Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C

Chapter 8
Stack and Recursive Functions

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Acknowledgement: Lecture slides based on Embedded Systems with ARM Cortex-M Microcontrollers in Assembly Language and C, University of Maine https://web.eece.maine.edu/~zhu/book/

Recursive Functions

- A recursive function is one that solves its task by calling itself on smaller pieces of data.
- An effective tactic is to
  - divide a problem into sub-problems of the same type as the original,
  - solve those sub-problems, and
  - combine the results

Defining Factorial(n)

Product of the first n numbers

1 × 2 × 3 × … × n

```
factorial(0) = 1
factorial(1) = 1               = 1 × factorial(0)
factorial(2) = 2×1             = 2 × factorial(1)
factorial(3) = 3×2×1           = 3 × factorial(2)
factorial(4) = 4×3×2×1         = 4 × factorial(3)
factorial(n) = n×(n-1)×…×1     = n × factorial(n-1)
```

Classic Example: Factorial

- Factorial is the classic example:
  - 6! = 6 × 5!
  - 6! = 6 × 5 x 4!

  ...
  - 6! = 6 × 5 × 4 × 3 × 2 × 1
- The factorial function can be easily written as a recursive function:

```
int Factorial(int n) {

    if (n < 2)
        return 1; /* base case */

    return (n * Factorial(n - 1));

}
```

Classic Example: Fibonacci Numbers

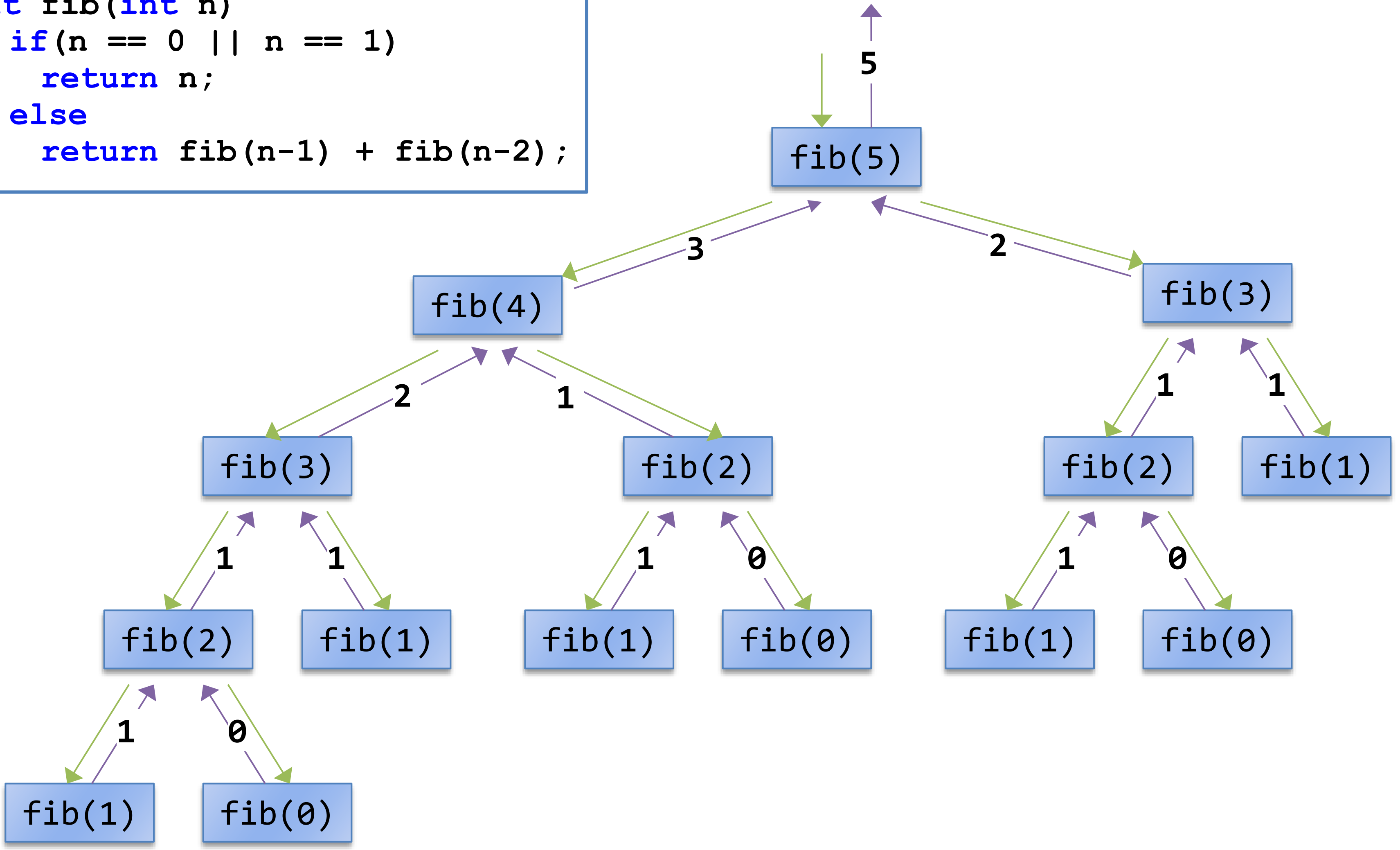
```
f(n) = f(n-1) + f(n-2)
f(0) = 1
f(1) = 1
```

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, …

```
int Fibonacci(int n) {

  if (n <= 1)
    return 1;    /* base case */

  return (Fibonacci(n-1) + Fibonacci(n-2));

}
```

Analysis of fib(5)

```
int fib(int n)
   if(n == 0 || n == 1)
     return n;
   else
     return fib(n-1) + fib(n-2);
```



Example of Recursive Function: Testing Palindrome

```
bool isPalindrome(char* s, int len) {
  if(len < 2)
    return TRUE;
  else
    return s[0] == s[len-1] && isPalindrome(&s[1], len-2);
}
```

Recursion vs Iteration

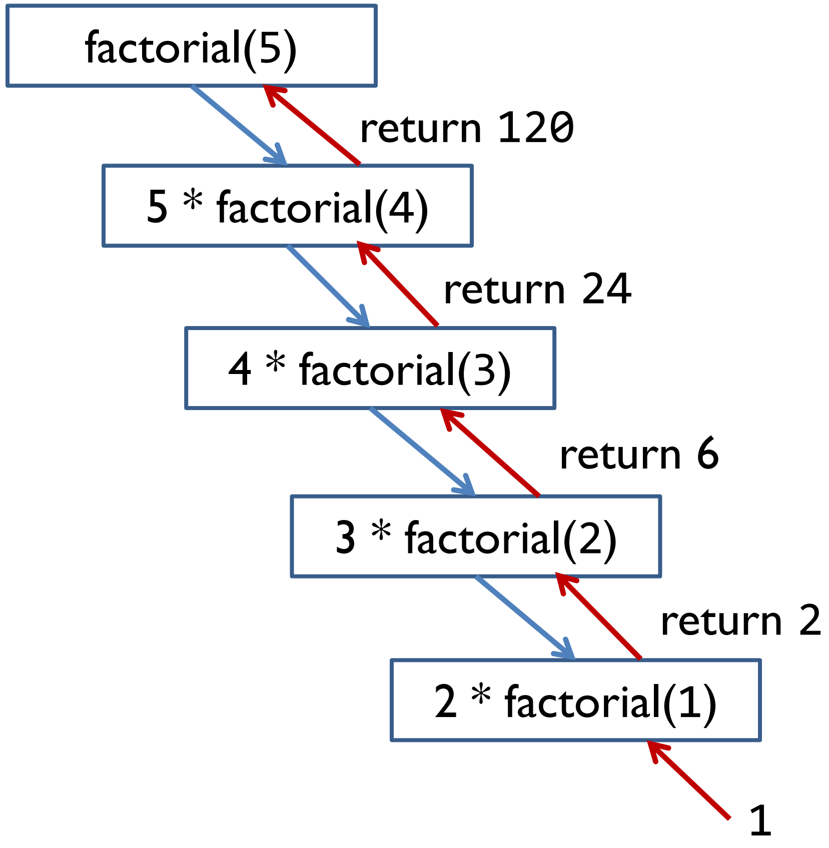
Any problem that can be solved recursively can also be solved iteratively (using loop).

Recursive functions vs Iterative functions

- Cons:
  - Recursive functions are slow
  - Recursive function take more memory
- Pros
  - Recursive functions resembles the problem more naturally
  - Recursive function are easier to program, and debug.

Recursive Factorial in C

```
int factorial(int n);

int main(void){
  factorial(5);
  return 0;
}

int factorial(int n) {
  int f;
  if(n==1)
    return 1;
  else
    f = n * factorial(n-1);
  return f;
}
```



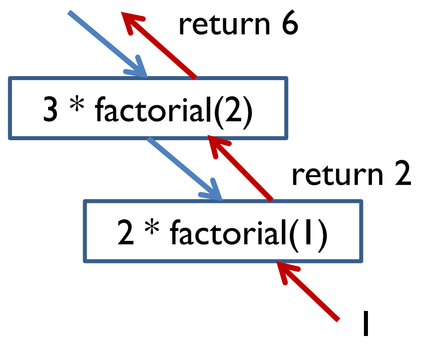
Recursive Functions

- `PUSH LR` (& working registers) onto stack before nested call
- `POP LR` (& working registers) off stack after nested return

Recursive Factorial in Assembly

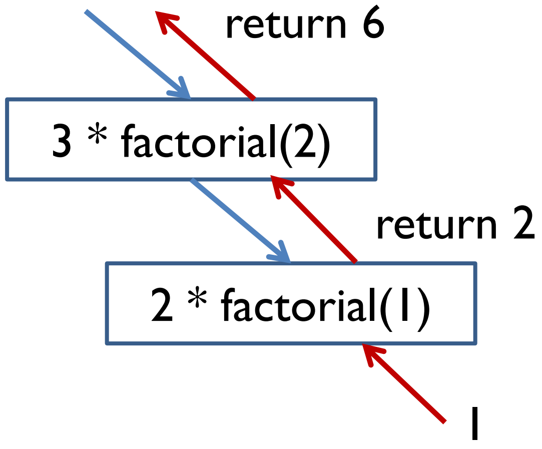
```
 AREA main, CODE, READONLY
     EXPORT  __main
     ENTRY
__main PROC
    MOV   r0, #0x03                 ; Set argument n = 3 in r0 (r0 holds first arg)
    BL    factorial                 ; Call factorial(n); LR gets return address;
                                              ; result returns in r0
stop B     stop                     ; Halt by branching to self (infinite loop)
    ENDP

; --- Recursive factorial(n) ---
factorial
    PUSH  {r4, lr}                  ; Save callee-used r4 and return address LR on stack
    MOV   r4, r0                    ; Preserve n in r4 across the recursive call
    CMP   r4, #0x01                 ; Check base case: n == 1 ?
    BNE   NZ                        ; If n != 1, branch to NZ for recursive case
    MOVS  r0, #0x01                 ; Base case: return 1 in r0
loop POP   {r4, pc}                 ; restore r4, and return by popping PC
NZ   SUBS  r0, r4, #1               ; Prepare argument r0 = n - 1 for recursive call
    BL    factorial                 ; r0 <- factorial(n-1) after return
    MUL   r0, r4, r0                ; r0 = n * factorial(n-1)
    B     loop
    END
```

