README.md

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CPE 325-08
Lab 05
10/01/2019

Lab 05 Solution

Part 1

In Lab 5 part 1, I wrote an assembly program to perform element-wise multiplication on two one-dimensional arrays and store the result in a third array. I implemented the multiplication using two seperate subroutines for software multiplication using shift and add algorithm, and hardware multiplication using MSP430 16-bit multiplier peripheral.

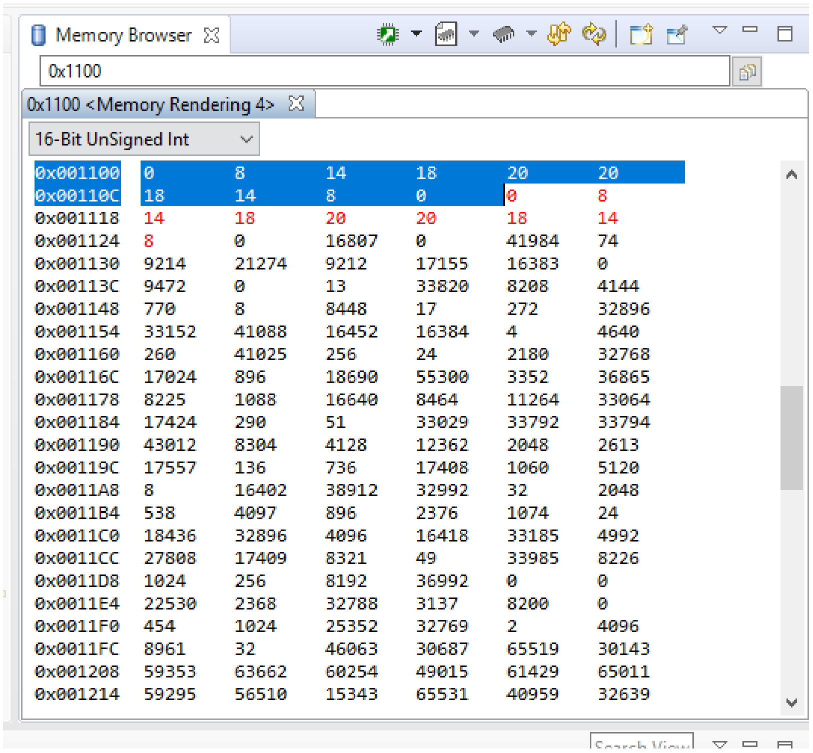
The two input arrays are

```
arr1:   .int 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
arr2:   .int 9, 8, 7, 6, 5, 4, 3, 2, 1, 0
```

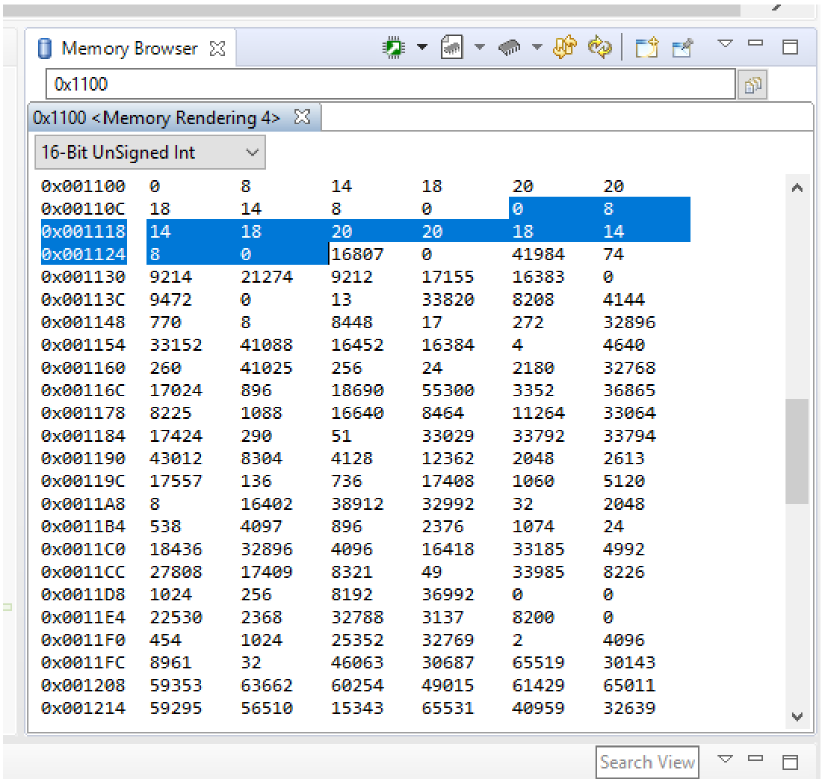
Uninitialized space was allocated for two output arrays, software multiplication output and hardware multipliciation output.

```
.bss arrOut_sw, 20, 2 ; Located at 0x1100
.bss arrOut_hw, 20, 2 ; Located at 0x1114
```

