Data Types

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Objectives

- **After completing this module, you will be able to:**
  - State various data types of C, C++, and SystemC are supported
  - Identify advantages and pitfalls of using arbitrary precision
  - List various supported quantization and overflow modes
  - Describe the floating point support

Outline

- > *C and C++ Data Types*
- > Arbitrary Precision Data Types
- > System C Data Types
- > Floating Point Support
- > Summary

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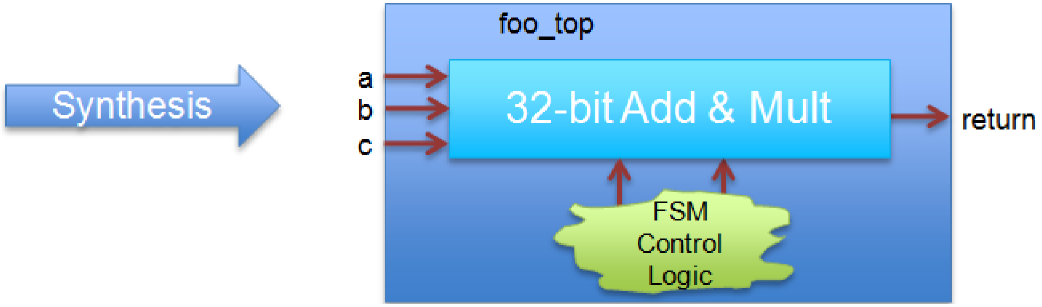
Data Types and Bit-Accuracy

- C and C++ have standard types created on the 8-bit boundary
  - char (8-bit), short (16-bit), int (32-bit), long long (64-bit)
    - Also provides stdint.h (for C), and stdint.h and cstdint (for C++)
    - Types: int8_t, uint16_t, uint32_t, int_64_t etc.
  - They result in hardware which is not bit-accurate and can give sub-standard QoR
- Vivado HLS provides bit-accurate types in both C and C++
  - Allow any arbitrary bit-width to be specified
  - Hence designers can improve the QoR of the hardware by specifying exact data widths
    - Can be specified in the code and simulated to ensure there is no loss of accuracy
- Vivado HLS also provides half-precision floating-point data types

Why is arbitrary precision Needed?

> **Code using native C int type**

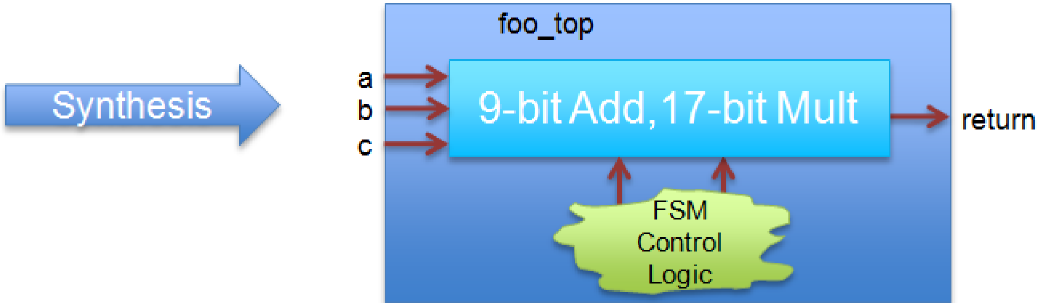
```
int foo_top(int a, int b, int c)
{
    int sum, mult;
    sum=a+b;
    mult=sum*c;
    return mult;
}
```



> **However, if the inputs will only have a max range of 8-bit**

>> Arbitrary precision data-types should be used

```
int17 foo_top(int8 a, int8 b, int8 c)
{
    int9 sum;
    int17 mult
    sum=a+b;
    mult=sum*c;
    return mult;
}
```



>> It will result in smaller & faster hardware with the full required precision

>> With arbitrary precision types on function interfaces, Vivado HLS can propagate the correct bit-widths throughout the design

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HLS & C Types

> **There are 4 basic types you can use for HLS**
>> Standard C/C++ Types
>> Vivado HLS enhancements to C: apint
>> Vivado HLS enhancements to C++: ap_int, ap_fixed
>> SystemC types