Trace Function Execution for this Call Sequence



Recursive Factorial in Assembly

```
                  AREA main, CODE, READONLY
                  EXPORT   __main

                  ENTRY

             __main PROC
                  MOV r0, #0x03
0x08000130        BL  factorial
0x08000134   stop B   stop
                  ENDP

             factorial
0x08000136        PUSH {r4, lr}
0x08000138        MOV  r4, r0
0x0800013A        CMP  r4, #0x01
0x0800013C        BNE  NZ
0x0800013E        MOVS r0, #0x01
0x08000140   loop POP  {r4, pc}
0x08000142   NZ   SUBS r0, r4, #1
0x08000144        BL   factorial
0x08000148        MUL  r0, r4, r0
0x0800014C        B    loop

                  END
```

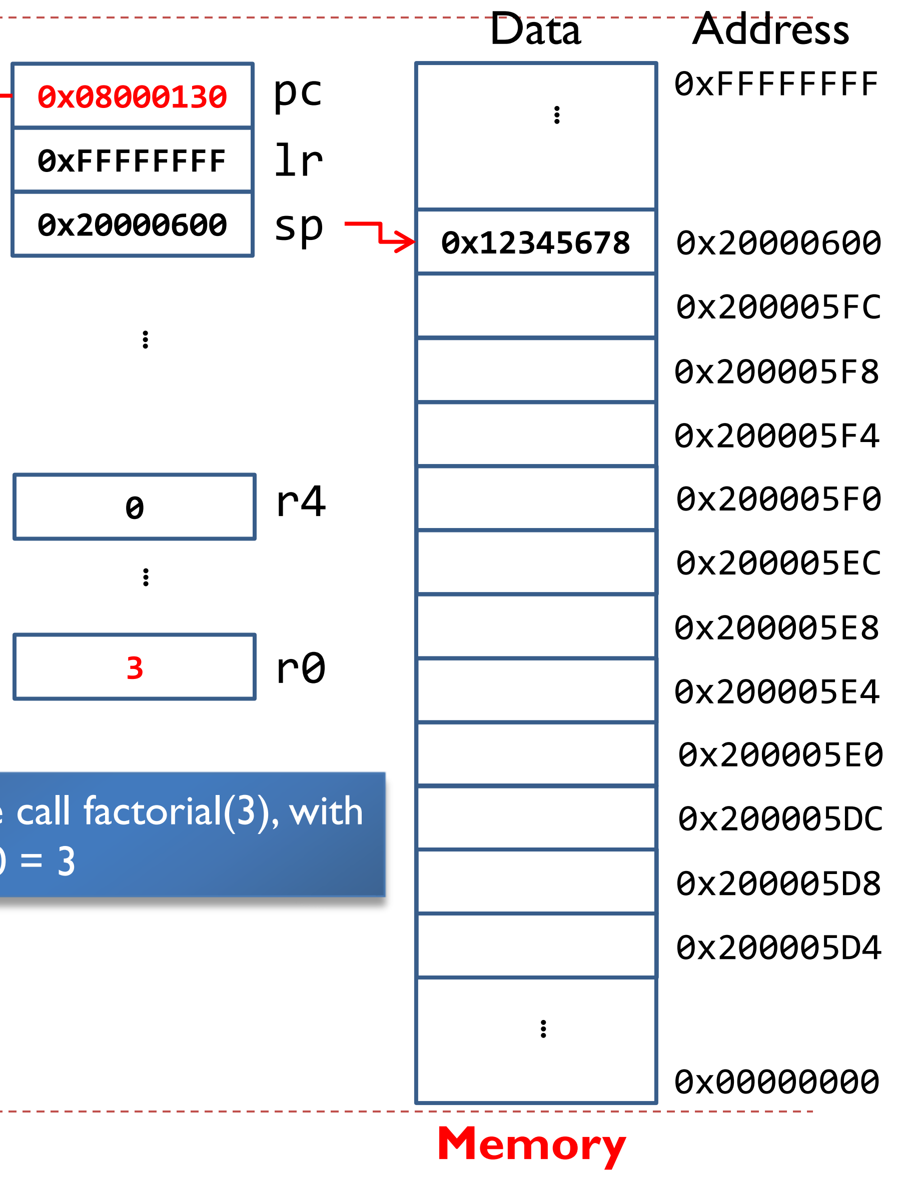


Recursive Factorial in Assembly

```
 AREA main, CODE, READONLY
     EXPORT  __main
     ENTRY
__main PROC
    MOV   r0, #0x03                ; Set argument n = 3 in r0 (r0 holds first arg)
    BL    factorial                ; Call factorial(n); LR gets return address;
                                    ; result returns in r0
stop
    B     stop                     ; Halt by branching to self (infinite loop)
    ENDP
; --- Recursive factorial(n) ---
factorial
    PUSH  {r4, lr}                 ; Save callee-used r4 and return address LR on
stack
    MOV   r4, r0                   ; Preserve n in r4 across the recursive call
    CMP   r4, #0x01                ; Check base case: n == 1 ?
    BNE   NZ                       ; If n != 1, branch to NZ for recursive case
    MOVS  r0, #0x01                ; Base case: return 1 in r0
loop
    POP   {r4, pc}                 ; restore r4, and return by popping PC
NZ
    SUBS  r0, r4, #1               ; Prepare argument r0 = n - 1 for recursive call
    BL    factorial                ; r0 <- factorial(n-1) after return
    MUL   r0, r4, r0               ; r0 = n * factorial(n-1)
    B     loop
    END
```

Recursive Factorial in Assembly

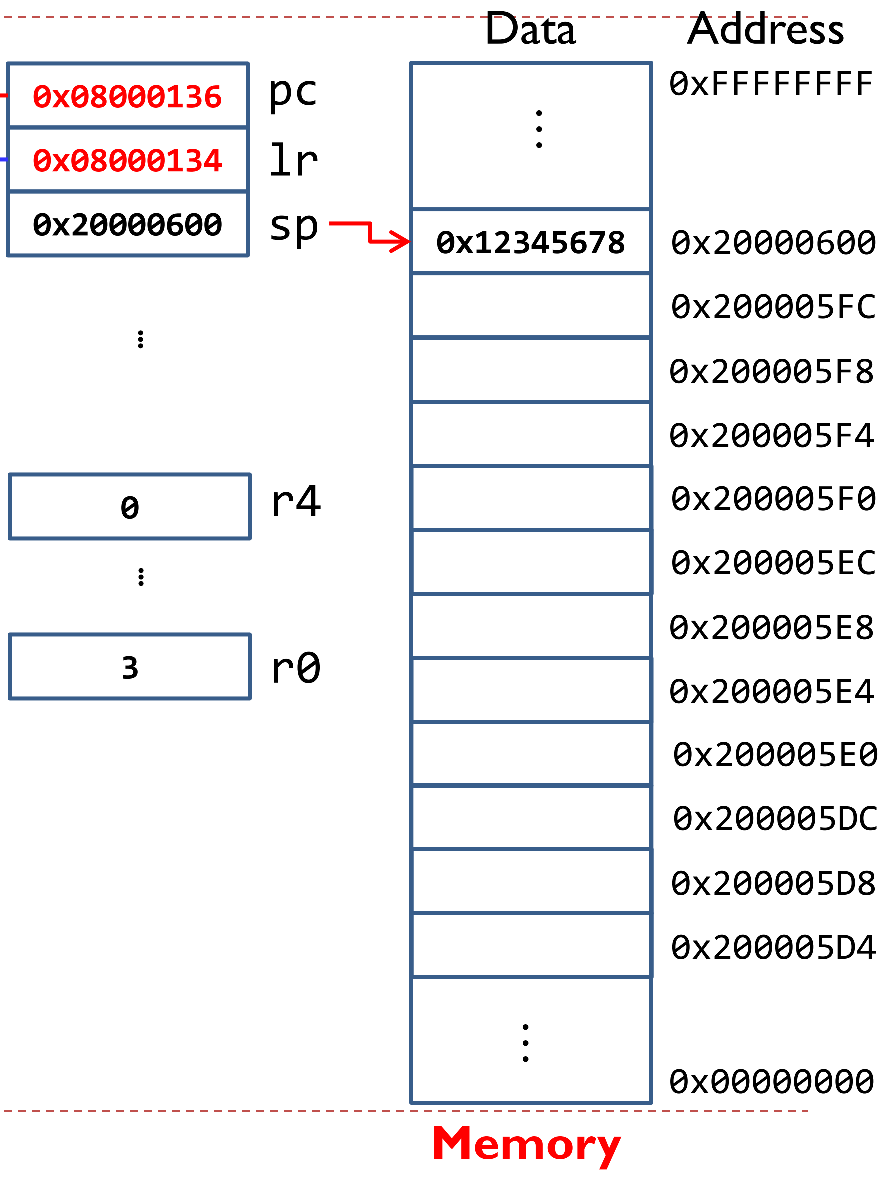
```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

            __main PROC
                 MOV r0, #0x03
0x08000130       BL   factorial
0x08000134  stop B    stop
                 ENDP

            factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140  loop POP  {r4, pc}
0x08000142  NZ   SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



1st recursive call factorial(3), with argument r0 = 3

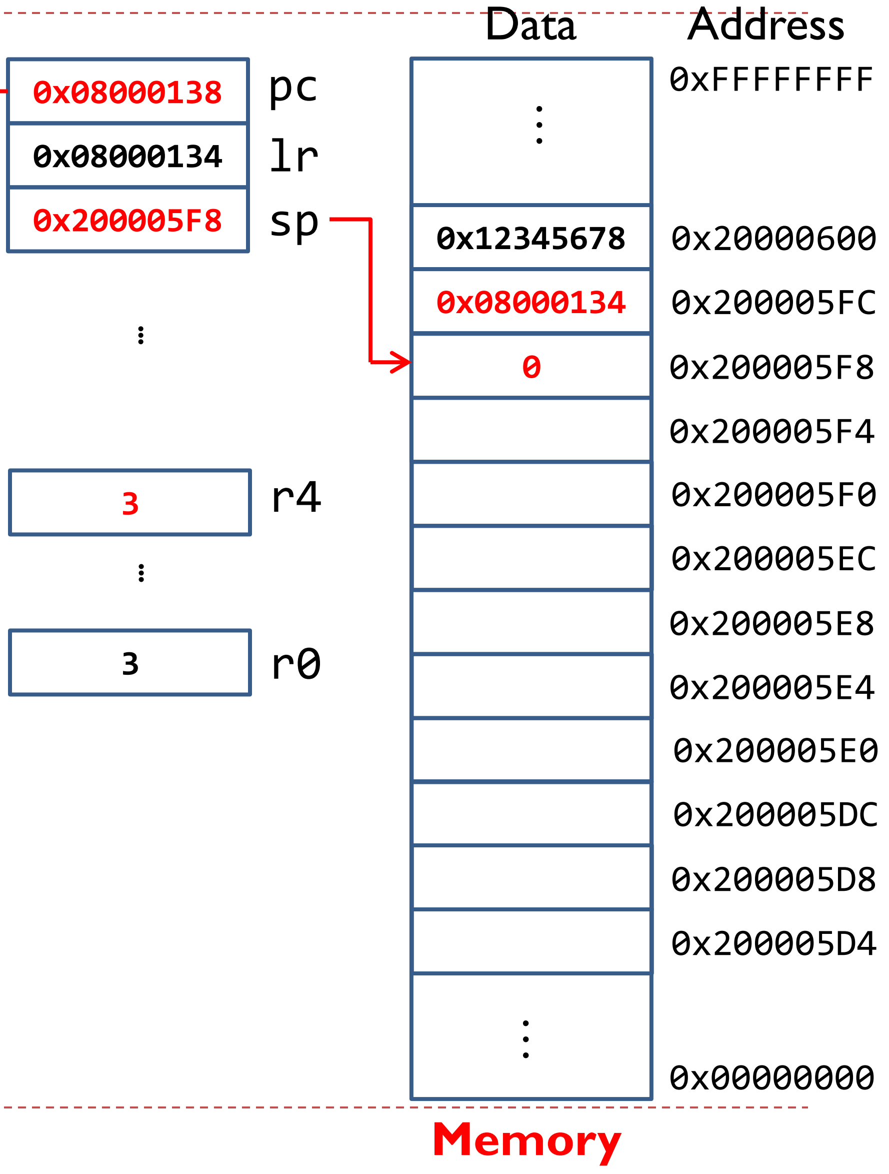
Recursive Factorial in Assembly