I used the processor stack to pass the input parameters and return values between the main function and the subroutines. After running the program, the contents of the output arrays are:



```
0x001100  0      8      14     18     20     20
0x00110C  18     14     8      0      0      8
0x001118  14     18     20     20     18     14
0x001124  8      0      16807  0      41984  74
0x001130  9214   21274  9212   17155  16383  0
0x00113C  9472   0      13     33820  8208   4144
0x001148  770    8      8448   17     272    32896
0x001154  33152  41088  16452  16384  4      4640
0x001160  260    41025  256    24     2180   32768
0x00116C  17024  896    18690  55300  3352   36865
0x001178  8225   1088   16640  8464   11264  33064
0x001184  17424  290    51     33029  33792  33794
0x001190  43012  8304   4128   12362  2048   2613
0x00119C  17557  136    736    17408  1060   5120
0x0011A8  8      16402  38912  32992  32     2048
0x0011B4  538    4097   896    2376   1074   24
0x0011C0  18436  32896  4096   16418  33185  4992
0x0011CC  27808  17409  8321   49     33985  8226
0x0011D8  1024   256    8192   36992  0      0
0x0011E4  22530  2368   32788  3137   8200   0
0x0011F0  454    1024   25352  32769  2      4096
0x0011FC  8961   32     46063  30687  65519  30143
0x001208  59353  63662  60254  49015  61429  65011
0x001214  59295  56510  15343  65531  40959  32639
```



```
0x001100  0      8      14     18     20     20
0x00110C  18     14     8      0      0      8
0x001118  14     18     20     20     18     14
0x001124  8      0      16807  0      41984  74
0x001130  9214   21274  9212   17155  16383  0
0x00113C  9472   0      13     33820  8208   4144
0x001148  770    8      8448   17     272    32896
0x001154  33152  41088  16452  16384  4      4640
0x001160  260    41025  256    24     2180   32768
0x00116C  17024  896    18690  55300  3352   36865
0x001178  8225   1088   16640  8464   11264  33064
0x001184  17424  290    51     33029  33792  33794
0x001190  43012  8304   4128   12362  2048   2613
0x00119C  17557  136    736    17408  1060   5120
0x0011A8  8      16402  38912  32992  32     2048
0x0011B4  538    4097   896    2376   1074   24
0x0011C0  18436  32896  4096   16418  33185  4992
0x0011CC  27808  17409  8321   49     33985  8226
0x0011D8  1024   256    8192   36992  0      0
0x0011E4  22530  2368   32788  3137   8200   0
0x0011F0  454    1024   25352  32769  2      4096
0x0011FC  8961   32     46063  30687  65519  30143
0x001208  59353  63662  60254  49015  61429  65011
0x001214  59295  56510  15343  65531  40959  32639
```

Execution Time and Efficiency

The software emulated multiplication subroutine took 867 clock cycles to evaluate 10 elements, averaging approximately 87 cycles per element. At a speed of 1 MHz, the MSP430 can evaluate 11,494 elements per second using software-emulated multiplication.

