IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

<table>
<thead>
<tr>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>Audio</td>
</tr>
<tr>
<td>Data Converters</td>
<td>Automotive</td>
</tr>
<tr>
<td>DSP</td>
<td>Broadband</td>
</tr>
<tr>
<td>Interface</td>
<td>Digital Control</td>
</tr>
<tr>
<td>Logic</td>
<td>Military</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>Optical Networking</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>Security</td>
</tr>
<tr>
<td></td>
<td>Telephony</td>
</tr>
<tr>
<td></td>
<td>Video &amp; Imaging</td>
</tr>
<tr>
<td></td>
<td>Wireless</td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments
Post Office Box 655303 Dallas, Texas 75265

Copyright © 2003, Texas Instruments Incorporated
About This Manual

Welcome to the TMS320C64x digital signal processor (DSP) Library, or DSPLIB for short. The DSPLIB is a collection of high-level optimized DSP functions for the TMS320C64x device. This source code library includes C-callable functions (ANSI-C language compatible) for general signal processing math and vector functions.

This document contains a reference for the DSPLIB functions and is organized as follows:

- Overview – an introduction to the TI C64x DSPLIB
- DSPLIB Functions – a quick reference table listing of routines in the library
- DSPLIB Reference – a description of all DSPLIB functions complete with calling convention, algorithm details, special requirements and implementation notes
- Information about performance, Fractional Q format and customer support

How to Use This Manual

The information in this document describes the contents of the TMS320C64x DSPLIB in several different ways.

- Chapter 1 – Introduction provides a brief introduction to the TI C64x DSPLIB, shows the organization of the routines contained in the library, and lists the features and benefits of the DSPLIB.

- Chapter 3 – DSPLIB Function Tables provides a quick overview of all DSPLIB functions in table format for easy reference. The information shown for each function includes the syntax, a brief description, and a page reference for obtaining more detailed information.

- Chapter 4 – DSPLIB Reference provides a list of the routines within the DSPLIB organized into functional categories. The functions within each category are listed in alphabetical order and include arguments, descriptions, algorithms, benchmarks, and special requirements.
Notational Conventions

- **Appendix A - Performance/Fractional Q Formats** describes performance considerations related to the C64x DSPLIB and provides information about the Q format used by DSPLIB functions.

- **Appendix B - Software Updates and Customer Support** provides information about software updates and customer support.

**Notational Conventions**

This document uses the following conventions:

- Program listings, program examples, and interactive displays are shown in a special typeface.

- In syntax descriptions, the function or macro appears in a **bold typeface** and the parameters appear in plainface within parentheses. Portions of a syntax that are in **bold** should be entered as shown; portions of a syntax that are within parentheses describe the type of information that should be entered.

- Macro names are written in uppercase text; function names are written in lowercase.

- The TMS320C64x is also referred to in this reference guide as the C64x.

**Related Documentation From Texas Instruments**

The following books describe the TMS320C6x devices and related support tools. To obtain a copy of any of these TI documents, call the Texas Instruments Literature Response Center at (800) 477-8924. When ordering, please identify the book by its title and literature number. Many of these documents can be found on the Internet at http://www.ti.com.

- **TMS320C64x Technical Overview** (literature number SPRU395) gives an introduction to the TMS320C64x digital signal processor and discusses the application areas that are enhanced by the TMS320C64x VelociTI.2 extensions to the C62x/C67x architecture.

- **TMS320C6000 CPU and Instruction Set Reference Guide** (literature number SPRU189) describes the C6000 CPU architecture, instruction set, pipeline, and interrupts for these digital signal processors.

- **TMS320C6000 Peripherals Reference Guide** (literature number SPRU190) describes common peripherals available on the TMS320C6000 digital signal processors. This book includes information on the internal data
and program memories, the external memory interface (EMIF), the host port interface (HPI), multichannel buffered serial ports (McBSPs), direct memory access (DMA), enhanced DMA (EDMA), expansion bus, clocking and phase-locked loop (PLL), and the power-down modes.

**TMS320C6000 Programmer’s Guide** (literature number SPRU198) describes ways to optimize C and assembly code for the TMS320C6000 DSPs and includes application program examples.

**TMS320C6000 Assembly Language Tools User’s Guide** (literature number SPRU186) describes the assembly language tools (assembler, linker, and other tools used to develop assembly language code), assembler directives, macros, common object file format, and symbolic debugging directives for the C6000 generation of devices.

**TMS320C6000 Optimizing C Compiler User’s Guide** (literature number SPRU187) describes the C6000 C compiler and the assembly optimizer. This C compiler accepts ANSI standard C source code and produces assembly language source code for the C6000 generation of devices. The assembly optimizer helps you optimize your assembly code.

**TMS320C6000 Chip Support Library** (literature number SPRU401) describes the application programming interfaces (APIs) used to configure and control all on-chip peripherals.

**TMS320C64x Image/Video Processing Library** (literature number SPRU023) describes the optimized image/video processing functions including many C-callable, assembly-optimized, general-purpose image/video processing routines.

**Signal Processing Examples Using TMS320C64x Digital Signal Processing Library** (literature number SPRA884) describes the usage and performance of key DSPLIB functions.

**TMS320C6000 DSP Cache User’s Guide** (literature number SPRU656A) describes cache architectures in detail and presents how to optimize algorithms and function calls for better cache performance.

**Big-Endian Signal Processing Library (DSPLIB) for TMS320C64x** (literature number SPRA925A) describes how to use DSPLIB on TMS320C64x running in big–endian mode.

**Trademarks**

TMS320C6000, TMS320C64x, TMS320C62x, and Code Composer Studio are trademarks of Texas Instruments.
1 Introduction ................................................................. 1-1
Provides a brief introduction to the TI C64x DSPLIB, shows the organization of the routines contained in the library, and lists the features and benefits of the DSPLIB.
1.1 Introduction to the TI C64x DSPLIB .................................. 1-2
1.2 Features and Benefits ................................................. 1-4

2 Installing and Using DSPLIB ........................................... 2-1
Provides information on how to install and rebuild the TI C64x DSPLIB.
2.1 How to Install DSPLIB ................................................ 2-2
   Code Composer Studio Users ........................................... 2-3
2.2 Using DSPLIB ........................................................... 2-4
   2.2.1 DSPLIB Arguments and Data Types ......................... 2-4
   2.2.2 Calling a DSPLIB Function From C .......................... 2-5
      Code Composer Studio Users ...................................... 2-5
   2.2.3 Calling a DSP Function From Assembly .................... 2-6
   2.2.4 How DSPLIB is Tested — Allowable Error ................ 2-6
   2.2.5 How DSPLIB Deals With Overflow and Scaling Issues ...... 2-6
   2.2.6 Interrupt Behavior of DSPLIB Functions .................. 2-7
2.3 How to Rebuild DSPLIB .............................................. 2-8

3 DSPLIB Function Tables ................................................ 3-1
Provides tables containing all DSPLIB functions, a brief description of each, and a page reference for more detailed information.
3.1 Arguments and Conventions Used .................................. 3-2
3.2 DSPLIB Functions ..................................................... 3-3
3.3 DSPLIB Function Tables .............................................. 3-4

4 DSPLIB Reference ........................................................ 4-1
Provides a list of the functions within the DSPLIB organized into functional categories.
4.1 Adaptive Filtering ..................................................... 4-2
   DSP_firms2 ........................................................... 4-2
4.2 Correlation ............................................................. 4-4
   DSP_autocor ......................................................... 4-4
4.3 FFT ................................................................. 4-6
   DSP_bitrev_cplx ................................................... 4-6
DSP_radix2 ...................................................... 4-9
DSP_rfft ......................................................... 4-11
DSP_fft .......................................................... 4-14
DSP_fft16x16r .................................................. 4-23
DSP_fft16x16i .................................................. 4-33
DSP_fft16x32 .................................................. 4-47
DSP_fft32x32 .................................................. 4-49
DSP_fft32x32s .................................................. 4-51
DSP_ifft16x32 .................................................. 4-53
DSP_ifft32x32 .................................................. 4-55
4.4 Filtering and Convolution .................................. 4-57
DSP_fir_cplx .................................................... 4-57
DSP_fir_gen ..................................................... 4-59
DSP_fir_r4 ....................................................... 4-61
DSP_fir_r8 ....................................................... 4-63
DSP_fir_sym ..................................................... 4-65
DSP_iir .......................................................... 4-67
DSP_iirlat ....................................................... 4-69
4.5 Math ........................................................ 4-71
DSP_dotp_sqr ................................................... 4-71
DSP_dotprod .................................................... 4-73
DSP_maxval ..................................................... 4-75
DSP_maxidx ..................................................... 4-76
DSP_minval ..................................................... 4-78
DSP_mul32 ...................................................... 4-79
DSP_neg32 ...................................................... 4-81
DSP_recip16 .................................................... 4-82
DSP_vecsumsq .................................................. 4-84
DSP_w_vec ..................................................... 4-85
4.6 Matrix ....................................................... 4-86
DSP_mat_mul ................................................... 4-86
DSP_mat_trans ................................................ 4-88
4.7 Miscellaneous ............................................... 4-89
DSP_bexp ....................................................... 4-89
DSP_blk_eswap16 ............................................... 4-91
DSP_blk_eswap32 ............................................... 4-93
DSP_blk_eswap64 ............................................... 4-95
DSP_blk_move .................................................. 4-97
DSP_fltoq15 .................................................... 4-98
DSP_minerror ................................................... 4-99
DSP_q15tofl .................................................... 4-101
A Performance/Fractional Q Formats .................................................. A-1
Describes performance considerations related to the C64x DSPLIB and provides information
about the Q format used by DSPLIB functions.

A.1 Performance Considerations ................................................. A-2
A.2 Fractional Q Formats .......................................................... A-3
  A.2.1 Q3.12 Format ............................................................. A-3
  A.2.2 Q.15 Format ................................................................ A-3
  A.2.3 Q.31 Format ................................................................. A-4

B Software Updates and Customer Support ........................................ B-1
Provides information about warranty issues, software updates, and customer support.

B.1 DSPLIB Software Updates ..................................................... B-2
B.2 DSPLIB Customer Support ...................................................... B-2

C Glossary .................................................................................. C-1
Defines terms and abbreviations used in this book.
## Tables

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–1</td>
<td>DSPLIB Data Types</td>
<td>2-4</td>
</tr>
<tr>
<td>3–1</td>
<td>Argument Conventions</td>
<td>3-2</td>
</tr>
<tr>
<td>3–2</td>
<td>Adaptive Filtering</td>
<td>3-4</td>
</tr>
<tr>
<td>3–3</td>
<td>Correlation</td>
<td>3-4</td>
</tr>
<tr>
<td>3–4</td>
<td>FFT</td>
<td>3-4</td>
</tr>
<tr>
<td>3–5</td>
<td>Filtering and Convolution</td>
<td>3-5</td>
</tr>
<tr>
<td>3–6</td>
<td>Math</td>
<td>3-6</td>
</tr>
<tr>
<td>3–7</td>
<td>Matrix</td>
<td>3-6</td>
</tr>
<tr>
<td>3–8</td>
<td>Miscellaneous</td>
<td>3-7</td>
</tr>
<tr>
<td>A–1</td>
<td>Q3.12 Bit Fields</td>
<td>A-3</td>
</tr>
<tr>
<td>A–2</td>
<td>Q.15 Bit Fields</td>
<td>A-3</td>
</tr>
<tr>
<td>A–3</td>
<td>Q.31 Low Memory Location Bit Fields</td>
<td>A-4</td>
</tr>
<tr>
<td>A–4</td>
<td>Q.31 High Memory Location Bit Fields</td>
<td>A-4</td>
</tr>
</tbody>
</table>
This chapter provides a brief introduction to the TI C64x DSP Library (DSPLIB), shows the organization of the routines contained in the library, and lists the features and benefits of the DSPLIB.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Introduction to the TI C64x DSPLIB</td>
<td>1-2</td>
</tr>
<tr>
<td>1.2 Features and Benefits</td>
<td>1-4</td>
</tr>
</tbody>
</table>
1.1 Introduction to the TI C64x DSPLIB

The TI C64x DSPLIB is an optimized DSP Function Library for C programmers using TMS320C64x devices. It includes many C-callable, assembly-optimized, general-purpose signal-processing routines. These routines are typically used in computationally intensive real-time applications where optimal execution speed is critical. By using these routines, you can achieve execution speeds considerably faster than equivalent code written in standard ANSI C language. In addition, by providing ready-to-use DSP functions, TI DSPLIB can significantly shorten your DSP application development time.

The TI DSPLIB includes commonly used DSP routines. Source code is provided that allows you to modify functions to match your specific needs.

The routines contained in the library are organized into the following seven different functional categories:

- Adaptive filtering
  - DSP_firlms2

- Correlation
  - DSP_autocor

- FFT
  - DSP_bitrev_cplx (obsolete, use DSP_fft16x16r or DSP_fft16x16t)
  - DSP_radix 2 (obsolete, use DSP_fft16x16r or DSP_fft16x16t)
  - DSP_r4fft (obsolete, use DSP_fft16x16r or DSP_fft16x16t)
  - DSP_fft (obsolete, use DSP_fft16x16r or DSP_fft16x16t)
  - DSP_fft16x16r
  - DSP_fft16x16t
  - DSP_fft16x32
  - DSP_fft32x32
  - DSP_fft32x32s
  - DSP_ifft16x32
  - DSP_ifft32x32

- Filtering and convolution
  - DSP_fir_cplx
  - DSP_fir_gen
  - DSP_fir_r4
  - DSP_fir_r8
  - DSP_fir_sym
  - DSP_iir
Math
- DSP_dotp_sqr
- DSP_dotprod
- DSP_maxval
- DSP_maxidx
- DSP_minval
- DSP_mul32
- DSP_neg32
- DSP_recip16
- DSP_vecsumsq
- DSP_w_vec

Matrix
- DSP_mat_mul
- DSP_mat_trans

Miscellaneous
- DSP_bexp
- DSP_blk_eswap16
- DSP_blk_eswap32
- DSP_blk_eswap64
- DSP_blk_move
- DSP_fitq15
- DSP_minerror
- DSP_q15tofl
1.2 Features and Benefits

- Hand-coded assembly-optimized routines
- C and linear assembly source code
- C-callable routines, fully compatible with the TI C6x compiler
- Fractional Q.15-format operands supported on some benchmarks
- Benchmarks (time and code)
- Tested against C model
- Big-endian support (SPRA925A)
Chapter 2

Installing and Using DSPLIB

This chapter provides information on how to install and rebuild the TI C64x DSPLIB.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 How to Install DSPLIB</td>
<td>2-2</td>
</tr>
<tr>
<td>2.2 Using DSPLIB</td>
<td>2-4</td>
</tr>
<tr>
<td>2.3 How to Rebuild DSPLIB</td>
<td>2-8</td>
</tr>
</tbody>
</table>
2.1 How to Install DSPLIB

Note:
You should read the README.txt file for specific details of the release.

The archive has the following structure:

dsp64x.zip
  |
  +− README.txt  Top-level README file
  |
  +− lib
    |
    +− dsp64x.lib  Library archive
    |
    +− dsp64x.src  Full source archive
      |
      +− dsp64x_sa.src  Full source archive
        (Hand-assembly and headers)
      +− dsp64x_c.src  Full source archive
        (Linear asm and headers)
      |
      +− include
        |
        +− header files  Unpacked header files
        |
        +− support  Support files
        |
        +− doc
          |
          +− dsp64xlib.pdf  This document

Step 1: De-archive DSPLIB

The lib directory contains the library archive and the source archive. Please install the contents of the lib directory in a directory pointed by your C_DIR environment. If you choose to install the contents in a different directory, make
How to Install DSPLIB

sure you update the C_DIR environment variable, for example, by adding the following line in autoexec.bat file:

    SET C_DIR=<install_dir>/lib;<install_dir>/include;%C_DIR%

or under Unix/csh:

    setenv C_DIR "<install_dir>/lib;<install_dir>/include;
$C_DIR"

or under Unix/Bourne Shell:

    C_DIR="<install_dir>/lib;<install_dir>/include;$C_DIR";
    export C_DIR

**Code Composer Studio Users**

If you set up a project under Code Composer Studio, you could add DSPLIB by choosing dsp64x.lib from the menu Project → Add Files to Project. Also, you should make sure that you link with the correct run-time support library and DSPLIB by having the following lines in your linker command file:

    -lrts6400.lib
    -ldsp64x.lib

The *include* directory contains the header files necessary to be included in the C code when you call a DSPLIB function from C code.
2.2 Using DSPLIB

2.2.1 DSPLIB Arguments and Data Types

2.2.1.1 DSPLIB Types

Table 2–1 shows the data types handled by the DSPLIB.

<table>
<thead>
<tr>
<th>Name</th>
<th>Size (bits)</th>
<th>Type</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>short</td>
<td>16</td>
<td>integer</td>
<td>−32768</td>
<td>32767</td>
</tr>
<tr>
<td>int</td>
<td>32</td>
<td>integer</td>
<td>−2147483648</td>
<td>2147483647</td>
</tr>
<tr>
<td>long</td>
<td>40</td>
<td>integer</td>
<td>−549755813888</td>
<td>549755813887</td>
</tr>
<tr>
<td>pointer</td>
<td>32</td>
<td>address</td>
<td>0000:0000h</td>
<td>FFFF:FFFFh</td>
</tr>
<tr>
<td>Q.15</td>
<td>16</td>
<td>fraction</td>
<td>−0.99999694824…</td>
<td>0.99999694824…</td>
</tr>
<tr>
<td>Q.31</td>
<td>32</td>
<td>fraction</td>
<td>−0.99999999953…</td>
<td>0.99999999953…</td>
</tr>
<tr>
<td>IEEE float</td>
<td>32</td>
<td>floating point</td>
<td>1.17549435e−38</td>
<td>3.40282347e+38</td>
</tr>
<tr>
<td>IEEE double</td>
<td>64</td>
<td>floating point</td>
<td>2.2250738585072014e−308</td>
<td>1.7976931348623157e+308</td>
</tr>
</tbody>
</table>

Unless specifically noted, DSPLIB operates on Q.15-fractional data type elements. Appendix A presents an overview of Fractional Q formats.

2.2.1.2 DSPLIB Arguments

TI DSPLIB functions typically operate over vector operands for greater efficiency. Even though these routines can be used to process short arrays, or even scalars (unless a minimum size requirement is noted), they will be slower for these cases.

- Vector stride is always equal to 1: Vector operands are composed of vector elements held in consecutive memory locations (vector stride equal to 1).
- Complex elements are assumed to be stored in consecutive memory locations with Real data followed by Imaginary data.
- In-place computation is not allowed, unless specifically noted: Source operand cannot be equal to destination operand.
2.2.2 Calling a DSPLIB Function From C

In addition to correctly installing the DSPLIB software, you must follow these steps to include a DSPLIB function in your code:

- Include the function header file corresponding to the DSPLIB function
- Link your code with dsp64x.lib
- Use a correct linker command file for the platform you use. Remember most functions in dsp64x.lib are written assuming little-endian mode of operation.

For example, if you want to call the Autocorrelation DSPLIB function, you would add:

```c
#include <DSP_autocor.h>
```

in your C file and compile and link using

```
c16x main.c -z -o autocor_drv.out -lrts6400.lib -ldsp64x.lib
```

**Code Composer Studio Users**

Assuming your C_DIR environment is correctly set up (as mentioned in Section 2.1, How to Install DSPLIB), you would have to add DSPLIB under Code Composer Studio environment by choosing dsp64x.lib from the menu Project → Add Files to Project. Also, you should make sure that you link with the correct run-time support library and DSPLIB by having the following lines in your linker command file:

```
-lrts6400.lib
-ldsp64x.lib
```
2.2.3 Calling a DSP Function From Assembly

The C64x DSPLIB functions were written to be used from C. Calling the functions from assembly language source code is possible as long as the calling function conforms to the Texas Instruments C64x C compiler calling conventions. For more information, refer to Section 8 (Runtime Environment) of *TMS320C6000 Optimizing C Compiler User’s Guide* (SPRU187).

2.2.4 How DSPLIB is Tested – Allowable Error

DSPLIB is tested under the Code Composer Studio environment against a reference C implementation. You can expect identical results between Reference C implementation and its Assembly implementation when using test routines that deal with fixed-point type results. The test routines that deal with floating points typically allow an error margin of 0.000001 when comparing the results of reference C code and DSPLIB assembly code.

2.2.5 How DSPLIB Deals With Overflow and Scaling Issues

The DSPLIB functions implement the same functionality of the reference C code. The user is expected to conform to the range requirements specified in the API function, and in addition, take care to restrict the input range in such a way that the outputs do not overflow.

In FFT functions, twiddle factors are generated with a fixed scale factor, i.e., 32767(=2^15−1) for all 16-bit FFT functions, 1073741823(=2^30−1) for DSP_fft32x32s, 2147483647(=2^31−1) for all other 32-bit FFT functions. Twiddle factors cannot be scaled further to not scale input data. Since DSP_fft16x16r and DSP_fft32x32s performs scaling by 2 at each radix-4 stage, the input data must be scaled by 2^(log2(nx)−ceil(log4(nx)−1)) to completely prevent overflow. In all other FFT functions, the input data must be scaled by 2^(log2(nx)) since no scaling is done by the functions.
2.2.6 Interrupt Behavior of DSPLIB Functions

All of the functions in this library are designed to be used in systems with interrupts. That is, it is not necessary to disable interrupts when calling any of these functions. The functions in the library will disable interrupts as needed to protect the execution of code in tight loops and so on. Functions in this library fall into three categories:

- **Fully-interruptible**: These functions do not disable interrupts. Interrupts are blocked by at most 5 to 10 cycles at a time (not counting stalls) by branch delay slots.

- **Partially-interruptible**: These functions disable interrupts for long periods of time, with small windows of interruptibility. Examples include a function with a nested loop, where the inner loop is non-interruptible and the outer loop permits interrupts between executions of the inner loop.

- **Non-interruptible**: These functions disable interrupts for nearly their entire duration. Interrupts may happen for a short time during their setup and exit sequence.

