

Vivado Design Suite User Guide

High-Level Synthesis

UG902 (v2014.3) October 1, 2014

This document applies to the following software versions: Vivado Design Suite 2014.3 and 2014.4.



Revision History

The following table shows the revision history for this document.

Date	Version	Revision
10/01/2014	2014.3	<p>Updated Introduction to C-Based FPGA Design, updated directory information in Creating a New Synthesis Project, updated Archiving the Project, updated additional options in Using the Command Prompt and Tcl Interface, added 2D_convolution_with_linebuffer in Table 1-5, added cpp_math in Table 1-6, updated Pipelined Tasks, updated Synthesis of Arrays, updated Pipeline for Performance, updated Improving the Area, updated Table 1-17, added PyrDown and PyrUp to Table 1-19, updated Packing Structs into AXI4-Stream Interfaces, updated AXI4-Lite Interface, added XExample_Get_ARG_BaseAddress through XExample_Read_ARG_Bytes to Table 1-22, added Controlling the Address Offset in an AXI4 Master Interface, added note about dataflow optimization in Task Level Pipelining: Data Flow Optimization, updated Configuring Dataflow Memory Channels, updated Table 1-26 through Table 1-28, added Controlling Operator Pipelining, and updated RTL Simulator Support in Chapter 1, High-Level Synthesis.</p> <p>Added CFLAG information to HLS Math Library Accuracy, added Table 2-11 through Table 2-16, added PyrDown and PyrUp to Table 2-17, and updated Table 2-23 in Chapter 2, High-Level Synthesis C Libraries.</p> <p>Added note about input arguments to C Test Bench, updated Arrays on the Interface, added RESOURCE directive to Array Interfaces, and added Synthesis of Loops in Chapter 3, High-Level Synthesis Coding Styles.</p> <p>Added config_compile, updated example in set_directive_function_instantiate, updated set_directive_resource, updated Resolving Header File Information, added XDut_Get_ARG_BaseAddress through XDut_Read_ARG_Bytes to Table 4-1, added XDut_Get_ARG_BaseAddress through XDut_Read_ARG_Bytes, updated template for hls::GaussianBlur, added hls::PyrDown and hls::PyrUp, updated size values for hls::Sobel, added Compile Time Access to Data Type Attributes in C++ Arbitrary Precision Types, and added Compile Time Access to Data Type Attributes in C++ Arbitrary Precision Fixed-Point Types in Chapter 4, High-Level Synthesis Reference Guide.</p> <p>Updated Figure 1-3, Figure 1-7, Figure 1-15, Figure 1-28, Figure 1-29, Figure 1-30, Figure 1-49, and Figure 4-4.</p>
06/04/2014	2014.2	No technical updates. Re-release only.
05/30/2014	2014.1	Fixed linking targets. No content changes were implemented in the revision.
04/02/2014	2014.1	Updated Vivado Design Suite User Guide: High-Level Synthesis content organization and added the new HLS UltraFast Design Methodology section.

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High-Level Synthesis

Introduction to C-Based FPGA Design

The Xilinx® Vivado® High-Level Synthesis (HLS) tool transforms a C specification into a register transfer level (RTL) implementation that you can synthesize into a Xilinx field programmable gate array (FPGA). You can write C specifications in C, C++, or SystemC, and the FPGA provides a massively parallel architecture with benefits in performance, cost, and power over traditional processors. This chapter provides an overview of high-level synthesis.

Note: For more information on FPGA architectures and Vivado HLS basic concepts, see the *Introduction to FPGA Design with Vivado High-Level Synthesis* (UG998) [Ref 1].

High-Level Synthesis Benefits

High-level synthesis bridges hardware and software domains, providing the following primary benefits:

- Improved productivity for hardware designers
 - Allows hardware designers to work at a higher level of abstraction while creating high-performance hardware.
- Improved system performance for software designers
 - Allows software developers to accelerate the computationally intensive parts of their algorithms on a new compilation target, the FPGA.

Using a high-level synthesis design methodology allows you to:

- Develop algorithms at the C-level
 - Enables you to work at a level that is abstract from the implementation details, which consume development time.
- Verify at the C-level
 - Enables you to validate the functional correctness of the design more quickly than with traditional hardware description languages.

- Control the C synthesis process through optimization directives
 - Enables you to create specific high-performance hardware implementations.
- Create multiple implementations from the C source code using optimization directives
 - Enables you to explore the design space, which increases the likelihood of finding an optimal implementation.
- Create readable and portable C source code
 - Enables you to retarget the C source into different devices as well as incorporate the C source into new projects.

High-Level Synthesis Basics

High-level synthesis includes the following phases:

- Scheduling

Determines which operations occur during each clock cycle based on:

- Length of the clock cycle or clock frequency
- Time it takes for the operation to complete, as defined by the target device
- User-specified optimization directives

If the clock period is longer or a faster FPGA is targeted, more operations are completed within a single clock cycle, and all operations might complete in one clock cycle. Conversely, if the clock period is shorter or a slower FPGA is targeted, high-level synthesis automatically schedules the operations over more clock cycles, and some operations might need to be implemented as multicycle resources.

- Binding

Determines which hardware resource implements each scheduled operation. To implement the optimal solution, high-level synthesis uses information about the target device.

- Control logic extraction

Extracts the control logic to create a finite state machine (FSM) that sequences the operations in the RTL design.

High-level synthesis synthesizes the C code as follows:

- Top-level function arguments synthesize into RTL I/O ports
- C functions synthesize into blocks in the RTL hierarchy

If the C code includes a hierarchy of sub-functions, the final RTL design includes a hierarchy of modules or entities that have a one-to-one correspondence with the original C function hierarchy. All instances of a function use the same RTL implementation or block.

- Loops in the C functions are kept *rolled* by default

When loops are rolled, synthesis creates the logic for one iteration of the loop, and the RTL design executes this logic for each iteration of the loop in sequence. Using optimization directives, you can *unroll* loops, which allows all iterations to occur in parallel.

- Arrays in the C code synthesize into block RAM in the final FPGA design

If the array is on the top-level function interface, high-level synthesis implements the array as ports to access a block RAM outside the design.

High-level synthesis creates the optimal implementation based on default behavior, constraints, and any optimization directives you specify. You can use optimization directives to modify and control the default behavior of the internal logic and I/O ports. This allows you to generate variations of the hardware implementation from the same C code.

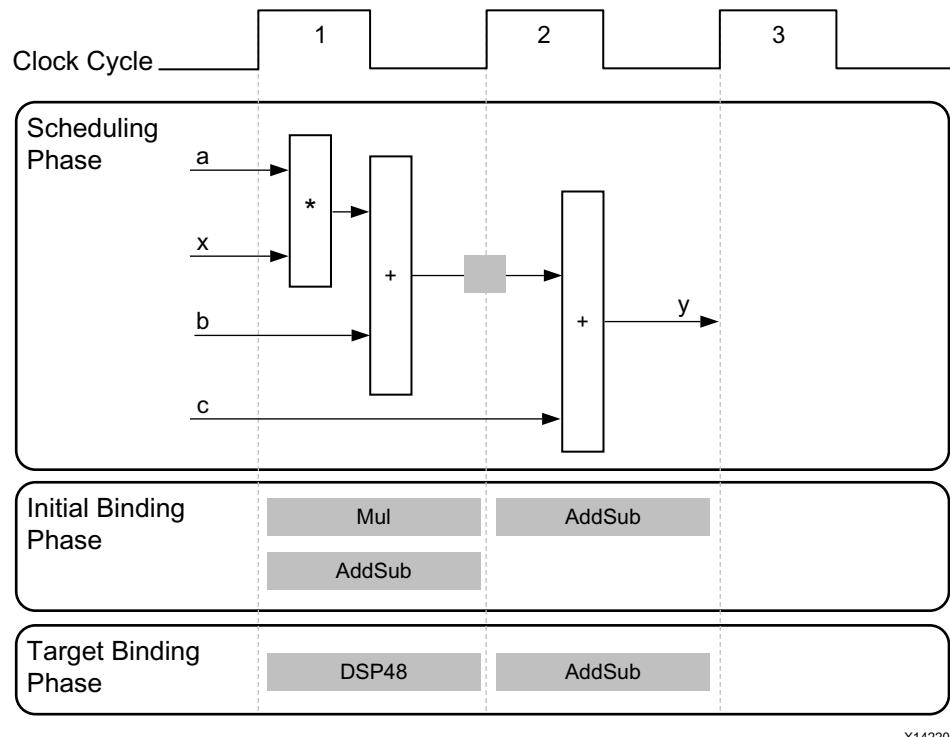
To determine if the design meets your requirements, you can review the performance metrics in the synthesis report generated by high-level synthesis. After analyzing the report, you can use optimization directives to refine the implementation. The synthesis report contains information on the following performance metrics:

- Area: Amount of hardware resources required to implement the design based on the resources available in the FPGA, including look-up tables (LUT), registers, block RAMs, and DSP48s.
- Latency: Number of clock cycles required for the function to compute all output values.
- Initiation interval (II): Number of clock cycles before the function can accept new input data.
- Loop iteration latency: Number of clock cycles it takes to complete one iteration of the loop.
- Loop initiation interval: Number of clock cycle before the next iteration of the loop starts to process data.
- Loop latency: Number of cycles to execute all iterations of the loop.

Scheduling and Binding Example

The following figure shows an example of the scheduling and binding phases for this code example:

```
int foo(char x, char a, char b, char c) {
    char y;
    y = x*a+b+c;
    return y
}
```



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Figure 1-1: Scheduling and Binding Example

In the scheduling phase of this example, high-level synthesis schedules the following operations to occur during each clock cycle:

- First clock cycle: Multiplication and the first addition
- Second clock cycle: Second addition and output generation

Note: In the preceding figure, the square between the first and second clock cycles indicates when an internal register stores a variable. In this example, high-level synthesis only requires that the output of the addition is registered across a clock cycle. The first cycle reads x , a , and b data ports. The second cycle reads data port c and generates output y .

In the final hardware implementation, high-level synthesis implements the arguments to the top-level function as input and output (I/O) ports. In this example, the arguments are simple data ports. Because each input variables is a `char` type, the input data ports are all 8-bits wide. The function `return` is a 32-bit `int` data type, and the output data port is 32-bits wide.



IMPORTANT: *The advantage of implementing the C code in the hardware is that all operations finish in a shorter number of clock cycles. In this example, the operations complete in only two clock cycles. In a central processing unit (CPU), even this simple code example takes more clock cycles to complete.*

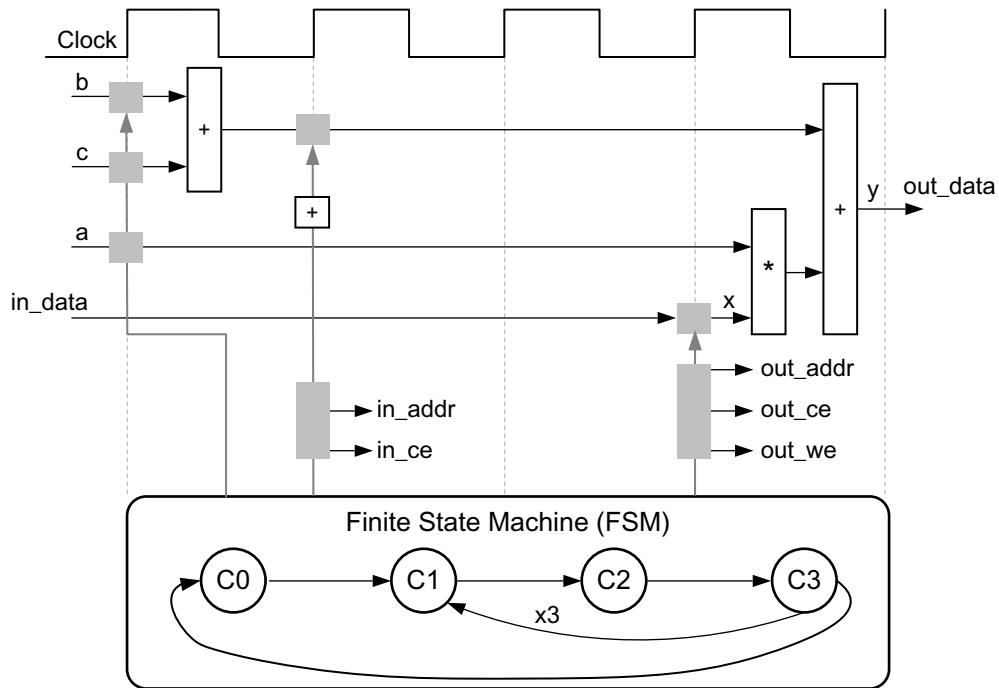
In the initial binding phase of this example, high-level synthesis implements the multiplier operation using a combinational multiplier (Mul) and implements both add operations using a combinational adder/subtractor (AddSub).

In the target binding phase, high-level synthesis implements both the multiplier and one of the addition operations using a DSP48 resource. The DSP48 resource is a computational block available in the FPGA architecture that provides the ideal balance of high-performance and efficient implementation.

Control Logic Extraction and I/O Port Implementation Example

The following figure shows the extraction of control logic and implementation of I/O ports for this code example:

```
void foo(int in[3], char a, char b, char c, int out[3]) {
    int x,y;
    for(int i = 0; i < 3; i++) {
        x = in[i];
        y = a*x + b + c;
        out[i] = y;
    }
}
```



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Figure 1-2: Control Logic Extraction and I/O Port Implementation Example

This code example performs the same operations as the previous example. However, it performs the operations inside a for-loop, and two of the function arguments are arrays. The resulting design executes the logic inside the for-loop three times when the code is scheduled. High-level synthesis automatically extracts the control logic from the C code and creates an FSM in the RTL design to sequence these operations. High-level synthesis implements the top-level function arguments as ports in the final RTL design. The scalar variable of type `char` maps into a standard 8-bit data bus port. Array arguments, such as `in` and `out`, contain an entire collection of data.

In high-level synthesis, arrays are synthesized into block RAM by default, but other options are possible, such as FIFOs, distributed RAM, and individual registers. When using arrays as arguments in the top-level function, high-level synthesis assumes that the block RAM is outside the top-level function and automatically creates ports to access a block RAM outside the design, such as data ports, address ports, and any required chip-enable or write-enable signals.

The FSM controls when the registers store data and controls the state of any I/O control signals. The FSM starts in the state C0. On the next clock, it enters state C1, then state C2, and then state C3. It returns to state C1 (and C2, C3) a total of three times before returning to state C0.

Note: This closely resembles the control structure in the C code for-loop. The full sequence of states are: C0, {C1, C2, C3}, {C1, C2, C3}, {C1, C2, C3}, and return to C0.

The design requires the addition of `b` and `c` only one time. High-level synthesis moves the operation outside the for-loop and into state `C0`. Each time the design enters state `C3`, it reuses the result of the addition.

The design reads the data from `in` and stores the data in `x`. The FSM generates the address for the first element in state `C1`. In addition, in state `C1`, an adder increments to keep track of how many times the design must iterate around states `C1`, `C2`, and `C3`. In state `C2`, the block RAM returns the data for `in` and stores it as variable `x`.

High-level synthesis reads the data from port `a` with other values to perform the calculation and generates the first `y` output. The FSM ensures that the correct address and control signals are generated to store this value outside the block. The design then returns to state `C1` to read the next value from the array/block RAM `in`. This process continues until all output is written. The design then returns to state `C0` to read the next values of `b` and `c` to start the process again.

Performance Metrics Example

The following figure shows the complete cycle-by-cycle execution for the code in the [Control Logic Extraction and I/O Port Implementation Example](#), including the states for each clock cycle, read operations, computation operations, and write operations.

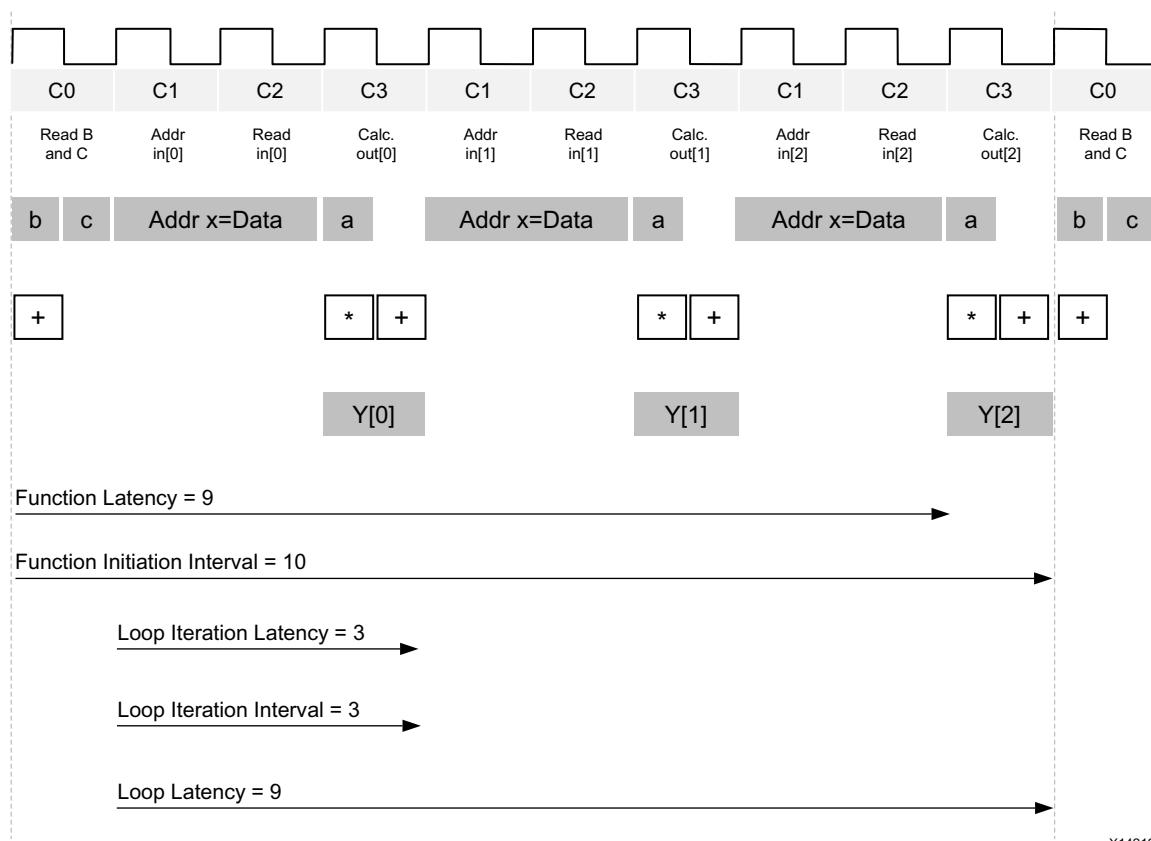


Figure 1-3: Latency and Initiation Interval Example

Following are the performance metrics for this example:

- **Latency:** It takes the function 9 clock cycles to output all values.
- Note:** When the output is an array, the latency is measured to the last array value output.
- **II:** The II is 10, which means it takes 10 clock cycles before the function can initiate a new set of input reads and start to process the next set of input data.

