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Application Note

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Introduction to the StarCore™ SC140 Tools: An Approach in Nine Exercises

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This document presents a quick, comprehensive hands-on introduction to the StarCore™ SC140 DSP core using programming examples and exercises. The goal is to help the software developer start writing high-level language applications in C. Included are software-related tips on how to get the most from the StarCore hardware architecture.

We recommend that you complete the exercises in sequential order. The exercises require the use of the SC140 C tools (including compiler, assembler, linker, and simulator) to generate executable files from C and assembly language source files and to verify the code performance. The tools are invoked from a command prompt (DOS or UNIX). If you desire, you can use an integrated development environment (IDE). Be sure to consult the appropriate IDE manuals. This application note provides step-by-step instructions to walk you through the exercises included in the software accompanying it, AN2009SW.zip. You can download this zip file at the web site listed on the back cover of this document. Solutions to the exercises are provided at the end of this application note.

The following StarCore software development tools were used in the development of the SC140 exercises. Later versions of the SC140 tools should generate similar or better results:

- *StarCore 100 C Compiler*. Produces highly optimized code. Compiler features include ANSI C-standard compliance, fixed-point optimization, global optimization, and a standard C library.

CONTENTS

- *StarCore 100 Assembler*. Translates assembly language files into machine-readable object files.
- *Linker*. Links and relocates the object files and produces executable program files. Complex memory configurations can be specified, and detailed linker maps can be generated.
- *StarCore 100 Simulator and Run-time Simulator*. The StarCore 100 simulator can run from either a text-based or a graphical user interface (GUI). A separate simulator utility (runsc100) is included for run-time I/O support.

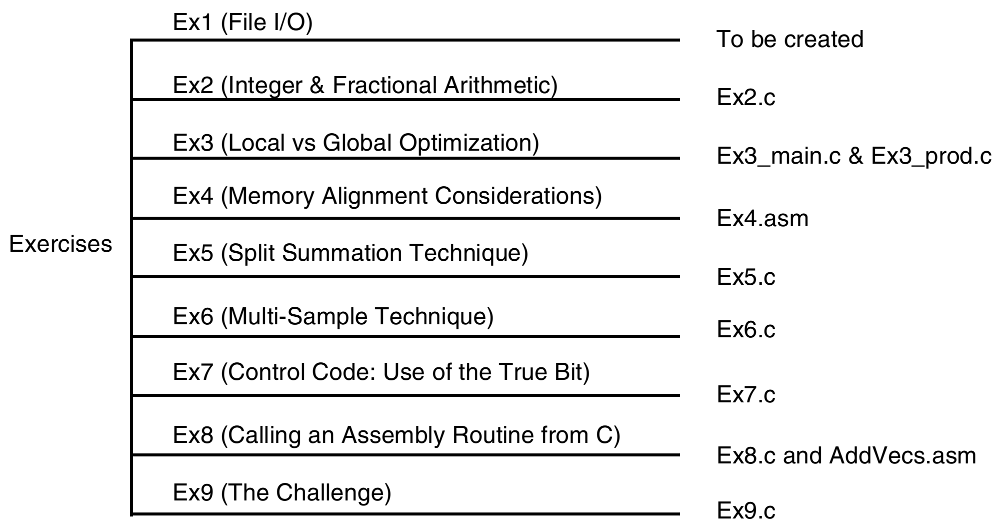
Before starting the exercises, install the files in `AN2009SW.zip` on your computer in the following directory:

- On a Windows platform: `C: \FreescaleDSP\SC140\`
- On a UNIX platform: `~/FreescaleDSP/SC140/`

The exercises directory structure and files are represented in **Figure 1**. This directory structure is only a recommendation; any location can be used. Once you have installed the exercise files (and if you are running on a Windows platform), all the exercises are located in:

- `c:\FreescaleDSP\SC140\Exercises\`

This path is the reference path for all exercises discussed in this document.



Exercises
Ex1 (File I/O)
To be created
Ex2 (Integer & Fractional Arithmetic)
Ex2.c
Ex3 (Local vs Global Optimization)
Ex3_main.c & Ex3_prod.c
Ex4 (Memory Alignment Considerations)
Ex4.asm
Ex5 (Split Summation Technique)
Ex5.c
Ex6 (Multi-Sample Technique)
Ex6.c
Ex7 (Control Code: Use of the True Bit)
Ex7.c
Ex8 (Calling an Assembly Routine from C)
Ex8.c and AddVecs.asm
Ex9 (The Challenge)
Ex9.c

Figure 1. Directory Structure and Files for SC140 Exercises

A typical development process is represented in **Figure 2**.

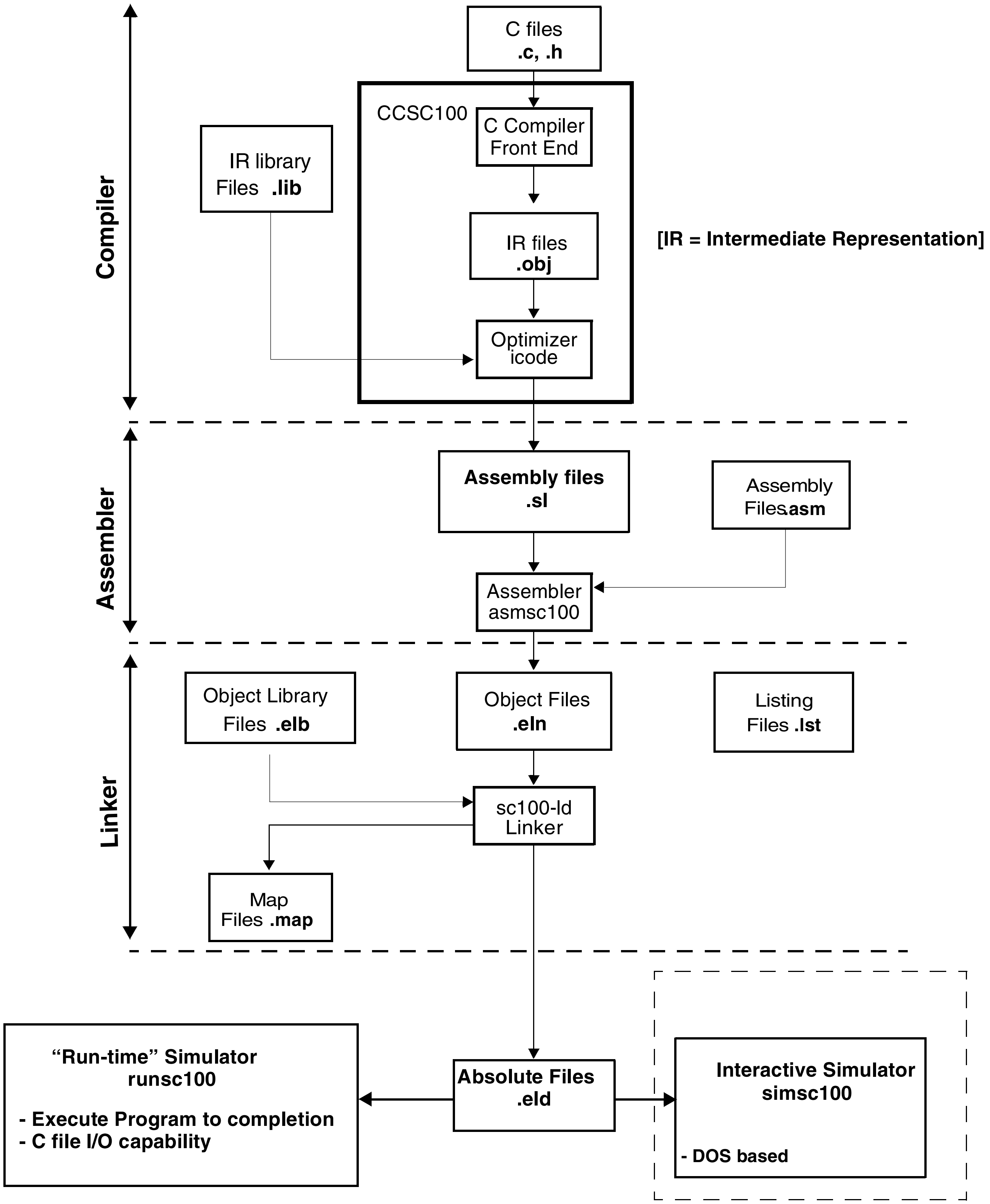


Figure 2. StarCore Development Process

1 File I/O Exercise

The file I/O exercise shows how to use standard ANSI C I/O features within the current tools suite.

1. Create a new text file called `io.c`.
2. Within the `io.c` file, write code using the ANSI C **printf** function to display **`Welcome to StarCore SC140 Tools`** on the screen (remember to include the header file `stdio.h`),
3. Compile the file using `ccsc100 io.c -o io.eld`.

   The `-o` option specifies the output file name (for example, `io.eld`). If the application does not compile successfully, correct the reported mistake(s) and recompile the application until a successful compilation occurs.
4. Run the executable `runsc100 io.eld` to display **`Welcome to StarCore SC140 Tools`**.

   The runsc100 executable is a cycle-accurate run-time simulator. It allows you to run an application to completion and print out intermediate/final results. You can use this executable for quick code verification and/or debugging purposes.

Congratulations, you have completed Exercise 1.

Good To Know

The SC140 core supports both Big Endian and Little Endian data representations. Therefore, the SC140 tools support both modes. By default, ccsc100 and runsc100 use Little Endian mode.

Big Endian mode can be selected by:

- specifying the -be option for ccsc100
- specifying the -e option for runsc100

If the code is built using Big Endian mode, it must be run using Big Endian mode.

Reminder: (memory storage of a = 0x12345678)

Table 1-1.

Big Endian Mode		Little Endian Mode	
p:00	1234	p:00	7856
p:02	5678	p:02	3412

2 Integer and Fractional Arithmetic Exercise

One of the strengths of both the StarCore architecture and the StarCore compiler is the ability to perform both fractional and integer arithmetic. This exercise presents a reminder about integer and fractional arithmetic representation and then shows how to use the StarCore compiler fractional intrinsics. Values stored in memory or registers are interpreted differently depending on the operation performed. For integers, the binary point is considered to be immediately to the right of the *LSB*. For the fractional case, the binary point is considered to be immediately to the right of the *MSB*. **Table 1** illustrates this for 16-bit data values.

Table 1. Interpretation of 16-bit Integer and Fractional Data Values

Binary Representation	Hexadecimal Representation	Integer Value (decimal)	Fractional value (decimal)
0100 0000 0000 0000	0x4000	16384	0.5
0001 0000 0000 0000	0x1000	4096	0.125
0000 0000 0000 0000	0x0000	0	0.0
1100 0000 0000 0000	0xC000	-16384	-0.5
1111 0000 0000 0000	0xF000	-4096	-0.125

2.1 Hardware Support on StarCore

StarCore has a dual instruction set for operations that produce different results depending on whether fractional or integer arithmetic is used. The instruction set is complementary when an integer or a fractional operation leads to the same result, regardless of the operation type: for example, an addition. The instruction set is dual (as shown in **Table 2**) in two cases, which automatically take care of data alignment, zero filling, and sign extension:

- When an integer or a fractional operation leads to a different result depending on the operation type: for example, a multiplication.
- When data is transferred from/to memory.