The hardware multiplication subroutine took 212 cycles to evaluate the same 10 elements, at an average of 22 cycles per element. At 1 MHz, the processor can evalute 45,454 elements per second.

The hardware multiplier is more efficient because it completes the exact same task in a quarter of the cycles required for software multiplication.

Source Code

```
            .cdecls C,LIST,"msp430.h"           ; Include device header file

;-------------------------------------------------------------------------------
            .def    RESET                       ; Export program entry-point to
                                                ; make it known to linker.
;-------------------------------------------------------------------------------
            .text                                               ; Assemble into program memory.
            .retain                                             ; Override ELF conditional linking
                                                                ; and retain current section.
            .retainrefs                                         ; And retain any sections that have
                                                                ; references to current section.

arr1:                   .int 0, 1, 2, 3, 4, 5, 6, 7, 8, 9       ; Declare input array 1
arr2:                   .int 9, 8, 7, 6, 5, 4, 3, 2, 1, 0       ; Declare input array 2

                        .bss arrOut_sw, 20, 2                   ; Allocate unitialized space
                        .bss arrOut_hw, 20, 2                   ; for output arrays

;-------------------------------------------------------------------------------
RESET:                  mov.w   #__STACK_END,SP         ; Initialize stackpointer
                        mov.w   #WDTPW|WDTHOLD,&WDTCTL  ; Stop watchdog timer
;-------------------------------------------------------------------------------
; Main loop here
;-------------------------------------------------------------------------------
                        mov.b #10, R4           ; Number of array elements
                        mov.w #arr1, R5         ; Starting address of input array 1
                        mov.w #arr2, R6         ; Starting address of input array 2
                        mov.w #arrOut_sw, R7    ; Starting address of output arrays
                        mov.w #arrOut_hw, R8    ;
                        push R4                 ;
                        push R5                 ;
                        push R6                 ;
                        push R7                 ;
                        call #SW_product
                        add.w #8, SP            ; Collapse stack after subroutine execution
                        mov.b #10, R4           ;
                        mov.w #arr1, R5         ; Reload program for hardware multiplication
                        mov.w #arr2, R6         ;
                        push R4                 ;
                        push R5                 ;
                        push R6                 ;
                        push R8                 ;
                        call #HW_product
                        add.w #8, SP            ; Collapse stack after subroutine execution

progEnd:                jmp $                   ; End of program
;-------------------------------------------------------------------------------
; SW_Multiply Subroutine - Only supports up to 8-bit multiplication
;-------------------------------------------------------------------------------
SW_product:             push R9                 ; Save current program state
                        push R10
                        push R11
                        push R12
                                                ; Retrieve parameters from stack
                        mov.w 16(SP), R4        ; Array length
                        mov.w 14(SP), R5        ; arr1 address
                        mov.w 12(SP), R6        ; arr2 address
                        mov.w 10(SP), R7        ; arrOut address
getNext:                clr.w R12
                        mov.w @R5+, R9          ; Get next operands
                        mov.w @R6+, R10         ; -
                        sxt R9                  ; Sign extend the operands
                        sxt R10                 ; -
                        mov.b #8, R11           ; Use R11 as loop counter
mul_loop:               bit.w #1, R10           ; Test bit 0 of R10
```

