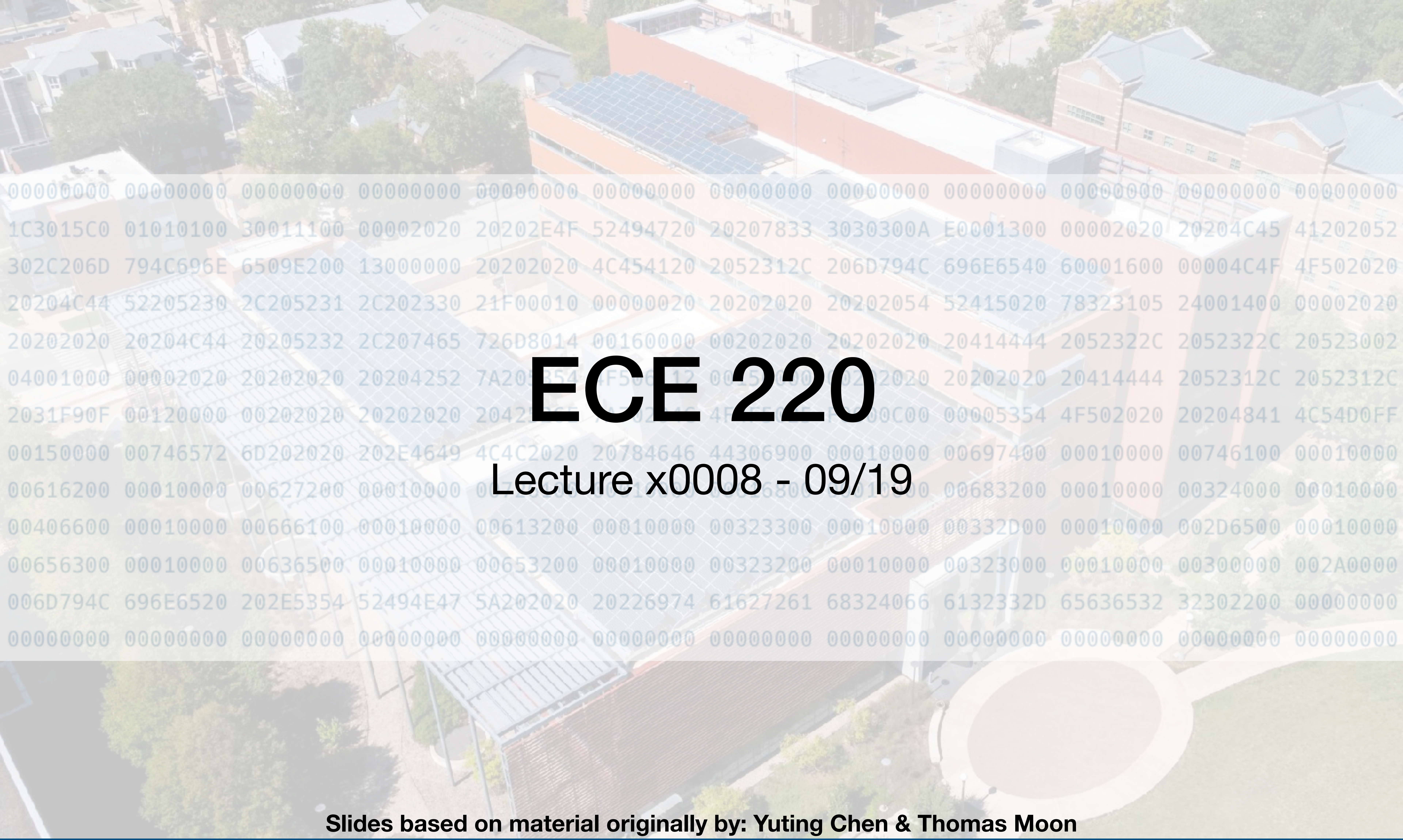

ECE 220

Lecture x0008 - 09/19

```
00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
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302C206D 794C696E 6509E200 13000000 20202020 4C454120 2052312C 206D794C 696E6540 60001600 00004C4F 4F502020
20204C44 52205230 2C205231 2C202330 21F00010 00000020 20202020 20202054 52415020 78323105 24001400 00002020
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04001000 00002020 20202020 20204252 [illegible] [illegible] [illegible] [illegible] 20202020 20414444 2052312C 2052312C
2031F90F 00120000 00202020 20202020 [illegible] [illegible] [illegible] [illegible] 00005354 4F502020 20204841 4C54D0FF
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00656300 00010000 00636500 00010000 00653200 00010000 00323200 00010000 00323000 00010000 00300000 002A0000
006D794C 696E6520 202E5354 52494E47 5A202020 20226974 61627261 68324066 6132332D 65636532 32302200 00000000
00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
```

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

Recap + reminders

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  - Implementation in assembly & intro to RTS

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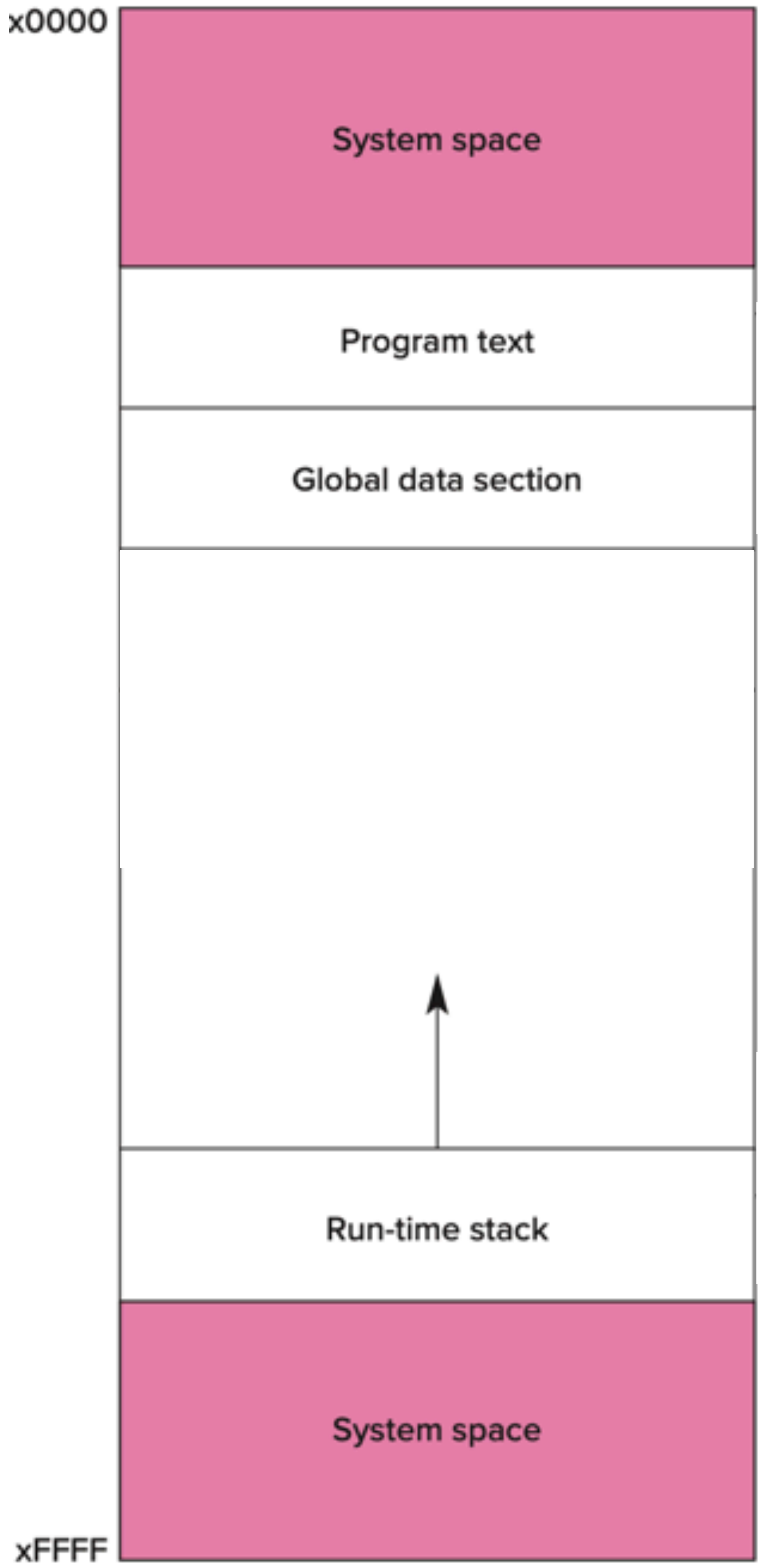
Why are some offsets negative and others positive?

Example: In LC3 memory map



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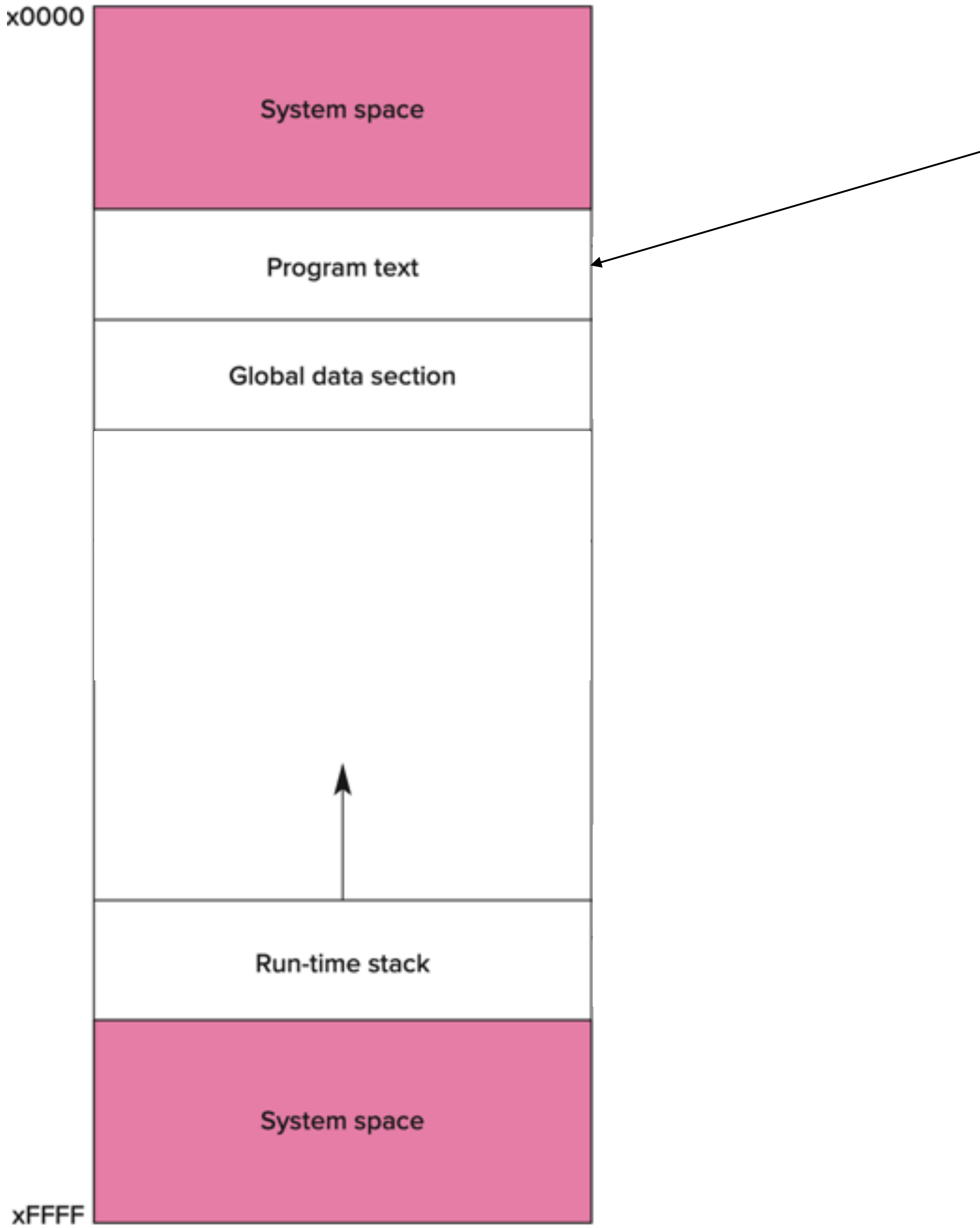

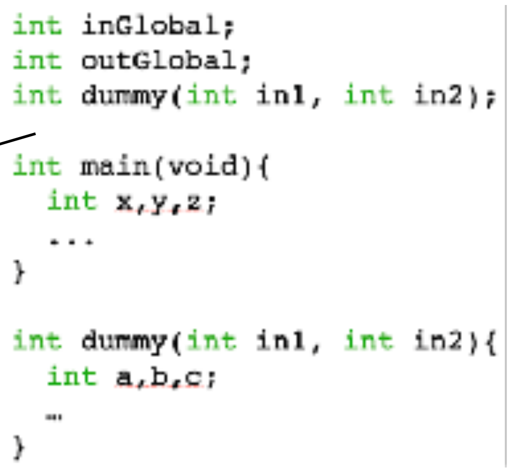

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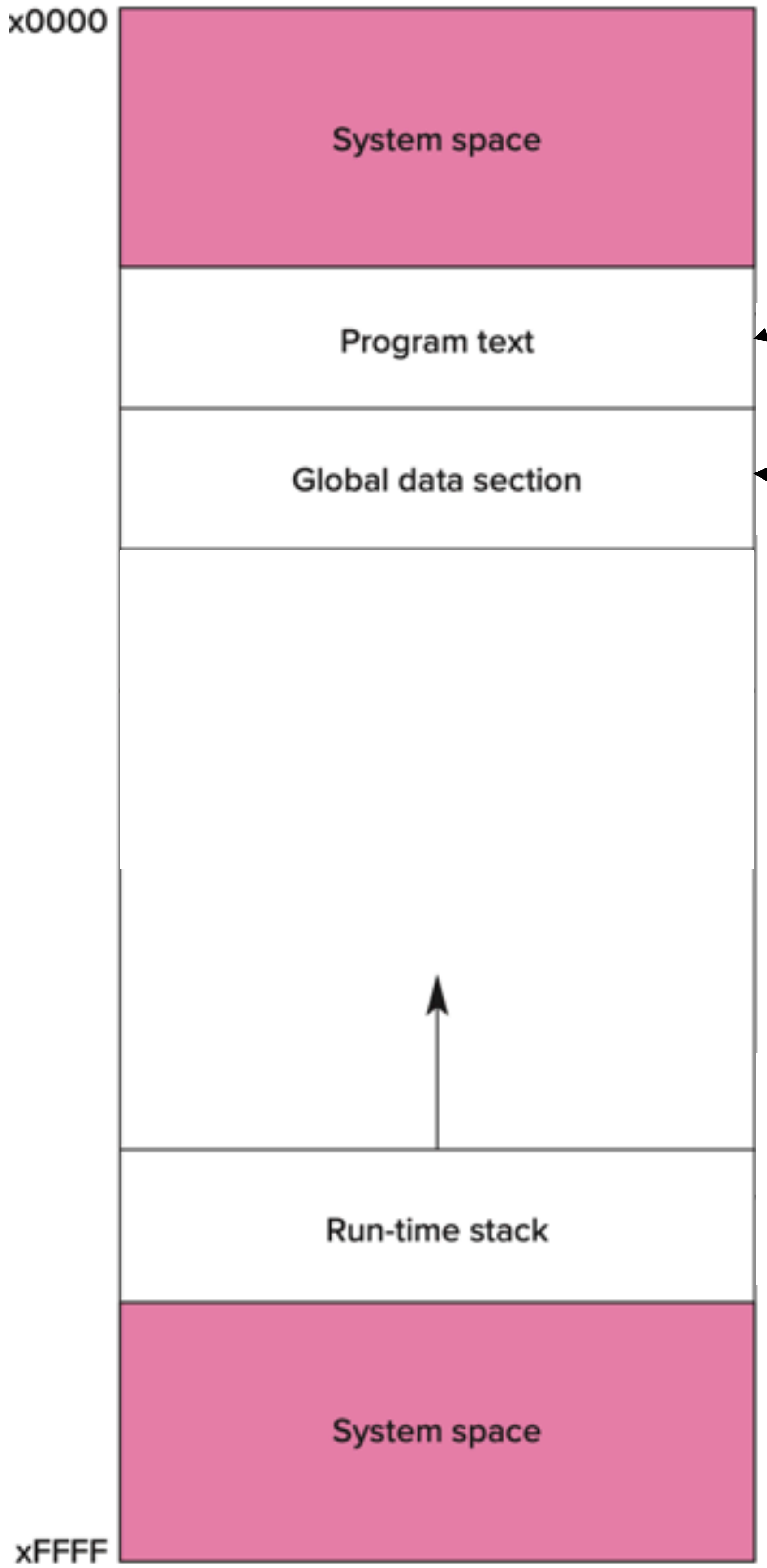

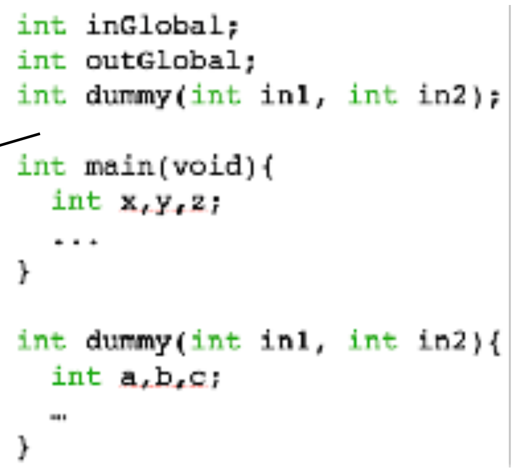

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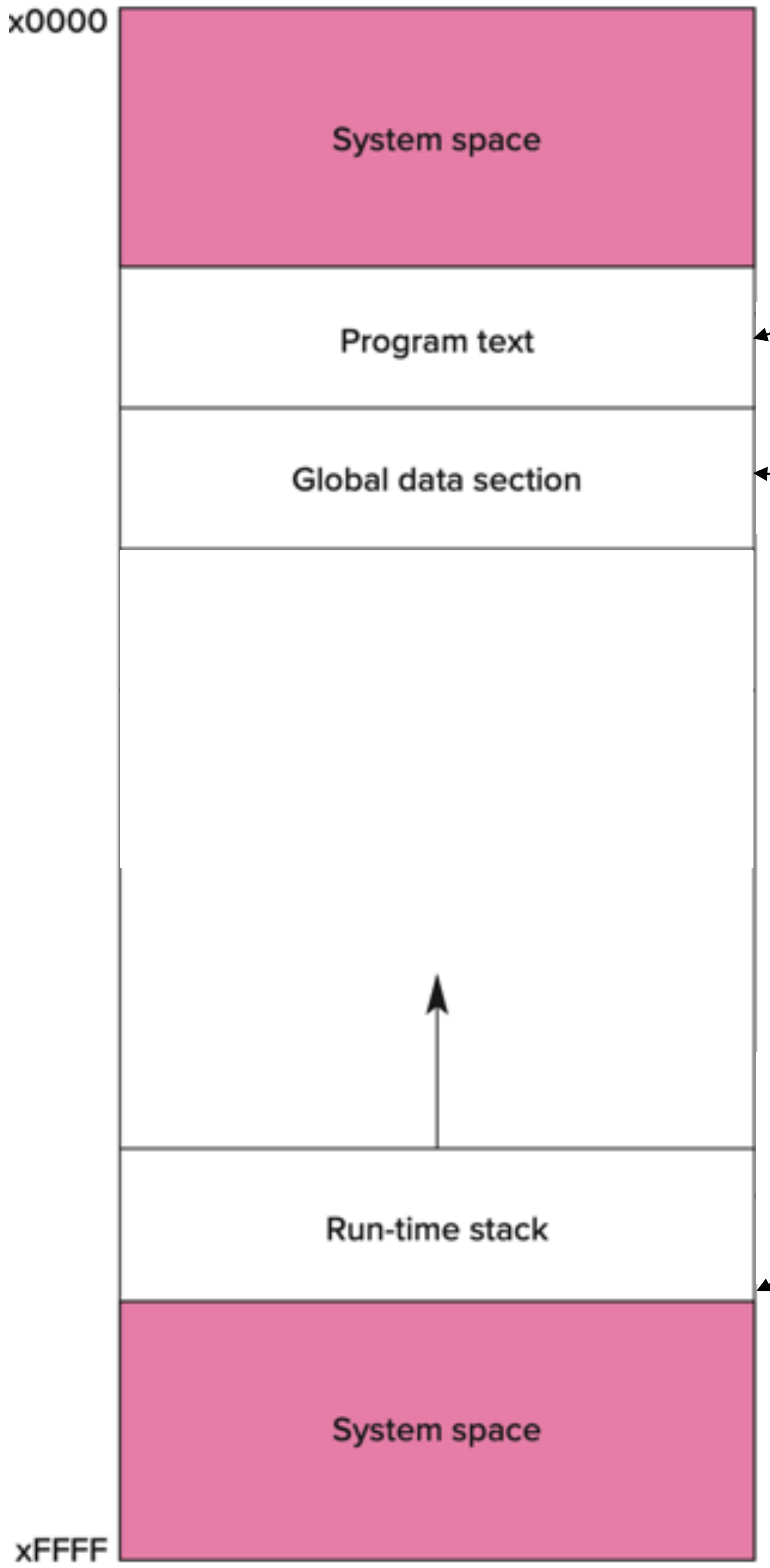

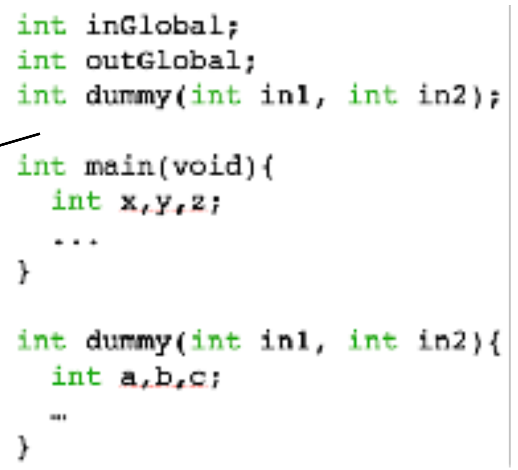

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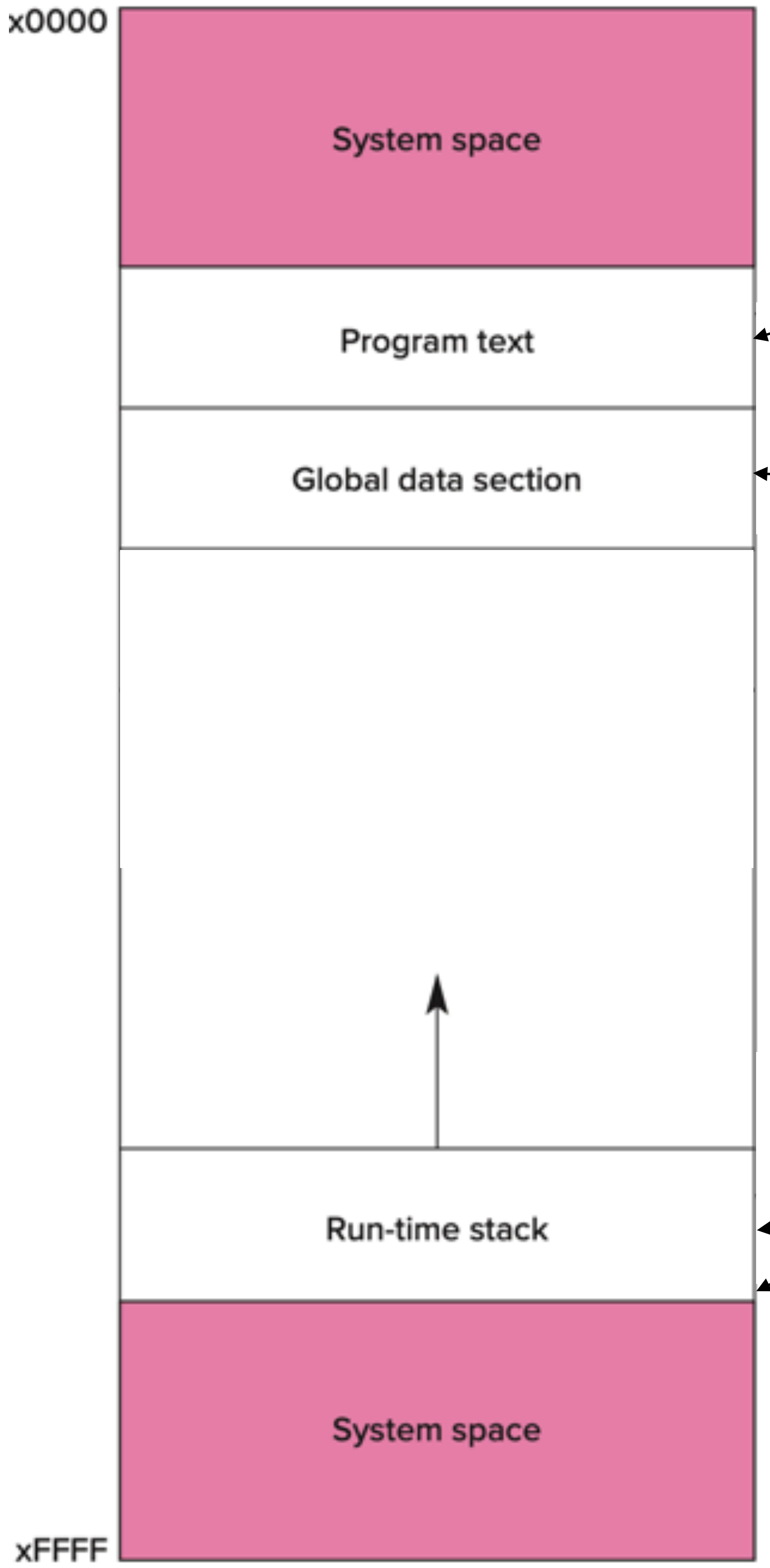

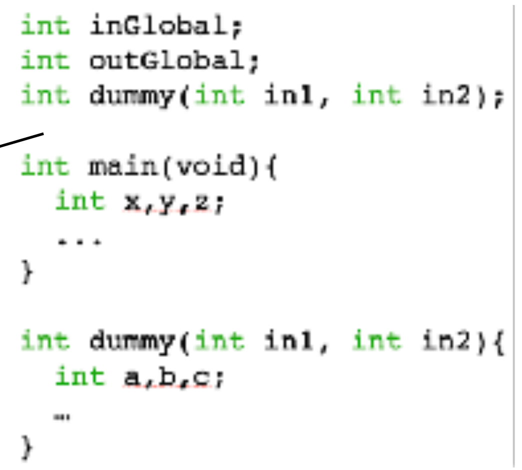

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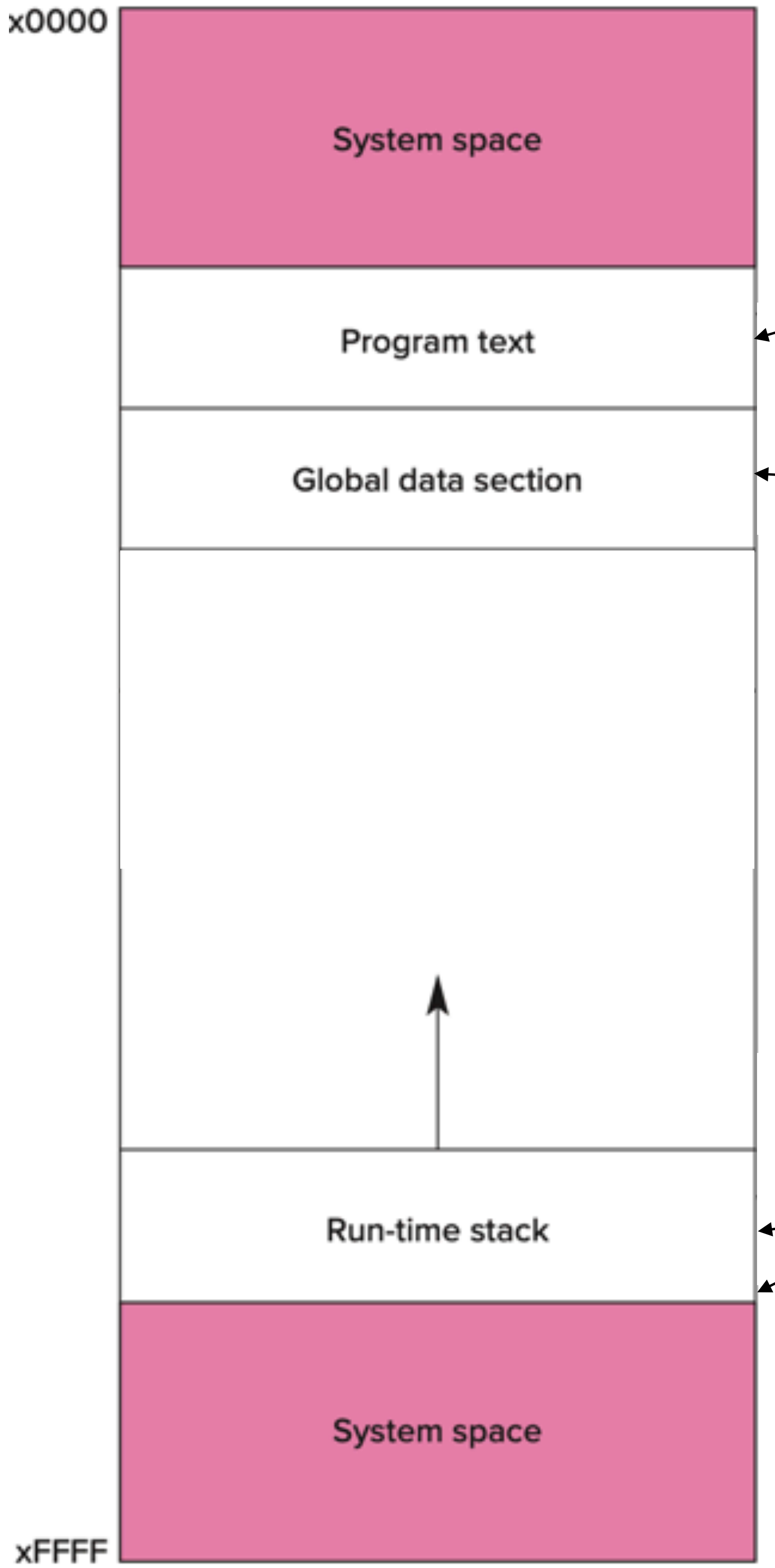

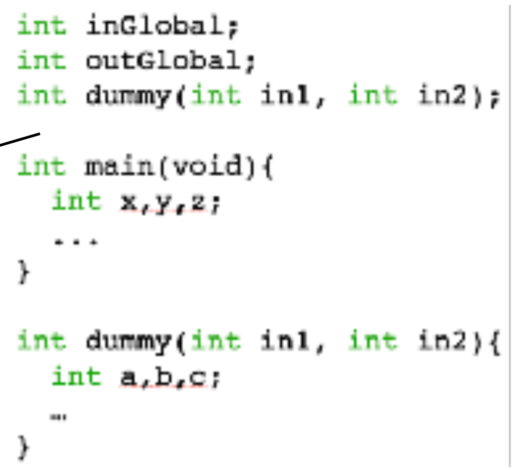

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Because function calls are implemented using a stack ADT.

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

Arguments passed in
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Example: function call

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  z = dummy(x, y);
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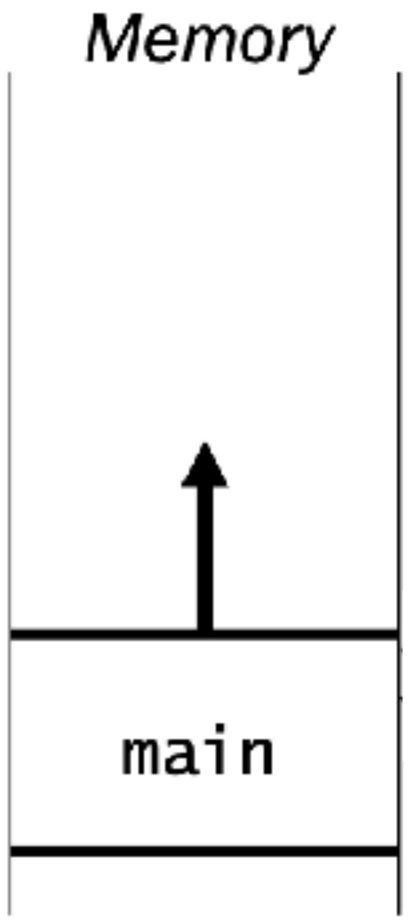

Before the dummy call

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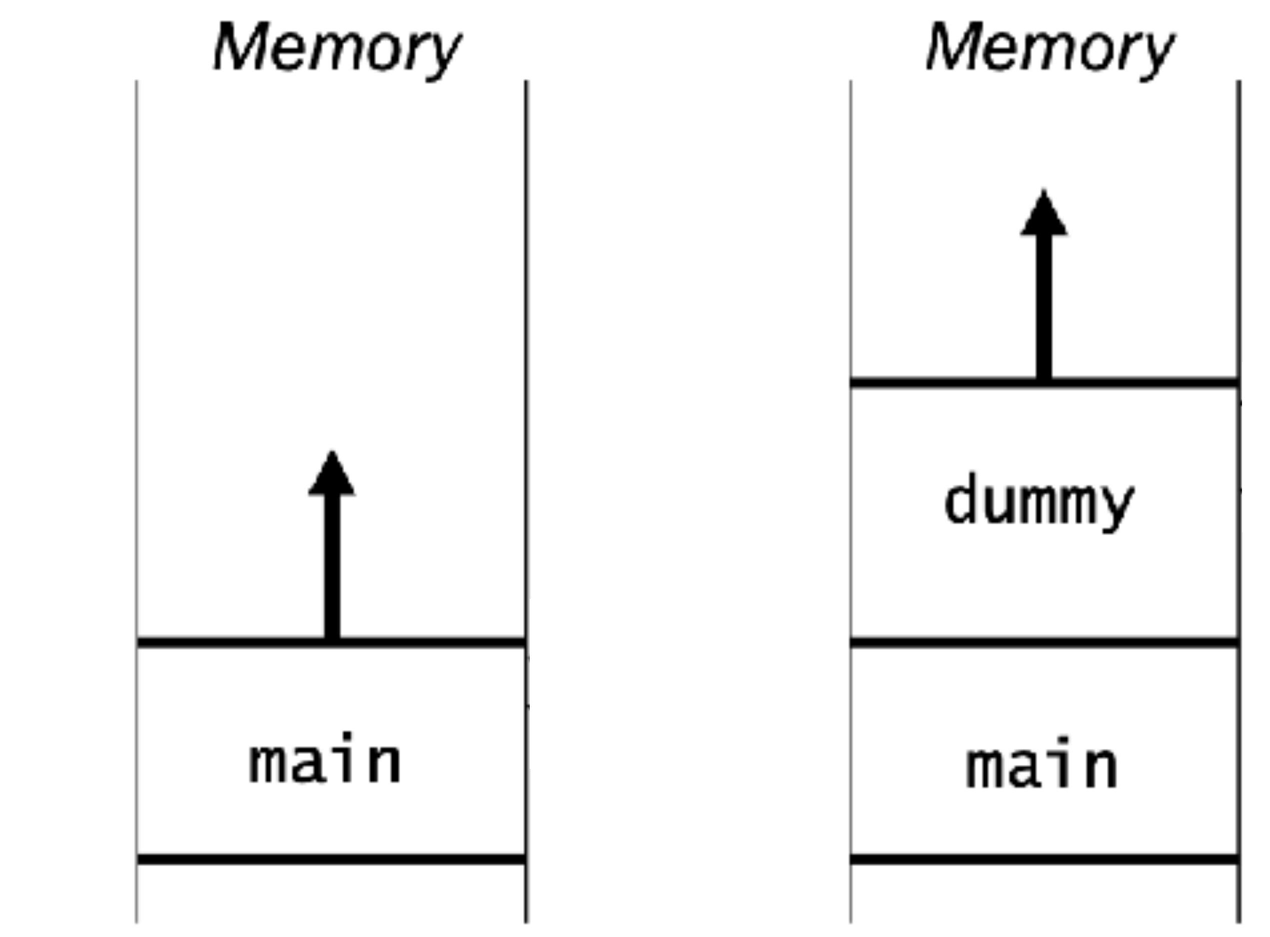

Before the dummy call

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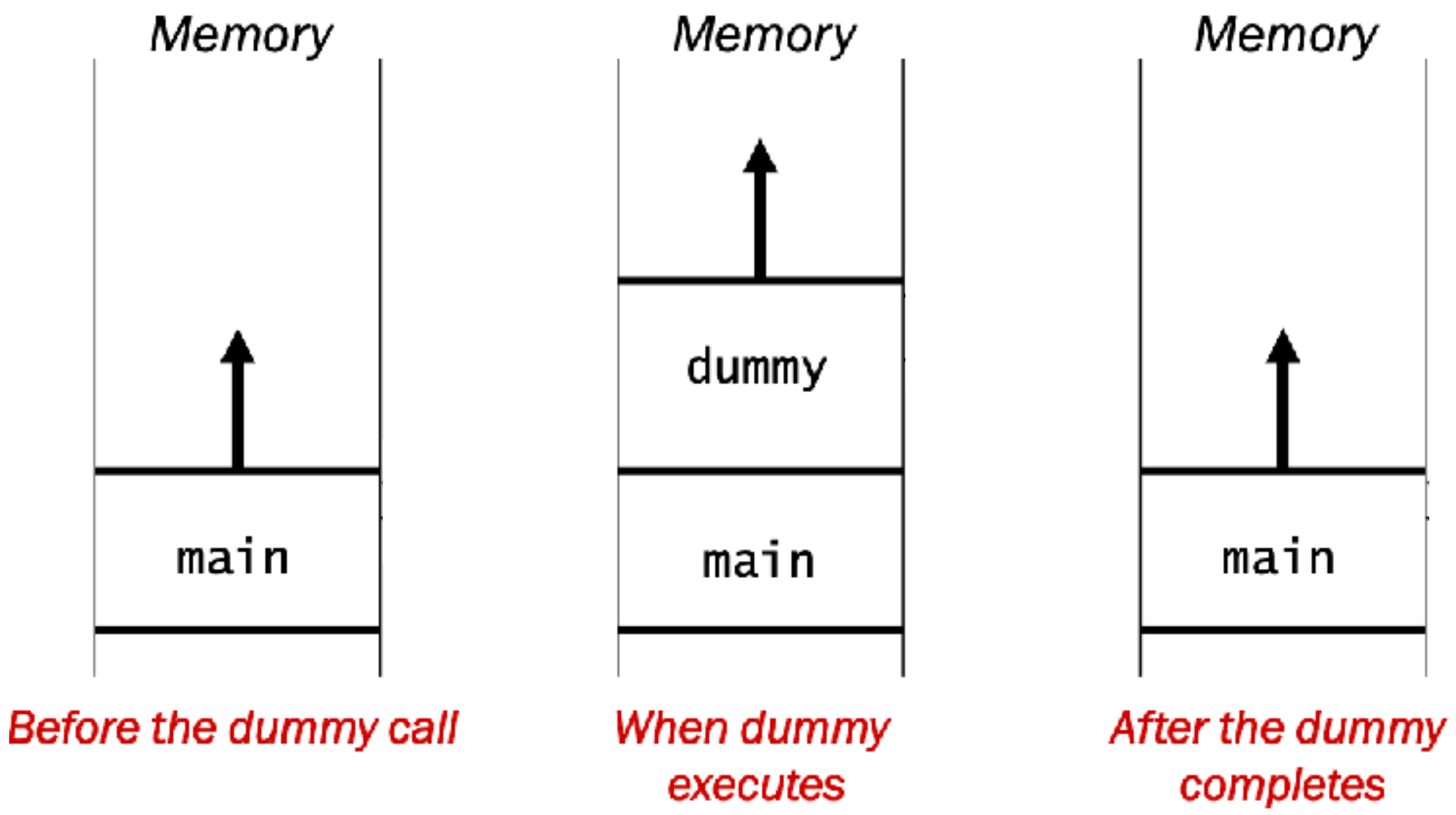

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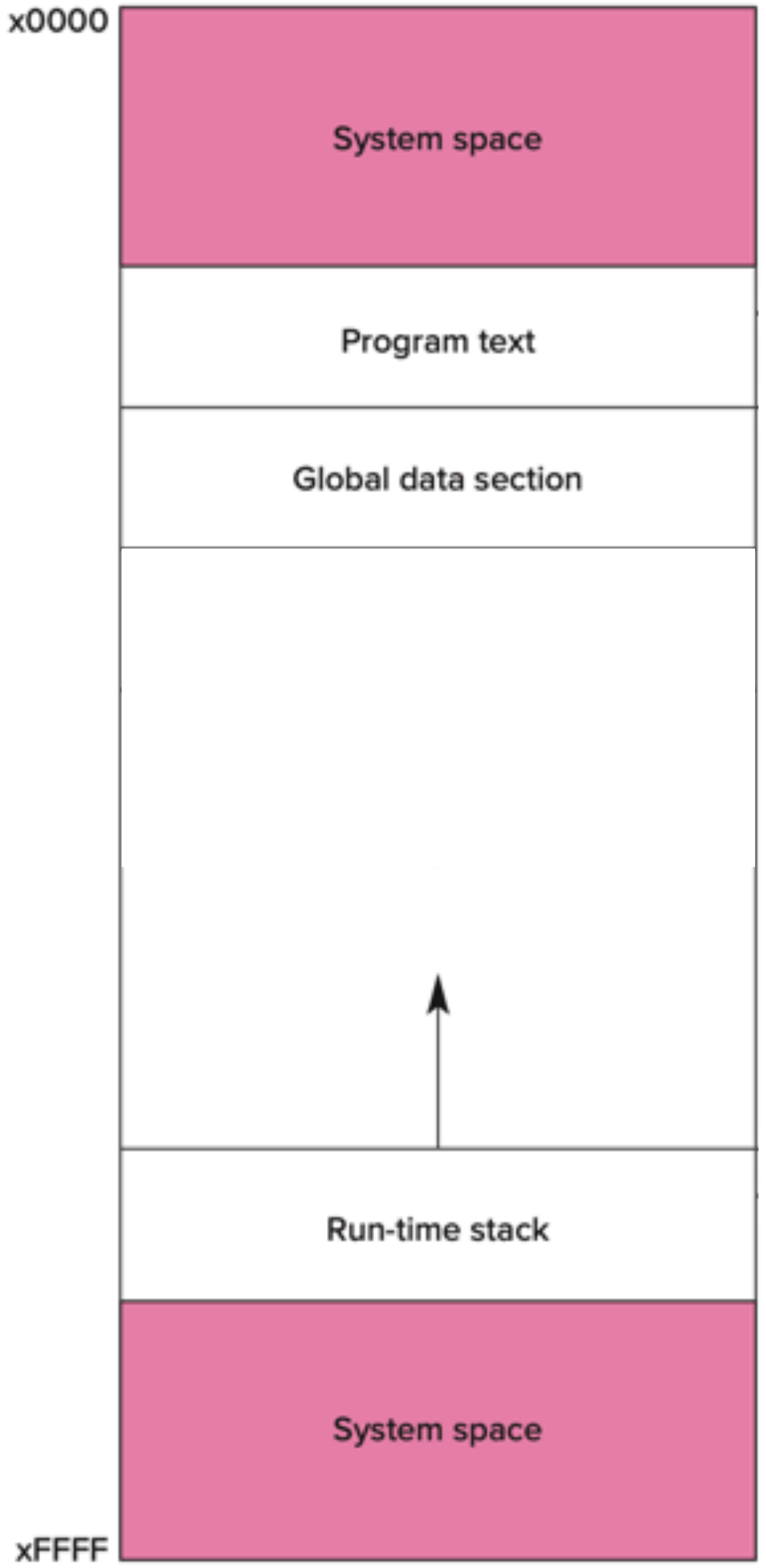
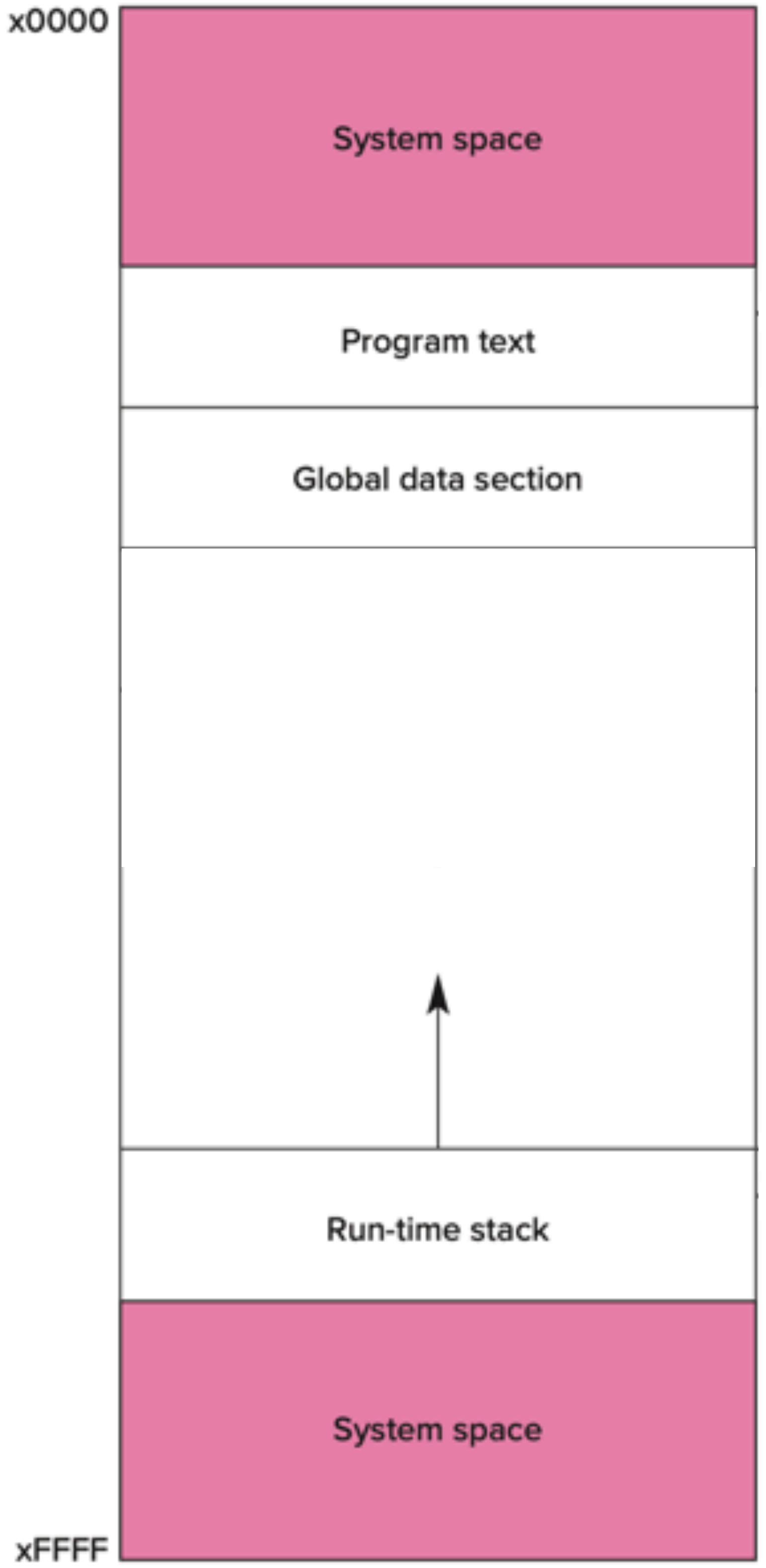


How to keep track?

- Store pointers:



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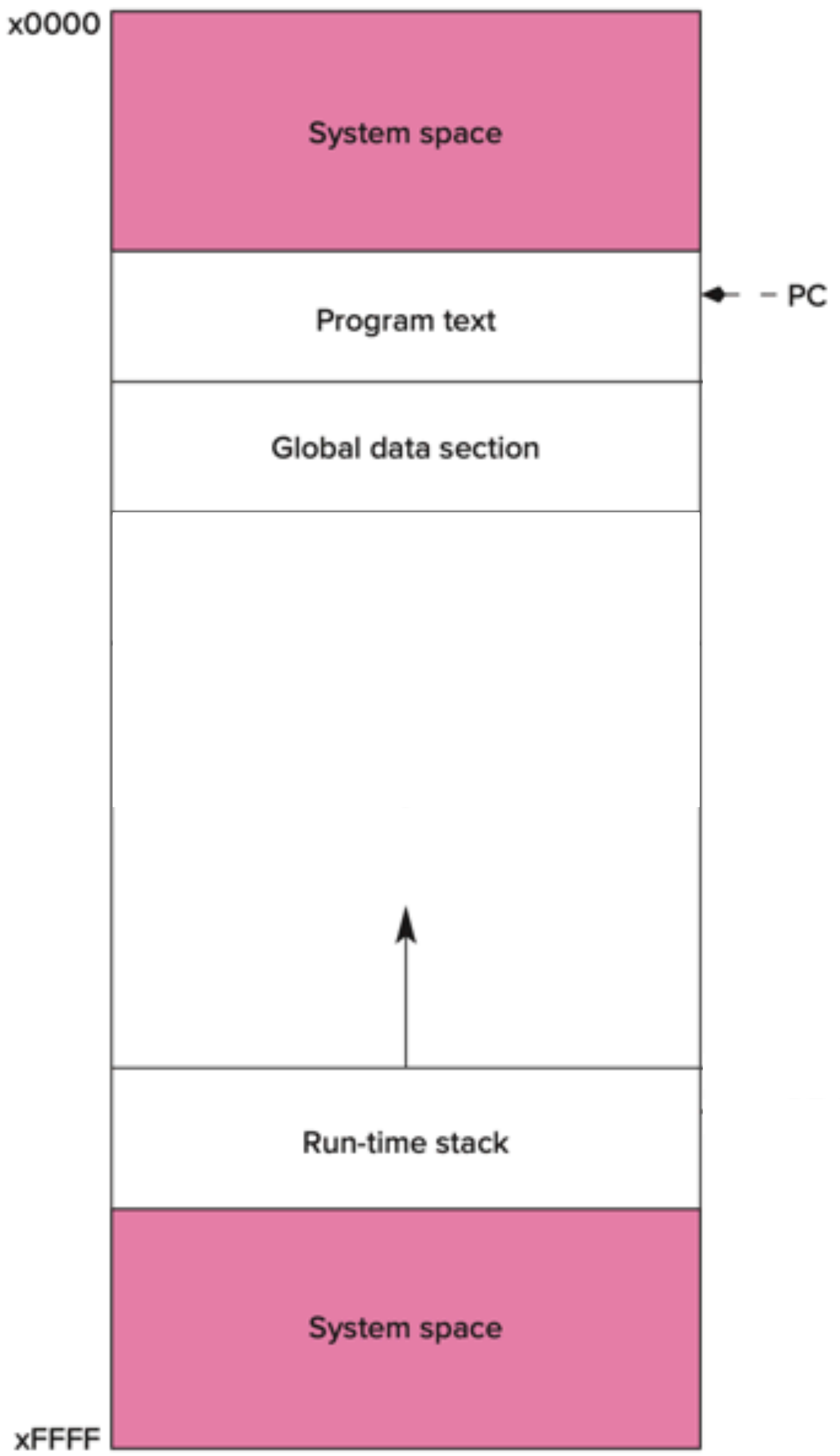

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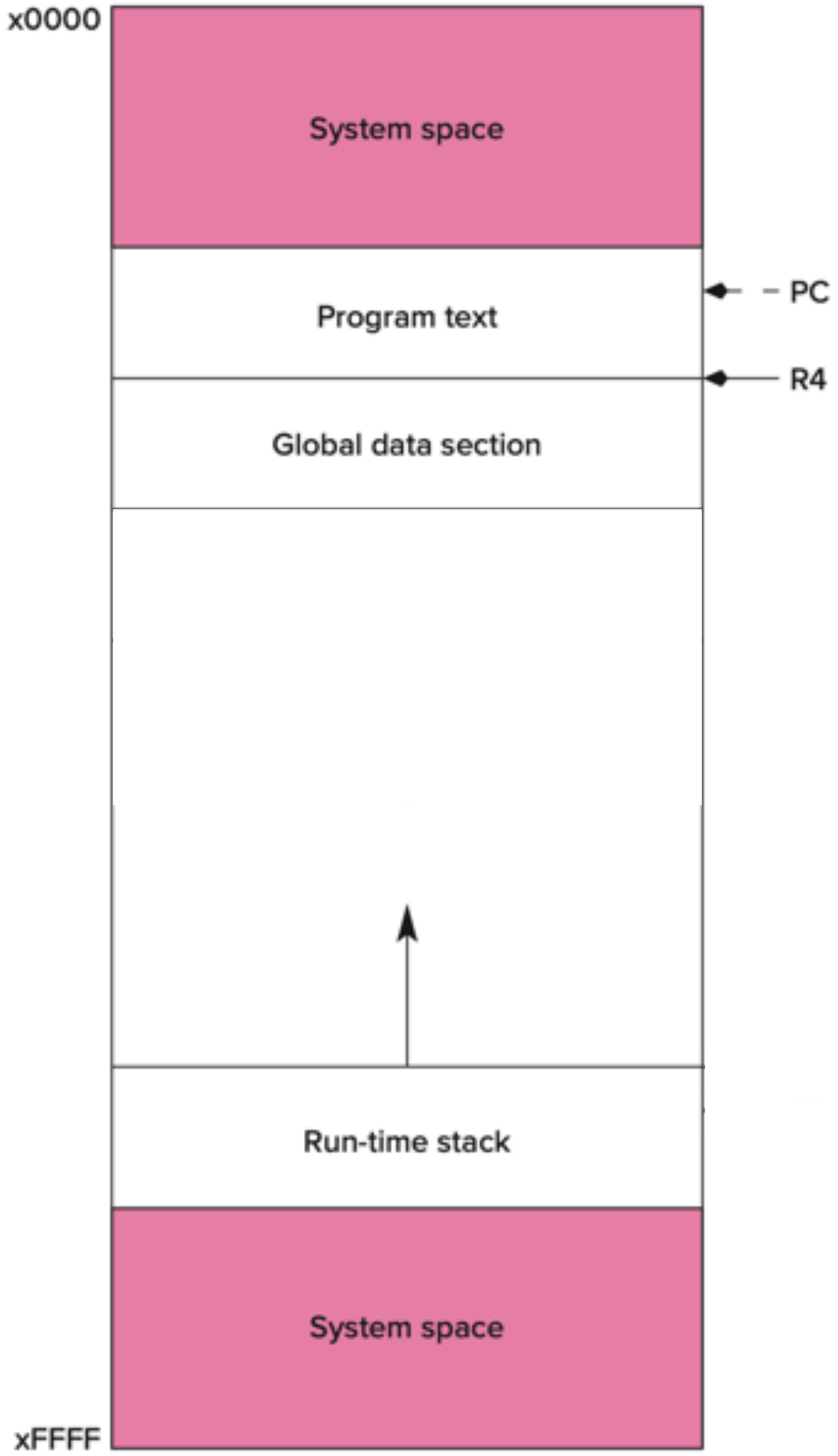

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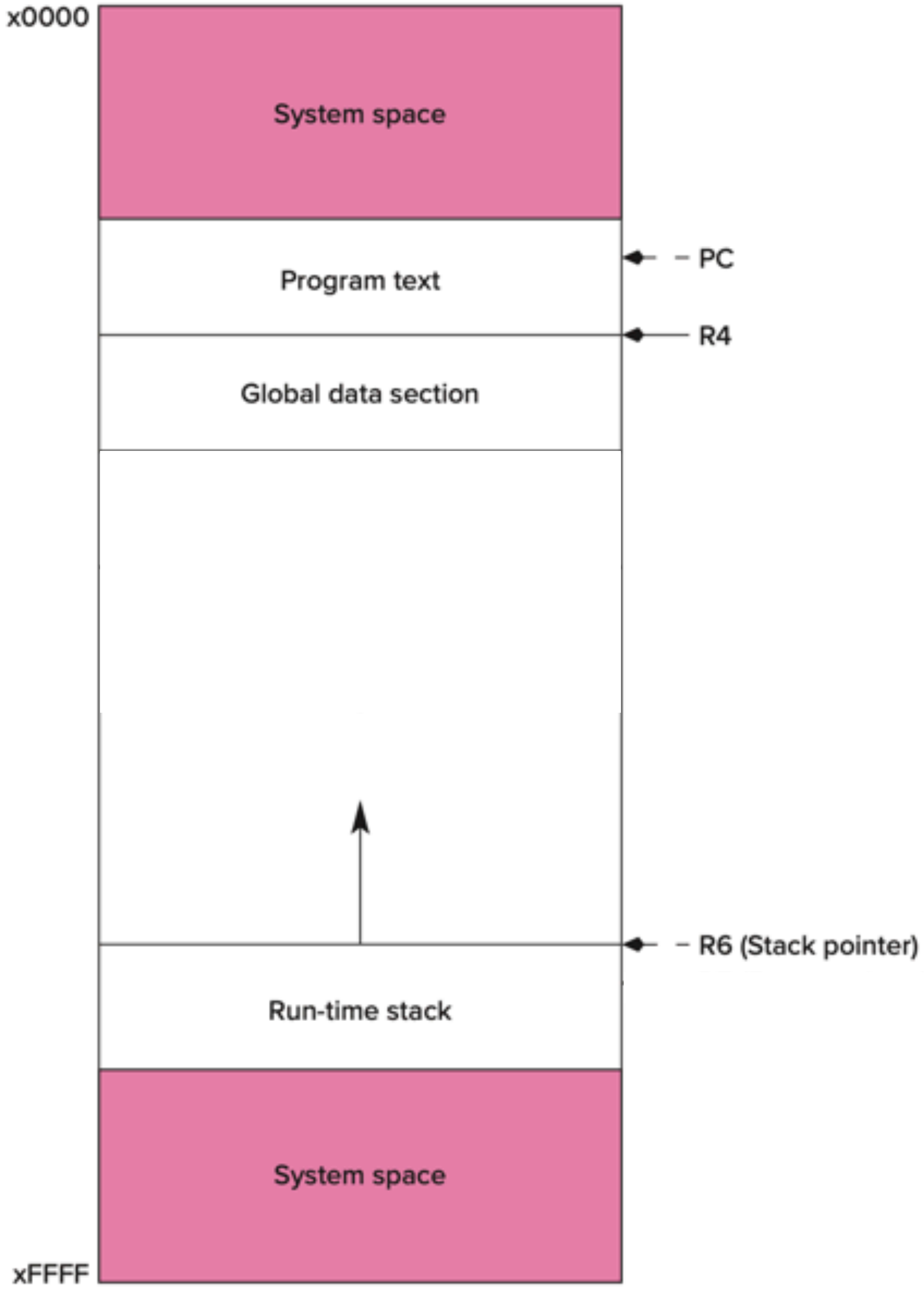

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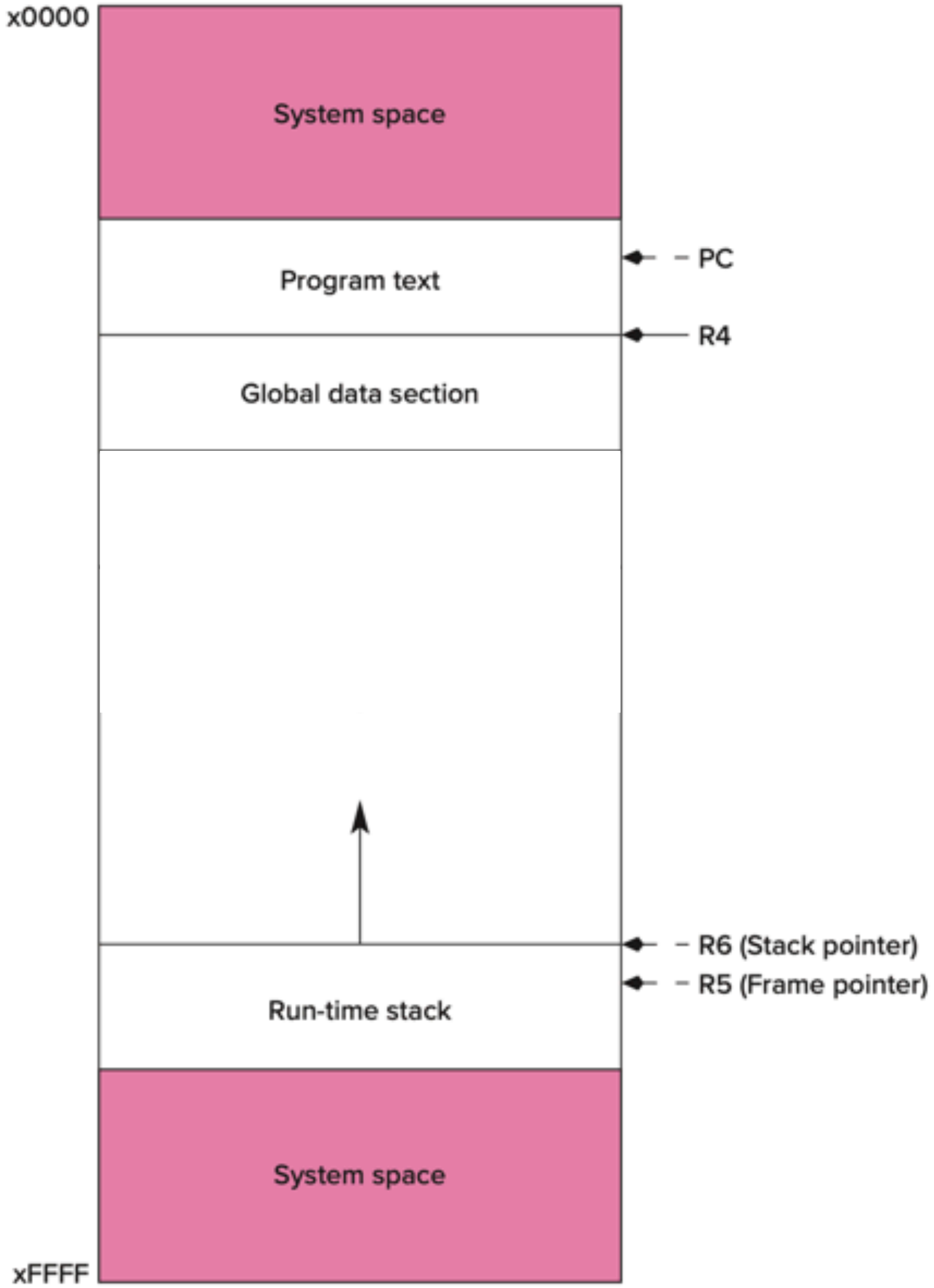

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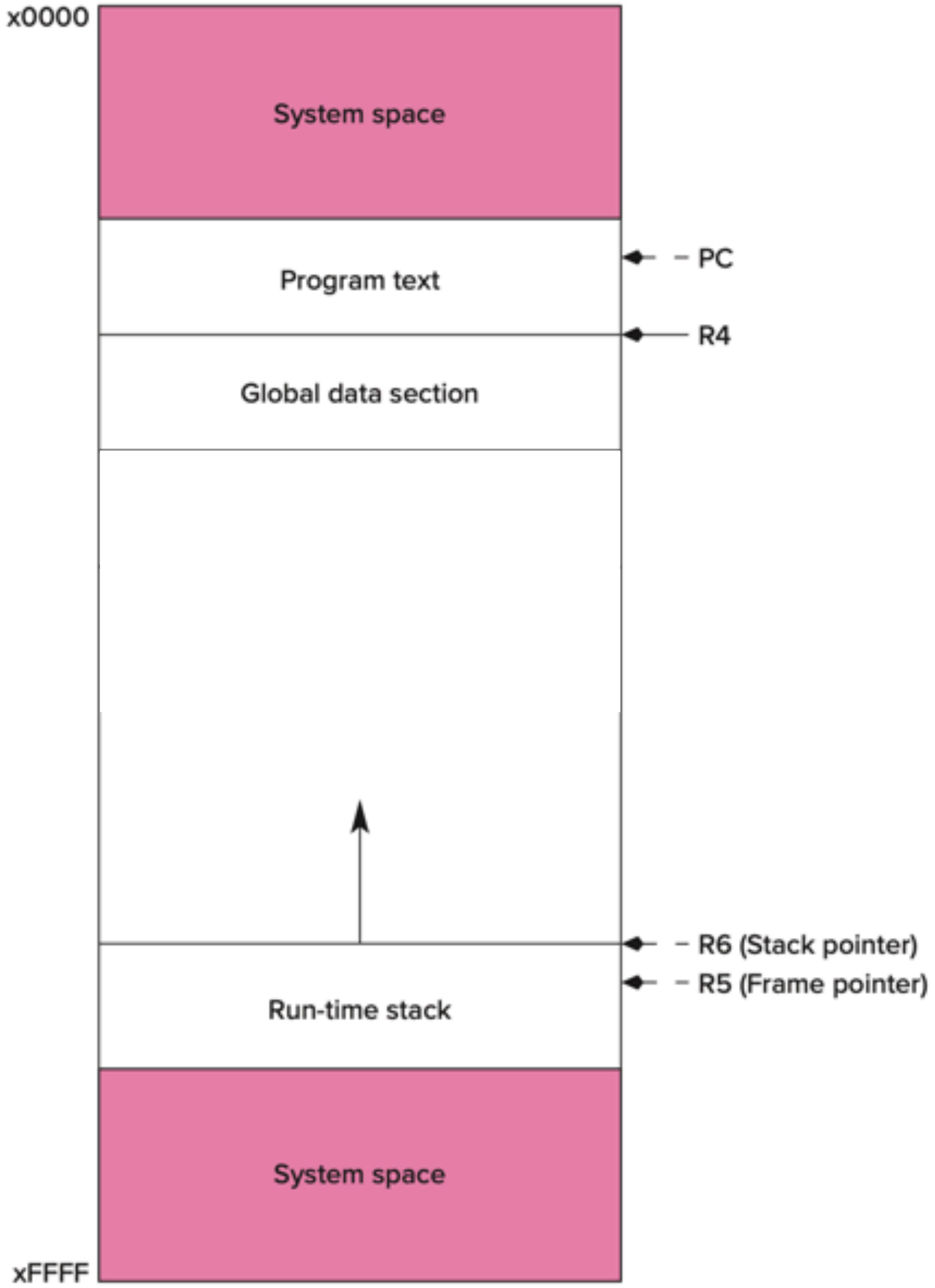

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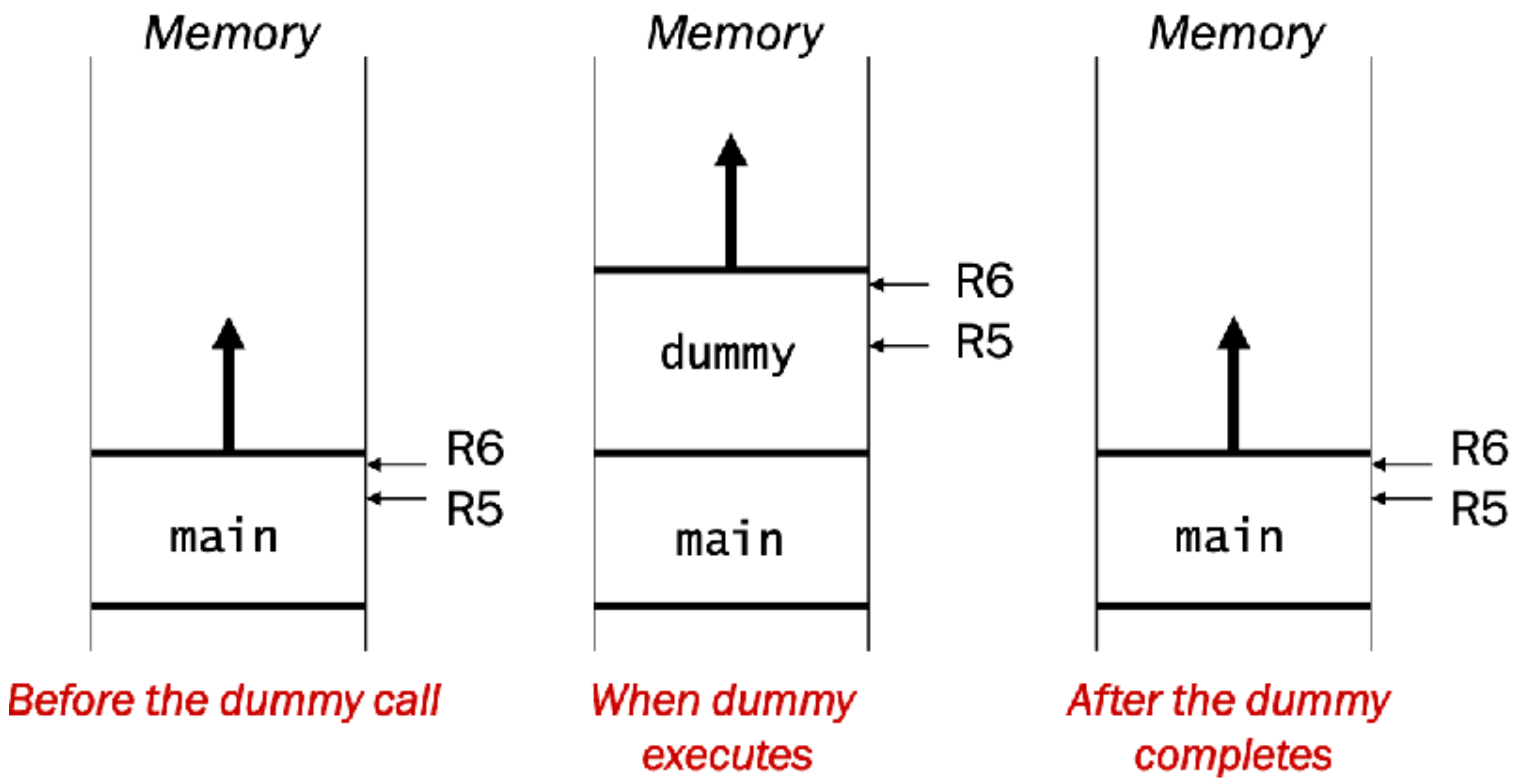

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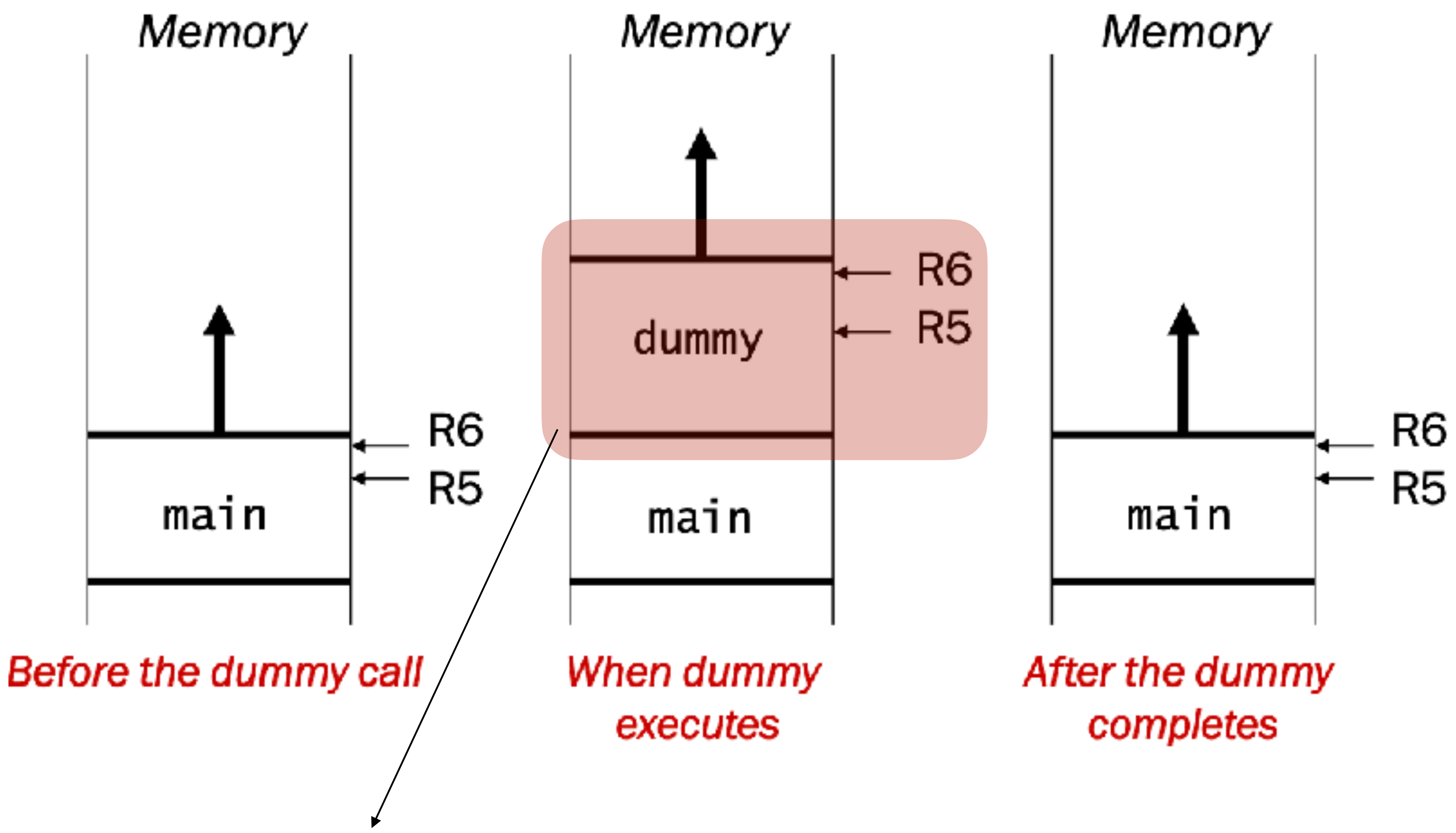

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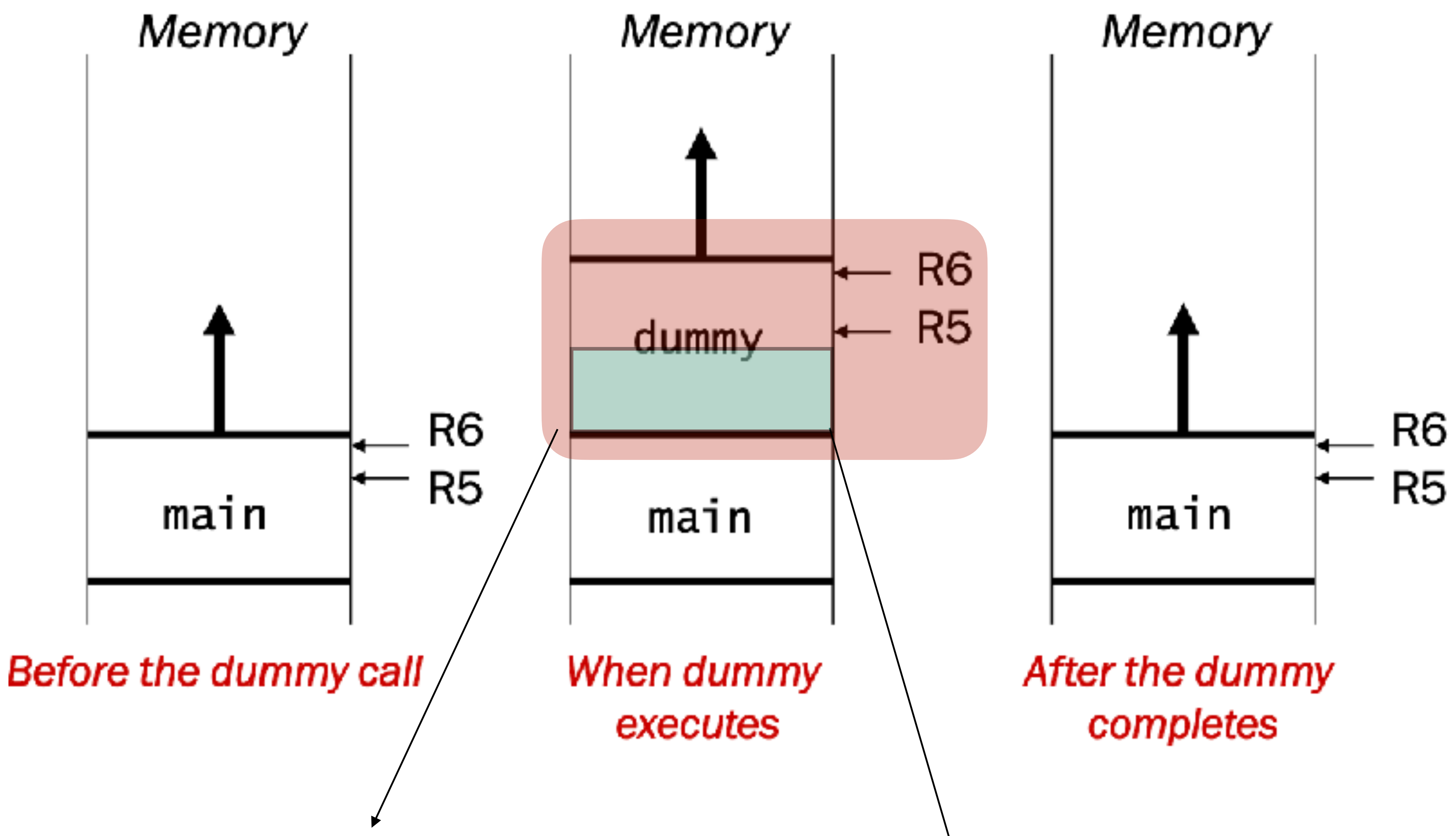

Activation record for dummy

If R5 is first local variable, what goes here?