Note that all three categories of function tolerate interrupts. That is, an interrupt can occur at any time without affecting the correctness of the function. The interruptibility of the function only determines how long the kernel might delay the processing of the interrupt.
2.3 How to Rebuild DSPLIB

If you would like to rebuild DSPLIB (for example, because you modified the source file contained in the archive), you will have to use the mk6x utility as follows:

```
mk6x dsp64x.src -l dsp64x.lib
```
This chapter provides tables containing all DSPLIB functions, a brief description of each, and a page reference for more detailed information.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Arguments and Conventions Used</td>
<td>3-2</td>
</tr>
<tr>
<td>3.2 DSPLIB Functions</td>
<td>3-3</td>
</tr>
<tr>
<td>3.3 DSPLIB Function Tables</td>
<td>3-4</td>
</tr>
</tbody>
</table>
3.1 Arguments and Conventions Used

The following convention has been followed when describing the arguments for each individual function:

Table 3–1. Argument Conventions

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x,y$</td>
<td>Argument reflecting input data vector</td>
</tr>
<tr>
<td>$r$</td>
<td>Argument reflecting output data vector</td>
</tr>
<tr>
<td>$nx,ny,nr$</td>
<td>Arguments reflecting the size of vectors $x,y$, and $r$, respectively. For functions in the case $nx = ny = nr$, only $nx$ has been used across.</td>
</tr>
<tr>
<td>$h$</td>
<td>Argument reflecting filter coefficient vector (filter routines only)</td>
</tr>
<tr>
<td>$nh$</td>
<td>Argument reflecting the size of vector $h$</td>
</tr>
<tr>
<td>$w$</td>
<td>Argument reflecting FFT coefficient vector (FFT routines only)</td>
</tr>
</tbody>
</table>
3.2 DSPLIB Functions

The routines included in the DSP library are organized into eight functional categories and listed below in alphabetical order.

- Adaptive filtering
- Correlation
- FFT
- Filtering and convolution
- Math
- Matrix functions
- Miscellaneous
### 3.3 DSPLIB Function Tables

#### Table 3–2. Adaptive Filtering

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>long DSP_firlms2(short *h, short *x, short b, int nh)</td>
<td>LMS FIR</td>
<td>4-2</td>
</tr>
</tbody>
</table>

#### Table 3–3. Correlation

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>void DSP_autocor(short *r,short *x, int nx, int nr)</td>
<td>Autocorrelation</td>
<td>4-4</td>
</tr>
</tbody>
</table>

#### Table 3–4. FFT

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>void DSP_bitrev_cplx (int *x, short *index, int nx)</td>
<td>Complex Bit-Reverse</td>
<td>4-6</td>
</tr>
<tr>
<td>void DSP_radix2 (int nx, short *x, short *w)</td>
<td>Complex Forward FFT (radix 2)</td>
<td>4-9</td>
</tr>
<tr>
<td>void DSP_r4ft (int nx, short *x, short *w)</td>
<td>Complex Forward FFT (radix 4)</td>
<td>4-11</td>
</tr>
<tr>
<td>void DSP_fft(short *w, int nx, short *x, short *y)</td>
<td>Complex out of place, Forward FFT (radix4) with digit reversal.</td>
<td>4-14</td>
</tr>
<tr>
<td>void DSP_fft16x16r(int nx, short *x, short *w, unsigned char *brev, short *y, int radix, int offset, int n_max)</td>
<td>Cache-optimized mixed radix FFT with scaling and rounding, digit reversal, out of place. Input and output: 16 bits, Twiddle factor: 16 bits</td>
<td>4-23</td>
</tr>
<tr>
<td>void DSP_fft16x16t(short *w, int nx, short *x, short *y)</td>
<td>Mixed radix FFT with truncation, digit reversal, out of place. Input and output: 16 bits, Twiddle factor: 16 bits</td>
<td>4-33</td>
</tr>
<tr>
<td>void DSP_fft16x32(short *w, int nx, int *x, int *y)</td>
<td>Extended precision, mixed radix FFT, rounding, digit reversal, out of place. Input and output: 32 bits, Twiddle factor: 16 bits</td>
<td>4-47</td>
</tr>
<tr>
<td>void DSP_fft32x32(int *w, int nx, int *x, int *y)</td>
<td>Extended precision, mixed radix FFT, rounding, digit reversal, out of place. Input and output: 32 bits, Twiddle factor: 32 bits</td>
<td>4-49</td>
</tr>
<tr>
<td>void DSP_fft32x32s(int *w, int nx, int *x, int *y)</td>
<td>Extended precision, mixed radix FFT, digit reversal, out of place., with scaling and rounding. Input and output: 32 bits, Twiddle factor: 32 bits</td>
<td>4-51</td>
</tr>
</tbody>
</table>
### Table 3-4. FFT (Continued)

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>void DSP_ifft16x32(short *w, int nx, int *x, int *y)</td>
<td>Extended precision, mixed radix IFFT, rounding, digit reversal, out of place. Input and output: 32 bits, Twiddle factor: 16 bits</td>
<td>4-53</td>
</tr>
<tr>
<td>void DSP_ifft32x32(int *w, int nx, int *x, int *y)</td>
<td>Extended precision, mixed radix IFFT, digit reversal, out of place., with scaling and rounding. Input and output: 32 bits, Twiddle factor: 32 bits</td>
<td>4-55</td>
</tr>
</tbody>
</table>

### Table 3-5. Filtering and Convolution

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>void DSP_fir_cplx (short *x, short *h, short *r, int nh, int nx)</td>
<td>Complex FIR Filter (nh is a multiple of 2)</td>
<td>4-57</td>
</tr>
<tr>
<td>void DSP_fir_gen (short *x, short *h, short *r, int nh, int nr)</td>
<td>FIR Filter (any nh)</td>
<td>4-59</td>
</tr>
<tr>
<td>void DSP_fir_r4 (short *x, short *h, short *r, int nh, int nr)</td>
<td>FIR Filter (nh is a multiple of 4)</td>
<td>4-61</td>
</tr>
<tr>
<td>void DSP_fir_r8 (short *x, short *h, short *r, int nh, int nr)</td>
<td>FIR Filter (nh is a multiple of 8)</td>
<td>4-63</td>
</tr>
<tr>
<td>void DSP_fir_sym (short *x, short *h, short *r, int nh, int nr, int s)</td>
<td>Symmetric FIR Filter (nh is a multiple of 8)</td>
<td>4-65</td>
</tr>
<tr>
<td>void DSP_iir(short *r1, short *x, short *r2, short *h2, short *h1, int nr)</td>
<td>IIR with 5 Coefficients</td>
<td>4-67</td>
</tr>
<tr>
<td>void DSP_iirlat(short *x, int nx, short *k, int nk, int *b, short *)</td>
<td>All-pole IIR Lattice Filter</td>
<td>4-69</td>
</tr>
</tbody>
</table>
### Table 3–6. Math

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>int DSP_dotp_sqr(int G, short *x, short *y, int *r, int nx)</td>
<td>Vector Dot Product and Square</td>
<td>4-71</td>
</tr>
<tr>
<td>int DSP_dotprod(short *x, short *y, int nx)</td>
<td>Vector Dot Product</td>
<td>4-73</td>
</tr>
<tr>
<td>short DSP_maxval (short *x, int nx)</td>
<td>Maximum Value of a Vector</td>
<td>4-75</td>
</tr>
<tr>
<td>int DSP_maxidx (short *x, int nx)</td>
<td>Index of the Maximum Element of a Vector</td>
<td>4-76</td>
</tr>
<tr>
<td>short DSP_minval (short *x, int nx)</td>
<td>Minimum Value of a Vector</td>
<td>4-78</td>
</tr>
<tr>
<td>void DSP_mul32(int *x, int *y, int *r, short nx)</td>
<td>32-bit Vector Multiply</td>
<td>4-79</td>
</tr>
<tr>
<td>void DSP_neg32(int *x, int *r, short nx)</td>
<td>32-bit Vector Negate</td>
<td>4-81</td>
</tr>
<tr>
<td>void DSP_recip16 (short *x, short *frac, short *exp, short nx)</td>
<td>16-bit Reciprocal</td>
<td>4-82</td>
</tr>
<tr>
<td>int DSP_vecsumsq (short *x, int nx)</td>
<td>Sum of Squares</td>
<td>4-84</td>
</tr>
<tr>
<td>void DSP_w_vec(short *x, short *y, short m, short *r, short nr)</td>
<td>Weighted Vector Sum</td>
<td>4-85</td>
</tr>
</tbody>
</table>

### Table 3–7. Matrix

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>void DSP_mat_mul(short *x, int r1, int c1, short *y, int c2, short *r, int qs)</td>
<td>Matrix Multiplication</td>
<td>4-86</td>
</tr>
<tr>
<td>void DSP_mat_trans(short *x, short rows, short columns, short *r)</td>
<td>Matrix Transpose</td>
<td>4-88</td>
</tr>
</tbody>
</table>
### Table 3–8. Miscellaneous

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>short DSP_bexp(int *x, short nx)</td>
<td>Max Exponent of a Vector (for scaling)</td>
<td>4-89</td>
</tr>
<tr>
<td>void DSP_blk_eswap16(void *x, void *r, int nx)</td>
<td>Endian-swap a block of 16-bit values</td>
<td>4-91</td>
</tr>
<tr>
<td>void DSP_blk_eswap32(void *x, void *r, int nx)</td>
<td>Endian-swap a block of 32-bit values</td>
<td>4-93</td>
</tr>
<tr>
<td>void DSP_blk_eswap64(void *x, void *r, int nx)</td>
<td>Endian-swap a block of 64-bit values</td>
<td>4-95</td>
</tr>
<tr>
<td>void DSP_blk_move(short *x, short *r, int nx)</td>
<td>Move a Block of Memory</td>
<td>4-97</td>
</tr>
<tr>
<td>void DSP_fltoq15 (float *x,short *r, short nx)</td>
<td>Float to Q15 Conversion</td>
<td>4-98</td>
</tr>
<tr>
<td>int DSP_minerror (short *GSP0_TABLE,short *errCoefs, int *savePtr_ret)</td>
<td>Minimum Energy Error Search</td>
<td>4-99</td>
</tr>
<tr>
<td>void DSP_q15tof1 (short *x, float *r, short nx)</td>
<td>Q15 to Float Conversion</td>
<td>4-101</td>
</tr>
</tbody>
</table>
This chapter provides a list of the functions within the DSP library (DSPLIB) organized into functional categories. The functions within each category are listed in alphabetical order and include arguments, descriptions, algorithms, benchmarks, and special requirements.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Adaptive Filtering</td>
<td>4-2</td>
</tr>
<tr>
<td>4.2 Correlation</td>
<td>4-4</td>
</tr>
<tr>
<td>4.3 FFT</td>
<td>4-6</td>
</tr>
<tr>
<td>4.4 Filtering and Convolution</td>
<td>4-57</td>
</tr>
<tr>
<td>4.5 Math</td>
<td>4-71</td>
</tr>
<tr>
<td>4.6 Matirx</td>
<td>4-86</td>
</tr>
<tr>
<td>4.7 Miscellaneous</td>
<td>4-89</td>
</tr>
</tbody>
</table>
DSP_firlms2

4.1 Adaptive Filtering

DSP_firlms2

**LMS FIR**

**Function**

long DSP_firlms2(short * restrict h, const short * restrict x, short b, int nh)

**Arguments**

h[nh] Coefficient Array

x[nh+1] Input Array

b Error from previous FIR

nh Number of coefficients. Must be multiple of 4.

return long return value

**Description**

The Least Mean Square Adaptive Filter computes an update of all nh coefficients by adding the weighted error times the inputs to the original coefficients. The input array includes the last nh inputs followed by a new single sample input. The coefficient array includes nh coefficients.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
long DSP_firlms2(short h[], short x[], short b, int nh)
{
    int i;
    long r = 0;
    for (i = 0; i < nh; i++) {
        h[i] += (x[i] * b) >> 15;
        r += x[i + 1] * h[i];
    }
    return r;
}
```

**Special Requirements**

- This routine assumes 16-bit input and output.
- The number of coefficients nh must be a multiple of 4.
Implementation Notes

- The loop is unrolled 4 times.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is ENDIAN NEUTRAL.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

**Benchmarks**

<table>
<thead>
<tr>
<th></th>
<th>Cycles</th>
<th>Codesize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3 \times \text{nh}/4 + 17$</td>
<td>148 bytes</td>
</tr>
</tbody>
</table>
DSP_autocor

4.2 Correlation

DSP_autocor

<table>
<thead>
<tr>
<th>Function</th>
<th>void DSP_autocor(short * restrict r, const short * restrict x, int nx, int nr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arguments</td>
<td>r[nr] Output array &lt;br&gt; x[nx+nr] Input array. Must be double-word aligned. &lt;br&gt; nx Length of autocorrelation. Must be a multiple of 8. &lt;br&gt; nr Number of lags. Must be a multiple of 4.</td>
</tr>
<tr>
<td>Description</td>
<td>This routine accepts an input array of length nx + nr and performs nr autocorrelations each of length nx producing nr output results. This is typically used in VSELP code.</td>
</tr>
<tr>
<td>Algorithm</td>
<td>This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.</td>
</tr>
</tbody>
</table>

```c
void DSP_autocor(short r[ ],short x[ ], int nx, int nr) {
    int i,k,sum;
    for (i = 0; i < nr; i++){
        sum = 0;
        for (k = nr; k < nx+nr; k++)
            sum += x[k] * x[k-i];
        r[i] = (sum >> 15);
    }
}
```

| Special Requirements | nx must be a multiple of 8. <br> nr must be a multiple of 4. <br> x[] must be double-word aligned. |
| Implementation Notes | The inner loop is unrolled 8 times. <br> The outer loop is unrolled 4 times. |
The outer loop is conditionally executed in parallel with the inner loop. This allows for a zero overhead outer loop.

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

<table>
<thead>
<tr>
<th>Benchmarks</th>
<th>Cycles</th>
<th>nx * nr/4 + 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codesize</td>
<td>496 bytes</td>
<td>496 bytes</td>
</tr>
</tbody>
</table>
DSP_bitrev_cplx

4.3 FFT

Complex Bit-Reverse

NOTE: This function is provided for backward compatibility with the C62x DSPLIB. It has not been optimized for the C64x architecture. The user is advised to use one of the newly added FFT functions which have been optimized for the C64x.

Function
void DSP_bitrev_cplx (int *x, short *index, int nx)

Arguments
x[nx] Pointer to complex input vector x of size nx
index[ ] Array of size \( \sqrt{n} \) created by the routine digitrev_index (provided in the directory 'support/fft').

nx Number of elements in vector x. nx must be a power of 2.

Description
This function bit-reverses the position of elements in complex vector x. This function is used in conjunction with FFT routines to provide the correct format for the FFT input or output data. The bit-reversal of a bit-reversed order array yields a linear-order array.

Algorithm
TI retains all rights, title and interest in this code and only authorizes the use of this code on TI TMS320 DSPs manufactured by TI. This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

void DSP_bitrev_cplx (int *x, short *index, int nx)
{
    int i;
    short i0, i1, i2, i3;
    short j0, j1, j2, j3;
    int xi0, xi1, xi2, xi3;
    int xj0, xj1, xj2, xj3;
    short t;
    int a, b, ia, ib, ibs;
    int mask;
    int nbits, nbot, ntop, ndiff, n2, halfn;
    short *xs = (short *) x;
}
nbits = 0;
i = nx;
while (i > 1) {
    i = i >> 1;
    nbits++;
}  
nbot = nbits >> 1;
ndiff = nbits & 1;
ntop = nbot + ndiff;
n2 = 1 << ntop;
mask = n2 - 1;
halfn = nx >> 1;

for (i0 = 0; i0 < halfn; i0 += 2) {
    b = i0 & mask;
a = i0 >> nbot;
if (!b) ia = index[a];
ib = index[b];
ibs = ib << nbot;

    j0 = ibs + ia;
t = i0 < j0;
xi0 = x[i0];
xj0 = x[j0];
if (t) {x[i0] = xj0;
    x[j0] = xi0;}
i1 = i0 + 1;
j1 = j0 + halfn;
xi1 = x[i1];
xj1 = x[j1];
x[i1] = xj1;
x[j1] = xi1;
i3 = i1 + halfn;
j3 = j1 + 1;
xi3 = x[i3];
xj3 = x[j3];
if (t) {x[i3] = xj3;
    x[j3] = xi3;}
}
DSP_bitrev_cplx

} } 

Special Requirements

- nx must be a power of 2.
- The array index[] is generated by the routine bitrev_index provided in the directory 'support\fft'.
- If nx ≤ 4K, one can use the char (8-bit) data type for the "index" variable. This would require changing the LDH when loading index values in the assembly routine to LDB. This would further reduce the size of the Index Table by half its size.

Implementation Notes

- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

The performance of this function has not yet been characterized on the C64x.
DSP_radix2

Complex Forward FFT (radix 2)

NOTE: This function is provided for backward compatibility with the C62x DSPLIB. It has not been optimized for the C64x architecture. The user is advised to use one of the newly added FFT functions which have been optimized for the C64x.

Function
void DSP_radix2 (int nx, short * restrict x, const short * restrict w)

Arguments
nx Number of complex elements in vector x. Must be a power of 2 such that 4 ≤ nx ≤ 65536.


w[nx] Pointer to vector of FFT coefficients of size nx elements.

Description
This routine is used to compute FFT of a complex sequence of size nx, a power of 2, with "decimation-in-frequency decomposition" method. The output is in bit-reversed order. Each complex value is with interleaved 16-bit real and imaginary parts.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_radix2 (short x[], short nx, short w[])
{
    short n1, n2, ie, ia, i, j, k, l;
    short xt, yt, c, s;

    n2 = nx;
    ie = 1;
    for (k=nx; k > 1; k = (k >> 1) ) {
        n1 = n2;
        n2 = n2>>1;
        ia = 0;
        for (j=0; j < n2; j++) {
            c = w[2*ia];
            s = w[2*ia+1];
            ia = ia + ie;
            for (i=j; i < nx; i += n1) {
                l = i + n2;
                xt = x[l];
                x[l] = xt * c + y[l] * s;
                yt = y[l];
                y[l] = xt * s - y[l] * c;
            }
        }
    }
}```
DSP_radix2

\[
\begin{align*}
    x_t &= x[2*l] - x[2*i]; \\
    x[2*i] &= x[2*i] + x[2*l]; \\
    y_t &= x[2*l+1] - x[2*i+1]; \\
    x[2*i+1] &= x[2*i+1] + x[2*l+1]; \\
    x[2*l] &= (c*x_t + s*y_t)>>15; \\
    x[2*l+1] &= (c*y_t - s*x_t)>>15;
\end{align*}
\]

\[\}
\]

ie = ie<<1;

Special Requirements

- \(2 \leq nx \leq 32768\) (\(nx\) is a power of 2)
- Input \(x\) and coefficients \(w\) should be in different data sections or memory spaces to eliminate memory bank hits. If this is not possible, they should be aligned on different word boundaries to minimize memory bank hits.
- \(x\) data is stored in the order real[0], image[0], real[1], ...
- The FFT coefficients (twiddle factors) are generated using the program tw_radix2 provided in the directory 'support\fft'.

Implementation Notes

- Loads input \(x\) and coefficient \(w\) as words.
- Both loops \(j\) and \(i0\) shown in the C code are placed in the INNERLOOP of the assembly code.
- **Bank Conflicts:** See Benchmarks.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

The performance of this function has not yet been characterized on the C64x.
DSP_r4fft

Complex Forward FFT (radix 4)

NOTE: This function is provided for backward compatibility with the C62x DSPLIB. It has not been optimized for the C64x architecture. The user is advised to use one of the newly added FFT functions which have been optimized for the C64x.

Function

```c
void DSP_r4fft (int nx, short * restrict x, const short * restrict w)
```

Arguments

- **nx** Number of complex elements in vector x. Must be a power of 4 such that $4 \leq nx \leq 65536$.
- **x[2*nx]** Pointer to input and output sequences. Size 2*nx elements.
- **w[nx]** Pointer to vector of FFT coefficients of size nx elements.

Description

This routine is used to compute FFT of a complex sequence size nx, a power of 4, with "decimation-in-frequency decomposition" method. The output is in digit-reversed order. Each complex value is with interleaved 16-bit real and imaginary parts.

Algorithm

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_r4fft (int nx, short x[], short w[]) {
    int n1, n2, ie, i1, ia1, ia2, ia3, i0, i1, i2, i3,
        j, k;
    short t, r1, r2, s1, s2, col, co2, co3, si1,
        si2, si3;
    n2 = nx;
    ie = 1;
    for (k = nx; k > 1; k >>= 2) {
        n1 = n2;
        n2 >>= 2;
        i1 = 0;
        for (j = 0; j < n2; j++) {
            ia2 = i1 + i1;
            ia3 = ia2 + i1;
            col = w[ia1 * 2 + 1];
        }
    }
}
```
DSP_r4fft

```c
si1 = w[ia1 * 2];
co2 = w[ia2 * 2 + 1];
si2 = w[ia2 * 2];
co3 = w[ia3 * 2 + 1];
si3 = w[ia3 * 2];
ial = iial + ie;
for (i0 = j; i0 < nx; i0 += n1) {
    i1 = i0 + n2;
    i2 = i1 + n2;
    i3 = i2 + n2;
    r1 = x[2 * i0] + x[2 * i2];
    r2 = x[2 * i0] − x[2 * i2];
    t = x[2 * i1] + x[2 * i3];
    x[2 * i0] = r1 + t;
    r1 = r1 − t;
    s1 = x[2 * i0 + 1] + x[2 * i2 + 1];
    s2 = x[2 * i0 + 1] − x[2 * i2 + 1];
    t = x[2 * i1 + 1] + x[2 * i3 + 1];
    x[2 * i0 + 1] = s1 + t;
    s1 = s1 − t;
    x[2 * i2] = (r1 * co2 + s1 * si2) >> 15;
    x[2 * i2 + 1] = (s1 * co2 − r1 * si2) >> 15;
    t = x[2 * i1 + 1] − x[2 * i3 + 1];
    r1 = r2 + t;
    r2 = r2 − t;
    t = x[2 * i1] − x[2 * i3];
    s1 = s2 − t;
    s2 = s2 + t;
    x[2 * i1] = (r1 * co1 + s1 * si1) >> 15;
    x[2 * i1 + 1] = (s1 * co1 − r1 * si1) >> 15;
    x[2 * i3] = (r2 * co3 + s2 * si3);
```
DSP_r4fft

```c
>>15;
x[2 * i3 + 1] = (s2 * co3 − r2 * si3) >> 15;
```

Special Requirements

- \(4 \leq nx \leq 65536\) (\(nx\) a power of 4)
- \(x\) is aligned on a \(4*nx\) byte boundary for circular buffering
- Input \(x\) and coefficients \(w\) should be in different data sections or memory spaces to eliminate memory bank hits. If this is not possible, \(w\) should be aligned on an odd word boundary to minimize memory bank hits
- \(x\) data is stored in the order real[0], image[0], real[1], ...
- The FFT coefficients (twiddle factors) are generated using the program `tw_r4fft` provided in the directory `support\fft`.

Implementation Notes

- Loads input \(x\) and coefficient \(w\) as words.
- Both loops \(j\) and \(i0\) shown in the C code are placed in the INNERLOOP of the assembly code.