Table 2. Fractional and Integer Assembly Language Instructions

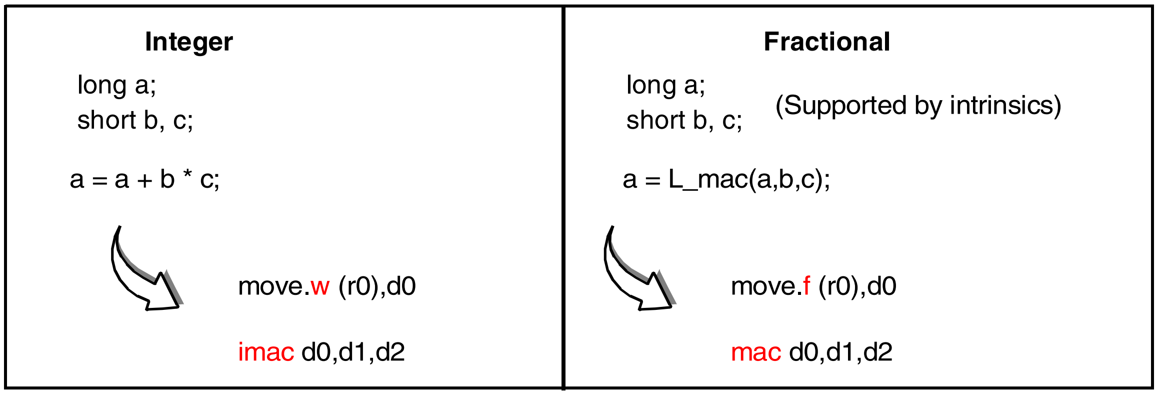
Operation	Integer	Fractional
Multiply	impy	mpy
Multiply accumulate	imac	mac
Move	move.b, move.w, move.2w, move.4w	move.f, move.2f, move.4f

2.2 Compiler Support on StarCore

The StarCore compiler implements fractional arithmetic using built-in intrinsic functions based on integer data types. Any fractional values or constants must therefore be defined using their integer equivalent. Useful relationships for deriving these integer representations from the fractional vales are as follows:

- 16-bit Integer Value = Fractional Value $\times 2^{15}$
- 32-bit Integer Value = Fractional Value $\times 2^{31}$
- 40-bit Integer Value = Fractional Value $\times 2^{39}$

The names of the built-in intrinsics conform to the ITU/ETSI basic operation functions. For instance, the L_mac() intrinsic function is used in the following example (see **Figure 3**), and a complete list of the intrinsic functions for fractional arithmetic can be found in the *SC100 C/C++ Compiler User's Manual*. The example illustrates how the instructions are mapped based on the type of the arithmetic required. For integer arithmetic, the compiler generates integer instructions (for example, **imac**). For fractional arithmetic, it generates fractional instructions (for example, **mac**). Also, move instructions are generated with correct data alignment.



```
long a;
short b, c;

a = a + b * c;

move.w (r0),d0
imac d0,d1,d2
```

```
long a;
short b, c;

a = L_mac(a,b,c);

move.f (r0),d0
mac d0,d1,d2
```

Figure 3. Integer and Fractional Compiler Support

The energy of a signal, *x*, represented by **Equation 1**, is considered:

$$y = \sum_{i=0}^{N-1} x^2(i)\,, \qquad \text{Equation 1}$$

where *x(i)* is the signal input sample at iteration *i*, *y* is the energy of the signal, and *N* is the signal length.

1. Open the example file `Ex2.c`.

Integer Arithmetic

2. Compile the file using `ccsc100 -Ot2 Ex2.c -o Ex2.eld` where the `-Ot2` option optimizes the code for time (Force Parallelization).
3. Run the executable using runsc100.
4. Recompile the file with the `-S` option, which stops the compiler after compilation.
5. Open the generated assembly file `Ex2.sl` and look at the integer instructions within the loop.
6. In the box provided here, write down the integer C code and the generated assembly instructions for the loop. Notice that the first data load is automatically pipelined in the software.

Integer Arithmetic	
C code	Generated Assembly code

Fractional Arithmetic

7. For fractional arithmetic, copy and paste the loop of `Ex2.c`.

The first loop remains unchanged and performs integer calculation while the second loop is modified to perform fractional arithmetic.

8. In the second loop, replace the integer arithmetic operation with the appropriate fractional intrinsic.

   Remember, fractional arithmetic is performed using C compiler intrinsics. In this example, the L_mac intrinsic is used. Its prototype is: `long int L_mac(long int, short int, short int).` Therefore, the code modifications should be:

   a. Create a new variable "fres" of type "long int."
   b. Replace "res += x[i] * x[i];" with the instruction "fres = L_mac(fres,x[i],x[i])."
   c. Include the file `prototype.h`, which contains all the intrinsics prototypes.
   d. Add another **printf** statement to print out the fractional result. The result is still a "long int," so "%d" should still be used.

9. Recompile the code with the `-S` option and look at the generated assembly file `Ex2.sl` within the second loop.
10. In the box provided below, write the fractional C code and the generated assembly instructions for that loop.

Fractional Arithmetic	
C code	Generated Assembly code

11. Compare the fractional assembly instructions generated to the assembly integer instructions.
12. Recompile the code without the `-S` option to produce an executable file.
13. Run the code using runsc100. The variables "res" and "fres" should print to the screen. What is the algebraic relationship between these two variables?

Congratulations, you have completed Exercise 2.

Good To Know

To perform fractional operations:

- Intrinsics are used.
- The variable types remain integer.
- The header file prototype.h should be included in the C source file.

All assembly instructions (compiler generated or hand written) between square brackets [ ] execute in parallel as a single execution set.

3 Local Versus Global Optimization Exercise

The local versus global optimization exercise shows the difference between two C compiler options: local optimization (the default) and global optimization. Local optimization compiles each file of the project individually as represented in **Figure 4**. Global optimization acts as a global binder that links all the intermediate representation (IR) files into one file before optimizing the application. Since all the application code information is available, this approach enables further optimizations beyond those achieved using local optimization alone. (Compilation takes longer when global optimization is enabled.) Global optimization compilation flow is represented in **Figure 5**.