```
                AREA main, CODE, READONLY
                EXPORT   __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL   factorial
0x08000134 stop B    stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



Recursive Factorial in Assembly

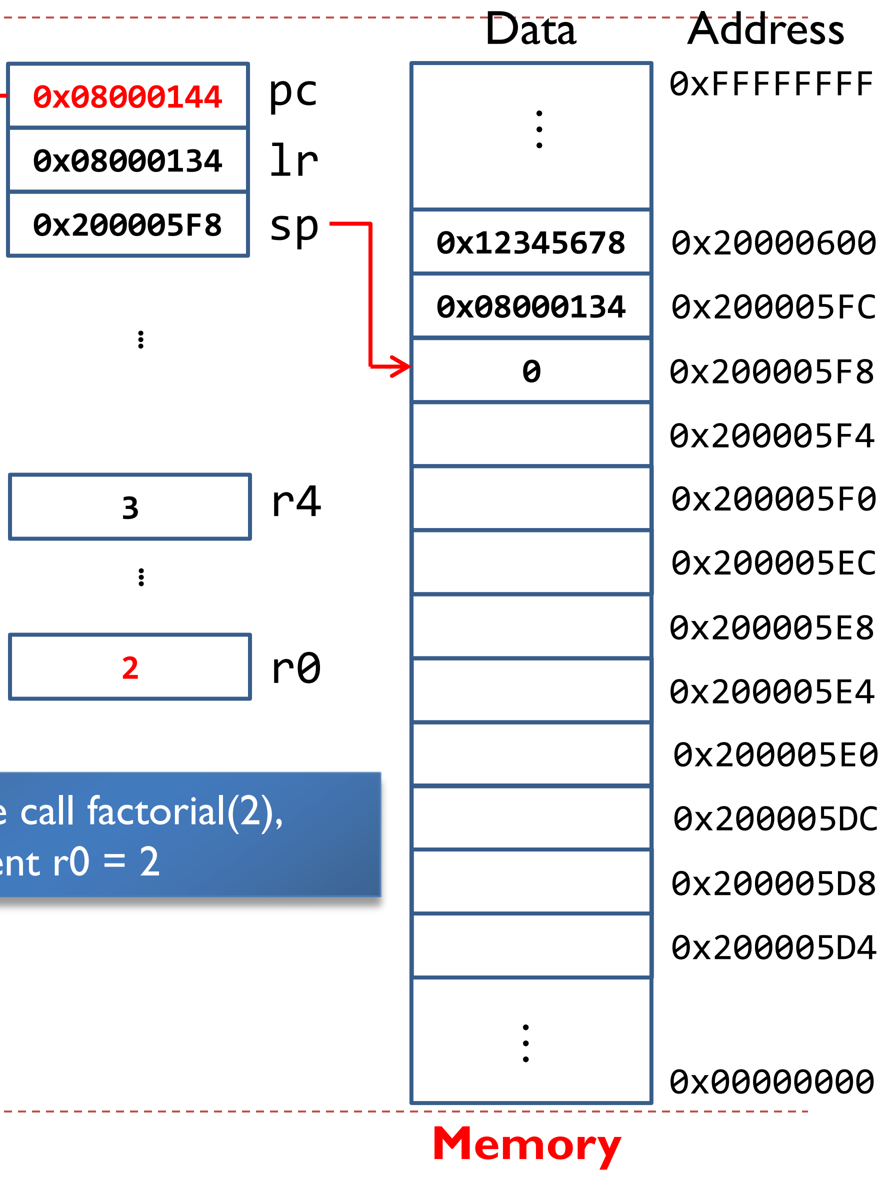
```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

            __main PROC
                 MOV r0, #0x03
0x08000130       BL  factorial
0x08000134  stop B   stop
                 ENDP

            factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140  loop POP  {r4, pc}
0x08000142  NZ   SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



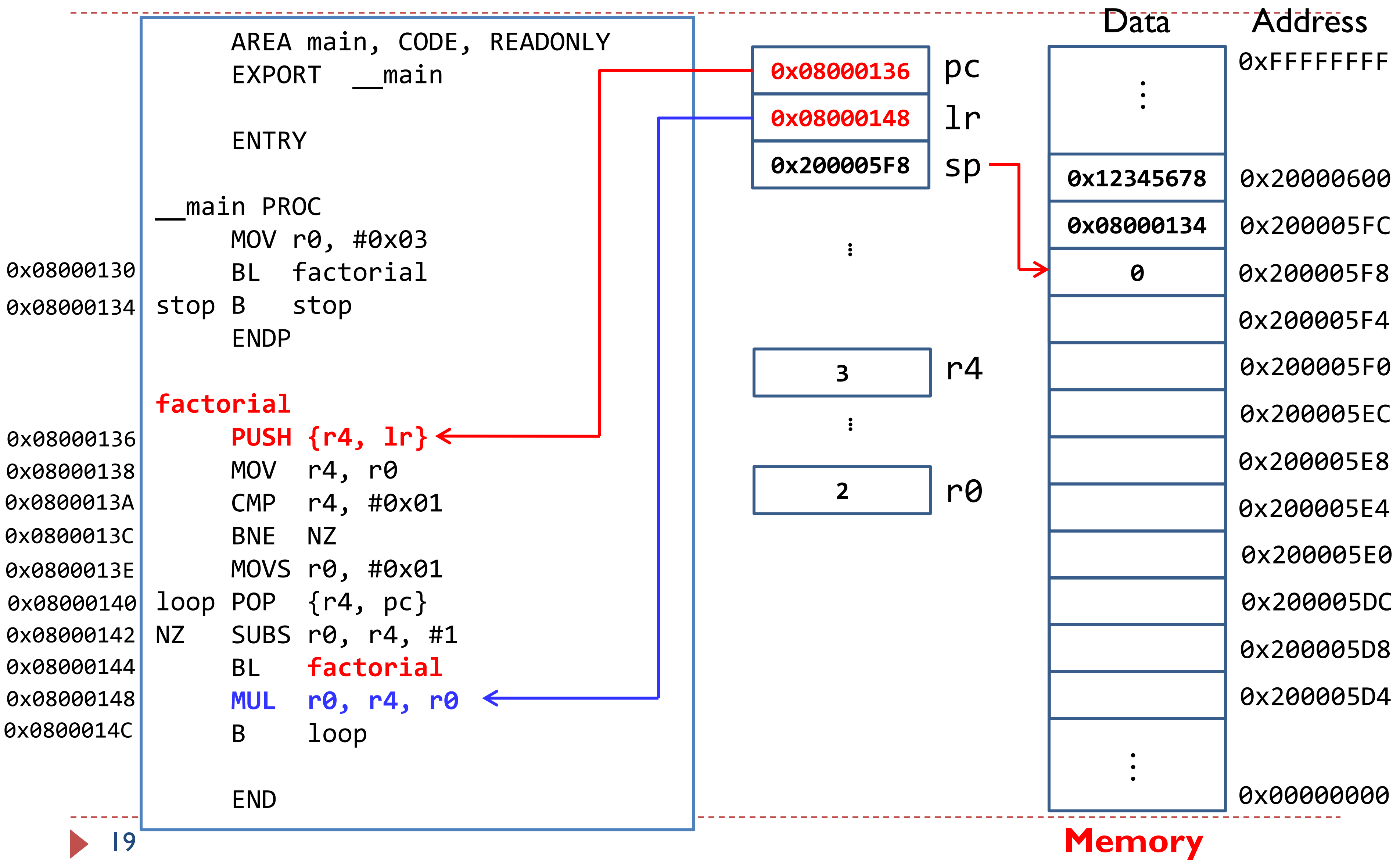
Recursive Factorial in Assembly

