INTEGRIT
Embedded Software Design House

NatureDSP Signal for HiFi4

Digital Signal Processing

Library Reference

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IMPORTANT NOTICE

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Preface

About This Manual

Welcome to the **NatureDSP Signal Processing Library**, or **NatureDSP Signal** or library for short. The library is a collection of number highly optimized DSP functions for the DSP targets.

This source code library includes C-callable functions (ANSI-C language compatible) for general signal processing (filtering, correlation, convolution), math and vector functions. Library supports both fixed-point and single precision floating data types.

Supported Targets

Library supports Cadence HiFi4 with VFPU/SFPU little endian targets. Call **IntegrIT** to support more targets or other CPUs.
In general, library API is the same for all supported cores, but some functionality might be missing depending on core abilities. Common rules are:

- functions with floating point inputs/outputs require VFPU/SFPU option of the core

Presence of specific functions might be detected in runtime using library identification routines, see para 2.12.3.

About this Release

This is version 4.0.0 of the library which is tested on the Xtensa Xplorer and tools version RG-2018.9. The major change with respect to previous version is about APIs, which are unified with that of HiFi3/3z, along with addition of LogMel and MFCC APIs and performance improvements of various functions. Support for LLVM compilation is also added. This library is fine tuned for better performance on HiFi4 VFPU on RG-2018.9. The core used for testing is HiFi4_VFPU, with xclib. Performance measurement is covered in a separate document.

Notations

This document uses the following conventions:

- program listings, program examples, interactive displays, filenames, variables and another software elements are shown in a special typeface (Courier);
- tables use smaller fonts.

Abbreviations

API	Application program interface
DCT	Discrete Cosine Transform
DSP	Digital signal processing
FFT	Fast Fourier transform
FIR	Finite impulse response
IDE	Integrated development environment
IFFT	Inverse Fast Fourier transform
IIR	Infinite impulse response
IR	Impulse response

LMS	Least mean squares
MFCC	Mel frequency cepstrum coefficients

1 General Library Organization

1.1 Headers

The library is delivered in several packages. The API for each package is defined in the appropriate header file which describes particular functions in the package. When the appropriate `#include` preprocessor directive is included in your source, the compiler uses the prototypes to check that each function is called with the correct arguments.

./library/include/NatureDSP_types.h	Declarations of basic data types and compiler auto detection	1.3
./library/include/NatureDSP_Signal.h	Declarations of all library functions	
./library/include/NatureDSP_Signal_fir.h	FIR Filters and Related Functions	2.1
./library/include/NatureDSP_Signal_iir.h	IIR Filters	2.1.13
./library/include/NatureDSP_Signal_math.h	Math Functions	2.3
./library/include/NatureDSP_Signal_complex.h	Complex Math Functions	2.4
./library/include/NatureDSP_Signal_vector.h	Vector Operations	2.5, 2.6
./library/include/NatureDSP_Signal_matop.h	Matrix Operations	2.7
./library/include/NatureDSP_Signal_matinv.h	Matrix Decomposition and Inversion Functions	2.8
./library/include/NatureDSP_Signal_fit.h	Fitting/interpolation	2.9
./library/include/NatureDSP_Signal_fft.h	FFT/DCT Routines	2.10
./library/include/NatureDSP_ Signal_audio.h	Mel frequency cepstrum coefficients functions	2.11
./library/include/NatureDSP_ Signal_id.h	Identification functions	2.12

1.2 Static Variables and Usage of C Standard Libraries

All library functions are re-entrant. Library functions do not call functions from standard C-library.

1.3 Types

Library uses the following C types with defined length

Name	Description	Alignment, bytes
F24	24-bit fractional type	4
int16_t	16-bit signed value	2
int32_t	32-bit signed value	4
uint32_t	32-bit unsigned value	4
int64_t	64-bit signed value	8
float32_t	32-bit single precision floating point value	4
complex_float	complex single precision floating point (pair of two 32-bit values)	8
complex_fract16	complex 16-bit fractional value (pair of two 16-bit values)	4
complex_fract32	complex 32-bit fractional value (pair of two 32-bit values)	8

It is assumed throughout this Reference that constant pointers passed through function arguments point at read-only data.
Normally, f24 fractional data are stored 3 higher bytes of 32-bit words and 8 LSBs are ignored, however, few routines use packed 24-bit data where 24-bit fractional numbers allocates only 3 consecutive bytes.

Data of given type should be aligned on its `sizeof()`, see table above.

1.4 Fractional Formats

Unless specifically noted, library functions use that `Q31` format, or, in another words, `Q0.31`. 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 $[-2^m, 2^m-1]$ and the finest fractional resolution is 2^{-n}. Normally, m from `Q` notation is omitted (because total length is defined of data type used for operand) and it is simply written as `Qn`.

Example data type and their formats are collected in the table below:

Data type	Format	Range	Resolution	Minimum value	Maximum value
int16_t	Q15	-1 … 0,999969	3e-5	-32768	32767
int16_t	Q6.9	-64 … 63,998	2e-3	-32768	32767
int32_t	Q1.30	-2 … 1,9999999991	9e-10	-2147483648	2147483647
int32_t	Q31	-1 … 0,9999999995	5e-10	-2147483648	2147483647
int32_t	Q6.25	-64… 63,999999970	3e-8	-2147483648	2147483647
int32_t	Q16.15	-65536… 65535,99997	3e-5	-2147483648	2147483647
int32_t	Q23.8	-8388608... 8388607.996	4e-3	-2147483648	2147483647

The most-significant binary digit is interpreted as the sign bit in any `Q` format number. Thus, in `Q15` 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.

1.5 Compiler Requirements

When building the library source files or library-dependent modules it is assumed that the target is a Cadence processor implementing the Xtensa HiFi4 Audio Engine Instruction Set Architecture with VFPU. For better performance of Floating point variant of functions configuration should have vector FPU.

1.6 Call Conventions

Library uses ANSI-C call conventions.

1.7 Overflow Control and Intermediate Data Format

If not especially noted, library does not check real dynamic range of input data so it is user's responsibility to select parameters and the scale of input data according to specific case. However, if possible library use saturated arithmetic to prevent overflows.
In the most fixed-point routines operating with summing of multiple elements (i.e. FIR, matrix multiplies, etc.), library stores intermediate values in 64-bit accumulators using Q16.47 fixed-point representation thus protecting from the overflows in the intermediate stages. Floating point routines use single precision floating point format for storing intermediate data.
The user is expected to conform to the range requirements if specified and take care to restrict the input range in such a way that the outputs do not overflow.

1.8 Exceptions and Processor Control Registers

Except for some mathematical routines, compatible with IEEE-754 and C99 standards (see para 2.3), all library functions do not touch global `errno` variable and do not modify the FPU enabled bits. FPU flags may be set during the execution of the routines. It is up to the caller to decide how to proceed given the flags.

Example of use cases are:

- The caller could enable floating point control bits before calling functions. This would result in an external signal that indicates an exceptional condition has occurred. We expect the customer to use that signal to control an external interrupt – thus enabling an imprecise interrupt.
- The caller could zero the status flags before a function and check them when the function returns to see if any exceptional conditions occurred.

1.9 Special Numbers

The IEEE754 standard specifies some special values, and their representation: positive infinity ($+\infty$ or `+Inf`), negative infinity ($-\infty$ or `–Inf`), a negative zero (`–0`) distinct from ordinary ("positive") zero (`+0`), and "not a number" values (`NaN`s). In general, the following rules are applied:

- negative zero is treated as usual negative number
- the result of operations under `NaN` is `NaN`
- operations with infinity return `NaN` except for few routines which require to interpret only the sign of infinity
- If a result depends on several values (E.g. in filters and correlations), and one or more of them is `NaN` or `Inf`, the propagation of those special values is complicated. The library routines will propagate the value in a way that minimizes cycles and code size. A special value will still appear in the output.
- outputs for mathematical functions for special numbers on their inputs follows ISO/IEC 9899 if not explicitly mentioned

1.10 Endianess

Library supports little-endian mode.

1.11 Performance Issues

Real-time performance of all functions depends on fulfillment special restrictions applied to input/output arguments. Typically, for maximum performance, user have to use **aligned data arrays (on 8 byte boundary)** for storing input and output arguments, number of data should be **multiple of 2 or 4** and should be **greater than 4**. Specific requirements are given for each function in its API description.
Data alignment may be achieved by several methods:

- placing the data into special data section and make alignment at the link-time
- use `__attribute__((aligned(x)))` modifiers in the data declarations

- dynamically allocate arrays of slighter bigger size and align pointers[1]

Test examples use two last methods.

1.12 Object Model

Effective use of all HiFi4 core benefits requires specific processing and special data moves minimizing the overhead. That is why many functions are supplied with object-like interface simplifying real-time processing chain but requiring special initialization before processing. Besides, function wrapped by object-like interface use best possible alignment for data storage and may utilize HiFi4 core better in some cases.

Initialization normally done once at the initialization time and do not affect to the real-time performance. Sequence consists of three stages

- call `<obj>_alloc()` function with parameters that define the block size, filter length, etc. This function/macro returns the size of memory has to be allocated for object for that specific parameters
- allocate the memory somehow. It may be done dynamically if `<obj>_alloc()` function is used
- pass the pointer to allocated memory to the function `<obj>_init`. It cleans up that memory block, reorder filter coefficients appropriately, etc. and returns the handle to the object. This handle will be used later for data processing by this given object, .i.e. block filtering.

Here we denote the symbolic name of object as `<obj>`. For example, corresponding functions for block FIR filtering will be named as:

`bkfir_alloc()`	request the memory size for object
`bkfir_init()`	initialize the object
`bkfir_process()`	make filtering of block

1.13 Scratch Memory

Some functions require scratch memory area for saving temporary data during the execution. It can be shared between objects if they are called in the same processing thread. Scratch memory area must always be aligned on a 8-bytes boundary. For each algorithm that requires a scratch area, its minimum size (either in bytes or in 16-bit words) is specified in such a way that both static and dynamic allocation are possible. Most often the required scratch size is specified through a macro or function that takes a number of algorithm parameters. For example, one might use the following wrapping function to perform a autocorrelation with the scratch area being allocated on the stack:

```
#define N  80
int run_autocorrelation( int16_t * y, const int16_t *x )
{
  // Allocate the scratch memory. Macro returns required size in bytes
  int8_t scratch[FIR_ACORRA16X16_SCRATCH_SIZE(N) attribute__ ((aligned(8)));
  // Invoke the autocorrelation routine
  fir_acorra16x16  (scratch, y, x, N);
}
```

1.14 Brief Function List

Vectorized version	Scalar version	Purpose	Reference

[1] xcc `malloc()` always returns pointer aligned on 64-bit boundary special additional alignment procedure is not required

Vectorized version	Scalar version	Purpose	Reference
FIR filters and related functions			
bkfir		Block real FIR filter	2.1.1, 2.1.2
cxfir		Complex block FIR filter	2.1.3
firdec		Decimating block real FIR filter	2.1.4
firinterp		Interpolating block real FIR filter	2.1.5
fir_convol, cxfir_convol		Circular/linear convolution	2.1.6, 2.1.7
fir_xcorr		Circular/linear correlation	2.1.8, 2.1.9
fir_acorr		Circular/linear autocorrelation	2.1.10, 2.1.11
fir_blms		Blockwise Adaptive LMS algorithm	2.1.12
IIR filters			
bqriir, bqciir		Biquad Real block IIR	2.2.1
latr		Lattice block Real IIR	2.2.2
Mathematics			
vec_recip	scl_recip	Reciprocal on a vector of Q31 numbers	2.3.1
vec_divide	scl_divide	Division	2.3.2
vec_logn vec_log2 vec_logn	scl_logn scl_log2 scl_logn	Different kinds of logarithm	2.3.3
vec_recip	scl_recip	Reciprocal on a vector of Q31 numbers	2.3.1
vec_divide	scl_divide	Division	2.3.2
vec_logn vec_log2 vec_logn	scl_logn scl_log2 scl_logn	Different kinds of logarithm	2.3.3
vec_antilog2 vec_antilog10 vec_antilogn	scl_antilog2 scl_antilog10 scl_antilogn	Different kinds of antilogarithm	2.3.4
vec_pow		Power function	2.3.5
vec_sqrt	scl_sqrt	Square root	2.3.6
vec_rsqrt	scl_rsqrt	Reciprocal square root	2.3.7
vec_sine	scl_sine	Sine	2.3.8
vec_cosine	scl_cosine	Cosine	
vec_tan	scl_tan	Tangent	2.3.9
vec_atan, vec_atan2	scl_atan, scl_atan2	Arctangent	2.3.10, 2.3.11
vec_tanh	vec_tanh	Hyperbolic tangent	2.3.12
vec_sigmoid	scl_sigmoid	Sigmoid	2.3.13
vec_relu	scl_relu	Rectifier function (ReLU)	2.3.14
vec_softmax		Softmax	2.3.15
vec_int2float	scl_int2float	Integer to float conversion	2.3.16
vec_float2int	scl_float2int	Float to integer conversion	2.3.17
Complex Mathematics			
vec_complex2mag	scl_complex2mag	Complex magnitude	2.4.1
vec_complex2invmag	scl_complex2invmag	Reciprocal of complex magnitude	2.4.1
Vector operations			
vec_dot		Vector dot product	2.5.1, 2.6.4
vec_add		Vector sum	2.5.2, 2.6.1
vec_mul		Vector multiply, multiply-accumulate	2.6.2, 2.6.3
vec_power		Power of a vector	2.5.3
vec_shift vec_scale		Vector scaling with saturation	2.5.4
vec_bexp	scl_bexp	Common exponent	2.5.5
vec_min, vec_max		Find a maximum/minimum in a vector	2.5.6

Vectorized version	Scalar version	Purpose	Reference
Matrix operations			
`mtx_mpy`		Matrix multiply	2.7.1
`mtx_vecmpy`		Matrix by vector multiple	2.7.2
Matrix Decomposition and Inversion Functions			
`mtx_inv`		Matrix inversion	2.8.1
Fitting/Interpolation			
`vec_poly`		Polynomial approximation	2.9.1
FFT/DCT			
`fft_cplx`		FFT on complex data	2.10.1
`fft_real`		FFT on real data	2.10.2
`ifft_cplx`		Inverse FFT on complex data	2.10.3
`ifft_real`		Inverse FFT forming real data	2.10.4
`fft_cplx_ie`		FFT on complex data with optimized memory usage	2.10.5
`fft_real_ie`		FFT on real data with optimized memory usage	2.10.6
`ifft_cplx_ie`		Inverse FFT on complex data with optimized memory usage	2.10.7
`ifft_real_ie`		Inverse FFT forming real data with optimized memory usage	2.10.8
`fft_powerspectrum`			2.10.9
`dct,mdct`		Discrete cosine transform	2.10.10, 2.10.11
`dct2d, idct2d`		2D Discrete cosine transforms	2.10.12, 2.10.13
Mel frequency cepstrum coefficients functions			
`LogMel`		Mel frequency extraction	2.11.1
`MFCC`		MFCC	2.11.2
Idenitification			
`NatureDSP_Signal_get_library_version`		Library Version Request	2.12.1
`NatureDSP_Signal_get_library_api_version`		Library API Version Request	2.12.2
`NatureDSP_Signal_isPresent`		Library API Capability Request	2.12.3

2 Reference

2.1 FIR Filters and Related Functions

FIR filtering APIs excepting correlation/convolution, autocorrelation and blockwise LMS algorithm require instantiation. In particular, filter objects encapsulate the delay line buffer, which is organized in such a way that advanced processor capabilities (e.g. circular data addressing) are efficiently utilized. When allocating and initializing a filter instance through `xfir_alloc()` and `xfir_init()` function calls, the user has to specify the length of filters and its coefficients. On the data processing stage the user application sequentially calls an `xfir_process()` function, providing it with a block of `N` input samples on each call. `xfir_process()` function updates the internal delay line with input samples, and computes `N` filter output samples, which are returned to the calling application via the output data buffer argument.

2.1.1 Block Real FIR Filter

Description

Computes a real FIR filter (direct-form) using IR stored in vector `h`. The real data input is stored in vector `x`. The filter output result is stored in vector `y`. The filter calculates `N` output samples using `M` coefficients and requires last `M-1` samples in the delay line which is updated in circular manner for each new sample.
User has an option to set IR externally or copy from original location (i.e. from the slower constant memory). In the first case, user is responsible for right alignment, ordering and zero padding of filter coefficients – usually array is composed from zeroes (left padding), reverted IR and right zero padding.

Precision

6 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit outputs. Ordinary (single channel) variant and stereo
24x24p	use 24-bit data packing for internal delay line buffer and internal coefficients storage
32x16	32-bit data, 16-bit coefficients, 32-bit outputs
32x32	32-bit data, 32-bit coefficients, 32-bit outputs. Ordinary (single channel) variant and stereo
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations. Available for HiFi4 only
f	floating point. Requires VFPU/SFPU core option. Ordinary (single channel) variant and stereo

Algorithm

$$y_n = \sum_{m=0}^{M-1} h_{M-1-m} x_{n+m}, n = \overline{0...N-1}$$

NOTE:
This is formal description of algorithm, in reality processing in done using circular buffers, so user application is not responsible for management of delay lines

Object allocation

```
size_t bkfir24x24p_alloc(int M, int extIR)
size_t bkfir16x16_alloc (int M, int extIR)
size_t bkfir32x16_alloc (int M, int extIR)
size_t bkfir32x32_alloc (int M, int extIR)
size_t bkfir32x32ep_alloc(int M, int extIR)
size_t bkfirf_alloc (int M, int extIR)
size_t stereo_bkfir16x16_alloc (int M, int extIR)
size_t stereo_bkfir32x32_alloc (int M, int extIR)
size_t stereo_bkfirf_alloc (int M, int extIR)
```

Type	Name	Size	Description
Input			

int	M		length of filter, should be a multiple of 4
int	extIR		if zero, IR is copied from original location, otherwise not but user should keep alignment, order of coefficients and zero padding requirements shown below

Returns: size of memory in bytes to be allocated

NOTE:
Approximate amount of requested memory is listed below

Function	Approximate memory requirements, bytes	
	extIR=0	**extIR!=0**
bkfir24x24p_alloc	80+M*6	56+M*3
bkfir16x16_alloc	72+M*4	56+M*2
bkfir32x16_alloc	72+M*6	64+M*4
bkfir32x32_alloc	72+M*8	48+M*4
bkfir32x32ep_alloc	72+M*8	48+M*4
bkfirf_alloc	72+M*8	48+M*4
stereo_bkfir16x16_alloc	72+M*8	56+M*4
stereo_bkfir32x32_alloc	72+M*16	48+M*8
stereo_bkfirf_alloc	72+M*16	48+M*8

Object initialization

```
bkfir24x24p_handle_t bkfir24x24p_init
           (void * objmem, int M, int extIR, const f24 * h)
bkfir16x16_handle_t bkfir16x16_init
           (void * objmem, int M, int extIR, const int16_t *  h)
bkfir32x16_handle_t bkfir32x16_init
           (void * objmem, int M, int extIR, const int16_t*  h)
bkfir32x32_handle_t bkfir32x32_init
           (void * objmem, int M, int extIR, const int32_t*  h)
bkfir32x32ep_handle_t bkfir32x32ep_init
           (void * objmem, int M, int extIR, const int32_t* h)
bkfirf_handle_t bkfirf_init
           (void * objmem, int M, int extIR, const float32_t*  h)
stereo_bkfir16x16_handle_t stereo_bkfir16x16_init
           (void * objmem, int M, int extIR,
            const int16_t *  hl, const int16_t *  hr)
stereo_bkfir32x32_handle_t stereo_bkfir32x32_init
           (void * objmem, int M, int extIR,
            const int32_t *  hl, const int32_t *  hr)
stereo_bkfirf_handle_t stereo_bkfirf_init
           (void * objmem, int M, int extIR,
            const float32_t *  hl, const float32_t *  hr)
```

Type	Name	Size	Description
Input			
void*	objmem		allocated memory block
f24, int16_t, int32_t, float32_t	h	M	filter coefficients; h[0] is to be multiplied with the newest sample
int16_t, int32_t, float32_t	hl	M	for stereo filters: filter coefficients for left channel
int16_t, int32_t, float32_t	hr	M	for stereo filters: filter coefficients for right channel
int	M		length of filter
int	extIR		if zero, IR is copied from original location, otherwise not but user should keep alignment, order of coefficients and zero padding requirements shown below

Returns: handle to the object

Alignment, ordering and zero padding for external IR (`extIR!=0`)

Function	Alignment, bytes	Left zero padding, bytes	Coefficient order	Right zero padding, bytes
bkfir24x24p_init	8	((-M&4)+5)*3	inverted	7
bkfir16x16_init	8	2	inverted	6
bkfir32x16_init (M>32)	8	10	inverted	6
bkfir32x16_init (M<=32)	8	2	inverted	6
bkfir32x32_init	8	4	inverted	12
bkfir32x32ep_init	8	4	inverted	12
bkfirf_init	8	0	direct	0
stereo_bkfir16x16_init	8	2	inverted	6
stereo_bkfir32x32_init	8	4	inverted	12
stereo_bkfirf_init	8	0	direct	0

Update the delay line and compute filter output

```
void bkfir24x24p_process( bkfir24x24p_handle_t handle,
                       f24* y,  const f24 * x, int N )
void bkfir16x16_process (
              bkfir16x16_handle_t  handle,
              int16_t *  y, const int16_t *  x, int N )
void bkfir32x16_process (
              bkfir32x16_handle_t  handle,
              int32_t *  y, const int32_t *  y, int N)
void bkfir32x32_process (
              bkfir32x32_handle_t  handle,
              int32_t *  y, const int32_t *  y, int N)
void bkfir32x32ep_process ( bkfir32x32ep_handle_t  handle,
                      int32_t * y, const int32_t * y, int N)
void bkfirf_process (
              bkfirf_handle_t  handle,
              float32_t * y, const float32_t * x, int N);
void stereo_bkfir16x16_process (
              stereo_bkfir16x16_handle_t  handle,
              int16_t *  y, const int16_t *  x, int N )
void stereo_bkfir32x32_process (
              stereo_bkfir32x32_handle_t  handle,
              int32_t *  y, const int32_t *  x, int N)
void stereo_bkfirf_process (
              stereo_bkfirf_handle_t  handle,
              float32_t * y, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
f24, int16_t, int32_t, float32_t	x	N*S	input samples
int	N		length of sample block
	S		1 for ordinary (single channel) filters, 2 - for stereo variant
Output			
f24, int16_t, int32_t, float32_t	y	N*S	output samples

Returns: none

Restrictions

`x,y` – should not overlap
`x,h` - aligned on a 8-bytes boundary
`N,M` - multiples of 4

2.1.2 Block Real FIR Filter with Arbitrary Parameters

Description

These functions implement FIR filter described in previous chapter with no limitation on size of data block, alignment and length of impulse response for the cost of performance.

Precision

5 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit outputs
32x16	32-bit data, 16-bit coefficients, 32-bit outputs
32x32	32-bit data, 32-bit coefficients, 32-bit outputs
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$y_n = \sum_{m=0}^{M-1} h_{M-1-m} x_{n+m}, n = \overline{0 \ldots N-1}$$

NOTE:
This is formal description of algorithm, in reality processing in done using circular buffers, so user application is not responsible for management of delay lines

Object allocation

```
size_t bkfira16x16_alloc(int M)
size_t bkfira32x16_alloc(int M)
size_t bkfira32x32_alloc(int M)
size_t bkfira32x32ep_alloc(int M)
size_t bkfiraf_alloc(int M)
```

Type	Name	Size	Description
Input			
int	M		length of filter

Returns: size of memory in bytes to be allocated

Approximate amount of requested memory is listed below

Function	Approximate memory requirements, bytes
bkfira16x16_alloc	72+ M*4
bkfira32x16_alloc	72+ M*6
bkfira32x32_alloc	80+ M*8
bkfira32x32ep_alloc	80+ M*8
bkfiraf_alloc	80+ M*8

Object initialization

```
bkfira16x16_handle_t bkfira16x16_init
           (void * objmem, int M, const int16_t *  h)
bkfira32x16_handle_t bkfira32x16_init
           (void * objmem, int M, const int16_t*  h)
bkfira32x32_handle_t bkfira32x32_init
           (void * objmem, int M, const int32_t*  h)
bkfira32x32ep_handle_t bkfira32x32ep_init
           (void * objmem, int M, const int32_t*  h)
bkfiraf_handle_t bkfiraf_init
           (void * objmem, int M, const int16_t*  h)
```

Type	Name	Size	Description
Input			
void*	objmem		allocated memory block
int16_t, int32_t, float32_t	h	M	filter coefficients; `h[0]` is to be multiplied with the newest sample
int	M		length of filter

Returns: handle to the object

Update the delay line and compute filter output

```
void bkfira16x16_process (
                  bkfira16x16_handle_t  handle,
                  int16_t *  y, const int16_t *  x, int N );
void bkfira32x16_process (
                  bkfira32x16_handle_t  handle,
                  int32_t *  y, const int32_t *  y, int N);
void bkfira32x32_process (
                  bkfira32x32_handle_t  handle,
                  int32_t *  y, const int32_t *  y, int N);
void bkfira32x32ep_process (
                  bkfira32x32ep_handle_t  handle,
                  int32_t *  y, const int32_t *  y, int N);
void bkfiraf_process (
               bkfiraf_handle_t  handle,
               float32_t * y, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
`int16_t, int32_t, float32_t`	`x`	`N`	input samples
`int`	`N`		length of sample block
Output			
`int16_t, int32_t, float32_t`	`y`	`N`	output samples

Returns: none

Restrictions

`x,y` – should not overlap

2.1.3 Complex Block FIR Filter

Description

Computes a complex FIR filter (direct-form) using complex IR stored in vector `h`. The complex data input is stored in vector `x`. The filter output result is stored in vector `y`. The filter calculates `N` output samples using `M` coefficients, requires last `M-1` samples in the delay line which is updated in circular manner for each new sample. Real and imaginary parts are interleaved and real parts go first (at even indexes).
User has an option to set IR externally or copy from original location (i.e. from the slower constant memory). In the first case, user is responsible for right alignment, ordering and zero padding of filter coefficients – usually array is composed from zeroes (left padding), reverted IR and right zero padding.

Precision

5 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit outputs
32x16	32-bit data, 16-bit coefficients, 32-bit outputs
32x32	32-bit data, 32-bit coefficients, 32-bit outputs
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$y_n = \sum_{m=0}^{M-1} h_{M-1-m} x_{n+m}, n = \overline{0 \ldots N-1}$$

NOTE:
This is formal description of algorithm, in reality processing in done using circular buffers, so user application is not responsible for management of delay lines

Object allocation

```
size_t cxfir16x16_alloc(int M, int extIR)
size_t cxfir32x16_alloc(int M, int extIR)
size_t cxfir32x32_alloc(int M, int extIR)
size_t cxfir32x32ep_alloc(int M, int extIR)
size_t cxfirf_alloc(int M, int extIR)
```

Type	Name	Size	Description
Input			

int	M		length of filter

Returns: size of memory in bytes to be allocated
NOTE:
Approximate amount of requested memory is listed below

Function	Approximate memory requirements, bytes	
	extIR=0	**extIR!=0**
cxfir16x16_alloc	80+12*M	40+4*M
cxfir32x16_alloc	80+12*M	64+8*M
cxfir32x32_alloc	80+16*M	72+8*M
cxfir32x32ep_alloc	80+16*M	72+8*M
cxfirf_alloc	64+16*M	72+8*M

Object initialization

```
cxfir16x16_handle_t cxfir16x16_init(void * objmem,
                          int M, int extIR, const complex_fract16 *  h)
cxfir32x16_handle_t cxfir32x16_init(void * objmem,
                          int M, int extIR, const complex_fract16 *  h)
cxfir32x32_handle_t cxfir32x32_init(void * objmem,
                          int M, int extIR, const complex_fract32 *  h)
cxfir32x32ep_handle_t cxfir32x32ep_init(void * objmem,
                          int M, int extIR, const complex_fract32 *  h)
cxfirf_handle_t cxfirf_init(void * objmem,
                          int M, int extIR, const complex_float *  h)
```

Type	Name	Size	Description
Input			
void*	objmem		allocated memory block
complex_fract32, complex_fract16, complex_float	h	M	complex filter coefficients; `h[0]` is to be multiplied with the newest sample , Q31, Q15 or floating point
int	M		length of filter
int	extIR		if zero, IR is copied from original location, otherwise not but user should keep alignment, order of coefficients and zero padding requirements shown below

Returns: handle to the object

Alignment, ordering and zero padding for external IR (`extIR!=0`)

Function	Alignment, bytes	Left zero padding, bytes	Coefficient order	Right zero padding, bytes
cxfir16x16_alloc	8	2 before each copy	inverted: conjugated copy and (imaginary; real) copy at 4*(M+4) bytes offset	6 after each copy
cxfir32x16_init	8	4	inverted	4
cxfir32x32_init	8	0	inverted and conjugated	0
cxfir32x32ep_init	8	0	inverted and conjugated	0
cxfirf_init	8	0	direct	0

Update the delay line and compute filter output

```
void cxfir16x16_process(
            cxfir16x16_handle_t handle,
            complex_fract16 *  y,
            const complex_fract16*  x, int N );
void cxfir32x16_process(cxfir32x16_handle_t handle,
            complex_fract32 *  y,
            const complex_fract32 *  x, int N );
void cxfir32x32_process(cxfir32x32_handle_t handle,
            complex_fract32 *  y,
            const complex_fract32 *  x, int N );
void cxfir32x32ep_process(cxfir32x32ep_handle_t handle,
            complex_fract32 *  y,
            const complex_fract32 *  x, int N );
void cfirf_process (  cxfirf_handle_t handle,
              complex_float * y, const complex_float * x, int N);
```

Type	Name	Size	Description
Input			
`complex_fract16, complex_fract32, complex_float`	`x`	`N`	input samples , Q15, Q31 or floating point
`int`	`N`		length of sample block
Output			
`complex_fract16, complex_fract32, complex_float`	`y`	`N`	output samples , Q15, Q31 or floating point

Returns: none

Restrictions

`x,y` – should not overlap
`x,h` - aligned on a 8-bytes boundary
`N,M` - multiples of 4

2.1.4 Decimating Block Real FIR Filter

Description

Computes a real FIR filter (direct-form) with decimation using IR stored in vector `h`. The real data input is stored in vector `x`. The filter output result is stored in vector `y`. The filter calculates `N` output samples from `N*D` input samples using `M` coefficients, requires last `M-1` samples on the delay line and updated in circular manner for each new `D` samples.
NOTE:
To avoid aliasing IR should be synthesized in such a way to be narrower than input sample rate divided to 2D.