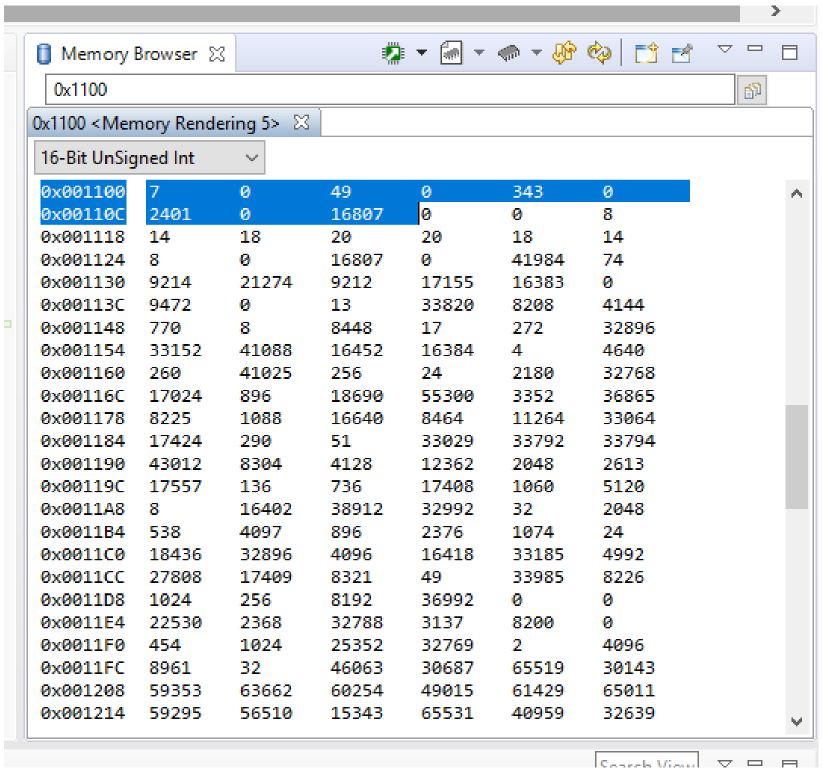
```
                        jz shift
                        add.w R9, R12
shift:                  rla.w R9
                        rra.w R10
                        dec.w R11
                        jnz mul_loop
                        bit.w #1, R10
                        jz mul_end
                        inv.w R9                ; 2's complement of R9
                        add.w #1, R9
                        add.w R9, R12
mul_end:                mov.w R12, 0(R7)
                        add.w #2, R7            ; Point arrOut to the next element
                        dec.w R4                ; Decrement loop counter
                        jnz getNext
                        pop R12                 ; Collapse stack and
                        pop R11                 ; return from subroutine
                        pop R10
                        pop R9
                        ret
;-------------------------------------------------------------------------------
; HW_Multiply Subroutine
;-------------------------------------------------------------------------------
HW_product:             push R9
                        push R10
                        mov.w 12(SP), R4        ; Array length
                        mov.w 10(SP), R5        ; arr1 address
                        mov.w 8(SP), R6         ; arr2 address
                        mov.w 6(SP), R8         ; arrOut address
loop:                   mov.w @R5+, R9          ; Get operands
                        mov.w @R6+, R10         ; -
                        mov.b R9, &MPYS         ; Load first operand - Use signed multiply mode
                        mov.b R10, &OP2         ; Load second operand
                        mov.w &RESLO, 0(R8)     ; Store result in arrOut
                        add.w #2, R8
                        dec.w R4
                        jnz loop
                        pop R10                 ; Collapse stack and
                        pop R9                  ; return from subroutine
                        ret
;-------------------------------------------------------------------------------
; Stack Pointer definition
;-------------------------------------------------------------------------------
            .global __STACK_END
            .sect   .stack

;-------------------------------------------------------------------------------
; Interrupt Vectors
;-------------------------------------------------------------------------------
            .sect   ".reset"                ; MSP430 RESET Vector
            .short  RESET
```

Part 2 (Bonus)

In Lab 5 part 2, I created an assembly program to compute the first five powers of a given positive integer base. Since the assignment states that results are assumed to be no longer than 16 bits, we are restricted to 8-bit multiplication. Thus, valid inputs would be 1, 2, and 3. By extending the program to support 16-bit multiplication, valid inputs are integers between 1 and 8. Again, the resulting arrays are stored in memory. Since the program supports 16-bit multipliction, results in the output arrays are double words (4 bytes in length).