Details of a function call

- To *successfully* transfer execution between the caller and callee a few things need to be taken care of:

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Activation record

Pushed before local variables

Generating an activation record

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Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
2. Pass control to callee (`JSR/JSRR`)

Caller

3. *Callee* build-up: (push bookkeeping info and local variables onto stack)

Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
2. Pass control to callee (`JSR/JSRR`)
3. *Callee* build-up: (push bookkeeping info and local variables onto stack)
4. Execute function

Caller

Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
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Caller

3. *Callee* build-up: (push bookkeeping info and local variables onto stack)
4. Execute function
5. *Callee* tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)

Generating an activation record

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3. *Callee* build-up: (push bookkeeping info and local variables onto stack)
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6. Return to caller (`RET`)

Generating an activation record

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Callee

Generating an activation record

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Caller

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Callee

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

Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
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Callee

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

Caller

Generating an activation record

1. *Caller* build-up: Push callee's arguments onto stack
2. Pass control to callee (`JSR/JSRR`)

Stack build up

Caller

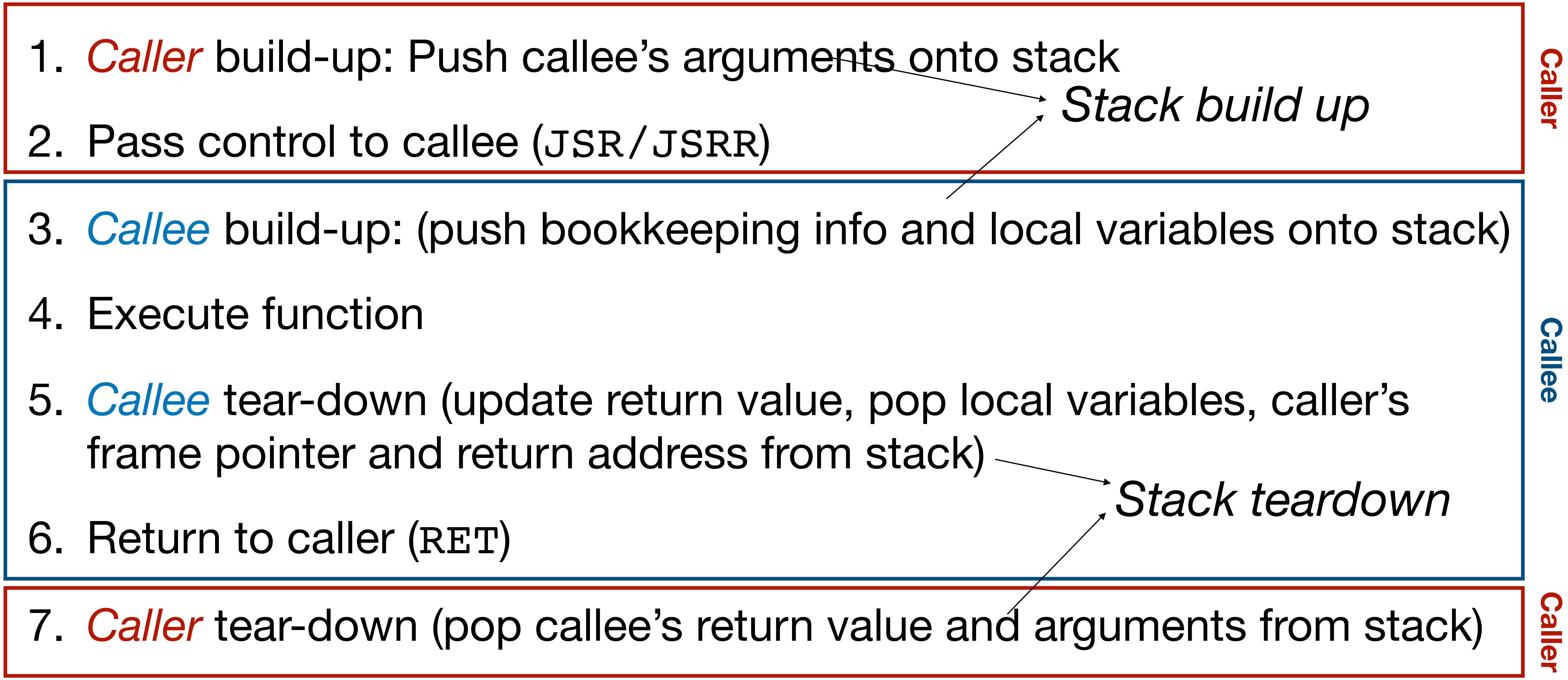
3. *Callee* build-up: (push bookkeeping info and local variables onto stack)
4. Execute function
5. *Callee* tear-down (update return value, pop local variables, caller's frame pointer and return address from stack)
6. Return to caller (`RET`)

Callee

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

Caller

Generating an activation record



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

Stack build up

Stack teardown

Example function call

Example function call

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

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

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

Run-time stack

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

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

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

Run-time stack

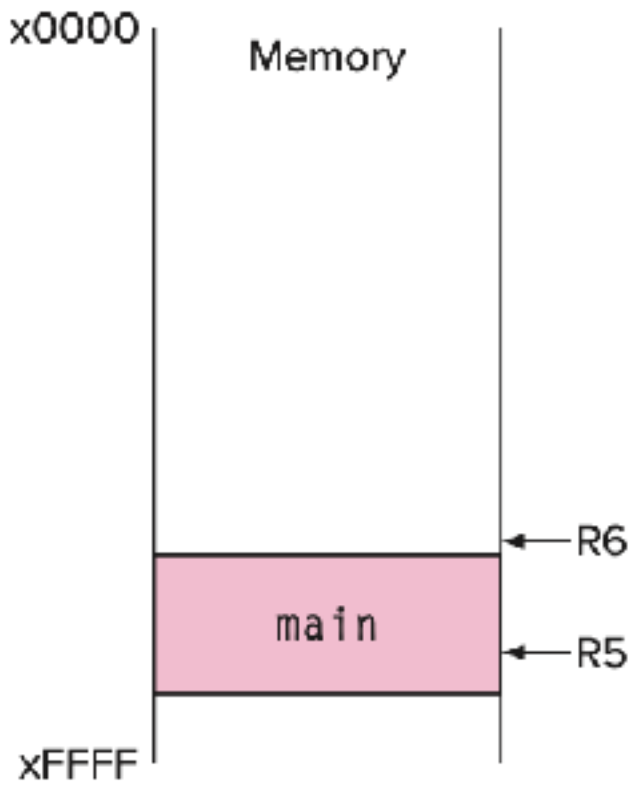
```c
int main (void){
     int a;
     int b;
     …
     b = Watt(a);
     b = Volt(a, b);
}
```

```c
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;
}
```



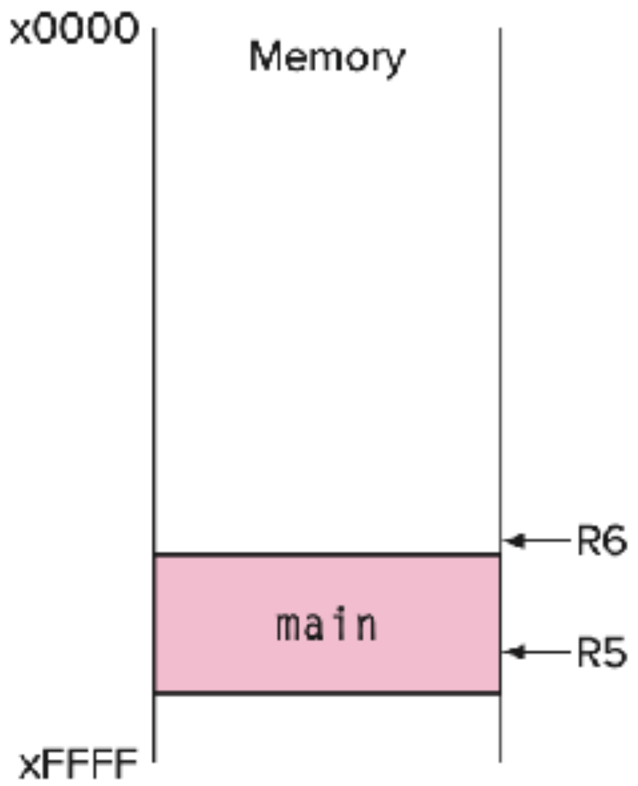
(a) Run-time stack
when execution starts

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;
}
```



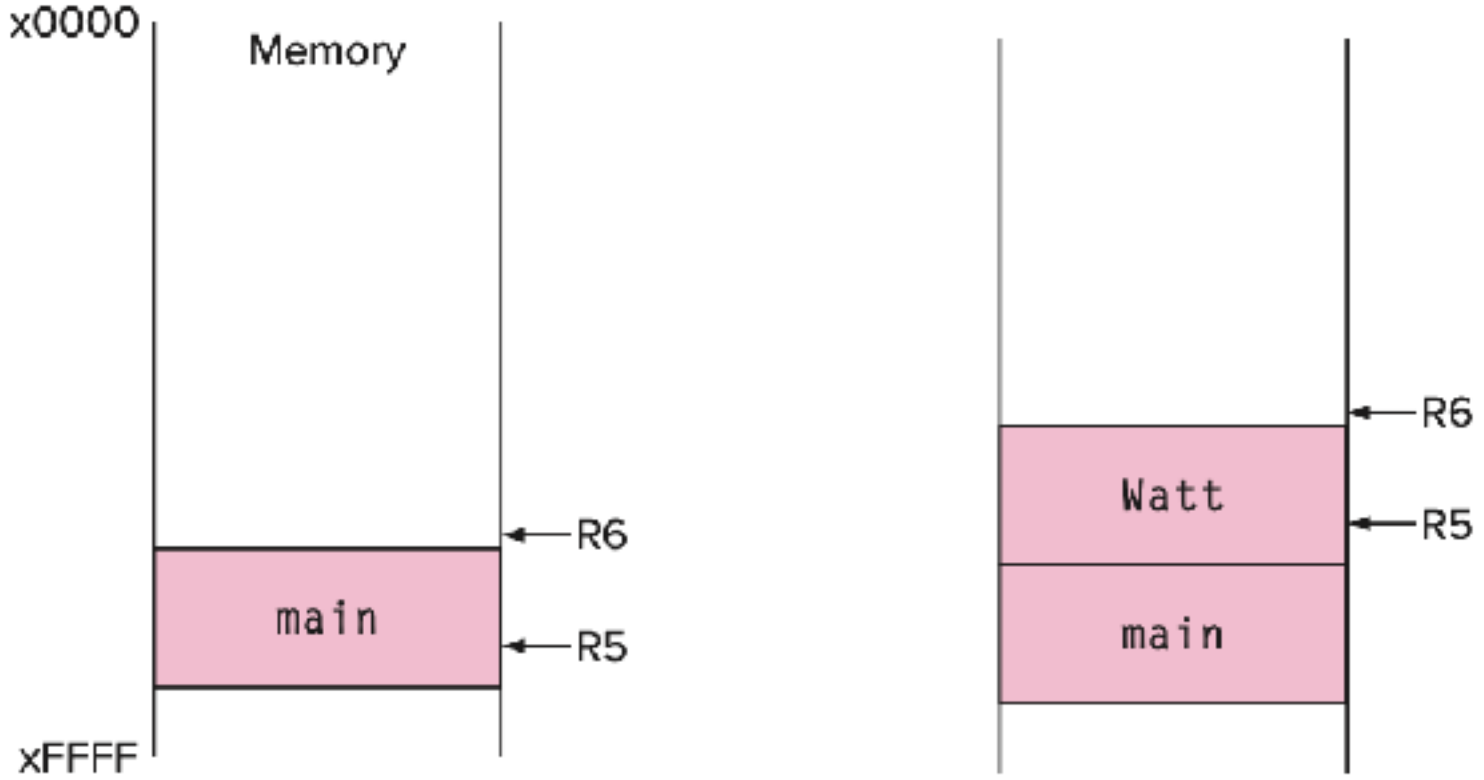
(a) Run-time stack
when execution starts

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

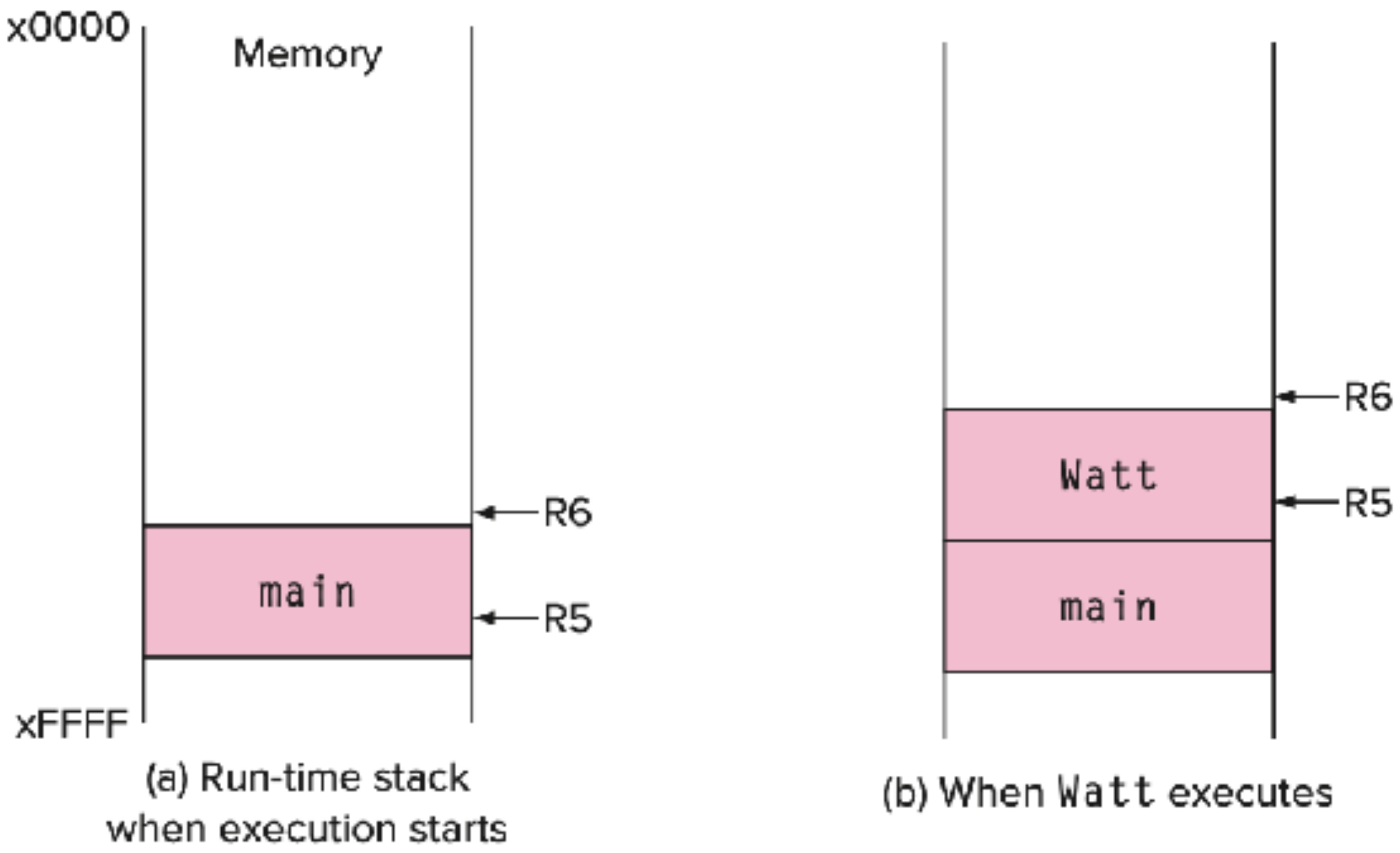
(b) When Watt executes

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

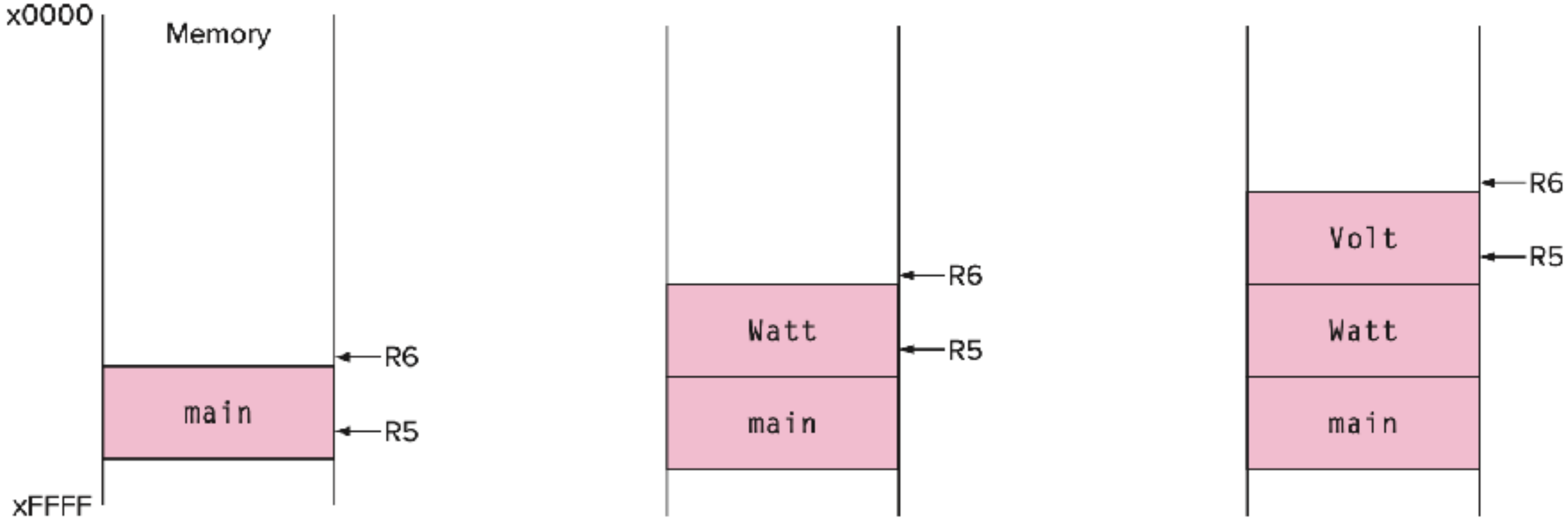
(b) When Watt executes

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

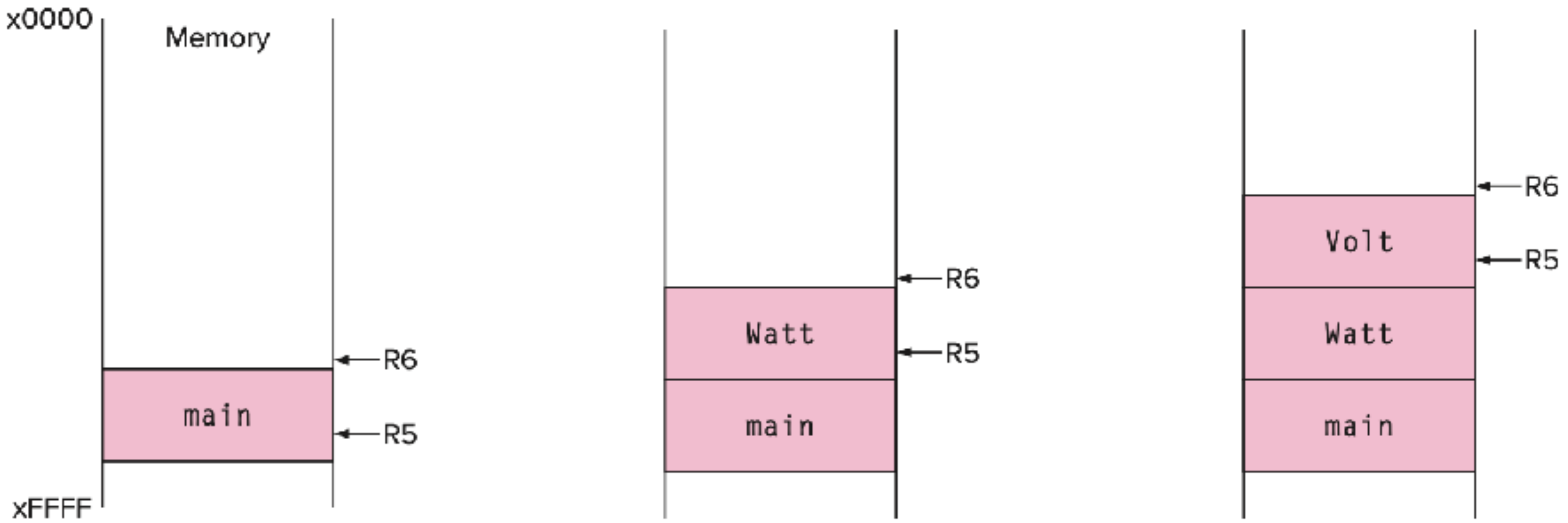
(c) When Volt executes

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

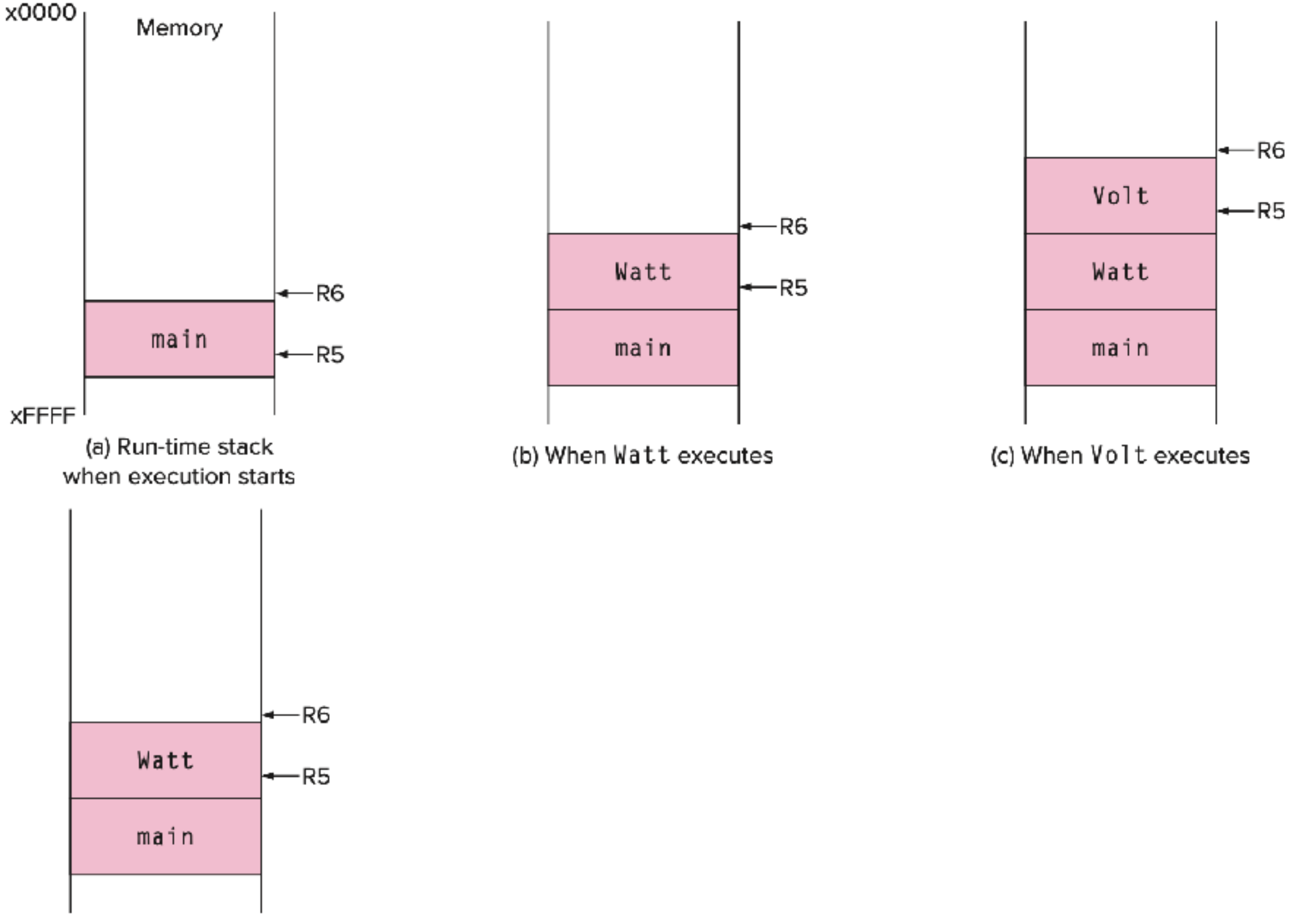
(c) When Volt executes

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

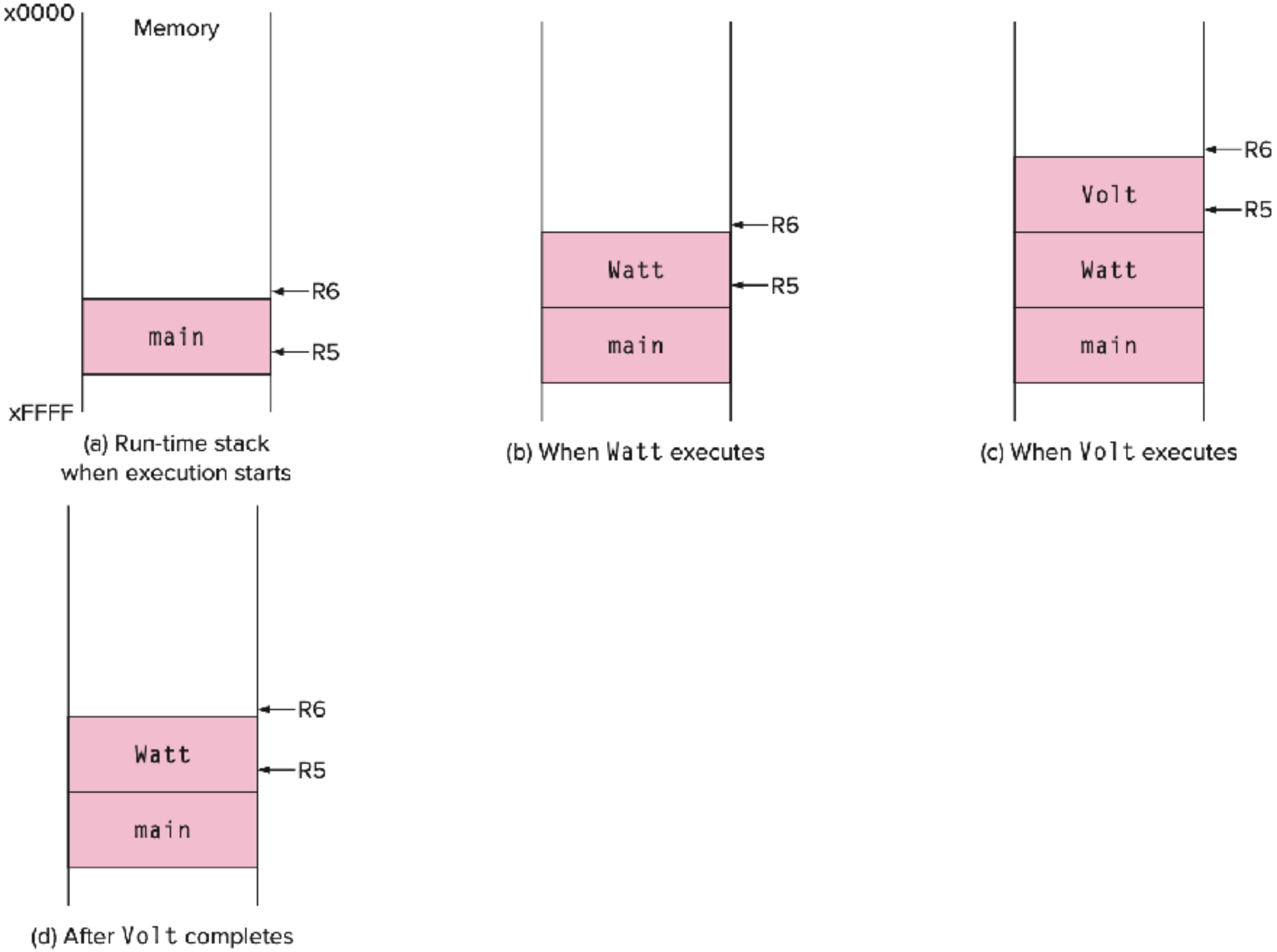
(b) When Watt executes

(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

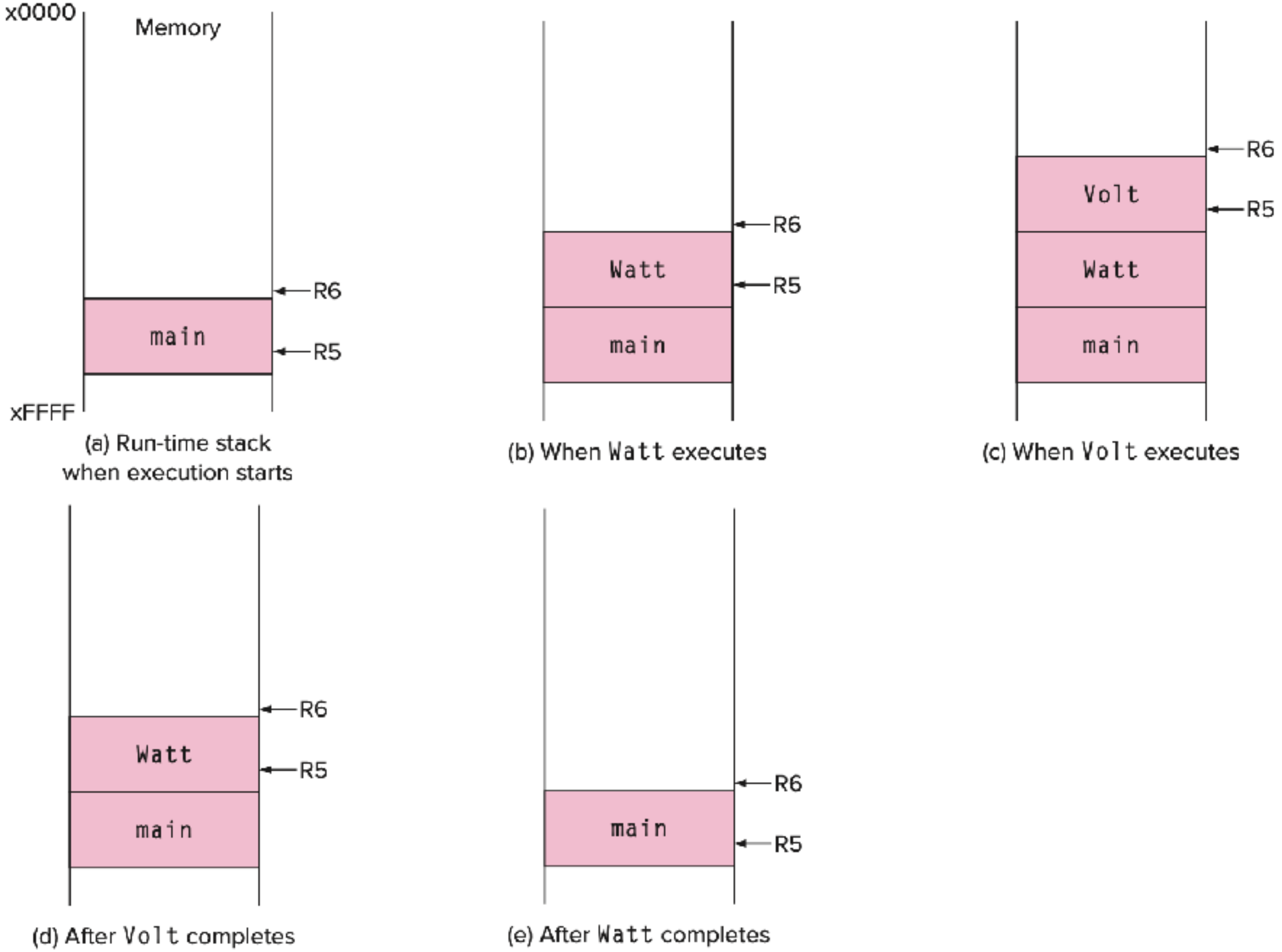
(c) When Volt executes

(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

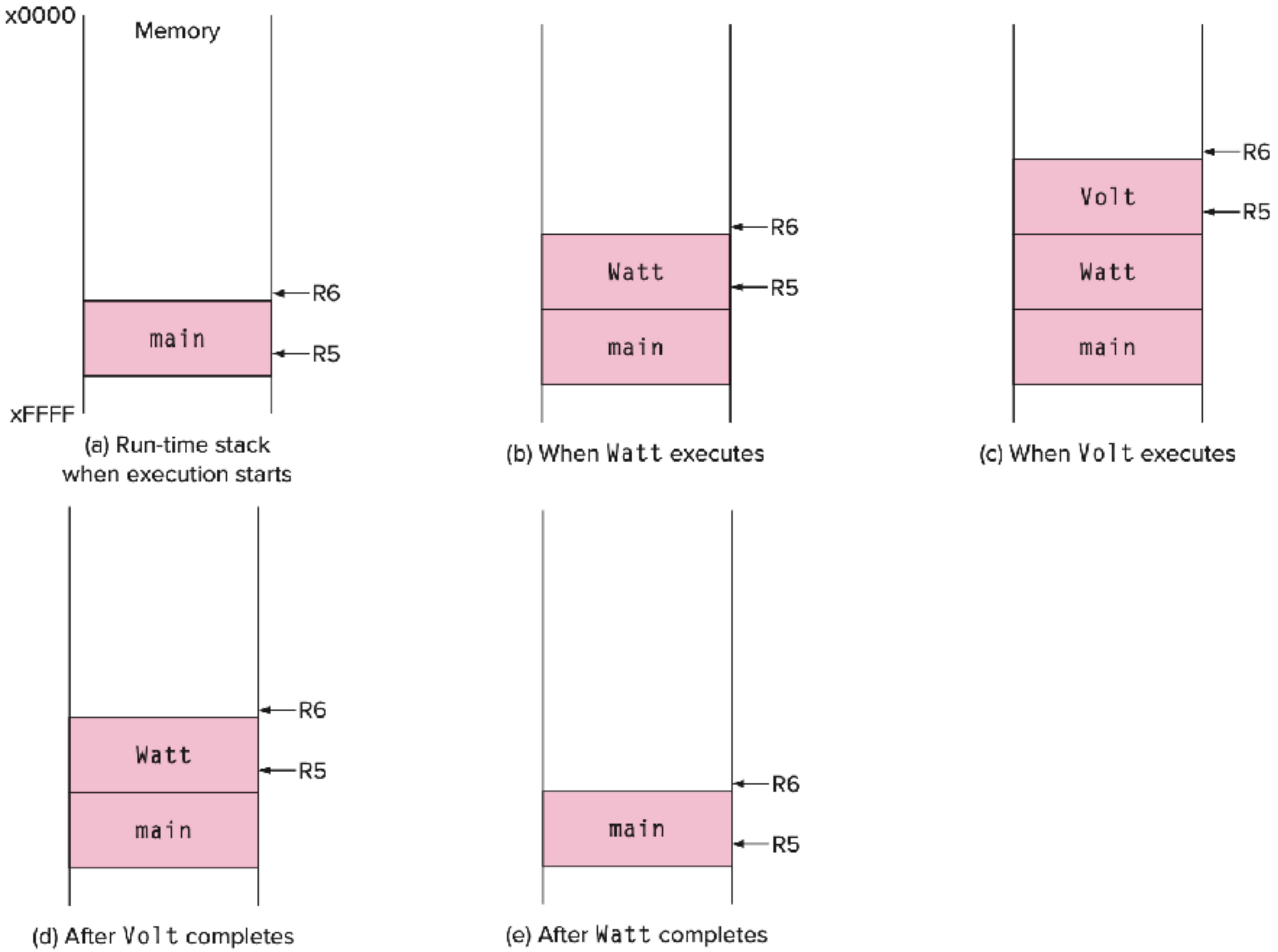
(e) After Watt completes

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

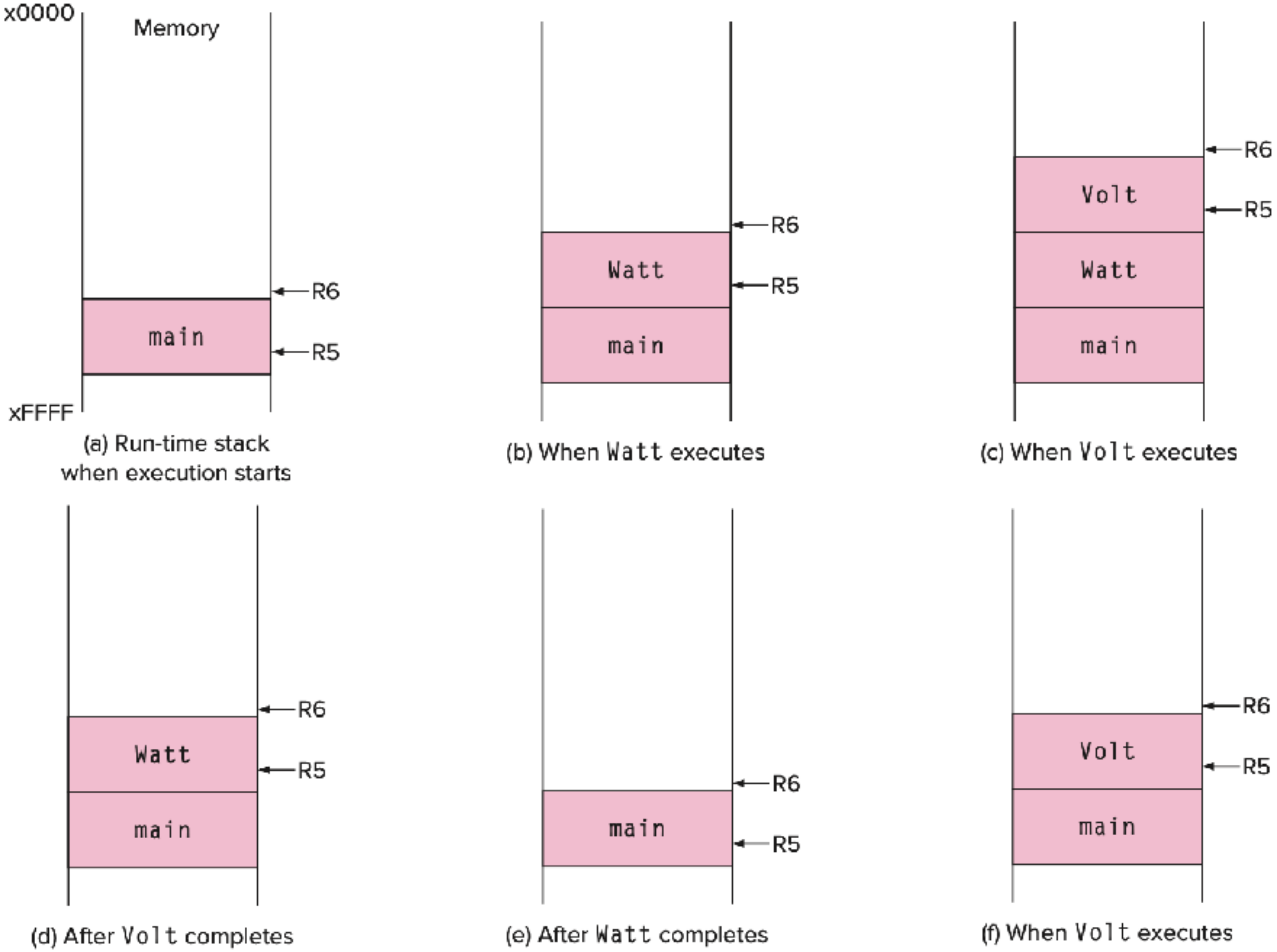
(e) After Watt completes

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.

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- **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.

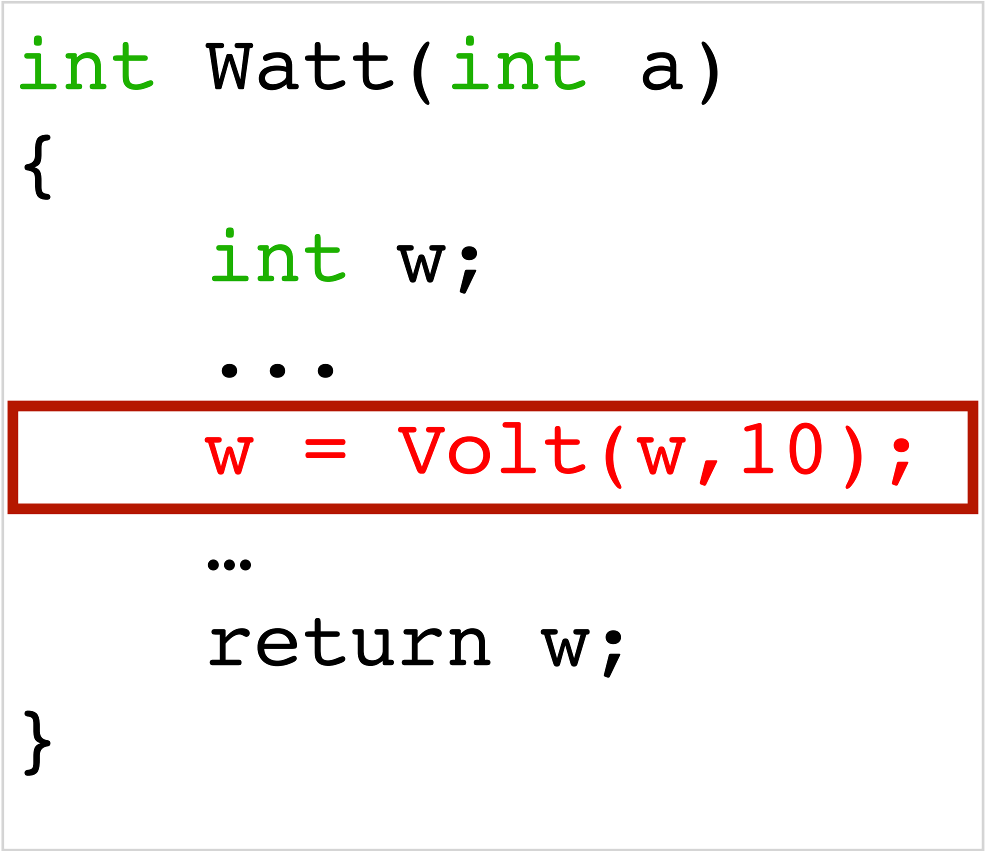
- **STEP 3**: The callee executes

- **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`.

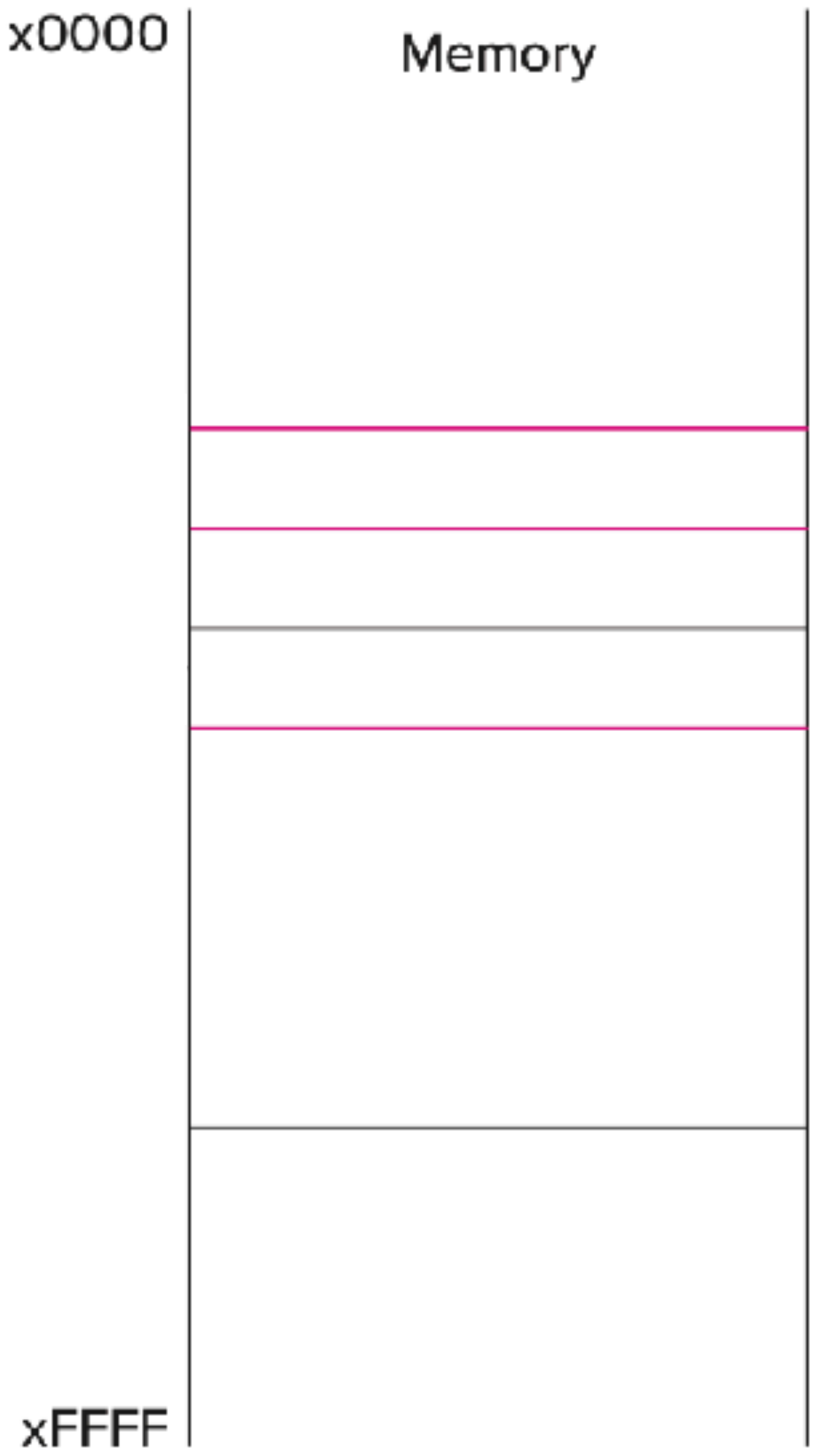
```
int Watt(int a)
{
    int w;
    ...
    w = Volt(w,10);
    …
    return w;
}
```

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;
}
```

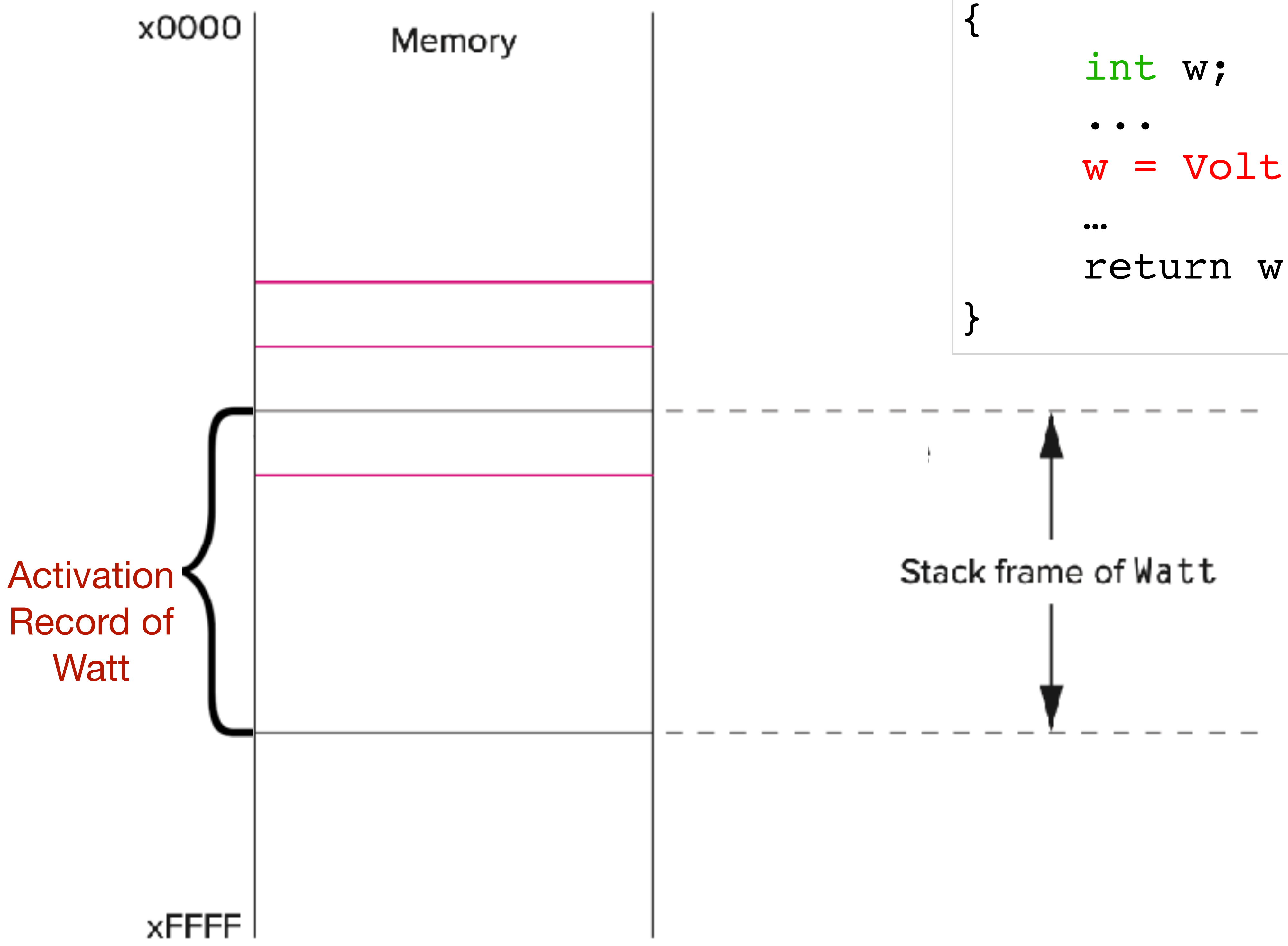
LC-3 Implementation



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

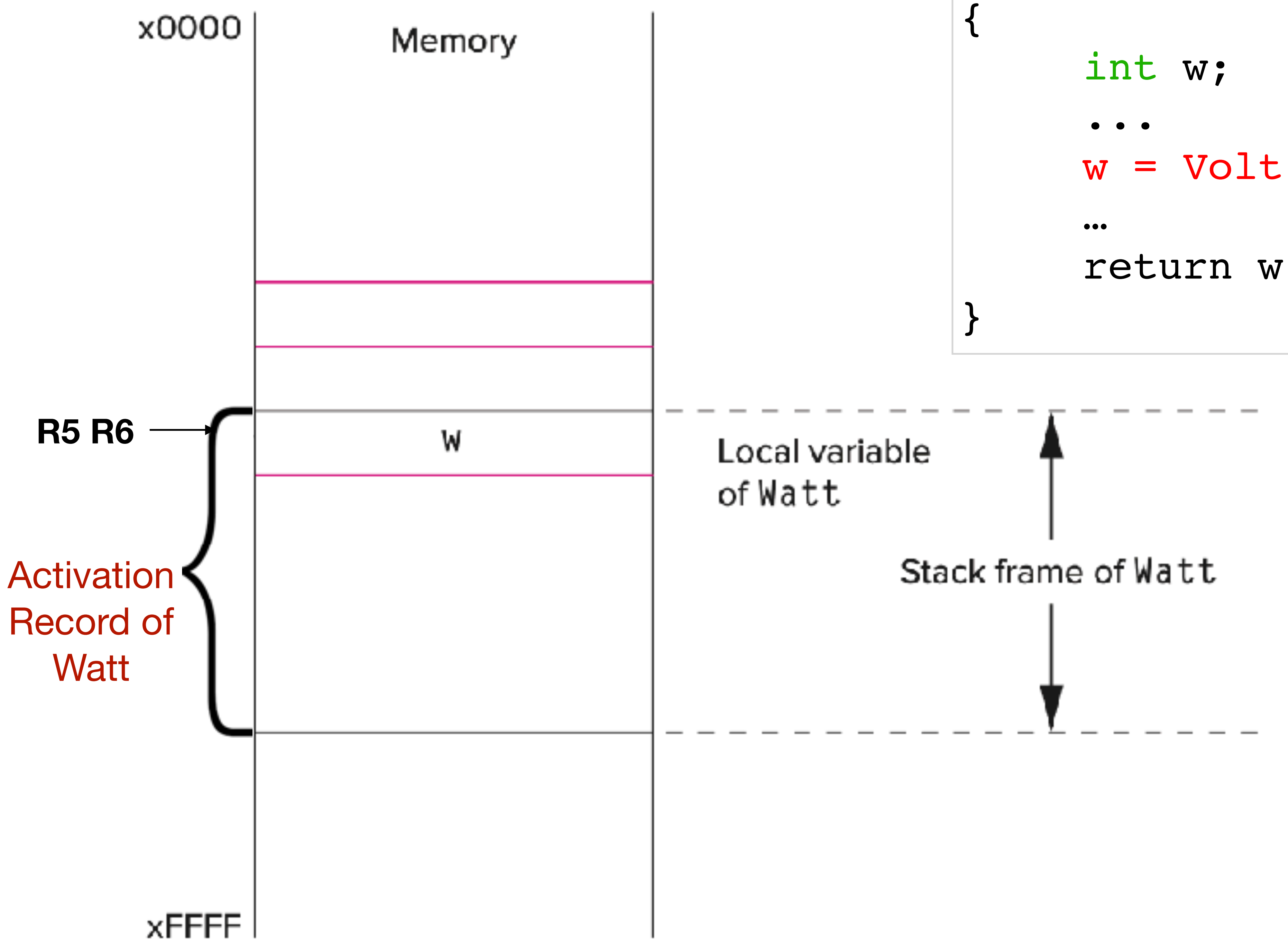
LC-3 Implementation

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



LC-3 Implementation

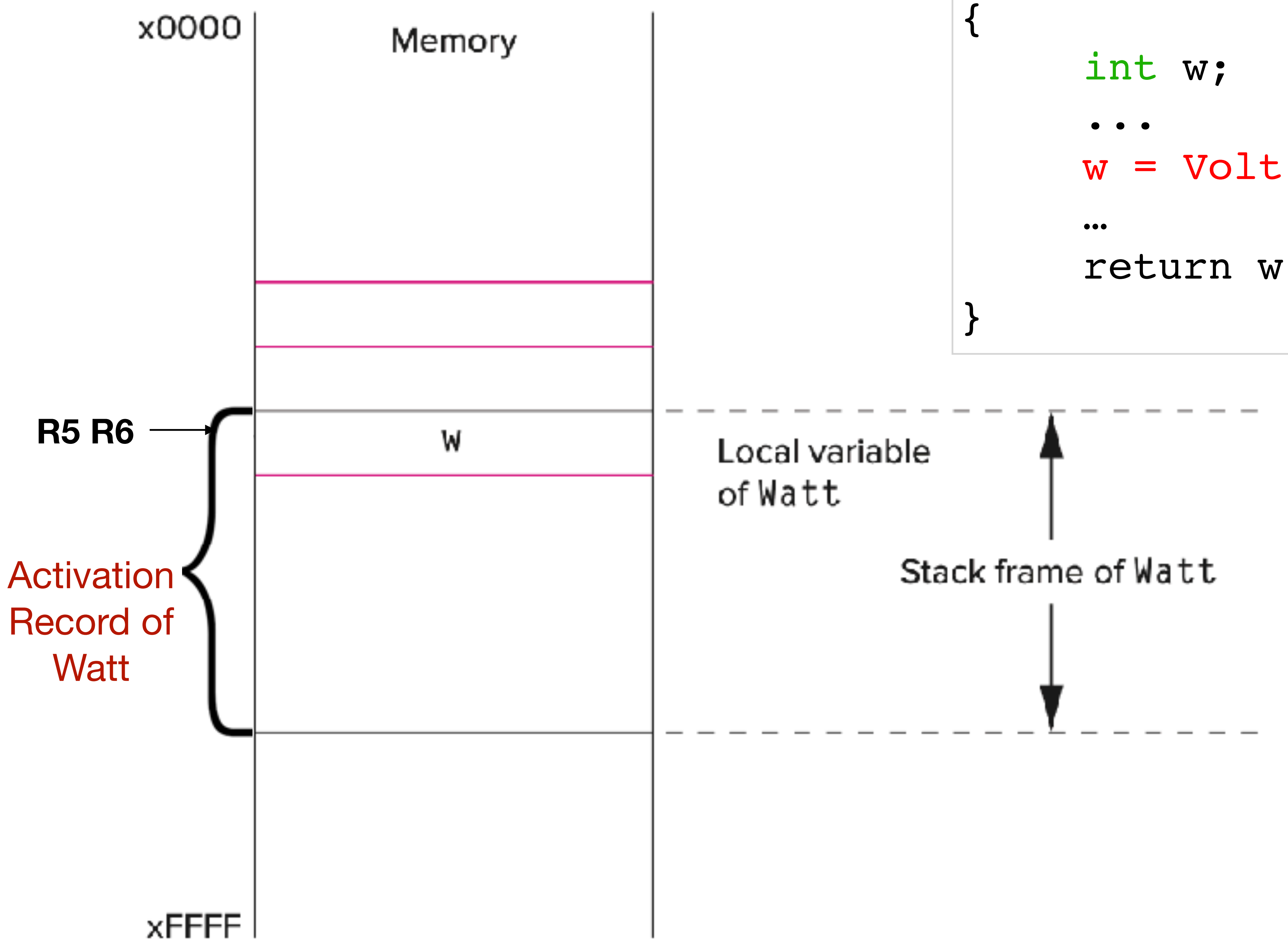
```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



LC-3 Implementation

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

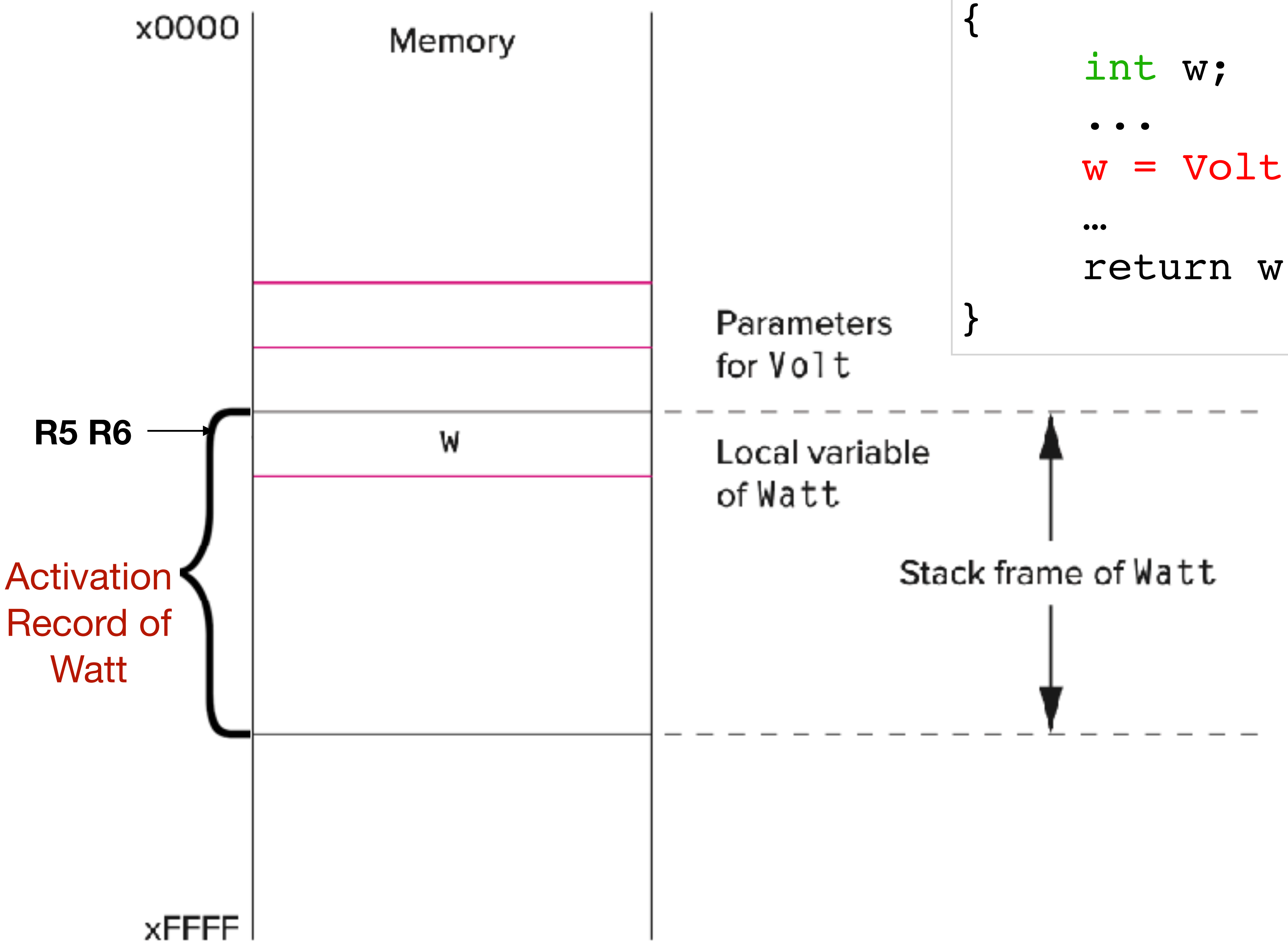
```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



LC-3 Implementation

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

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

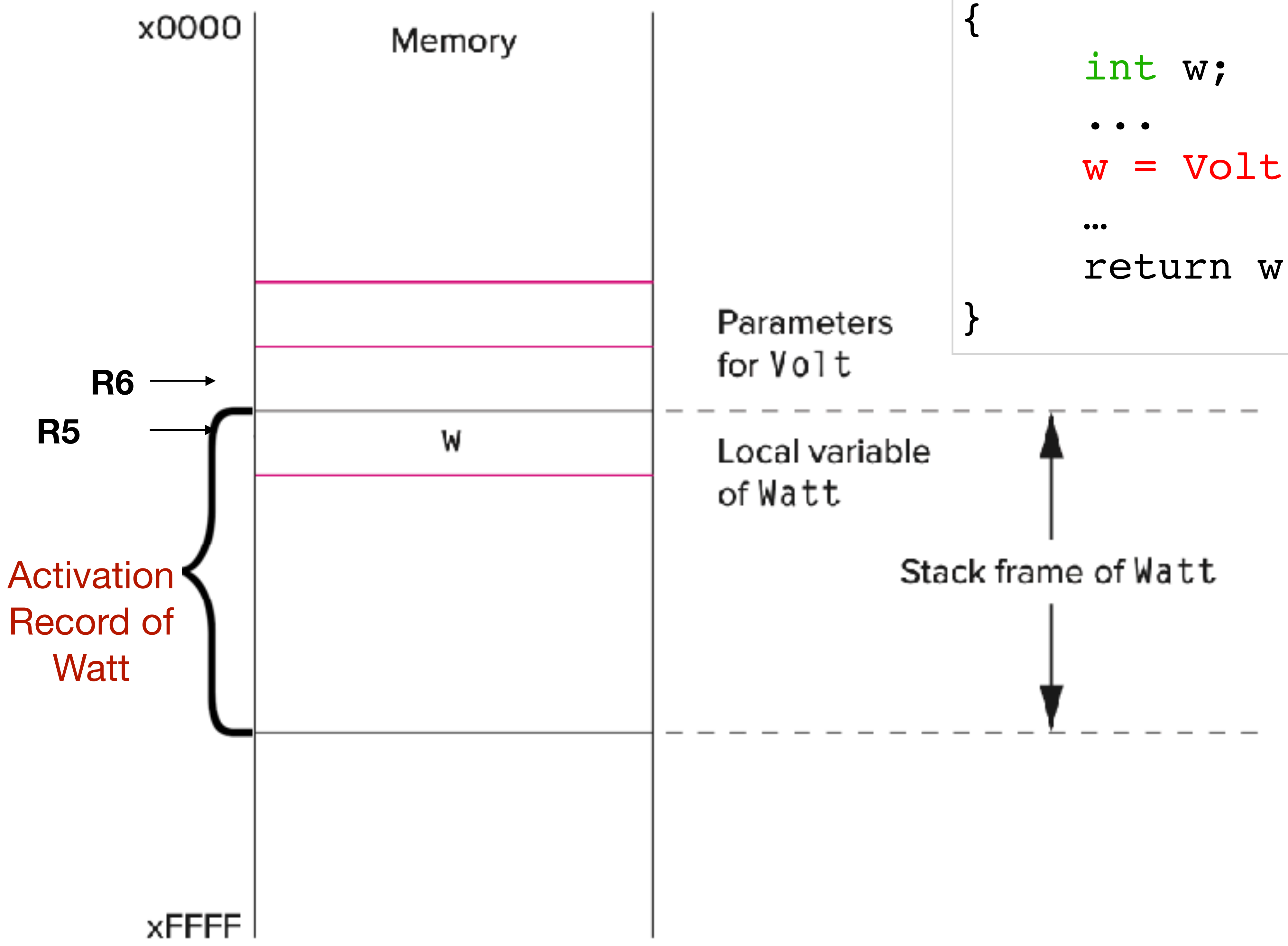


LC-3 Implementation

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;
}
```

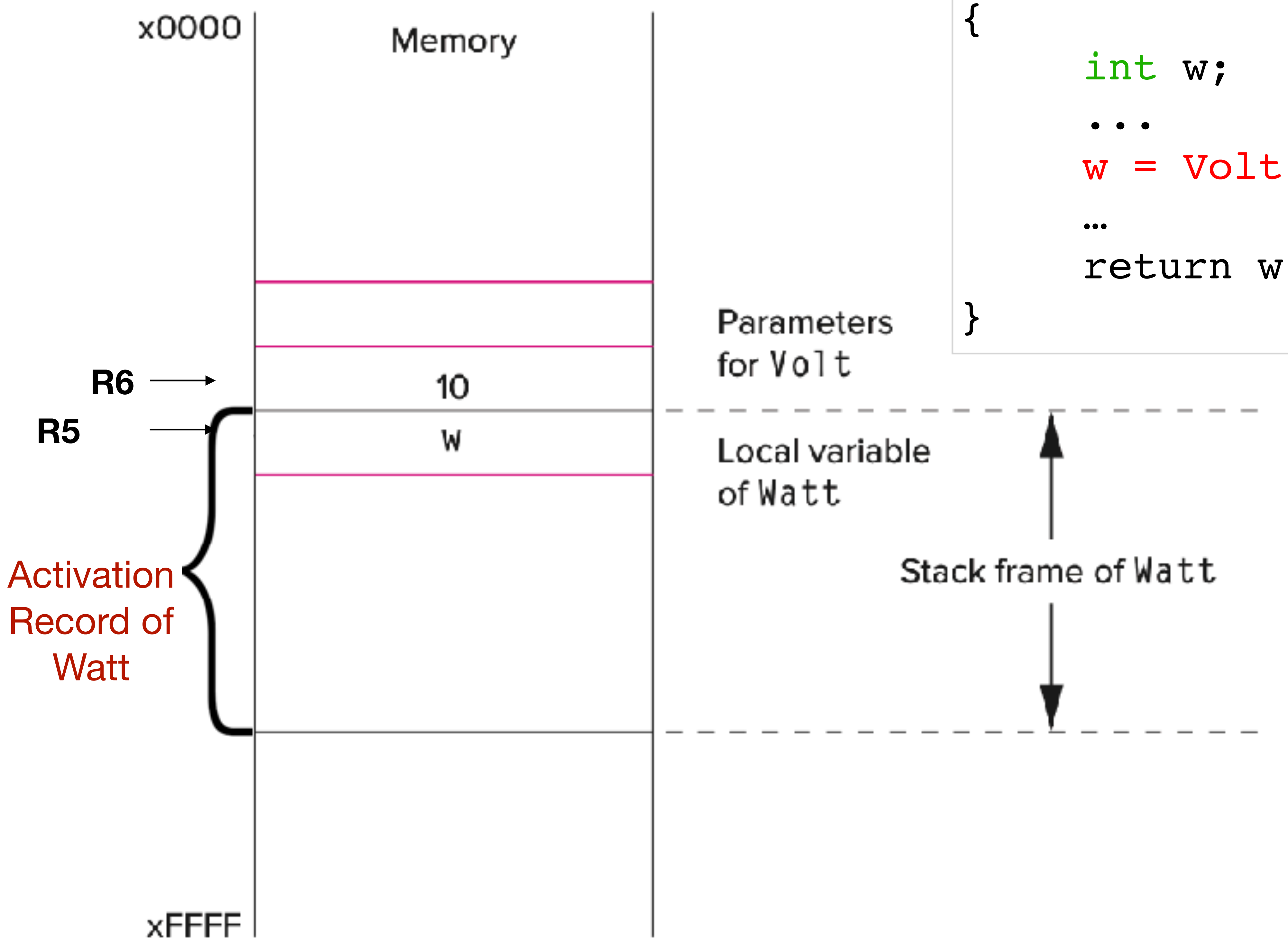


LC-3 Implementation

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
```

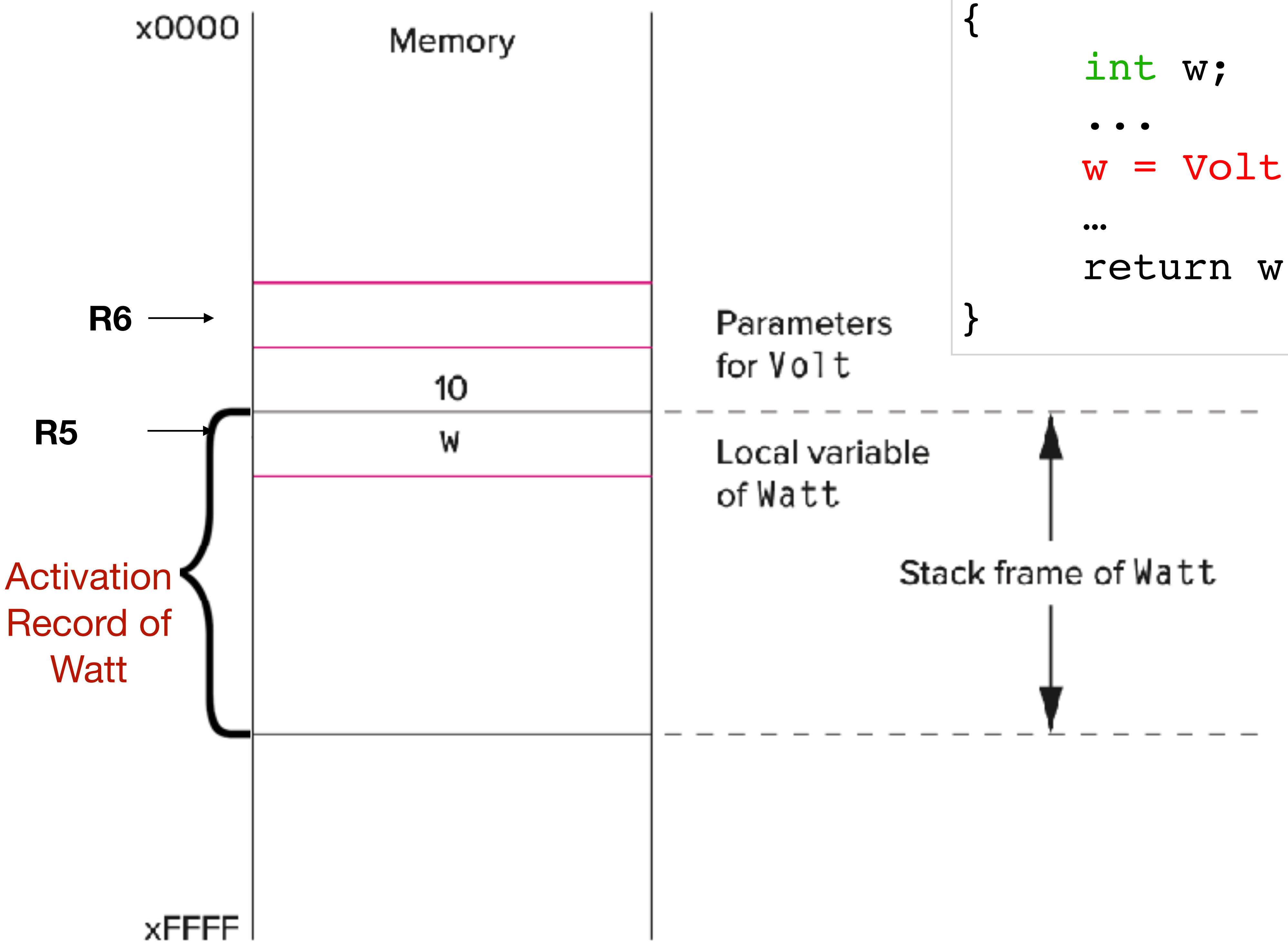
```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```



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
```



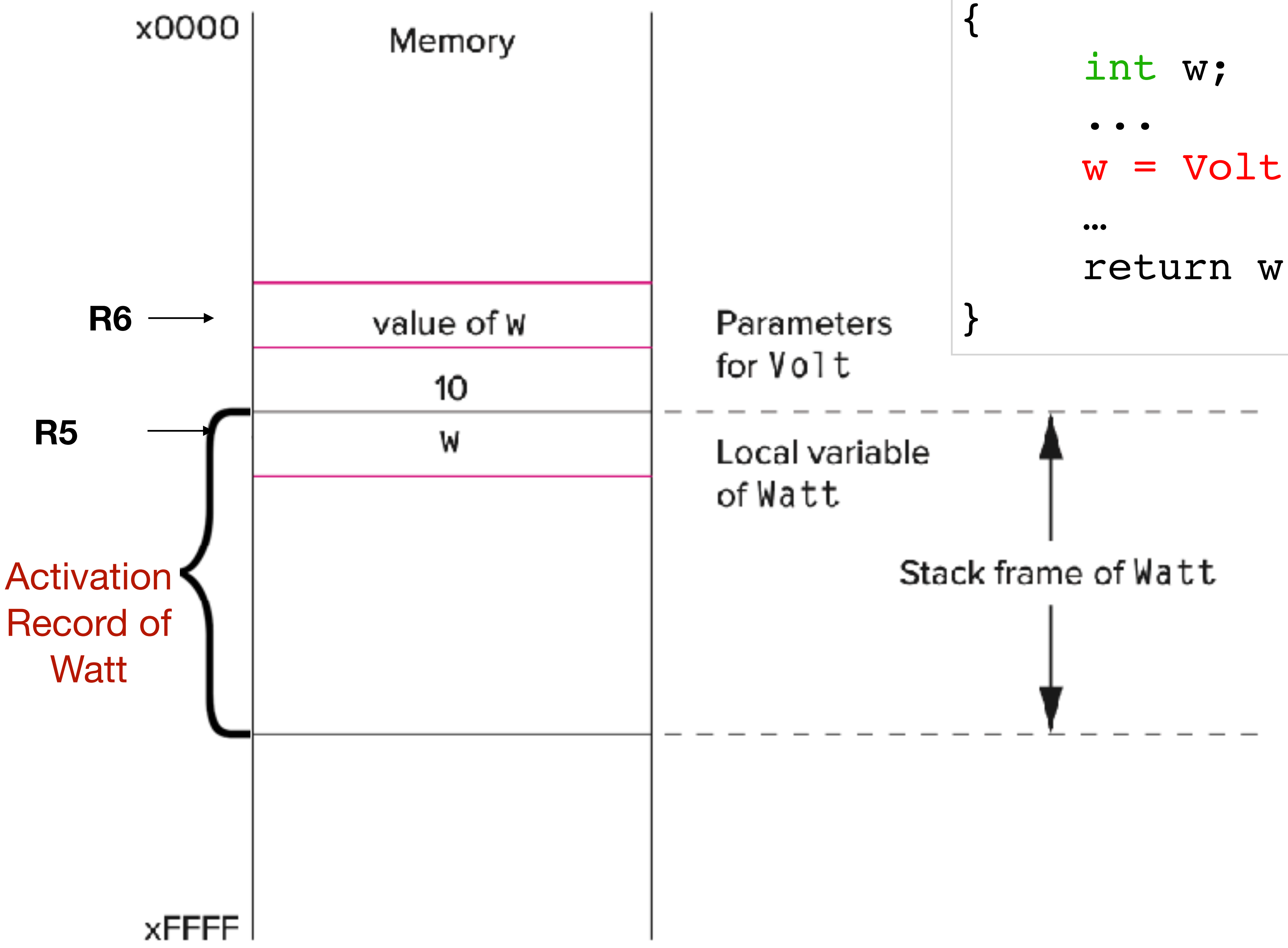
```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

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
```