Type of C	C(C99) / C++	Vivado HLS ap_cint (bit-accurate with C)	Vivado HLS ap_int (bit-accurate with C++)	OSCI SystemC (IEEE 1666-2005 :bit-accurate)
Description		Used with standard C	Used with standard C++	IEEE standard
Requires		#include "ap_cint.h"	#include "ap_int.h" #include "ap_fixed.h" #include "hls_stream.h"	#include "systemc.h"
Pre-Synthesis Validation	gcc/g++		g++ Vivado HLS GUI	g++ Vivado HLS GUI
Fixed Point	NA	NA	ap_fixed	#define SC_INCLUDE_FX sc_fixed
Signal Modeling	Variables	Variables	Variables Streams	Signals, Channels, TLM (1.0)

Arbitrary Precision Data Types

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Arbitrary Precision : C apint types

- **For C**
  - Vivado HLS types apint can be used
  - Range: 1 to 1024 bits
  - Specify the integers as shown and just use them like any other variable

Include header file

```
#include ap_cint.h

void foo_top (…) {

   int9         var1;          // 9-bit
   uint10       var2;          // 10-bit unsigned
```

- **There are two issues to be aware of**
  - C compilation : YOU MUST use apcc to simulate (no debugger support)
  - Be aware of integer promotion issues

Failure to use apcc to compile the C will result in INCORRECT results

This only applies to C NOT C++ or SystemC

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Using apcc

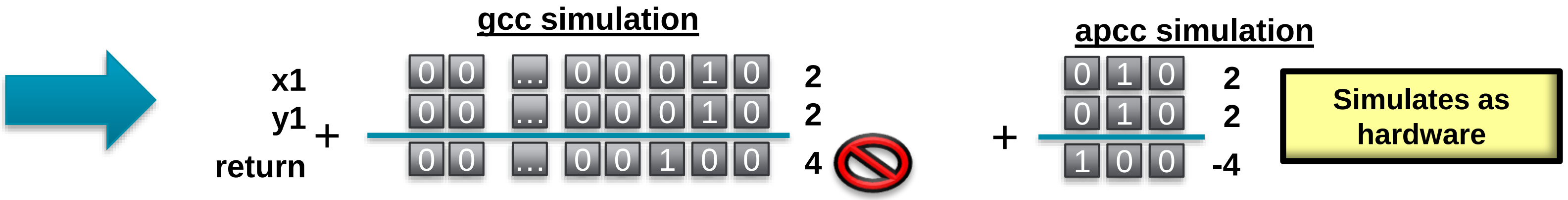
- **apcc**
  - Command line compatible with gcc
  - Required to support arbitrary precision for C
  - Use apcc at the Vivado HLS CLI (shell)

```
shell> apcc –o my_test test.c test_tb.c
```

  - HLS uses apcc automatically when it sees arbitrary precision is used in C model
- **apcc understands bit-accurate types**

```
#include "ap_cint.h"
int3 ex_bit_accurate (
  int3 x1,
  int3 y1
  ) {
  return x1+y1;
}
```