Note: The time to perform one complete execution of a function is referred to as one *transaction*. In this example, it takes 11 clock cycles before the function can accept data for the next transaction.

- **Loop iteration latency:** The latency of each loop iteration is 3 clock cycles.
- **Loop II:** The interval is 3.
- **Loop latency:** The latency is 9 clock cycles.

Understanding Vivado HLS

The Xilinx Vivado HLS tool synthesizes a C function into an IP block that you can integrate into a hardware system. It is tightly integrated with the rest of the Xilinx design tools and provides comprehensive language support and features for creating the optimal implementation for your C algorithm.

Following is the Vivado HLS design flow:

1. Compile, execute (simulate), and debug the C algorithm.

Note: In high-level synthesis, running the compiled C program is referred to as *C simulation*. Executing the C algorithm simulates the function to validate that the algorithm is functionally correct.

2. Synthesize the C algorithm into an RTL implementation, optionally using user optimization directives.
3. Generate comprehensive reports and analyze the design.
4. Verify the RTL implementation using a pushbutton flow.
5. Package the RTL implementation into a selection of IP formats.

Inputs and Outputs

Following are the inputs to Vivado HLS:

- C function written in C, C++, or SystemC

This is the primary input to Vivado HLS. The function can contain a hierarchy of sub-functions.

- Constraints

Constraints are required and include the clock period, clock uncertainty, and FPGA target. The clock uncertainty defaults to 12.5% of the clock period if not specified.

- Directives

Directives are optional and direct the synthesis process to implement a specific behavior or implementation.

- C test bench and any associated files

Vivado HLS uses the C test bench to simulate the C function prior to synthesis and to automatically verify the RTL output using C/RTL co-simulation.

You can add the C input files, directives, and constraints to a Vivado HLS project interactively using the Vivado HLS graphical user interface (GUI) or using Tcl commands at the command prompt. You can also create a Tcl file and execute the commands in batch mode.

Following are the outputs from Vivado HLS:

- RTL implementation files in hardware description language (HDL) format

This is the primary output from Vivado HLS. Using logic synthesis, you can synthesize the RTL into a gate-level implementation and an FPGA bitstream file. The RTL is available in the following industry standard formats:

- VHDL (IEEE 1076-2000)
- Verilog (IEEE 1364-2001)

Vivado HLS packages the implementation files as an IP block for use with other tools in the Xilinx design flow. Using logic synthesis, you can synthesize the packaged IP into an FPGA bitstream, which includes the Verilog and VHDL design files.

- RTL implementation files in SystemC format (IEEE 1666-2006, version 2.2)

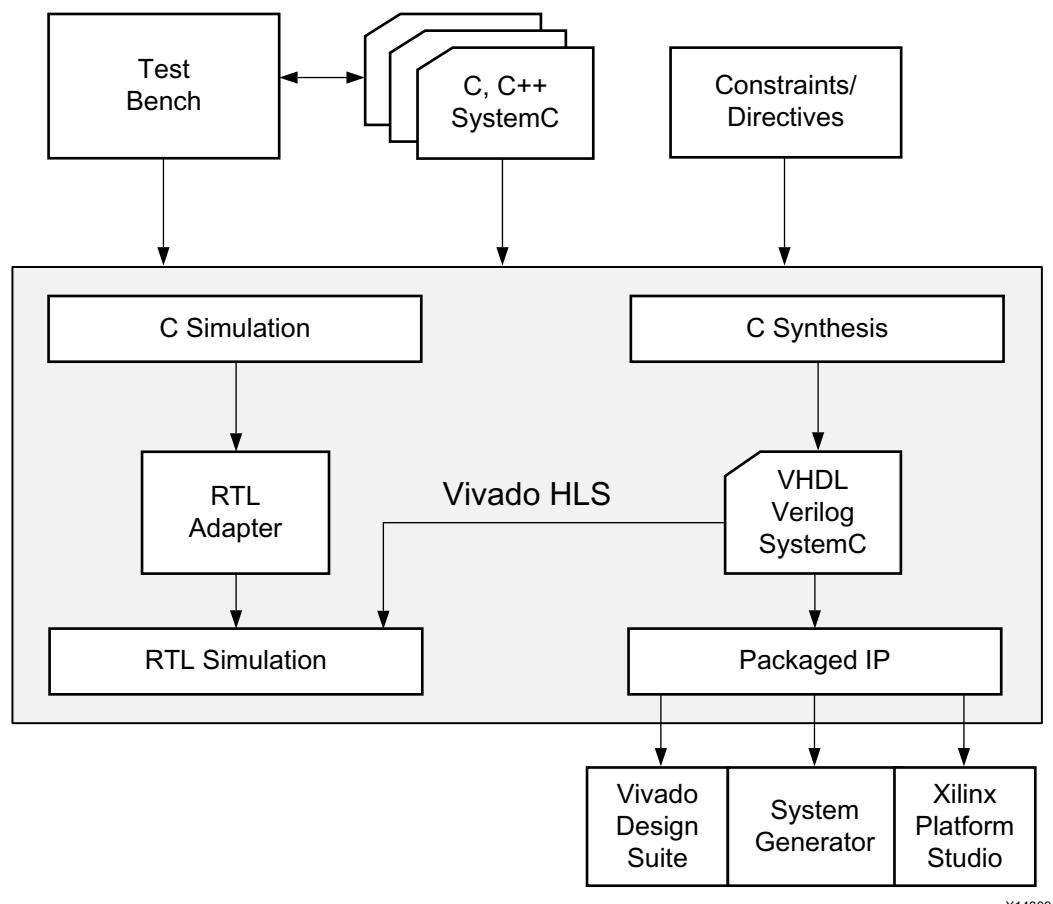
This output is provided primarily as a simulation model and is not included in the packaged IP.

Note: Xilinx does not provide design tools that can synthesize SystemC in RTL format into a bitstream.

- Report files

This output is the result of synthesis, C/RTL co-simulation, and IP packaging.

The following figure shows an overview of the Vivado HLS input and output files.



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Figure 1-4: Vivado HLS Design Flow

Test Bench, Language Support, and C Libraries

In any C program, the top-level function is called `main()`. In the Vivado HLS design flow, you can specify any sub-function below `main()` as the top-level function for synthesis. You *cannot* synthesize the top-level function `main()`. Following are additional rules:

- Only one function is allowed as the top-level function for synthesis.
- Any sub-functions in the hierarchy under the top-level function for synthesis are also synthesized.
- If you want to synthesize functions that are not in the hierarchy under the top-level function for synthesis, you must merge the functions into a single top-level function for synthesis.

Test Bench

When using the Vivado HLS design flow, it is time consuming to synthesize a functionally incorrect C function and then analyze the implementation details to determine why the function does not perform as expected. To improve productivity, use a test bench to validate that the C function is functionally correct prior to synthesis.

The C test bench includes the function `main()` and any sub-functions that are not in the hierarchy under the top-level function for synthesis. These functions verify that the top-level function for synthesis is functionally correct by providing stimuli to the function for synthesis and by consuming its output.

Vivado HLS uses the test bench to compile and execute the C simulation. During the compilation process, you can select the **Launch Debugger** option to open a full C-debug environment, which enables you to analyze the C simulation. For more information on test benches, see [C Test Bench in Chapter 3](#).



RECOMMENDED: Because Vivado HLS uses the test bench to both verify the C function prior to synthesis and to automatically verify the RTL output, using a test bench is highly recommended.

Language Support

Vivado HLS supports the following standards for C compilation/simulation:

- ANSI-C (GCC 4.6)
- C++ (G++ 4.6)
- SystemC (IEEE 1666-2006, version 2.2)

Vivado HLS supports many C, C++, and SystemC language constructs and all native data types for each language, including float and double types. However, synthesis is *not* supported for some constructs, including:

- Dynamic memory allocation

An FPGA has a fixed set of resources, and the dynamic creation and freeing of memory resources is not supported.

- Operating system (OS) operations

All data to and from the FPGA must be read from the input ports or written to output ports. OS operations, such as file read/write or OS queries like time and date, are not supported. Instead, the C test bench can perform these operations and pass the data into the function for synthesis as function arguments.

For details on the supported and unsupported C constructs and examples of each of the main constructs, see [Chapter 3, High-Level Synthesis Coding Styles](#).

C Libraries

C libraries contain functions and constructs that are optimized for implementation in an FPGA. Using these libraries helps to ensure high quality of results (QoR), that is, the final output is a high-performance design that makes optimal use of the resources. Because the libraries are provided in C, C++, or SystemC, you can incorporate the libraries into the C function and simulate them to verify the functional correctness before synthesis.

Vivado HLS provides the following C libraries to extend the standard C languages:

- Arbitrary precision data types
- Math operations
- Video functions
- Xilinx IP functions, including fast fourier transform (FFT) and finite impulse response (FIR)
- FPGA resource functions to help maximize the use of shift register LUT (SRL) resources

For more information on the C libraries provided by Vivado HLS, see [Chapter 2, High-Level Synthesis C Libraries](#).

C Library Example

C libraries ensure a higher QoR than standard C types. Standard C types are based on 8-bit boundaries (8-bit, 16-bit, 32-bit, 64-bit). However, when targeting a hardware platform, it is often more efficient to use data types of a specific width.

For example, a design with a filter function for a communications protocol requires 10-bit input data and 18-bit output data to satisfy the data transmission requirements. Using standard C data types, the input data must be at least 16-bits and the output data must be at least 32-bits. In the final hardware, this creates a datapath between the input and output that is wider than necessary, uses more resources, has longer delays (for example, a 32-bit by 32-bit multiplication takes longer than an 18-bit by 18-bit multiplication), and requires more clock cycles to complete.

Using an arbitrary precision data type in this design instead, you can specify the exact bit-sizes to be specified in the C code prior to synthesis, simulate the updated C code, and verify the quality of the output using C simulation prior to synthesis. Arbitrary precision data types are provided for C and C++ and allow you to model data types of any width from 1 to 1024-bit. For example, you can model some C++ types up to 32768 bits. For more information on arbitrary precision data types, see [Data Types for Efficient Hardware](#).

Note: Arbitrary precision types are only required on the function boundaries, because Vivado HLS optimizes the internal logic and removes data bits and logic that do not fanout to the output ports.

Synthesis, Optimization, and Analysis

Vivado HLS is project based. Each project holds one set of C code and can contain multiple solutions. Each solution can have different constraints and optimization directives. You can analyze and compare the results from each solution in the Vivado HLS GUI.

Following are the synthesis, optimization, and analysis steps in the Vivado HLS design process:

1. Create a project with an initial solution.
2. Verify the C simulation executes without error.
3. Run synthesis to obtain a set of results.
4. Analyze the results.

After analyzing the results, you can create a new solution for the project with different constraints and optimization directives and synthesize the new solution. You can repeat this process until the design has the desired performance characteristics. Using multiple solutions allows you to proceed with development while still retaining the previous results.

Optimization

Using Vivado HLS, you can apply different optimization directives to the design, including the following:

- Instruct a task to execute in a pipeline, allowing the next execution of the task to begin before the current execution is complete.
- Specify a latency for the completion of functions, loops, and regions.
- Specify a limit on the number of resources used.
- Override the inherent or implied dependencies in the code and permit specified operations. For example, if it is acceptable to discard or ignore the initial data values, such as in a video stream, allow a memory read before write if it results in better performance.
- Select the I/O protocol to ensure the final design can be connected to other hardware blocks with the same I/O protocol.

Note: Vivado HLS automatically determines the I/O protocol used by any sub-functions. You *cannot* control these ports except to specify whether the port is registered. For more information on working with I/O interfaces, see [Managing Interfaces](#).

You can use the Vivado HLS GUI to place optimization directives directly into the source code. Alternatively, you can use Tcl commands to apply optimization directives. For more information on the various optimizations, see [Design Optimization](#).



RECOMMENDED: It is highly recommended that you review the [HLS UltraFast Design Methodology](#) before applying optimization directives to the design.

Analysis

When synthesis completes, Vivado HLS automatically creates synthesis reports to help you understand the performance of the implementation. In the Vivado HLS GUI, the Analysis Perspective includes the Performance tab, which allows you to interactively analyze the results in detail. The following figure shows the Performance tab for the [Control Logic Extraction and I/O Port Implementation Example](#).

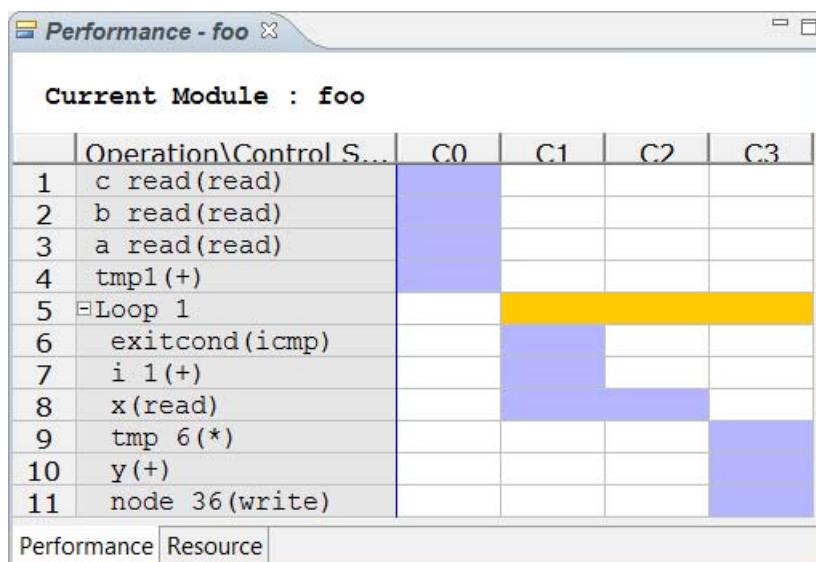


Figure 1-5: Vivado HLS Analysis Example

The Performance tab shows the following for each state:

- C0: The first state includes read operations on ports a, b, and c and the addition operation.
- C1 and C2: The design enters a loop and checks the loop increment counter and exit condition. The design then reads data into variable x, which requires two clock cycles. Two clock cycles are required, because the design is accessing a block RAM, requiring an address in one cycle and a data read in the next.
- C3: The design performs the calculations and writes output to port y. Then, the loop returns to the start.

RTL Verification

If you added a C test bench to the project, you can use it to verify that the RTL is functionally identical to the original C. The C test bench verifies the output from the top-level function for synthesis and returns zero to the top-level function `main()` if the RTL is functionally identical. Vivado HLS uses this return value for both C simulation and C/RTL co-simulation to determine if the results are correct. If the C test bench returns a non-zero value, Vivado HLS reports that the simulation failed.



IMPORTANT: *Even if the output data is correct and valid, Vivado HLS reports a simulation failure if the test bench does not return the value zero to function `main()`.*



TIP: *For test bench examples that you can use for reference, see [Design Examples and References](#).*

Vivado HLS automatically creates the infrastructure to perform the C/RTL co-simulation and automatically executes the simulation using one of the following supported RTL simulators:

- Vivado Simulator (XSim)
- QuestaSim simulator
- VCS
- NCSim
- ISE Simulator (ISim)
- Riviera
- Open SystemC Initiative (OSCI)

If you select Verilog or VHDL HDL for simulation, Vivado HLS uses the HDL simulator you specify. The Xilinx design tools include Vivado Simulator and ISE Simulator. Third-party HDL simulators require a license from the third-party vendor. The VCS, NCSim, and Riviera HDL simulators are only supported on the Linux operating system. For more information, see [Using C/RTL Co-Simulation](#).

Note: Vivado HLS verifies SystemC RTL output using the built-in SystemC kernel, which does not require a third-party simulator or license.

RTL Export

Using Vivado HLS, you can export the RTL and package the final RTL output files as IP in any of the following Xilinx IP formats:

- Vivado IP Catalog

Import into the Vivado IP catalog for use in the Vivado Design Suite.

- System Generator for DSP (Vivado Design Suite edition)

Import into System Generator for DSP for use in the Vivado Design Suite.

- System Generator for DSP (ISE® Design Suite edition)

Import into System Generator for DSP for use in the ISE Design Suite.

- Pcore for Embedded Development Kit (EDK)

Import into Xilinx Platform Studio (XPS).

- Synthesized Checkpoint (.dcp)

Import directly into the Vivado Design Suite the same way you import any Vivado Design Suite checkpoint.