```
                   AREA main, CODE, READONLY
                   EXPORT   __main

                   ENTRY

              __main PROC
                   MOV r0, #0x03
0x08000130         BL  factorial
0x08000134    stop B   stop
                   ENDP

              factorial
0x08000136         PUSH {r4, lr}
0x08000138         MOV  r4, r0
0x0800013A         CMP  r4, #0x01
0x0800013C         BNE  NZ
0x0800013E         MOVS r0, #0x01
0x08000140    loop POP  {r4, pc}
0x08000142    NZ   SUBS r0, r4, #1
0x08000144         BL   factorial
0x08000148         MUL  r0, r4, r0
0x0800014C         B    loop

                   END
```

2nd recursive call factorial(2), with argument r0 = 2



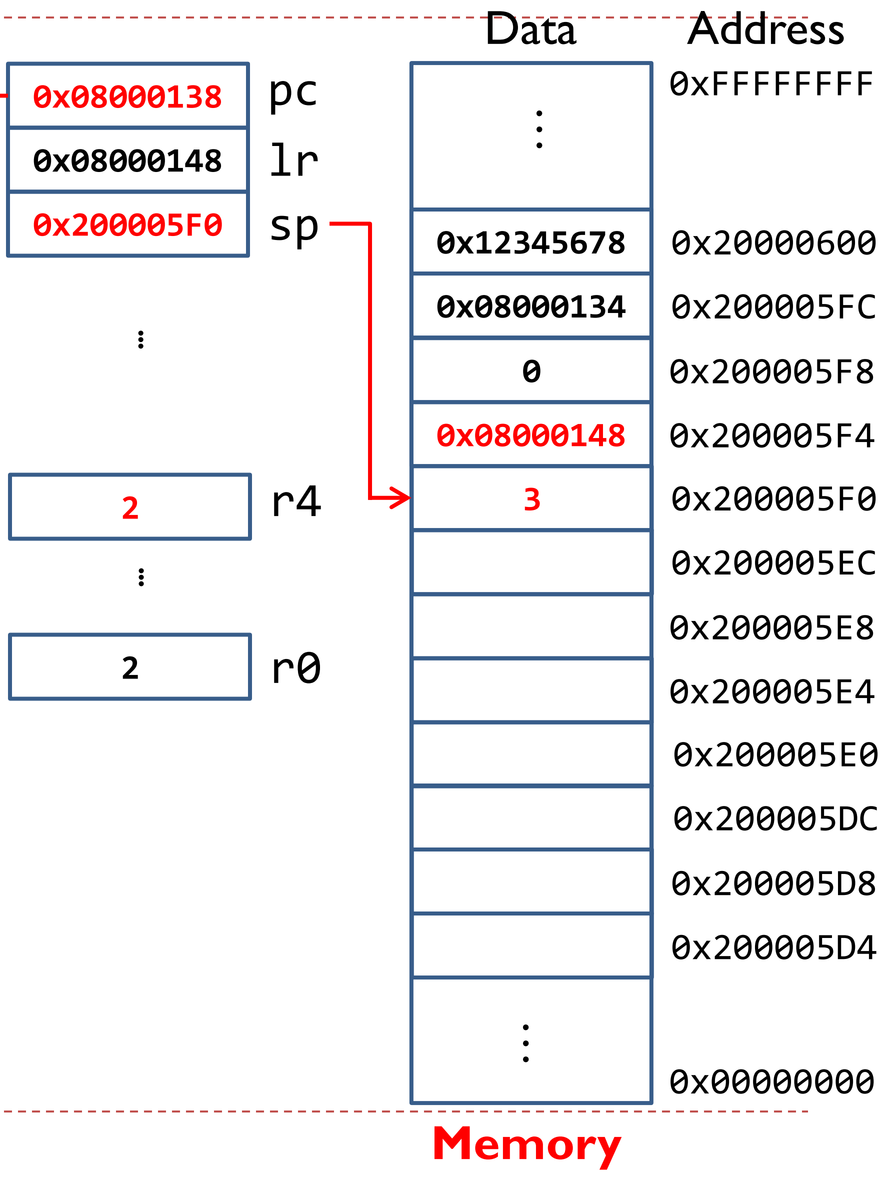
Recursive Factorial in Assembly



```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

            __main PROC
                 MOV r0, #0x03
0x08000130       BL   factorial
0x08000134  stop B    stop
                 ENDP

            factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV   r4, r0
0x0800013A       CMP   r4, #0x01
0x0800013C       BNE   NZ
0x0800013E       MOVS  r0, #0x01
0x08000140  loop POP   {r4, pc}
0x08000142  NZ   SUBS  r0, r4, #1
0x08000144       BL    factorial
0x08000148       MUL   r0, r4, r0
0x0800014C       B     loop

                 END
```

Recursive Factorial in Assembly

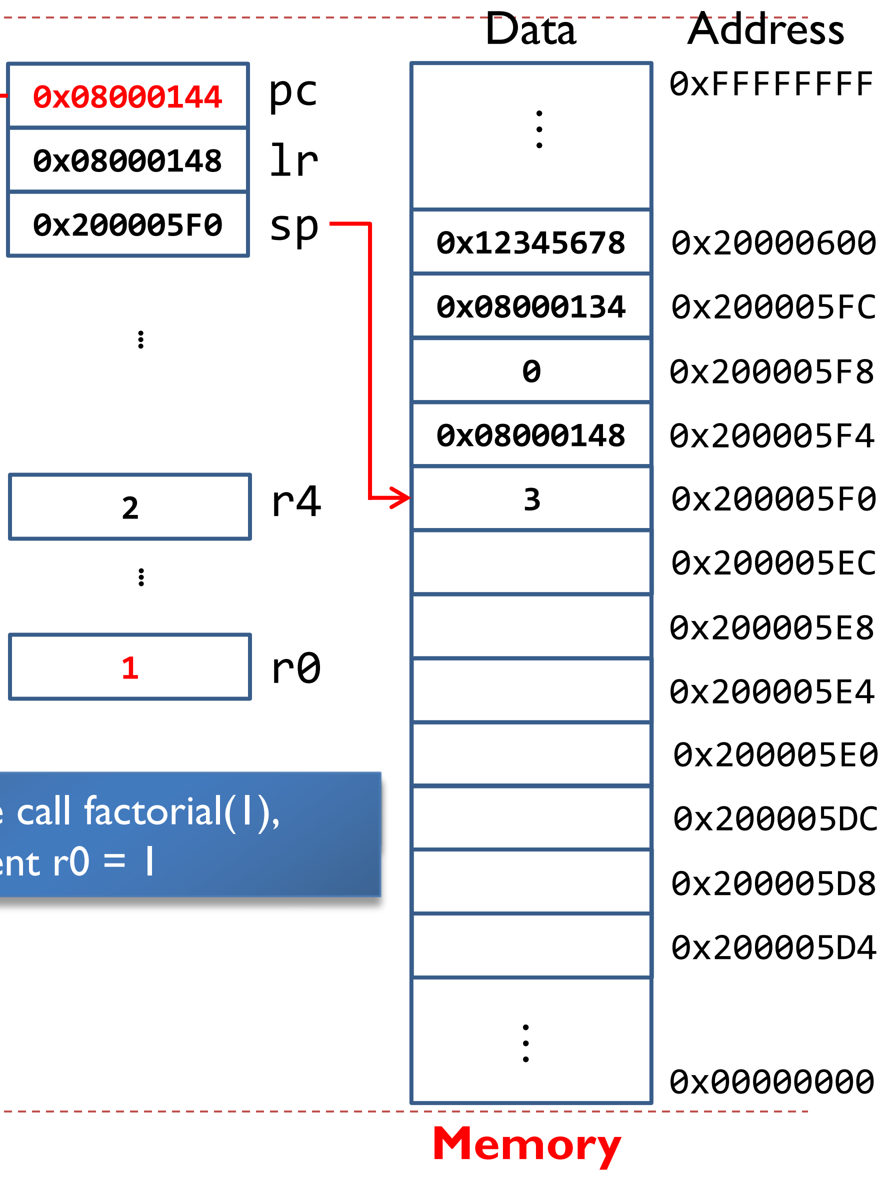
```
                AREA main, CODE, READONLY
                EXPORT  __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