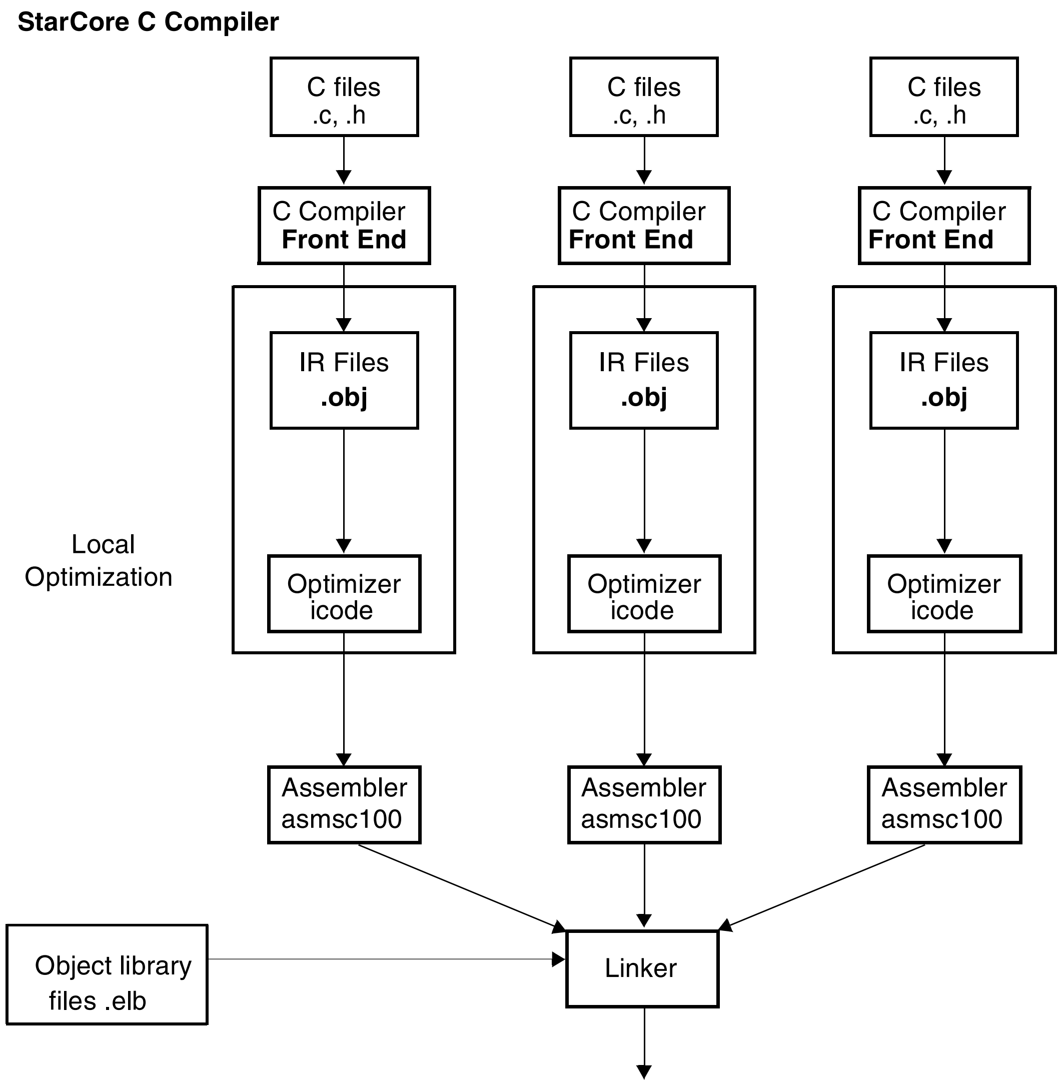


Figure 4. StarCore Local Optimization

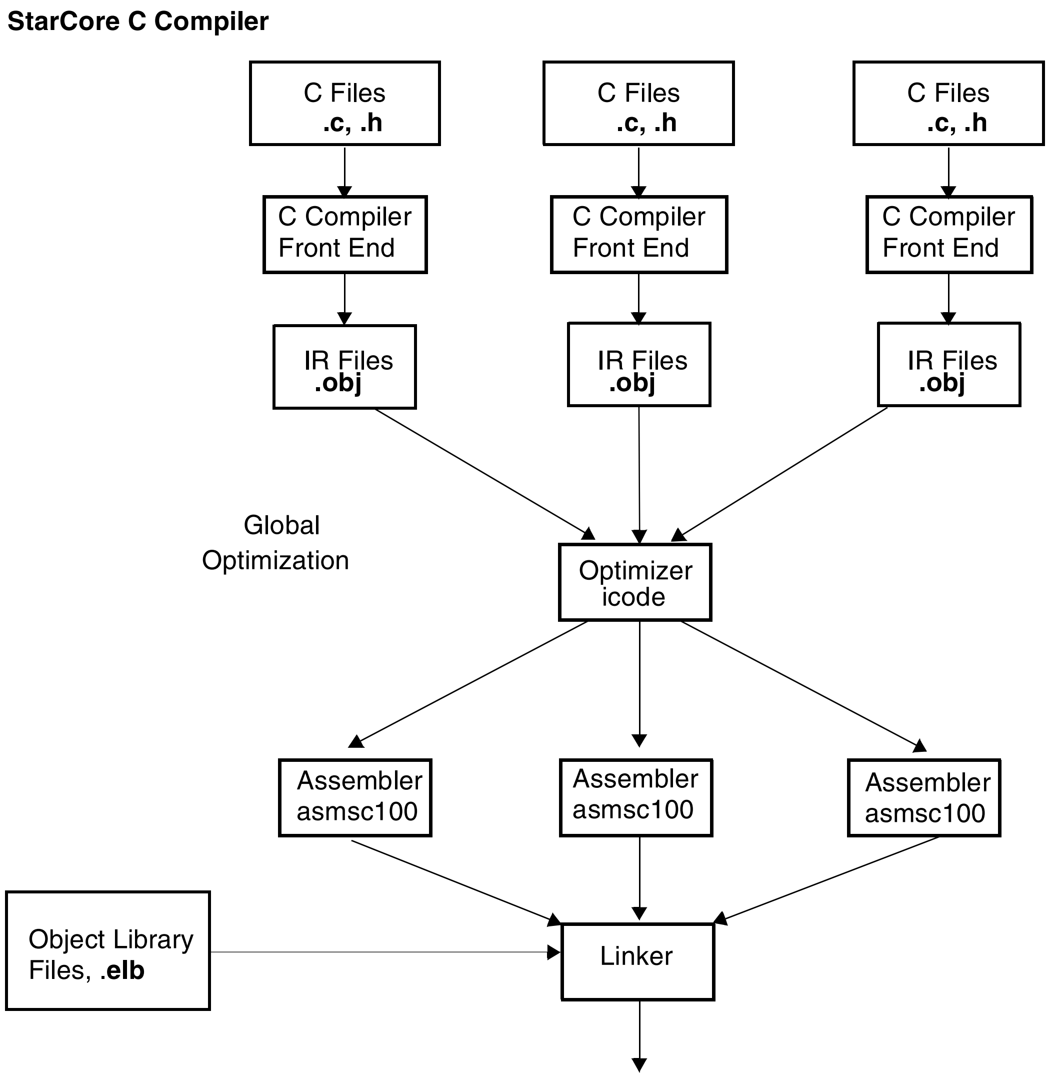


Figure 5. StarCore Global Optimization

The benefit of Global Optimization is most apparent when several files containing cross references are used, as is often the case in any sizeable application. In this example, two files are used:

- the main file called `Ex3_main.c`
- a function file called `Ex3_prod.c`

The main file, `Ex3_main.c`, calls a routine defined in the function file `Ex3_prod.c`, as shown in **Figure 6**.

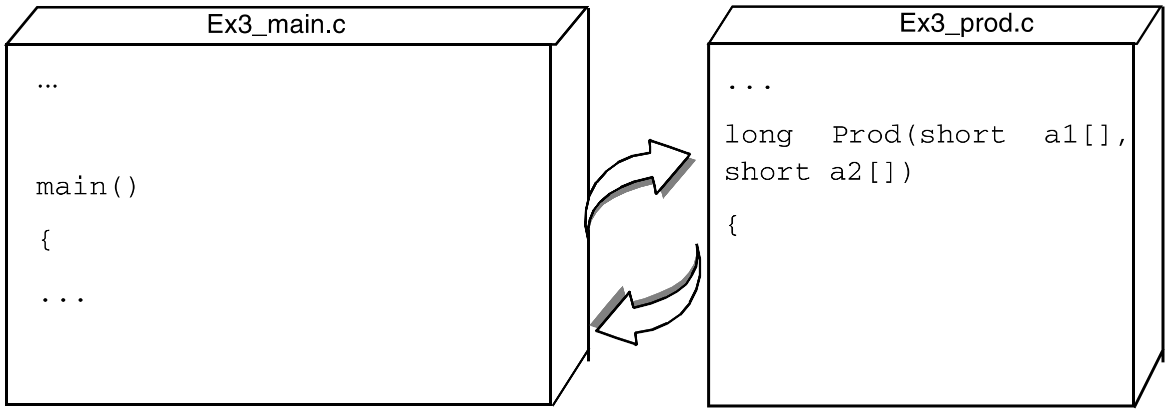


Figure 6. Files for the Local Versus Global Optimization Exercise

1. Open the two files and understand their functionality.

Local Optimization

2. Compile the two files:

```
ccsc100 -Ot2 Ex3_main.c Ex3_prod.c -o Ex3.eld
```

3. Run the code: `runsc100 -t Ex3.eld`.

   The `-t` option for runsc100 enables the cycle count generation. Write the cycle count in the box below:

Local Optimization (Default Mode) Cycle Count

Global Optimization

4. Compile the files using global optimization:

```
    ccsc100 -Ot2 -Og Ex3_main.c Ex3_prod.c -o Ex3_glo.eld
```

   where `-Og` is the global optimization option.

5. Run the code: `runsc100 -t Ex3_glo.eld`. Write the cycle count in the box below:

Global Optimization (-Og option) Cycle Count

To understand how global optimization makes best use of available information, perform these steps:

1. Recompile the application with `-S` option (Stop After Compilation) and with the local optimization: `ccsc100 -Ot2 Ex3_main.c Ex3_prod.c -S`.
2. Rename the `.sl` files as `Ex3_main1.sl` and `Ex3_prod1.sl`.
3. Open the files to see what the compiler has produced.
4. Enable global optimization: `ccsc100 -Ot2 -Og Ex3_main.c Ex3_prod.c -S`.
5. Open `Ex3_main.sl` to see what the compiler has produced.

   Since the compiler has all information on the application, it optimizes the application further than with local optimization. The compiler avoids calling the function by in-lining the function into the main code (as shown in `Ex3_main.sl`). Therefore, it eliminates the cycle overhead associated with jumping to and returning from the function and passing the parameters to the functions.

Congratulations, you have completed Exercise 3.

Good To Know

- Global optimization requires a longer compilation time than local optimization.
- Global optimization further optimizes the application speed.

4 Memory Alignment Exercise

The memory alignment exercise shows the usage of wide data moves and the necessary alignments for performing these moves. The SC140 memory has byte granularity (as represented in **Figure 7**). Two arithmetic address units (AAUs) transfer the data from memory to the 4 ALUs (and *vice versa*) via two 64-bit data buses. Each data bus allows the transfer of up to eight bytes from memory to the data registers in one cycle (and *vice versa*).

If the compiler must generate the wide data move instructions available in the StarCore instruction set—such as move.2w, move.2f, move.4w, and so on—data must be correctly aligned in memory. This is due to the way the address and data buses operate for multi-byte accesses in the StarCore architecture. The compiler does not generate wide data move instructions if alignment is not guaranteed. However, if a function is implemented in assembly language and uses wide data move instructions, you must ensure that the data is aligned on the appropriate boundary. Otherwise, the wrong data is transferred.

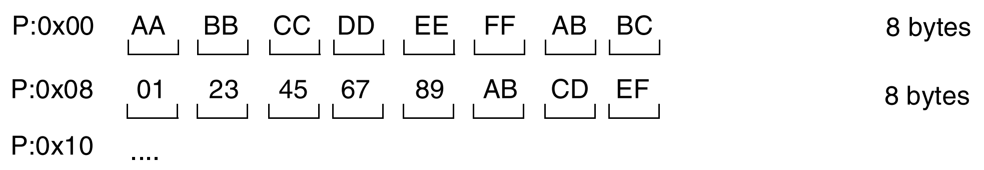


Figure 7. Memory Granularity

The following instructions bring more than one byte at a time to the data register:

move.w (Rx), Dn	Transfer one 16-bit word from memory (2 bytes)
move.f (Rx), Dn	Transfer one 16-bit word from memory (2 bytes)

move.2w (Rx), Dh	Transfer two 16-bit words from memory (4 bytes)
move.2f (Rx), Dh	Transfer two 16-bit words from memory (4 bytes)
move.4w (Rx), Dk	Transfer four 16-bit words from memory (8 bytes)
move.4f (Rx), Dk	Transfer four 16-bit words from memory (8 bytes)
move.2l (Rx), Dh	Transfer two 32-bit words from memory (8 bytes)

where x spans from 0 to 15 and the data register notations are as follows:

- Dn represents D0, D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11, D12, D13, D14, or D15.
- Dh represents D0:D1, D2:D3, D4:D5, D6:D7, D8:D9, D10:D11, D12:D13, or D14:D15.
- Dk represents D0:D1:D2:D3, D4:D5:D6:D7, D8:D9:D10:D11, or D12:D13:D14:D15.

Most processors require operands to be aligned in memory and multiple-operand load/stores to be aligned. For example, a double operand load requires an even address, and a quad operand load requires a double even address. These restrictions reduce the complexity of the address generation hardware, particularly for modulo addressing. For example, let us consider the move.4w (Rx), Dk instruction—more specifically, `move.4w (R0),D0:D1:D2:D3` (four 16-bit words are moved from the memory address of R0 into the data registers D0, D1, D2, and D3, respectively). The data must align on an 8-byte boundary, so the address contained in R0 should be a multiple of eight. The examples in **Figure 8** further illustrate this point.