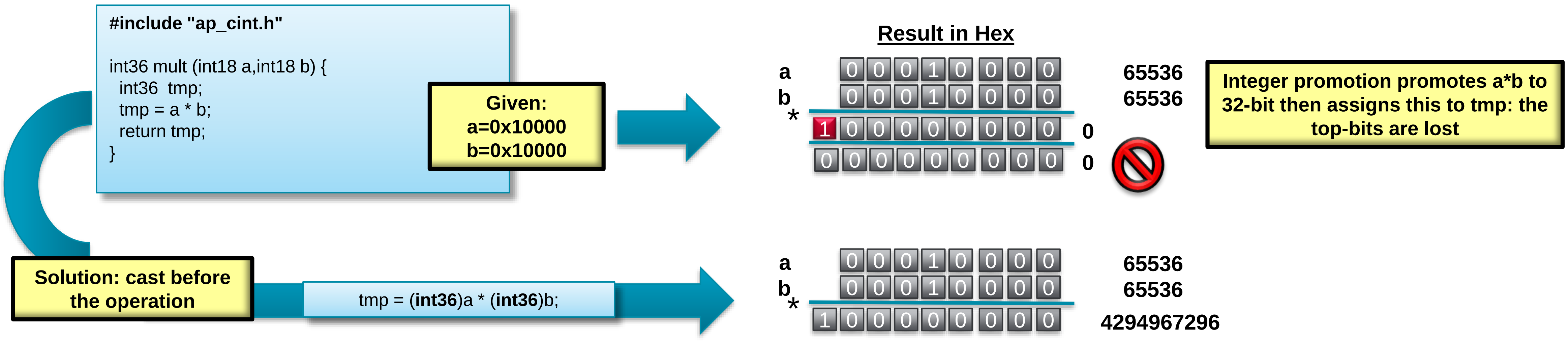
**Given: x1=2
y1=2**



  - Once you create bit-accurate types you must re-validate the C
  - It's the only way to discover rounding and truncation issues
    - It's fast in C !!!

Integer Promotion

- **Integer promotion**
  - The apcc utility must still obey standard C/gcc rules and protocols
  - Integer promotion:
    - If the operator result is a larger type ➔
    - The result is promoted to the target type (on 8, 16, 32 or 64 boundaries)



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C apint types: Bit-Selection & Manipulation

Function		Example
Length	Returns the length of the variable.	res=apint_bitwidthof(var);
Concatenation	Concatenation low to high	res=apint_concatenate(var_high, var_low)
Get a range	Return a bit-range from high to low.	res= apint_get_range(var, high,low)
Set a range	Reserve the bits in the variable	apint_set_range(res, high, low, res)
(n)and_reduce	(N)And reduce all bits.	bool t = apint_(n)and_reduce(var);
(n)or_reduce	(N)Or reduce all bits	bool t = apint_(n)or_reduce(var);
X(n)or_reduce	X(N)or reduce all bits	bool t = apint_x(n)or_reduce(var);
Get a bit	Get a specific bit	res=apint_get_bit(var, bit-number)
Set bit value	Sets the value of a specific bit	apint_set_bit(res, bit-number)
Print value	Print the value of an apint variable	apint_print(int#N value, int radix));
Print value to file	Print the value of an apint variable to a file	apint_fprint(FILE* file, int#N value, int radix)

Arbitrary Precision : C++ ap_int types

> **For C++**

- Vivado HLS types ap_int can be used
- Range: 1 to 1024 bits
  - Signed: ap_int<W>
  - Unsigned: ap_uint<W>
- The bit-width is specified by W

Include header file

```
#include ap_int.h

void foo_top (…) {

   ap_int<9>        var1;   // 9-bit
   ap_uint<10>      var2;   // 10-bit unsigned
```