Recursive Factorial in Assembly

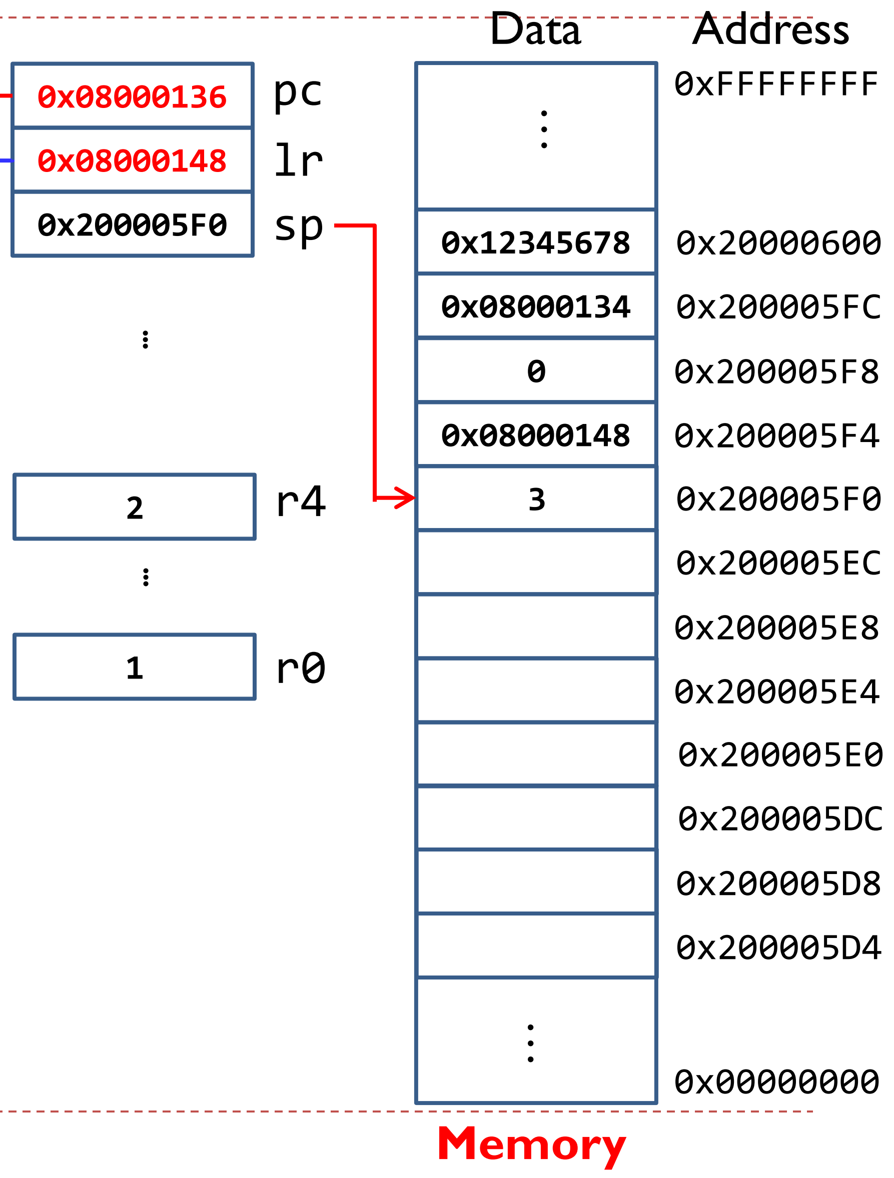
```
                AREA main, CODE, READONLY
                EXPORT  __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```

3rd recursive call factorial(1), with argument r0 = 1



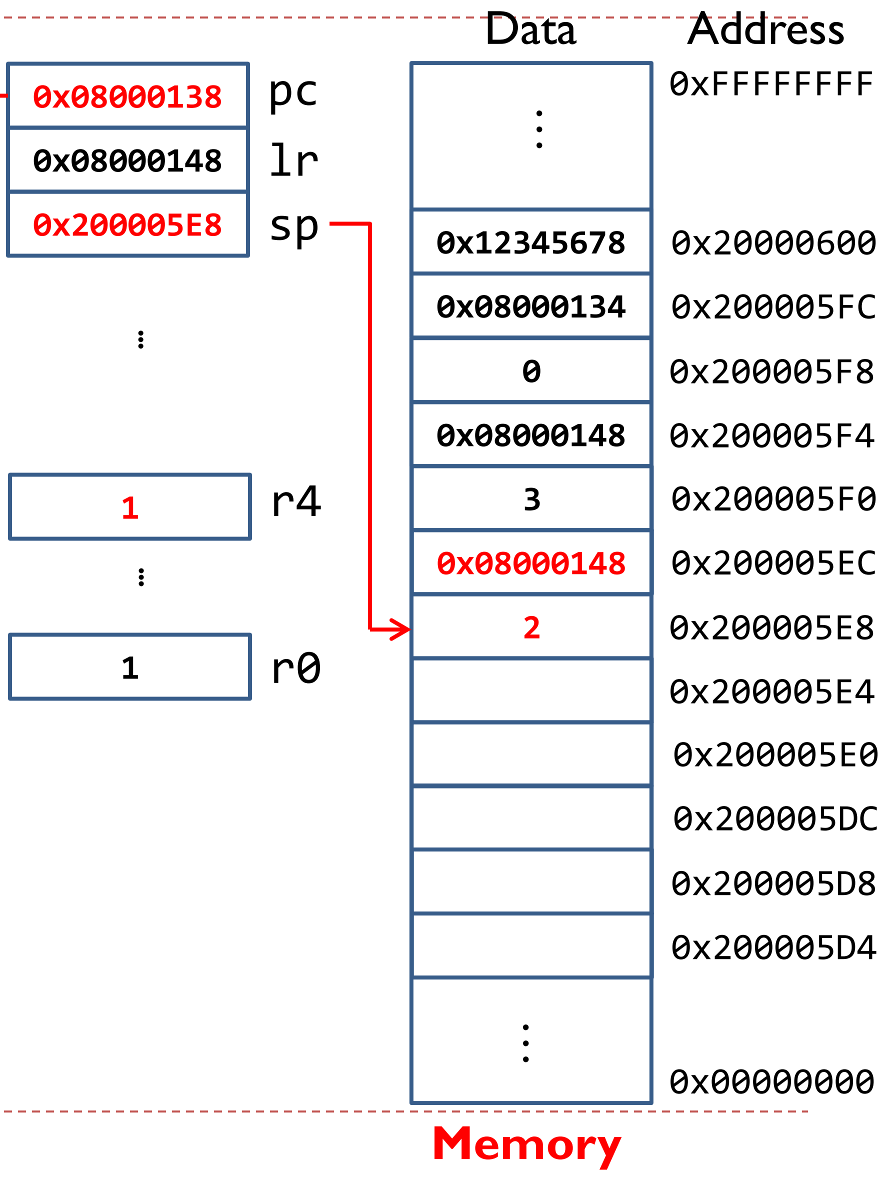
Recursive Factorial in Assembly

```
                AREA main, CODE, READONLY
                EXPORT  __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



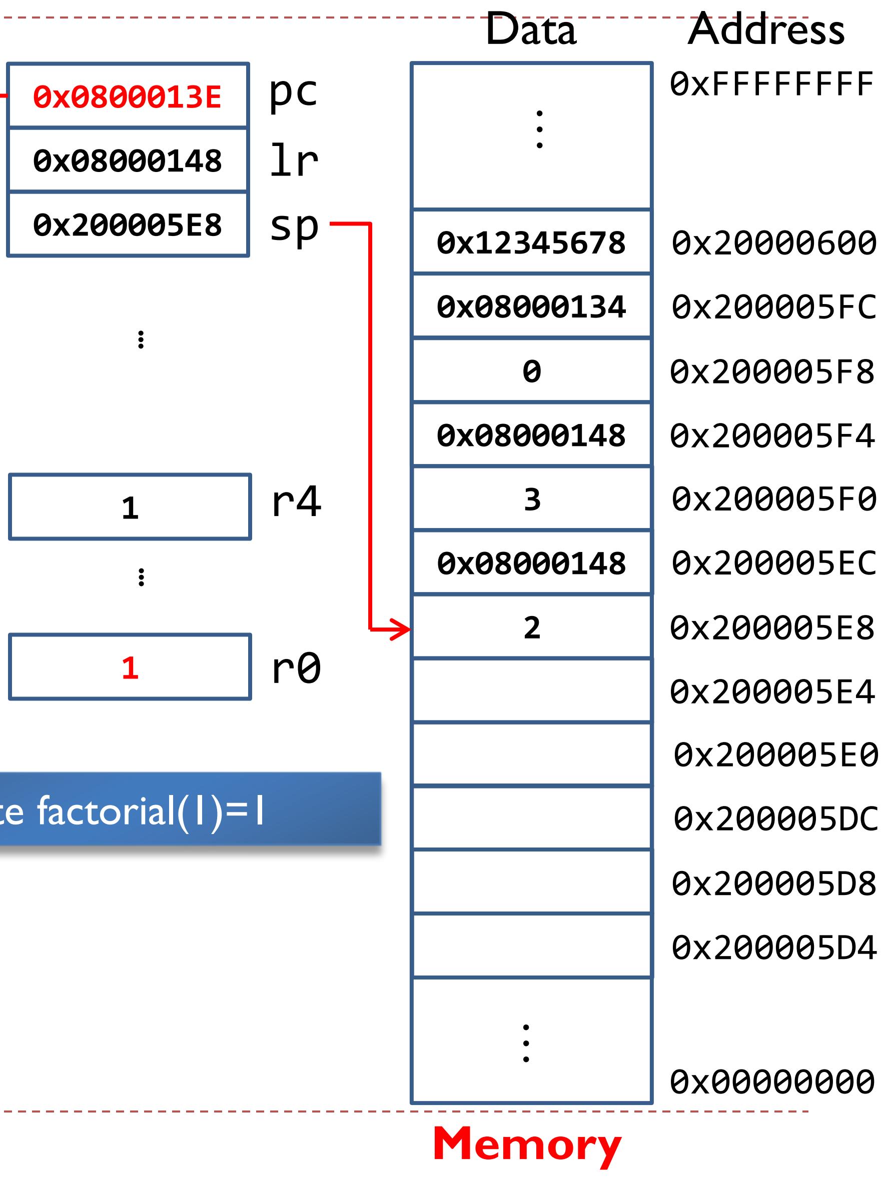
Recursive Factorial in Assembly

```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

           __main PROC
                 MOV r0, #0x03
0x08000130       BL  factorial
0x08000134 stop  B   stop
                 ENDP

           factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140 loop  POP  {r4, pc}
0x08000142 NZ    SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



Recursive Factorial in Assembly

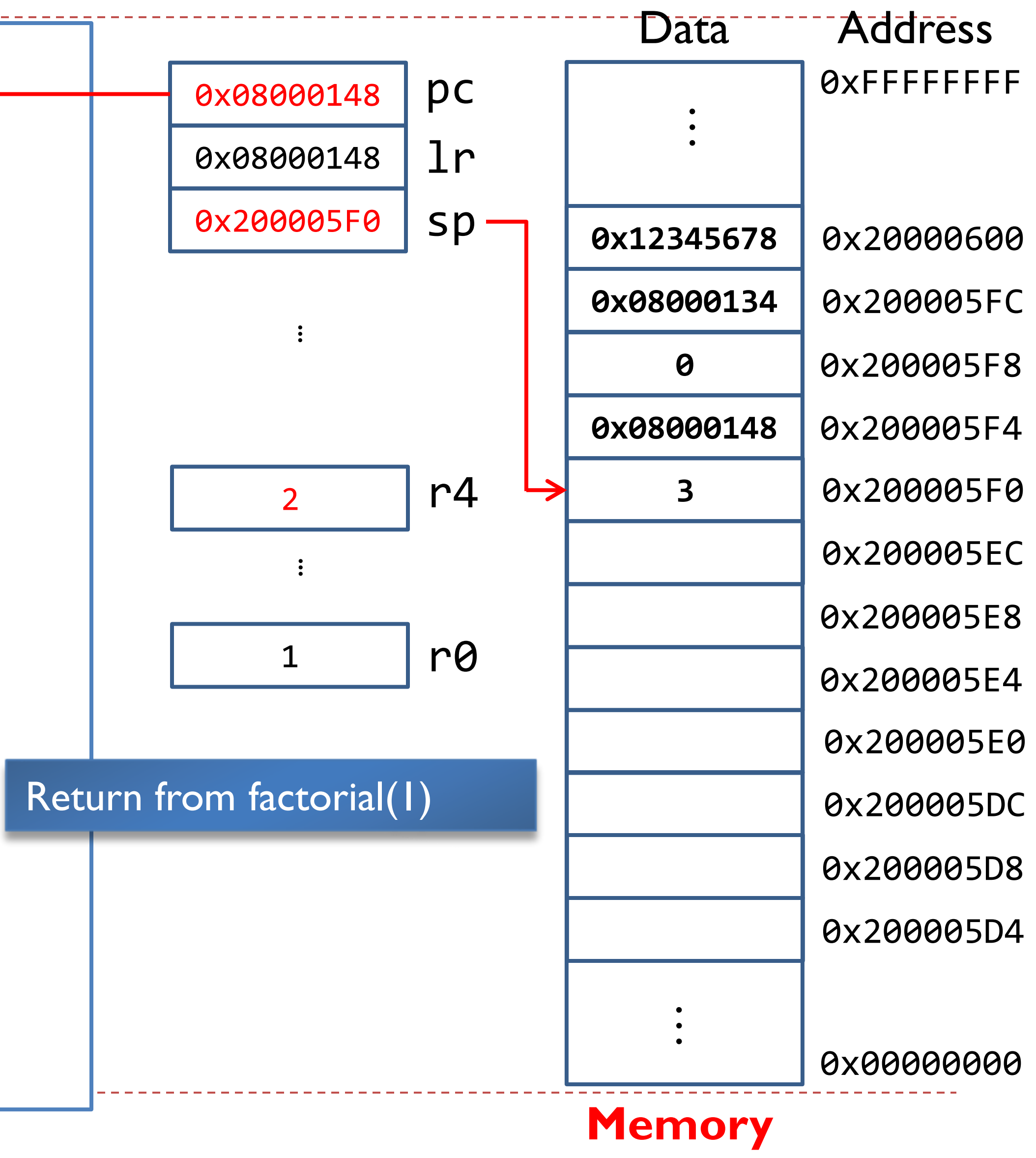
```
                AREA main, CODE, READONLY
                EXPORT   __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