Note: The synthesized checkpoint format invokes logic synthesis and compiles the RTL implementation into a gate-level implementation, which is included in the IP package.

For all IP formats except the synthesized checkpoint, you can optionally execute logic synthesis from within Vivado HLS to evaluate the results of RTL synthesis. This optional step allows you to confirm the estimates provided by Vivado HLS for timing and area before handing off the IP package. These gate-level results are *not* included in the packaged IP.

Note: Vivado HLS estimates the timing and area resources based on built-in libraries for each FPGA. When you use logic synthesis to compile the RTL into a gate-level implementation, perform physical placement of the gates in the FPGA, and perform routing of the inter-connections between gates, logic synthesis might make additional optimizations that change the Vivado HLS estimates.

For more information, see [Exporting the RTL Design](#).

Using Vivado HLS

To invoke Vivado HLS on a Windows platform double-click the desktop button as shown in the following figure.



Figure 1-6: Vivado HLS GUI Button

To invoke High-Level Synthesis on a Linux platform (or from the Vivado HLS Command Prompt on Windows) execute the following command at the command prompt.

```
$ vivado_hls
```

The Vivado HLS GUI opens as shown in the following figure.

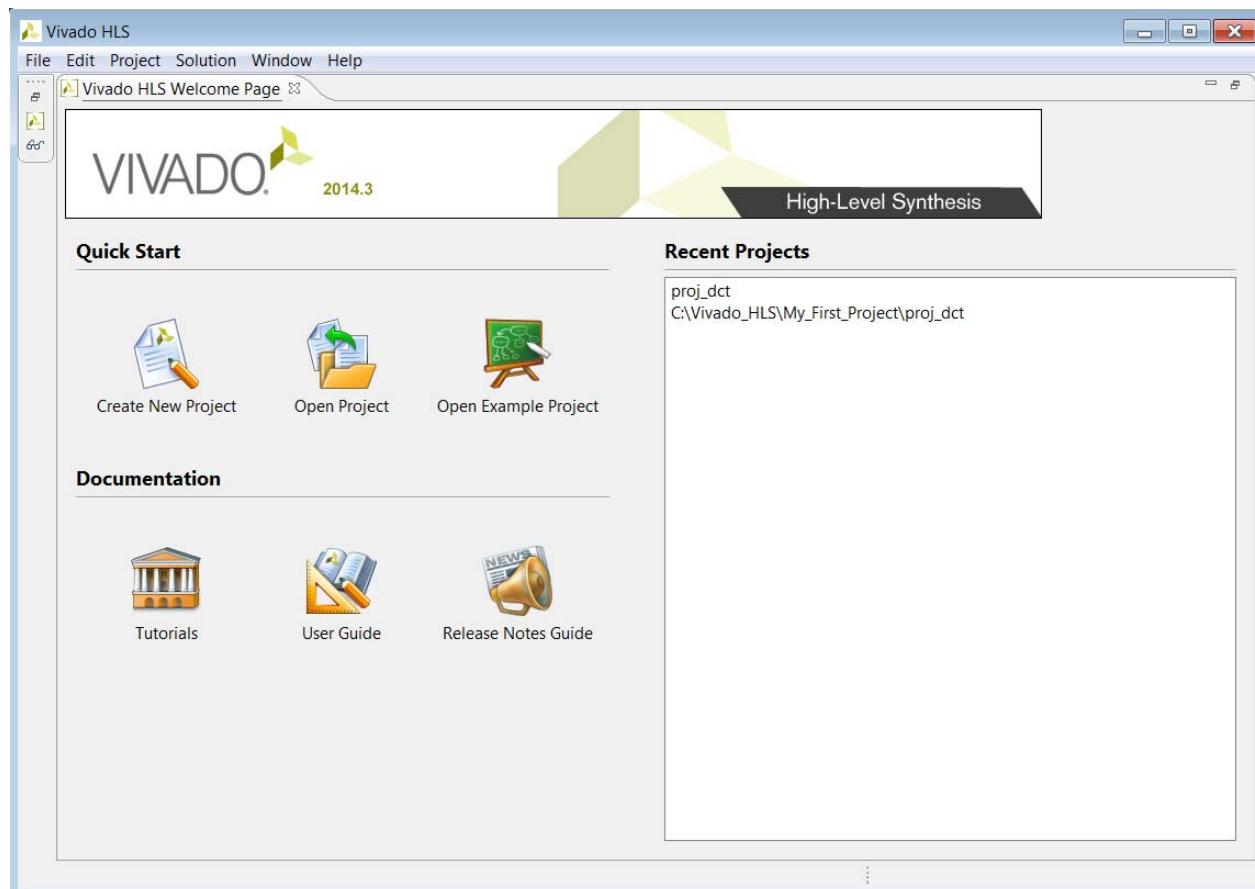


Figure 1-7: Vivado HLS GUI Welcome Page

You can use the Quick Start options to perform the following tasks:

- **Create New Project:** Launch the project setup wizard.
- **Open Project:** Navigate to an existing project or select from a list of recent projects.
- **Open Example Project:** Open Vivado HLS examples. For details on these examples, see [Design Examples and References](#).

You can use the Documentation options to perform the following tasks:

- **Tutorials:** Opens the *Vivado Design Suite Tutorial: High-Level Synthesis* (UG871) [\[Ref 2\]](#). For details on the tutorial examples, see [Design Examples and References](#).
- **User Guide:** Opens this document, the *Vivado Design Suite User Guide: High-Level Synthesis* (UG902).
- **Release Notes Guide:** Opens the *Vivado Design Suite User Guide: Release Notes, Installation, and Licensing* (UG973) [\[Ref 3\]](#) for the latest software version.

The primary controls for using Vivado HLS are shown in the toolbar in the following figure. Project control ensures only commands that can be currently executed are highlighted. For example, synthesis must be performed before C/RTL co-simulation can be executed. The C/RTL co-simulation toolbar buttons remain gray until synthesis completes.

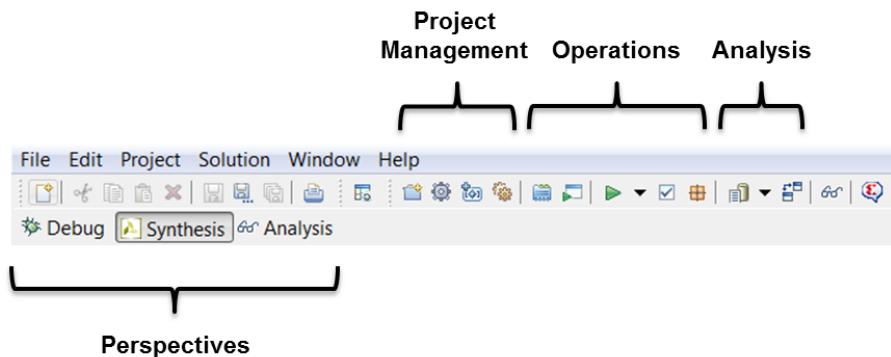


Figure 1-8: Vivado HLS Controls

In the Project Management section, the buttons are (from left to right):

- **Create New Project** opens the new project wizard.
- **Project Settings** allows the current project settings to be modified.
- **New Solution** opens the new solution dialog box.
- **Solution Settings** allows the current solution settings to be modified.

The next group of toolbar buttons control the tool operation (from left to right):

- **Index C Source** refreshes the annotations in the C source.

- **Run C Simulation** opens the C Simulation dialog box.
- **C Synthesis** starts C source code High-Level Synthesis.
- **Run C/RTL Cosimulation** verifies the RTL output.
- **Export RTL** packages the RTL into the desired IP output format.

The final group of toolbar buttons are for design analysis (from left to right):

- **Open Report** opens the C synthesis report or drops down to open other reports.
- **Compare Reports** allows the reports from different solutions to be compared.

Each of the buttons on the toolbar has an equivalent command in the menus. In addition, Vivado HLS GUI provides three perspectives. When you select a perspective, the windows automatically adjust to a more suitable layout for the selected task.

- The **Debug** perspective opens the C debugger.
- The **Synthesis** perspective is the default perspective and arranges the windows for performing synthesis.
- The **Analysis** perspective is used after synthesis completes to analyze the design in detail. This perspective provides considerable more detail than the synthesis report.

Changing between perspectives can be done at any time by selecting the desired perspective button.

The remainder of this chapter discusses how to use Vivado HLS. The following topics are discussed:

- How to create a Vivado HLS synthesis project.
- How to simulate and debug the C code.
- How to synthesize the design, create new solutions and add optimizations.
- How to perform design analysis.
- How to verify and package the RTL output.
- How to use the Vivado HLS Tcl commands and batch mode.

This chapter ends with a review of the design examples, tutorials, and resources for more information.

Creating a New Synthesis Project

A new project can be created by clicking on the **Create New Project** link on the Welcome page shown in [Figure 1-7](#) or by using the menu command **File > New Project**. This opens project wizard.

The first screen of the project wizard asks for details on the project specification as shown in the following figure.

The fields for entering the project specification are:

- **Project Name:** In addition to being the project name, this file is also the name of the directory in which the project details are stored.
- **Location:** This is where the project is stored.

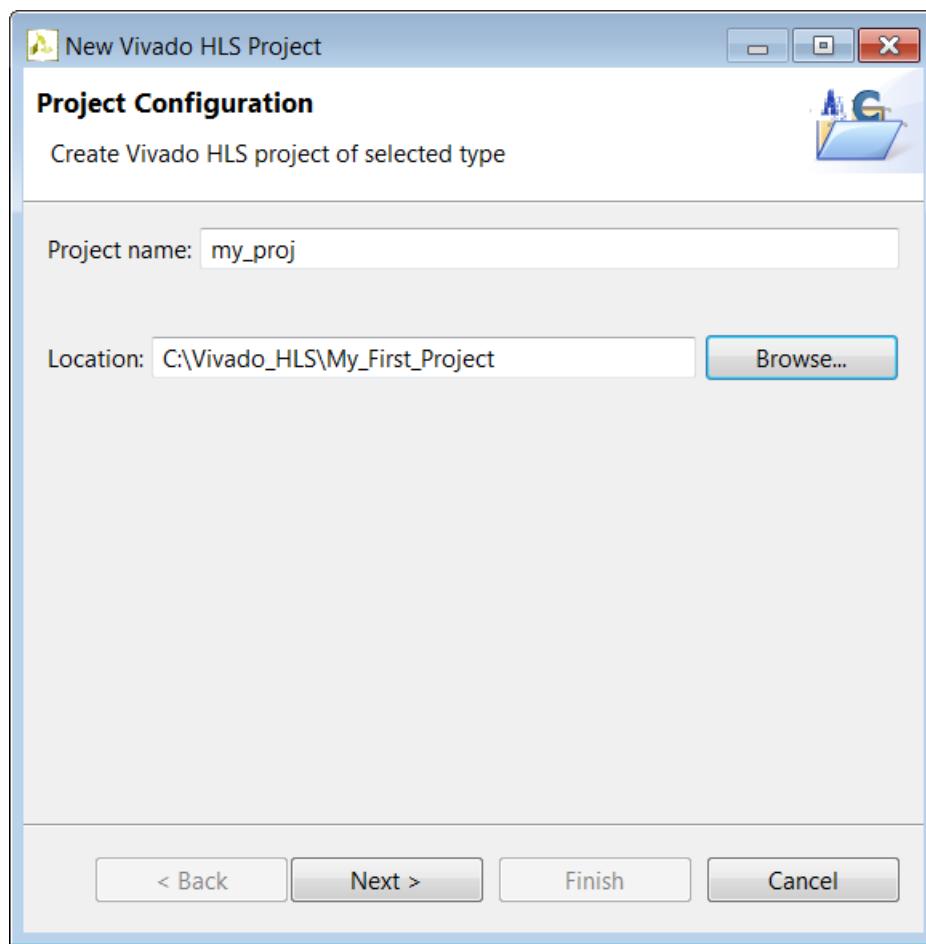


Figure 1-9: Project Specification

Selecting the **Next >** button moves the wizard to the second screen where you can enter details in the project C source files ([Figure 1-10](#)).

- **Top Function:** The name of the top-level function to be synthesized is specified here.

Note: This step is not required when the project is specified as SystemC. Vivado HLS automatically identifies the top-level functions.

Use the **Add Files** button to add the source code files to the project.



IMPORTANT: Do not add header files (with the .h suffix) to the project using the **Add Files** button (or with the associated `add_files` Tcl command).

Vivado HLS automatically adds the following directories to the search path:

- Working directory
 - Note:** The working directory contains the Vivado HLS project directory.
- Any directory that contains C files added to the project

Header files that reside in these directories are automatically included in the project. You must specify the path to all other header files using the **Edit CFLAGS** button.

The **Edit CFLAGS** button specifies the C compiler flags options required to compile the C code. These compiler flag options are the same used in gcc or g++. C compiler flags include the pathname to header files, macro specifications, and compiler directives, as shown in the following examples:

- **-I/project/source/headers:** provides the search path to associated header files
 - Note:** You must specify relative path names in relation to the working directory *not* the project directory.
- **-DMACRO_1:** defines macro MACRO_1 during compilation
- **-fnested:** defines directive required for any design that contains nested functions

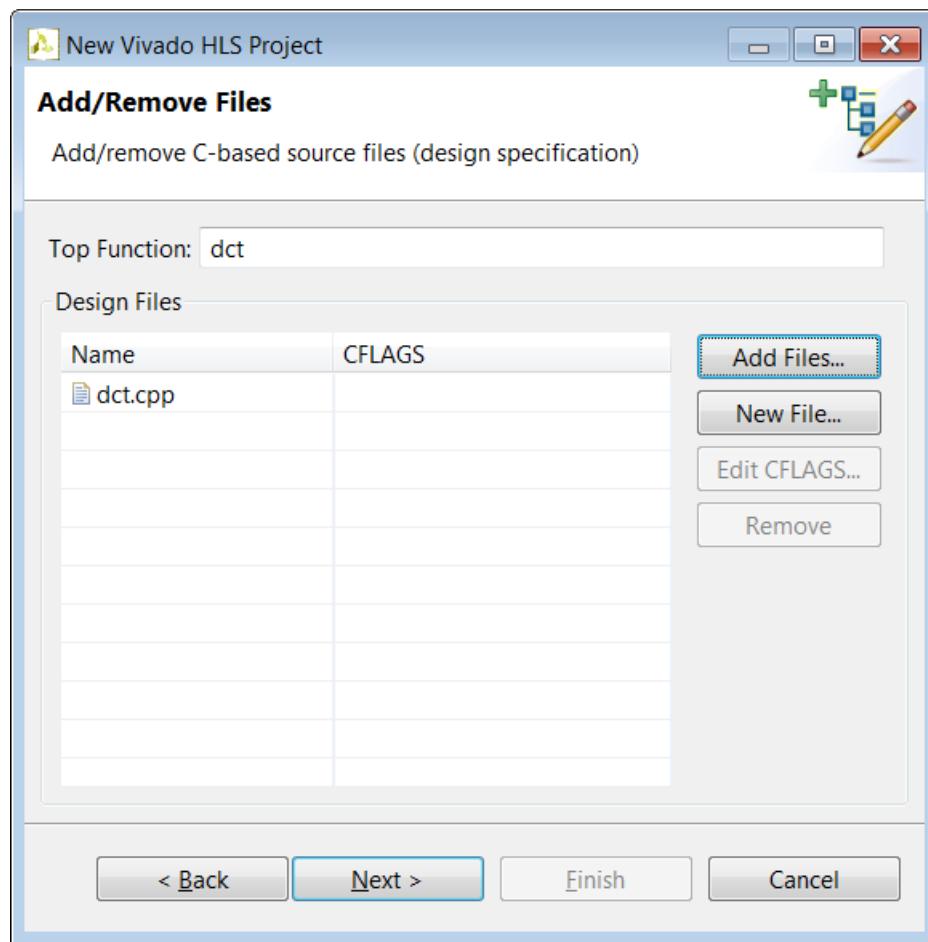


Figure 1-10: Project Source Files

The next window in the project wizard allows you to add the files associated with the test bench to the project.

In most of the example designs provided with Vivado HLS, the test bench is in a separate file from the design. Having the test bench and the function to be synthesized in separate files keeps a clean separation between the process of simulation and synthesis. If the test bench is in the same file as the function to be synthesized, the file should be added as a source files and, as shown in the next step, a test bench file.

