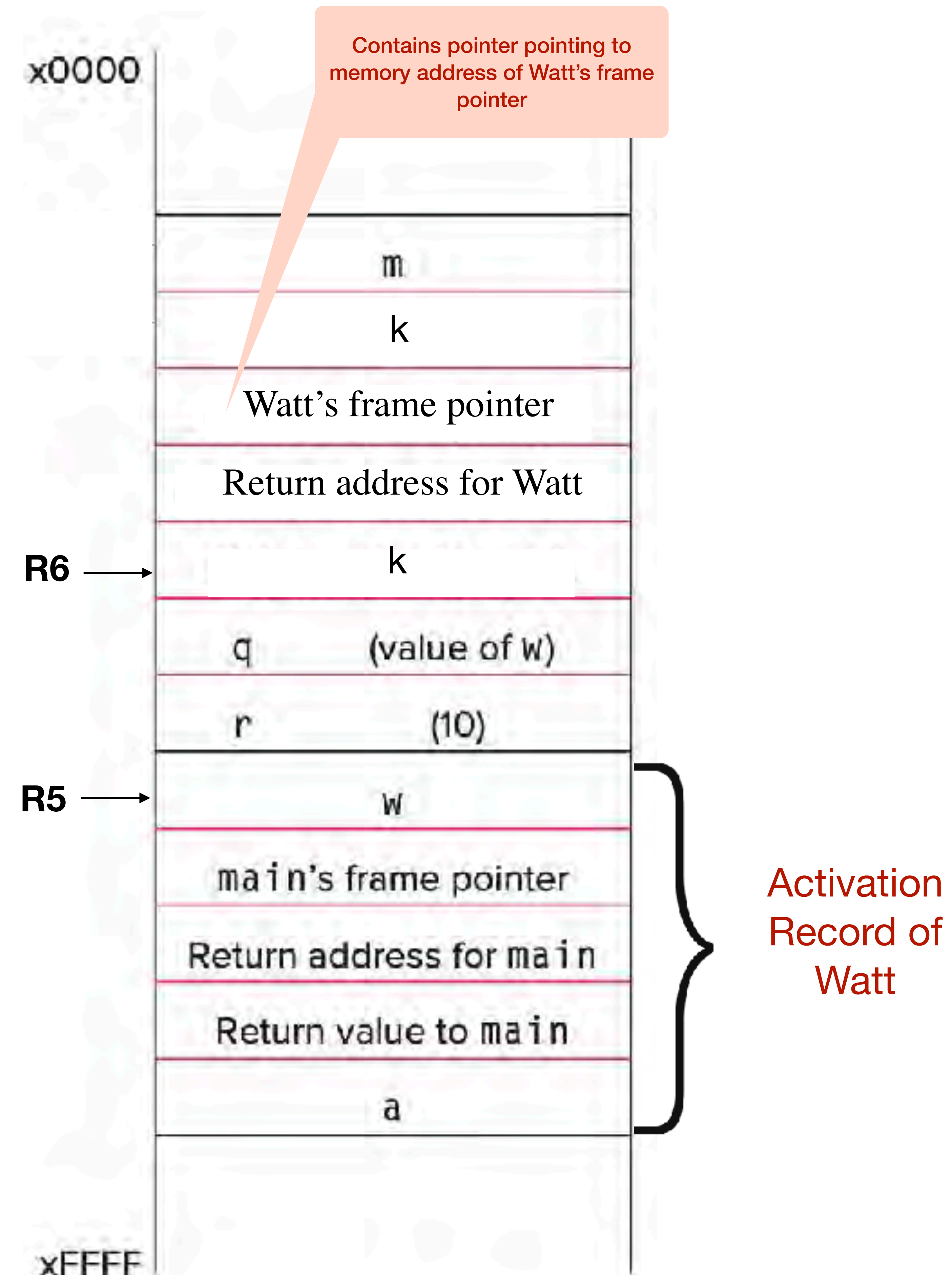
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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

; return control to caller
RET
```







UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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

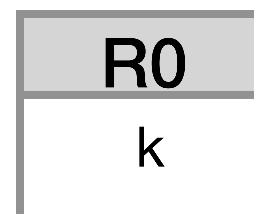
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

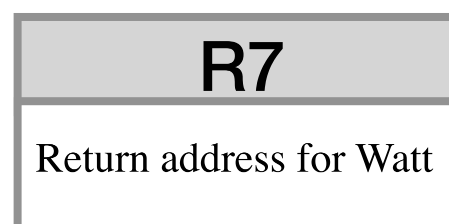
; pop local variables
ADD R6, R5, #1

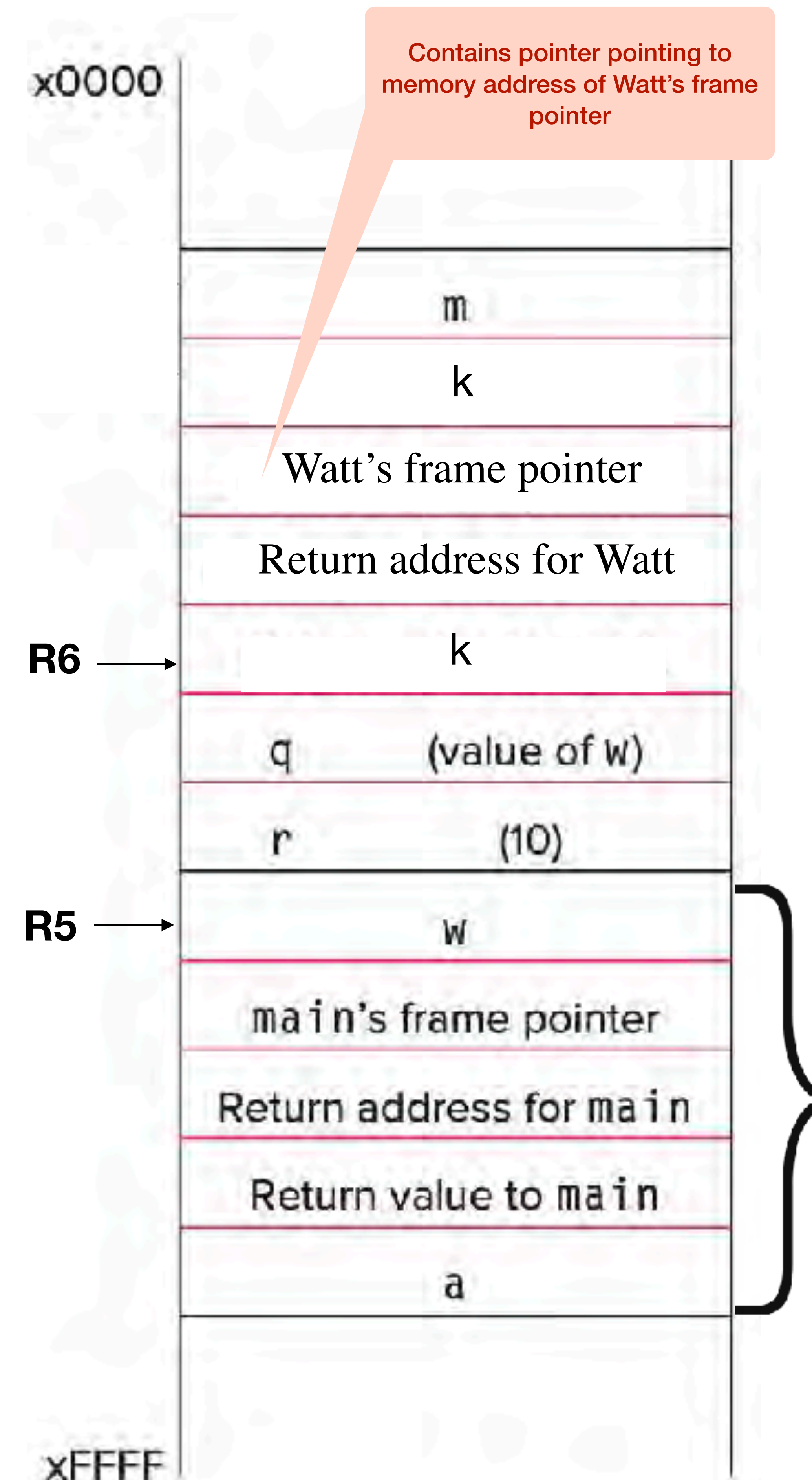
; pop Watt's frame pointer (to R5)
LDR R5, R6, #0
ADD R6, R6, #1

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

; return control to caller
RET
```

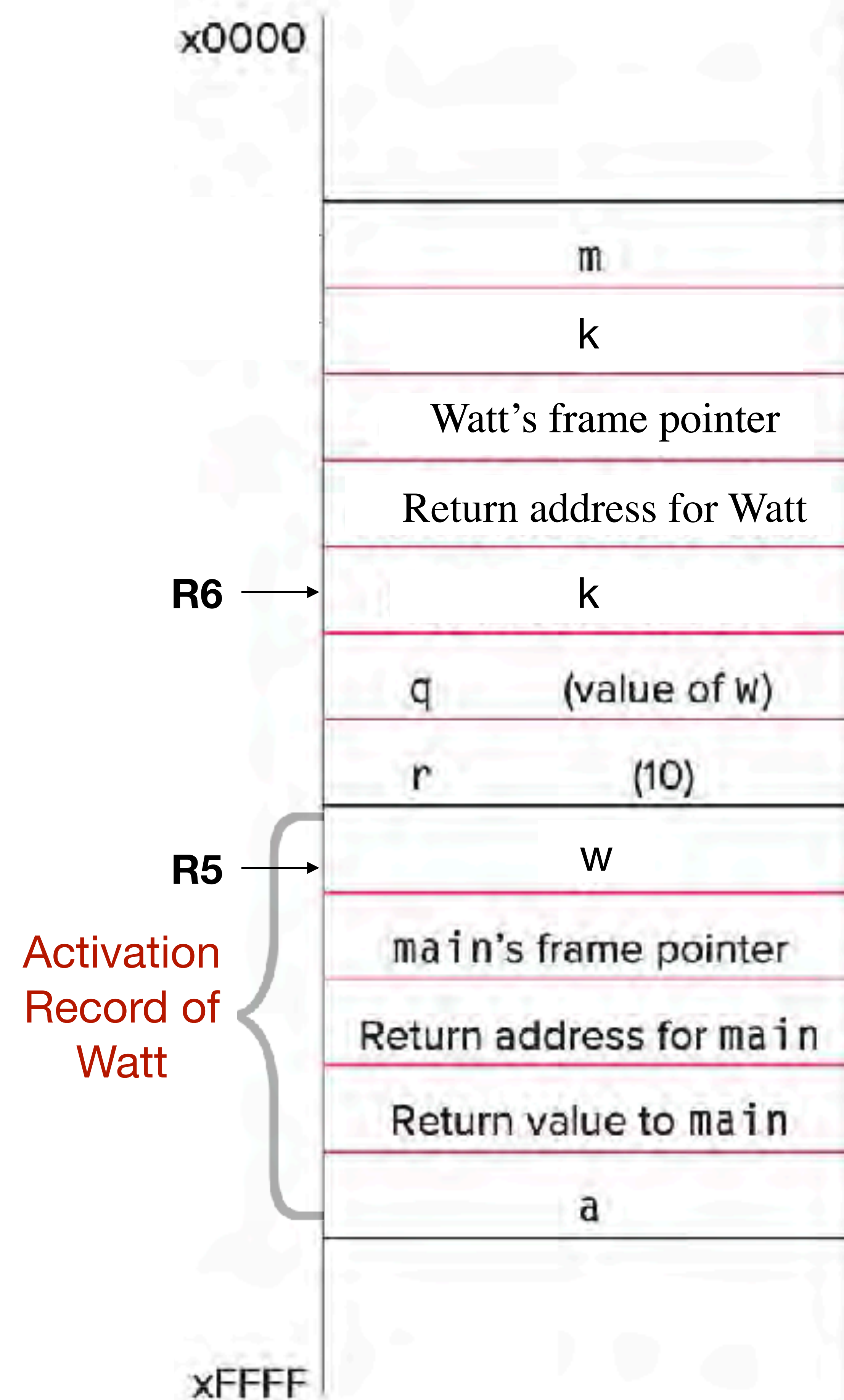






Note :
Even though the stack frame for `Volt` is popped off the stack, its values remain in memory until they are explicitly overwritten

LC-3 Implementation



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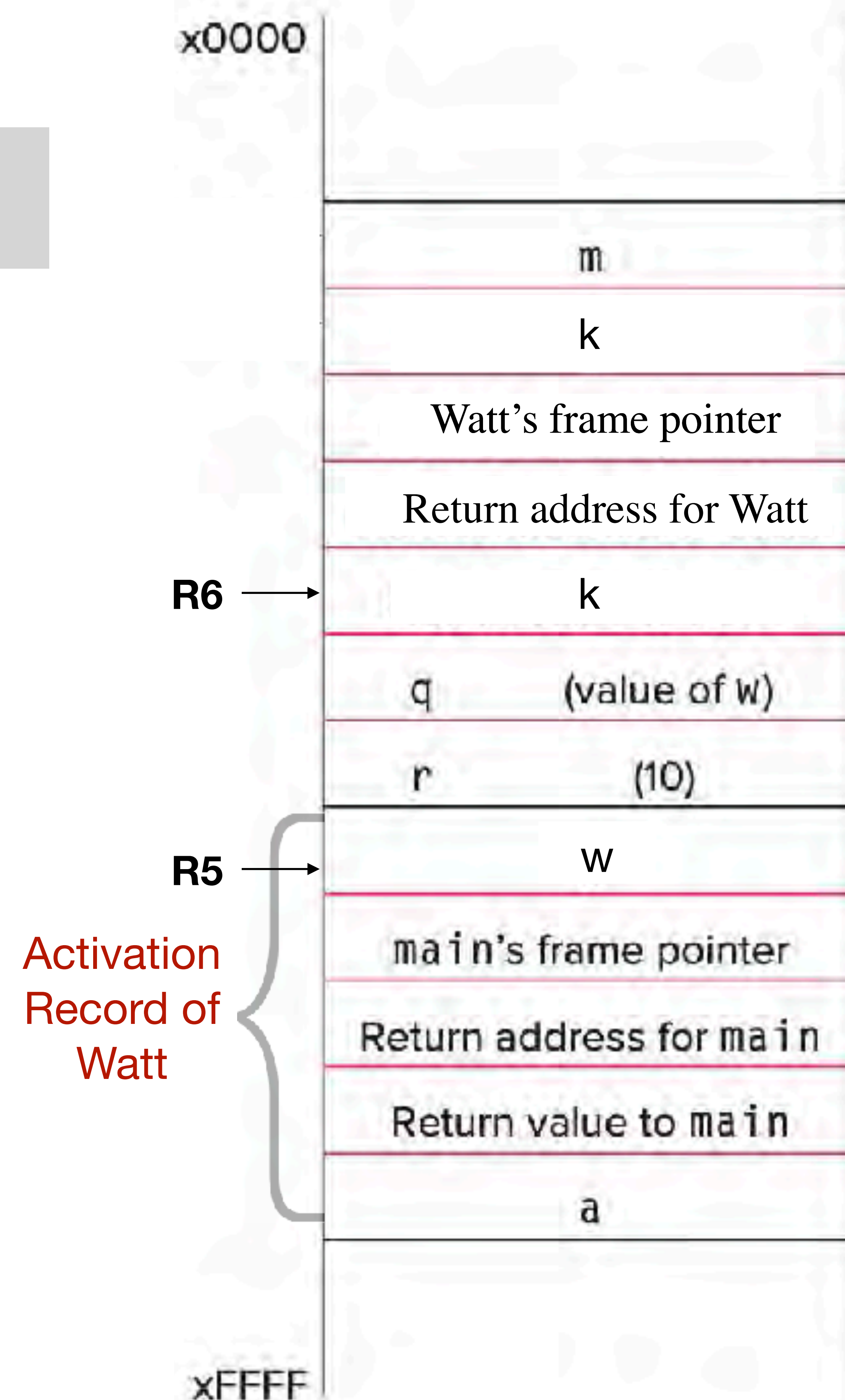
LC-3 Implementation

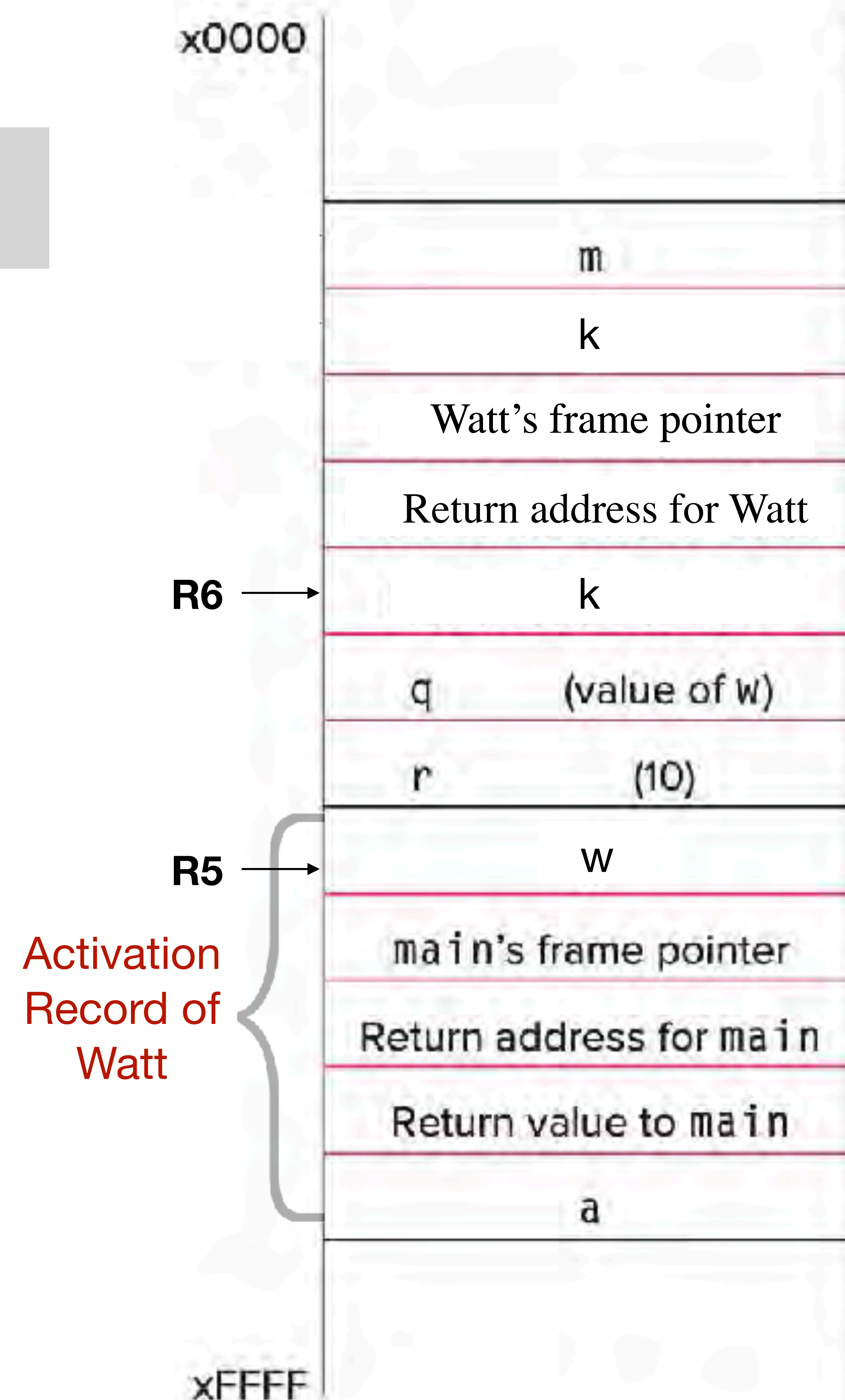
7. Caller tear-down (pop callee's return value and arguments from stack)



LC-3 Implementation

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

```
JSR VOLT
```

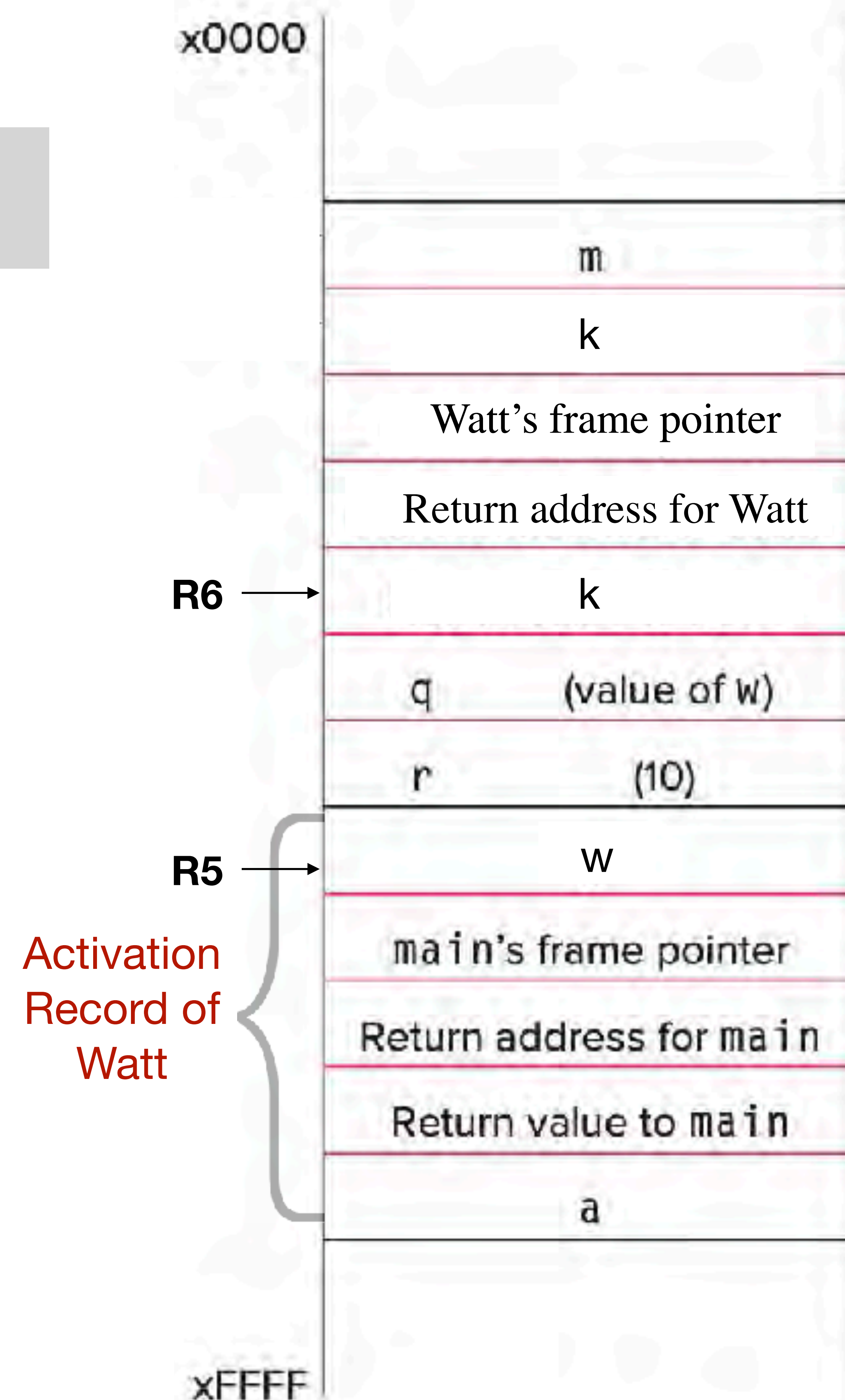


UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

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

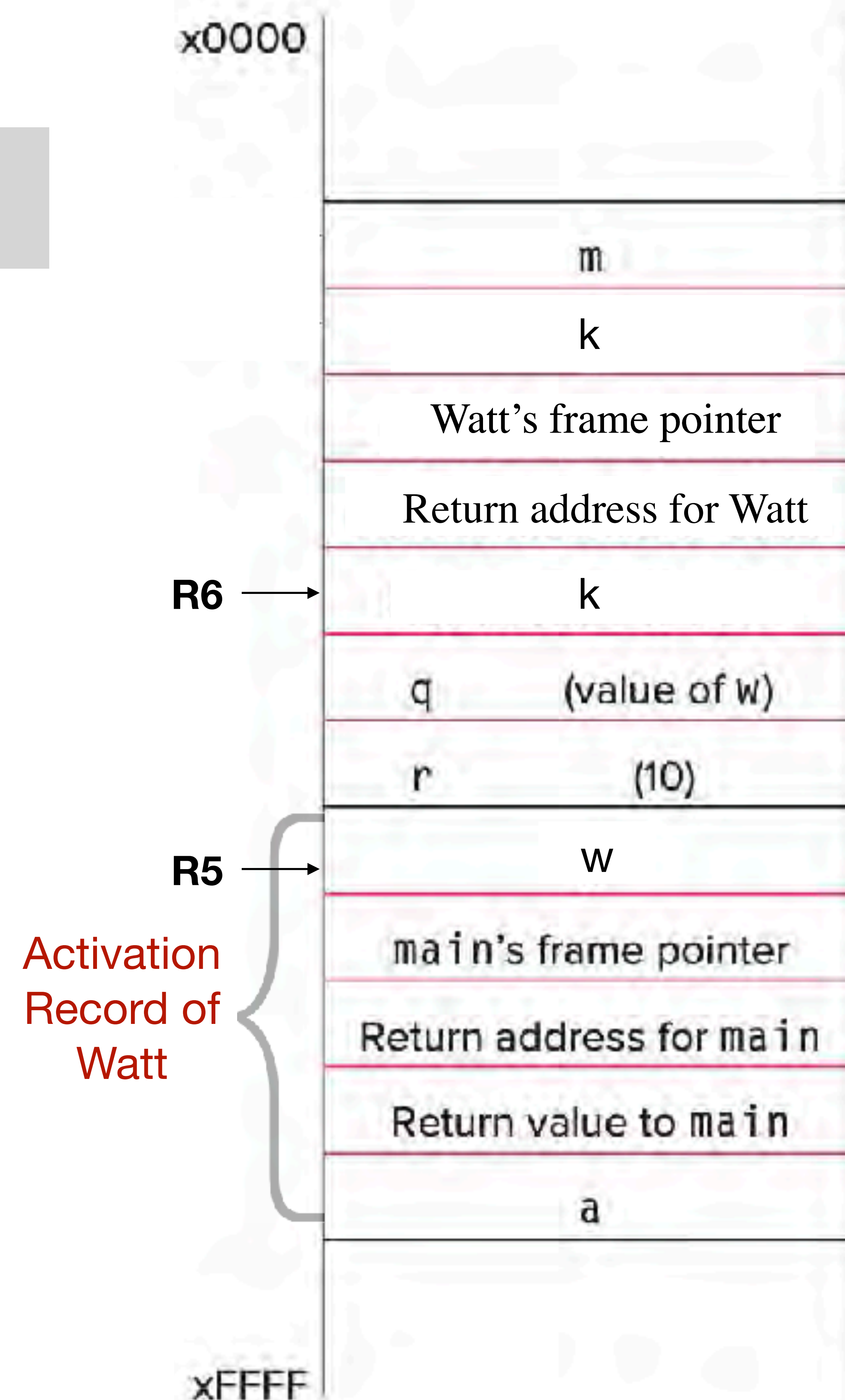
```
JSR VOLT
; load return value (top of stack)
```



LC-3 Implementation

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

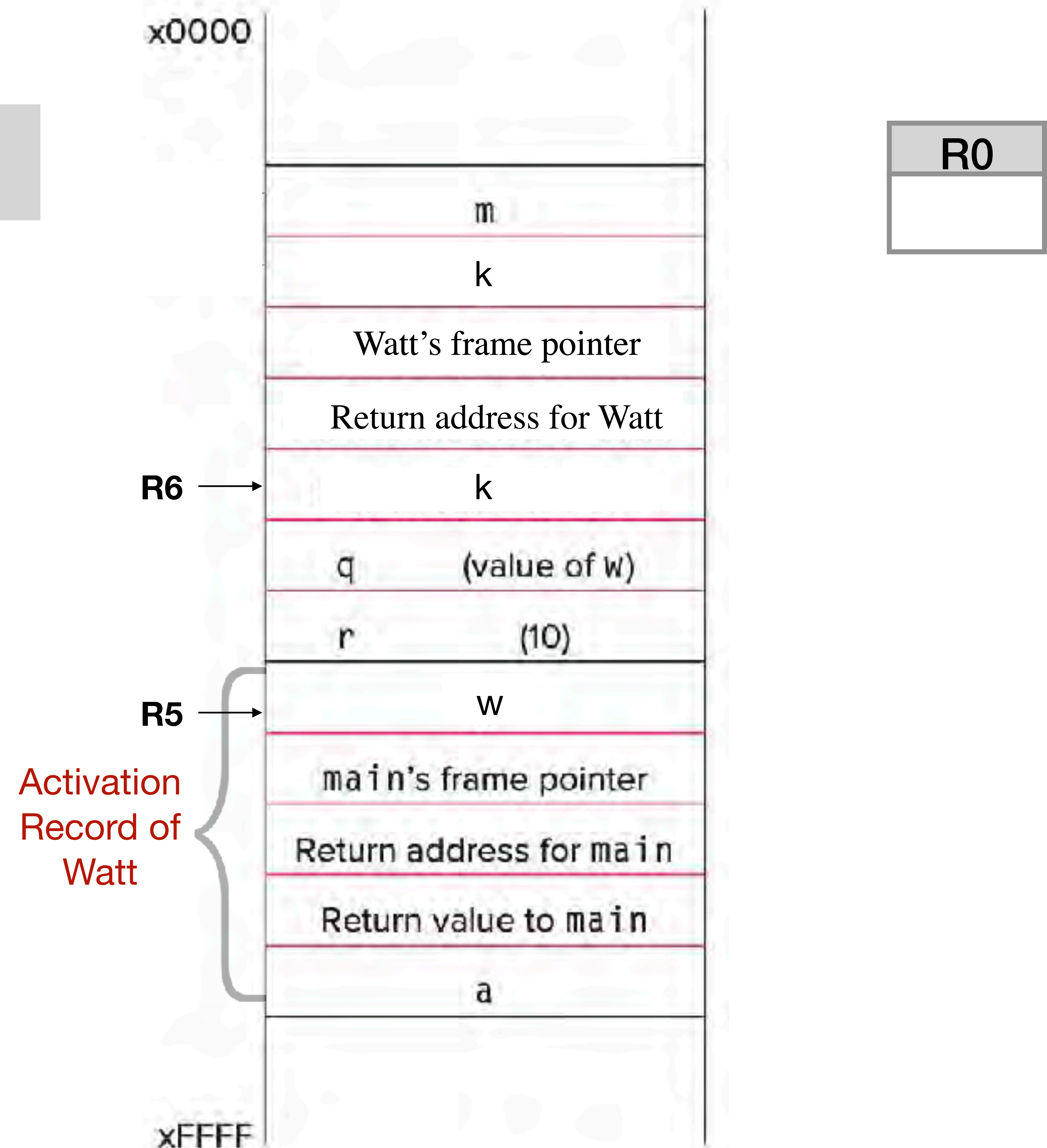
```
JSR VOLT
; load return value (top of stack)
LDR R0, R6, #0
```