Precision

5 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit outputs
32x16	32-bit data, 16-bit coefficients, 32-bit outputs
32x32	32-bit data, 32-bit coefficients, 32-bit outputs
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r_n = \sum_{m=0}^{M-1} h_{M-1-m} x_{D \cdot n+m}, n = \overline{0...N-1}$$

NOTE:
This is formal description of algorithm, in reality processing in done using circular buffers, so user application is not responsible for management of delay lines

Object allocation

```
size_t firdec16x16_alloc(int D, int M)
size_t firdec32x16_alloc(int D, int M)
size_t firdec32x32_alloc(int D, int M)
size_t firdec32x32ep_alloc(int D, int M)size_t firdecf_alloc    (int D, int M)
```

Type	Name	Size	Description
Input			
`int`	`D`		decimation factor
`int`	`M`		length of filter

Returns: size of memory in bytes to be allocated

NOTE:
Approximate amount of requested memory is listed below

Function	Approximate memory requirements, bytes
`firdec32x16_alloc`	`40+(M+8*D)*4+(M+4)*2`
`firdec16x16_alloc`	`40+(M+8*D)*2+(M+4)*2`
`firdec32x32_alloc`	`40+(M+8*D)*4+(M+4)*4`
`firdec32x32ep_alloc`	`40+(M+8*D)*4+(M+4)*4`
`firdecf_alloc`	`40+(M+8*D)*4+(M+4)*4`

Object initialization

```
firdec16x16_handle_t firdec16x16_init(void * objmem,
                          int D, int M, const int16_t *  h)
firdec32x16_handle_t firdec32x16_init(void * objmem,
                          int D, int M, const int16_t *  h)
firdec32x32_handle_t firdec32x32_init(void * objmem,
                          int D, int M, const int32_t *  h)
firdec32x32ep_handle_t firdec32x32ep_init(void * objmem,
                          int D, int M, const int32_t *  h)
firdecf_handle_t firdecf_init(void * objmem,
                          int D, int M, const float32_t *  h)
```

Type	Name	Size	Description
Input			
`void*`	`objmem`		allocated memory block
`int32_t, int16_t, float32_t`	`h`	`M`	filter coefficients; `h[0]` is to be multiplied with the newest sample, Q31, Q15 or floating point
`int`	`D`		decimation factor
`int`	`M`		length of filter

Returns: handle to the object

Update the delay line and compute decimator output

```
void firdec16x16_process(firdec16x16_handle_t handle,
                         int16_t *  y, const int16_t * x, int N );
void firdec32x16_process(firdec32x16_handle_t handle,
                         int32_t *  y, const int32_t * x, int N );
void firdec32x32_process(firdec32x32_handle_t handle,
                         int32_t *  y, const int32_t * x, int N );
void firdec32x32ep_process(firdec32x32ep_handle_t handle,
                         int32_t *  y, const int32_t * x, int N );
void firdecf_process (firdecf_handle_t handle,
                      float32_t * y, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
`int16_t`, `int32_t`, `float32_t`	`x`	`D*N`	input samples , Q15, Q31 or floating point
`int`	`N`		length of output sample block, should be a multiple of 8
Output			
`int16_t`, `int32_t`, `float32_t`	`y`	`N`	output samples, Q15, Q31 or floating point

Returns: none

Restrictions

`x,h,r` should not overlap
`x, h` - aligned on a 8-bytes boundary
`N` – multiple of 8
`D >1`

Conditions for optimum performance

`D` – 2, 3 or 4

2.1.5 Interpolating Block Real FIR Filter

Description

Computes a real FIR filter (direct-form) with interpolation using IR stored in vector `h`. The real data input is stored in vector `x`. The filter output result is stored in vector `y`. The filter calculates `N*D` output samples using `M*D` coefficients from `N` inputs. Delay line holds `M*D-1` last samples and updated in circular manner for each new sample.

Precision

5 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit outputs
32x16	32-bit data, 16-bit coefficients, 32-bit outputs
32x32	32-bit data, 32-bit coefficients, 32-bit outputs
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$y_{n\cdot D+d} = D\cdot\sum_{m=0}^{M-1} h_{D(M-1-m)+d}\, x_{n+m},\, n=\overline{0...N-1}, d=\overline{0...D-1},$$

NOTE:
This is formal description of algorithm, in reality processing in done using circular buffers, so user application is not responsible for management of delay lines

Object allocation

```
size_t firinterp16x16_alloc(int D, int M)
size_t firinterp32x16_alloc(int D, int M)
size_t firinterp32x32_alloc(int D, int M)
size_t firinterp32x32ep_alloc(int D, int M)
size_t firinterpf_alloc     (int D, int M)
```

Type	Name	Size	Description
Input			
int	D		interpolation ratio
int	M		length of subfilter. Total length of filter is M*D

Returns: size of memory in bytes to be allocated
NOTE:
Approximate amount of requested memory is listed below

Function	Approximate memory requirements, bytes
firinterp16x16_alloc	40+(M+8)*2+(M+4)*D*2
firinterp32x16_alloc	40+(M+8)*4+(M+4)*D*2
firinterp32x32_alloc	40+(M+8)*4+(M+4)*D*4
firinterp32x32ep_alloc	40+(M+8)*4+(M+4)*D*4
firinterpf_alloc	40+(M+8)*4+(M+4)*D*4

Object initialization

```
firinterp16x16_handle_t firinterp16x16_init(void * objmem,
                          int D, int M, const int16_t*  h)
firinterp32x16_handle_t firinterp32x16_init(void * objmem,
                          int D, int M, const int16_t *  h)
firinterp32x32_handle_t firinterp32x32_init(void * objmem,
                          int D, int M, const int32_t *  h)
firinterp32x32ep_handle_t firinterp32x32ep_init(void * objmem,
                          int D, int M, const int32_t *  h)
firinterpf_handle_t firinterpf_init(void * objmem,
                          int D, int M, const float32_t *  h)
```

Type	Name	Size	Description
Input			
void*	objmem		allocated memory block
int32_t, int16_t, float32_t	h	M*D	filter coefficients; h[0] is to be multiplied with the newest sample,Q31, Q15 or floating point
int	D		interpolation ratio
int	M		length of subfilter. Total length of filter is M*D

Returns: handle to the object

Update the delay line and compute interpolator output

```
void firinterp16x16_process(firinterp16x16_handle_t handle,
                            int16_t *  y, const int16_t *  x, int N);
void firinterp32x16_process(firinterp32x16_handle_t handle,
                            int32_t*  y, const int32_t*  x, int N);
void firinterp32x32_process(firinterp32x32_handle_t handle,
                            int32_t*  y, const int32_t*  x, int N);
void firinterp32x32ep_process(firinterp32x32ep_handle_t handle,
                            int32_t*  y, const int32_t*  x, int N);
void firinterpf_process     (firinterpf_handle_t handle,
                            float32_t * y, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
int16_t, int32_t, float32_t	x	N	input samples, Q15, Q31 or floating point
int	N		length of input sample block
Output			
int16_t, int32_t, float32_t	y	N*D	output samples, Q15, Q31 or floating point

Returns: none

Restrictions	`x,h,y` should not overlap `x,h` - aligned on a 8-bytes boundary `M` - multiples of 4 `N` - multiples of 8 `D` should be >1
Conditions for optimum performance	`D` - 2, 3 or 4

2.1.6 Circular convolution

Description

Performs circular convolution between vectors `x` (of length `N`) and `y` (of length `M`) resulting in vector `r` of length `N`.
Two versions of these functions available: faster version (`fir_convol16x16, fir_convol32x16, fir_convol32x32, fir_convol32x32ep, cxfir_convol32x16, fir_convolf`) with some restrictions on input arguments and slower version (`fir_convola16x16, fir_convola32x16, fir_convola32x32, fir_convola32x32ep, cxfir_convola32x16, fir_convolaf`) for arbitrary arguments. In addition, these slower version implementations require scratch memory area.

Precision

5 variants available:

Type	Description
16x16	16x16-bit data, 16-bit outputs
32x16	32x16-bit data, 32-bit outputs (both real and complex)
32x32	32x32-bit data, 32-bit outputs
32x32ep	32-bit data, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r_k = \sum_{m=0}^{M-1} x_{\mathrm{mod}(k-m,N)} y_m, k = \overline{0...(N-1)}$$

Prototype

```
void fir_convol16x16  ( int16_t *  r, const int16_t *  x,const int16_t *  y,
                        int N, int M);
void fir_convol32x16  ( int32_t *  r, const int32_t *  x, const int16_t *  y,
                        int N, int M);
void fir_convol32x32  ( int32_t *  r, const int32_t *  x, const int32_t *  y,
                        int N, int M);
void fir_convol32x32ep( int32_t *  r, const int32_t *  x, const int32_t *  y,
                        int N, int M);
void cxfir_convol32x16( complex_fract32 *  r,
                        const complex_fract32 *  x, const complex_fract16 *  y,
                        int N,int M);
void fir_convolf      ( float32_t *  r,
                        const float32_t *  x, const float32_t *  y,
                        int N, int M);

void fir_convola16x16 ( void *  s,
                        int16_t  *  r, const int16_t  *  x, const int16_t  *  y,
                        int N, int M);
void fir_convola32x16 ( void    *  s,
                        int32_t *  r, const int32_t *  x, const int16_t *  y,
                        int N, int M);
void fir_convola32x32 ( void    *  s,
                        int32_t *  r, const int32_t *  x, const int32_t *  y,
                        int N, int M);
void fir_convola32x32ep(void    *  s,
                        int32_t *  r, const int32_t *  x, const int32_t *  y,
                        int N, int M);
void cxfir_convola32x16(void    *  s,
                        complex_fract32 *  r,
                        const complex_fract32 *  x, const complex_fract16 *  y,
                        int N, int M);
void fir_convolaf      (void      *  s,
                        float32_t  *  r,
                        const float32_t  *  x, const float32_t  *  y,
                        int N, int M);
```

Arguments

Type	Name	Size	Description
Input			
`int16_t, int32_t, complex_fract32, float32_t`	`x`	`N`	input data (Q15, Q31 or floating point)
`int16_t, complex_fract16, or float32_t`	`y`	`M`	input data (Q31, Q15 or floating point)
`int`	`N`		length of `x`
`int`	`M`		length of `y`
Output			
`int16_t, int32_t, complex_fract32, float32_t`	`r`	`N`	output data, Q15, Q31 or floating point
Temporary			
`void`	`s`		Scratch memory, `FIR_CONVOLA16X16_SCRATCH_SIZE( N, M )` `FIR_CONVOLA32X16_SCRATCH_SIZE( N, M )` `FIR_CONVOLA32X32_SCRATCH_SIZE( N, M )` `FIR_CONVOLA32X32EP_SCRATCH_SIZE( N, M )` `CXFIR_CONVOLA32X16_SCRATCH_SIZE(N,M)` `FIR_CONVOLAF_SCRATCH_SIZE( N, M )` bytes

Returned value

none

Restrictions

For slow versions (`fir_convola16x16, fir_convola32x16, fir_convola32x32, fir_convola32x32ep, cxfir_convola32x16, fir_convolaf`):
`x,y,r,s` should not overlap
`s` should be aligned on 8-byte boundary
`N>=M-1`

For fast versions (`fir_convol16x16, fir_convol32x16, fir_convol32x32, fir_convol32x32ep, cxfir_convol32x16, fir_convolf`):
`x,y,r` should not overlap
`x,y,r` should be aligned on 8-byte boundary
`N,M` – multiples of 4

2.1.7 Linear Convolution

Description

Functions perform linear convolution between vectors `x` (of length `N`) and `y` (of length `M`) resulting in vector `r` of length `N+M-1`.

Precision

2 variants available:

Type	Description
16x16	16x16-bit data, 16-bit outputs
32x32	32x32-bit data, 32-bit outputs

Algorithm

$$r_k = \sum_{j=\max(k-M+1,0)}^{\min(N-1,k)} x_j y_{k-j}, k = \overline{0...(M+N-2)}$$

Prototype

```
void fir_lconvola16x16 (void     *  s,
                        int16_t  *  r,
                  const int16_t  *  x, const int16_t  *  y, int N, int M);
void fir_lconvola32x32 (void     *  s,
                        int32_t  *  r,
                  const int32_t  *  x, const int32_t  *  y, int N, int M);
```

Arguments

Type	Name	Size	Description
Input			
`int16_t, int32_t`	`x`	`N`	input data (Q15, Q31)
`int16_t, int32_t`	`y`	`M`	input data (Q31, Q15)
`int`	`N`		length of `x`
`int`	`M`		length of `y`
Output			
`int16_t, int32_t`	`r`	`M+N-1`	output data, Q15, Q31
Temporary			
`void`	`s`		Scratch memory, `FIR_LCONVOLA16X16_SCRATCH_SIZE( N, M)` `FIR_LCONVOLA32X32_SCRATCH_SIZE( N, M)` bytes

Returned value

none

Restrictions

`x,y,r,s` should not overlap
`s` should be aligned on 8-byte boundary
`N>0, M>0`
`N>=M-1`

2.1.8 Circular Correlation

Description

Estimates the circular cross-correlation between vectors `x` (of length `N`) and `y` (of length `M`) resulting in vector `r` of length `N`. It is a similar to correlation but `y` is read in opposite direction.
Two versions of these functions available: faster version (`fir_xcorr16x16, fir_xcorr32x16, fir_xcorr32x32, fir_xcorr32x32ep, fir_xcorrf, cxfir_xcorrf`) with some restrictions on input arguments and slower version (`fir_xcorra16x16, fir_xcorra32x16, fir_xcorra32x32, fir_xcorra32x32ep, fir_xcorraf, cxfir_xcorraf`) for arbitrary arguments. In addition, these slower version implementations require scratch memory area.

Precision

5 variants available:

Type	Description
16x16	16x16-bit data, 16-bit outputs
32x16	32x16-bit data, 32-bit outputs
32x32	32x32-bit data, 32-bit outputs (both real and complex data)
32x32ep	32-bit data, 32-bit outputs, use 72-bit accumulators for intermediate computations.
f	floating point (both real and complex data). Requires VFPU/SFPU core option

Algorithm

$$r_k = \sum_{m=0}^{M-1} x_{\mathrm{mod}(k+m,N)} y_m, k = \overline{0\ldots(N-1)}$$

Prototype

```
void fir_xcorr16x16 ( int16_t *  r, const int16_t *  x, const int16_t *  y,
                      int N, int M);
void fir_xcorr32x16 ( int32_t *  r, const int32_t *  x, const int16_t *  y,
                      int N, nt M);
void fir_xcorr32x32 ( int32_t *  r, const int32_t *  x, const int32_t *  y,
                      int N, int M);
void fir_xcorr32x32ep(int32_t *  r, const int32_t *  x, const int32_t *  y,
                      int N, int M);
void cxfir_xcorr32x32 ( complex_fract32 *  r,
                      const complex_fract32 *  x, const complex_fract32 *  y,
                      int N, int M);
void fir_xcorrf      (float32_t *  r,
                      const float32_t *  x, const float32_t *  y,
                      int N, int M);
void cxfir_xcorrf    (complex_float *  r,
                      const complex_float *  x, const complex_float *  y,
                      int N, int M);
```

```
void fir_xcorra32x16 (void     *  s,
                      int32_t *  r, const int32_t *  x, const int16_t *  y,
                      int N, int M);
void fir_xcorra32x32 (void     *  s,
                      int32_t *  r, const int32_t *  x, const int32_t *  y,
                      int N, int M);
void cxfir_xcorra32x32 (void     *  s, complex_fract32 *  r,
                        const complex_fract32 *  x, const complex_fract32 *  y,
                        int N, int M);
void fir_xcorra32x32ep(void     *  s,
                      int32_t *  r, const int32_t *  x, const int32_t *  y,
                      int N, int M);
void fir_xcorraf     (void      *  s,
                      float32_t *  r, const float32_t * x, const float32_t * y,
                      int N, int M);
void cxfir_xcorraf   (void      *  s,
                      complex_float *  r,
                      const complex_float *  x, const complex_float *  y,
                      int N, int M);
```

Arguments

	Name	Size	Description
Input			
int16_t, int32_t, float32_t, complex_fract32, complex_float	x	N	input data (Q15, Q31 or floating point)
int16_t, float32_t, complex_fract32, complex_float	y	M	input data (Q31, Q15 or floating point)
int	N		length of x
int	M		length of y
Output			
int16_t, int32_t, float32_t, complex_fract32, complex_float	r	N	output data, Q15, Q31 or floating point
Temporary			
void	s		Scratch memory, FIR_XCORRA16X16_SCRATCH_SIZE(N, M) FIR_XCORRA32X16_SCRATCH_SIZE(N,M) FIR_XCORRA32X32_SCRATCH_SIZE(N, M) FIR_XCORRA32X32EP_SCRATCH_SIZE(N, M) FIR_XCORRAF_SCRATCH_SIZE(N, M) CXFIR_XCORRA32X32_SCRATCH_SIZE(N, M) CXFIR_XCORRAF_SCRATCH_SIZE(N, M) bytes

Returned value

none

Restrictions

For slow versions (fir_xcorra16x16, fir_xcorra32x16, fir_xcorra32x32ep, fir_xcorra32x32, fir_cxcorra32x32, fir_xcorraf, cxfir_xcorraf):

x,y,r,s should not overlap

s should be aligned on 8-byte boundary

N>=M-1

For fast versions (fir_xcorr16x16, fir_xcorr32x16, fir_xcorr32x32, fir_xcorr32x32ep, cxfir_xcorr32x32, fir_xcorrf, cxfir_xcorrf):

x,y,r should not overlap

x,y,r should be aligned on 8-byte boundary

N,M – multiples of 4

2.1.9 Linear Correlation

Description

Functions estimate the linear cross-correlation between vectors `x` (of length `N`) and `y` (of length `M`) resulting in vector `r` of length `N+M-1`. It is a similar to convolution but `y` is read in opposite direction.

Precision

2 variants available:

Type	Description
16x16	16x16-bit data, 16-bit outputs
32x32	32x32-bit data, 32-bit outputs

Algorithm

$$r_k = \sum_{j=\max(k-M+1,0)}^{\min(N-1,k)} x_j y^*_{M-1-(k-j)}, k = \overline{0...(M+N-2)}$$

Prototype

```
void fir_lxcorra16x16 ( void      *  s,
                        int16_t   *  r,
                  const int16_t   *  x, const int16_t   *  y, int N, int M);
void fir_lxcorra32x32 ( void      *  s,
                        int32_t   *  r,
                  const int32_t   *  x, const int32_t   *  y, int N, int M);
```

Arguments

Type	Name	Size	Description
Input			
`int16_t, int32_t`	`x`	`N`	input data (Q15, Q31)
`int16_t, int32_t`	`y`	`M`	input data (Q31, Q15)
`int`	`N`		length of `x`
`int`	`M`		length of `y`
Output			
`int16_t, int32_t,`	`r`	`M+N-1`	output data, Q15, Q31
Temporary			
`void`	`s`		Scratch memory, `FIR_LXCORRA16X16_SCRATCH_SIZE(N, M)` `FIR_LXCORRA32X32_SCRATCH_SIZE(N, M)` bytes

Returned value

none

Restrictions

`x,y,r,s` should not overlap
`s` should be aligned on 8-byte boundary
`N>0, M>0`
`N>=M-1`

2.1.10 Circular Autocorrelation

Description

Estimates the auto-correlation of vector `x`. Returns autocorrelation of length `N`.
Two versions of these functions available: faster version (`fir_acorr16x16, fir_acorr32x32, fir_acorr32x32ep, fir_acorrf`) with some restrictions on input arguments and slower version (`fir_acorra16x16, fir_acorra32x32, fir_acorra32x32ep, fir_acorraf`) for arbitrary arguments. In addition, this slower version implementations require scratch memory area.

Precision

4 variants available:

Type	Description
16x16	16-bit data, 16-bit outputs
32x32	32-bit data, 32-bit outputs
32x32ep	32-bit data, 32-bit outputs, use 72-bit accumulators for intermediate computations.
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r_k = \sum_{n=0}^{N-1} x_{\mathrm{mod}(n+k,N)} x_n, k = \overline{0...(N-1)}$$

Prototype

```
void fir_acorr16x16  ( int16_t  *  r, const int16_t  *  x, int N);
void fir_acorr32x32  ( int32_t  *  r, const int32_t  *  x, int N);
void fir_acorr32x32ep( int32_t  *  r, const int32_t  *  x, int N);
void fir_acorrf      ( float32_t*  r, const float32_t*  x, int N);

void fir_acorra16x16  (void* s, int16_t  *  r, const int16_t  *  x, int N);
void fir_acorra32x32  (void* s, int32_t  *  r, const int32_t  *  x, int N);
void fir_acorra32x32ep(void* s, int32_t  *  r, const int32_t  *  x, int N);
void fir_acorraf      (void* s, float32_t*  r, const float32_t*  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
int16_t, int32_t or float32_t	x	N	input data (Q15, Q31 or floating point)
int	N		length of x
Output			
int16_t, int32_t or float32_t	r	N	output data, Q15, Q31 or floating point
Temporary			
void	s		Scratch memory, FIR_ACORRA16X16_SCRATCH_SIZE(N) FIR_ACORRA32X32_SCRATCH_SIZE(N)FIR_ACORRAF_SCRATCH_SIZE(N) bytes

Returned value

none

Restrictions

For slow versions (`fir_acorr16x16, fir_acorr32x32, fir_acorr32x32ep, fir_acorrf`):
`x,r,s` should not overlap
`N` - must be non-zero
`s` - aligned on an 8-bytes boundary
For fast versions (`fir_acorra16x16, fir_acorra32x32, fir_acorra32x32ep, fir_acorraf`):
`x,r` should not overlap
`x,r` should be aligned on 8-byte boundary
`N` – non-zero multiple of 4

2.1.11 Linear Autocorrelation

Description

Functions estimate the linear auto-correlation of vector `x`. Returns autocorrelation of length `N`.

Precision

2 versions available:

Type	Description
16x16	16-bit data, 16-bit outputs
32x32	32-bit data, 32-bit outputs

Algorithm

$$r_k = \sum_{n=0}^{N-k-1} x_{n+k} x_n , k = \overline{0...(N-1)}$$

Prototype

```
void fir_lacorra16x16 (void* s, int16_t  *  r, const int16_t  *  x, int N);
void fir_lacorra32x32 (void* s, int32_t  *  r, const int32_t  *  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int16_t, int32_t`	`x`	`N`	input data (Q15, Q31)
`int`	`N`		length of `x`
Output			
`int16_t, int32_t`	`r`	`N`	output data, Q15, Q31
Temporary			
`void`	`s`		Scratch memory, `FIR_LACORRA16X16_SCRATCH_SIZE( N )` `FIR_LACORRA32X32_SCRATCH_SIZE( N )` bytes

Returned value

none

Restrictions

`x,r,s` should not overlap
`N>0`
`s` - aligned on an 8-bytes boundary

2.1.12 Blockwise Adaptive LMS Algorithm for Real Data

Description

Blockwise LMS algorithm performs filtering of reference samples `x[N+M-1]`, computation of error `e[N]` over a block of input samples `r[N]` and makes blockwise update of IR to minimize the error output. Algorithm includes FIR filtering, calculation of correlation between the error output `e[N]` and reference signal `x[N+M-1]` and IR taps update based on that correlation.
NOTES:
1. The algorithm must be provided with the normalization factor, which isthe power of the reference signal times `N` - the number of samples in a data block. This can be calculated using the `vec_power32x32()` or `vec_power16x16()` function. In order to avoid the saturation of the normalization factor, it may be biased, i.e. shifted to the right. If it's the case, then the adaptation coefficient must be also shifted to the right by the same number of bit positions.
2. This algorithm consumes less CPU cycles per block than single sample algorithm at similar convergence rate.
3. Right selection of `N` depends on the change rate of impulse response: on static or slow varying channels convergence rate depends on selected `mu` and `M`, but not on `N`.
4. 16x16 routine may converge slower on small errors due to roundoff errors. In that cases, 16x32 routine will give better results although convergence rate on bigger errors is the same

Precision

5 variants available:

Type	Description
16x16	16-bit coefficients, 16-bit data, 16-bit output
16x32	32-bit coefficients, 16-bit data, 16-bit output
32x32	32-bit coefficients, 32-bit data, 32-bit output, complex and real
32x32ep	32-bit data, 32-bit coefficients, 32-bit outputs, use 72-bit accumulators for intermediate computations
f	floating point, both complex and real data. Requires VFPU/SFPU core option

Algorithm

$$b = \frac{\mu}{norm}$$

$$e_n = r_n - \sum_{m=0}^{M-1} h_{M-1-m} x_{m+n}, n = \overline{0...N-1}$$

$$h_{M-1-m} = h_{M-1-m} + b \cdot \sum_{n=0}^{N-1} e_n^* x_{n+m}, m = \overline{0...M-1}$$

Prototype

```
void fir_blms16x16 (  int16_t*  e, int16_t *  h,
                      const int16_t *  r,
                      const int16_t *  x,
                      int16_t norm, int16_t   mu,
                      int   N,   int   M);
void fir_blms16x32 (  int32_t *  e, int32_t *  h,
                      const int16_t *  r,
                      const int16_t *  x,
                      int32_t   norm,int16_t   mu,
                      int       N,   int       M);
void fir_blms32x32 (  int32_t *  e, int32_t *  h,
                      const int32_t *  r,
                      const int32_t *  x,
                      int32_t   norm, int32_t mu,
                      int       N,   int       M);
void cxfir_blms32x32 (complex_fract32 *  e, complex_fract32 *  h,
                      const complex_fract32 *  r,
                      const complex_fract32 *  x,
                      int32_t   norm, int32_t mu,
                      int       N,   int       M);

void fir_blms32x32ep(  int32_t *  e, int32_t *  h,
                      const int32_t *  r,
                      const int32_t *  x,
                      int32_t   norm, int32_t mu,
                      int       N,   int       M);
void fir_blmsf      ( float32_t * e, float32_t * h, const float32_t * r,
                      const float32_t * x,
                      float32_t norm, float32_t mu,
                      int          N, int       M );
void cxfir_blmsf    ( complex_float * e, complex_float * h,
                      const complex_float * r,
                      const complex_float * x,
                      float32_t norm, float32_t mu,
                      int          N, int       M );
```

Arguments

Type	Name	Size	Description
Input			
int16_t, int32_t, complex_fract32, float32_t, complex_float	h	M	impulse response, Q15, Q31 or floating point
int16_t, int32_t complex_fract32, float32_t, complex_float	r	N	reference (near end) data vector. First in time value is in r[0], Q31, Q15 or floating point
int16_t, int32_t, complex_fract32, float32_t, complex_float	x	N+M-1	input (far end) data vector. First in time value is in x[0], Q31, Q15 or floating point
int16_t, int32_t, float32_t	norm		normalization factor: power of signal multiplied by N, Q31, Q15 or floating point
int16_t int32_t, float32_t	mu		adaptation coefficient in Q31, Q15 or floating point (LMS step)
int	N		length of data block
int	M		length of h
Output			
int16_t, int32_t, complex_fract32, float32_t, complex_float	e	N	estimated error, Q31, Q15 or floating point
int16_t, int32_t, float32_t, complex_float	h	M	updated impulse response, Q31, Q15 or floating point

Returned value none

Restrictions
`h,x,r,y,e` – should not overlap
`x,e,h,r` - aligned on a 8-bytes boundary
`N,M` - multiples of 8

2.1.13 2D Convolution

Description The `conv2d()` functions compute the two-dimensional convolution of input matrix `x[M][N]` and `y[P][Q]` and store the result in matrix `z[M+P-1][N+Q-1]`
Additional parameter `rsh` allows to control fixed point representation of output data.