**Bank Conflicts**: See Benchmarks.

**Endian**: The code is LITTLE ENDIAN.

**Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks

The performance of this function has not yet been characterized on the C64x.
**DSP_fft**

**Complex Forward FFT With Digital Reversal**

**Function**

void DSP_fft (const short * restrict w, int nx, short * restrict x, short * restrict y)

**Arguments**

- **w[2*nx]** Pointer to vector of Q.15 FFT coefficients of size 2 * nx elements. Must be double-word aligned.
- **nx** Number of complex elements in vector x. Must be a power of 4 and 4 ≤ nx ≤ 65536.
- **x[2*nx]** Pointer to input sequence of size 2 * nx elements. Must be double-word aligned.
- **y[2*nx]** Pointer to output sequence of size 2 * nx elements. Must be double-word aligned.

**Description**

This routine is used to compute an FFT of a complex sequence of size nx, a power of 4, with "decimation-in-frequency decomposition" method. The output is returned in a separate array y in normal order. This routine also performs digit reversal as a special last step. Each complex value is stored as interleaved 16-bit real and imaginary parts. The code uses a special ordering of FFT factors and memory accesses to improve performance in the presence of cache.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
/* The following macro is used to obtain a digit reversed index, of a given */
/* number i, into j where the number of bits in "i" is "m". For the natural */
/* form of C code, this is done by first interchanging every set of "2 bit" */
/* pairs, followed by exchanging nibbles, followed by exchanging bytes, and */
/* finally halfwords. To give an example, consider the following number: */
/* 16-bit real and imaginary parts. The code uses a special ordering of */
/* FFT factors and memory accesses to improve performance in the presence */
/* of cache. */

/* Since only 16 digits were considered this represents the digit reversed */
/* index. Since the numbers are represented as 32 bits, there is one more */
```
#include <stdio.h>
#include <stdlib.h>

#define DIG_REV(i, m, j) do { 
  unsigned _ = (i); 
  _ = ((_ & 0x33333333) <<  2) | ((_ & ~0x33333333) >>  2); 
  _ = ((_ & 0x0F0F0F0F) <<  4) | ((_ & ~0x0F0F0F0F) >>  4); 
  _ = ((_ & 0x00FF00FF) <<  8) | ((_ & ~0x00FF00FF) >>  8); 
  _ = ((_ & 0x0000FFFF) << 16) | ((_ & ~0x0000FFFF) >> 16); 
  (j) = _ >> (m); 
} while (0)

void fft_cn(const short *restrict w, int n, short       *restrict x, short       *restrict y) {
  int stride, i, j, k, t, s, m;
  short xh0, xh1, xh20, xh21;
  short xl0, xl1, xl20, xl21;
  short xt0, yt0, xt1, yt1;
  short xt2, yt2, xt3, yt3;

  /* step typically of exchanging the half words as well. */
  /* -----------------------------------------------------*/
  #define DIG_REV(i, m, j) (_shfl(_rotl(_bitr(_deal(i)), 16)) >> (m))
  #endif

  /* Inform the compiler that the input array “x”, twiddle factor array */
  /* “w” and output array “y” are double word aligned. In addition the */
  /* number of points to be transformed is assumed to be greater than or */
  /* equal to 16, and less than 32768. */
}
DSP_fft

/* -----------------------------------------------*/
#ifndef NOASSUME
_nassert((int)x % 8 == 0);
_nassert((int)y % 8 == 0);
_nassert((int)w % 8 == 0);
_nassert(n >= 16);
_nassert(n < 32768);
#endif

/*-------------------------------------------------*/
/* Perform initial stages of FFT in place w/out digit reversal. */
/*-------------------------------------------------*/
#ifndef NOASSUME
#pragma MUST_ITERATE(1,,1);
#endif
for (stride = n, t = 0; stride > 4; stride >>= 2)
{
    /* -----------------------------------------------*/
    /* Perform each of the butterflies for this particular stride. */
    /* -----------------------------------------------*/
    s = stride >> 2;
    /* -----------------------------------------------*/
    /* stride represents the separation between the inputs of the radix */
    /* 4 butterfly. The C code breaks the FFT, into two cases, one when */
    /* the stride between the elements is greater than 4, other when */
    /* the stride is less than 4. Since stride is greater than 16, it */
    /* can be guaranteed that "s" is greater than or equal to 4. */
    /* In addition it can also be shown that the loop that shares this */
    /* stride will iterate at least once. The number of times this */
    /* loop iterates depends on how many butterflies in this stage */
    /* share a twiddle factor. */
    /* -----------------------------------------------*/

#ifndef NOASSUME
    _nassert(stride >= 16);
    _nassert(s >= 4);
    #pragma MUST_ITERATE(1,,1);
#endif

4-16
DSP_fft

#define

for (i = 0; i < n; i += stride)
{
    #ifndef NOASSUME
        _nassert(i % 4 == 0);
        _nassert(s >= 4);
    #pragma MUST_ITERATE(2,,2);
    #endif

    for (j = 0; j < s; j += 2)
    {
        for (k = 0; k < 2; k++)
        {
            short           w1c, w1s, w2c, w2s, w3c, w3s;
            short x0r, x0i, x1r, x1i, x2r, x2i, x3r, x3i;
            short y0r, y0i, y1r, y1i, y2r, y2i, y3r, y3i;

            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
            /*  Read the four samples that are the input to this     */
            /*  particular butterfly.                                */
            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
            x0r = x[2*(i+j+k      ) + 0]; x0i = x[2*(i+j+k      ) + 1];
            x1r = x[2*(i+j+k +   s) + 0]; x1i = x[2*(i+j+k +   s) + 1];
            x2r = x[2*(i+j+k + 2*s) + 0]; x2i = x[2*(i+j+k + 2*s) + 1];
            x3r = x[2*(i+j+k + 3*s) + 0]; x3i = x[2*(i+j+k + 3*s) + 1];

            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
            /*  Read the six twiddle factors that are needed for 3   */
            /*  of the four outputs. (The first output has no mpys.) */
            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
            w1s = w[t + 2*k + 6*j + 0];    w1c = w[t + 2*k + 6*j + 1];
            w2s = w[t + 2*k + 6*j + 4];    w2c = w[t + 2*k + 6*j + 5];
            w3s = w[t + 2*k + 6*j + 8];    w3c = w[t + 2*k + 6*j + 9];

            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
            /*  Calculate the four outputs, remembering that radix4  */
            /*  FFT accepts 4 inputs and produces 4 outputs. If we   */
            /*  imagine the inputs as being complex, and look at the */
            /*  first stage as an example:                            */
            /* −−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
        }
    }
}

C64x DSPLIB Reference 4-17
/* Four inputs are x(n) x(n+N/4) x(n+N/2) x(n+3N/4)   */
/* In general the four inputs can be generalized using */
/* the stride between the elements as follows:       */
/* x(n), x(n+s), x(n+2s), x(n+3s).                */
/*                                              */
/* These four inputs are used to calculate four outputs*/
/* as shown below:                               */
/*                                              */
/* X(4k) = x(n) + x(n + N/4) + x(n + N/2) + x(n + 3N/4) */
/* X(4k+1)= x(n) -jx(n + N/4) - x(n + N/2) +jx(n + 3N/4) */
/* X(4k+2)= x(n) - x(n +N/4) + x(N + N/2) - x(n + 3N/4) */
/* X(4k+3)= x(n) +jx(n + N/4) - x(n + N/2) -jx(n + 3N/4) */
/*                                              */
/* These four partial results can be re-written to show */
/* the underlying DIF structure similar to DSP_radix2 as */
/* follows:                                      */
/*                                              */
/* X(4k) = (x(n)+x(n + N/2)) + (x(n+N/4)+ x(n + 3N/4)) */
/* X(4k+1)= (x(n)-x(n + N/2)) -j(x(n+N/4) - x(n + 3N/4)) */
/* x(4k+2)= (x(n)+x(n + N/2)) - (x(n+N/4)+ x(n + 3N/4)) */
/* X(4k+3)= (x(n)-x(n + N/2)) +j(x(n+N/4) - x(n + 3N/4)) */
/*                                              */
/* which leads to the real and imaginary values as foll: */
/*                                              */
/* y0r = x0r + x2r + x1r + x3r = xh0 + xh20 */
/* y0i = x0i + x2i + x1i + x3i = xh1 + xh21 */
/* y1r = x0r - x2r + (x1i - x3i) = x10 + xl21 */
/* y1i = x0i - x2i - (x1r - x3r) = x11 - xl20 */
/* y2r = x0r + x2r - (x1r + x3r) = xh0 - xh20 */
/* y2i = x0i + x2i - (x1i + x3i) = xh1 - xh21 */
/* y3r = x0r - x2r - (x1i - x3i) = x10 - xl21 */
/* y3i = x0i - x2i + (x1r - x3r) = x11 + xl20 */
/*                                              */
/* ------------------------------------------------ */

xh0 = x0r + x2r;

xh1 = x0i + x2i;

xh20 = x1r + x3r;
DSP_fft

```
xh21 = x1i + x3i;
x0 = x0r - x2r;
x11 = x0i - x2i;
x120 = x1r - x3r;
x121 = x1i - x3i;
xt0 = xh0 + xh20;
yt0 = xh1 + xh21;
x1 = x10 + x121;
yt1 = xl1 - x120;
x2 = xh0 - xh20;
yt2 = xh1 - xh21;
x3 = x10 - x121;
yt3 = x11 + x120;

/*------------------------------*/
/* Perform twiddle factor multiplies of three terms,top  */
/* term does not have any multiplies. Note the twiddle */
/* factors for a normal FFT are C + j (-S). Since the */
/* factors that are stored are C + j S, this is        */
/* corrected for in the multiplies.                   */
/*                                                     */
/* Y1 = (xt1 + jyt1) (c + js) = (xc + ys) + (yc -xs)   */
/* ________________________________ */

y0r = xt0;
y0i = yt0;
y1r = (xt1 * w1c + yt1 * w1s) >> 15;
y1i = (yt1 * w1c - xt1 * w1s) >> 15;
y2r = (xt2 * w2c + yt2 * w2s) >> 15;
y2i = (yt2 * w2c - xt2 * w2s) >> 15;
y3r = (xt3 * w3c + yt3 * w3s) >> 15;
y3i = (yt3 * w3c - xt3 * w3s) >> 15;

/* --------------------------------------- */
/* Store the final results back to the input array. */
/* --------------------------------------- */
```

C64x DSPLIB Reference 4-19
DSP_fft

\[x[2*(i+j+k) + 0] = y0r; x[2*(i+j+k) + 1] = y0i;\]
\[x[2*(i+j+k + s) + 0] = y1r; x[2*(i+j+k + s) + 1] = y1i;\]
\[x[2*(i+j+k + 2*s) + 0] = y2r; x[2*(i+j+k + 2*s) + 1] = y2i;\]
\[x[2*(i+j+k + 3*s) + 0] = y3r; x[2*(i+j+k + 3*s) + 1] = y3i;\]

// Offset to next subtable of twiddle factors. With each iteration
// of the above block, six twiddle factors get read, s times,
// hence the offset into the twiddle factor array is advanced by
// this amount.

t += 6 * s;

/* Get the magnitude of "n", so we know how many digits to reverse. */
for (i = 31, m = 1; (n & (1 << i)) == 0; i--, m++) ;

/* Perform final stage with digit reversal. */
s = n >> 2;

/* One of the nice features, of this last stage are that, no multiplies */
/* are required. In addition the data always strides by a fixed amount */
/* namely 8 elements. Since the data is stored as interleaved pairs, of */
/* real and imaginary data, the first eight elements contain the data */
/* for the first four complex inputs. These are the inputs to the first */
/* radix4 butterfly. */

#ifndef NOASSUME
#pragma MUST_ITERATE(4,,4);
#endif

for (i = 0; i < n; i += 4)
short x0r, x0i, x1r, x1i, x2r, x2i, x3r, x3i;
short y0r, y0i, y1r, y1i, y2r, y2i, y3r, y3i;

/* Read the four samples that are the input to this butterfly. */
x0r = x[2*(i + 0) + 0]; x0i = x[2*(i + 0) + 1];
x1r = x[2*(i + 1) + 0]; x1i = x[2*(i + 1) + 1];
x2r = x[2*(i + 2) + 0]; x2i = x[2*(i + 2) + 1];
x3r = x[2*(i + 3) + 0]; x3i = x[2*(i + 3) + 1];

/* Calculate the final FFT result from this butterfly. */
y0r = (x0r + x2r) + (x1r + x3r);
y0i = (x0i + x2i) + (x1i + x3i);
y1r = (x0r − x2r) + (x1i − x3i);
y1i = (x0i − x2i) − (x1r − x3r);
y2r = (x0r + x2r) − (x1r + x3r);
y2i = (x0i + x2i) − (x1i + x3i);
y3r = (x0r − x2r) − (x1i − x3i);
y3i = (x0i − x2i) + (x1r − x3r);

/* Digit reverse our address to convert the digit-reversed input into a linearized output order. This actually results in a digit-reversed store pattern since we're loading linearly, but the end result is that the FFT bins are in linear order. */
DIG_REV(i, m, j); /* Note: Result is assigned to ‘j’ by the macro. */

/* Store out the final FFT results. */
y[2*(j + 0) + 0] = y0r; y[2*(j + 0) + 1] = y0i;
y[2*(j + s) + 0] = y1r; y[2*(j + s) + 1] = y1i;
y[2*(j + 2*s) + 0] = y2r; y[2*(j + 2*s) + 1] = y2i;
y[2*(j + 3*s) + 0] = y3r; y[2*(j + 3*s) + 1] = y3i;
DSP_fft


Special Requirements

☐ In-place computation is not allowed.
☐ nx must be a power of 4 and \(4 \leq nx \leq 65536\).
☐ Input x[ ] and output y[ ] are stored on double-word aligned boundaries.
☐ Input data x[ ] is stored in the order real0, img0, real1, img1, ...
☐ The FFT coefficients (twiddle factors) must be double-word aligned and are generated using the program tw_fft16x16 provided in the directory 'support/fft'.

Implementation Notes

☐ Loads input x[ ] and coefficient w[ ] as double words.
☐ Both loops j and i0 shown in the C code are placed in the inner loop of the assembly code.

☐ **Bank Conflicts:** No bank conflicts occur.
☐ **Endian:** The code is LITTLE ENDIAN.
☐ **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>(1.25 * nx * \log_4(nx) - 0.5 * nx + 23 * \log_4(nx) - 1)</td>
</tr>
<tr>
<td>Codesize</td>
<td>984 bytes</td>
</tr>
</tbody>
</table>


**DSP_fft16x16r**

**Complex Forward Mixed Radix 16- x 16-bit FFT With Rounding**

**Function**

```c
void DSP_fft16x16r(int nx, short * restrict x, const short * restrict w, const unsigned char * restrict brev, short * restrict y, int radix, int offset, int nmax)
```

**Arguments**

- **nx** Length of FFT in complex samples. Must be power of 2 or 4, and ≤16384
- **x[2*nx]** Pointer to complex 16-bit data input
- **w[2*nx]** Pointer to complex FFT coefficients
- **brev[64]** Pointer to bit reverse table containing 64 entries. Only required for C code. Use NULL for assembly code since BITR instruction is used instead.
- **y[2*nx]** Pointer to complex 16-bit data output
- **radix** Smallest FFT butterfly used in computation used for decomposing FFT into sub-FFTs. See notes.
- **offset** Index in complex samples of sub-FFT from start of main FFT.
- **nmax** Size of main FFT in complex samples.

**Description**

This routine implements a cache-optimized complex forward mixed radix FFT with scaling, rounding and digit reversal. Input data `x[]`, output data `y[]` and coefficients `w[]` are 16-bit. The output is returned in the separate array `y[]` in normal order. Each complex value is stored as interleaved 16-bit real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors).

This redundant set of twiddle factors is size 2*N short samples. As pointed out later dividing these twiddle factors by 2 will give an effective divide by 4 at each stage to guarantee no overflow. The function is accurate to about 68dB of signal to noise ratio to the DFT function below:

```c
void dft(int n, short x[], short y[])
{
    int k, i, index;
    const double PI = 3.14159654;
    short * p_x;
    double arg, fx_0, fx_1, fy_0, fy_1, co, si;
```
DSP_fft16x16r

for(k = 0; k<n; k++)
{
    p_x = x;
    fy_0 = 0;
    fy_1 = 0;
    for(i=0; i<n; i++)
    {
        fx_0 = (double)p_x[0];
        fx_1 = (double)p_x[1];
        p_x += 2;
        index = (i*k) % n;
        arg = 2*PI*index/n;
        co = cos(arg);
        si = sin(arg);
        fy_0 += ((fx_0 * co) - (fx_1 * si));
        fy_1 += ((fx_1 * co) + (fx_0 * si));
    }
    y[2*k] = (short)2*fy_0/sqrt(n);
    y[2*k+1] = (short)2*fy_1/sqrt(n);
}

Scaling by 2 (i.e., >>1) takes place at each radix−4 stage except the last one. A radix−4 stage could give a maximum bit−growth of 2 bits, which would require scaling by 4. To completely prevent overflow, the input data must be scaled by $2^{(BT−BS)}$, where $BT$ (total number of bit growth) = log₂(nx) and BS (number of scales by the functions) = ceil[log₄(nx)−1]. All shifts are rounded to reduce truncation noise power by 3dB.

The function takes the twiddle factors and input data, and calculates the FFT producing the frequency domain data in the y[] array. As the FFT allows every input point to effect every output point, in a cache based system this causes cache thrashing. This is mitigated by allowing the main FFT of size N to be divided into several steps, allowing as much data reuse as possible. For example the following function:

DSP_fft16x16r(1024,&x[0], &w[0], y,brev,4, 0,1024);

is equivalent to:
Notice how the 1st FFT function is called on the entire 1K data set it covers the 1st pass of the FFT until the butterfly size is 256.

The following 4 FFTs do 256-point FFTs 25% of the size. These continue down to the end when the butterfly is of size 4. They use an index to the main twiddle factor array of 0.75*2*N. This is because the twiddle factor array is composed of successively decimated versions of the main array.

N not equal to a power of 4 can be used, i.e. 512. In this case to decompose the FFT the following would be needed:

\[
\text{DSP_fft16x16r}(512, \ &x[0], \ &w[0], \ y, \text{brev}, 2, \ 0, 512);
\]

is equivalent to:

\[
\text{DSP_fft16x16r}(512, \ &x[0], \ &w[0], \ y, \text{brev}, 128, \ 0, 512);
\]

\[
\text{DSP_fft16x16r}(128, \ &x[2*0], \ &w[2*3*128], \ y, \text{brev}, 2, \ 0, 512);
\]

\[
\text{DSP_fft16x16r}(128, \ &x[2*128], \ &w[2*3*128], \ y, \text{brev}, 2, \ 128, 512);
\]

\[
\text{DSP_fft16x16r}(128, \ &x[2*256], \ &w[2*3*128], \ y, \text{brev}, 2, \ 256, 512);
\]

\[
\text{DSP_fft16x16r}(128, \ &x[2*384], \ &w[2*3*128], \ y, \text{brev}, 2, \ 384, 512);
\]

The twiddle factor array is composed of \(\log_4(N)\) sets of twiddle factors, \((3/4)*N, (3/16)*N, (3/64)*N, \text{etc.}\) The index into this array for each stage of the FFT is calculated by summing these indices up appropriately. For multiple FFTs they can share the same table by calling the small FFTs from further down in the twiddle factor array, in the same way as the decomposition works for more data reuse.

Thus, the above decomposition can be summarized for a general N, radix “rad” as follows:

\[
\text{DSP_fft16x16r}(N, \ &x[0], \ &w[0], \ \text{brev}, y, N/4, 0, \ N)
\]

\[
\text{DSP_fft16x16r}(N/4, \ &x[0], \ &w[2*3*N/4], \ \text{brev}, y, \text{rad}, 0, \ N)
\]

\[
\text{DSP_fft16x16r}(N/4, \ &x[2*N/4], \ &w[2*3*N/4], \ \text{brev}, y, \text{rad}, N/4, \ N)
\]

\[
\text{DSP_fft16x16r}(N/4, \ &x[2*N/2], \ &w[2*3*N/4], \ \text{brev}, y, \text{rad}, N/2, \ N)
\]

\[
\text{DSP_fft16x16r}(N/4, \ &x[2*3*N/4], \ &w[2*3*N/4], \ \text{brev}, y, \text{rad}, 3*N/4, N)
\]

As discussed previously, N can be either a power of 4 or 2. If N is a power of 4, then rad = 4, and if N is a power of 2 and not a power of 4, then rad = 2. “rad"
is used to control how many stages of decomposition are performed. It is also used to determine whether a radix4 or DSP_radix2 decomposition should be performed at the last stage. Hence when “rad” is set to “N/4” the first stage of the transform alone is performed and the code exits. To complete the FFT, four other calls are required to perform N/4 size FFT’s. In fact, the ordering of these 4 FFT’s amongst themselves does not matter and hence from a cache perspective, it helps to go through the remaining 4 FFTs in exactly the opposite order to the first. This is illustrated as follows:

```
DSP_fft16x16r(N, &x[0], &w[0], brev,y,N/4,0, N)
DSP_fft16x16r(N/4,&x[2*3*N/4],&w[2*3*N/4],brev,y,rad,3*N/4, N)
DSP_fft16x16r(N/4,&x[2*N/2], &w[2*3*N/4],brev,y,rad,N/2, N)
DSP_fft16x16r(N/4,&x[2*N/4], &w[2*3*N/4],brev,y,rad,N/4, N)
DSP_fft16x16r(N/4,&x[0], &w[2*3*N/4],brev,y,rad,0, N)
```

In addition this function can be used to minimize call overhead, by completing the FFT with one function call invocation as shown below:

```
DSP_fft16x16r(N, &x[0], &w[0], y, brev, rad, 0, N)
```

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void fft16x16r
(
    int      n,
    short    *ptr_x,
    short    *ptr_w,
    unsigned char   *brev,
    short    *y,
    int      radix,
    int      offset,
    int      nmax
)
{
    int      i, l0, l1, l2, h2, predj;
    int      l1p1, l2p1, h2p1, tw_offset, stride, fft_jmp;
    short    xt0, yt0, xt1, yt1, xt2, yt2;
    short    si1, si2, si3, co1, co2, co3;
    short    xh0, xh1, xh20, xh21, xl0, xl1, xl20, xl21;
    short    x_0, x_1, x_l1, x_l1p1, x_h2, x_h2p1, x_l2, x_l2p1;
```
DSP_fft16x16r

short *x,*w;
short *ptr_x0, *ptr_x2, *y0;
unsigned int j, k, j0, j1, k0, k1;
short x0, x1, x2, x3, x4, x5, x6, x7;
short xh0_0, xh1_0, xh0_1, xh1_1;
short x10_0, x11_0, x10_1, x11_1;
short yt3, yt4, yt5, yt6, yt7;
unsigned a, num;
stride = n; /* n is the number of complex samples */
tw_offset = 0;
while (stride > radix)
{
    j = 0;
    fft_jmp = stride + (stride>>1);
    h2 = stride>>1;
    l1 = stride;
    l2 = stride + (stride>>1);
    x = ptr_x;
    w = ptr_w + tw_offset;
    for (i = 0; i < n>>1; i += 2)
    {
        co1 = w[j+0];
        si1 = w[j+1];
        co2 = w[j+2];
        si2 = w[j+3];
        co3 = w[j+4];
        si3 = w[j+5];
        j += 6;
        x_0 = x[0];
        x_1 = x[1];
        x_h2 = x[h2];
        x_h2p1 = x[h2+1];
        x_11 = x[11];
        x_11p1 = x[11+1];
        x_12 = x[12];
        x_12p1 = x[12+1];
    }
}
DSP_fft16x16r

\[
xh0 = x_0 + x_{l1}; \\
xh1 = x_1 + x_{l1p1}; \\
xl0 = x_0 - x_{l1}; \\
xl1 = x_1 - x_{l1p1}; \\
xh20 = x_{h2} + x_{l2}; \\
xh21 = x_{h2p1} + x_{l2p1}; \\
xl20 = x_{h2} - x_{l2}; \\
xl21 = x_{h2p1} - x_{l2p1}; \\
ptr_x0 = x; \\
ptr_x0[0] = ((short)(xh0 + xh20)) >> 1; \\
ptr_x0[1] = ((short)(xh1 + xh21)) >> 1; \\
ptr_x2 = ptr_x0; \\
x += 2; \\
predj = (j - fft_jmp); \\
if (!predj) x += fft_jmp; \\
if (!predj) j = 0; \\
xt0 = xh0 - xh20; \\
yt0 = xh1 - xh21; \\
xt1 = xl0 + xl21; \\
yt2 = xl1 + xl20; \\
xt2 = xl0 - xl21; \\
yt1 = xl1 - xl20; \\
l1p1 = l1+1; \\
h2p1 = h2+1; \\
l2p1 = l2+1; \\
ptr_x2[l1] = (xt1 * co1 + yt1 * si1 + 0x00008000) >> 16; \\
ptr_x2[l1p1] = (yt1 * co1 - xt1 * si1 + 0x00008000) >> 16; \\
ptr_x2[h2] = (xt0 * co2 + yt0 * si2 + 0x00008000) >> 16; \\
ptr_x2[h2p1] = (yt0 * co2 - xt0 * si2 + 0x00008000) >> 16; \\
ptr_x2[l2] = (xt2 * co3 + yt2 * si3 + 0x00008000) >> 16; \\
ptr_x2[l2p1] = (yt2 * co3 - xt2 * si3 + 0x00008000) >> 16; 
\]

tw_offset += fft_jmp;
stride = stride>>2;
} /* end while */
j = offset>>2;
ptr_x0 = ptr_x;
y0 = y;
/* determine _norm(nmax) − 17 */
l0 = 31;
if (((nmax>>31)&1)==1)
    num = ~nmax;
else
    num = nmax;
if (!num)
    l0 = 32;
else
{
    a=num&0xFFFF0000; if (a) { l0-=16; num=a; }
    a=num&0xFF00FF00; if (a) { l0-= 8; num=a; }
    a=num&0xF0F0F0F0; if (a) { l0-= 4; num=a; }
    a=num&0xCCCCCCCC; if (a) { l0-= 2; num=a; }
    a=num&0xAABAABAAB; if (a) { l0-= 1; }
}
l0 -= 1;
l0 -= 17;
if(radix == 2 || radix == 4)
    for (i = 0; i < n; i += 4)
    {
        /* reversal computation */
        j0 = (j     ) & 0x3F;
        j1 = (j >> 6) & 0x3F;
        k0 = brev[j0];
        k1 = brev[j1];
        k = (k0 << 6) |  k1;
        if (l0 < 0)
            k = k << -l0;
        else
            k = k >> l0;
        j++; /* multiple of 4 index */
x0   = ptr_x0[0];  x1 = ptr_x0[1];
x2 = ptr_x0[2]; x3 = ptr_x0[3];
x4 = ptr_x0[4]; x5 = ptr_x0[5];
x6 = ptr_x0[6]; x7 = ptr_x0[7];
ptr_x0 += 8;

xh0_0 = x0 + x4;
xh1_0 = x1 + x5;
xh0_1 = x2 + x6;
xh1_1 = x3 + x7;
if (radix == 2)
{
xh0_0 = x0;
xh1_0 = x1;
xh0_1 = x2;
xh1_1 = x3;
}

yt0 = xh0_0 + xh0_1;
yt1 = xh1_0 + xh1_1;
yt4 = xh0_0 − xh0_1;
yt5 = xh1_0 − xh1_1;
xl0_0 = x0 − x4;
xl1_0 = x1 − x5;
xl0_1 = x2 − x6;
xl1_1 = x3 − x7;
if (radix == 2)
{
xl0_0 = x4;
xl1_0 = x5;
xl1_1 = x6;
xl0_1 = x7;
}

yt2 = xl0_0 + xl1_1;
yt3 = xl1_0 − xl0_1;
yt6 = xl0_0 − xl1_1;
yt7 = xl1_0 + xl0_1;
if (radix == 2)
{
    yt7  = x11_0  - x10_1;
    yt3  = x11_0  + x10_1;
}
y0[k] = yt0; y0[k+1] = yt1;
k += n>>1;
y0[k] = yt2; y0[k+1] = yt3;
k += n>>1;
y0[k] = yt4; y0[k+1] = yt5;
k += n>>1;
y0[k] = yt6; y0[k+1] = yt7;
}

Special Requirements

- In-place computation is not allowed.
- nx must be a power of 2 or 4.
- Complex input data x[ ], twiddle factors w[ ], and output array y[ ] must be double-word aligned.
- Real values are stored in even word, imaginary in odd.
- All data are in short precision or Q.15 format. Allowed input dynamic range is $16 - (\log_2(nx) - \text{ceil}[\log_4(nx) - 1])$.
- Output results are returned in normal order.
- The FFT coefficients (twiddle factors) are generated using the program tw_fft16x16 provided in the directory 'support\fft'. The scale factor must be 32767.5. The input data must be scaled by $2^\left(\log_2(nx) - \text{ceil}[\log_4(nx) - 1]\right)$ to completely prevent overflow.

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.
- The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on nx. If nx
is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.

- A special sequence of coefficients used as generated above produces the FFT. This collapses the inner 2 loops in the traditional Burrus and Parks implementation.

- The revised FFT uses a redundant sequence of twiddle factors to allow a linear access through the data. This linear access enables data and instruction level parallelism.

- The butterfly is bit reversed, i.e. the inner 2 points of the butterfly are crossed over, this has the effect of making the data come out in bit reversed rather than in radix 4 digit reversed order. This simplifies the last pass of the loop. The BITR instruction is used to do the bit reversal out of place.

**Benchmarks**

<table>
<thead>
<tr>
<th>Cycles</th>
<th>( \text{ceil}[\log_4(nx) - 1] \cdot (5 \cdot \frac{nx}{4} + 25) + 5 \cdot \frac{nx}{4} + 26 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codesize</td>
<td>868 bytes</td>
</tr>
</tbody>
</table>
DSP_fft16x16t

Complex Forward Mixed Radix 16- x 16-bit FFT With Truncation

Function
void DSP_fft16x16t(const short * restrict w, int nx, short * restrict x, short * restrict y)

Arguments

nx          Length of FFT in complex samples. Must be power of 2 or 4 , and 16 ≤ nx ≤ 32768.

x[2*nx]     Pointer to complex 16-bit data input.

y[2*nx]     Pointer to complex 16-bit data output.

Description
This routine computes a complex forward mixed radix FFT with truncation and
digit reversal. Input data x[], output data y[] and coefficients w[] are 16-bit.
The output is returned in the separate array y[] in normal order. Each complex
value is stored with interleaved real and imaginary parts. The code uses a spe-
cial ordering of FFT coefficients (also called twiddle factors) and memory ac-
cesses to improve performance in the presence of cache.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that
the assembly code is hand optimized and restrictions may apply.

/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* The following macro is used to obtain a digit reversed index, of a given */
/* number i, into j where the number of bits in "i" is "m". For the natural */
/* form of C code, this is done by first interchanging every set of "2 bit" */
/* pairs, followed by exchanging nibbles, followed by exchanging bytes, and */
/* finally halfwords. To give an example, consider the following number:    */
/*                                                                          */
/* N = FEDCBA9876543210, where each digit represents a bit, the following */
/* steps illustrate the changes as the exchanges are performed:             */
/* M = DCFE98BA54761032 is the number after every "2 bits" are exchanged.  */
/* O = 98BADCFE10325476 is the number after every nibble is exchanged.     */
/* P = 1032547698BADCFE is the number after every byte is exchanged.       */
/* Since only 16 digits were considered this represents the digit reversed */
/* index. Since the numbers are represented as 32 bits, there is one more */
/* step typically of exchanging the half words as well.                     */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
#if TMS320C6X

C64x DSPLIB Reference 4-33
# define DIG_REV(i, m, j) ((j) = (_shfl(_rotl(_bitr(_deal(i)), 16)) >> (m)))
#else
#define DIG_REV(i, m, j) do {
unsigned _ = (i);
_ = (_ & 0x33333333) <<  2) | ((_ & -0x33333333) >>  2);
_ = (_ & 0x0F0F0F0F) <<  4) | ((_ & -0x0F0F0F0F) >>  4);
_ = (_ & 0x00FF00FF) <<  8) | ((_ & -0x00FF00FF) >>  8);
_ = (_ & 0x0000FFFF) << 16) | ((_ & -0x0000FFFF) >> 16);
(j) = _ >> (m);
} while (0)
#endif

void DSP_fft16x16t_cn(const short *restrict ptr_w, int npoints, short * ptr_x, short * ptr_y) {
    int i, j, l1, l2, h2, predj, tw_offset, stride, fft_jmp;
    short xt0_0, yt0_0, xt1_0, yt1_0, xt2_0, yt2_0;
    short xt0_1, yt0_1, xt1_1, yt1_1, xt2_1, yt2_1;
    short xh0_0, xh1_0, xh20_0, xh21_0, xl0_0, xl1_0, xl20_0, xl21_0;
    short xh1_1, xh21_1, xh01_1, xh02_1, xh12_1, xh20_1, xh21_0, xh20_0;
    short x_l1_0, x_l1_1, x_l1_2, x_l1_3, x_l2_0, x_l2_1;
    short x_l2_2, x_l2_3, x_l2_4, x_l2_5, x_l2_6, x_l2_7, x_l2_8, x_l2_9;
    short x_h2_0, x_h2_1, x_h2_2, x_h2_3, x_h2_4, x_h2_5, x_h2_6, x_h2_7;
    short x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_10, x_11, x_12, x_13, x_14, x_15;
    short y0r, y0i, y4r, y4i;
    int n0, j0;
    int radix, m;
    int norm;
    const short *w;
/* Determine the number of points to be transformed. */
/* Check whether we can use a radix4 decomposition or a mixed radix */
/* transformation, by determining modulo 2. */

for (i = 31, m = 1; (npoints & (1 << i)) == 0; i--, m++) ;
radix = m & 1 ? 2 : 4;
norm = m - 2;

/* The stride is quartered with every iteration of the outer loop. It */
/* denotes the separation between any two adjacent inputs to the butter */
/* fly. This should start out at N/4, hence stride is initially set to */
/* N. For every stride, 6*stride twiddle factors are accessed. The */
/* "tw_offset" is the offset within the current twiddle factor sub- */
/* table. This is set to zero, at the start of the code and is used to */
/* obtain the appropriate sub-table twiddle pointer by offsetting it */
/* with the base pointer "ptr_w". */

stride = npoints;
tw_offset = 0;
fft_jmp = 6 * stride;
while (stride > radix)
{
    /* At the start of every iteration of the outer loop, "j" is set */
    /* to zero, as "w" is pointing to the correct location within the */
    /* twiddle factor array. For every iteration of the inner loop */
    /* 6 * stride twiddle factors are accessed. For eg, */
    /* */
    /* #Iteration of outer loop  # twiddle factors  #times cycled */
    /* 1 6 N/4 1 */
    /* 2 6 N/16 4 */
    /* */
    /* */
    j = 0;
    fft_jmp >>= 2;
DSP_fft16x16t

/* Set up offsets to access "N/4", "N/2", "3N/4" complex point or */
/* "N/2", "N", "3N/2" half word */
/* Set up offsets to access "N/4", "N/2", "3N/4" complex point or */

h2 = stride>>1;
l1 = stride;
l2 = stride + (stride >> 1);
/* Reset "x" to point to the start of the input data array. */
/* "tw_offset" starts off at 0, and increments by "6 * stride" */
/* The stride quarters with every iteration of the outer loop */
/* Reset "x" to point to the start of the input data array. */
/* "tw_offset" starts off at 0, and increments by "6 * stride" */
/* The stride quarters with every iteration of the outer loop */

x = ptr_x;
w = ptr_w + tw_offset;
tw_offset += fft_jmp;
stride >>=   2;
/* The following loop iterates through the different butterflies, */
/* within a given stage. Recall that there are logN to base 4 */
/* stages. Certain butterflies share the twiddle factors. These */
/* are grouped together. On the very first stage there are no */
/* butterflies that share the twiddle factor, all N/4 butter- */
/* flies have different factors. On the next stage two sets of */
/* N/8 butterflies share the same twiddle factor. Hence after */
/* half the butterflies are performed, j the index into the */
/* factor array resets to 0, and the twiddle factors are reused. */
/* When this happens, the data pointer 'x' is incremented by the */
/* fft_jmp amount. In addition the following code is unrolled to */
/* perform "2" radix4 butterflies in parallel. */

for (i = 0; i < npoints; i += 8)
{
    /* Read the first 12 twiddle factors, six of which are used */
    /* for one radix 4 butterfly and six of which are used for */
    /* next one. */
}
DSP_fft16x16t

```c
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
co10 = w[j+1];    si10 = w[j+0];
co11 = w[j+3];    si11 = w[j+2];
co20 = w[j+5];    si20 = w[j+4];
co21 = w[j+7];    si21 = w[j+6];
co30 = w[j+9];    si30 = w[j+8];
co31 = w[j+11];   si31 = w[j+10];
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* Read in the first complex input for the butterflies.       */
/* 1st complex input to 1st butterfly: x[0] + jx[1]           */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
x_0 = x[0];       x_1 = x[1];
x_2 = x[2];       x_3 = x[3];
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* Read in the complex inputs for the butterflies. Each of the*/
/* successive complex inputs of the butterfly are seperated   */
/* by a fixed amount known as stride. The stride starts out   */
/* at N/4, and quarters with every stage.                     */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
x_l1_0 = x[l1  ]; x_l1_1 = x[l1+1];
x_l1_2 = x[l1+2]; x_l1_3 = x[l1+3];
x_l2_0 = x[l2  ]; x_l2_1 = x[l2+1];
x_l2_2 = x[l2+2]; x_l2_3 = x[l2+3];
x_h2_0 = x[h2  ]; x_h2_1 = x[h2+1];
x_h2_2 = x[h2+2]; x_h2_3 = x[h2+3];
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* Two butterflies are evaluated in parallel. The following */
/* results will be shown for one butterfly only, although   */
/* both are being evaluated in parallel.                     */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
xh0_0  = x_0    + x_l1_0;     xh1_0  = x_1    + x_l1_1;
xh0_1  = x_2    + x_l1_2;     xh1_1  = x_3    + x_l1_3;
x10_0  = x_0    − x_l1_0;     x11_0  = x_1    − x_l1_1;
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
```

\[
x_{101} = x_2 - x_{112}; \quad x_{111} = x_3 - x_{113}; \\
x_{120_0} = x_{h2_0} + x_{l2_0}; \quad x_{121_0} = x_{h2_1} + x_{l2_1}; \\
x_{120_1} = x_{h2_2} + x_{l2_2}; \quad x_{121_1} = x_{h2_3} + x_{l2_3}; \\
x_{l20_0} = x_{h2_0} - x_{l2_0}; \quad x_{l21_0} = x_{h2_1} - x_{l2_1}; \\
x_{l20_1} = x_{h2_2} - x_{l2_2}; \quad x_{l21_1} = x_{h2_3} - x_{l2_3}; \\
\]

/*-----------------------------------------------*/
/* Derive output pointers using the input pointer "x" */
/*-----------------------------------------------*/
x0 = x;
x2 = x0;

/*-----------------------------------------------*/
/* When the twiddle factors are not to be re-used, j is */
/* incremented by 12, to reflect the fact that 12 half words */
/* are consumed in every iteration. The input data pointer */
/* increments by 4. Note that within a stage, the stride */
/* does not change and hence the offsets for the other three */
/* legs, 0, h2, l1, l2. */
/*-----------------------------------------------*/
j += 12;
x += 4;
predj = (j - fft_jmp);
if (!predj) x += fft_jmp;
if (!predj) j = 0;

/*-----------------------------------------------*/
/* These four partial results can be re-written to show */
/* the underlying DIF structure similar to DSP_radix2 as */
/* follows: */
/*
/* X(4k) = (x(n)+x(n + N/2)) + (x(n+N/4) + x(n + 3N/4)) */
/* X(4k+1) = (x(n)−x(n + N/2)) −j(x(n+N/4) − x(n + 3N/4)) */
/* X(4k+2) = (x(n) +x(n + N/2)) − (x(n+N/4) + x(n + 3N/4)) */
/* X(4k+3) = (x(n)−x(n + N/2)) +j(x(n+N/4) − x(n + 3N/4)) */
/*
/* which leads to the real and imaginary values as foll: */
/*
/* y0r = x0r + x2r + x1r + x3r = xh0 + xh20 */

4-38
DSP_fft16x16t

/* y0i = x0i + x2i + x1i + x3i = xh1 + xh21 */
/* y1r = x0r - x2r + (x1i - x3i) = x10 + x121 */
/* y1i = x0i - x2i - (x1r - x3r) = x11 - x120 */
/* y2r = x0r + x2r - (x1r + x3r) = xh0 - xh20 */
/* y2i = x0i + x2i - (x1i + x3i) = xh1 - xh21 */
/* y3r = x0r - x2r - (x1i - x3i) = x10 - x121 */
/* y3i = x0i - x2i + (x1r - x3r) = x11 + x120 */
/* -----------------------------------------------*/
y0r = xh0_0 + xh20_0; y0i = xh1_0 + xh21_0;
y4r = xh0_1 + xh20_1; y4i = xh1_1 + xh21_1;
xt0_0 = xh0_0 - xh20_0; yt0_0 = xh1_0 - xh21_0;
xt0_1 = xh0_1 - xh20_1; yt0_1 = xh1_1 - xh21_1;
xt1_0 = x10_0 + x121_0; yt1_0 = x11_0 - x120_0;
xt2_0 = x10_0 + x121_0; yt1_0 = x11_0 - x120_0;
xt1_1 = x10_1 + x121_1; yt2_1 = x11_1 + x120_1;
xt2_1 = x10_1 + x121_1; yt1_1 = x11_1 - x120_1;
/*-----------------------------------------------*/
/* Store out first output, of the four outputs of a radix4 */
/* butterfly. Since two such radix4 butterflies are per- */
/* formed in parallel, there are 2 such 1st outputs.       */
/*-----------------------------------------------*/
x2[0] = y0r; x2[1] = y0i;
x2[2] = y4r; x2[3] = y4i;
/*-----------------------------------------------*/
/* Perform twiddle factor multiplies of three terms,top */
/* term does not have any multiplies. Note the twiddle */
/* factors for a normal FFT are C + j (-S). Since the */
/* factors that are stored are C + j S, this is */
/* corrected for in the multiplies. */
/*
*/
/* Y1 = (xt1 + jyt1) (c + js) = (xc + ys) + (yc -xs) */
/* Perform the multiplies using 16 by 32 multiply macro */
/* defined. This treats the twiddle factor as 16 bits */
/* and incoming data as 32 bits. */
/*-----------------------------------------------*/
x2[h2] = (si10 * yt1_0 + co10 * xt1_0) >> 15;

C64x DSPLIB Reference 4-39
DSP_radix2 pass. Two pointers are used to access the input data.

The input data is read "N/4" complex samples apart or "N/2" words apart using pointers "x0" and "x2". This produces outputs that are 0, N/4, N/2, 3N/4 for a radix4 FFT, and 0, N/8, N/2, 3N/8 for radix 2.