The contents of memory after running with input base 7 and using software-emulated multiplication are:



```
0x001100  7      0      49     0      343    0
0x00110C  2401   0      16807  0      0      8
0x001118  14     18     20     20     18     14
0x001124  8      0      16807  0      41984  74
0x001130  9214   21274  9212   17155  16383  0
0x00113C  9472   0      13     33820  8208   4144
0x001148  770    8      8448   17     272    32896
0x001154  33152  41088  16452  16384  4      4640
0x001160  260    41025  256    24     2180   32768
0x00116C  17024  896    18690  55300  3352   36865
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0x001190  43012  8304   4128   12362  2048   2613
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0x0011A8  8      16402  38912  32992  32     2048
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0x0011CC  27808  17409  8321   49     33985  8226
0x0011D8  1024   256    8192   36992  0      0
0x0011E4  22530  2368   32788  3137   8200   0
0x0011F0  454    1024   25352  32769  2      4096
0x0011FC  8961   32     46063  30687  65519  30143
0x001208  59353  63662  60254  49015  61429  65011
0x001214  59295  56510  15343  65531  40959  32639
```
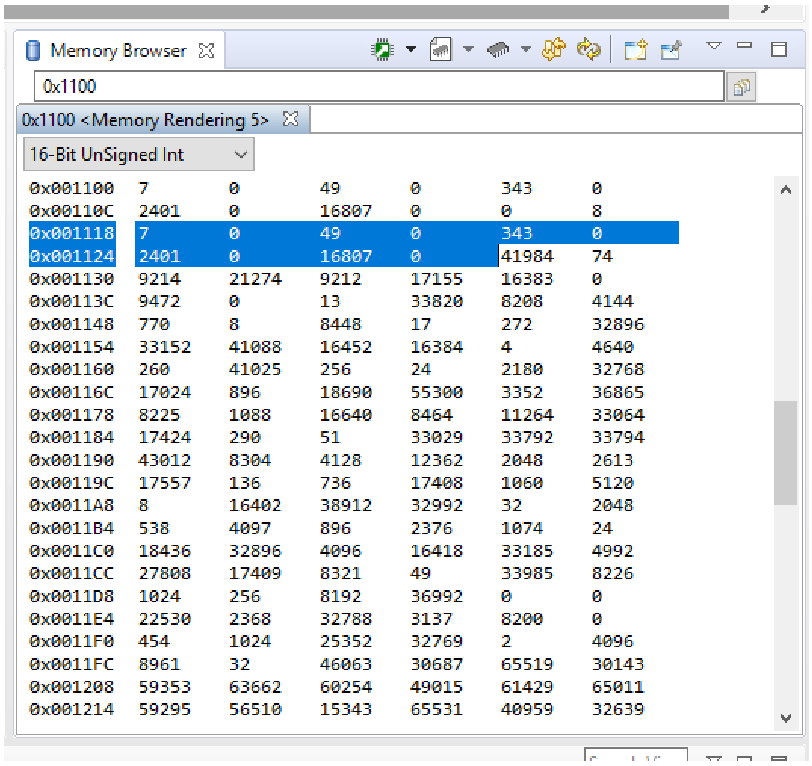