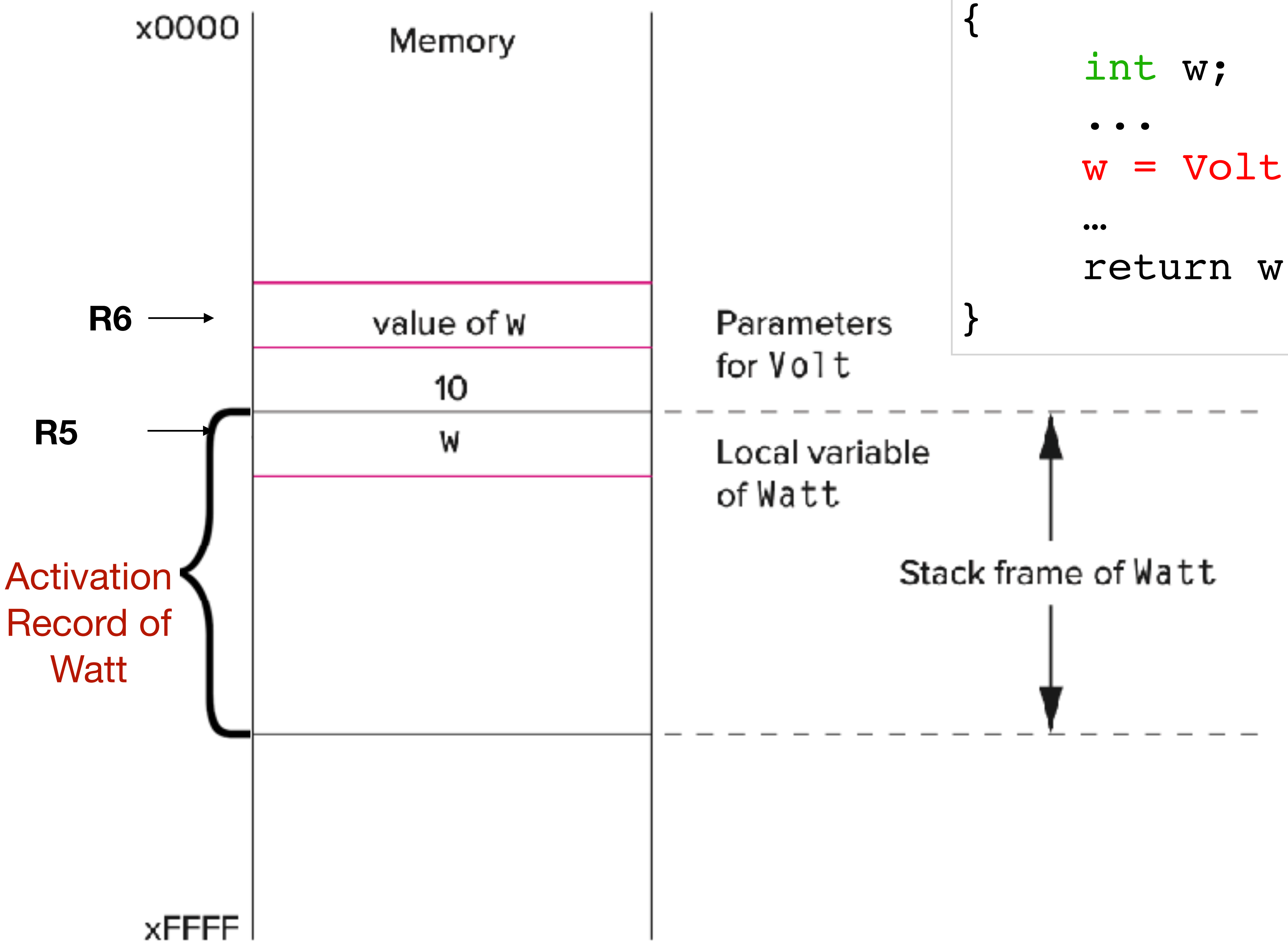
```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```



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
```

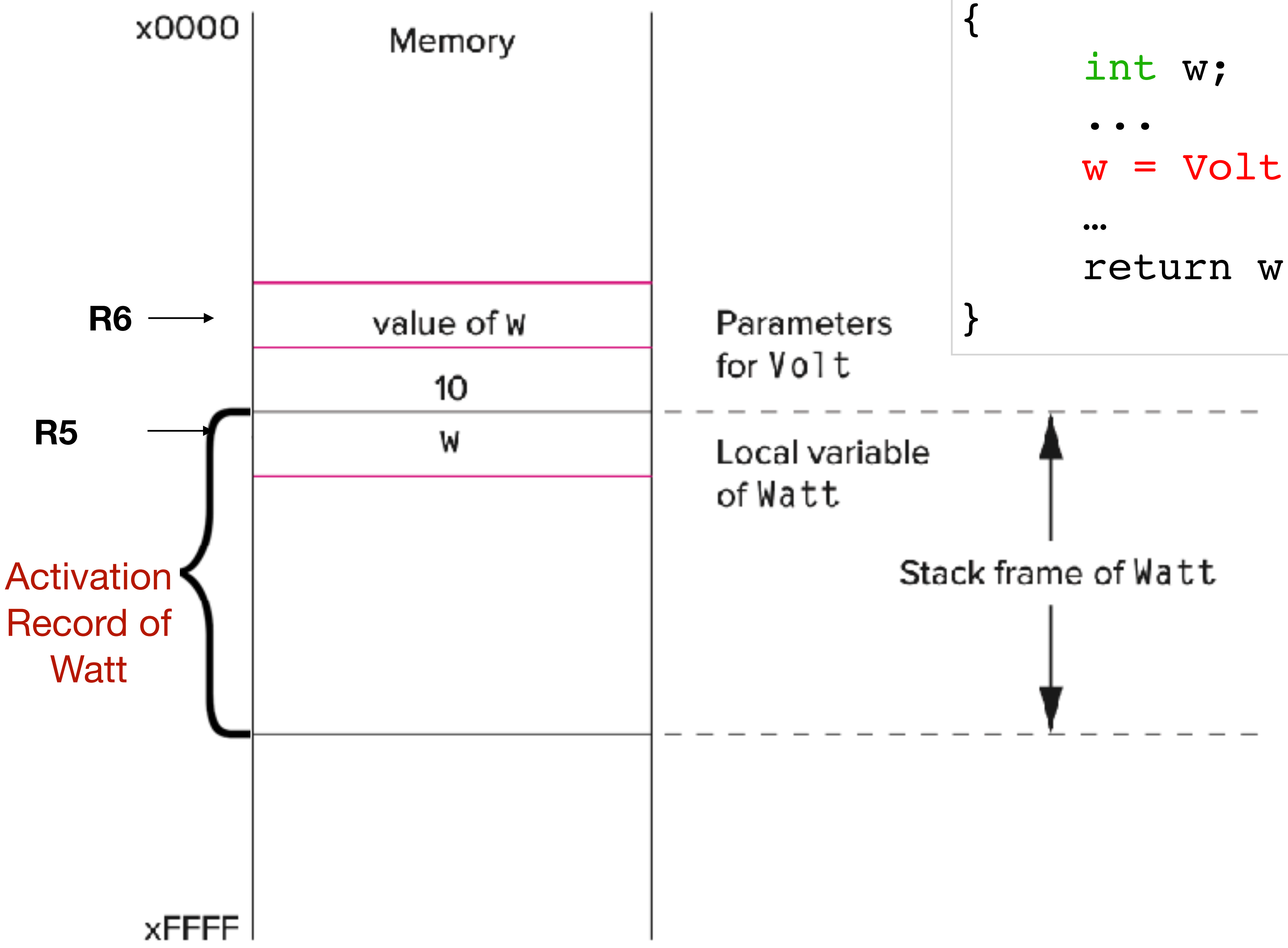


```
int Watt(int a)
{
      int w;
      ...
      w = Volt(w,10);
      …
      return w;
}
```

LC-3 Implementation

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

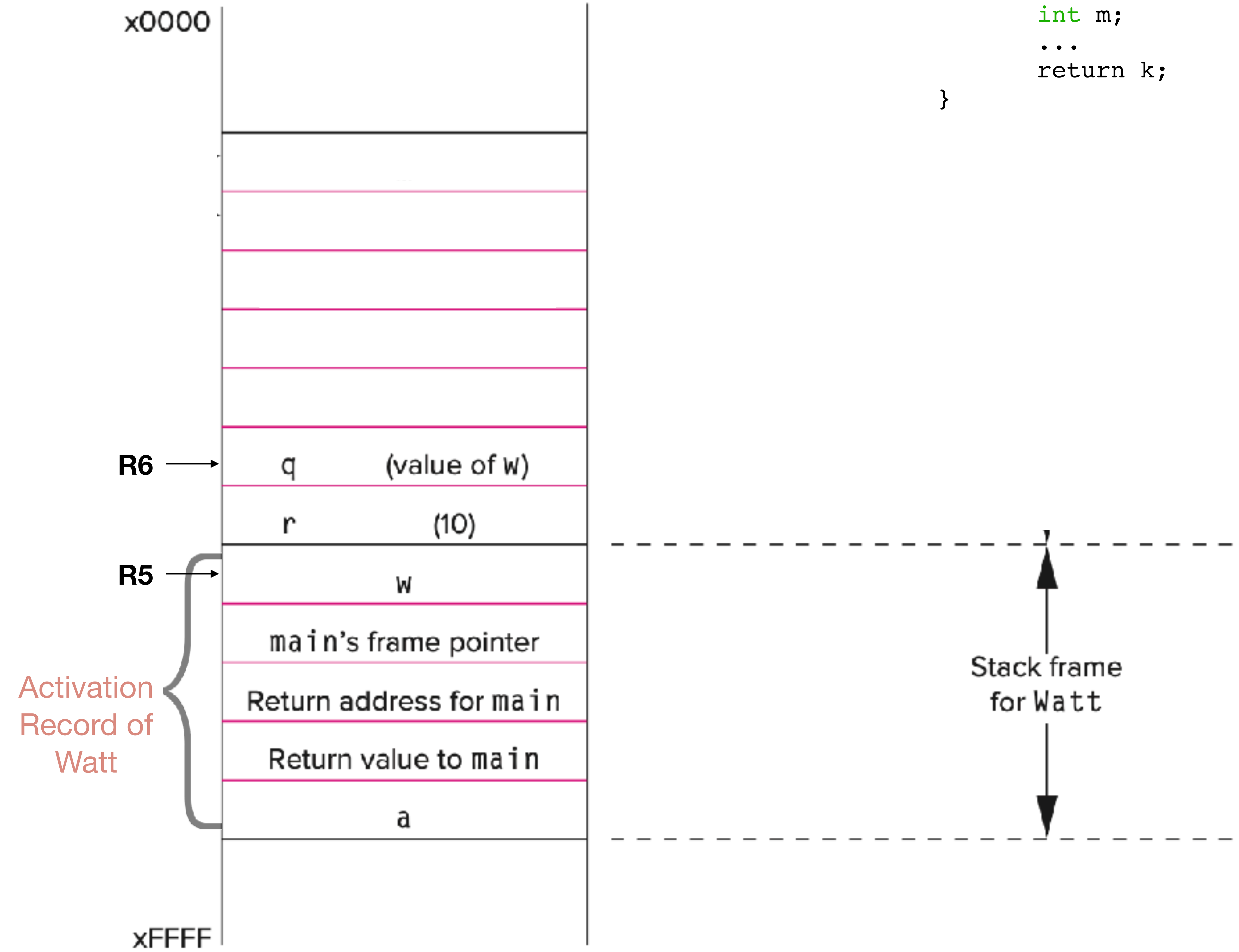
```
; push second arg
AND R0, R0, #0
ADD R0, R0, #10
ADD R6, R6, #-1
STR R0, R6, #0

; 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

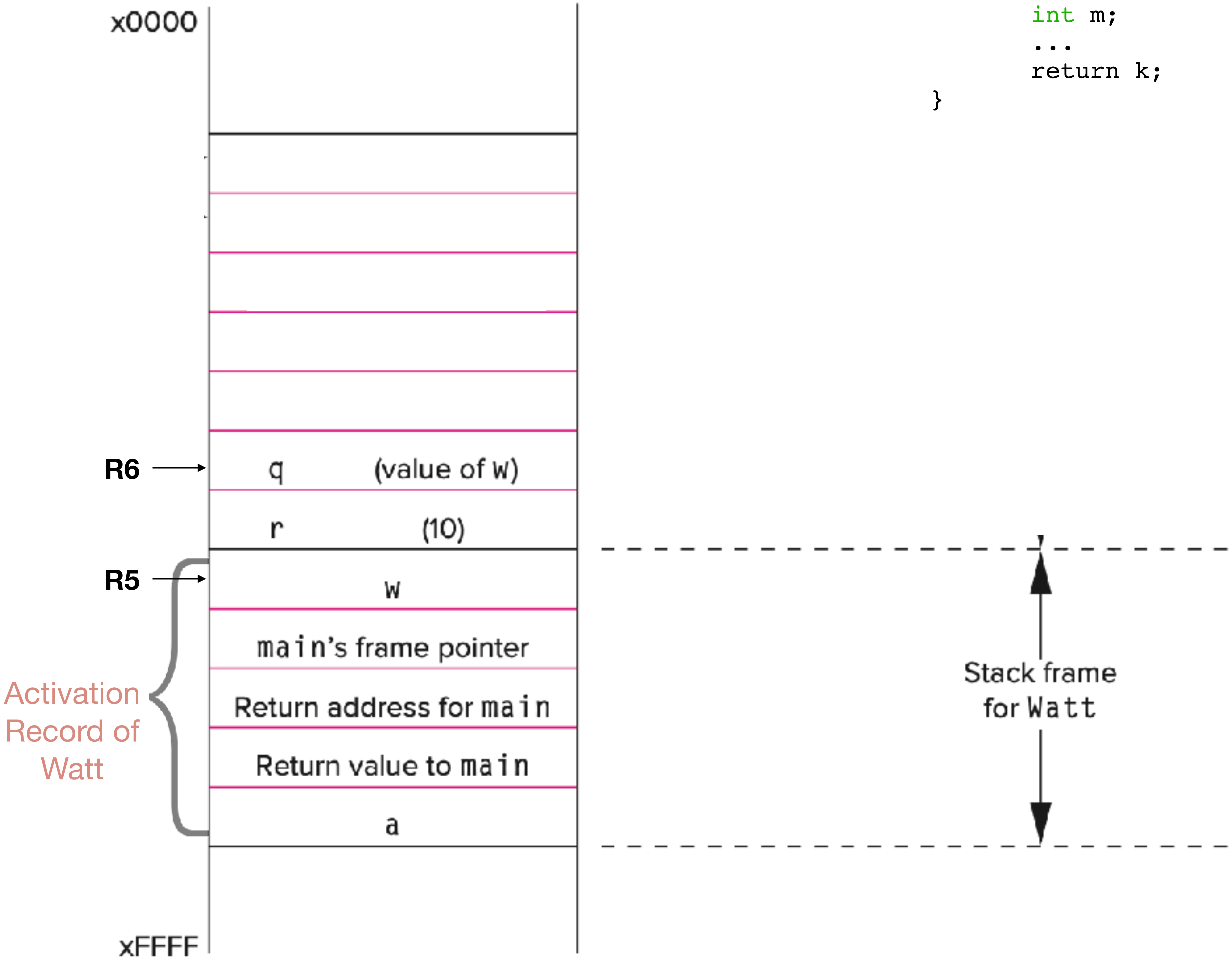
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

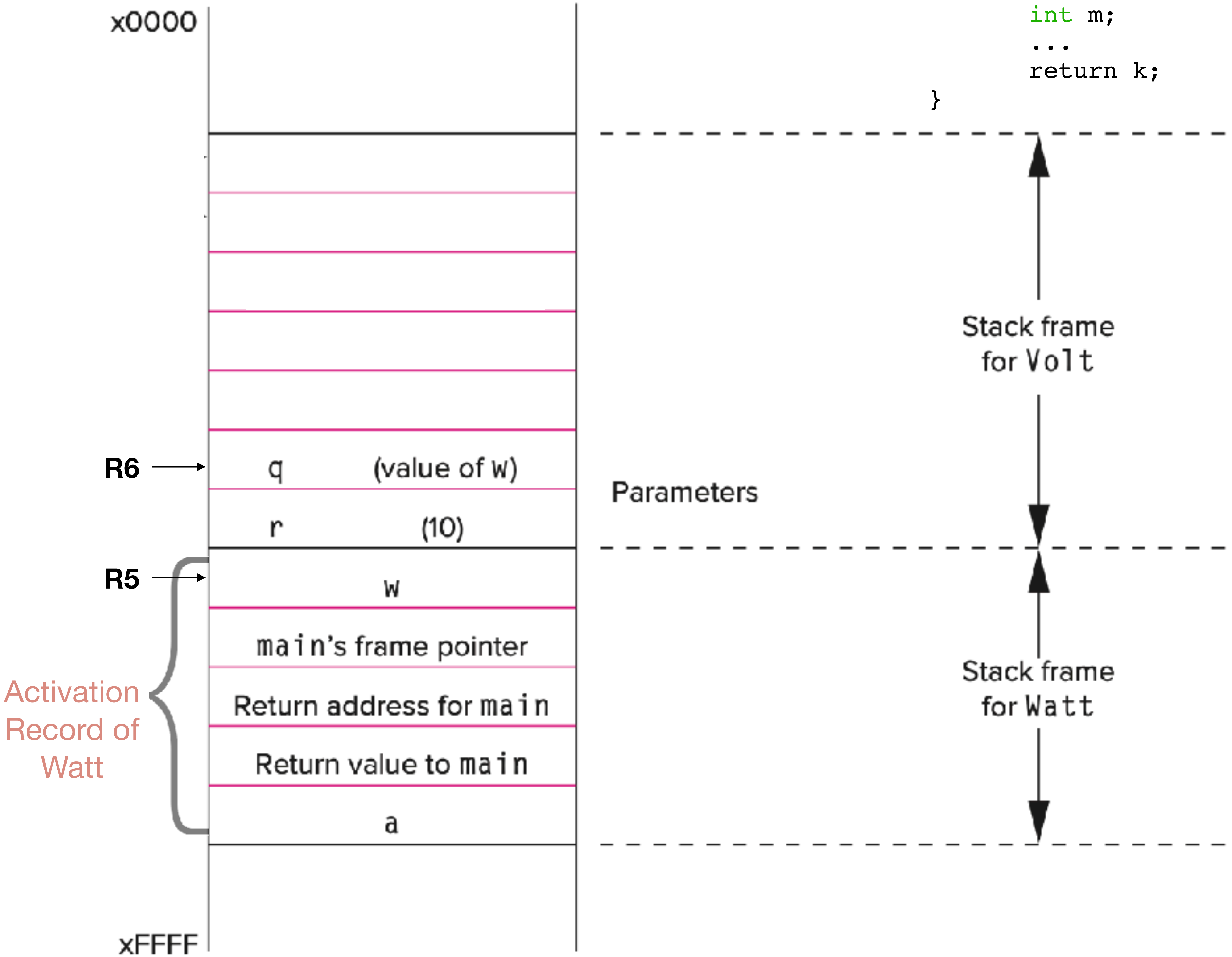
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

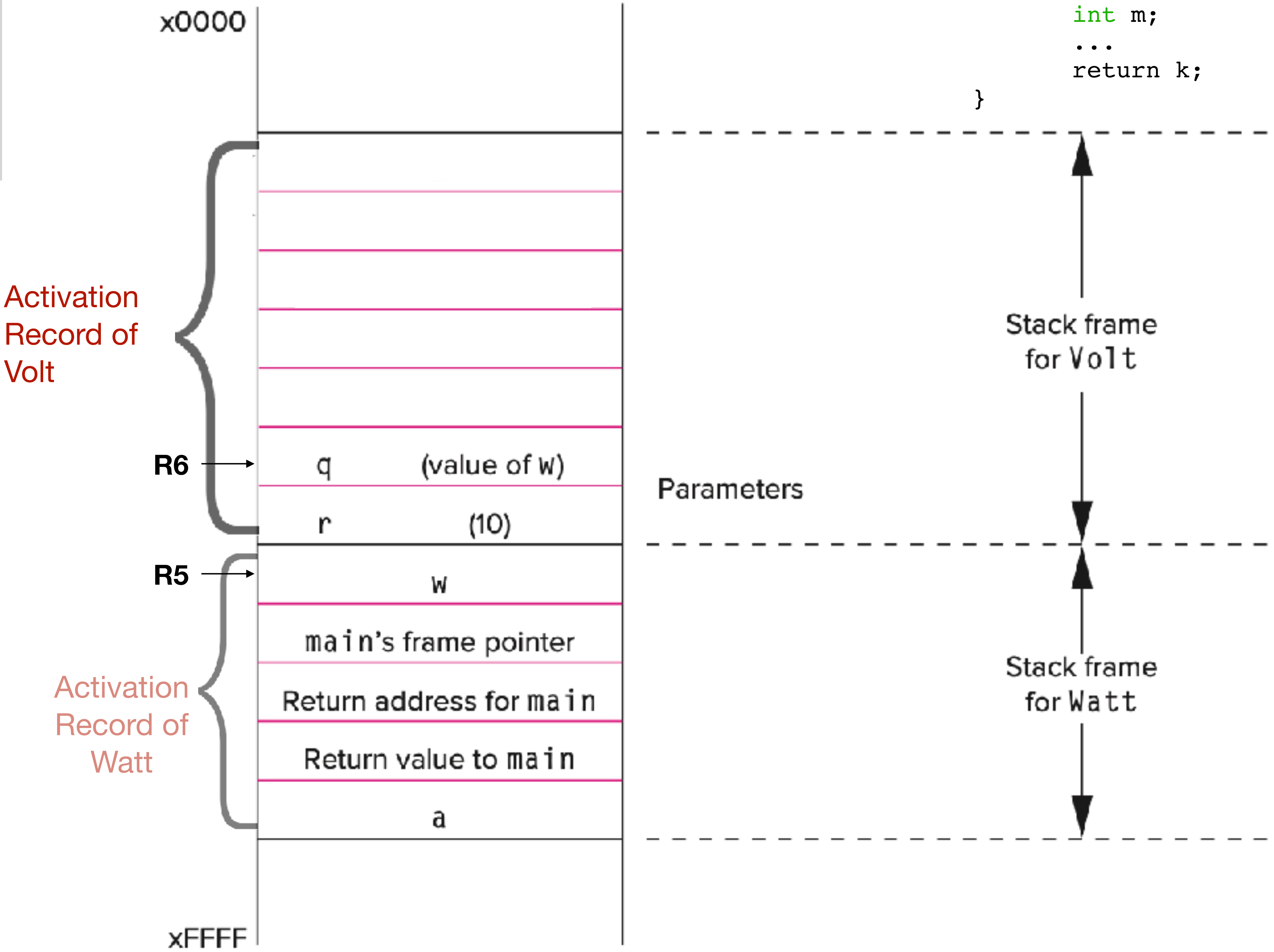
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

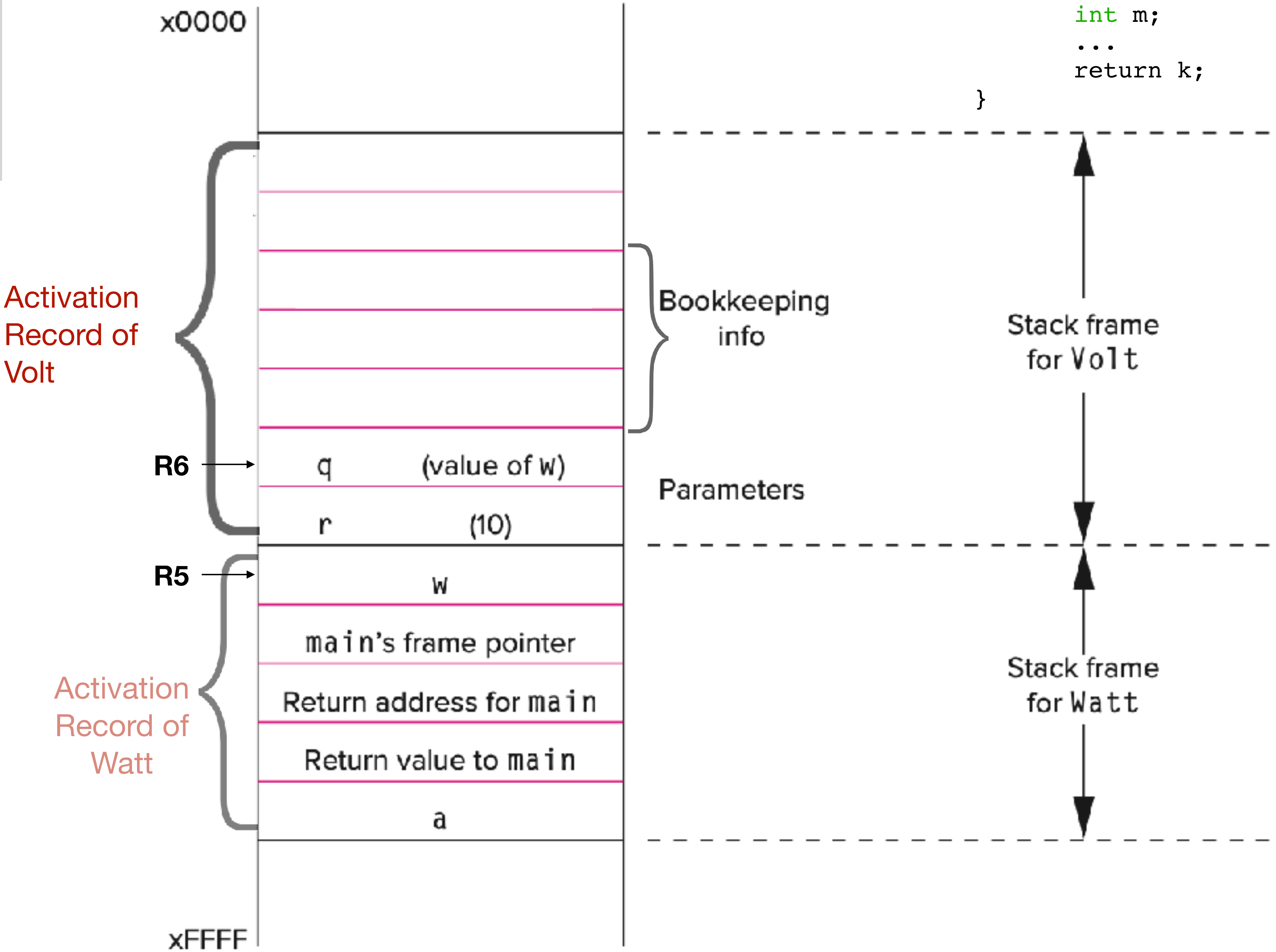
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```



LC-3 Implementation

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

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

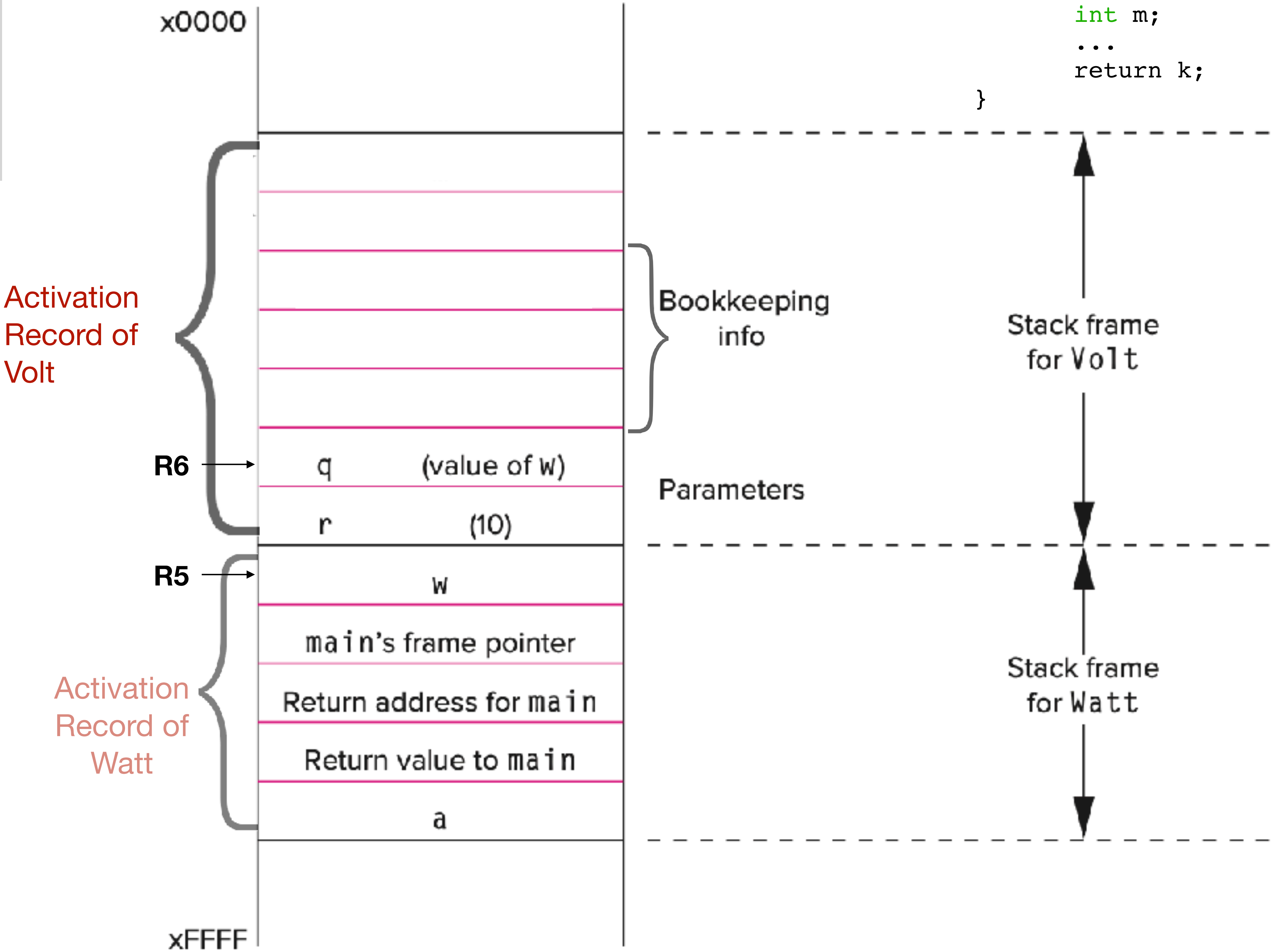


LC-3 Implementation

```
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
```

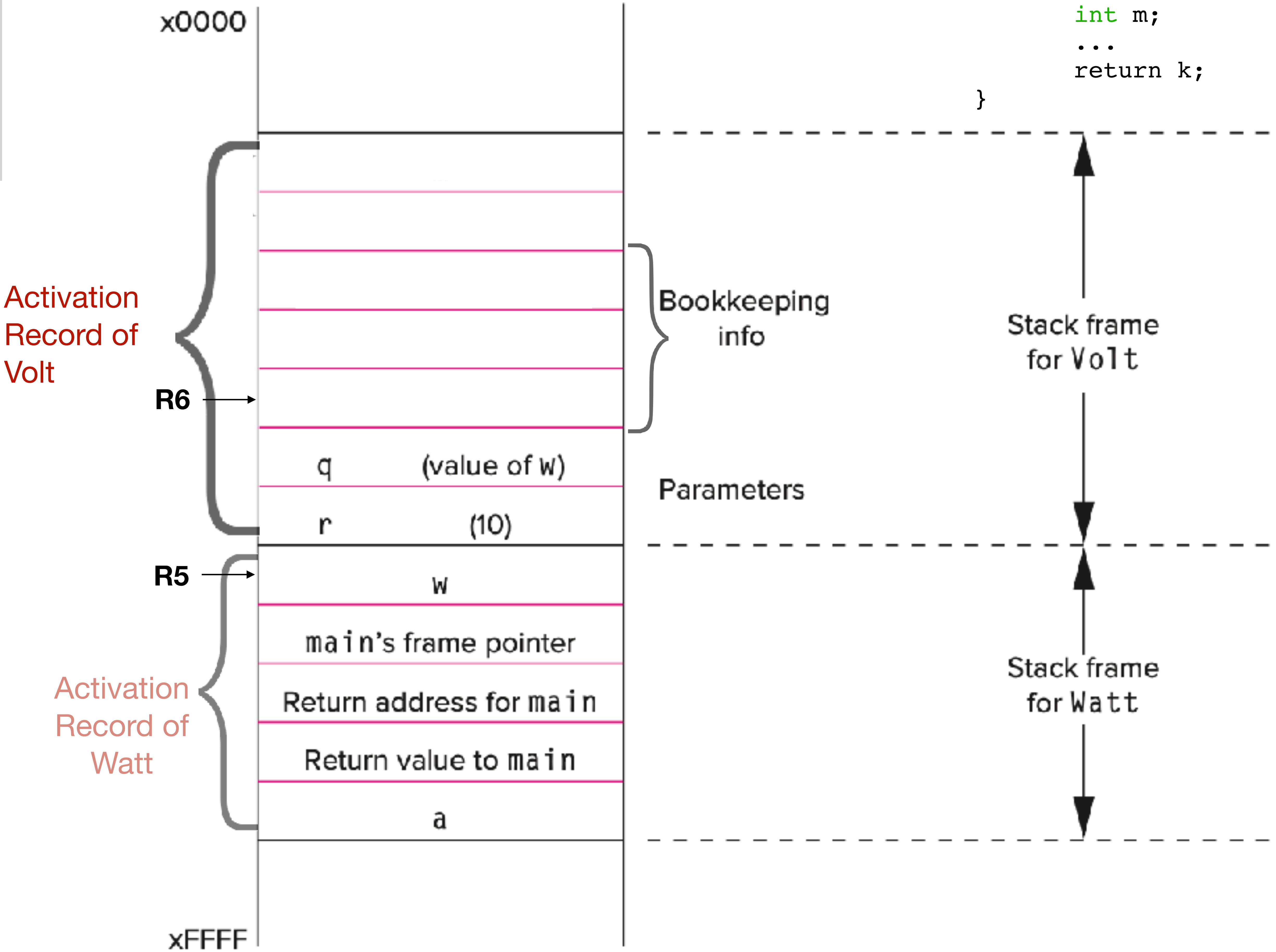


LC-3 Implementation

```
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
```

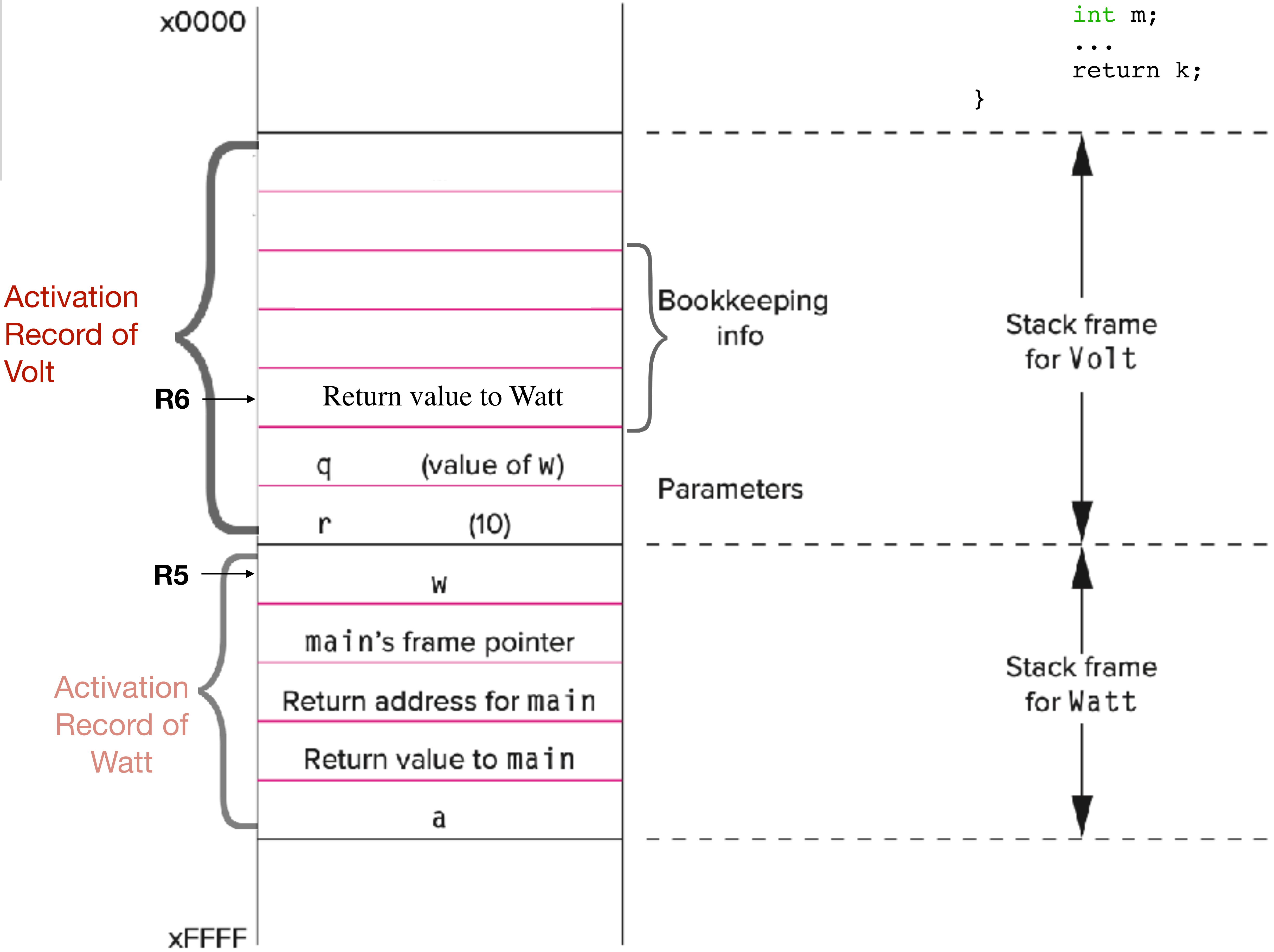


LC-3 Implementation

```
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
```

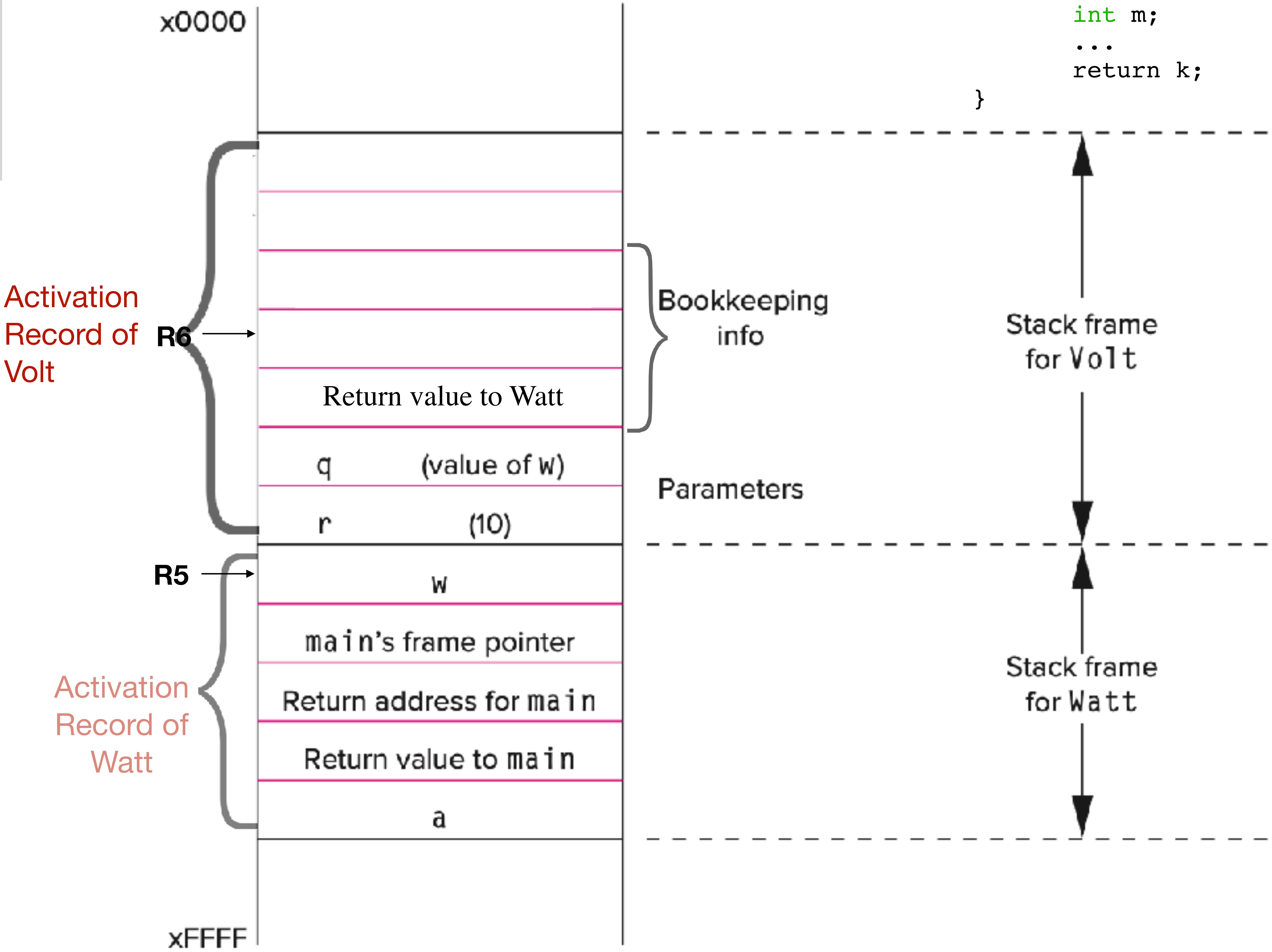


LC-3 Implementation

```
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

ADD R6, R6, #-1
```

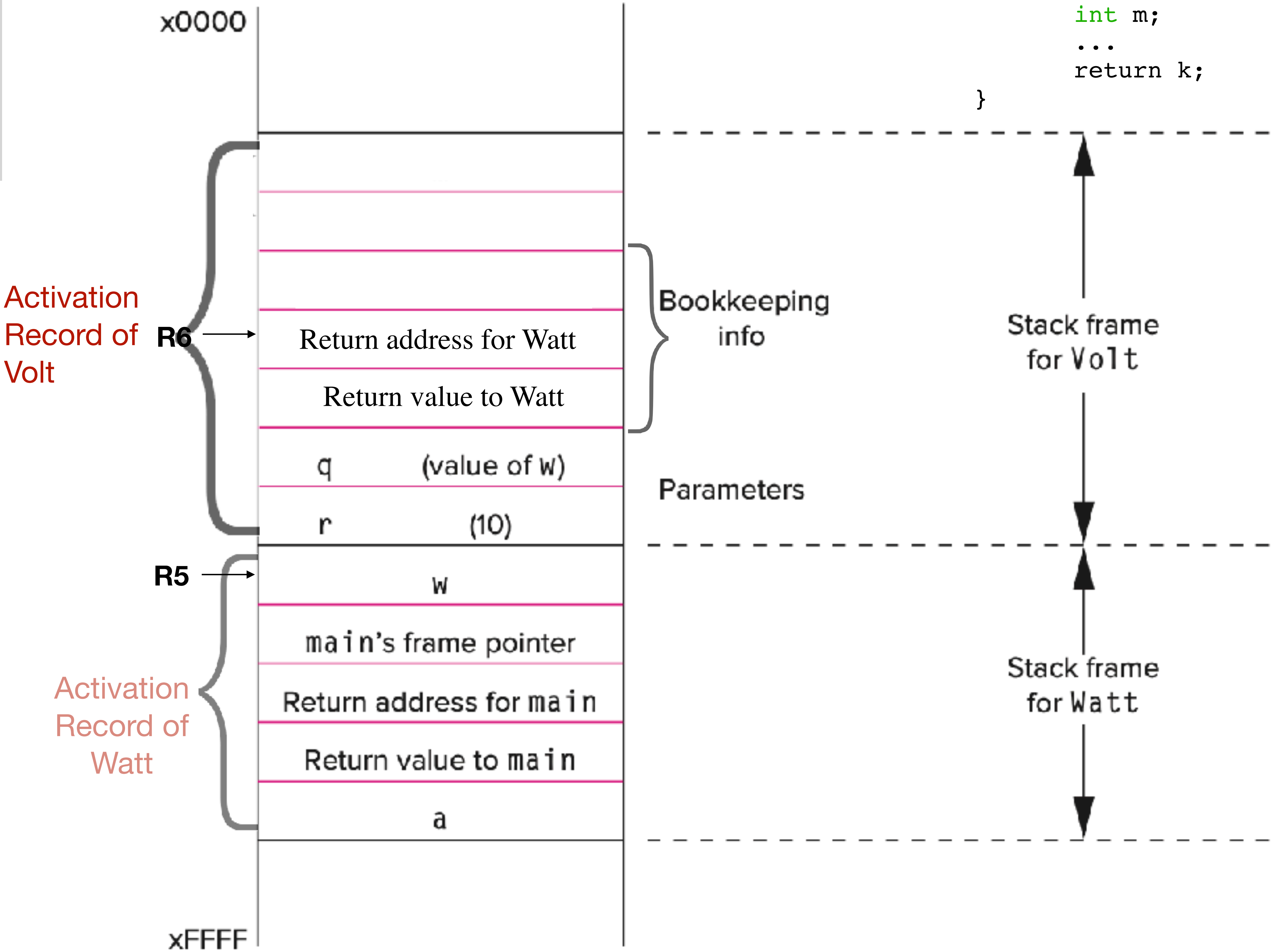


LC-3 Implementation

```
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

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

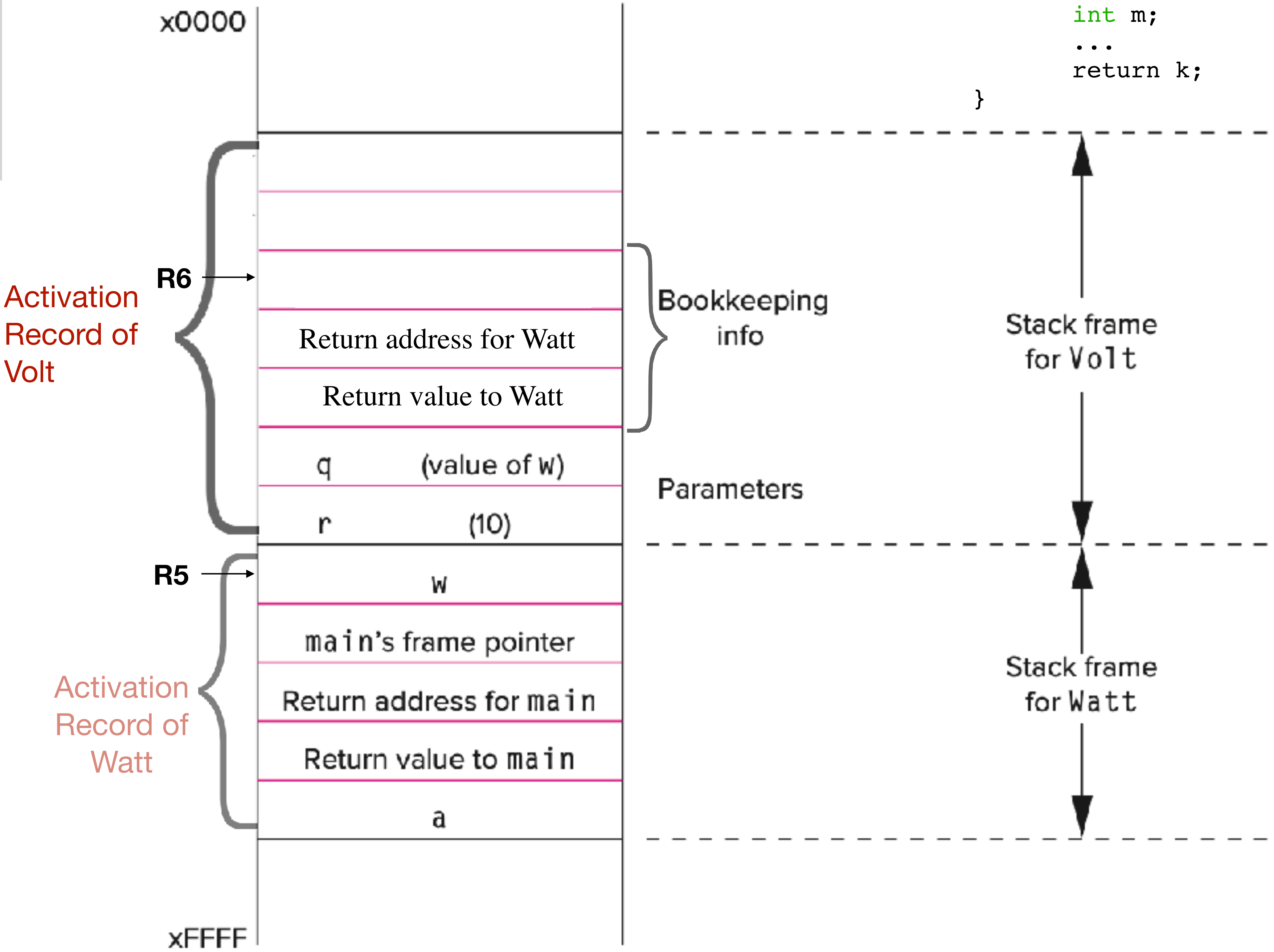


LC-3 Implementation

```
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

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

ADD R6, R6, #-1
```

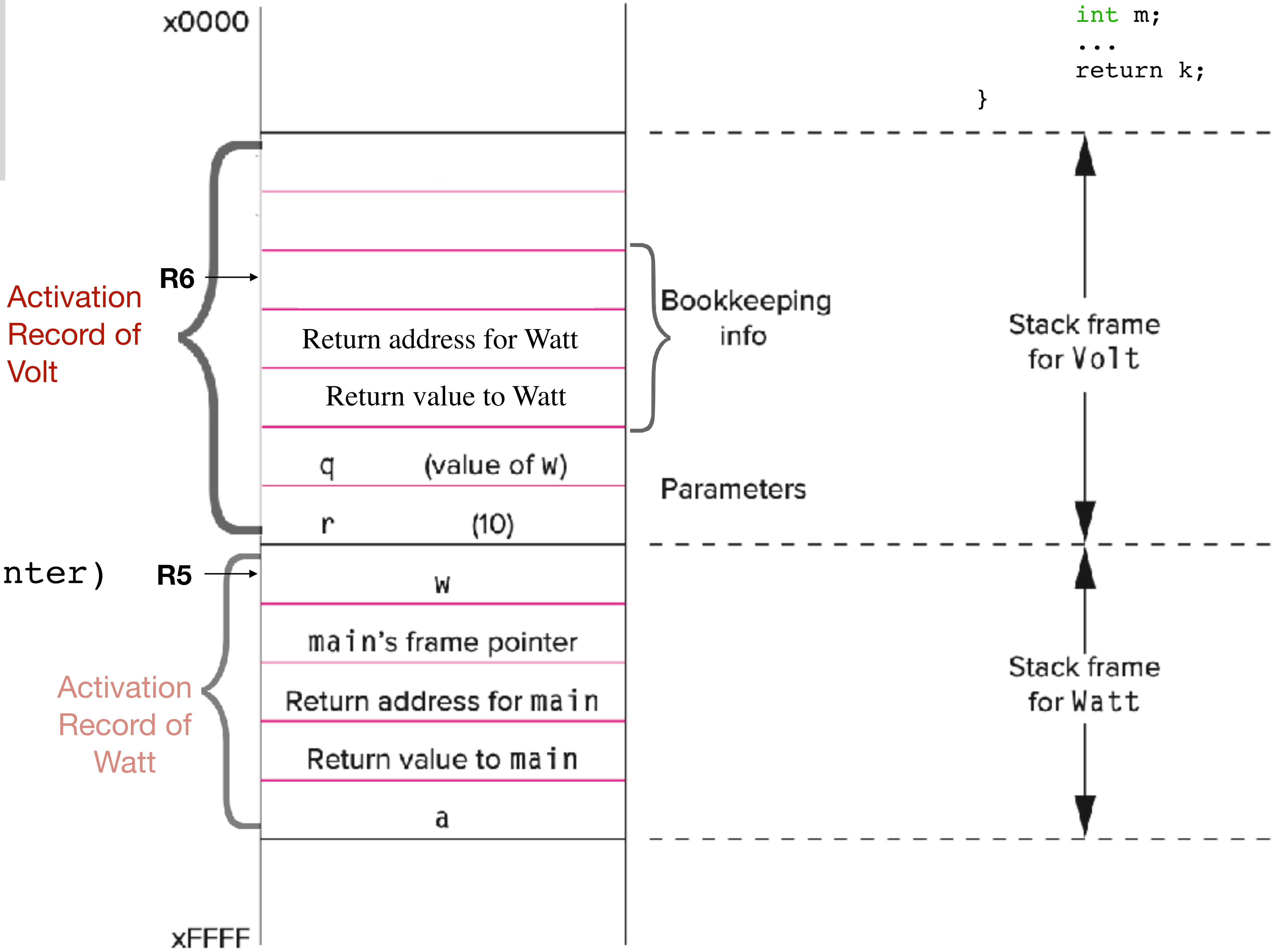


LC-3 Implementation

```
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

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
```

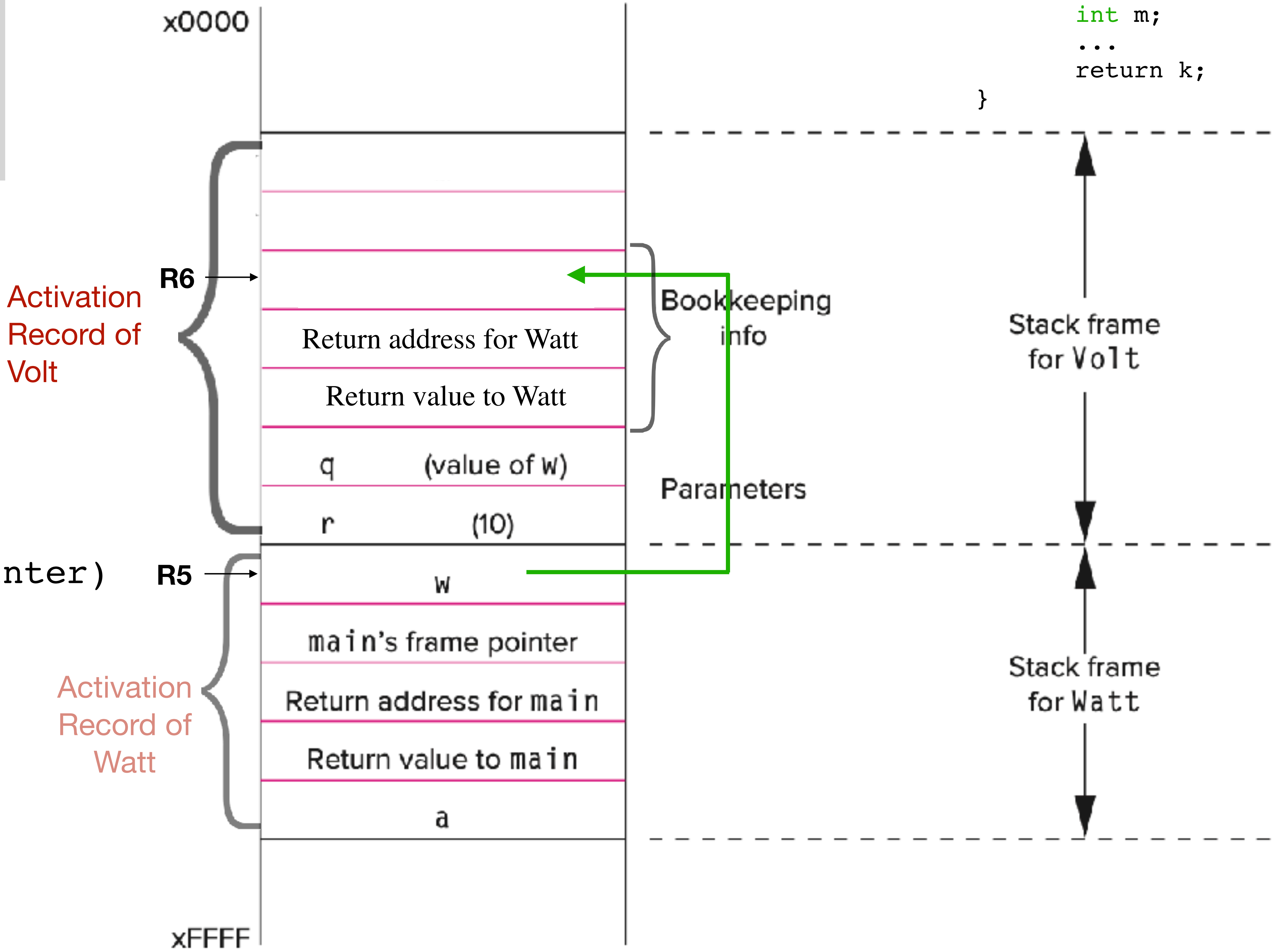


LC-3 Implementation

```
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

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
```

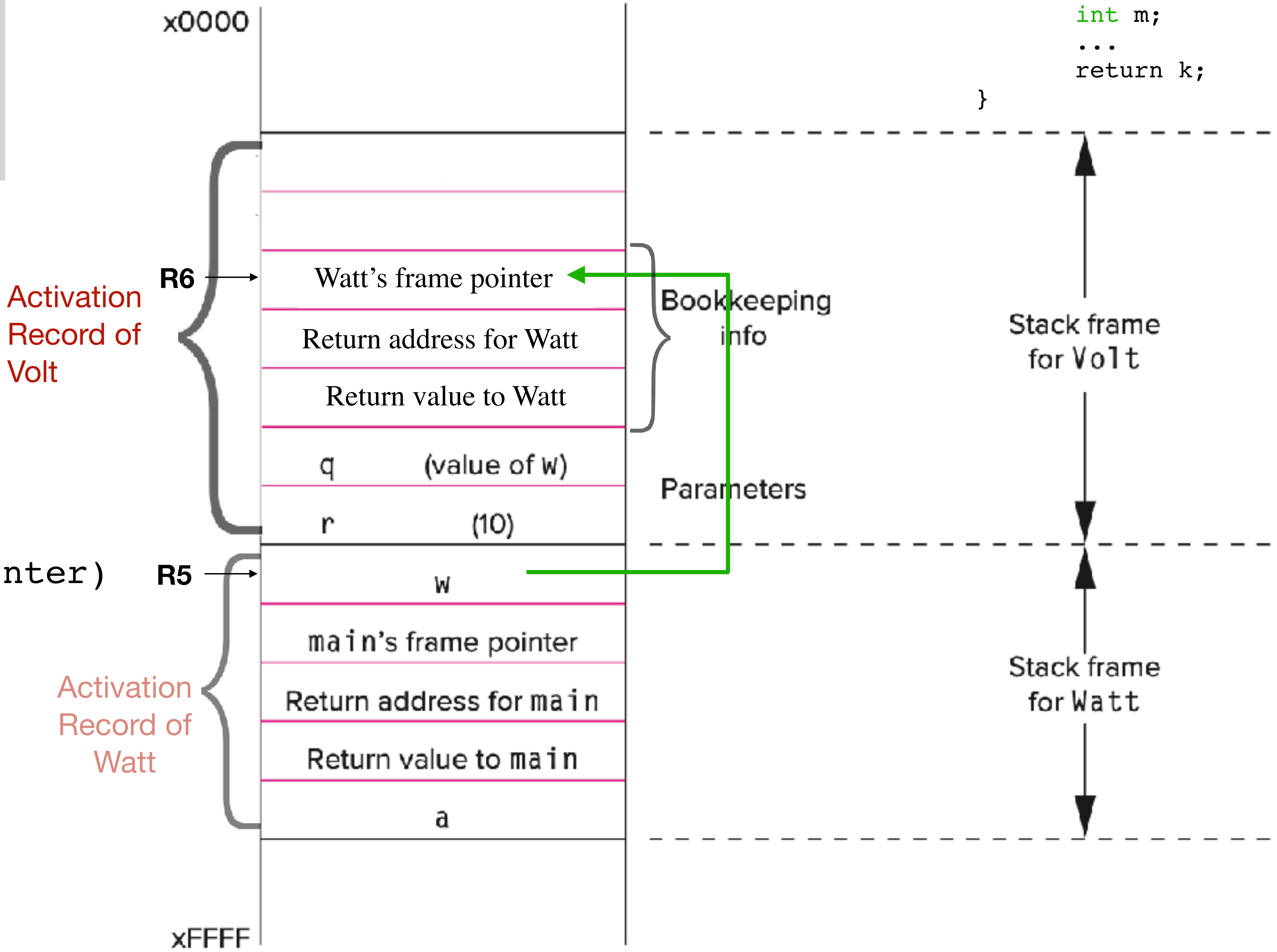


LC-3 Implementation

```
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

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
```

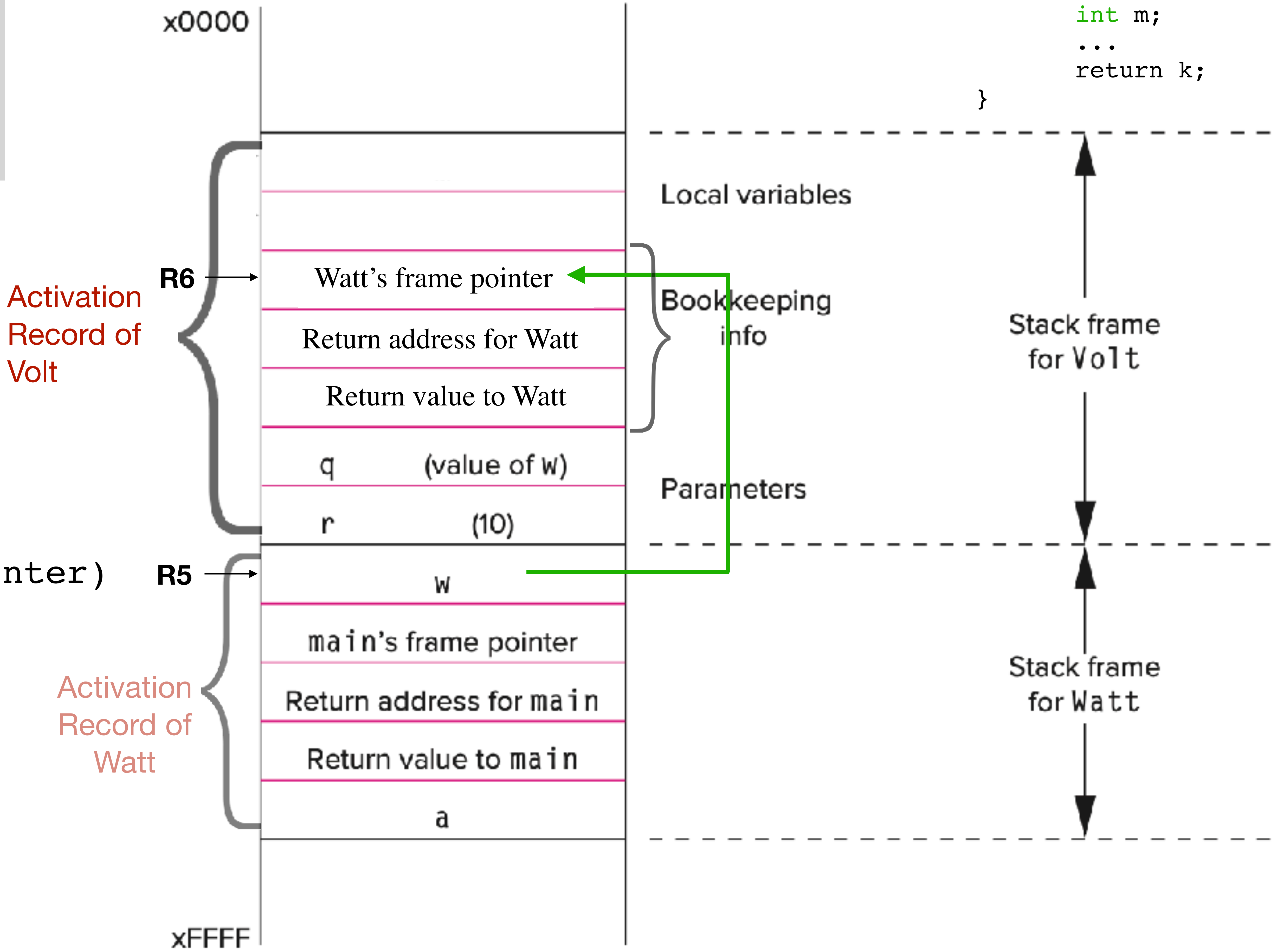


LC-3 Implementation

```
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

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
```

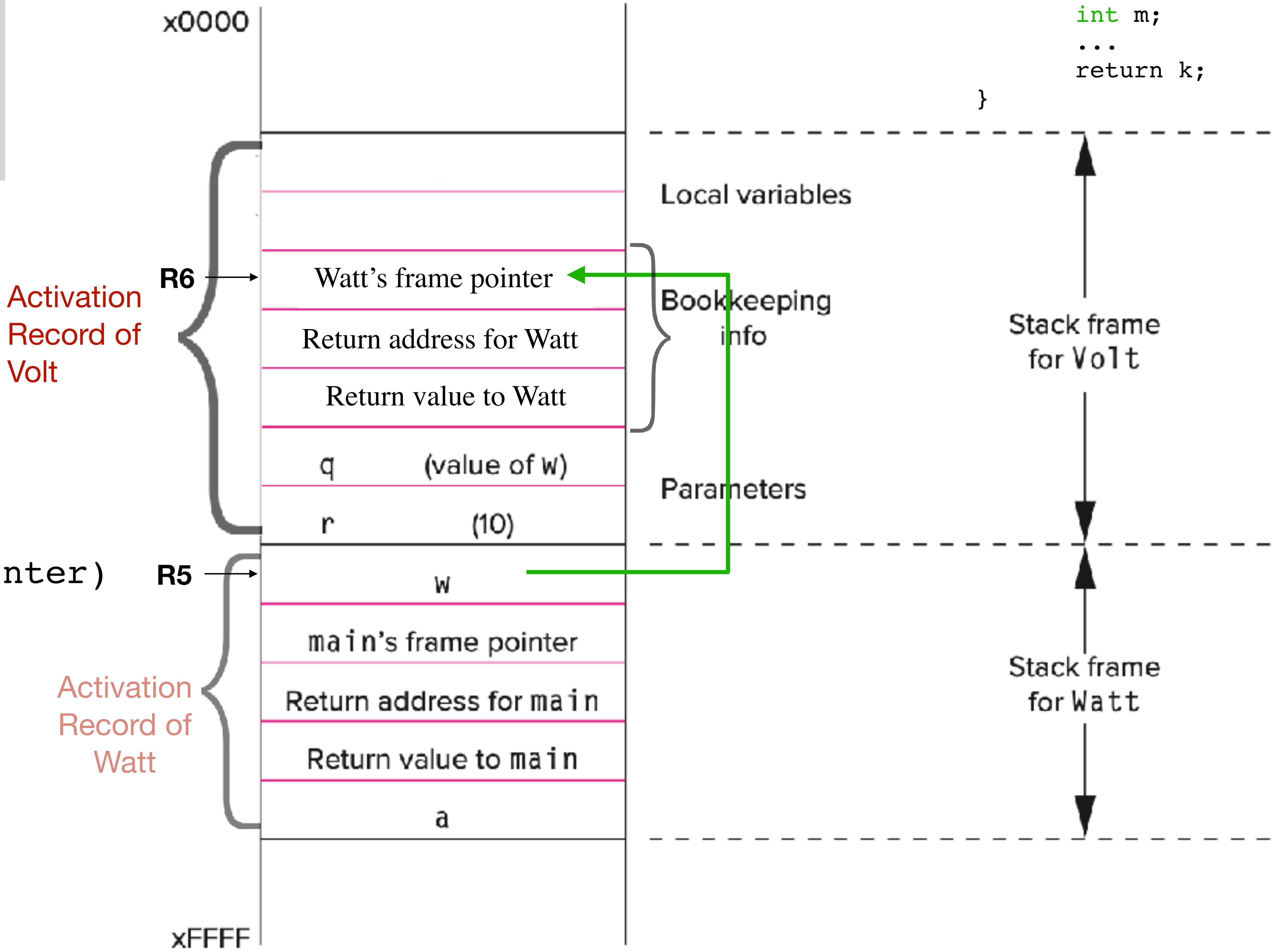


LC-3 Implementation

```
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

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
```

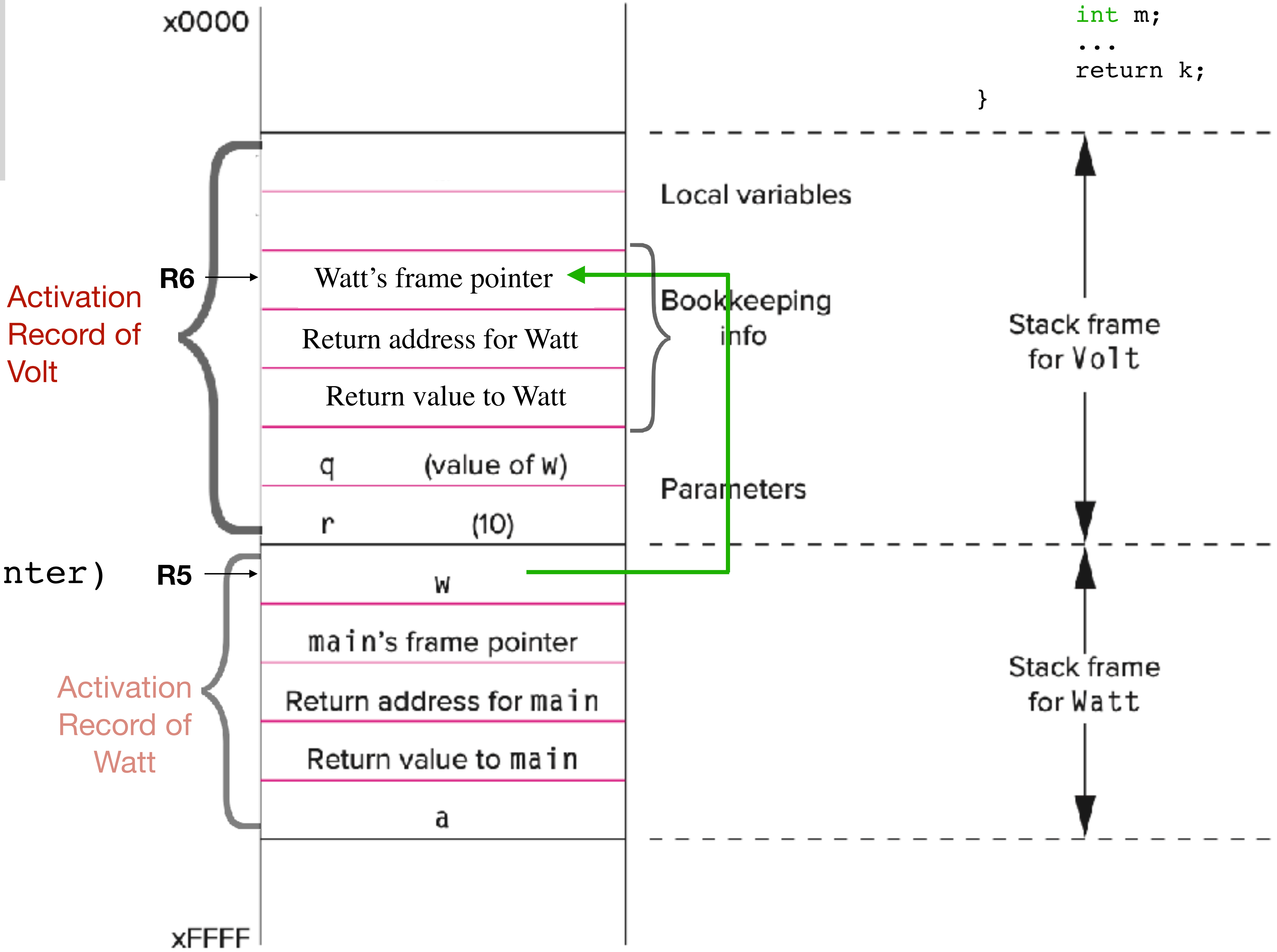


LC-3 Implementation

```
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

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
```

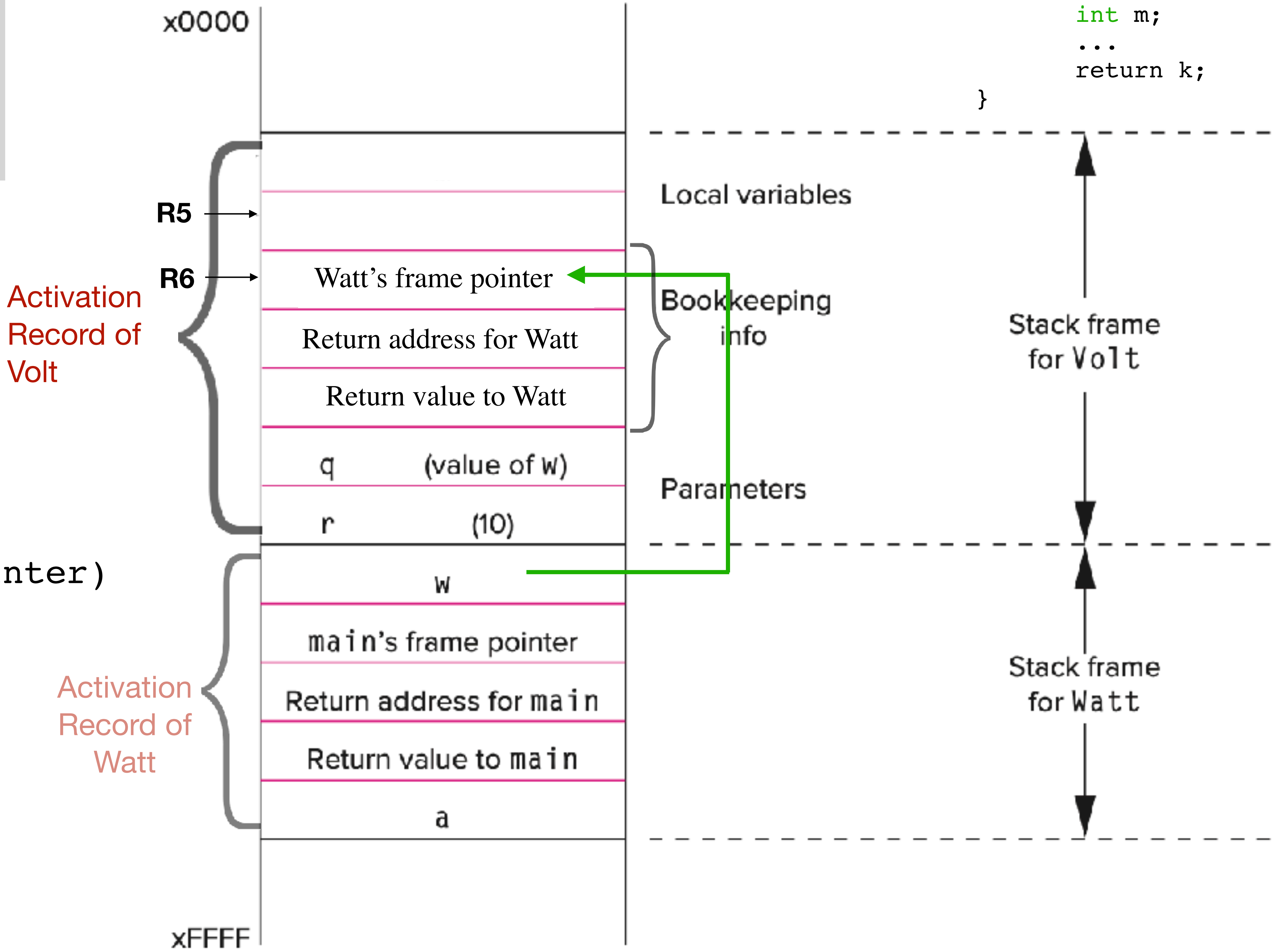


LC-3 Implementation

```
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
;
```