The pointers are set at the following locations which are half the offsets of a radix4 FFT.

y0 = ptr_y;
y2 = ptr_y + (int) npoints;
x0 = ptr_x;
x2 = ptr_x + (int) (npoints >> 1);
if (radix == 2)
{
    
y1 = y0 + (int) (npoints >> 2);
y3 = y2 + (int) (npoints >> 2);
l1 = norm + 1;
j0 = 8;
    n0 = npoints >> 1;
}
else
{
    y1 = y0 + (int) (npoints >> 1);
    y3 = y2 + (int) (npoints >> 1);
    l1 = norm + 2;
    j0 = 4;
    n0 = npoints >> 2;
}
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* The following code reads data indentically for either a radix 4    */
/* or a radix 2 style decomposition. It writes out at different       */
/* locations though. It checks if either half the points, or a        */
/* quarter of the complex points have been exhausted to jump to       */
/* prevent double reversal.                                           */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
j = 0;
for (i = 0; i < npoints; i += 8)
{
    /*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
    /* Digit reverse the index starting from 0. The increment to “j”  */
    /* is either by 4, or 8.                                          */
    /*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
    DIG_REV(j, l1, h2);
    /*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
    /* Read in the input data, from the first eight locations. These  */
    /* are transformed either as a radix4 or as a radix 2.            */
    /*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
    x_0 = x0[0];             x_1 = x0[1];
    x_2 = x0[2];             x_3 = x0[3];
    x_4 = x0[4];             x_5 = x0[5];
    x_6 = x0[6];             x_7 = x0[7];
    x0 += 8;
    xh0_0 = x_0 + x_4;       xh1_0 = x_1 + x_5;
    xl0_0 = x_0 − x_4;       xl1_0 = x_1 − x_5;
    xh0_1 = x_2 + x_6;       xh1_1 = x_3 + x_7;
DSP_fft16x16t

x10_1 = x_2 - x_6;     x11_1 = x_3 - x_7;

n00 = xh0_0 + xh0_1;    n01 = xh1_0 + xh1_1;
n10 = x10_0 + x11_1;    n11 = x11_0 - x10_1;
n20 = xh0_0 - xh0_1;    n21 = xh1_0 - xh1_1;
n30 = x10_0 - x11_1;    n31 = x11_0 + x10_1;

if (radix == 2)
{
    /* Perform DSP_radix2 style decomposition. */
    n00 = x_0 + x_2;     n01 = x_1 + x_3;
    n20 = x_0 - x_2;     n21 = x_1 - x_3;
    n10 = x_4 + x_6;     n11 = x_5 + x_7;
    n30 = x_4 - x_6;     n31 = x_5 - x_7;
}

y0[2*h2] = n00;           y0[2*h2 + 1] = n01;
y1[2*h2] = n10;           y1[2*h2 + 1] = n11;
y3[2*h2] = n30;           y3[2*h2 + 1] = n31;

x_8 = x2[0];              x_9 = x2[1];
x_a = x2[2];              x_b = x2[3];
x_c = x2[4];              x_d = x2[5];
x_e = x2[6];              x_f = x2[7];
x2 += 8;

xh0_2 = x_8 + x_c;        xh1_2 = x_9 + x_d;
x10_2 = x_8 - x_c;        x11_2 = x_9 - x_d;
xh0_3 = x_a + x_e;        xh1_3 = x_b + x_f;
x10_3 = x_a - x_e;        x11_3 = x_b - x_f;
n02 = xh0_2 + xh0_3;      n03 = xh1_2 + xh1_3;
n12 = x10_2 + x11_3;      n13 = x11_2 - x10_3;
n22 = xh0_2 - xh0_3;      n23 = xh1_2 - xh1_3;
n32 = x10_2 - x11_3;      n33 = x11_2 + x10_3;
if (radix == 2)
{
    n02 = x_8 + x_a;        n03 = x_9 + x_b;
    n22 = x_8 − x_a;        n23 = x_9 − x_b;
    n12 = x_c + x_e;        n13 = x_d + x_f;
    n32 = x_c − x_e;        n33 = x_d − x_f;
}

/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* Points that are read from successive locations map to y, y\[N/4\]  */
/* y\[N/2\], y\[3N/4\] in a radix4 scheme, y, y\[N/8\], y\[N/2\],y\[5N/8\]   */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/

y0[2*h2+2] = n02;         y0[2*h2+3] = n03;
y1[2*h2+2] = n12;         y1[2*h2+3] = n13;
y3[2*h2+2] = n32;         y3[2*h2+3] = n33;
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/
/* Increment “j” by “j0”. If j equals n0, then increment both “x0” */
/* and “x2” so that double inversion is avoided. */
/*−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−*/

j += j0;
if (j == n0)
{
    j  += n0;
    x0 += (int) npoints>>1;
    x2 += (int) npoints>>1;
}
}

Special Requirements

- In-place computation is not allowed.
- The size of the FFT, nx, must be power of 2 or 4, and 16 ≤ nx ≤ 32768.
- The arrays for the complex input data x[ ], complex output data y[ ] and twiddle factors w[ ] must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are
stored at even array indices, and the imaginary components are stored at odd array indices. All data are in short precision or Q.15 format.

- The FFT coefficients (twiddle factors) are generated using the program `tw_fft16x16` provided in the directory 'support\fft'. The scale factor must be 32767.5. No scaling is done with the function; thus the input data must be scaled by $2^{\log_2(nx)}$ to completely prevent overflow.

Implementation Notes

- **Bank Conflicts:** nx/8 bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on nx. If nx is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform. The conventional Cooley Tukey FFT, is written using three loops. The outermost loop “k” cycles through the stages. There are $\log N$ to the base 4 stages in all. The loop “j” cycles through the groups of butterflies with different twiddle factors, loop “i” reuses the twiddle factors for the different butterflies within a stage. It is interesting to note the following:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Groups</th>
<th>Butterflies With Common Twiddle Factors</th>
<th>Groups*Butterflies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/4</td>
<td>1</td>
<td>N/4</td>
</tr>
<tr>
<td>2</td>
<td>N/16</td>
<td>4</td>
<td>N/4</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>logN</td>
<td>1</td>
<td>N/4</td>
<td>N/4</td>
</tr>
</tbody>
</table>

The following statements can be made based on above observations:

1) Inner loop “i0” iterates a variable number of times. In particular the number of iterations quadruples every time from 1..N/4. Hence software pipelining a loop that iterates a variable number of times is not profitable.

2) Outer loop “j” iterates a variable number of times as well. However the number of iterations is quartered every time from N/4 ..1. Hence the behavior in (a) and (b) are exactly opposite to each other.

3) If the two loops “i” and “j” are coalesced together then they will iterate for a fixed number of times namely N/4. This allows us to combine the “i” and “j” loops into 1 loop. Optimized implementations will make use of this fact.
In addition the Cooley Tukey FFT accesses three twiddle factors per iteration of the inner loop, as the butterflies that re-use twiddle factors are lumped together. This leads to accessing the twiddle factor array at three points each separated by “ie”. Note that “ie” is initially 1, and is quadrupled with every iteration. Therefore these three twiddle factors are not even contiguous in the array.

In order to vectorize the FFT, it is desirable to access twiddle factor array using double word wide loads and fetch the twiddle factors needed. In order to do this a modified twiddle factor array is created, in which the factors WN/4, WN/2, W3N/4 are arranged to be contiguous. This eliminates the separation between twiddle factors within a butterfly. However this implies that as the loop is traversed from one stage to another, that we maintain a redundant version of the twiddle factor array. Hence the size of the twiddle factor array increases as compared to the normal Cooley Tukey FFT. The modified twiddle factor array is of size “2 * N” where the conventional Cooley Tukey FFT is of size “3N/4” where N is the number of complex points to be transformed. The routine that generates the modified twiddle factor array was presented earlier. With the above transformation of the FFT, both the input data and the twiddle factor array can be accessed using double-word wide loads to enable packed data processing.

The final stage is optimized to remove the multiplication as w0 = 1. This stage also performs digit reversal on the data, so the final output is in natural order. In addition if the number of points to be transformed is a power of 2, the final stage applies a DSP_radix2 pass instead of a radix 4. In any case the outputs are returned in normal order.

The code shown here performs the bulk of the computation in place. However, because digit-reversal cannot be performed in-place, the final result is written to a separate array, y[].

There is one slight break in the flow of packed processing that needs to be comprehended. The real part of the complex number is in the lower half, and the imaginary part is in the upper half. The flow breaks in case of “xl0” and “xl1” because in this case the real part needs to be combined with the imaginary part because of the multiplication by “j”. This requires a packed quantity like “xl21xl20” to be rotated as “xl20xl21” so that it can be combined using ADD2’s and SUB2’s. Hence the natural version of C code shown below is transformed using packed data processing as shown:

\[
\begin{align*}
\text{x10} & = x[2 * i0] - x[2 * i2]; \\
\text{x11} & = x[2 * i0 + 1] - x[2 * i2 + 1]; \\
\text{x120} & = x[2 * i1] - x[2 * i3]; \\
\text{x121} & = x[2 * i1 + 1] - x[2 * i3 + 1];
\end{align*}
\]
DSP_fft16x16t

xt1 = x10 + x121;
yt2 = x11 + x120;
xt2 = x10 - x121;
yt1 = x11 - x120;

xl1_xl0   = _sub2(x21_x20, x21_x20)
xl21_xl20 = _sub2(x32_x22, x23_x22)
xl20_xl21 = _rotl(xl21_xl20, 16)

yt2_xt1   = _add2(xl1_xl0, xl20_xl21)
yt1_xt2   = _sub2(xl1_xl0, xl20_xl21)

Also notice that xt1, yt1 end up on separate words, these need to be packed together to take advantage of the packed twiddle factors that have been loaded. In order for this to be achieved they are re-aligned as follows:

yt1_xt1 = _packhl2(yt1_xt2, yt2_xt1)
yt2_xt2 = _packhl2(yt2_xt1, yt1_xt2)

The packed words “yt1_xt1” allows the loaded “sc” twiddle factor to be used for the complex multiplies. The real part of the complex multiply is implemented using DOTP2. The imaginary part of the complex multiply is implemented using DOTPN2 after the twiddle factors are swizzled within the half word.

\[(X + jY) (C + j S) = (XC + YS) + j (YC - XS).\]

The actual twiddle factors for the FFT are cosine, - sine. The twiddle factors stored in the table are cosine and sine, hence the sign of the “sine” term is comprehended during multiplication as shown above.

**Benchmarks**

<table>
<thead>
<tr>
<th>Cycles</th>
<th>((10 * nx/8 + 19) \times \text{ceil}[\log_4(nx)] + (nx/8 + 2) \times 7 + 28 + BC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codesize</td>
<td>1004 bytes</td>
</tr>
</tbody>
</table>
**DSP_fft16x32**

**Complex Forward Mixed Radix 16- x 32-bit FFT With Rounding**

**Function**

void DSP_fft16x32(const short * restrict w, int nx, int * restrict x, int * restrict y)

**Arguments**

- nx Length of FFT in complex samples. Must be power of 2 or 4, and 16 ≤ nx ≤ 32768.
- x[2*nx] Pointer to complex 32-bit data input.

**Description**

This routine computes an extended precision complex forward mixed radix FFT with rounding and digit reversal. Input data x[] and output data y[] are 32-bit, coefficients w[] are 16-bit. The output is returned in the separate array y[] in normal order. Each complex value is stored with interleaved real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors) and memory accesses to improve performance in the presence of cache. The C code to generate the twiddle factors is the same as the one used for the DSP_fft16x16r routine.

**Algorithm**

The C equivalent of the assembly code without restrictions is similar to the one shown for the DSP_fft16x16t routine. For further details refer to the source code of the C version of this function which is provided with this library. Note that the assembly code is hand optimized and restrictions may apply.

**Special Requirements**

- In-place computation is not allowed.
- The size of the FFT, nx, must be a power of 4 or 2 and greater than or equal to 16 and less than 32768.
- The arrays for the complex input data x[], complex output data y[] and twiddle factors w[] must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are stored at even array indices, and the imaginary components are stored at odd array indices.
- The FFT coefficients (twiddle factors) are generated using the program tw_fft16x32 provided in the directory 'support/fft'. The scale factor must be 32767.5. No scaling is done with the function; thus the input data must be scaled by 2^ log2(nx) to completely prevent overflow.
Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.
- The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on nx. If nx is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.
- Refer to fft16x16t implementation notes, as similar ideas are used.

**Benchmarks**

| Cycles | \((13 \* \text{nx}/8 + 24) \* \text{cei}[\log_4(\text{nx}) - 1] + (\text{nx} + 8) \* 1.5 + 27\) |
| Codesize | 1068 bytes |
**Complex Forward Mixed Radix 32- x 32-bit FFT With Rounding**

**Function**

```c
void DSP_fft32x32(const int * restrict w, int nx, int * restrict x, int * restrict y)
```

**Arguments**

- `nx` Length of FFT in complex samples. Must be power of 2 or 4, and $16 \leq nx \leq 32768$.
- `x[2*nx]` Pointer to complex 32-bit data input.

**Description**

This routine computes an extended precision complex forward mixed radix FFT with rounding and digit reversal. Input data `x[]`, output data `y[]` and coefficients `w[]` are 32-bit. The output is returned in the separate array `y[]` in normal order. Each complex value is stored with interleaved real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors) and memory accesses to improve performance in the presence of cache. The C code to generate the twiddle factors is similar to the one used for the DSP_fft16x16t routine except that the factors are maintained at 32-bit precision.

**Algorithm**

The C equivalent of the assembly code without restrictions is similar to the one shown for the DSP_fft16x16t routine. For further details refer to the source code of the C version of this function which is provided with this library. Note that the assembly code is hand optimized and restrictions may apply.

**Special Requirements**

- In-place computation is not allowed.
- The size of the FFT, `nx`, must be a power of 4 or 2 and greater than or equal to 16 and less than 32768.
- The arrays for the complex input data `x[]`, complex output data `y[]` and twiddle factors `w[]` must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are stored at even array indices, and the imaginary components are stored at odd array indices.
- The FFT coefficients (twiddle factors) are generated using the program `tw_fft32x32` provided in the directory `support/fft`. The scale factor must be 2147483647.5. No scaling is done with the function; thus the input data must be scaled by $2^\log_2(nx)$ to completely prevent overflow.
DSP_fft32x32

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on nx. If nx is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.

The 32 by 32 multiplies are done with a 1.5 bit loss in accuracy. This comes about because the contribution of the low 16 bits to the 32 bit result is not computed. In addition the contribution of the low * high term is shifted by 16 as opposed to 15, for a loss of 0.5 bits after rounding.

- Refer fft16x16t implementation notes, as similar ideas are used.

**Benchmarks**

<table>
<thead>
<tr>
<th>Cycles</th>
<th>[10 \times (nx/4 + 1) + 10] \times \text{ceil}[\log_4(nx) - 1] + 6 \times (nx/4 + 2) + 27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codesize</td>
<td>932 bytes</td>
</tr>
</tbody>
</table>

4-50
### DSP_fft32x32s

**Complex Forward Mixed Radix 32- x 32-bit FFT With Scaling**

**Function**

```c
void DSP_fft32x32s(const int * restrict w, int nx, int * restrict x, int * restrict y)
```

**Arguments**
- `nx` Length of FFT in complex samples. Must be power of 2 or 4, and $16 \leq nx \leq 32768$.
- `x[2*nx]` Pointer to complex 32-bit data input.

**Description**

This routine computes an extended precision complex forward mixed radix FFT with scaling, rounding and digit reversal. Input data `x[]`, output data `y[]` and coefficients `w[]` are 32-bit. The output is returned in the separate array `y[]` in normal order. Each complex value is stored with interleaved real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors) and memory accesses to improve performance in the presence of cache. The C code to generate the twiddle factors is the same one used for the DSP_fft32x32 routine.

Scaling by 2 (i.e., $\gg 1$) takes place at each radix−4 stage except for the last one. A radix−4 stage can add a maximum of 2 bits, which would require scaling by 4 to completely prevent overflow. Thus, the input data must be scaled by $2^{\log_2(nx) - \text{ceil}[\log_4(nx) - 1]}$.

**Algorithm**

The C equivalent of the assembly code without restrictions is similar to the one shown for the fft16x16t routine. For further details refer to the source code of the C version of this function which is provided with this library. Note that the assembly code is hand optimized and restrictions may apply.

**Special Requirements**
- In-place computation is not allowed.
- The size of the FFT, `nx`, must be a power of 4 or 2 and greater than or equal to 16 and less than 32768.
- The arrays for the complex input data `x[]`, complex output data `y[]` and twiddle factors `w[]` must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are stored at even array indices, and the imaginary components are stored at odd array indices.
The FFT coefficients (twiddle factors) are generated using the program `tw_fft32x32` provided in the directory `support/fft`. The scale factor must be 1073741823.5. The input data must be scaled by $2^{\left(\log_2(nx) - \text{ceil}\left[\log_4(nx) - 1\right]\right)}$ to completely prevent overflow.

Implementation Notes

- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is LITTLE ENDIAN.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.
- Scaling is performed at each stage by shifting the results right by 1 preventing overflow.
- The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on $nx$. If $nx$ is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.
- The 32 by 32 multiplies are done with a 1.5 bit loss in accuracy. This comes about because the contribution of the low 16 bits to the 32 bit result is not computed. In addition the contribution of the low * high term is shifted by 16 as opposed to 15, for a loss of 0.5 bits after rounding.
- Refer `fft16x16t` implementation notes, as similar ideas are used.

Benchmarks

Cycles $\left[10 \times (nx/4 + 1) + 10\right] \times \text{ceil}\left[\log_4(nx) - 1\right] + 6 \times (nx/4 + 2) + 27$

Codesize 932 bytes
DSP_ifft16x32

Complex Inverse Mixed Radix 16- x 32-bit FFT With Rounding

Function

```c
void DSP_ifft16x32(const short * restrict w, int nx, int * restrict x, int * restrict y)
```

Arguments

- `nx` Length of FFT in complex samples. Must be power of 2 or 4, and 16 ≤ nx ≤ 32768.
- `x[2*nx]` Pointer to complex 32-bit data input.

Description

This routine computes an extended precision complex inverse mixed radix FFT with rounding and digit reversal. Input data `x[ ]` and output data `y[ ]` are 32-bit, coefficients `w[ ]` are 16-bit. The output is returned in the separate array `y[ ]` in normal order. Each complex value is stored with interleaved real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors) and memory accesses to improve performance in the presence of cache.

In reality one can re-use `fft16x32` to perform IFFT, by first conjugating the input, performing the FFT, conjugating again. This allows `fft16x32` to perform the IFFT as well. However if the double conjugation needs to be avoided then this routine uses the same twiddle factors as the FFT and performs an IFFT. The change in the sign of the twiddle factors is adjusted for in the routine. Hence this routine uses the same twiddle factors as the `fft16x32` routine.

Algorithm

The C equivalent of the assembly code without restrictions is similar to the one shown for the `fft16x16t` routine. For further details refer to the source code of the C version of this function which is provided with this library. Note that the assembly code is hand optimized and restrictions may apply.

Special Requirements

- In-place computation is not allowed.
- The size of the FFT, `nx`, must be a power of 4 or 2 and greater than or equal to 16 and less than 32768.
- The arrays for the complex input data `x[ ]`, complex output data `y[ ]` and twiddle factors `w[ ]` must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are
DSP_ifft16x32

stored at even array indices, and the imaginary components are stored at odd array indices.

- The FFT coefficients (twiddle factors) are generated using the program tw_fft16x32 provided in the directory 'support\fft'. The scale factor must be 32767.5. No scaling is done with the function; thus the input data must be scaled by \(2^{\log_2(nx)}\) to completely prevent overflow.

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

- The routine uses \(\log_4(nx) - 1\) stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on \(nx\). If \(nx\) is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.

- Refer fft16x16t implementation notes, as similar ideas are used.

Benchmarks

Cycles \((13 * nx/8 + 25) * \text{ceil}[\log_4(nx) - 1] + (nx + 8) * 1.5 + 30\)

Codesize 1064 bytes
DSP_ifft32x32

Function
void DSP_ifft32x32(const int * restrict w, int nx, int * restrict x, int * restrict y)

Arguments

nx Length of FFT in complex samples. Must be power of 2 or 4, and 16 ≤ nx ≤ 32768.

x[2*nx] Pointer to complex 32-bit data input.


Description
This routine computes an extended precision complex inverse mixed radix FFT with rounding and digit reversal. Input data x[], output data y[] and coefficients w[] are 32-bit. The output is returned in the separate array y[] in normal order. Each complex value is stored with interleaved real and imaginary parts. The code uses a special ordering of FFT coefficients (also called twiddle factors) and memory accesses to improve performance in the presence of cache.

In reality one can re-use fft32x32 to perform IFFT, by first conjugating the input, performing the FFT, conjugating again. This allows fft32x32 to perform the IFFT as well. However if the double conjugation needs to be avoided then this routine uses the same twiddle factors as the FFT and performs an IFFT. The change in the sign of the twiddle factors is adjusted for in the routine. Hence this routine uses the same twiddle factors as the fft32x32 routine.

Algorithm
The C equivalent of the assembly code without restrictions is similar to the one shown for the fft16x16t routine. For further details refer to the source code of the C version of this function which is provided with this library. Note that the assembly code is hand optimized and restrictions may apply.

Special Requirements
- In-place computation is not allowed.
- The size of the IFFT, nx, must be a power of 4 or 2 and greater than or equal to 16 and less than 32768.
- The arrays for the complex input data x[], complex output data y[] and twiddle factors w[] must be double-word aligned.
- The input and output data are complex, with the real/imaginary components stored in adjacent locations in the array. The real components are stored at even array indices, and the imaginary components are stored at odd array indices.
- The FFT coefficients (twiddle factors) are generated using the program tw_fft32x32 provided in the directory 'support/fft'. The scale factor must be
DSP_i fft32x32

2147483647.5. No scaling is done with the function; thus the input data must be scaled by $2^\log_2(nx)$ to completely prevent overflow.

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.
- The routine uses $\log_4(nx) - 1$ stages of radix-4 transform and performs either a radix-2 or radix-4 transform on the last stage depending on $nx$. If $nx$ is a power of 4, then this last stage is also a radix-4 transform, otherwise it is a radix-2 transform.
- Refer to fft16x16t implementation notes, as similar ideas are used.

Benchmarks

| Cycles | $[(nx/4 + 1) \times 10 + 10] \times \text{ceil}(\log_4(nx) - 1) + 6 \times (nx/4 + 2) + 27$ |
| Codesize | 932 bytes |
4.4 Filtering and Convolution

**DSP Fir Cplx**

**Complex FIR Filter**

**Function**

void DSP_fir_cplx (const short * restrict x, const short * restrict h, short * restrict r, int nh, int nr)

**Arguments**

- x[2*(nr+nh−1)] Complex input data. x must point to x[2*(nh−1)].
- r[2*nr] Complex output data.
- nh Number of complex coefficients. Must be a multiple of 2.
- nr Number of complex output samples. Must be a multiple of 4.

**Description**

This function implements the FIR filter for complex input data. The filter has nr output samples and nh coefficients. Each array consists of an even and odd term with even terms representing the real part and the odd terms the imaginary part of the element. The pointer to input array x must point to the (nh)th complex sample, i.e., element 2*(nh−1), upon entry to the function. The coefficients are expected in normal order.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_fir_cplx(short *x, short *h, short *r, short nh, short nr)
{
    short i,j;
    int imag, real;
    for (i = 0; i < 2*nr; i += 2){
        imag = 0;
        real = 0;
        for (j = 0; j < 2*nh; j += 2){
            real += h[j] * x[i−j] − h[j+1] * x[i+1−j];
            imag += h[j] * x[i+1−j] + h[j+1] * x[i−j];
        }
        r[i] = (real >> 15);
        r[i+1] = (imag >> 15);
    }
}
```
DSP_fir_cplx

}{
}

Special Requirements
- The number of coefficients nh must be a multiple of 2.
- The number of output samples nr must be a multiple of 4.

Implementation Notes
- The outer loop is unrolled 4 times while the inner loop is not unrolled.
- Both inner and outer loops are collapsed in one loop.
- ADDAH and SUBAH are used along with PACKH2 to perform accumulation, shift and data packing.
- Collapsed one stage of epilog and prolog each.
- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is LITTLE ENDIAN.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks
- Cycles: \( nr \times nh + 24 \)
- Codesize: 432 bytes
### DSP_fir_gen

**FIR Filter**

**Function**

```c
void DSP_fir_gen (const short * restrict x, const short * restrict h, short * restrict r, int nh, int nr)
```

**Arguments**

- `x[nr+nh−1]` Pointer to input array of size `nr + nh − 1`.
- `h[nh]` Pointer to coefficient array of size `nh` (coefficients must be in reverse order).
- `r[nr]` Pointer to output array of size `nr`. Must be word aligned.
- `nh` Number of coefficients. Must be ≥5.
- `nr` Number of samples to calculate. Must be a multiple of 4.

**Description**

Computes a real FIR filter (direct-form) using coefficients stored in vector `h[ ]`. The real data input is stored in vector `x[ ]`. The filter output result is stored in vector `r[ ]`. It operates on 16-bit data with a 32-bit accumulate. The filter calculates `nr` output samples using `nh` coefficients.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_fir_gen(short *x, short *h, short *r, int nh, int nr) {
    int i, j, sum;
    
    for (j = 0; j < nr; j++) {
        sum = 0;
        for (i = 0; i < nh; i++)
            sum += x[i + j] * h[i];
        r[j] = sum >> 15;
    }
}
```

**Special Requirements**

- `nh`, the number of coefficients, must be greater than or equal to 5. Coefficients must be in reverse order.
- `nr`, the number of outputs computed, must be a multiple of 4 and greater than or equal to 4.
- Array `r[ ]` must be word aligned.
Implementation Notes

- Load double-word instruction is used to simultaneously load four values in a single clock cycle.
- The inner loop is unrolled four times and will always compute a multiple of 4 of nh and nr. If nh is not a multiple of 4, the code will fill in zeros to make nh a multiple of 4.
- This code yields best performance when ratio of outer loop to inner loop is less than or equal to 4.