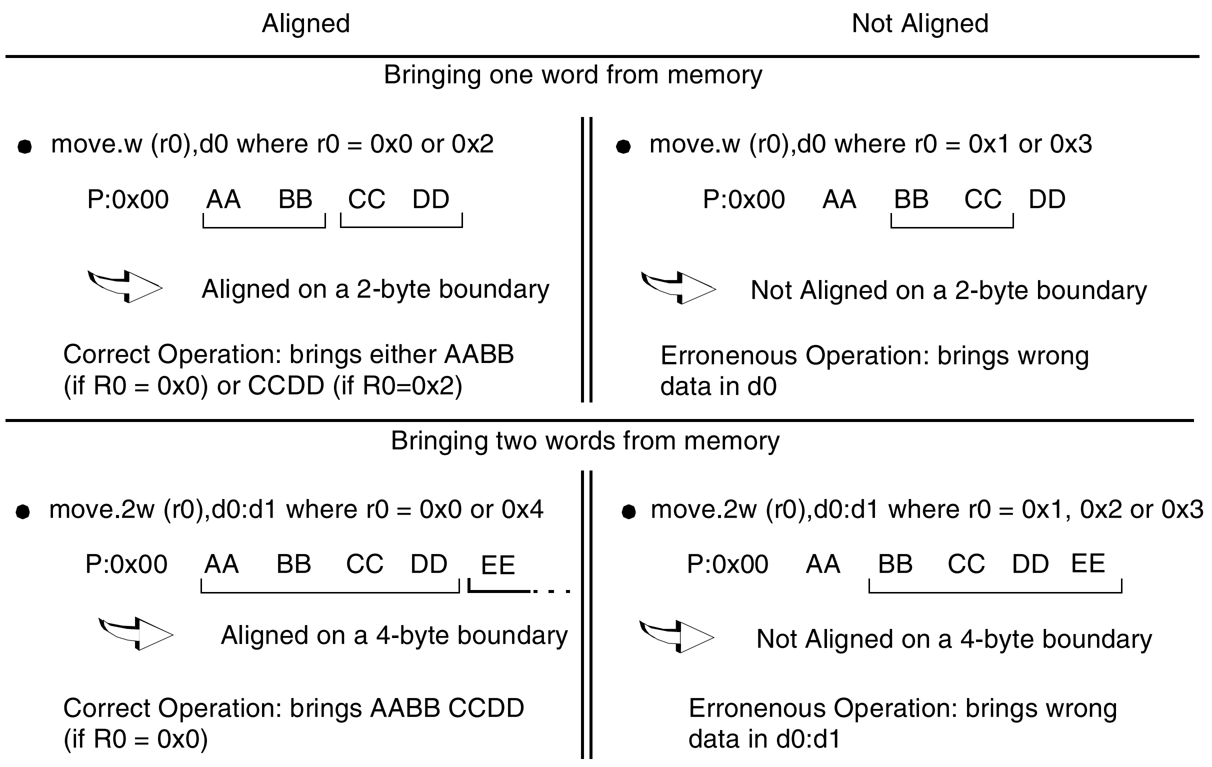

Aligned
Not Aligned
Bringing one word from memory
move.w (r0),d0 where r0 = 0x0 or 0x2
P:0x00 AA BB CC DD
Aligned on a 2-byte boundary
Correct Operation: brings either AABB (if R0 = 0x0) or CCDD (if R0=0x2)
move.w (r0),d0 where r0 = 0x1 or 0x3
P:0x00 AA BB CC DD
Not Aligned on a 2-byte boundary
Erronenous Operation: brings wrong data in d0
Bringing two words from memory
move.2w (r0),d0:d1 where r0 = 0x0 or 0x4
P:0x00 AA BB CC DD EE
Aligned on a 4-byte boundary
Correct Operation: brings AABB CCDD (if R0 = 0x0)
move.2w (r0),d0:d1 where r0 = 0x1, 0x2 or 0x3
P:0x00 AA BB CC DD EE
Not Aligned on a 4-byte boundary
Erronenous Operation: brings wrong data in d0:d1

Figure 8. Alignment Considerations

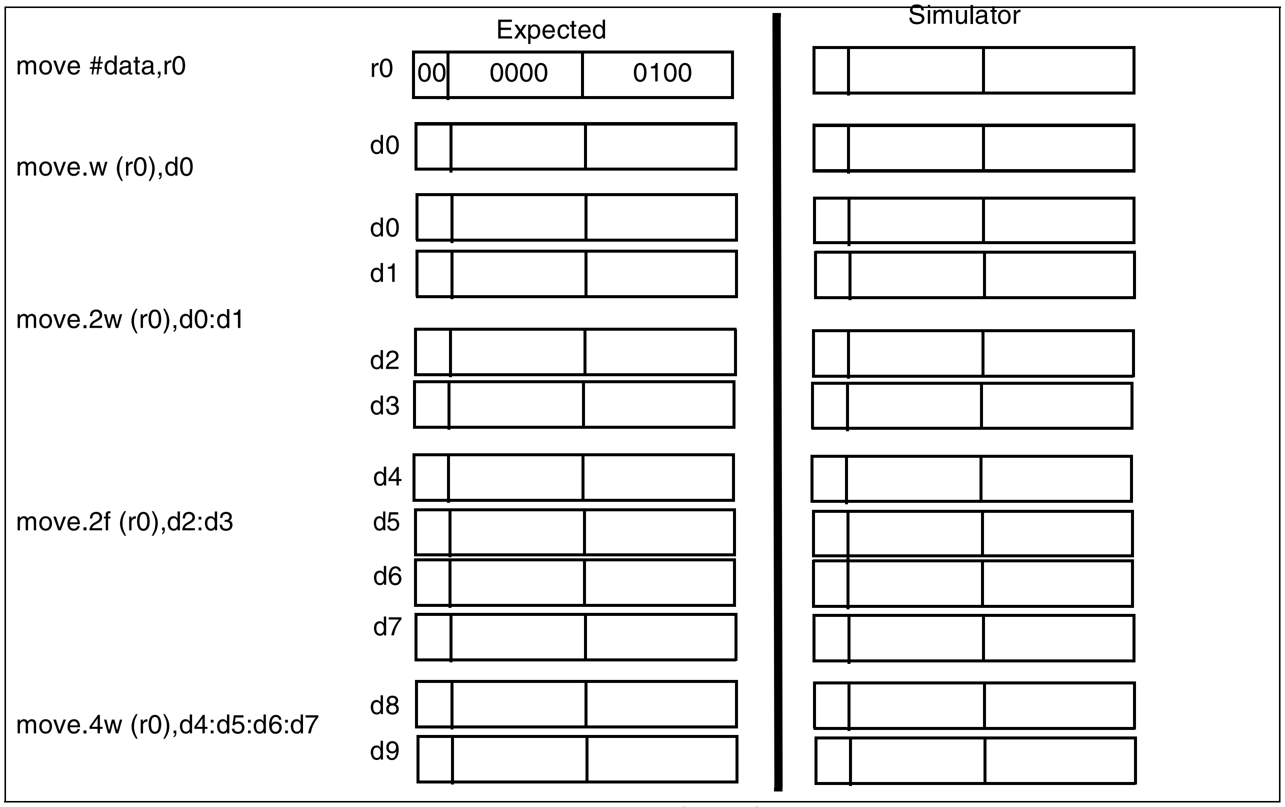
The following instructions require data to be aligned on the specified boundaries:

move.w	(r0),d0	2-byte boundary
move.f	(r0),d0	2-byte boundary
move.2w	(r0), d0:d1	4-byte boundary

move.2f	(r0), d0:d1	4-byte boundary
move.4w	(r0),d0:d1:d2:d3	8-byte boundary
move.4f	(r0),d0:d1:d2:d3	8-byte boundary
move.l	(r0),d0	8-byte boundary
move.2l	(r0),d0:d1	8-byte boundary

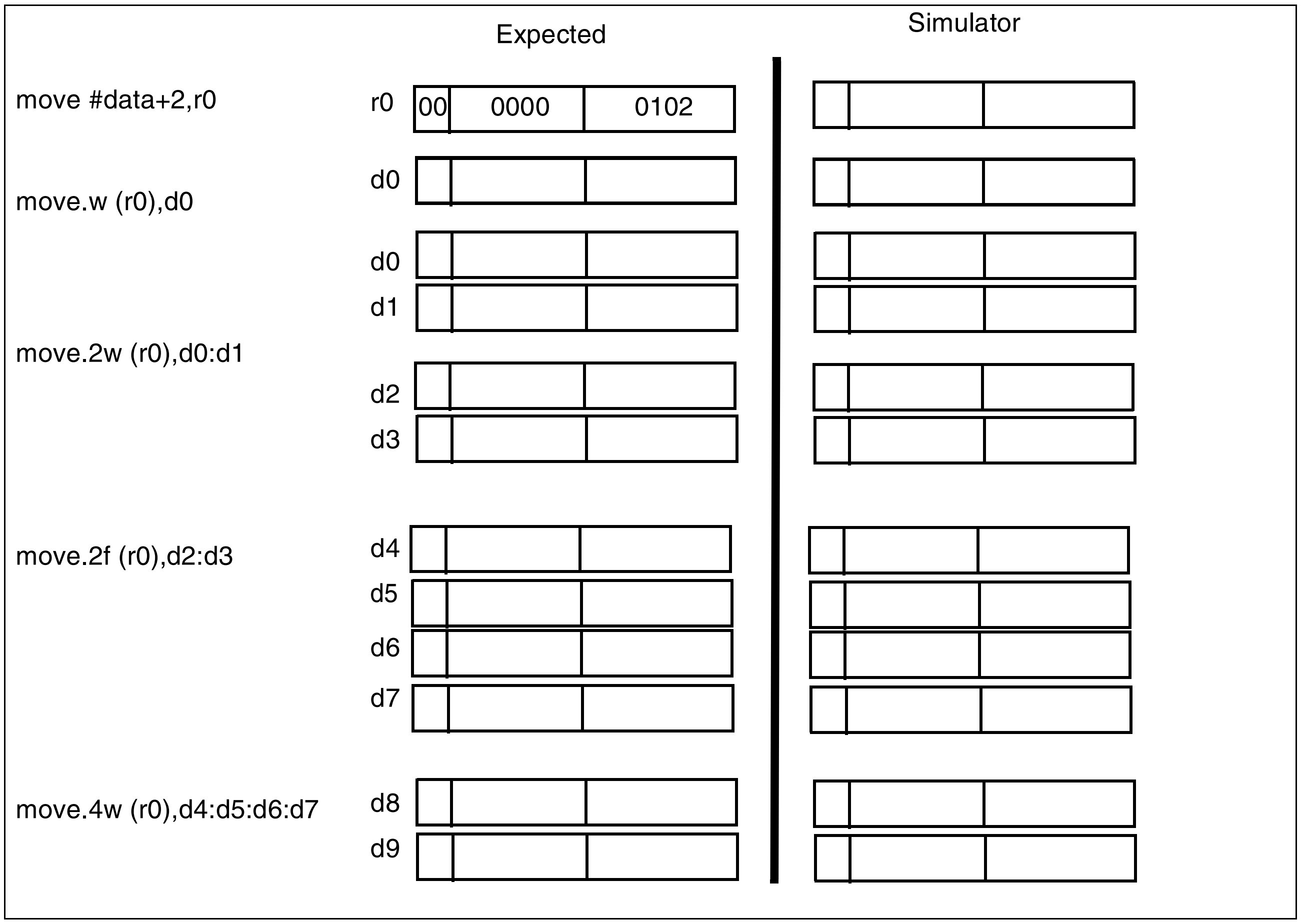
1. Open the `Ex4.c` file, which contains a series of assembly instructions within a C framework using *asm* statements. For alternative (and nicer) ways of incorporating assembly code, consult the *SC100 C/C++ Compiler User's Manual.*
2. Look at the assembly instructions to understand the wide data move instructions. Notice that the code comprises two sections: the first section with aligned data and the second with non-aligned data.
3. For each instruction, write the result you expect from each section in the boxes provided here (in the *Expected* Columns). Array "data[ ]" is of type long int and therefore aligns on a 4-byte boundary.

data: 0x01 0x231 0x45 0x67 0x89 0xAB 0xCD 0xEF
0xAA 0xBB 0xCC 0xDD 0xEE 0xFF 0x11 0x22



First Code Section

data: 0x01 0x23 0x45 0x67 0x89 0xAB 0xCD 0xEF 0xAA 0xBB 0xCC 0xDD
0xEE 0xFF 0x11 0x22



Second Code Section

1. Compile the `Ex4.c` file: `ccsc100 -be Ex4.c -o Ex4.eld`.

   The Big Endian (`-be`) option is used in this exercise to make it easier to read the data in the simulator memory window. If desired, the Little Endian mode can also be used.
2. Run the GUI simulator: guisc100. In the simulator command window, type `reset d m1` to put the simulator in Big Endian mode.
3. Open an assembly window: Windows->Assembly.
4. Load the file: `Load Ex4.eld`.
5. Set a breakpoint on “main” by typing `break _main` into the command window.
6. Type `go`. The code should now be at the start of main.
7. Open a memory window: Windows->Memory and click OK.
8. Type `data` into the Scroll box (of the memory window) to display the contents of the array data[ ] defined in `Ex4.c`. Verify that these contents are as expected.
9. Type `next` to step through the code.
10. Look at the register contents in the session window and write the values in the ***Simulator*** Columns boxes above for both sections.