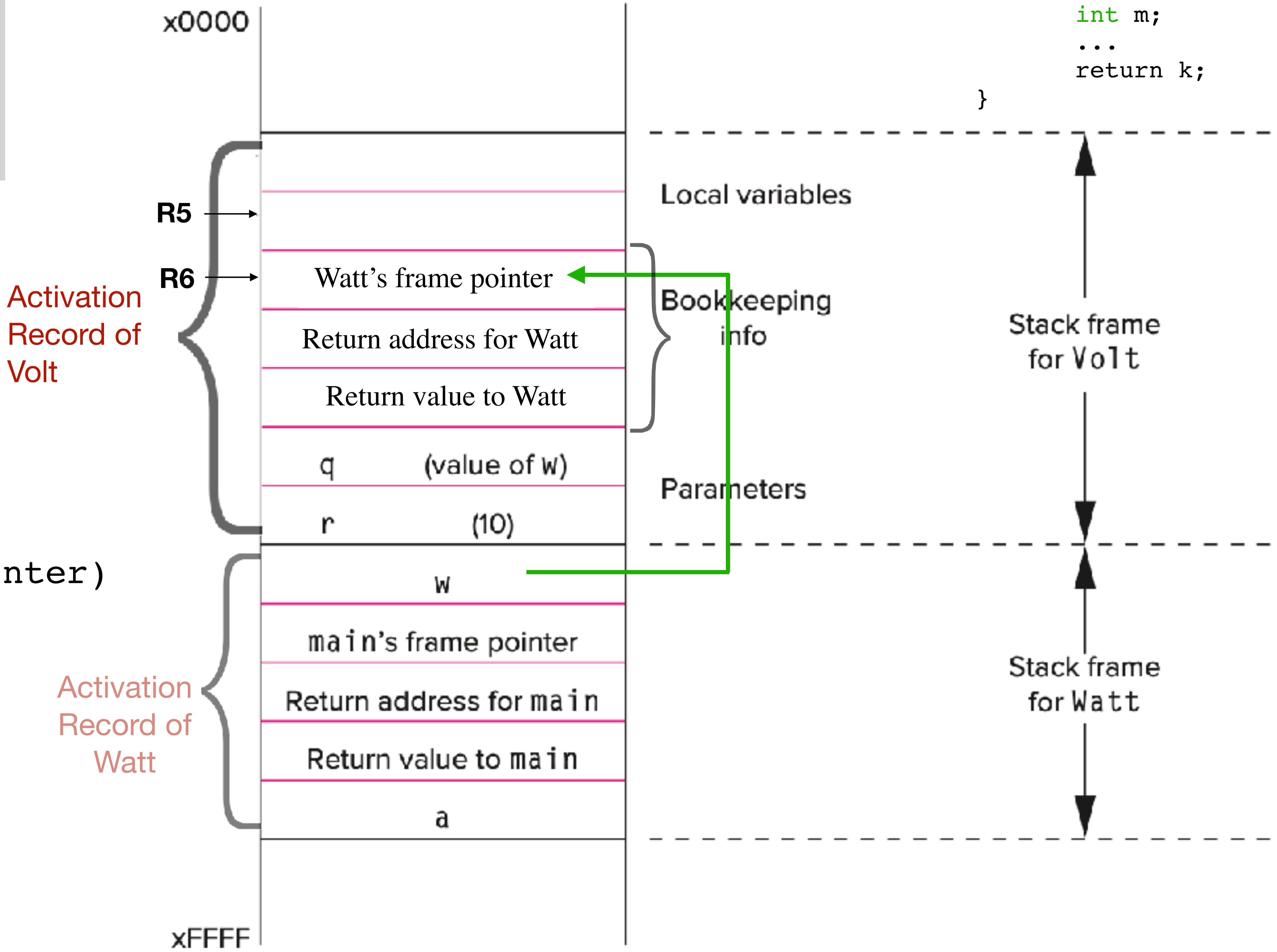


LC-3 Implementation

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
;
```

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

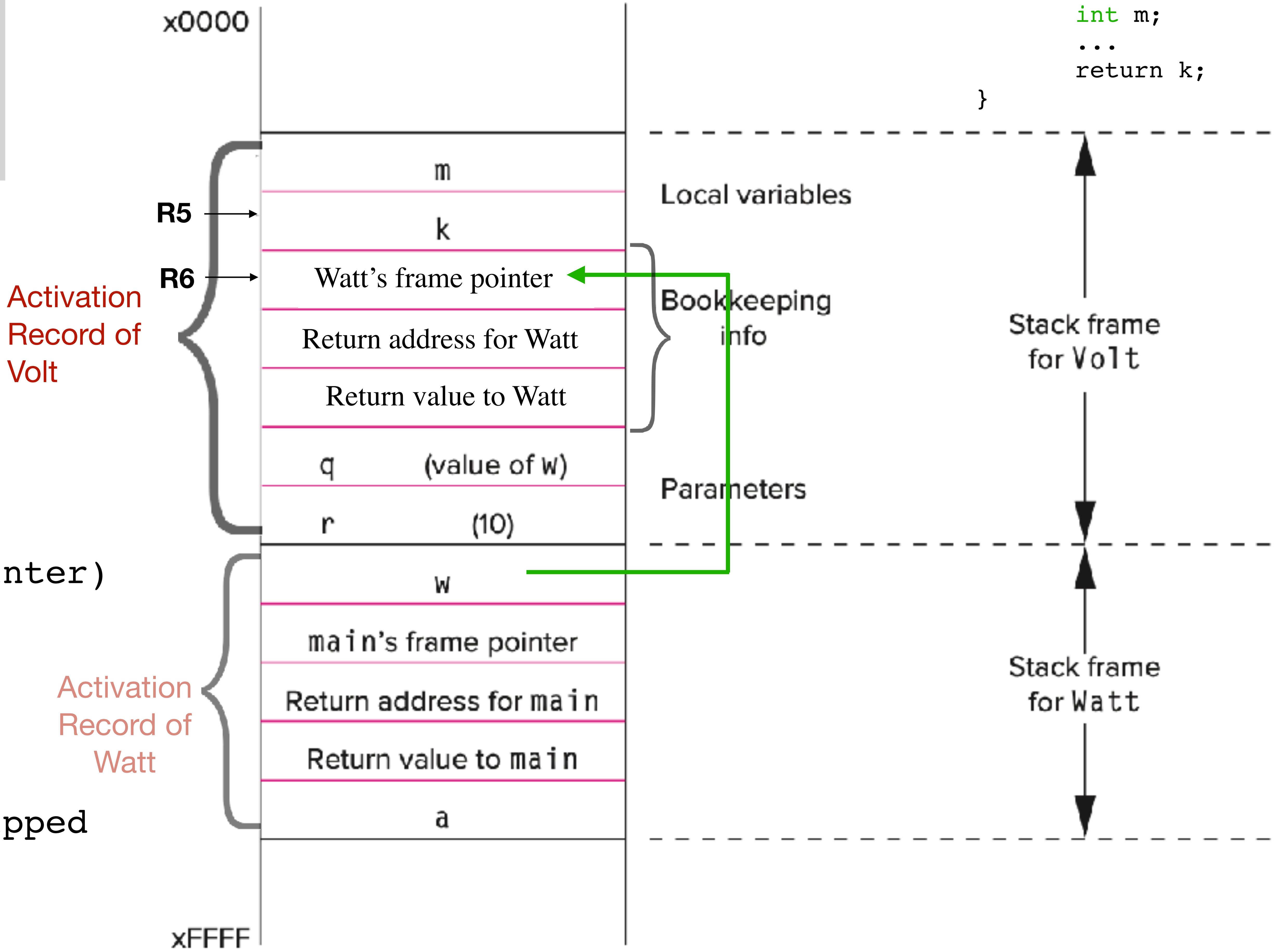


LC-3 Implementation

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

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

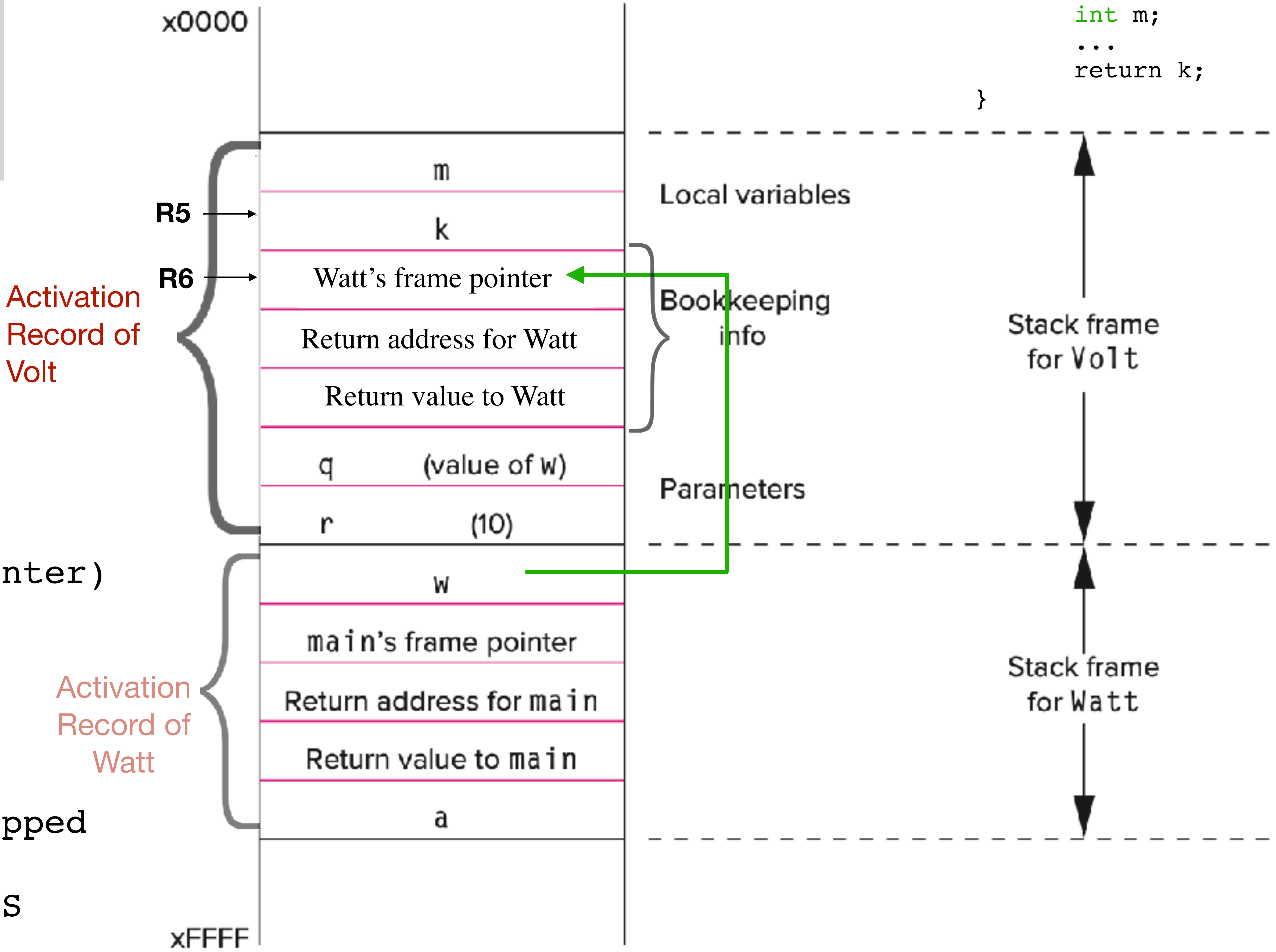


LC-3 Implementation

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

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

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

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

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

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

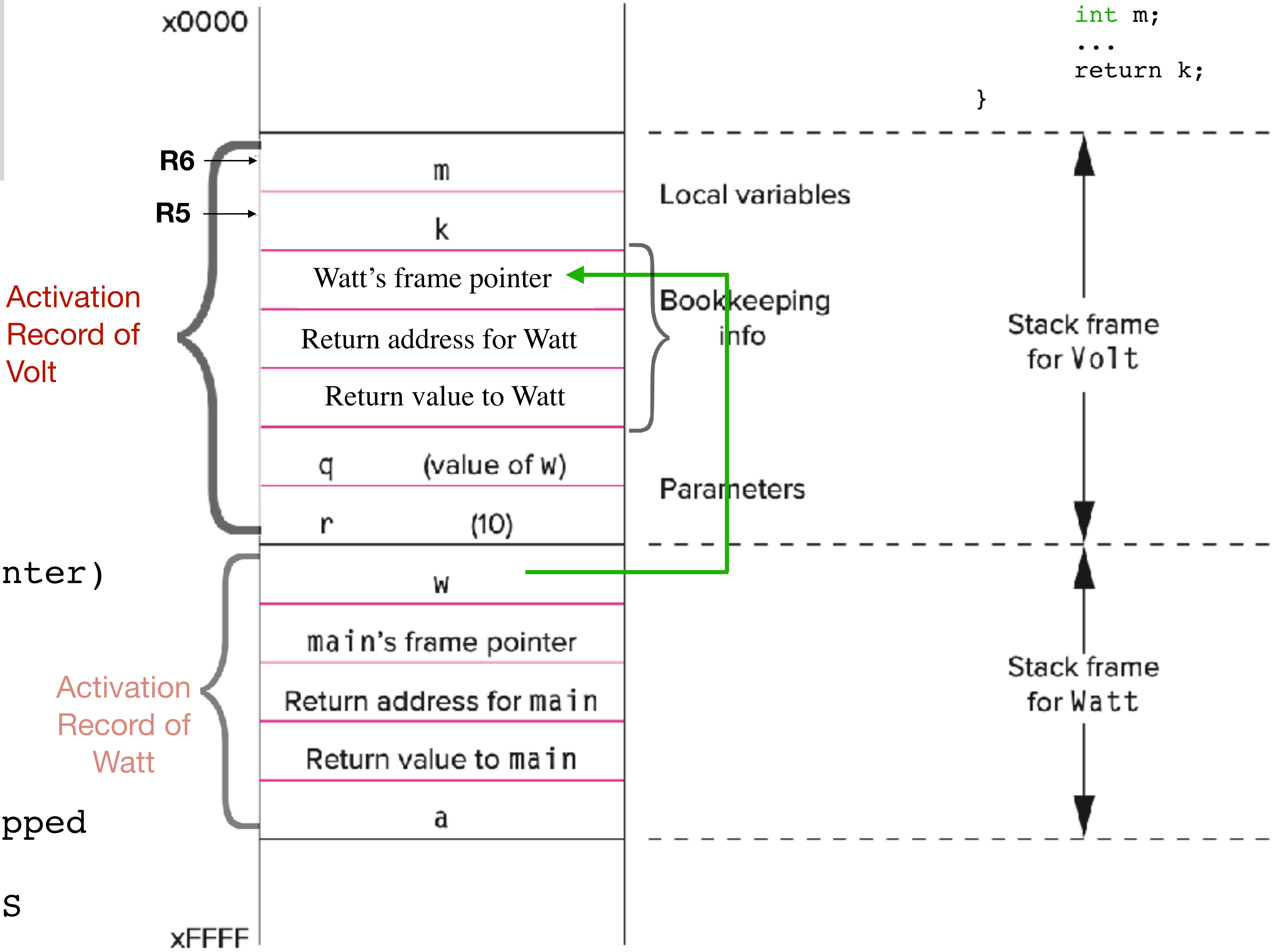


LC-3 Implementation

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

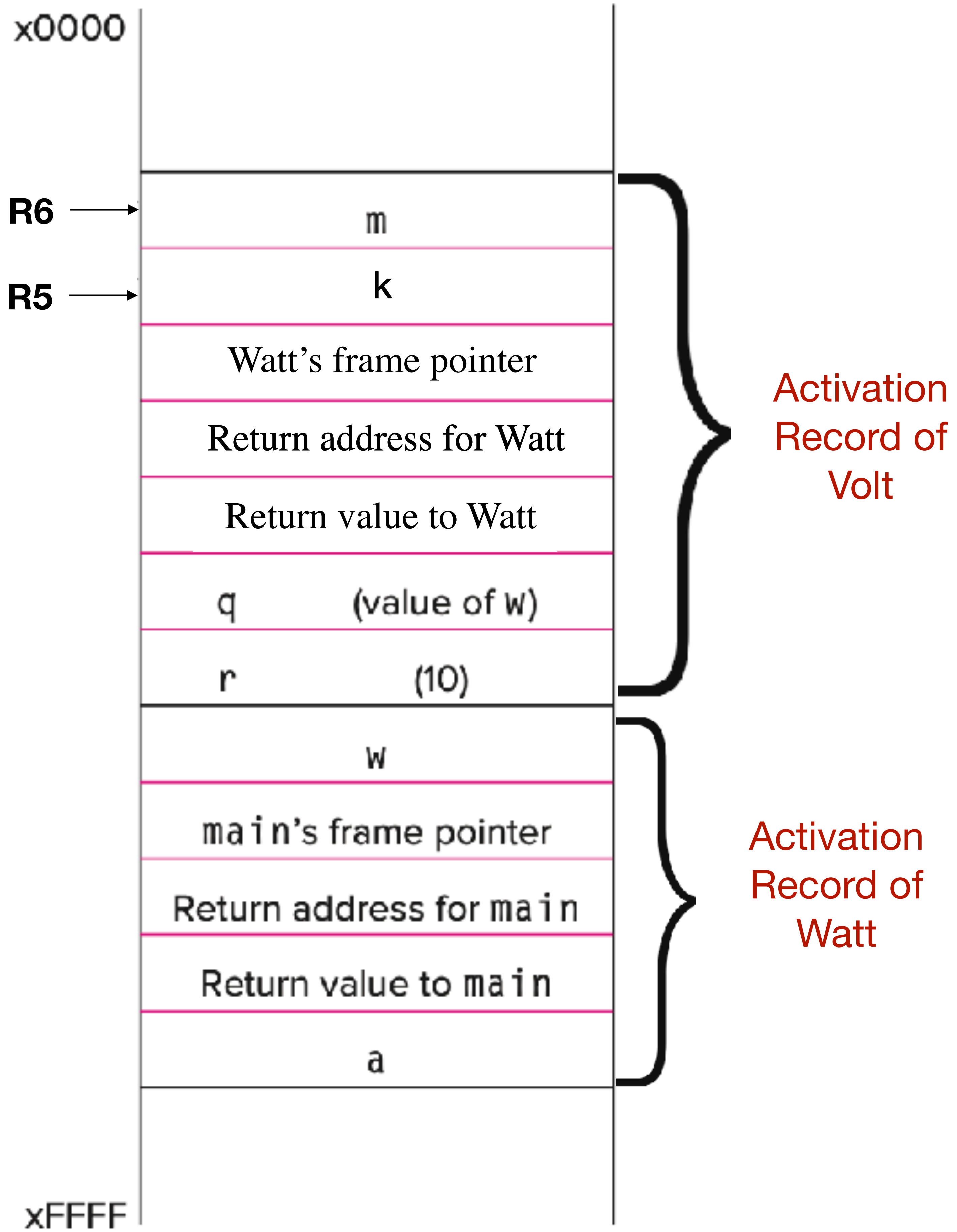
3. Callee setup (push bookkeeping info and local variables onto stack)
4. Execute function

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

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

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

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



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

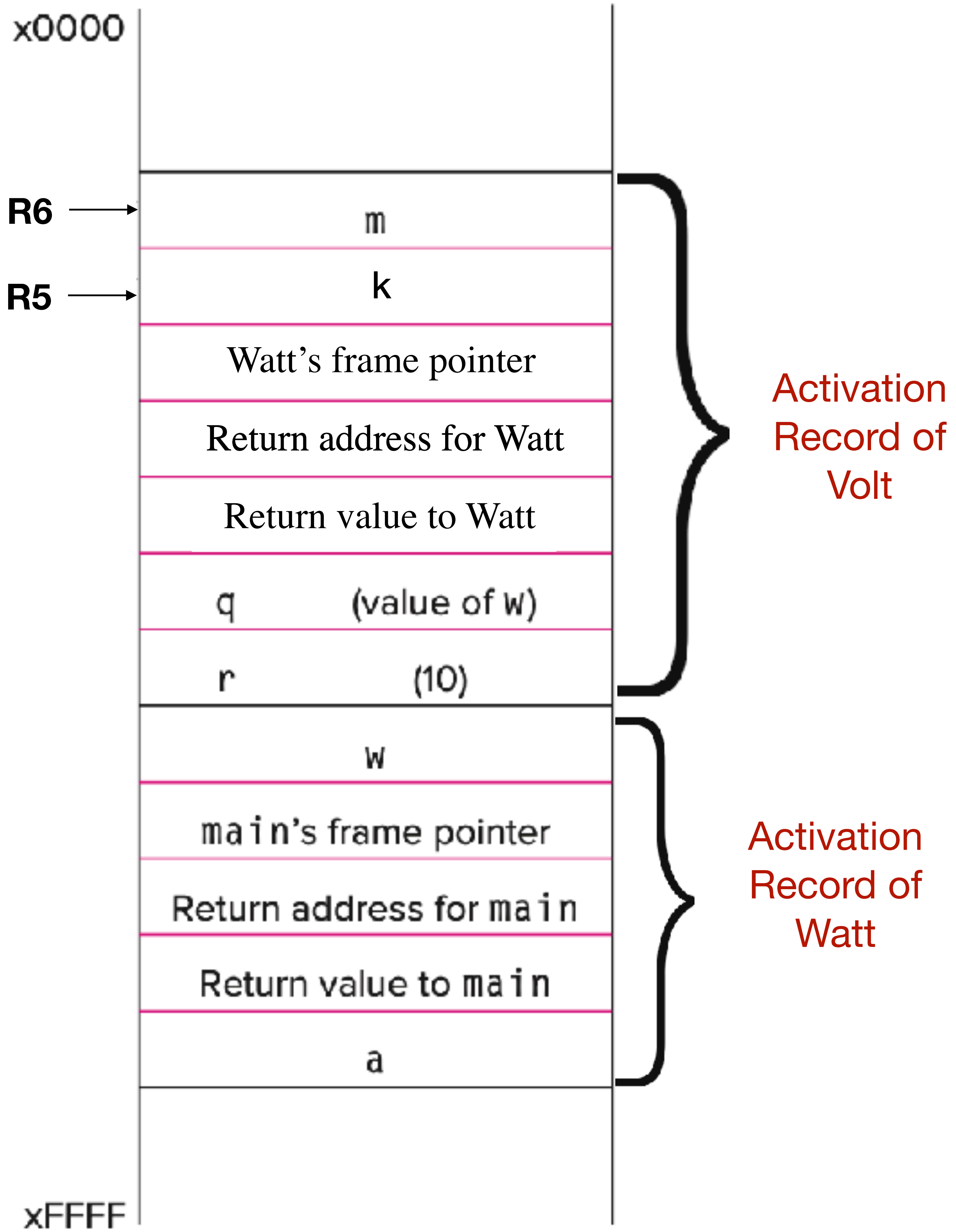
LC-3 Implementation



```
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)

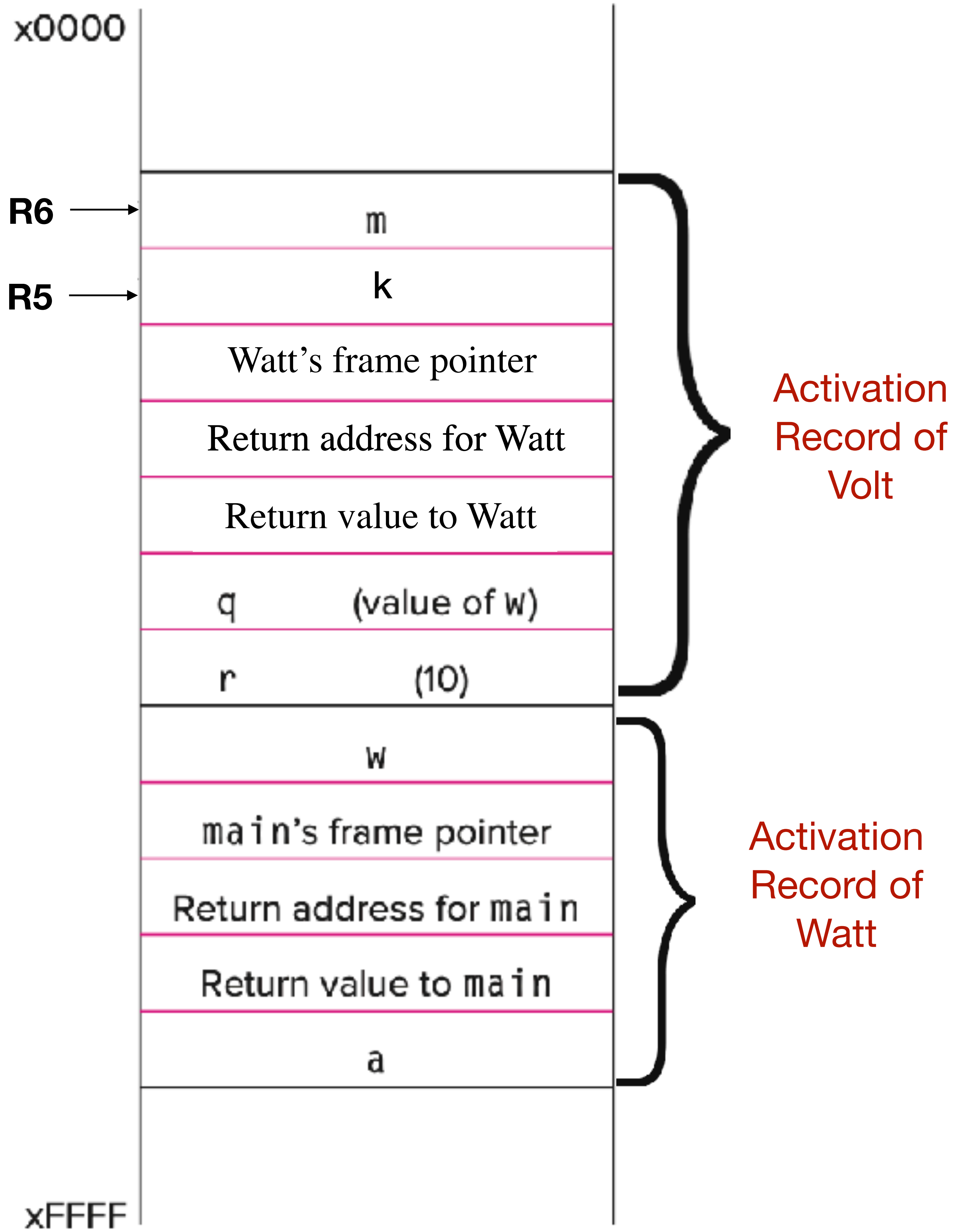


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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)
```

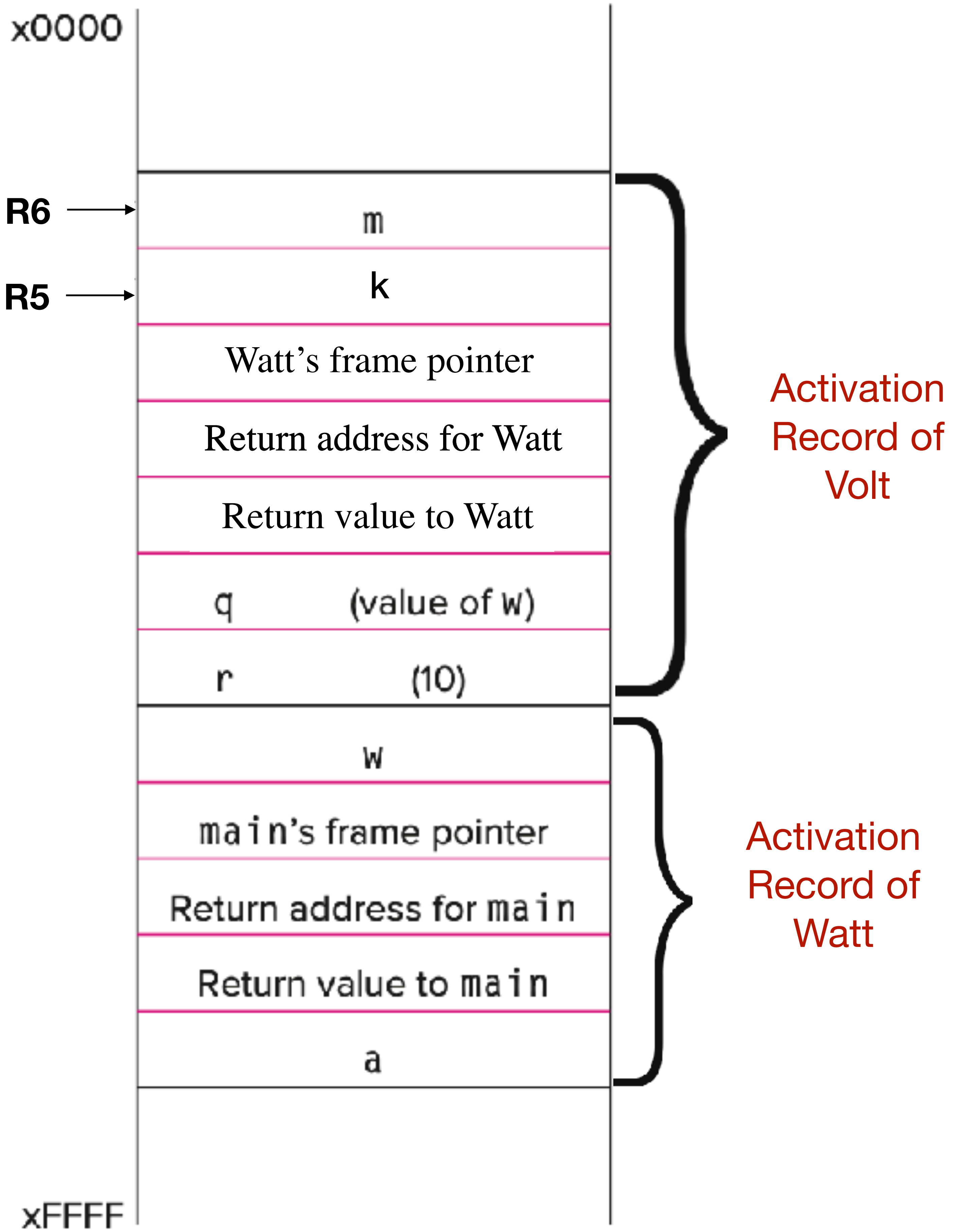


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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
```



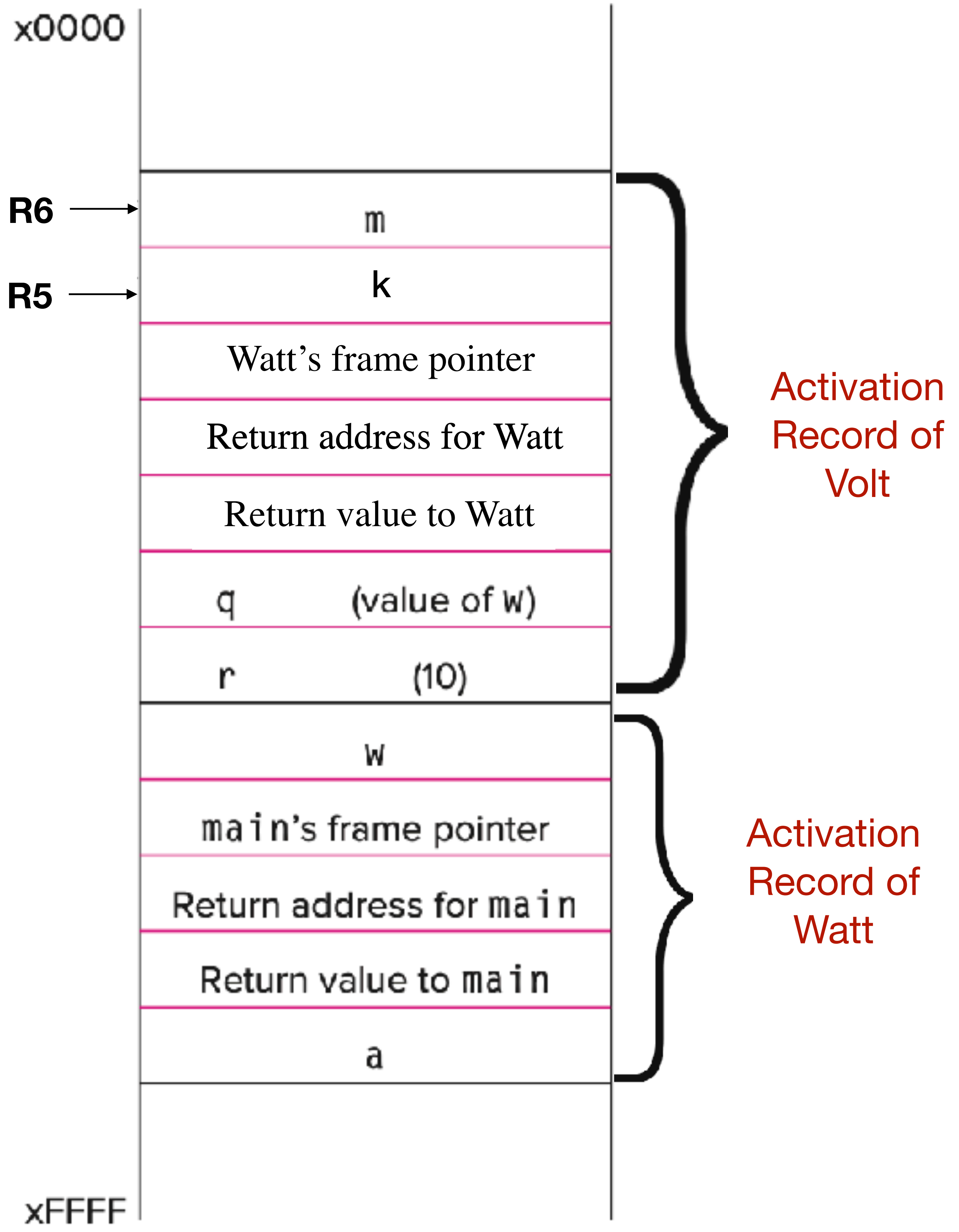
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



x0000

R6 → m

R5 → k

Watt’s frame pointer

Return address for Watt

Return value to Watt

q (value of w)

r (10)

w

main’s frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Volt

Activation Record of Watt

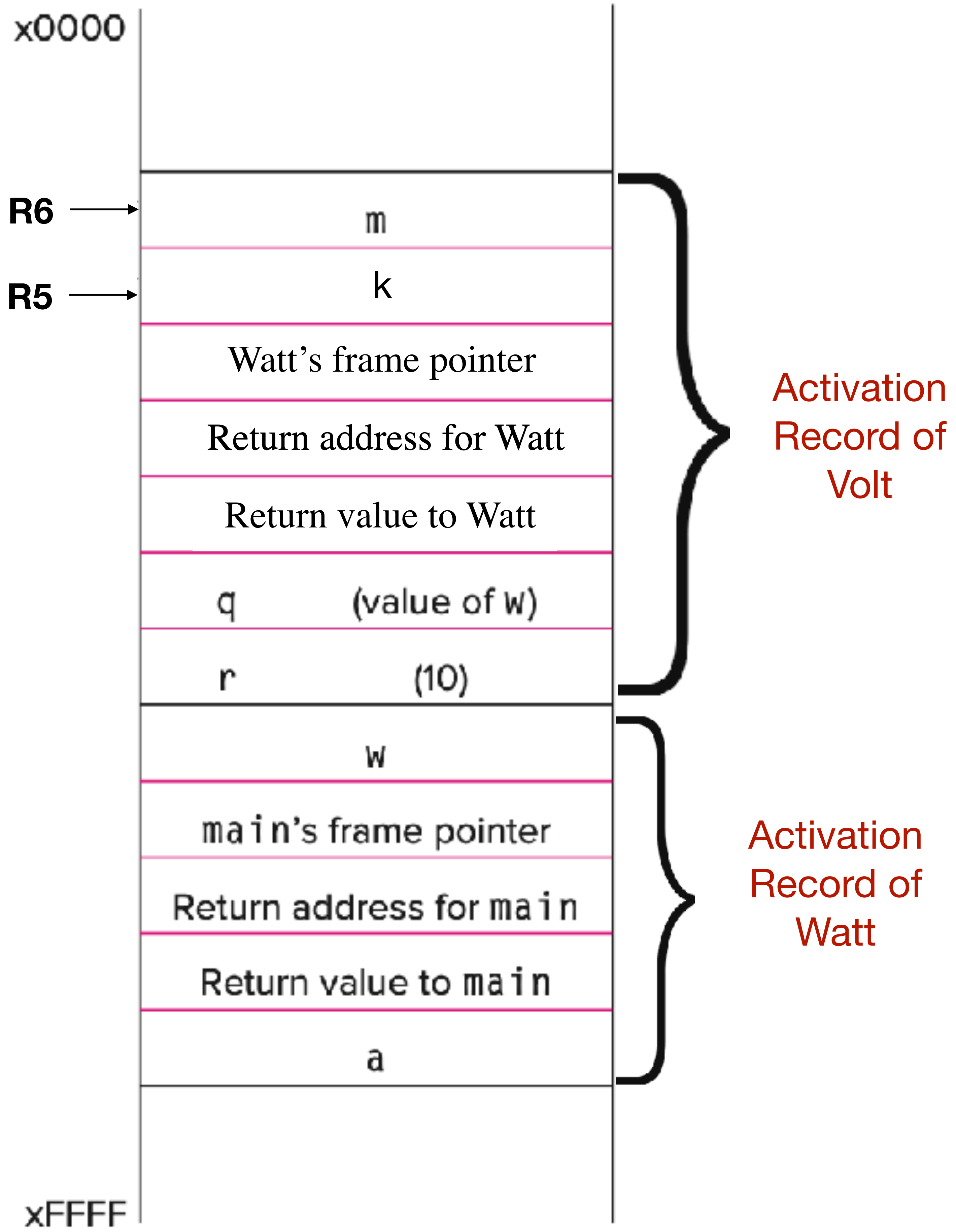
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



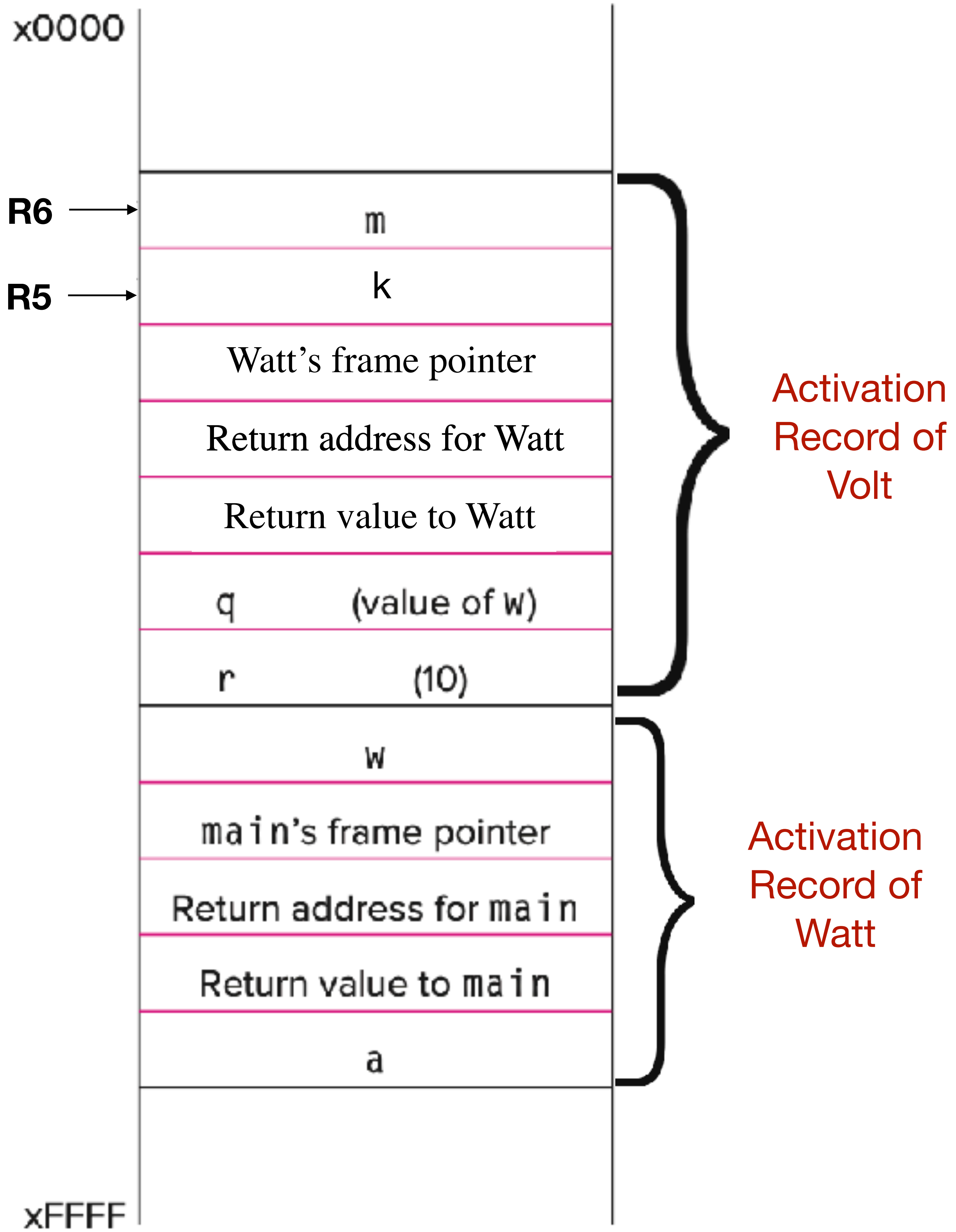
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



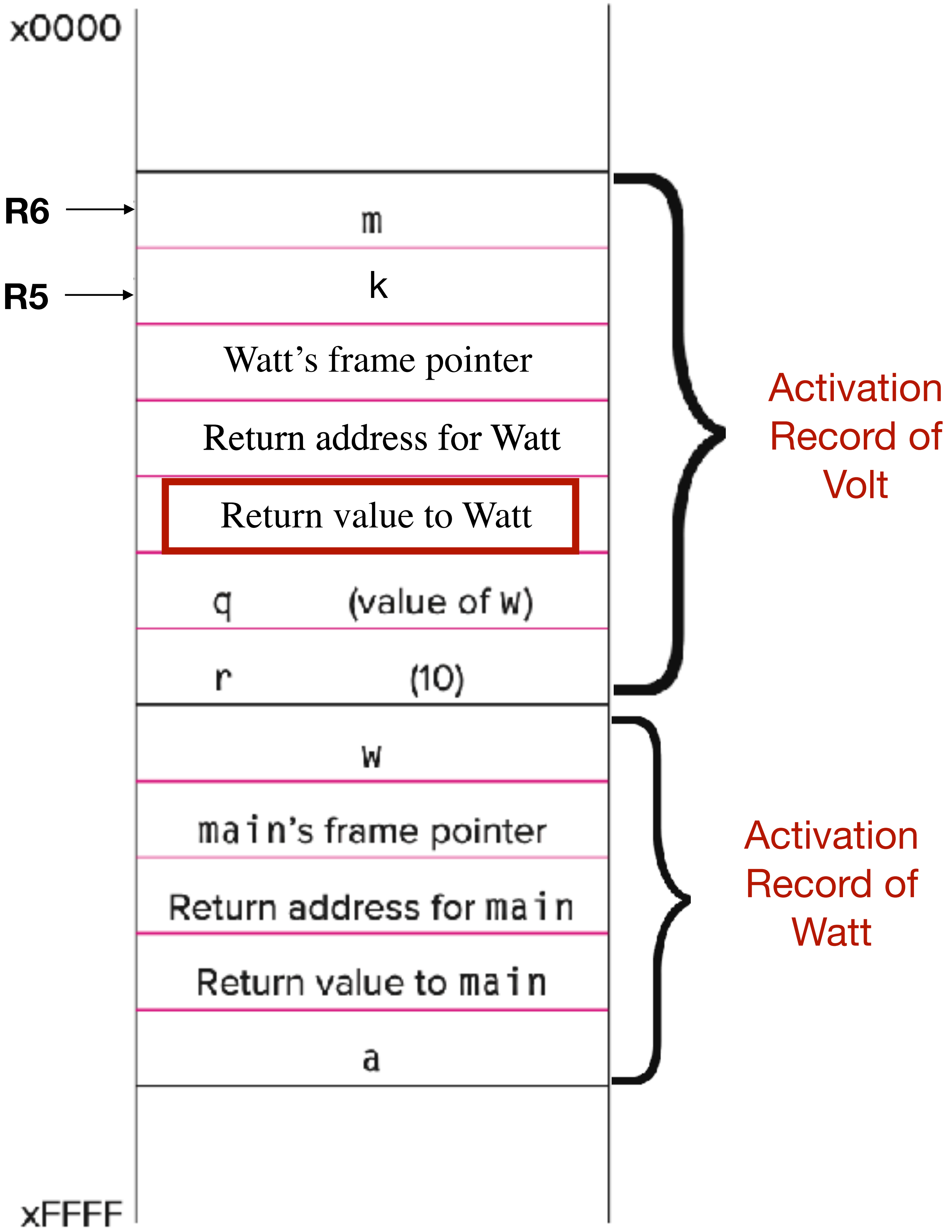
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



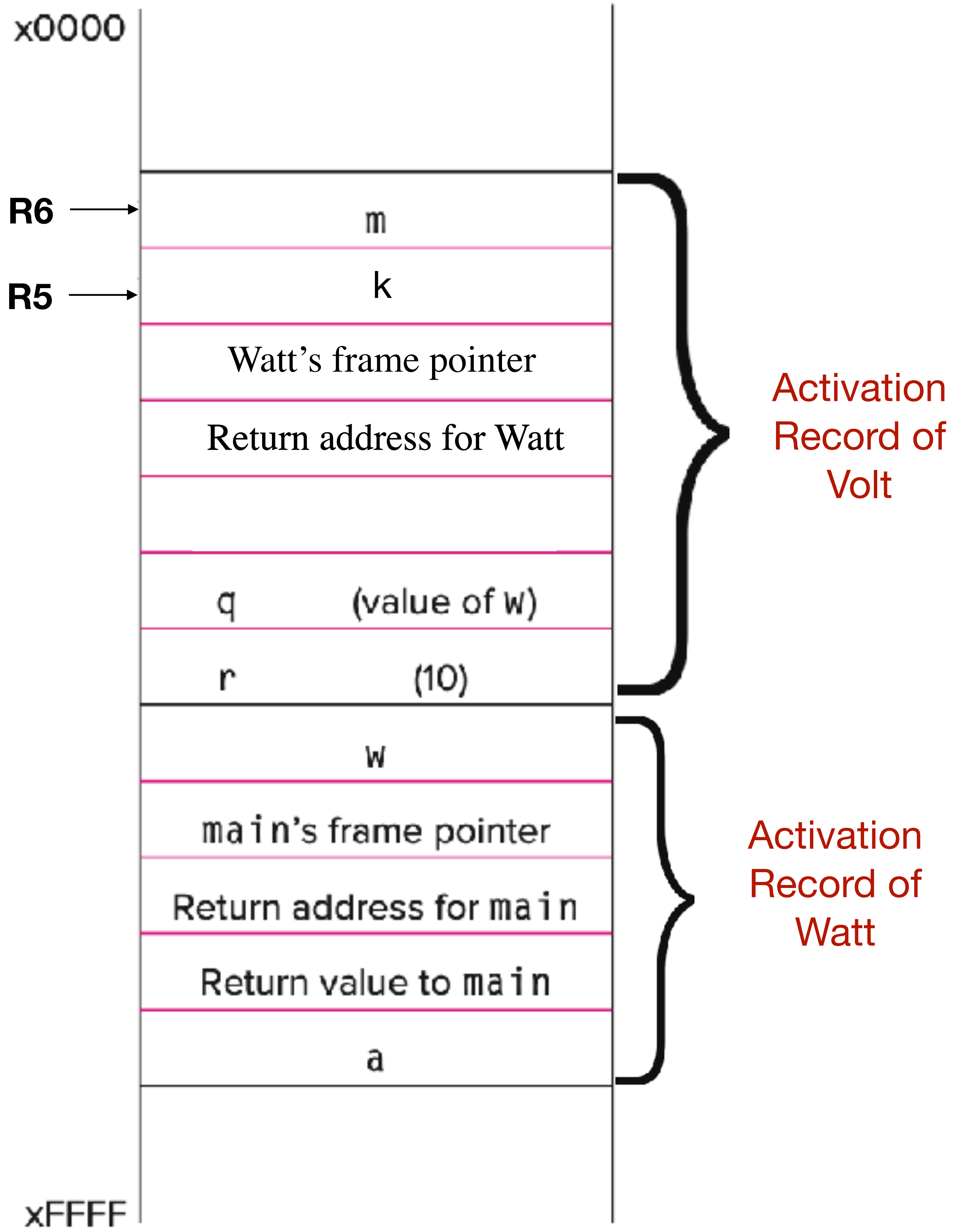
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



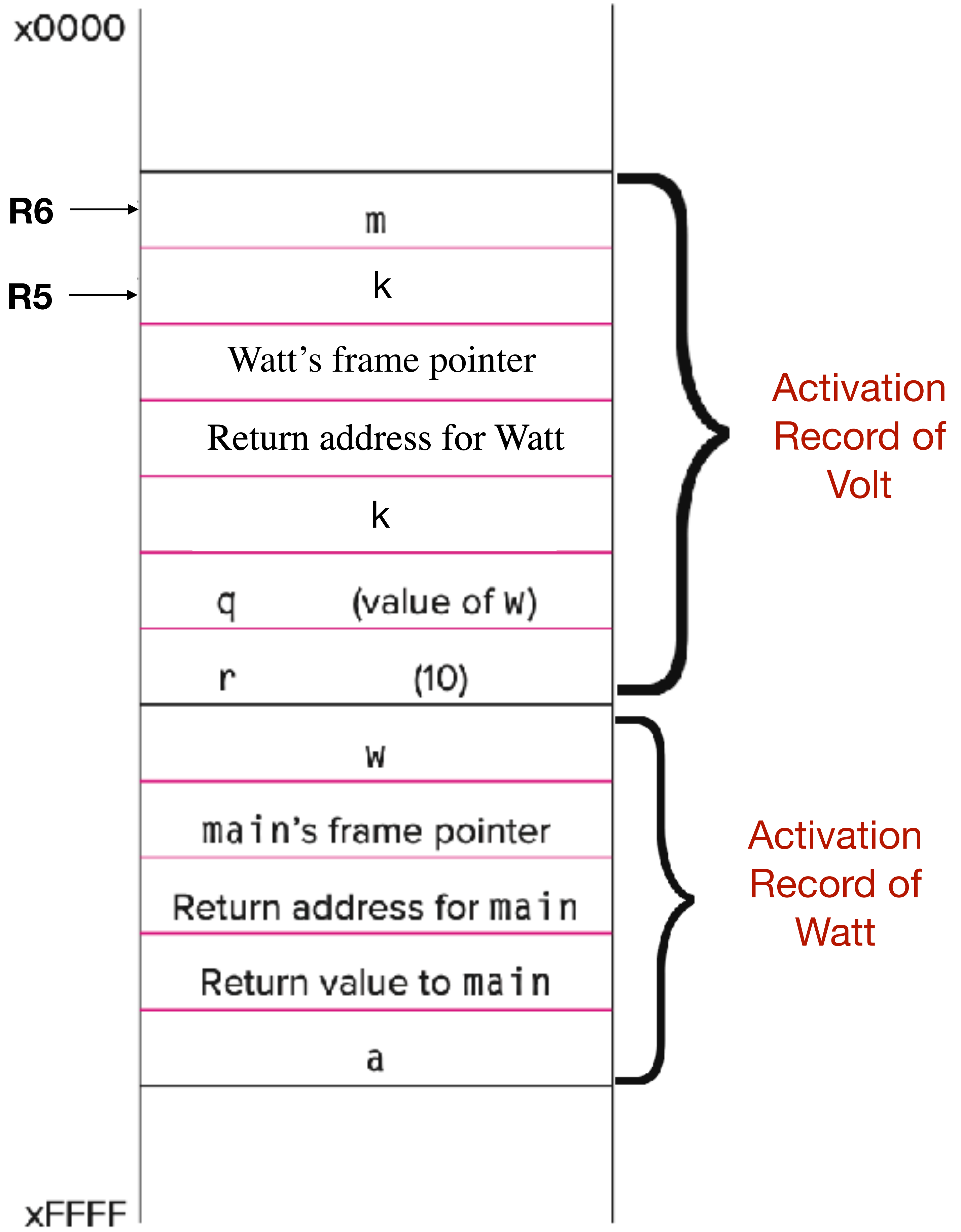
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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
```

R0
k



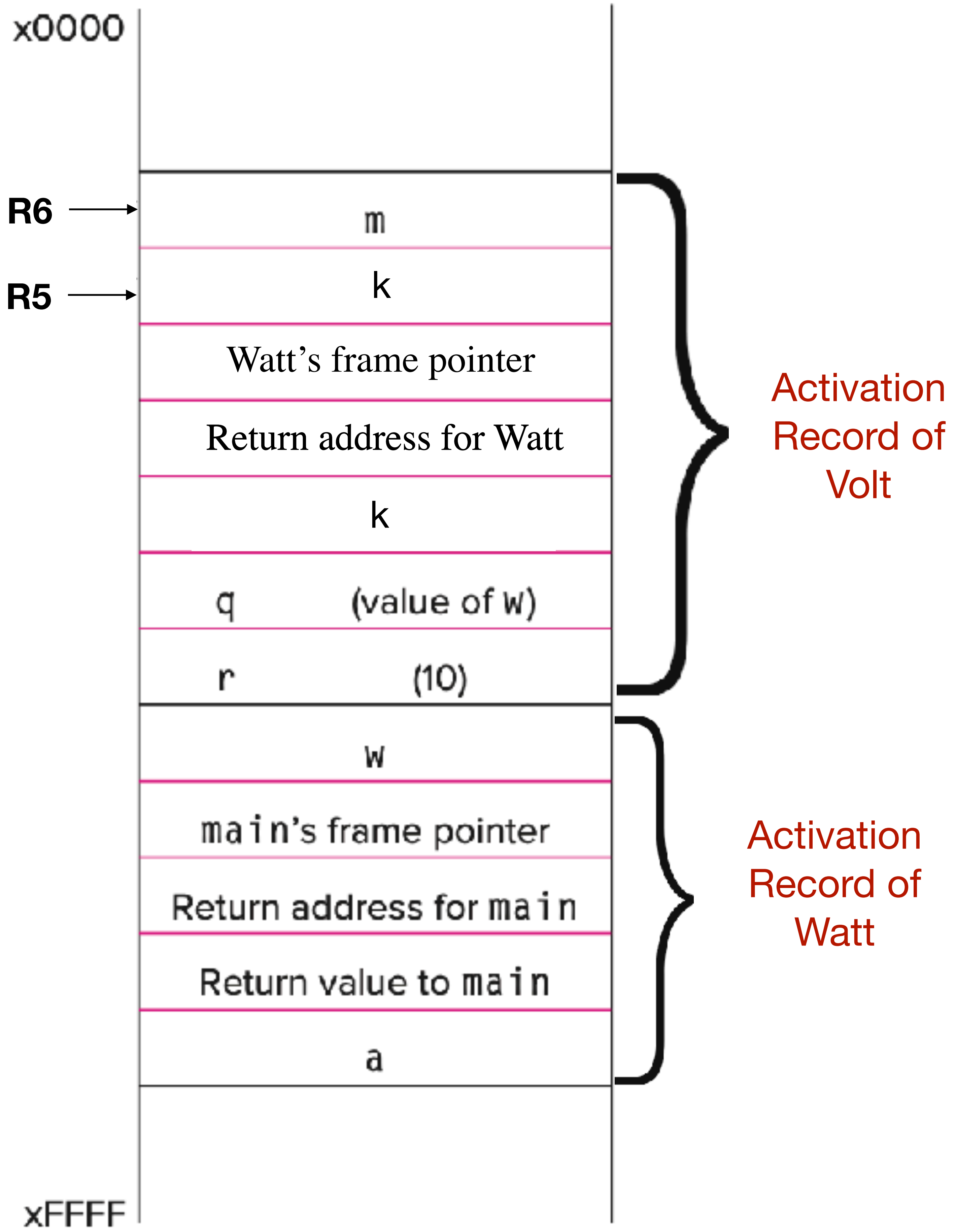
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



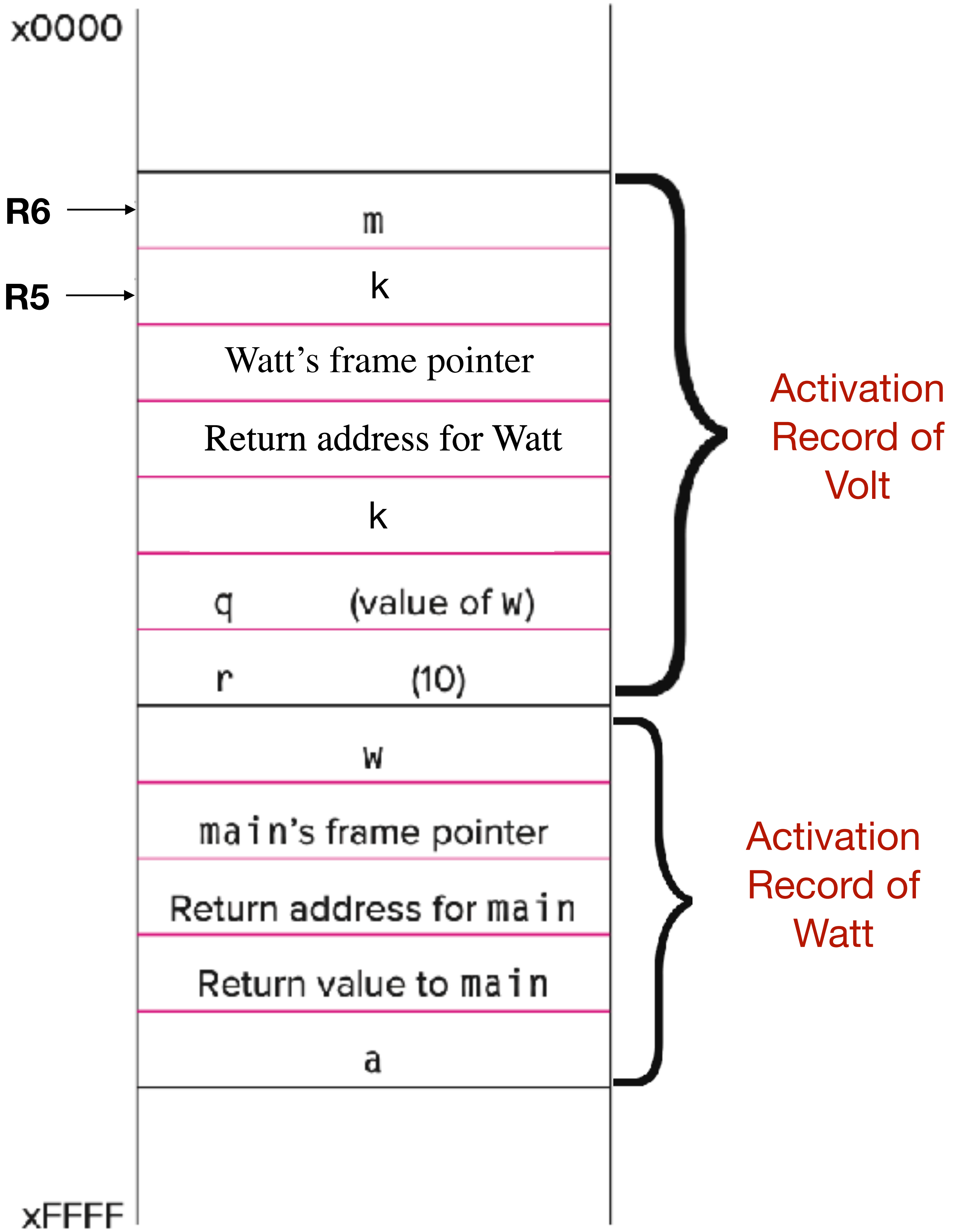
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



x0000
R6 →
R5 →
m
k
Watt's frame pointer
Return address for Watt
k
q (value of w)
r (10)
w
main's frame pointer
Return address for main
Return value to main
a
xFFFF

Activation Record of Volt

Activation Record of Watt

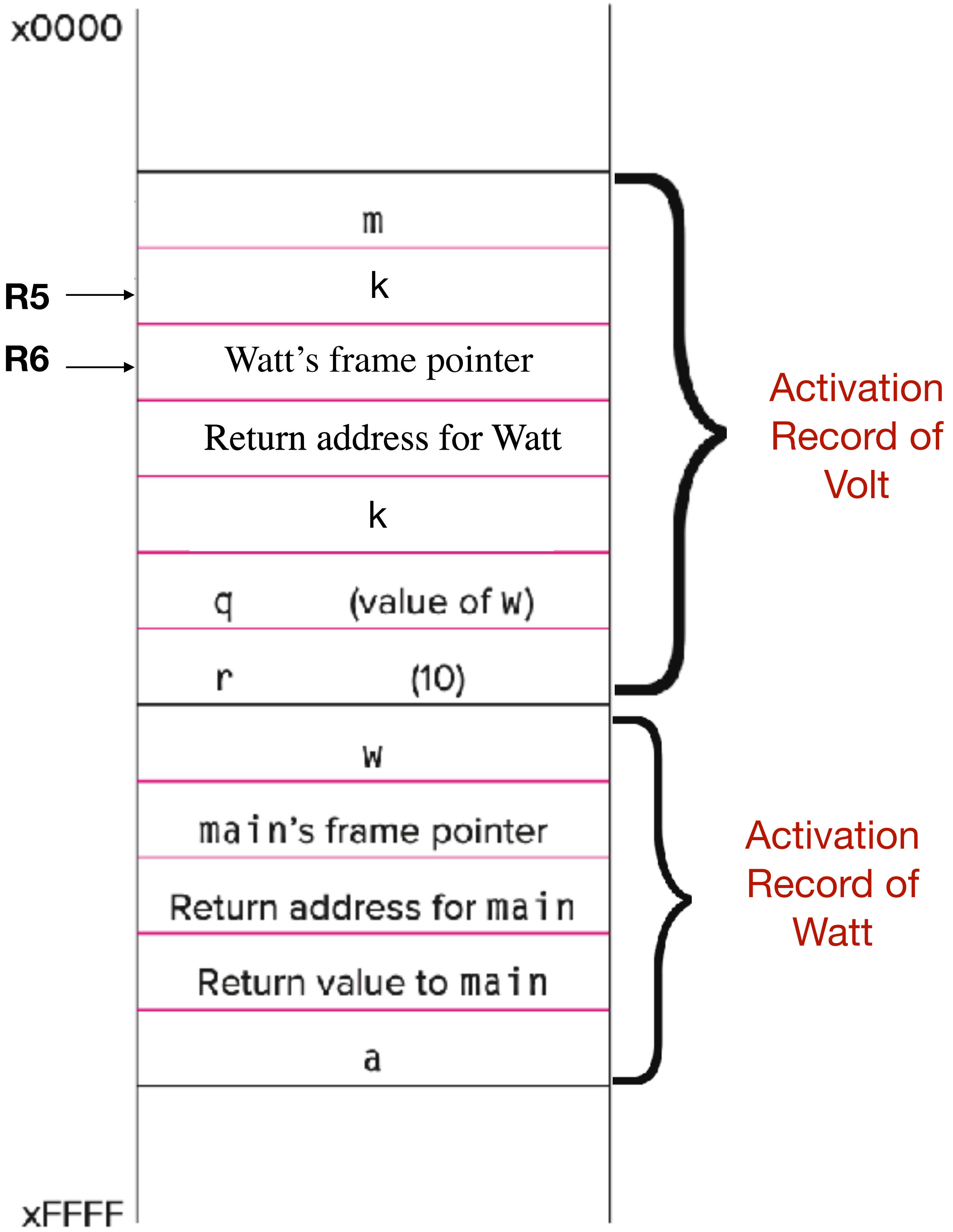
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



x0000

R5

R6

m

k

Watt's frame pointer

Return address for Watt

k

q (value of w)

r (10)

w

main's frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Volt

Activation Record of Watt

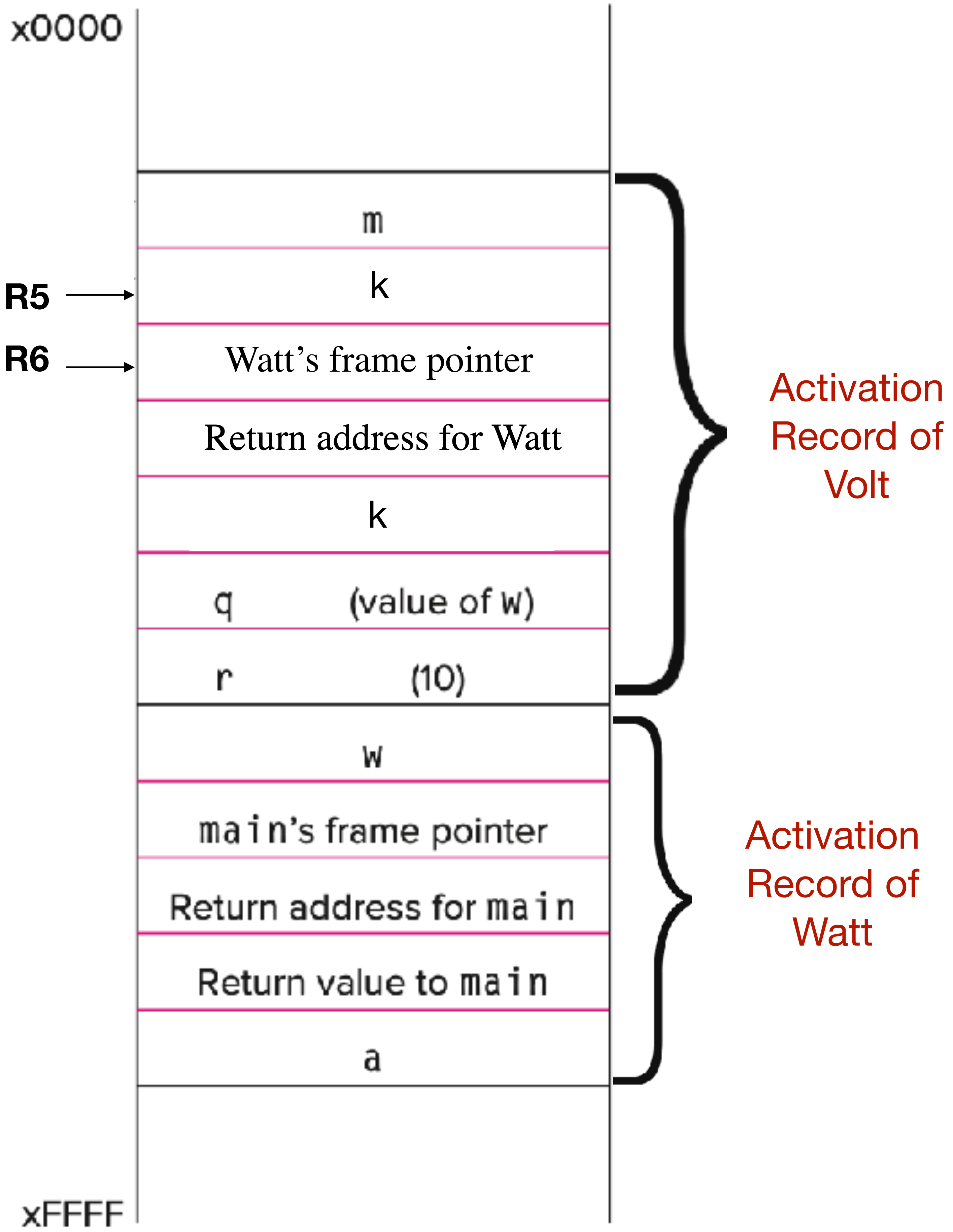
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



x0000

m

R5 → k

R6 → Watt's frame pointer

Return address for Watt

k

q (value of w)

r (10)

w

main's frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Volt

Activation Record of Watt

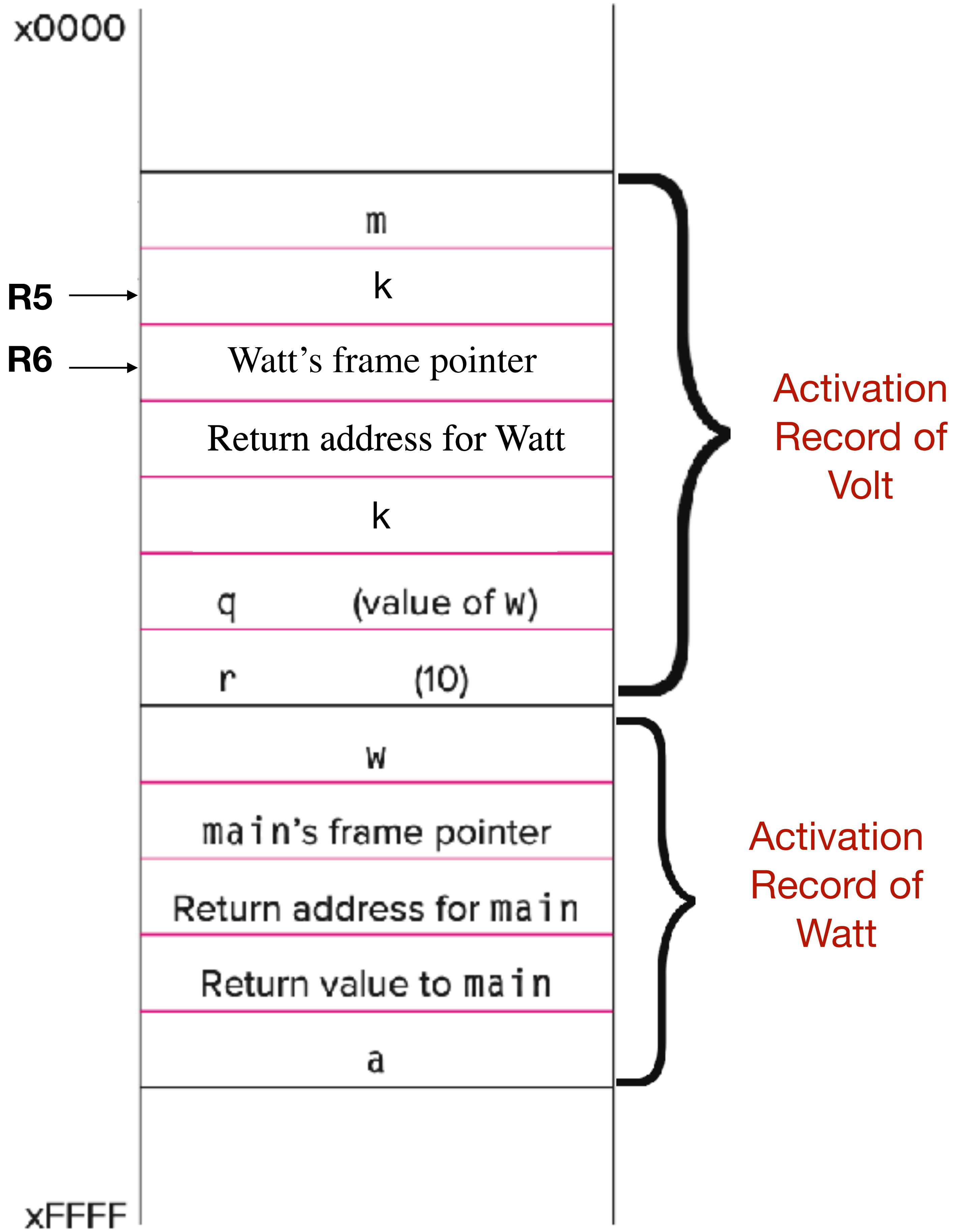
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



x0000

R5 → k

R6 → Watt's frame pointer

m
k
Watt's frame pointer
Return address for Watt
k
q (value of w)
r (10)
w
main's frame pointer
Return address for main
Return value to main
a

Activation Record of Volt

Activation Record of Watt

xFFFF

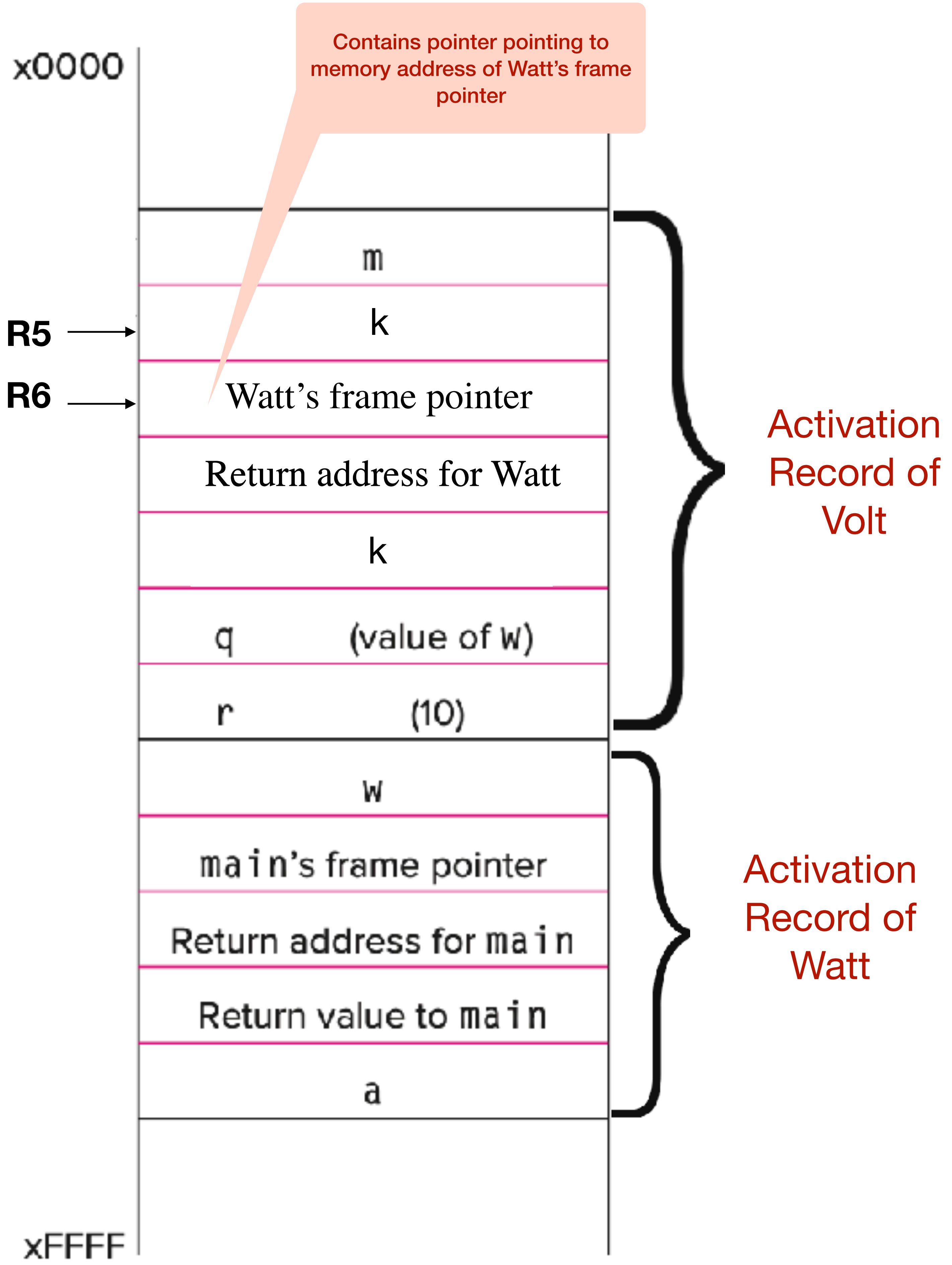
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



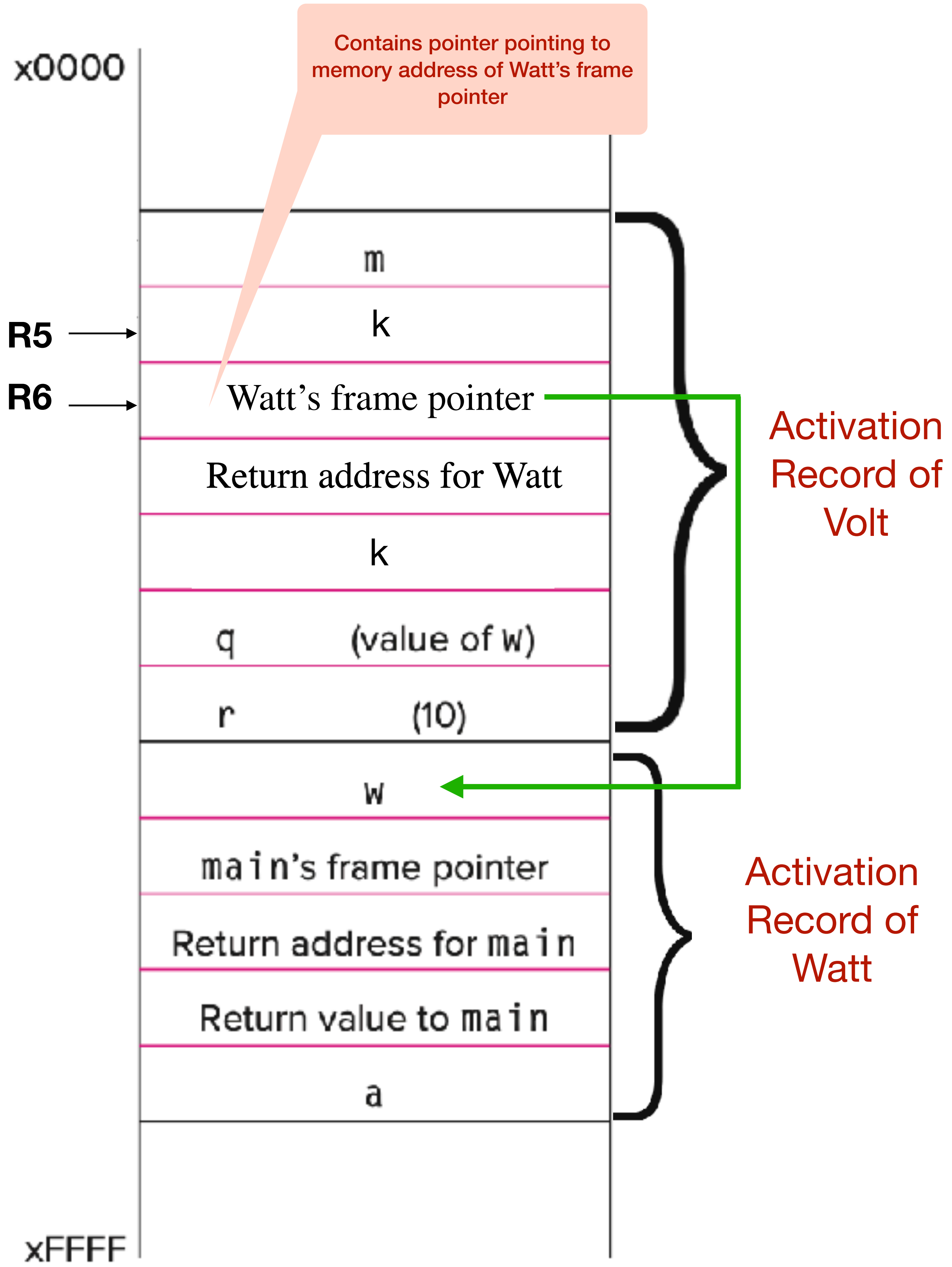
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



Contains pointer pointing to memory address of Watt's frame pointer

x0000

m

R5

k

R6

Watt's frame pointer

Return address for Watt

k

q (value of w)

r (10)

w

main's frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Volt

Activation Record of Watt

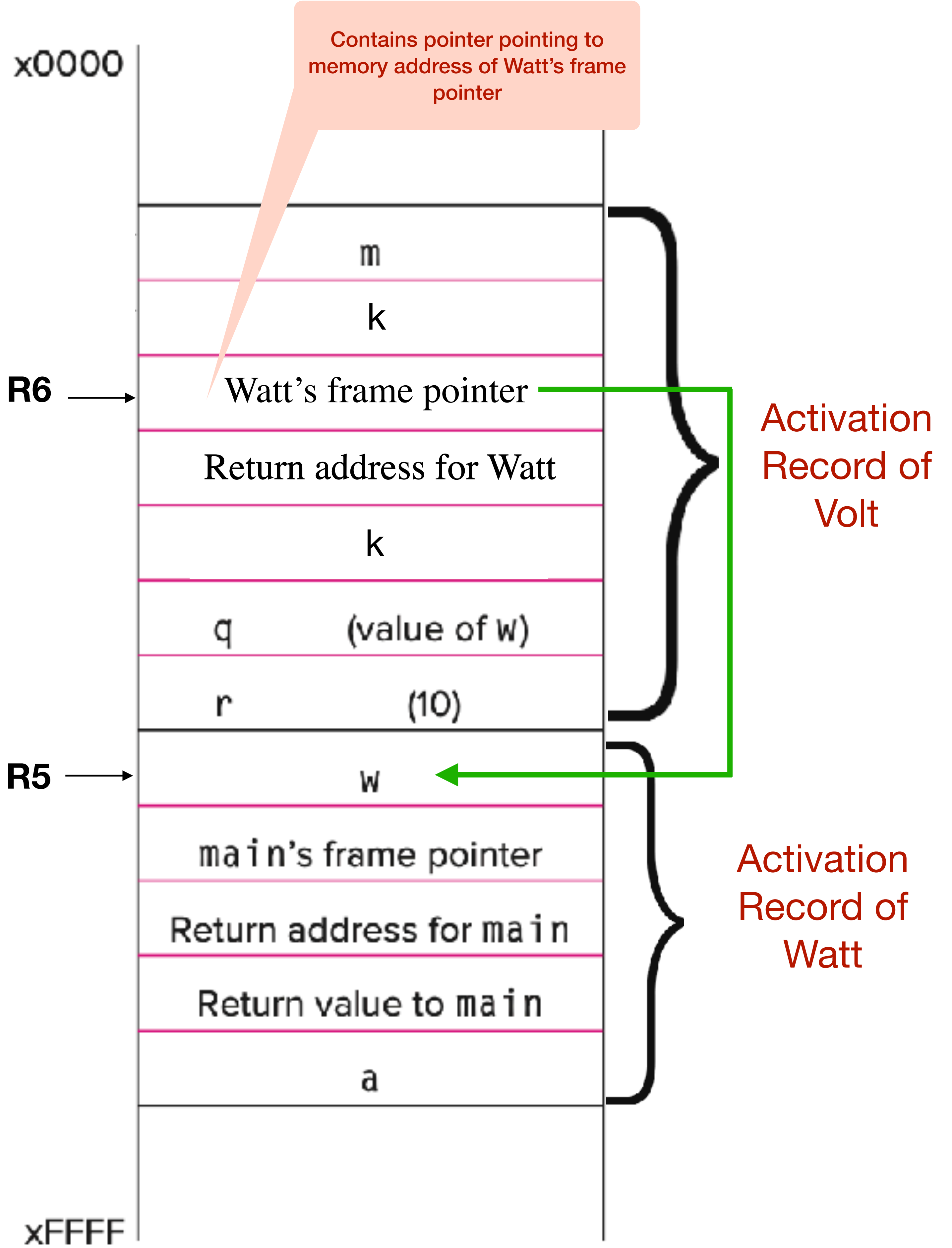
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



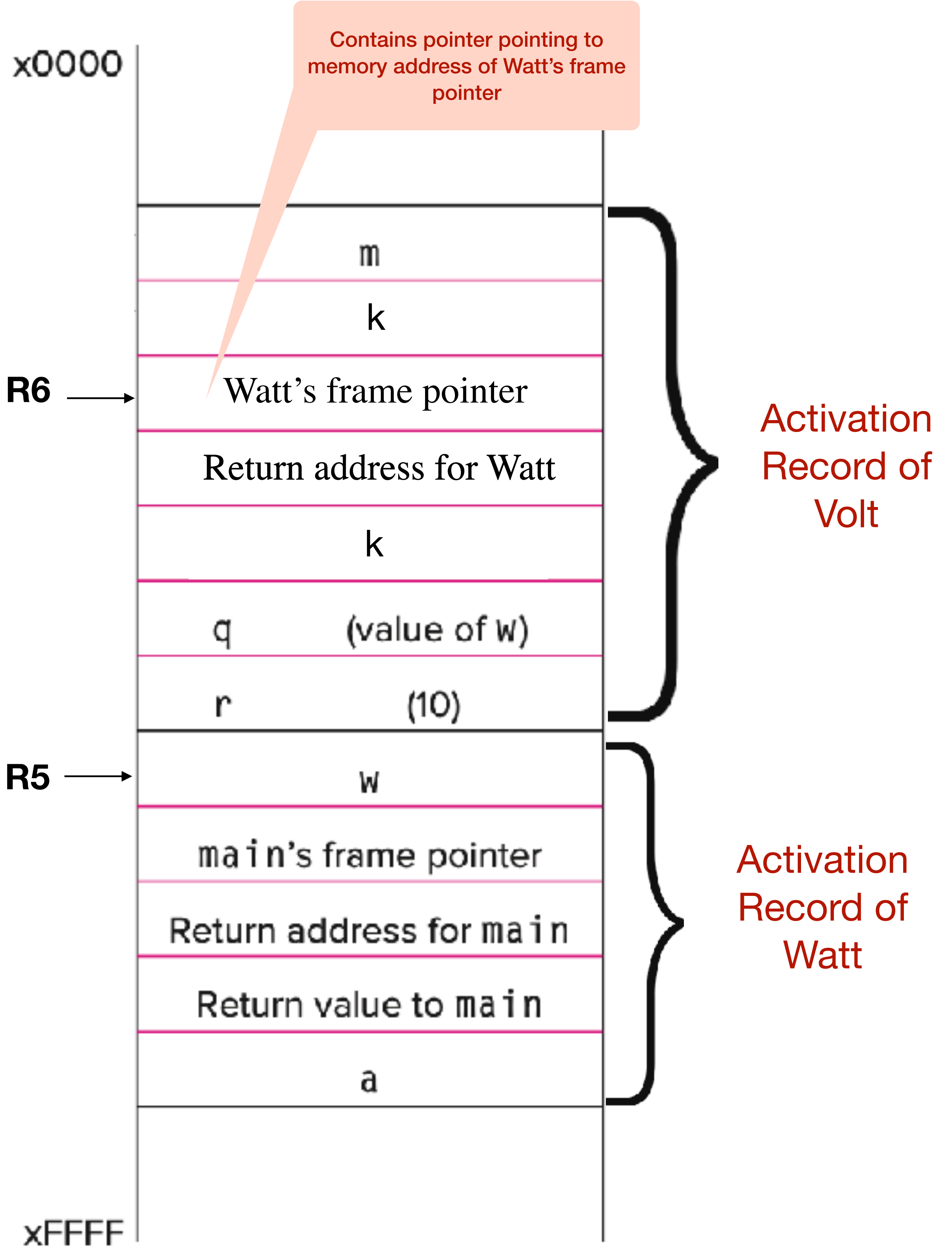
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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

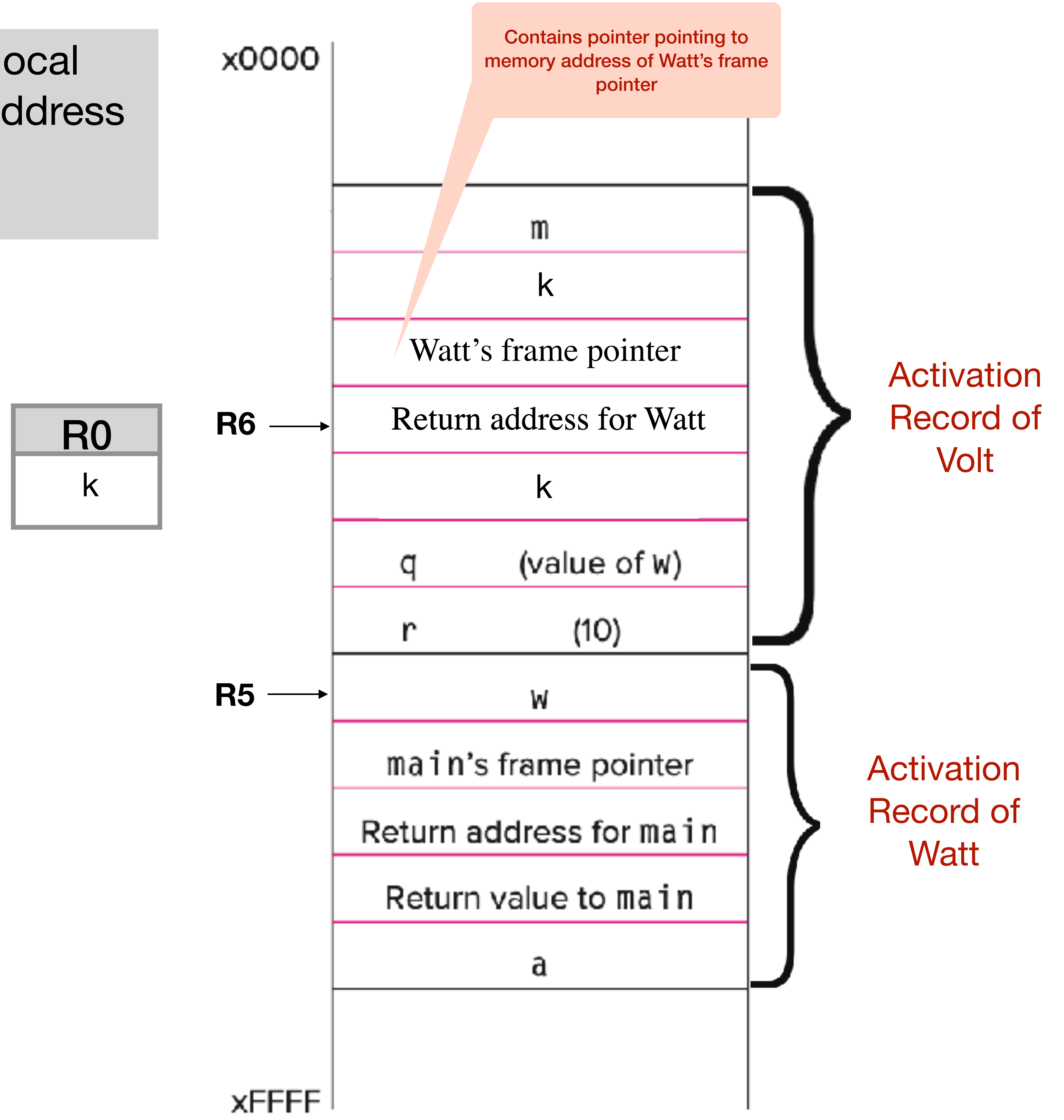


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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
```