Precision 6 variants available:

Type	Description
8x8	8-bit coefficients, 8-bit data, 8-bit output, Q7
8x16	8-bit coefficients Q7, 16-bit data, 16-bit output, Q15
16x16	16-bit coefficients, 16-bit data, 16-bit output, Q15

Algorithm

$$y_{i,j} = 2^{-rsh} \sum_{m=\max(i-P+1,0)}^{\min(i,M-1)} \sum_{n=\max(j-Q+1,0)}^{\min(j,N-1)} x_{m,n} \cdot y_{j-m,i-n} \text{ where } i = \overline{0...M+P-2},\ j = \overline{0...N+Q-2}$$

Prototypes

```
void conv2d_8x8 (void *pScr, int8_t *z, const int8_t * x, const int8_t * y,
                 int rsh, int P, int Q);
void conv2d_8x16(void *pScr, int16_t *z, const int8_t * x, const int16_t * y,
                 int rsh, int P, int Q);
void conv2d_16x16(void *pScr, int16_t *z, const int16_t * x, const int16_t * y,
                  int rsh, int P, int Q);
```

Function	API	Scratch allocation function	Dimensions
			MxN
`conv2d_3x3_8x8`	`conv2d_8x8`	`conv2d_3x3_8x8_getScratchSize`	3x3
`conv2d_5x5_8x8`	`conv2d_8x8`	`conv2d_5x5_8x8_getScratchSize`	5x5
`conv2d_11x7_8x8`	`conv2d_8x8`	`conv2d_11x7_8x8_getScratchSize`	11x7
`conv2d_3x3_8x16`	`conv2d_8x16`	`conv2d_3x3_8x16_getScratchSize`	3x3
`conv2d_5x5_8x16`	`conv2d_8x16`	`conv2d_5x5_8x16_getScratchSize`	5x5
`conv2d_11x7_8x16`	`conv2d_8x16`	`conv2d_11x7_8x16_getScratchSize`	11x7
`conv2d_3x3_16x16`	`conv2d_16x16`	`conv2d_3x3_16x16_getScratchSize`	3x3
`conv2d_5x5_16x16`	`conv2d_16x16`	`conv2d_5x5_16x16_getScratchSize`	5x5
`conv2d_11x7_16x16`	`conv2d_16x16`	`conv2d_11x7_16x16_getScratchSize`	11x7

Arguments

Type	Name	Size	Description
Input			
`int8_t, int16_t`	`x`	`[M][N]`	input data, Q15, Q7
`int8_t, int16_t`	`y`	`[P][Q]`	input data, Q15, Q7
`int`	`rsh`		additional right shift
	`M`		number of rows in the matrix `x`
	`N`		number of columns in the matrix `x`
`int`	`P`		number of rows in the matrix `y`
`int`	`Q`		number of columns in the matrix `y`
Temporary:			
`pScr`			scratch data. Should have size in bytes at least as requested by corresponding

			scratch allocation function
Output			
`int8_t, int16_t`	`z`	`[M+P-1]*[N+Q-1]`	output data, Q(7-rsh), Q(15-rsh)

Returned value None

Restrictions

`M,N,P,Q` must be positive

`P, Q` must be bigger than zero and multiplies of 8

`x,y,z` aligned on a 8-bytes boundary

2.2 IIR filters

2.2.1 Bi-quad Real Block IIR

Description

Computes a real IIR filter (cascaded IIR direct form I or II using 5 coefficients per bi-quad + gain term) . Input data are stored in vector `x`. Filter output samples are stored in vector `r`. The filter calculates `N` output samples using SOS and G matrices.

NOTE:

- Bi-quad coefficients may be derived from standard SOS and G matrices generated by MATLAB. However, typically biquad stages have big peaks in their step response which may cause undesirable overflows at the intermediate outputs. To avoid that the additional scale factors `coef_g[M]` may be applied. These per-section scale factors may require some tuning to find a compromise between quantization noise and possible overflows. Output of the last section is directed to an additional multiplier, with the gain factor being a power of two, either negative or non-negative. It is specified through the total gain shift amount parameter `gain` of each filter initialization function
- 16x16 filters may suffer more from accumulation of the roundoff errors, so filters should be properly designed to match noise requirements

Precision

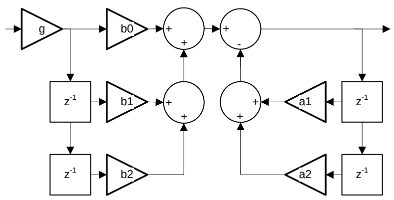
4 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients, 16-bit intermediate stage outputs (DF1, DF1 stereo, DF II form)
32x16	32-bit data, 16-bit coefficients, 32-bit intermediate stage outputs (DF1, DF1 stereo, DF II form)
32x32	32-bit data, 32-bit coefficients, 32-bit intermediate stage outputs (DF I, DF1 stereo, DF II form)
f	floating point (DF I, DF1 stereo, DF II and DF IIt). Requires VFPU/SFPU core option

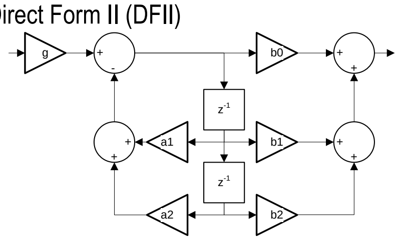
Algorithm

A block of N real input samples is sequentially passed through M bi-quad sections. There are two options for the implementation structure of a single section:

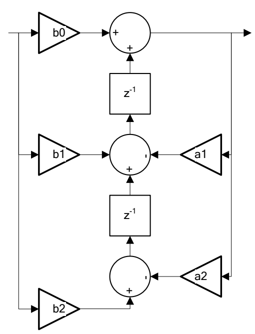
Direct Form I (DFI)



Direct Form II (DFII)



Direct Form II transposed (DF IIt)



Object allocation

```
size_t bqriir16x16_df1_alloc(int M)
size_t bqriir16x16_df2_alloc(int M)
size_t bqriir32x16_df1_alloc(int M)
size_t bqriir32x16_df2_alloc(int M)
size_t bqriir32x32_df1_alloc(int M)
size_t bqriir32x32_df2_alloc(int M)
size_t bqriirf_df1_alloc(int M)
size_t bqriirf_df2_alloc(int M)
size_t bqriirf_df2t_alloc(int M)
size_t bqciirf_df1_alloc(int M)
size_t stereo_bqriir16x16_df1_alloc(int M)
size_t stereo_bqriir32x16_df1_alloc(int M)
size_t stereo_bqriir32x32_df1_alloc(int M)
size_t stereo_bqriirf_df1_alloc    (int M)
```

Type	Name	Size	Description
Input			
`int`	`M`		number of bi-quad sections

Returns: size of memory in bytes to be allocated

Object initialization

```
bqriir16x16_df1_handle_t bqriir16x16_df1_init(void * objmem, int M,
           const int16_t * coef_sos, const int16_t * coef_g, int16_t gain );
bqriir16x16_df2_handle_t bqriir16x16_df2_init(void * objmem, int M,
           const int16_t * coef_sos, const int16_t * coef_g,  int16_t gain);
bqriir32x16_df1_handle_t bqriir32x16_df1_init(void * objmem, int M,
           const int16_t * coef_sos, const int16_t * coef_g, int16_t gain);
bqriir32x16_df2_handle_t bqriir32x16_df2_init(void * objmem, int M,
           const int16_t * coef_sos, const int16_t * coef_g, int16_t gain);
bqriir32x32_df1_handle_t bqriir32x32_df1_init(void * objmem, int M,
           const int32_t * coef_sos, const int16_t * coef_g, int16_t gain)
bqriir32x32_df2_handle_t bqriir32x32_df2_init(void * objmem, int M,
           const int32_t * coef_sos, const int16_t * coef_g, int16_t gain)
bqriirf_df1_handle_t bqriirf_df1_init(void * objmem, int M,
           const float32_t* coef_sos, int16_t gain );
bqriirf_df2_handle_t bqriirf_df2_init(void * objmem, int M,
           const float32_t * coef_sos, int16_t gain);
bqriirf_df2t_handle_t bqriirf_df2t_init(void * objmem, int M,
           const float32_t * coef_sos, int16_t gain);
bqciirf_df1_handle_t bqciirf_df1_init(void * objmem, int M,
           const float32_t * coef_sos, int16_t gain);

stereo_bqriir16x16_df1_handle_t stereo_bqriir16x16_df1_init
          (void * objmem, int M,
           const int16_t * coef_sosl, const int16_t * coef_gl, int16_t gainl,
           const int16_t * coef_sosr, const int16_t * coef_gr, int16_t gainr );
stereo_bqriir32x16_df1_handle_t stereo_bqriir32x16_df1_init
          (void * objmem, int M,
           const int16_t * coef_sosl, const int16_t * coef_gl, int16_t gainl,
           const int16_t * coef_sosr, const int16_t * coef_gr, int16_t gainr);
stereo_bqriir32x32_df1_handle_t stereo_bqriir32x32_df1_init
          (void * objmem, int M,
           const int32_t * coef_sosl, const int16_t * coef_gl, int16_t gainl,
           const int32_t * coef_sosr, const int16_t * coef_gr, int16_t gainr);
stereo_bqriirf_df1_handle_t stereo_bqriirf_df1_init
          (void * objmem, int M,
           const float32_t* coef_sosl, int16_t gainl,
           const float32_t* coef_sosr, int16_t gainr );
```

Type	Name	Size	Description
Input			
`void*`	`objmem`		allocated memory block
`int`	`M`		number of bi-quad sections
`int32_t`, `int16_t`, `float32_t`	`coef_sos`	`M*5`	filter coefficients stored in blocks of 5 numbers: `b0 b1 b2 a1 a2`. For fixed-point functions, fixed point format of filter coefficients is Q1.14 for 16x16 and 32x16, or Q1.30 for 32x32.
`int32_t`, `int16_t`, `float32_t`	`coef_sosl`	`M*5`	filter coefficients for the left channel (stereo filters only)
`int32_t`, `int16_t`, `float32_t`	`coef_sosr`	`M*5`	filter coefficients for the right channel (stereo filters only)
`int16_t`	`coef_g`	`M`	scale factor for each section, Q15 (for fixed-point functions only).
`int16_t`	`coef_gl`	`M`	scale factor for the left channel (stereo filters only)
`int16_t`	`coef_gr`	`M`	scale factor for the right channel (stereo filters only)
`int16_t`	`gain`		total gain shift amount, -48..15
`int16_t`	`gainl`		total gain shift amount for the left channel (stereo filters only)
`int16_t`	`gainr`		total gain shift amount for the right channel (stereo filters only)

Returns: handle to the object

Update the delay line and compute filter output

```
void bqriir16x16_df1(bqriir16x16_df1_handle_t _bqriir,
                void *  s,int16_t *  r,const int16_t *x, int N);
void bqriir16x16_df2(bqriir16x16_df2_handle_t _bqriir,
                void *  s,int16_t *  r,const int16_t *x, int N);
void bqriir32x16_df1(bqriir32x16_df1_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void bqriir32x16_df2(bqriir32x16_df2_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void bqriir32x32_df1(bqriir32x32_df1_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void bqriir32x32_df2(bqriir32x32_df2_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void bqriirf_df1 (bqriirf_df1_handle_t,
                      float32_t     * r, const float32_t * x, int N);
void bqriirf_df2 (bqriirf_df2_handle_t,
                      float32_t     * r, const float32_t * x, int N);
void bqriirf_df2t (bqriirf_df2t_handle_t,
                      float32_t     * r, const float32_t * x, int N);
void bqciirf_df1 (bqciirf_df1_handle_t,
                      complex_float* r, const complex_float * x, int N);
void stereo_bqriir16x16_df1(stereo_bqriir16x16_df1_handle_t _bqriir,
                void *  s,int16_t *  r,const int16_t *x, int N);
void stereo_bqriir32x16_df1(stereo_bqriir32x16_df1_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void stereo_bqriir32x32_df1(stereo_bqriir32x32_df1_handle_t _bqriir,
                void *  s,int32_t *  r,const int32_t *x, int N);
void stereo_bqriirf_df1 (stereo_bqriirf_df1_handle_t,
                      float32_t     * r, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
int16_t, int32_t, float32_t, complex_float	x	N*S	input samples, Q31, Q15 or floating point. Stereo samples go in interleaved order (left, right)
int	N		length of input sample block
	S		1 for mono, 2 for stereo API
Output			
int16_t, int32_t, float32_t, complex_float	r	N*S	output data, Q31, Q15 or floating point . Stereo samples go in interleaved order (left, right)
Temporary			
void*	s		scratch memory area (for fixed-point functions only). Minimum number of bytes depends on selected filter structure and precision (see spreadsheet below) If a particular macro returns zero, then the corresponding IIR doesn't require a scratch area and parameter `s` may hold zero

Returns: none

Functon	Scratch memory, bytes
bqriir16x16_df1	BQRIIR16X16_DF1_SCRATCH_SIZE(N,M)
bqriir16x16_df2	BQRIIR16X16_DF2_SCRATCH_SIZE(N,M)
bqriir32x16_df1	BQRIIR32X16_DF1_SCRATCH_SIZE(N,M)
bqriir32x16_df2	BQRIIR32X16_DF2_SCRATCH_SIZE(N,M)
bqriir32x32_df1	BQRIIR32X32_DF1_SCRATCH_SIZE(N,M)
bqriir32x32_df2	BQRIIR32X32_DF2_SCRATCH_SIZE(N,M)
stereo_bqriir16x16_df1	STEREO_BQRIIR16X16_DF1_SCRATCH_SIZE(N,M)
stereo_bqriir32x16_df1	STEREO_BQRIIR32X16_DF1_SCRATCH_SIZE(N,M)
stereo_bqriir32x32_df1	STEREO_BQRIIR32X32_DF1_SCRATCH_SIZE(N,M)
stereo_bqriirf_df1	STEREO_BQRIIRF_DF1_SCRATCH_SIZE(N,M)

Returned value

none

Restrictions	`x`,`r`,`s`,`coef_g`,`coef_sos` must not overlap `N` - must be a multiple of 2 `s` - whenever supplied must be aligned on an 8-bytes boundary

2.2.2 Lattice Block Real IIR

Description

Computes a real cascaded lattice autoregressive IIR filter using reflection coefficients stored in vector `k`. The real data input are stored in vector `x`. The filter output result is stored in vector `r`. Input scaling is done before the first cascade for normalization and overflow protection.

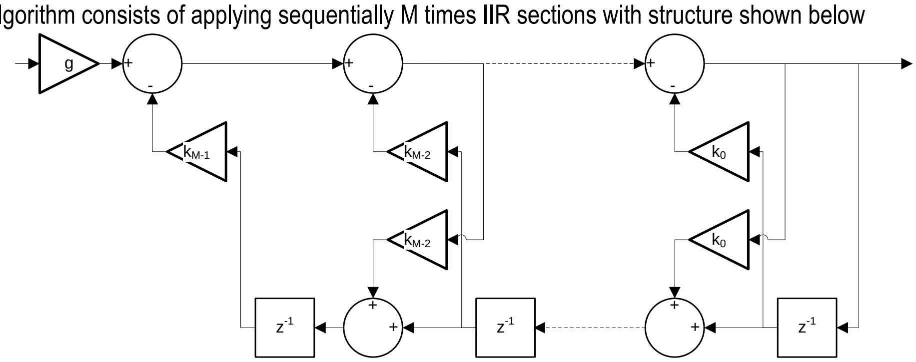
Precision

4 variants available:

Type	Description
16x16	16-bit data, 16-bit coefficients
32x16	32-bit data, 16-bit coefficients
32x32	32-bit data, 32-bit coefficients
f	floating point. Requires VFPU/SFPU core option

Algorithm

Algorithm consists of applying sequentially M times IIR sections with structure shown below



Object allocation

```
size_t latr16x16_alloc(int M);
size_t latr32x16_alloc(int M);
size_t latr32x32_alloc(int M);
size_t latrf_alloc    (int M);
```

Type	Name	Size	Description
Input			
`int`	`M`		number of sections

Returns: size of memory in bytes to be allocated

Object initialization

```
latr16x16_handle_t latr16x16_init
   (void * objmem, int M,const int16_t    *  k, int16_t   scale);
latr32x16_handle_t latr32x16_init
   (void * objmem, int M, const int16_t   *  k, int16_t   scale);
latr32x32_handle_t latr32x32_init
   (void * objmem, int M, const int32_t   *  k, int32_t   scale);
latrf_handle_t     latrf_init
   (void * objmem, int M, const float32_t *  k, float32_t scale);
```

Type	Name	Size	Description
Input			
`void*`	`objmem`		allocated memory block
`int`	`M`		number of sections
`int16_t`, `int32_t` or `float32_t`	`k`	`M`	reflection coefficients, Q31, Q15 or floating point
`int16_t`, `int32_t` or `float32_t`	`scale`	`M`	input scale factor g, Q31, Q15 or floating point

Returns: handle to the object

Update the delay line and compute filter output

```
void latr16x16_process
    (latr16x16_handle_t handle, int16_t   * r, const int16_t   * x, int N);
void latr32x16_process
    (latr32x16_handle_t handle, int32_t   * r, const int32_t   * x, int N);
void latr32x32_process
    (latr32x32_handle_t handle, int32_t   * r, const int32_t   * x, int N);
void latrf_process
    (latrf_handle_t     handle, float32_t * r, const float32_t * x, int N);
```

Type	Name	Size	Description
Input			
`int16_t`, `int32_t` or `float32_t`	`x`	`N`	input samples, Q31, Q15 or floating point
`int`	`N`		length of input sample block
Output			
`int16_t`, `int32_t` or `float32_t`	`r`	`N`	output data, Q31, Q15 or floating point

Returns: none

Returned value

none

Restrictions

`x`,`r`,`k` should not overlap

Conditions for optimum performance

For optimum performance `M` should be in range `1…8`

2.3 Mathematics

A number of DSP Library functions supersede standard floating-point mathematical functions similar to defined in `<math.h>`, as listed below:

ANSI function	Scalar function	reference
atanf	scl_atanf	2.3.10
atan2f	scl_atan2f	2.3.11
cosf	scl_cosinef	2.3.8
sinf	scl_sinef	2.3.8
tanf	scl_tanf	2.3.9
logf	scl_lognf	2.3.3
log2f	scl_log2f	2.3.3
log10f	scl_log10f	2.3.3
expf	scl_antilognf	2.3.4
exp2f	scl_antilog2f	2.3.4
alog10f	scl_antilog10f	2.3.4
tanhf	scl_tanhf	2.3.12

All these functions conform to ISO/IEC 9899 standard (commonly referred to as C99) in respect to function semantics, parameters and return value specification. Moreover, floating-point mathematical functions handle error conditions in a way that differs from general DSP Library approach as stated in 1.8. Aforementioned functions follow the next ground rules:

- Each function executes as if it were a single operation, and may generate any of “invalid”, “overflow” or “divide-by-zero” floating-point exceptions only to reflect the result of that operation.
- A domain error occurs if input argument(s) fall out of the function domain as defined in function specification. In such a case, the function assigns `EDOM` to the integer expression `errno`, raises the “invalid” floating-point exception, and returns a quiet `NaN`.
- `NaN` as an input argument is a special kind of domain error. Namely, the integer expression `errno` acquires `EDOM` and returned value is a quiet `NaN`, but the function raises the “invalid” floating-point exception only if the input argument is a *signaling* `NaN`.
- A floating-point result overflows if the magnitude of the mathematical result is finite but so large that the target floating-point type cannot represent the mathematical result without extraordinary round-off error (for example, `scl_antilognf(100.0f)`). If a function detects a floating-point result overflow, it assigns `ERANGE` to the integer expression `errno`, raises the “overflow” floating-point exception and returns the properly signed infinity value.

The set of floating-point mathematical functions conforming to ISO/IEC 9899 includes vectorized variants of all the functions listed above. Due to the performance reasons, these vectorized functions do not handle `errno` and may generate exceptions in bit different manner to minimize the overhead.

2.3.1 Reciprocal on Q63/Q31/Q15 Numbers

Description

These routines return the fractional and exponential portion of the reciprocal of a vector `x` of Q63, Q31 or Q15 numbers. Since the reciprocal is always greater than 1, it returns fractional portion `frac` in Q(63-`exp`), Q(31-`exp`) or Q(15-`exp`) format and exponent exp so true reciprocal value in the Q0.31/Q0.15 may be found by shifting fractional part left by exponent value.
NOTE: `scl_recip64x64(), scl_recip32x32()` use packed output for mantissa/exponent. To take a full precision, just call vectorized counterparts.

Mantissa accuracy is 1 LSB, so relative accuracy is:

`vec_recip16x16, scl_recip16x16`	6.2e-5
`scl_recip32x32`	2.4e-7
`vec_recip32x32`	9.3e-10
`vec_recip64x64`	2.2e-19

Precision

3 variants available:

Type	Description
64x64	64-bit input, 64-bit output.
32x32	32-bit input, 32-bit output.
16x16	16-bit input, 16-bit output.

Algorithm

$$frac_n \cdot 2^{exp_n} = 1/x_n, n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_recip64x64 (int64_t *  frac, int16_t *exp, const int64_t *  x, int N)
void vec_recip32x32 (int32_t *  frac, int16_t *exp, const int32_t *  x, int N)
void vec_recip16x16 (int16_t *  frac, int16_t *exp, const int16_t *  x, int N)
```

Arguments

Type	Name	Size	Description
Input			
`int64_t, int32_t or int16_t`	`x`	`N`	input data, Q63, Q31 or Q15
`int`	`N`		length of vectors
Output			
`int64_t, int32_t or int16_t`	`frac`	`N`	fractional part of result, Q(63-`exp`), Q(31-`exp`) or Q(15-`exp`)
`int16_t`	`exp`	`N`	exponent of result

Returned value

None

Restrictions

`x,frac,exp` should not overlap

Conditions for optimum performance

`frac,x` - aligned on 8-byte boundary
`N` - multiple of 4 and >4

Scalar versions

Prototype

```
uint64_t scl_recip64x64 (int64_t x)
uint32_t scl_recip32x32 (int32_t x)
uint32_t scl_recip16x16 (int16_t x)
```

Arguments

Type	Name	Description
Input		
`int64_t, int32_t or int16_t`	`x`	input data, Q63, Q31 or Q15

Returned value

packed value:
`scl_recip64x64():`
bits 57…0 fractional part
bits 63…58 exponent

`scl_recip32x32():`
bits 23…0 fractional part
bits 31…24 exponent

`scl_recip16x16():`
bits 15…0 fractional part
bits 31…16 exponent

2.3.2 Division of Q63/Q31/Q15 Numbers

Description

These routines perform pair-wise division of vectors written in Q63, Q31 or Q15 format. They return the fractional and exponential portion of the division result. Since the division may generate result greater than 1, it returns fractional portion frac in Q(63-`exp`), Q(31-`exp`) or or Q(15-`exp`) format and exponent exp so true division result in the Q0.63, Q0.31 may be found by shifting fractional part left by exponent value.
For division to 0, the result is not defined

Two versions of routines are available: regular versions (`vec_divide32x32, vec_divide16x16`) work with arbitrary arguments, faster versions (`vec_divide32x32_fast, vec_divide16x16_fast`) apply some restrictions.

NOTE: `scl_divide32x32(), scl_divide64x64()` uses packed output for mantissa/exponent. To take a full precision, just call vectorized counterpart.

Mantissa accuracy is 2 LSB, so relative accuracy is:

`vec_divide16x16, scl_divide16x16`	1.2e-4
`scl_divide32x32`	4.8e-7
`vec_divide32x32`	1.8e-9
`vec_divide64x64`	4.3e-19

Precision

4 variants available:

Type	Description
64x64	64-bit inputs, 64-bit output.
64x32i	integer division, 64-bit nominator, 32-bit denominator, 32-bit output
32x32	32-bit inputs, 32-bit output.
16x16	16-bit inputs, 16-bit output.

Algorithm

$$frac_n \cdot 2^{exp_n} = x_n / y_n, n = \overline{0...N-1}$$

Prototype

```
void vec_divide64x64
                (int64_t * frac, int16_t *exp,
                 const int64_t * x, const int64_t * y, int N);
void vec_divide64x32i
                (int32_t * frac, const int64_t * x, const int32_t * y, int N);
void vec_divide32x32
                (int32_t * frac, int16_t *exp,
                 const int32_t *  x, const int32_t *  y, int N)
void vec_divide16x16
                (int16_t *  frac, int16_t *exp,
                 const int16_t *  x, const int16_t *  y, int N)
void vec_divide32x32_fast
                (int32_t *  frac, int16_t *exp,
                 const int32_t *  x, const int32_t *  y, int N);
void vec_divide16x16_fast
                (int16_t *  frac, int16_t *exp,
                 const int16_t *  x, const int16_t *  y, int N);
```

Arguments

Type	Name	Size	Description
Input			

`int64_t, int32_t or int16_t`	`x`	`N`	nominator, 64-bit integer, Q63, Q31 or Q15
`int64_t, int32_t or int16_t`	`y`	`N`	denominator, 32-bit integer, Q63, Q31 or Q15
`int`	`N`		length of vectors
Output			
`int64_t, int32_t or int16_t`	`frac`	`N`	fractional parts of result, Q(63-`exp`), Q(31-`exp`) or Q(15-`exp`)
`int16_t`	`exp`	`N`	exponents of result

Returned value

none

Restrictions

For regular versions (`vec_divide64x32i, vec_divide64x64, vec_divide32x32, vec_divide16x16`) :
`x,y,frac,exp` should not overlap

For faster versions (`vec_divide32x32_fast, vec_divide16x16_fast`) :
`x,y,frac,exp` should not overlap
`x, y, frac` to be aligned by 8-byte boundary
`N` - multiple of 4.

Scalar versions

Prototype

```
uint64_t scl_divide64x64(int64_t x,int64_t y);
int32_t  scl_divide64x32(int64_t x,int32_t y);
uint32_t scl_divide32x32 (int32_t x, int32_t y)
uint32_t scl_divide16x16 (int16_t x, int16_t y)
```

Arguments

Type	Name	Description
Input		
`int64_t, int32_t or int16_t`	`x`	nominator, 64-bit integer, Q63, Q31 or Q15
`int64_t, int32_t or int16_t`	`y`	denominator, 32-bit integer, Q63, Q31 or Q15

Returned value

`scl_divide64x64()`	packed value: bits 57…0 fractional part,bits 63…58 exponent
`scl_divide64x32()`	integer remainder
`scl_divide32x32()`	packed value: bits 23…0 fractional part,bits 31…24 exponent
`scl_divide16x16()`	packed value: bits 15…0 fractional part, bits 31…16 exponent

2.3.3 Logarithm

Description

Different kinds of logarithm (base 2, natural, base 10). 32-bit fixed point functions interpret input as Q16.15, represent results in Q6.25 format or return 0x80000000 on negative of zero input
Accuracy :

`vec_log2_32x32,scl_log2_32x32`	`730 (2.2e-5)`
`vec_logn_32x32,scl_logn_32x32`	`510 (1.5e-5)`
`vec_log10_32x32,scl_log10_32x32`	`230 (6.9e-6)`
floating point	`2 ULP`

NOTES:
1. Floating point functions are compatible with standard ANSI C routines and set `errno` and exception flags accordingly.
2. Floating point functions limit the range of allowable input values:
   - If `x<0`, the result is set to `NaN`. In addition, scalar floating point functions assign the value `EDOM` to `errno` and raise the "invalid" floating-point exception.
   - If `x==0`, the result is set to minus infinity. Scalar floating point functions assign the value `ERANGE` to `errno` and raise the "divide-by-zero" floating-point exception.