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
```

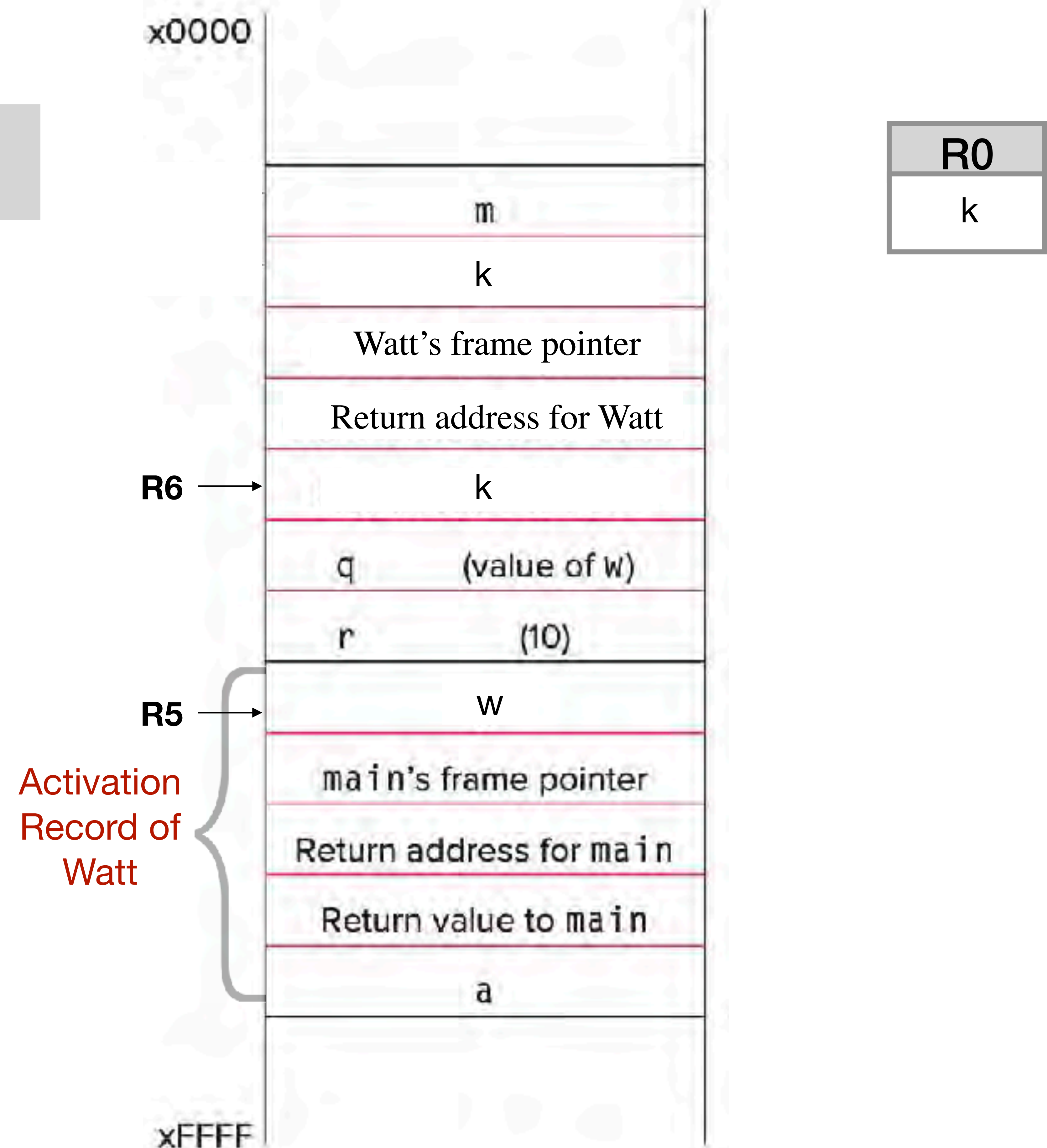


R0

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
```

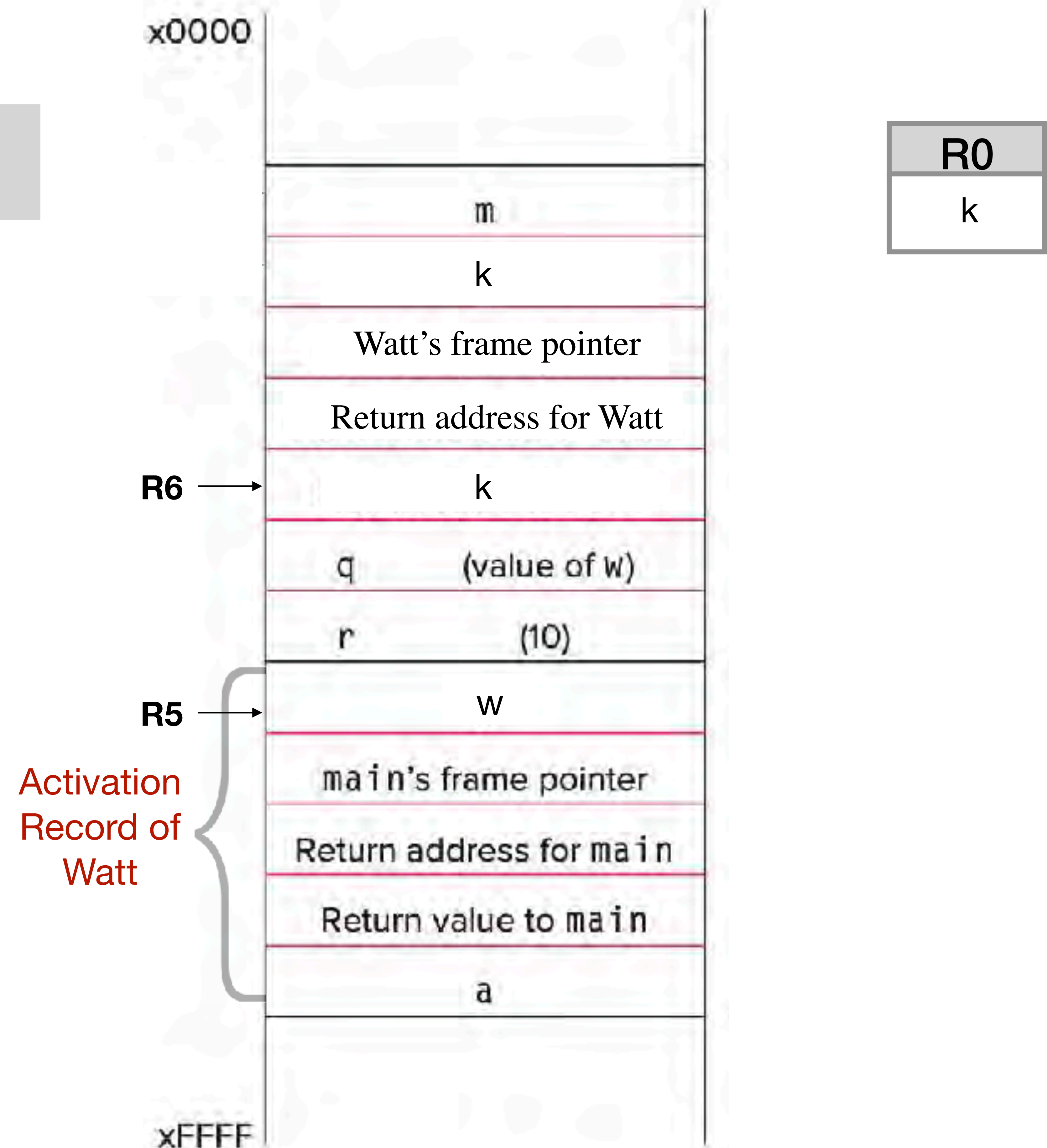


LC-3 Implementation

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
```

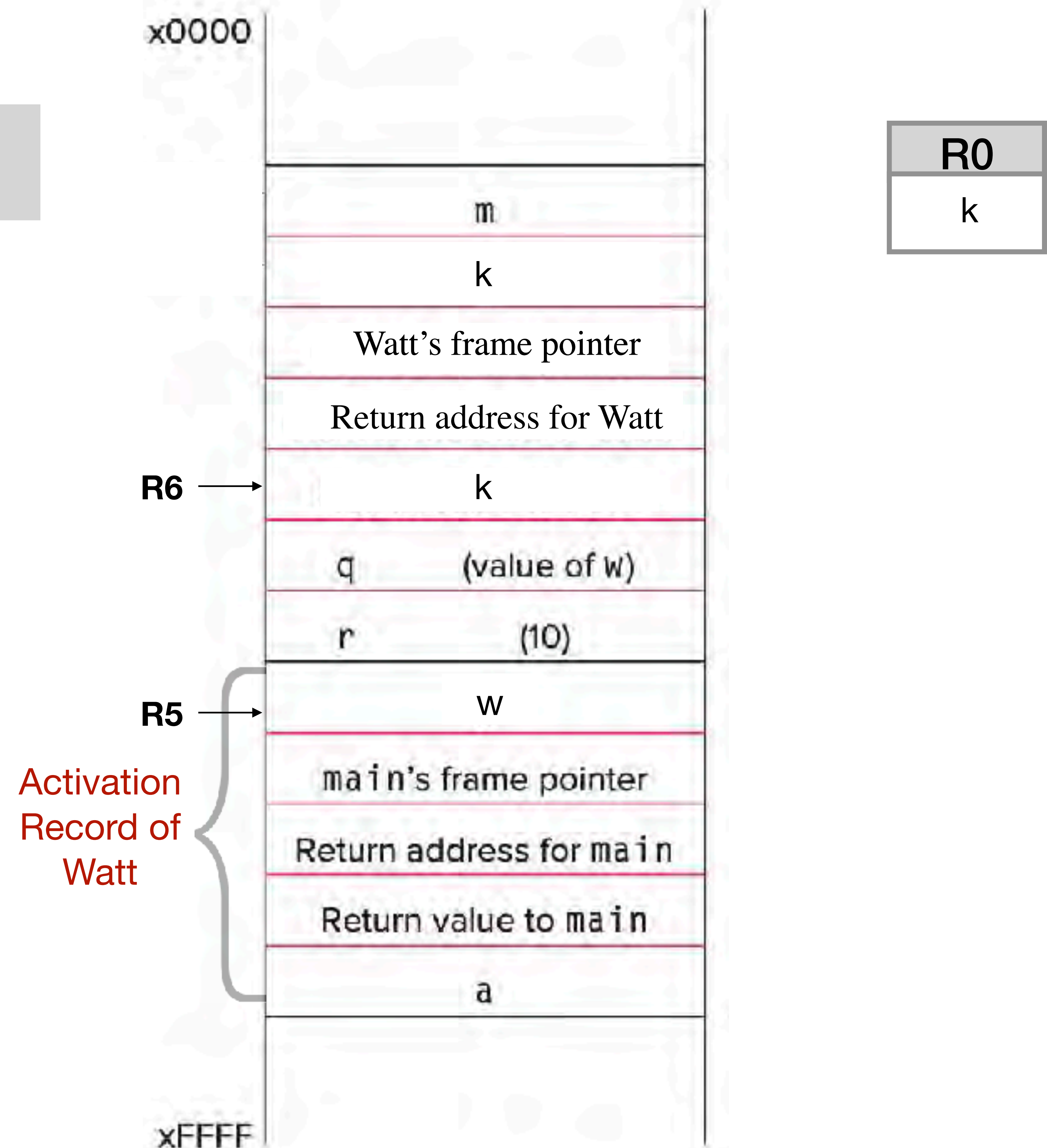


LC-3 Implementation

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
```



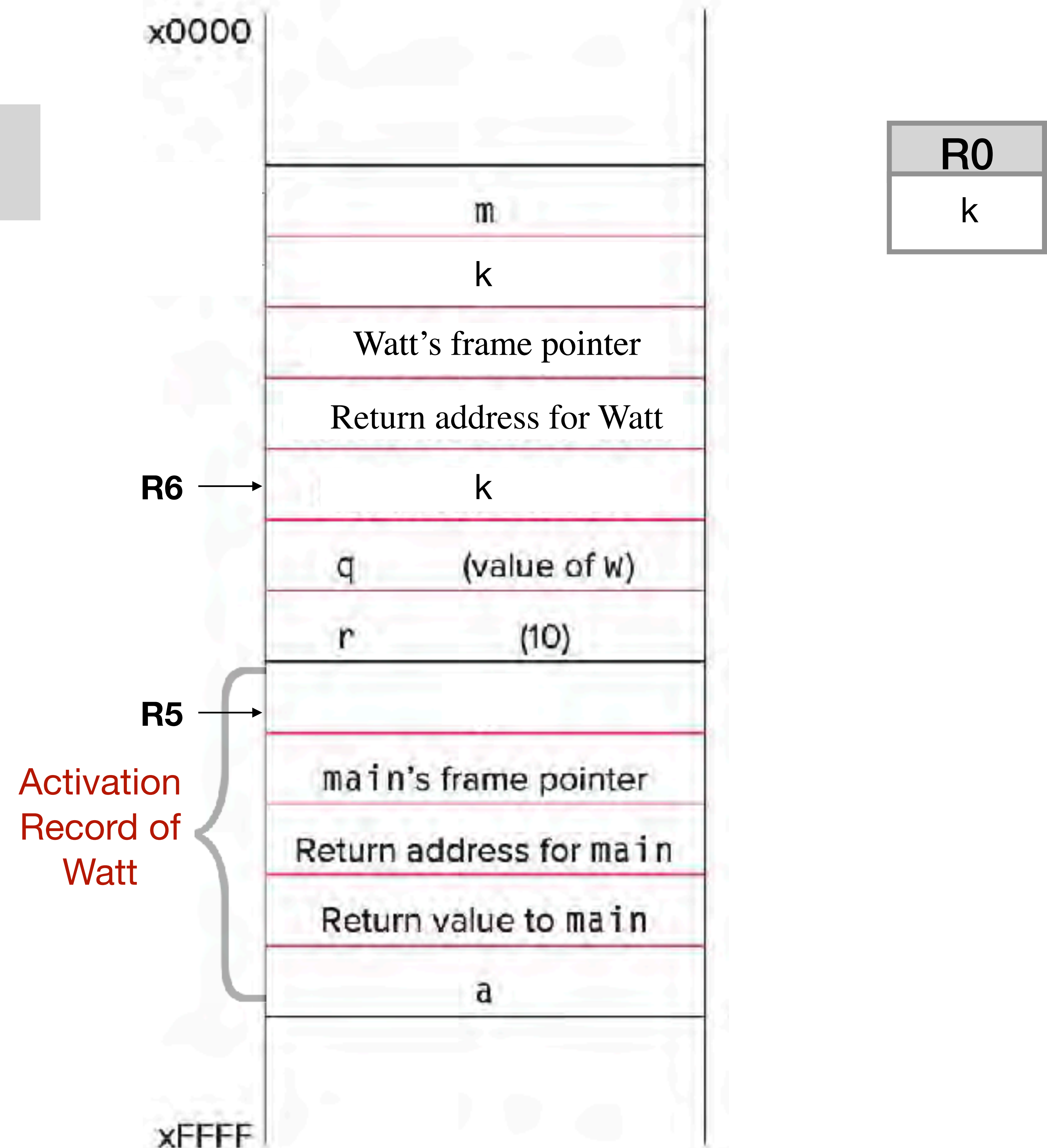
R0
k

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
```

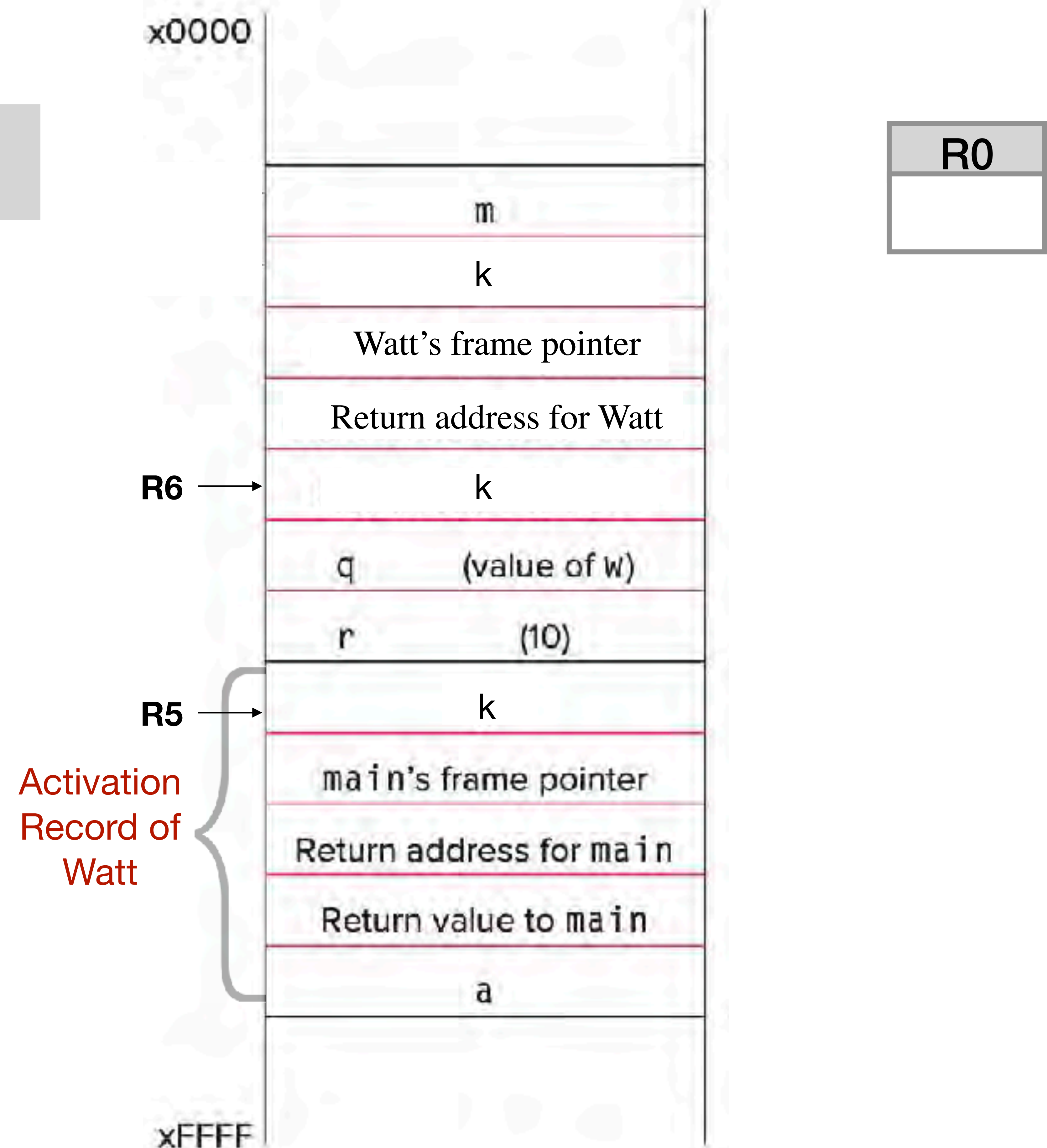


LC-3 Implementation

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
```



R0

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

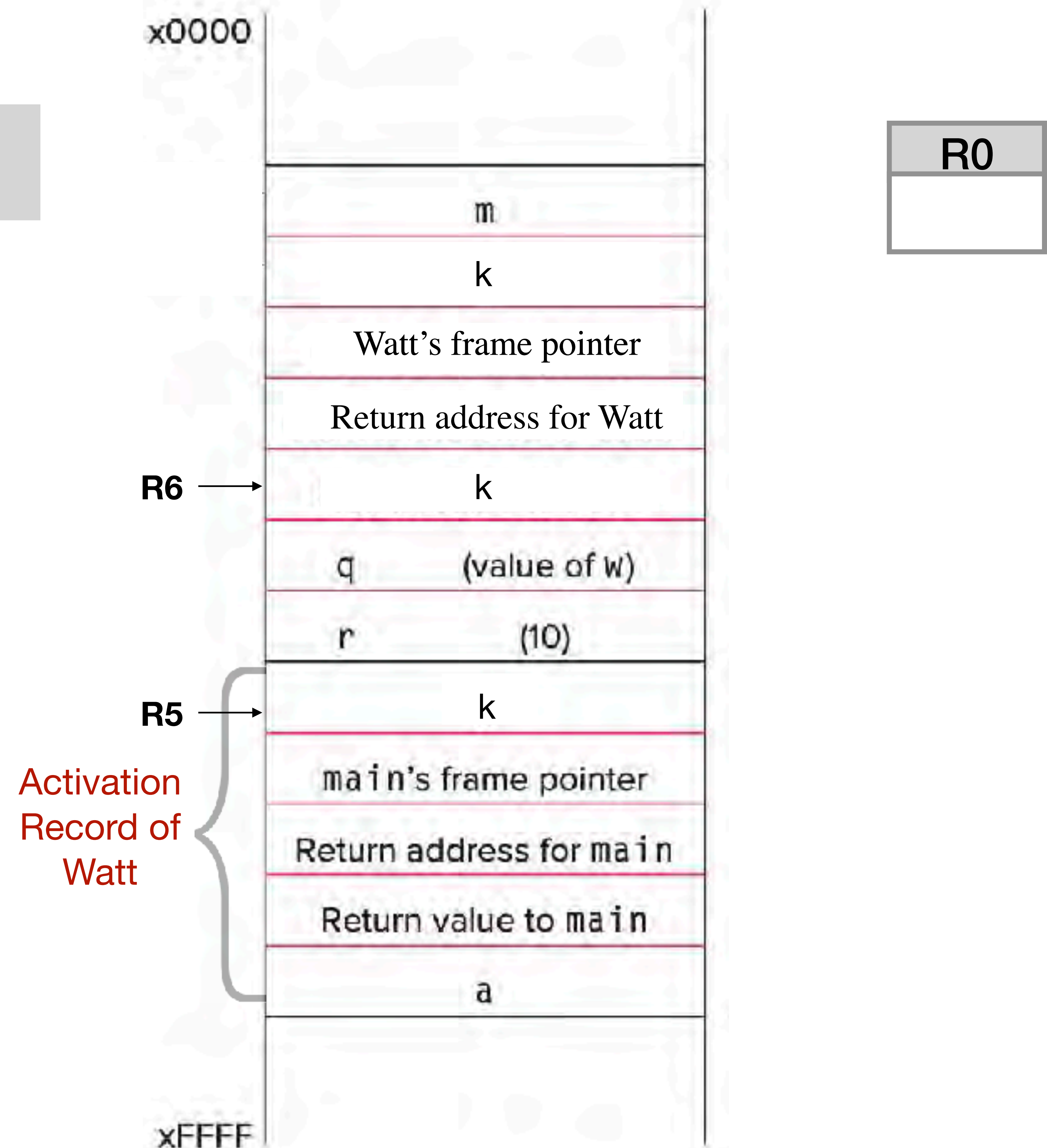
LC-3 Implementation

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
```



R0

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

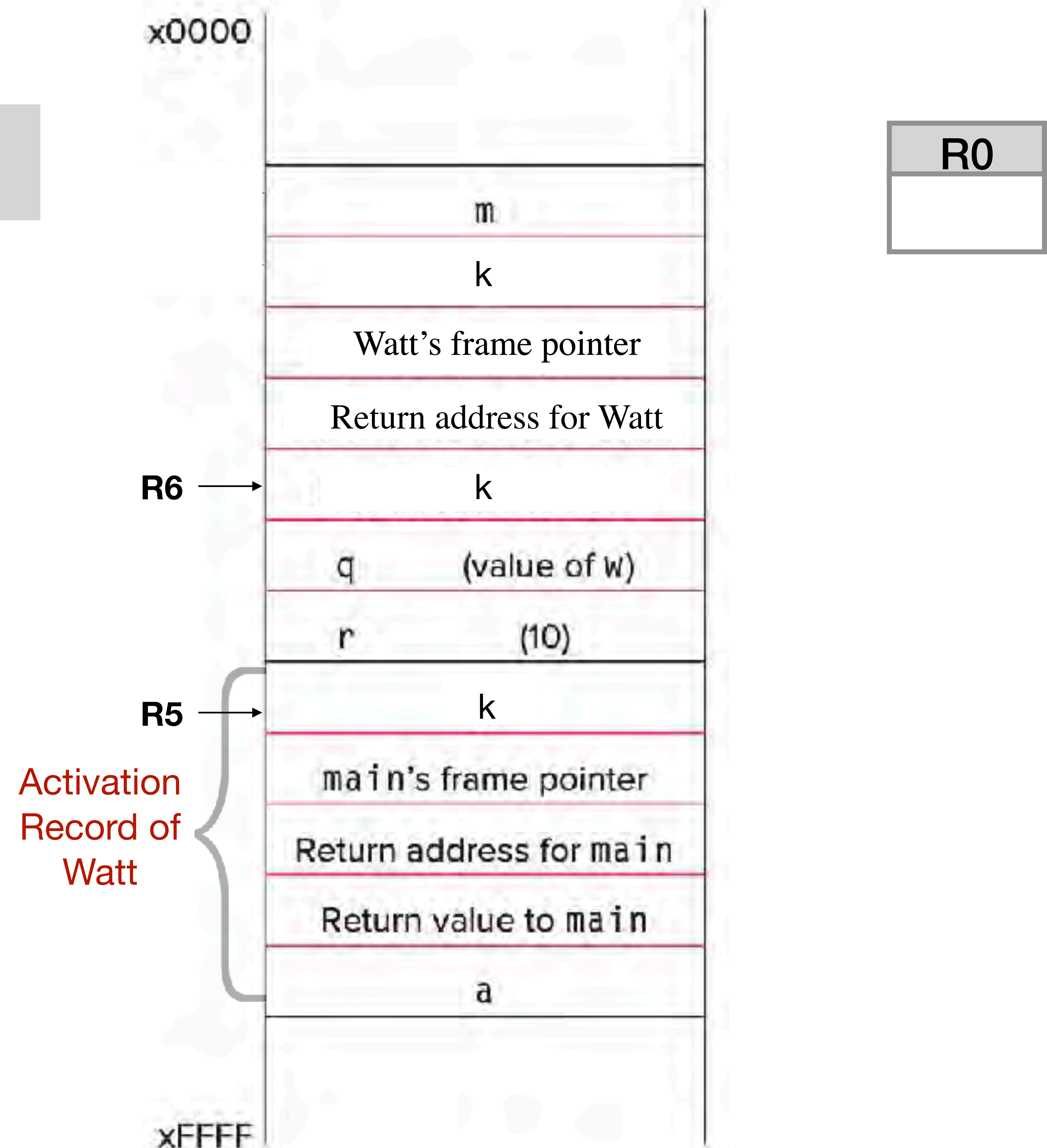
LC-3 Implementation

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
```