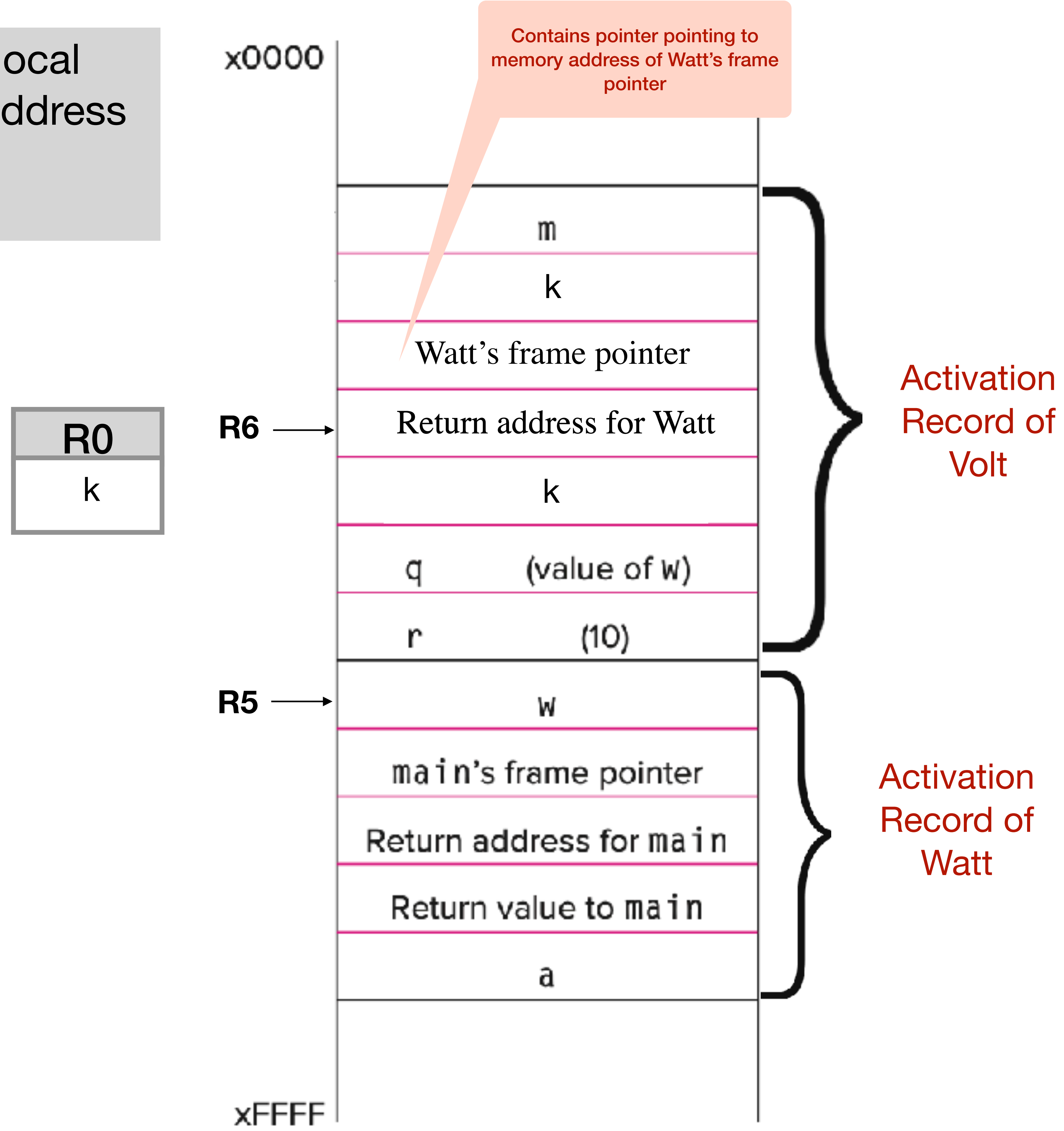


```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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
```



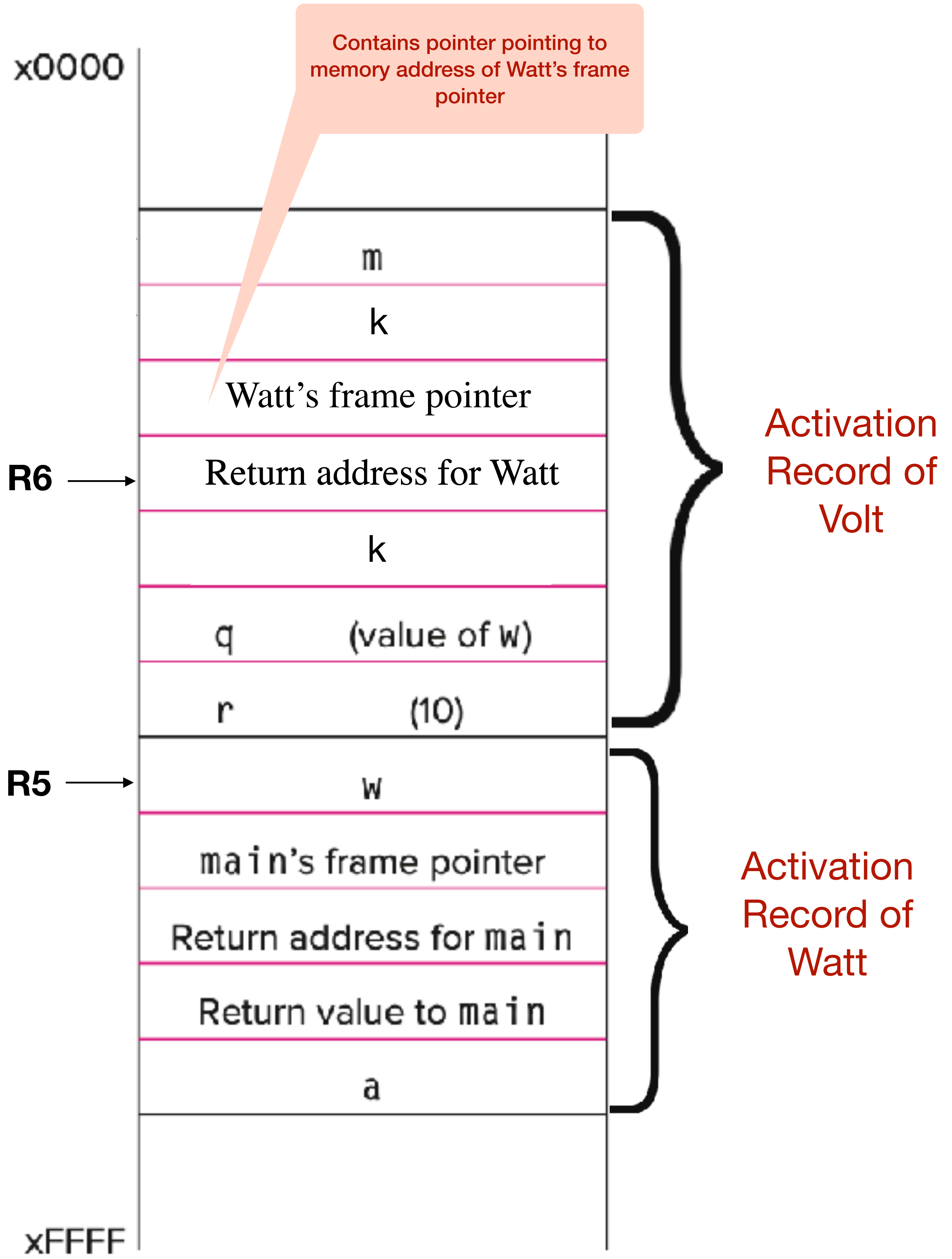
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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



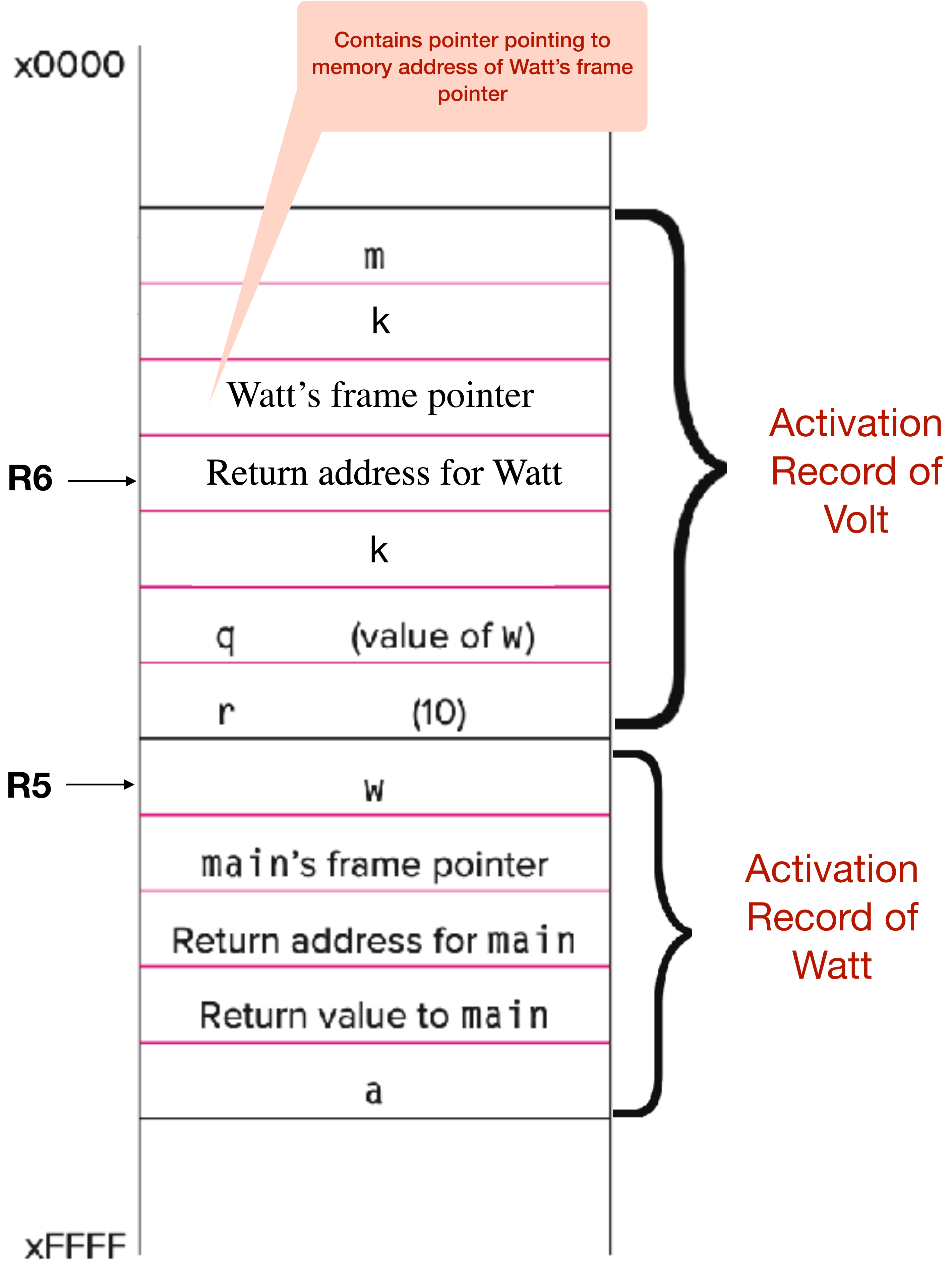
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

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;
}
```

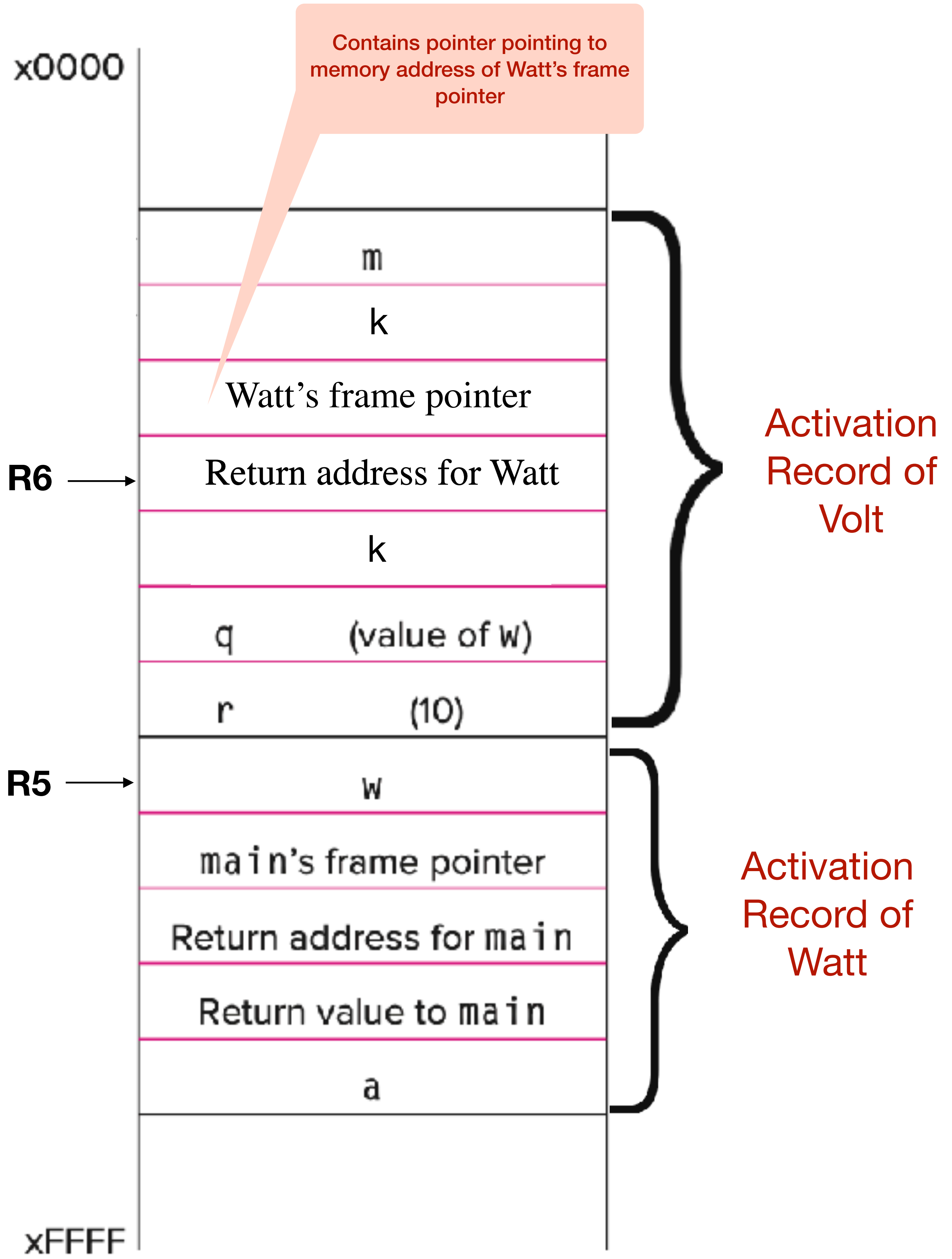
LC-3 Implementation

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



Contains pointer pointing to memory address of Watt’s frame pointer

x0000

m

k

Watt’s frame pointer

R6 → Return address for Watt

k

q (value of w)

r (10)

R5 → w

main’s frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Volt

Activation Record of Watt

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

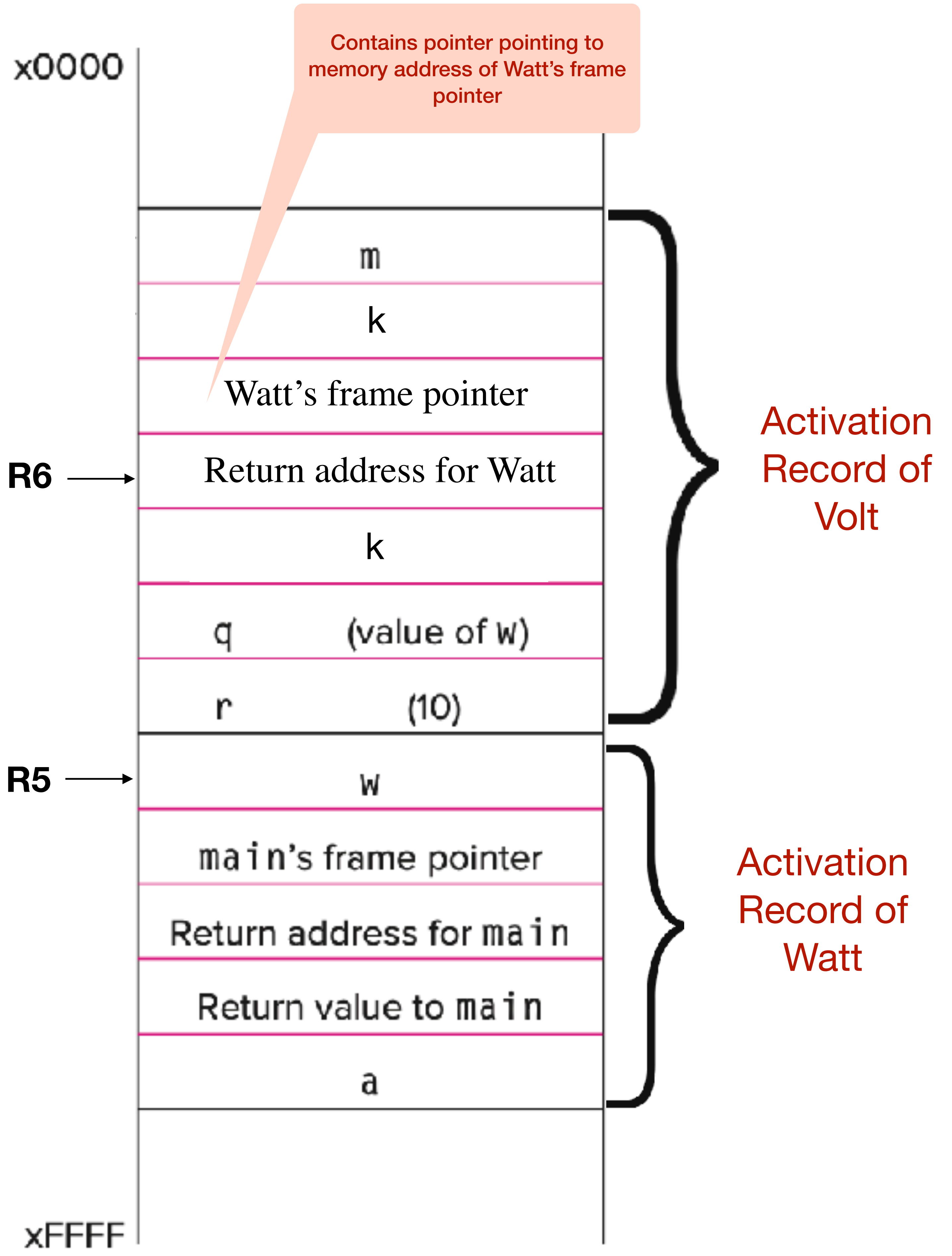
LC-3 Implementation

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



Contains pointer pointing to memory address of Watt's frame pointer

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

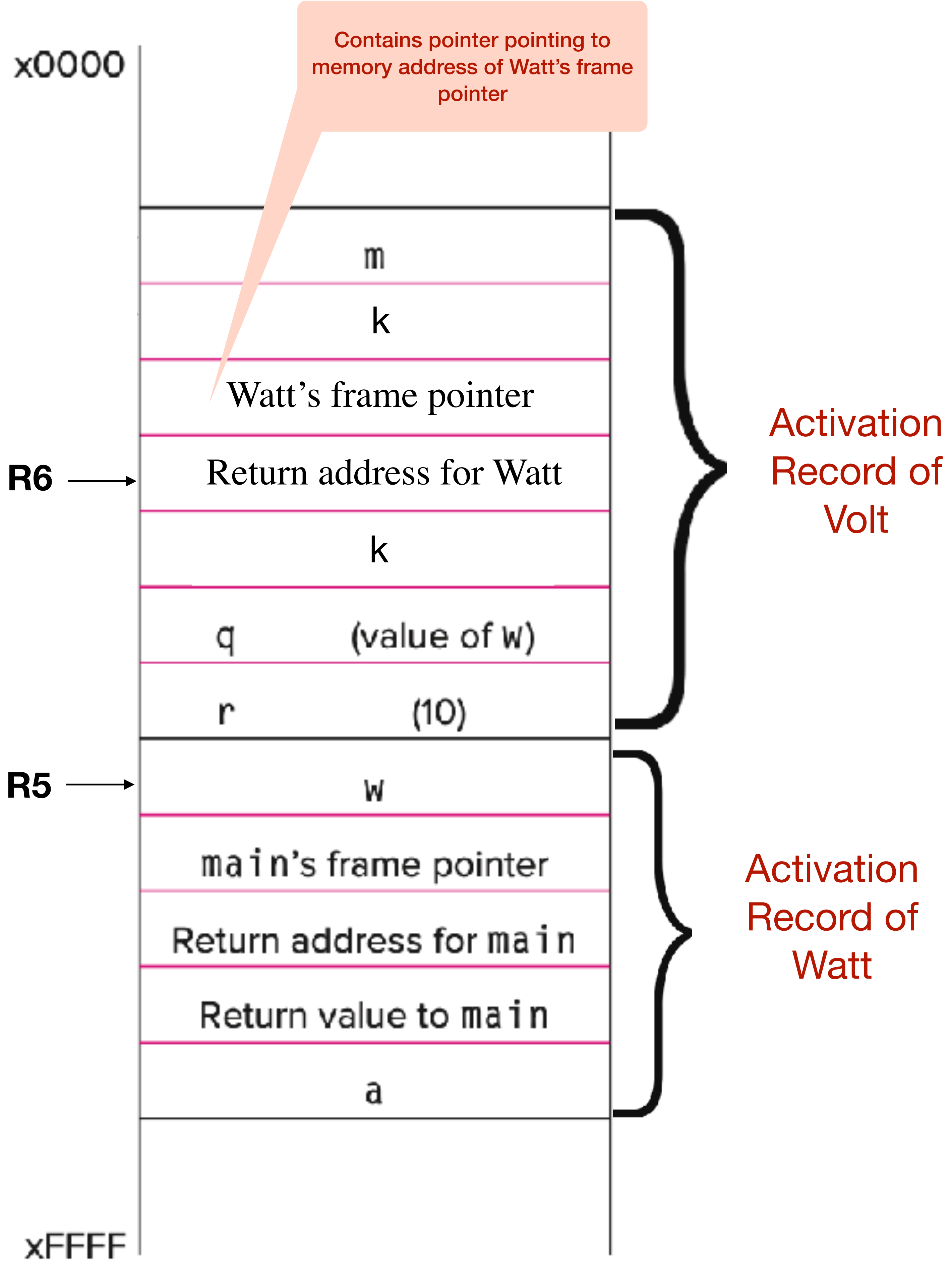
LC-3 Implementation

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
ADD R6, R6, #1
```

R0
k

R7
Return address for Watt



```
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)

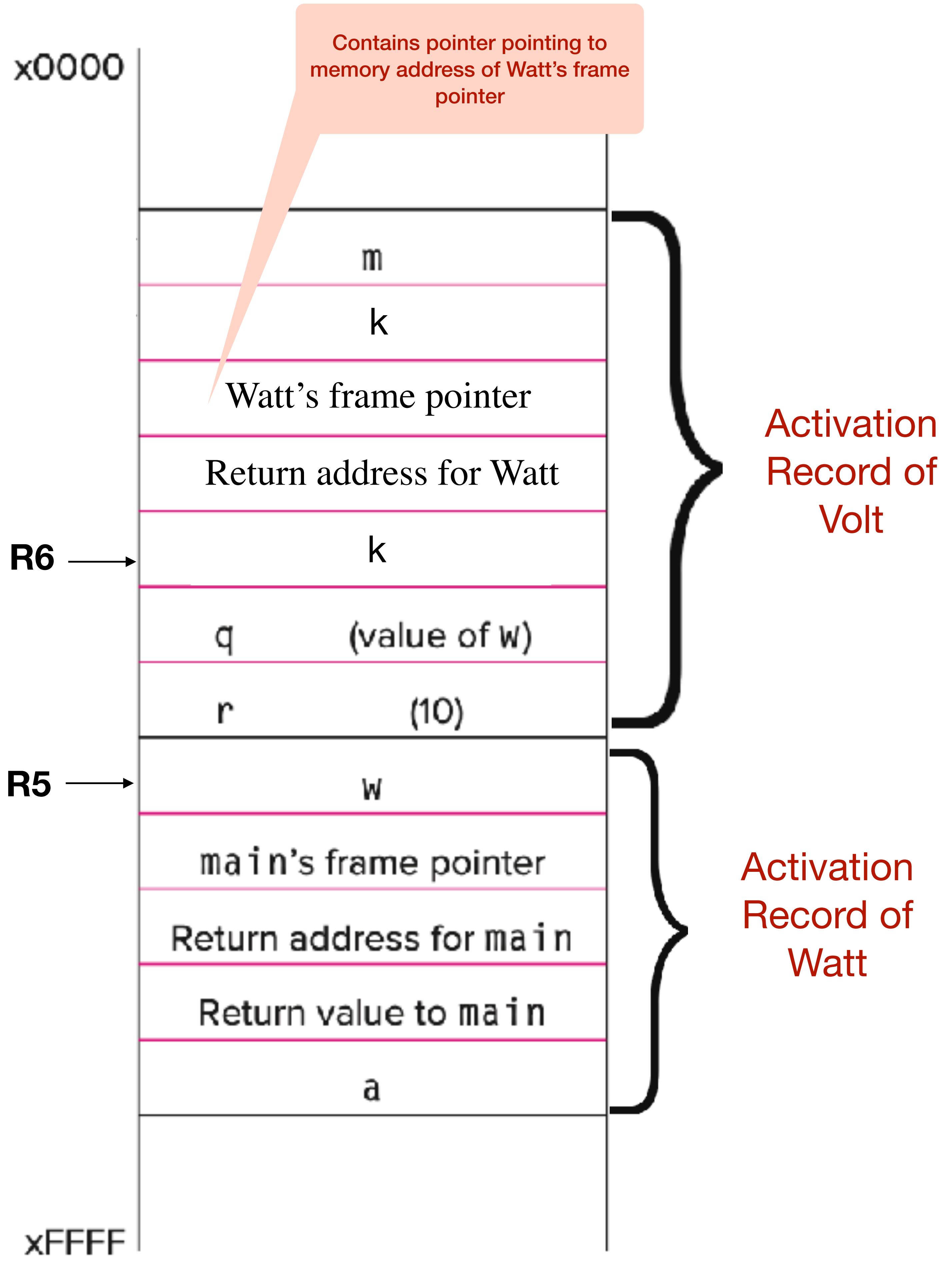
```
; copy k into return value(R5+3)
LDR R0, R5, #0
STR R0, R5, #3

; 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
ADD R6, R6, #1
```

R0

k

R7

Return address for Watt



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

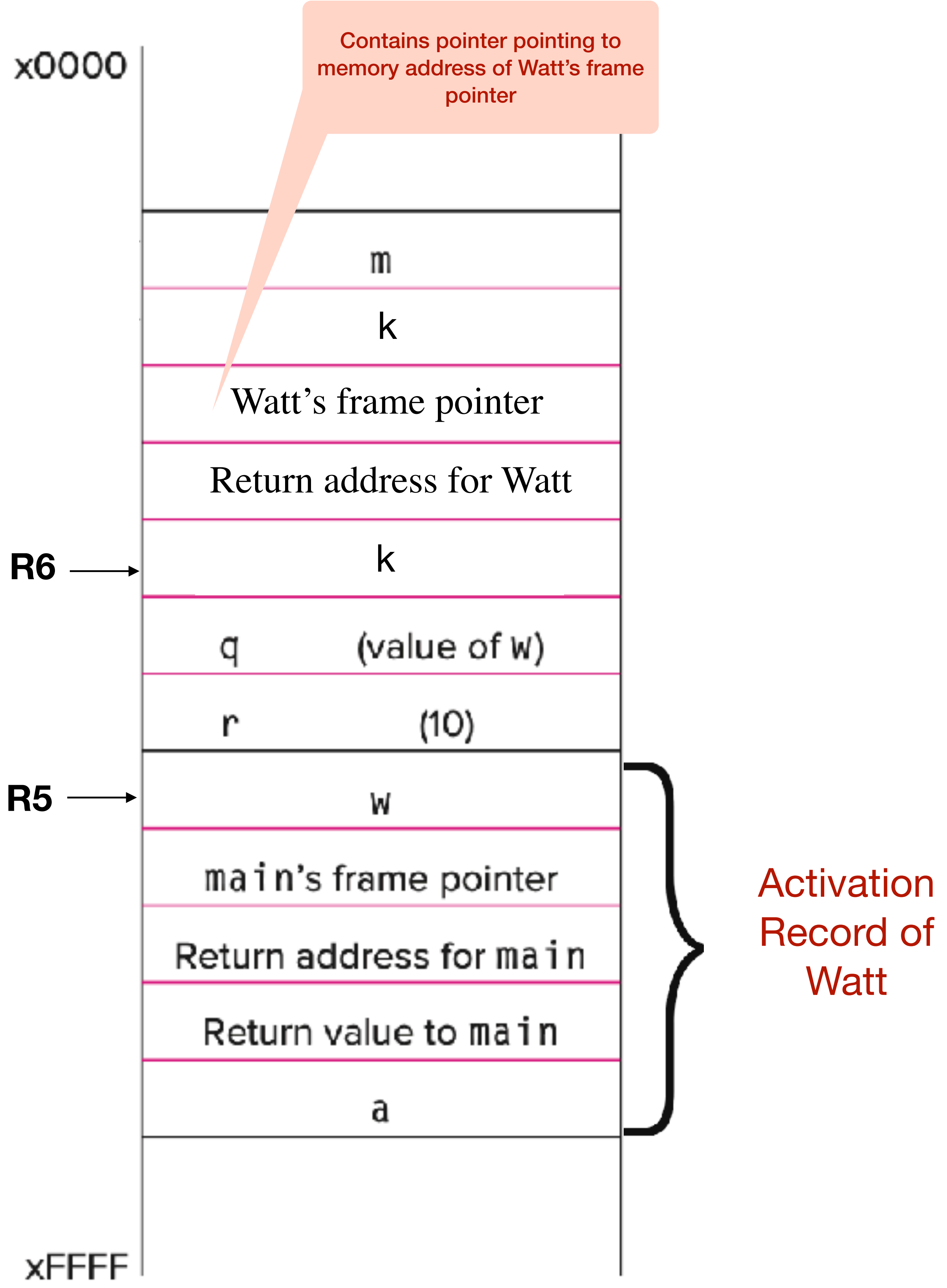
LC-3 Implementation

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
ADD R6, R6, #1
```

R0
k

R7
Return address for Watt



Contains pointer pointing to memory address of Watt's frame pointer

x0000

m

k

Watt's frame pointer

Return address for Watt

R6 →

k

q (value of w)

r (10)

R5 →

w

main's frame pointer

Return address for main

Return value to main

a

xFFFF

Activation Record of Watt

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

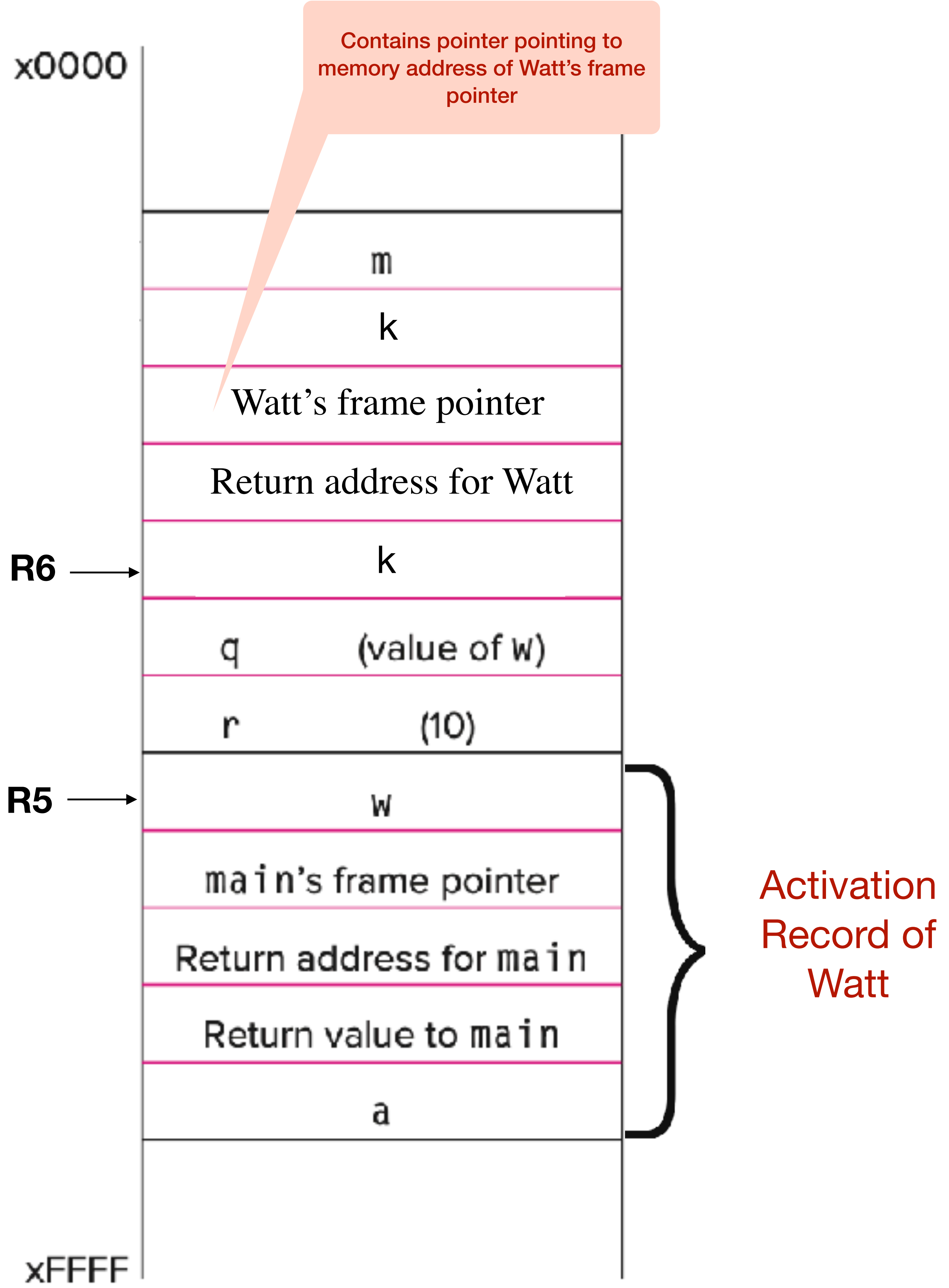
LC-3 Implementation

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
ADD R6, R6, #1

; return control to caller
```

R0
k

R7
Return address for Watt

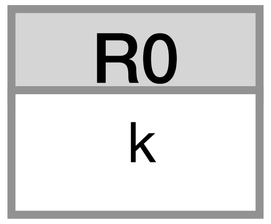


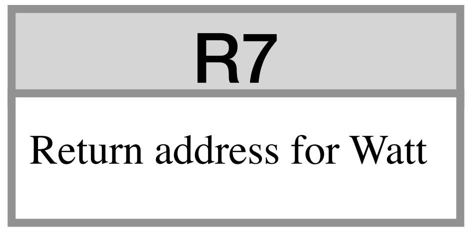
```
int Volt(int q, int r)
{
        int k;
        int m;
        ...
        return k;
}
```

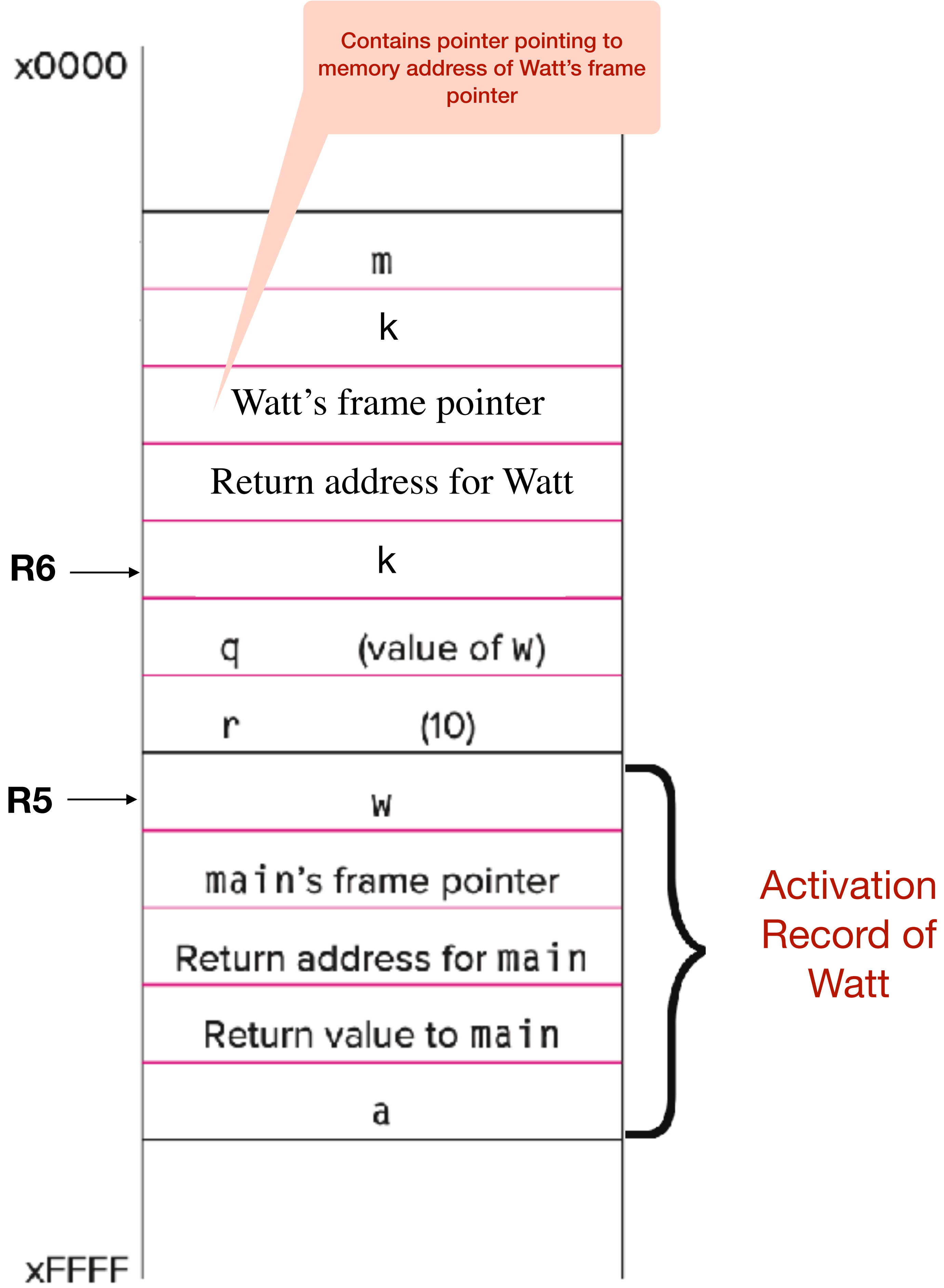
LC-3 Implementation

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
ADD R6, R6, #1

; return control to caller
RET
```







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

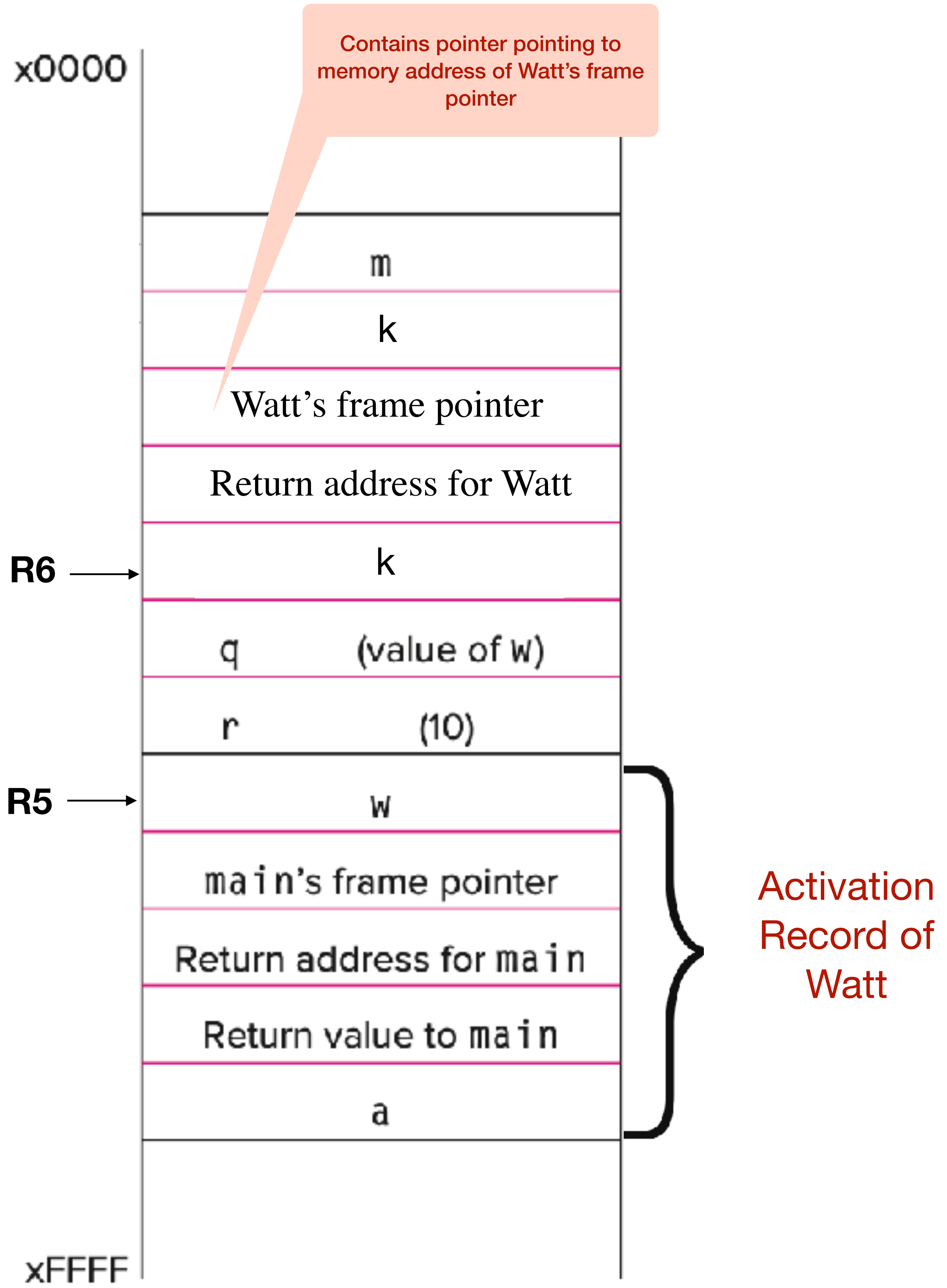
LC-3 Implementation

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



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

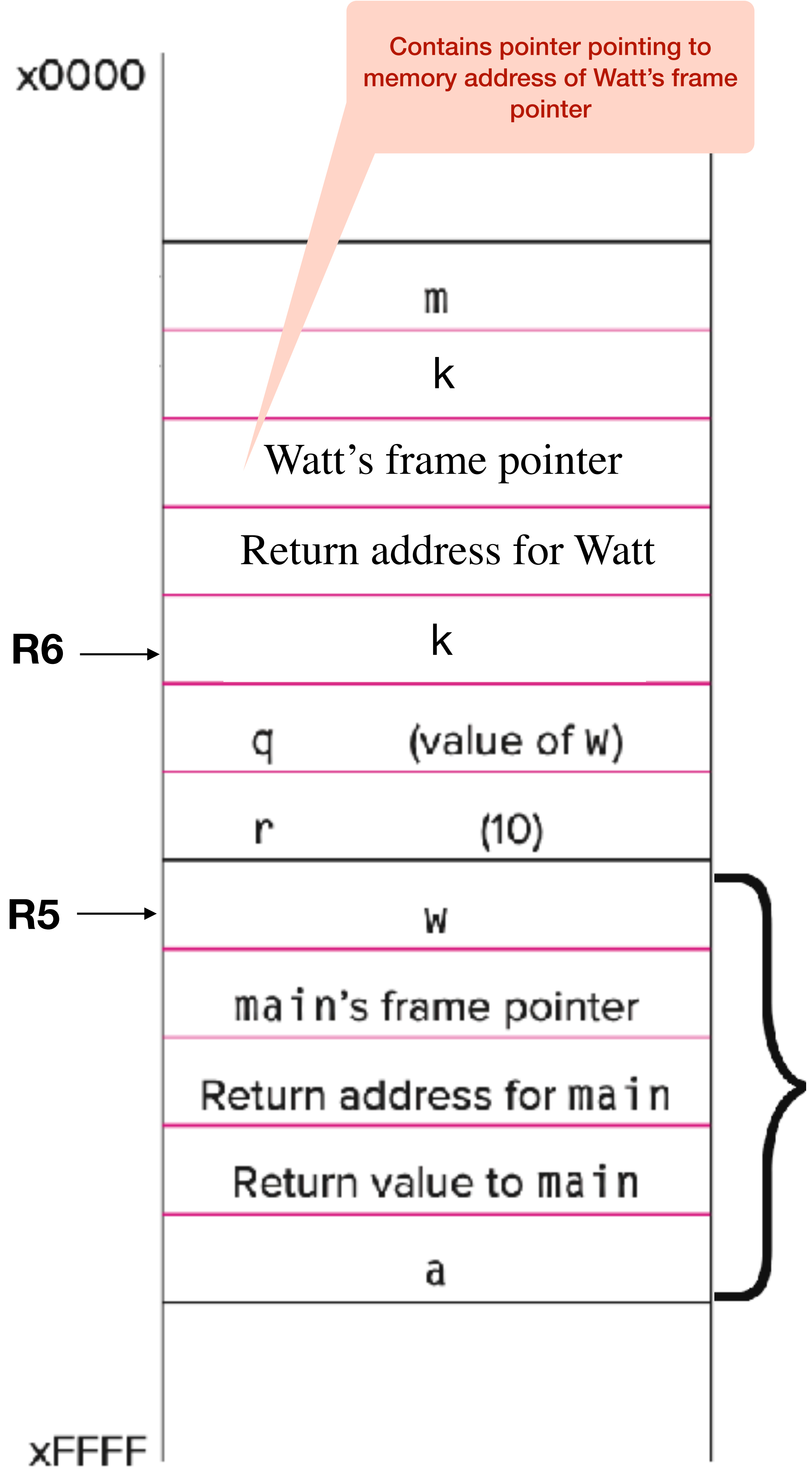
LC-3 Implementation

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

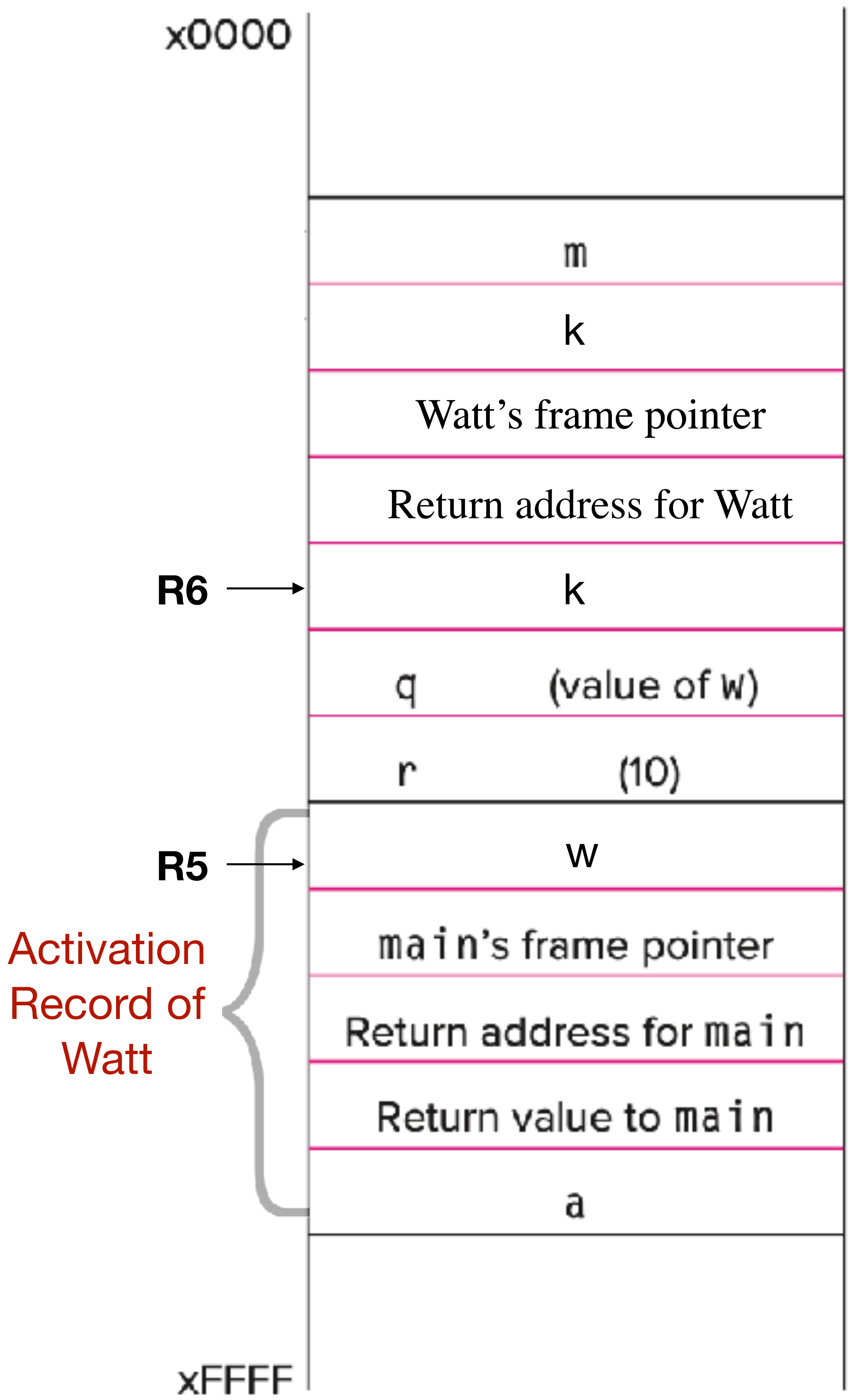


Activation Record of Watt

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;
}
```

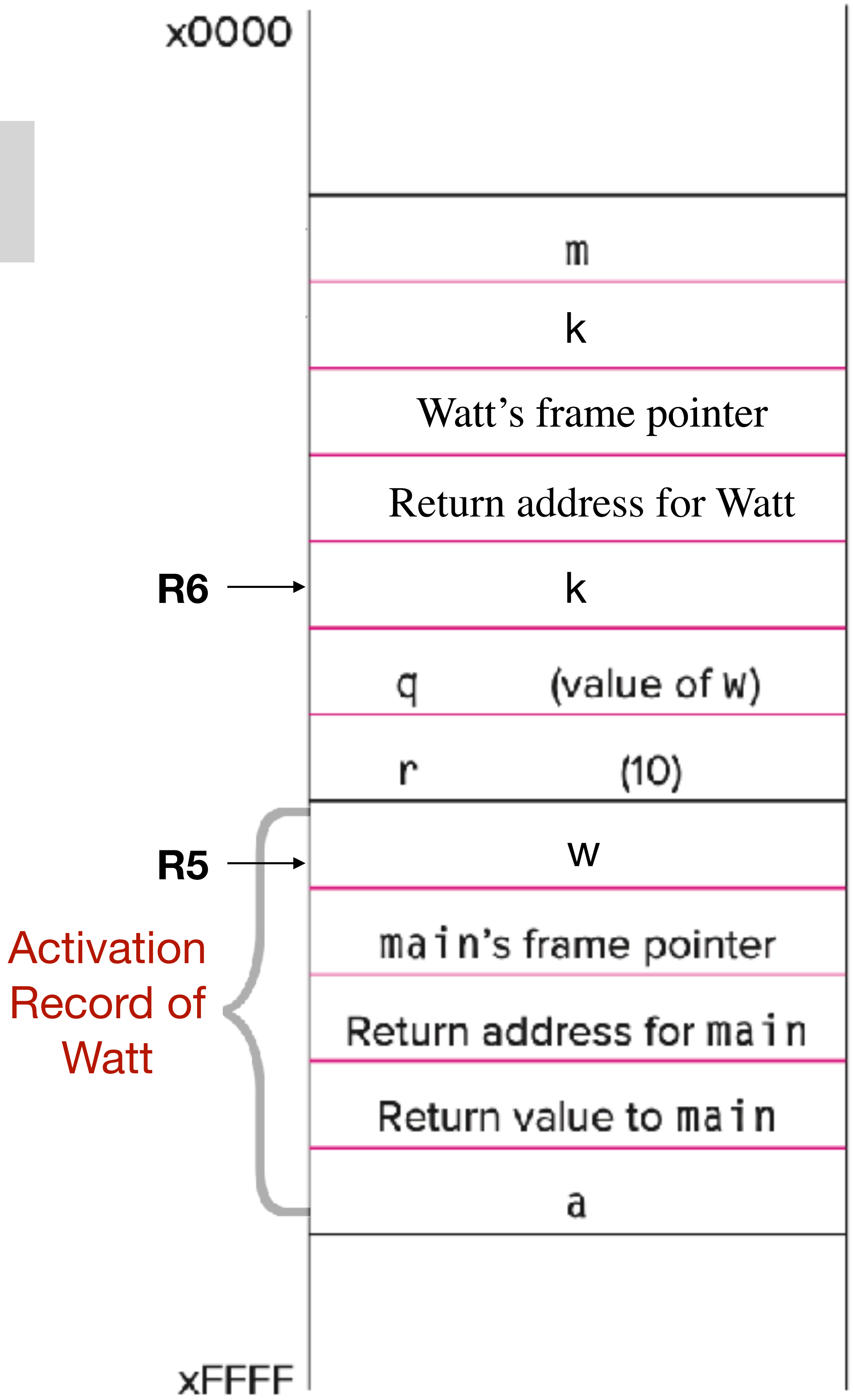
LC-3 Implementation



```
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)

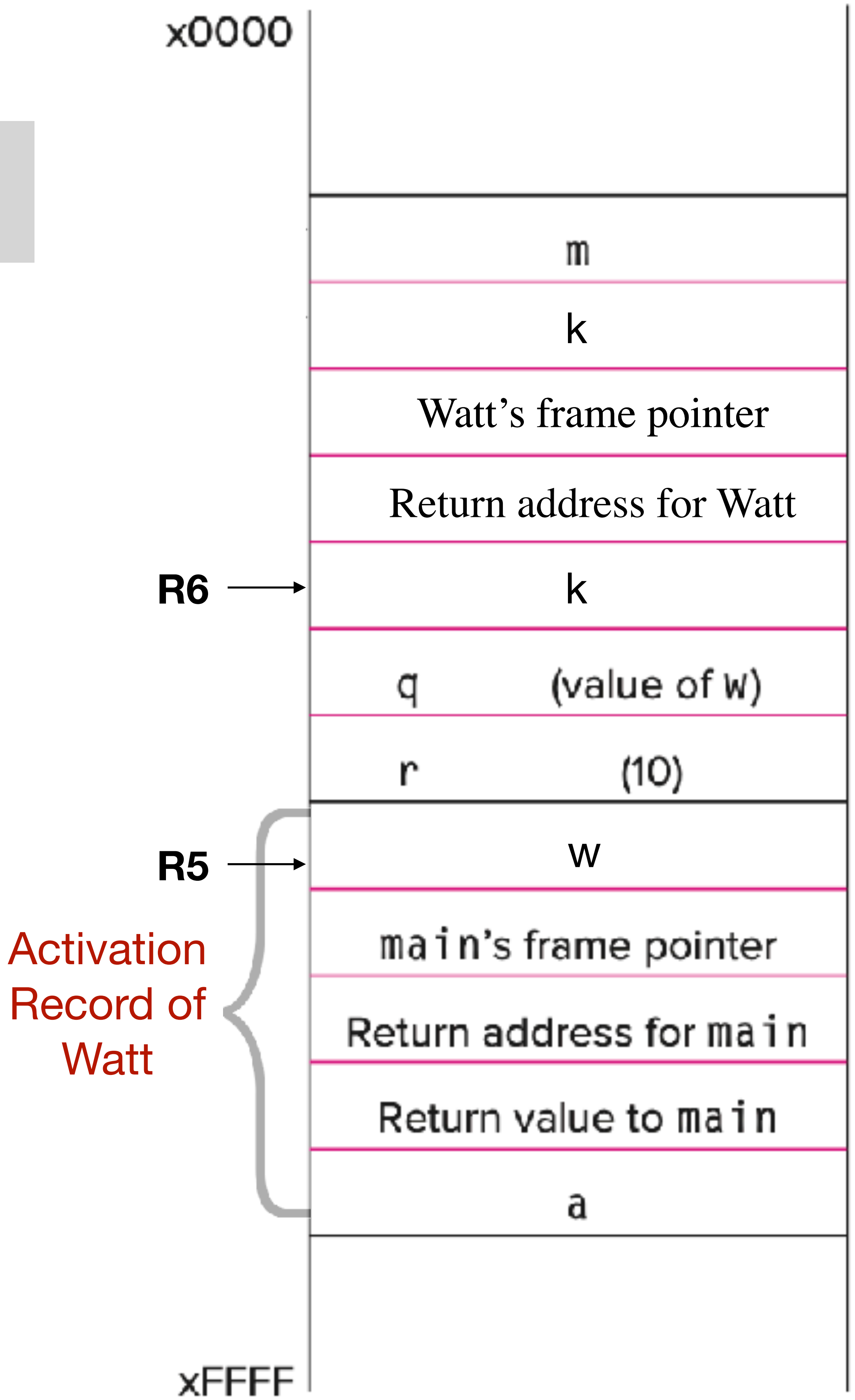


LC-3 Implementation

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

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

```
JSR VOLT
```

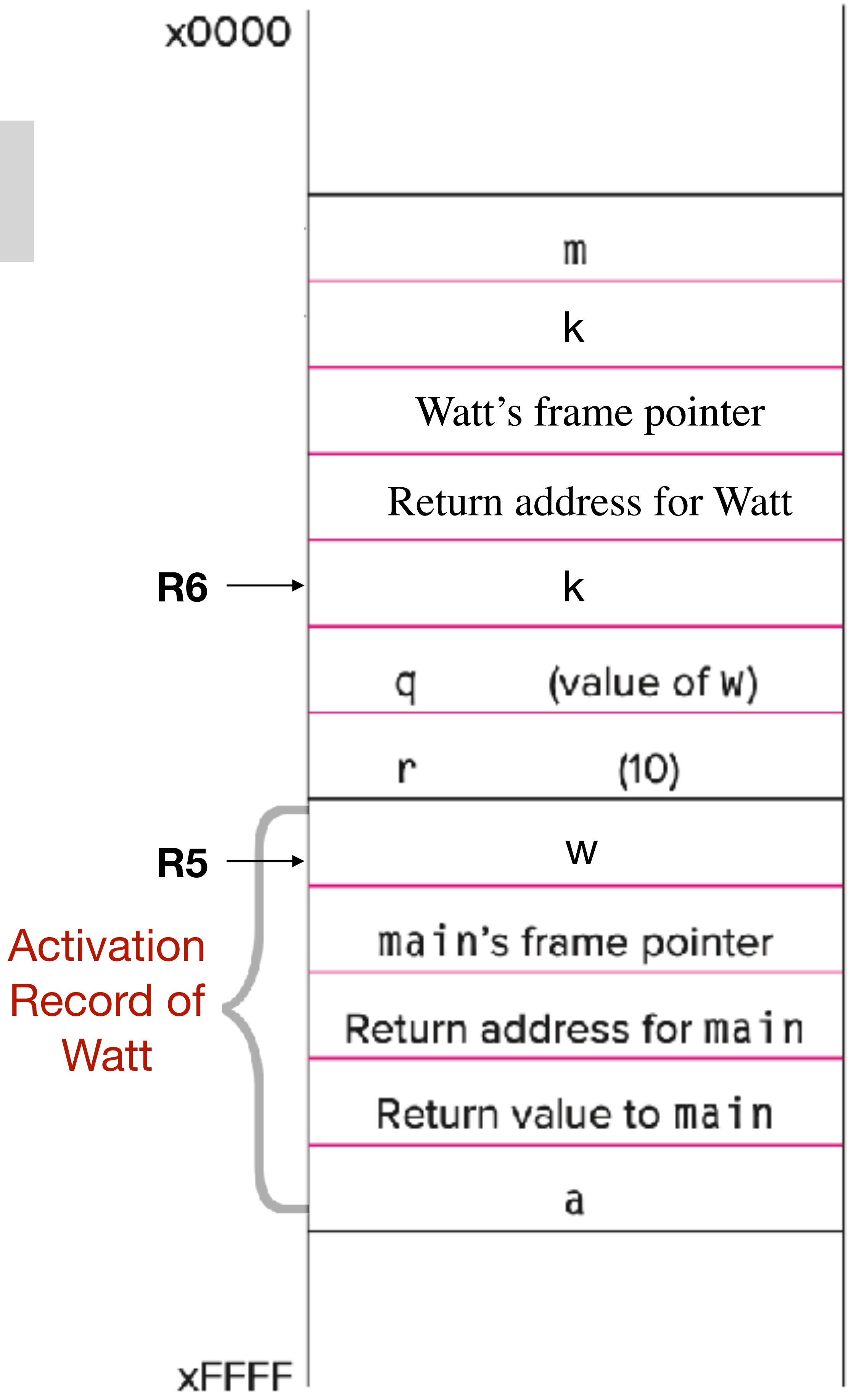


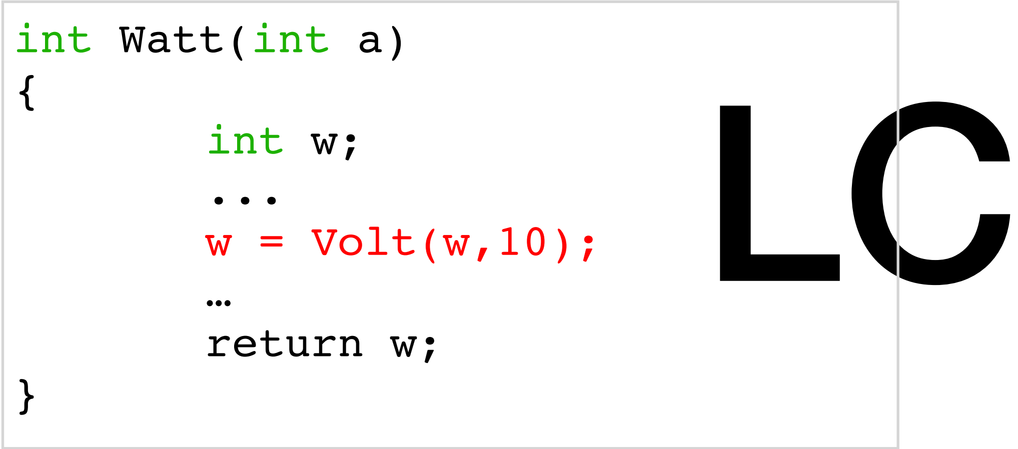
```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

LC-3 Implementation

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

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



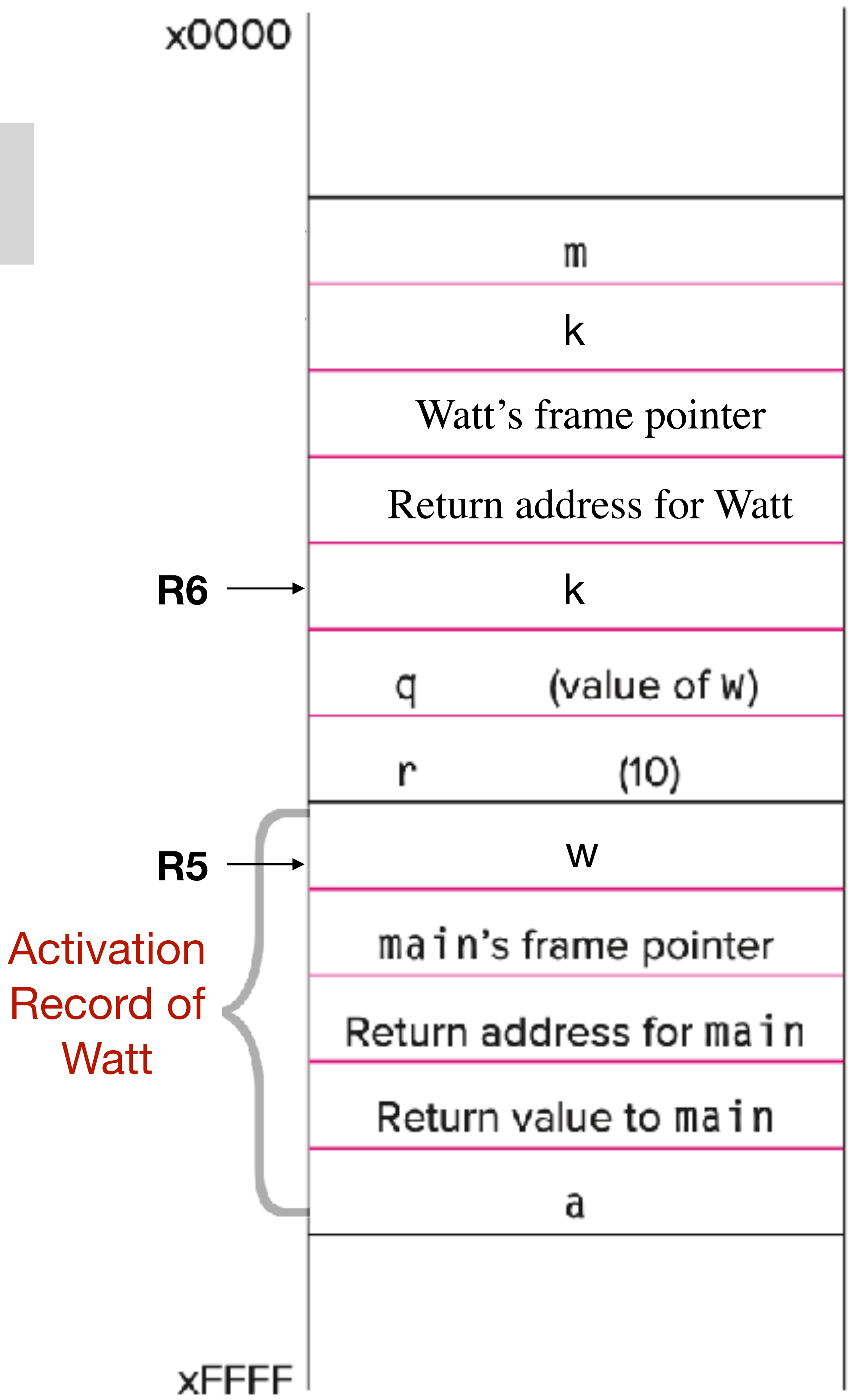


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```

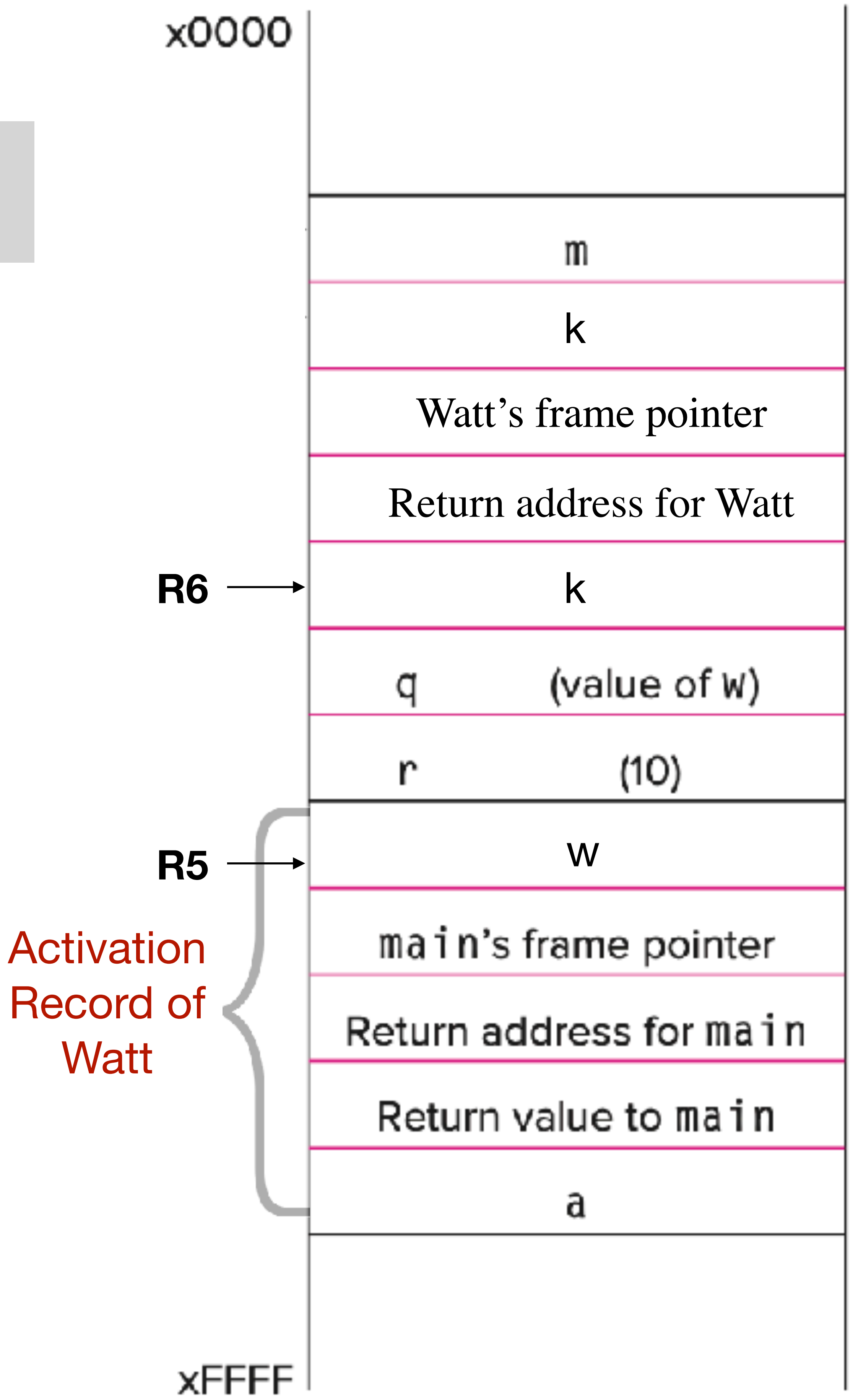


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



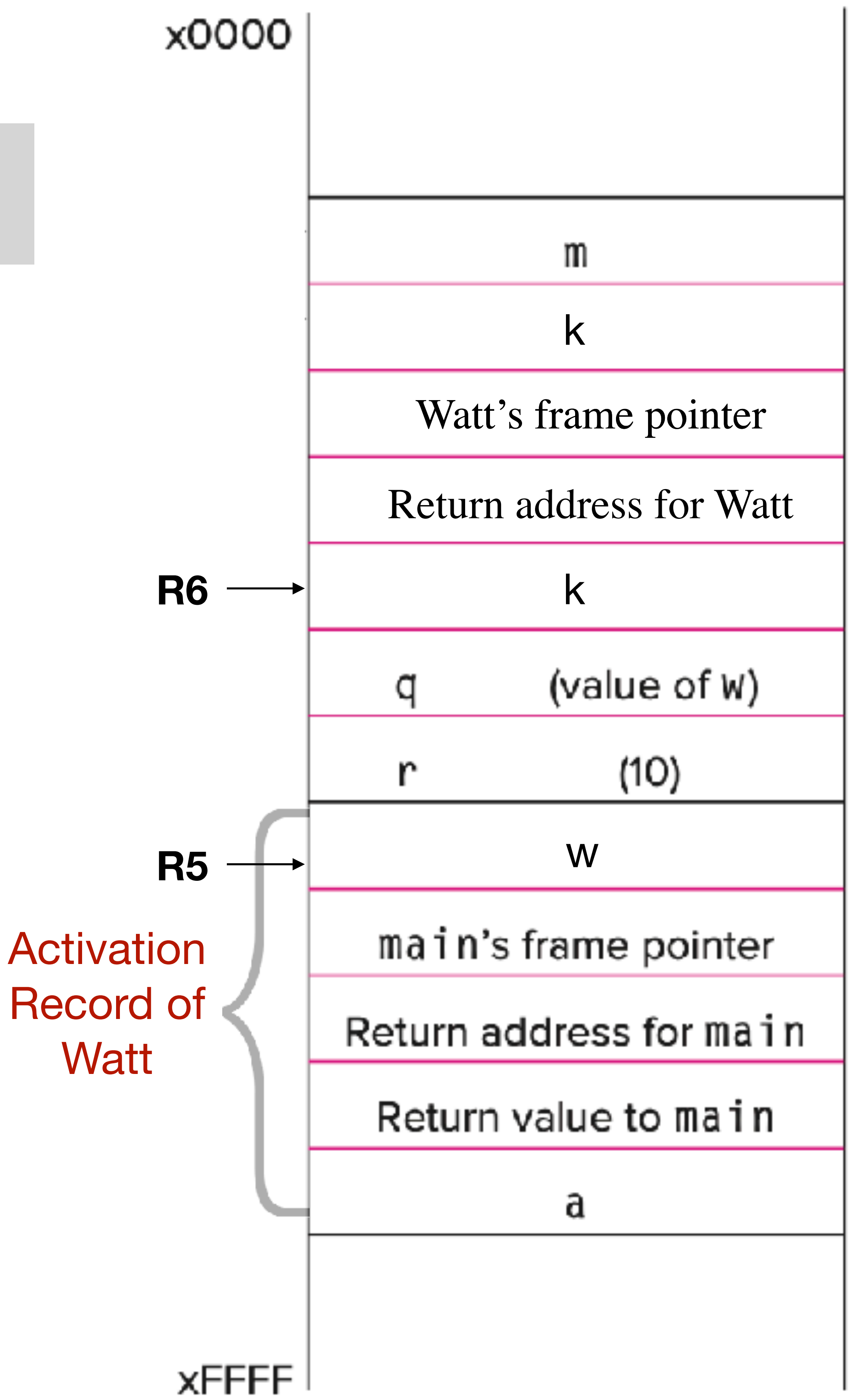
R0