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit outputs
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$z_n = \log_K x_n, n = \overline{0...N-1}, K = 2, e, 10$$

Prototypes

```
void vec_log2_32x32 (  int32_t *  z, const int32_t *  x, int N);
void vec_logn_32x32 (  int32_t *  z, const int32_t *  x, int N);
void vec_log10_32x32(  int32_t *  z, const int32_t *  x, int N);
void vec_log2f      (float32_t *  z, const float32_t *  x, int N);
void vec_lognf      (float32_t *  z, const float32_t *  x, int N);
void vec_log10f     (float32_t *  z, const float32_t *  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
int32_t, float32_t	x	N	input data, Q16.15 or floating point
int	N		length of vectors
Output			
int32_t, float32_t	z	N	Q6.25 or floating point

Returned value

none

Restrictions

x, z – should not overlap

Scalar versions

Prototypes

```
int32_t scl_log2_32x32 (int32_t x);
int32_t scl_logn_32x32 (int32_t x);
int32_t scl_log10_32x32(int32_t x);
float32_t scl_log2f (float32_t x);
float32_t scl_lognf  (float32_t x);
float32_t scl_log10f(float32_t x);
```

Arguments

Type	Name	Description
Input		
int32_t, float32_t	x	input data, Q16.15 or floating point

Returned value

result, Q6.25 or floating point

2.3.4 Antilogarithm

Description

These routines calculate antilogarithm (base2, natural and base10). 32-bit fixed-point functions accept inputs in Q6.25 and form outputs in Q16.15 format and return 0x7FFFFFFF in case of overflow and 0 in case of underflow.

NOTES:

1. Floating point functions are compatible with standard ANSI C routines and set `errno` and exception flags accordingly.

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit outputs. Accuracy: 8e-6*y+1LSB
f	floating point. Accuracy: 2 ULP. Requires VFPU/SFPU core option

Algorithm

$$y_n = 2^{x_n}$$

$$y_n = e^{x_n}$$

$$y_n = 10^{x_n}$$

Prototype

```
void vec_antilog2_32x32(int32_t *  y, const int32_t*  x, int N);
void vec_antilogn_32x32(int32_t *  y, const int32_t*  x, int N);
void vec_antilog10_32x32(int32_t*  y, const int32_t*  x, int N);
void vec_antilog2f (float32_t *  y, const float32_t*  x, int N);
void vec_antilognf (float32_t *  y, const float32_t*  x, int N);
void vec_antilog10f(float32_t *  y, const float32_t*  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
int32_t, float32_t	x	N	input data,Q6.25 or floating point
int	N		length of vectors
Output			
int32_t, float32_t	y	N	output data,Q16.15 or floating point

Returned value none

Restrictions x,y – should not overlap

Conditions for optimum performance
x,y - aligned on 8-byte boundary
N - multiple of 2

Scalar versions

Prototypes

```
int32_t scl_antilog2_32x32 (int32_t x);
int32_t scl_antilogn_32x32 (int32_t x);
int32_t scl_antilog10_32x32(int32_t x);
float32_t scl_antilog2f (float32_t x);
float32_t scl_antilognf (float32_t x);
float32_t scl_antilog10f(float32_t x);
```

Arguments

Type	Name	Description
Input		
int32_t, float32_t	x	input data, Q6.25 or floating point

Returned value result, Q16.15 or floating point

2.3.5 Power Function

Description

This routine calculates power function for 32-bit fixed-point numbers. The base is represented in Q31, the exponent is represented in Q6.25. Results are represented as normalized fixed point number with separate mantissa in Q31 and exponent..
NOTE: function returns 0 for negative base

Precision

1 variant available:

Type	Description
32x32	32-bit inputs, 32-bit outputs. Accuracy: 2 ULP

Algorithm

$$m_n \cdot 2^{e_n} = x_n^{\,y_n}$$

Prototype

```
void vec_pow_32x32(int32_t *  m, int16_t *e,
                   const uint32_t*  x, const int32_t*  y, int N);
```

Arguments

Type	Name	Size	Description
Input			
uint32_t	x	N	input data,Q1.31 (unsigned)
int32_t	y	N	input data,Q6.25
int	N		length of vectors
Output			
int32_t	m	N	mantissa of output, Q31
int16_t	e	N	exponent of output

Returned value none

Restrictions `x,y,m` – should not overlap

2.3.6 Square Root

Description

These routines calculate square root.
NOTE: functions return 0x80000000 on negative argument for 32-bit outputs or 0x8000 for 16-bit outputs

Two versions of functions available: regular version (`vec_sqrt16x16, vec_sqrt32x32, vec_sqrt64x32, vec_sqrt32x16`) with arbitrary arguments and faster version (`vec_sqrt32x32_fast`) that apply some restrictions.

Precision

4 variants available:

Type	Description
16x16	16-bit inputs, 16-bit output. Accuracy: 2 LSB
32x32	32-bit inputs, 32-bit output. Accuracy: (2.6e-7*y+1LSB)
32x16	32-bit input, 16-bit output. Accuracy: 2 LSB
64x32	64-bit input, 32-bit output. Accuracy: 2 LSB

Algorithm

$$y_n = \sqrt{x_n}$$

Prototype

```
void vec_sqrt16x16 (      int16_t*   y, const int16_t  *  x, int N);
void vec_sqrt32x32 (      int32_t*  y, const int32_t*  x, int N);
void vec_sqrt32x16 (      int16_t*  y, const int32_t*  x, int N);
void vec_sqrt64x32 (      int32_t*  y, const int64_t *  x, int N);
void vec_sqrt32x32_fast(  int32_t*  y, const int32_t*  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int64_t, int32_t, int16_t`	`x`	`N`	input data, Q63, Q31, Q15
`int`	`N`		length of vectors
Output			
`int32_t, int16_t`	`y`	`N`	output data, Q31, Q15

Returned value none

Restrictions

Regular versions (`vec_sqrt16x16, vec_sqrt32x32, vec_sqrt32x16, vec_sqrt64x32`):
`x,y` – should not overlap

Faster versions (`vec_sqrt32x32_fast`):
`x,y` – should not overlap
`x,y` - aligned on 8-byte boundary
`N` - multiple of 2

Scalar versions

Prototypes

```
int16_t  scl_sqrt16x16(int16_t x);
int16_t  scl_sqrt32x16(int32_t x);
int32_t  scl_sqrt32x32(int32_t x);
int32_t  scl_sqrt64x32(int64_t x);
```

Arguments

Type	Name	Description
Input		
`int64_t, int32_t, int16_t`	`x`	input data, Q63, Q31, Q15

Returned value result, Q31, Q15

2.3.7 Reciprocal Square Root

Description

These routines return the fractional and exponential portion of the reciprocal square root of a vector `x` of Q31 or Q15 numbers. Since the reciprocal square root is always greater than 1, they return fractional portion `frac` in Q(31-`exp`) or Q(15-`exp`) format and exponent exp so true reciprocal value in the Q0.31/Q0.15 may be found by shifting fractional part left by exponent value.
NOTE: `scl_rsqrt32x32()` uses packed output for mantissa/exponent. To take a full precision, just call vectorized counterpart.
Mantissa accuracy is 1 LSB, so relative accuracy is:

`vec_rsqrt16x16, scl_rsqrt16x16`	6.2e-5
`scl_rsqrt32x32`	2.4e-7
`vec_rsqrt32x32`	9.2e-10

Precision

2 variants available:

Type	Description
32x32	32-bit input, 32-bit output.
16x16	16-bit input, 16-bit output.

Algorithm

$$frac_n \cdot 2^{exp_n} = 1/\sqrt{x_n}, n = 0 \ldots N-1$$

Prototype

```
void vec_rsqrt32x32 (
                    int32_t *  frac, int16_t *exp,
                    const int32_t *  x, int N)
void vec_rsqrt16x16 (
                    int16_t *  frac, int16_t *exp,
                    const int16_t *  x, int N)
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,int16_t`	`x`	`N`	input data, Q31 or Q15
`int`	`N`		length of vectors
Output			
`int32_t, int16_t`	`frac`	`N`	fractional part of result, Q(31-`exp`) or Q(15-`exp`)
`int16_t`	`exp`	`N`	exponent of result

Returned value

None

Restrictions

`x,frac,exp` should not overlap

Scalar versions

Prototype

```
uint32_t scl_rsqrt32x32 (int32_t x)
uint32_t scl_rsqrt16x16 (int16_t x)
```

Arguments

Type	Name	Description
Input		
`int32_t, int16_t`	`x`	input data, Q31 or Q15

Returned value

packed value:
`scl_rsqrt32x32():`
bits 23…0 fractional part
bits 31…24 exponent
`scl_rsqrt16x16():`
bits 15…0 fractional part
bits 31…16 exponent

2.3.8 Sine/Cosine

Description

Fixed-point functions calculate `sin(pi*x)` or `cos(pi*x)` for numbers written in Q31 format. Return results in the same format. Floating point functions compute `sin(x)` or `cos(x)`.
Two versions of functions available: regular version (`vec_sine32x32, vec_cosine32x32, vec_sinef, vec_cosinef`) with arbitrary arguments and faster version (`vec_sine32x32_fast, vec_cosine32x32_fast`) that apply some restrictions.

NOTE:
1. Scalar floating point functions are compatible with standard ANSI C routines and set `errno` and exception flags accordingly.
2. Floating point functions limit the range of allowable input values: [-102940.0, 102940.0] Whenever the input value does not belong to this range, the result is set to `NaN`.

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 1700 (7.9e-7)
f	floating point. Accuracy 2 ULP. Requires VFPU/SFPU core option

Algorithm

For fixed point:

$$y_n = \sin(\pi x_n), n = \overline{0 \ldots N-1}$$ or

$$y_n = \cos(\pi x_n), n = \overline{0 \ldots N-1}$$

For floating point:

$$y_n = \sin(x_n), n = \overline{0 \ldots N-1}$$ or

$$y_n = \cos(x_n), n = \overline{0 \ldots N-1}$$

Prototypes

```
void vec_sine32x32  (  int32_t *  y, const int32_t *  x, int N);
void vec_cosine32x32(int32_t *  y, const int32_t *  x, int N);
void vec_sinef      (  float32_t *  y, const float32_t *  x, int N);
void vec_cosinef    (float32_t *  y, const float32_t *  x, int N);
void vec_sine32x32_fast  (int32_t *  y, const int32_t *  x, int N);
void vec_cosine32x32_fast(int32_t *  y, const int32_t *  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, float32_t`	`x`	`N`	input data,Q31 or floating point
`int`	`N`		length of vectors
Output			
`int32_t, float32_t`	`y`	`N`	Result,Q31 or floating point

Returned value

None

Restrictions

Regular versions (`vec_sine32x32, vec_cosine32x32, vec_sinef, vec_cosinef`):
`x,y` – should not overlap

Faster versions (`vec_sine32x32_fast, vec_cosine32x32_fast`):
`x,y` – should not overlap
`x,y` - aligned on 8-byte boundary
`N` - multiple of 2

Scalar versions

Prototypes

```
int32_t scl_sine32x32   (int32_t x);
int32_t scl_cosine32x32 (int32_t x);
float32_t scl_sinef   (float32_t x);
float32_t scl_cosinef (float32_t x);
```

Arguments

Type	Name	Description
Input		
`int32_t, float32_t`	`x`	input data, Q31 or floating point

Returned value

result, Q31 or floating point

2.3.9 Tangent

Description

Fixed point functions calculate `tan(pi*x)` for number written in Q31. Floating point functions compute `tan(x)`.

NOTE:

1. Scalar floating point function is compatible with standard ANSI C routines and sets `errno` and exception flags accordingly.
2. Floating point functions limit the range of allowable input values: [-9099, 9099]. Whenever the input value does not belong to this range, the result is set to `NaN`.

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit outputs. Accuracy: (1.3e-4*`y`+1 LSB) if `abs(y)<=464873` (`14.19` in Q15) or `abs(x)<pi*0.4776`
f	floating point, Accuracy: 2 ULP. Requires VFPU/SFPU core option

Algorithm

for fixed point:

$$y_n = \tan(\pi x_n), n = \overline{0 \ldots N-1}$$

for floating point

$$y_n = \tan(x_n), n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_tan32x32 (int32_t*    y, const int32_t * x, int N);
void vec_tanf (float32_t * y, const float32_t * x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t`, `float32_t`	`x`	`N`	input data, Q31 or floating point
`int`	`N`		length of vectors
Output			
`int32_t`, `float32_t`	`y`	`N`	result, Q16.15 or floating point

Returned value

none

Restrictions

`x,y` – should not overlap

Conditions for optimum performance

`x,y` - aligned on 8-byte boundary
`N` - multiple of 2

Scalar versions

Prototype

```
int32_t scl_tan32x32 (int32_t x);
float32_t scl_tanf (float32_t x);
```

Arguments

Type	Name	Description
Input		
`int32_t`, `float32_t`	`x`	input data,Q31 or floating point

Returned value

result, Q16.15 or floating point

2.3.10 Arctangent

Description

Functions calculate arctangent of number. Fixed point functions scale down the output to `pi`

NOTE:

1. Scalar floating point function is compatible with standard ANSI C routines and sets `errno` and

exception flags accordingly

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 42 (2.0e-8)
f	floating point. Accuracy: 2 ULP. Requires VFPU/SFPU core option

Algorithm

for fixed point

$$z_n = \arctan(x_n)/\pi, n = \overline{0 \ldots N-1}$$

for floating point

$$z_n = \arctan(x_n), n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_atan32x32 (int32_t *  z,
              const int32_t *  x,
              int N );
void vec_atanf (    float32_t *  z,
              const float32_t *  x,
              int N );
```

Arguments

Type	Name	Size	Description
Input			
int32_t, float32_t	x	N	input data, Q31 or floating point
int	N		length of vectors
Output			
int32_t, float32_t	z	N	result, Q31 or floating point

Returned value

None

Restrictions

`x,z` should not overlap

Conditions for optimum performance

`x,z` aligned on 8-byte boundary
`N` multiple of 2

Scalar versions

Prototype

```
int32_t scl_atan32x32 (int32_t x);
float32_t scl_atanf (float32_t x);
```

Arguments

Type	Name	Description
Input		
int32_t, float32_t	x	input data, Q31 or floating point

Returned value

result, Q31 or floating point

2.3.11 Full Quadrant Arctangent

Description

The functions compute the full quadrant arc tangent of the ratio `y/x`. Floating point finctions is in radians. Fixed point functions scale its output by pi.
NOTE:

1. Scalar floating point function is compatible with standard ANSI C routines and sets `errno` and exception flags accordingly
2. Scalar floating point function assigns `EDOM` to `errno` whenever `y==0` and `x==0`.

Precision

1 variant available:

Type	Description
f	floating point. Accuracy: 2 ULP. Requires VFPU/SFPU core option

Algorithm

$$z_n = \arctan(y_n / x_n), n = \overline{0...N-1}$$

Prototype

```
void vec_atan2f (float32_t * z, const float32_t * y, const float32_t * x,int N);
```

Arguments

Type	Name	Size	Description
Input			
`float32_t`	`x`	`N`	input data, Q31 or floating point
`float32_t`	`y`	`N`	input data, Q31 or floating point
`int`	`N`		length of vectors
Output			
`float32_t`	`z`	`N`	result, Q31 or floating point

Returned value None

Restrictions `x, y, z` should not overlap

Scalar versions

Prototype

```
float32_t scl_atan2f (float32_t y, float32_t x);
```

Arguments

Type	Name	Description
Input		
`float32_t`	`y`	input data, Q31 or floating point
`float32_t`	`x`	input data, Q31 or floating point

Returned value result, Q31 or floating point

2.3.12 Hyperbolic Tangent

Description The functions compute the hyperbolic tangent of input argument. 32-bit fixed-point functions accept inputs in Q6.25 and form outputs in Q16.15 format.

Precision 2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 2 LSB
f	floating point input, floating point output, Accuracy: 2 ULP

Algorithm

$$y_n = \tanh(x_n), n = \overline{0...N-1}$$

Prototype

```
void vec_tanh32x32 (int32_t * y, const int32_t * x,int N);
void vec_tanhf     (float32_t * y, const float32_t * x,int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, float32_t`	`x`	`N`	input data, Q6.25 or floating point
`int`	`N`		length of vectors
Output			
`int32_t, float32_t`	`y`	`N`	result, Q16.15 or floating point

Returned value None

Restrictions `x, y` should not overlap

Scalar versions

Prototype

```
int32_t scl_tanh32x32 (int32_t x);
float32_t scl_tanhf     (float32_t x);
```

Arguments

Type	Name	Description
Input		
`int32_t, float32_t`	`x`	input data, Q6.25 or floating point

Returned value result, Q16.15 or floating point

2.3.13 Sigmoid

Description The functions compute the sigmoid of input argument. 32-bit fixed-point functions accept inputs in Q6.25 and form outputs in Q16.15 format.

Precision 2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 2 LSB
f	floating point input, floating point output. Accuracy 2 ULP

Algorithm

$$y_n = \frac{1}{1+\exp(-x_n)}, n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_sigmoid32x32 (int32_t   * y, const int32_t   * x,int N);
void vec_sigmoidf     (float32_t * y, const float32_t * x,int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, float32_t`	`x`	`N`	input data, Q6.25 or floating point
`int`	`N`		length of vectors
Output			
`int32_t, float32_t`	`y`	`N`	result, Q16.15 or floating point

Returned value None

Restrictions `x`, `y` should not overlap

Scalar versions

Prototype

```
int32_t scl_sigmoid32x32 (int32_t   x);
float32_t scl_sigmoidf     (float32_t x);
```

Arguments

Type	Name	Description
Input		
`int32_t, float32_t`	`x`	input data, Q6.25 or floating point

Returned value result, Q16.15 or floating point

2.3.14 Rectifier function

Description The functions compute the rectifier linear unit function of input argument. 32-bit fixed-point functions accept inputs in Q6.25 and form outputs in Q16.15 format. Parameter `K` allows to set upper threshold for proper compression of output signal.

Precision 2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 2 LSB
f	floating inputs, floating output. Accuracy: 2 ULP

Algorithm

$$y_n = \max(0, \min(x, K)), n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_relu32x32 (int32_t   * y, const int32_t   * x, int32_t   K, int N);
void vec_reluf     (float32_t * y, const float32_t * x, float32_t K, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, float32_t`	`x`	`N`	input data, Q6.25 or floating point

`int32_t, float32_t`	`K`		threshold, Q16.15 or floating poin
`int`	`N`		length of vectors
Output			
`int32_t, float32_t`	`y`	`N`	result, Q16.15 or floating poin

Returned value None

Restrictions `x, y` should not overlap

Scalar versions

Prototype

```
int32_t   scl_relu32x32 (int32_t   x, int32_t   K);
float32_t scl_reluf     (float32_t x, float32_t K);
```

Arguments

Type	Name	Description
Input		
`int32_t`	`x`	input data, Q6.25 or floating point
`int32_t`	`K`	threshold, Q16.15 or floating point

threshould.

Returned value result, Q16.15 or floating point

2.3.15 Softmax

Description The function computes the softmax (normalized exponential function) of input data. 32-bit fixed-point functions accept inputs in Q6.25 and form outputs in Q16.15 format.

Precision 2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output. Accuracy: 2 LSB (see Note below)
f	floating point input, floating point output

Note: Accuracy of function may depend on amount of data and their distribution. Given accuracy is achieved for N=2 for any pair of data from input domain.

Algorithm

$$y_n = \frac{\exp(x_n)}{\sum_k \exp(x_k)}, n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_softmax32x32 (int32_t   * y, const int32_t   * x,int N);
void vec_softmaxf     (float32_t * y, const float32_t * x,int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, float32_t`	`x`	`N`	input data, Q6.25 or floating point
`int`	`N`		length of vectors
Output			
`int32_t, float32_t`	`y`	`N`	result, Q16.15 or floating point

Returned value None

Restrictions `x, y` should not overlap

2.3.16 Integer to Float Conversion

Description Routine converts integer to float and scales result up by `2^t`.

Precision 1 variant available:

Type	Description

f	32-bit input, floating point output. Requires VFPU/SFPU core option

Algorithm

$$y_n = x_n \cdot 2^t, n = \overline{0...N-1}$$

Prototype

```
void   vec_int2float
      ( float32_t  *  y,
        const int32_t  *  x,
        int t, int N);
```

Arguments

Type	Name	Size	Description
Input			
int32_t	x	N	input data, integer
int	t		scale factor
int	N		length of vectors
Output			
float32_t	y	N	Conversion result, floating point

Returned value

None

Restrictions

`t` should be in range `-126...126`

Scalar version

Prototype

```
float32_t scl_int2float (int32_t x, int t);
```

Arguments

Type	Name	Description
Input		
int32_t	x	input data, integer

Returned value

result, floating point

Restrictions

`t` should be in range `-126...126`

2.3.17 Float to Integer Conversion

Description

Routine scales floating point input down by `2^t` and converts it to integer with saturation

Precision

1 variant available:

Type	Description
f	floating point input, 32-bit output. Requires VFPU core option

Algorithm

$$y_n = x_n \cdot 2^{-t}, n = \overline{0...N-1}$$

Prototype

```
void   vec_float2int
         (  int32_t *  y,
            const float32_t *  x,
            int t, int N);
```

Arguments

Type	Name	Size	Description
Input			
float32_t	x	N	input data, floating point
int	t		scale factor
int	N		length of vectors
Output			
int32_t	y	N	Conversion results, integers

Returned value

None

Restrictions

`t` should be in range `-126...126`

Scalar version

Prototype

```
int32_t scl_float2int (float32_t x, int t);
```

Arguments

Type	Name	Description
Input		

`float32_t`	`x`	input data, floating point

Returned value result, integer

Restrictions `t` should be in range `-126...126`

2.4 Complex Mathematics

2.4.1 Complex Magnitude

Description

Routines compute complex magnitude or its reciprocal

Precision

1 variant available:

Type	Description
f	floating point input, 32-bit output. Requires VFPU/SFPU core option

Algorithm

$$y_n = abs(x_n), n = \overline{0...N-1}$$

$$y_n = 1/abs(x_n), n = \overline{0...N-1}$$

Prototype

```
void vec_complex2mag    (float32_t  *  y, const complex_float  *  x, int N);
void vec_complex2invmag (float32_t  *  y, const complex_float  *  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
complex_float	x	N	input data
int	N		length of vectors
Output			
float32_t	y	N	magnitude or its reciprocal

Returned value

None

Restrictions

None

Scalar version

Prototype

```
float32_t  scl_complex2mag    (complex_float x);
float32_t  scl_complex2invmag (complex_float x);
```

Arguments

Type	Name	Description
Input		
complex_float	x	input data

Returned value

result, floating point

Restrictions

None

2.5 Vector Operations

2.5.1 Vector Dot Product

Description

These routines take two vectors and calculates their dot product. Two versions of routines are available: regular versions (`vec_dot32x16`, `vec_dot32x32`, `vec_dot16x16`, `vec_dotf`) work with arbitrary arguments, faster versions (`vec_dot32x16_fast`, `vec_dot32x32_fast`, `vec_dot16x16_fast`) apply some restrictions.

Precision

7 variants available:

Type	Description
64x32	64x32-bit data, 64-bit output (fractional multiply Q63xQ31->Q63)
64x64	64x64-bit data, 64-bit output (fractional multiply Q63xQ63->Q63)
64x64i	64x64-bit data, 64-bit output (low 64 bit of integer multiply)
32x16	32x16-bit data, 64-bit output
32x32	32x32-bit data, 64-bit output
16x16	16x16-bit data, 64-bit output for regular version and 32-bit for fast version
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r = \sum_{n=0}^{N-1} x_n y_n$$

Prototype

```
int64_t vec_dot64x32 (const int64_t   *  x,const int32_t * y, int N);
int64_t vec_dot64x64 (const int64_t   *  x,const int64_t * y, int N);
int64_t vec_dot64x64i(const int64_t   *  x,const int64_t * y, int N);
int64_t vec_dot32x16 (const int32_t   *x, const int16_t  * y, int N);
int64_t vec_dot16x16 (const int16_t   *x, const int16_t  * y, int N);
int64_t vec_dot32x32 (const int32_t   *x, const int32_t  * y, int N);
float32_t vec_dotf   (const float32_t *x, const float32_t* y, int N);

int64_t vec_dot64x32_fast (const int64_t * x,const int32_t * y,int N);
int64_t vec_dot64x64_fast (const int64_t * x,const int64_t * y,int N);
int64_t vec_dot64x64i_fast(const int64_t * x,const int64_t * y,int N);
int64_t vec_dot32x16_fast (const int32_t *  x, const int16_t *  y, int N);
int64_t vec_dot32x32_fast (const int32_t *  x, const int32_t *  y, int N);
int32_t vec_dot16x16_fast (const int16_t *  x, const int16_t *  y, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int64_t`, `int32_t`, `int16_t`, `float32_t`	`x`	`N`	input data, Q63, Q31, Q15 or floating point
`int64_t`, `int16_t`, `float32_t`	`y`	`N`	input data, Q63, Q31, Q15 or floating point
`int`	`N`		length of vectors

Returned value

dot product of all data pairs, Q63, Q31 or floating point

Restrictions

Regular versions (`vec_dot64x32`, `vec_dot64x64`, `vec_dot64x64i`, `vec_dot32x16`, `vec_dot32x32`, `vec_dot16x16`, `vec_dotf`):
None

Faster versions (`vec_dot64x32_fast`, `vec_dot64x64_fast`, `vec_dot64x64i_fast`, `vec_dot32x16_fast`, `vec_dot32x32_fast`, `vec_dot16x16_fast`):
`x,y` - aligned on 8-byte boundary
`N` - multiple of 4

`vec_dot16x16_fast` utilizes 32-bit saturating accumulator, so, input data should be scaled properly to avoid erroneous results especially in case of heterogenic data.

2.5.2 Vector Sum

Description

This routine makes pair wise saturated summation of vectors. Two versions of routines are available: regular versions (`vec_add32x32, vec_add16x16, vec_addf`) work with arbitrary arguments, faster versions (`vec_add32x32_fast, vec_add16x16_fast`) apply some restrictions.

Precision

3 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output
16x16	16-bit inputs, 16-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$z_n = x_n + y_n, n = \overline{0...N-1}$$

Prototype

```
void vec_add32x32 ( int32_t*  z, const int32_t*  x, const int32_t*  y, int N);
void vec_add16x16 ( int16_t*  z, const int16_t*  x, const int16_t*  y, int N);
void vec_addf(float32_t*  z, const float32_t*  x, const float32_t*  y, int N);

void vec_add32x32_fast(int32_t*  z, const int32_t*  x, const int32_t*  y,int N);
void vec_add16x16_fast(int16_t*  z, const int16_t*  x, const int16_t*  y,int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t or float32_t`	`x`	`N`	input data
`int32_t, int16_t or float32_t`	`y`	`N`	input data
`int`	`N`		length of vectors
Output			
`int32_t, int16_t or float32_t`	`z`	`N`	output data

Returned value

none

Restrictions

Regular versions (`vec_add32x32, vec_add16x16, vec_addf`):
`x,y,z` - should not be overlapped

Faster versions (`vec_add32x32_fast, vec_add16x16_fast`):
`z,x,y` - aligned on 8-byte boundary
`N` - multiple of 4

2.5.3 Power of a Vector

Description

These routines compute power of vector with scaling output result by `rsh` bits. Fixed point rountines make accumulation in the 64-bit wide accumulator and output may scaled down with saturation by `rsh` bits. So, if representation of `x` input is `Qx`, result will be represented in `Q(2x-rsh)` format.
Two versions of routines are available: regular versions (`vec_power32x32, vec_power16x16, vec_powerf`) work with arbitrary arguments,
faster versions (`vec_power32x32_fast, vec_power16x16_fast`) apply some restrictions.