Compute factorial(1)=1

Recursive Factorial in Assembly

```
                 AREA main, CODE, READONLY
                 EXPORT  __main

                 ENTRY

           __main PROC
                 MOV r0, #0x03
0x08000130       BL  factorial
0x08000134 stop  B   stop
                 ENDP

           factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140 loop  POP  {r4, pc}
0x08000142 NZ    SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



Recursive Factorial in Assembly

```
                  AREA main, CODE, READONLY
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                  ENTRY

             __main PROC
                  MOV r0, #0x03
0x08000130        BL   factorial
0x08000134   stop B    stop
                  ENDP

             factorial
0x08000136        PUSH {r4, lr}
0x08000138        MOV  r4, r0
0x0800013A        CMP  r4, #0x01
0x0800013C        BNE  NZ
0x0800013E        MOVS r0, #0x01
0x08000140   loop POP  {r4, pc}
0x08000142   NZ   SUBS r0, r4, #1
0x08000144        BL   factorial
0x08000148        MUL  r0, r4, r0
0x0800014C        B    loop

                  END
```
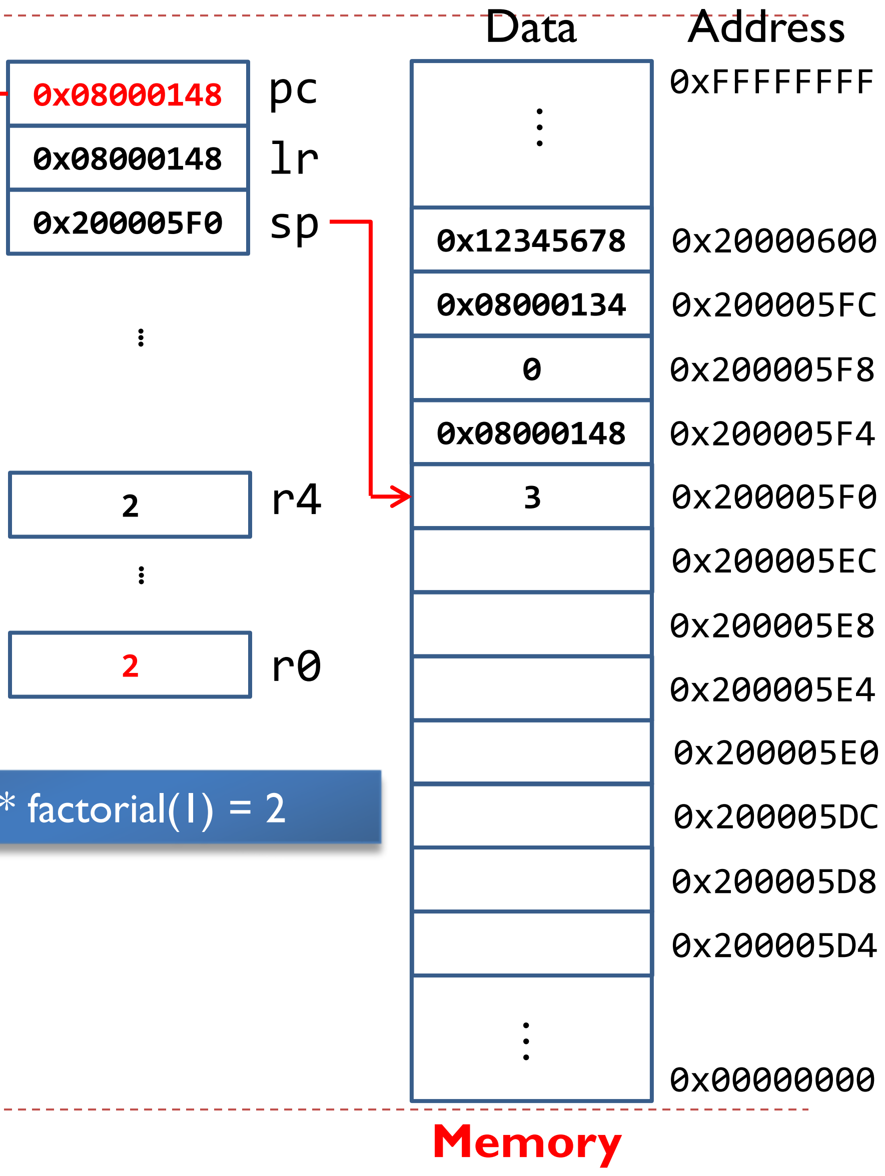
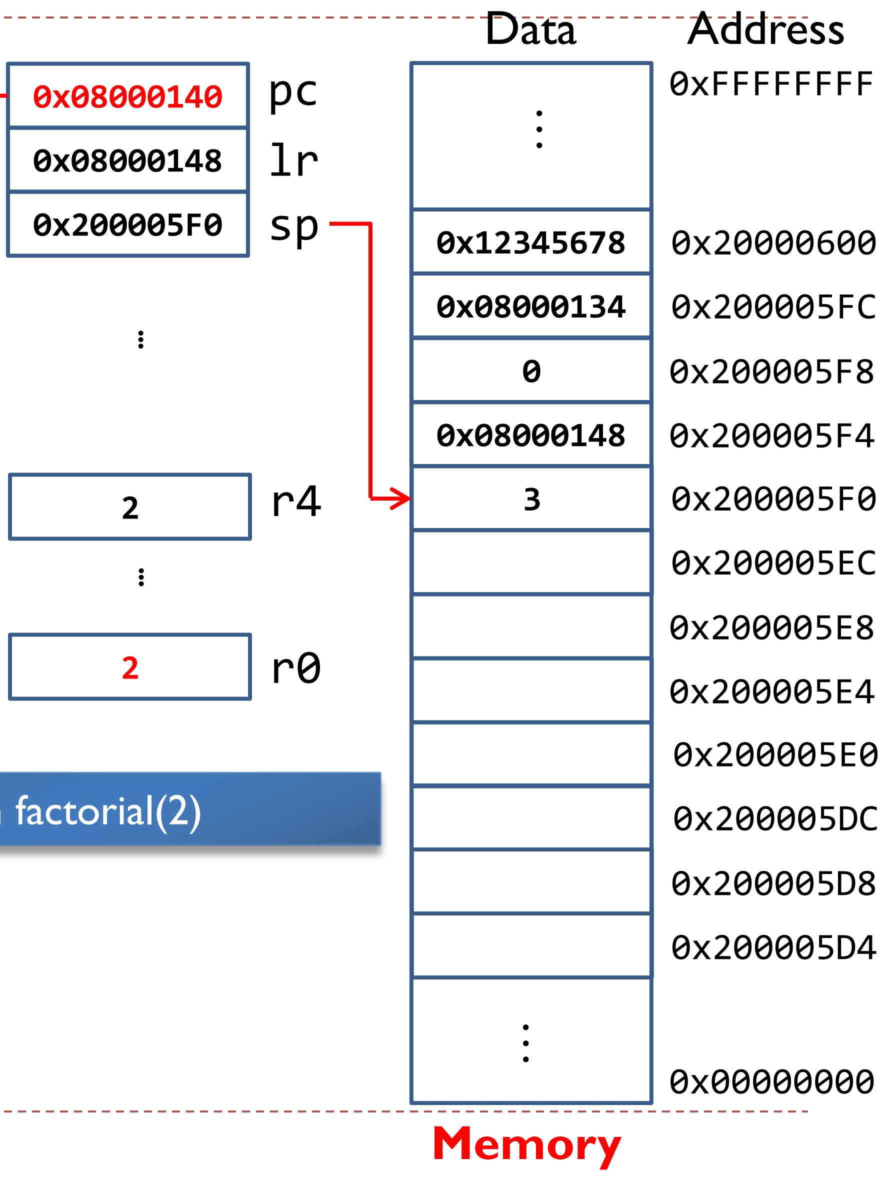



Compute 2 * factorial(1) = 2

Recursive Factorial in Assembly

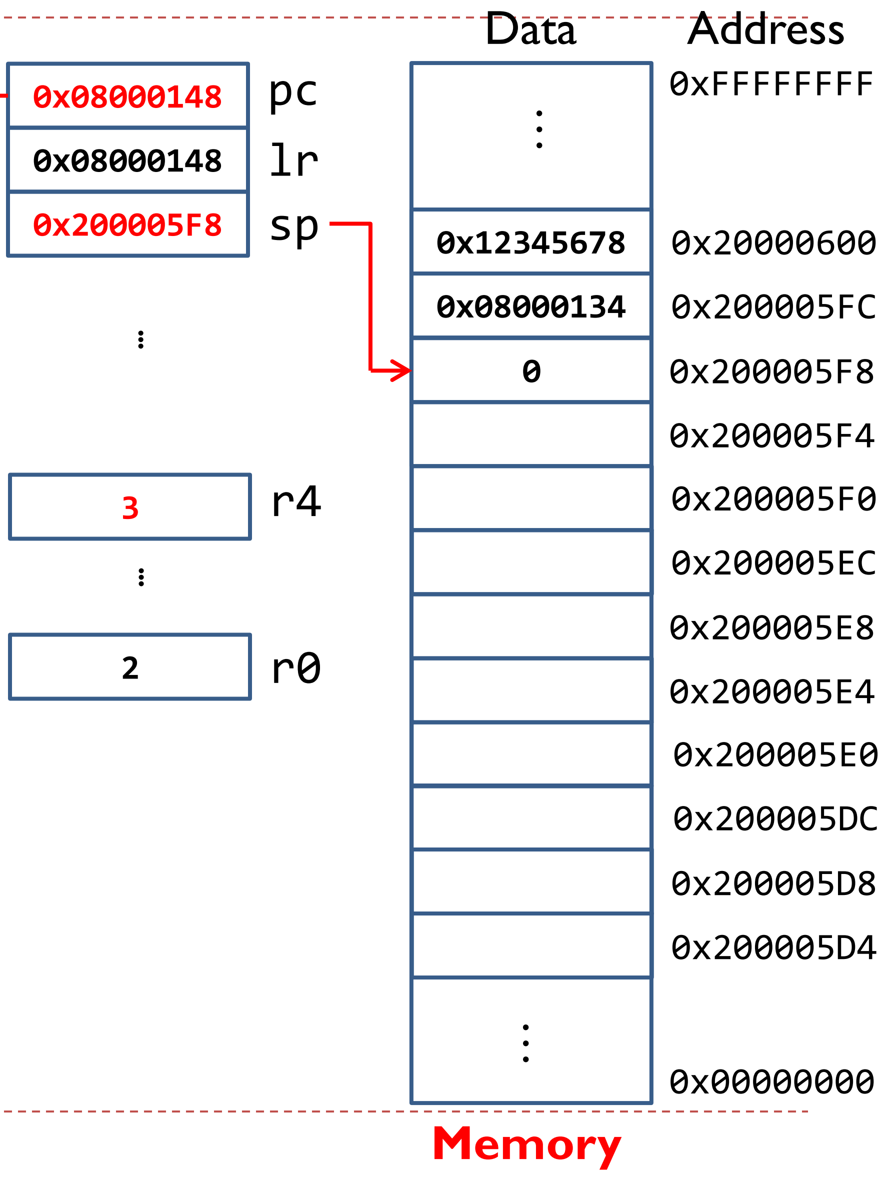
```
                AREA main, CODE, READONLY
                EXPORT  __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```