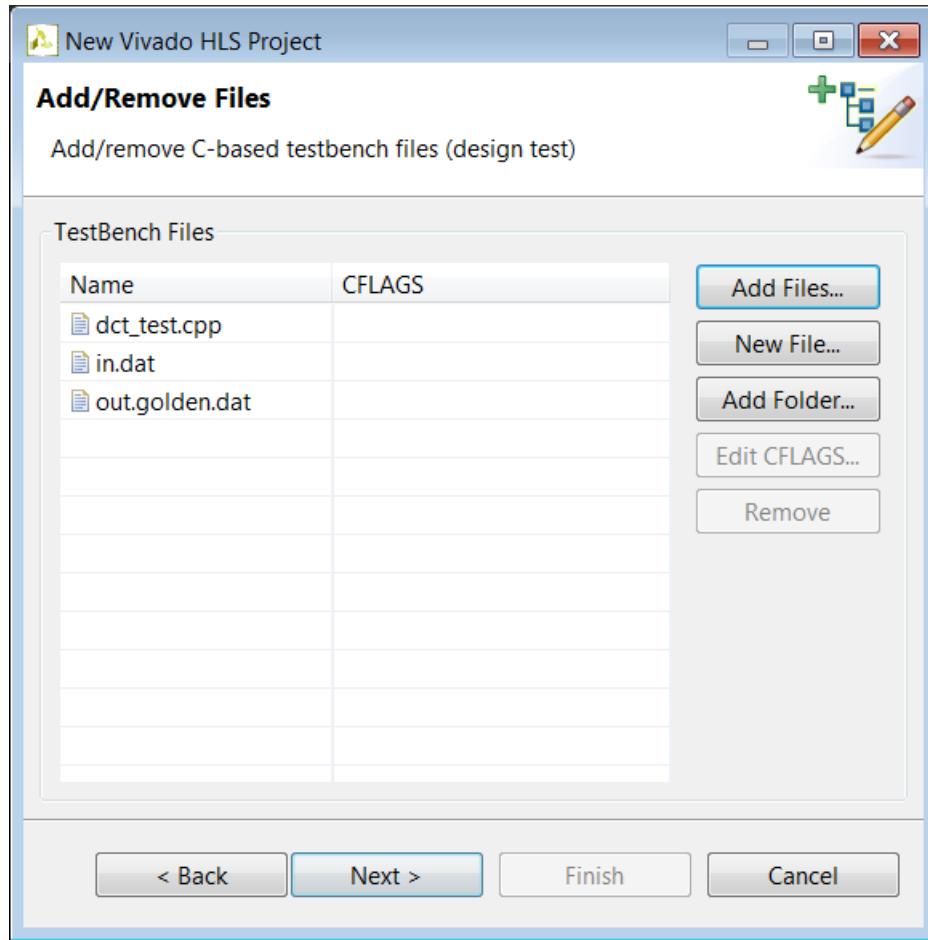


Figure 1-11: Project Test Bench Files

As with the C source files, click the **Add Files** button to add the C test bench and the **Edit CFLAGS** button to include any C compiler options.

In addition to the C source files, all files read by the test bench must be added to the project. In the example shown in [Figure 1-11](#), the test bench opens file `in.dat` to supply input stimuli to the design and file `out.golden.dat` to read the expected results. Because the test bench accesses these files, both files must be included in the project.

If the test bench files exist in a directory, the entire directory might be added to the project, rather than the individual files, using the **Add Folders** button.

If there is no C test bench, there is no requirement to enter any information here and the **Next >** button opens the final window of the project wizard, which allows you to specify the details for the first solution, as shown in the following figure.



RECOMMENDED: It is strongly recommended that you use a test bench. See [C Test Bench: Required for Productivity](#) for important productivity information on the reasons for adding a test bench to the project.

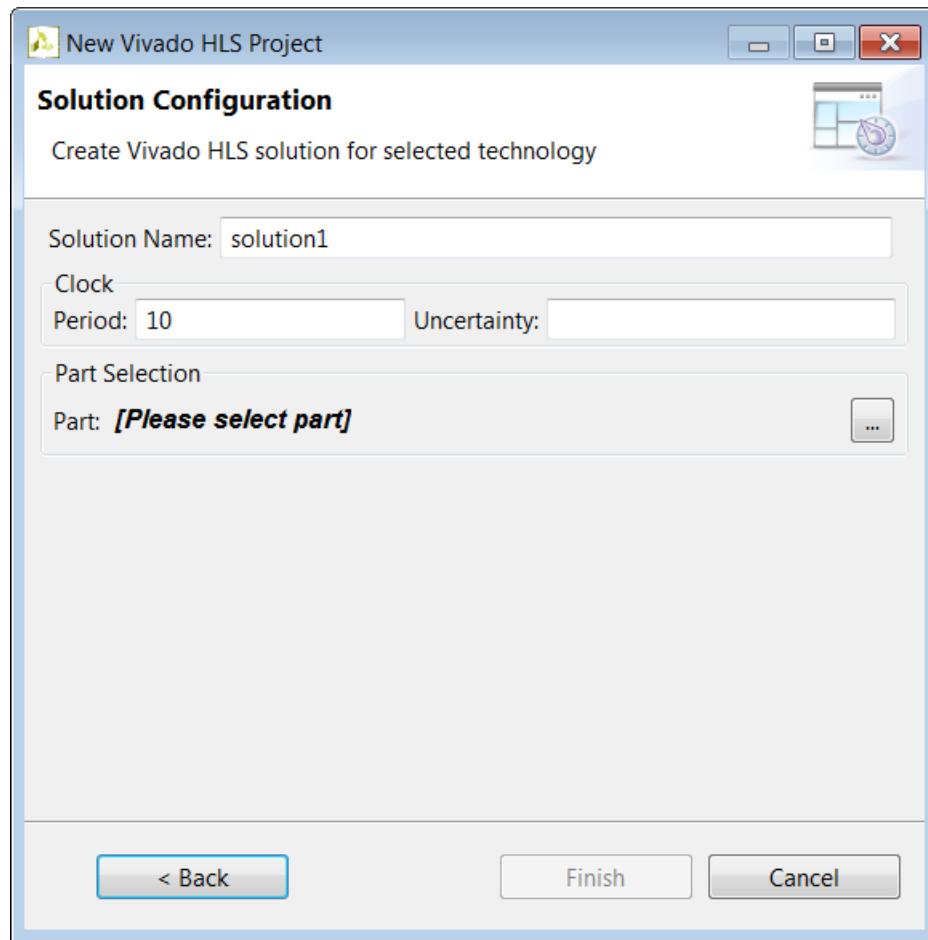


Figure 1-12: Initial Solution Settings

The final window in the new project wizard allows you to specify the details of the first solution:

- **Solution Name:** Vivado HLS provides the initial default name `solution1`, but you can specify any name for the solution.
- **Clock Period:** The clock period specified in units of ns or a frequency value specified with the MHz suffix (For example, 150MHz).
- **Uncertainty:** The clock period used for synthesis is the clock period minus the clock uncertainty. Vivado HLS uses internal models to estimate the delay of the operations for each FPGA device. The clock uncertainty value provides a controllable margin to account for any increases in net delays due to RTL logic synthesis, place, and route. If not specified in ns, the clock uncertainty defaults to 12.5% of the clock period.
- **Part:** Click to select the appropriate technology, as shown in the following figure.

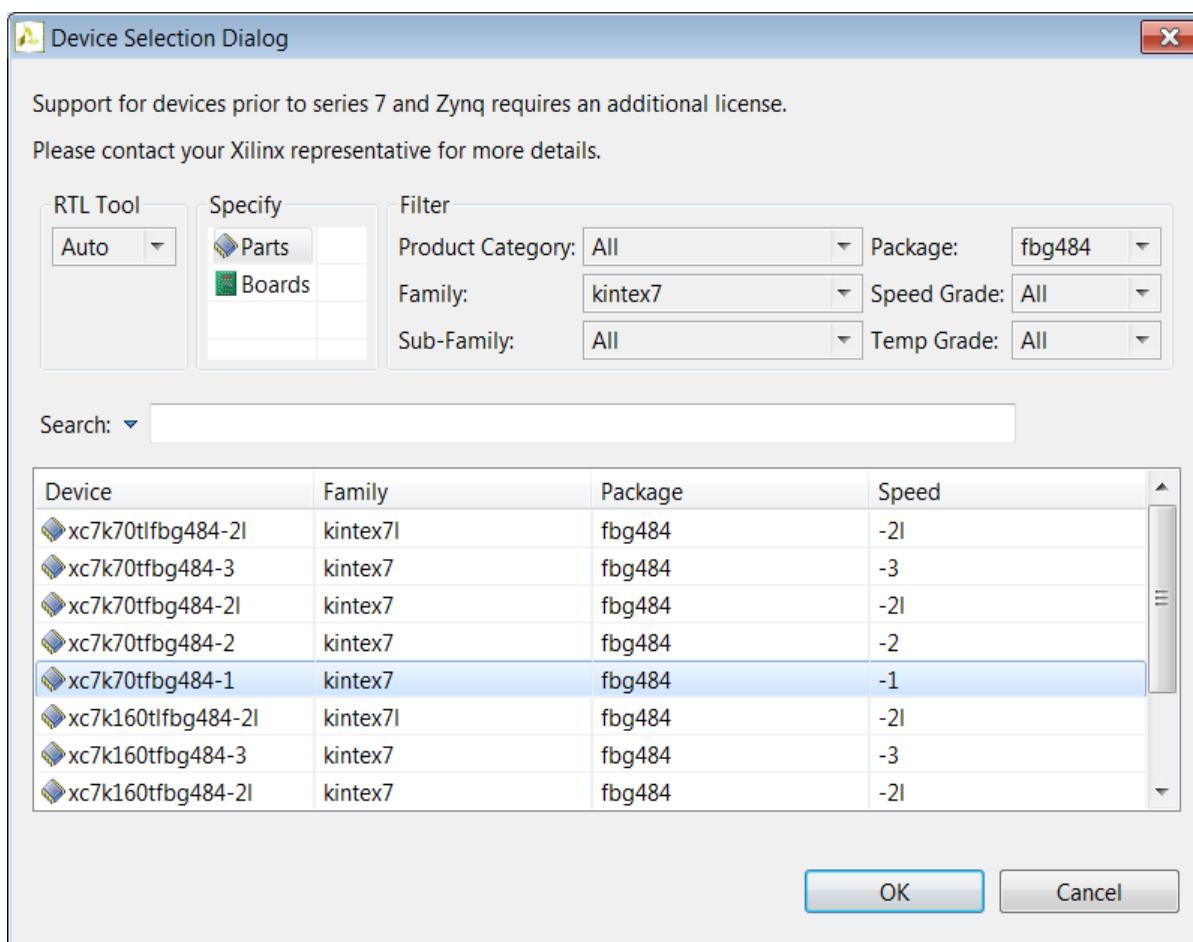


Figure 1-13: Part Selection

The RTL tool selection can be set as `auto`, `ISE`, or `Vivado`. Starting with the 2013.2 release, the ISE and Vivado RTL synthesis tools use different models for the floating-point cores. This setting is used to ensure that the correct floating-point core is used for the target synthesis tool. If this is left as the default `auto` setting, it is assumed that RTL synthesis for 7 series and Zynq®-7000 All Programmable (AP) SoC parts is performed with Vivado and all other devices are synthesized with ISE. If this is not the case, the RTL synthesis tool should be explicitly set.

Select the FPGA to be targeted - the filter can be used to reduce the number of device in the device list. If the target is a board, specify boards in the top-left corner and the device list is replaced by a list of the supported boards (and Vivado HLS automatically selects the correct target device).

Clicking **Finish** opens the project as shown in the following figure.

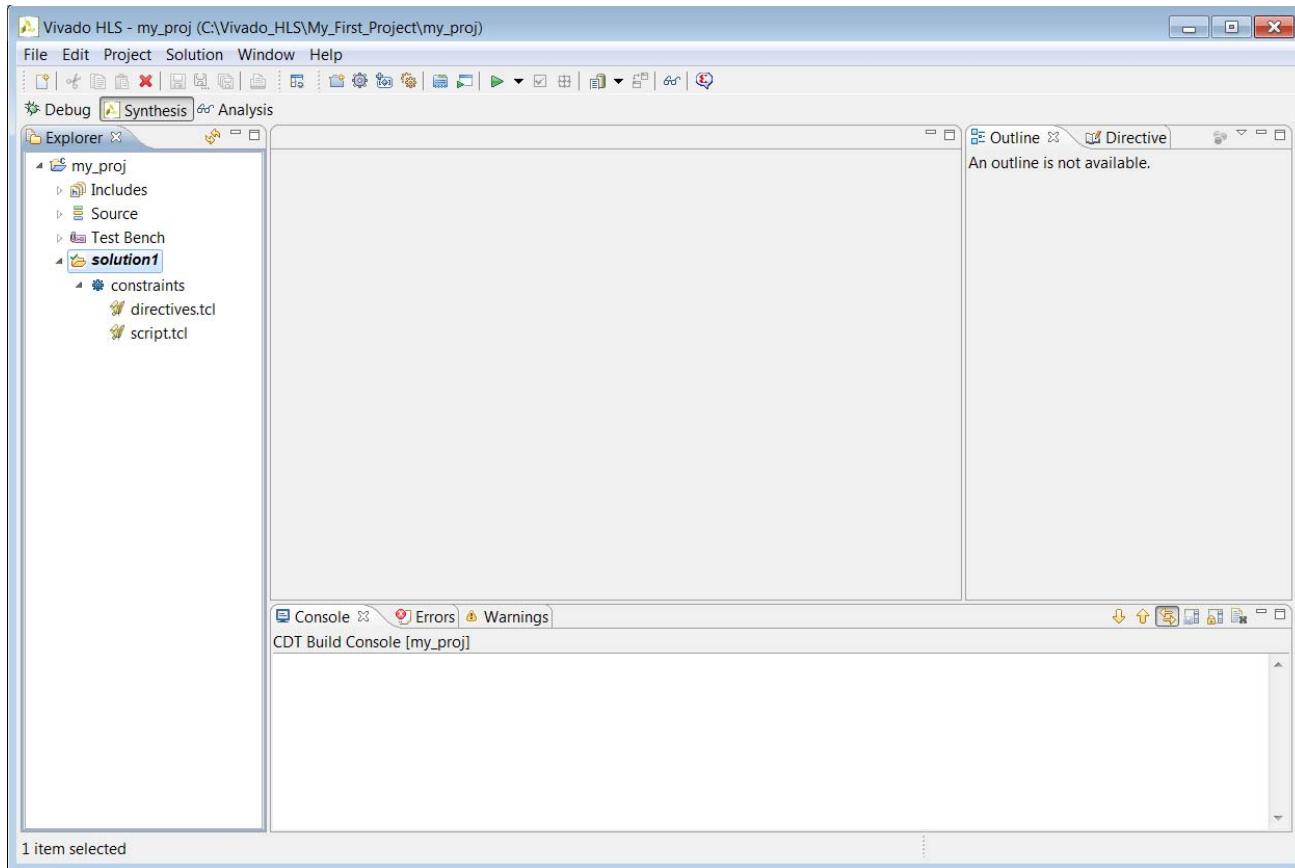


Figure 1-14: New Project in the Vivado HLS GUI

The Vivado HLS GUI consists of four panes:

- On the left hand side, the Explorer pane lets you navigate through the project hierarchy. A similar hierarchy exists in the project directory on the disk.
- In the center, the Information pane displays files. Files can be opened by double-clicking on them in the Explorer Pane.
- On the right, the Auxiliary pane shows information relevant to whatever file is open in the Information pane,
- At the bottom, the Console Pane displays the output when Vivado HLS is running.

Simulating the C Code

Verification in the Vivado HLS flow can be separated into two distinct processes.

- Pre-synthesis validation that validates the C program correctly implements the required functionality.
- Post-synthesis verification that verifies the RTL is correct.

Both processes are referred to as simulation: C simulation and C/RTL co-simulation.

Before synthesis, the function to be synthesized should be validated with a test bench using C simulation. A C test bench includes a top-level function `main()` and the function to be synthesized. It might include other functions. An ideal test bench has the following attributes:

- The test bench is self-checking and verifies the results from the function to be synthesized are correct.
- If the results are correct the test bench returns a value of 0 to `main()`. Otherwise the test bench should return any non-zero values

More details on test benches are provided in [C Test Bench in Chapter 3](#).

Clicking the **Run C Simulation** toolbar button  opens the C Simulation Dialog box, shown in the following figure.

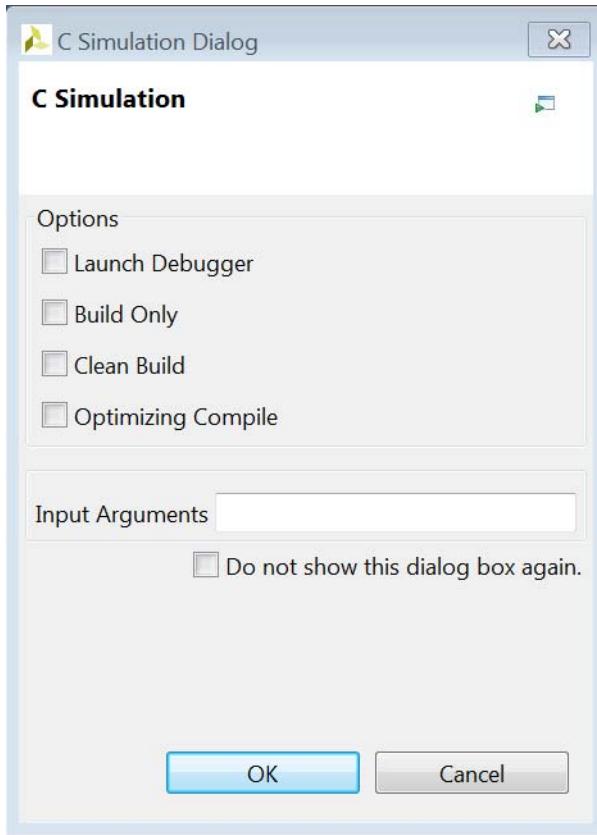


Figure 1-15: C Simulation Dialog Box

If no option is selected in the dialog box, the C code is compiled and the C simulation is automatically executed. The results are shown in the following figure.

When the C code simulates successfully, the message SIM-1 is displayed in the console window, as shown in the following figure. The test bench echoes to the console any `printf` commands used with the message "Test Passed!"