R0

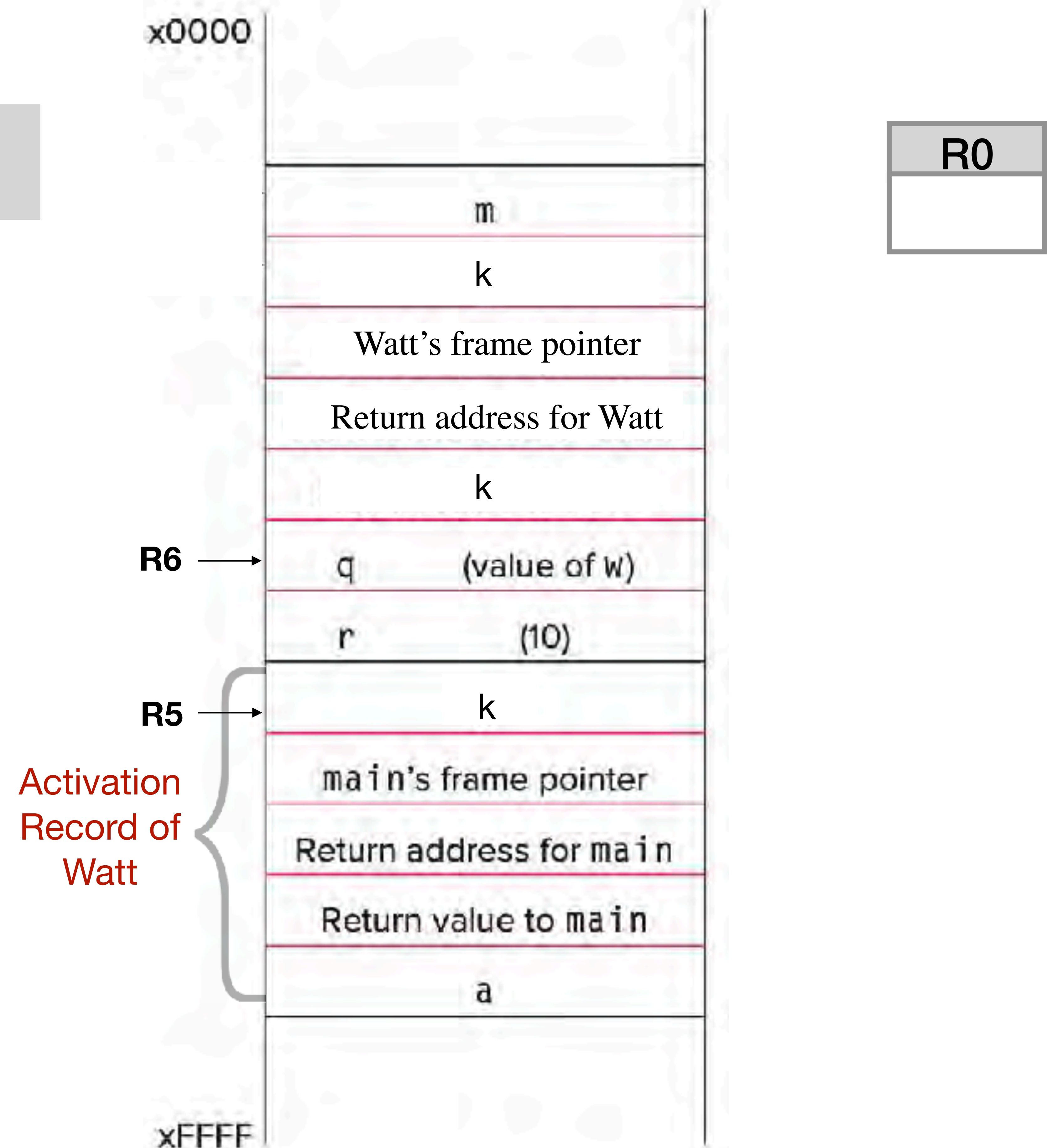
LC-3 Implementation

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
```



R0

LC-3 Implementation

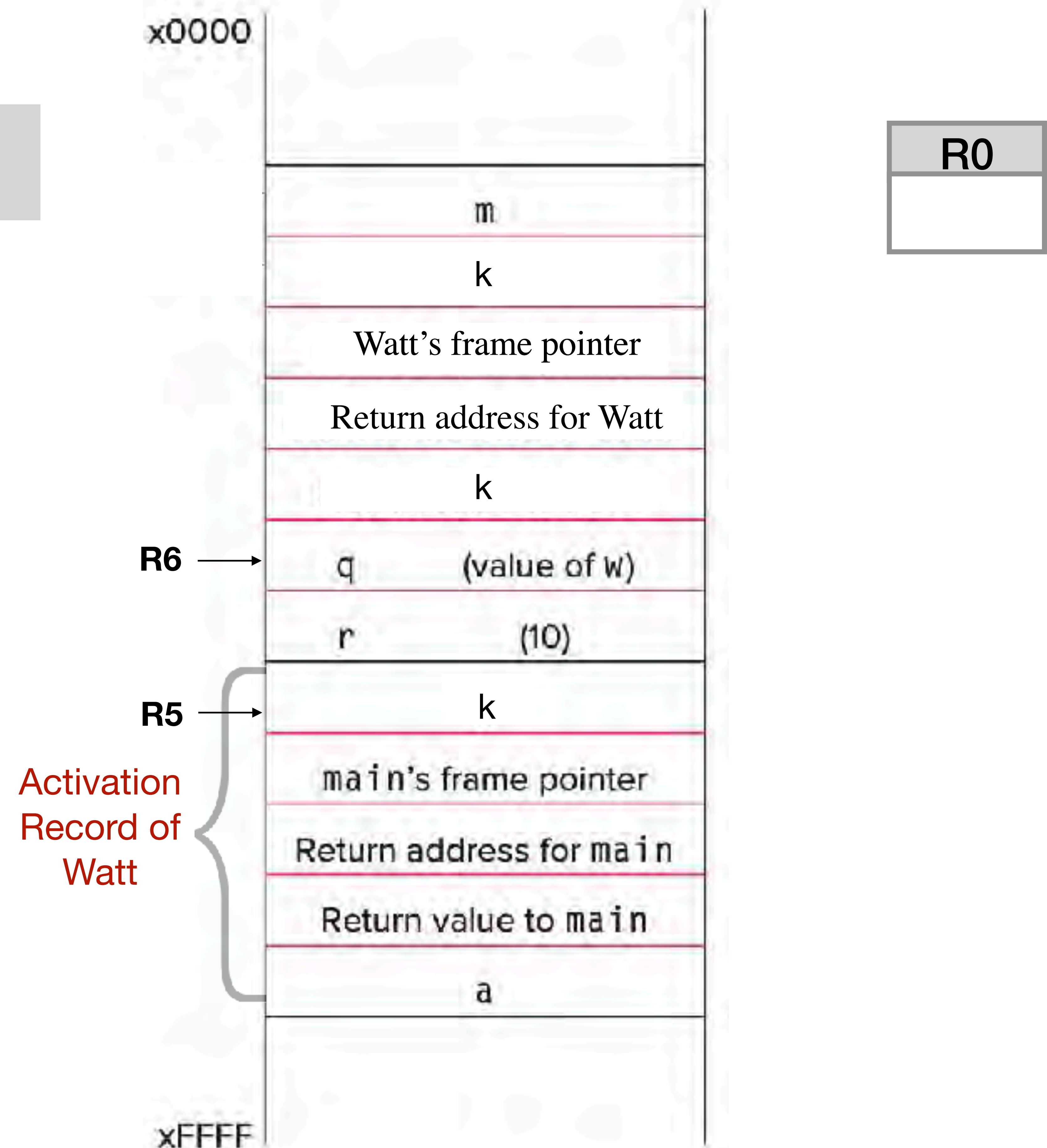
7. Caller tear-down (pop callee's return value and arguments from stack)

```
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
```



R0

LC-3 Implementation

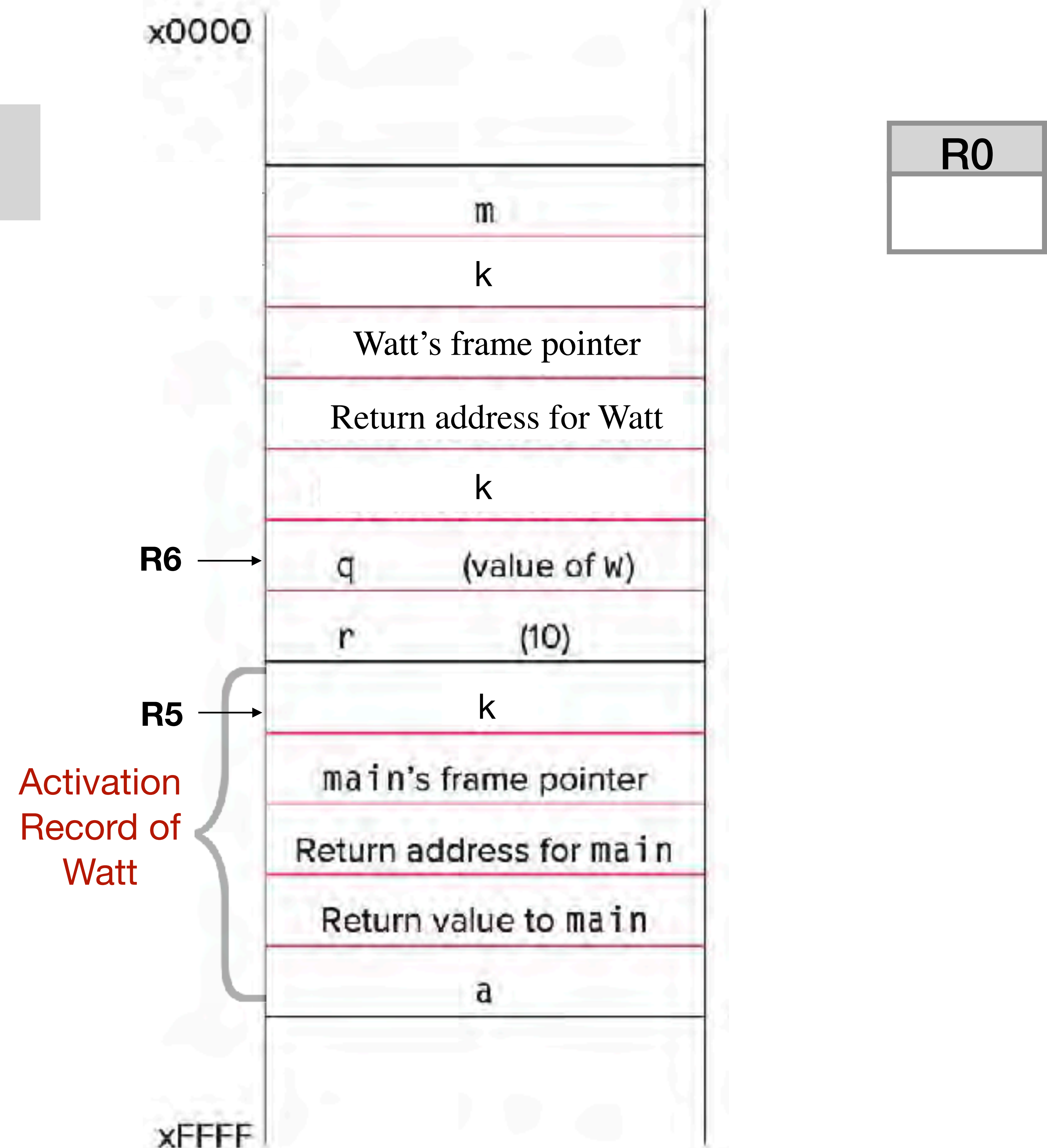
7. Caller tear-down (pop callee's return value and arguments from stack)

```
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
```



R0

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LC-3 Implementation

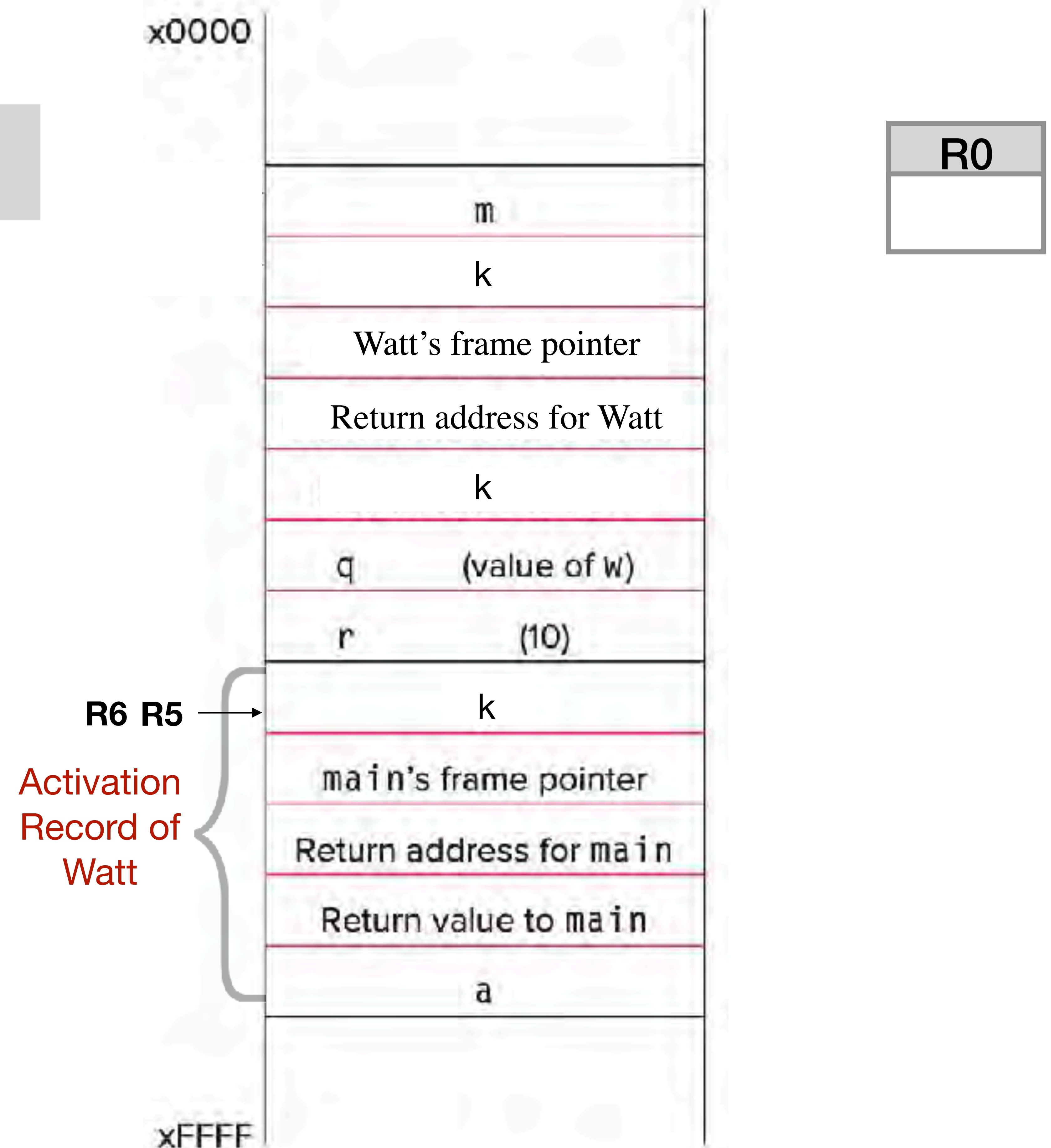
7. Caller tear-down (pop callee's return value and arguments from stack)

```
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

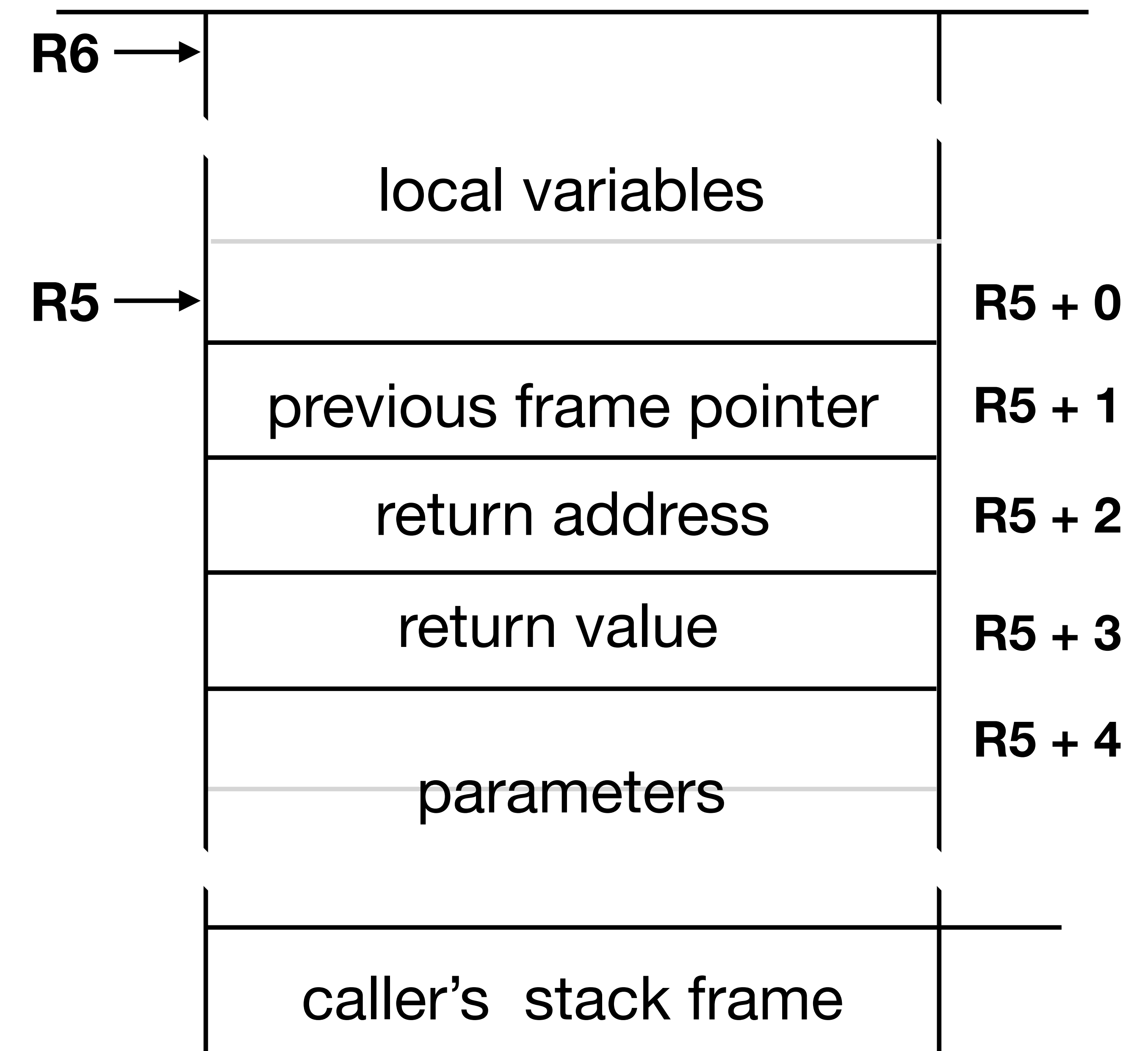
; pop arguments
ADD R6, R6, #2
```



R0

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);

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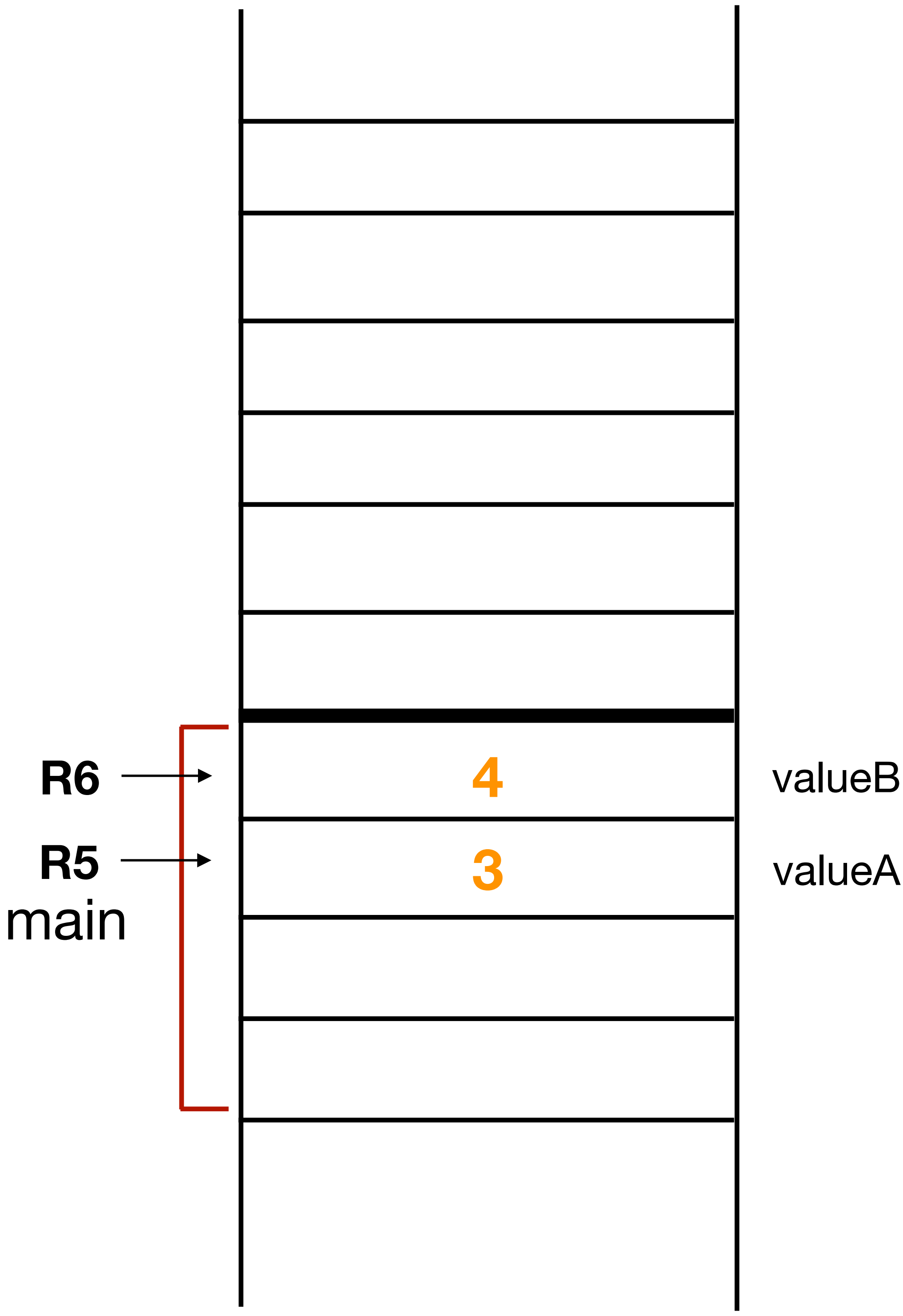

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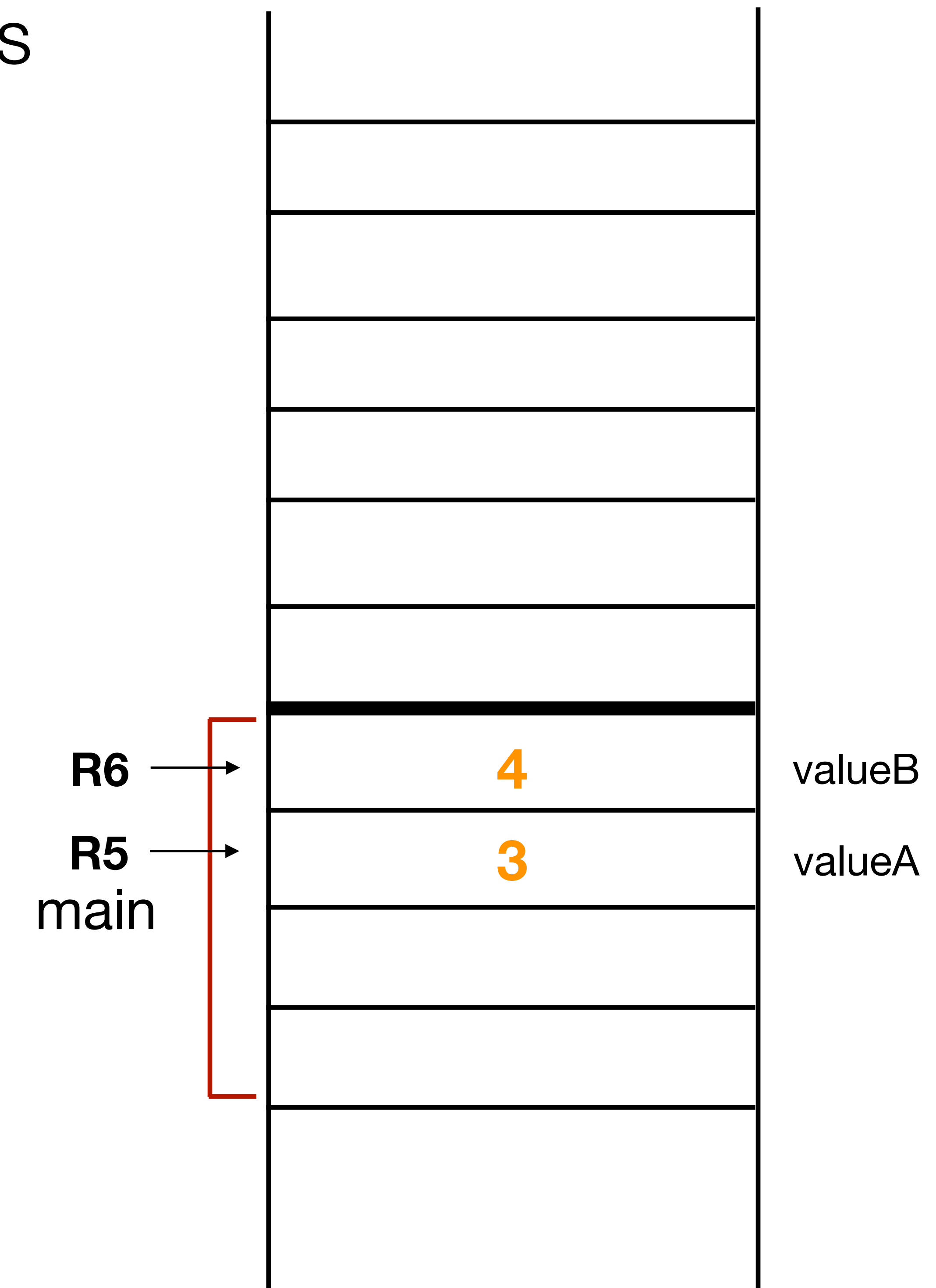
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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



Goal:
Swap valueA and valueB in main.

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Exercise: build the activation frame

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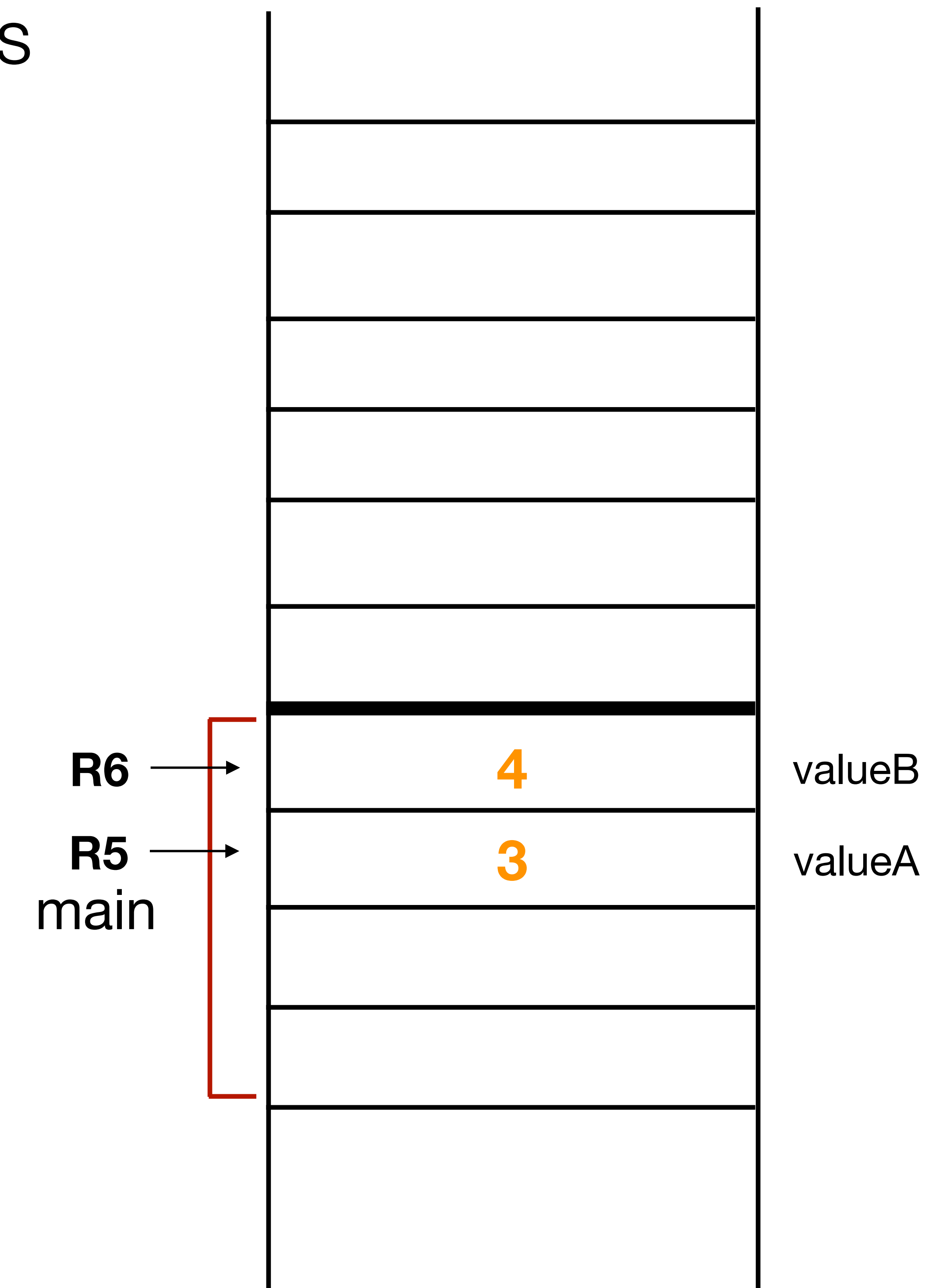
}
```

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



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UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Exercise: build the activation frame

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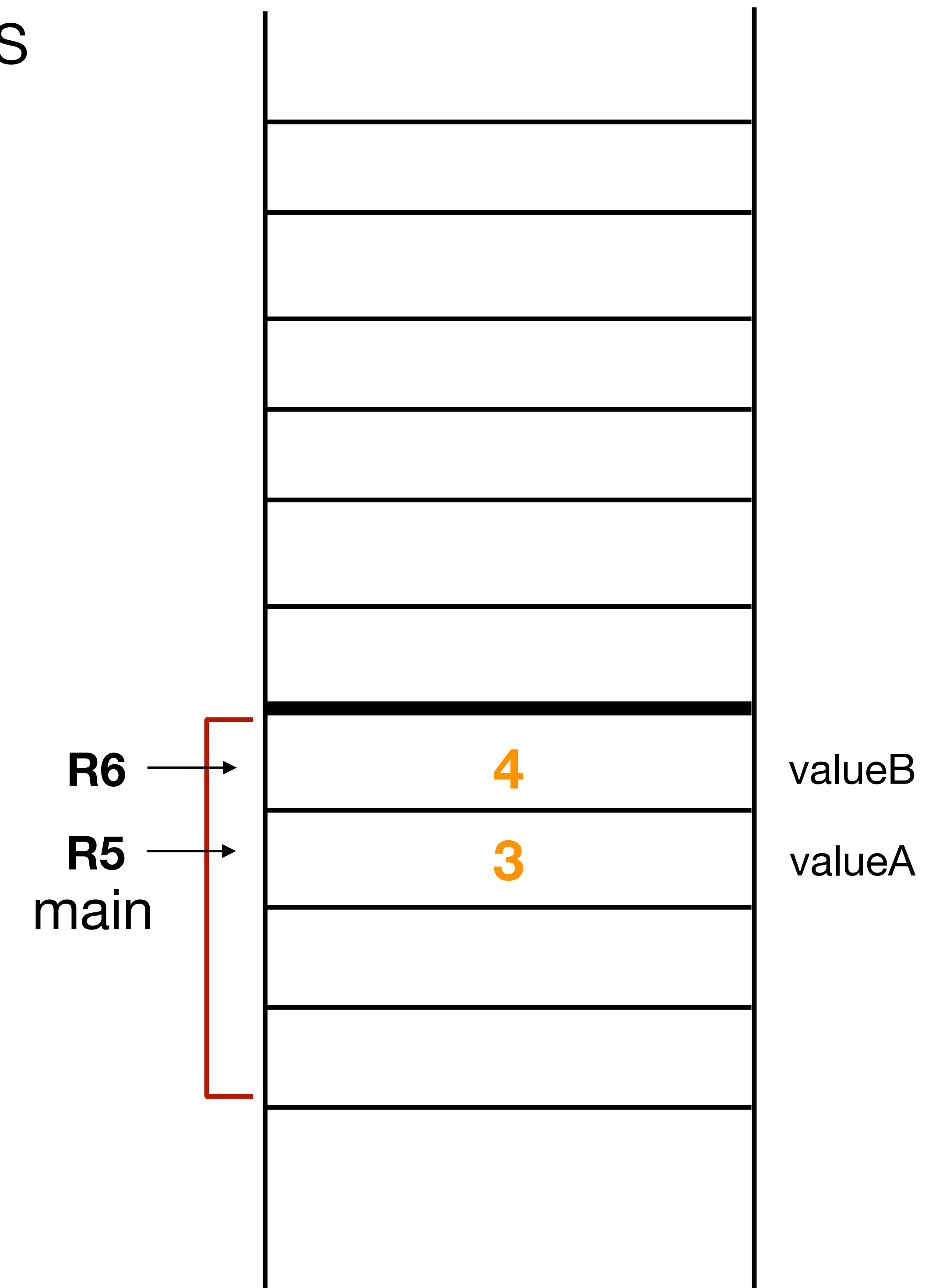
   Swap(valueA, valueB);
}

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

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

Before call



Goal:
Swap valueA and valueB in main.