Return from factorial(2)



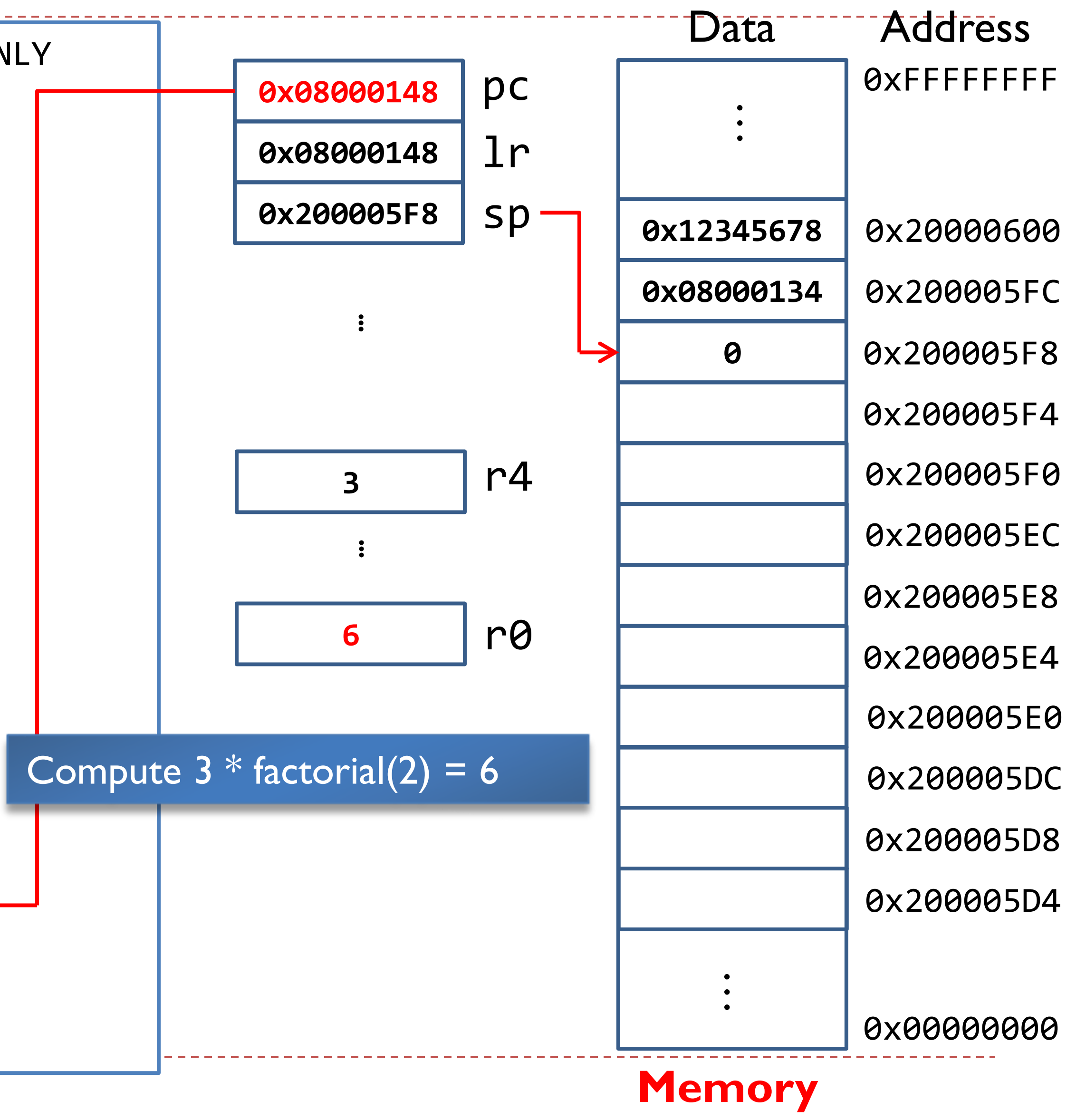
Recursive Factorial in Assembly

```
                  AREA main, CODE, READONLY
                  EXPORT   __main

                  ENTRY

            __main PROC
                  MOV r0, #0x03
0x08000130        BL   factorial
0x08000134  stop  B    stop
                  ENDP

            factorial
0x08000136        PUSH {r4, lr}
0x08000138        MOV  r4, r0
0x0800013A        CMP  r4, #0x01
0x0800013C        BNE  NZ
0x0800013E        MOVS r0, #0x01
0x08000140  loop  POP  {r4, pc}
0x08000142  NZ    SUBS r0, r4, #1
0x08000144        BL   factorial
0x08000148        MUL  r0, r4, r0
0x0800014C        B    loop

                  END
```