Congratulations, you have completed Exercise 4.

Good To Know

- Unaligned data accesses lead to erroneous results. You must consider these issues when developing assembly code.

5 Split Summation Exercise

The split summation exercise shows how to modify C code using the split summation technique to get better parallelization. The split summation technique helps to maximize the multiple-ALU loading by performing arithmetic operations in parallel while requiring little algorithmic or code modifications. To illustrate this technique, the example performs the the optimization of the energy of a signal calculation already considered in Exercise 2. The power calculation is represented in **Equation 2**:

$$y = \sum_{i=0}^{N-1} x^2(i)\,, \qquad \textbf{Equation 2}$$

where *x(i)* is the signal input sample at iteration *i*, *y* is the power of the signal, and *N* is the signal length. As Exercise 2 shows, computing the signal energy directly from **Equation 2** results in the use of only one ALU out of the four with one multiply-accumulate operation performed at each iteration. However, the split summation technique can load all four ALUs. **Equation 2** is expanded as follows:

$$y = \sum_{i=0,4,8,\ldots}^{N-1} x(i)x(i) + x(i+1)x(i+1) + x(i+2)x(i+2) + x(i+3)x(i+3) \qquad \textbf{Equation 3}$$

Equation 3 explicitly highlights the four multiply-accumulate operations that can be performed in parallel. **Figure 9** highlights where each parallel execution is represented by Group 0, Group 1, and so on. It also shows that the sample number, *i*, from one group to the other is incremented by four.

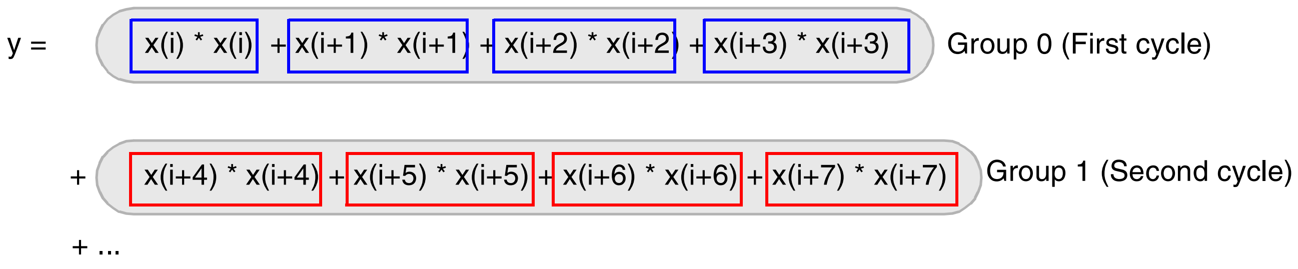


Figure 9. Signal Power Calculation Using the Split Summation Technique

1. Open the `Ex5.c` file.
2. Build the code with `-Ot2`, then run it and notice the output result.
3. Split the current implementation of the loop (that is, `res = L_mac(res, x[i], x[i]);`) into four independent equations as represented in **Figure 9**.

   "Independent" means that the four equations are accumulated into different variables. Therefore, create four variables for each product. Tip: Watch your index increment.

4. Recompile the file and run it. The output result should be the same as before.
5. Recompile with the `-S` option and view the `.sl` file.
6. Your code is optimized when the loop is only one cycle and computes four operations at a time.

   If the inner loop is equal to one cycle for four operations and the result is still correct, congratulations. You have completed Exercise 5.
7. In the box provided below, write the optimized inner loop code:

C Code	Generated Assembly Code

The split summation technique allows full use of all four ALUs, reducing the cycle time by more than 70 percent relative to use of a single ALU. The 4-ALU technique does not guarantee bit-exactness with the single-ALU technique because the order of accumulation is different. Using the 4-ALU technique therefore has implications in applications that are defined by bit-exact standards, such as speech coding standards from ITU, ETSI,TIA/EIA, and so on.

Good To Know

- The use of four variables removes the accumulation dependency that is required for parallelism.
- Bit exact considerations must be understood if this technique is used: overflow/saturation characteristics may change during split summation.

6 Multi-Sample Exercise

The multi-sample exercise demonstrates the multisample technique. As the exercise in **Section 5** shows, the split summation technique allows a sum of products operation to be calculated using all four ALUs by evaluating four intermediate products at a time. However, it does not guarantee bit-exact agreement with serially accumulating each intermediate product using a single ALU. To ensure bit-exactness, the order of summation must be preserved by performing each intermediate product/accumulation in turn.Therefore, the intermediate products cannot be evaluated in parallel. Furthermore, the split summation technique may not be suited for the application. Other techniques can be used where it is possible to evaluate one intermediate product from each of four output sample calculations in parallel. Consider the FIR filtering operation described by Equation 4:

$$y(n) = \sum_{i=0}^{N-1} a_i\, x(n-i)\,, \qquad \textbf{for } 0 \le n < L \qquad \textbf{Equation 4}$$

A C code implementation of this operation typically resembles the implementation of `Ex6.c`. To use all four ALUs, the operations can be grouped as illustrated in the following equation:

$$\begin{array}{rcl}
y(n) &=& a_0x(n) \quad + a_1x(n-1) + a_2x(n-2) + a_3x(n-3) + \ldots + a_{N-2}x(n-N+2) + a_{N-1}x(n-N+1) \\
+\,1) &=& a_0x(n+1) + a_1x(n) \quad + a_2x(n-1) + a_3x(n-2) + \ldots + a_{N-2}x(n-N+3) + a_{N-1}x(n-N+2) \\
+\,2) &=& a_0x(n+2) + a_1x(n+1) + a_2x(n) \quad + a_3x(n-1) + \ldots + a_{N-2}x(n-N+4) + a_{N-1}x(n-N+3) \\
+\,3) &=& a_0x(n+3) + a_1x(n+2) + a_2x(n+1) + a_3x(n) \quad + \ldots + a_{N-2}x(n-N+5) + a_{N-1}x(n-N+4)
\end{array} \qquad \textbf{Equation 5}$$

Group 0 Group 1 Group 2 Group 3 Group N-2 Group N-1

In Equation 5, the products and accumulations within each group are calculated in parallel, but the groups themselves are evaluated in sequence, thus preserving the order of accumulation, which in turn preserves the bit-exactness of Equation 4. Therefore, parallelization is achieved by processing multiple samples in parallel rather than multiple intermediate products belonging to only one output sample. When one group (for example, Group 2) is evaluated, only two words of data need to be loaded for the next group (Group 3): a_3 and x(n-3). The other values needed for the calculations in Group 3—x(n-2), x(n-1), and x(n)—should already exist in the DSP registers from the calculation of Group 2. The result is a reduction in memory bandwidth requirements that increases code efficiency.

1. Open the `Ex6.c` file.
2. Compile `Ex6.c` using the `-Ot2` option. Run the code and verify that the output is correct.

   See the comments in `Ex6.c` for the correct values of y[].
3. Recompile `Ex6.c` using the `-Ot2` and `-S` options. Examine the assembly language file `Ex6.sl` to see how the inner loop is compiled.

Intermediate Version: Compromise Between Memory and Speed

4. Save `Ex6.c` as `Ex6_1.c`.
5. Change the C code of `Ex6_1.c` according to the following steps:
   - **a.** Process the first four samples at a time:

     Replace the implementation of “y(n) = a_i * x(n)” with the equations defined as Group 0 in Equation 5.

b. Replace x(n), x(n+1), x(n+2), x(n+3) with variables (for example, var0, var1, var2, var3, respectively), as follows:

```
res0 += a[i] * var0;
res1 += a[i] * var1;
res2 += a[i] * var2;
res3 += a[i] * var3;
```

Group 0

This processes the first group (Group 0). To process the remaining groups, Group 1 and so on, the values from var0, var1, and var2 from Group 0 must be transferred to var1, var2, var3, respectively, for processing Group 1.

c. Transfer the values in var1, var2, and var3 and load the new sample (x(n-1)) into var0.

6. Compile the code with the `-Ot2` option, and run the code to verify that the correct output values are obtained.

7. Recompile `Ex6_1.c` using the `-Ot2` and `-S` options. The inner loop should be only two cycles long. If not, return to Step 5.

During each iteration of the loop, the coefficient, `a[i]`, is loaded into a data register. The data value, `x[n-1-i]`, is loaded into another data register. The values in the other three registers are reused, but they must first be transferred into the registers where the four MAC instructions expect them. This transfer results in two clock cycles for every four MAC instructions.

8. In the box on the following page, write the code for the intermediate version.

C Code	Generated Assembly Code

Further Speed Optimization

The register-to-register transfers can be eliminated by expanding the inner loop so that each group of four MAC instructions uses the data registers already containing the required data values. This yields faster code, but code size is greater.

1. Save `Ex6_1.c` as `Ex6_2.c`.
2. In `Ex6_2.c`, “unroll” the inner loop instructions four times so that the first four groups (Group 0, Group 1, Group 2, and Group 3) are all processed in the loop. This loop expansion avoids transferring data. You must reduce the number of loop iterations by a factor of four to compensate for the fact that the loop is unrolled by a factor of 4.

If your inner loop consumes just four cycles, and your code still produces the correct output, congratulations. You have completed Exercise 6.

Notice that each group of four MAC operations and two data load operations now requires just one processor cycle, which is half the time required by the `filtering operation` and a quarter of the time required by a single-ALU DSP device. However, the code size for the inner loop has increased by a significant amount (approximately four times that of `the second implementation`), and this must be weighed up against the cycle-count performance improvements obtained. **Table 3** summarizes the main characteristics of the multi-sample technique.