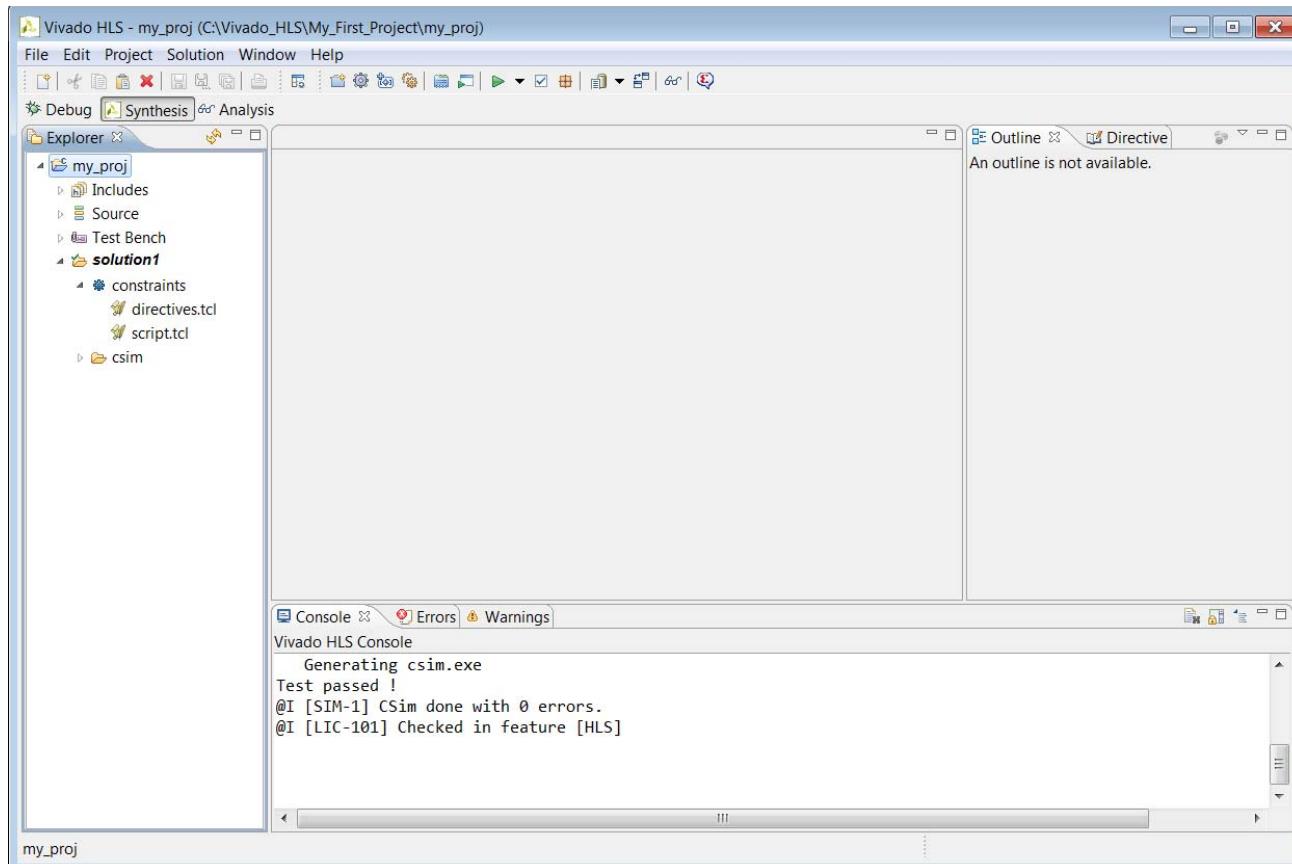


Figure 1-16: C Compiled with Build

The other options in the C Simulation dialog box are:

- **Launch Debugger:** This compiles the C code and automatically opens the debug perspective. From within the debug perspective the Synthesis perspective button (top left) can be used to return the windows to synthesis perspective.
- **Build Only:** The C code compiles, but the simulation does not run. Details on executing the C simulation are covered in [Reviewing the Output of C Simulation](#).
- **Clean Build:** Remove any existing executable and object files from the project before compiling the code.
- **Optimized Compile:** By default the design is compiled with debug information, allowing the compilation to be analyzed in the debug perspective. This option uses a higher level of optimization effort when compiling the design but removes all information required by the debugger. This increases the compile time but should reduce the simulation run time.

If you select the **Launch Debugger** option, the windows automatically switch to the debug perspective and the debug environment opens as shown in the following figure. This is a full featured C debug environment. The step buttons (red box in the following figure) allow you to step through code, breakpoints can be set and the value of the variables can be directly viewed.

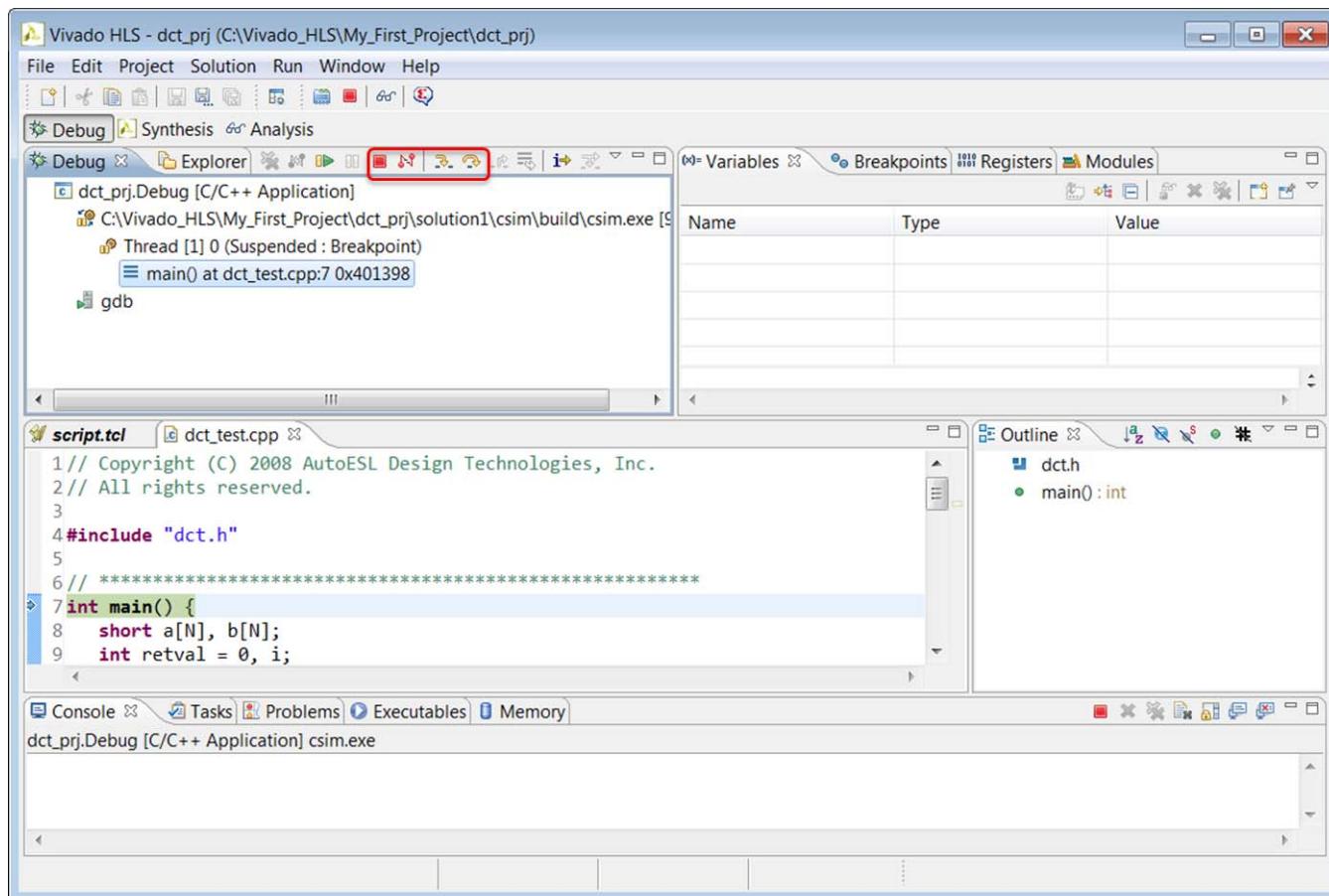


Figure 1-17: C Debug Environment

TIP: Click the **Synthesis** perspective button to return to the standard synthesis windows.



Reviewing the Output of C Simulation

When C simulation completes, a folder `csim` is created inside the solution folder as shown.

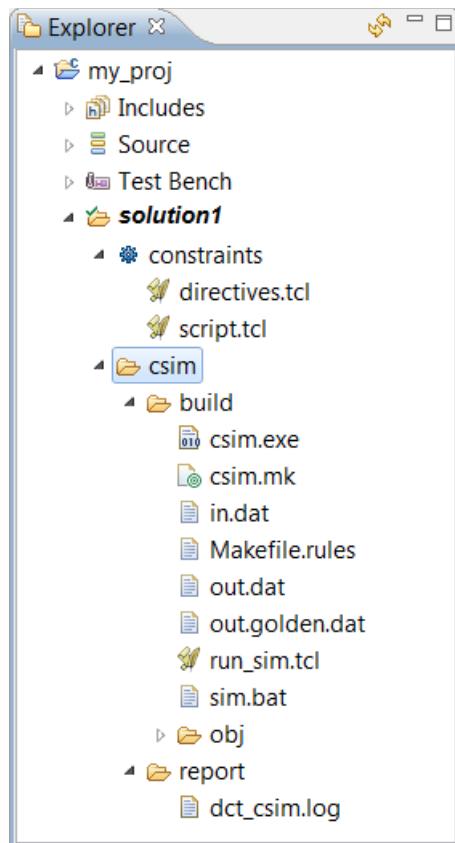


Figure 1-18: C Simulation Output Files

The folder `csim/build` is the primary location for all files related to the C simulation.

- Any files read by the test bench are copied to this folder.
- The C executable file `csim.exe` is created and run in this folder.
- Any files written by the test bench are created in this folder.

If the Build Only option is selected in the C simulation dialog box, the file `csim.exe` is created in this folder but the file is not executed. The C simulation is run manually by executing this file from a command shell. On Windows the Vivado HLS command shell is available through the start menu.

The folder `csim/report` contains a log file of the C simulation.

The next step in the Vivado HLS design flow is to execute synthesis.

Synthesizing the C Code

The following topics are discussed in this section:

- Creating an Initial Solution.
- Reviewing the Output of C Synthesis.
- Analyzing the Results of Synthesis.
- Creating a New Solution.
- Applying Optimization Directives.

Creating an Initial Solution

Use the **C Synthesis** toolbar button  or the menu **Solution > Run C Synthesis** to synthesize the design to an RTL implementation. During the synthesis process messages are echoed to the console window.

The message include information messages showing how the synthesis process is proceeding:

```
@I [SYN-201] Setting up clock 'default' with a period of 4ns.
@I [HLS-10] Setting target device to 'xc7k160tfg484-1'
@I [HLS-10] Analyzing design file 'array_RAM.c' ...
@I [HLS-10] Validating synthesis directives ...
@I [HLS-10] Starting code transformations ...
@I [HLS-10] Checking synthesizability ...
@I [HLS-111] Elapsed time: 4.342 seconds; current memory usage: 46.2 MB.
```

The messages also provide details on the synthesis process. The following example shows a case where some functions are automatically inlined. Vivado HLS automatically inlines functions which contain small amounts of logic (The **INLINE** directive with the **-off** option is used to prevent this if required).

```
@I [XFORM-602] Inlining function 'read_data' into 'dct' (dct.cpp:85) automatically.
@I [XFORM-602] Inlining function 'write_data' into 'dct' (dct.cpp:90) automatically.
```

When synthesis completes, the synthesis report for the top-level function opens automatically in the information pane as shown in the following figure.

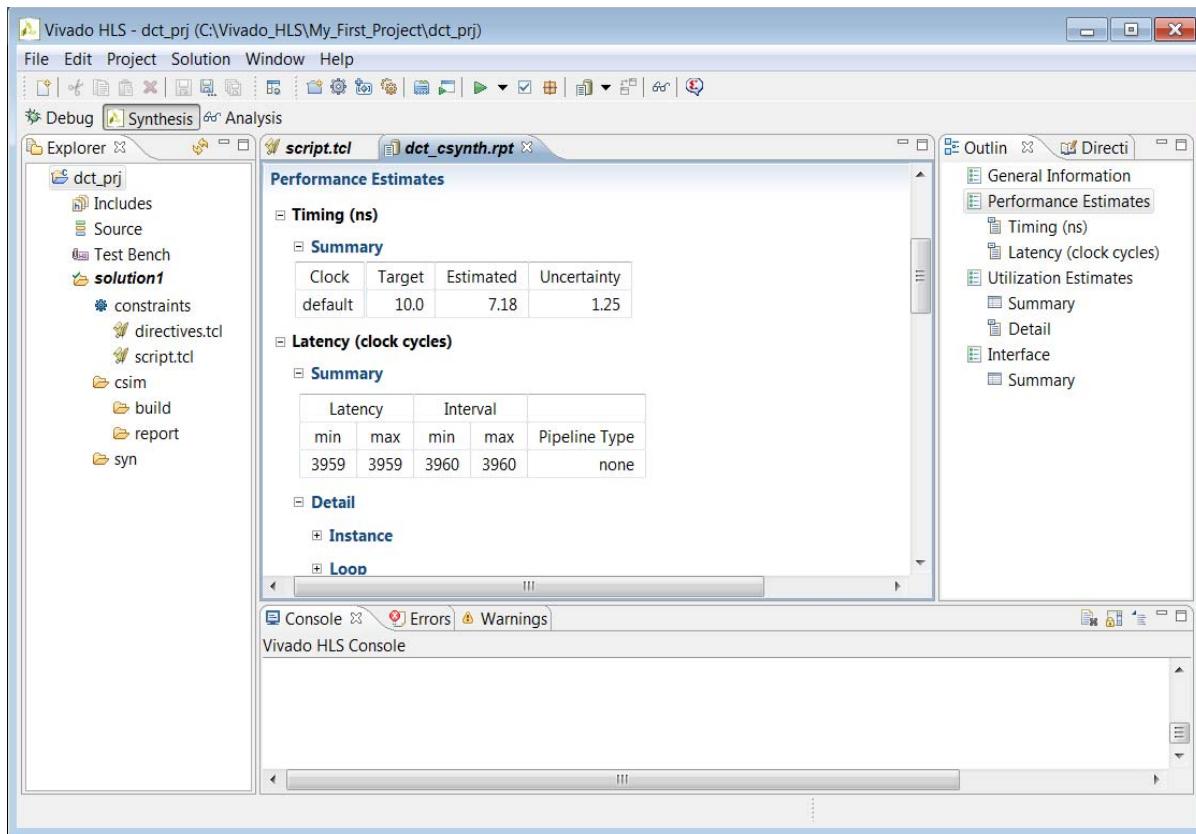


Figure 1-19: Synthesis Report

Reviewing the Output of C Synthesis

When synthesis completes, the folder `syn` is now available in the solution folder.

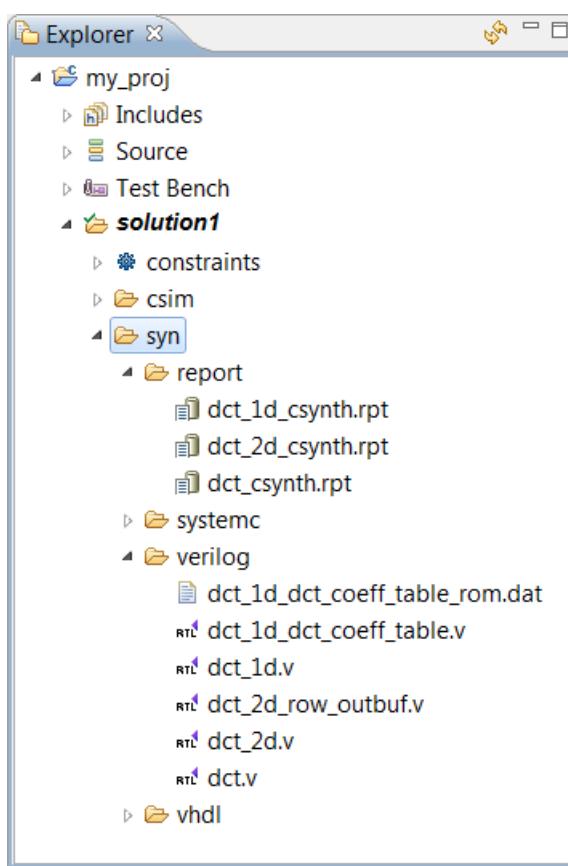


Figure 1-20: C Synthesis Output Files

The `syn` folder contains 4 sub-folders. A `report` folder and one folder for each of the RTL output formats.

The `report` folder contains a report file for the top-level function and one for every sub-function in the design: provided the function was not inlined using the `INLINE` directive or inlined automatically by Vivado HLS. The report for the top-level function provides details on the entire design.

The `verilog`, `vhdl` and `systemc` folders contain the output RTL files. [Figure 1-20](#) shows the `verilog` folder expanded. The top-level file has the same name as the top-level function for synthesis. In the C design there is one RTL file for each function (not inlined). There might be additional RTL files to implement sub-blocks (block RAM, pipelined multipliers, etc).



IMPORTANT: *It is not recommended to use these files for RTL synthesis. Instead, it is recommended to use the packaged IP output files discussed later in this design flow. Carefully read the text which immediately follows this note.*

In cases where Vivado HLS uses Xilinx IP in the design, such as with floating point designs, the RTL directory includes a script to create the IP during RTL synthesis. If the files in the syn folder are used for RTL synthesis, it is your responsibility to correctly use any script files present in those folders. If the package IP is used, this process is performed automatically by the design Xilinx tools.

Analyzing the Results of C Synthesis

The two primary features provided to analyze the RTL design are:

- The Synthesis reports
- The Analysis Perspective

In addition, if you are more comfortable working in an RTL environment, Vivado HLS creates two projects during the IP packaging process:

- A Vivado project.
- An IP Integrator Project.

The RTL projects are discussed in [Reviewing the Output of IP Packaging](#).