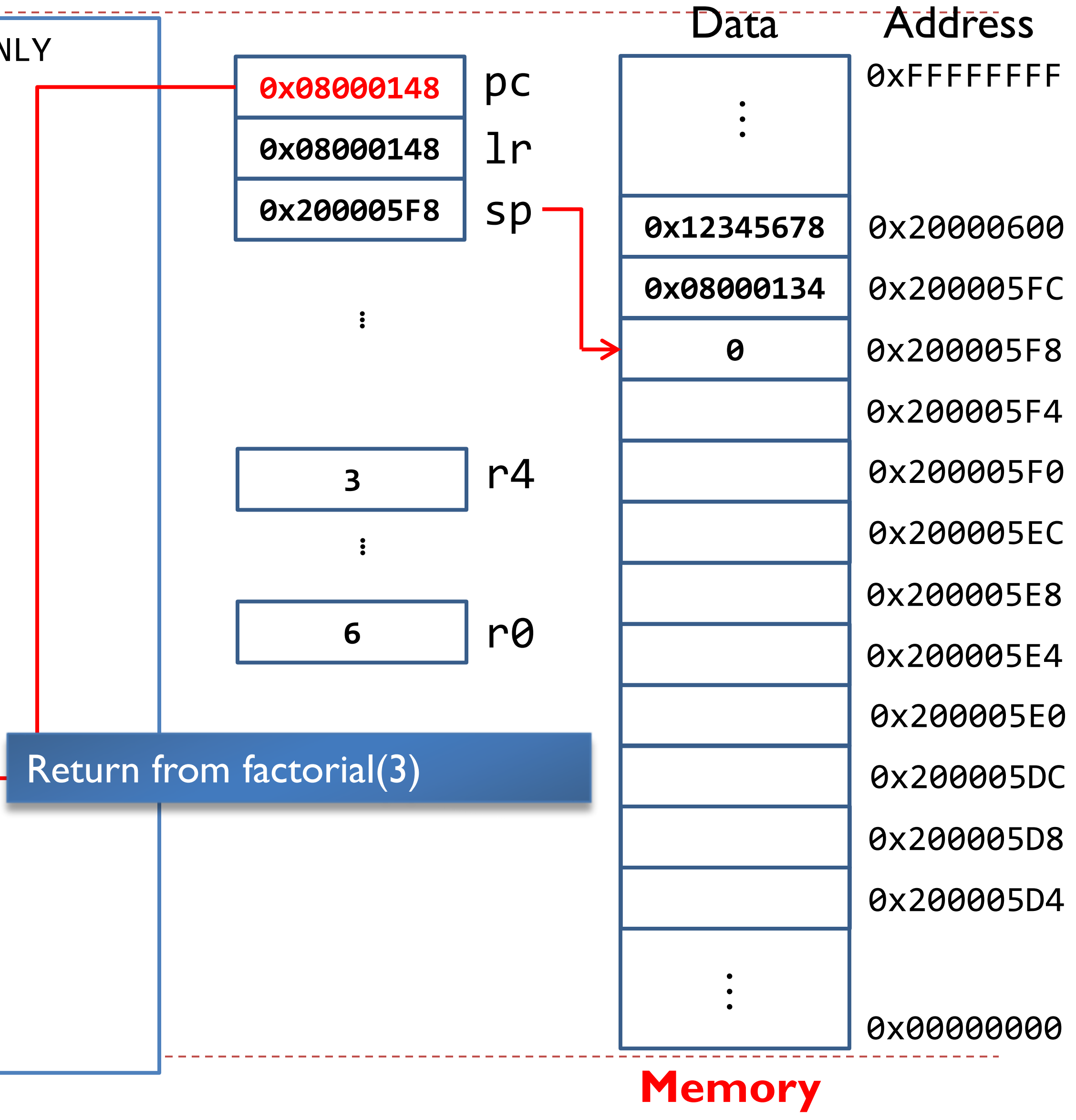
Recursive Factorial in Assembly

```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

            __main PROC
                 MOV r0, #0x03
0x08000130       BL  factorial
0x08000134  stop B   stop
                 ENDP

            factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140  loop POP  {r4, pc}
0x08000142  NZ   SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



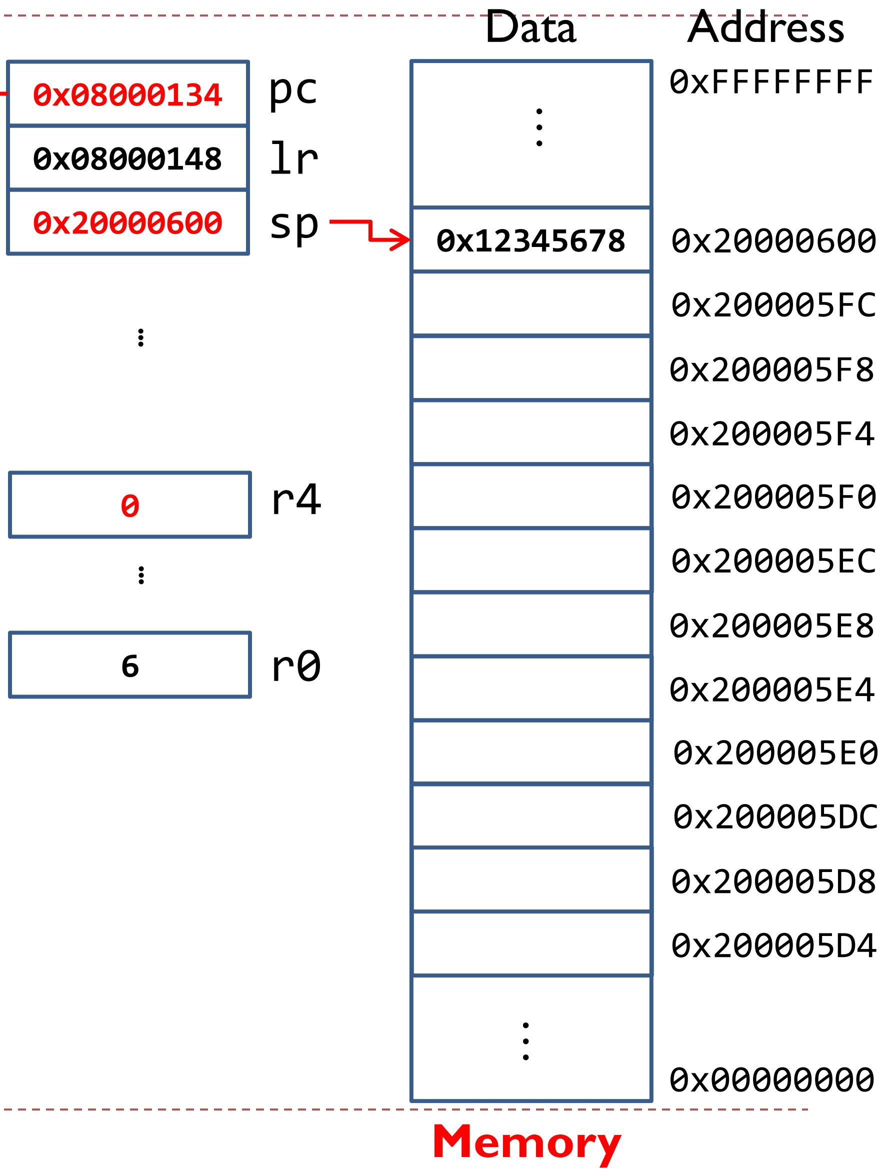
Recursive Factorial in Assembly

```
                AREA main, CODE, READONLY
                EXPORT   __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



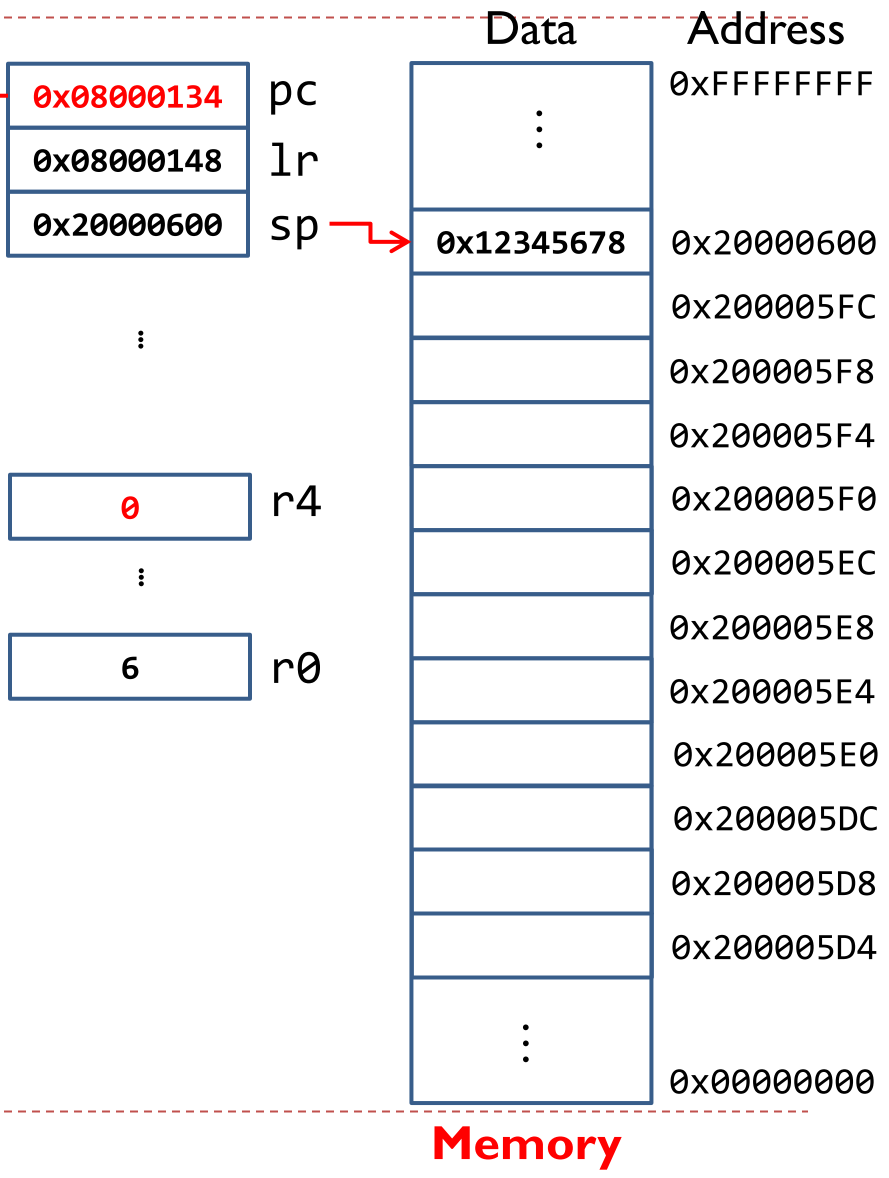
Recursive Factorial in Assembly

```
                AREA main, CODE, READONLY
                EXPORT  __main

                ENTRY

           __main PROC
                MOV r0, #0x03
0x08000130      BL  factorial
0x08000134 stop B   stop
                ENDP

           factorial
0x08000136      PUSH {r4, lr}
0x08000138      MOV  r4, r0
0x0800013A      CMP  r4, #0x01
0x0800013C      BNE  NZ
0x0800013E      MOVS r0, #0x01
0x08000140 loop POP  {r4, pc}
0x08000142 NZ   SUBS r0, r4, #1
0x08000144      BL   factorial
0x08000148      MUL  r0, r4, r0
0x0800014C      B    loop

                END
```



Recursive Factorial in Assembly

```
                 AREA main, CODE, READONLY
                 EXPORT   __main

                 ENTRY

            __main PROC
                 MOV r0, #0x03
0x08000130       BL   factorial
0x08000134  stop B    stop
                 ENDP

            factorial
0x08000136       PUSH {r4, lr}
0x08000138       MOV  r4, r0
0x0800013A       CMP  r4, #0x01
0x0800013C       BNE  NZ
0x0800013E       MOVS r0, #0x01
0x08000140  loop POP  {r4, pc}
0x08000142  NZ   SUBS r0, r4, #1
0x08000144       BL   factorial
0x08000148       MUL  r0, r4, r0
0x0800014C       B    loop

                 END
```



0x08000134 pc
0x08000148 lr
0x20000600 sp
0 r4
6 r0
Data
Address
0xFFFFFFFF
0x12345678
0x20000600
0x200005FC
0x200005F8
0x200005F4
0x200005F0
0x200005EC
0x200005E8
0x200005E4
0x200005E0
0x200005DC
0x200005D8
0x200005D4
0x00000000
Memory