Table 3. Inner Loop Characteristics of Multi-sample and Single-sample Techniques.

Characteristic	Single-sample Algorithm	Multi-sample Algorithm
Cycle count	N	N/4
Registers used	Fewer	More
Sample delay	1	4
Number of memory moves (bandwidth)	2N	N/2
Code size	Small	Large

7 Control Code: The True Bit Exercise

The True bit exercise shows how the compiler uses the True bit and how you can help the compiler to improve the performance. The True bit is set/cleared by compare or test instructions. The use of the True bit as a control flag together with DSP-specific code makes the SC140 very powerful for applications including both control and DSP code. The True bit can affect conditional branching as well as conditional execution of groups of instructions.

Conditional branching includes:

- BT/BF: Branch relative if True bit is True/False.
- BTD:BFD: Branch delayed relative if True bit is True/False.
- JT/JF: Jump if True bit is True/False.
- JTD/JFD: Jump delayed if True bit is True/False.

Conditional execution of instructions includes:

- IFT/IFF: IF True bit is True/False.
- IFA: IF always, which is unconditionally executed with IFT/IFF.

The conditional execution set combinations are very flexible and are represented in **Figure 10**, which represents the maximum number of ALUs (that is, two) and one Arithmetic Address Unit (AAU) per subset. The C compiler automatically generates the conditional execution set, and some examples are provided to highlight potential code optimization.

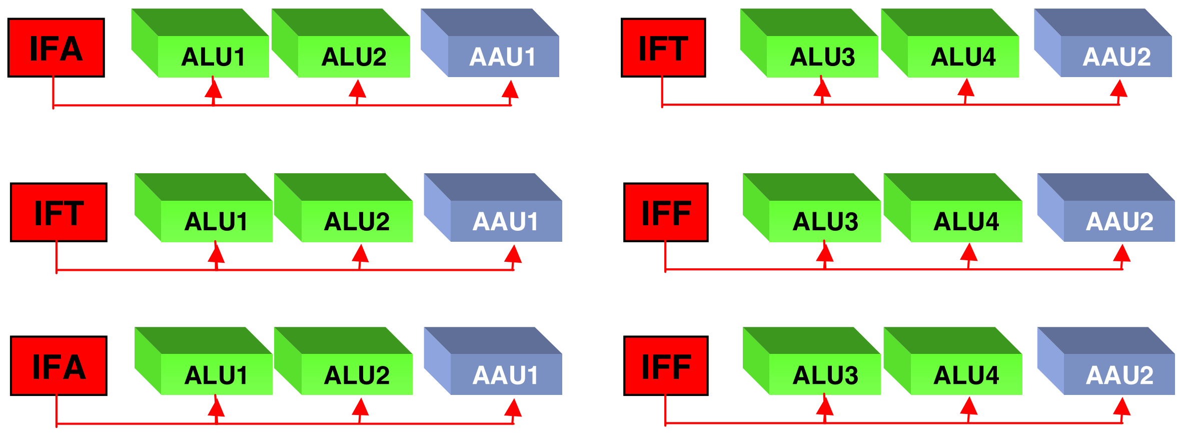


Figure 10. Control Instructions Using the True Bit

1. Open the example `Ex7.c` file.
2. Understand the conditional test in the code.
3. Compile the project with the `-Ot2` and `-S` options.
4. Open the generated assembly file `Ex7.sl`, and look at the conditional instructions within the loop.
5. In the box provided here, write down how many execution sets are within the loop:

Optimized for Time	Optimized for Space

6. Recompile using the compiler optimization option for code size (`-Os` option).
7. Open the generated assembly file `Ex7.sl`, and look at the conditional instructions within the loop. Write down how many execution sets are within the loop in the box.
8. Save `Ex7.c` as `Ex7_1.c`.
9. Modify the program to obtain two cycles within the loop. Tip: consider using a temporary variable for both storing the immediate value of the `array1` and the conditional test.
10. Compile the code using the `-Ot2` option.
11. Open the file `Ex7_1.sl`.
12. If you have obtained two cycles for the inner loop, congratulations. If you have not, please try again.
13. In the following box, write the optimized C code.

C Code	Generated Assembly Code

8 Calling an Assembly Routine From C Exercise

Practical DSP application commonly use a mixture of C and assembly language. This exercise shows how an assembly language function can be called from C code. The code for this exercise is contained in two files: `Ex8.c` and `addvecs.asm`. The C code in `Ex8.c` calls the assembly language function, addvecs(), in file `addvecs.asm`, to add two vectors together and return the sum of all the elements of the resultant vector. The prototype for addvecs() is as follows:

```
short add_vecs
(
  short x[],      /* Input vector      */
  short y[],      /* Input vector      */
  short z[],      /* Output vector     */
  short length    /* Length of vectors */
);
```

Four parameters are passed to addvecs(). The first three are pointers to arrays and are therefore 32-bit values (addresses are 32-bits in StarCore). The fourth parameter is the length of the vectors and is a 16-bit value. The mechanism by which parameters are passed is specified in the application binary interface (ABI). Generally speaking, this ABI specifies the following calling convention:

- The first parameter is passed in d0 if it is a numeric scalar or in r0 if it is an address.
- The second parameter is passed in d1 if it is a numeric scalar or in r1 if it is an address.
- Subsequent parameters are pushed onto the stack.
- The return value (if any) is passed back to the calling function in d0 if it is a numeric scalar or in r0 if it is an address.

For simple functions with two parameters or fewer, the stack is not used to pass parameters, and it may be possible to write the entire assembly language function without explicitly using the stack at all. In general, however, the stack is used to pass parameters into the function and to store local variables. Its contents are as shown in **Figure 11**. Just prior to the function call, parameters 3, 4, 5, and so on are pushed onto the stack (in reverse order), and parameters 1 and 2 are stored in d0/r0 and d1/r1, as described previously. The function is then called, and the return address and status register contents are pushed onto the stack by the **jsr** or **bsr** instruction. If the called function modifies register d6, d7, r6, or r7, it should first save them on the stack and then restore them before returning. All other registers are free for use without saving or restoring them. The calling function must save these registers if it needs their values to be preserved. On function exit, the status register contents and return address are popped from the stack (by the **rts** instruction), and the calling function deallocates the stack space used to pass parameters 3, 4, 5, and so on.

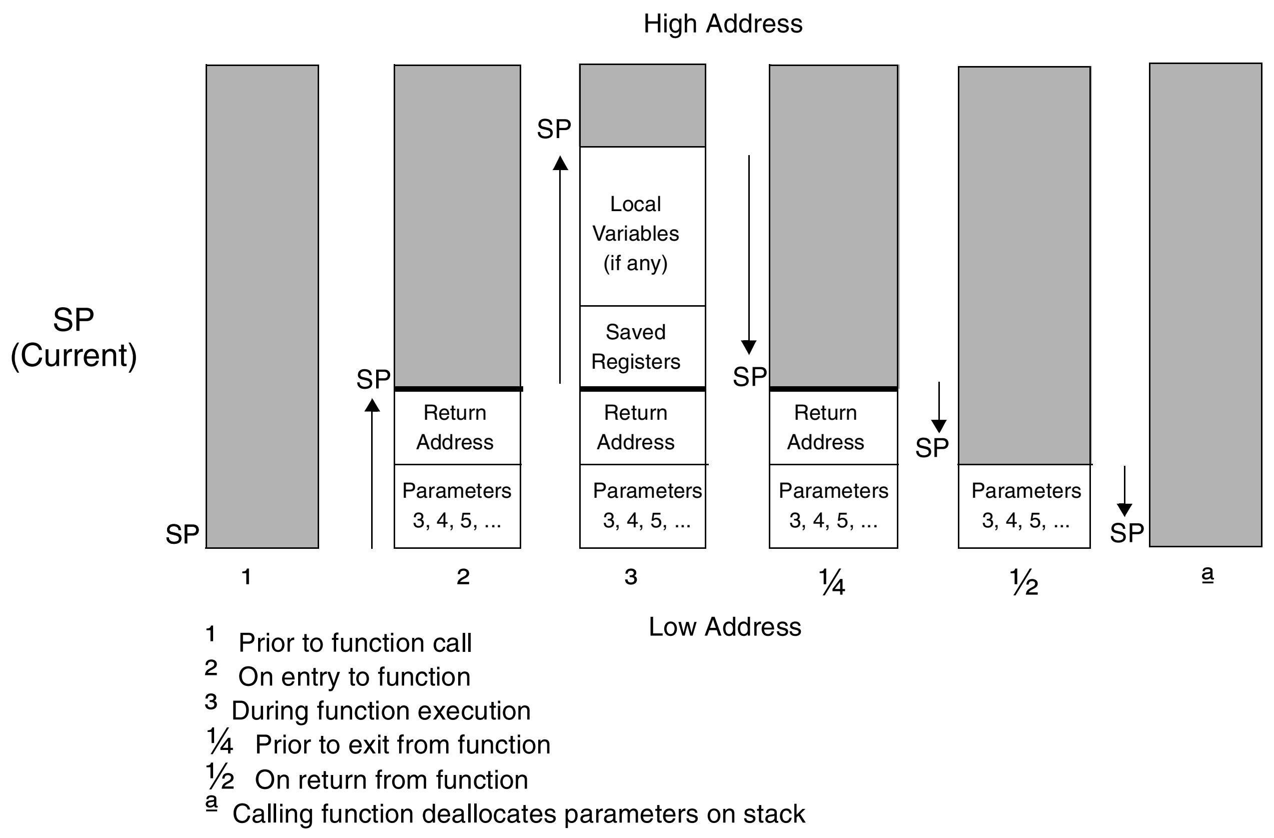


Figure 11. Typical Stack Contents During Function Execution

Therefore, for the function addvecs(), parameters x[], and y[] are passed in r0 and r1, while z[] and M are passed on the stack.

1. Open the `Ex8.c` and `addvecs.asm` files, and familiarize yourself with the code.
2. In `addvecs.asm` are two constants, Z_OFFSET and M_OFFSET, whose values are not set and which are represented by question marks (???). These offsets pull z[] and M from the stack. Find the lines of code that perform this task.
3. Before the code can be built, you must assign values to Z_OFFSET and M_OFFSET. To help you to do this, **Figure 12** shows the stack on entry to addvecs().