Precision

3 variants available:

Type	Description
32x32	32x32-bit data, 64-bit output
16x16	16x16-bit data, 64-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r = \frac{1}{2^{rsh}} \sum_{n=0}^{N-1} |x_n|^2$$

Prototype

```
int64_t     vec_power32x32 ( const int32_t *  x,
                             int rsh, int N);
int64_t     vec_power16x16 ( const int16_t *  x,
                             int rsh, int N);
float32_t   vec_powerf     ( const float32_t *  x, int N);

int64_t     vec_power32x32_fast ( const int32_t *  x,
                             int rsh, int N)
int64_t     vec_power16x16_fast ( const int16_t *  x,
                             int rsh, int N)
```

Arguments

Type	Name	Size	Description
Input			
`int32_t`, `int16_t`, `float32_t`	`x`	`N`	input data, Q31, Q15 or floating point
`int`	`rsh`		right shift of result (only for fixed point routines): for `vec_power32x32()`: `rsh` should be in range 31...62 for `vec_power16x16()`: `rsh` should be in range 0...31
`int`	`N`		length of vector

Returned value

Sum of squares of a vector, Q(`2x-rsh`) or floating point

Restrictions

For regular versions (`vec_power32x32, vec_power16x16, vec_powerf`):
none

For faster versions (`vec_power32x32_fast, vec_power16x16_fast`)
`x` - aligned on 8-byte boundary
`N` - multiple of 4

2.5.4 Vector Scaling with Saturation

Description

These routines make shift with saturation of data values in the vector by given scale factor (degree of 2).
Functions `vec_scale()` make multiplication of vector to coefficient which is not a power of 2.
Two versions of routines are available: regular versions (`vec_shift32x32, vec_shift16x16, vec_shiftf, vec_scale32x32, vec_scale16x16, vec_scalef, vec_scale_sf`) work with arbitrary arguments, faster versions (`vec_shift32x32_fast, vec_shift16x16_fast, vec_scale32x32_fast, vec_scale16x16_fast`) apply some restrictions.
For floating point:
Function `vec_shiftf()` makes scaling without saturation of data values in the vector by given scale factor (degree of 2). Functions `vec_scalef()` and `vec_scale_sf()` make multiplication of input vector to coefficient which is not a power of 2. `vec_scalef()` makes scaling without saturations, `vec_scale_sf()` allows to saturate results on given boundaries.

Precision

3 variants available:

Type	Description
32x32	32-bit input, 32-bit output
16x16	16-bit input, 16-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$r_n = x_n \cdot 2^t$$

Prototype

```
void vec_shift32x32 (      int32_t *  y,
                     const int32_t *  x, int t, int N);
void vec_shift16x16 (      int16_t *  y,
                     const int16_t *  x, int t, int N);
void vec_shiftf     (      float32_t *  y,
                     const float32 *  x, int t, int N);
void vec_shift32x32_fast (      int32_t *  y,
                     const int32_t *  x, int t, int N);
void vec_shift16x16_fast (      int16_t *  y,
                     const int16_t *  x, int t, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t or float32_t`	`x`	`N`	input data, Q31, Q15 or floating point
`int`	`t`		shift count. If positive, it shifts left with saturation, if negative it shifts right
`int`	`N`		length of vector
Output			
`int32_t, int16_t or float32_t`	`y`	`N`	output data, Q31, Q15 or floating point

Prototype

non-power 2 scaling

```
void vec_scale32x32 (      int32_t *  y,
                     const int32_t *  x, int32_t s, int N);
void vec_scale16x16 (      int16_t *  y,
                     const int16_t *  x, int16_t s, int N);
void vec_scalef     (      float32_t *  y,
                     const float32_t *  x, float32_t s, int N);
void vec_scale_sf   (      float32_t * y,
                     const float32_t * x,
                     float32_t s, float32_t fmin, float32_t fmax, int N);
void vec_scale32x32_fast (      int32_t*  y,
                     const int32_t *  x, int32_t s, int N);
void vec_scale16x16_fast (      int16_t *  y,
                     const int16_t *  x, int16_t s, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t or float32_t`	`x`	`N`	input data, Q31, Q15 or floating point
`int16_t, float32_t`	`s`		scale factor, Q31, Q15 or floating point
`int`	`N`		length of vector
`float32_t`	`fmin`		lower bound of resulted values (for `vec_scale_sf()` only)
`float32_t`	`fmax`		upper bound of resulted values (for `vec_scale_sf()` only)
Output			
`int32_t, int16_t or float32_t`	`y`	`N`	output data, Q31, Q15 or floating point

Returned value

None

Restrictions

For regular versions (`vec_shift32x32, vec_shift16x16, vec_shiftf, vec_scale32x32, vec_scale16x16, vec_scalef, vec_scalesf`):
`x,y` should not overlap
`t` should be in range -31...31 for fixed-point functions and -129...146 for floating point

For faster versions (`vec_shift32x32_fast, vec_shift16x16_fast, vec_scale32x32_fast, vec_scale16x16_fast`):
`x,y` should not overlap
`t` should be in range -31…31
`x,y` - aligned on 8-byte boundary
`N` - multiple of 4

2.5.5 Common Exponent

Description

These functions determine the number of redundant sign bits for each value (as if it was loaded in a 32-bit register) and returns the minimum number over the whole vector. This may be useful for a FFT implementation to normalize data.
Floating point function returns `0-floor(log2(max(abs(x))))`. Returned result will be always in range

`[-129...146].`

Special cases

Input	Result
0	0
+/-Inf	-129
NaN	0

NOTES:
Faster versions of functions make the same task but in a different manner – they compute exponent of maximum absolute value in the array. It allows faster computations but not bitexact results – if minimum value in the array will be -2^n , fast function returns `max(0,30-n)` while non-fast function returns `(31-n)`. Functions return zero if `N<=0`

Precision

3 variants available:

Type	Description
32	32-bit inputs
16	16-bit inputs
f	floating point inputs. Requires VFPU/SFPU core option

Algorithm

$$z_n = \min_{n=0...N-1}\left(norm(x_n) \right) \quad \text{non-fast version}$$

$$z_n = \min_{n=0...N-1}\left(norm(abs(x_n)) \right) \quad \text{fast version}$$

$$z_n = -floor\left(\log_2(\max_{n=0...N-1}(abs(x_n))) \right) \quad \text{for floating point}$$

where `norm` is exponent value (maximum possible shift count) for 32-bit data.

Prototype

```
int vec_bexp32 (const int32_t *  x, int N);
int vec_bexp16 (const int16_t *  x, int N);
int vec_bexpf  (const float32_t *  x, int N);

int vec_bexp32_fast (const int32_t *  x, int N);
int vec_bexp16_fast (const int16_t *  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t, float32_t`	`x`	`N`	input data
`int`	`N`		length of vector

Returned value

minimum exponent

Restrictions

non-fast functions (`vec_bexp16, vec_bexp32, vec_bexpf`):
none
for fast functions (`vec_bexp16_fast, vec_bexp32x32_fast`):
`x,y` - aligned on 8-byte boundary
`N` - multiple of 4

Scalar versions

Prototype

```
int scl_bexp32 (int32_t x);
int scl_bexp16 (int16_t x);
int scl_bexpf  (float32_t x);
```

Arguments

Type	Name	Description
Input		
`int32_t, int16_t,`	`x`	input data

`float32_t`		

Returned value result

2.5.6 Vector Min/Max

Description

These routines find maximum/minimum value in a vector.
Two versions of functions available: regular version (`vec_min32x32, vec_max32x32, vec_max16x16, vec_min16x16,vec_maxf, vec_minf`) with arbitrary arguments and faster version (`vec_min32x32_fast, vec_max32x32_fast, vec_min16x16_fast, vec_min16x16_fast`) that apply some restrictions
NOTE: functions return zero if `N` is less or equal to zero

Precision

3 variants available:

Type	Description
32x32	32-bit data, 32-bit output
16x16	16-bit data, 16-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$v = \min(x_n), n = \overline{0...N-1}$$

or

$$v = \max(x_n), n = \overline{0...N-1}$$

Prototype

```
int32_t   vec_min32x32 (const int32_t  *  x, int N);
int16_t   vec_min16x16 (const int16_t  *  x, int N);
float32_t vec_minf     (const float32_t*  x, int N);
int32_t vec_max32x32   (const int32_t  *  x, int N);
int16_t vec_max16x16   (const int16_t  *  x, int N);
float32_t vec_maxf     (const float32_t*  x, int N);
int32_t vec_min32x32_fast (const int32_t*  x, int N);
int16_t vec_min16x16_fast (const int16_t*  x, int N);
int32_t vec_max32x32_fast (const int32_t*  x, int N);
int16_t vec_max16x16_fast (const int16_t*  x, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t, float32_t`	`x`	`N`	input data
`int`	`N`		length of vector

Returned value minimum or maximum value

Restrictions

For regular routines (`vec_min32x32, vec_max32x32, vec_max16x16, vec_min16x16,vec_maxf, vec_minf`) :
none
For faster routines (`vec_min32x32_fast, vec_max32x32_fast, vec_min16x16_fast, vec_min16x16_fast`):
`x` aligned on 8-byte boundary
`N` - multiple of 4

2.6 Emulated Floating Point Operations

These routines make basic operations with emulated floating point data representing in pairs 32-bit mantissa/16-bit exponent. Mantissa is represented in 2's complement format (as usual integer numbers). Input data might be normalized (positive mantissa from 0x40000000 to 0x7FFFFFFF, negative mantissa from 0x80000000 to 0xBFFFFFFF) or denormalized (mantissa in range from 0xC0000000 to 0x3FFFFFFF). Denormalized numbers are allowed on input, but may cause degraded accuracy. However, on output all functions form normalized numbers.
Exponent bias is 31 so floating point number 1 might be represented as:
- mantissa 0x7FFFFFFF (1 in Q31 representation), exponent 0 (this not exact 1,0 but 0,99999999953)

- mantissa 0x40000000, (1 in Q30 representation), exponent 1
- mantissa 0x20000000, (1 in Q29 representation), exponent 2

and so on.

Special numbers are represented as following:
- zero: mantissa is `0`, exponent does not care. Negative zero is not representable
- positive infinity: mantissa `0x7fffffff`, exponent `0x7fff`
- negative infinity: mantissa `0x80000000`, exponent `0x7fff`

Not a numbers (NaNs) do not have special encoding and cannot be carried by this format.

Comparing with usual single precision floating point computations, these emulation functions

- have wider dynamic range (approximately from 10^{-9873} to 10^{9864})
- have better resolution (31-bit mantissa vs 23-bit in single precision floating point)
- underflowed numbers are converted to zeroes so denormalized numbers are never occurred on the output (but allowable on input)
- result of zero to infinity multiply is not defined
- rounding mode is not specified

It is important to note that similarly as for usual floating point computations, the results of emulated floating point operations may depend on the data order so (a+b)+c may not be exactly the same as a+(b+c) and (a+b)*c may not be equal to a*c+b*c. The difference is explained by different sequence of rounding and normalization.

2.6.1 Vector Addition for Emulated Floating Point

Description add two vectors represented in emulated floating point format

Algorithm $z_n = x_n + y_n, n = \overline{0 \ldots N-1}$

Prototype

```
void   vec_add_32x16ef (      int32_t  *  zmant,       int16_t  *  zexp,
                        const int32_t  *  xmant, const int16_t  *  xexp,
                        const int32_t  *  ymant, const int16_t  *  yexp,
                        int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant, ymant`	`N`	mantissa of input data, Q31
`int16_t,`	`xexp, yexp`	`N`	exponent of input data
`int`	`N`		length of vector
Output			
`int32_t,`	`zmant`	`N`	mantissa of output data, Q31
`int16_t,`	`zexp`	`N`	exponent of output data

Returned value none

Scalar function

```
void   scl_add_32x16ef (      int32_t  * zmant, int16_t *  zexp,
                              int32_t    xmant, int16_t    xexp,
                              int32_t    ymant, int16_t    yexp);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant, ymant`		mantissa of input data, Q31
`int16_t,`	`xexp, yexp`		exponent of input data
Output			
`int32_t,`	`zmant`	`1`	mantissa of output data, Q31
`int16_t,`	`zexp`	`1`	exponent of output data

Restrictions `xmant,ymant,xexp,yexp,zmant,zexp` should not overlap

2.6.2 Vector Multiply for Emulated Floating Point

Description multiply two vectors represented in emulated floating point format

Algorithm

$$z_n = x_n \cdot y_n, n = \overline{0 \ldots N-1}$$

Prototype

```
void   vec_mul_32x16ef (      int32_t  *  zmant,       int16_t  *  zexp,
                        const int32_t  *  xmant, const int16_t  *  xexp,
                        const int32_t  *  ymant, const int16_t  *  yexp,
                        int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant, ymant`	N	mantissa of input data, Q31
`int16_t,`	`xexp, yexp`	N	exponent of input data
`int`	`N`		length of vector
Output			
`int32_t,`	`zmant`	N	mantissa of output data, Q31
`int16_t,`	`zexp`	N	exponent of output data

Returned value none

Scalar function

```
void   scl_mul_32x16ef (      int32_t  * zmant, int16_t *   zexp,
                              int32_t    xmant, int16_t     xexp,
                              int32_t    ymant, int16_t     yexp);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant, ymant`		mantissa of input data, Q31
`int16_t,`	`xexp, yexp`		exponent of input data
Output			
`int32_t,`	`zmant`	1	mantissa of output data, Q31
`int16_t,`	`zexp`	1	exponent of output data

Restrictions `xmant,ymant,xexp,yexp,zmant,zexp` should not overlap

2.6.3 Vector Multiply-Accumulate for Emulated Floating Point

Description make multiply-accumulate with scalar for data represented in emulated floating point format

Algorithm

$$z_n = z_n + x_n \cdot y, n = \overline{0 \ldots N-1}$$

Prototype

```
void   vec_mac_32x16ef (      int32_t  *  zmant,       int16_t  *  zexp,
                        const int32_t  *  xmant, const int16_t  *  xexp,
                              int32_t     ymant,       int16_t     yexp,
                        int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant`	N	mantissa of input data, Q31
`int16_t,`	`xexp`	N	exponent of input data
`int32_t,`	`ymant`		mantissa of scalar, Q31
`int16_t,`	`yexp`		exponent of scalar
`int`	`N`		length of vector
Input/Output			
`int32_t,`	`zmant`	N	mantissa of input/output data, Q31
`int16_t,`	`zexp`	N	exponent of input/output data

Returned value none

Scalar function

```
void   scl_mac_32x16ef (      int32_t  * zmant, int16_t *   zexp,
                              int32_t    xmant, int16_t     xexp,
                              int32_t    ymant, int16_t     yexp);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant, ymant`		mantissa of input data, Q31
`int16_t,`	`xexp, yexp`		exponent of input data
Output			
`int32_t,`	`zmant`	1	mantissa of input/output data, Q31
`int16_t,`	`zexp`	1	exponent of input/output data

Restrictions `xmant,xexp, zmant,zexp` should not overlap

2.6.4 Vector Dot Product for Emulated Floating Point

Description dot product of input data represented in emulated floating point format

Algorithm

$$z = \sum_{n=0}^{N-1} x_n \cdot y_n$$

Prototype

```
void   vec_dot_32x16ef (      int32_t  *  zmant,       int16_t  *  zexp,
                        const int32_t  *  xmant, const int16_t  *  xexp,
                        const int32_t  *  ymant, const int16_t  *  yexp,
                        int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t,`	`xmant`	N	mantissa of input data, Q31
`int16_t,`	`xexp`	N	exponent of input data
`int32_t,`	`ymant`	N	mantissa of input data, Q31
`int16_t,`	`yexp`	N	exponent of input data
`int`	`N`		length of vector
Input/Output			
`int32_t,`	`zmant`	1	mantissa of input/output data, Q31
`int16_t,`	`zexp`	1	exponent of input/output data

Returned value none

Restrictions `xmant,ymant,xexp,yexp,zmant,zexp` should not overlap

2.7 Matrix Operations

2.7.1 Matrix Multiply

Description

These functions compute the expression `z = 2^lsh * x * y` for the matrices `x` and `y`. The column 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`.
Transposing API allows to interpret input `yt` as transposed matrix `y`.
NOTE: `lsh` factor is not relevant for floating point routines.

Functions require scratch memory for storing intermediate data. This scratch memory area should be aligned on 8 byte boundary and its size is calculated by corresponding funcitons

Two versions of functions available: regular version (`mtx_mpy[t]32x32, mtx_mpy[t]16x16, mtx_mpy[t]8x16, mtx_mpy[t]8x8, mtx[t]_mpyf`) with arbitrary arguments and faster version (`mtx_mpy[t]32x32_fast, mtx_mpy[t]16x16_fast, mtx_mpy[t]8x16_fast, mtx_mpy[t]8x8_fast, mtx_mpy[t]f_fast`) that apply some restrictions.

Precision

5 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output
16x16	16-bit inputs, 16-bit output
8x8	8-bit inputs, 8-bit output
8x16	8/16-bit inputs, 16-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

For fixed-point routines:

$$z_{m,p} = 2^{lsh} \sum_{n=0}^{N-1} x_{m,n} \cdot y_{n,p}, m = \overline{0...M-1}, p = \overline{0...P-1}$$

For floating point routines:

$$z_{m,p} = \sum_{n=0}^{N-1} x_{m,n} \cdot y_{n,p}, m = \overline{0...M-1}, p = \overline{0...P-1}$$

Prototype

```
void mtx_mpy32x32 (  void* pScr,
                     int32_t*  z, const int32_t*  x, const int32_t*  y,
                     int M, int N, int P, int lsh );
void mtx_mpy16x16 (  void* pScr,
                     int16_t*  z, const int16_t*  x, const int16_t*  y,
                     int M, int N, int P, int lsh );
void mtx_mpy8x8   (  void* pScr,
                     int8_t*  z, const int8_t*  x, const int8_t*  y,
                     int M, int N, int P, int lsh );
void mtx_mpy8x16 (  void* pScr,
                     int16_t*  z, const int8_t*  x, const int16_t*  y,
                     int M, int N, int P, int lsh );
void mtx_mpyf (       void* pScr,
                     float32_t*   z, const float32_t*   x, const float32_t*   y,
                     int M, int N, int P);
```

```
void mtx_mpy32x32_fast (  void* pScr,
                  int32_t* z,const int32_t* x, const int32_t* y,
                  int M, int N, int P, int lsh );
void mtx_mpy16x16_fast (  void* pScr,
                  int16_t* z, const int16_t* x, const int16_t* y,
                  int M, int N, int P, int lsh );
void mtx_mpy8x8_fast (  void* pScr,
                  int8_t* z, const int8_t* x, const int8_t* y,
                  int M, int N, int P, int lsh );
void mtx_mpy8x16_fast (  void* pScr,
                  int16_t* z, const int8_t* x, const int16_t* y,
                  int M, int N, int P, int lsh );
void mtx_mpyf_fast (void* pScr,
                  float32_t*   z, const float32_t*   x, const float32_t*   y,
                  int M, int N, int P);
```

Prototype (transposing API)

```
void mtx_mpyt16x16 ( void* pScr,
                     int16_t*  z, const int16_t*  x, const int16_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt8x8  ( void* pScr,
                     int8_t*  z, const int8_t*  x, const int8_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt8x16( void* pScr,
                     int16_t*  z, const int8_t*  x, const int16_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt32x32 ( void* pScr,
                     int32_t*  z, const int32_t*  x, const int32_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpytf (     void* pScr,
                     float32_t* z, const float32_t* x, const float32_t* yt,
                     int M, int N, int P);
void mtx_mpyt16x16_fast (  void* pScr,
                     int16_t*  z, const int16_t*  x, const int16_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt8x8_fast (  void* pScr,
                     int8_t*  z, const int8_t*  x, const int8_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt8x16_fast (  void* pScr,
                     int16_t*  z, const int8_t*  x, const int16_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpyt32x32_fast (  void* pScr,
                     int32_t*  z, const int32_t*  x, const int32_t*  yt,
                     int M, int N, int P, int lsh );
void mtx_mpytf_fast( void* pScr,
                     float32_t* z, const float32_t* x, const float32_t* yt,
                     int M, int N, int P);
```

Function name	Scratch allocation function
mtx_mpy16x16	mtx_mpy16x16_getScratchSize
mtx_mpy8x8	mtx_mpy8x8_getScratchSize
mtx_mpy8x16	mtx_mpy8x16_getScratchSize
mtx_mpy32x32	mtx_mpy32x32_getScratchSize
mtx_mpyf	mtx_mpyf_getScratchSize
mtx_mpy16x16_fast	mtx_mpy16x16_fast_getScratchSize
mtx_mpy8x8_fast	mtx_mpy8x8_fast_getScratchSize
mtx_mpy8x16_fast	mtx_mpy8x16_fast_getScratchSize
mtx_mpy32x32_fast	mtx_mpy32x32_fast_getScratchSize
mtx_mpyf_fast	mtx_mpyt_fast_getScratchSize
mtx_mpyt16x16	mtx_mpyt16x16_getScratchSize
mtx_mpyt8x8	mtx_mpyt8x8_getScratchSize
mtx_mpyt8x16	mtx_mpyt8x16_getScratchSize
mtx_mpyt32x32	mtx_mpyt32x32_getScratchSize
mtx_mpytf	mtx_mpytf_getScratchSize
mtx_mpyt16x16_fast	mtx_mpyt16x16_fast_getScratchSize
mtx_mpyt32x32_fast	mtx_mpyt32x32_fast_getScratchSize
mtx_mpytf_fast	mtx_mpytf_fast_getScratchSize

Arguments

Type	Name	Size	Description
Input			
`int8_t, int16_t, int32_t, float32_t`	`x`	`M*N`	input matrix,Q31,Q15, Q7 floating point
`int8_t, int16_t, int32_t, float32_t`	`y`	`N*P`	input matrix `y`. Q31,Q15, Q7 floating point.
`int8_t, int16_t, int32_t, float32_t`	`yt`	`P*N`	transposed input matrix `y`. Q31,Q15, Q7 floating point. (for transposing API only)
`int`	`M`		number of rows in matrix `x` and `z`
`int`	`N`		number of columns in matrix x and number of rows in matrix `y`
`int`	`P`		number of columns in matrices `y` and `z`
`int`	`lsh`		left shift applied to the result (applied to the fixed-point functions only)
Output			
`int8_t, int16_t, int32_t, float32_t`	`z`	`M*P`	output matrix `z`,Q31,Q15, Q7 floating point
Temporary			
`void*`	`pScr`		Scratch memory area with size in bytes defined by corresponding functions

Returned value

none

Restrictions

For regular routines (`mtx_mpy[t]32x32, mtx_mpy[t]16x16, mtx_mpy[t]8x8, mtx_mpy[t]8x16, mtx_mpy[t]f`):

`x,y,z` should not overlap

For faster routines (`mtx_mpy[t]32x32_fast, mtx_mpy[t]16x16_fast, mtx_mpy[t]8x8_fast, mtx_mpy[t]8x16_fast, mtx_mpy[t]f_fast`):

`x,y,z` should not overlap
`x,y,z` aligned on 8-byte boundary
`M,N,P` multiplies of 4
`lsh` -31...31 for `mtx_mpy[t]32x32, mtx_mpy[t]32x32_fast`
-15...15 for `mtx_mpy[t]16x16, mtx_mpy[t]16x16_fast, mtx_mpy[t]8x8, mtx_mpy[t]8x8_fast, mtx_mpy[t]8x16, mtx_mpy[t]8x16_fast`

2.7.2 Matrix by Vector Multiply

Description

These functions compute the expression `z = 2^lsh * x * y` for the matrices `x` and vector `y`.
NOTE: `lsh` factor is not relevant for floating point routines.
Two versions of functions available: regular version (`mtx_vecmpy32x32, mtx_vecmpy16x16, mtx_vecmpy8x8, mtx_vecmpy8x16, mtx_vecmpyf`) with arbitrary arguments and faster version (`mtx_vecmpy32x32_fast, mtx_vecmpy16x16_fast, mtx_vecmpy8x8_fast, mtx_vecmpy8x16_fast, mtx_vecmpyf_fast`) that apply some restrictions.

Precision

5 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output
16x16	16-bit inputs, 16-bit output
8x8	8-bit inputs, 8-bit output
8x16	8/16-bit inputs, 16-bit output
f	floating point. Requires VFPU/SFPU core option

Algorithm

For fixed-point routines:

$$z_n = 2^{lsh} \sum_{m=0}^{M-1} x_{n,m} \cdot y_m, n = 0 \ldots \overline{N-1}$$

For floating-point routines:

$$z_n = \sum_{m=0}^{M-1} x_{n,m} \cdot y_m, n = 0 \ldots \overline{N-1}$$

Prototype

```
void mtx_vecmpy32x32 (  int32_t*  z,
               const int32_t*  x,
               const int32_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy16x16 (  int16_t*  z,
               const int16_t*  x,
               const int16_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy8x8 ( int8_t*  z,
               const int8_t*  x,
               const int8_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy8x16( int16_t*  z,
               const int8_t *  x,
               const int16_t*  y,
               int M, int N, int lsh);
void mtx_vecmpyf (   float32_t*  z,
               const float32_t*  x,
               const float32_t*  y,
               int M, int N);

void mtx_vecmpy32x32_fast (  int32_t*  z,
               const int32_t*  x,
               const int32_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy16x16_fast (  int16_t*  z,
               const int16_t*  x,
               const int16_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy8x8_fast ( int8_t*  z,
               const int8_t*  x,
               const int8_t*  y,
               int M, int N, int lsh);
void mtx_vecmpy8x16_fast ( int16_t*  z,
               const int8_t *  x,
               const int16_t*  y,
               int M, int N, int lsh);
void mtx_vecmpyf_fast (   float32_t*  z,
               const float32_t*  x,
               const float32_t*  y,
               int M, int N);
```

Arguments

Type	Name	Size	Description
Input			
int32_t, int16_t, int8_t, float32_t	x	M*N	input matrix,Q31, Q15, Q7 or floating point
int32_t, int16_t, int8_t, float32_t	y	N	input vector,Q31, Q15, Q7 or floating point
int	M		number of rows in matrix x
int	N		number of columns in matrix x
int	lsh		left shift applied to the result (applied to the fixed-point functions only)
Output			

`int32_t, int16_t, int8_t, float32_t`	`z`	`M`	output vector,Q31, Q15, Q7 or floating point

Returned value

None

Restrictions

For regular routines (`mtx_vecmpy32x32, mtx_vecmpy16x16, mtx_vecmpy8x8, mtx_vecmpy8x16, mtx_vecmpyf`):

`x,y,z` should not overlap

For faster routines (`mtx_vecmpy32x32_fast, mtx_vecmpy16x16_fast, mtx_vecmpy8x8_fast, mtx_vecmpy8x16_fast, mtx_vecmpyf_fast`):

`x,y,z` should not overlap
`x,y,z` aligned on 8-byte boundary
`N,M` multiples of 4
`lsh` -31...31 for `mtx_vecmpy32x32, mtx_vecmpy32x32_fast`
-15...15 for `mtx_vecmpy16x16, mtx_vecmpy16x16_fast, mtx_vecmpy8x8_fast, mtx_vecmpy8x16_fast`

2.7.3 Matrix Transpose

Description

These functions transpose matrices.

Precision

4 variants available:

Type	Description
32x32	32-bit inputs, 32-bit output
16x16	16-bit inputs, 16-bit output
8x8	8-bit inputs, 8-bit output
f	floating point

Algorithm

$$y_{n,m} = x_{m,n}, m = 0\ldots\overline{M-1}, n = 0\ldots\overline{N-1}$$

Prototype

```
void mtx_transpose32x32 (int32_t*    y, const int32_t*     x, int M, int N);
void mtx_transpose16x16 (int16_t*    y, const int16_t*     x, int M, int N);
void mtx_transpose8x8   (int8_t *    y, const int8_t *     x, int M, int N);
void mtx_transposef      (float32_t*  y, const float32_t *  x, int M, int N);

void mtx_transpose32x32_fast (int32_t*  y, const int32_t*     x, int M, int N);
void mtx_transpose16x16_fast (int16_t*  y, const int16_t*     x, int M, int N);
void mtx_transpose8x8_fast   (int8_t *  y, const int8_t *     x, int M, int N);
void mtx_transposef_fast    (float32_t*  y, const float32_t *  x, int M, int N);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t, int16_t, int8_t, float32_t`	`x`	`M*N`	input matrix,Q31, Q15, Q7 or floating point
`int`	`M`		number of rows in matrix `x`
`int`	`N`		number of columns in matrix `x`
Output			
`int32_t, int16_t, int8_t, float32_t`	`y`	`M*N`	output vector,Q31, Q15, Q7 or floating point

Returned value

None

Restrictions

For regular routines (`mtx_transpose_32x32, mtx_transpose_16x16, mtx_transpose_8x8, mtx_transposef`):

`x,y` should not overlap

For faster routines (`mtx_transpose 32x32_fast, mtx_transpose 16x16_fast, mtx_transpose_8x8_fast, mtx_transposef_fast`):

`x,y` should not overlap
`x,y` aligned on 8-byte boundary
`N, M` multiples of 4

2.8 Matrix Decomposition/Inversion

2.8.1 Gauss-Jordan Matrix Inverse

Description

These functions implement in-place matrix inversion by Gauss elimination with full pivoting.
NOTE: user may detect "invalid" or "divide-by-zero" exception in the CPU flags which MAY indicate that inversion results are not accurate. Also it's responsibility of the user to provide valid input matrix for inversion.
Fixed point version takes representation of input matrix and forms representation of output matrix with proper scaling.