Exercise: build the activation frame

```
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   Swap(valueA, valueB);
}

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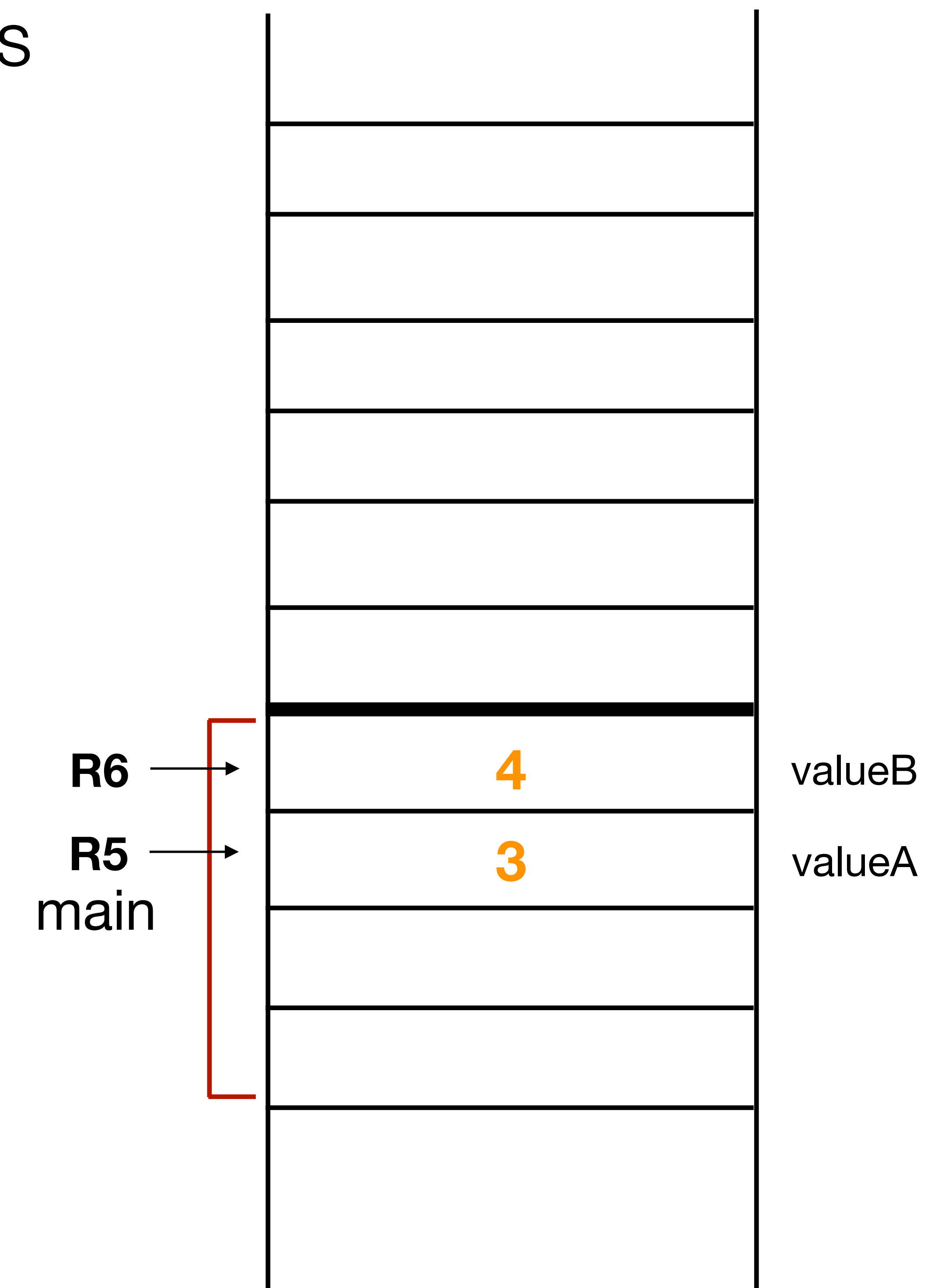
   first = second;
   second = temp;
}
```

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



Goal:
Swap valueA and valueB in main.

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Exercise: build the activation frame

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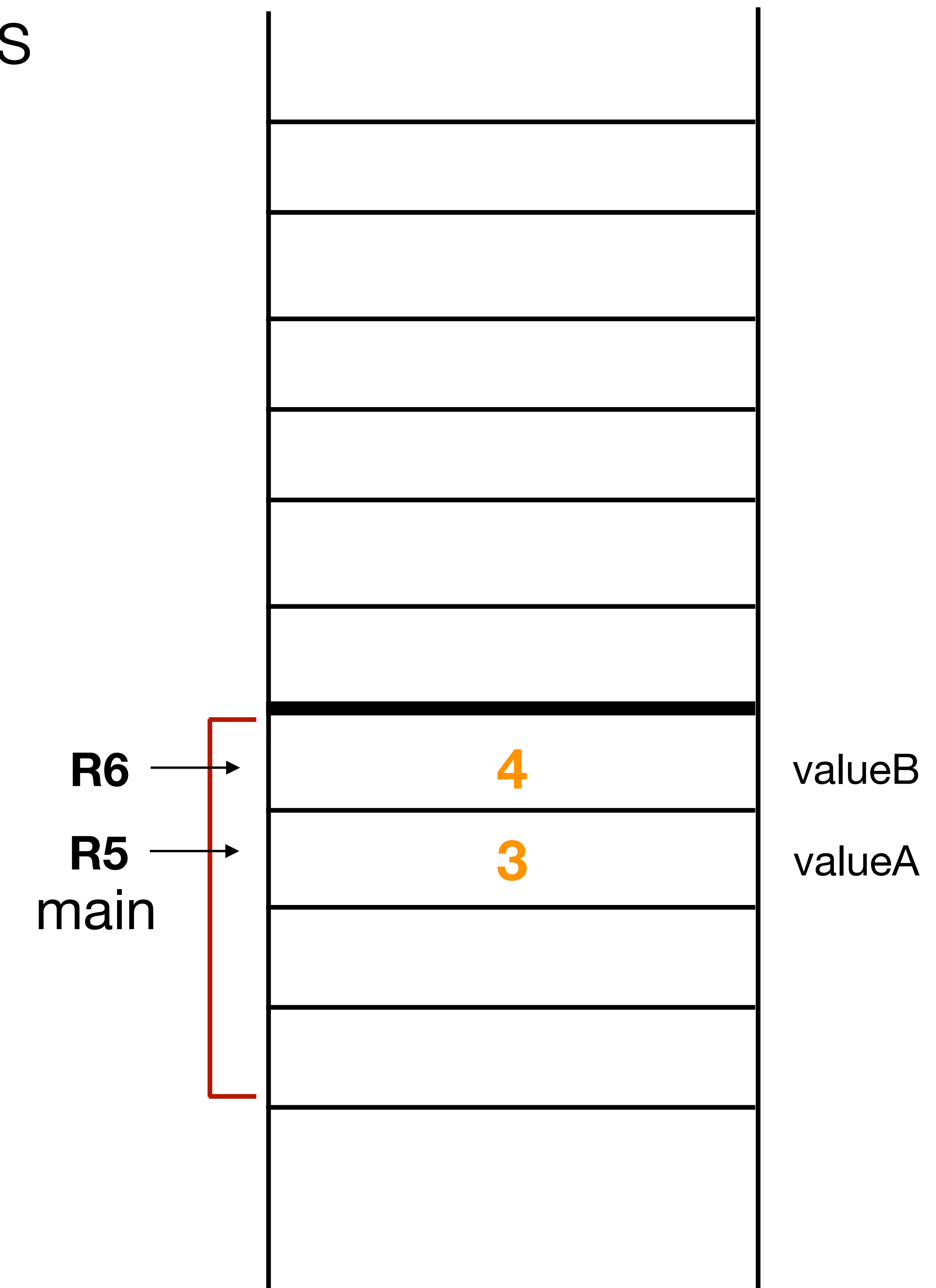
   second = temp;
}
```

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



Goal:
Swap valueA and valueB in main.

Exercise: build the activation frame

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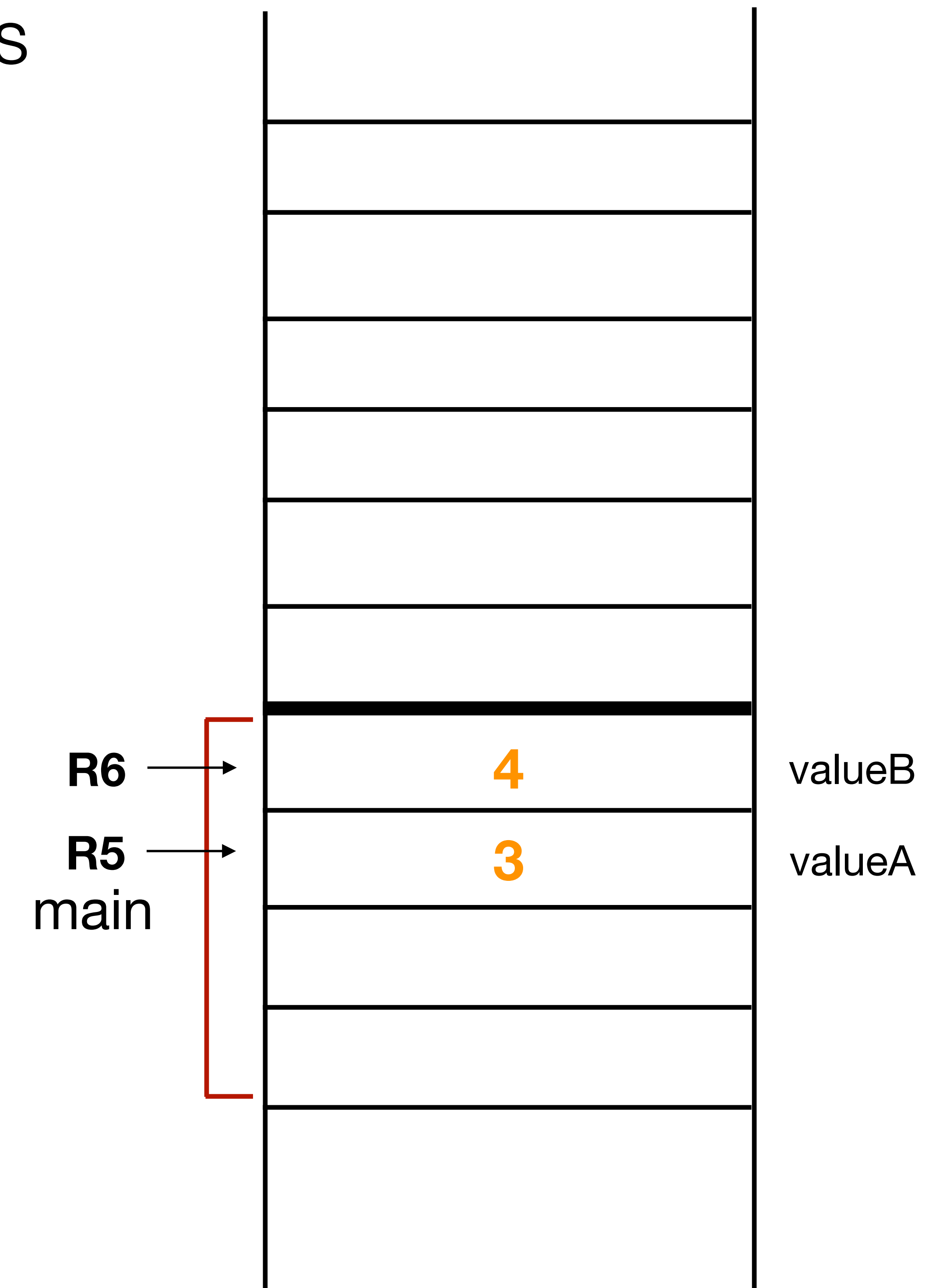
   Swap(valueA, valueB);
}

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

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



Goal:
Swap valueA and valueB in main.

Exercise: build the activation frame

```
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}

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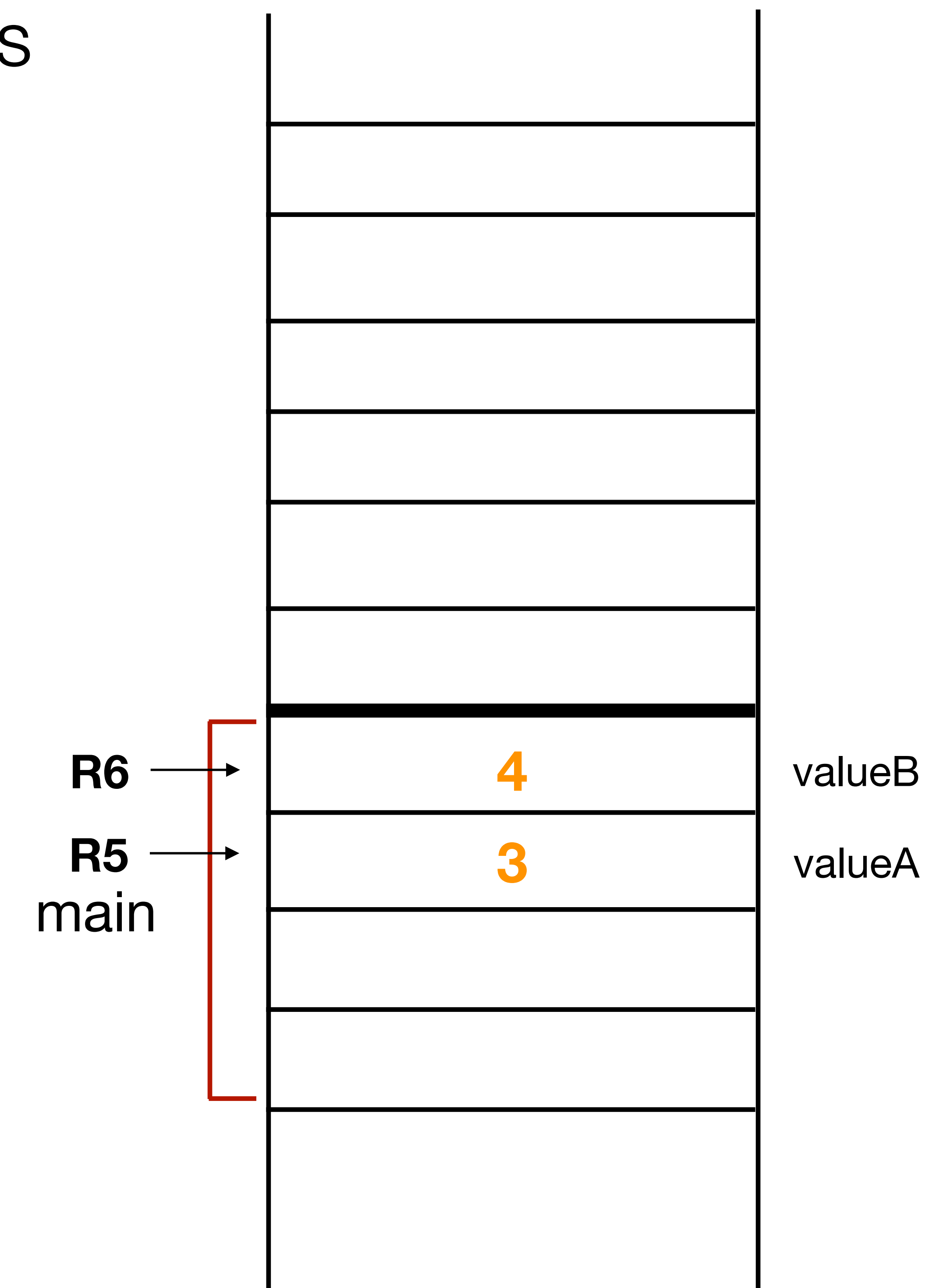
   temp = first;
   first = second;
   second = temp;
}
```

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



Goal:
Swap valueA and valueB in main.

`swap` function - build up

Build up

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

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

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

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

`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
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   G. Pop CFP (into R5)
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6. RET
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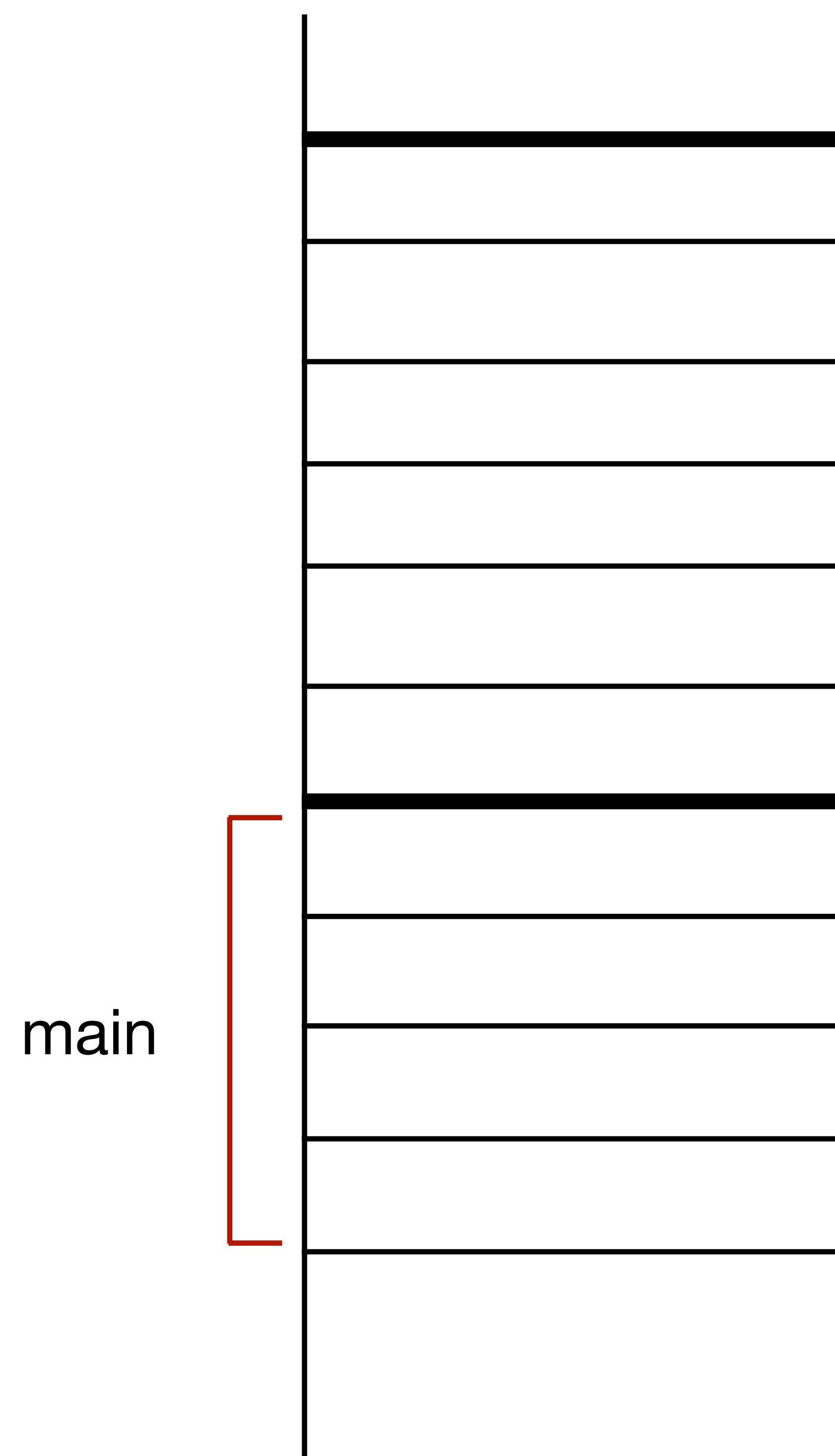


```c
void Swap(int first, int second);

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

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

swap function - build up

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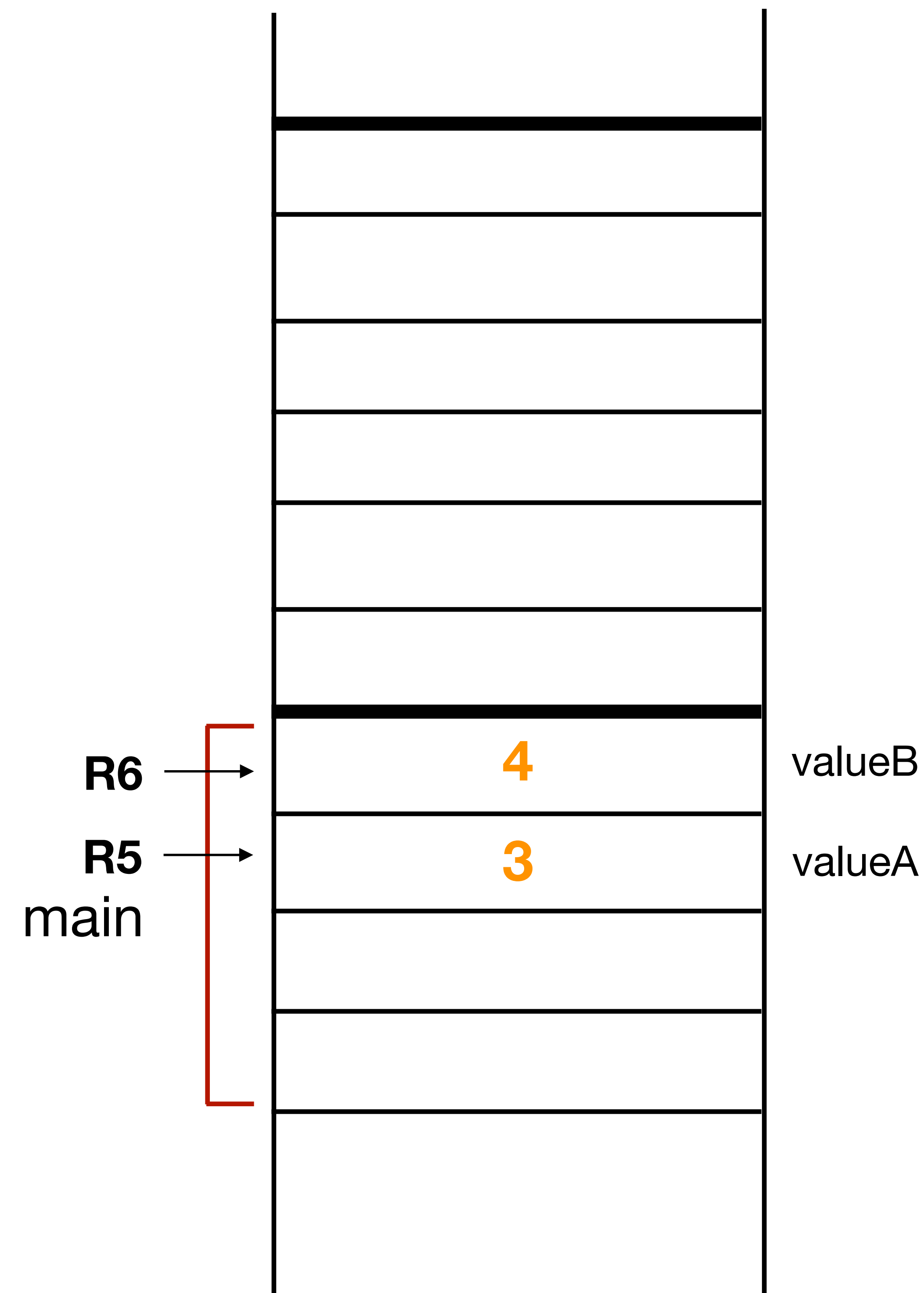


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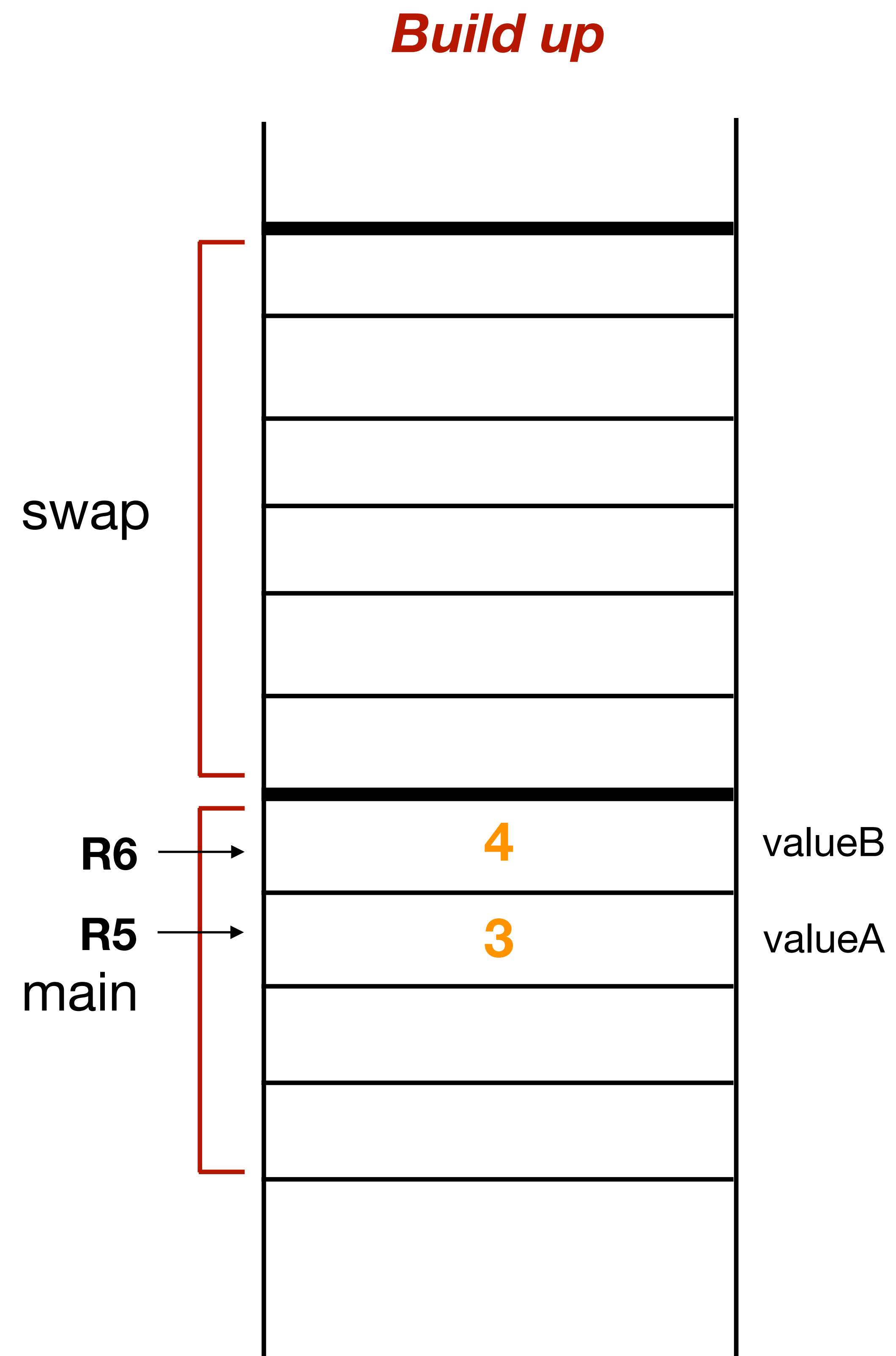