and with hardware multiplication the contents are:



```
0x001100  7      0      49     0      343    0
0x00110C  2401   0      16807  0      0      8
0x001118  7      0      49     0      343    0
0x001124  2401   0      16807  0      41984  74
0x001130  9214   21274  9212   17155  16383  0
0x00113C  9472   0      13     33820  8208   4144
0x001148  770    8      8448   17     272    32896
0x001154  33152  41088  16452  16384  4      4640
0x001160  260    41025  256    24     2180   32768
0x00116C  17024  896    18690  55300  3352   36865
0x001178  8225   1088   16640  8464   11264  33064
0x001184  17424  290    51     33029  33792  33794
0x001190  43012  8304   4128   12362  2048   2613
0x00119C  17557  136    736    17408  1060   5120
0x0011A8  8      16402  38912  32992  32     2048
0x0011B4  538    4097   896    2376   1074   24
0x0011C0  18436  32896  4096   16418  33185  4992
0x0011CC  27808  17409  8321   49     33985  8226
0x0011D8  1024   256    8192   36992  0      0
0x0011E4  22530  2368   32788  3137   8200   0
0x0011F0  454    1024   25352  32769  2      4096
0x0011FC  8961   32     46063  30687  65519  30143
0x001208  59353  63662  60254  49015  61429  65011
0x001214  59295  56510  15343  65531  40959  32639
```