```
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
```



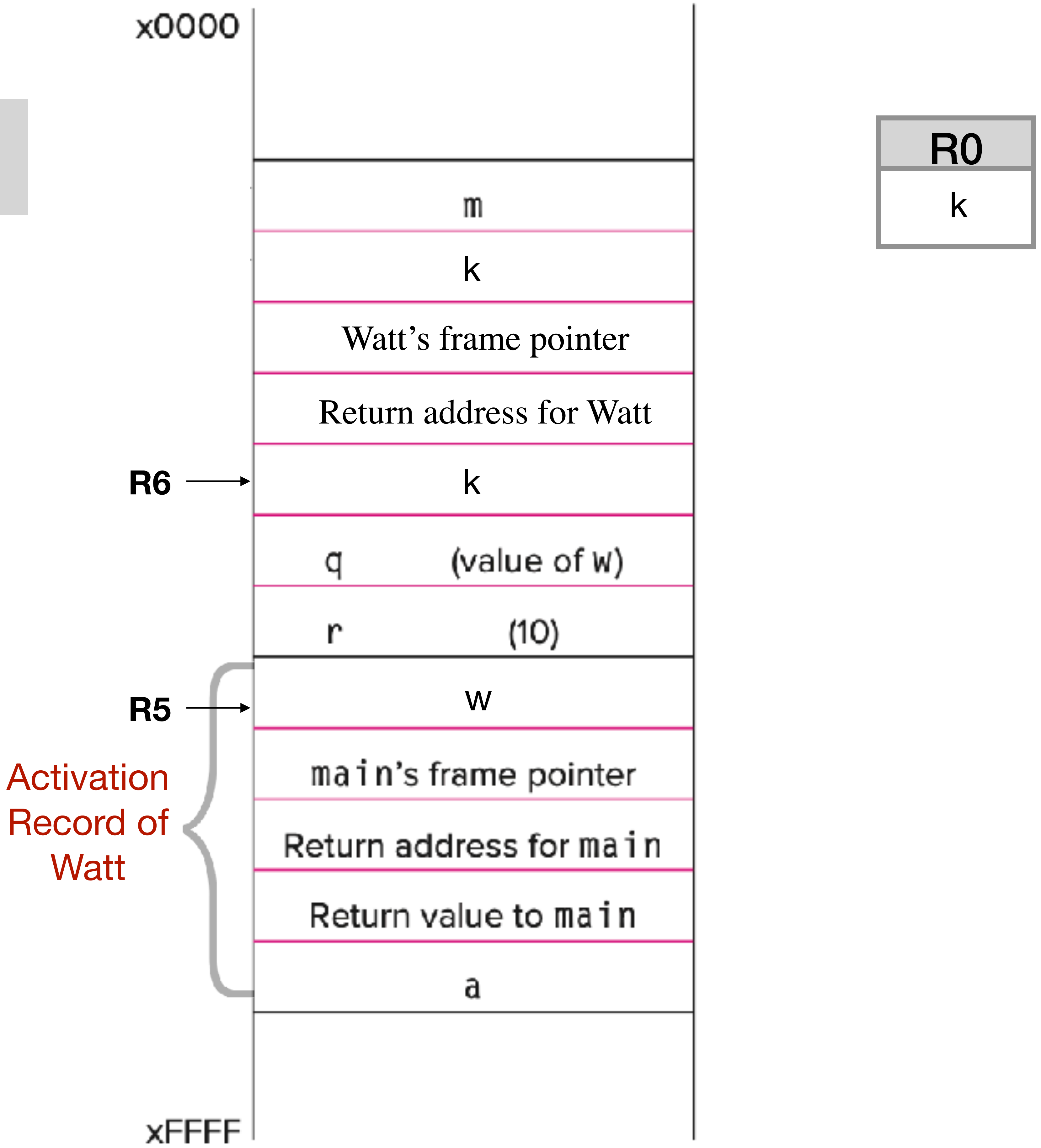
R0
k

```
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
```

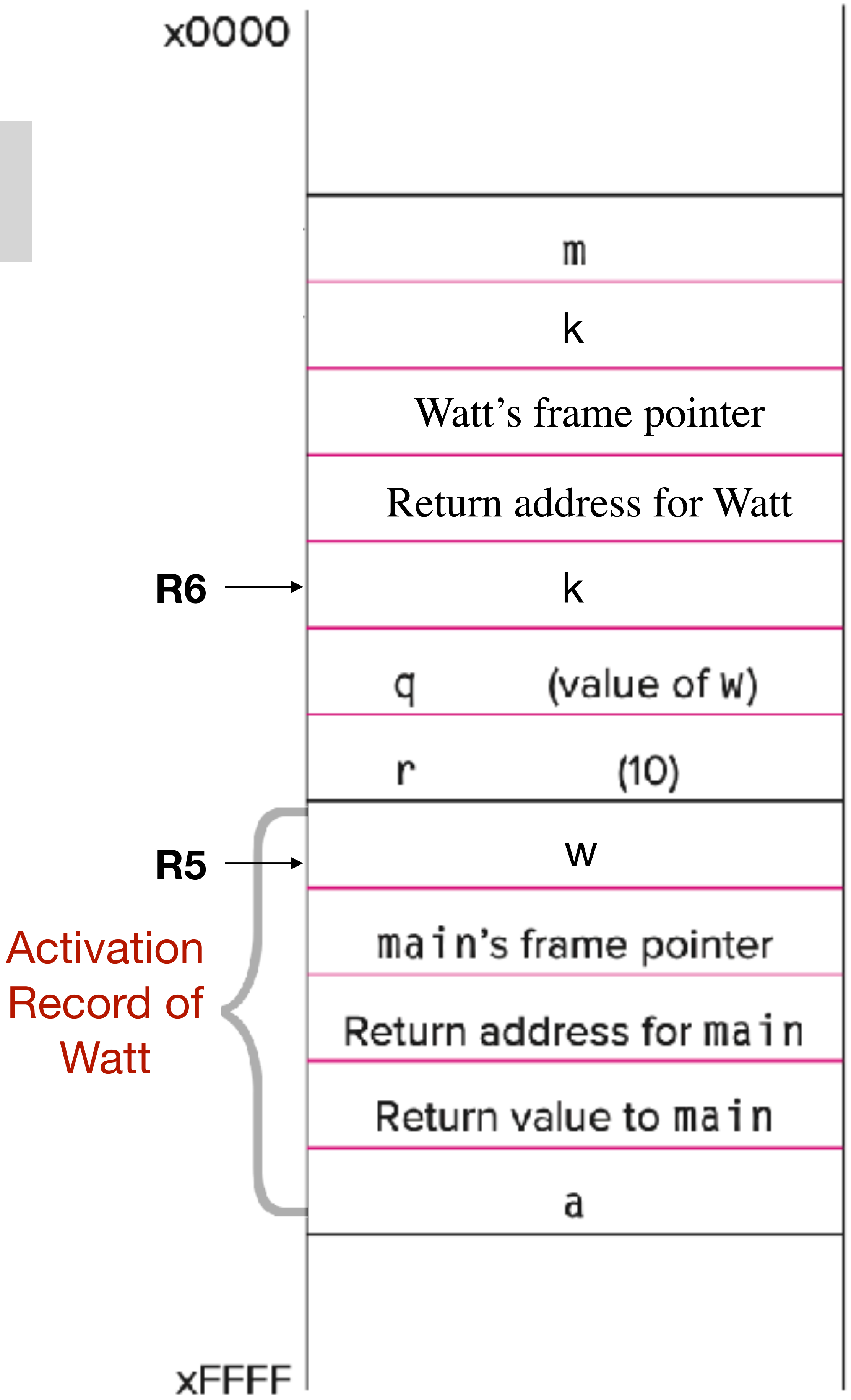


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



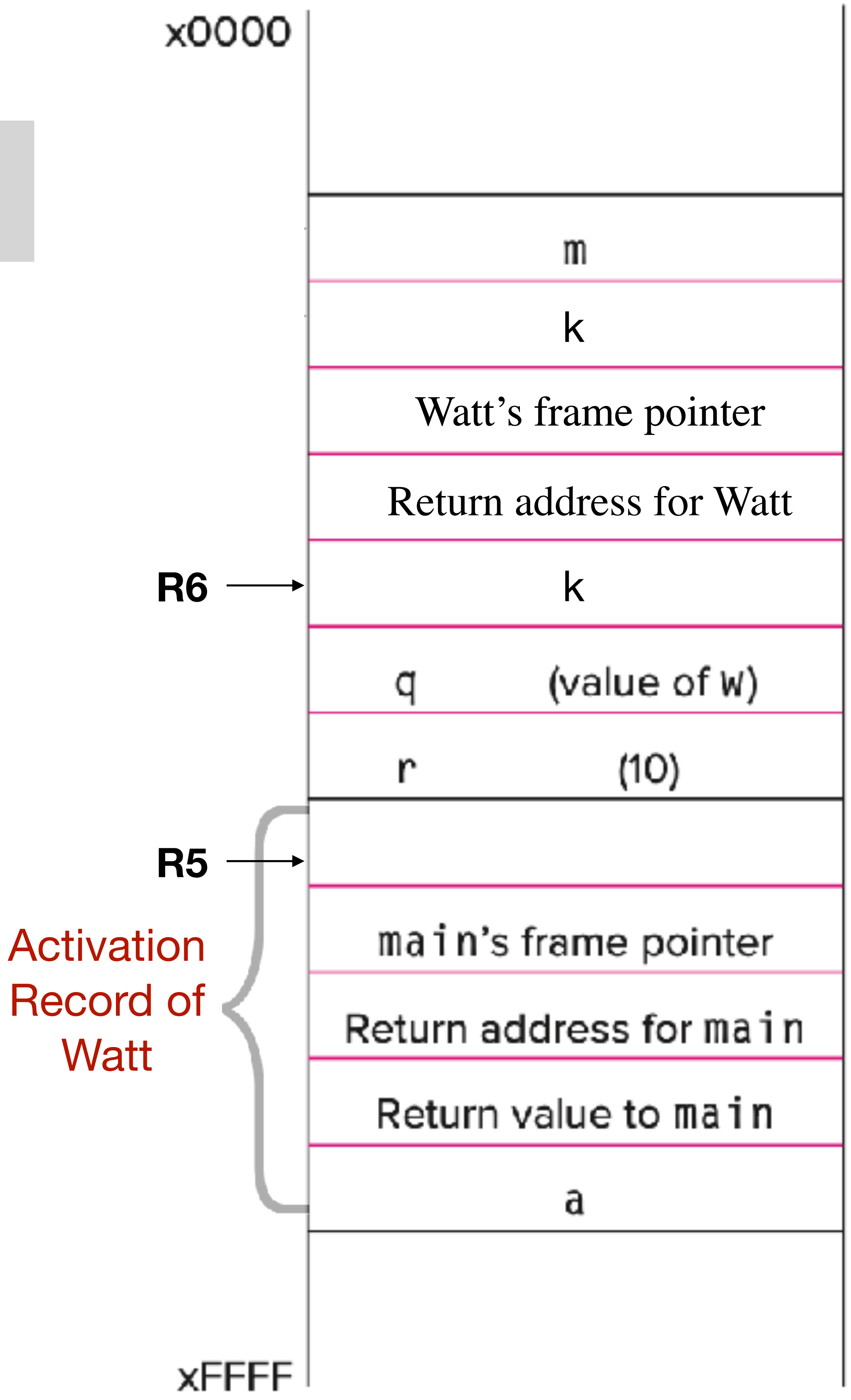
R0
k

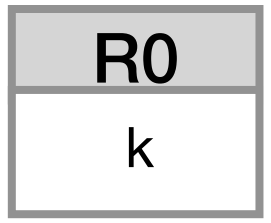
```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

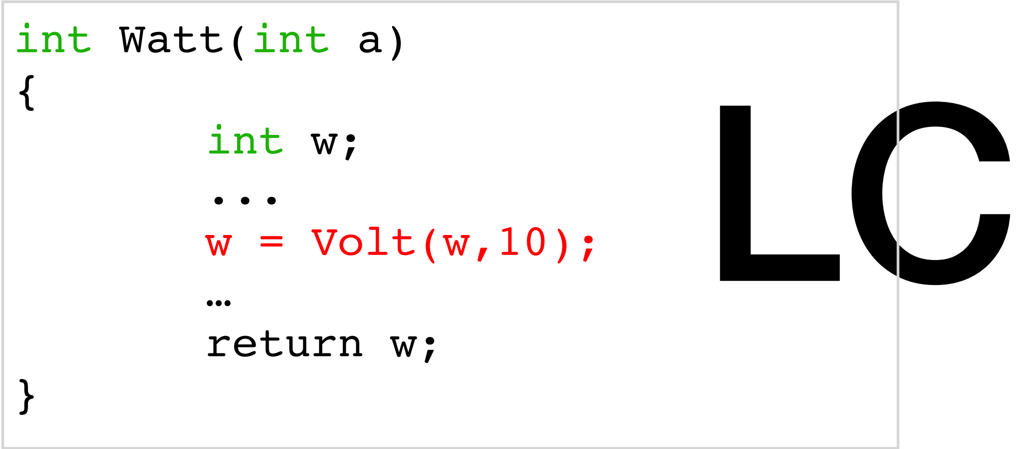
LC-3 Implementation

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
```





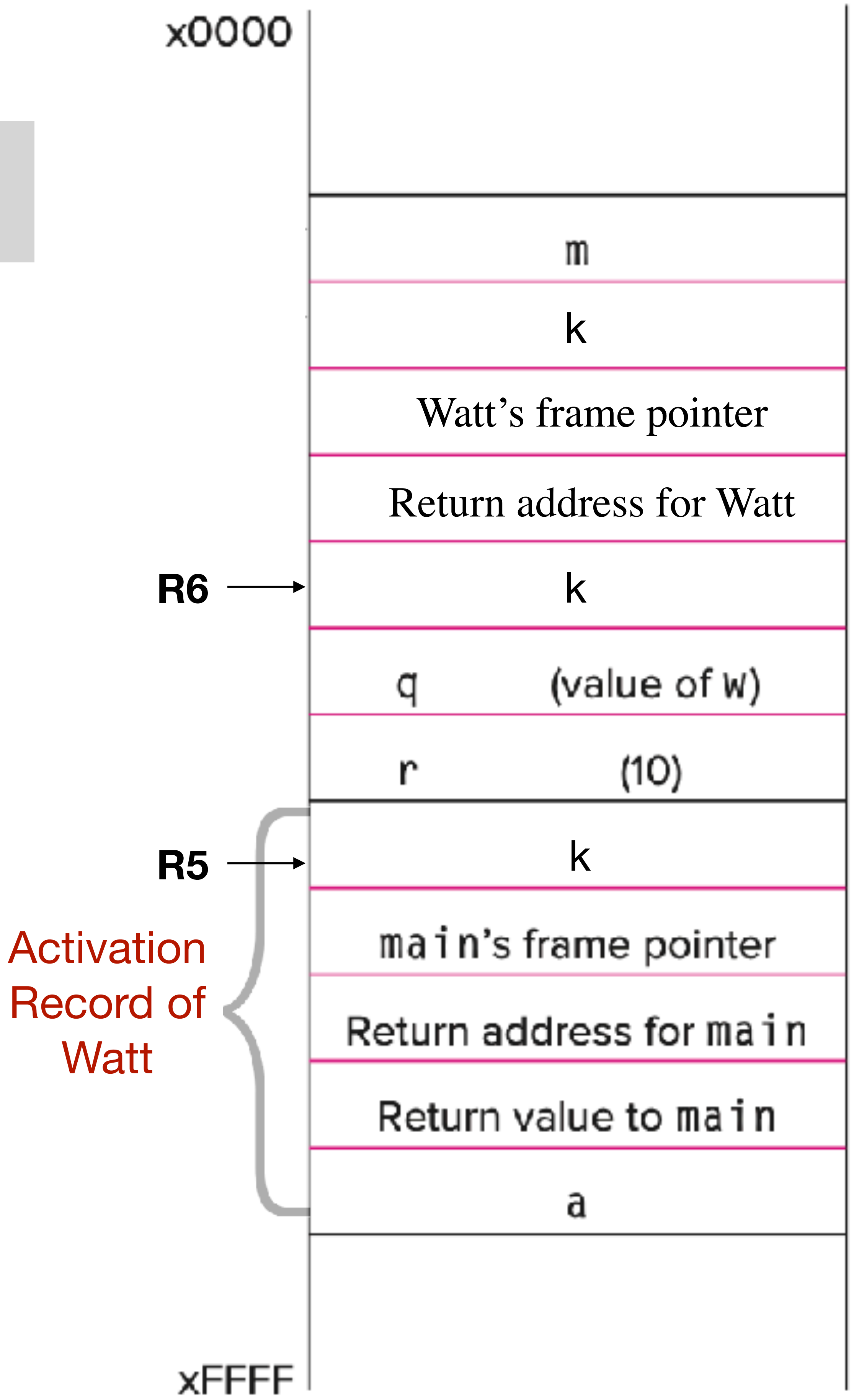


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



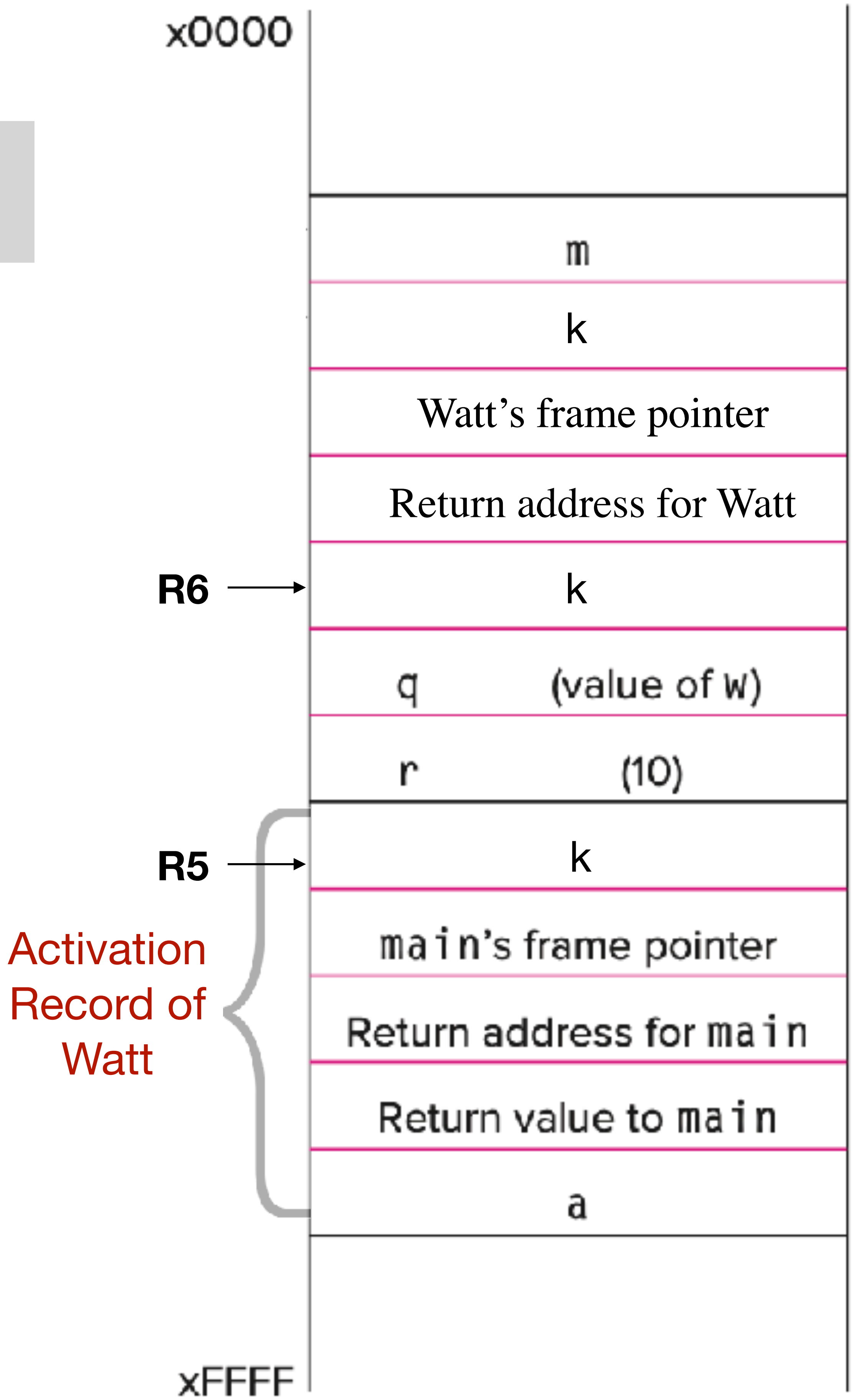
R0

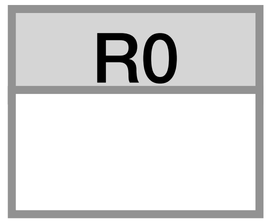
```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

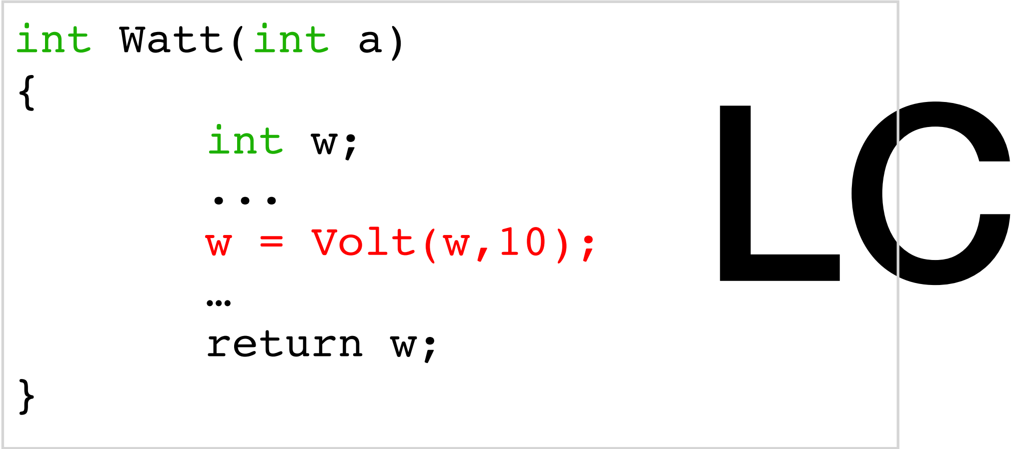
LC-3 Implementation

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
```





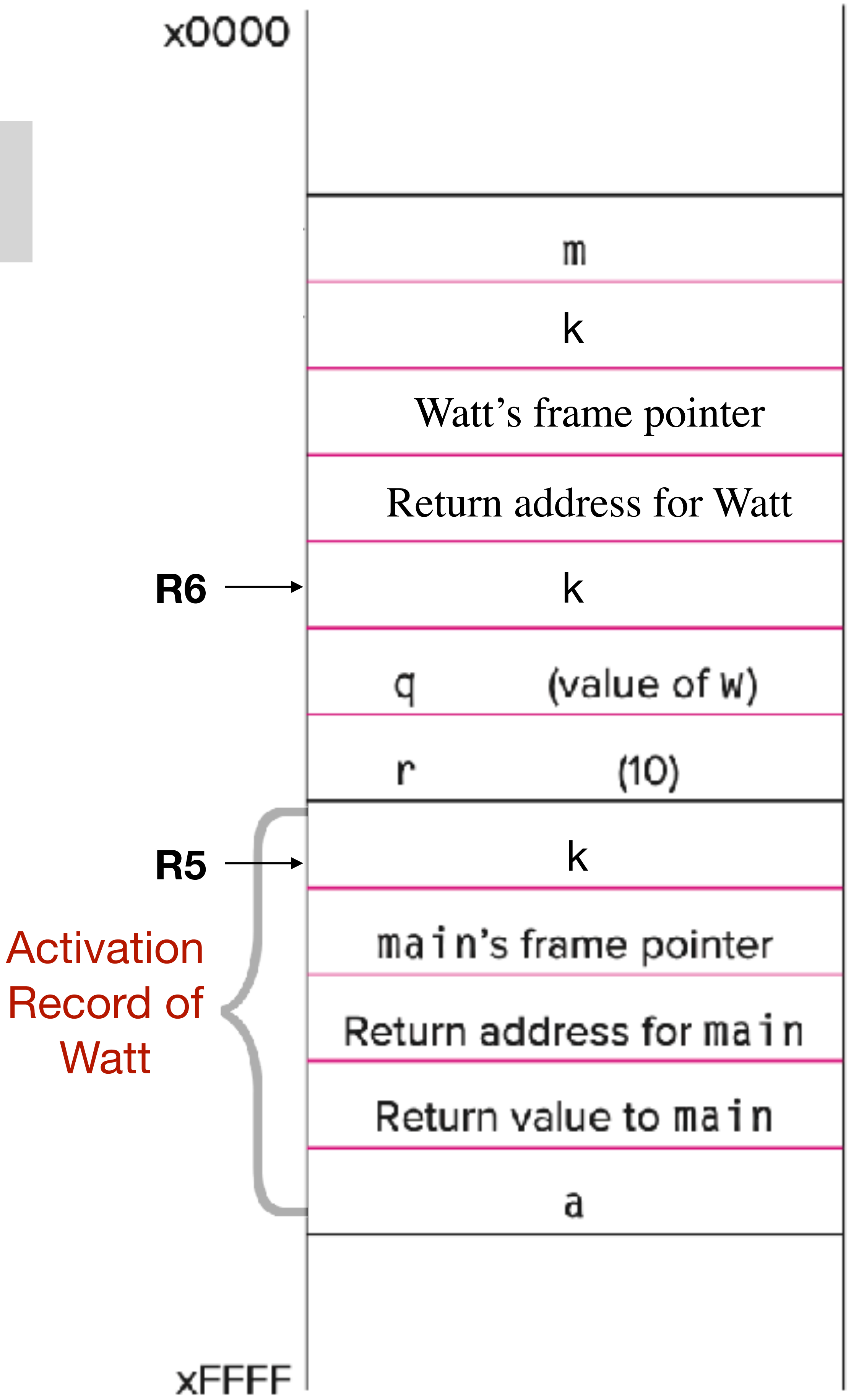


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



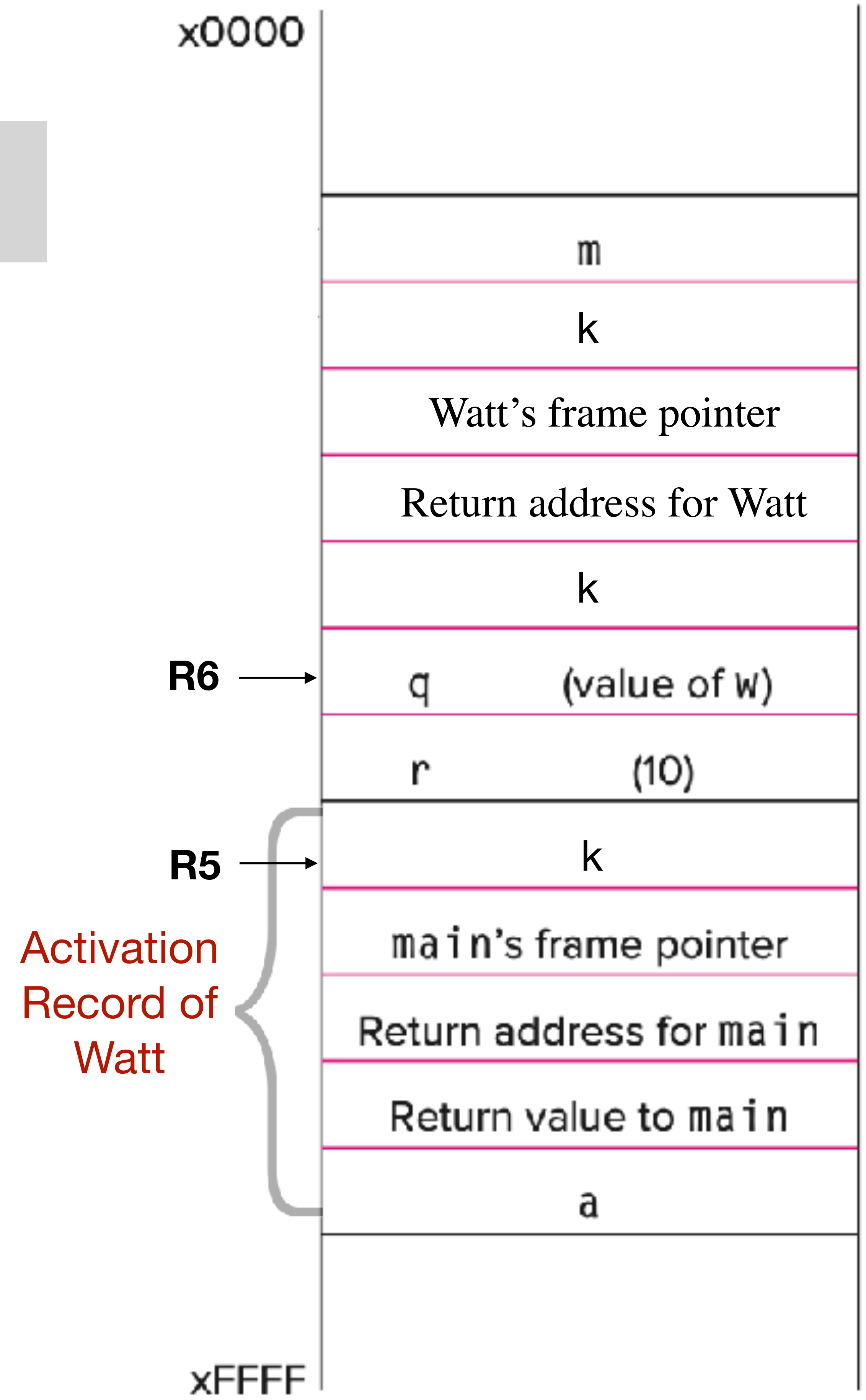
R0

```
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
```



x0000

m

k

Watt's frame pointer

Return address for Watt

k

R6 → q (value of w)

r (10)

R5 → k

main's frame pointer

Return address for main

Return value to main

a

Activation Record of Watt

xFFFF

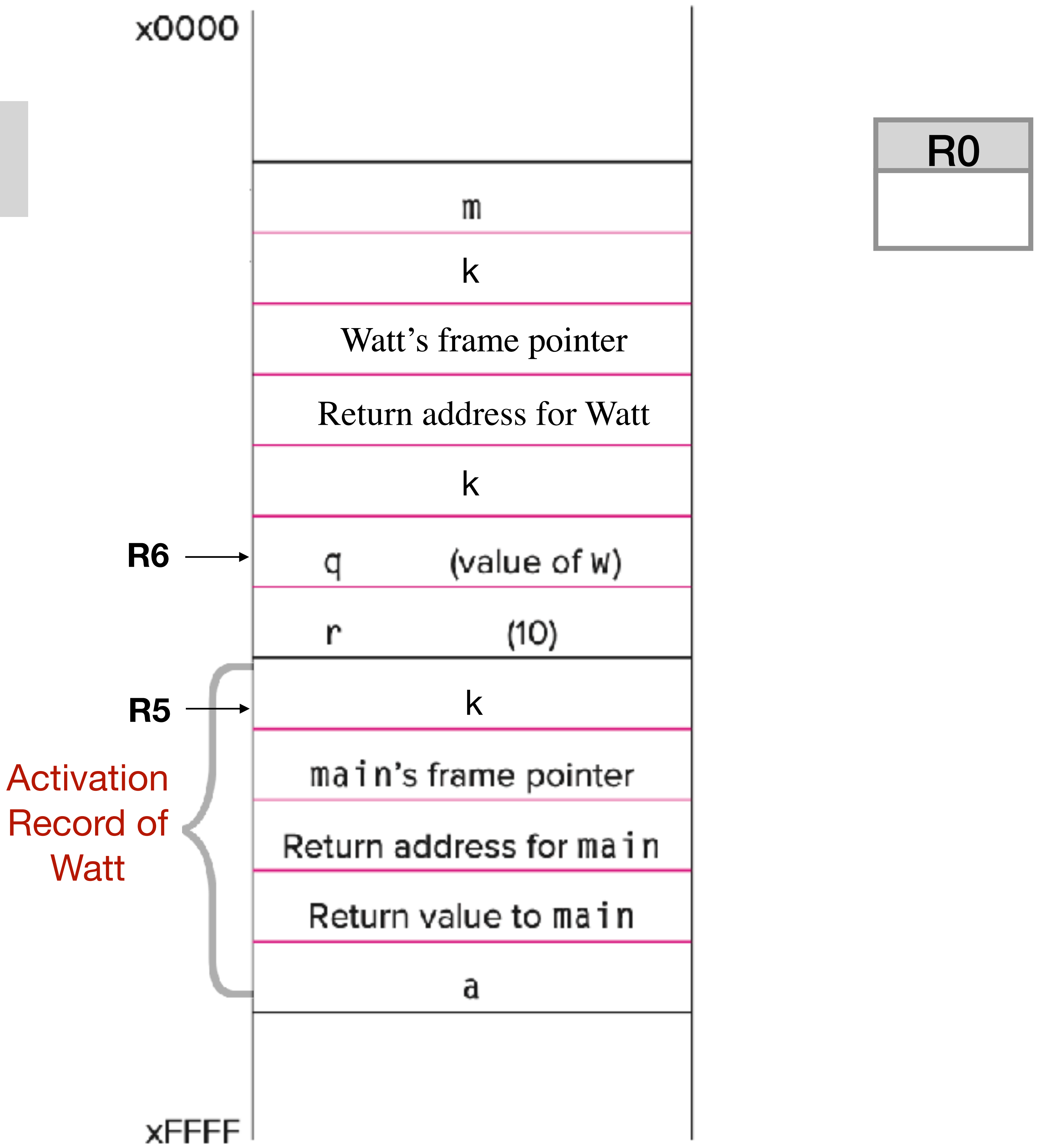
R0

```
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
```

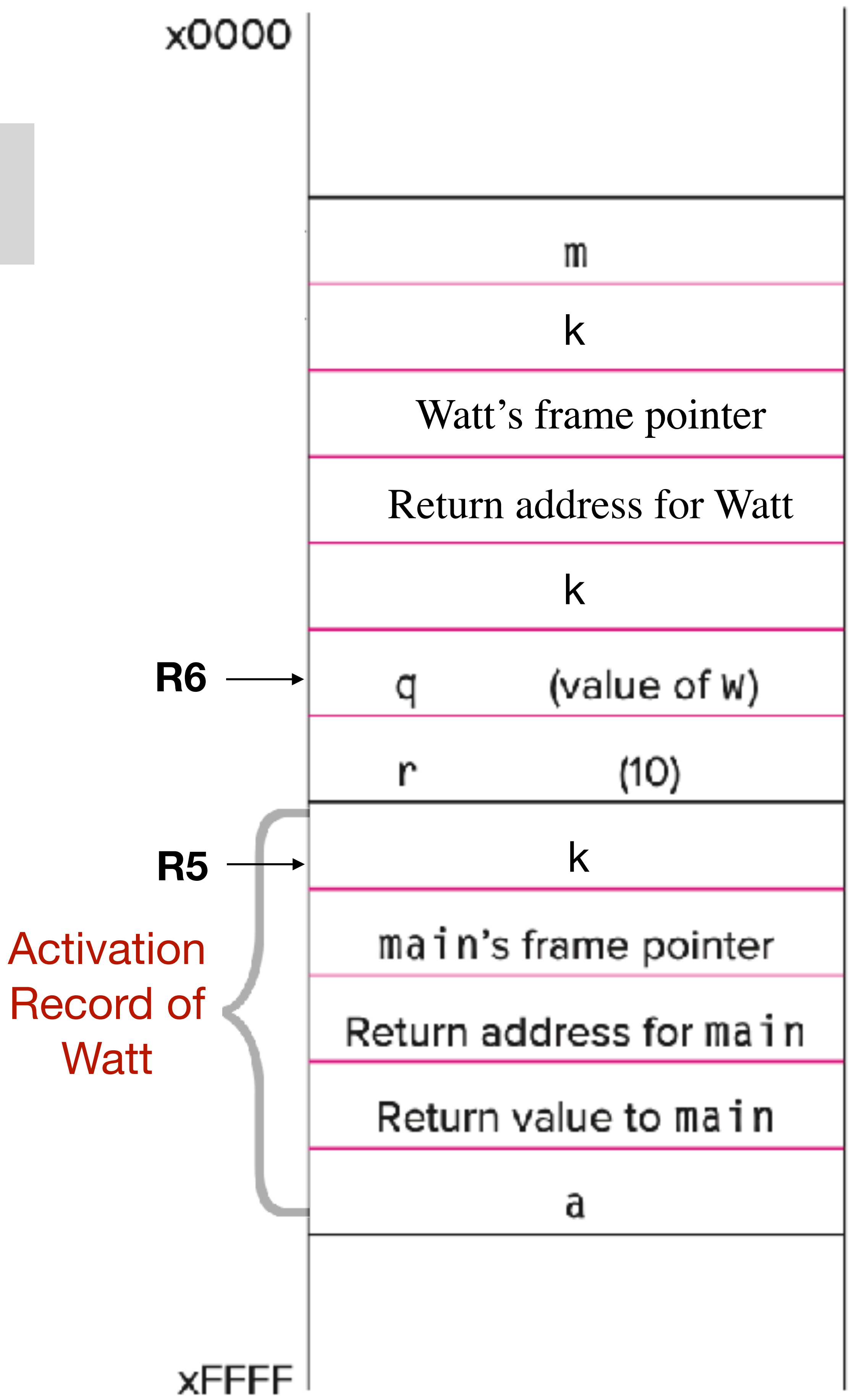


```
int Watt(int a)
{
        int w;
        ...
        w = Volt(w,10);
        …
        return w;
}
```

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
```



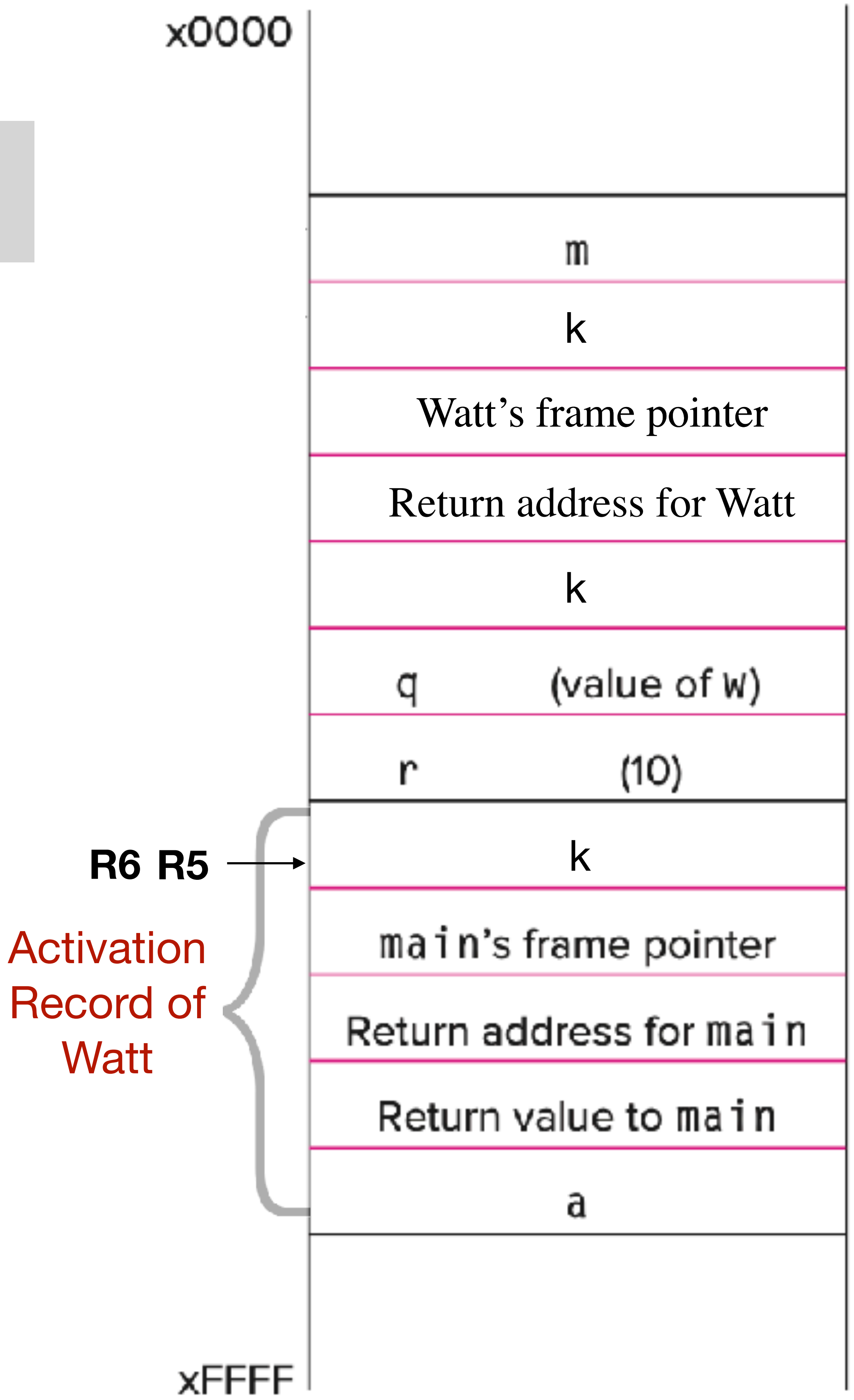
R0

```
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)

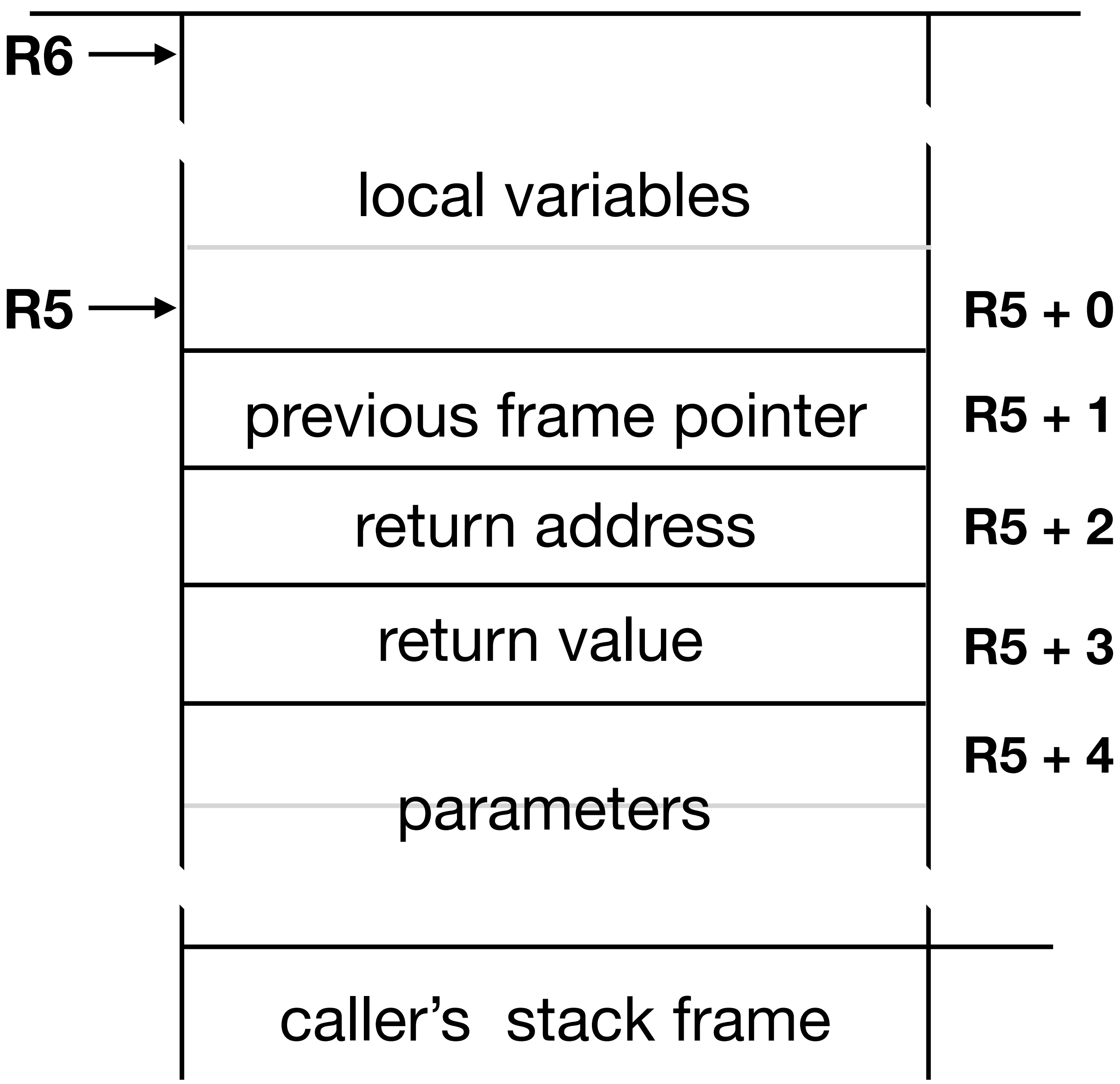
```
JSR VOLT
; load return value (top of stack)
LDR R0, R6, #0

; perform assignment
STR R0, R5, #0

; pop return value
ADD R6, R6, #1

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



R0

General principles

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



Exercise: build the activation frame

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

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

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

Goal:

Swap valueA and valueB in main.

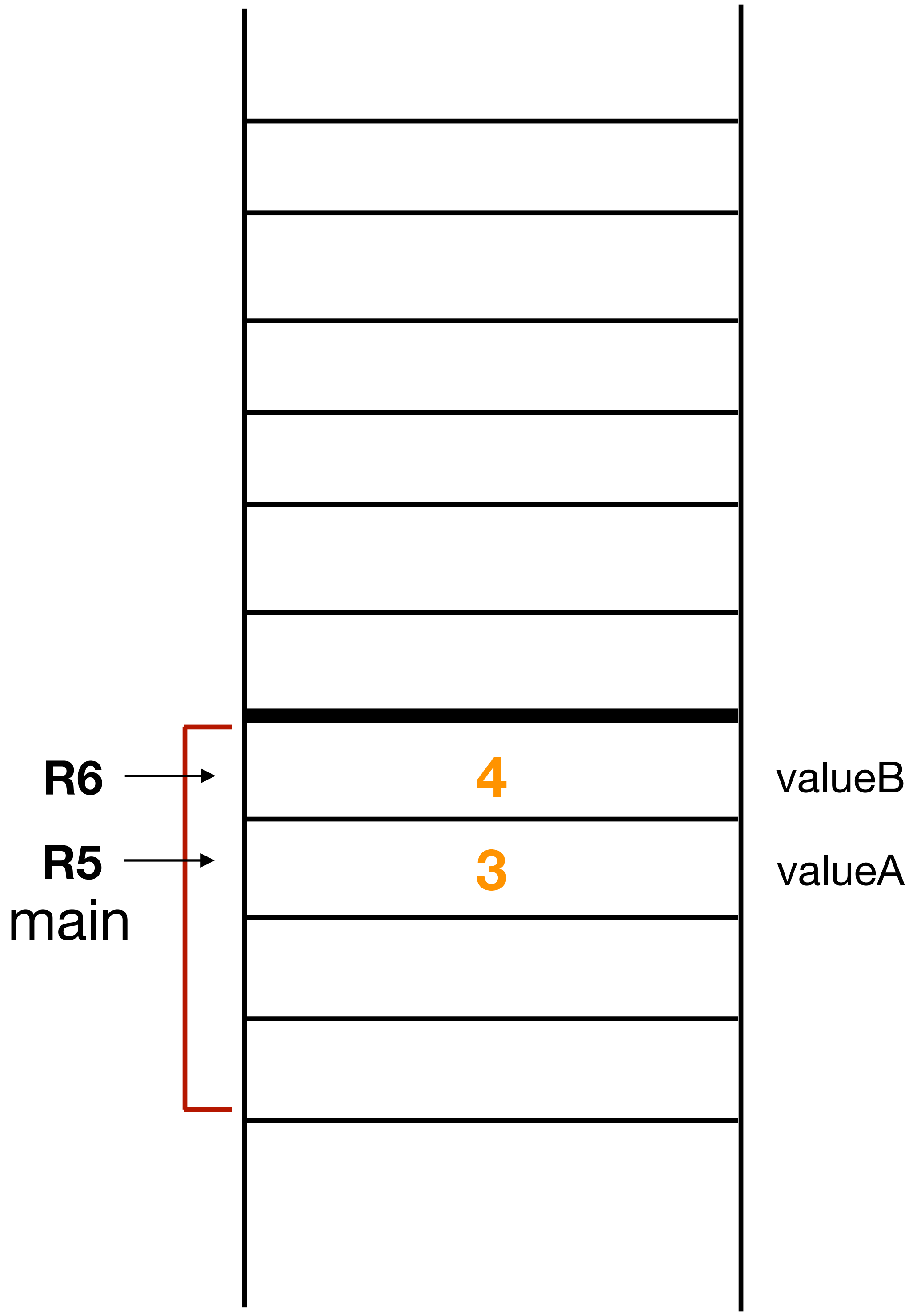
Exercise: build the activation frame

```
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;
}
```

Before call



Goal:

Swap valueA and valueB in main.

Exercise: build the activation frame

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

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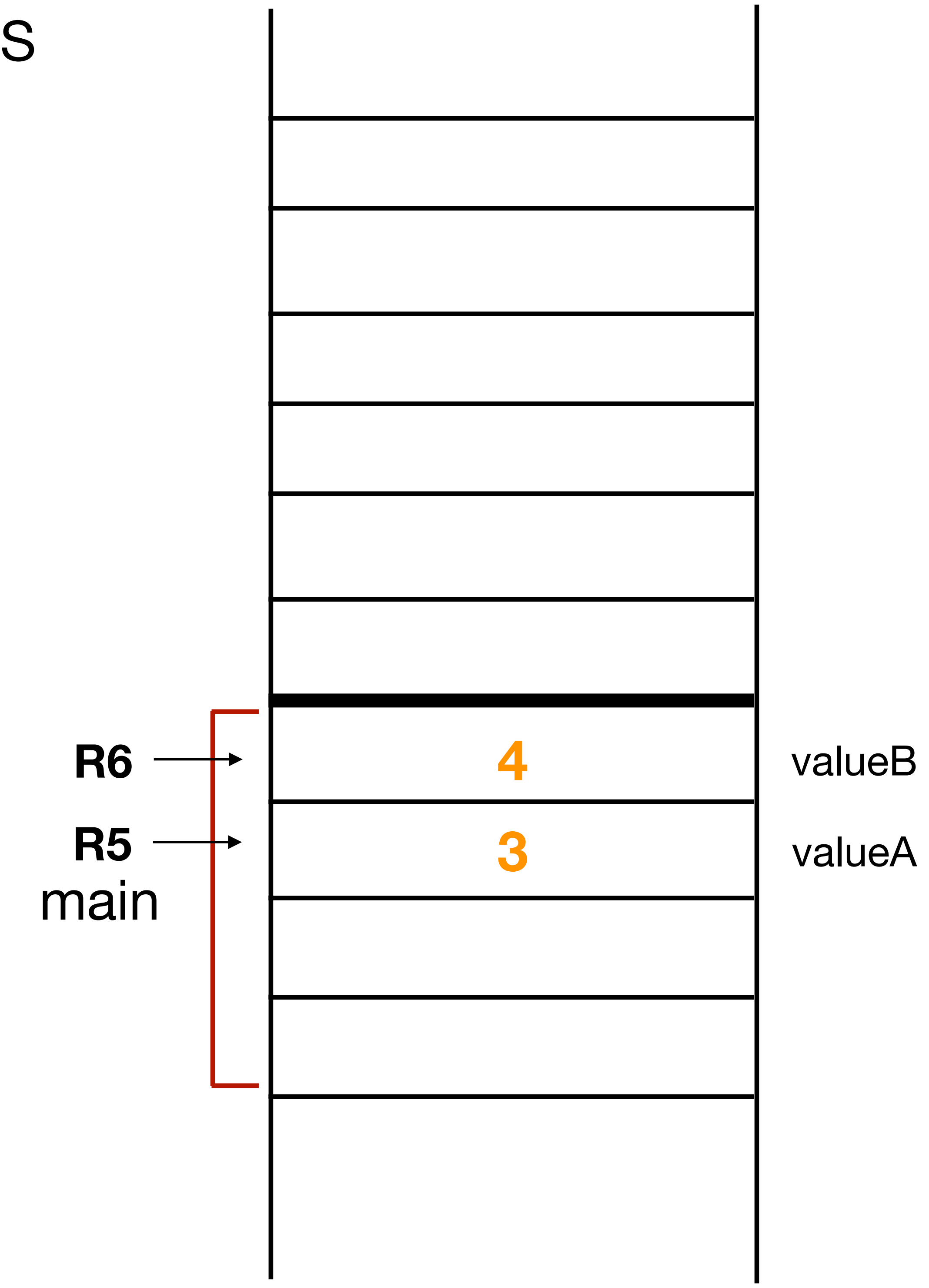
   int valueB = 4;
   Swap(valueA, valueB);
}

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

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

Before call



Goal:

Swap valueA and valueB in main.

Exercise: build the activation frame

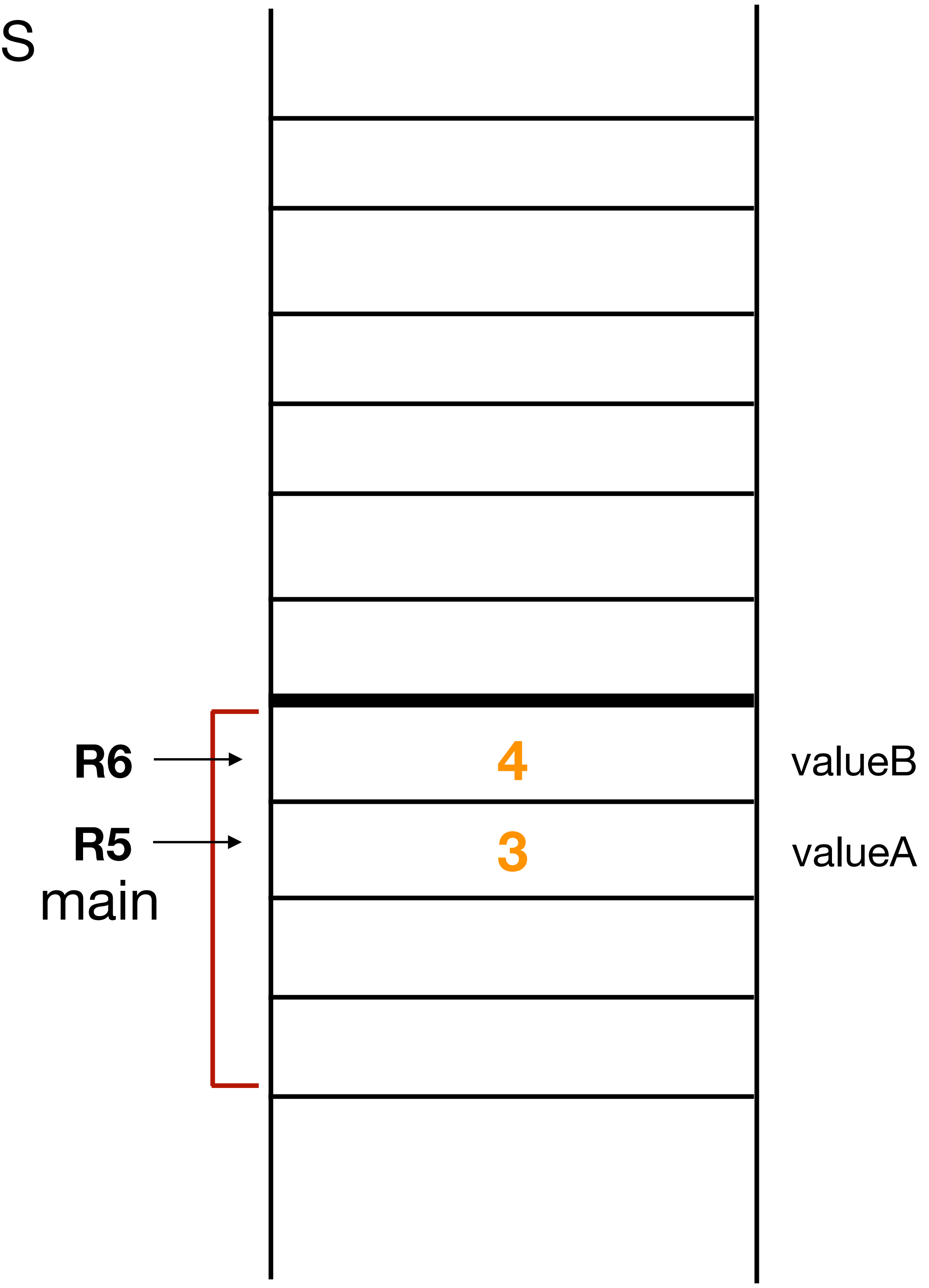
```
void Swap(int first, int second);

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
2. JSR

Before call



Goal:

Swap valueA and valueB in main.

Exercise: build the activation frame

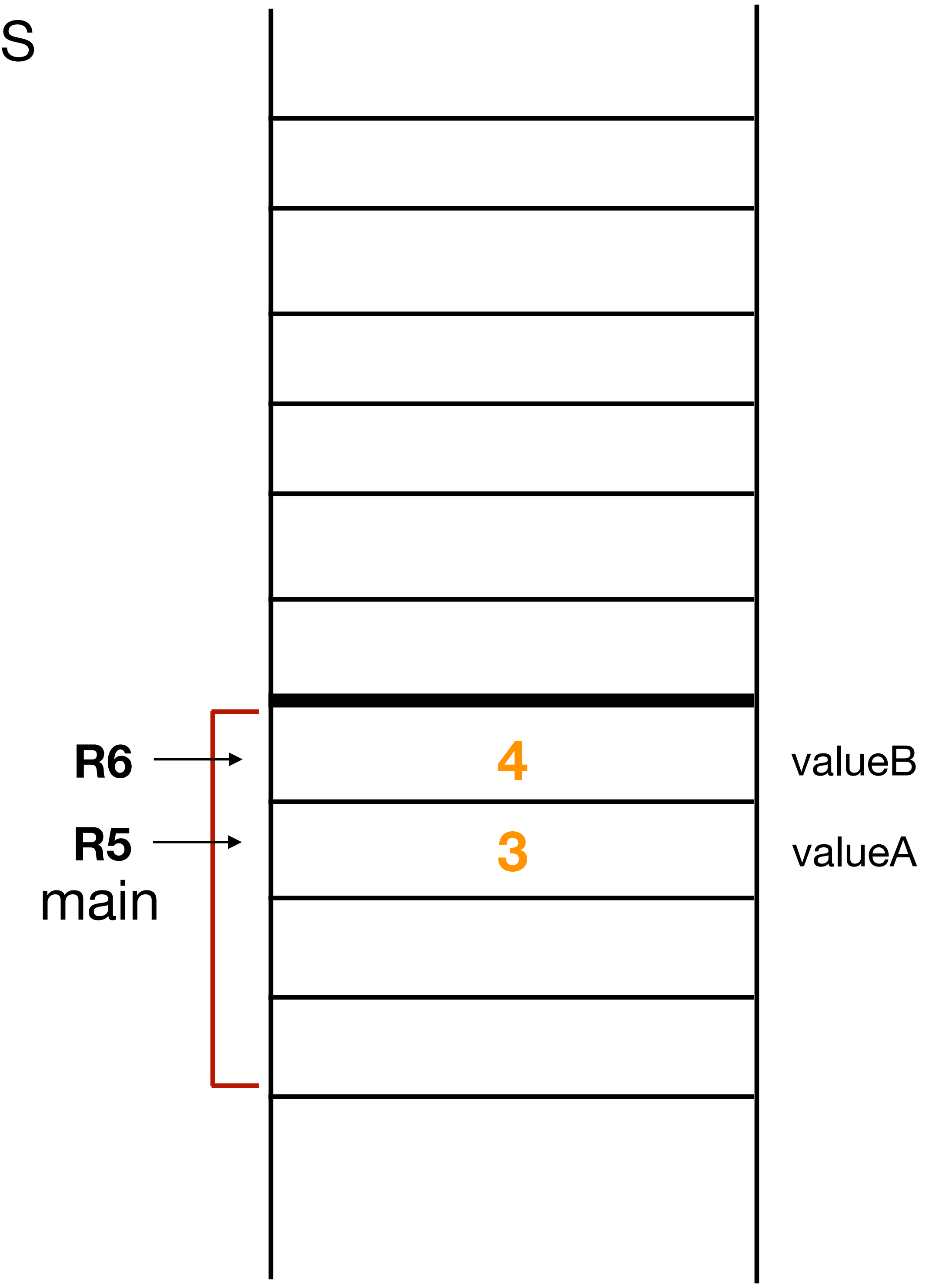
```
void Swap(int first, int second);

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
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

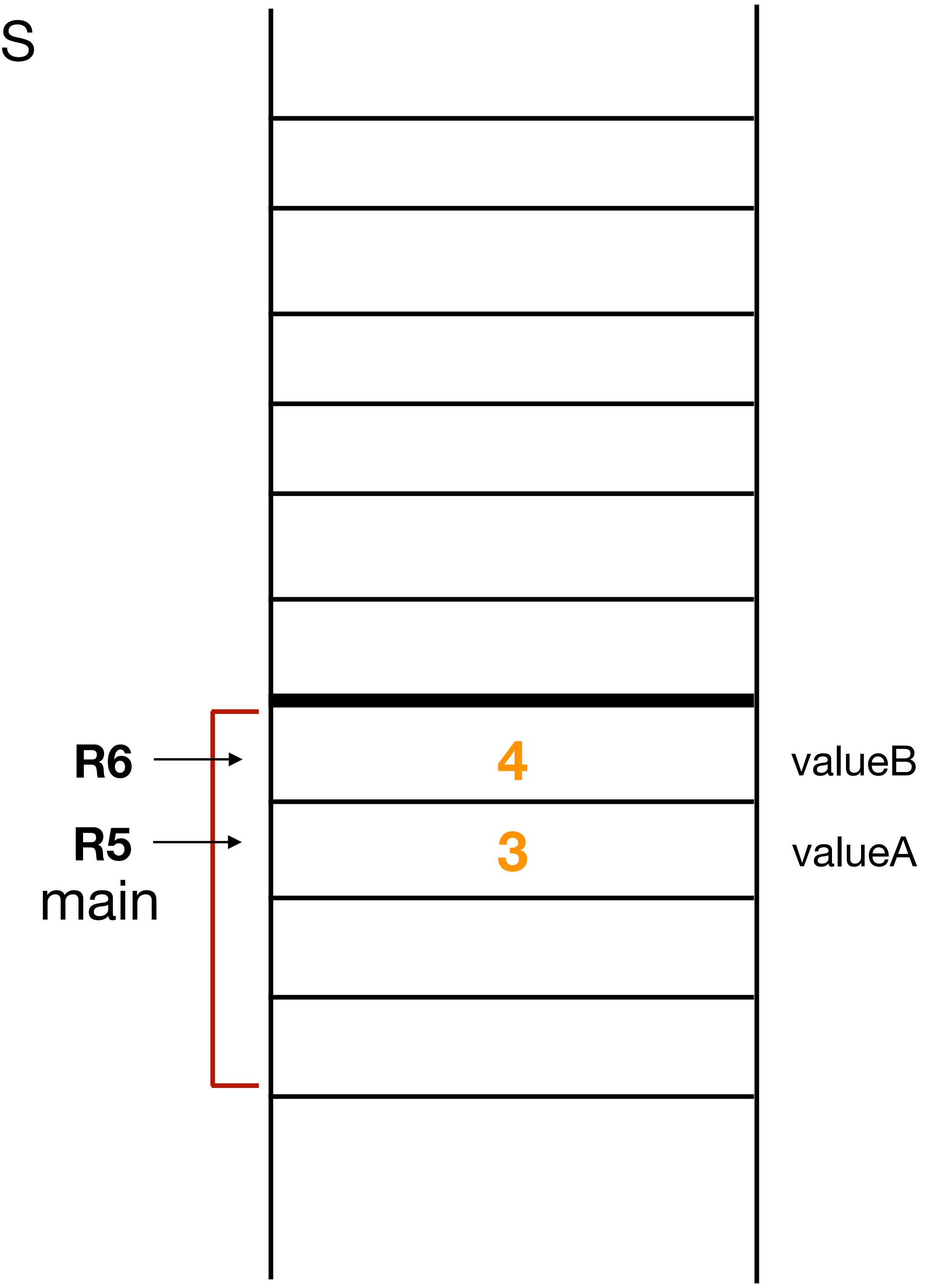
```
void Swap(int first, int second);

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

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

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

Before call



Goal:
Swap valueA and valueB in main.

Exercise: build the activation frame

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

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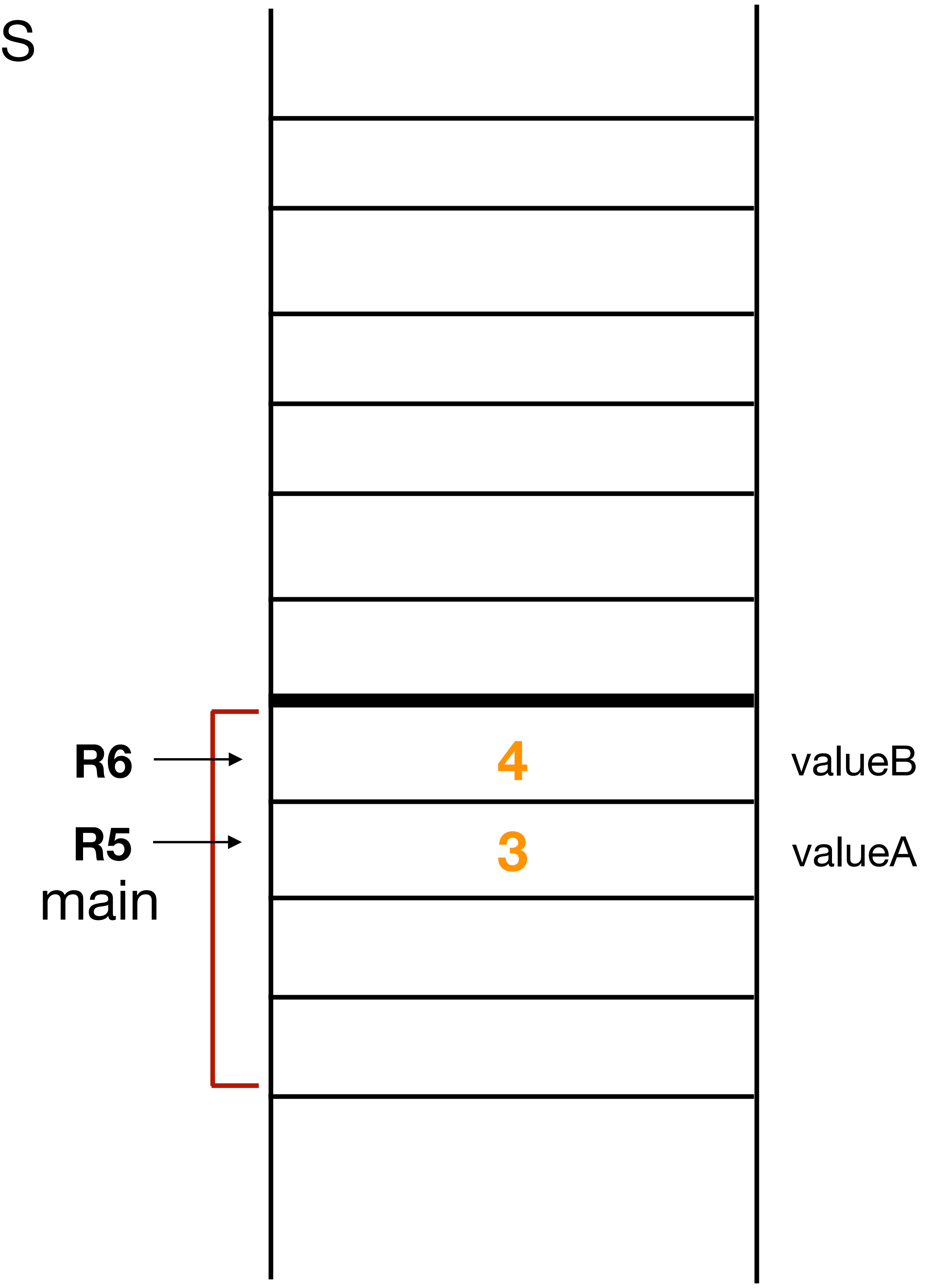
   int valueB = 4;
   Swap(valueA, valueB);
}

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

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

Before call



Goal:
`Swap valueA and valueB in main.`

Exercise: build the activation frame

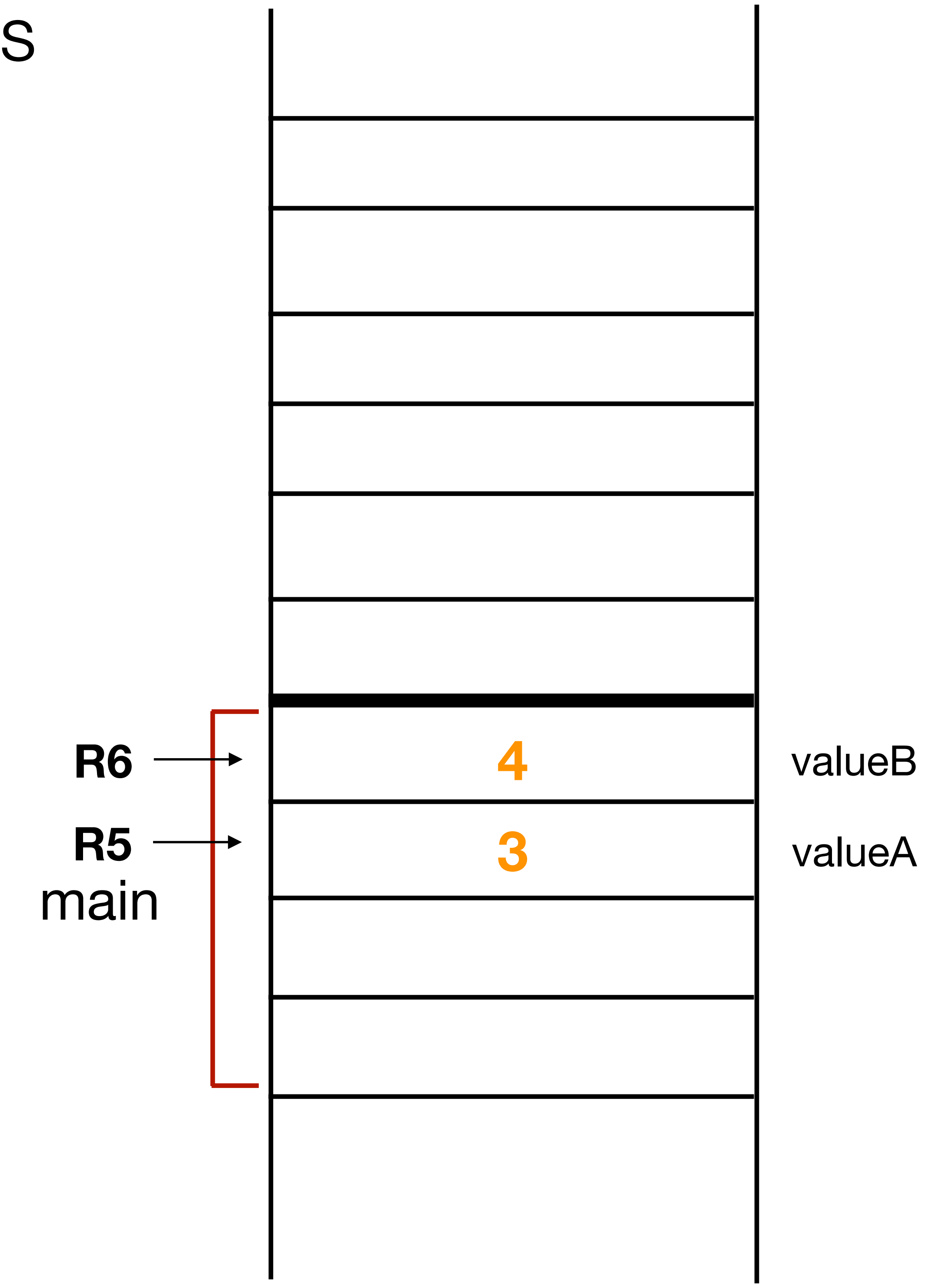
```
void Swap(int first, int second);

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
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

Before call



Goal:

Swap valueA and valueB in main.