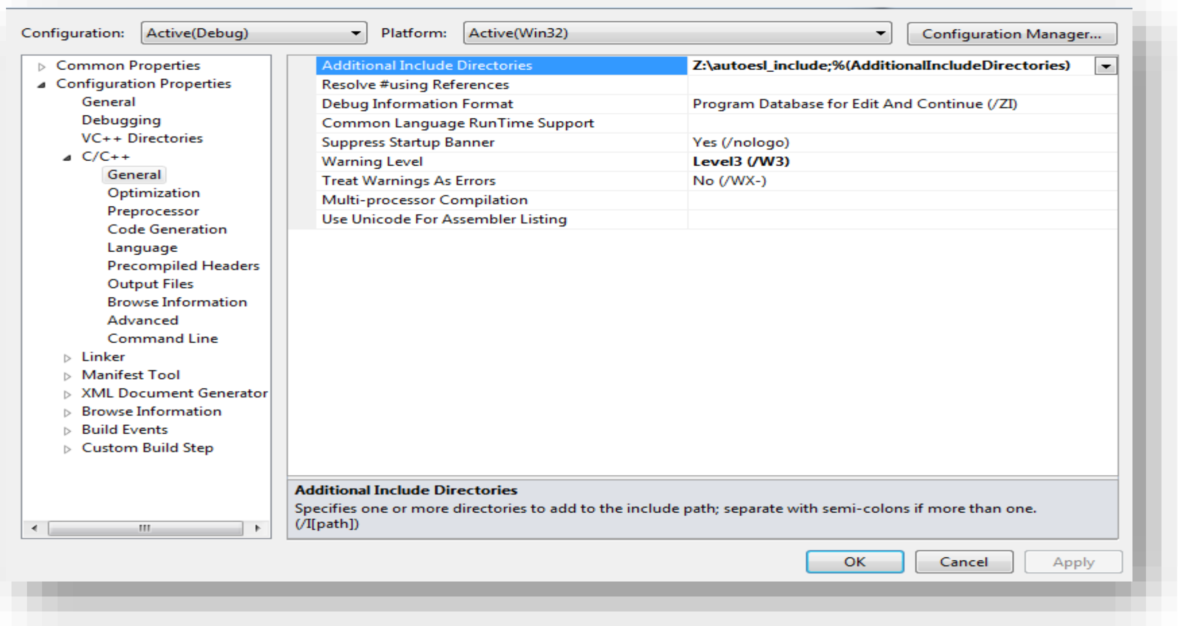
> **C++ compilation**

- Use g++ at the Vivado HLS CLI (shell)
  – Include the path to the Vivado HLS header file

```
shell> g++ –o my_test test.c test_tb.c -I$VIVADO_HLS_HOME/include
```

Microsoft Visual Studio Support

- **C++ Arbitrary Precision Types are supported in Microsoft Visual Studio Compiler**
  - Simply include the Vivado HLS directory $(VIVADO_HLS_HOME)/include
  - **Note**: C designs using arbitrary precision types (apint) must still use apcc
- **C++ Designs using AP_INT types**
  - In the MVS Project
    - Click Project
    - Click Properties
    - In the panel that shows up, select C/C++
    - Select general
    - Click on additional include directories and add the path



AP_INT operators & conversions

- **Fully Supported for all Arithmetic operator**

Operations	
Arithmetic	+ - * / % ++ --
Logical	~ !
Bitwise	& | ^
Relational	> < <= >= == !=
Assignment	*= /= %= += -= <<= >>= &= ^= |=

- **Methods for type conversion**

Methods		Example
To integer	Convert to a integer type	res = var.to_int();
To unsigned integer	Convert to an unsigned integer type	res = var.to_uint();
To 64-bit integer	Convert to a 64-bit long long type	res = var.to_int64();
To 64-bit unsigned integer	Convert to an unsigned long long type	res = var.to_uint64();
To double	Convert to double type	res = var.double();

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AP_INT Bit Manipulation methods

Methods		Example
Length	Returns the length of the variable.	res=var.length;
Concatenation	Concatenation low to high	res=var_hi.concat(var_lo); Or res= (var_hi,var_lo)
Range or Bit-select	Return a bit-range from high to low or a specific bit.	res=var.range(high bit,low bit); Or res=var[bit-number]
(n)and_reduce	(N)And reduce all bits.	bool t = var.and_reduce();
(n)or_reduce	(N)Or reduce all bits	bool t = var.or_reduce();
X(n)or_reduce	X(N)or reduce all bits	bool t = var.xor_reduce();
Reverse	Reserve the bits in the variable	var.reverse();
Test bit	Tests if a bit is true	bool t = var.test(bit-number)
Set bit value	Sets the value of a specific bit	var.set_bit(bit-number, value)
Set bit	Set a specific bit to one	var.set(bit-number);
Clear bit	Clear a specific bit to zero	var.clear(bit-number);
Invert Bit	Invert a specific bit	var.invert(bit-number);
Rotate right	Rotate the N-bits to the right	var.rrotate(N);
Rotate left	Rotate the N-bits to the left	var.lrotate(N);
Bitwise Invert	Invert all bits	var.b_not();
Test sign	Test if the sign is negative (return true)	bool t = var.sign();

Arbitrary Precision : C++ ap_fixed types

- **Support for fixed point datatypes in C++**
  - Include the path to the ap_fixed.h header file
  - Both signed (ap_fixed) and unsigned types (ap_ufixed)