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

**Benchmarks**

<table>
<thead>
<tr>
<th>Cycles</th>
<th>([11 + 4 \times \text{ceil}(nh/4)] \times nr/4 + 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codesize</td>
<td>544 bytes</td>
</tr>
</tbody>
</table>
DSP_fir_r4

**FIR Filter (when the number of coefficients is a multiple of 4)**

**Function**

```c
void DSP_fir_r4 (const short * restrict x, const short * restrict h, short * restrict r, int nh, int nr)
```

**Arguments**

- `x[nr+nh-1]` Pointer to input array of size nr + nh – 1.
- `h[nh]` Pointer to coefficient array of size nh (coefficients must be in reverse order).
- `r[nr]` Pointer to output array of size nr.
- `nh` Number of coefficients. Must be multiple of 4 and ≥8.
- `nr` Number of samples to calculate. Must be multiple of 4.

**Description**

Computes a real FIR filter (direct-form) using coefficients stored in vector `h[]`. The real data input is stored in vector `x[]`. The filter output result is stored in vector `r[]`. This FIR operates on 16-bit data with a 32-bit accumulate. The filter calculates `nr` output samples using `nh` coefficients.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_fir_r4(short *x, short *h, short *r, int nh, int nr)
{
    int i, j, sum;

    for (j = 0; j < nr; j++) {
        sum = 0;
        for (i = 0; i < nh; i++)
            sum += x[i + j] * h[i];
        r[j] = sum >> 15;
    }
}
```

**Special Requirements**

- `nh`, the number of coefficients, must be a multiple of 4 and greater than or equal to 8. Coefficients must be in reverse order.
- `nr`, the number of outputs computed, must be a multiple of 4 and greater than or equal to 4.
Implementation Notes

- The load double-word instruction is used to simultaneously load four values in a single clock cycle.
- The inner loop is unrolled four times and will always compute a multiple of 4 output samples.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>$(8 + nh) \times \frac{nr}{4} + 9$</td>
</tr>
<tr>
<td>Codesize</td>
<td>308 bytes</td>
</tr>
</tbody>
</table>
DSP_fir_r8

**DSP_fir_r8**

**FIR Filter (when the number of coefficients is a multiple of 8)**

**Function**

void DSP_fir_r8 (short *x, short *h, short *r, int nh, int nr)

**Arguments**

- x[nr+nh-1] Pointer to input array of size nr + nh – 1.
- h[nh] Pointer to coefficient array of size nh (coefficients must be in reverse order).
- r[nr] Pointer to output array of size nr. Must be word aligned.
- nh Number of coefficients. Must be multiple of 8, \( \geq 8 \).
- nr Number of samples to calculate. Must be multiple of 4.

**Description**

Computes a real FIR filter (direct-form) using coefficients stored in vector h[]. The real data input is stored in vector x[]. The filter output result is stored in vector r[]. This FIR operates on 16-bit data with a 32-bit accumulate. The filter calculates nr output samples using nh coefficients.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_fir_r8 (short *x, short *h, short *r, int nh, int nr) {
    int i, j, sum;

    for (j = 0; j < nr; j++) {
        sum = 0;
        for (i = 0; i < nh; i++)
            sum += x[i + j] * h[i];
        r[j] = sum >> 15;
    }
}
```

**Special Requirements**

- nh, the number of coefficients, must be a multiple of 8 and greater than or equal to 8. Coefficients must be in reverse order.

- nr, the number of outputs computed, must be a multiple of 4 and greater than or equal to 4.

- Array r[] must be word aligned.
**DSP_fir_r8**

**Implementation Notes**

- The load double-word instruction is used to simultaneously load four values in a single clock cycle.
- The inner loop is unrolled 4 times and will always compute a multiple of 4 output samples.
- The outer loop is conditionally executed in parallel with the inner loop. This allows for a zero overhead outer loop.

**Bank Conflicts:** No bank conflicts occur.

**Endian:** The code is LITTLE ENDIAN.

**Interruptibility:** The code is interrupt-tolerant but not interruptible.

**Benchmarks**

Cycles \( nh \times nr/4 + 17 \)

Codesize 336 bytes
DSP_fir_sym

**DSP_fir_sym**

**Symmetric FIR Filter**

**Function**

```c
void DSP_fir_sym (const short  * restrict x, const short  * restrict h, short * restrict r, int nh, int nr, int s)
```

**Arguments**

- `x[nr+2*nh]` Pointer to input array of size `nr + 2*nh`. Must be double-word aligned.
- `h[nh+1]` Pointer to coefficient array of size `nh + 1`. Coefficients are in normal order and only half (`nh+1` out of `2*nh+1`) are required. Must be double-word aligned.
- `r[nr]` Pointer to output array of size `nr`. Must be word aligned.
- `nh` Number of coefficients. Must be multiple of 8. The number of original symmetric coefficients is `2*nh+1`.
- `nr` Number of samples to calculate. Must be multiple of 4.
- `s` Number of insignificant digits to truncate, e.g., 15 for Q.15 input data and coefficients.

**Description**

This function applies a symmetric filter to the input samples. The filter tap array `h[]` provides `nh+1` total filter taps. The filter tap at `h[nh]` forms the center point of the filter. The taps at `h[nh−1]` through `h[0]` form a symmetric filter about this central tap. The effective filter length is thus `2*nh+1` taps.

The filter is performed on 16-bit data with 16-bit coefficients, accumulating intermediate results to 40-bit precision. The accumulator is rounded and truncated according to the value provided in `s`. This allows a variety of Q-points to be used.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_fir_sym(short *x, short *h, short *r, int nh, int nr, int s)
{
    int i, j;
    long y0;
    long round = (long) 1 << (s − 1);
    for (j = 0; j < nr; j++) {
        y0 = round;
        for (i = 0; i < nh; i++)
```
DSP_fir_sym

```c
    y0 += (short) (x[j + i] + x[j + 2 * nh - i]) * h[i];
    y0 += x[j + nh] * h[nh];
    r[j] = (int) (y0 >> s);
```

Special Requirements

- nh must be a multiple of 8. The number of original symmetric coefficients is 2*nh+1. Only half (nh+1) are required.
- nr must be a multiple of 4.
- x[ ] and h[ ] must be double-word aligned.
- r[ ] must be word aligned.

Implementation Notes

- The load double-word instruction is used to simultaneously load four values in a single clock cycle.
- The inner loop is unrolled eight times.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

- Cycles: \((10 * \text{nh}/8 + 15) * \text{nr}/4 + 26\)
- Codesize: 664 bytes
DSP_iir

IIR With 5 Coefficients

Function
void DSP_iir (short * restrict r1, const short * restrict x, short * restrict r2, const short * restrict h2, const short * restrict h1, int nr)

Arguments
r1[nr+4] Output array (used in actual computation. First four elements must have the previous outputs.)

x[nr+4] Input array

r2[nr] Output array (stored)

h2[5] Moving-average filter coefficients

h1[5] Auto-regressive filter coefficients. h1[0] is not used.

nr Number of output samples. Must be \( \geq 8 \).

Description
The IIR performs an auto-regressive moving-average (ARMA) filter with 4 auto-regressive filter coefficients and 5 moving-average filter coefficients for nr output samples.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_iir(short *r1, short *x, short *r2, short *h2,
short *h1, int nr)
{
  int j,i;
  int sum;
  for (i=0; i<nr; i++){
    sum = h2[0] * x[4+i];
    for (j = 1; j <= 4; j++)
      sum += h2[j]*x[4+i−j]−h1[j]*r1[4+i−j];
    r1[4+i] = (sum >> 15);
    r2[i] = r1[4+i];
  }
}
```

Special Requirements
- nr is greater than or equal to 8.
- Input data array x[ ] contains nr + 4 input samples to produce nr output samples.
DSP_iir

Implementation Notes

- Output array r1[] contains nr + 4 locations, r2[] contains nr locations for storing nr output samples. The output samples are stored with an offset of 4 into the r1[] array.

- The inner loop that iterated through the filter coefficients is completely unrolled.

- **Bank Conflicts**: No bank conflicts occur.

- **Endian**: The code is ENDIAN NEUTRAL.

- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**

- **Cycles**: 4 * nr + 21
- **Codesize**: 276 bytes
DSP_iirlat

**All-pole IIR Lattice Filter**

**Function**

void DSP_iirlat(const short * restrict x, int nx, const short * restrict k, int nk, int * restrict b, short * restrict r)

**Arguments**

- x[nx] Input vector (16-bit)
- nx Length of input vector.
- k[nk] Reflection coefficients in Q.15 format
- nk Number of reflection coefficients/lattice stages. Must be >=4. Make multiple of 2 to avoid bank conflicts.
- b[nk+1] Delay line elements from previous call. Should be initialized to all zeros prior to the first call.
- r[nx] Output vector (16-bit)

**Description**

This routine implements a real all-pole IIR filter in lattice structure (AR lattice). The filter consists of nk lattice stages. Each stage requires one reflection coefficient k and one delay element b. The routine takes an input vector x[] and returns the filter output in r[]. Prior to the first call of the routine the delay elements in b[] should be set to zero. The input data may have to be pre-scaled to avoid overflow or achieve better SNR. The reflections coefficients lie in the range \(-1.0 < k < 1.0\). The order of the coefficients is such that k[nk-1] corresponds to the first lattice stage after the input and k[0] corresponds to the last stage.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void iirlat(short *x, int nx, short *k, int nk, int *b, short *r)
{
  int rt;  /* output */
  int i, j;

  for (j=0; j<nx; j++)
  {
    rt = x[j] << 15;
    for (i = nk - 1; i >= 0; i--)
    {
      rt = rt - (short)(b[i] >> 15) * k[i];
    }
  }
}"
```
DSP_iirlat

```c
b[i + 1] = b[i] + (short)(rt >> 15) * k[i];
}
b[0] = rt;
r[j] = rt >> 15;
}
```

**Special Requirements**
- nk must be >= 4.
- no special alignment requirements
- see Bank Conflicts for avoiding bank conflicts

**Implementation Notes**
- Prolog and epilog of the inner loop are partially collapsed and overlapped to reduce outer loop overhead.
- **Bank Conflicts**: nk should be a multiple of 2, otherwise bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**
- Cycles: \((2 * nk + 7) * nx + 9\) (without bank conflicts)
- Codesize: 352 bytes
DSP_dotp_sqr

4.5 Math

DSP_dotp_sqr  Vector Dot Product and Square

Function  int DSP_dotp_sqr(int G, const short * restrict x, const short * restrict y, int * restrict r, int nx)

Arguments  G  Calculated value of G (used in the VSELP coder).

x[nx]  First vector array

y[nx]  Second vector array

r  Result of vector dot product of x and y.

nx  Number of elements. Must be multiple of 4, ≥12.

return int  New value of G.

Description  This routine performs a nx element dot product of x[] and y[] and stores it in r. It also squares each element of y[] and accumulates it in G. G is passed back to calling function in register A4. This computation of G is used in the VSELP coder.

Algorithm  This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
int DSP_dotp_sqr(int G, short *x, short *y, int *r, int nx)
{
    short *y2;
    short *endPtr2;
    y2 = x;
    for (endPtr2 = y2 + nx; y2 < endPtr2; y2++){
        *r += *y * *y2;
        G += *y * *y;
        y++;
    }
    return(G);
}
```
DSP_dotp_sqr

Special Requirements  nx must be a multiple of 4 and greater than or equal to 12.

Implementation Notes

- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks

- Cycles  \( \frac{nx}{2} + 21 \)
- Codesize  128
DSP_dotprod

**Vector Dot Product**

### Function

```c
int DSP_dotprod(const short * restrict x, const short * restrict y, int nx)
```

### Arguments

- **x[nx]**: First vector array. Must be double-word aligned.
- **y[nx]**: Second vector array. Must be double word-aligned.
- **nx**: Number of elements of vector. Must be multiple of 4.

### Description

This routine takes two vectors and calculates their dot product. The inputs are 16-bit short data and the output is a 32-bit number.

### Algorithm

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
int DSP_dotprod(short x[], short y[], int nx)
{
    int sum;
    int i;
    sum = 0;
    for(i=0; i<nx; i++){
        sum += (x[i] * y[i]);
    }
    return (sum);
}
```

### Special Requirements

- The input length must be a multiple of 4.
- The input data x[] and y[] are stored on double-word aligned boundaries.
- To avoid bank conflicts the input arrays x[] and y[] must be offset by 4 half-words (8 bytes).

### Implementation Notes

- The code is unrolled 4 times to enable full memory and multiplier bandwidth to be utilized.
- Interrupts are masked by branch delay slots only.
- Prolog collapsing has been performed to reduce codesize.
DSP_dotprod

- **Bank Conflicts**: No bank conflicts occur if the input arrays x[ ] and y[ ] are offset by 4 half-words (8 bytes).

- **Endian**: The code is ENDIAN NEUTRAL.

- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**

- Cycles: \( \frac{nx}{4} + 15 \)
- Codesize: 132 bytes
DSP_maxval

Maximum Value of Vector

Function
short DSP_maxval (const short *x, int nx)

Arguments
x[nx] Pointer to input vector of size nx.
nx Length of input data vector. Must be multiple of 8 and ≥ 32.

return short Maximum value of a vector.

Description
This routine finds the element with maximum value in the input vector and returns that value.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
short DSP_maxval(short x[], int nx)
{
    int i, max;
    max = −32768;

    for (i = 0; i < nx; i++)
        if (x[i] > max)
            max = x[i];
    return max;
}
```

Special Requirements
nx is a multiple of 8 and greater than or equal to 32.

Implementation Notes

- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks
Cycles nx / 4 + 10
Codesize 116 bytes
DSP_maxidx

**Index of Maximum Element of Vector**

**Function**

int DSP_maxidx (const short *x, int nx)

**Arguments**

- x[nx] Pointer to input vector of size nx. Must be double-word aligned.
- nx Length of input data vector. Must be multiple of 16 and ≥ 48.

**Description**

This routine finds the max value of a vector and returns the index of that value. The input array is treated as 16 separate "columns" that are interleaved throughout the array. If values in different columns are equal to the maximum value, then the element in the leftmost column is returned. If two values within a column are equal to the maximum, then the one with the lower index is returned. Column takes precedence over index.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
int DSP_maxidx(short x[], int nx)
{
    int max, index, i;
    max = -32768;
    for (i = 0; i < nx; i++)
        if (x[i] > max) {
            max = x[i];
            index = i;
        }
    return index;
}
```

**Special Requirements**

- nx must be a multiple of 16 and greater than or equal to 48.
- The input vector x[] must be double-word aligned.

**Implementation Notes**

- The code is unrolled 16 times to enable the full bandwidth of LDDW and MAX2 instructions to be utilized. This splits the search into 16 sub-ranges. The global maximum is then found from the list of maximums of the sub-ranges. Then, using this offset from the sub-ranges, the global maximum and the index of it are found using a simple match. For common maximums in multiple ranges, the index will be different to the above C code.
DSP_maxidx

- This code requires 40 bytes of stack space for a temporary buffer.

- **Bank Conflicts:** No bank conflicts occur.

- **Endian:** The code is ENDIAN NEUTRAL.

- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

### Benchmarks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>$5 \times nx / 16 + 42$</td>
</tr>
<tr>
<td>Codesize</td>
<td>388 bytes</td>
</tr>
</tbody>
</table>
DSP_minval

**Minimum Value of Vector**

**Function**  
short DSP_minval (const short *x, int nx)

**Arguments**  
- x [nx] Pointer to input vector of size nx.
- nx Length of input data vector. Must be multiple of 4 and ≥20.
- return short Maximum value of a vector.

**Description**  
This routine finds the minimum value of a vector and returns the value.

**Algorithm**  
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
short DSP_minval(short x[], int nx)  
{
    int i, min;
    min = 32767;

    for (i = 0; i < nx; i++)
        if (x[i] < min)
            min = x[i];
    return min;
}
```

**Special Requirements**  
x is a multiple of 4 and greater than or equal to 20.

**Implementation Notes**
- The input data is loaded using double word wide loads, and the MIN2 instruction is used to get to the minimum.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is ENDIAN NEUTRAL.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

**Benchmarks**
- Cycles nx / 4 +10
- Codesize 116 bytes
**DSP_mul32**

### 32-bit Vector Multiply

**Function**
void DSP_mul32(const int * restrict x, const int * restrict y, int * restrict r, short nx)

**Arguments**
- **x[nx]** Pointer to input data vector 1 of size nx. Must be double-word aligned.
- **y[nx]** Pointer to input data vector 2 of size nx. Must be double-word aligned.
- **r[nx]** Pointer to output data vector of size nx. Must be double-word aligned.
- **nx** Number of elements in input and output vectors. Must be multiple of 8 and ≥16.

**Description**
The function performs a Q.31 x Q.31 multiply and returns the upper 32 bits of the result. The result of the intermediate multiplies are accumulated into a 40-bit long register pair as there could be potential overflow. The contribution of the multiplication of the two lower 16-bit halves are not considered. The output is in Q.30 format. Results are accurate to least significant bit.

**Algorithm**

In the comments below, X and Y are the two input values. Xhigh and Xlow represent the upper and lower 16 bits of X. This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_mul32(const int *x, const int *y, int *r, short nx)
{
    short i;
    int a,b,c,d,e;
    for(i=nx;i>0;i--)
    {
        a=*x++;
        b=*y++;
        c=_mpyluhs(a,b); /* Xlow*Yhigh */
        d=_mpyhslu(a,b); /* Xhigh*Ylow */
        e=_mpyh(a,b); /* Xhigh*Yhigh */
        d+=c;        /* Xhigh*Ylow+Xlow*Yhigh */
        d=d>>16;     /* (Xhigh*Ylow+Xlow*Yhigh)>>16 */
    }
}
```

---

*C64x DSPLIB Reference* 4-79
DSP_mul32

```c
  e+=d;  /* Xhigh*Yhigh + */
  /* (Xhigh*Ylow+Xlow*Yhigh)>>16 */
  *(r++)=e;
}
```

Special Requirements

- nx must be a multiple of 8 and greater than or equal to 16.
- Input and output vectors must be double-word aligned.

Implementation Notes

- The MPYHI instruction is used to perform 16 x 32 multiplies to form 48-bit intermediate results.
- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks

- Cycles: \(9 \times \frac{nx}{8} + 18\)
- Codesize: 512 bytes
DSP_neg32

32-bit Vector Negate

Function
void DSP_neg32(int *x, int *r, short nx)

Arguments
x[nx] Pointer to input data vector 1 of size nx with 32-bit elements.
Must be double-word aligned.
r[nx] Pointer to output data vector of size nx with 32-bit elements.
Must be double-word aligned.
rx Number of elements of input and output vectors. Must be a
multiple of 4 and ≥8.

Description
This function negates the elements of a vector (32-bit elements). The input and
output arrays must not be overlapped except for the special case where the
input and output pointers are exactly equal.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that
the assembly code is hand optimized and restrictions may apply.

void DSP_neg32(int *x, int *r, short nx)
{
    short i;
    for(i=nx; i>0; i--)
      *(r++)=−*(x++);
}

Special Requirements
- nx must be a multiple of 4 and greater than or equal to 8.
- The arrays x[ ] and r[ ] must be double-word aligned.

Implementation Notes
- The loop is unrolled twice and pipelined.
- Bank Conflicts: No bank conflicts occur.
- Endian: The code is ENDIAN NEUTRAL.
- Interruptibility: The code is interrupt-tolerant but not interruptible.

Benchmarks
Cycles      nx/2 + 19
Codesize    124 bytes
DSP_recip16

16-bit Reciprocal

Function
void DSP_recip16 (short *x, short *rfrac, short *rexp, short nx)

Arguments
x[nx] Pointer to Q.15 input data vector of size nx.
rfrac[nx] Pointer to Q.15 output data vector for fractional values.
rexp[nx] Pointer to output data vector for exponent values.
nx Number of elements of input and output vectors.

Description
This routine returns the fractional and exponential portion of the reciprocal of an array x[] of Q.15 numbers. The fractional portion rfrac is returned in Q.15 format. Since the reciprocal is always greater than 1, it returns an exponent such that:

\[(rfrac[i] * 2rexp[i]) = \text{true reciprocal}\]

The output is accurate up to the least significant bit of rfrac, but note that this bit could carry over and change rexp. For a reciprocal of 0, the procedure will return a fractional part of 7FFFh and an exponent of 16.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_recip16(short *x, short *rfrac, short *rexp, short nx)
{
    int i,j,a,b;
    short neg, normal;
    for(i=nx; i>0; i--)
    {
        a=*x++;
        if(a<0) /* take absolute value */
        {
            a=-a;
            neg=1;
        }
        else neg=0;
        normal=_norm(a); /* normalize number */
a=a<<normal;
    }
```
DSP_recip16

*(rexpp++)=normal−15; /* store exponent */
b=0x80000000; /* dividend = 1 */
for(j=15;j>0;j--)
    b=_subc(b,a); /* divide */
b=b&0x7FFF; /* clear remainder */
    /* (clear upper half) */
if(neg) b=−b; /* if originally */
    /* negative, negate */
*((rfrac++)=b; /* store fraction */
}
}

Special Requirements none

Implementation Notes

☐ The conditional subtract instruction, SUBC, is used for division. SUBC is
    used once for every bit of quotient needed (15).

☐ Bank Conflicts: No bank conflicts occur.

☐ Endian: The code is ENDIAN NEUTRAL.

☐ Interruptibility: The code is interruptible.