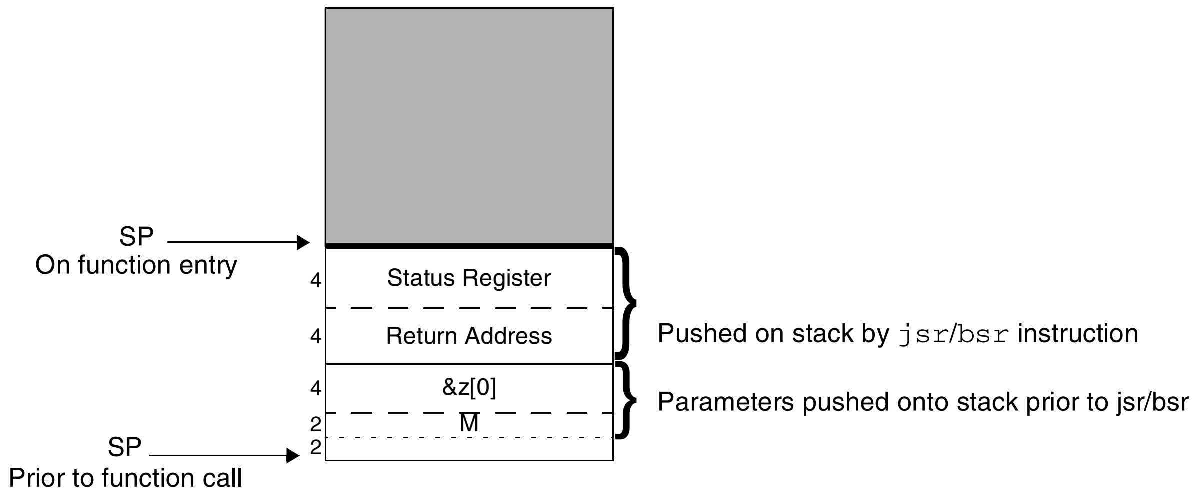

SP
On function entry
SP
Prior to function call
4
Status Register
4
Return Address
4
&z[0]
2
M
2
Pushed on stack by jsr/bsr instruction
Parameters pushed onto stack prior to jsr/bsr

Figure 12. Stack Contents on Entry to advecs()

4. In the box provided here, write what you think the offsets should be:

Z_OFFSET	
M_OFFSET	

5. Modify the `addvecs.asm` file to incorporate your offset values.
6. Build the code.
7. Run the code: `runsc100 Ex8.eld`.
8. The following output should be displayed:

```
z = [3, 5, 7, 9, 11, 13, 15, 17]
sum = 80
```

9. If the above output is displayed, your offset values are correct.
10. Rebuild the code, this time with the `-S` option.
11. Open the generated assembly file `Ex8.sl`, and find the call to addvecs().
12. Find the instructions that put z[] and M onto the stack just prior to the function call. Write the offsets in the box provided here:

Z_OFFSET	
M_OFFSET	

13. Are the offsets used in `Ex8.c` the same as the offsets used in `addvecs.asm`? If not, can you explain why?

Congratulations, you have completed Exercise 8.

Good To Know

The stack pointer must always be a multiple of 8. It is illegal to increment it by a non-multiple of 8.

9 The Challenge

This section presents you with a challenge involving an example that implements a complex scalar product. The objective of this session is to optimize the code from `Ex9.c` for speed and obtain the minimum number of cycles.

1. Put into practice the techniques previously explained to optimize `Ex9.c`.

   The original number of cycles in the inner loop is:

Original (Inner loop)

   So far, after having modified the code, your best result is:

Your Best (Inner loop)

   The optimized C code result is:

Target (Inner loop)
1 cycle with ALUs and AAUs 100 percent used

If your best result is within 10 percent of the target result, congratulations. You have completed all the exercises and the challenge as well.

10 Solutions to Exercises

Exercise 1:

```
/*****************************************************************************
*                               Freescale Semiconductor, Inc.
*                                 COPYRIGHT 1999
******************************************************************************
*                     INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/

#include <stdio.h>

main()
{
   printf("Welcome to StarCore SC140 Tools\n");
}
```

Exercise 2:

```
/*****************************************************************************
*                    Freescale Semiconductor, Inc.
*                        COPYRIGHT 1999 Freescale Semiconductor, Inc.
******************************************************************************
*                     INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/

#include <stdio.h>
#include <prototype.h>

short x[12] = {0,1,2,3,4,5,6,7,8,9,10,11};

main()
{
       short i;
       long res=0;
       long fres=0;

       for(i=0;i<12;i++)
       {
              res += x[i] * x[i];
       }

        for(i=0;i<12;i++)
       {
              fres = L_mac(fres,x[i],x[i]);
       }

        printf("The integer result is:    %d  (0x%x)\n",res,res);
        printf("The fractional result is:    %d  (0x%x)\n",fres,fres);
}
```

Exercise 3:

No code modification is required.

Exercise 4:

data: 0x01 0x23 0x45 0x67 0x89 0xAB 0xCD 0xEF

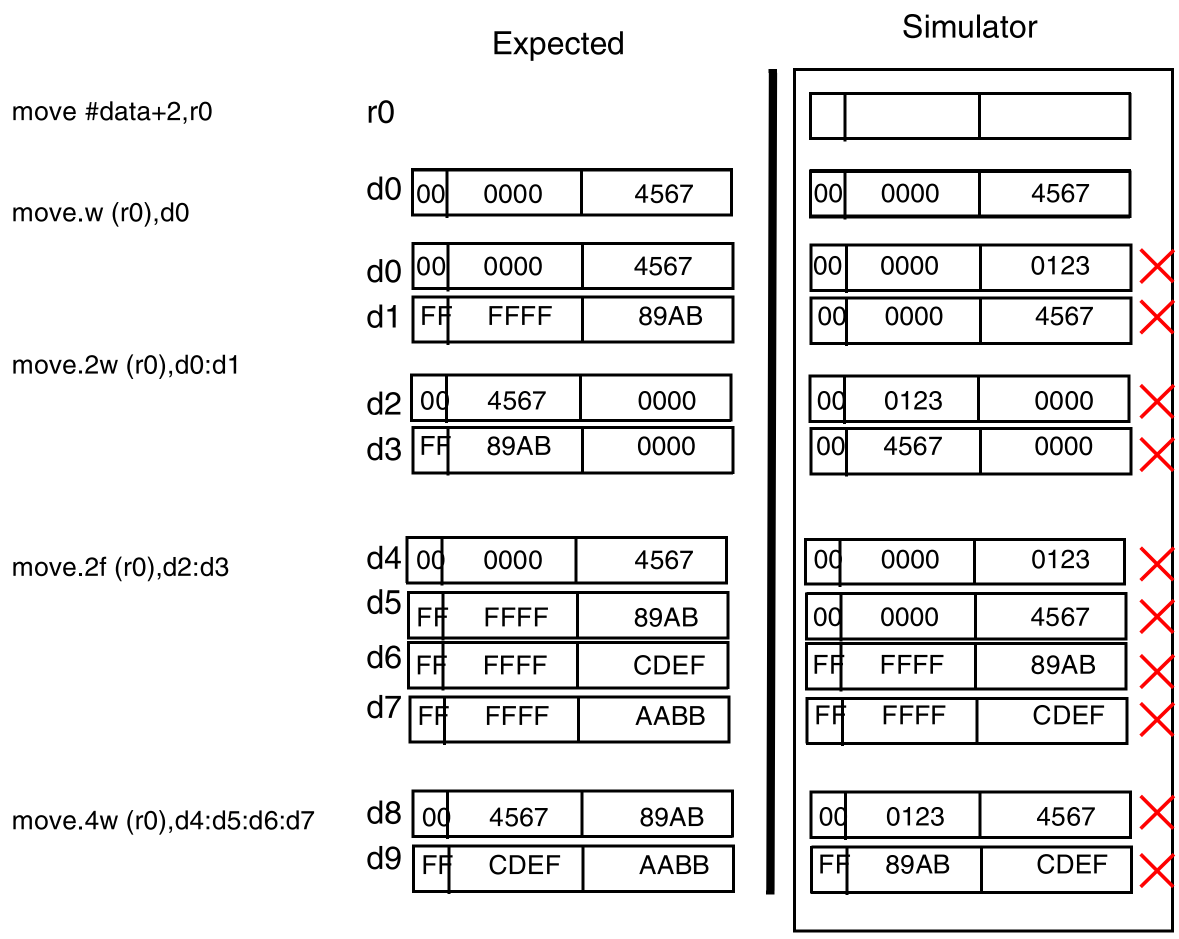
0xAA 0xBB 0xCC 0xDD 0xEE 0xFF 0x11 0x22

		Expected			Simulator		
move #data,r0	r0						
	d0	00	0000	0123	00	0000	0123
move.w (r0),d0	d0	00	0000	0123	00	0000	0123
	d1	00	0000	4567	00	0000	4567
move.2w (r0),d0:d1	d2	00	0123	0000	00	0123	0000
	d3	00	4567	0000	00	4567	0000
	d4	00	0000	0123	00	0000	0123
move.2f (r0),d2:d3	d5	00	0000	4567	00	0000	4567
	d6	FF	FFFF	89AB	FF	FFFF	89AB
	d7	FF	FFFF	CDEF	FF	FFFF	CDEF
move.4w (r0),d4:d5:d6:d7	d8	00	0123	4567	00	0123	4567
	d9	FF	89AB	CDEF	FF	89AB	CDEF

Aligned

data: 0x01 0x23 0x45 0x67 0x89 0xAB 0xCD 0xEF

0xAA 0xBB 0xCC 0xDD 0xEE 0xFF 0x11 0x22



Aligned/Not Aligned

The crosses indicate that the results provided by the simulator are not-aligned operations. If this is not taken into account, unpredictable results can occur when migrating to the hardware (which requires aligned data).

Exercise 5:

```
/*****************************************************************************
*                              Freescale Semiconductor, Inc.
*                        COPYRIGHT 1999 Freescale Semiconductor, Inc.
******************************************************************************
*                      INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/
/* Split Summation Technique Exercise */

#include <stdio.h>
#include <prototype.h>

short x[12] = {0,1,2,3,4,5,6,7,8,9,10,11};

main()
{
       short i;
       long res1=0, res2=0, res3=0, res4=0;

       for(i=0;i<12;i+=4)
       {
              res1 = L_mac(res1, x[i], x[i]);
              res2 = L_mac(res2, x[i+1], x[i+1]);
              res3 = L_mac(res3, x[i+2], x[i+2]);
              res4 = L_mac(res4, x[i+3], x[i+3]);
       }
       /* To optimise the code further break the following dependency */
       /* res1 = res1 + res2 + res3 + res4; */

       /* into */
       res1 = res1 + res2;
       res3 = res3 + res4;

       res1 = res1 + res3;

       printf("Result = %d  (0x%x)\n", res1,res1);
}
```