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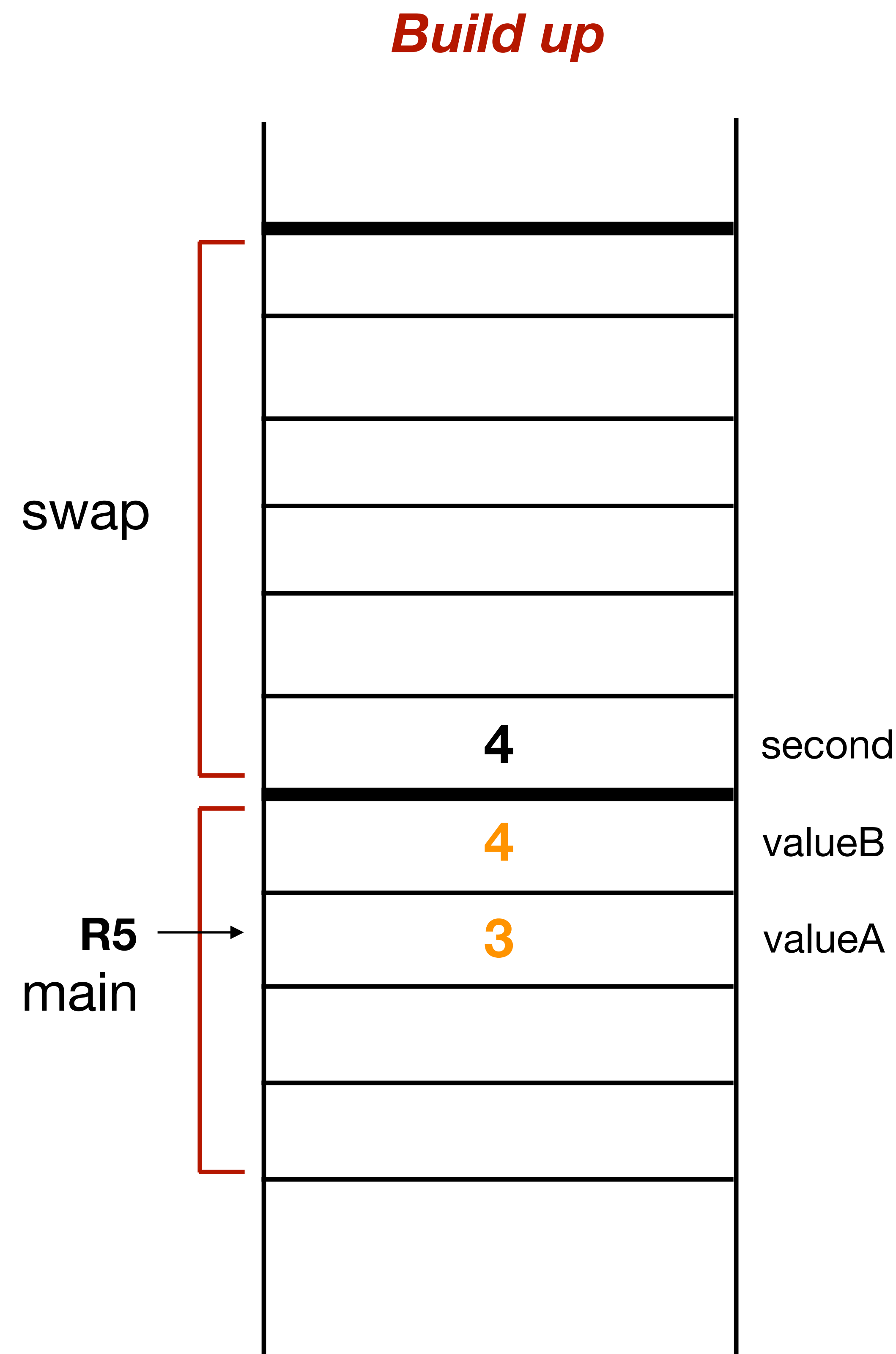


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```

```
LDR R0, R5, #-1
JSR PUSH
```

`swap` function - build up

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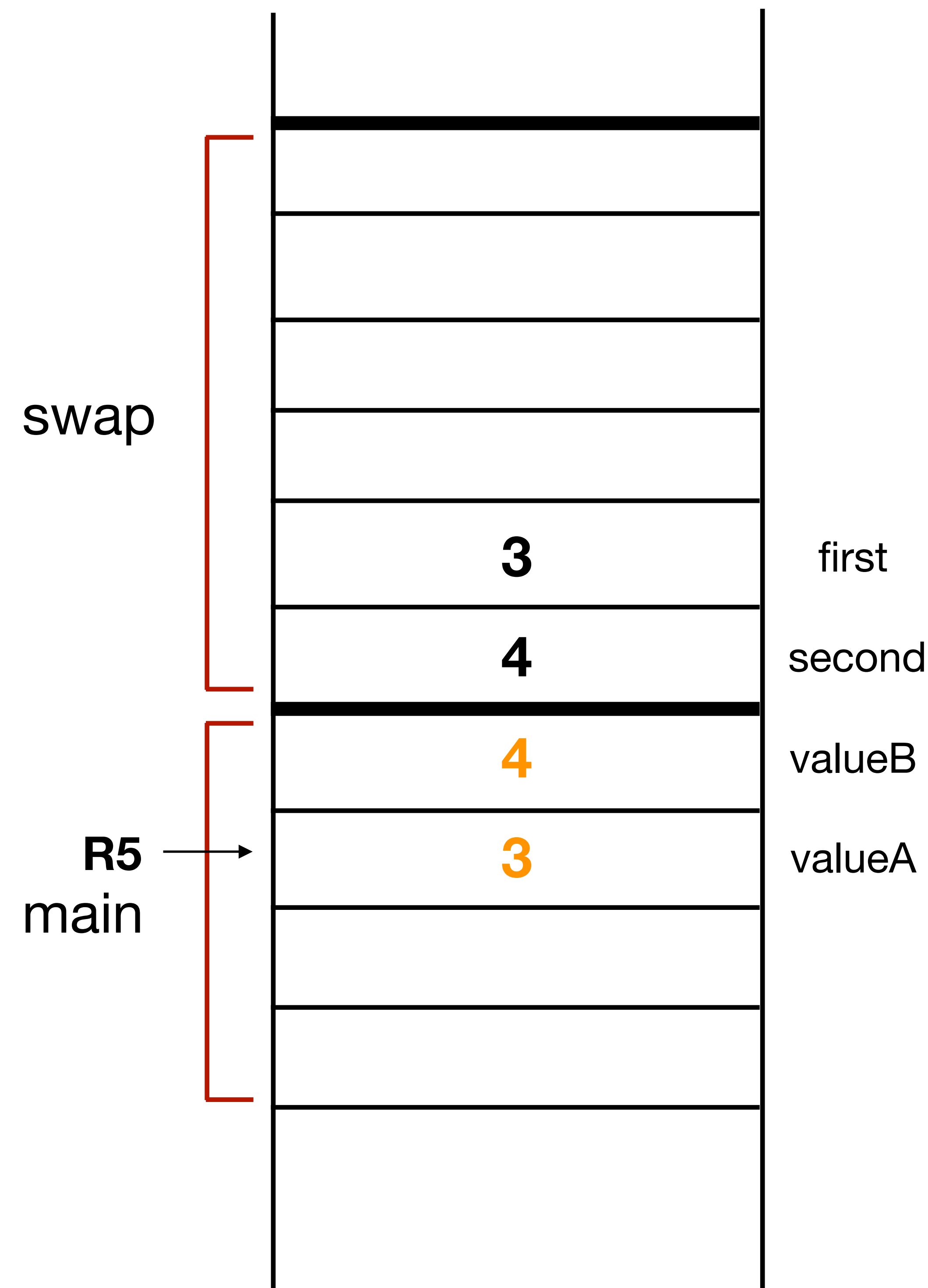


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   Swap(valueA, valueB);
}

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

```
LDR R0, R5, #0
JSR PUSH
```

`swap` function - build up

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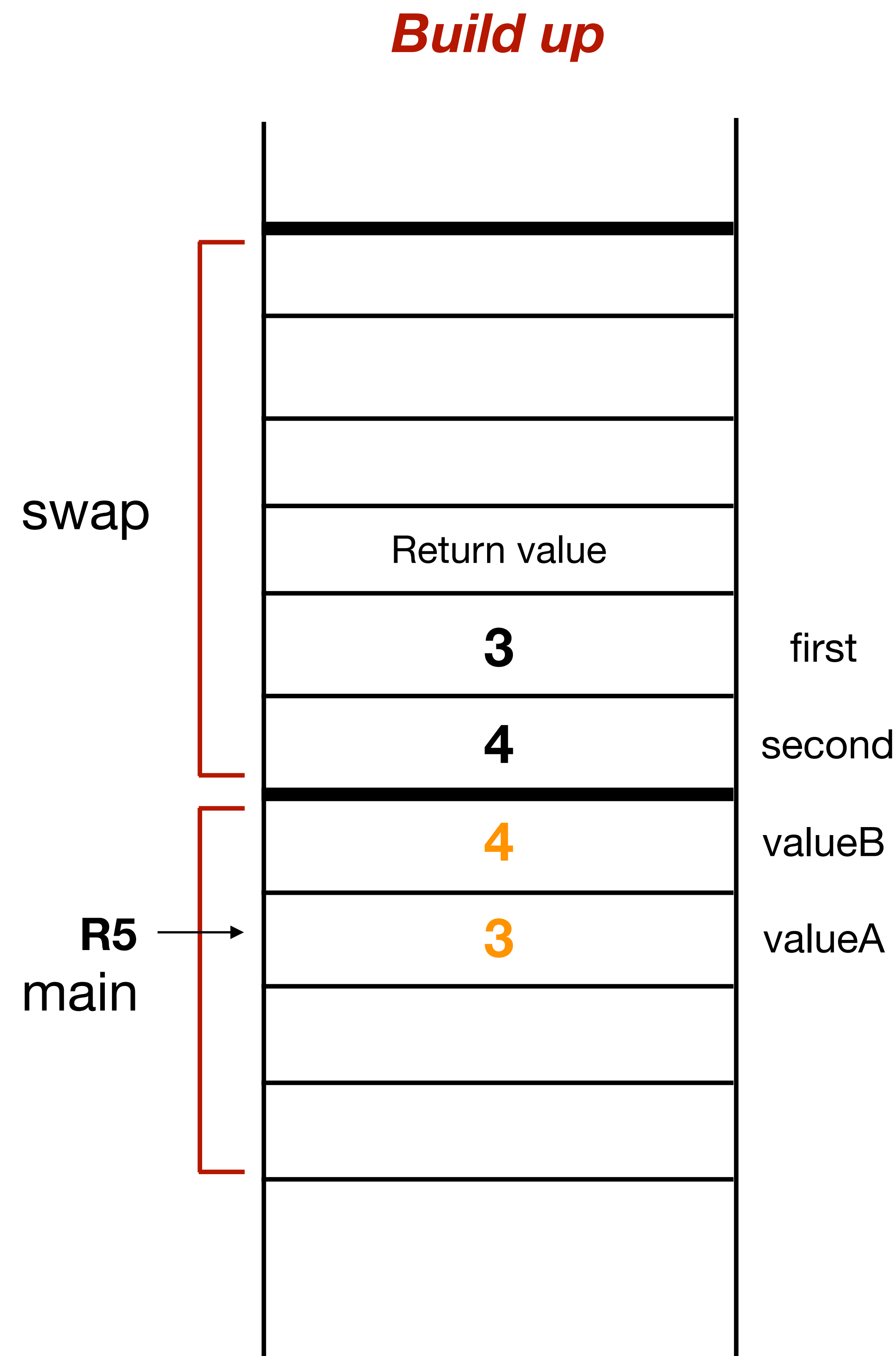


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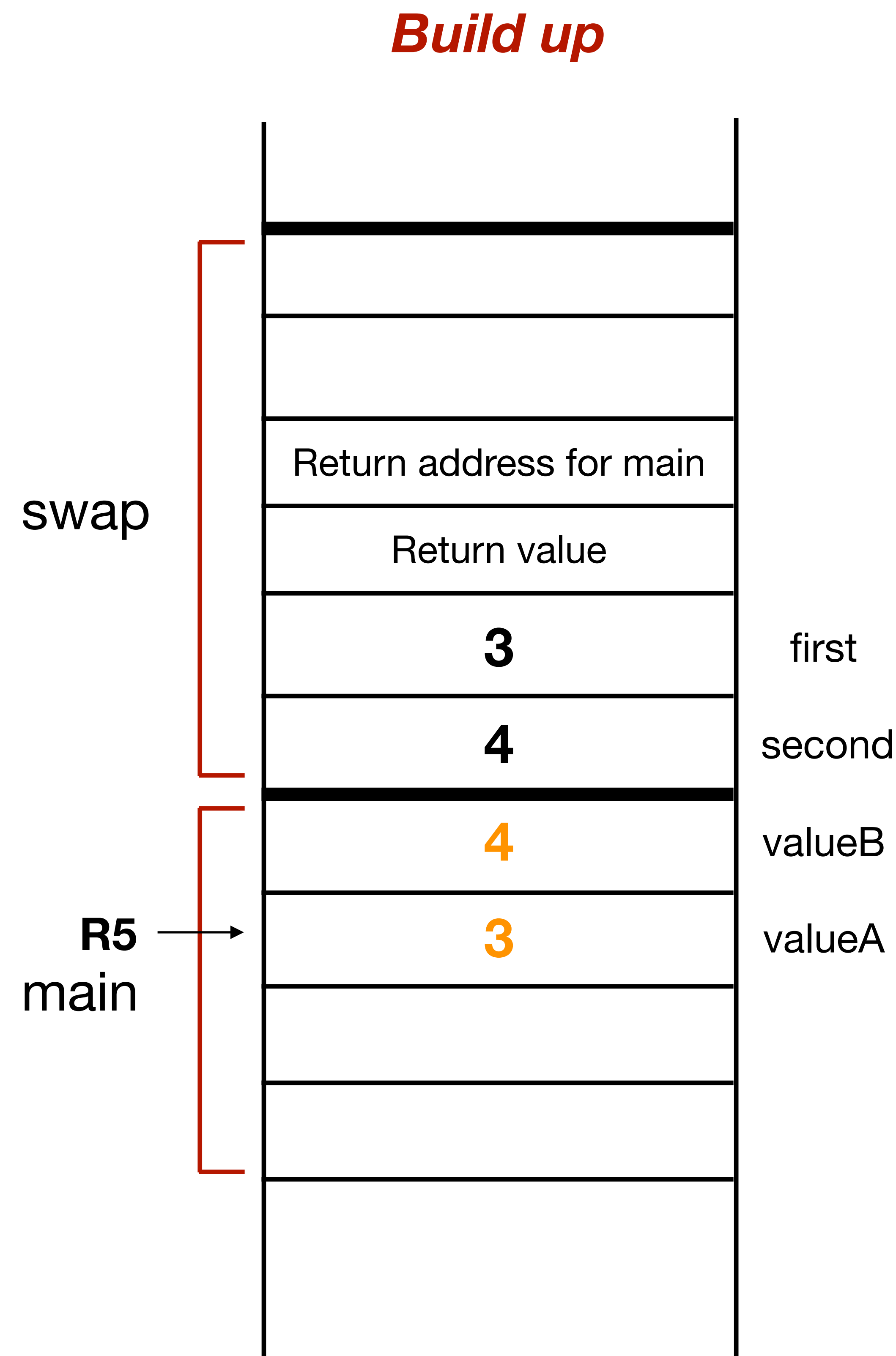


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int main(){
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   Swap(valueA, valueB);
}

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

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

`swap` function - build up

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   E. Update return value
   F. Pop local variables
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6. RET
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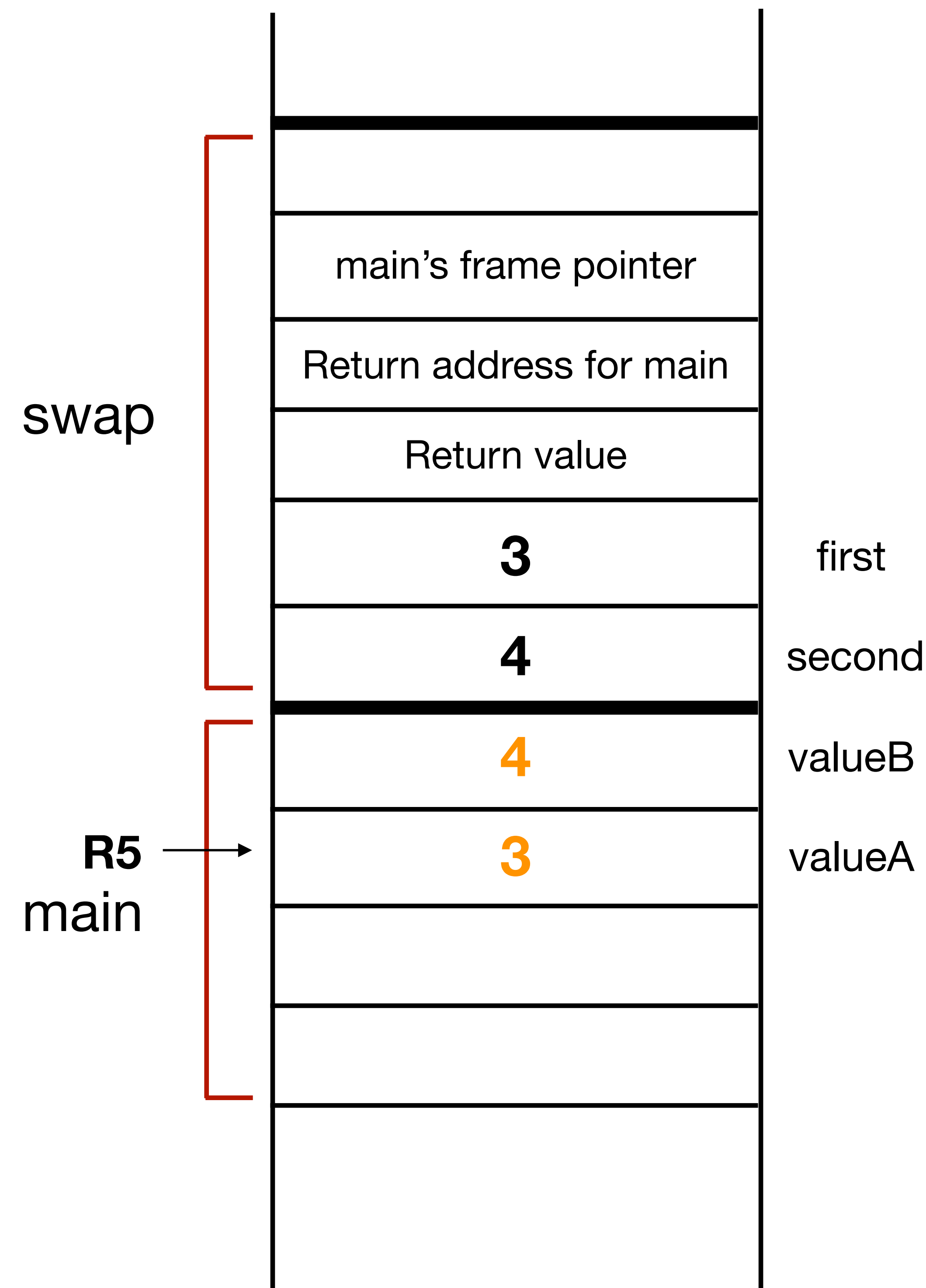
   I. Pop return value
   J. Pop arguments

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

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

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

swap function - build up

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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
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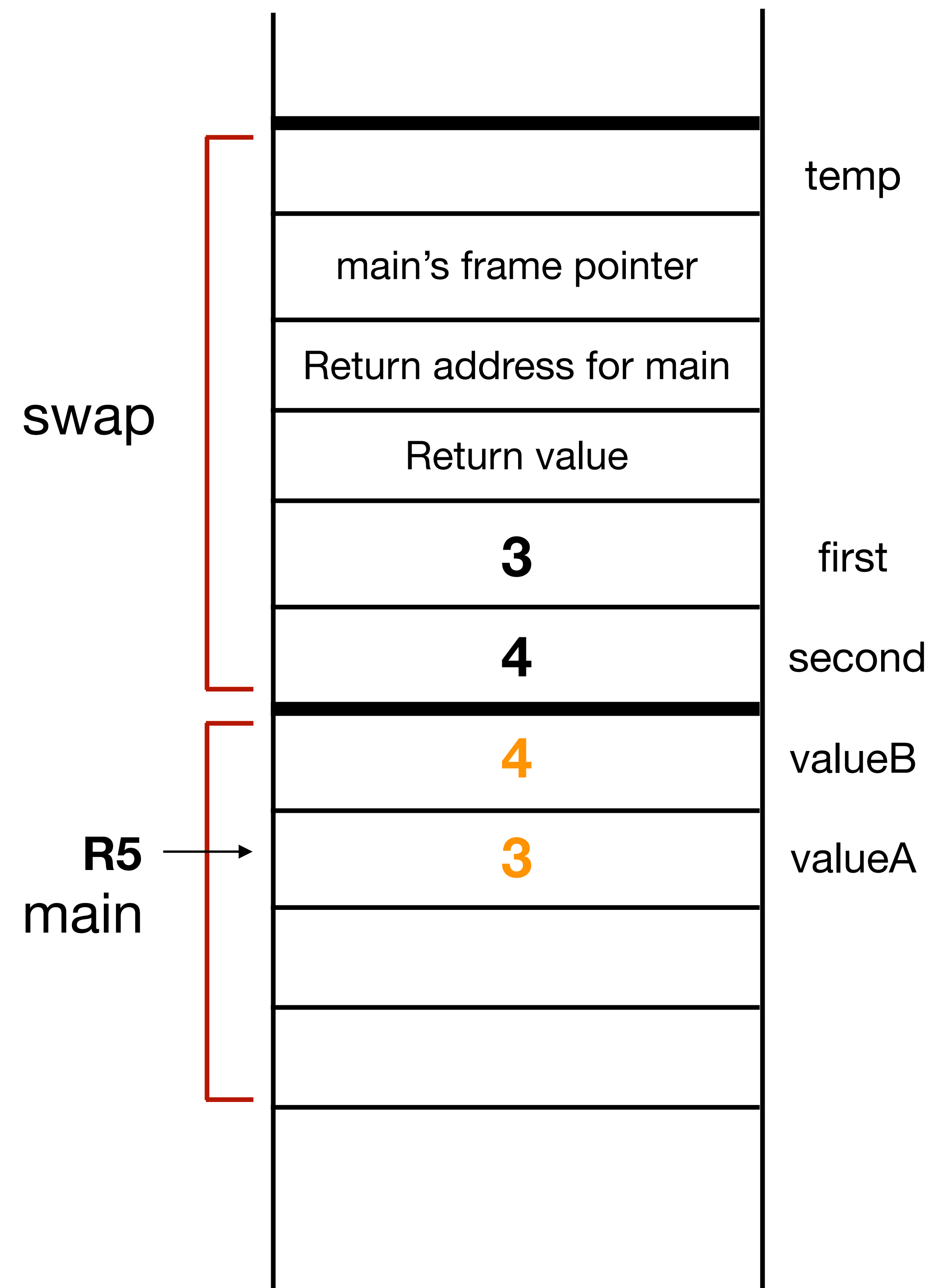
   F. Pop local variables
   G. Pop CFP (into R5)
   H. Pop return address (into R7)
6. RET
7. Caller tear down
   I. Pop return value
   J. Pop arguments

Build up

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swap function - build up

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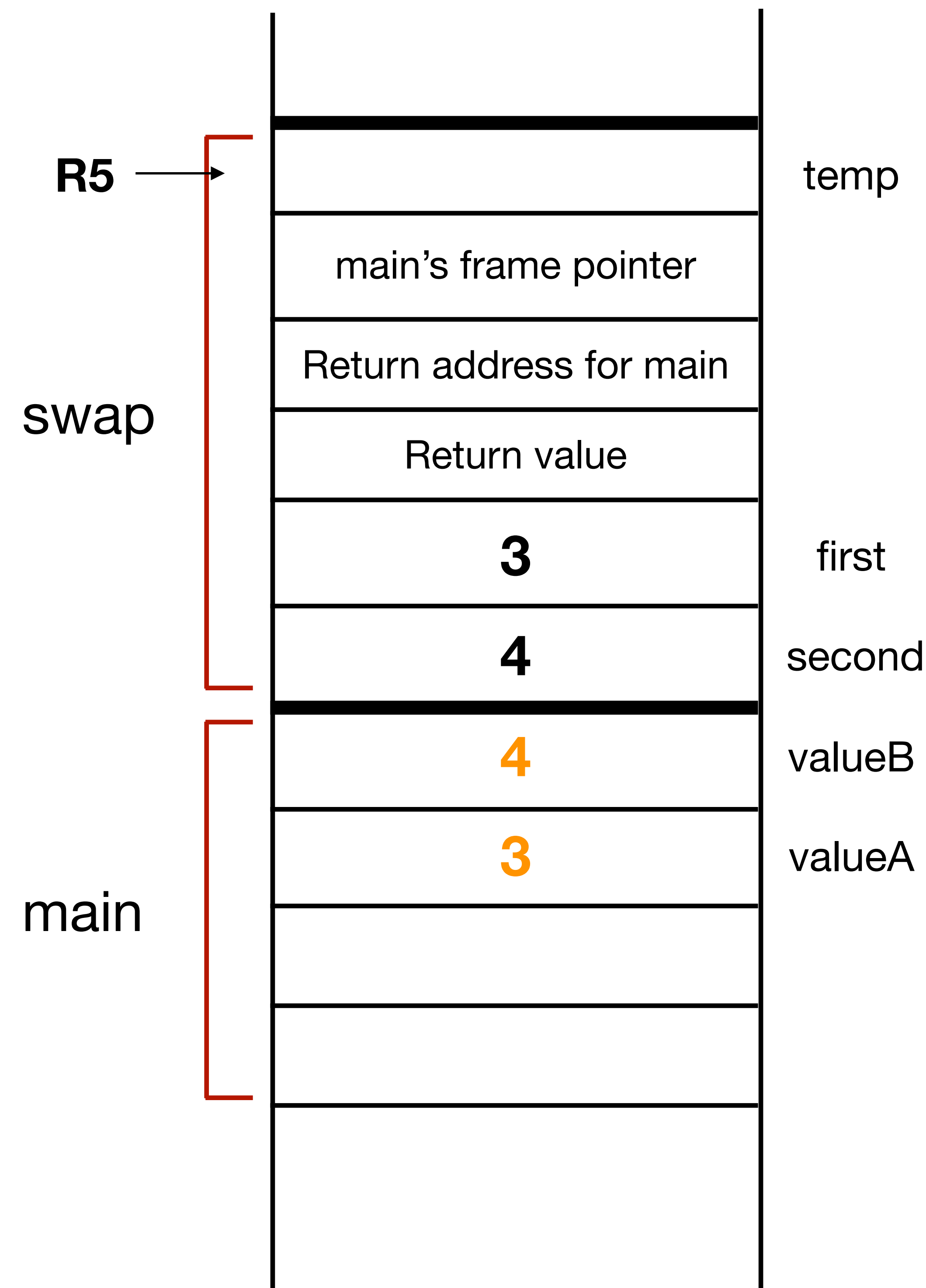
   I. Pop return value
   J. Pop arguments