Benchmarks Cycles 8 * nx + 14
    Codesize 196 bytes
DSP_vecsumsq

**DSP_vecsumsq**  
*Sum of Squares*

**Function**  
`int DSP_vecsumsq (const short *x, int nx)`

**Arguments**

- `x[nx]`  
  Input vector
- `nx`  
  Number of elements in x. Must be multiple of 4 and ≥8.

**return**  
Sum of the squares

**Description**

This routine returns the sum of squares of the elements contained in the vector `x[]`.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
int DSP_vecsumsq(short x[], int nx)
{
    int i, sum=0;

    for(i=0; i<nx; i++)
    {
        sum += x[i]*x[i];
    }
    return(sum);
}
```

**Special Requirements**

- `nx` must be a multiple of 4 and greater than or equal to 32.

**Implementation Notes**

- The code is unrolled 4 times to enable full memory and multiplier bandwidth to be utilized.
- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**

- **Cycles**: `nx/4 + 11`
- **Codesize**: 188 bytes
<table>
<thead>
<tr>
<th><strong>DSP_w_vec</strong></th>
<th><strong>Weighted Vector Sum</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>void DSP_w_vec(const short * restrict x, const short * restrict y, short m, short * restrict r, short nr)</td>
</tr>
<tr>
<td><strong>Arguments</strong></td>
<td>x[nr] Vector being weighted. Must be double-word aligned.</td>
</tr>
<tr>
<td></td>
<td>y[nr] Summation vector. Must be double-word aligned.</td>
</tr>
<tr>
<td></td>
<td>m Weighting factor</td>
</tr>
<tr>
<td></td>
<td>r[nr] Output vector</td>
</tr>
<tr>
<td></td>
<td>nr Dimensions of the vectors. Must be multiple of 8 and ≥8.</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>This routine is used to obtain the weighted vector sum. Both the inputs and output are 16-bit numbers.</td>
</tr>
<tr>
<td><strong>Algorithm</strong></td>
<td>This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.</td>
</tr>
<tr>
<td></td>
<td>void DSP_w_vec(short x[], short y[], short m, short r[], short nr)</td>
</tr>
<tr>
<td></td>
<td>{</td>
</tr>
<tr>
<td></td>
<td>short i;</td>
</tr>
<tr>
<td></td>
<td>for (i=0; i&lt;nr; i++) {</td>
</tr>
<tr>
<td></td>
<td>r[i] = ((m * x[i]) &gt;&gt; 15) + y[i];</td>
</tr>
<tr>
<td></td>
<td>}</td>
</tr>
<tr>
<td><strong>Special Requirements</strong></td>
<td>nr must be a multiple of 8 and greater than or equal to 8.</td>
</tr>
<tr>
<td></td>
<td>Vectors x[] and y[] must be double-word aligned.</td>
</tr>
<tr>
<td><strong>Implementation Notes</strong></td>
<td>Input is loaded in double-words.</td>
</tr>
<tr>
<td></td>
<td>Use of packed data processing to sustain throughput.</td>
</tr>
<tr>
<td></td>
<td><strong>Bank Conflicts:</strong> No bank conflicts occur.</td>
</tr>
<tr>
<td></td>
<td><strong>Endian:</strong> The code is ENDIAN NEUTRAL.</td>
</tr>
<tr>
<td></td>
<td><strong>Interruptibility:</strong> The code is interrupt-tolerant but not interruptible.</td>
</tr>
<tr>
<td><strong>Benchmarks</strong></td>
<td>Cycles $3 \times \frac{nr}{8} + 18$</td>
</tr>
<tr>
<td></td>
<td>Codesize 144 bytes</td>
</tr>
</tbody>
</table>
DSP_mat_mul

4.6 Matrix

**DSP_mat_mul**  
*Matrix Multiplication*

**Function**  
void DSP_mat_mul(const short * restrict x, int r1, int c1, const short * restrict y, int c2, short * restrict r, int qs)

**Arguments**  
- x [r1*c1] Pointer to input matrix of size r1*c1.
- r1 Number of rows in matrix x.
- c1 Number of columns in matrix x. Also number of rows in y.
- y [c1*c2] Pointer to input matrix of size c1*c2.
- c2 Number of columns in matrix y.
- r [r1*c2] Pointer to output matrix of size r1*c2.
- qs Final right-shift to apply to the result.

**Description**  
This function computes the expression “r = x * y” for the matrices x and y. The columnar dimension of x must match the row dimension of y. The resulting matrix has the same number of rows as x and the same number of columns as y.

The values stored in the matrices are assumed to be fixed-point or integer values. All intermediate sums are retained to 32-bit precision, and no overflow checking is performed. The results are right-shifted by a user-specified amount, and then truncated to 16 bits.

**Algorithm**  
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_mat_mul(short *x, int r1, int c1, short *y, int c2, short *r, int qs)
{
    int i, j, k;
    int sum;

    /* Multiply each row in x by each column in y. The */
    /* product of row m in x and column n in y is placed */
```
/* in position (m,n) in the result. */
/* ------------------------------------------------------------------------ */

for (i = 0; i < r1; i++)
    for (j = 0; j < c2; j++)
    {
        sum = 0;

        for (k = 0; k < c1; k++)
            sum += x[k + i*c1] * y[j + k*c2];

        r[j + i*c2] = sum >> qs;
    }

Special Requirements

- The arrays x[], y[], and r[] are stored in distinct arrays. That is, in-place processing is not allowed.
- The input matrices have minimum dimensions of at least 1 row and 1 column, and maximum dimensions of 32767 rows and 32767 columns.

Implementation Notes

- The 'i' loop and 'k' loops are unrolled 2x. The 'j' loop is unrolled 4x. For dimensions that are not multiples of the various loops' unroll factors, this code calculates extra results beyond the edges of the matrix. These extra results are ultimately discarded. This allows the loops to be unrolled for efficient operation on large matrices while not losing flexibility.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** This code blocks interrupts during its innermost loop. Interrupts are not blocked otherwise. As a result, interrupts can be blocked for up to 0.25*c1' + 16 cycles at a time.

Benchmarks

Cycles  \(0.25 \times (r1' \times c2' \times c1') + 2.25 \times (r1' \times c2') + 11\), where:
- \(r1' = 2 \times \text{ceil}(r1/2.0)\) (r1 rounded up to next even)
- \(c1' = 2 \times \text{ceil}(c1/2.0)\) (c1 rounded up to next even)
- \(c2' = 4 \times \text{ceil}(c2/4.0)\) (c2 rounded up to next mult of 4)

For r1= 1, c1= 1, c2= 1: 33 cycles
For r1= 8, c1=20, c2= 8: 475 cycles

Codesize  416 bytes
DSP_mat_trans

Matrix Transpose

Function

void DSP_mat_trans (const short *x, short rows, short columns, short *r)

Arguments

x[rows*columns]  Pointer to input matrix.
rows  Number of rows in the input matrix. Must be a multiple of 4.
columns  Number of columns in the input matrix. Must be a multiple of 4.
r[columns*rows]  Pointer to output data vector of size rows*columns.

Description

This function transposes the input matrix x[ ] and writes the result to matrix r[ ].

Algorithm

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

void DSP_mat_trans(short *x, short rows, short columns, short *r)
{
  short i,j;
  for(i=0; i<columns; i++)
    for(j=0; j<rows; j++)
      *(r+i*rows+j)=*(x+i+columns*j);
}

Special Requirements

☐ Rows and columns must be a multiple of 4.
☐ Matrices are assumed to have 16-bit elements.

Implementation Notes

☐ Data from four adjacent rows, spaced “columns” apart are read, and a local 4x4 transpose is performed in the register file. This leads to four double words, that are “rows” apart. These loads and stores can cause bank conflicts, hence non-aligned loads and stores are used.

☐ **Bank Conflicts:** No bank conflicts occur.

☐ **Endian:** The code is LITTLE ENDIAN.

☐ **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

Cycles  (2 * rows + 9) * columns/4 + 3

Codesize  224 bytes
4.7 Miscellaneous

**DSP_bexp**

*Block Exponent Implementation*

**Function**

short DSP_bexp(const int *x, short nx)

**Arguments**

- x[nx] Pointer to input vector of size nx. Must be double-word aligned.
- nx Number of elements in input vector. Must be multiple of 8.
- return short Return value is the maximum exponent that may be used in scaling.

**Description**

Computes the exponents (number of extra sign bits) of all values in the input vector x[ ] and returns the minimum exponent. This will be useful in determining the maximum shift value that may be used in scaling a block of data.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
short DSP_bexp(const int *x, short nx)
{
    int        min_val = _norm(x[0]);
    short      n;
    int        i;
    for(i=1;i<nx;i++)
    {
        n = _norm(x[i]); /* _norm(x) = number of */
        /* redundant sign bits */
        if(n<min_val) min_val=n;
    }
    return min_val;
}
```

**Special Requirements**

- nx must be a multiple of 8.
- The input vector x[ ] must be double-word aligned.
DSP_bexp

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is ENDIAN NEUTRAL.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>$nx/2 + 21$</td>
</tr>
<tr>
<td>Codesize</td>
<td>216 bytes</td>
</tr>
</tbody>
</table>
DSP_blk_eswap16

Endian-swap a block of 16-bit values

Function
void blk_eswap16(void * restrict x, void * restrict r, int nx)

Arguments
x [nx] Source data. Must be double-word aligned.

r [nx] Destination array. Must be double-word aligned.

nx Number of 16-bit values to swap. Must be multiple of 8.

Description
The data in the x[] array is endian swapped, meaning that the byte-order of the
bytes within each half-word of the r[] array is reversed. This is meant to facilitate
moving big-endian data to a little-endian system or vice-versa.

When the r pointer is non-NULL, the endian-swap occurs out-of-place, similar
to a block move. When the r pointer is NULL, the endian-swap occurs in-place,
allowing the swap to occur without using any additional storage.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the
assembly code is hand optimized and restrictions may apply.

void DSP_blk_eswap16(void *x, void *r, int nx)
{
    int i;
    char * _x, * _r;
    if (r)
    {
        _x = (char *)x;
        _r = (char *)r;
    } else
    {
        _x = (char *)x;
        _r = (char *)r;
    }

    for (i = 0; i < nx; i++)
    {
        char t0, t1;
        t0 = _x[i*2 + 1];
        t1 = _x[i*2 + 0];
        _r[i*2 + 0] = t0;
        _r[i*2 + 1] = t1;
    }
}
DSP_blk_eswap16

Special Requirements

- Input and output arrays do not overlap, except in the very specific case that “r == NULL” so that the operation occurs in-place.
- The input array and output array are expected to be double-word aligned, and a multiple of 8 half-words must be processed.

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

- Cycles: $nx/8 + 18$
- Codesize: 104 bytes
DSP_blk_eswap32

**DSP_blk_eswap32**  
**Endian-swap a block of 32-bit values**

**Function**  
void blk_eswap32(void * restrict x, void * restrict r, int nx)

**Arguments**
- **x [nx]**  
  Source data. Must be double-word aligned.
- **r [nx]**  
  Destination array. Must be double-word aligned.
- **nx**  
  Number of 32-bit values to swap. Must be multiple of 4.

**Description**

The data in the x[] array is endian swapped, meaning that the byte-order of the bytes within each word of the r[] array is reversed. This is meant to facilitate moving big-endian data to a little-endian system or vice-versa.

When the r pointer is non-NULL, the endian-swap occurs out-of-place, similar to a block move. When the r pointer is NULL, the endian-swap occurs in-place, allowing the swap to occur without using any additional storage.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_blk_eswap32(void *x, void *r, int nx)
{
    int i;
    char *x, *r;

    if (r)
    {
        _x = (char *)x;
        _r = (char *)r;
    } else
    {
        _x = (char *)x;
        _r = (char *)r;
    }

    for (i = 0; i < nx; i++)
    {
        char t0, t1, t2, t3;
        t0 = _x[i*4 + 3];
        t1 = _x[i*4 + 2];
    }
}
```
DSP_blk_eswap32

t2 = _x[i*4 + 1];
t3 = _x[i*4 + 0];
_r[i*4 + 0] = t0;
_r[i*4 + 1] = t1;
_r[i*4 + 2] = t2;
_r[i*4 + 3] = t3;
}
}

Special Requirements

- Input and output arrays do not overlap, except in the very specific case that “r == NULL” so that the operation occurs in-place.

- The input array and output array are expected to be double-word aligned, and a multiple of 4 words must be processed.

Implementation Notes

- **Bank Conflicts:** No bank conflicts occur.

- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

- **Cycles:** nx/4 + 20
- **Codesize:** 116 bytes
DSP_blk_eswap64

**Endiian-swap a block of 64-bit values**

**Function**

```c
void blk_eswap64(void * restrict x, void * restrict r, int nx)
```

**Arguments**

- `x[nx]` Source data. Must be double-word aligned.
- `r[nx]` Destination array. Must be double-word aligned.
- `nx` Number of 64-bit values to swap. Must be multiple of 2.

**Description**

The data in the `x[]` array is endian swapped, meaning that the byte-order of the bytes within each double-word of the `r[]` array is reversed. This is meant to facilitate moving big-endian data to a little-endian system or vice-versa.

When the `r` pointer is non-NULL, the endian-swap occurs out-of-place, similar to a block move. When the `r` pointer is NULL, the endian-swap occurs in-place, allowing the swap to occur without using any additional storage.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_blk_eswap64(void *x, void *r, int nx) {
    int i;
    char *_x, *_r;

    if (r) {
        _x = (char *)x;
        _r = (char *)r;
    } else {
        _x = (char *)x;
        _r = (char *)r;
    }

    for (i = 0; i < nx; i++) {
        char t0, t1, t2, t3, t4, t5, t6, t7;
        t0 = _x[i*8 + 7];
        t1 = _x[i*8 + 6];
        ...
    }
}
```
DSP_blk_eswap64

t2 = _x[i*8 + 5];
t3 = _x[i*8 + 4];
t4 = _x[i*8 + 3];
t5 = _x[i*8 + 2];
t6 = _x[i*8 + 1];
t7 = _x[i*8 + 0];
_r[i*8 + 0] = t0;
_r[i*8 + 1] = t1;
_r[i*8 + 2] = t2;
_r[i*8 + 3] = t3;
_r[i*8 + 4] = t4;
_r[i*8 + 5] = t5;
_r[i*8 + 6] = t6;
_r[i*8 + 7] = t7;
}
}

Special Requirements

- Input and output arrays do not overlap, except in the very specific case that "r == NULL" so that the operation occurs in-place.
- The input array and output array are expected to be double-word aligned, and a multiple of 2 double-words must be processed.

Implementation Notes

- **Bank Conflicts**: No bank conflicts occur.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

Benchmarks

- **Cycles**: nx/2 + 20
- **Codesize**: 116 bytes
DSP_blk_move

Block Move (Overlapping)

Function
void DSP_blk_move(short * x, short * r, int nx)

Arguments
x [nx]    Block of data to be moved.

r [nx]    Destination of block of data.

nx        Number of elements in block. Must be multiple of 8 and \( \geq 32 \).

Description
This routine moves nx 16-bit elements from one memory location pointed to by x to another pointed to by r. The source and destination blocks can be overlapped.

Algorithm
This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_blk_move(short *x, short *r, int nx) {
    int i;
    if( r < x )
    {
        for (I = 0; I < nx; i++)
            r[i] = x[i];
    } else
    {
        for (I = nx−1; I >= 0; i−−)
            r[i] = x[i];
    }
}
```

Special Requirements
nx must be a multiple of 8 and greater than or equal to 32.

Implementation Notes

- Twin input and output pointers are used.
- Bank Conflicts: No bank conflicts occur.
- Endian: The code is ENDIAN NEUTRAL.
- Interruptibility: The code is interrupt-tolerant but not interruptible.

Benchmarks

Cycles   \( nx/4 + 18 \)

Codesize  112 bytes
### DSP_fltoq15

**Float to Q15 Conversion**

**Function**

```c
void DSP_fltoq15 (float *x, short *r, short nx)
```

**Arguments**
- `x[nx]`: Pointer to floating-point input vector of size `nx`. `x` should contain the numbers normalized between [-1,1).
- `r[nx]`: Pointer to output data vector of size `nx` containing the Q.15 equivalent of vector `x`.
- `nx`: Length of input and output data vectors. Must be multiple of 2.

**Description**

Convert the IEEE floating point numbers stored in vector `x[]` into Q.15 format numbers stored in vector `r[]`. Results are truncated toward zero. Values that exceed the size limit will be saturated to 0x7fff if value is positive and 0x8000 if value is negative. All values too small to be correctly represented will be truncated to 0.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void fltoq15(float x[], short r[], short nx)
{
  int i, a;
  for(i = 0; i < nx; i++)
  {
    a = 32768 * x[i];
    // saturate to 16-bit //
    if (a>32767)  a =  32767;
    if (a<−32768) a = −32768;
    r[i] = (short) a;
  }
}
```

**Special Requirements**

- `nx` must be a multiple of 2.

**Implementation Notes**

- Loop is unrolled twice.
- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**

- Cycles: $3 \times \frac{nx}{2} + 14$
- Codesize: 224 bytes
DSP_minerror

Minimum Energy Error Search

Function

int minerror (const short * restrict GSP0_TABLE, const short * restrict errCoefs, int * restrict max_index)

Arguments

GSP0_TABLE[9*256]    GSP0 terms array. Must be double-word aligned.
max_index            Pointer to GSP0_TABLE[max_index] found.
return int           Maximum dot product result.

Algorithm

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
int minerr
{
    const short *restrict GSP0_TABLE,
    const short *restrict errCoefs,
    int             *restrict max_index
}
{
    int val, maxVal = -50;
    int i, j;
    for (i = 0; i < GSP0_NUM; i++)
    {
        for (val = 0, j = 0; j < GSP0_TERMS; j++)
            val += GSP0_TABLE[i*GSP0_TERMS+j] * errCoefs[j];

        if (val > maxVal)
        {
            maxVal = val;
            *max_index = i*GSP0_TERMS;
        }
    }
    return (maxVal);
}
```

Special Requirements Array GSP0_TABLE[] must be double-word aligned.
DSP_minerror

Implementation Notes

- The load double-word instruction is used to simultaneously load four values in a single clock cycle.
- The inner loop is completely unrolled.
- The outer loop is 4 times unrolled.
- **Bank Conflicts:** No bank conflicts occur.
- **Endian:** The code is LITTLE ENDIAN.
- **Interruptibility:** The code is interrupt-tolerant but not interruptible.

Benchmarks

- Cycles: $256/4 \times 9 + 17 = 593$
- Codesize: 352 bytes
### DSP_q15tofl

**Q15 to Float Conversion**

**Function**

```c
void DSP_q15tofl (short *x, float *r, int nx)
```

**Arguments**

- `x[nx]` Pointer to Q.15 input vector of size `nx`.
- `r[nx]` Pointer to floating-point output data vector of size `nx` containing the floating-point equivalent of vector `x`.
- `nx` Length of input and output data vectors. Must be multiple of 2.

**Description**

Converts the values stored in vector `x[]` in Q.15 format to IEEE floating point numbers in output vector `r[]`.

**Algorithm**

This is the C equivalent of the assembly code without restrictions. Note that the assembly code is hand optimized and restrictions may apply.

```c
void DSP_q15tofl(short *x, float *r, int nx)
{
    int i;
    for (i=0;i<nx;i++)
        r[i] = (float) x[i] / 0x8000;
}
```

**Special Requirements**

- `nx` must be a multiple of 2.

**Implementation Notes**

- Loop is unrolled twice
- **Bank Conflicts**: No bank conflicts occur.
- **Endian**: The code is ENDIAN NEUTRAL.
- **Interruptibility**: The code is interrupt-tolerant but not interruptible.

**Benchmarks**

- Cycles: `2 * nx + 14`
- Codesize: 184 bytes
This appendix describes performance considerations related to the C64x DSPLIB and provides information about the Q format used by DSPLIB functions.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 Performance Considerations</td>
<td>A-2</td>
</tr>
<tr>
<td>A.2 Fractional Q Formats</td>
<td>A-3</td>
</tr>
</tbody>
</table>
A.1 Performance Considerations

The ceil( ) is used in some benchmark formulas to accurately describe the number of cycles. It returns a number rounded up, away from zero, to the nearest integer. For example, ceil(1.1) returns 2.

Although DSPLIB can be used as a first estimation of processor performance for a specific function, you should be aware that the generic nature of DSPLIB might add extra cycles not required for customer specific usage.

Benchmark cycles presented assume best case conditions, typically assuming all code and data are placed in L1 memory. Any extra cycles due to placement of code or data in L2/external memory or cache-associated effects (cache-hits or misses) are not considered when computing the cycle counts.

You should also be aware that execution speed in a system is dependent on where the different sections of program and data are located in memory. You should account for such differences when trying to explain why a routine is taking more time than the reported DSPLIB benchmarks.

For more information on additional stall cycles due to memory hierarchy, see the Signal Processing Examples Using TMS320C64x Digital Signal Processing Library (SPRA884). The TMS320C6000 DSP Cache User’s Guide (SPRU656A) presents how to optimize algorithms and function calls for better cache performance.
A.2 Fractional Q Formats

Unless specifically noted, DSPLIB functions use Q15 format, or to be more exact, Q0.15. In a Qm.n format, there are m bits used to represent the two's complement integer portion of the number, and n bits used to represent the two's complement fractional portion. m+n+1 bits are needed to store a general Qm.n number. The extra bit is needed to store the sign of the number in the most-significant bit position. The representable integer range is specified by \((-2^m, 2^m)\) and the finest fractional resolution is \(2^{-n}\).

For example, the most commonly used format is Q.15. Q.15 means that a 16-bit word is used to express a signed number between positive and negative one. The most-significant binary digit is interpreted as the sign bit in any Q format number. Thus, in Q.15 format, the decimal point is placed immediately to the right of the sign bit. The fractional portion to the right of the sign bit is stored in regular two's complement format.

A.2.1 Q3.12 Format

Q.3.12 format places the sign bit after the fourth binary digit from the right, and the next 12 bits contain the two’s complement fractional component. The approximate allowable range of numbers in Q.3.12 representation is \((-8, 8)\) and the finest fractional resolution is \(2^{-12} = 2.441 \times 10^{-4}\).

Table A-1. Q3.12 Bit Fields

<table>
<thead>
<tr>
<th>Bit</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>...</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>S</td>
<td>I3</td>
<td>I2</td>
<td>I1</td>
<td>Q11</td>
<td>Q10</td>
<td>Q9</td>
<td>...</td>
<td>Q0</td>
</tr>
</tbody>
</table>

A.2.2 Q.15 Format

Q.15 format places the sign bit at the leftmost binary digit, and the next 15 leftmost bits contain the two’s complement fractional component. The approximate allowable range of numbers in Q.15 representation is \((-1, 1)\) and the finest fractional resolution is \(2^{-15} = 3.05 \times 10^{-5}\).