When synthesis completes, the synthesis report for the top-level function opens automatically in the information pane ([Figure 1-19](#)). The report provides details on both the performance and area of the RTL design. The outline tab on the right-hand side can be used to navigate through the report.

The following table explains the categories in the synthesis report.

Table 1-1: Synthesis Report Categories

Category	Description
General Information	Details on when the results were generated, the version of the software used, the project name, the solution name, and the technology details.
Performance Estimates > Timing	The target clock frequency, clock uncertainty, and the estimate of the fastest achievable clock frequency.
Performance Estimates > Latency > Summary	<p>Reports the latency and initiation interval for this block and any sub-blocks instantiated in this block.</p> <p>Each sub-function called at this level in the C source is an instance in this RTL block, unless it was inlined.</p> <p>The latency is the number of cycles it takes to produce the output. The initiation interval is the number of clock cycles before new inputs can be applied.</p> <p>In the absence of any PIPELINE directives, the latency is one cycle less than the initiation interval (the next input is read when the final output is written).</p>

Table 1-1: Synthesis Report Categories (Cont'd)

Category	Description
Performance Estimates > Latency > Detail	<p>The latency and initiation interval for the instances (sub-functions) and loops in this block. If any loops contain sub-loops, the loop hierarchy is shown.</p> <p>The min and max latency values indicate the latency to execute all iterations of the loop. The presence of conditional branches in the code might make the min and max different.</p> <p>The Iteration Latency is the latency for a single iteration of the loop.</p> <p>If the loop has a variable latency, the latency values cannot be determined and are shown as a question mark (?). See the text after this table.</p> <p>Any specified target initiation interval is shown beside the actual initiation interval achieved.</p> <p>The tripcount shows the total number of loop iterations.</p>
Utilization Estimates > Summary	This part of the report shows the resources (LUTS, Flip-Flops, DSP48s) used to implement the design.
Utilization Estimates > Details > Instance	<p>The resources specified here are used by the sub-blocks instantiated at this level of the hierarchy.</p> <p>If the design only has no RTL hierarchy, there are no instances reported.</p> <p>If any instances are present, clicking on the name of the instance opens the synthesis report for that instance.</p>
Utilization Estimates > Details > Memory	<p>The resources listed here are those used in the implementation of memories at this level of the hierarchy.</p> <p>Vivado HLS reports a single-port BRAM as using one bank of memory and reports a dual-port BRAM as using two banks of memory.</p>
Utilization Estimates > Details > FIFO	The resources listed here are those used in the implementation of any FIFOs implemented at this level of the hierarchy.
Utilization Estimates > Details > Shift Register	<p>A summary of all shift registers mapped into Xilinx SRL components.</p> <p>Additional mapping into SRL components can occur during RTL synthesis.</p>
Utilization Estimates > Details > Expressions	<p>This category shows the resources used by any expressions such as multipliers, adders, and comparators at the current level of hierarchy.</p> <p>The bit-widths of the input ports to the expressions are shown.</p>
Utilization Estimates > Details > Multiplexors	<p>This section of the report shows the resources used to implement multiplexors at this level of hierarchy.</p> <p>The input widths of the multiplexors are shown.</p>

Table 1-1: Synthesis Report Categories (Cont'd)

Category	Description
Utilization Estimates > Details > Register	A list of all registers at this level of hierarchy is shown here. The report includes the register bit-widths.
Interface Summary > Interface	<p>This section shows how the function arguments have been synthesized into RTL ports.</p> <p>The RTL port names are grouped with their protocol and source object: these are the RTL ports created when that source object is synthesized with the stated I/O protocol.</p>

A common issue for new users of Vivado HLS is seeing a synthesis report similar to the following figure. The latency values are all shown as a "?" (question mark).

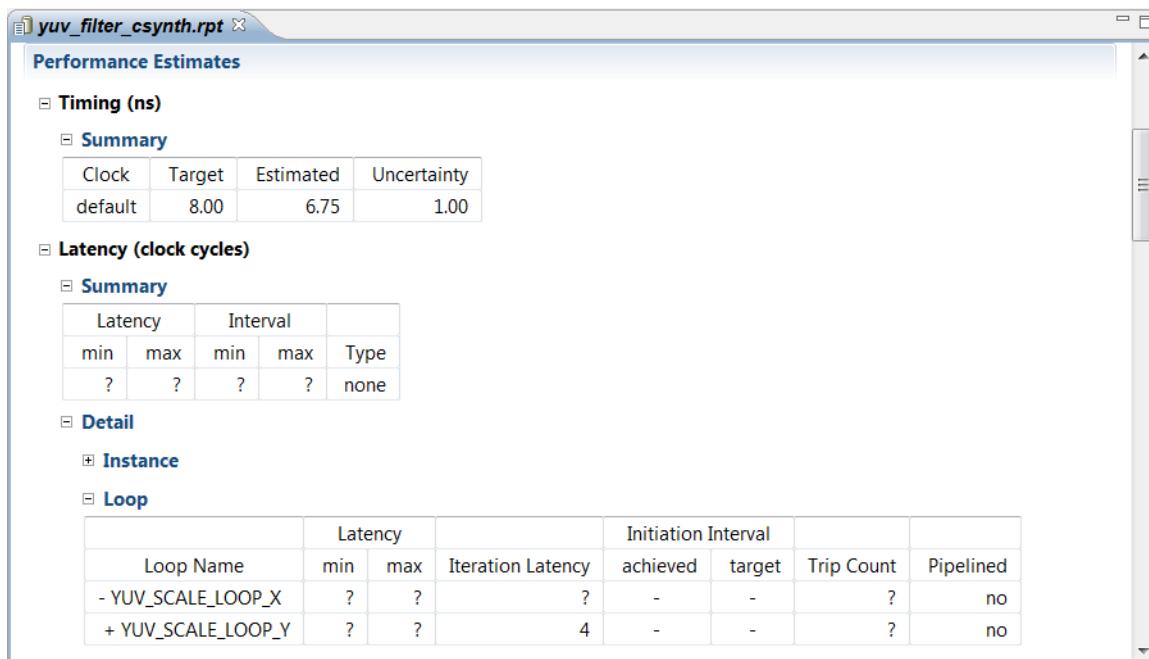


Figure 1-21: Analysis Perspective

Vivado HLS performs analysis to determine the number of iteration of each loop. If the loop iteration limit is a variable, Vivado HLS cannot determine the maximum upper limit.

In the following example, the maximum iteration of the for-loop is determined by the value of input num_samples. The value of num_samples is not defined in the C function, but comes into the function from the outside.

```
void foo (char num_samples, ...);

void foo (num_samples, ...) {
    int i;
    ...
    loop_1: for(i=0;i< num_samples;i++) {
        ...
        result = a + b;
    }
}
```

If the latency or throughput of the design is dependent on a loop with a variable index, Vivado HLS reports the latency of the loop as being unknown (represented in the reports by a question mark "?").

The TRIPCOUNT directive can be applied to the loop to manually specify the number of loop iterations and ensure the report contains useful numbers. The -max option tells Vivado HLS the maximum number of iterations that the loop iterates over, the -min option specifies the minimum number of iterations performed and the -avg option specifies an average tripcount.

Note: The TRIPCOUNT directive does not impact the results of synthesis.

The tripcount values are used only for reporting, to ensure the reports generated by Vivado HLS show meaningful ranges for latency and interval. This also allows a meaningful comparison between different solutions.

If the C assert macro is used in the code, Vivado HLS can use it to both determine the loop limits automatically and create hardware that is exactly sized to these limits. See [Assertions in Chapter 3](#) for more information.

In addition to the synthesis report, you can use the Analysis Perspective to analyze the results. To open the Analysis Perspective, click the **Analysis** button as shown in the following figure.

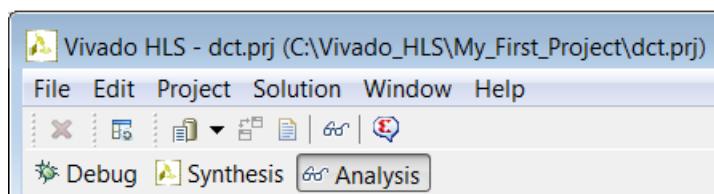


Figure 1-22: Analysis Perspective

The Analysis Perspective provides both a tabular and graphical view of the design performance and resources and supports cross-referencing between both views. The following figure shows the default window configuration when the Analysis Perspective is first opened.

The Module Hierarchy pane provides an overview of the entire RTL design.

- This view can navigate throughout the design hierarchy.
- The Module Hierarchy pane shows the resources and latency contribution for each block in the RTL hierarchy.

The following figure shows the dct design uses 6 block RAMs, approximately 300 LUTs and has a latency of around 3000 clock cycles. Sub-block dct_2d contributes 4 block RAMs, approximately 250 LUTs and about 2600 cycle of latency to the total. It is immediately clear that most of the resources and latency in this design are due to sub-block dct_2d and this block should be analyzed first.

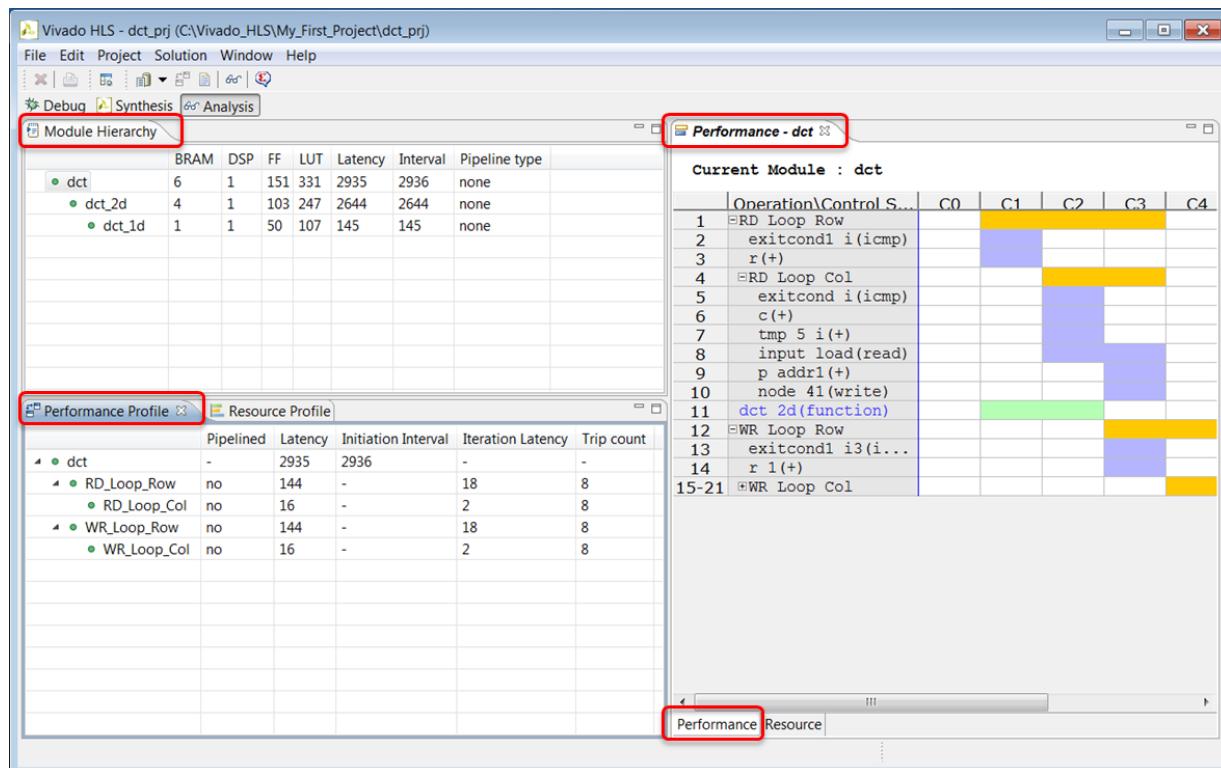


Figure 1-23: Analysis Perspective in the Vivado HLS GUI

The Performance Profile pane provides details on the performance of the block currently selected in the Module Hierarchy pane - in this case, the dct block highlighted in the Module Hierarchy pane.

- The performance of the block is a function of the sub-blocks it contains and any logic within this level of hierarchy. The Performance Profile pane shows items at this level of hierarchy that contribute to the overall performance.
- Performance is measured in terms of latency and the initiation interval. This pane also includes details on whether the block was pipelined or not.
- In this example, you can see that two loops are implemented as logic at this level of hierarchy and both contain sub-loops and both contribute 144 clock cycles to the latency. Add the latency of both loops to the latency of dct_2d which is also inside dct and you get the total latency for the dct block.

The Schedule View pane shows how the operations in this particular block are scheduled into clock cycles. The default view is the Performance view.

- The left-hand column lists the resources.
 - Sub-blocks are green.
 - Operations resulting from loops in the source are colored yellow.
 - Standard operations are purple.
- The dct has three main resources:
 - A loop called RD_Loop_Row. In [Figure 1-23](#) the loop hierarchy for loop RD_Loop_Row has been expanded.
 - A sub-block called dct_2d.
 - A loop called WR_Loop_Row. The plus symbol "+" indicates this loop has hierarchy and the loop can be expanded to view it.
- The top row lists the control states in the design. Control states are the internal states used by Vivado HLS to schedule operations into clock cycles. There is a close correlation between the control states and the final states in the RTL FSM, but there is no one-to-one mapping.

The information presented in the Schedule View is explained here by reviewing the first set of resources to be execute: the RD_Loop_Row loop.

- The design starts in the C0 state.
 - It then starts to execute the logic in loop RD_Loop_Row.
- Note:** In the first state of the loop, the exit condition is checked and there is an add operation.
- The loop executes over 3 states: C1, C2, and C3.

- The Performance Profile pane shows this loop has a tripcount of 8: it therefore iterates around these 3 states 8 times.
- The Performance Profile pane shows loop RD_Loop_Rows takes 144 clock cycles to execute.
 - One cycle at the start of loop RD_Loop_Row.
 - The Performance Profile pane indicates it takes 16 clock cycles to execute all operations of loop RD_Loop_Cols.
 - Plus a clock cycle to return to the start of loop RD_Loop_Row.
 - 8 iterations of 18 cycles is why it takes 144 clock cycles to complete.
- Within loop RD_Loop_Col you can see there are some adders, a 2 cycle read operation and a write operation.

The following figure shows that you can select an operation and right-click the mouse to open the associated variable in the source code view. You can see that the write operation is implementing the writing of data into the array from the input variable.

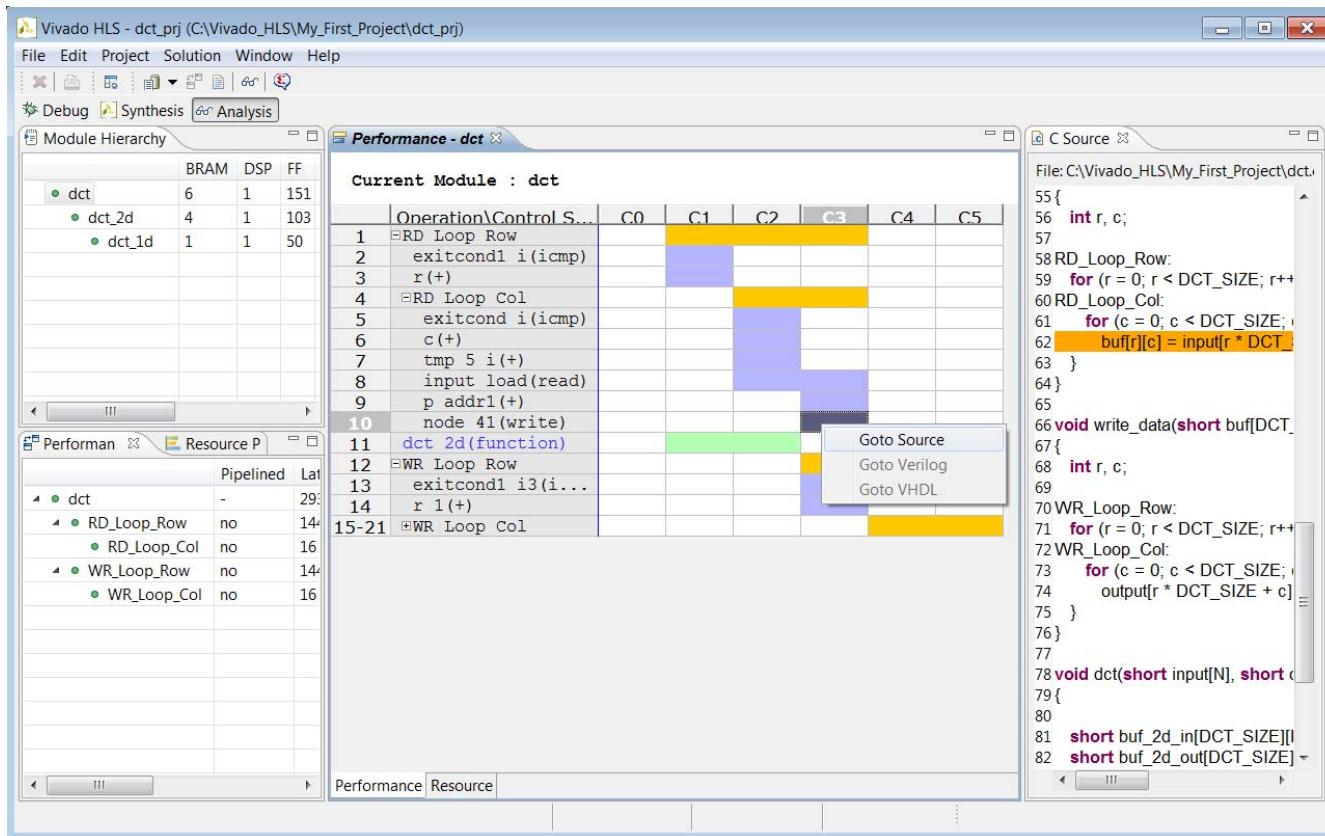


Figure 1-24: C Source Code Correlation

The Analysis Perspective also allows you to analyze resource usage. The following figure shows the resource profile and the resource sharing panes.