Exercise 6:

```
Intermediate version: Compromise between Memory and Speed

/******************************************************************************
*                              Freescale Semiconductor, Inc.
*                         COPYRIGHT 1999 Freescale Semiconductor, Inc.
*******************************************************************************
*                       INTRODUCTION TO THE SC140 TOOLS
*******************************************************************************/
/* Multi-sample technique Exercise on an FIR Filter */

#include <stdio.h>
#include <prototype.h>

short a[12]={0x1000,0x2000,0x3000,0x4000,0x5000,0x6000,
             0x7000,0x8000,0x9000,0xA000,0xB000,0xC000};

short input[32+11]={0,0,0,0,0,0,0,0,0,0,0,  /* zero-padding */
                    0x0100,0x0200,0x0300,0x0400,0x0500,0x0600,0x0700,0x0800,
                    0x0900,0x0A00,0x0B00,0x0C00,0x0D00,0x0E00,0x0F00,0x1000,
                    0x1100,0x1200,0x1300,0x1400,0x1500,0x1600,0x1700,0x1800,
                    0x1900,0x1A00,0x1B00,0x1C00,0x1D00,0x1E00,0x1F00,0x2000};
short y[32];

/***********************************************************************
 *** For reference, the following output should be observed after   ***
 *** running the code.                                                ***
 ***********************************************************************
 *                                                                     *
 * y[0] = 0x0020                                                        *
 * y[1] = 0x0080                                                        *
 * y[2] = 0x0140                                                        *
 * y[3] = 0x0280                                                        *
 * y[4] = 0x0460                                                        *
 * y[5] = 0x0700                                                        *
 * y[6] = 0x0A80                                                        *
 * y[7] = 0x0D00                                                        *
 * y[8] = 0x0EA0                                                        *
 * y[9] = 0x0F80                                                        *
 * y[10] = 0x0FC0                                                       *
 * y[11] = 0x0F80                                                       *
 * y[12] = 0x0F40                                                       *
 * y[13] = 0x0F00                                                       *
 * y[14] = 0x0EC0                                                       *
 * y[15] = 0x0E80                                                       *
 * y[16] = 0x0E40                                                       *
 * y[17] = 0x0E00                                                       *
 * y[18] = 0x0DC0                                                       *
 * y[19] = 0x0D80                                                       *
 * y[20] = 0x0D40                                                       *
 * y[21] = 0x0D00                                                       *
 * y[22] = 0x0CC0                                                  *
 * y[23] = 0x0C80                                                  *
 * y[24] = 0x0C40                                                  *
 * y[25] = 0x0C00                                                  *
 * y[26] = 0x0BC0                                                  *
 * y[27] = 0x0B80                                                  *
 * y[28] = 0x0B40                                                  *
 * y[29] = 0x0B00                                                  *
 * y[30] = 0x0AC0                                                  *
 * y[31] = 0x0A80                                                  *
 *******************************************************************/
main()
{

  long res0, res1, res2, res3;
  short var0, var1, var2, var3;
  short n, i, *x_ptr;

   x_ptr = &input[14];  /* x_ptr points to input[11], which is x[3] */

  for(n=0; n<32; n+=4)
  {
    res0 = 0;
    res1 = 0;
    res2 = 0;
    res3 = 0;

    var3 = *x_ptr--;  /* var3 = x[n+3] */
    var2 = *x_ptr--;  /* var3 = x[n+2] */
    var1 = *x_ptr--;  /* var3 = x[n+1] */
    var0 = *x_ptr--;  /* var3 = x[n]   */

    /*** x_ptr now points to x[n-1] ***/

    for(i=0; i<12; i++)
    {
      res0 = L_mac(res0, a[i], var0);
      res1 = L_mac(res1, a[i], var1);
      res2 = L_mac(res2, a[i], var2);
      res3 = L_mac(res3, a[i], var3);

      var3 = var2;
      var2 = var1;
      var1 = var0;
      var0 = *x_ptr--;     /* var0 = x[n-i-1] */
    }

    /*** Truncate results and store in y[] ***/
    y[n]   = extract_h(res0);
    y[n+1] = extract_h(res1);
    y[n+2] = extract_h(res2);
    y[n+3] = extract_h(res3);

    x_ptr += 20;  /* Increment pointer by 20 to point to x[n+7]
                     for next iteration */
  }

  /*** Print results, y[] ***/
  for (n=0; n<32; n++)
  {
    printf ("y[%d] = 0x%04hX\n", n, y[n]);
  }
}
```

Further Optimizing the Speed

```
/*****************************************************************************
*                              Freescale Semiconductor, Inc.
*                        COPYRIGHT 1999 Freescale Semiconductor, Inc.
******************************************************************************
*                      INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/
/* Multi-sample technique Exercise on an FIR Filter */

#include <stdio.h>
#include <prototype.h>

short a[12]={0x1000,0x2000,0x3000,0x4000,0x5000,0x6000,
             0x7000,0x8000,0x9000,0xA000,0xB000,0xC000};

short input[32+11]={0,0,0,0,0,0,0,0,0,0,0,  /* zero-padding */
                    0x0100,0x0200,0x0300,0x0400,0x0500,0x0600,0x0700,0x0800,
                    0x0900,0x0A00,0x0B00,0x0C00,0x0D00,0x0E00,0x0F00,0x1000,
                    0x1100,0x1200,0x1300,0x1400,0x1500,0x1600,0x1700,0x1800,
                    0x1900,0x1A00,0x1B00,0x1C00,0x1D00,0x1E00,0x1F00,0x2000};
short y[32];
/**********************************************************************
 *** For reference, the following output should be observed after   ***
 *** running the code.                                               ***
 **********************************************************************
 *                                                                     *
 * y[0] = 0x0020                                                        *
 * y[1] = 0x0080                                                        *
 * y[2] = 0x0140                                                        *
 * y[3] = 0x0280                                                        *
 * y[4] = 0x0460                                                        *
 * y[5] = 0x0700                                                        *
 * y[6] = 0x0A80                                                        *
 * y[7] = 0x0D00                                                        *
 * y[8] = 0x0EA0                                                        *
 * y[9] = 0x0F80                                                        *
 * y[10] = 0x0FC0                                                       *
 * y[11] = 0x0F80                                                     *
 * y[12] = 0x0F40                                                     *
 * y[13] = 0x0F00                                                     *
 * y[14] = 0x0EC0                                                     *
 * y[15] = 0x0E80                                                     *
 * y[16] = 0x0E40                                                     *
 * y[17] = 0x0E00                                                     *
 * y[18] = 0x0DC0                                                     *
 * y[19] = 0x0D80                                                     *
 * y[20] = 0x0D40                                                     *
 * y[21] = 0x0D00                                                     *
 * y[22] = 0x0CC0                                                     *
 * y[23] = 0x0C80                                                     *
 * y[24] = 0x0C40                                                     *
 * y[25] = 0x0C00                                                     *
 * y[26] = 0x0BC0                                                     *
 * y[27] = 0x0B80                                                     *
 * y[28] = 0x0B40                                                     *
 * y[29] = 0x0B00                                                     *
 * y[30] = 0x0AC0                                                     *
 * y[31] = 0x0A80                                                     *
 **********************************************************************/

main()
{

  long res0, res1, res2, res3;
  short var0, var1, var2, var3;
  short n, i, *x_ptr;

  x_ptr = &input[14];  /* x_ptr points to input[14], which is x[3] */
  for(n=0; n<32; n+=4)
  {
    res0 = 0;
    res1 = 0;
    res2 = 0;
    res3 = 0;

    var3 = *x_ptr--;  /* var3 = x[n+3] */
    var2 = *x_ptr--;  /* var3 = x[n+2] */
    var1 = *x_ptr--;  /* var3 = x[n+1] */
    var0 = *x_ptr--;  /* var3 = x[n]   */

    /*** x_ptr now points to x[n-1] ***/
for(i=0; i<12; i+=4)
    {
      res0 = L_mac(res0, a[i], var0);
      res1 = L_mac(res1, a[i], var1);
      res2 = L_mac(res2, a[i], var2);
      res3 = L_mac(res3, a[i], var3);
      var3 = *x_ptr--;  /* var3 = x[n-i-1] */
```

```
        res0 = L_mac(res0, a[i+1], var3);
        res1 = L_mac(res1, a[i+1], var0);
        res2 = L_mac(res2, a[i+1], var1);
        res3 = L_mac(res3, a[i+1], var2);
        var2 = *x_ptr--; /* var2 = x[n-i-2] */

        res0 = L_mac(res0, a[i+2], var2);
        res1 = L_mac(res1, a[i+2], var3);
        res2 = L_mac(res2, a[i+2], var0);
        res3 = L_mac(res3, a[i+2], var1);
        var1 = *x_ptr--; /* var1 = x[n-i-3] */

        res0 = L_mac(res0, a[i+3], var1);
        res1 = L_mac(res1, a[i+3], var2);
        res2 = L_mac(res2, a[i+3], var3);
        res3 = L_mac(res3, a[i+3], var0);
        var0 = *x_ptr--; /* var0 = x[n-i-4] */
      }

      /*** Truncate results and store in y[] ***/
        y[n]   = extract_h(res0);
        y[n+1] = extract_h(res1);
        y[n+2] = extract_h(res2);
        y[n+3] = extract_h(res3);

        x_ptr += 20;  /* Increment pointer by 20 to point to x[n+7]
                         for next iteration */
    }
/*** Print results, y[] ***/
  for (n=0; n<32; n++)
  {
    printf ("y[%d] = 0x%04hX\n", n, y[n]);
  }
}
```

Exercise 7:

```
/*****************************************************************************
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******************************************************************************
*                     INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/


short array1[10]={1,-1,-1,-2,2,-2,2,-2,3,-3};
short array2[10];

main()
{
short i;
short *array2_ptr;
short tmp;

       array2_ptr = &array2[0];
```

```
        for(i=0;i<10;i++)
        {
                tmp = array1[i];
                if( tmp < 0)
                {
                        tmp = -tmp;
                }
                *array2_ptr++ = tmp;
        }

}
```

Exercise 8:

```
Z_OFFSET  equ  -12
M_OFFSET  equ  -14
```

Exercise 9:

```
/*****************************************************************************
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******************************************************************************
*                     INTRODUCTION TO THE SC140 TOOLS
******************************************************************************/
#include <prototype.h>

#define DATA_LENGTH 6

Word16 y[2];
Word16 a[12]={0x0200, 0x0400, 0x0200, 0x0400,
              0x0200, 0x0400, 0x0200, 0x0400,
              0x0200, 0x0400, 0x0200, 0x0400};

Word16 b[12] = {0x0100, 0x0800, 0x1000, 0x2000,
                0x1000, 0x0800, 0x0200, 0x0100,
                0x1000, 0x0800, 0x0200, 0x0100};

void main()
{

  Word16 i;
  Word32 L_Re1, L_Re2, L_Im1, L_Im2;

  L_Re1 = L_Re2 = L_Im1 = L_Im2 = 0;

  for(i=0; i<2*DATA_LENGTH; i+=2)
  {
    L_Re1 = L_mac(L_Re1, a[i], b[i]);
    L_Im1 = L_mac(L_Im1, a[i], b[i+1]);
    L_Im2 = L_mac(L_Im2, a[i+1], b[i]);
    L_Re2 = L_mac(L_Re2, a[i+1], b[i+1]);
  }
  y[0] = round(L_Re1 - L_Re2);
  y[1] = round(L_Im1 + L_Im2);
}
```

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