Build up

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   Swap(valueA, valueB);
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}
```

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

`swap` function - build up

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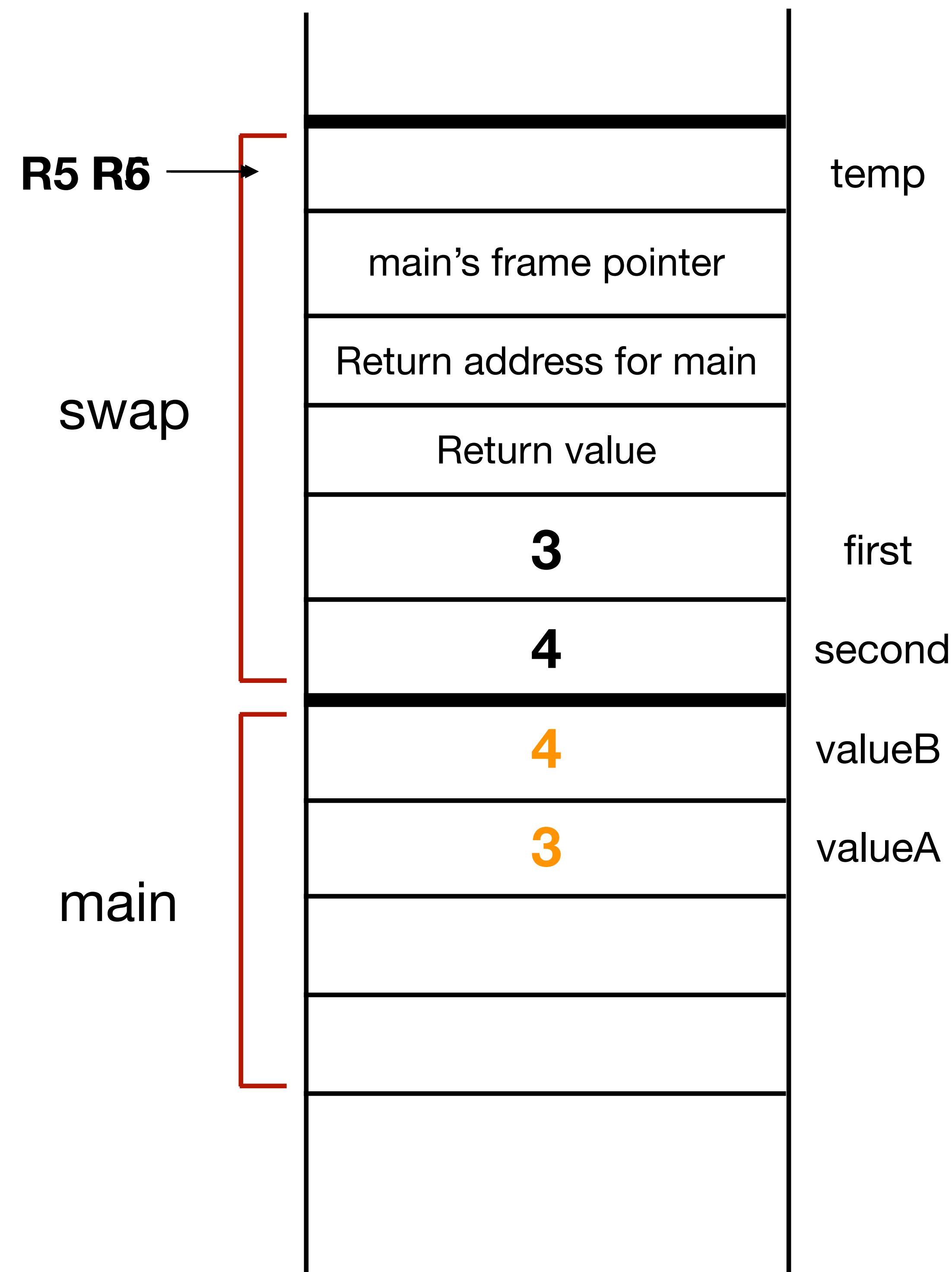
Build up

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   Swap(valueA, valueB);
}

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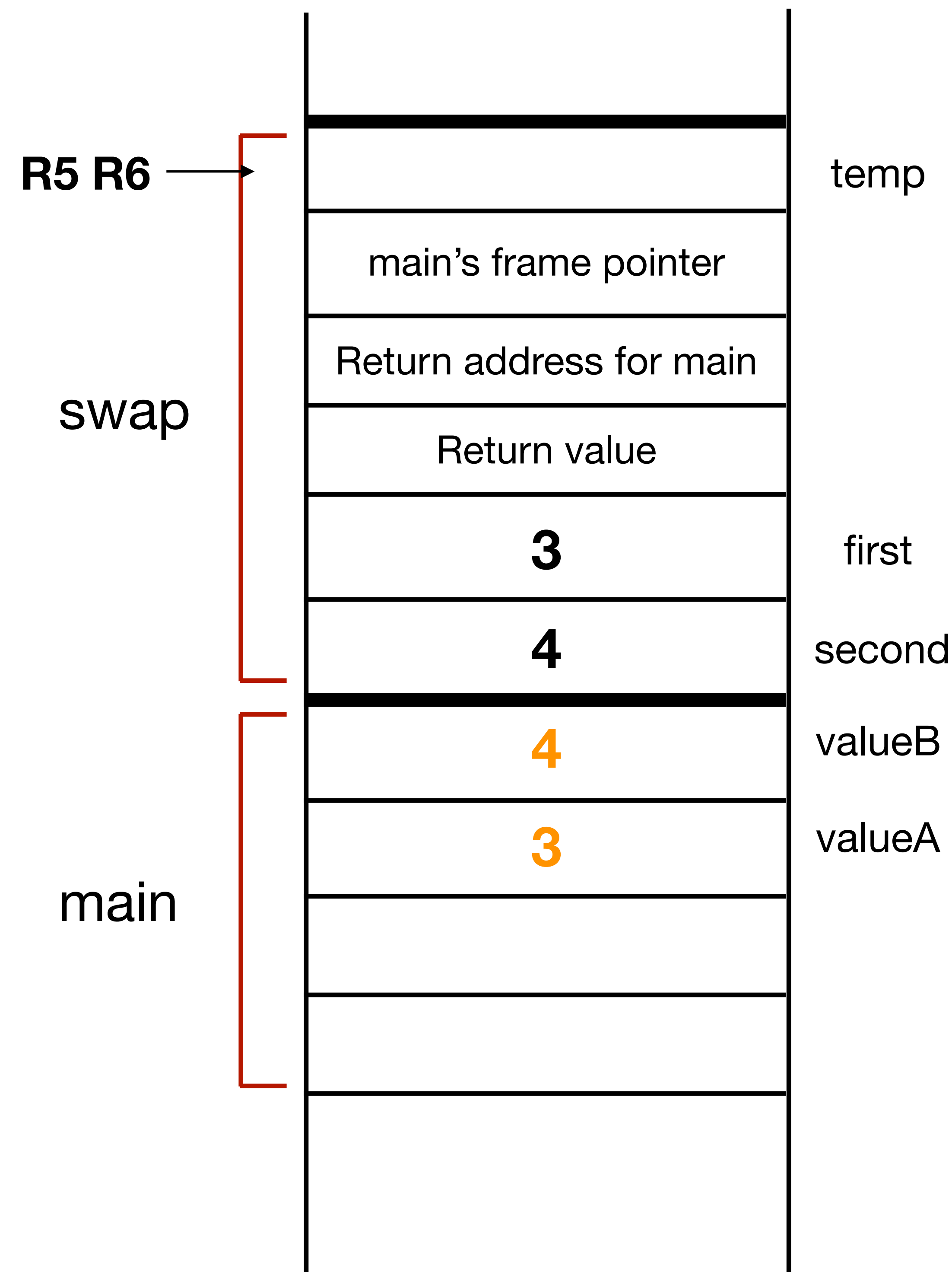

```
ADD R5, R6, #-1
ADD R6, R6, #-1
```

`swap` function - execute

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

Execution

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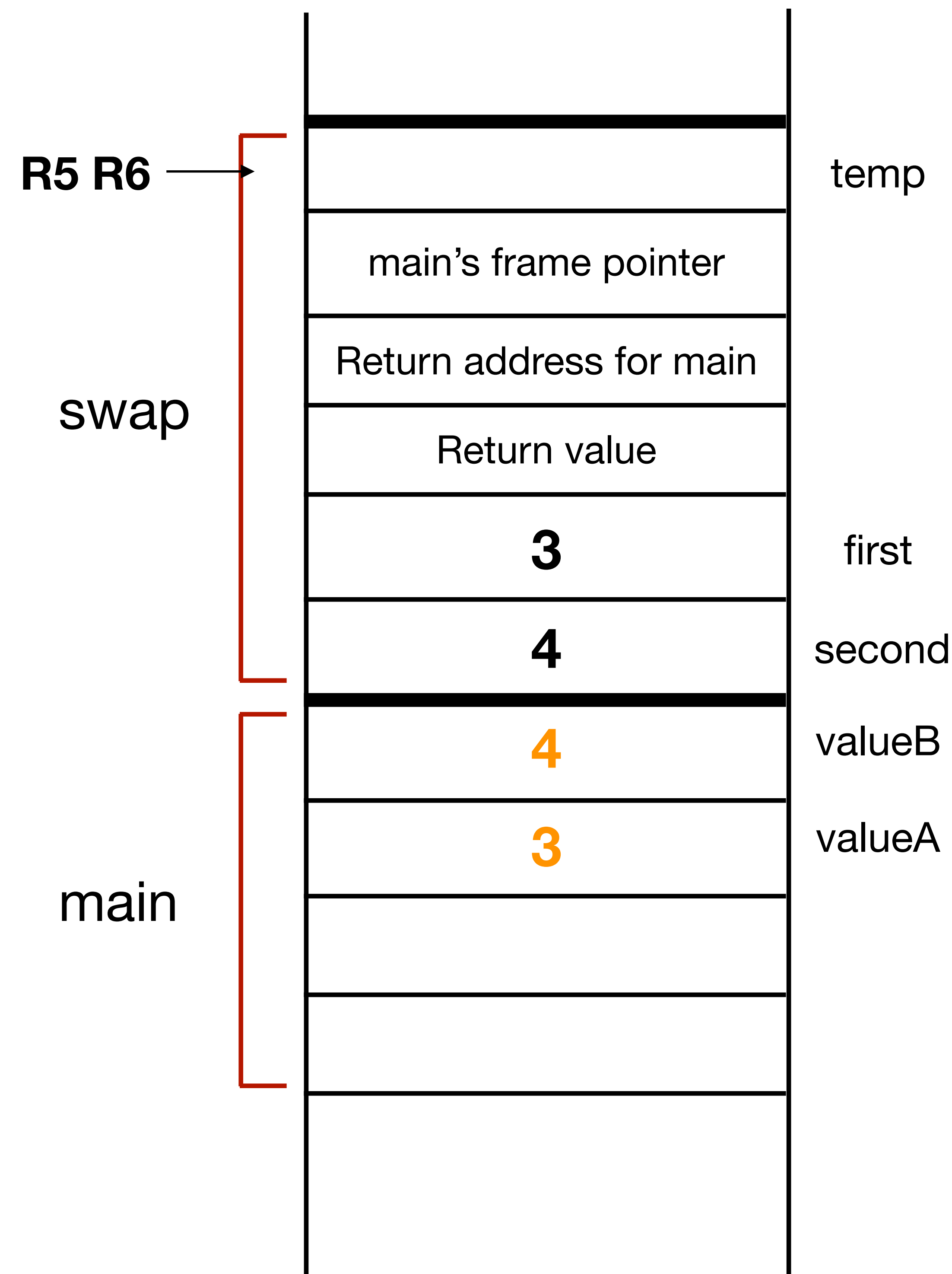
Execution




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

int main(){
   int valueA = 3;
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   Swap(valueA, valueB);
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void Swap(int first, int second){
   int temp;
   temp = first;
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}
```

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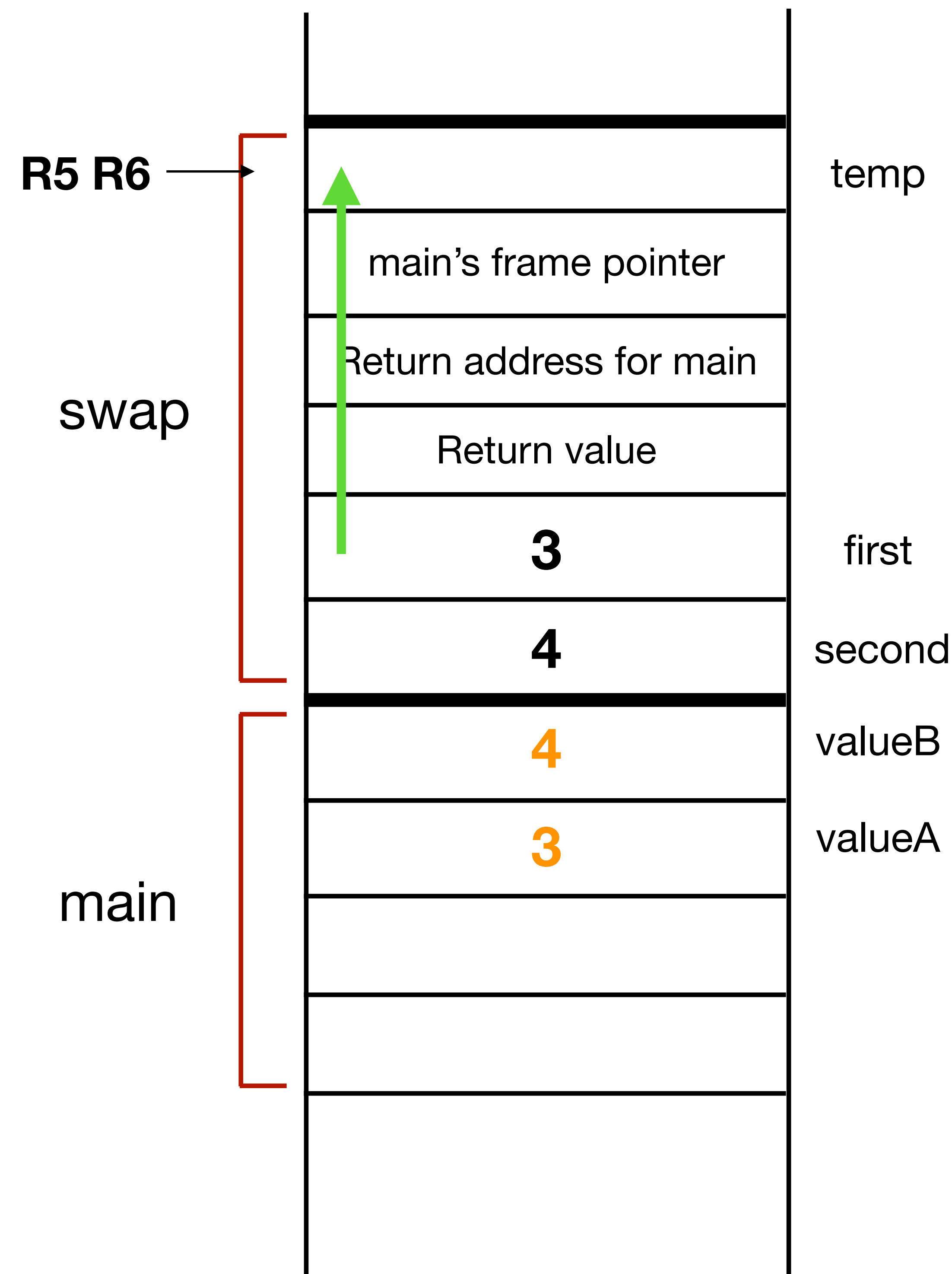


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`swap` function - execute

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Frame	Stack	Label
swap (R5 R6 →)	3	temp
swap	main's frame pointer	
swap	Return address for main	
swap	Return value	
swap	3	first
swap	4	second
main	4	valueB
main	3	valueA
main		
main		

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

int main(){
   int valueA = 3;
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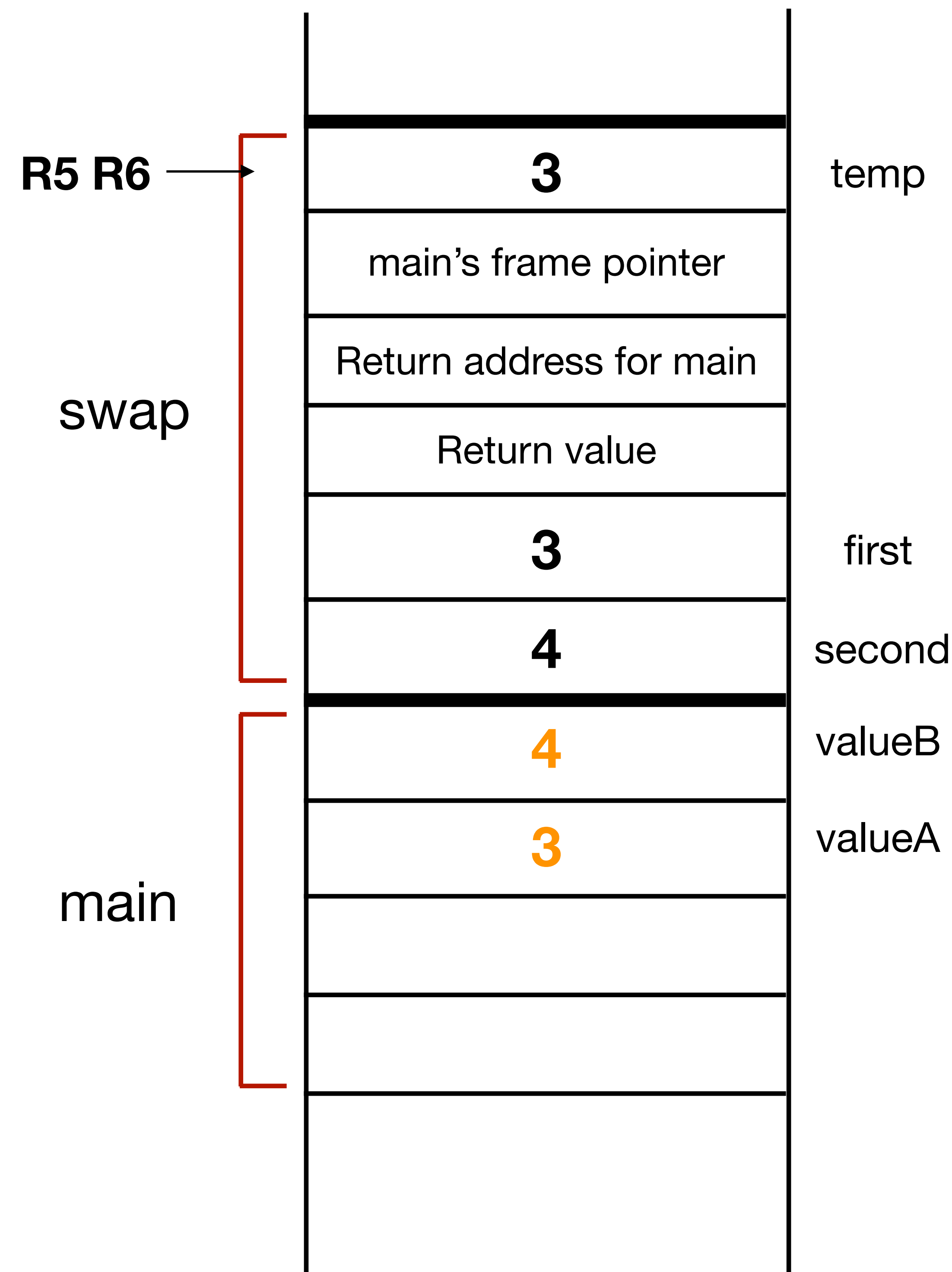


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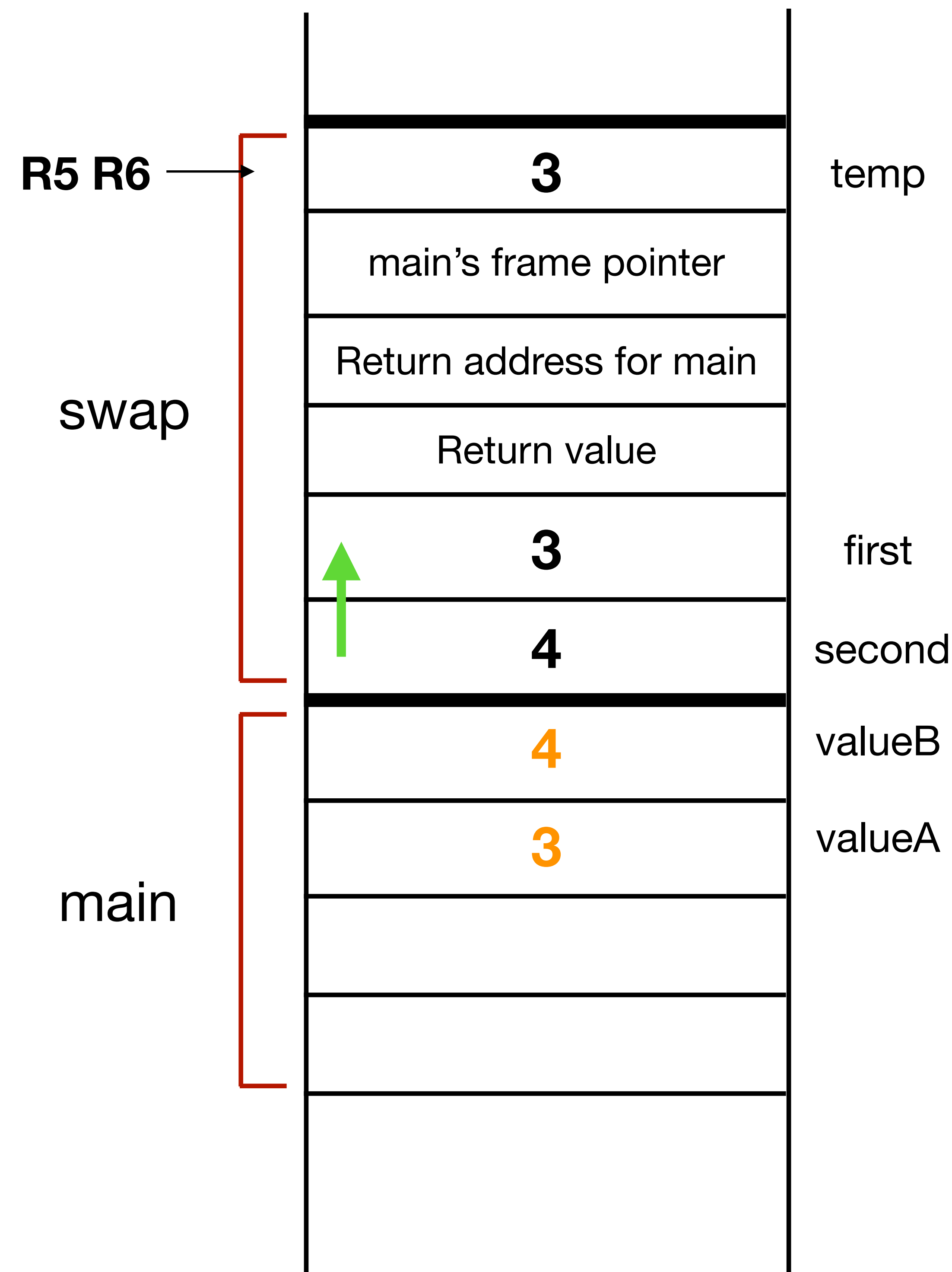


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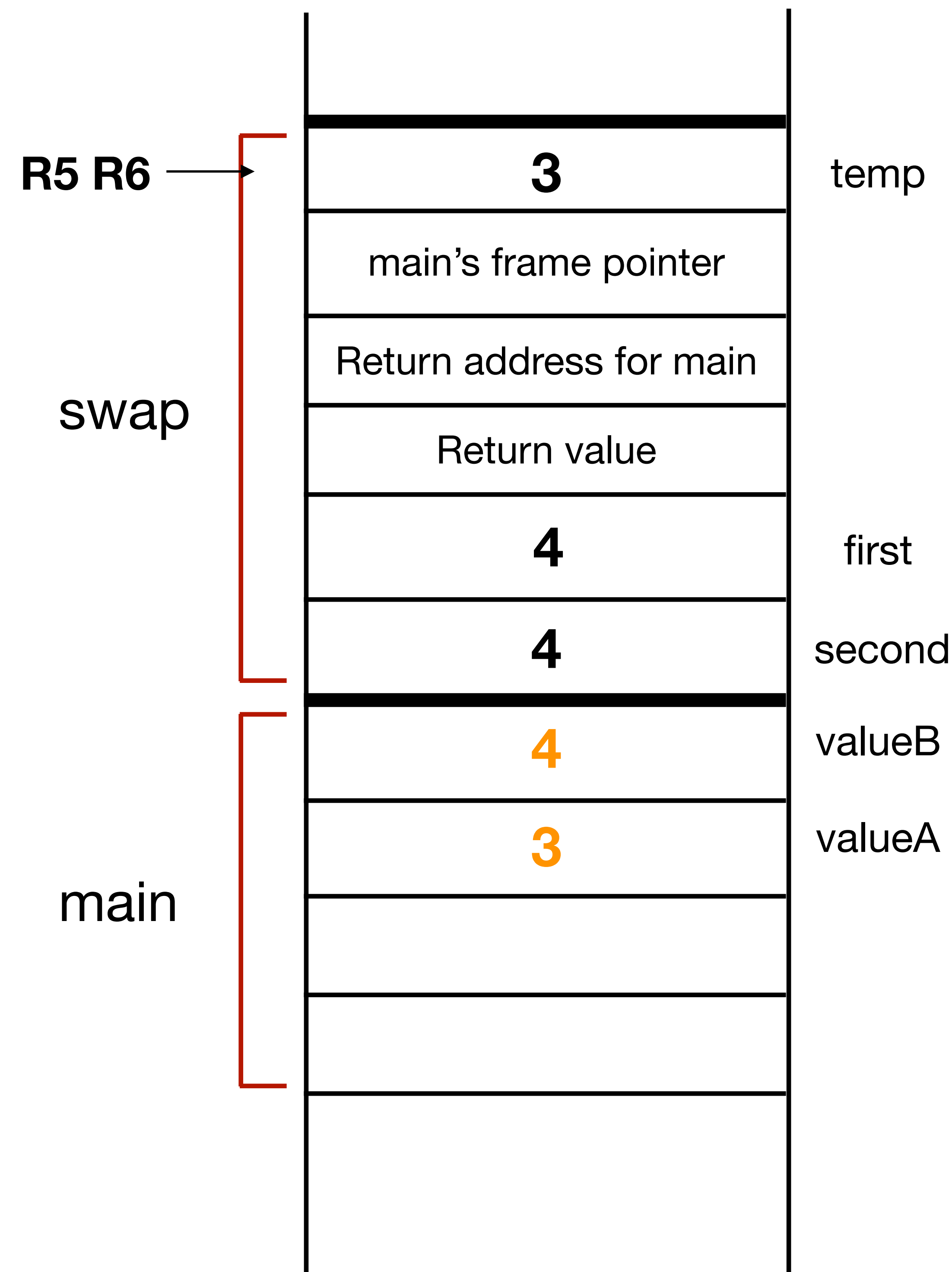


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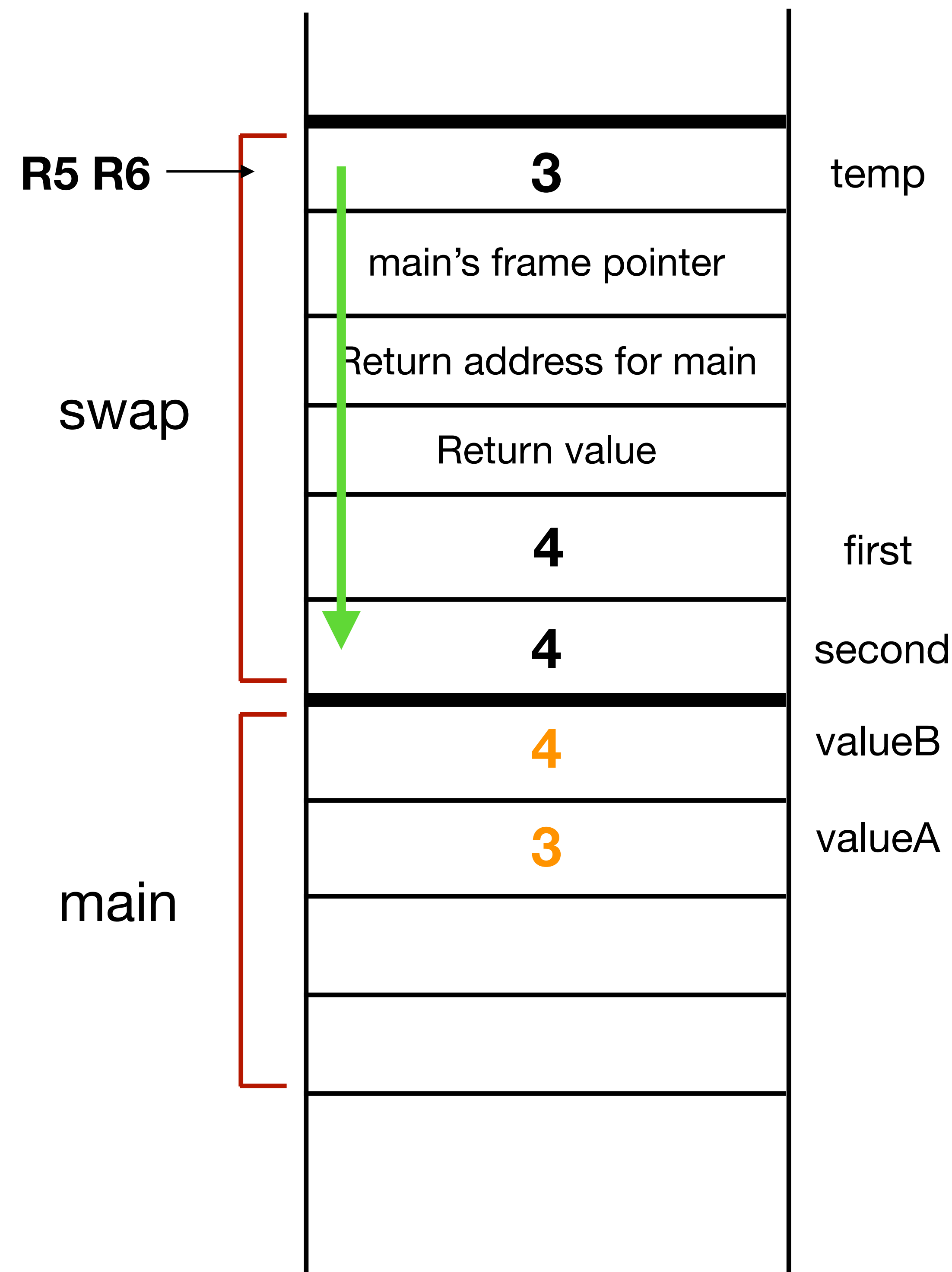
Execution

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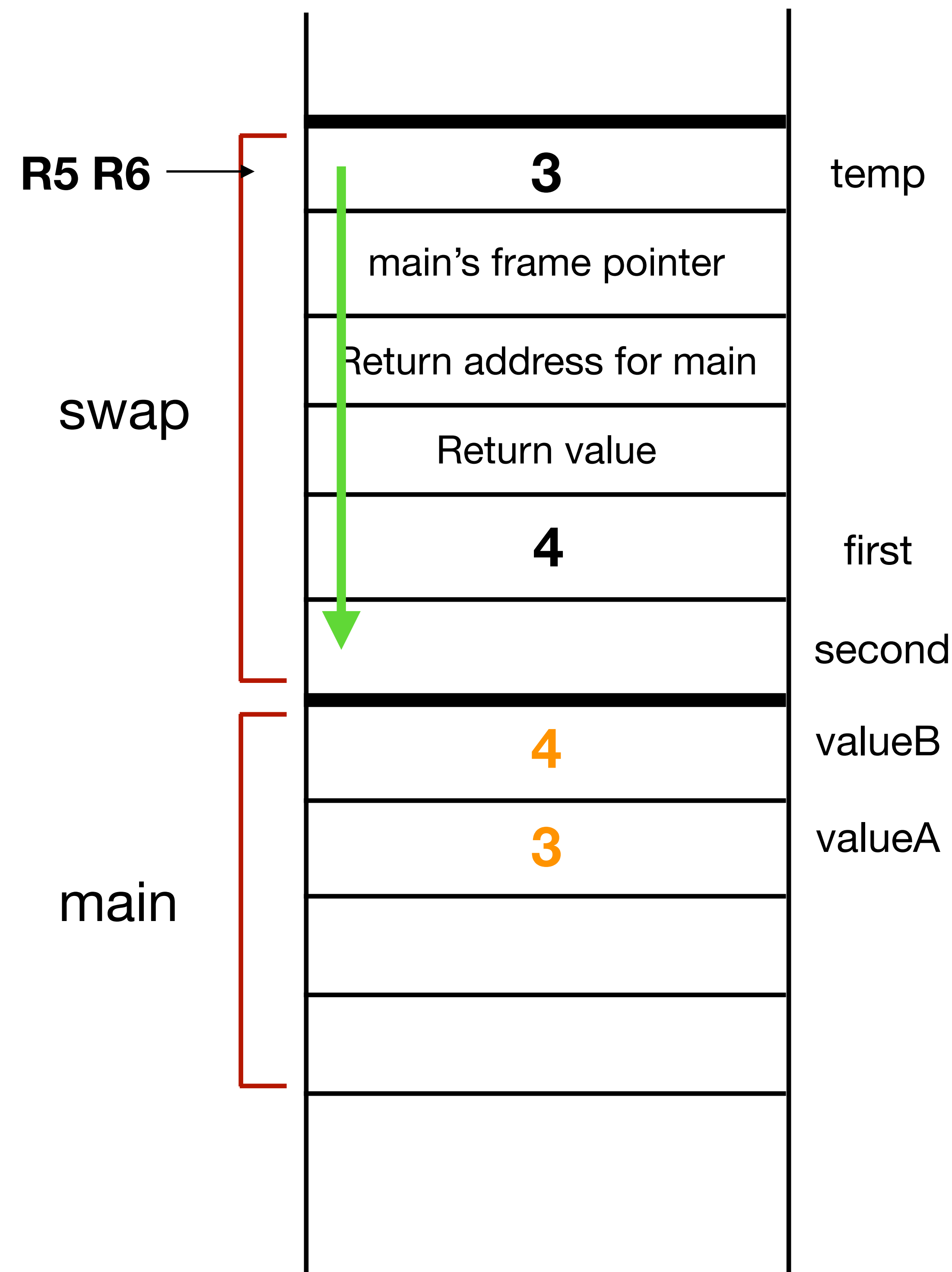