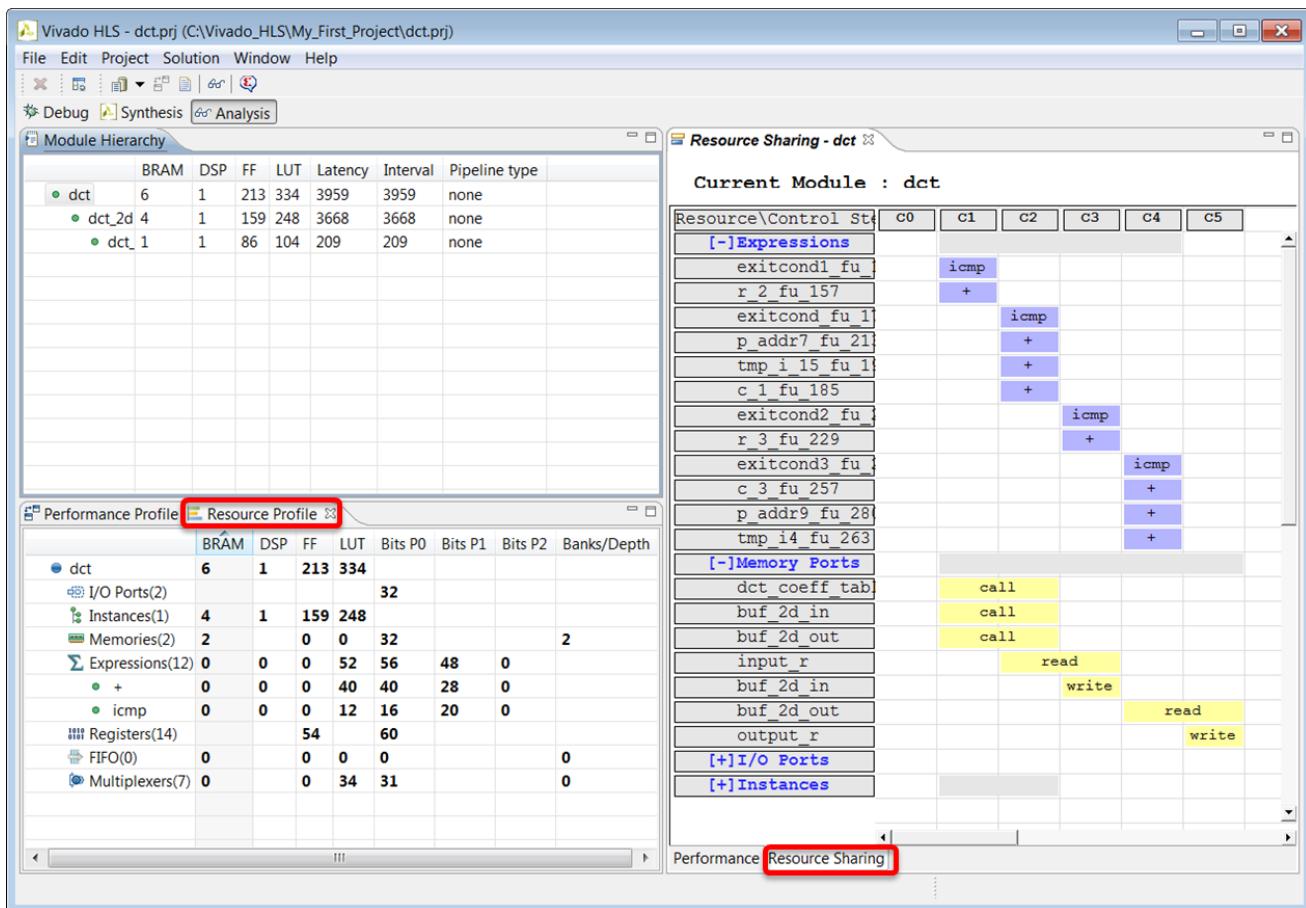


Figure 1-25: Analysis Perspective with Resource Profile

The Resource Profile pane shows the resources used at this level of hierarchy. In this example, you can see that most of the resources are due to the instances: blocks that are instantiated inside this block.

You can see by expanding the Expressions that most of the resources at this level of hierarchy are used to implement adders.

The Resource pane shows the control state of the operations used. In this example, all the adder operations are associated with a different adder resource - there is no sharing of the adders (more than one add operation are on each horizontal line indicates the same resource is used multiple times in different states or clock cycles).

The adders are used in the same cycles that are memory accessed and are dedicated to each memory - cross correlation with the C code can be used to confirm.

The Analysis Perspective is a highly interactive feature. More information on the Analysis Perspective can be found in the *Design Analysis* section of the *Vivado Design Suite Tutorial: High-Level Synthesis* (UG871) [Ref 2].



TIP: Remember, even if a *Tcl* flow is used to create designs, the project can still be opened in the GUI and the Analysis Perspective used to analyze the design.

The Synthesis perspective button is used to return to the synthesis view.

Generally after design analysis you can create a new solution to apply optimization directives. Using a new solution for this allows the different solutions to be compared.

Creating a New Solution

The most typical use of Vivado HLS is to create an initial design, then perform optimizations to meet the desired area and performance goals. Solutions offer a convenient way to ensure the results from earlier synthesis runs can be both preserved and compared.

Use the **New Solution** toolbar button  or the menu **Project > New Solution** to create a new solution. This opens the Solution Wizard as shown in the following figure.

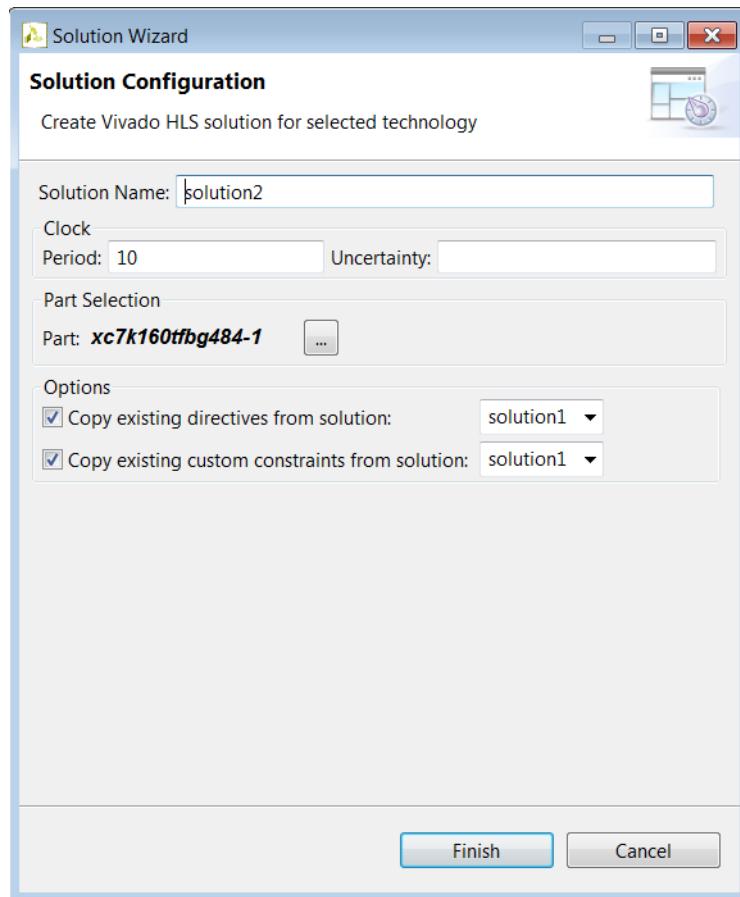


Figure 1-26: New Solution Wizard

The Solution Wizard has the same options as the final window in the New Project wizard ([Figure 1-12](#)) plus two additional options that allow any directives and customs constraints applied to an existing solution to be conveniently copied to the new solution, where they can be modified or removed.

After the new solution has been created, optimization directives can be added (or modified if they were copied from the previous solution). The next section explains how directives can be added to solutions. Custom constraints are applied using the configuration options and are discussed in [Design Optimization](#).

Applying Optimization Directives

The first step in adding optimization directives is to open the source code in the Information pane. As shown in the following figure, expand the Source container, located at the top of the Explorer pane, and double-click the source file to open it for editing in the Information pane.

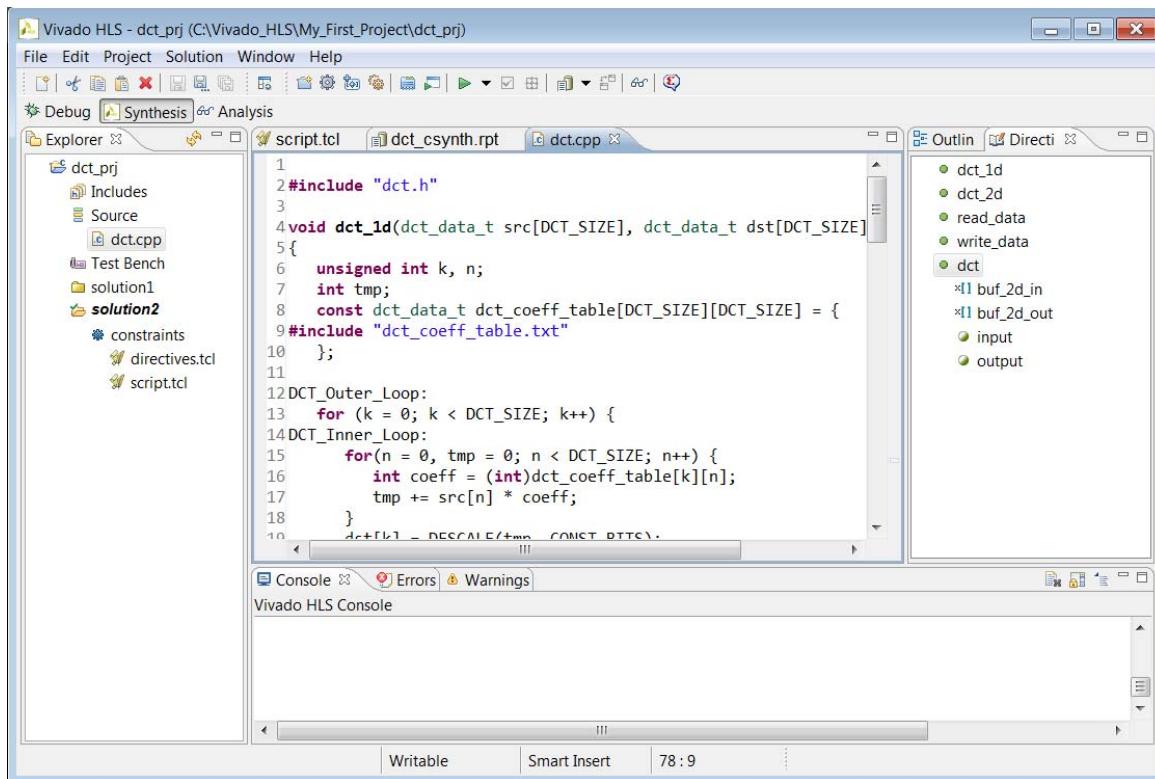


Figure 1-27: Source and Directive

With the source code active in the Information pane, the directives tab on the right-hand side becomes active. The directives tab contains all the objects or scopes, in the currently opened source code, to which directives can be applied.

Note: To apply directives to objects in other C files, the file must be opened and made active in the information pane.

Optimization directives can be applied to the following objects and scopes:

- **Interfaces**

Directives applied to interfaces are applied to that object (top-level function argument, global variable or top-level function return).

- **Functions**

Directives applied to functions are applied on all objects within the scope of the function. The effect of any directive stops at the next level of function hierarchy except in the case of the PIPELINE directive which recursively unrolls all loops in the hierarchy, or any directive which supports and uses a recursive option.

- **Loops**

Directives applied to loops apply to all objects within the scope of the loop. For example, if a LOOP_MERGE directive is applied to a loop, the directive applies to any sub-loops within the loop to which it is applied, but not to the loop itself. The loop to which it is applied is not merged with siblings at the same level of hierarchy.

- **Arrays**

Directives can be directly applied to arrays. In this case, the directive is applied to an object and only applies to the object: the array itself. Directives can also be applied to functions, loops, or regions that contain multiple arrays. In this case, the directive applies to all arrays within the scope.

- **Regions**

A region is any area enclosed within two braces.

```
{  
    the scope between these braces is a region  
}
```

Directives can be applied to a region in the same manner as they are applied to functions and loops. The directive applies to the entire scope of the region.

To apply a directive, select an object in the directives tab, right-click and select **Insert Directive** to open the Directives Editor dialog box. For example, the following figure shows the addition of the DATAFLOW directive.

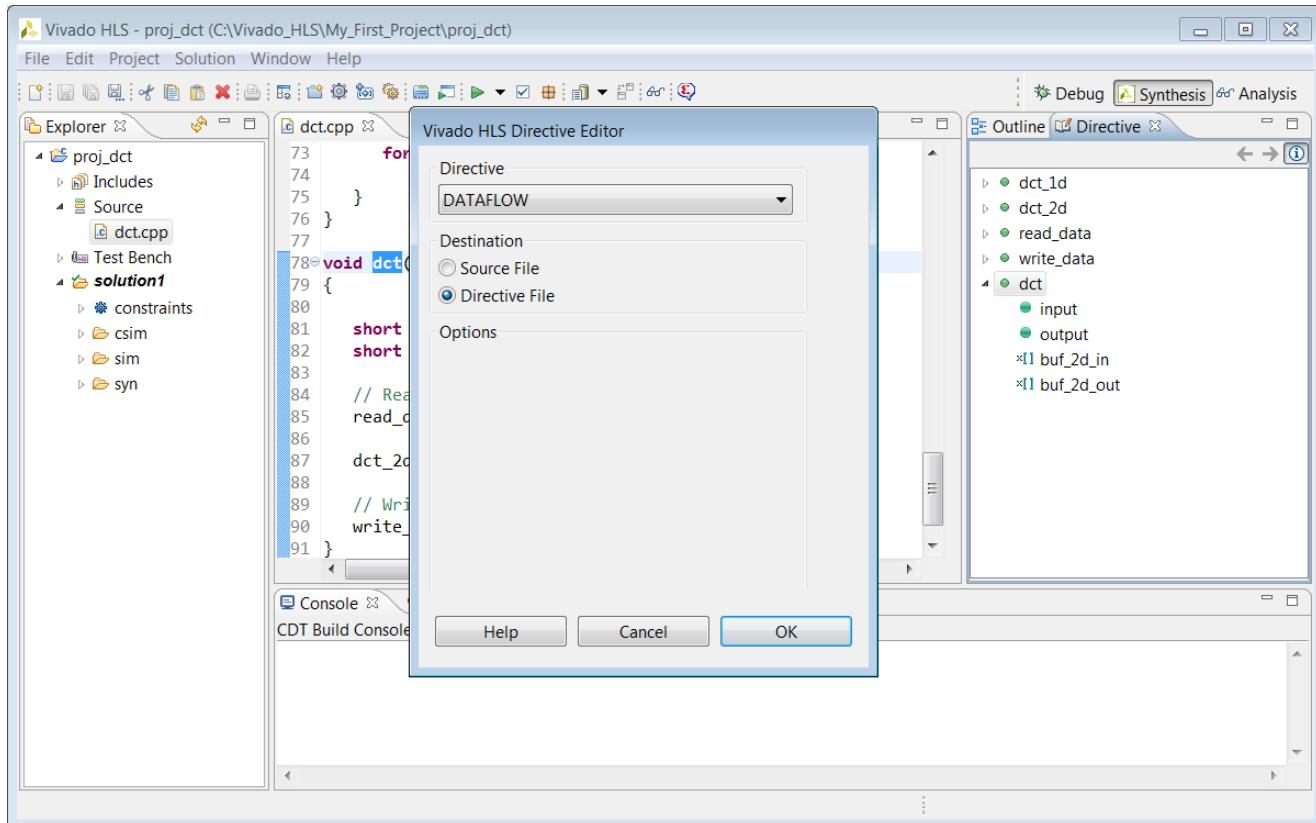


Figure 1-28: Adding Directives

The drop-down menu allows the appropriate directive to be selected. The drop-down menu only shows directives which can be added to the selected object or scope, for example, an array cannot be pipelined and so the drop-down menu does not show any PIPELINE directive in the list of directives.

Using Tcl Commands or Embedded Pragmas

Also any options for the optimization directive, the Directives Editor dialog box allows the directive Destination to be:

- **Directive File:** The directive is inserted as a Tcl command into the file directives.tcl in the solution directory.
- **Source File:** The directive is inserted directly into the C source file as a pragma.

The following table describes the advantages and disadvantages of both approaches.

Table 1-2: Tcl Commands Versus Pragmas

Directive Format	Advantages	Disadvantages
Directives file (Tcl Command)	<p>Each solution has independent directives. This approach is ideal for design exploration.</p> <p>If any solution is re-synthesized, only the directives specified in that solution are applied.</p>	<p>If the C source files are transferred to a third-party or archived, the directives.tcl file might be included.</p> <p>The directives.tcl file is required if the results are to be re-created.</p>
Source Code (Pragma)	<p>The optimization directives are embedded into the C source code.</p> <p>Ideal when the C sources files are shipped to a third-party as C IP. No other files are required to re-create the same results.</p> <p>Also a useful approach for directives which are unlikely to change, such as TRIPCOUNT and INTERFACE.</p>	<p>If the optimization directives are embedded in the code, they are automatically applied when a previous solution is re-synthesized.</p>

The following figure shows the DATAFLOW directive being added to the Directive File. The directives.tcl file is shown located in the solution constraints folder and opened in the information pane with the resulting Tcl command.