Exercise: build the activation frame

```
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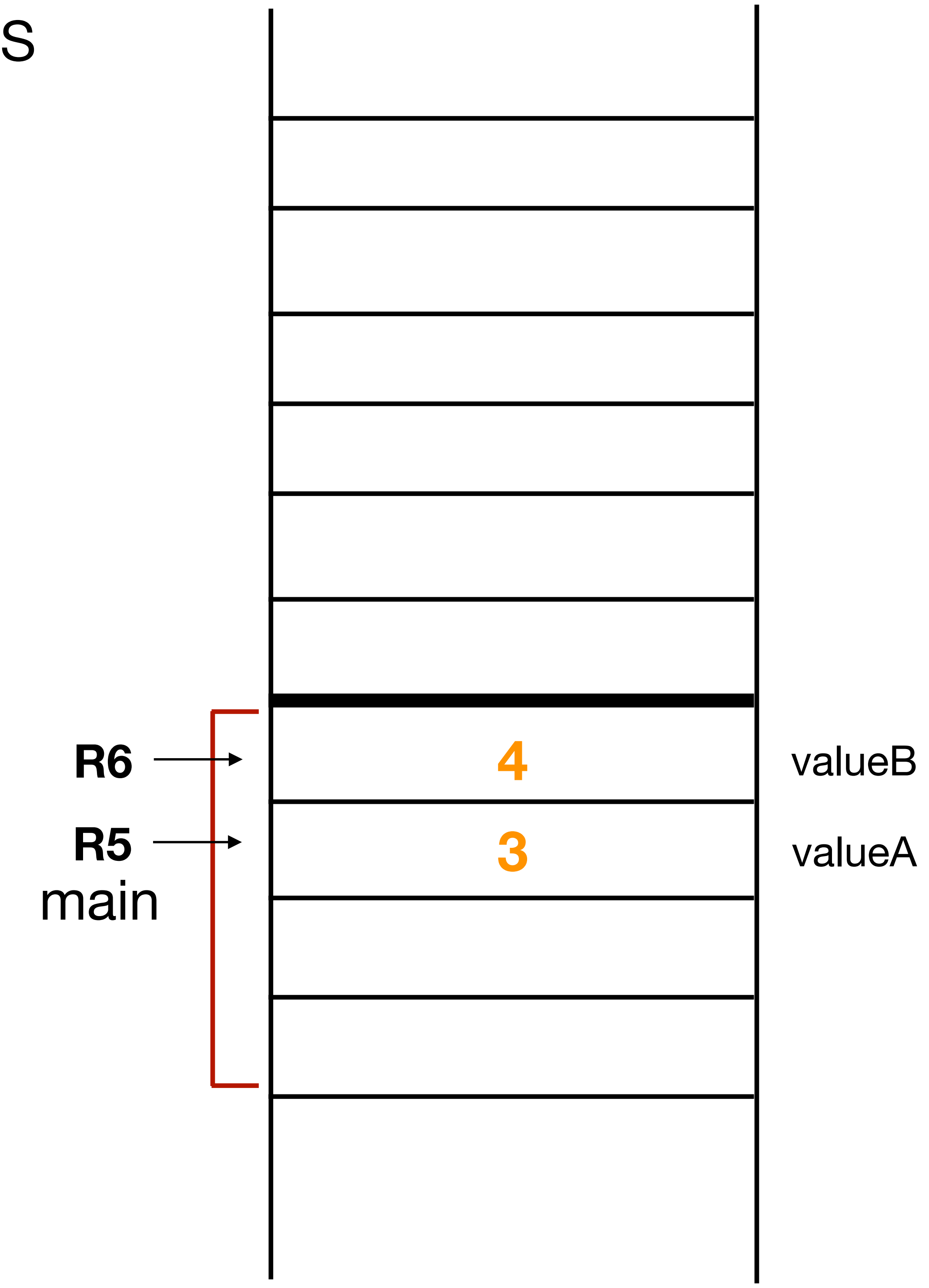
}

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

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

Before call



Goal:
Swap valueA and valueB in main.

`swap` function - build up

Build up

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

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

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

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

`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)
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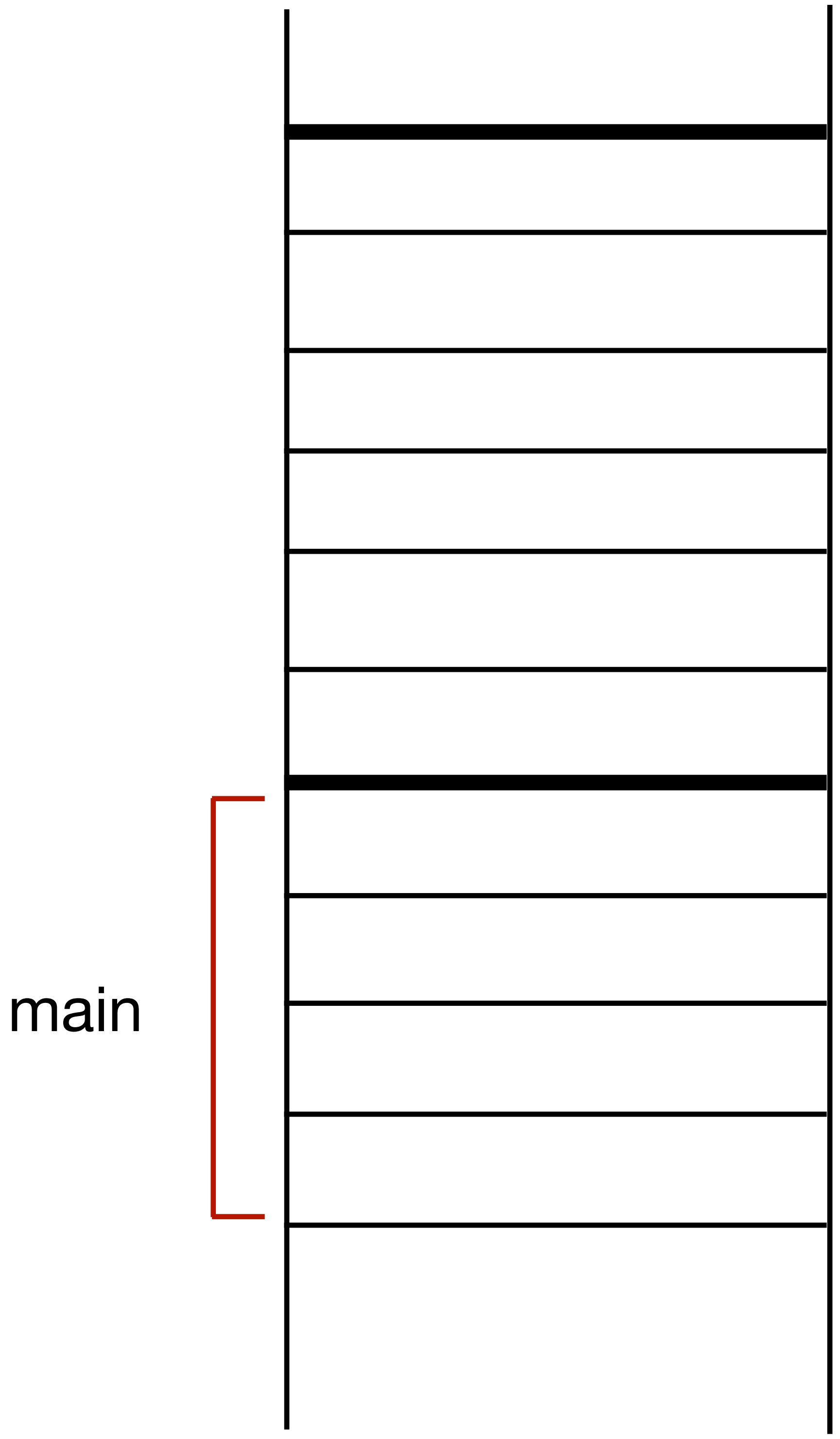
   - D. Local variables
4. Execute
5. Callee tear down
   - E. Update return value
   - F. Pop local variables
   - G. Pop CFP (into R5)
   - H. Pop return address (into R7)
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Build up



```
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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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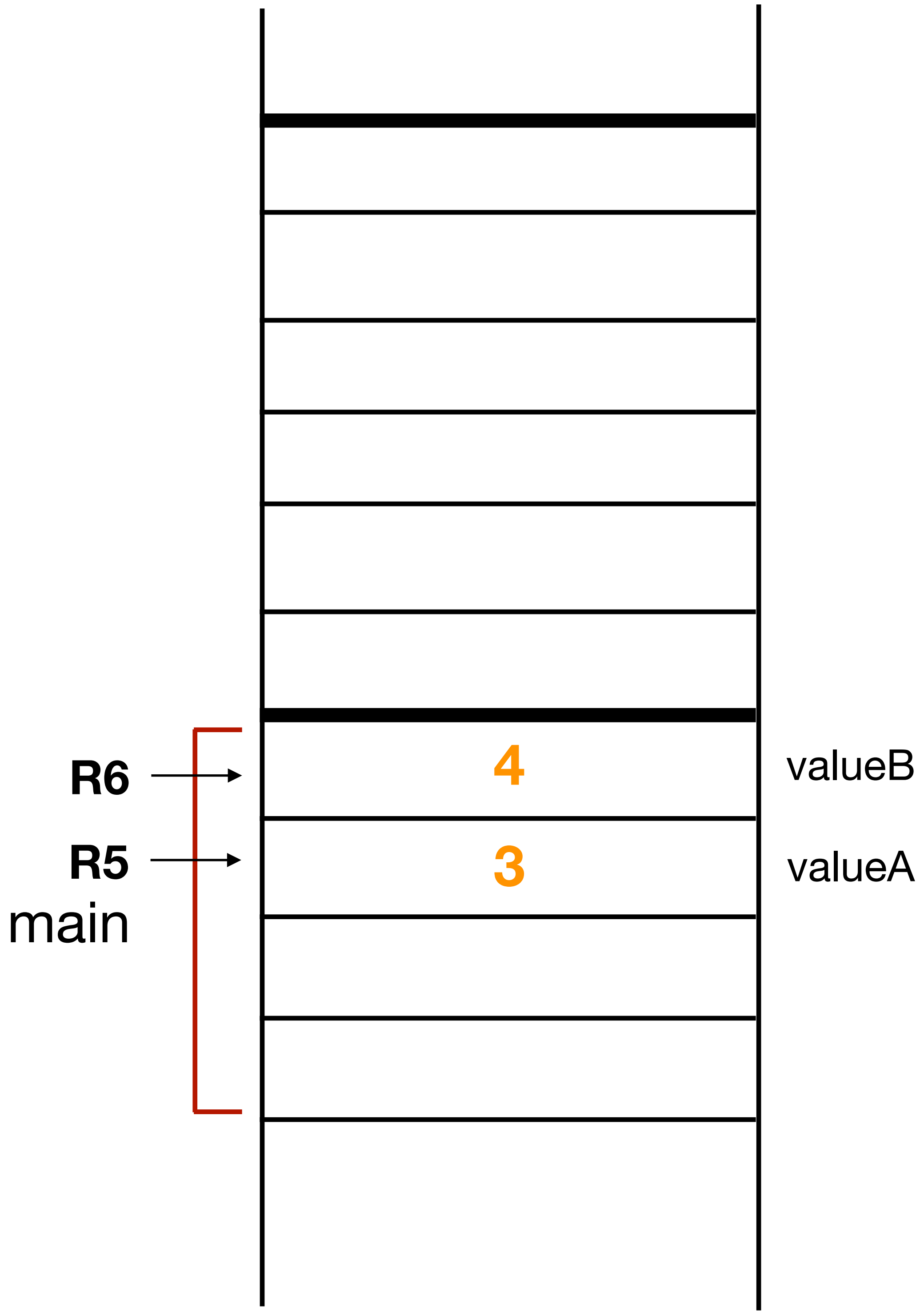
}
```

`swap` function - build up

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

Build up



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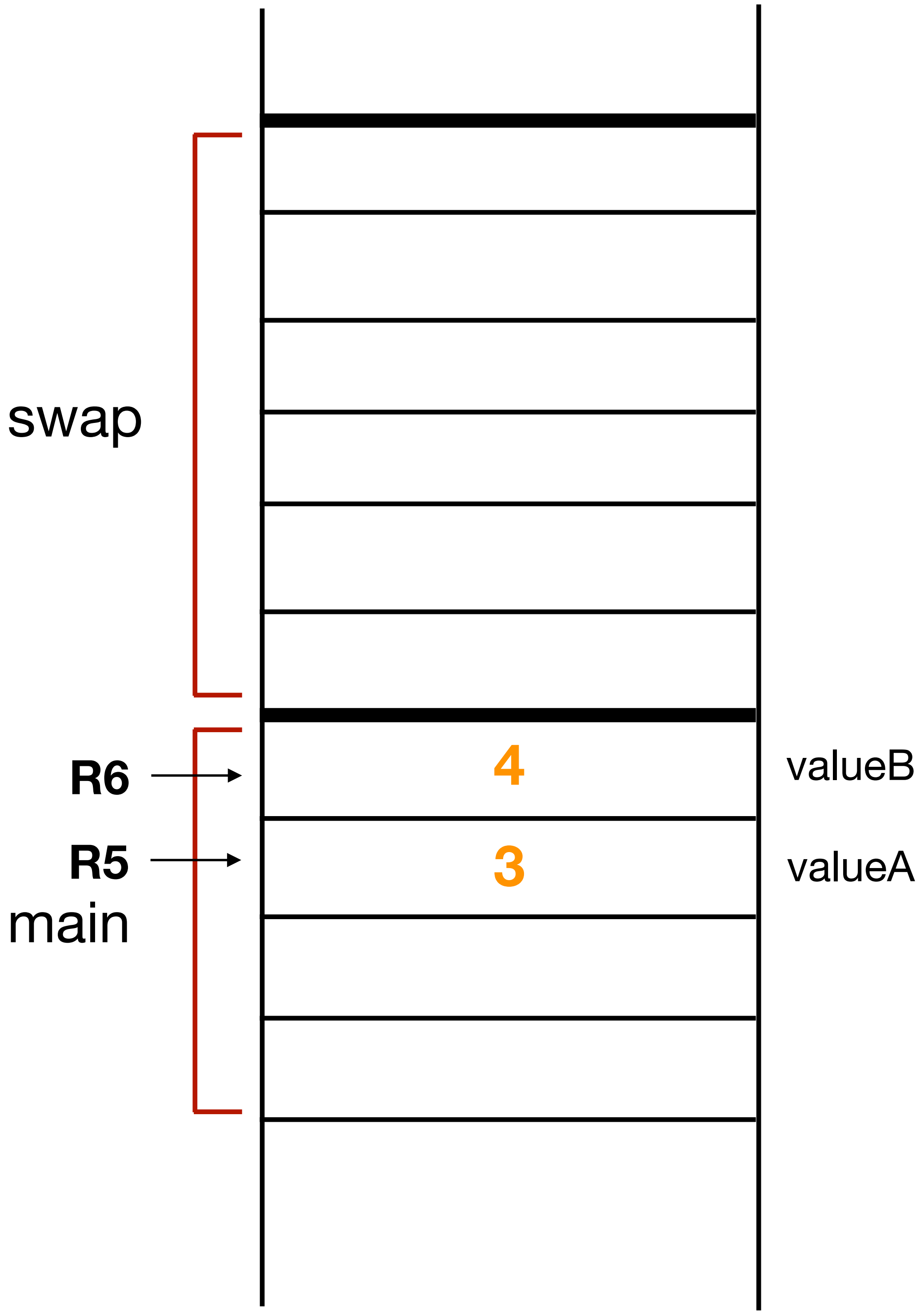
   Swap(valueA, valueB);
}

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

`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
    - 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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   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)
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4. Execute
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   - E. Update return value
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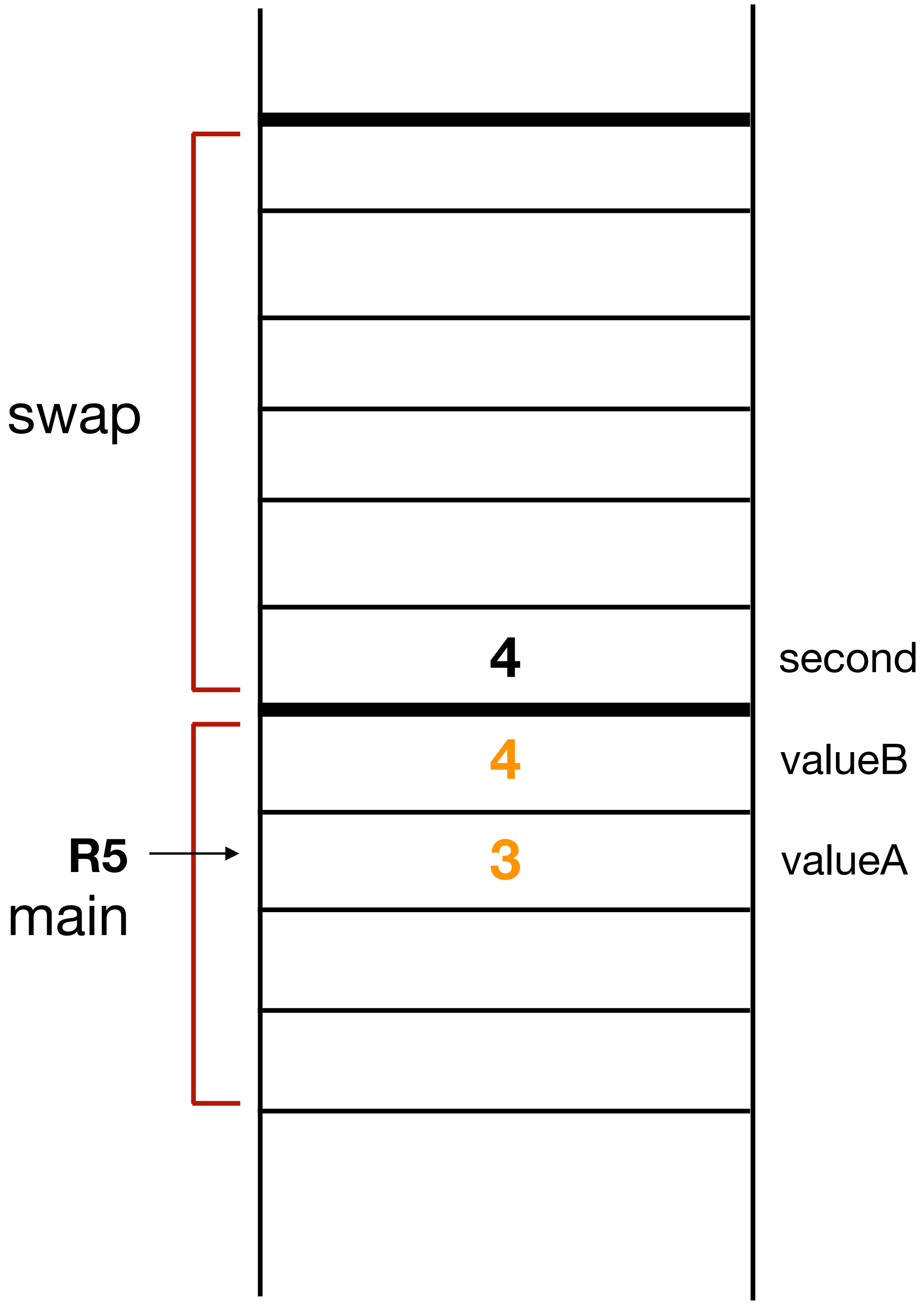
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Build up



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

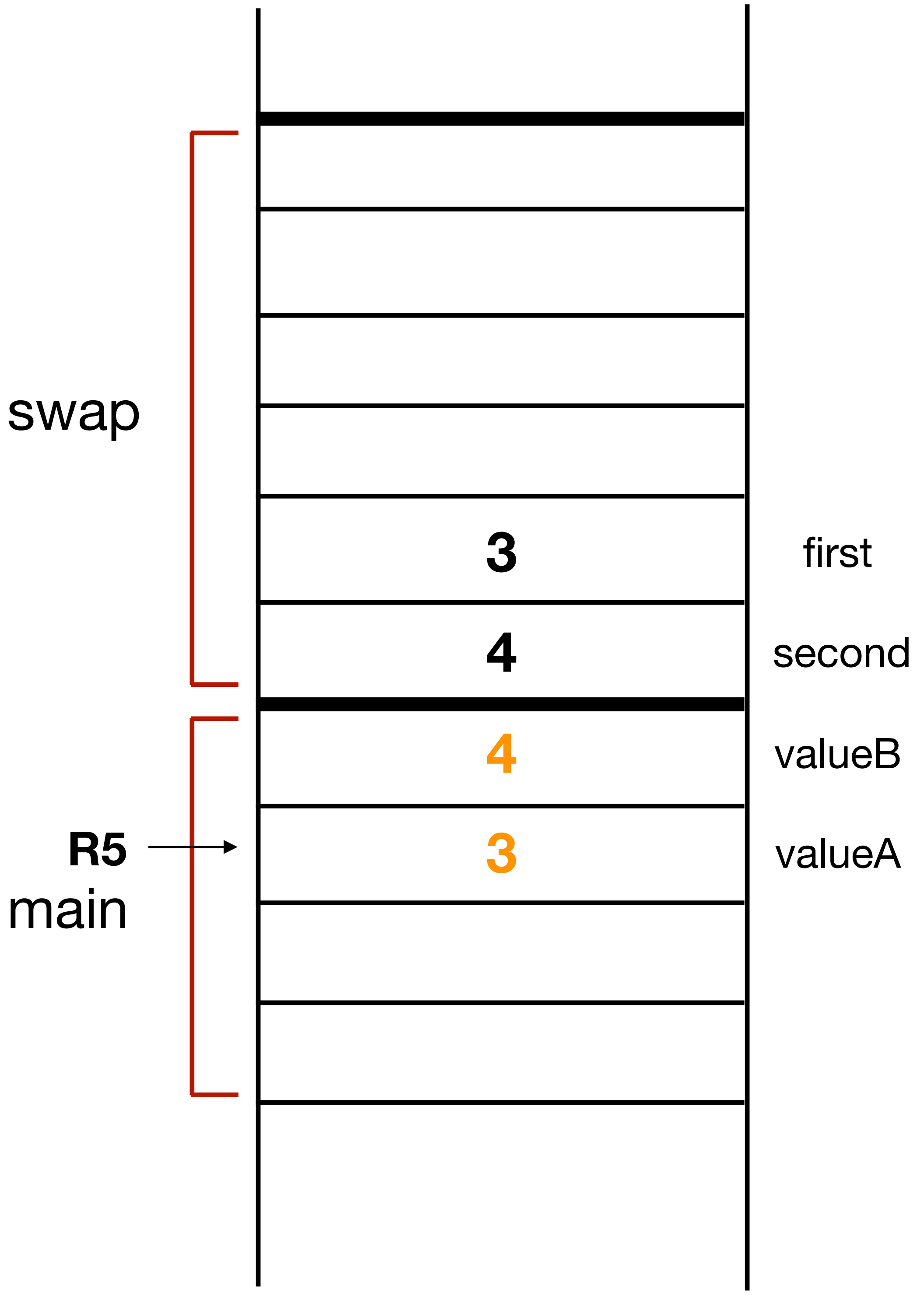
void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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

`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
   - 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



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

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

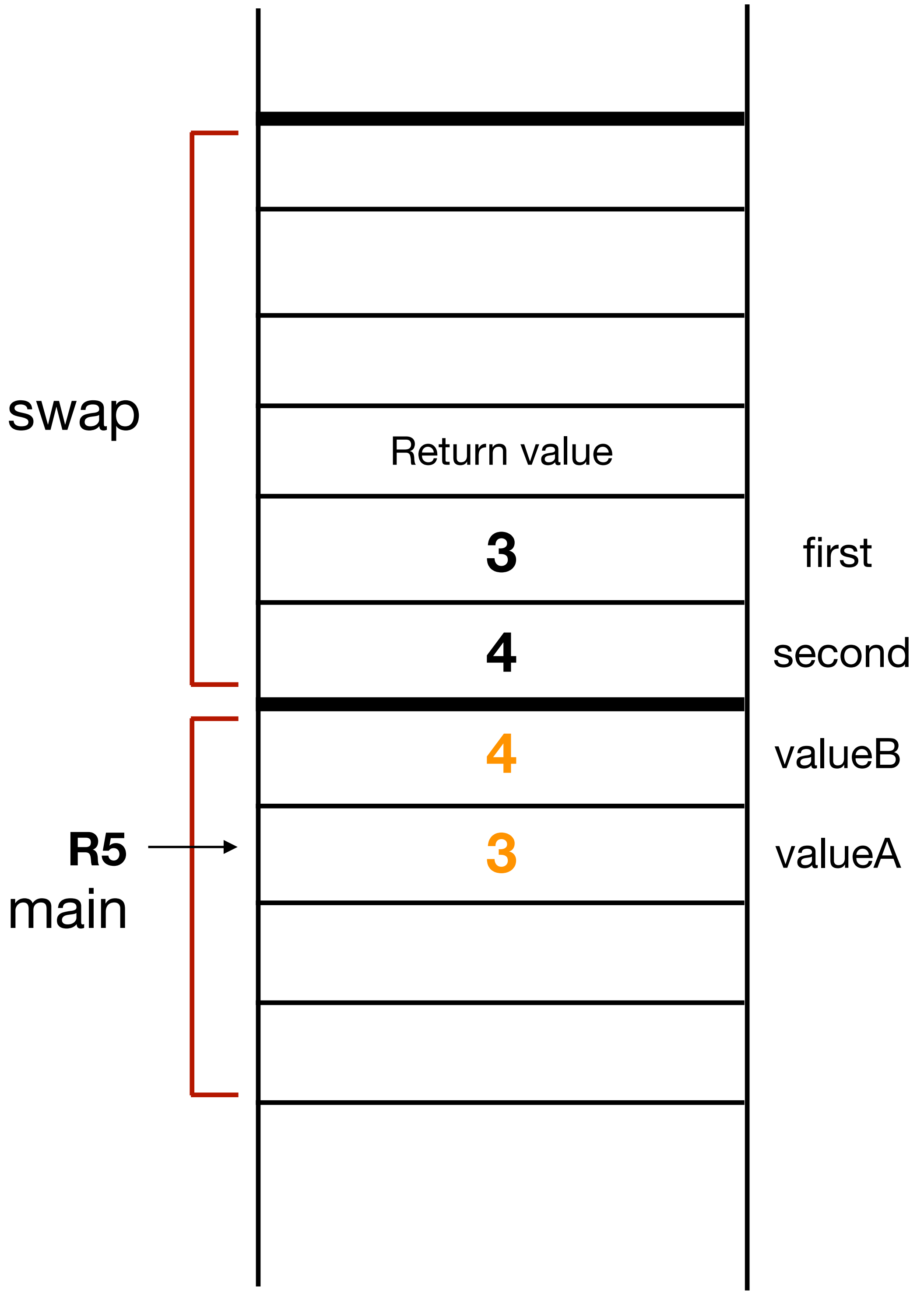
void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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

`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
   - 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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int main(){
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   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

`swap` function - build up

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    E. Update return value
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    G. Pop CFP (into R5)
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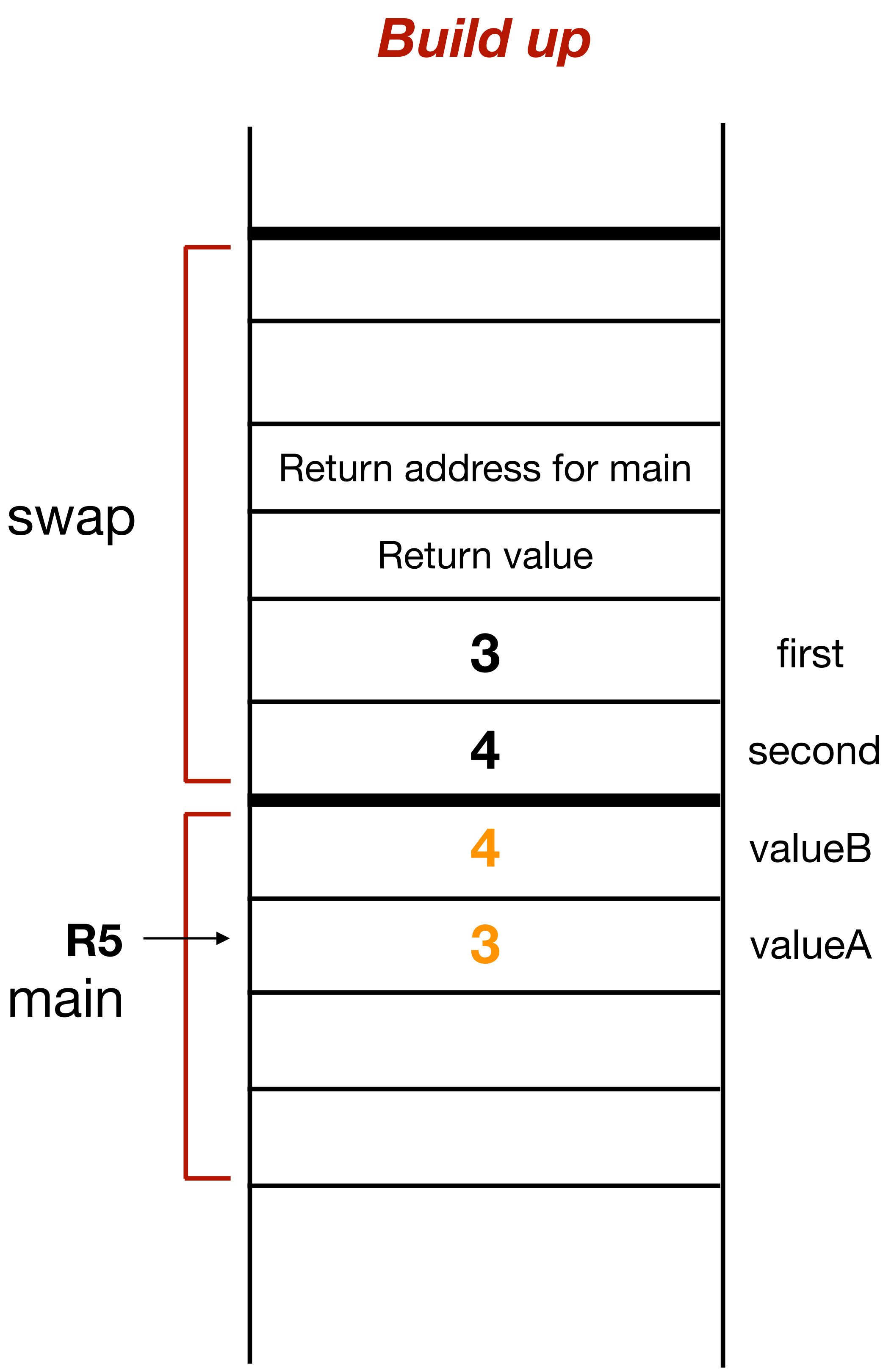
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments



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

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

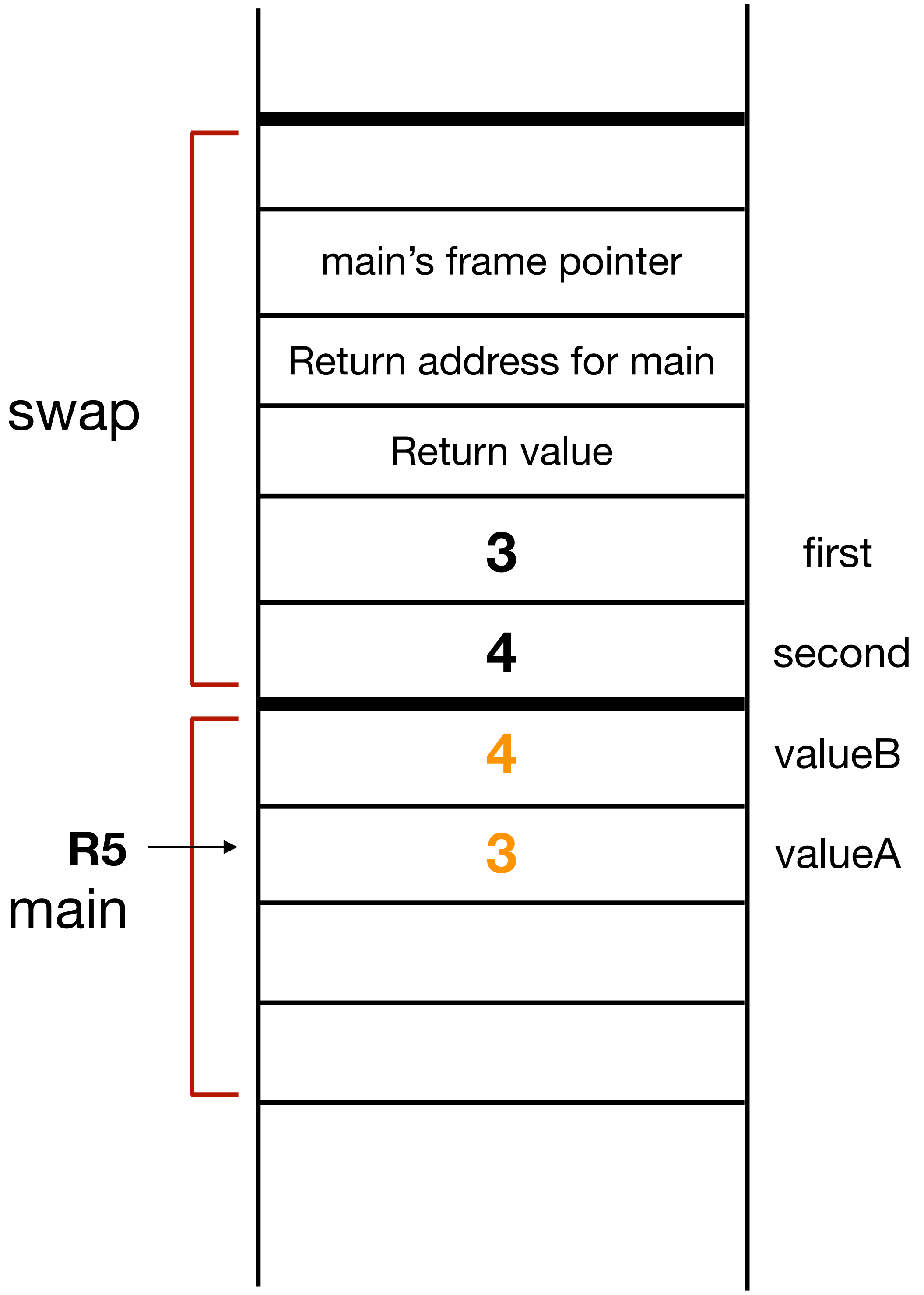
void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

```
ADD 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
    - 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



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

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

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

```
ADD R6, R6, #-1
STR R5, 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)
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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
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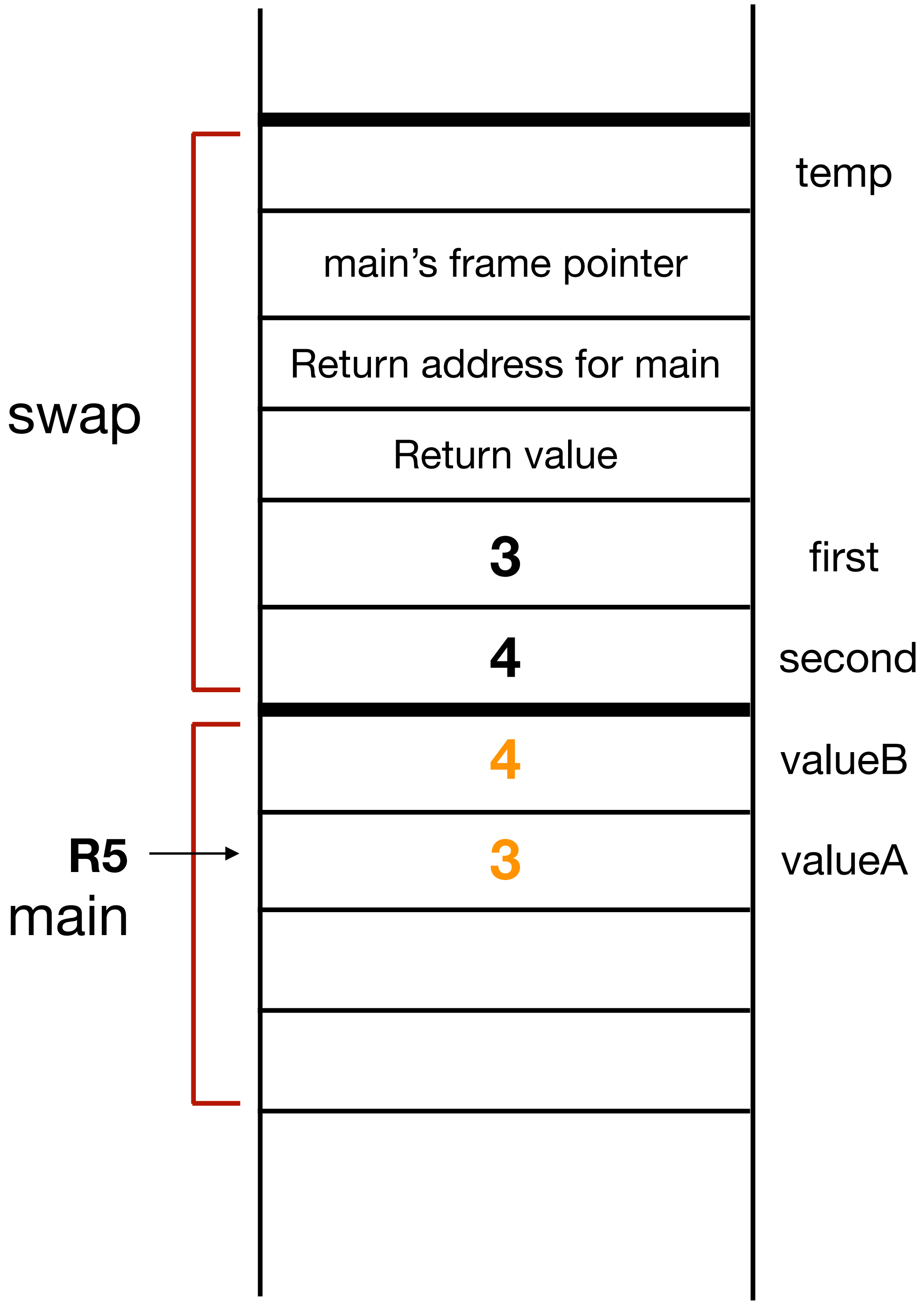
   - I. Pop return value
   - J. Pop arguments

Build up



```
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int main(){
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   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)
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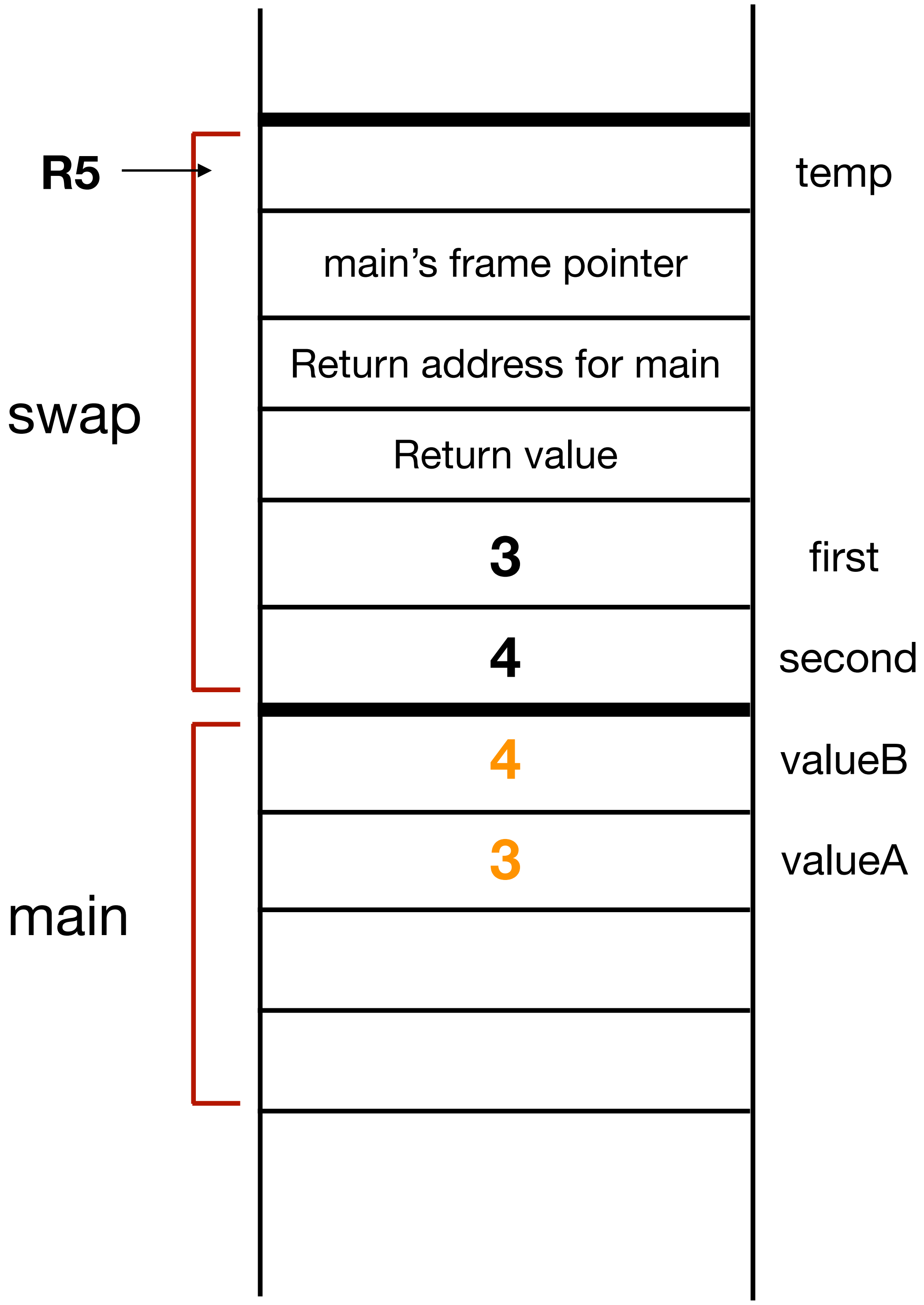
   - E. Update return value
   - F. Pop local variables
   - G. Pop CFP (into R5)
   - H. Pop return address (into R7)
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Build up



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

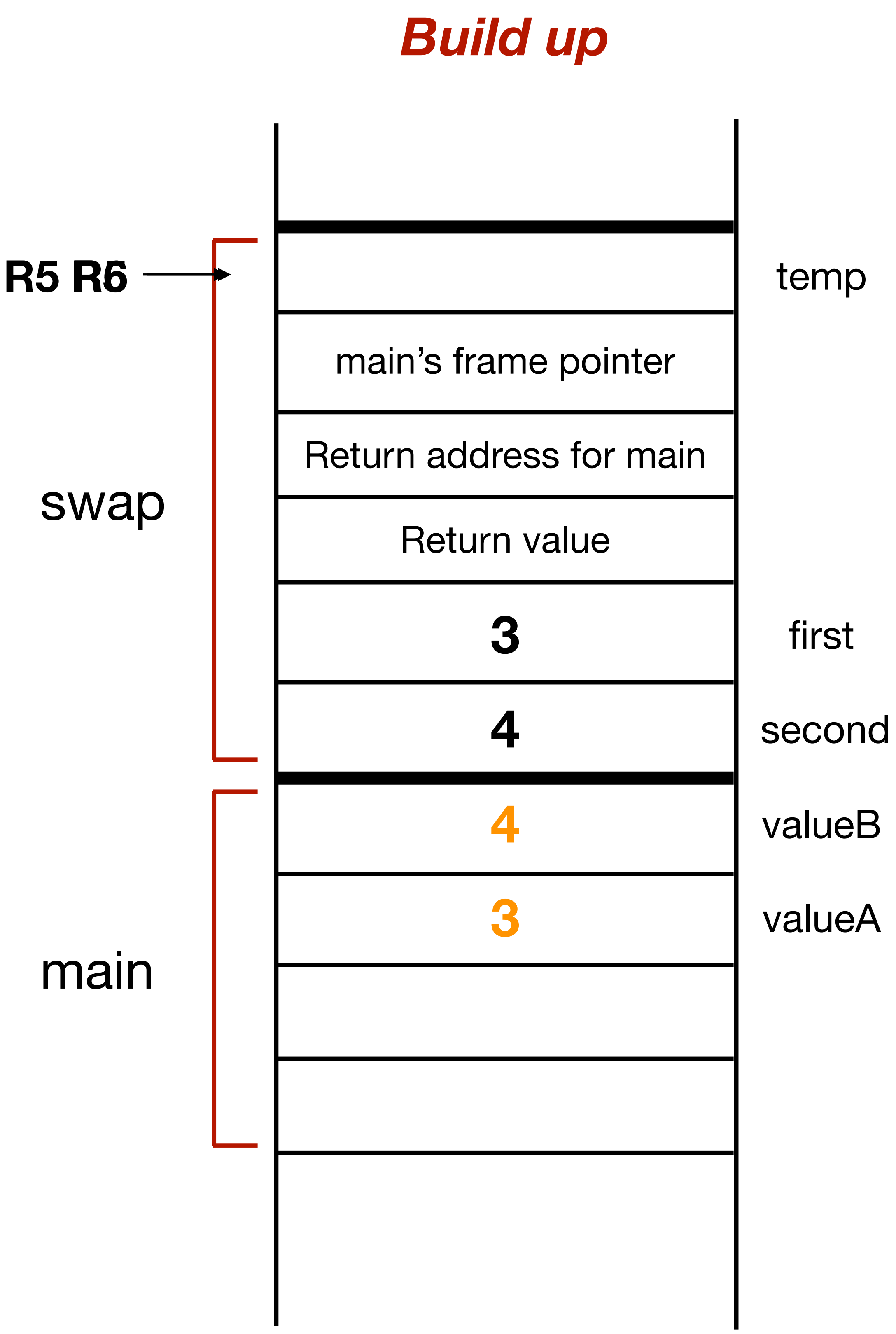
int main(){
   int valueA = 3;
   int valueB = 4;
   Swap(valueA, valueB);
}

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

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

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



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

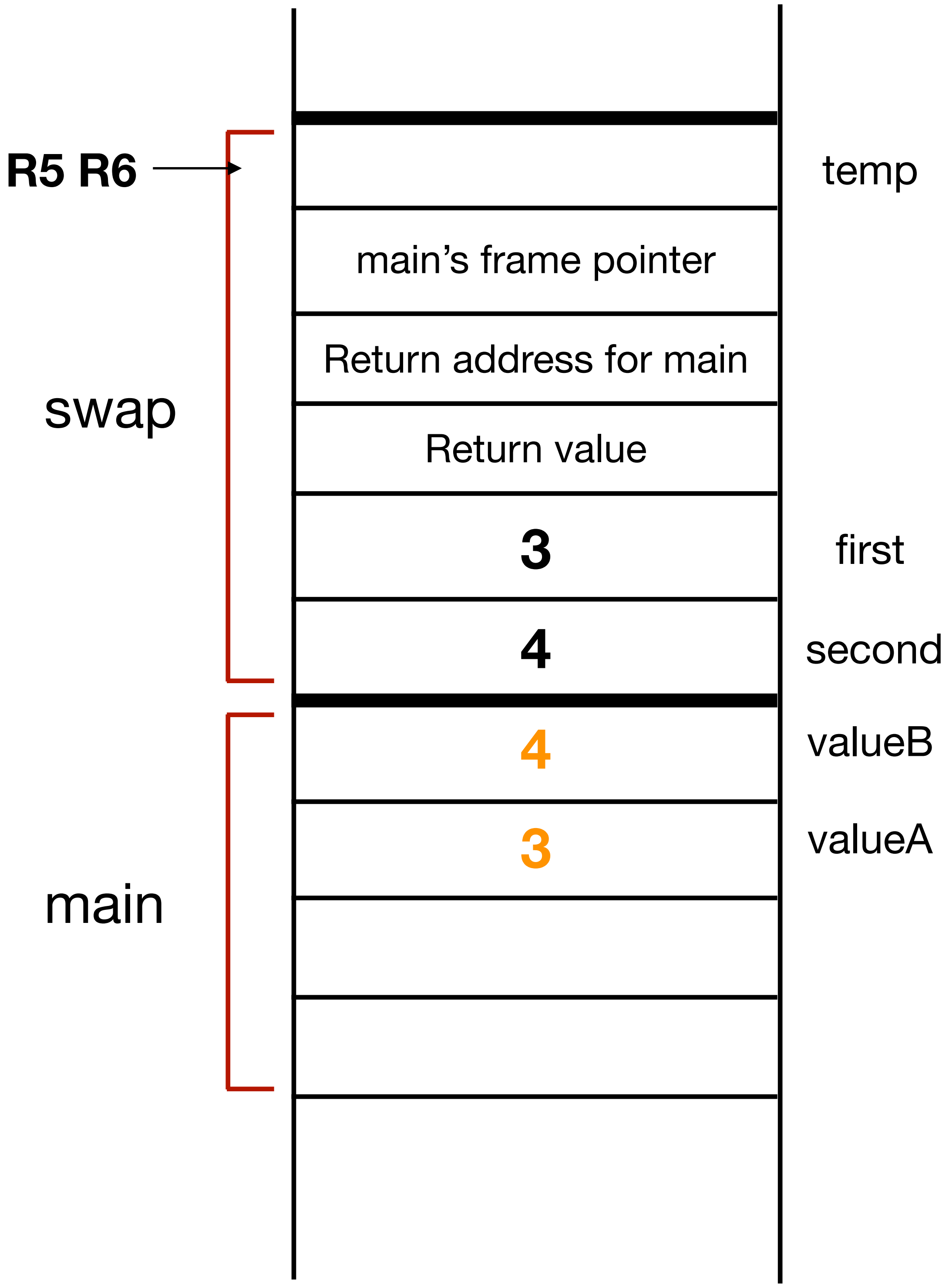
void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

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

swap function - execute

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

Execution



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

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`swap` function - execute

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   B. Return address (from R7)
   C. Caller frame pointer (CFP)
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   F. Pop local variables
   G. Pop CFP (into R5)
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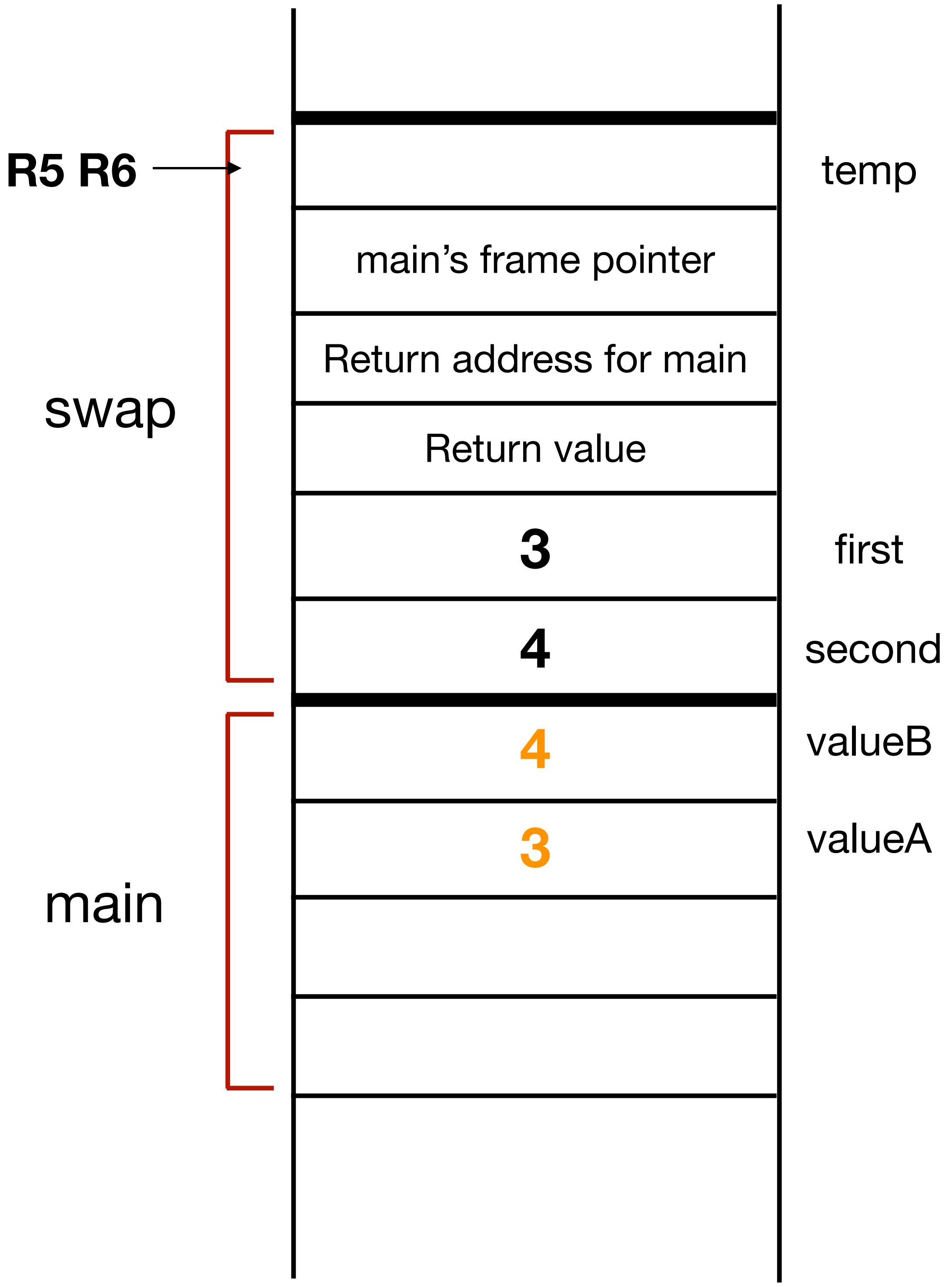
   I. Pop return value
   J. Pop arguments

Execution



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   second = temp;
}
```

`swap` function - execute

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    A. Return value (allocate)
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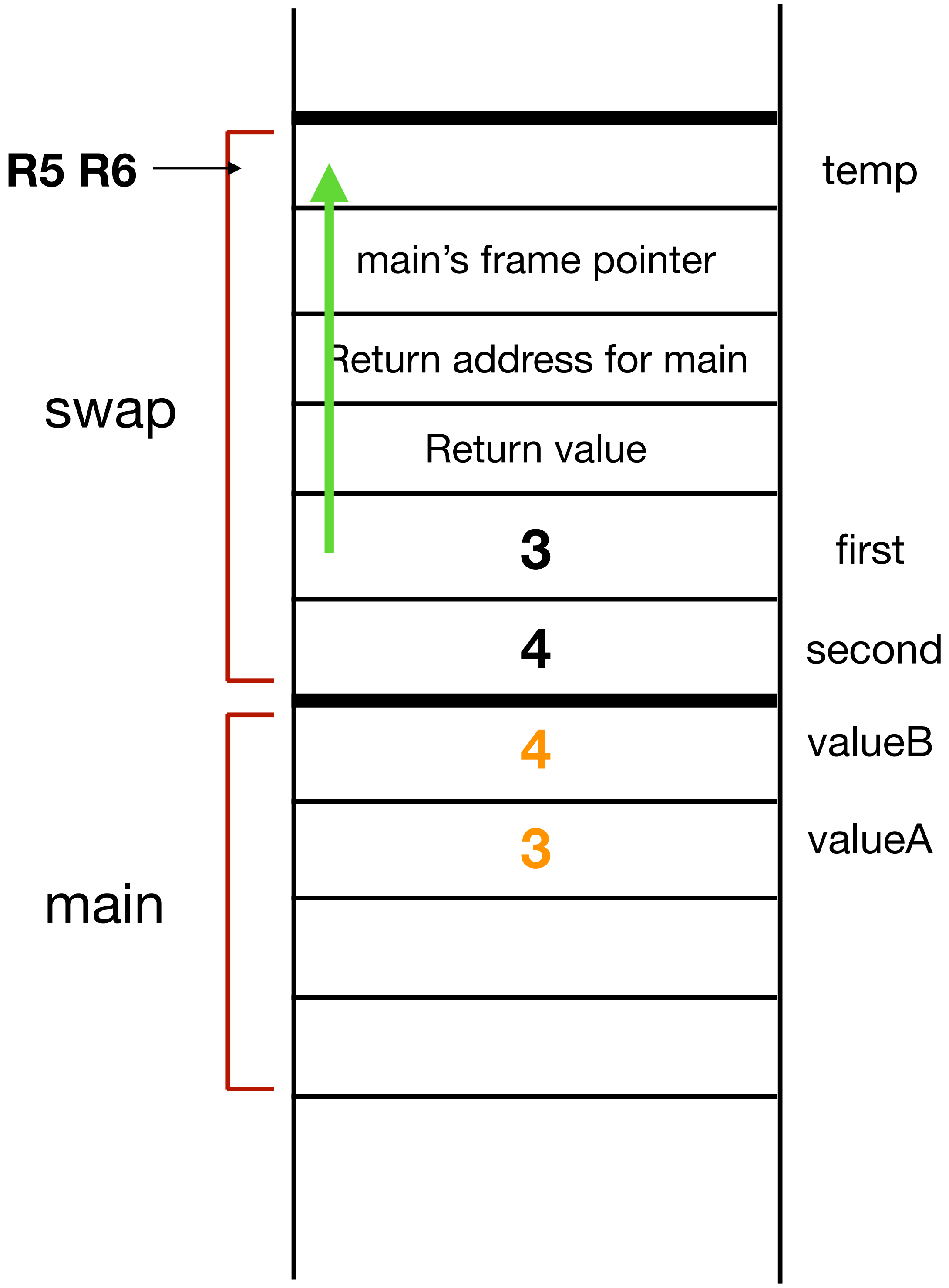
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Execution



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}

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   second = temp;
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```

`swap` function - execute

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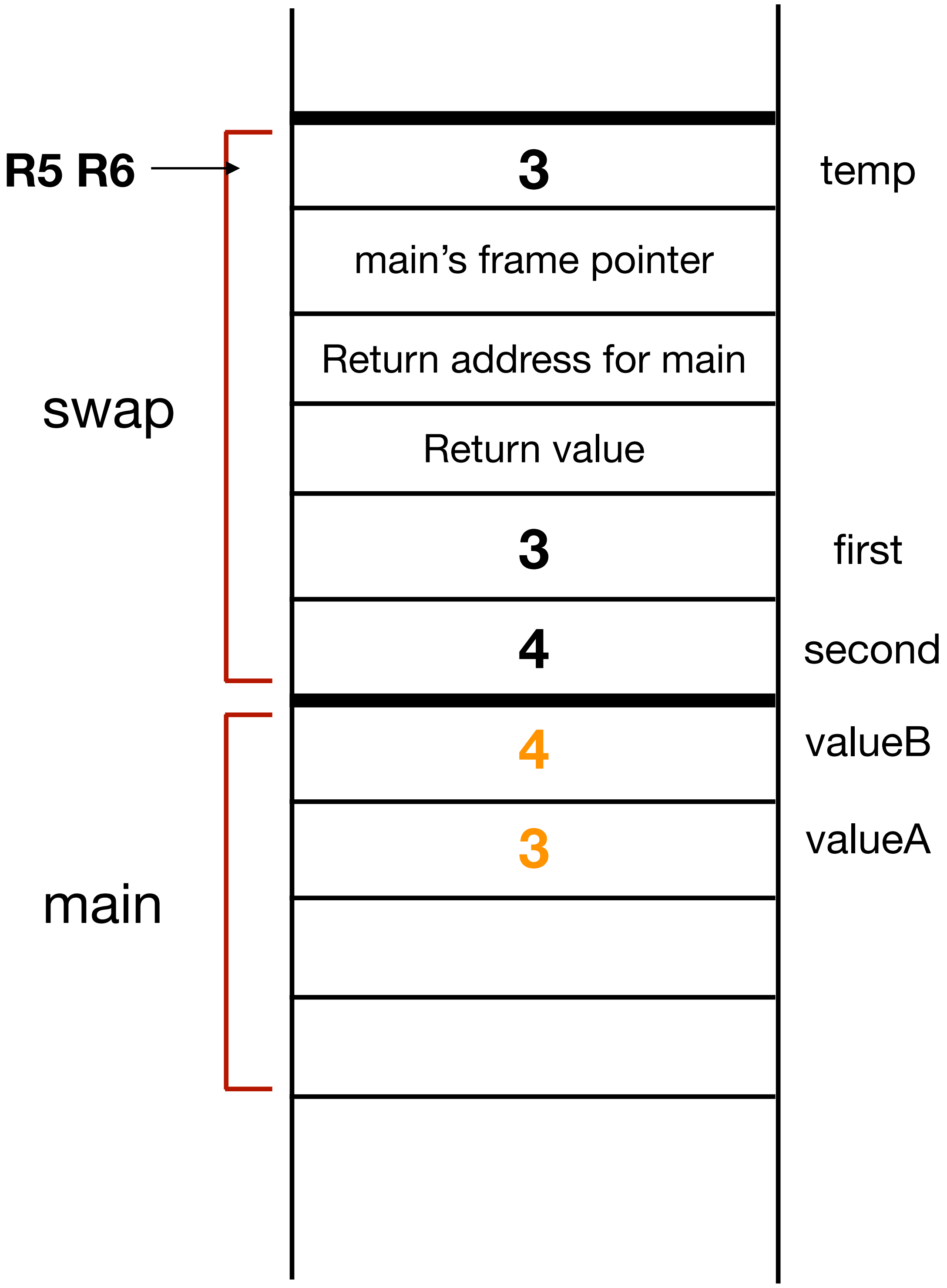
    I. Pop return value
    J. Pop arguments

Execution



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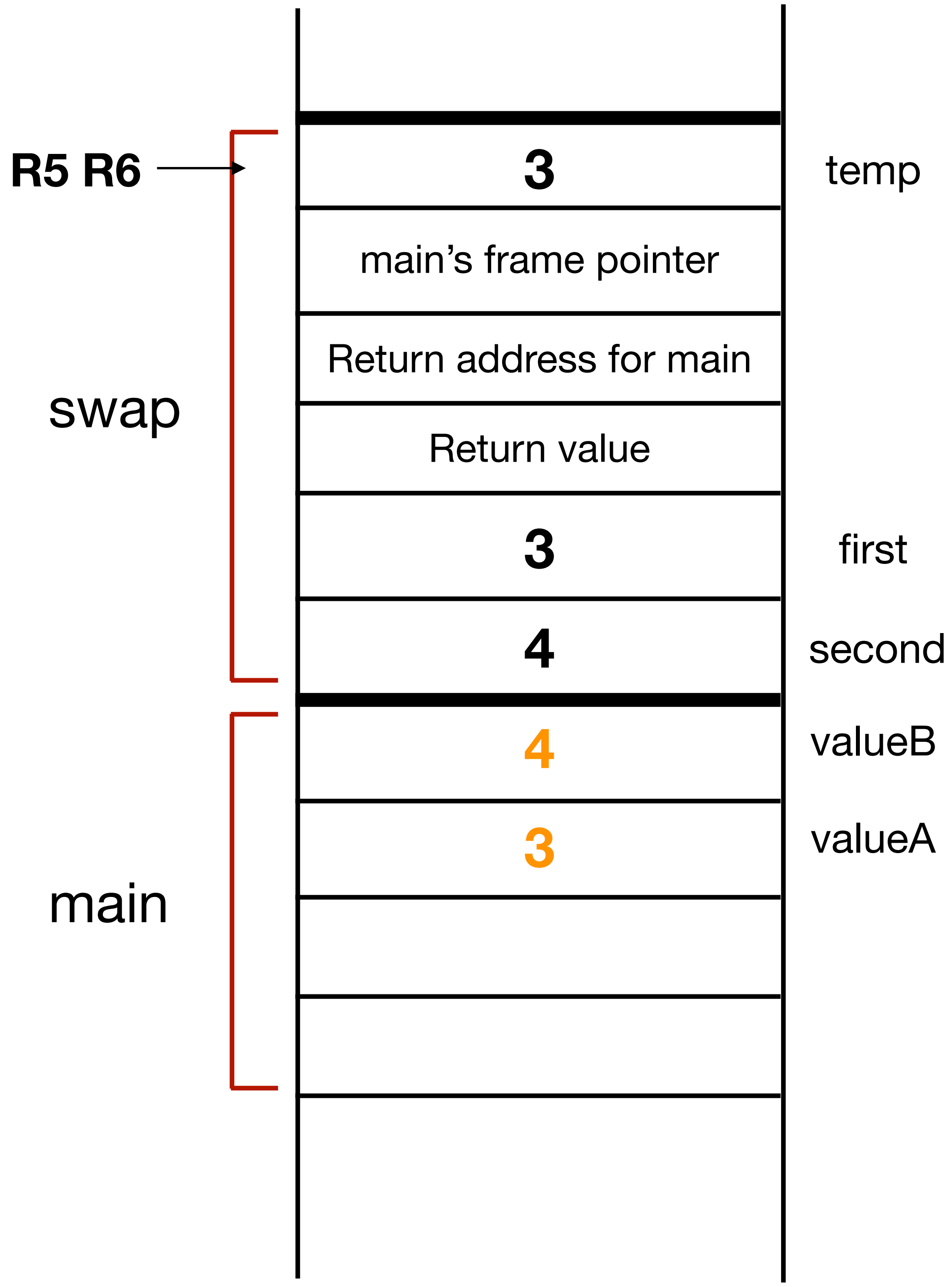
    - I. Pop return value
    - J. Pop arguments

Execution



R5 R6

swap

3 temp

main's frame pointer

Return address for main

Return value

3 first

4 second

main

4 valueB

3 valueA

```
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 - execute

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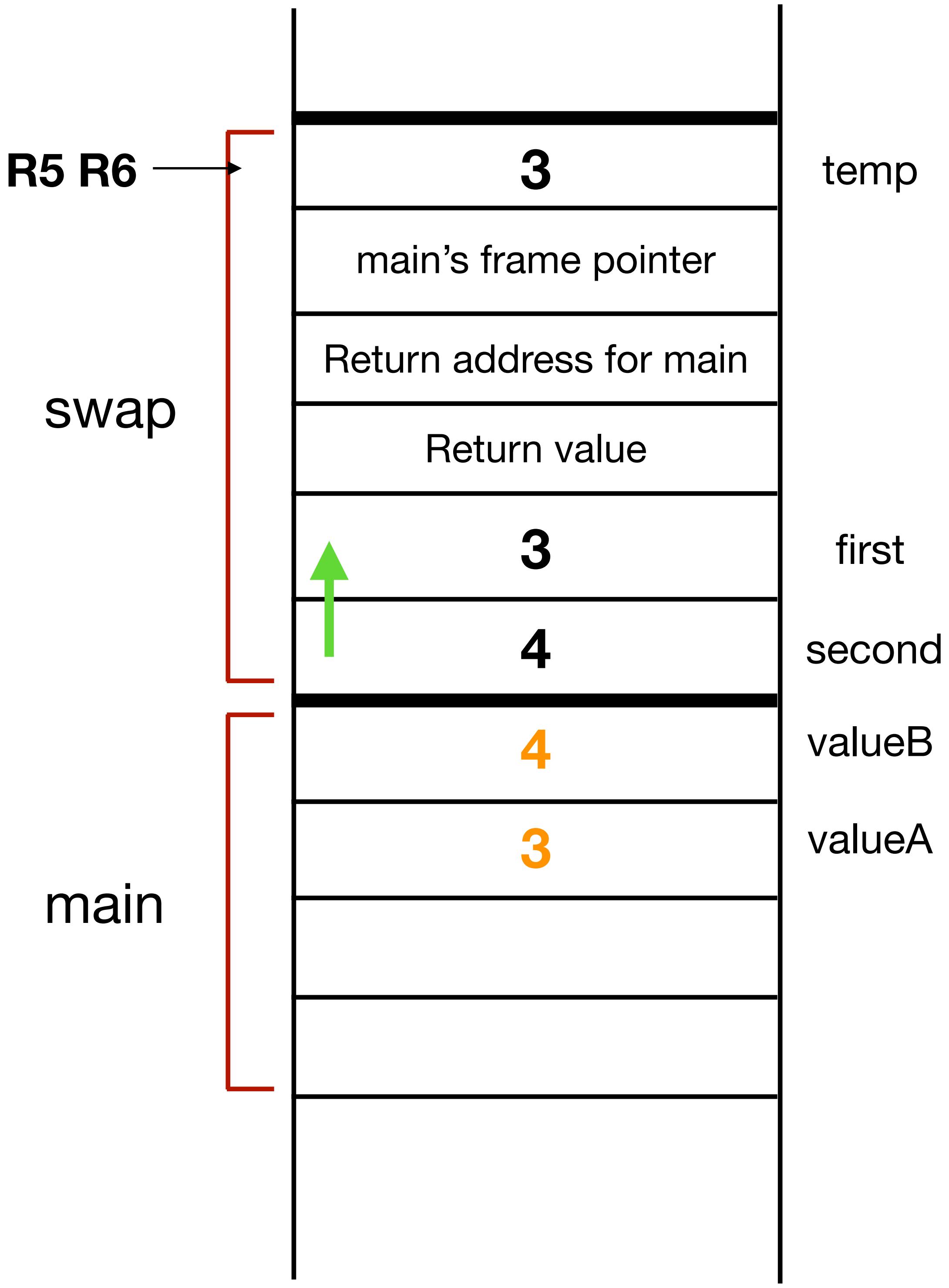
    E. Update return value
    F. Pop local variables
    G. Pop CFP (into R5)
    H. Pop return address (into R7)
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Execution



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`swap` function - execute

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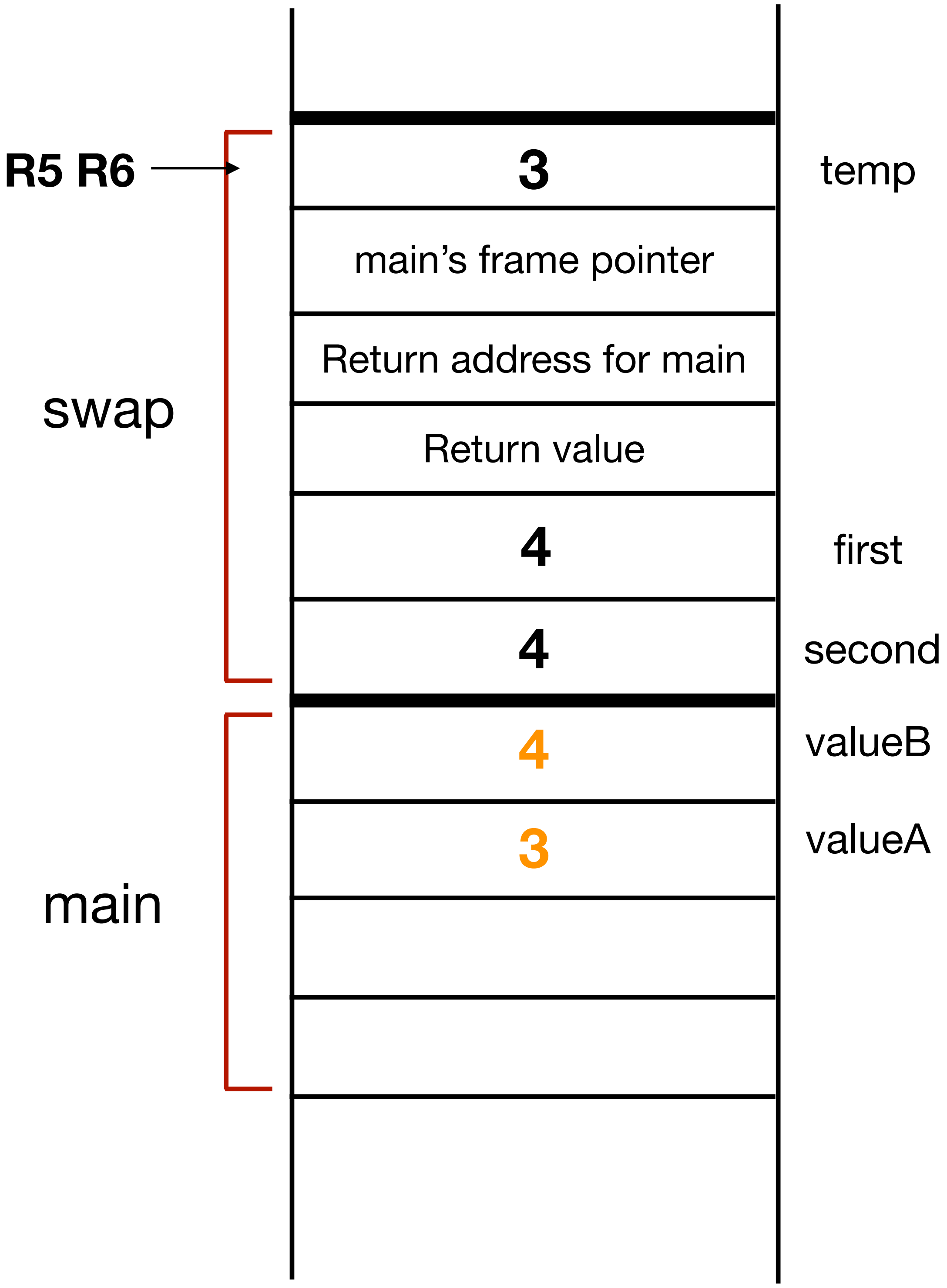
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Execution