$VIVADO_HLS_HOME/include/ap_fixed.h

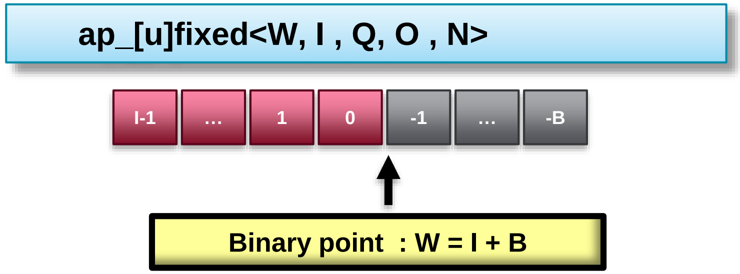
```
#include ap_fixed.h

void foo_top (…) {

 ap_fixed<9, 5, AP_RND_CONV, AP_SAT>  var1;          //  9-bit,
                                                     //  5 integer  bits, 4 decimal places

 ap_ufixed<10, 7, AP_RND_CONV, AP_SAT>  var2;        // 10-bit unsigned
                                                     //   7 integer bits, 3 decimal places
```

- **Advantages of Fixed Point types**
  - The result of variables with different sizes is automatically taken care of
  - The binary point is automatically aligned
    - Quantization: Underflow is automatically handled
    - Overflow: Saturation is automatically handled

Alternatively, make the result variable large enough such that overflow or underflow does not occur

Definition of ap_fixed type

> **Fixed point types are specified by**
>> Total bit width (W)
>> The number of integer bits (I)
>> The quantization/rounding mode (Q)
>> The overflow/saturation mode (O)
>> The number of saturation bits



	Description	
W	Word length in bits	
I	The number of bits used to represent the integer value (the number of bits above the decimal point)	
Q	Quantization mode (modes detailed below) dictates the behavior when greater precision is generated than can be defined by the LSBs.	
	AP_Fixed Mode	**Description**
	AP_RND	Rounding to plus infinity
	AP_RND_ZERO	Rounding to zero
	AP_RND_MIN_INF	Rounding to minus infinity
	AP_RND_INF	Rounding to infinity
	AP_RND_CONV	Convergent rounding
	AP_TRN	Truncation to minus infinity
	AP_TRN_ZERO	Truncation to zero (default)
O	Overflow mode (modes detailed below) dictates the behavior when more bits are required than the word contains.	
	AP_Fixed Mode	**Description**
	AP_SAT	Saturation
	AP_SAT_ZERO	Saturation to zero
	AP_SAT_SYM	Symmetrical saturation
	AP_WRAP	Wrap around (default)
	AP_WRAP_SM	Sign magnitude wrap around
N	The number of saturation bits in wrap modes.	

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Quantization Modes

- **Quantization mode**
  - Determines the behavior when an operation generates more precision in the LSBs than is available

- **Quantization Modes (rounding):**
  - AP_RND, AP_RND_MIN_IF, AP_RND_IF
  - AP_RND_ZERO, AP_RND_CONV

- **Quantization Modes (truncation):**
  - AP_TRN, AP_TRN_ZERO

Quantization Modes: Rounding

- **AP_RND_ZERO: rounding to zero**
  - For positive numbers, the redundant bits are truncated
  - For negative numbers, add MSB of removed bits to the remaining bits.
  - The effect is to round towards zero.
    - 01.01 (1.25 using 4 bits) rounds to 01.0 (1 using 3 bits)
    - 10.11 (-1.25 using 4 bits) rounds to 11.0 (-1 using 3 bits)

- **AP_RND_CONV: rounded to the nearest value**
  - The rounding depends on the least significant bit
  - If the least significant bit is set, rounding towards plus infinity
  - Otherwise, rounding towards minus infinity
    - 00.11 (0.75 using 4-bit) rounds to 01.0 (1.0 using 3-bit)
    - 10.11 (-1.25 using 4-bit) rounds to 11.0 (-1.0 using 3-bit)

Quantization Modes: Truncation

- **AP_TRN: truncate**
  - Remove redundant bits. Always rounds to minus infinity
  - This is the default.
    - 01.01(1.25) ➔ 01.0 (1)

- **AP_TRN_ZERO: truncate to zero**
  - For positive numbers, the same as AP_TRN
    - For positive numbers: 01.01(1.25) ➔ 01.0(1)
  - For negative numbers, round to zero
    - For negative numbers: 10.11 (-1.25) ➔ 11.0(-1)

Overflow Modes

> **Overflow mode**
>> Determines the behavior when an operation generates more bits than can be satisfied by the MSB

> **Overflow Modes (saturation)**
>> AP_SAT, AP_SAT_ZERO, AP_SAT_SYM

> **Overflow Modes (wrap)**
>> AP_WRAP, AP_WRAP_SM
>> The number of saturation bits, N, is considered when wrapping