Table A-2. Q.15 Bit Fields

<table>
<thead>
<tr>
<th>Bit</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>...</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>S</td>
<td>Q14</td>
<td>Q13</td>
<td>Q12</td>
<td>Q11</td>
<td>Q10</td>
<td>Q9</td>
<td>...</td>
<td>Q0</td>
</tr>
</tbody>
</table>
A.2.3 Q.31 Format

Q.31 format spans two 16-bit memory words. The 16-bit word stored in the lower memory location contains the 16 least significant bits, and the higher memory location contains the most significant 15 bits and the sign bit. The approximate allowable range of numbers in Q.31 representation is \((-1,1)\) and the finest fractional resolution is \(2^{-31} = 4.66 \times 10^{-10}\).

Table A–3. Q.31 Low Memory Location Bit Fields

<table>
<thead>
<tr>
<th>Bit</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>...</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Q15</td>
<td>Q14</td>
<td>Q13</td>
<td>Q12</td>
<td>...</td>
<td>Q3</td>
<td>Q2</td>
<td>Q1</td>
<td>Q0</td>
</tr>
</tbody>
</table>

Table A–4. Q.31 High Memory Location Bit Fields

<table>
<thead>
<tr>
<th>Bit</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>...</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>S</td>
<td>Q30</td>
<td>Q29</td>
<td>Q28</td>
<td>...</td>
<td>Q19</td>
<td>Q18</td>
<td>Q17</td>
<td>Q16</td>
</tr>
</tbody>
</table>
This appendix provides information about software updates and customer support.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1 DSPLiB Software Updates</td>
<td>B-2</td>
</tr>
<tr>
<td>B.2 DSPLiB Customer Support</td>
<td>B-2</td>
</tr>
</tbody>
</table>
B.1 DSPLIB Software Updates

C64x DSPLIB Software updates may be periodically released incorporating product enhancements and fixes as they become available. You should read the README.TXT available in the root directory of every release.

B.2 DSPLIB Customer Support

If you have questions or want to report problems or suggestions regarding the C64x DSPLIB, contact Texas Instruments at dsph@ti.com.
address: The location of program code or data stored; an individually accessible memory location.

A-law companding: See compress and expand (compand).

API: See application programming interface.

application programming interface (API): Used for proprietary application programs to interact with communications software or to conform to protocols from another vendor’s product.

assembler: A software program that creates a machine language program from a source file that contains assembly language instructions, directives, and macros. The assembler substitutes absolute operation codes for symbolic operation codes and absolute or relocatable addresses for symbolic addresses.

assert: To make a digital logic device pin active. If the pin is active low, then a low voltage on the pin asserts it. If the pin is active high, then a high voltage asserts it.

bit: A binary digit, either a 0 or 1.

big endian: An addressing protocol in which bytes are numbered from left to right within a word. More significant bytes in a word have lower numbered addresses. Endian ordering is specific to hardware and is determined at reset. See also little endian.

block: The three least significant bits of the program address. These correspond to the address within a fetch packet of the first instruction being addressed.
**board support library (BSL):** The BSL is a set of application programming interfaces (APIs) consisting of target side DSP code used to configure and control board level peripherals.

**boot:** The process of loading a program into program memory.

**boot mode:** The method of loading a program into program memory. The C6x DSP supports booting from external ROM or the host port interface (HPI).

**BSL:** See *board support library*.

**byte:** A sequence of eight adjacent bits operated upon as a unit.

---

**cache:** A fast storage buffer in the central processing unit of a computer.

**cache controller:** System component that coordinates program accesses between CPU program fetch mechanism, cache, and external memory.

**CCS:** Code Composer Studio.

**central processing unit (CPU):** The portion of the processor involved in arithmetic, shifting, and Boolean logic operations, as well as the generation of data- and program-memory addresses. The CPU includes the central arithmetic logic unit (CALU), the multiplier, and the auxiliary register arithmetic unit (ARAU).

**chip support library (CSL):** The CSL is a set of application programming interfaces (APIs) consisting of target side DSP code used to configure and control all on-chip peripherals.

**clock cycle:** A periodic or sequence of events based on the input from the external clock.

**clock modes:** Options used by the clock generator to change the internal CPU clock frequency to a fraction or multiple of the frequency of the input clock signal.

**code:** A set of instructions written to perform a task; a computer program or part of a program.

**coder-decoder or compression/decompression (codec):** A device that codes in one direction of transmission and decodes in another direction of transmission.

**compiler:** A computer program that translates programs in a high-level language into their assembly-language equivalents.
compress and expand (compand): A quantization scheme for audio signals in which the input signal is compressed and then, after processing, is reconstructed at the output by expansion. There are two distinct companding schemes: A-law (used in Europe) and µ-law (used in the United States).

control register: A register that contains bit fields that define the way a device operates.

control register file: A set of control registers.

CSL: See chip support library.

device ID: Configuration register that identifies each peripheral component interconnect (PCI).

digital signal processor (DSP): A semiconductor that turns analog signals—such as sound or light—into digital signals, which are discrete or discontinuous electrical impulses, so that they can be manipulated.

direct memory access (DMA): A mechanism whereby a device other than the host processor contends for and receives mastery of the memory bus so that data transfers can take place independent of the host.

DMA: See direct memory access.

DMA source: The module where the DMA data originates. DMA data is read from the DMA source.

DMA transfer: The process of transferring data from one part of memory to another. Each DMA transfer consists of a read bus cycle (source to DMA holding register) and a write bus cycle (DMA holding register to destination).

DSP_autocor: Autocorrelation

DSP_bexp: Block exponent implementation

DSP_bitrev_cplx: Complex bit reverse.

DSP_blk_eswap16: Endian-swap a block of 16-bit values.

DSP_blk_eswap32: Endian-swap a block of 32-bit values.

DSP_blk_eswap64: Endian-swap a block of 64-bit values.
DSP_blk_move: Block move
DSP_dotp_sqr: Vector dot product and square.
DSP_dotprod: Vector dot product.
DSP_fft: Complex forward FFT with digital reversal.
DSP_fft16x16r: Complex forward mixed radix 16- x 16-bit FFT with rounding.
DSP_fft16x16t: Complex forward mixed radix 16- x 16-bit FFT with truncation.
DSP_fft16x32: Complex forward mixed radix 16- x 32-bit FFT with rounding.
DSP_fft32x32: Complex forward mixed radix 32- x 32-bit FFT with rounding.
DSP_fft32x32s: Complex forward mixed radix 32- x 32-bit FFT with scaling.
DSP_fir_cplx: Complex FIR filter (radix 2).
DSP_fir_gen: FIR filter (general purpose).
DSP_firlms2: LMS FIR (radix 2).
DSP_fir_r4: FIR filter (radix 4).
DSP_fir_r8: FIR filter (radix 8).
DSP_fir_sym: Symmetric FIR filter (radix 8).
DSP_fltoq15: Float to Q15 conversion.
DSP_ifft16x32: Complex inverse mixed radix 16- x 32-bit FFT with rounding.
DSP_ifft32x32: Complex inverse mixed radix 32- x 32-bit FFT with rounding.
DSP_iir: IIR with 5 coefficients per biquad.
DSP_mat_mul: Matrix multiplication.
DSP_mat_trans: Matrix transpose.
DSP_maxidx: Index of the maximum element of a vector.
DSP_maxval: Maximum value of a vector.
DSP_minerror: Minimum energy error search.
DSP_minval: Minimum value of a vector.
DSP_mul32: 32-bit vector multiply.
DSP_neg32: 32-bit vector negate.
DSP_q15tofl: Q15 to float conversion.
DSP_radix2: Complex forward FFT (radix 2)
DSP_recip16: 16-bit reciprocal.
DSP_r4fft: Complex forward FFT (radix 4)
DSP_vecsumsq: Sum of squares.
DSP_w_vec: Weighted vector sum.

evaluation module (EVM): Board and software tools that allow the user to evaluate a specific device.

external interrupt: A hardware interrupt triggered by a specific value on a pin.

external memory interface (EMIF): Microprocessor hardware that is used to read to and write from off-chip memory.

fast Fourier transform (FFT): An efficient method of computing the discrete Fourier transform algorithm, which transforms functions between the time domain and the frequency domain.

fetch packet: A contiguous 8-word series of instructions fetched by the CPU and aligned on an 8-word boundary.

FFT: See fast fourier transform.

flag: A binary status indicator whose state indicates whether a particular condition has occurred or is in effect.

frame: An 8-word space in the cache RAMs. Each fetch packet in the cache resides in only one frame. A cache update loads a frame with the requested fetch packet. The cache contains 512 frames.

global interrupt enable bit (GIE): A bit in the control status register (CSR) that is used to enable or disable maskable interrupts.
HAL: Hardware abstraction layer of the CSL. The HAL underlies the service layer and provides it a set of macros and constants for manipulating the peripheral registers at the lowest level. It is a low-level symbolic interface into the hardware providing symbols that describe peripheral registers/bitfields and macros for manipulating them.

host: A device to which other devices (peripherals) are connected and that generally controls those devices.

host port interface (HPI): A parallel interface that the CPU uses to communicate with a host processor.

HPI: See host port interface; see also HPI module.

index: A relative offset in the program address that specifies which of the 512 frames in the cache into which the current access is mapped.

indirect addressing: An addressing mode in which an address points to another pointer rather than to the actual data; this mode is prohibited in RISC architecture.

instruction fetch packet: A group of up to eight instructions held in memory for execution by the CPU.

internal interrupt: A hardware interrupt caused by an on-chip peripheral.

interrupt: A signal sent by hardware or software to a processor requesting attention. An interrupt tells the processor to suspend its current operation, save the current task status, and perform a particular set of instructions. Interrupts communicate with the operating system and prioritize tasks to be performed.

interrupt service fetch packet (ISFP): A fetch packet used to service interrupts. If eight instructions are insufficient, the user must branch out of this block for additional interrupt service. If the delay slots of the branch do not reside within the ISFP, execution continues from execute packets in the next fetch packet (the next ISFP).

interrupt service routine (ISR): A module of code that is executed in response to a hardware or software interrupt.

interrupt service table (IST): A table containing a corresponding entry for each of the 16 physical interrupts. Each entry is a single-fetch packet and has a label associated with it.
Internal peripherals: Devices connected to and controlled by a host device.

The C6x internal peripherals include the direct memory access (DMA) controller, multichannel buffered serial ports (McBSPs), host port interface (HPI), external memory-interface (EMIF), and runtime support timers.

IST: See interrupt service table.

least significant bit (LSB): The lowest-order bit in a word.

linker: A software tool that combines object files to form an object module, which can be loaded into memory and executed.

little endian: An addressing protocol in which bytes are numbered from right to left within a word. More significant bytes in a word have higher-numbered addresses. Endian ordering is specific to hardware and is determined at reset. See also big endian.

maskable interrupt: A hardware interrupt that can be enabled or disabled through software.

memory map: A graphical representation of a computer system’s memory, showing the locations of program space, data space, reserved space, and other memory-resident elements.

memory-mapped register: An on-chip register mapped to an address in memory. Some memory-mapped registers are mapped to data memory, and some are mapped to input/output memory.

most significant bit (MSB): The highest order bit in a word.

μ-law companding: See compress and expand (compand).

multichannel buffered serial port (McBSP): An on-chip full-duplex circuit that provides direct serial communication through several channels to external serial devices.

multiplexer: A device for selecting one of several available signals.

nonmaskable interrupt (NMI): An interrupt that can be neither masked nor disabled.
Glossary

O

object file: A file that has been assembled or linked and contains machine language object code.

off chip: A state of being external to a device.

on chip: A state of being internal to a device.

P

peripheral: A device connected to and usually controlled by a host device.

program cache: A fast memory cache for storing program instructions allowing for quick execution.

program memory: Memory accessed through the C6x’s program fetch interface.

PWR: Power; see PWR module.

PWR module: PWR is an API module that is used to configure the power-down control registers, if applicable, and to invoke various power-down modes.

R

random-access memory (RAM): A type of memory device in which the individual locations can be accessed in any order.

register: A small area of high speed memory located within a processor or electronic device that is used for temporarily storing data or instructions. Each register is given a name, contains a few bytes of information, and is referenced by programs.

reduced-instruction-set computer (RISC): A computer whose instruction set and related decode mechanism are much simpler than those of microprogrammed complex instruction set computers. The result is a higher instruction throughput and a faster real-time interrupt service response from a smaller, cost-effective chip.

reset: A means of bringing the CPU to a known state by setting the registers and control bits to predetermined values and signaling execution to start at a specified address.

RTOS Real-time operating system.
**service layer:** The top layer of the 2-layer chip support library architecture providing high-level APIs into the CSL and BSL. The service layer is where the actual APIs are defined and is the layer the user interfaces to.

**synchronous-burst static random-access memory (SBSRAM):** RAM whose contents does not have to be refreshed periodically. Transfer of data is at a fixed rate relative to the clock speed of the device, but the speed is increased.

**synchronous dynamic random-access memory (SDRAM):** RAM whose contents is refreshed periodically so the data is not lost. Transfer of data is at a fixed rate relative to the clock speed of the device.

**syntax:** The grammatical and structural rules of a language. All higher-level programming languages possess a formal syntax.

**system software:** The blanketing term used to denote collectively the chip support libraries and board support libraries.

**tag:** The 18 most significant bits of the program address. This value corresponds to the physical address of the fetch packet that is in that frame.

**timer:** A programmable peripheral used to generate pulses or to time events.

**TIMER module:** TIMER is an API module used for configuring the timer registers.

**word:** A multiple of eight bits that is operated upon as a unit. For the C6x, a word is 32 bits in length.
Index

A
adaptive filtering functions 3-4
DSPLIB reference 4-2
address, defined C-1
A-law companding, defined C-1
API, defined C-1
application programming interface, defined C-1
argument conventions 3-2
arguments, DSPLIB 2-4
assembler, defined C-1
assert, defined C-1

B
big endian, defined C-1
bit, defined C-1
block, defined C-1
board support library, defined C-2
boot, defined C-2
boot mode, defined C-2
BSL, defined C-2
byte, defined C-2

cache, defined C-2
cache controller, defined C-2
CCS, defined C-2
central processing unit (CPU), defined C-2
clock cycle, defined C-2
clock modes, defined C-2
code, defined C-2
coder-decoder, defined C-2

compiler, defined C-2
compress and expand (compand), defined C-3
control register, defined C-3
control register file, defined C-3
correlation functions 3-4
DSPLIB reference 4-4
CSL, defined C-3
customer support B-2

D
data types, DSPLIB, table 2-4
device ID, defined C-3
digital signal processor (DSP), defined C-3
direct memory access (DMA)
defined C-3
source, defined C-3
transfer, defined C-3
DMA, defined C-3
DSP_autocor
defined C-3
DSPLIB reference 4-4
DSP_bexp
defined C-3
DSPLIB reference 4-89
DSP_bitrev_cplx
defined C-3
DSPLIB reference 4-6
DSP_blik_16
defined C-3
DSPLIB reference 4-91
DSP_blik_16_32
defined C-3
DSP_blik_16_64
defined C-3
DSP_blik_move
defined C-4
DSPLIB reference 4-91
DSP_dotp_sgr
defined C-4
DSPLIB reference 4-71
DSP_dotprod
defined C-4
DSPLIB reference 4-73

DSP_fft
defined C-4
DSPLIB reference 4-14

DSP_fft16x16r
defined C-4
DSPLIB reference 4-23

DSP_fft16x16t
defined C-4
DSPLIB reference 4-33

DSP_fft16x32
defined C-4
DSPLIB reference 4-47

DSP_fft32x32
defined C-4
DSPLIB reference 4-49

DSP_fft32x32s
defined C-4
DSPLIB reference 4-51

DSP_fir_cplx
defined C-4
DSPLIB reference 4-57

DSP_fir_gen
defined C-4
DSPLIB reference 4-59

DSP_fir_lms2
defined C-4
DSPLIB reference 4-2

DSP_fir_r4
defined C-4
DSPLIB reference 4-61

DSP_fir_r8
defined C-4
DSPLIB reference 4-63

DSP_fir_sym
defined C-4
DSPLIB reference 4-65

DSP_fltoq15
defined C-4
DSPLIB reference 4-98

DSP_flt16x32
defined C-4
DSPLIB reference 4-53

DSP_flt32x32
defined C-4

DSP_iir
defined C-4
DSPLIB reference 4-67

DSP_iirlat, DSPLIB reference 4-69

DSP_lat_fwd, DSPLIB reference 4-69

DSP_mat_trans
defined C-4
DSPLIB reference 4-88

DSP_maxidx
defined C-4
DSPLIB reference 4-76

DSP_maxval
defined C-4
DSPLIB reference 4-75

DSP_minerror
defined C-4
DSPLIB reference 4-99

DSP_minval
defined C-5
DSPLIB reference 4-78

DSP_mmul
defined C-4
DSPLIB reference 4-86

DSP_mul32
defined C-5
DSPLIB reference 4-79

DSP_neg32
defined C-5
DSPLIB reference 4-81

DSP_q15tofl
defined C-5
DSPLIB reference 4-101

DSP_r4fft
defined C-5
DSPLIB reference 4-11

DSP_radix2
defined C-5
DSPLIB reference 4-9

DSP_recip16
defined C-5
DSPLIB reference 4-82

DSP_vectsumsq
defined C-5
DSPLIB reference 4-84

DSP_w_vec
defined C-5
DSPLIB reference 4-85
DSPLIB
argument conventions, table 3-2
arguments 2-4
arguments and data types 2-4
calling a function from Assembly 2-6
calling a function from C 2-5
Code Composer Studio users 2-5
customer support B-2
data types, table 2-4
features and benefits 1-4
fractional Q formats A-3
functional categories 1-2
functions 3-3
adaptive filtering 3-4
correlation 3-4
FFT (fast Fourier transform) 3-4
filtering and convolution 3-5
math 3-6
matrix 3-6
miscellaneous 3-7
how DSPLIB deals with overflow and scaling 2-6, 2-7
how to install under Code Composer Studio 2-2
how to rebuild DSPLIB 2-8
include directory 2-3
introduction 1-2
lib directory 2-2
performance considerations 3-3
Q.3.12 bit fields A-3
Q.3.12 format A-3
Q.3.15 bit fields A-3
Q.3.15 format A-3
Q.31 format A-4
Q.31 high-memory location bit fields A-4
Q.31 low-memory location bit fields A-4
reference 4-1
software updates B-2
testing, how DSPLIB is tested using DSPLIB 2-6
DSPLIB reference
adaptive filtering functions 4-2
correlation functions 4-4
DSP_autocor 4-4
DSP_bexp 4-89
DSP_bitrev_cpx 4-6
DSP_blk_move 4-91, 4-93, 4-95, 4-97
DSP_dotp_sqr 4-71
DSP_dotprod 4-73
DSP_fft 4-14
DSP_fft16x16r 4-23
DSP_fft16x16t 4-33
DSP_fft16x32 4-47
DSP_fft32x32 4-49
DSP_fft32x32s 4-51
DSP_fir_cpx 4-57
DSP_fir_gen 4-59
DSP_firfcms2 4-2
DSP_fir_r4 4-61
DSP_fir_r8 4-63
DSP_fir_sym 4-65
DSP_flt0415 4-98
DSP_ifft16x32 4-53
DSP_ifft32x32 4-55
DSP_iir 4-67
DSP_iirlat 4-69
DSP_lat_fwd 4-69
DSP_mat_trans 4-88
DSP_maxidx 4-76
DSP_maxval 4-75
DSP_minerror 4-99
DSP_minval 4-78
DSP_mmul 4-86
DSP_mul32 4-79
DSP_neg32 4-81
DSP_q15tofl 4-101
DSP_r4fft 4-11
DSP_radix2 4-9
DSP_recip16 4-82
DSP_vecsumq 4-84
DSP_w_vec 4-85
FFT functions 4-6
filtering and convolution functions 4-57
math functions 4-71
matrix functions 4-86
miscellaneous functions 4-89

E
evaluation module, defined C-5
external interrupt, defined C-5
external memory interface (EMIF), defined C-5

F
fetch packet, defined C-5
FFT (fast Fourier transform) defined C-5
functions 3-4
FFT (fast Fourier transform) functions, DSPLIB reference 4-6
filtering and convolution functions DSPLIB reference 4-57
flag, defined C-5
fractional Q formats A-3
frame, defined C-5
function
  calling a DSPLIB function from Assembly 2-6
calling a DSPLIB function from C 2-5
Code Composer Studio users 2-5
functions, DSPLIB 3-3

G
GIE bit, defined C-5

H
HAL, defined C-6
host, defined C-6
host port interface (HPI), defined C-6
HPI, defined C-6

I
include directory 2-3
index, defined C-6
indirect addressing, defined C-6
installing DSPLIB 2-2
instruction fetch packet, defined C-6
internal interrupt, defined C-6
internal peripherals, defined C-7
interrupt, defined C-6
interrupt service fetch packet (ISFP), defined C-6
interrupt service routine (ISR), defined C-6
interrupt service table (IST), defined C-6
IST, defined C-7

L
least significant bit (LSB), defined C-7
lib directory 2-2
linker, defined C-7
little endian, defined C-7

M
maskable interrupt, defined C-7
math functions DSPLIB reference 4-71
matrix functions DSPLIB reference 4-86
memory map, defined C-7
memory-mapped register, defined C-7
miscellaneous functions 3-7
DSPLIB reference 4-89
most significant bit (MSB), defined C-7
multichannel buffered serial port (McBSP), defined C-7
multiplexer, defined C-7

N
nonmaskable interrupt (NMI), defined C-7

O
object file, defined C-8
off chip, defined C-8
on chip, defined C-8
overflow and scaling 2-6, 2-7

P
performance considerations A-2
peripheral, defined C-8
program cache, defined C-8
program memory, defined C-8
PWR, defined C-8
PWR module, defined C-8

Q
Q.3.12 bit fields A-3
Q.3.12 format A-3
Q.3.15 bit fields A-3
Q.3.15 format A-3
Q.31 format A-4
Q.31 high-memory location bit fields A-4
Q.31 low-memory location bit fields A-4

Index-4
Index

R

random-access memory (RAM), defined C-8
rebuilding DSPLIB 2-8
reduced-instruction-set computer (RISC), defined C-8
register, defined C-8
reset, defined C-8
routines, DSPLIB functional categories 1-2
RTOS, defined C-8

S

service layer, defined C-9
software updates B-2
STDINC module, defined C-9
synchronous-burst static random-access memory (SBSRAM), defined C-9
synchronous dynamic random-access memory (SDRAM), defined C-9
syntax, defined C-9
system software, defined C-9

tag, defined C-9
testing, how DSPLIB is tested 2-6
timer, defined C-9
TIMER module, defined C-9
using DSPLIB 2-4

word, defined C-9