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swap function - execute

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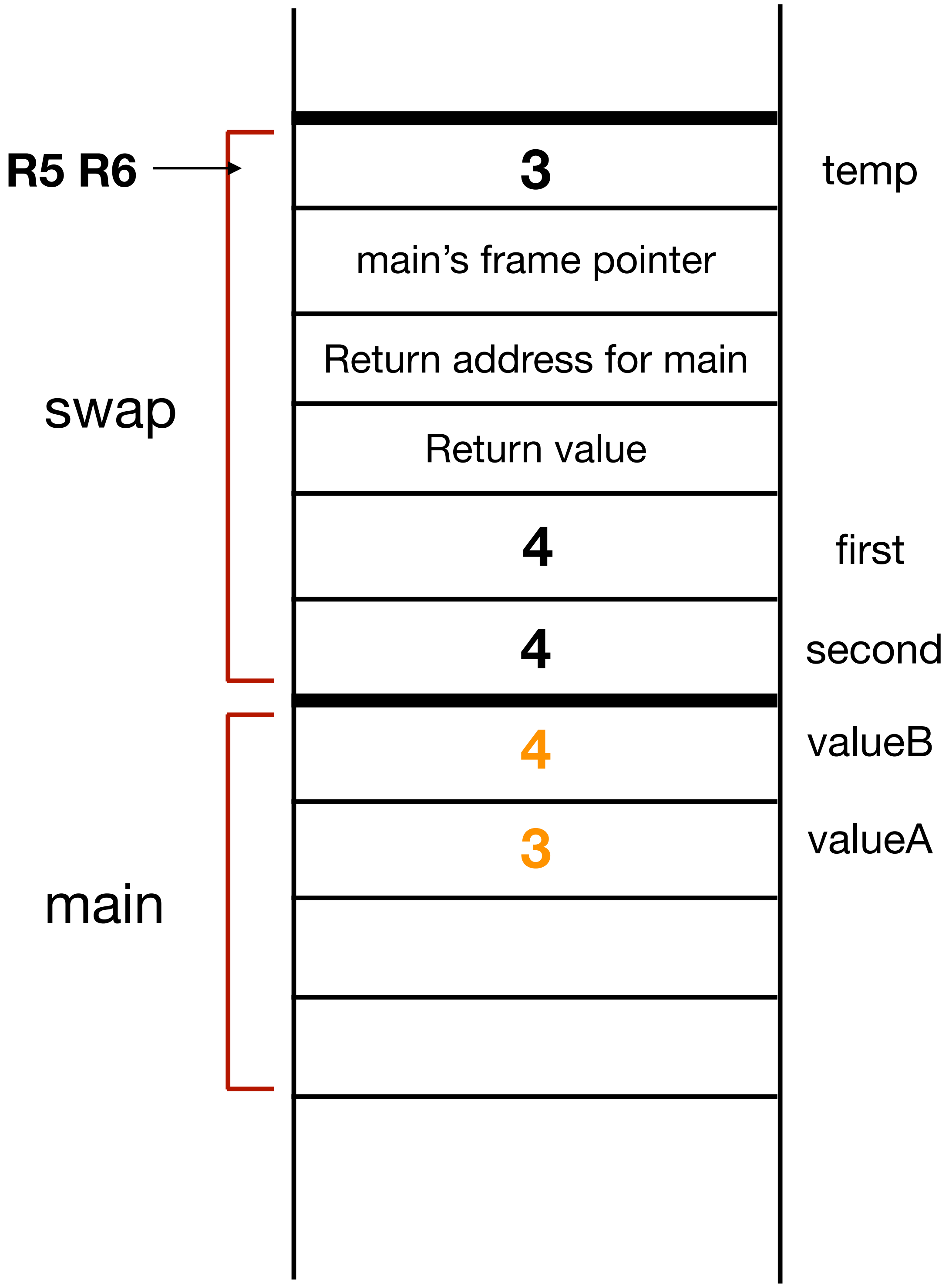
Execution



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`swap` function - execute

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   - H. Pop return address (into R7)
6. RET
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   - I. Pop return value
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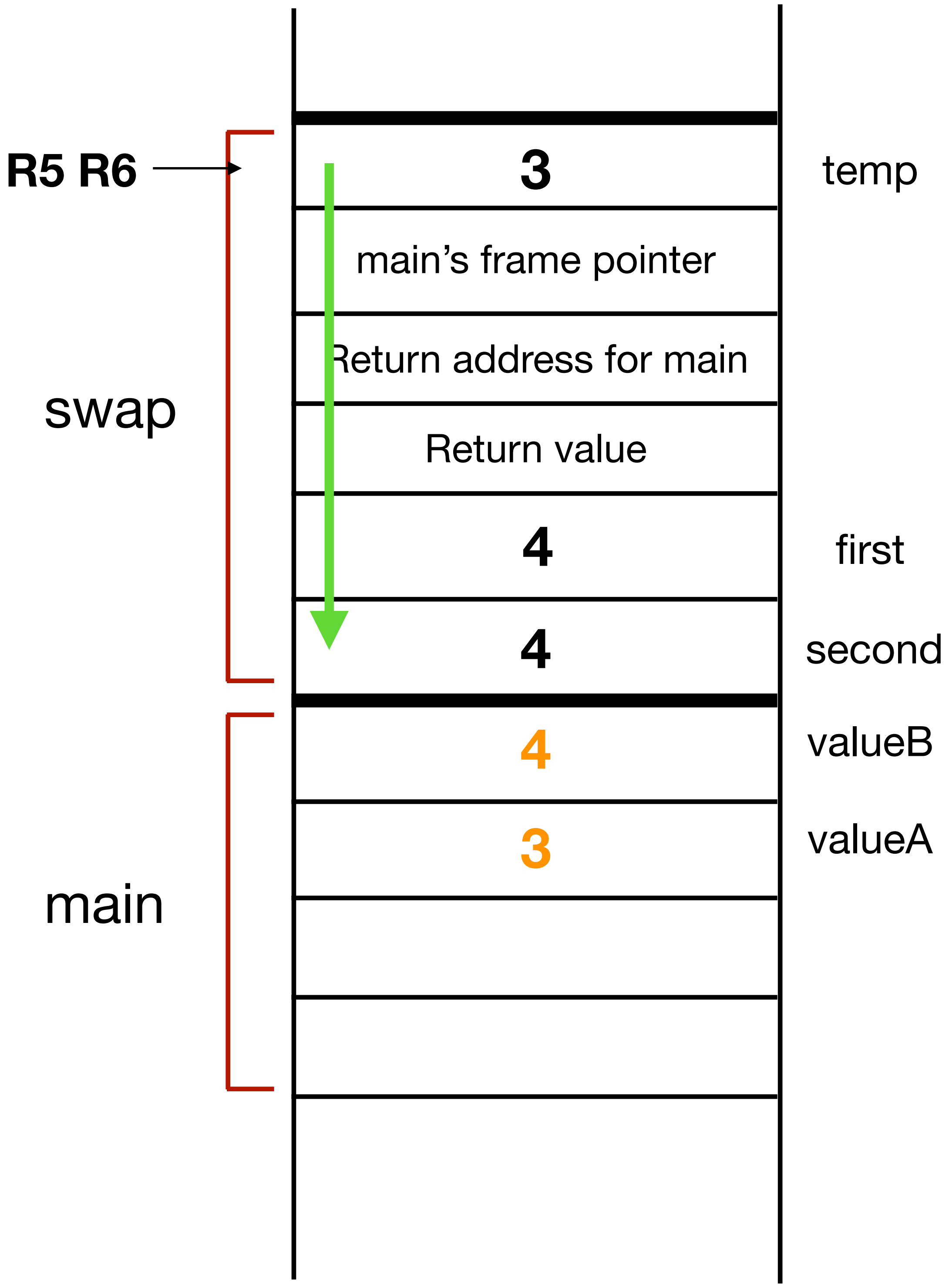
Execution



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   Swap(valueA, valueB);
}

void Swap(int first, int second){
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   second = temp;
}
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`swap` function - execute

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    E. Update return value
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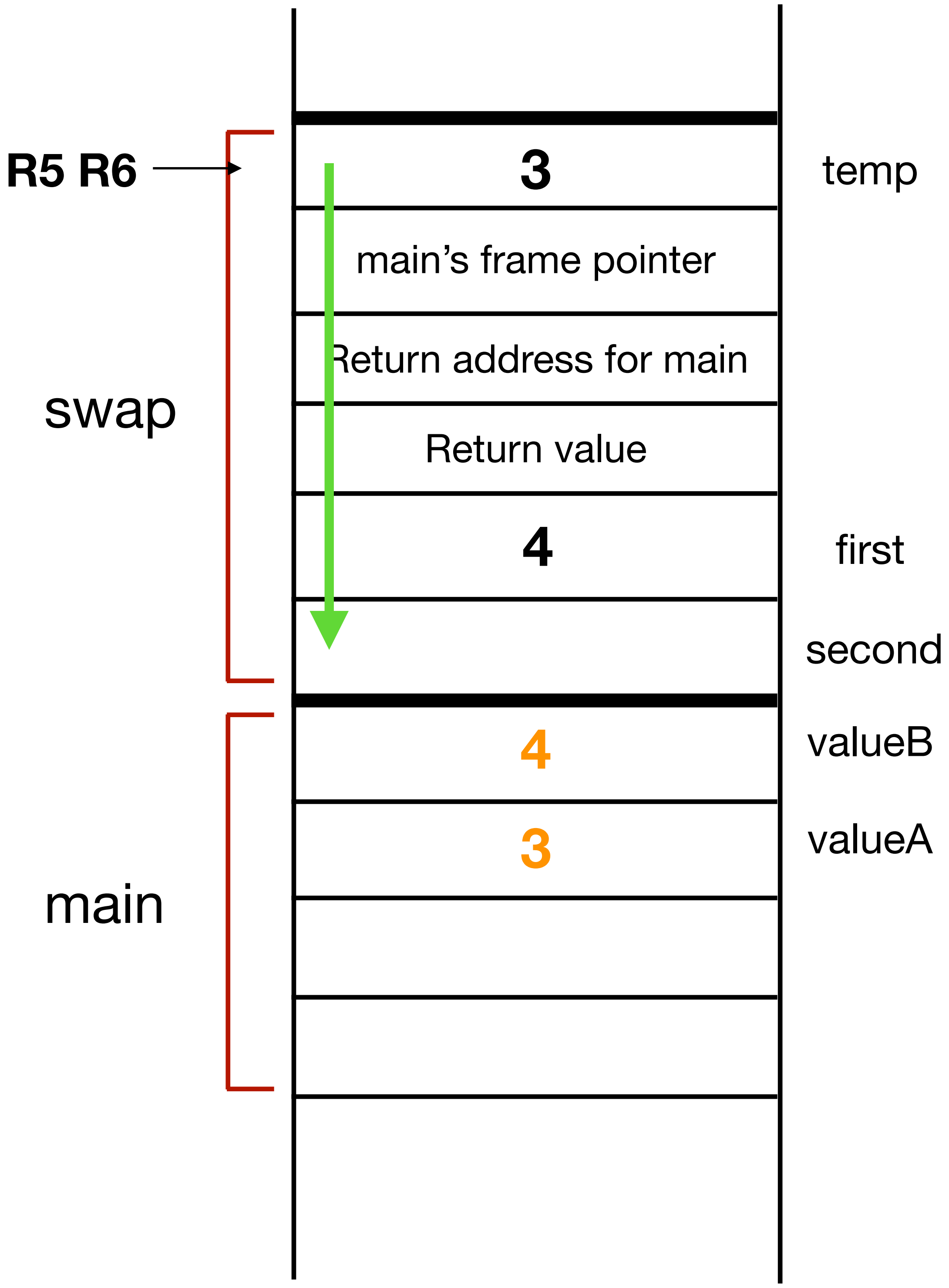
    H. Pop return address (into R7)
6. RET
7. Caller tear down
    I. Pop return value
    J. Pop arguments

Execution



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}
```

`swap` function - execute

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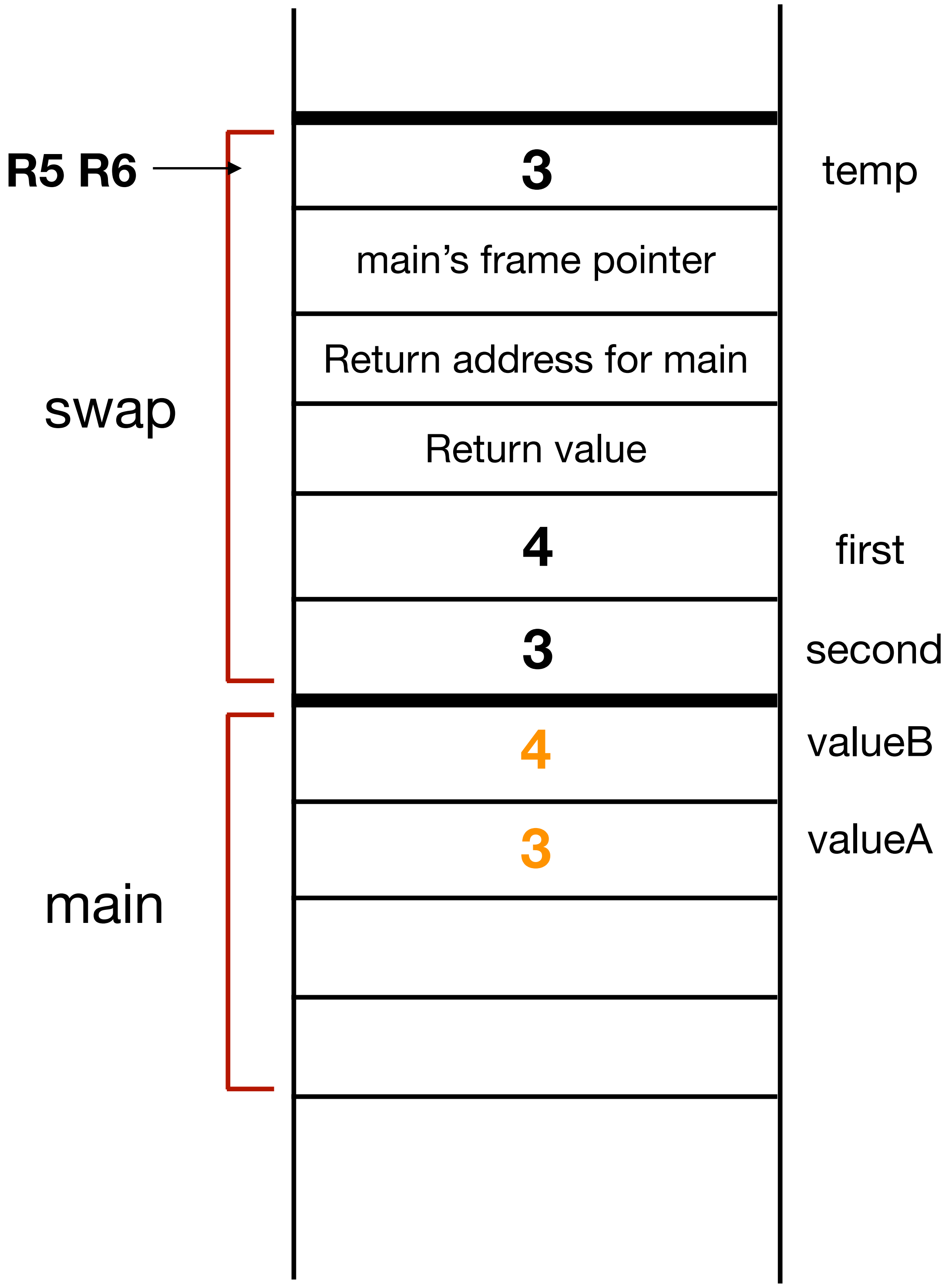
   - G. Pop CFP (into R5)
   - H. Pop return address (into R7)
6. RET
7. Caller tear down
   - I. Pop return value
   - J. Pop arguments

Execution



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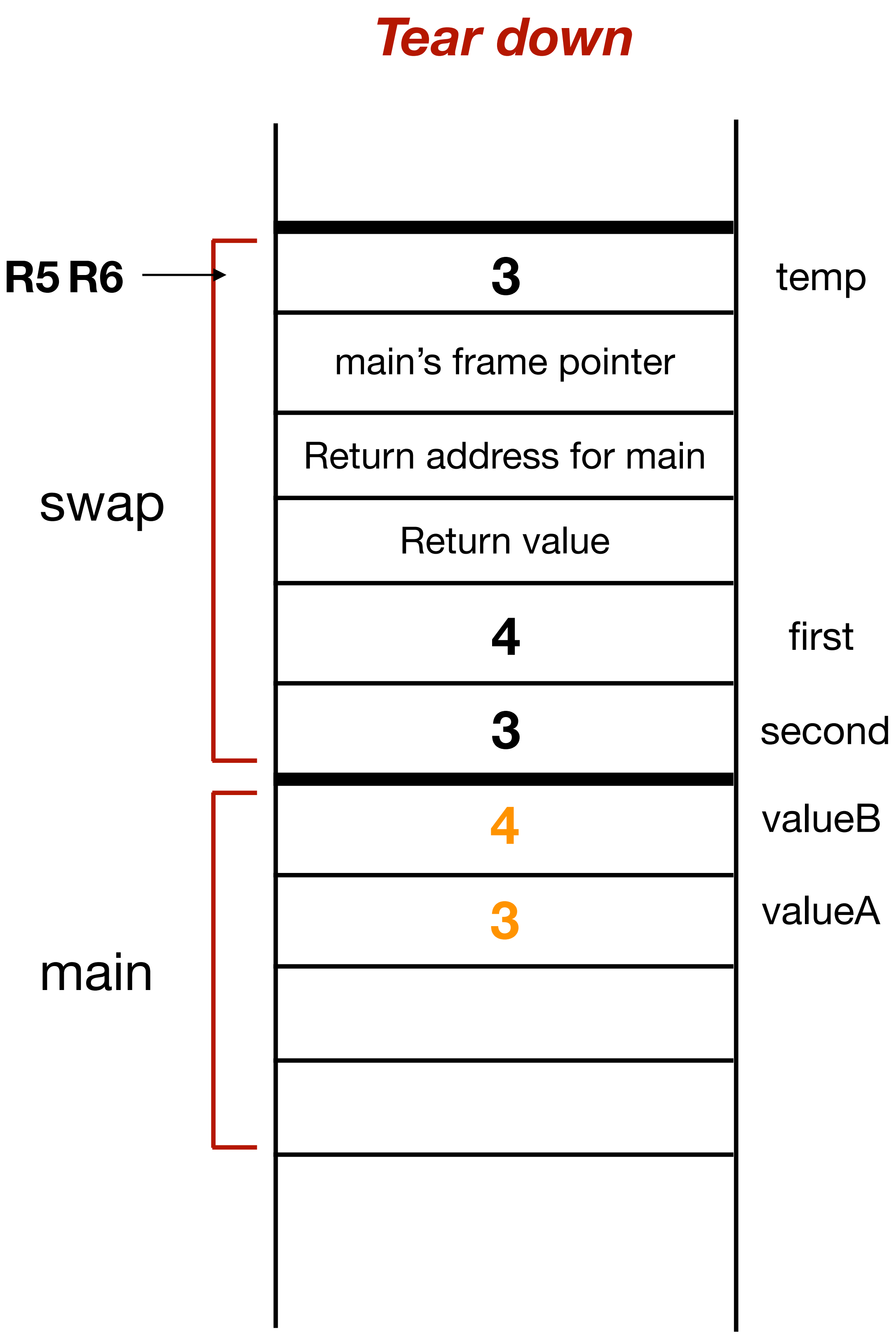
   int valueB = 4;
   Swap(valueA, valueB);
}

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

`swap` function - tear down

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



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

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

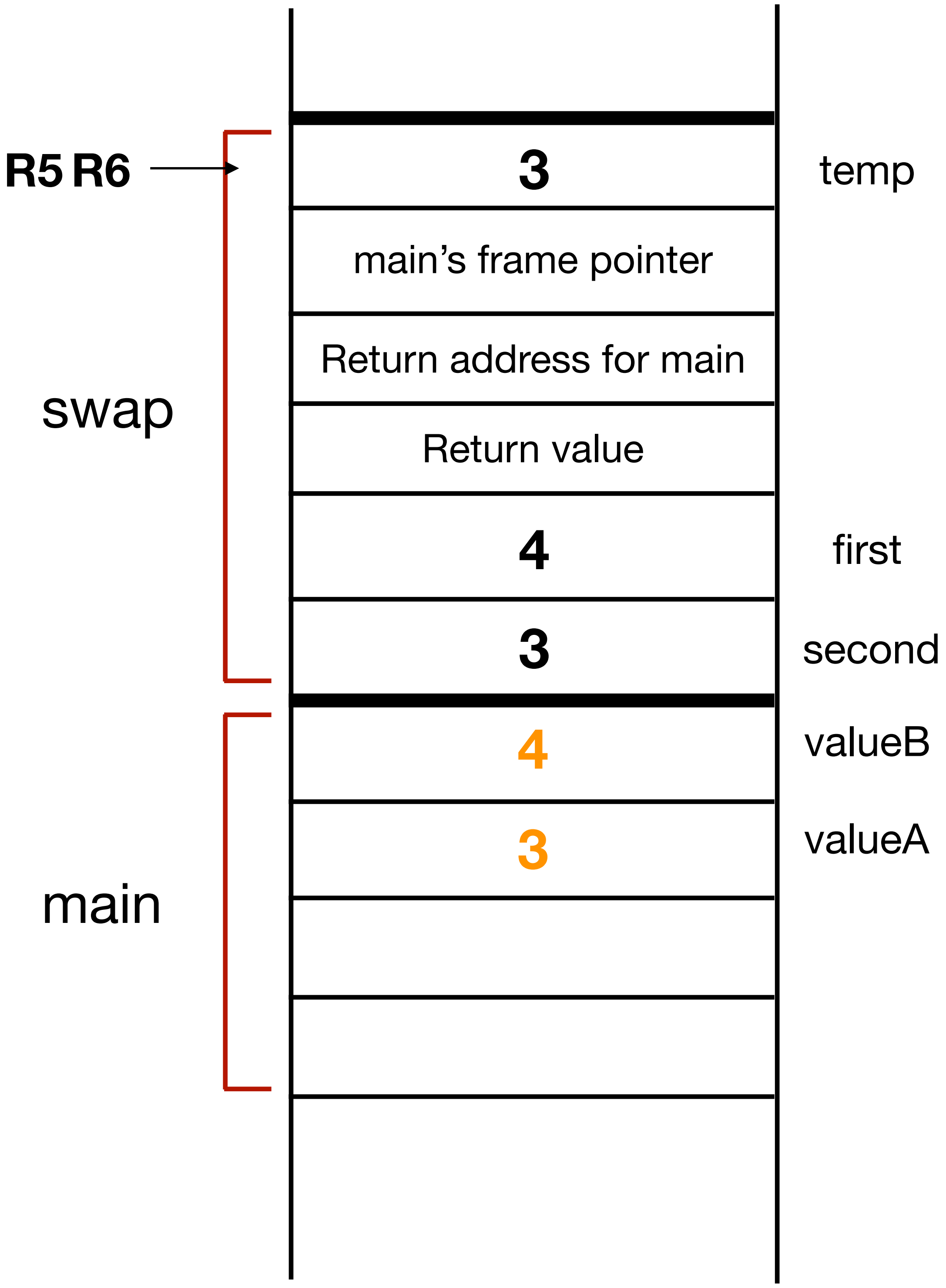
void Swap(int first, int second){
   int temp;
   temp = first;
   first = second;
   second = temp;
}
```

LC3 commands left as an exercise

`swap` function - tear down

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

Tear down



R5 R6

swap

3	temp
main's frame pointer	
Return address for main	
Return value	
4	first
3	second
4	valueB
3	valueA

main

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

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

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

LC3 commands left as an exercise

`swap` function - tear down

1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up (push onto RTS)
    A. Return value (allocate)
    B. Return address (from R7)
    C. Caller frame pointer (CFP)
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4. Execute
5. Callee tear down
    E. Update return value
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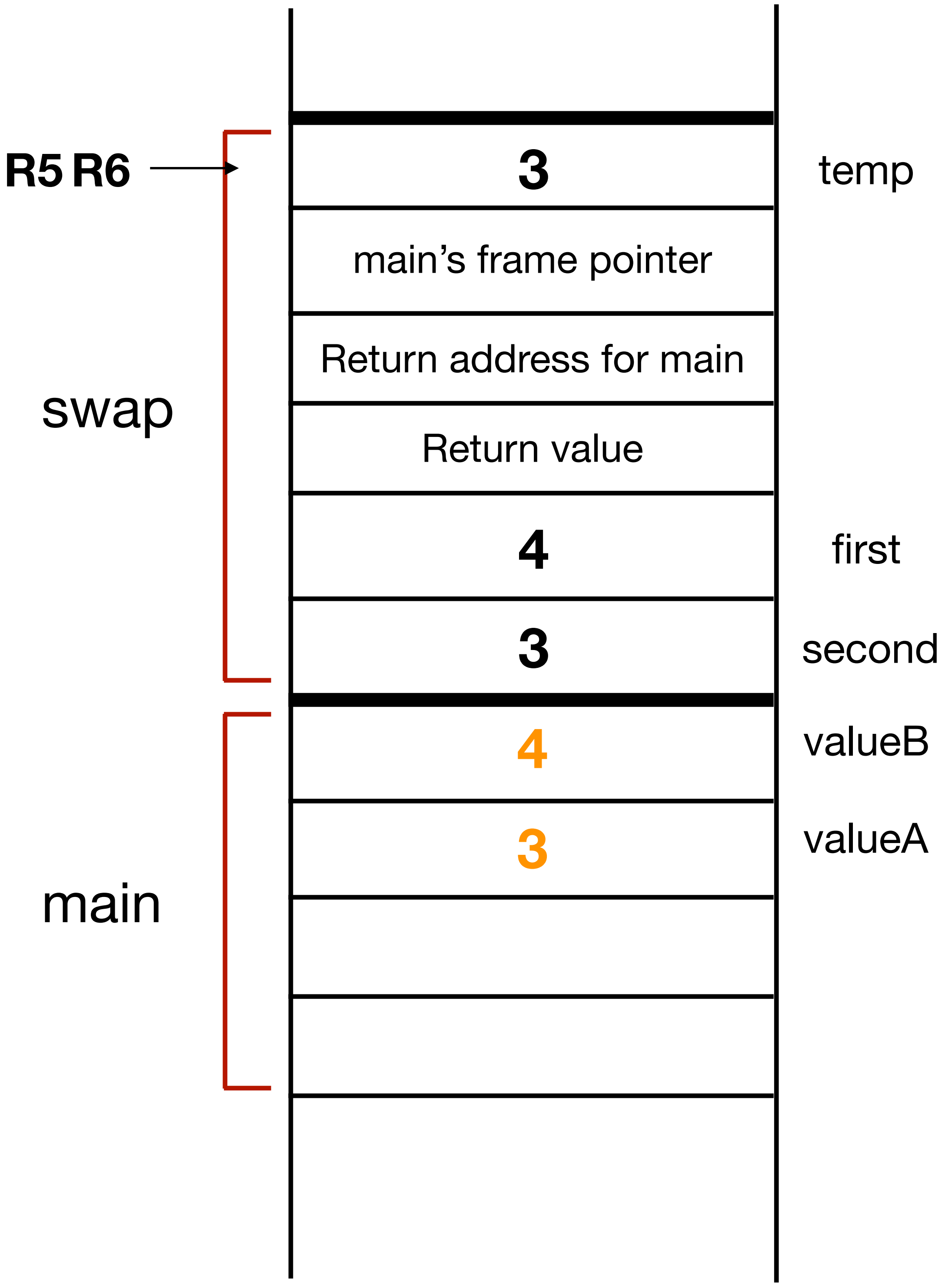
    I. Pop return value
    J. Pop arguments

Tear down



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

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

LC3 commands left as an exercise

`swap` function - tear down

1. Push arguments (R-to-L) onto RTS
2. JSR
3. Callee build up (push onto RTS)
   A. Return value (allocate)
   B. Return address (from R7)
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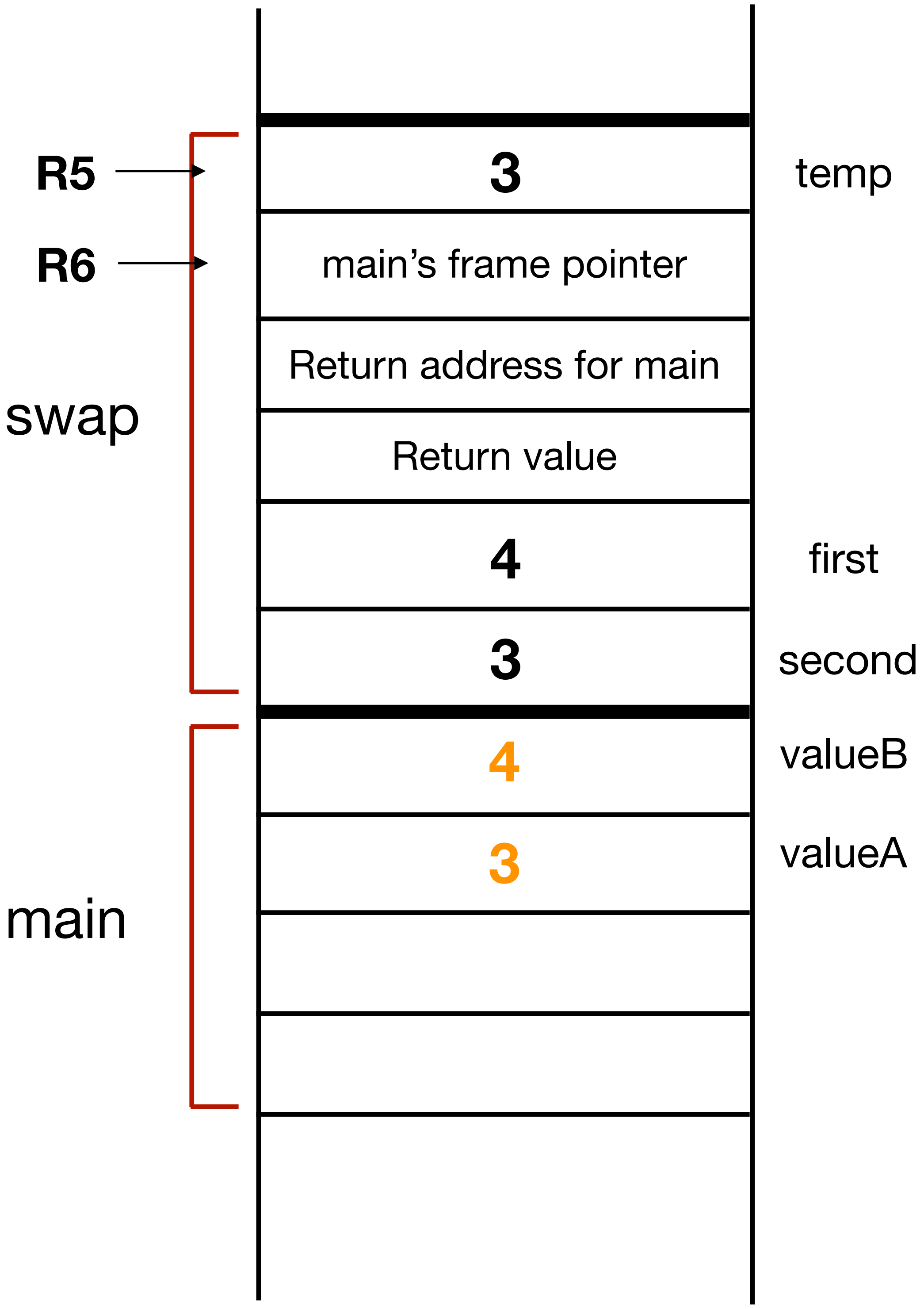
Tear down



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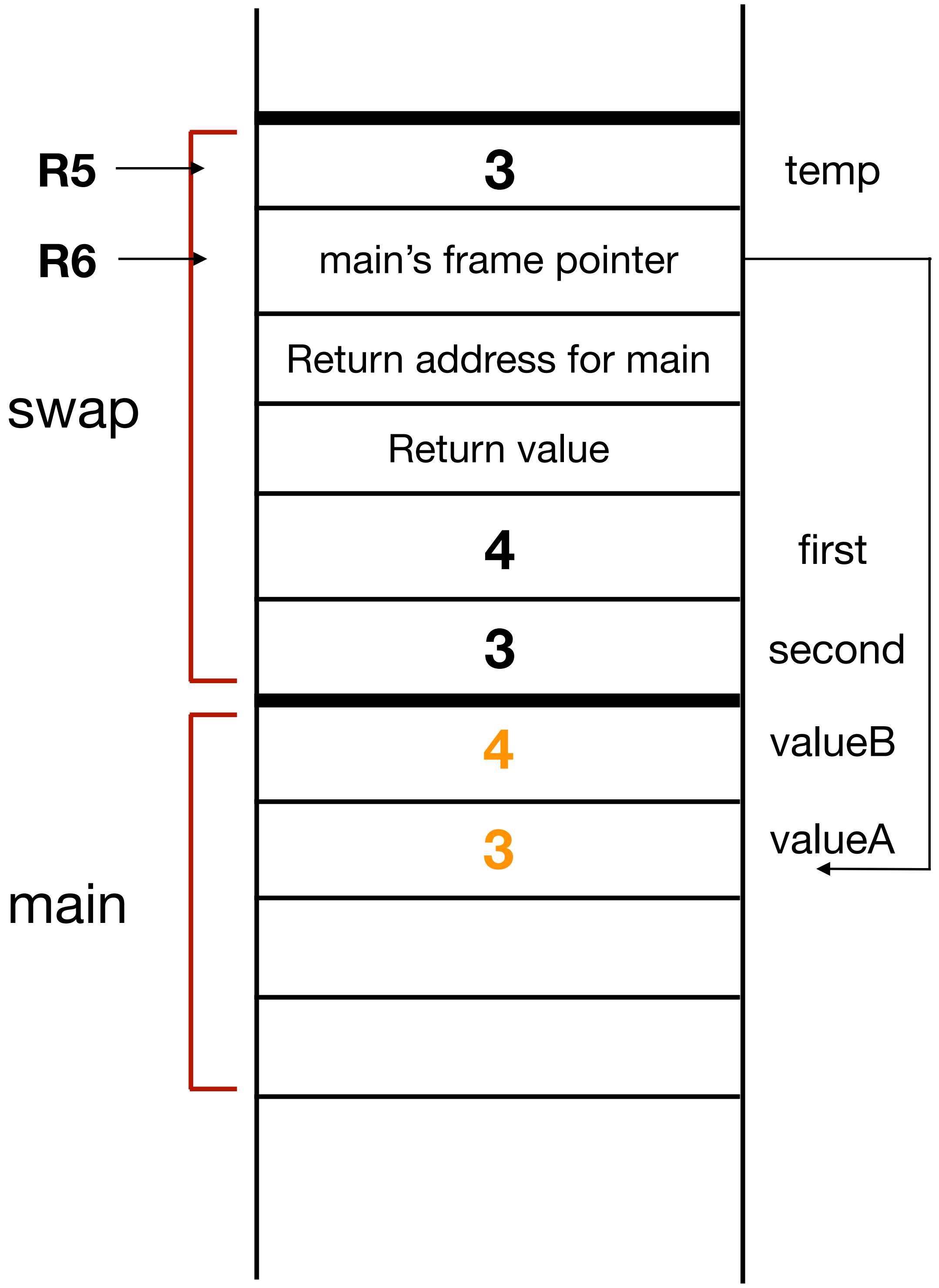

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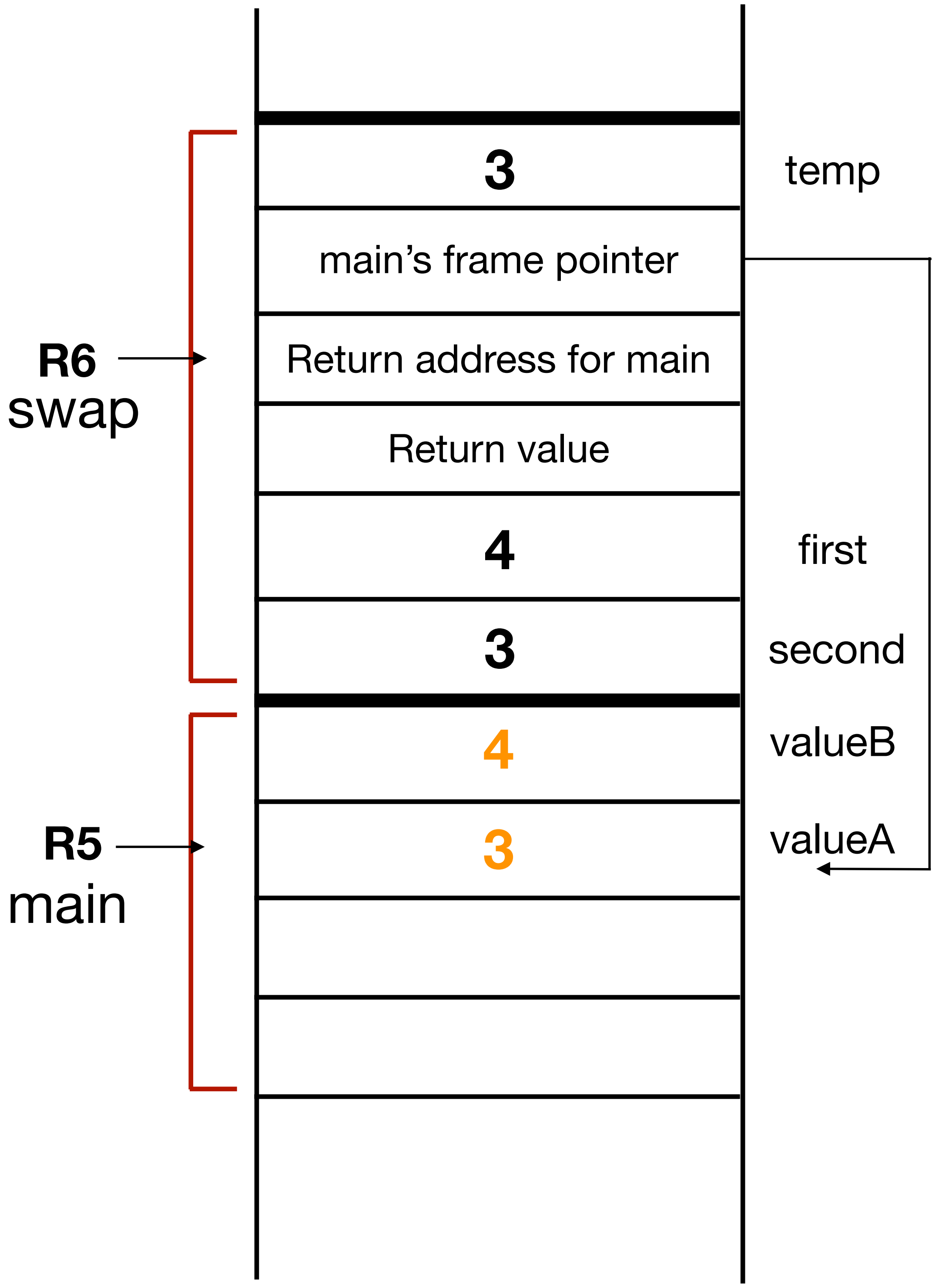

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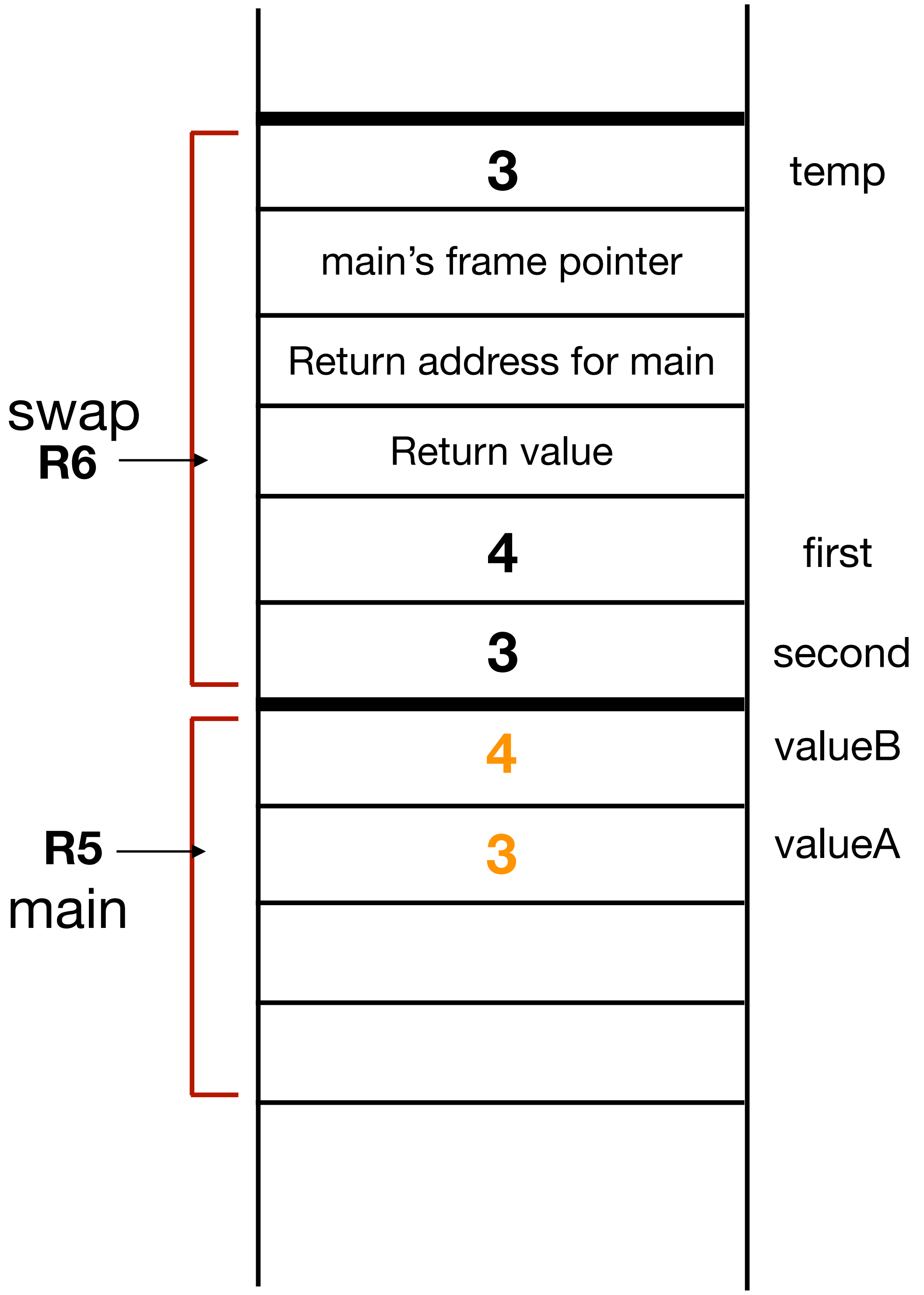

R7

Return address for main

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

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   Swap(valueA, valueB);
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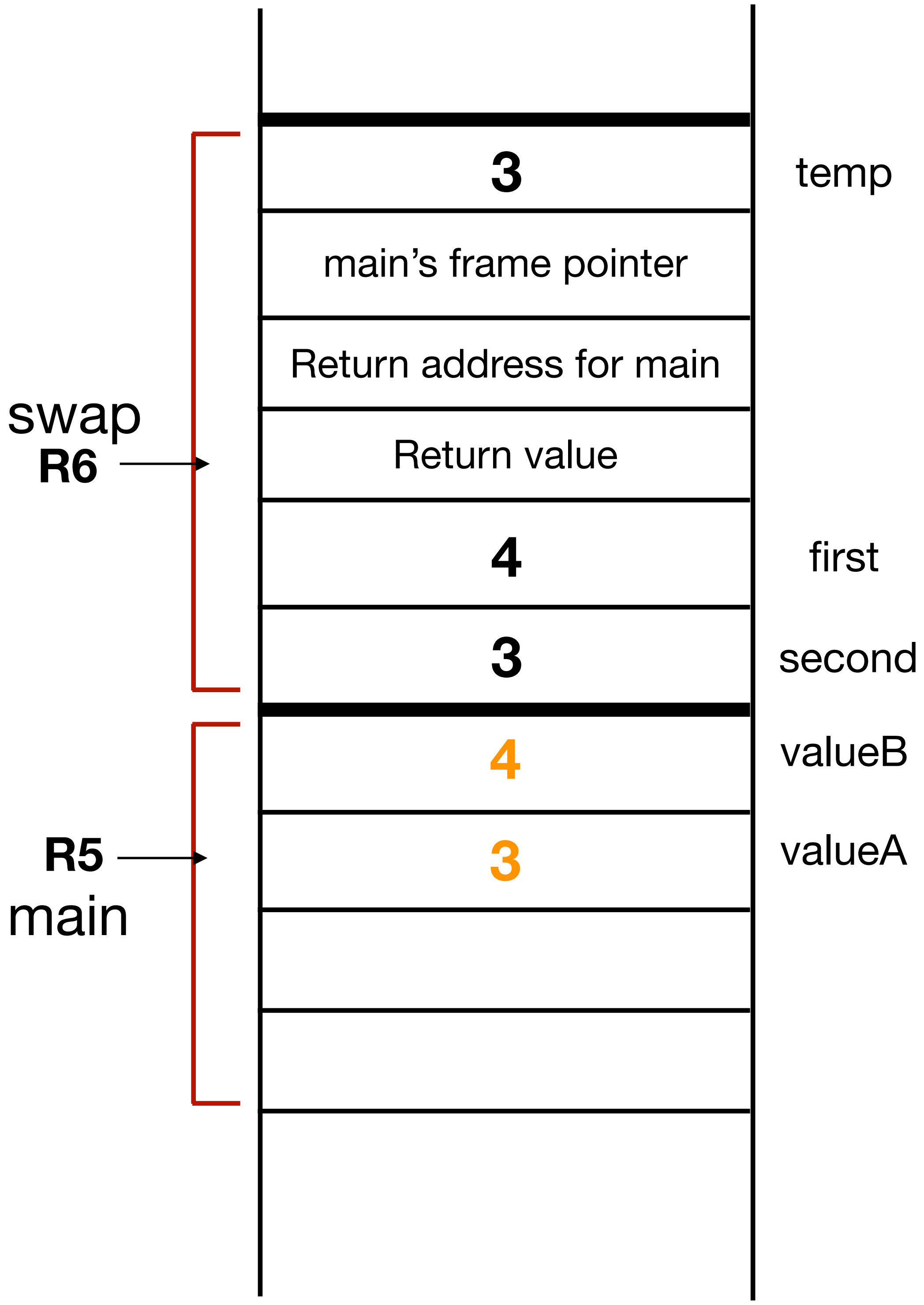

R7
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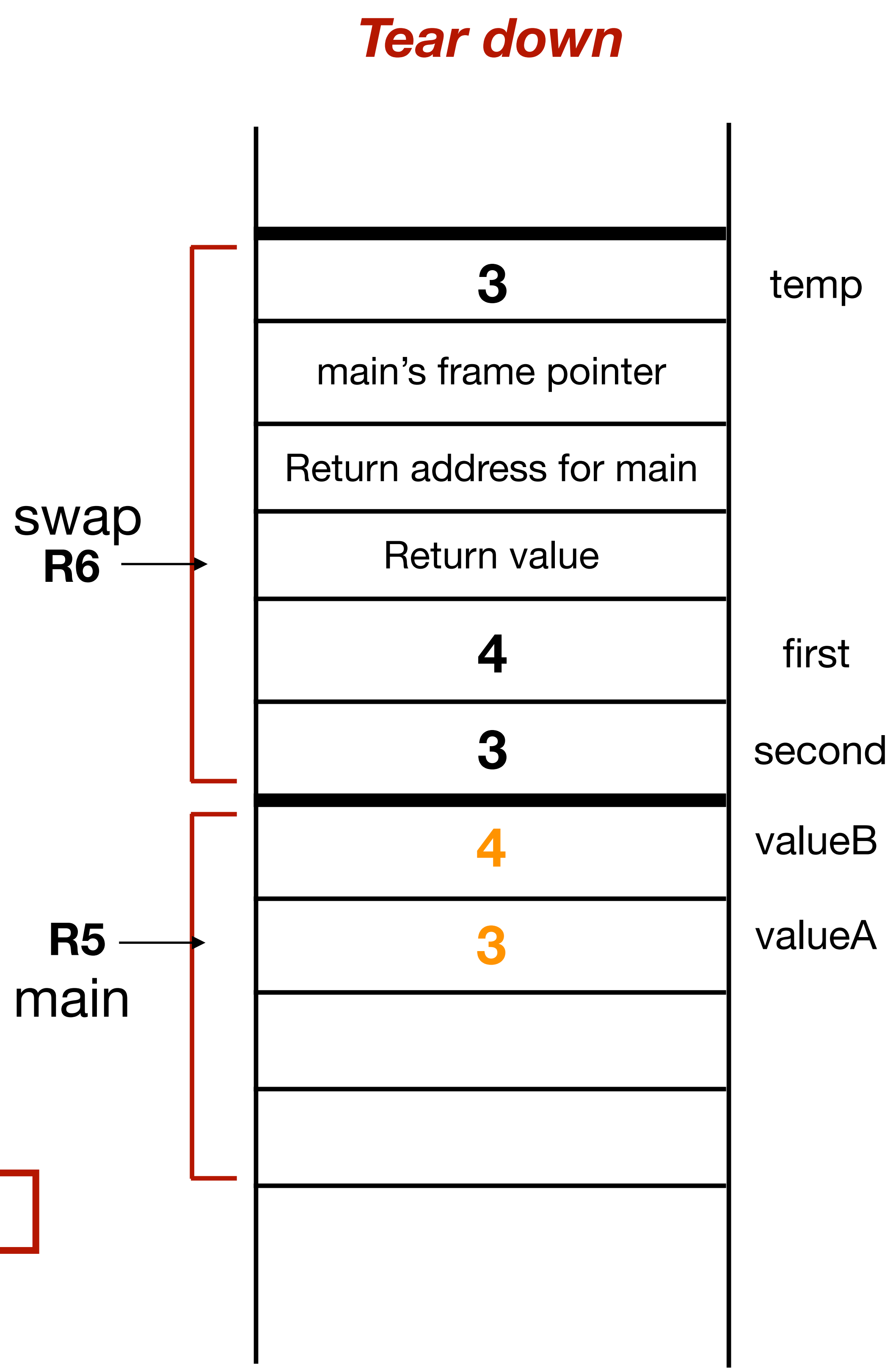

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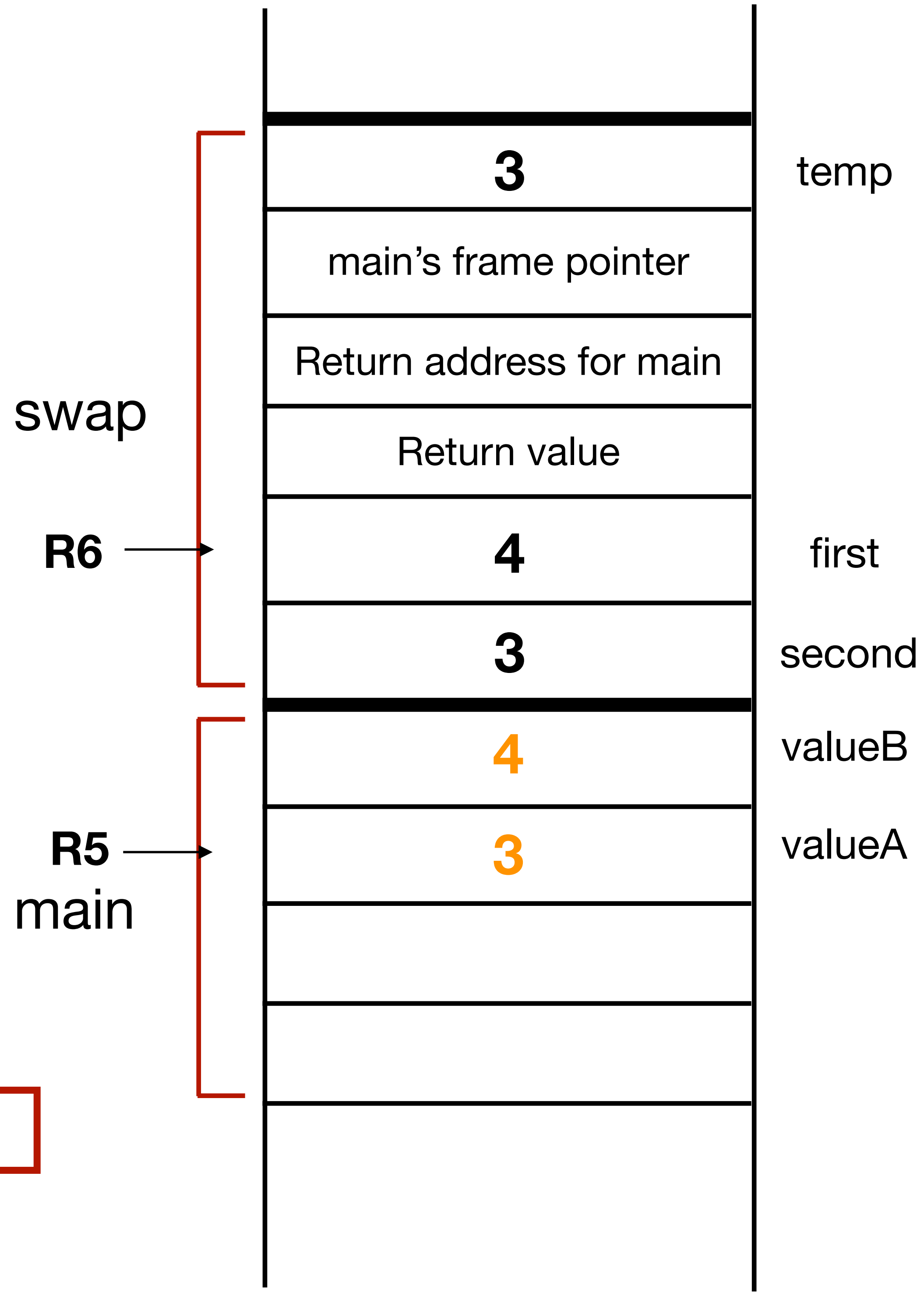

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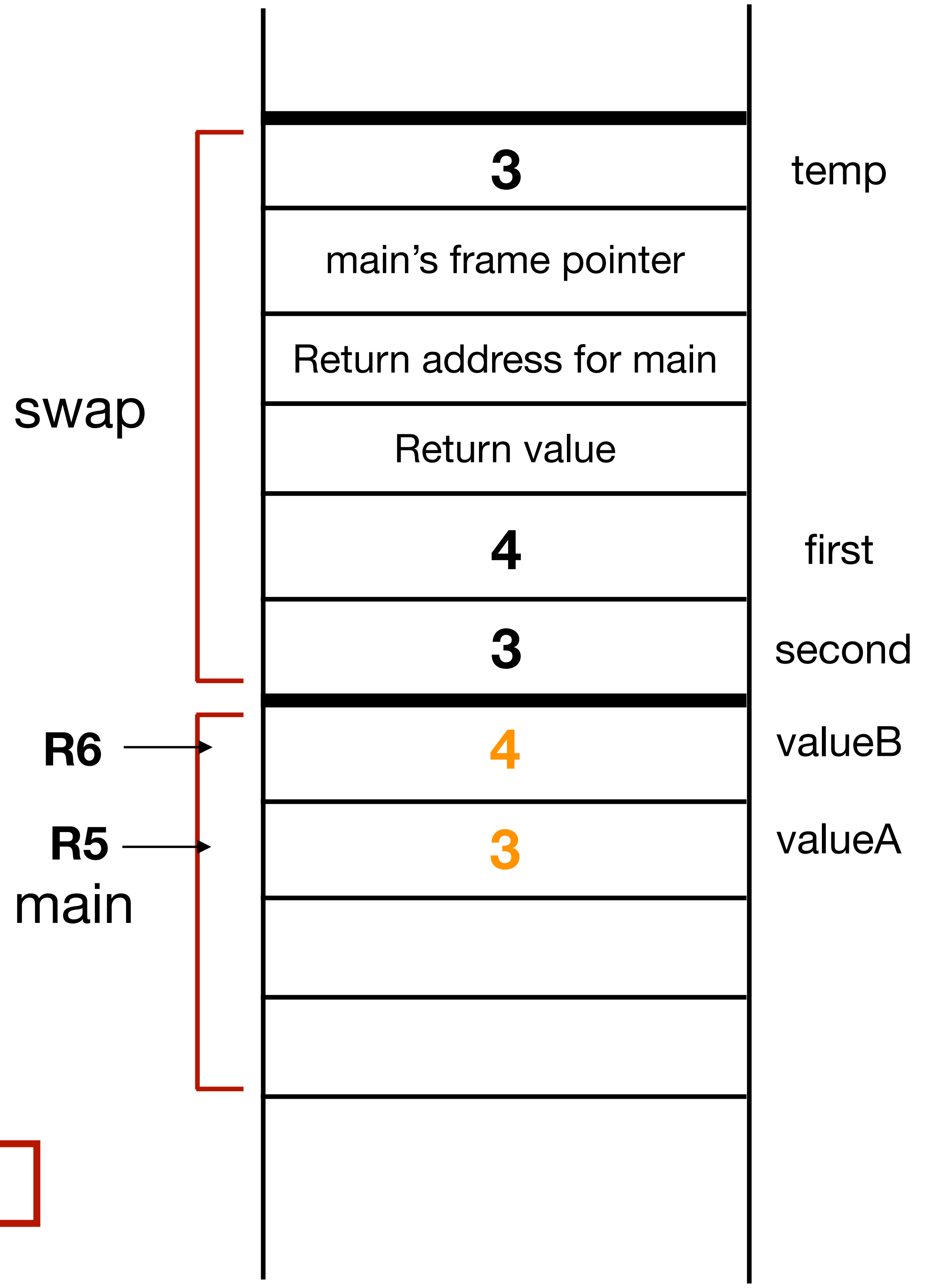

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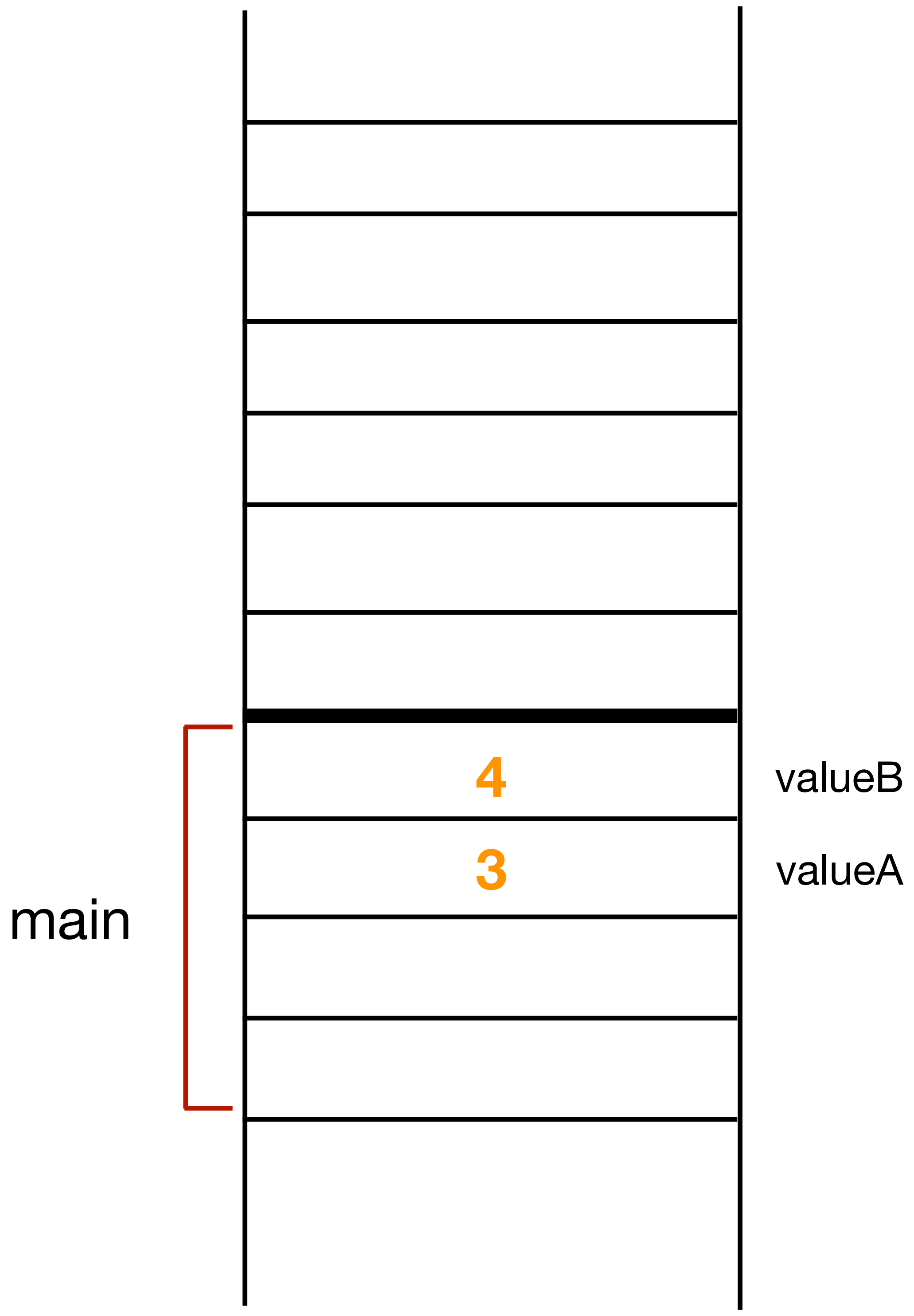
Swap function - did it work?

Before call

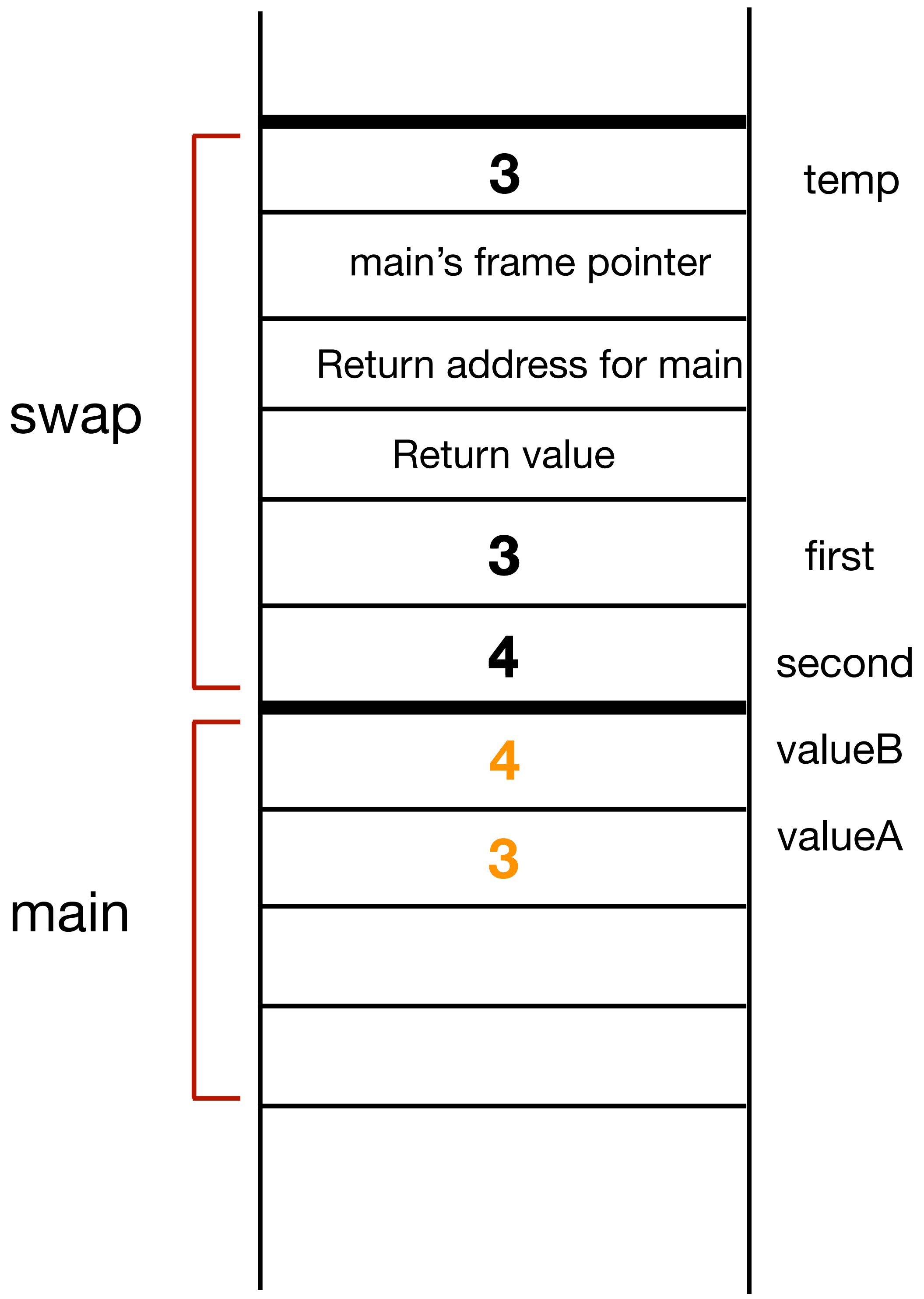


4 valueB

3 valueA

main

After call



3 temp

main’s frame pointer

Return address for main

Return value

3 first

4 second

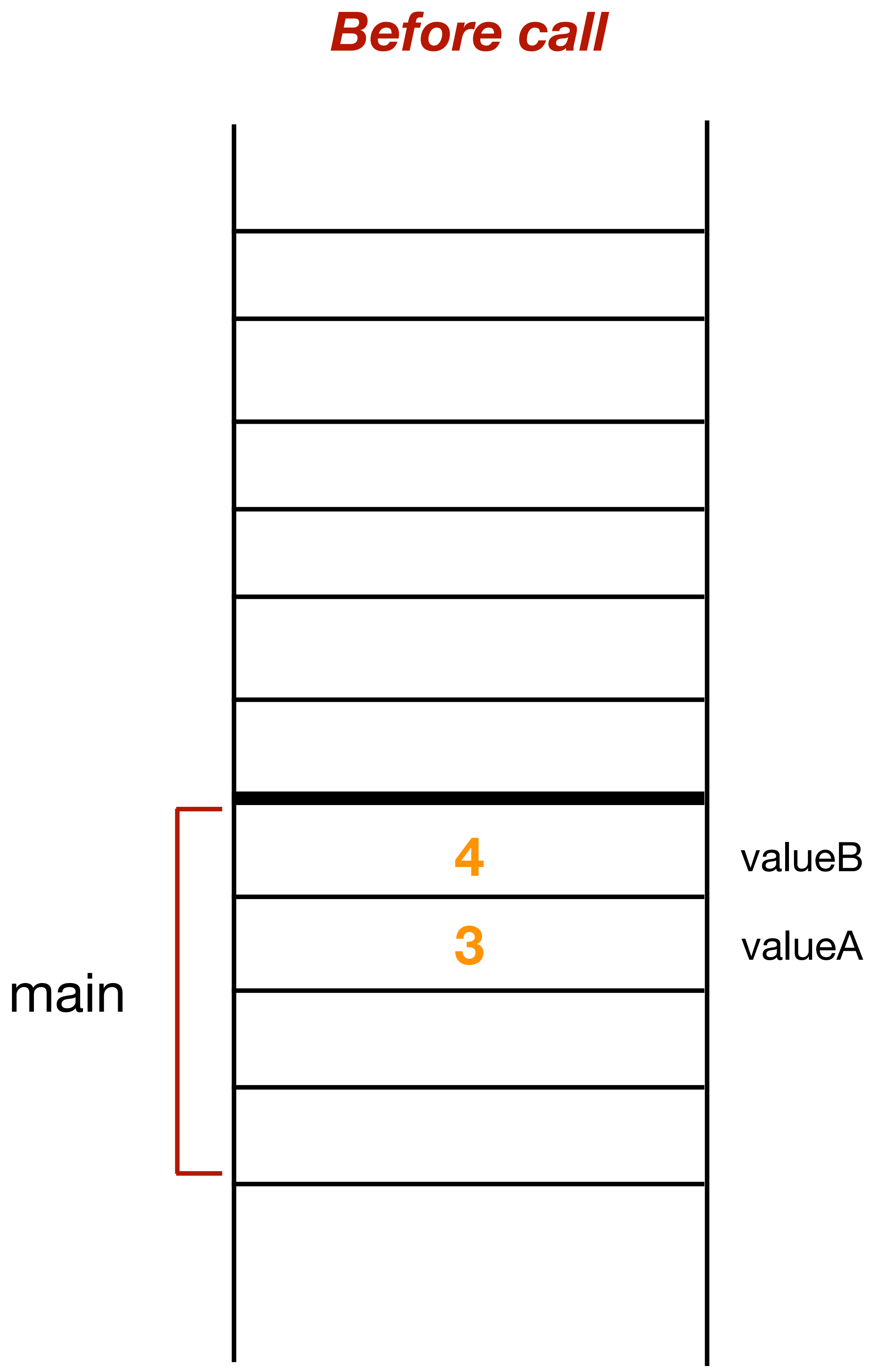
swap

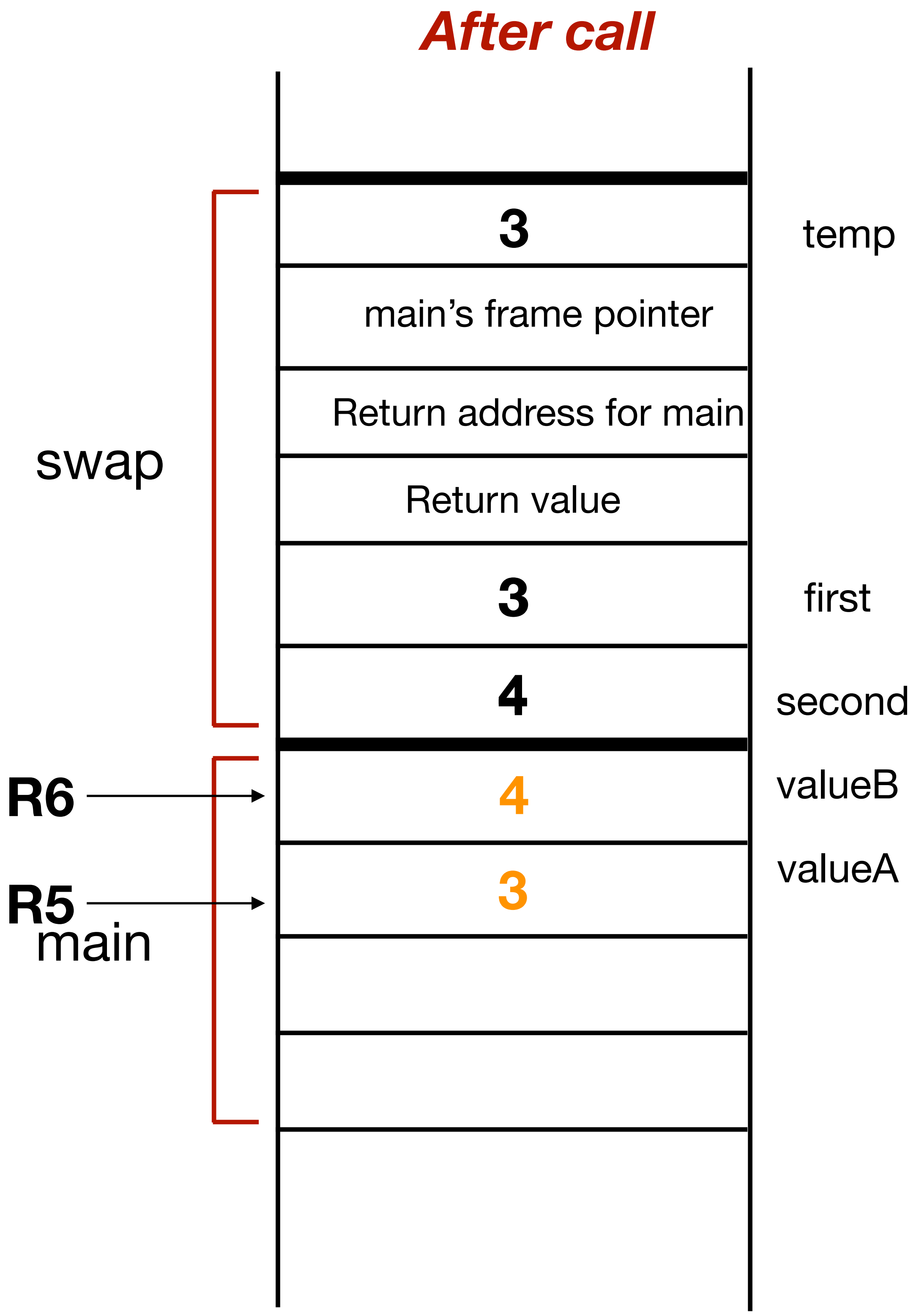
4 valueB

3 valueA

main

Swap function - did it work?





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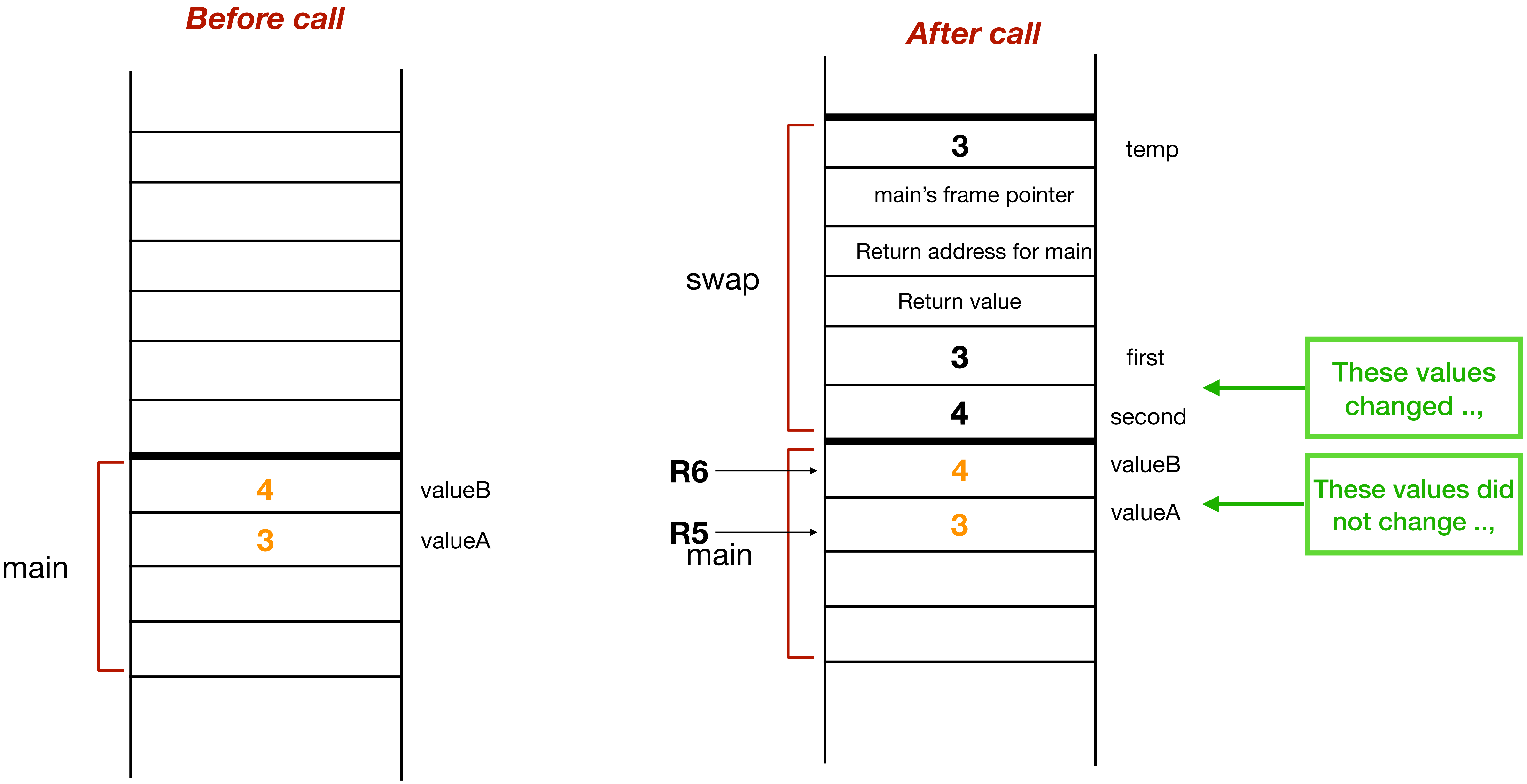

Argument passing

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- What needs to be changed for the `swap` function to work?
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  - Enter **pointers.**

Introduction to pointers

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

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

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

Introduction to pointers

Working version

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Pointers *take time* …

Don’t miss next class!

Time permitting

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- `gcc` compilation arguments

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```

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