Overflow Mode: Saturation

- **AP_SAT: saturation**
  - This overflow mode will convert the specified value to MAX for an overflow or MIN for an underflow condition
  - MAX and MIN are determined from the number of bits available
- **AP_SAT_ZERO: saturates to zero**
  - Will set the result to zero, if the result is out of range
- **AP_SAT_SYM: symmetrical saturation**
  - In 2's complement notation one more negative value than positive value can be represented
  - If it is desirable to have the absolute values of MIN and MAX symmetrical around zero, AP_SAT_SYM can be used
  - Positive overflow will generate MAX and negative overflow will generate -MAX
    - 0110(6) => 011(3)
    - 1011(-5) => 101(-3)

Overflow Mode: Wrap Sign Magnitude

- **AP_WRAP_SM, N = 0**
  - This mode uses sign magnitude wrapping
  - Sign bit set to the value of the least significant deleted bit
  - If the most significant remaining bit is different from the original MSB, all the remaining bits are inverted
  - IF MSBs are same, the other bits are copied over
    - Step 1: First delete redundant MSBs. 0100(4) => 100(-4)
    - Step 2: The new sign bit is the least significant bit of the deleted bits. 0 in this case
    - Step 3: Compare the new sign bit with the sign of the new value
  - If different, invert all the numbers. They are different in this case
    - 011 (3) 11

- **AP_WRAP_SM, N > 0**
  - Uses sign magnitude saturation
  - Here N MSBs will be saturated to 1
  - Behaves similar to case where N = 0, except that positive numbers stay positive and negative numbers stay negative

AP_FIXED operators & conversions

> Fully Supported for all Arithmetic operator

Operations	
Arithmetic	+ - * / % ++ --
Logical	~ !
Bitwise	& | ^
Relational	> < <= >= == !=
Assignment	*= /= %= += -= <<= >>= &= ^= |=

> Methods for type conversion

Methods		Example
To integer	Convert to a integer type	res = var.to_int();
To unsigned integer	Convert to an unsigned integer type	res = var.to_uint();
To 64-bit integer	Convert to a 64-bit long long type	res = var.to_int64();
To 64-bit unsigned integer	Convert to an unsigned long long type	res = var.to_uint64();
To double	Convert to double type	res = var.double();
To ap_int	Convert to an ap_int	res = var.to_ap_int();

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AP_FIXED methods

> **Methods for bit manipulation**

Methods		Example
Length	Returns the length of the variable.	res=var.length;
Concatenation	Concatenation low to high	res=var_hi.concat(var_lo); Or res= (var_hi,var_lo)
Range or Bit-select	Return a bit-range from high to low or a specific bit.	res=var.range(high bit,low bit); Or res=var[bit-number]

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Fixed Point Math Functions

- **The hls_math.h library**
  - Now includes fixed-point functions for sin, cos and sqrt

Function	*Type*	Accuracy (ULP)	Implementation Style
cos	ap_fixed<32,I>	16	Synthesized
sin	ap_fixed<32,I>	16	Synthesized
Sqrt	ap_fixed<W,I> ap_ufixed<W,I>	1	Synthesized

    - ULP- Units of Least Precision
  - The sin and cos functions are all 32-bit ap_fixed<32,Int_Bit>
    - Where Int_Bit specifies the number of integer bits
  - The sqrt function is any width but must have a decimal point
    - Cannot be all intergers or all bits
  - The accuracy above is quoted with respect to the equivalent floating point version

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Fixed Point Math Functions

Function	Data Type	Accuracy (ULP)	Implementation Style
abs	float double	Exact	Synthesized
atan	float double	2	Synthesized
atanf	float	2	Synthesized
atan2	float double	2	Synthesized
atan2f	float	2	Synthesized
ceil	float double	Exact	Synthesized
ceilf	float	Exact	Synthesized
copysign	float double	Exact	Synthesized
copysignf	float	Exact	Synthesized
cos	float double	10	Synthesized
	ap_fixed<32,I>	28-29	Synthesized
cosf	float	1	Synthesized
coshf	float	4	Synthesized
exp	float double	Exact	LogiCORE™ IP
expf	float	Exact	LogiCORE IP
fabs	float double	Exact	Synthesized
fabsf	float	Exact	Synthesized
floorf	float	Exact	Synthesized
fmax	float double	Exact	Synthesized
fmin	float double	Exact	Synthesized
logf	float	1	Synthesized
floor	float double	Exact	Synthesized
fpclassify	float double	Exact	Synthesized