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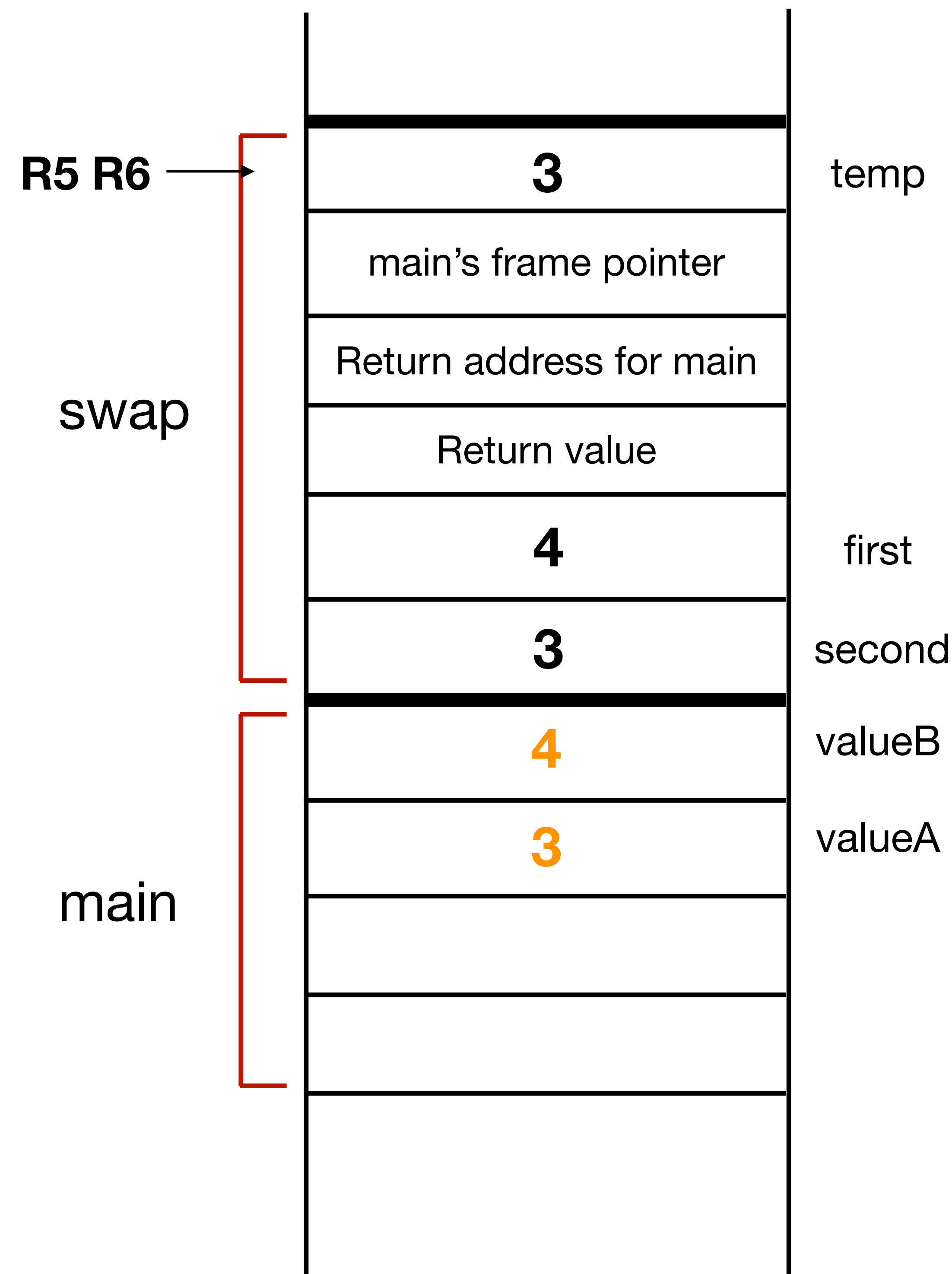


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`swap` function - tear down

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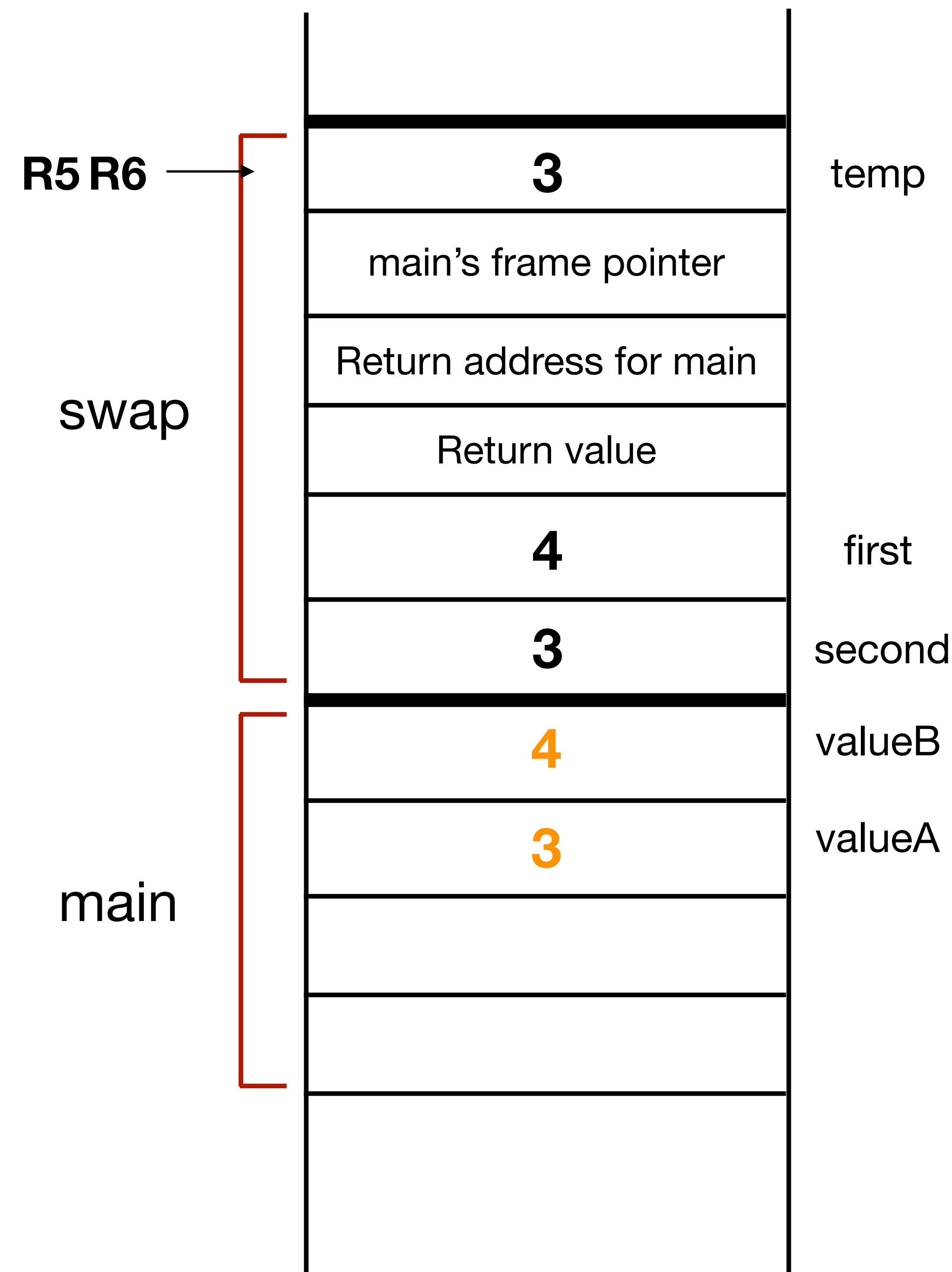
Tear down

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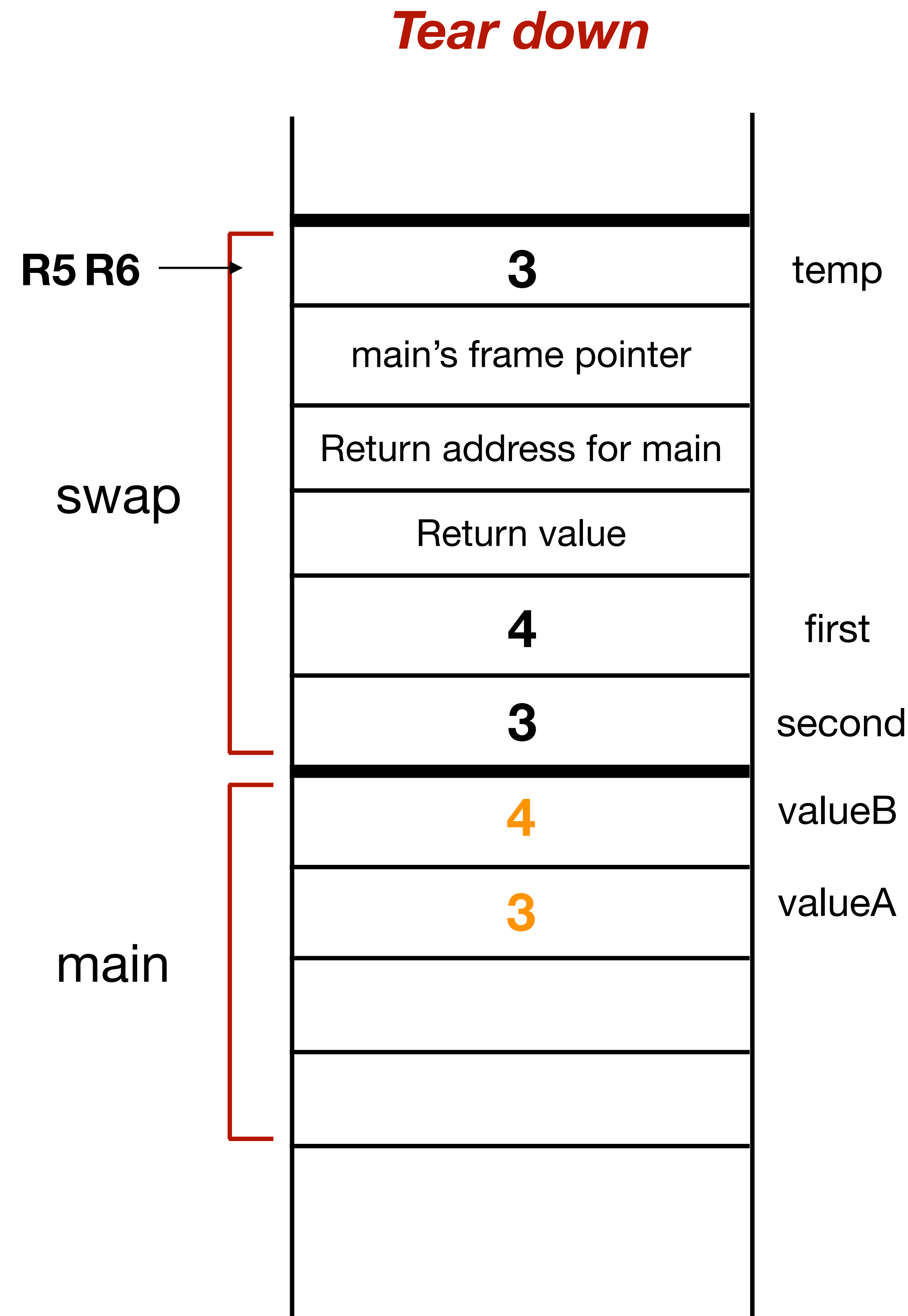


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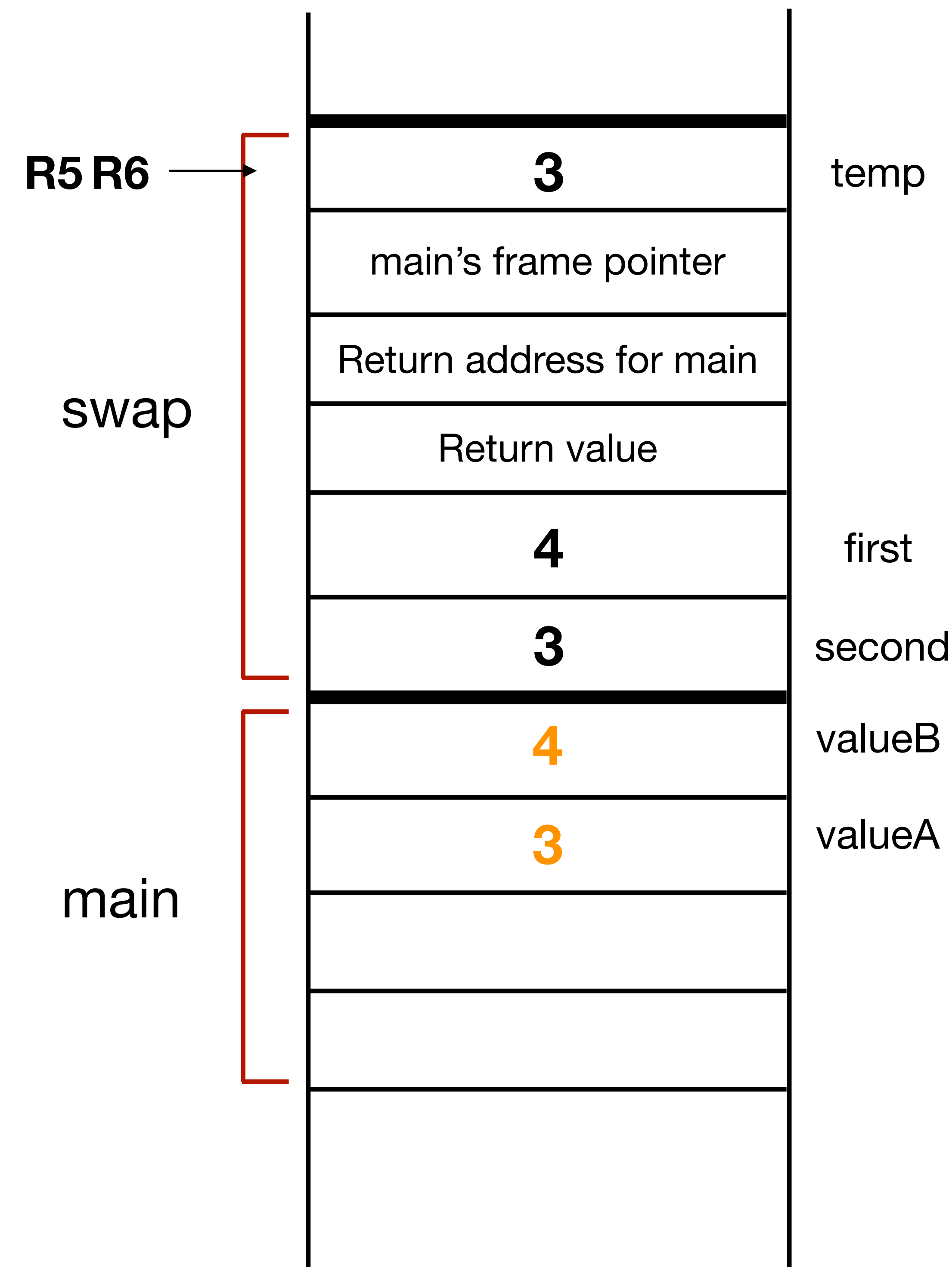


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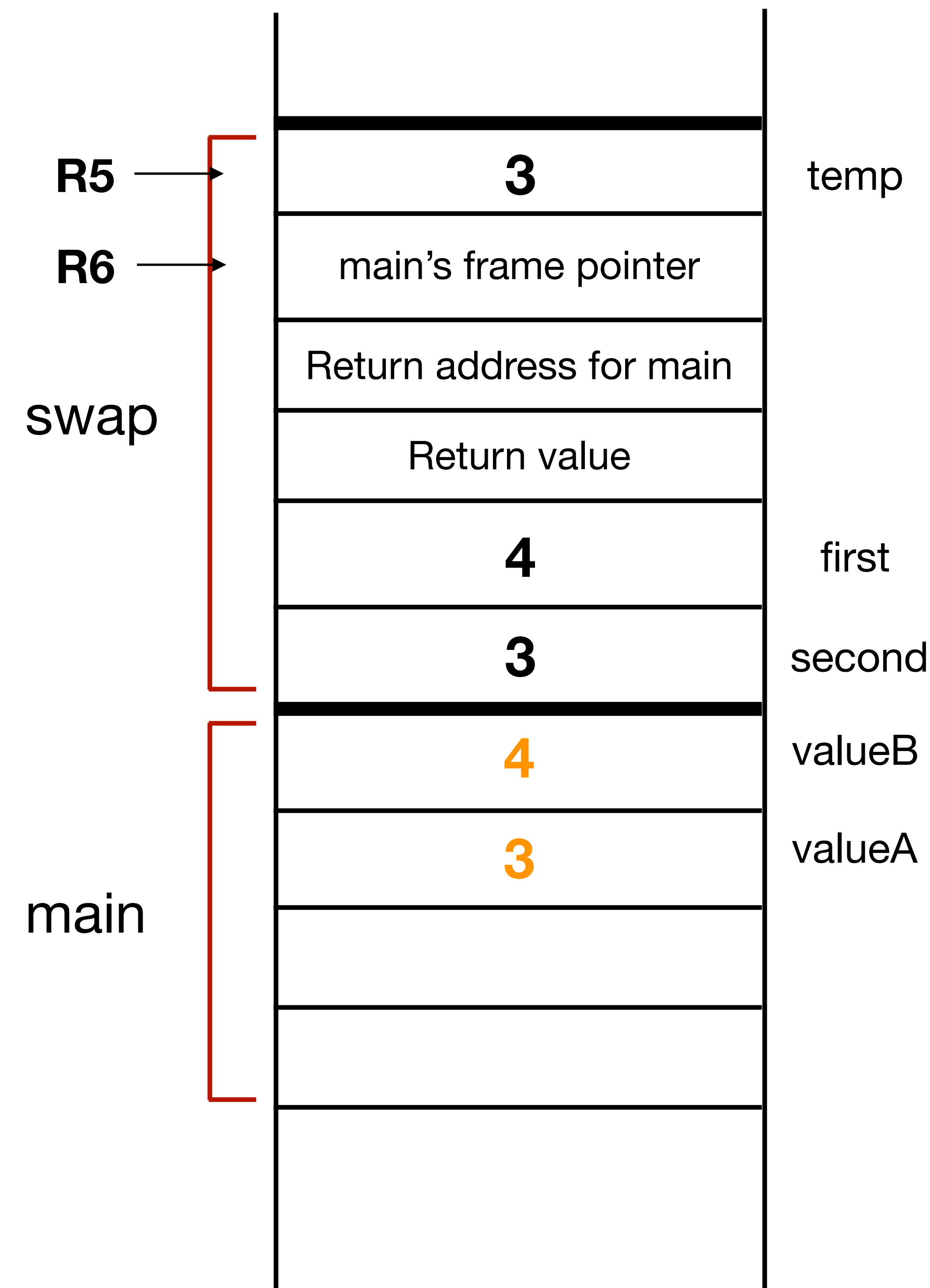


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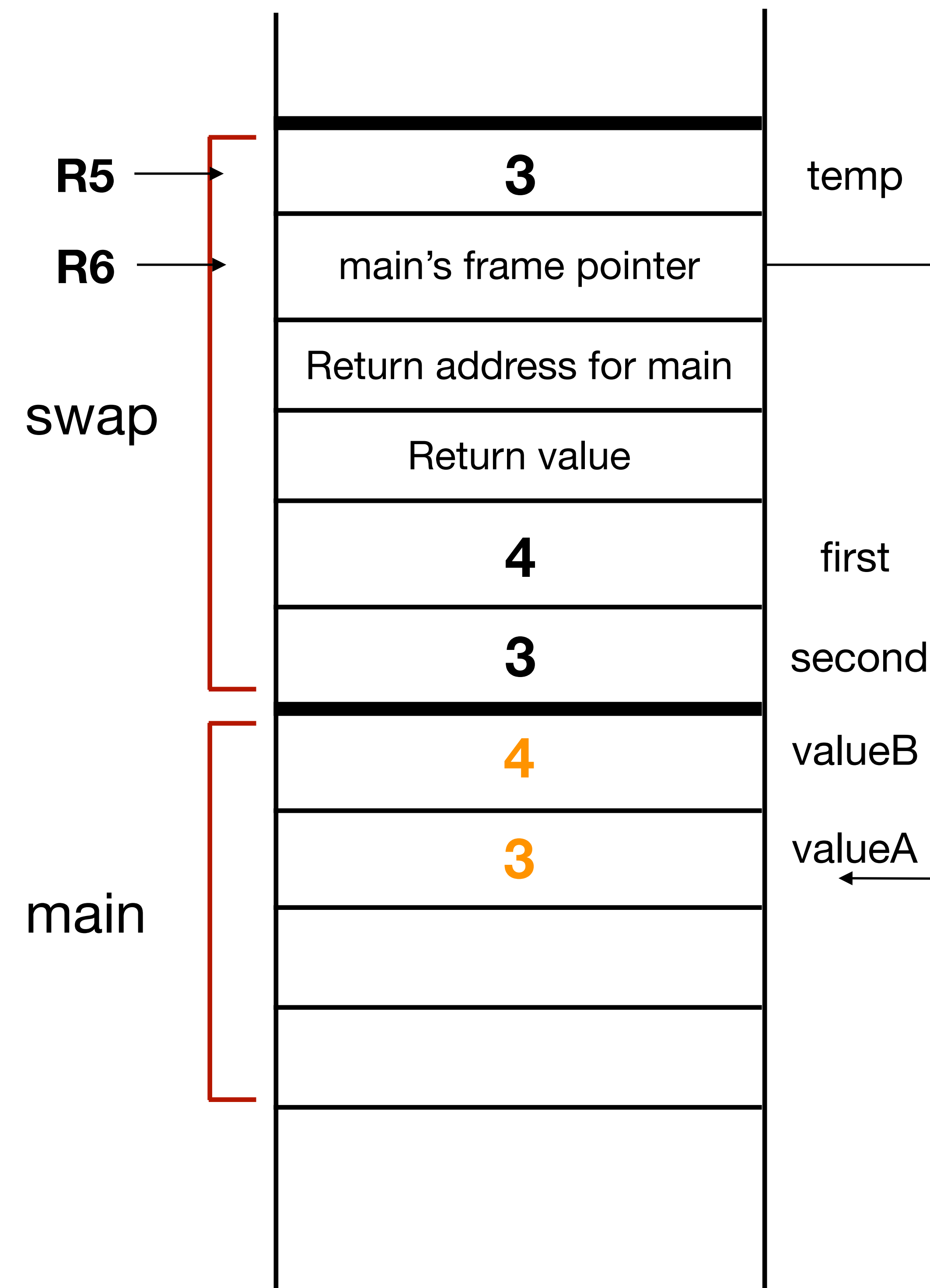


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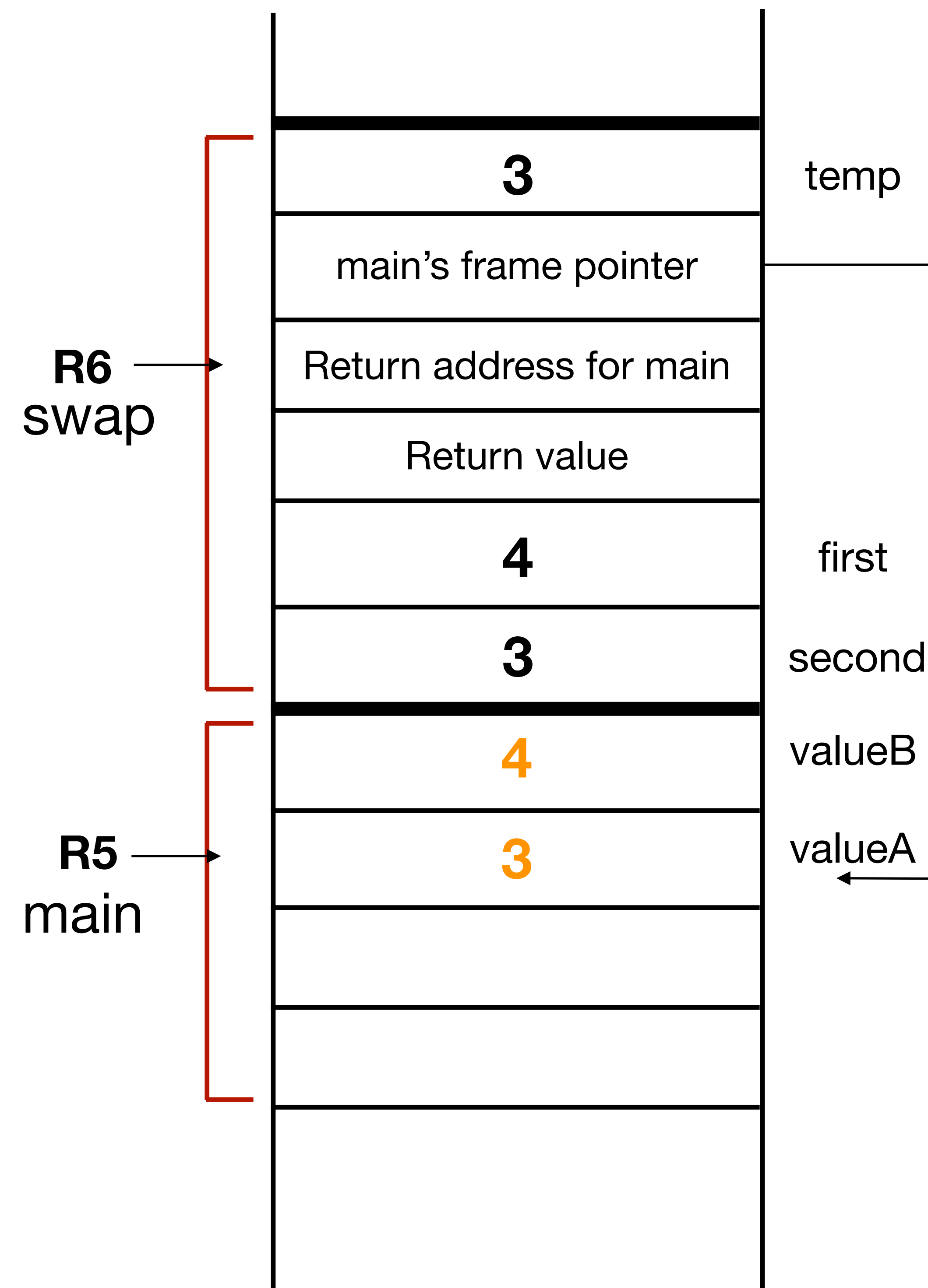


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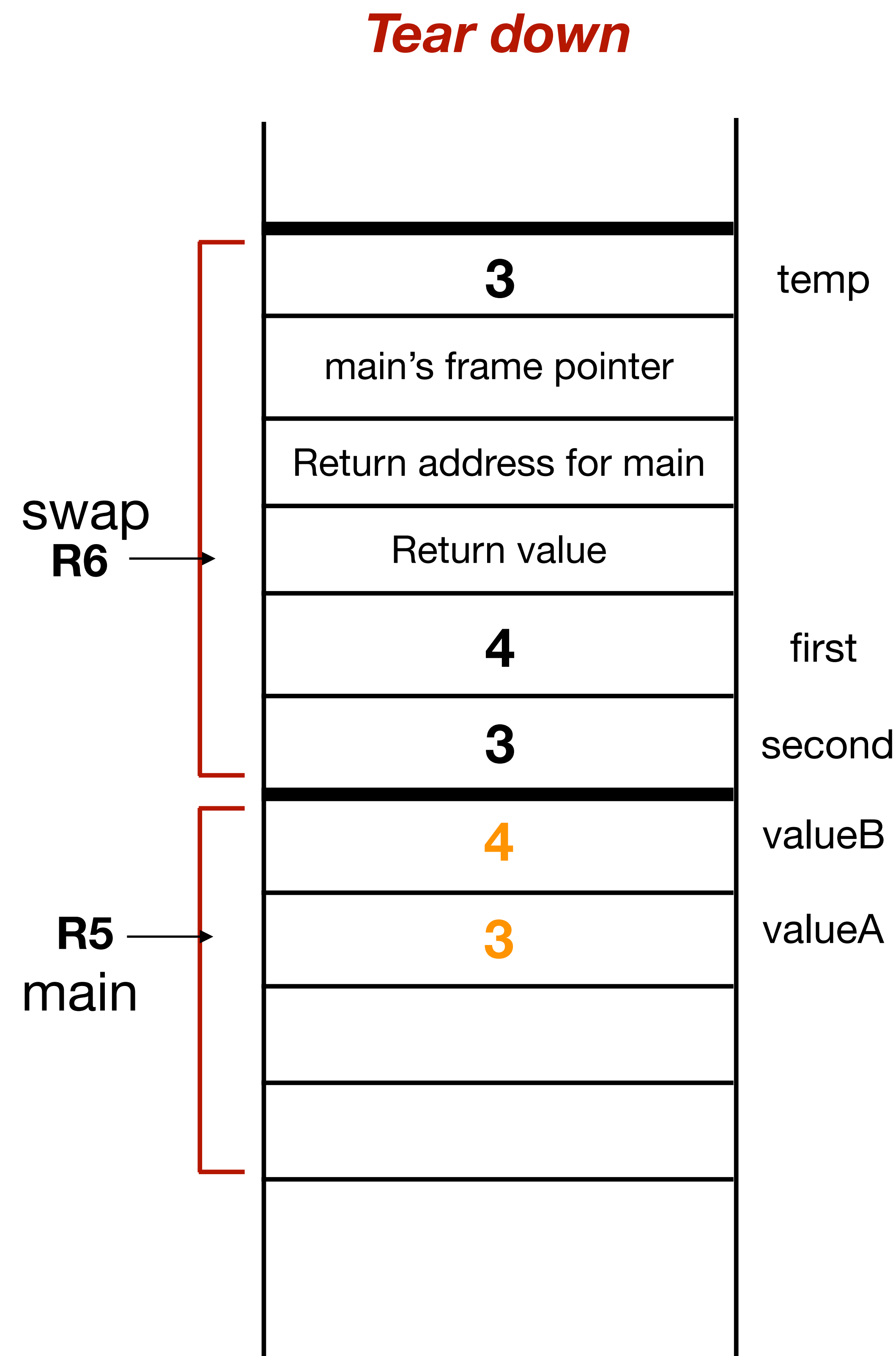