Source Code

```
            .cdecls C,LIST,"msp430.h"       ; Include device header file

;-------------------------------------------------------------------------------
            .def    RESET                   ; Export program entry-point to
                                            ; make it known to linker.
;-------------------------------------------------------------------------------
            .text                           ; Assemble into program memory.
            .retain                                     ; Override ELF conditional linking
                                                        ; and retain current section.
            .retainrefs                                 ; And retain any sections that have
                                                        ; references to current section.

                        .bss power_sw, 20, 2            ; Allocate unitialized space for outputs
                        .bss power_hw, 20, 2            ;
;-------------------------------------------------------------------------------
RESET:                  mov.w   #__STACK_END,SP         ; Initialize stackpointer
                        mov.w   #WDTPW|WDTHOLD,&WDTCTL  ; Stop watchdog timer
;-------------------------------------------------------------------------------
; Main loop here
;-------------------------------------------------------------------------------
                        mov.w #power_sw, R14    ; Load result address to register
                        mov.w #power_hw, R15    ;
                        mov.w #5, R4            ; Power
                        mov.w #7, R5            ; Base low word
                        mov.w #0, R6            ; Base high word
                        add.w #16, R14          ;
                        add.w #20, R15          ;
main_loop:              push R4                 ; Pass exponent on stack
                        push R5                 ; Pass base on stack
                        push R6                 ; -
                        push R7                 ; Pass space for return value on stack
                        push R8                 ; -
                        call #power_sp          ;
                        pop R8                  ; Pop return value from stack
                        pop R7                  ; -
                        add.w #6, SP            ; Collapse stack after subroutine return

;-------------------------------------------------------------------------------
; Uncomment this block for Software Multiply
;-------------------------------------------------------------------------------
                        mov.w R7, 0(R14)        ; Store result in memory
                        mov.w R8, 2(R14)        ; -
                        add.w #-4, R14          ; Decrement result pointer
;-------------------------------------------------------------------------------

;-------------------------------------------------------------------------------
; Uncomment this block for Hardware Multiply
;-------------------------------------------------------------------------------
;                       mov.w R7, 0(R15)        ; Store result in memory
;                       mov.w R8, 2(R15)        ; -
;                       add.w #-4, R15          ; Decrement result pointer
;-------------------------------------------------------------------------------

                        dec.w R4                ; Decrement exponent
                        jnz main_loop           ;
loop_end:               jmp $                           ; End of program
;-------------------------------------------------------------------------------
; Power Subroutine
;-------------------------------------------------------------------------------
power_sp:               push R4                 ; Save program state
                        push R5                 ;
                        push R6                 ;
                        push R7                 ;
                        push R8                 ;
                        mov.w 20(SP), R4        ; Retrieve loop counter from stack
                        mov.w 18(SP), R5        ; Retrieve OP1 LB
                        mov.w 16(SP), R6        ; Retrieve OP1 UB
                        mov.w #1, R7            ; Retrieve OP2 LB
                        mov.w #0, R8            ; Retrieve OP2 UB
power_loop:             push R5                 ; Pass OP1 on stack
                        push R6                 ; -
                        push R7                 ; Pass OP2 on stack
                        push R8                 ; -
;-------------------------------------------------------------------------------
; Uncomment this block for Software Multiply
```

```
;-------------------------------------------------------------------------------
                        call #swMult            ;
                        pop R8                  ; Pop return value from stack
                        pop R7                  ; -
;-------------------------------------------------------------------------------

;-------------------------------------------------------------------------------
; Uncomment this block for Hardware Multiply
;-------------------------------------------------------------------------------
;                       call #hwMult            ;
;                       pop R8                  ; Pop return value from stack
;                       pop R7                  ; -
;-------------------------------------------------------------------------------

                        add.w #4, SP            ; Collapse stack after subroutine return
                        dec.w R4                ; Decrement loop counter
                        jnz power_loop          ;
power_end:              mov.w R7, 14(SP)        ; Return result on stack
                        mov.w R8, 12(SP)        ; -
                        pop R8                  ; Restore program state
                        pop R7                  ;
                        pop R6                  ;
                        pop R5                  ;
                        pop R4                  ;
                        ret                     ;
;-------------------------------------------------------------------------------
; SW_Multiply Subroutine - Only supports up to 16-bit multiplication
;-------------------------------------------------------------------------------
swMult:                 push R4                 ; Save program state
                        push R5                 ;
                        push R6                 ;
                        push R7                 ;
                        push R8                 ;
                        push R9                 ;
                        push R10                ;
                        clr.w R9                ;
                        clr.w R10               ;
                        mov.w #16, R4           ;
                        mov.w 22(SP), R5        ; Retrieve OP1 LB from stack
                        mov.w 20(SP), R6        ; Retrieve OP1 UB
                        mov.w 18(SP), R7        ; Retrieve OP2 LB
                        mov.w 16(SP), R8        ; Retrieve OP2 UB
mul_loop:       bit.w #1, R7                    ; Test R7 bit 0
                        jz shift                ;
                        add.w R5, R9            ; 16-bit add
                        addc.w R6, R10          ; -
shift:          rla.w R5                        ; 16-bit left shift
                        rlc.w R6                ; -
                        rra.w R7                ; 16-bit right shift
                        rrc.w R8                ; -
                        dec.w R4                ;
                        jnz mul_loop            ;
                        bit.w #1, R7            ; Test R7 bit 0
                        jz mul_end              ;
                        inv.w R5                ; 16-bit 2's complement
                        inv.w R6                ; -
                        add.w #1, R5            ; -
                        addc.w #0, R6           ; -
                        add.w R5, R9            ; 16-bit add
                        addc.w R6, R10          ; -
mul_end:        mov.w R9, 18(SP)                ; Return result on stack
                        mov.w R10, 16(SP)       ; -
                        pop R10                 ; Restore program state
                        pop R9                  ;
                        pop R8                  ;
                        pop R7                  ;
                        pop R6                  ;
                        pop R5                  ;
                        pop R4                  ;
                        ret                     ;
;------------------------------------------------------------------------------
; HW_Multiply Subroutine
;------------------------------------------------------------------------------
hwMult:                 mov.w 8(SP), &MPYS      ; 16-bit signed multiply mode
                        mov.w 4(SP), &OP2       ;
                        mov.w &RESLO, 4(SP)     ;
                        mov.w &RESHI, 2(SP)     ;
                        ret                     ;
;------------------------------------------------------------------------------
; Stack Pointer definition
;------------------------------------------------------------------------------
            .global __STACK_END
            .sect   .stack

;------------------------------------------------------------------------------
; Interrupt Vectors
;------------------------------------------------------------------------------
            .sect   ".reset"                ; MSP430 RESET Vector
            .short  RESET


---------------------------------------------------------
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___/ \_,_| _|_|_| _.__/ \__,_| _| \___/ \_,_| \__, | _| _|
                                              ____/
---------------------------------------------------------
```