Function	Data Type	Accuracy (ULP)	Implementation Style
isfinite	float double	Exact	Synthesized
isinf	float double	Exact	Synthesized
isnan	float double	Exact	Synthesized
isnormal	float double	Exact	Synthesized
log	float	1	Synthesized
	double	16	Synthesized
log10	float	2	Synthesized
	double	3	Synthesized
modf	float double	Exact	Synthesized
modff	float	Exact	Synthesized
1/x (reciprocal)	float double	Exact	LogiCORE IP
recip	float double	1	Synthesized
recipf	float	1	Synthesized
round	float double	Exact	Synthesized
rsqrt	float double	1	Synthesized
rsqrtf	float	1	Synthesized
1/sqrt (reciprocal sqrt)	float double	Exact	LogiCORE IP
signbit	float double	Exact	Synthesized
sin	float double	10	Synthesized
	ap_fixed<32,I>	28-29	Synthesized
sincos	float	1	Synthesized
	double	5	Synthesized
sincosf	float	1	Synthesized
sinf	float	1	Synthesized
sinhf	float	6	Synthesized

Function	Data Type	Accuracy (ULP)	Implementation Style
sqrt	float double	Exact	LogiCORE IP
	ap_fixed<32,I>	28-29	Synthesized
tan	float double	20	Synthesized
tanf	float	3	Synthesized
trunc	float double	Exact	Synthesized

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System C Data Types

Arbitrary Precision : SystemC

- **SystemC is an IEEE standard (IEEE 1666)**
  - C++ class libraries
  - Allows design and simulation with concurrency
  - Provides a library of arbitrary precision types
    - sc_int, sc_uint, sc_bigint (int > 64 bit), sc_fixed, etc.
- **SystemC support**
  - Vivado HLS supports SystemC 2.1 and 1.3 Synthesizable subset[1]
- **SystemC Compilation**
  - Compile with g++
  - Include the SystemC files from the Vivado HLS tree

```
shell> g++ –o my_test test.c test_tb.c \
              -I$Vivado HLS_HOME\Win_x86\tools\systemc\include \
              -lsystemc  \
              -L$Vivado HLS_HOME\Win_x86\tools\systemc\include\lib
```

- **SC Types**
  - Can be used in C++ designs without the need to convert the entire design to SystemC

Floating Point Support

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Floating Point Support

- **Synthesis for floating point**
  - Data types (IEEE-754 standard compliant)
    - Single-precision
      - 32 bit: 24-bit fraction, 8-bit exponent
    - Double-precision
      - 64 bit: 53-bit fraction, 11-bit exponent
    - Half-precision
      - 16-bit:1-bit sign, 5-bit exponent, 10-bit mantissa
- **Support for Operators**
  - Vivado HLS supports the Floating Point (FP) cores for each Xilinx technology
    - If Xilinx has a FP core, Vivado HLS supports it
    - It will automatically be synthesized
  - If there is no such FP core in the Xilinx technology, it will not be in the library
    - The design will be still synthesized

Half-Precision Floating Point Operations

- **Supported operations**
  - Addition
  - Division
  - Multiplication
  - Subtraction
- **Include “hls_half.h”**

```
// Include half-float header file
#include “hls_half.h”
// Use data-type “half”
typedef half data_t;
// Use typedef or “half” on arrays and pointers
void top( data_t in[SIZE], half &out_sum);
```