Precision

2 variants available:

Type	Description
f	floating point. Requires VFPU/SFPU core option
32x32	32-bit input, 32-bit output

Algorithm

$$y = x^{-1}$$

Prototype

Floating point API:
```
void rinvf (void* pScr, float32_t *x);
```
Fixed point API:
```
int rinv32x32 (void* pScr, int32_t *x, int qX);
int cinv32x32 (void* pScr, complex_fract32 *x, int qX);
```

N	Function	API	Scratch allocation function
2	mtx_inv2x2f	rinvf	mtx_inv2x2f_getScratchSize
3	mtx_inv3x3f	rinvf	mtx_inv3x3f_getScratchSize
4	mtx_inv4x4f	rinvf	mtx_inv4x4f_getScratchSize
6	mtx_inv6x6f	rinvf	mtx_inv6x6f_getScratchSize
8	mtx_inv8x8f	rinvf	mtx_inv8x8f_getScratchSize
10	mtx_inv10x10f	rinvf	mtx_inv10x10f_getScratchSize
2	mtx_inv2x2_32x32	rinv32x32	mtx_inv2x2_32x32_getScratchSize
3	mtx_inv3x3_32x32	rinv32x32	mtx_inv3x3_32x32_getScratchSize
4	mtx_inv4x4_32x32	rinv32x32	mtx_inv4x4_32x32_getScratchSize
6	mtx_inv6x6_32x32	rinv32x32	mtx_inv6x6_32x32_getScratchSize
8	mtx_inv8x8_32x32	rinv32x32	mtx_inv8x8_32x32_getScratchSize
10	mtx_inv10x10_32x32	rinv32x32	mtx_inv10x10_32x32_getScratchSize
2	cmtx_inv2x2_32x32	cinv32x32	cmtx_inv2x2_32x32_getScratchSize
3	cmtx_inv3x3_32x32	cinv32x32	cmtx_inv3x3_32x32_getScratchSize
4	cmtx_inv4x4_32x32	cinv32x32	cmtx_inv4x4_32x32_getScratchSize
6	cmtx_inv6x6_32x32	cinv32x32	cmtx_inv6x6_32x32_getScratchSize
8	cmtx_inv8x8_32x32	cinv32x32	cmtx_inv8x8_32x32_getScratchSize
10	cmtx_inv10x10_32x32	cinv32x32	cmtx_inv10x10_32x32_getScratchSize

Arguments

Type	Name	Size	Description
Input			
float32_t, int32_t, complex_fract32	x	N*N	input matrix
int	qX		input matrix representation (for fixed point API only)
Output			
float32_t, int32_t, complex_fract32	x	N*N	output inverted matrix
Temporary			
void	pScr		scratch memory. Size in bytes is defined by corresponding scratch allocation function

Returned value floating functions return none, fixed point functions return fixed-point representation of inverted matrix

Restrictions none

2.8.2 Gauss-Jordan Matrix Equation Solver

Description These functions implement solution of matrix equation by Gauss elimination with full pivoting.
Fixed point functions take representation of input matrix and vector and form representation of output vector with proper scaling.

Precision 1 variant available:

Type	Description
32x32	32-bit input, 32-bit output

Algorithm $y = Ax$

Prototype Fixed point API:

```
int rinv32x32 (void* pScr,
               int32_t *y,
               const int32_t *A, const int32_t *x,
               int qA, int qX);
int cinv32x32 (void* pScr,
               complex_fract32 *x,
               const complex_fract32 *A, const complex_fract32 *x,
               int qA, int qX);
```

N	Function	API	Scratch allocation function
2	mtx_gjelim2x2_32x32	r32x32	mtx_gjelim2x2_32x32_getScratchSize
3	mtx_gjelim3x3_32x32	r32x32	mtx_gjelim3x3_32x32_getScratchSize
4	mtx_gjelim 4x4_32x32	r32x32	mtx_gjelim4x4_32x32_getScratchSize
6	mtx_gjelim 6x6_32x32	r32x32	mtx_gjelim6x6_32x32_getScratchSize
8	mtx_gjelim 8x8_32x32	r32x32	mtx_gjelim8x8_32x32_getScratchSize
10	mtx_gjelim10x10_32x32	r32x32	mtx_gjelim10x10_32x32_getScratchSize
2	cmtx_gjelim 2x2_32x32	c32x32	cmtx_gjelim2x2_32x32_getScratchSize
3	cmtx_gjelim 3x3_32x32	c32x32	cmtx_gjelim3x3_32x32_getScratchSize
4	cmtx_gjelim 4x4_32x32	c32x32	cmtx_gjelim4x4_32x32_getScratchSize
6	cmtx_gjelim 6x6_32x32	c32x32	cmtx_gjelim6x6_32x32_getScratchSize
8	cmtx_gjelim 8x8_32x32	c32x32	cmtx_gjelim8x8_32x32_getScratchSize
10	cmtx_gjelim10x10_32x32	c32x32	cmtx_gjelim10x10_32x32_getScratchSize

Arguments

Type	Name	Size	Description
Input			
int32_t, complex_fract32	A	N*N	input matrix, representation is defined by parameter qA
int32_t, complex_fract32	x	N	input rigth side of equation, representation is defined by parameter qX
int	qA		input matrix representation
int	qX		input vector representation
Output			
int32_t, complex_fract32	y	N	output vector
Temporary			
void	pScr		scratch memory. Size in bytes is defined by corresponding scratch allocation function

Returned value fixed point functions return fixed-point representation of output vector

Restrictions none

2.9 Fitting/Interpolation

2.9.1 Polynomial Approximation

Description

Functions calculate polynomial approximation for all values from given vector. Fixed point functions take polynomial coefficients in Q31 precision.
NOTE:
approximation is calculated like Taylor series that is why overflow may potentially occur if cumulative sum of coefficients given from the last to the first coefficient is bigger that 1. To avoid this negative effect for fixed point routines, all the coefficients may be scaled down and result will be shifted left after all intermediate computations. Amount of this left shift is controlled by `lsh` argument.

Precision

2 variants available:

Type	Description
32x32	32-bit inputs, 32-bit coefficients, 32-bit output.
f	floating point. Requires VFPU/SFPU core option

Algorithm

$$z_n = \sum_{m=0}^{M} c_m x_n^m, n = \overline{0 \ldots N-1}$$

Prototype

```
void vec_poly8f
              (float32_t *  z, const float32_t *  x,
               const float32_t *  c, int N );
void vec_poly4_32x32
              (int32_t *  z, const int32_t *  x,
               const int32_t *  c, int lsh, int N );
void vec_poly8_32x32
               (int32_t *  z, const int32_t *  x,
                const int32_t *  c, int lsh, int N );
void vec_poly4f
              (float32_t *  z, const float32_t *  x,
               const float32_t *  c, int N );
```

Arguments

Type	Name	Size	Description
Input			
`int32_t`, `float32_t`	`x`	`N`	input data, Q31 or floating point
`int32_t`, `float32_t`	`c`	`5 or 9`	coefficients (5 coefficients for `vec_poly4_xxx` and 9 coefficients for `vec_poly8_xxx`), Q31 or floating point
`int`	`lsh`		additional left shift for result (for fixed point routines only)
`int`	`N`		length of vectors
Output			
`int32_t`, `float32_t`	`z`	`N`	result, Q31 or floating point

Returned value

None

Restrictions

`x,c,z` should not overlap

Conditions for optimum performance

`x,c,z` - aligned on 8-byte boundary
`N` - multiple of 2

2.10 Fast Fourier Transforms

FFT functions make floating point, 32x32, 32x16, 16x16-bit scaling fast Fourier transforms for complex/real data. Also, they use bit-reversal permutations so spectral data appear in the usual order. They normally use in-place transformations so **input data may be damaged**.

Different types if data scaling are provided by FFT functions. For all types of scaling, the internal representation of the data is the same as the input/output data. For these functions, the internal representation of the data is `complex_fract32`.

Basic scaling modes:

- **dynamic scaling (**`scalingOption = 2`**)**, provides the best accuracy, but has less performance comparing with static scaling;
- **static scaling (**`scalingOption = 3`**),** has more performance but worse accuracy than dynamic scaling.

With dynamic scaling (`scalingOption = 2`), the input data are normalized in the first phase of the FFT, so that there is no overflow. In subsequent phases, the data are automatically shifted to the right, so that there is no overflow. The function returns a total shift count, which can be negative under certain conditions (i.e. weak input signals).

With static scaling (`scalingOption = 3`), the data are shifted to the right before each FFT phase, the amount of shift is independent of the input data and is chosen so that there is no overflow for any input data.

Example of prescaling data for `scalingOpt = 0`:

```
// const int32_t *x  - pointer to input complex data
int32_t tmp[2*N];    // temporary buffer
int s = 30 - XT_NSA(N) ;              //  1+log2(N);
int bexp = vec_bexp32(x, 2*N);    //  calculate block exponent
s = (bexp < s)? 0: s - bexp;            // calculate shift
vec_shift32x32(tmp, x, -s, 2*N);   // right shift data
fft_cplx32x32(     y,     tmp,  h, 0); // call fft function
```

FFT/IFFT functions family with improved memory efficiency (`fft_cplx<prec>_ie`, `fft_real<prec>_ie`) as well as floating point FFT functions[2] expose smaller program- and constant data memory footprint. They differ from regular FFT/IFFT functions in the following aspects:

- cycles performance is compromised in favor of memory efficiency
- twiddle factor tables are provided by user. A single table may be shared between FFTs/IFFTs of varying size (see para 4.2)

All fixed-point FFT functions (including scaling and non-scaling) return total number of right shifts (`t`) occurred during all stages. Floating point FFTs do not make additional scaling so they always return 0 to indicate this fact. So, FFT/IFFT output will be scaled by 2^t. Library functions from 2.5.4help to convert results to desired scale or Q-representation. In these computations you have to take into account the fact that FFT→IFFT chain amplifies signal by the length of FFT `N` for complex transforms and by `N/2` for real transforms.
For example, consider processing chain:

[2] Floating point FFT available only with improved memory efficiency API

`y=FFT(x)` → `w=some_processing(y)` → `z=IFFT(w)` where `N` is the length of FFT, FFT returns total shift amount t_{FFT} and IFFT returns t_{IFFT}.
To move `z` to the same scale as `x` you have to shift it by:
$t_{FFT} + t_{IFFT} + \log_2(N) \equiv t_{FFT} + t_{IFFT} + 31 - \mathrm{scl\_bexp32}(N)$

Alternatively, you may treat it as changing Q-representation. For example, DCT functions (with length 32) always return total number of shifts equals to $\log_2(32)=5$. So, if its input is Q31, output will be in Q26.

The table below summarizes how number of right shifts depends on selected scaled option.

Scaling option	FFT functions family	Returned number of right shifts
0	FFT/IFFT on complex data	0
0	FFT/IFFT on real data	0
1,2	all FFT functions	depends on input data
3	FFT/IFFT on complex data	`log2(N)+1`
3	FFT/IFFT on real data, DCT	`log2(N)+1`

There are limited combinations of precision, scaling options and restrictions on the dynamic range of the input signal available:

Precision	Scaling options	Restrictions on the dynamic range of the input signal
FFT/IFFT		
`cplx32x16`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`cplx32x32`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`cplx16x16`	2 – 16-bit dynamic scaling 3 – fixed scaling before each stage	None
`cplx16x16_ie`	2 – 16-bit dynamic scaling	None
`cplx32x16_ie`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`cplx32x32_ie`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`real32x16`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`real32x32`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`real16x16`	2 – 16-bit dynamic scaling 3 – fixed scaling before each stage	None
`real16x16_ie`	2 – 16-bit dynamic scaling	None
`real32x16_ie`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
`real32x32_ie`	2 – 32-bit dynamic scaling 3 – fixed scaling before each stage	None
DCT		

`dct_32x16,`
`dct_32x32,`
`dct_16x16,`
`dct4_32x16,`
`dct4_32x32,`
`mdct_32x16,`
`mdct_32x32,`
`imdct_32x16,`
`imdct_32x32`
	3 – fixed scaling before each stage	None

Precision	Scaling options	Restrictions on the dynamic range of the input signal
dct2d_8x16	0 – no scaling	None
idct2d_16x8	0 – no scaling	None

2.10.1 FFT on Complex Data

Description

These functions make FFT on complex data.
NOTES:
1. Bit-reversing permutation is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call
3. 32x32, 32x16,16x16 FFT supports mixed radix transforms

Precision

3 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles
32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles

Algorithm

$$y = FFT(x)$$

Prototype

```
int fft_cplx32x16(
              int32_t* y, int32_t* x, fft_handle_t h, int scalingOption)
int fft_cplx32x32(
              int32_t* y, int32_t* x, fft_handle_t h, int scalingOption)
int fft_cplx16x16(
              int16_t* y, int16_t* x, fft_handle_t h, int scalingOption)
```

FFT handles:

N	32x16	32x16	32x32
16	cfft16_16	cfft16_16	cfft32_16
32	cfft16_32	cfft16_32	cfft32_32
64	cfft16_64	cfft16_64	cfft32_64
128	cfft16_128	cfft16_128	cfft32_128
256	cfft16_256	cfft16_256	cfft32_256
512	cfft16_512	cfft16_512	cfft32_512
1024	cfft16_1024	cfft16_1024	cfft32_1024
2048	cfft16_2048	cfft16_2048	cfft32_2048
4096	cfft16_4096	cfft16_4096	cfft32_4096

FFT handles for mixed radix transforms (for 16x16, 32x16 only):

N	16x16	N	32x16
160	cnfft16_160	160	cnfft32x16_160
192	cnfft16_192	192	cnfft32x16_192
240	cnfft16_240	240	cnfft32x16_240
320	cnfft16_320	320	cnfft32x16_320
384	cnfft16_384	384	cnfft32x16_384
480	cnfft16_480	480	cnfft32x16_480

FFT handles for mixed radix transforms (for 32x32 only):

N	32x32	N	32x32	N	32x32
12	cnfft32_12	144	cnfft32_144	360	cnfft32_360
24	cnfft32_24	160	cnfft32_160	384	cnfft32_384
36	cnfft32_36	180	cnfft32_180	400	cnfft32_400
48	cnfft32_48	192	cnfft32_192	432	cnfft32_432

60	cnfft32_60	200	cnfft32_200	480	cnfft32_480
72	cnfft32_72	216	cnfft32_216	540	cnfft32_540
80	cnfft32_80	240	cnfft32_240	576	cnfft32_576
96	cnfft32_96	288	cnfft32_288	600	cnfft32_600
100	cnfft32_100	300	cnfft32_300	768	cnfft32_768
108	cnfft32_108	320	cnfft32_320	960	cnfft32_960
120	cnfft32_120	324	cnfft32_324		

`, where N -` FFT size

Arguments

Type	Name	Size	Description
Input			
`int32_t or int16_t`	`x`	`2*N`	complex input signal. Real and imaginary data are interleaved and real data goes first
`fft_handle_t`	`h`		handle to specific FFT tables
`int`	`scalingOption`		scaling option (see table in para 2.10)
Output			
`int32_t or int16_t`	`y`	`2*N`	output spectrum. Real and imaginary data are interleaved and real data goes first

Returned value total number of right shifts occurred during scaling procedure

Restrictions

`x,y` should not overlap
`x,y` aligned on a 8-bytes boundary

2.10.2 FFT on Real Data

Description

These functions make FFT on real data forming half of spectrum
NOTES:
1. Bit-reversing reordering is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call.
3. Real data FFT function calls `fft_cplx()` to apply complex FFT of size `N/2` to input data and then transforms the resulting spectrum.
4. 32x32, 32x16,16x16 FFT supports mixed radix transforms

Precision

3 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles
32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles

Algorithm

$$y = FFT(real(x))$$

Prototype

```
int fft_real32x16(
              int32_t* y, int32_t* x, fft_handle_t h, int scalingOpt)
int fft_real32x32(
              int32_t* y, int32_t* x, fft_handle_t h, int scalingOpt)
int fft_real16x16(
              int16_t* y, int16_t* x, fft_handle_t h, int scalingOpt)
```

FFT handles:

N	32x16	32x16	32x32
32	rfft16_32	rfft16_32	rfft32_32
64	rfft16_64	rfft16_64	rfft32_64
128	rfft16_128	rfft16_128	rfft32_128
256	rfft16_256	rfft16_256	rfft32_256
512	rfft16_512	rfft16_512	rfft32_512
1024	rfft16_1024	rfft16_1024	rfft32_1024
2048	rfft16_2048	rfft16_2048	rfft32_2048
4096	rfft16_4096	rfft16_4096	rfft32_4096
8192	rfft16_8192	rfft16_8192	rfft32_8192

FFT handles for mixed radix transforms (for 16x16, 32x16 only):

N	16x16	N	32x16
160	`rnfft16_160`	160	`rnfft32x16_160`
192	`rnfft16_192`	192	`rnfft32x16_192`
240	`rnfft16_240`	240	`rnfft32x16_240`
320	`rnfft16_320`	320	`rnfft32x16_320`
384	`rnfft16_384`	384	`rnfft32x16_384`
480	`rnfft16_480`	480	`rnfft32x16_480`

FFT handles for mixed radix transforms (for 32x32 only):

N	32x32	N	32x32	N	32x32
12	`rnfft32_12`	160	`rnfft32_160`	480	`rnfft32_480`
24	`rnfft32_24`	180	`rnfft32_180`	540	`rnfft32_540`
30	`rnfft32_30`	192	`rnfft32_192`	576	`rnfft32_576`
36	`rnfft32_36`	216	`rnfft32_216`	720	`rnfft32_720`
48	`rnfft32_48`	240	`rnfft32_240`	768	`rnfft32_768`
60	`rnfft32_60`	288	`rnfft32_288`	960	`rnfft32_960`
72	`rnfft32_72`	300	`rnfft32_300`	1152	`rnfft32_1152`
90	`rnfft32_90`	320	`rnfft32_320`	1440	`rnfft32_1440`
96	`rnfft32_96`	324	`rnfft32_324`	1536	`rnfft32_1536`
108	`rnfft32_108`	360	`rnfft32_360`	1920	`rnfft32_1920`
120	`rnfft32_120`	384	`rnfft32_384`		
144	`rnfft32_144`	432	`rnfft32_432`		

`, where N -` FFT size

Arguments

Type	Name	Size	Description
Input			
`int32_t or int16_t`	`x`	`N`	input signal
`fft_handle_t`	`h`		handle to specific FFT tables
`int`	`scalingOpt`		scaling option (see table in para 2.10)
Output			
`int32_t or int16_t`	`y`	`(N/2+1)*2`	output spectrum (positive side). Real and imaginary data are interleaved and real data goes first

Returned value

total number of right shifts occurred during scaling procedure

Restrictions

Arrays should not overlap
`x,y` - aligned on a 8-bytes boundary

2.10.3 Inverse FFT on Complex Data

Description

These functions make inverse FFT on complex data.
NOTES:
1. Bit-reversing reordering is done here.
2. FFT runs in-place algorithm so **INPUT DATA WILL APPEAR DAMAGED** after call
3. 32x32, 32x16,16x16 FFT supports mixed radix transforms

Precision

3 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles

32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles

Algorithm

$$y = FFT^{-1}(x)$$

Prototype

```
int ifft_cplx32x16(
              int32_t * y, int32_t* x, fft_handle_t h, int scalingOption)
int ifft_cplx32x32(
              int32_t * y, int32_t* x, fft_handle_t h, int scalingOption)
int ifft_cplx16x16(
              int16_t* y, int16_t* x, fft_handle_t h, int scalingOption)
```

FFT handles:

N	32x16	32x16	32x32
16	cifft16_16	cifft16_16	cifft32_16
32	cifft16_32	cifft16_32	cifft32_32
64	cifft16_64	cifft16_64	cifft32_64
128	cifft16_128	cifft16_128	cifft32_128
256	cifft16_256	cifft16_256	cifft32_256
512	cifft16_512	cifft16_512	cifft32_512
1024	cifft16_1024	cifft16_1024	cifft32_1024
2048	cifft16_2048	cifft16_2048	cifft32_2048
4096	cifft16_4096	cifft16_4096	cifft32_4096

FFT handles for mixed radix transforms (for 16x16, 32x16 only):

N	16x16	N	32x16
160	cinfft16_160	160	cinfft32x16_160
192	cinfft16_192	192	cinfft32x16_192
240	cinfft16_240	240	cinfft32x16_240
320	cinfft16_320	320	cinfft32x16_320
384	cinfft16_384	384	cinfft32x16_384
480	cinfft16_480	480	cinfft32x16_480

FFT handles for mixed radix transforms (for 32x32 only):

N	32x32	N	32x32	N	32x32
12	cinfft32_12	144	cinfft32_144	360	cinfft32_360
24	cinfft32_24	160	cinfft32_160	384	cinfft32_384
36	cinfft32_36	180	cinfft32_180	400	cinfft32_400
48	cinfft32_48	192	cinfft32_192	432	cinfft32_432
60	cinfft32_60	200	cinfft32_200	480	cinfft32_480
72	cinfft32_72	216	cinfft32_216	540	cinfft32_540
80	cinfft32_80	240	cinfft32_240	576	cinfft32_576
96	cinfft32_96	288	cinfft32_288	600	cinfft32_600
100	cinfft32_100	300	cinfft32_300	768	cinfft32_768
108	cinfft32_108	320	cinfft32_320	960	cinfft32_960
120	cinfft32_120	324	cinfft32_324		

, where N – IFFT size

Arguments

Type	Name	Size	Description
Input			
int32_t or int16_t	x	2*N	input spectrum. Real and imaginary data are interleaved and real data goes first
fft_handle_t	h		handle to specific FFT tables
int	scalingOpt		scaling option (see table in para 2.10)
Output			

`int32_t or int16_t`	`y`	`2*N`	complex output signal. Real and imaginary data are interleaved and real data goes first

Returned value total number of right shifts occurred during scaling procedure

Restrictions

`x,y` - should not overlap
`x,y` - aligned on 8-bytes boundary

2.10.4 Inverse FFT Forming Real Data

Description

These functions make inverse FFT on half spectral data forming real data samples
NOTES:
1. Bit-reversing reordering is done here.
2. IFFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after call.
3. Inverse FFT function for real signal transforms the input spectrum and then calls `ifft_cplx()` with FFT size set to `N/2`.
4. 32x32, 32x16,16x16 FFT supports mixed radix transforms

Precision

3 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles
32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles

Algorithm

$$y = real(FFT^{-1}(x))$$

Prototype

```
int ifft_real32x16(
              int32_t * y, int32_t* x, fft_handle_t h, int scalingOpt)
int ifft_real32x32(
              int32_t * y, int32_t* x, fft_handle_t h, int scalingOpt)
int ifft_real16x16(
              int16_t * y, int16_t* x, fft_handle_t h, int scalingOpt)
```

FFT handles:

N	32x16	32x16	32x32
32	`rifft16_32`	`rifft16_32`	`rifft32_32`
64	`rifft16_64`	`rifft16_64`	`rifft32_64`
128	`rifft16_128`	`rifft16_128`	`rifft32_128`
256	`rifft16_256`	`rifft16_256`	`rifft32_256`
512	`rifft16_512`	`rifft16_512`	`rifft32_512`
1024	`rifft16_1024`	`rifft16_1024`	`rifft32_1024`
2048	`rifft16_2048`	`rifft16_2048`	`rifft32_2048`
4096	`rifft16_4096`	`rifft16_4096`	`rifft32_4096`
8192	`rifft16_8192`	`rifft16_8192`	`rifft32_8192`

FFT handles for mixed radix transforms (for 16x16, 32x16 only):

N	16x16	N	32x16
160	`rinfft16_160`	160	`rinfft32x16_160`
192	`rinfft16_192`	192	`rinfft32x16_192`
240	`rinfft16_240`	240	`rinfft32x16_240`
320	`rinfft16_320`	320	`rinfft32x16_320`
384	`rinfft16_384`	384	`rinfft32x16_384`
480	`rinfft16_480`	480	`rinfft32x16_480`

FFT handles for mixed radix transforms (for 32x32 only):

N	32x32	N	32x32	N	32x32
12	`rinfft32_12`	160	`rinfft32_160`	480	`rinfft32_480`
24	`rinfft32_24`	180	`rinfft32_180`	540	`rinfft32_540`

30	`rinfft32_30`	192	`rinfft32_192`	576	`rinfft32_576`
36	`rinfft32_36`	216	`rinfft32_216`	720	`rinfft32_720`
48	`rinfft32_48`	240	`rinfft32_240`	768	`rinfft32_768`
60	`rinfft32_60`	288	`rinfft32_288`	960	`rinfft32_960`
72	`rinfft32_72`	300	`rinfft32_300`	1152	`rinfft32_1152`
90	`rinfft32_90`	320	`rinfft32_320`	1440	`rinfft32_1440`
96	`rinfft32_96`	324	`rinfft32_324`	1536	`rinfft32_1536`
108	`rinfft32_108`	360	`rinfft32_360`	1920	`rinfft32_1920`
120	`rinfft32_120`	384	`rinfft32_384`		
144	`rinfft32_144`	432	`rinfft32_432`		

`,where N -` IFFT size

Arguments

Type	Name	Size	Description
Input			
`int32_t or int16_t`	`x`	`(N/2+1)*2`	input spectrum. Real and imaginary data are interleaved and real data goes first
`fft_handle_t`	`h`		handle to specific FFT tables
`int`	`scalingOpt`		scaling option (see table in para 2.10)
Output			
`int32_t or int16_t`	`y`	`N`	real output signal

Returned value

total number of right shifts occurred during scaling procedure

Restrictions

`x,y` should not overlap

`x,y` - aligned on 8-bytes boundary

2.10.5 FFT on Complex Data with Optimized Memory Usage

Description

These functions make FFT on complex data with optimized memory usage
NOTES:
1. Bit-reversing permutation is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call
3. FFT of size `N` may be supplied with constant data (twiddle factors) of a larger-sized FFT `= N*twdstep`.
4. stereo FFTs accept inputs from and provides outputs in interleaved order: left complex sample, right complex sample

Precision

4 variants available:

Type	Description
`32x16`	32-bit input/outputs, 16-bit twiddles. Ordinary (single channel) variant and stereo
`32x32`	32-bit input/outputs, 32-bit twiddles. Ordinary (single channel) variant and stereo
`16x16`	16-bit input/outputs, 16-bit twiddles. Ordinary (single channel) variant and stereo
`f`	floating point. Requires VFPU/SFPU core option. Ordinary variant (single channel) and stereo

Algorithm

$$y = FFT(x)$$

Prototype (single channel variants)

```
int fft_cplx32x16_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int fft_cplx32x32_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int fft_cplx16x16_ie(
              complex_fract16* y, complex_fract16* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int fft_cplxf_ie (
             complex_float * y, complex_float * x,
             const complex_float* twd,
             int twdstep, int N );
```

Prototype (stereo variants)

```
int stereo_fft_cplx32x16_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int stereo_fft_cplx32x32_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int stereo_fft_cplx16x16_ie(
              complex_fract16* y, complex_fract16* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int stereo_fft_cplxf_ie (
             complex_float * y, complex_float * x,
             const complex_float* twd,
             int twdstep, int N );
```

Arguments

Type	Name	Size	Description
Input			
complex_fract16, complex_fract32, complex_float	x	N*S	complex input signal. Real and imaginary data are interleaved and real data goes first
complex_fract32, complex_fract16, complex_float	twd	N*3/4*twdstep	twiddle factor table of a complex-valued FFT of size N*twdstep
int	twdstep		twiddle step
int	N		FFT size
int	scalingOpt		scaling option (see table in para 2.10) , not applicable to the floating point function
Parameter			
	S		stereo option, 1 for ordinary (single channel) FFT, 2 - for stereo input/outputs. Note: it does not come in parameter list of functions, but just specifies the total size of input/output data
Output			
complex_fract16, complex_fract32, complex_float	y	N*S	output spectrum. Real and imaginary data are interleaved and real data goes first