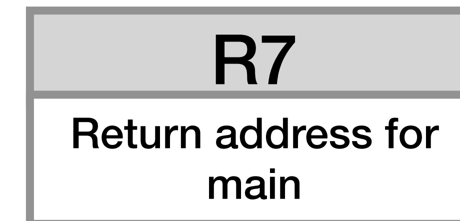


```c
void Swap(int first, int second);

int main(){
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   Swap(valueA, valueB);
}

void Swap(int first, int second){
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LC3 commands left as an exercise

`swap` function - tear down

R7: Return address for main

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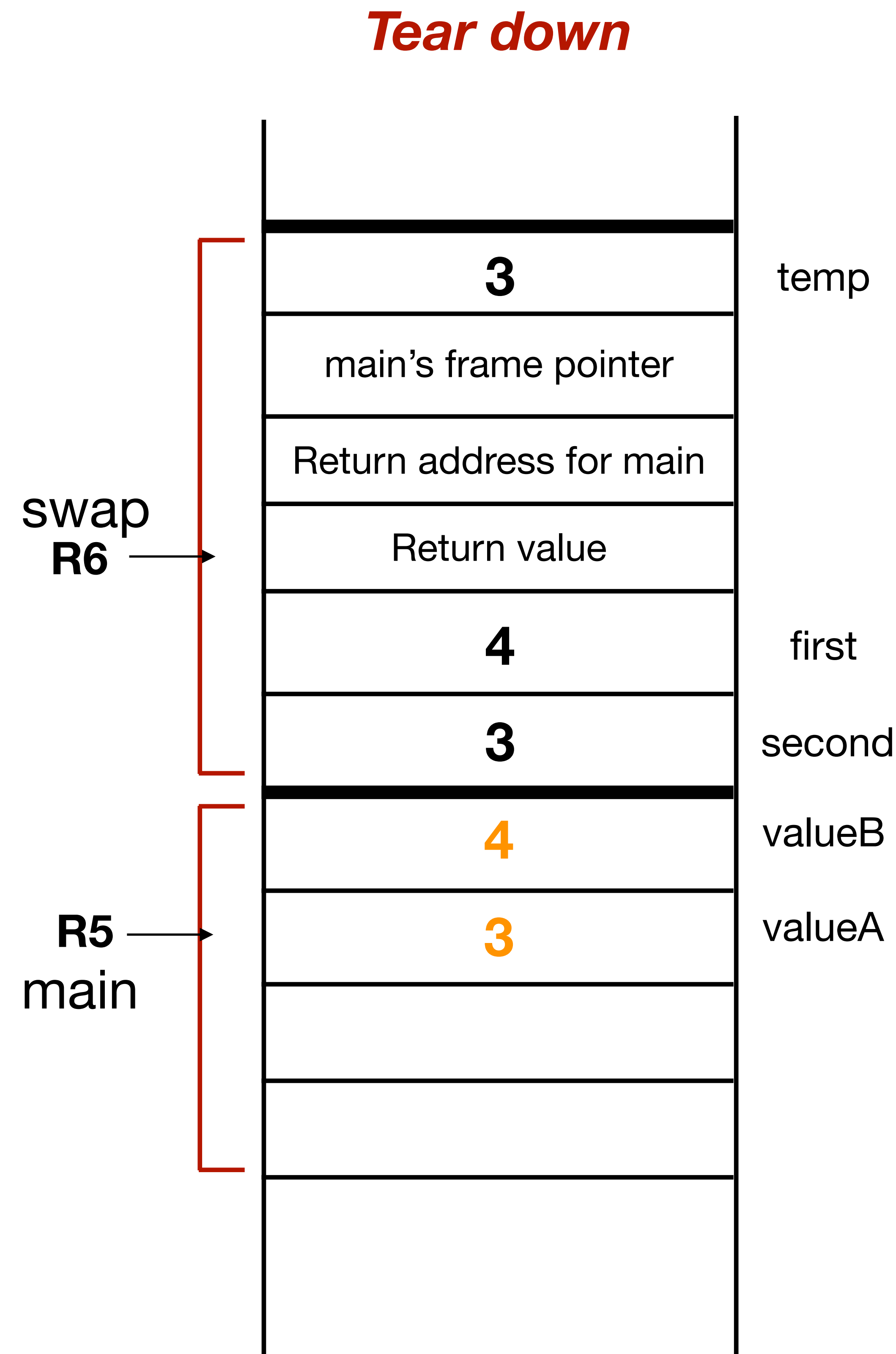


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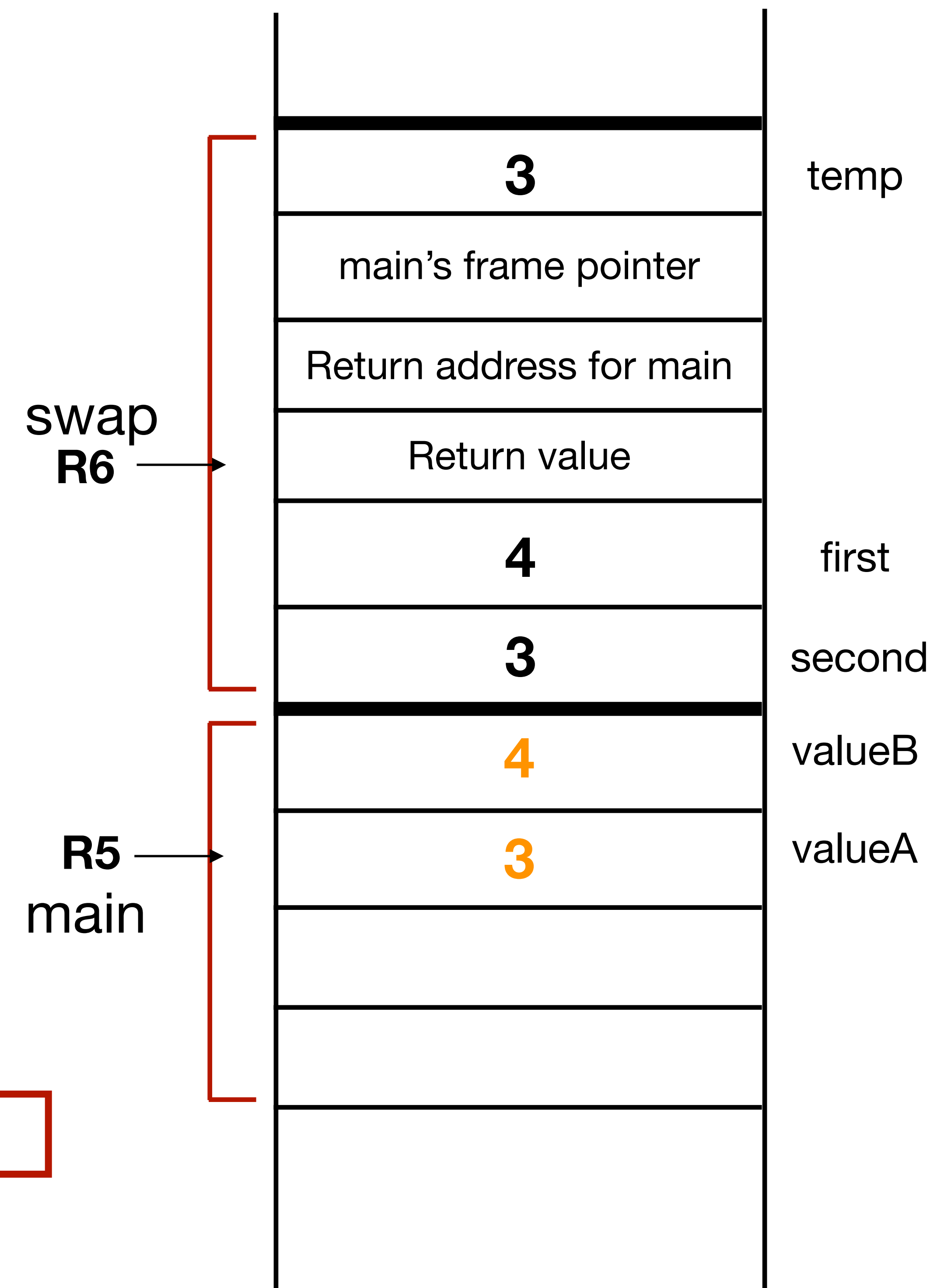


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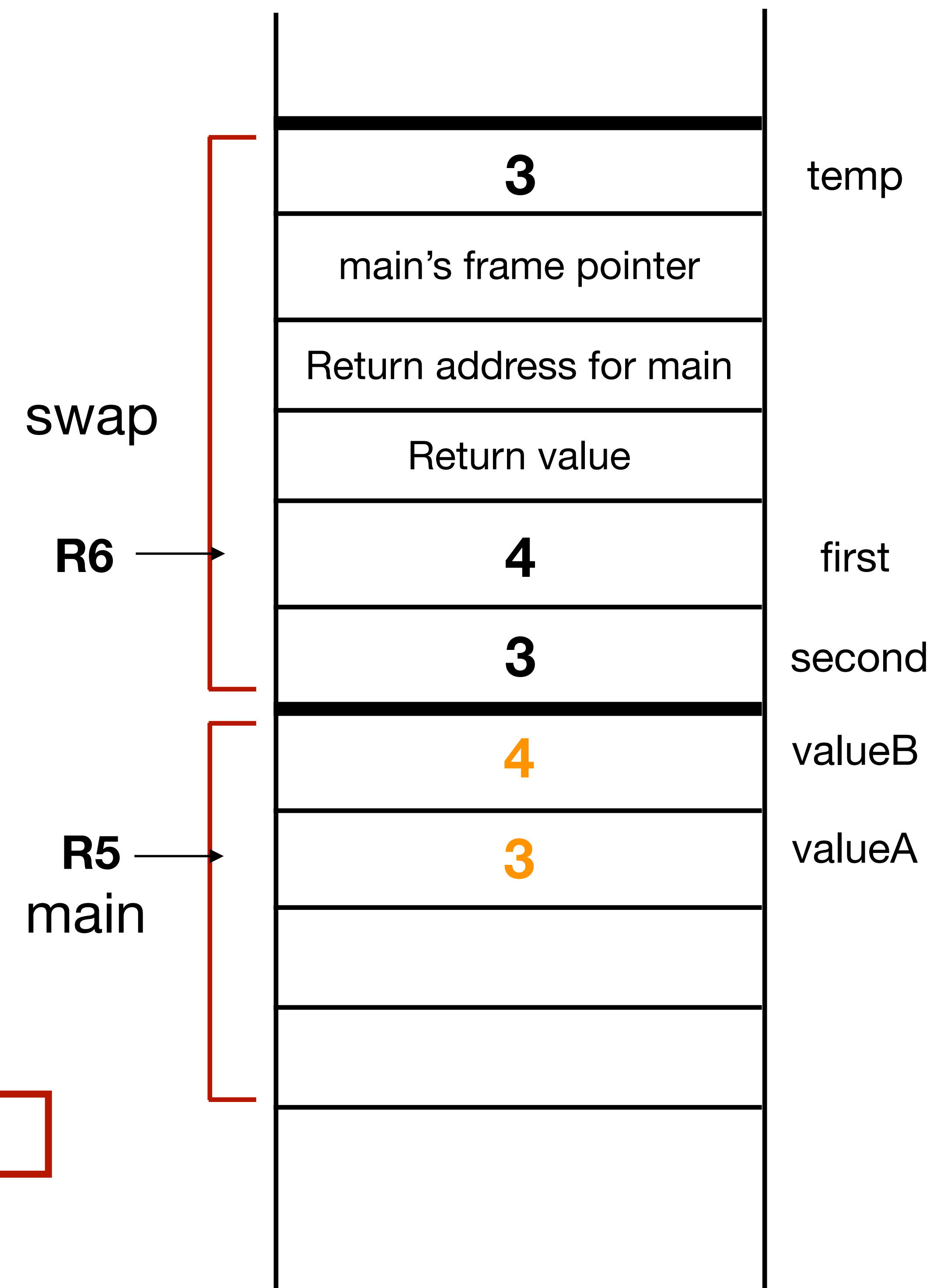


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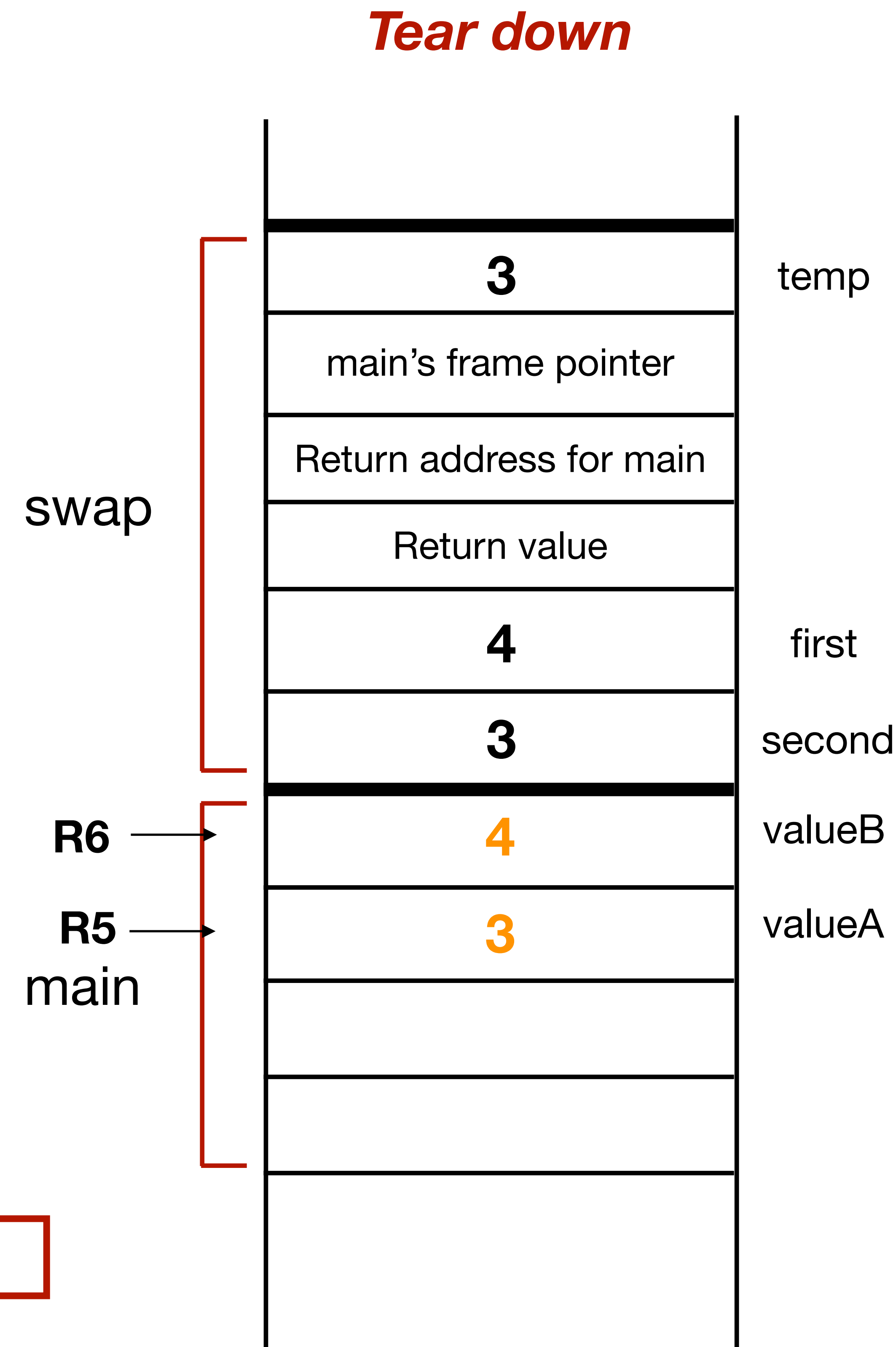


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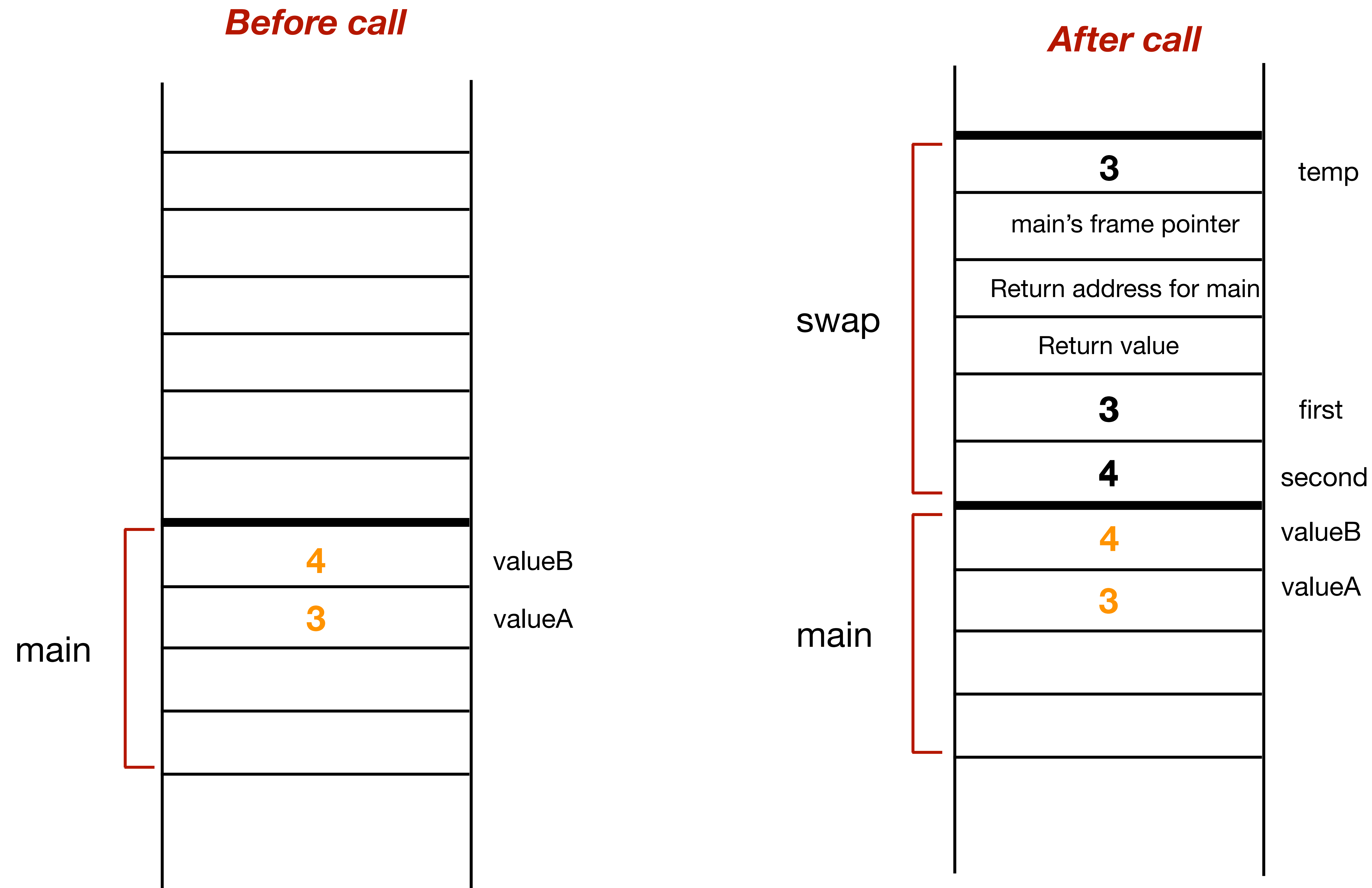
Swap function - did it work?



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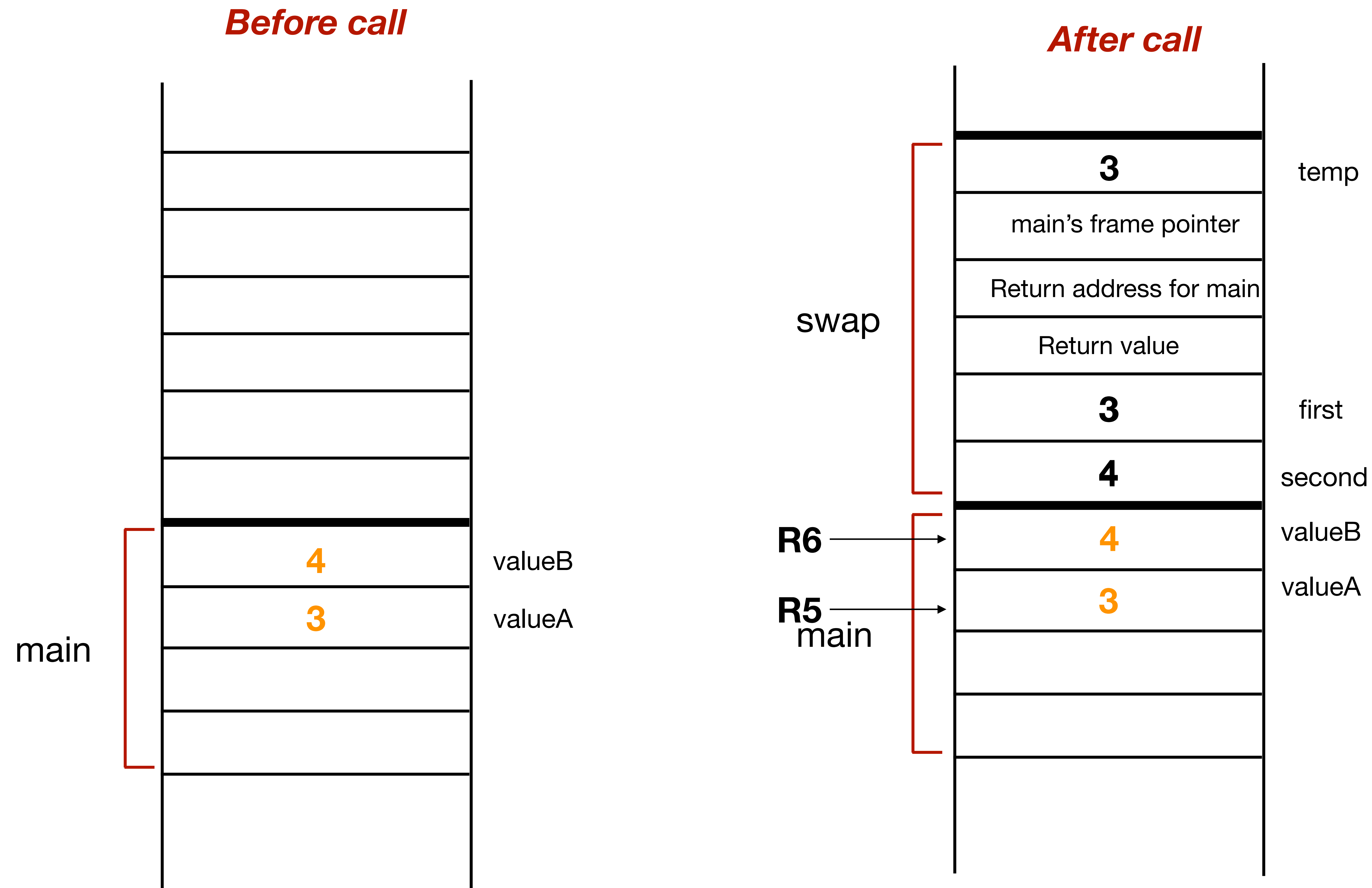

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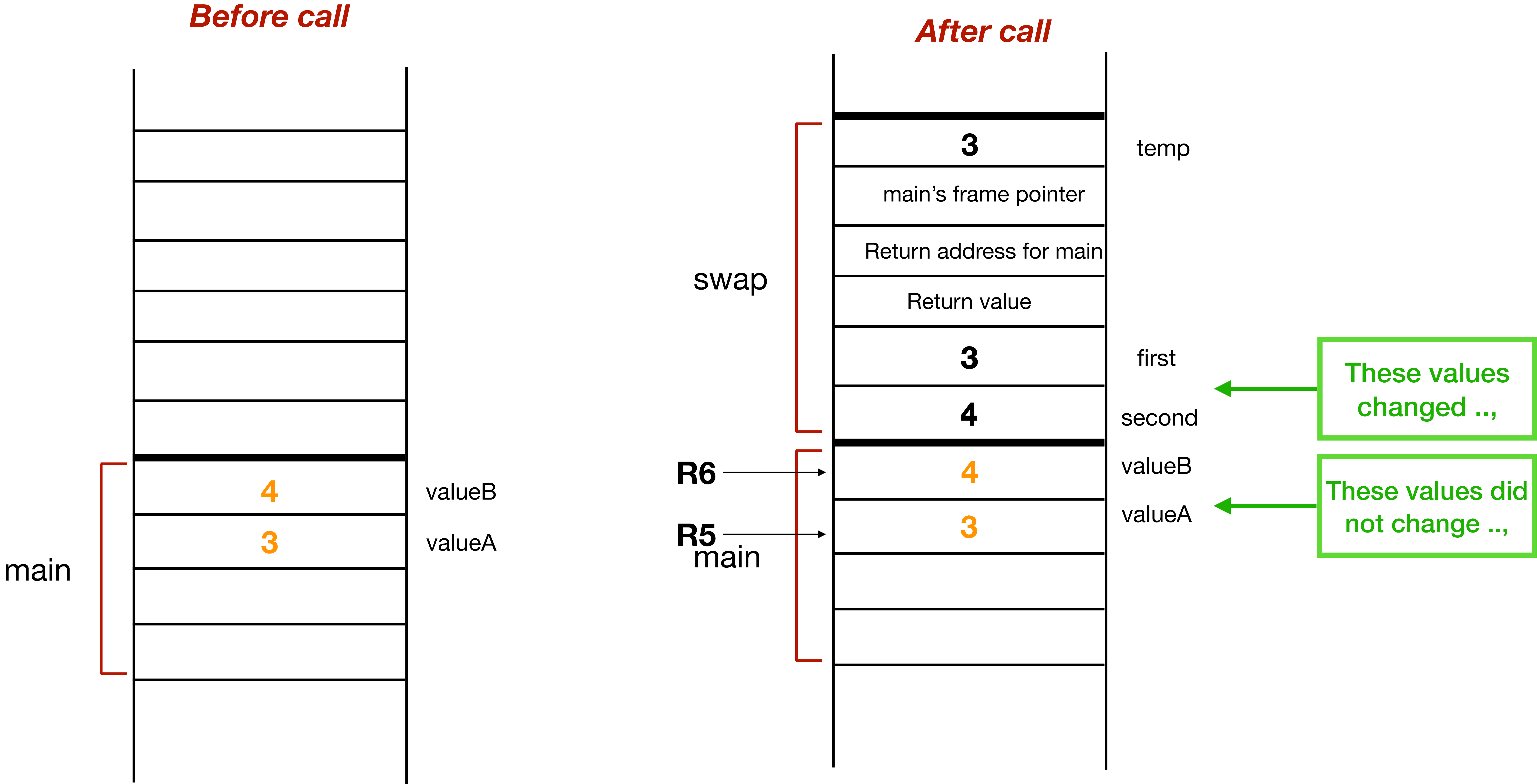

Argument passing

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  - Enter **pointers.**

Introduction to pointers

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

int main(){
  int valueA = 3;
  int valueB = 4;
  Swap(&valueA, &valueB);
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void Swap(int *first, int *second){
int temp;
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Introduction to pointers

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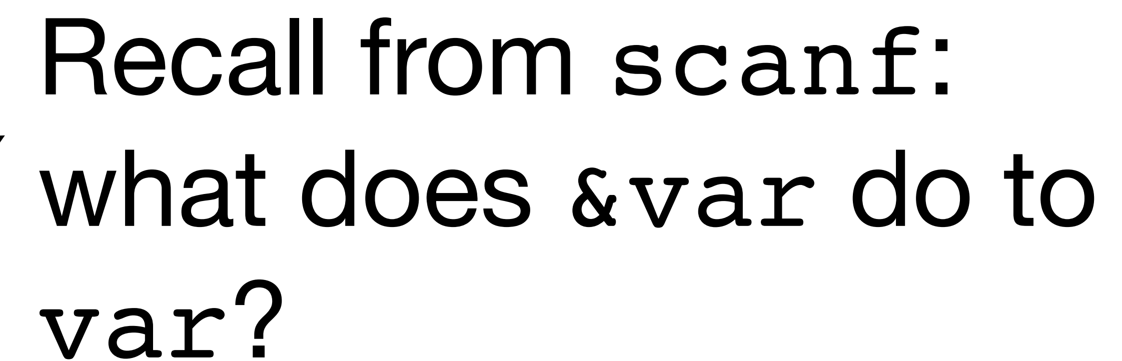

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Confused?

Don’t miss next class!

Time permitting

Time permitting

- `gcc` compilation arguments

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  - `-O0`
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Time permitting

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- Debugging
  - Preview of MP4

Time permitting

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