Floating-Point Cores

Core	Description
FAddSub_nodsp	Floating-point adder or subtractor implemented without any DSP48 primitives.
FAddSub_fulldsp	Floating-point adder or subtractor implemented using only DSP48s primitives.
FDiv	Floating-point divider.
FExp_nodsp	Floating-point exponential operation implemented without any DSP48 primitives.
FExp_meddsp	Floating-point exponential operation implemented with balance of DSP48 primitives.
FExp_fulldsp	Floating-point exponential operation implemented with only DSP48 primitives.
FLog_nodsp	Floating-point logarithmic operation implemented without any DSP48 primitives.
FLog_meddsp	Floating-point logarithmic operation with balance of DSP48 primitives.
FLog_fulldsp	Floating-point logarithmic operation with only DSP48 primitives.
FMul_nodsp	Floating-point multiplier implemented without any DSP48 primitives.
FMul_meddsp	Floating-point multiplier implemented with balance of DSP48 primitives.
FMul_fulldsp	Floating-point multiplier implemented with only DSP48 primitives.
FMul_maxdsp	Floating-point multiplier implemented the maximum number of DSP48 primitives.
FRSqrt_nodsp	Floating-point reciprocal square root implemented without any DSP48 primitives.
FRSqrt_fulldsp	Floating-point reciprocal square root implemented with only DSP48 primitives.
FRecip_nodsp	Floating-point reciprocal implemented without any DSP48 primitives.
FRecip_fulldsp	Floating-point reciprocal implemented with only DSP48 primitives.
FSqrt	Floating-point square root.
DAddSub_nodsp	Double precision floating-point adder or subtractor implemented without any DSP48 primitives.
DAddSub_fulldsp	Double precision floating-point adder or subtractor implemented using only DSP48s primitives.
DDiv	Double precision floating-point divider.
DExp_nodsp	Double precision floating-point exponential operation implemented without any DSP48 primitives.
DExp_meddsp	Double precision floating-point exponential operation implemented with balance of DSP48 primitives.

Core	Description
FAddSub_nodsp	Floating-point adder or subtractor implemented without any DSP48 primitives.
DExp_fulldsp	Double precision floating-point exponential operation implemented with only DSP48 primitives.
DLog_nodsp	Double precision floating-point logarithmic operation implemented without any DSP48 primitives.
DLog_meddsp	Double precision floating-point logarithmic operation with balance of DSP48 primitives.
DLog_fulldsp	Double precision floating-point logarithmic operation with only DSP48 primitives.
DMul_nodsp	Double precision floating-point multiplier implemented without any DSP48 primitives.
DMul_meddsp	Double precision floating-point multiplier implemented with a balance of DSP48 primitives.
DMul_fulldsp	Double precision floating-point multiplier implemented with only DSP48 primitives.
DMul_maxdsp	Double precision floating-point multiplier implemented with a maximum number of DSP48 primitives.
DRSqrt	Double precision floating-point reciprocal square root.
DRecip	Double precision floating-point reciprocal.
DSqrt	Double precision floating-point square root.
HAddSub_nodsp	Half-precision floating-point adder or subtractor implemented without DSP48 primitives.
HDiv	Half-precision floating-point divider.
HMul_nodsp	Half-precision floating-point multiplier implemented without DSP48 primitives.
HMul_fulldsp	Half-precision floating-point multiplier implemented with only DSP48 primitives.
HMul_maxdsp	Half-precision floating-point multiplier implemented with a maximum number of DSP48 primitives.
HSqrt	Half-precision floating-point square root.

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Summary

Summary

> **C and C++ have standard types created on the 8-bit boundary**
>> char (8-bit), short (16-bit), int (32-bit), long long (64-bit)

> **Vivado HLS supports SystemC 1.3 Synthesizable subset**

> **Arbitrary precision in C is supported using apint and ap_int in C++**
>> Compile using apcc for arbitrary precision
>> Arbitrary precision types can define bit-accurate operators leading to better QoR

> **Fixed point precision is supported in C++**
>> Both signed (ap_fixed) and unsigned types (ap_ufixed)

Summary

- **Various quantization and overflow modes supported**
  - Quantization
    - AP_RND, AP_RND_ZERO, AP_RND_MIN_INF, AP_RND_INF, AP_RND_CONV, AP_TRN, AP_TRN_ZERO
  - Overflow
    - AP_SAT, AP_SAT_ZERO, AP_SAT_SYM, AP_WRAP, AP_WRAP_SYM
- **Half-, single- and double-precision floating point data types are supported**
  - If a corresponding floating point core is available then it will automatically be used
  - If floating point core is not available then Vivado HLS will generate the RTL model

Adaptable.
Intelligent.

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