Returned value total number of right shifts occurred during scaling procedure. Floating function always return 0

Restrictions

x,y should not overlap

x,y - aligned on a 8-bytes boundary

2.10.6 FFT on Real Data with Optimized Memory Usage

Description

These functions make FFT on real data forming half of spectrum with optimized memory usage

NOTES:

1. Bit-reversing reordering is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call.
3. FFT functions use input and output buffers for temporary storage of intermediate 32-bit data, so FFT functions with 24-bit packed I/O (Nx3-byte data) require that the buffers are large enough to keep Nx4-byte data.
4. FFT of size N may be supplied with constant data (twiddle factors) of a larger-sized FFT = N*twdstep

Precision

4 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles

32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles
f	floating point. Requires VFPU/SFPU core option

Algorithm $y = FFT(real(x))$

Prototype

```
int fft_real32x16_ie(
              complex_fract32* y, int32_t* x, const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int fft_real32x32_ie(
              complex_fract32* y, int32_t* x, const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int fft_real16x16_ie(
              complex_fract16* y, int16_t* x, const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int fft_realf_ie(
              complex_float* y, float32_t* x, const complex_float* twd,
              int twdstep, int N);
```

Arguments

Type	Name	Size	Allocated Size	Description
Input				
int16_t, int32_t, float32_t	x	N	N	input signal
complex_fract32, complex_fract16, complex_float	twd	N*3/4 *twdstep		twiddle factor table of a complex-valued FFT of size N*twdstep
int	twdstep			twiddle step
int	N			FFT size
int	scalingOpt			scaling option (see table in para 2.10) , not applicable to the floating point function
Output				
complex_fract16, complex_fract32, complex_float	y	N/2+1	N/2+1	output spectrum (positive side). Real and imaginary data are interleaved and real data goes first

Returned value total number of right shifts occurred during scaling procedure. Floating function always return 0

Restrictions Arrays should not overlap
x,y - aligned on a 8-bytes boundary

2.10.7 Inverse FFT on Complex Data with Optimized Memory Usage

Description These functions make inverse FFT on complex data with optimized memory usage
NOTES:
1. Bit-reversing permutation is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call
3. FFT of size N may be supplied with constant data (twiddle factors) of a larger-sized FFT = N*twdstep.
4. stereo FFTs accept inputs from and provides outputs in interleaved order: left complex sample, right complex sample

Precision 4 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles. Ordinary (single channel) variant and stereo
32x32	32-bit input/outputs, 32-bit twiddles. Ordinary (single channel) variant and stereo
16x16	16-bit input/outputs, 16-bit twiddles. Ordinary (single channel) variant and stereo
f	floating point. Requires VFPU/SFPU core option. Ordinary (single channel) variant and stereo

Algorithm $y = FFT^{-1}(x)$

Prototype (single channel variant)

```
int ifft_cplx32x16_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int ifft_cplx32x32_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int ifft_cplx16x16_ie(
              complex_fract16* y, complex_fract16* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int ifft_cplxf_ie(
              complex_float* y, complex_float * x,
              const complex_float * twd,
              int twdstep, int N);
```

Prototype (streo variants)

```
int stereo_ifft_cplx32x16_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int stereo_ifft_cplx32x32_ie(
              complex_fract32* y, complex_fract32* x,
              const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int stereo_ifft_cplx16x16_ie(
              complex_fract16* y, complex_fract16* x,
              const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int stereo_ifft_cplxf_ie(
              complex_float* y, complex_float * x,
              const complex_float * twd,
              int twdstep, int N);
```

Arguments

Type	Name	Size	Description
Input			
complex_fract16, complex_float complex_fract32, complex_float	x	N*S	complex input signal. Real and imaginary data are interleaved and real data goes first
complex_fract32, complex_fract16, complex_float	twd	N*3/4*twdstep	twiddle factor table of a complex-valued FFT of size N*twdstep
int	twdstep		twiddle step
int	N		FFT size
int	scalingOpt		scaling option (see table in para 2.10) , not applicable to the floating point function
Parameter			
	S		stereo option, 1 for ordinary (single channel) FFT, 2 - for stereo input/outputs. Note: it does not come in parameter list of functions, but just specifies the total size of input/output data
Output			
complex_fract16, complex_fract32, complex_float	y	N*S	output spectrum. Real and imaginary data are interleaved and real data goes first

Returned value

total number of right shifts occurred during scaling procedure. Floating function always return 0

Restrictions

`x,y` should not overlap

`x,y` - aligned on a 8-bytes boundary

2.10.8 Inverse FFT on Real Data with Optimized Memory Usage

Description

These functions make inverse FFT on real data from half of spectrum with optimized memory usage
NOTES:
1. Bit-reversing reordering is done here.
2. FFT runs in-place algorithm so INPUT DATA WILL APPEAR DAMAGED after the call.
3. FFT functions use input and output buffers for temporary storage of intermediate 32-bit data, so FFT functions with 24-bit packed I/O (`Nx3`-byte data) require that the buffers are large enough to keep `Nx4`-byte data.
4. FFT of size `N` may be supplied with constant data (twiddle factors) of a larger-sized FFT = `N*twdstep`

Precision

4 variants available:

Type	Description
`32x16`	32-bit input/outputs, 16-bit twiddles
`32x32`	32-bit input/outputs, 32-bit twiddles
`16x16`	16-bit input/outputs, 16-bit twiddles
`f`	floating point. Requires VFPU/SFPU core option

Algorithm

$$y = real(FFT^{-1}(x))$$

Prototype

```
int ifft_real32x16_ie(
              int32_t* y, complex_fract32* x, const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int ifft_real32x32_ie(
              int32_t* y, complex_fract32* x, const complex_fract32* twd,
              int twdstep, int N, int scalingOpt);
int ifft_real16x16_ie(
              int32_t* y, complex_fract16* x, const complex_fract16* twd,
              int twdstep, int N, int scalingOpt);
int ifft_realf_ie(
              float32_t* y, complex_float * x, const complex_float* twd,
              int twdstep, int N);
```

Arguments

Type	Name	Size	Allocated Size	Description
Input				
`complex_fract16,` `complex_fract32,` `complex_float`	`x`	`N/2+1`	`N/2+1`	input spectrum (positive side). Real and imaginary data are interleaved and real data goes first
`complex_fract32,` `complex_fract16,` `complex_float`	`twd`	`N*3/4*twdstep`		twiddle factor table of a complex-valued FFT of size `N*twdstep`
`int`	`twdstep`			twiddle step
`int`	`N`			FFT size
`int`	`scalingOpt`			scaling option (see table in para 2.10) , not applicable to the floating point function
Output				
`int16_t,` `int32_t,` `float32_t`	`y`	`N`	`N`	output real signal

Returned value

total number of right shifts occurred during scaling procedure. Floating function always return 0

Restrictions

Arrays should not overlap
`x,y` - aligned on a 8-bytes boundary

2.10.9 Power Spectrum

Description

These functions compute a normalized power spectrum from the output signal generated by an FFT function.
The `N` argument specifies the size of the FFT and must be a power of 2.

The `mode` argument is used to specify the type of FFT function used to generate the `x` array. If the `x` array has been generated from a frequency-domain complex input signal (output of complex FFT function), the `mode` argument must be set to 0. Otherwise the `mode` argument must be set to 1 to signify that the `x` array has been generated from a frequency-domain real input signal (output of real FFT function).
The `block_exponent` argument is used to control the normalization of the power spectrum. It will usually be set to the `block_exponent` that is returned by corresponding FFT functions. If the input array was generated by some other means, then the value specified for the `block_exponent` argument will depend upon how the FFT was calculated. If the function used to calculate the FFT did not scale the intermediate results at any of the stages of the computation, then set `block_exponent` to zero; if the FFT function scaled the intermediate results at each stage of the computation, then set `block_exponent` to `-1`; otherwise set `block_exponent` to the sum of negated base-2 logarithm of all scaling factors applied to data at intermediate FFT stages. This value will be in the range `0` to `log2(N)`.
`fft_spectrum` functions write the power spectrum to the output array `y`. If `mode` is set to `0`, then the length of the power spectrum will be `N`. If `mode` is set to `1`, then the length of the power spectrum will be `(N/2+1)`

Precision

3 variants available:

Type	Description
16x32	16-bit inputs, 32-bit outputs
32x32	32-bit inputs/outputs
f	floating point inputs/outputs. Requires VFPU/SFPU core option

Algorithm

For `mode` = 0 (`cfft`-generated input data):

$$y_n = \frac{\sqrt{x_n \cdot x_n^*}}{N}, n = \overline{0 \ldots N-1}$$

For `mode` = 1 (`rfft`-generated input data):

$$y_n = \frac{2 \cdot \sqrt{x_n \cdot x_n^*}}{N}, n = \overline{0 \ldots N/2}$$

Prototype

```
void fft_spectrumf     ( float32_t* y, const complex_float * x,
                         int N, int mode );
void fft_spectrum16x32 ( int32_t* y, const complex_fract16 * x,
                         int N, int block_exponent, int mode );
void fft_spectrum32x32 ( int32_t* y, const complex_fract32 * x,
                         int N, int block_exponent, int mode );
```

Arguments

Type	Name	Size	Description
Input			
complex_fract16, complex_fract32, complex_float	x	N (for mode==0) N/2+1 (for mode==1)	input spectrum
int	N		FFT length
int	block_exponent		power spectrum normalization control
int	mode		power spectrum mode: 0 – complex signal 1 – real signal
Output			
complex_fract16, complex_fract32, complex_float	y	N (for mode==0) N/2+1 (for mode==1)	output power spectrum

Returned value

none

Restrictions

Arrays should not overlap

`x,y` - aligned on a 8-bytes boundary

2.10.10 Discrete Cosine Transform

Description

These functions apply DCT (Type II, Type IV) to input
NOTE:
DCT runs in-place algorithm so **INPUT DATA WILL APPEAR DAMAGED** after the call.

Precision

4 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles
32x32	32-bit input/outputs, 32-bit twiddles
16x16	16-bit input/outputs, 16-bit twiddles
f	floating point. Requires VFPU/SFPU core option

Algorithm

DCT Type II: $y_{k=0..N-1} = \sum_{n=0}^{N-1} x_n \cdot \cos\left(\frac{\pi}{N} \cdot (n+0.5) \cdot k\right), n = \overline{0...N-1}$

DCT Type IV: $y_{k=0..N-1} = \sum_{n=0}^{N-1} x_n \cdot \cos\left(\frac{\pi}{N} \cdot (n+0.5) \cdot [k+0.5]\right), n = \overline{0...N-1}$

Prototype (DCT Type II)

```
int dct_32x16(int32_t* y, int32_t* x, dct_handle_t h, int scalingOpt);
int dct_32x32(int32_t* y, int32_t* x, dct_handle_t h, int scalingOpt);
int dct_16x16(int16_t* y, int16_t* x, dct_handle_t h, int scalingOpt);
int dctf     ( float32_t * y,float32_t * x, dct_handle_t h  );
```

DCT-II handles:

N	32x32	N	32x16, 16x16	N	floating point
32	`dct2_32_32`	32	`dct2_16_32`	32	`dct2_f_32`
64	`dct2_32_64`	64	`dct2_16_64`	64	`dct4_f_64`

`,where N -` DCT size

Arguments

Type	Name	Size	Description
Input			
`int16_t, int32_t, float32_t`	`x`	`N`	input signal
`dct_handle_t`	`h`		DCT-II handle
`int`	`scalingOpt`		scaling option (see table in para 2.10), not applicable to the floating point function
Output			
`int16_t, int32_t, float32_t`	`y`	`N`	output of transform

Prototype (DCT Type IV)

```
int dct4_32x16(int32_t* y, int32_t* x, dct_handle h, int scalingOpt);
int dct4_32x32(int32_t* y, int32_t* x, dct_handle h, int scalingOpt);
```

DCT-IV handles:

N	32x32	N	32x16
32	`dct4_32_32`	32	`dct4_16_32`
64	`dct4_32_64`	64	`dct4_16_64`
128	`dct4_32_128`	128	`dct4_16_128`
256	`dct4_32_256`	256	`dct4_16_256`

512	dct4_32_512	512	dct4_16_512

, where N – DCT size

Arguments

Type	Name	Size	Description
Input			
int32_t	x	N	input signal
dct_handle_t	h		DCT-IV handle
int	scalingOpt		scaling option (see table in para 2.10), not applicable to the floating point function
Output			
int16_t, int32_t, float32_t	y	N	output of transform

Returned value total number of right shifts occurred during scaling procedure (0 for floating point function)

Restrictions

x,y should not overlap
x,y - aligned on 8-bytes boundary

2.10.11 Modified Discrete Cosine Transform

Description

These functions apply Modified DCT to input (convert 2N real data to N spectral components) and make inverse conversion forming 2N numbers from N inputs.

NOTE:
MDCT runs in-place algorithm so **INPUT DATA WILL APPEAR DAMAGED** after the call.

Precision

2 variants available:

Type	Description
32x16	32-bit input/outputs, 16-bit twiddles
32x32	32-bit input/outputs, 32-bit twiddles

Algorithm

MDCT: $y_{k=0..N-1} = \sum_{n=0}^{N-1} x_n \cdot \cos\left(\frac{\pi}{N} \cdot (n+0.5) \cdot k\right), n = \overline{0...N-1}$

Prototype (direct trasform)

```
int mdct_32x16(int32_t* y, int32_t* x, dct_handle_t h, int scalingOpt);
int mdct_32x32(int32_t* y, int32_t* x, dct_handle_t h, int scalingOpt);
```

MDCT/IMDCT handles:

N	32x32	N	32x16
32	mdct_32_32	32	mdct_16_32
64	mdct_32_64	64	mdct_16_64
128	mdct_32_128	128	mdct_16_128
256	mdct_32_256	256	mdct_16_256
512	mdct_32_512	512	mdct_16_512

, where N – MDCT/IMDCT size

Arguments

Type	Name	Size	Description
Input			
int32_t	x	N	input signal
dct_handle_t	h		MDCT handle
int	scalingOpt		scaling option (see table in para 2.10)
Output			
int32_t	y	2*N	output of transform

Algorithm

Inverse MDCT: $y_{k=0..N-1} = \sum_{n=0}^{N-1} x_n \cdot \cos\left(\frac{\pi}{N} \cdot (n+0.5) \cdot (k+0.5)\right), n = \overline{0 \ldots N-1}$

Prototype (inverse trasform)

```
int imdct_32x16(int32_t* y, int32_t* x, dct_handle h, int scalingOpt);
int imdct_32x32(int32_t* y, int32_t* x, dct_handle h, int scalingOpt);
```

Arguments

Type	Name	Size	Description
Input			
`int32_t`	`x`	`2*N`	input signal
`dct_handle_t`	`h`		IMDCT handle
`int`	`scalingOpt`		scaling option (see table in para 2.10)
Output			
`int32_t`	`y`	`N`	output of transform

Returned value total number of right shifts occurred during scaling procedure (0 for floating point function)

Restrictions

`x,y` should not overlap

`x,y` - aligned on 8-bytes boundary

2.10.12 2D Discrete Cosine Transform

Description These functions apply DCT (Type II) to the series of `L` input blocks of `NxN` pixels.

Precision 1 variant available:

Type	Description
8x16	8-bit unsigned input, 16-bit signed output

Algorithm Algorithm uses ITU-T T.81 (JPEG compression) DCT-II definition with bias 128 and left-to-right, top-to-bottom orientation.

$$y_{n,m}^{(l)} = \frac{1}{4} C_m C_n \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} (x_{j,i}^{(l)} - 128) \cos\frac{(2i+1)m\pi}{2N} \cos\frac{(2j+1)n\pi}{2N}, l = \overline{0 \ldots L-1}$$

$$C_k = \begin{cases} 1 & , k \neq 0 \\ 1/\sqrt{2} & , k \equiv 0 \end{cases}$$

$x_{j,i}^{(l)} = x[l \cdot N \cdot N + (N \cdot j + i)]$ - pixel from j-th row, i-th column from l-th NxN block

Prototype

```
int dct2d_8x16(int16_t* y, uint8_t * x, dct_handle_t h, int L, int scalingOpt);
```

2D-DCT handles :

N	8x16
8	`dct2d_16_8`

`, where N -` DCT size

Arguments

Type	Name	Size	Description
Input			
`uint8_t`	`x`	`N*N*L`	input pixels: `L NxN` blocks
`dct_handle_t`	`h`		DCT handle
`int`	`L`		number of input blocks
`int`	`scalingOpt`		scaling option (see table in para 2.10), should be 0
Output			
`int16_t`	`y`	`N*N*L`	output of transform: `L NxN` blocks

Returned value 0

Restrictions

`x,y` should not overlap
`x,y` - aligned on 8-bytes boundary

2.10.13 2D Inverse Discrete Cosine Transform

Description These functions apply inverse DCT (Type II) to the series of `L` input blocks of `NxN` pixels.

Precision 1 variant available:

Type	Description
16x8	16-bit signed input, 8-bit unsigned output

Algorithm Algorithm uses ITU-T T.81 (JPEG compression) IDCT-II definition with bias 128 and left-to-right, top-to-bottom orientation.

$$y_{j,i}^{(l)} = 128 + \frac{1}{4}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} C_m C_n x_{n,m}^{(l)} \cos\frac{(2i+1)m\pi}{2N}\cos\frac{(2j+1)n\pi}{2N}, l = \overline{0...L-1}$$

$$C_k = \begin{cases} 1 & ,k \neq 0 \\ 1/\sqrt{2} & ,k \equiv 0 \end{cases}$$

$x_{n,m}^{(l)} = x[l \cdot N \cdot N + (N \cdot n + m)]$ - sample from n-th row, m-th column from l-th 8x8 block

Prototype

```
int idct2d_16x8(uint8_t * y, int16_t* x, dct_handle_t h, int L, int scalingOpt);
```

2D-IDCT handles:

N	16x8
8	`idct2d_16_8`

`,where N -` IDCT size

Arguments

Type	Name	Size	Description
Input			
`int16_t`	`x`	`N*N*L`	input data: `L NxN` blocks
`dct_handle_t`	`h`		IDCT handle
`int`	`L`		number of input blocks
`int`	`scalingOpt`		scaling option (see table in para 2.10), should be 0
Output			
`uint8_t`	`y`	`N*N*L`	pixels: `L NxN` blocks

Returned value 0

Restrictions

`x,y` should not overlap
`x,y` - aligned on 8-bytes boundary

2.11 Mel-Frequency Cepstral Coefficients

Mel-Frequency Cepstral Coefficients (MFCC) is an industry-standard representation of audio data for advanced audio processing, such as speech recognition software.

The MFCC package of the Library comprises the MFCC features extractor and its subsidiary component, the Log-scale Mel-frequency (LogMel) filterbank. The interconnection of these components and their operation are depicted in the figure below:

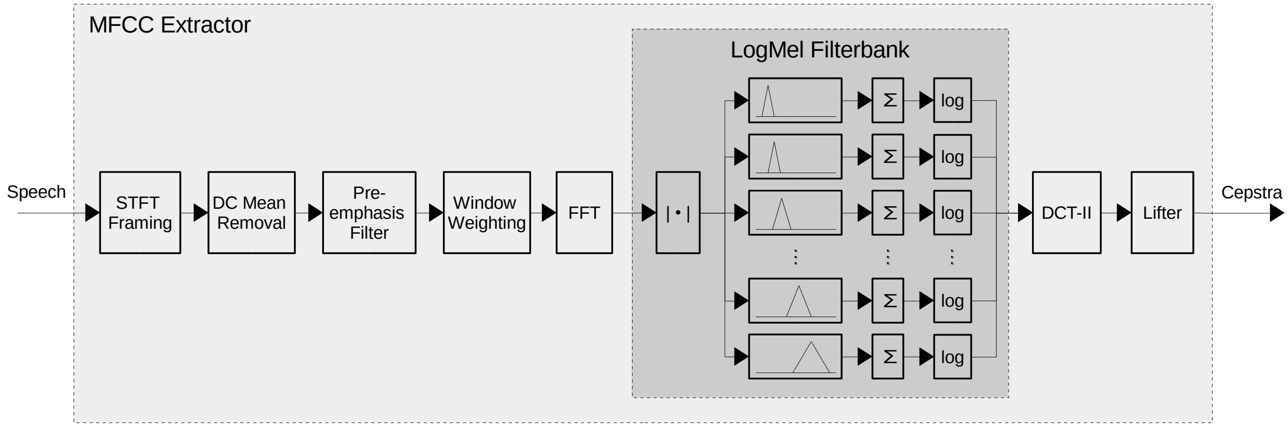


Figure 1. Block Diagram of the MFCC Extractor

Cepsral coefficient computation includes the following stages:

1. Input speech signal is optionally passed through a pre-emphasis filter (first order FIR).
2. Filtered signal is subject to short-time Fourier transform (STFT) followed by magnitude spectrum computation.
3. A set of filters is applied to the magnitude spectrum, with triangular weight functions constructed in such a way that the prescribed frequency range is divided into overlapping bands of equal mel-frequency width.
4. Log-scaled filterbank energies are decorrelated via a Discrete Cosine Transform Type II (DCT-II) to form cepstrum coefficients.
5. In the last step a sine lifter is optionally applied to cepstra to align coefficient magnitudes.

In general, the computation procedure follows the MFCC features extraction algorithm adopted in the Hidden Markov Models Toolkit (HTK), as descibed in:

S. Young, G. Evermann, M. Gales, T. Hain, D. Kershaw, X. Liu, G. Moo re, J. Odell, D. Ollason, D. Povey, V. Valtchev, P. Woodland, The HTK Book (for HTK version 3.4), Cambridge University Engineering Department, 2009. http://htk.eng.cam.ac.uk/docs/docs.shtml

In addition, a number of options provide an ability to emulate the operation of another popular package for speech analysis:

The Auditory Toolbox for MATLAB by Malcolm Slaney, Version 2, Interval Research Corporation https://engineering.purdue.edu/~malcolm/interval/1998-010/

Besides of the primary use of the LogMel filterbank as an integral part of the MFCC extractor, it may be utilized on its own by means of a dedicated API, as shown below.

2.11.1 Compute Log Mel Filterbank Energies

Description

In the initialization stage, split the specified frequency range into 1/2 overlapping bands of equal mel-frequency width, and compute triangular weighting function for each band.
Data processing functions are applied to Fourier image of real signal, specified through the input argument `spectra[fftSize/2+1]`. Fourier image is converted to magnitude spectrum. For every mel-frequency band, magnitude samples are multiplied by the corresponding triangular weighting function, and summed together to form filterbank energies (FBEs). Finally, log-scaled FBEs are stored to the output argument `logFbe[mfbBandNum]`.

Precision

2 variants available:

Type	Description
32x32	32-bit fixed-point input/output data
f	Single precision floating-point input/output data

Algorithm

$$logFbe = \log(coeffMatrix \cdot |spectra|)$$

Parameters of log mel filterbank operation

```
typedef struct logmel_params_tag
{
```

Type	Name	Description
`int`	`Fs`	Sampling rate, Hz
`int`	`fftSize`	FFT size
`fract32`	`mfbLowFreqQ8`	Lowest band's left frequency edge, Hz (Q8).
`fract32`	`mfbUppFreqQ8`	Uppermost band's right frequency edge, Hz (Q8).
`int`	`mfbBandNum`	Number of mel filterbank spectral bands.
`int`	`opt`	Options to control various aspects of MFCC features extraction, ORed combination of `LOGMEL_OPT_<...>` flags (see the table below).

```
} logmel_params_t;
```

Option flags:

Name	Value	Description
`LOGMEL_OPT_MELSCALE_HTK`	0<<0	Use HTK mapping between linear and mel-scale frequencies.
`LOGMEL_OPT_MELSCALE_AUDITORY`	1<<0	Use Auditory Toolbox mapping between linear and mel-scale frequencies.
`LOGMEL_OPT_FBELOG_NATURAL`	0<<1	Compute base-e logarithm of filterbank energies (HTK).
`LOGMEL_OPT_FBELOG_BASE10`	1<<1	Compute base-10 logarithm of filterbank energies (Auditory).
`LOGMEL_OPT_FBNORM_NONE`	0<<2	No normalization of filterbank weight functions, peak at 1.0 (HTK).
`LOGMEL_OPT_FBNORM_AREA`	1<<2	Perform area normalization of filterbank weight functions (Auditory).

Object allocation

```
size_t logmel32x32_alloc( const logmel_params_t * params );
size_t logmelf_alloc    ( const logmel_params_t * params );
```

Type	Name	Description
Input		
`logmel_params_t`	`params`	Parameters of log mel filterbank operation

Returns: size of memory to be allocated for an instance object, in bytes, or zero if parameters do not satisfy the restrictions.

Object initialization

```
logmel32x32_handle_t logmel32x32_init( void * objmem,
                                       const logmel_params_t * params);
logmelf_handle_t     logmelf_init    ( void * objmem,
                                       const logmel_params_t * params );
```

Type	Name	Description
Input		
`void *`	`objmem`	Memory block allocated for the instance object
`logmel_params_t`	`params`	Parameters of log mel filterbank operation

Returns: handle to the object, or `NULL` if initialization failed.

Compute log mel filterbank energies

```
void logmel32x32_process( logmel32x32_handle_t handle, void * restrict pScr,
                          fract32 * restrict logFbe,
                          const complex_fract32 * restrict spectra,
                          int scaleExp );
void logmelf_process    ( logmelf_handle_t handle, void * restrict pScr,
```

```
float32_t * restrict logFbe,
const complex_float * restrict spectra,
int scaleExp );
```

Type	Name	Size	Description
Input			
`complex_fract32,` `complex_float`	`spectra`	`fftSize/2+1`	Fourier image of real signal, positive frequencies only; Q31 for 32x32
`int`	`scaleExp`		Exponent value to scale the Fourier image by a factor of $2^{\mathtt{scaleExp}}$: **32x32** For full-scale Q31 real signal the scale exponent should be set to 15 plus the sum of bit shifts applied to data throughout the real-to-complex FFT transform, as indicated by the respective FFT routine. **f** For real signal varying in the range [-1,1] the scale exponent should be set to 15.
Output			
`fract32,` `float32_t`	`logFbe`	`mfbBandNum`	Log-scaled filterbank energies; Q6.25 for 32x32.
Temporary			
`void*`	`pScr`		Scratch memory area for the processing function. To determine the scratch area size, use the respective helper function: `logmel<32x32|f>_getScratchSize()`.

Determine size of the scratch memory area

```
size_t logmel32x32_getScratchSize( const logmel_params_t * params );
size_t logmelf_getScratchSize    ( const logmel_params_t * params );
```

Type	Name	Description
Input		
`logmel_params_t`	`params`	Parameters of log mel filterbank operation

Returns: size of scratch memory area, in bytes.

Restrictions

`logFbe[],spectra[]`	–	must not overlap, and must be aligned by 8-bytes
`Fs`	–	8000 <= `Fs` <= 48000
`fftSize`	–	256, 512, 1024 or 2048
`mfbLowFreqQ8, mfbUppFreqQ8`	–	0 <= `mfbLowFreqQ8` < `mfbUppFreqQ8` <= 16000*256
`mfbBandNum`	–	0 < `mfbBandNum` <= 40

2.11.2 Compute Mel-Frequency Cepstrum Coefficients

Description

In the initialization stage, perform preliminary computations that allow efficient processing of audio stream in real-time environment:

1. Setup an internal instance of log mel filterbank.
2. Optionally invoke a user-supplied callback function to calculate STFT weighting window.
3. Compute a DCT Type II transform matrix.
4. Optionally pre-compute the sine lifter coefficients.

Audio stream is split into chunks of `stftHopLen` speech samples, specified through the input argument `speech[stftHopLen]`. Processing of a speech chunk encompasses the following steps:

1. Update the STFT sliding frame.
2. Estimate and subtract the DC mean from the source signal (optional).
3. Perform pre-emphasis filtering (optional).
4. Apply the STFT weighting window (optional).
5. Invoke a user-supplied callback function to perform the real-to-complex FFT.
6. Pass the resulting Fourier image to log mel filterbank to obtain log-scaled filterbank energies (LogFBEs).
7. Decorrelate LogFBEs through the DCT Type II transform, this forms the cepstral coefficients.
8. Align magnitudes of cepstral coefficients by the sine lifter (optional).

Resulting cepstral coefficients are strored to the output argument cepstra[cepstraNum].

Precision

2 variants available:

Type	Description
32x32	32-bit fixed-point input/output data
f	Single precision floating-point input/output data

Parameters of MFCC features extraction

```
typedef struct mfcc_params_tag
{
```

Type	Name	Default Value	Description
int	Fs	16000	Sampling rate, Hz
int	scaleExp	15	Specifies the scaling factor applied to speech signal: 2^{scaleExp}.
fract16	preemph	31785	Pre-emphasis filter coefficient, Q15; set to 0 to disable the filter.
int	fftSize	512	FFT size
int	stftWinLen	400	Short-time Fourier transform window length, must not exceed fftSize.
int	stftHopLen	160	Number of audio samples between successive windows, must not exceed stftWinLen.
fract32	mfbLowFreqQ8	0	Lowest band's left frequency edge, Hz (Q8).
fract32	mfbUppFreqQ8	4000*256	Uppermost band's right frequency edge, Hz (Q8).
int	mfbBandNum	20	Number of mel filterbank spectral bands.
int	cepstraNum	12	Number of cepstral coefficients to compute, including the 0th coefficient.
int	lifter	22	Cepstral lifter parameter; zet to zero to disable the lifter.
int	opt	0	Options to control various aspects of MFCC features extraction, ORed combination of MFCC_OPT_<...> and LOGMEL_OPT_<...> flags (see the table below).

```
} mfcc_params_t;
```

Option flags:

Name	Value	Description
LOGMEL_OPT_MELSCALE_HTK	0<<0	Use HTK mapping between linear and mel-scale frequencies.
LOGMEL_OPT_MELSCALE_AUDITORY	1<<0	Use Auditory Toolbox mapping between linear and mel-scale frequencies.
LOGMEL_OPT_FBELOG_NATURAL	0<<1	Compute base-e logarithm of filterbank energies (HTK).
LOGMEL_OPT_FBELOG_BASE10	1<<1	Compute base-10 logarithm of filterbank energies (Auditory).
LOGMEL_OPT_FBNORM_NONE	0<<2	No normalization of filterbank weight functions, peak at 1.0 (HTK).
LOGMEL_OPT_FBNORM_AREA	1<<2	Perform area normalization of filterbank weight functions (Auditory).
MFCC_OPT_REMOVE_DC_MEAN	0<<3	For every STFT frame, evaluate and subtract the DC mean (HTK).
MFCC_OPT_DONT_REMOVE_DC_MEAN	1<<3	Do not remove DC mean (Auditory).
MFCC_OPT_PREEMPH_FRAMEBYFRAME	0<<4	Pre-emphasis filter state is reset between STFT frames (HTK).
MFCC_OPT_PREEMPH_CONTINUOUS	1<<4	Pre-emphasis filter state is reset once, during initialization (Auditory).
MFCC_OPT_DCT_NORMALIZED	0<<5	Multiply the DCT-II matrix by $\sqrt{2/N}$, where N is the transform size (HTK).

MFCC_OPT_DCT_ORTHOGONAL	1<<5	As above, and multiply the first row by $^{1}/_{\sqrt{2}}$ (Auditory).

STFT weighting window generator callback function

```
typedef void mfcc32x32_genWindow_cbfxn_t(void* host, fract32   * window, int len);
typedef void mfccf_genWindow_cbfxn_t    (void* host, float32_t * window, int len);
```

Type	Name	Size	Description
Input			
void*	host		User-supplied host handle
int	len		Length of the weighting window
Output			
fract32, float32_t	window	len	Generated weighting window samples; Q31 for 32x32; aligned by 8-bytes

Real-to-complex FFT callback function

```
typedef int  mfcc32x32_rfft_cbfxn_t( void * host, complex_fract32 * restrict y,
                                     fract32   * restrict x, int fftSize );
typedef void mfccf_rfft_cbfxn_t    ( void * host, complex_float   * restrict y,
                                     float32_t * restrict x, int fftSize );
```

Type	Name	Size	Description
Input			
void*	host		User-supplied host handle
int	fftSize		Transform size
fract32, float32_t	x	fftSize	Time-domain input signal
Output			
complex_fract32, complex_float	y	fftSize/2+1	Positive-frequency spectrum samples

32x32 variant of the function must return the block exponent of the Fourier image, which is the sum of bit shifts applied to data throughout the transform. Block exponent is a signed quantity, where positive values render shifting data to the right.

Notes:

1. Input and output arguments `x[fftSize]` and `y[fftSize/2+1]` do not overlap, and are aligned by 8-bytes.
2. The FFT function is allowed to re-use the input argument `x[fftSize]` for temporal storage of intermediate data.

Callbacks for fixed-point MFCC extractor (32x32).

```
typedef struct mfcc32x32_callback_tag
{
```

Type	Name	Description
void*	host	User-supplied host handle to be passed as the first input argument of a callback function.
mfcc32x32_genWindow_cbfxn_t *	genWindow	Optional STFT weighting window generator function. If `NULL`, then MFCC assumes the rectangular window, otherwise it invokes the user-supplied function during initialization.
mfcc32x32_rfft_cbfxn_t*	rfft	Real-to-complex FFT function, is called once per STFT sliding window update.

```
} mfcc32x32_callback_t;
```

Callbacks for floating-point MFCC extractor (single precision).

```
typedef struct mfccf_callback_tag
{
```

Type	Name	Description
void*	host	User-supplied host handle to be passed as the first input argument of a callback function.
mfccf_genWindow_cbfxn_t *	genWindow	Optional STFT weighting window generator

		function. If `NULL`, then MFCC assumes the rectangular window, otherwise it invokes the user-supplied function during initialization.
`mfccf_rfft_cbfxn_t*`	`rfft`	Real-to-complex FFT function, is called once per STFT sliding window update.

```
} mfccf_callback_t;
```

Fill the parameters structure with default values

```
void mfcc_getDefaultParams( mfcc_params_t * params );
```

Type	Name	Description
Output		
`mfcc_params_t`	`params`	Default parameters of MFCC features extraction.

Object allocation

```
size_t mfcc32x32_alloc( const mfcc_params_t * params );
size_t mfccf_alloc    ( const mfcc_params_t * params );
```

Type	Name	Description
Input		
`mfcc_params_t`	`params`	Parameters of MFCC features extraction.

Returns: size of memory to be allocated for an instance object, in bytes, or zero if parameters do not satisfy the restrictions (see below).

Object initialization

```
mfcc32x32_handle_t mfcc32x32_init( void * objmem, const mfcc_params_t * params,
                                   const mfcc32x32_callback_t * callback );
mfccf_handle_t     mfccf_init    ( void * objmem, const mfcc_params_t * params,
                                   const mfccf_callback_t * callback );
```

Type	Name	Description
Input		
`void *`	`objmem`	Memory block allocated for the instance object
`mfcc_params_t`	`params`	Parameters of MFCC features extraction.
`mfcc32x32_callback_t, mfccf_callback_t`	`callback`	User-supplied callback functions

Returns: handle to the object, or `NULL` if initialization failed.

Perform the sliding window STFT analysis and extract the MFCC features

```
void mfcc32x32_process( mfcc32x32_handle_t handle, void * restrict pScr,
                        fract32 * restrict cepstra,
                        const fract32 * restrict speech );
void mfccf_process    ( mfccf_handle_t handle, void * restrict pScr,
                        float32_t * restrict cepstra,
                        const float32_t * restrict speech );
```

Type	Name	Size	Description
Input			
`fract32, float32_t`	`speech`	`stftHopLen`	Speech samples; Q31 for 32x32.
Output			
`fract32, float32_t`	`cepstra`	`cepstraNum`	Cepstral coefficients; the number of fractional bits for 32x32 is defined by `MFCC_CEPSTRA_FRACT_BITS` macro constant.
Temporary			
`void*`	`pScr`		Scratch memory area for the processing function. To determine the scratch area size, use the respective helper function: `mfcc<32x32|f>_getScratchSize()`.

2.12 Identification Routines

2.12.1 Library Version Request

Description This function returns library version information.

Prototype

```
void NatureDSP_Signal_get_library_version(char *version_string);
```

Arguments

Type	Name	Size	Description
Output			
`char`	`version_string`	`>=30`	buffer to store version information

Returned value None

Restrictions version_string must points to a buffer large enough to hold up to 30 characters

Conditions for optimum performance: None

2.12.2 Library API Version Request

Description This function returns library API version information.

Prototype

```
void NatureDSP_Signal_get_library_api_version(char *version_string);
```

Arguments

Type	Name	Size	Description
Output			
`char`	`version_string`	`>=30`	buffer to store version information

Returned value None

Restrictions version_string must points to a buffer large enough to hold up to 30 characters

2.12.3 Library API Capability Request

Description This function returns non-zero if given function (by its address) is supported by specific processor capabilities (i.e. VFPU/SFPU option).

NOTE:

1. in the gcc/xcc environment, calls of this function are not necessary - if function pointer is non-zero it means it is supported. VisualStudio linker does not support section removal so this function might be used for running library under MSVC environment
2. Very few library functions may disable their capabilities dynamically (only for particular combination of input parameters). Behavior for such situation is defined in the description of those functions.

Prototype

```
int NatureDSP_Signal_isPresent(NatureDSP_Signal_funptr fun)
```

Arguments

Type	Name	Description
Input:		
`NatureDSP_Signal_funptr`	`fun`	one of library functions

Returned Value non-zero if function is supported by library

3 Test Environment and Examples

3.1 Supported Use Environment, Configurations and Targets

NatureDSP Signal library and corresponding testdriver is supported to be built and test using Xtensa Xplorer IDE running under Windows, or Linux operating system.

Library is compatible with HiFi cores having following options:

- HiFi4 base ISA
- HiFi4 Vector/Scalar FP
- NSA/NSAU ISA option
- MIN/MAX ISA option
- Boolean Registers ISA option
- Little endian target

3.2 Building the NatureDSP Signal Library and the Testdriver

3.2.1 Importing the workspaces in Xtensa Xplorer

NatureDSP Signal Library for HiFi4 VFPU is provided as two workspaces:

- Library workspace `HiFi4_VFPU_library.xws`

  This workspace contains optimized kernels, modules as required for demo workspaces

- Demo workspace `HiFi4_VFPU_demo.xws`

  This contains the `HiFi4_VFPU_demo` demo project.

Import these two workspaces (`.xws`) in Xtensa Xplorer (XX) as “Xtensa Xplorer workspace”.

Make sure that the library workspace is imported first. This is because the project in the demo workspace has a dependency on the library projects, and the dependency is not correctly set if the library projects are not present when the demo workspace is imported.

3.2.2 Building and Running Tests

To build the library: In XX, select the desired library project to build, and Debug or Release target, and build.

To build the test bench: In XX, select the `HiFi4_VFPU_demo` project, select Debug or Release target, and build.

To run the test bench, select `HiFi4_VFPU_demo` project, and Run. This will execute each routine in the `HiFi4_VFPU_library` in cycles performance (MIPS) mode.

For performance measurement with memory modeling, build the test bench with `MEM_MODEL=1` (set in build properties) and use `--mem_model` as runtime argument for execution.

Use `--turbo` as runtime argument to test library for functional correctness

3.2.3 Command-line Options

You may wish to launch a separate test by passing command-line options to the executable:

You may wish to launch a separate test by passing command-line options to the executable:
Running the Testdriver without options performs functional testing of library. Additionally, it may collect statistics and generate validation report showing the number of calls of each specific library function, amount of data passed to/from, sorts of specific tests performed, etc.
Running performance tests for all library functions or for specific category is controlled by command line option `–mips`. In that case, functional testing is not performed and validation report will be empty.
Brief performance data are formed with `–mips –verbose`. Detailed performance data are prepared with `–mips -full`.

You may wish to launch a separate test by passing command-line options to the executable:

Package	API	Meaning	Option
		List of available options	`-help or -h`
		Performance test	`-mips`
		Functional tests	`-func`
		Generate validation report and statistics after completion of functional testing	`-vreport`
		test fixed point functions only	`-phase1`
		test floating point functions only	`-phase2`
		For functional tests, this switch instructs to use bigger data vectors from directory `vectors_full` instead of `vectors_brief` (test time might be 3 to 5 times longer). For performance test, it controls amount of tests performed for each library function. With this switch the test tool forms detailed testing using bigger set of function parameters, if not - it just makes brief performance data.	`-full`
		This switch controls amount of tests executed (in contrary with `–full`)	`-brief`
		Verbose reporting. For functional tests, it controls verbosity of test reports (i.e. shows number, type of tests performed and detailed error statistics if some test is failed). For performance tests, it adds textual description of each function under the test to the performance log.	`-verbose`
FIR Filters and Related Functions	2.1	all FIR filters	**`-fir`**
		filtering	`-firblk`
		decimation	`-firdec`
		interpolation	`-firint`
		correlation, convolution, dispreading, LMS	`-firother`
		2D-convolution	`-conv2d`
IIR Filters	2.1.13	all IIR filters	**`-iir`**
		biquad filters	`-iirbq`
		lattice filters	`-iirlt`
Math Functions	2.3	all math functions	**`-math`**
		vectorized math	`-mathv`
		vectorized math (fast variants)	`-mathvf`
		scalar math	`-maths`
Complex Math Functions	2.4	all complex functions	**`-complex`**
		vectorized complex math	`-complexv`
		scalar complex math	`-complexs`
Vector Operations	2.5	vector operations tests	**`-vector`**

Package	API	Meaning	Option
Emulated Floating Point Operations	2.6	emulated floating point tests	**-ef**
Matrix Operations	2.7	all matrix operations tests	**-matop**
Matrix Decomposition and Inversion Functions	2.8	all matrix decomposition and inversion	**-matinv**
FFT Routines	2.10	all FFT and DCT	**-fft**
		complex FFT	-cfft
		real FFT	-rfft
		mixed radix complex FFT	-cnfft
		mixed radix real FFT	-rnfft
		complex FFT with optimized memory	-cfftie
		real FFT with optimized memory	-rfftie
		power spectrum	-spectrum
		DCT	-dct
MFCC	2.11	MFCC feature extraction	-mfcc
Fitting and Interpolation Routines	2.9	all fitting tests	**-fit**
		polynomial fitting	-pfit

3.2.4 Other Supported Environments

The library and testdriver project might be built under several toolchains and operating systems:

OS	Language	Environment	Tool
Linux	C	xcc	make
Linux	C++	gcc	make
Windows	C	xcc	xt-make
Windows	C++	MSVC	Visual Studio

4 Appendix

4.1 Matlab Code for Conversion of SOS Matrix to Coefficients of IIR Functions

Below is example Matlab code to simplify conversion of SOS+G matrices given from the filter design tools into the format of IIR filtering functions.

4.1.1 bqriir16x16_df1, bqriir32x16_df1 conversion

```
%--------------------------------------------------
% convert SOS+G to coefficients of IIR filter
% (bqriir32x16_df1 function)
% parameters:
% SOS,G     - SOS matrix and gain vector G
% Fs        - sample rate
% nfft      - FFT length for analisys
% output:
% coef      - vector with coefficients, Q30
% gain      - biquad gains, Q15
% scale     - final scale factor (amount of left shifts)
%--------------------------------------------------
function [coef,gain,scale]=cvtsos_bqriir32x16_df1(SOS,G,Fs,nfft)
sz=size(SOS);
M=sz(1);
coef=[];
f=(0:nfft-1)/nfft*(Fs/2);
tf0=sos2freqz(SOS,G,nfft);

Gtotal=prod(G);
G=ones(1,M+1);

% define gain for each stage to provide maximim of tf for intermediate output <=0.5
for m=1:M
    tf=sos2freqz(SOS(1:m,:),[G(1:m) 1],nfft);
    tfmax=max(abs(tf));
    G(m)=min(1,0.5/tfmax);
end

% define last stage shift
dg=Gtotal/prod(G);
scale=ceil(log2(dg));
% correct coefficient of the last stage
d=pow2(1,scale)/dg;
G(M)=G(M)/d;
% output b,a
coef=SOS; coef(:,4)=[]; coef=reshape(coef.',1,numel(coef));
% and convert coefficients to given format
coef = int16(round(16384.*coef));
gain = int16(round(32768.*G(1:M)));
scale= int16(scale);
% check results and plot final filter response
sos=reshape(double(coef),5,M).'/16384;
sos=[sos(:,1:3) ones(M,1) sos(:,4:5)];
g=double(gain)/32768;
g(M+1)=pow2(1,double(scale));
tf=sos2freqz(sos,g,nfft);
plot(f,20*log10(abs(tf)),f,20*log10(abs(tf0))); ylim([-80 0]); title('transfer function, dB'); grid
on;

% convert SOS/G to frequency response
function [tf]=sos2freqz(SOS,G,nfft)
sz=size(SOS);
M=sz(1);
[b,a]=sos2tf(SOS(1,:),[G(1) G(end)]);
```

```
tf=freqz(b,a,nfft);
for m=2:M
    [b,a]=sos2tf(SOS(m,:),[G(m) 1]);
    tf=tf.*freqz(b,a,nfft);
end
```

4.1.2 bqriir16x16_df2, bqriir32x16_df2 conversion

```
%---------------------------------------------------
% convert SOS+G to coefficients of IIR filter
% (bqriir32x16_df2 function)
% parameters:
% SOS,G    - SOS matrix and gain vector G
% Fs       - sample rate
% nfft     - FFT length for analisys
% output:
% coef     - vector with coefficients, Q14
% gain     - biquad gains, Q15
% scale    - final scale factor (amount of left shifts)
%---------------------------------------------------
function [coef,gain,scale]=cvtsos_bqriir32x16_df2(SOS,G,Fs,nfft)

sz=size(SOS);
M=sz(1);
coef=[];
f=(0:nfft-1)/nfft*(Fs/2);
tf0=sos2freqz(SOS,G,nfft);
Gtotal=prod(G);
G=ones(1,M+1);

% define gain for each stage to provide maximim of tf for
% intermediate outputs <=0.5
% note: for DF2 structure we have to check 2 points:
% b0,b1,b2,a1,a2 and 1,0,0,a1,a2
for m=1:M
    tf=sos2freqz(SOS(1:m,:),[G(1:m) 1],nfft);
    tfmax0=max(abs(tf));
    tf=sos2freqz([SOS(1:m-1,:);1 0 0 1 SOS(m,5:6)] ,[G(1:m) 1],nfft);
    tfmax1=max(abs(tf));
    tfmax = max(tfmax0,tfmax1);
    G(m)=min(1,0.5/tfmax);
end

% define last stage shift
dg=Gtotal/prod(G);
scale=ceil(log2(dg));
% correct coefficient of the last stage
d=pow2(1,scale)/dg;
G(M)=G(M)/d;
% output b,a
coef=SOS; coef(:,4)=[]; coef=reshape(coef.',1,numel(coef));
% and convert coefficients to given format
coef = int16(round(16384.*coef));
gain = int16(round(32768.*G(1:M)));
scale= int16(scale);

% check results and plot final filter response
sos=reshape(double(coef),5,M).'/16384;
sos=[sos(:,1:3) ones(M,1) sos(:,4:5)];
g=double(gain)/32768;
g(M+1)=pow2(1,double(scale));
tf=sos2freqz(sos,g,nfft);
plot(f,20*log10(abs(tf)),f,20*log10(abs(tf0))); ylim([-80 0]); title('transfer function, dB'); grid
on;

% convert SOS/G to frequency response
function [tf]=sos2freqz(SOS,G,nfft)
sz=size(SOS);
M=sz(1);
[b,a]=sos2tf(SOS(1,:),[G(1) G(end)]);
tf=freqz(b,a,nfft);
for m=2:M
```

```
    [b,a]=sos2tf(SOS(m,:),[G(m) 1]);
    tf=tf.*freqz(b,a,nfft);
end
```

4.1.3 bqriir32x32_df1 conversion

```
%--------------------------------------------------
% convert SOS+G to coefficients of IIR filter
% (bqriir32x32_df1 function)
% parameters:
% SOS,G     - SOS matrix and gain vector G
% Fs        - sample rate
% nfft      - FFT length for analisys
% output:
% coef      - vector with coefficients, Q30
% gain      - biquad gains, Q30
% scale     - final scale factor (amount of left shifts)
%--------------------------------------------------
function [coef,gain,scale]=cvtsos_bqriir32x32_df1(SOS,G,Fs,nfft)

sz=size(SOS);
M=sz(1);
coef=[];
f=(0:nfft-1)/nfft*(Fs/2);
tf0=sos2freqz(SOS,G,nfft);
Gtotal=prod(G);
G=ones(1,M+1);

% define gain for each stage to provide maximim of tf for intermediate output <=0.5
for m=1:M
    tf=sos2freqz(SOS(1:m,:),[G(1:m) 1],nfft);
    tfmax=max(abs(tf));
    G(m)=min(1,0.5/tfmax);
end

% define last stage shift
dg=Gtotal/prod(G);
scale=ceil(log2(dg));
% correct coefficient of the last stage
d=pow2(1,scale)/dg;
G(M)=G(M)/d;
% output b,a
coef=SOS; coef(:,4)=[]; coef=reshape(coef.',1,numel(coef));
% and convert coefficients to given format
coef = int32(round(1073741824.*coef));
gain = int16(round(32768.*G(1:M)));
scale= int16(scale);
% check results and plot final filter response
sos=reshape(double(coef),5,M).'/1073741824;
sos=[sos(:,1:3) ones(M,1) sos(:,4:5)];
g=double(gain)/32768;
g(M+1)=pow2(1,double(scale));
tf=sos2freqz(sos,g,nfft);
plot(f,20*log10(abs(tf)),f,20*log10(abs(tf0))); ylim([-80 0]); title('transfer function, dB'); grid
on;

% convert SOS/G to frequency response
function [tf]=sos2freqz(SOS,G,nfft)
sz=size(SOS);
M=sz(1);
[b,a]=sos2tf(SOS(1,:),[G(1) G(end)]);
tf=freqz(b,a,nfft);
for m=2:M
    [b,a]=sos2tf(SOS(m,:),[G(m) 1]);
    tf=tf.*freqz(b,a,nfft);
end
```

4.1.4 bqriir32x32_df2 conversion

```
%--------------------------------------------------
% convert SOS+G to coefficients of IIR filter
```

```
% (bqriir32x32_df2 function)
% parameters:
% SOS,G     - SOS matrix and gain vector G
% Fs        - sample rate
% nfft      - FFT length for analisys
% output:
% coef      - vector with coefficients, Q30
% gain      - biquad gains, Q15
% scale     - final scale factor (amount of left shifts)
%-----------------------------------------------
function [coef,gain,scale]=cvtsos_bqriir32x32_df2(SOS,G,Fs,nfft)

sz=size(SOS);
M=sz(1);
coef=[];
f=(0:nfft-1)/nfft*(Fs/2);
tf0=sos2freqz(SOS,G,nfft);
Gtotal=prod(G);
G=ones(1,M+1);

% define gain for each stage to provide maximim of tf for
% intermediate outputs <=0.5
% note: for DF2 structure we have to check 2 points:
% b0,b1,b2,a1,a2 and 1,0,0,a1,a2
for m=1:M
    tf=sos2freqz(SOS(1:m,:),[G(1:m) 1],nfft);
    tfmax0=max(abs(tf));
    tf=sos2freqz([SOS(1:m-1,:);1 0 0 1 SOS(m,5:6)] ,[G(1:m) 1],nfft);
    tfmax1=max(abs(tf));
    tfmax = max(tfmax0,tfmax1);
    G(m)=min(1,0.5/tfmax);
end

% define last stage shift
dg=Gtotal/prod(G);
scale=ceil(log2(dg));
% correct coefficient of the last stage
d=pow2(1,scale)/dg;
G(M)=G(M)/d;
% output b,a
coef=SOS; coef(:,4)=[]; coef=reshape(coef.',1,numel(coef));
% and convert coefficients to given format
coef = int32(round(1073741824.*coef));
gain = int16(round(32768.*G(1:M)));
scale= int16(scale);

% check results and plot final filter response
sos=reshape(double(coef),5,M).'/1073741824;
sos=[sos(:,1:3) ones(M,1) sos(:,4:5)];
g=double(gain)/32768;
g(M+1)=pow2(1,double(scale));
tf=sos2freqz(sos,g,nfft);
plot(f,20*log10(abs(tf)),f,20*log10(abs(tf0))); ylim([-80 0]); title('transfer function, dB'); grid
on;

% convert SOS/G to frequency response
function [tf]=sos2freqz(SOS,G,nfft)
sz=size(SOS);
M=sz(1);
[b,a]=sos2tf(SOS(1,:),[G(1) G(end)]);
tf=freqz(b,a,nfft);
for m=2:M
    [b,a]=sos2tf(SOS(m,:),[G(m) 1]);
    tf=tf.*freqz(b,a,nfft);
end
```

4.1.5 bqriirf_df1, bqriirf_df2, bqriirf_df2t conversion

```
%-----------------------------------------------
% convert SOS+G coefficients to the coefficients for
% iirdf1f,iirdf2f,iirdf2tf,ciirdf1f routines
% parameters:
```

```
% SOS,G     - SOS matrix and gain vector G
% Fs        - sample rate
% nfft      - FFT length for analisys
% output:
% coef      - vector with coefficients
%---------------------------------------------------
function [coef,scale]=cvtsos_iir(SOS,G,Fs,nfft)
% convert SOS+G to coefficients of IIR filter
sz=size(SOS);
M=sz(1);
coef=[];
f=(0:nfft-1)/nfft*(Fs/2);
tf0=sos2freqz(SOS,G,nfft);
Gtotal=prod(G);
G=ones(1,M+1);

% define gain for each stage to provide maximim of tf for intermediate output <=0.5
for m=1:M
    tf=sos2freqz(SOS(1:m,:),[G(1:m) 1],nfft);
    tfmax=max(abs(tf));
    G(m)=min(1,0.5/tfmax);
end
for m=1:M
    SOS(m,1:3)= SOS(m,1:3)*G(m);
end
% define last stage shift
dg=Gtotal/prod(G);
scale=round(log2(dg));
% correct coefficient of the last stage
d=pow2(1,scale)/dg;
G(M)=G(M)/d;
% output b,a
coef=SOS'; coef(4,:)=[]; coef=reshape(coef,1,numel(coef));
scale= int32(scale);

% check results and plot final filter response
sos=reshape(double(coef),5,M);
sos=sos';
sos=[sos(:,1:3) ones(M,1) sos(:,4:5)];
g(1:M)=ones(1,M);
g(M+1)=pow2(1,double(scale));
tf=sos2freqz(sos,g,nfft);
plot(f,20*log10(abs(tf)),f,20*log10(abs(tf0))); ylim([-80 0]); title('transfer function, dB'); grid
on;

% convert SOS/G to frequency response
function [tf]=sos2freqz(SOS,G,nfft)
sz=size(SOS);
M=sz(1);
[b,a]=sos2tf(SOS(1,:),[G(1) G(end)]);
tf=freqz(b,a,nfft);
for m=2:M
    [b,a]=sos2tf(SOS(m,:),[G(m) 1]);
    tf=tf.*freqz(b,a,nfft);
end
```

4.2 Matlab Code for Generation the Twiddle Tables

FFT with optimized memory usage require external twiddle tables. Matlab code below shows how to generate twiddles for different functions.

4.2.1 Twiddles for fft_cplx32x16_ie, ifft_cplx32x16_ie, fft_real32x16_ie, ifft_real32x16_ie, fft_cplx16x16_ie, ifft_cplx16x16_ie, fft_real16x16_ie, ifft_real16x16_ie

```
function [twd]=twd32x16_ie(N)
twd = exp(-2j*pi*[1;2;3]*(0:N/4-1)/N);
```

```
twd=twd.';
twd = reshape([imag(twd(:).');real(twd(:).')],1,2*numel(twd));
twd = int16(round(pow2(twd,15)));
```

4.2.2 Twiddles for fft_cplx32x32_ie, ifft_cplx32x32_ie, fft_real32x32_ie, ifft_real32x32_ie

```
function [twd]=twd32x32_ie(N)
twd = exp(-2j*pi*[1;2;3]*(0:N/4-1)/N);
twd=twd.';
twd = reshape([imag(twd(:).');real(twd(:).')],1,2*numel(twd));
twd = int32(round(pow2(twd,31)));
```

4.2.3 Twiddles for fft_cplxf_ie, ifft_cplxf_ie, fft_realf_ie, ifft_realf_ie

```
function [twd]=twdf_ie(N)
twd = exp(-2j*pi*[1;2;3]*(0:N/4-1)/N);
twd = reshape([real(twd(:).');imag(twd(:).')],1,2*numel(twd));
```

5 Customer Support

If you have questions, want to report problems or suggestions regarding the **NatureDSP Signal** library or want to port this library to another platforms, contact **IntegrIT** Ltd. at support@integrit.com. Visit www.integrit.com to get more information about products and services.