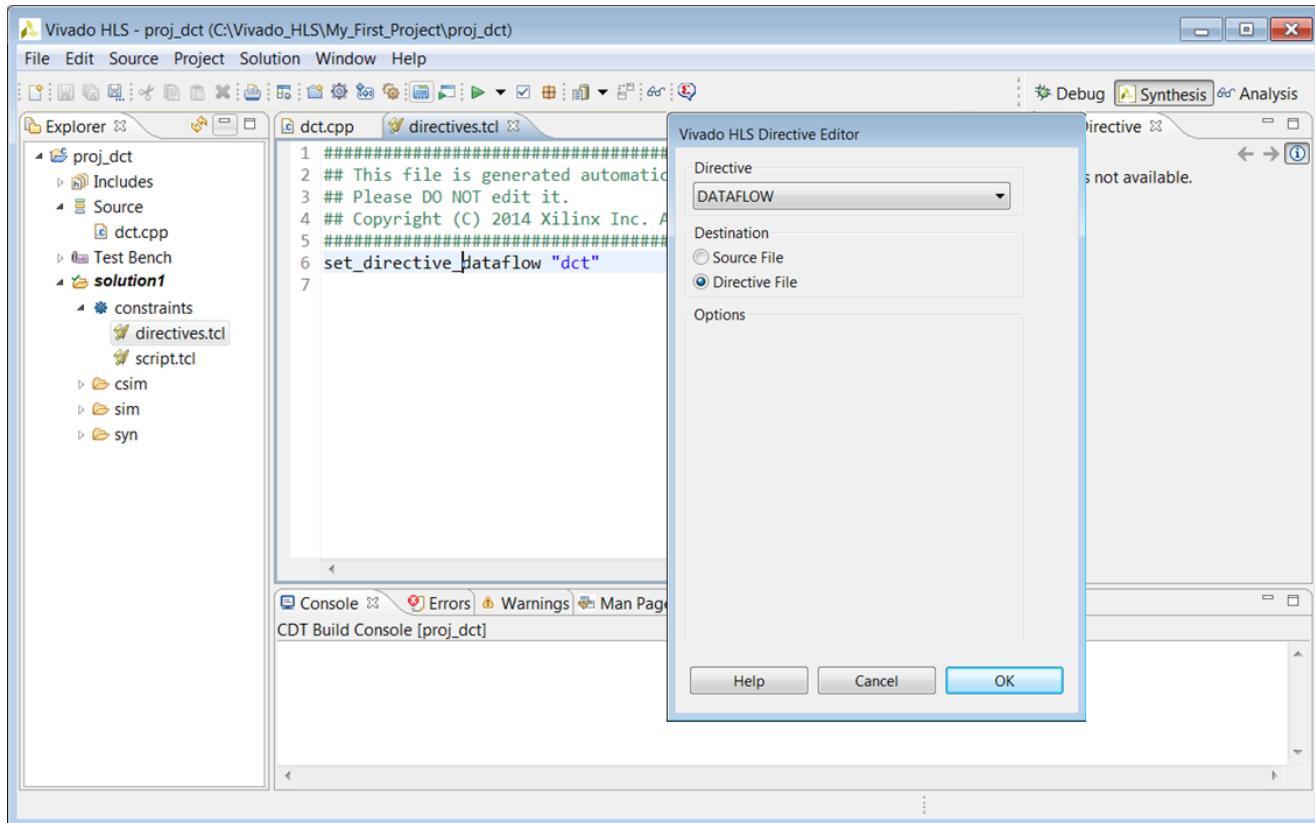


Figure 1-29: Adding Tcl Directives

When directives are applied as a Tcl command, the Tcl command specifies the scope or the scope and object within that scope. In the case of loops and regions, the Tcl command requires that these scopes be labelled. If the loop or region does not currently have a label, a pop-up dialog box asks for a label (Assigns a default name for the label).

The following shows examples of labelled and unlabeled loops and regions.

```
// Example of a loop with no label
for(i=0; i<3;i++ {
    printf("This is loop WITHOUT a label \n");
}

// Example of a loop with a label
My_For_Loop:for(i=0; i<3;i++ {
    printf("This loop has the label My_For_Loop \n");
}

// Example of an region with no label
{
    printf("The scope between these braces has NO label");
}

// Example of a NAMED region
My_Region:{  

    printf("The scope between these braces HAS the label My_Region");
}
```



TIP: *Named loops allow the synthesis report to be easily read. An auto-generated label is assigned to loops without a label.*

The following figure shows the DATAFLOW directive added to the Source File and the resultant source code open in the information pane. The source code now contains a pragma which specifies the optimization directive.

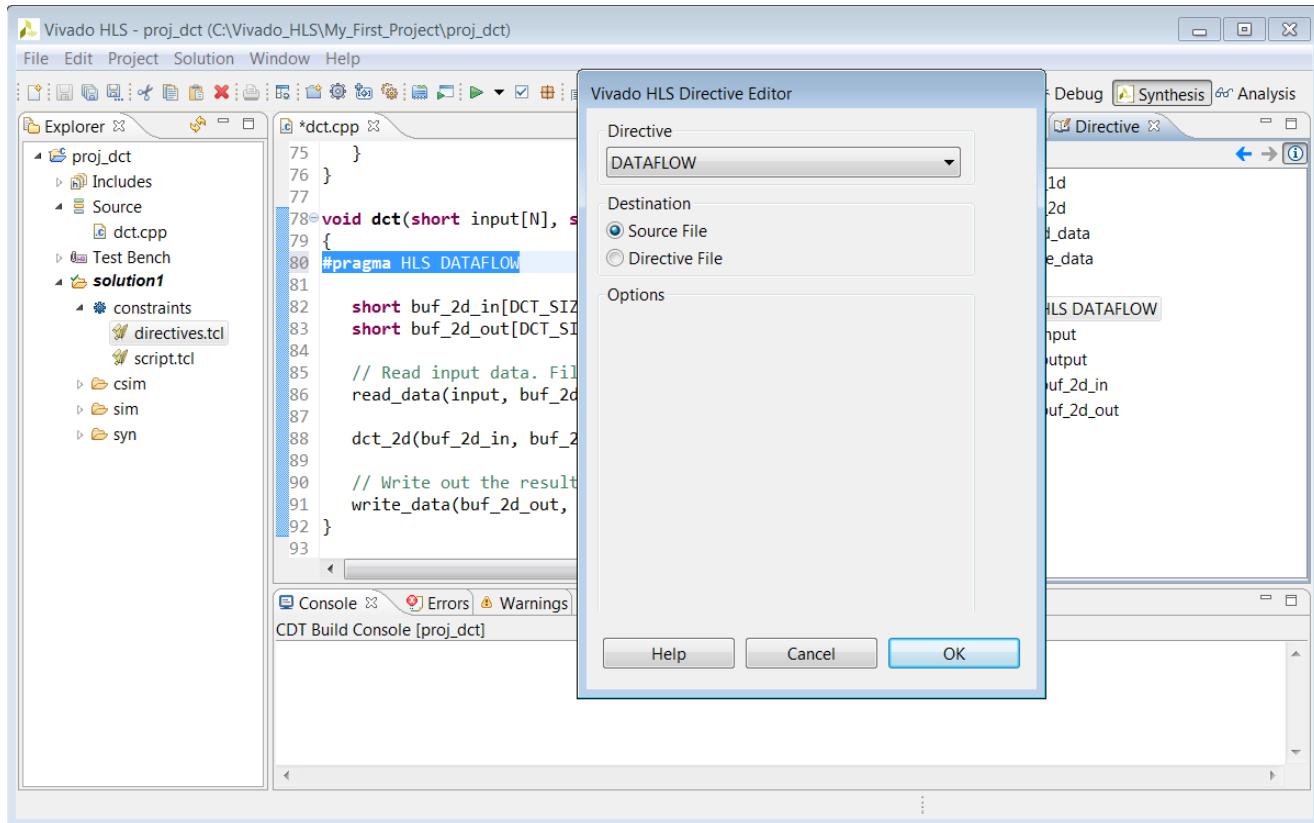


Figure 1-30: Adding Pragma Directives

In both cases, the directive is applied and the optimization performed when synthesis is executed. If the code was modified, either by inserting a label or pragma, a pop-up dialog box reminds you to save the code before synthesis.

A complete list of all directives and custom constraints can be found in [Design Optimization](#). For information on directives and custom constraints, see [Chapter 4, High-Level Synthesis Reference Guide](#).

Applying Optimization Directives to Global Variables

Directives can only be applied to scopes or objects within a scope. As such, they cannot be directly applied to global variables which are declared outside the scope of any function.

To apply a directive to a global variable, apply the directive to the scope (function, loop or region) where the global variable is used. Open the directives tab on a scope where the variable is used, apply the directive and enter the variable name manually in Directives Editor.

Applying Optimization Directives to Class Objects

Optimization directives can be also applied to objects or scopes defined in a class. The difference is typically that classes are defined in a header file. Use one of the following actions to open the header file:

- From the Explorer pane, open the Includes folder, navigate to the header file and double-click on it to open it.
- From within the C source, place the cursor over the header file (the #include statement), to open hold down the Ctrl key and click the header file.

The directives tab is then populated with the objects in the header file and directives can be applied.



CAUTION! *Care should be taken when applying directives as pragmas to a header file. The file might be used by other people or used in other projects. Any directives added as a pragma are applied each time the header file is included in a design.*

Applying Optimization Directives to Templates

To apply optimization directives manually on templates when using Tcl commands, specify the template arguments and class when referring to class methods. For example, given the following C++ code:

```
template <uint32 SIZE, uint32 RATE>
void DES10<SIZE,RATE>::calcRUN() {...}
```

The following Tcl command is used to specify the `INLINE` directive on the function:

```
set_directive_inline DES10<SIZE,RATE>::calcRUN
```

Using #Define with Pragma Directives

Pragma directives do not natively support the use of values specified by the define statement. The following code seeks to specify the depth of a stream using the define statement and will not compile.



TIP: *Specify the depth argument with an explicit value.*

```
#include <hls_stream.h>
using namespace hls;

#define STREAM_IN_DEPTH 8

void foo (stream<int> &InStream, stream<int> &OutStream) {

    // Illegal pragma
    #pragma HLS stream depth=STREAM_IN_DEPTH variable=InStream

    // Legal pragma
    #pragma HLS stream depth=8 variable=OutStream

}
```

You can use macros in the C code to implement this functionality. The key to using macros is to use a level of hierarchy in the macro. This allows the expansion to be correctly performed. The code can be made to compile as follows:

```
#include <hls_stream.h>
using namespace hls;

#define PRAGMA_SUB(x) _Pragma (#x)
#define PRAGMA_HLS(x) PRAGMA_SUB(x)
#define STREAM_IN_DEPTH 8

void foo (stream<int> &InStream, stream<int> &OutStream) {

    // Legal pragmas
    PRAGMA_HLS(HLS stream depth=STREAM_IN_DEPTH variable=InStream)
    #pragma HLS stream depth=8 variable=OutStream

}
```

Failure to Satisfy Optimization Directives

When optimization directives are applied, Vivado HLS outputs information to the console (and log file) detailing the progress. In the following example the PIPELINE directive was applied to the C function with an II=1 (iteration interval of 1) but synthesis failed to satisfy this objective.

```
@I [SCHED-11] Starting scheduling ...
@I [SCHED-61] Pipelining function 'array_RAM'.
@W [SCHED-69] Unable to schedule 'load' operation ('idx_load_2', array_RAM.c:52) on
array 'idx' due to limited memory ports.
@W [SCHED-63] Unable to schedule the whole 2 cycles 'load' operation ('d_i_load_1',
array_RAM.c:52) on array 'd_i' within the first 4 cycles (II = 4).
Please consider increasing the target initiation interval of the pipeline.
@I [SCHED-61] Pipelining result: Target II: 1, Final II: 4, Depth: 8.
```



IMPORTANT: If Vivado HLS fails to satisfy an optimization directive, it automatically relaxes the optimization target and seek to create a design with a lower performance target. If it cannot relax the target it will halt with an error.

By seeking to create a design which satisfies a lower optimization target, Vivado HLS is able to provide three important types of information:

- What target performance can be achieved with the current C code and optimization directives.
- A list of the reasons why it was unable to satisfy the higher performance target.
- A design which can be analyzed to provide more insight and help understand the reason for the failure.

In message SCHED-69, the reason given for failing to reach the target II, is due to limited ports. The design must access a block RAM, and a block RAM only has a maximum of two ports.

The next step after a failure such as this is to analyze what the issue is. In this example, analyze line 52 of the code and/or use the Analysis perspective to determine the bottleneck and if the requirement for more than two ports can be reduced or determine how the number of ports can be increased. More details on how to optimize designs for higher performance are provided in [HLS UltraFast Design Methodology](#) and [Design Optimization](#).

After the design is optimized and the desired performance achieved, the RTL can be verified and the results of synthesis packaged as IP.

Verifying the RTL is Correct

Use the **C/RTL cosimulation** toolbar button  or the menu **Solution > Run C/RTL cosimulation** verify the RTL results.

The C/RTL co-simulation dialog box shown in the following figure allows you to select which type of RTL output to use for verification (Verilog, VHDL or SystemC) and which HDL simulator to use for the simulation (if Verilog or VHDL are selected).

A complete description of all C/RTL co-simulation options are provided in [RTL Verification](#).

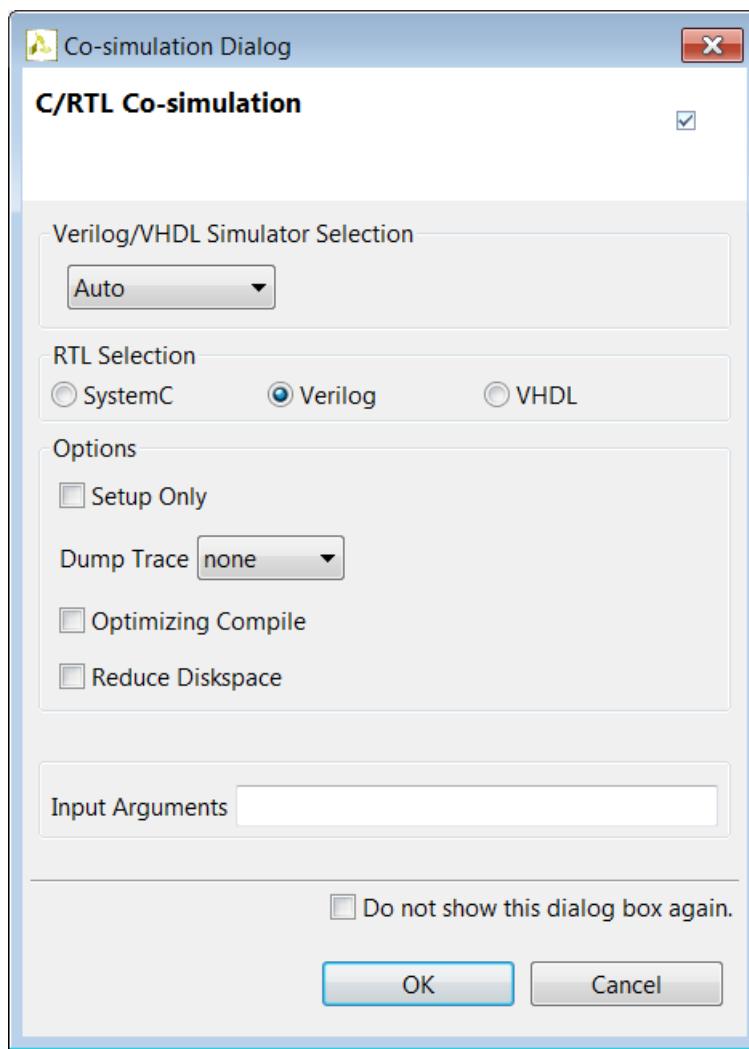


Figure 1-31: C/RTL Co-Simulation Dialog Box

When verification completes, the console displays message SIM-1000 to confirm the verification was successful. The result of any `printf` commands in the C test bench are echoed to the console.

```
@I [SIM-316] Starting C post checking ...
Test passed !
@I [SIM-1000] *** C/RTL co-simulation finished: PASS ***
@I [LIC-101] Checked in feature [HLS]
```

The simulation report opens automatically in the Information pane, showing the pass or fail status and the measured statistics on latency and II.



IMPORTANT: The C/RTL co-simulation only passes if the C test bench returns a value of zero. See [C Test Bench: Required for Productivity](#) for more details on this requirement.

Reviewing the Output of C/RTL Co-Simulation

A sim directory is created in the solution folder when RTL verification completes. The following figure shows the sub-folders created.

- The report folders contains the report and log file for each type of RTL simulated.
- A verification folder is created for each type of RTL which is verified. The verification folder is named verilog, vhdl or SystemC. If an RTL format is not verified, no folder is created.
- The RTL files used for simulation are stored in the verification folder.
- The RTL simulation is executed in the verification folder.
- Any outputs, such as trace files, are written to the verification folder.
- Folders autowrap, tv, wrap and wrap_pc are work folders used by Vivado HLS. There are no user files in these folders.

If the **Setup Only** option was selected in the C/RTL Co-Simulation dialog boxes, an executable is created in the verification folder but the simulation is not run. The simulation can be manually run by executing the simulation executable at the command prompt.

Note: For more information on the RTL verification process, see [RTL Verification](#).

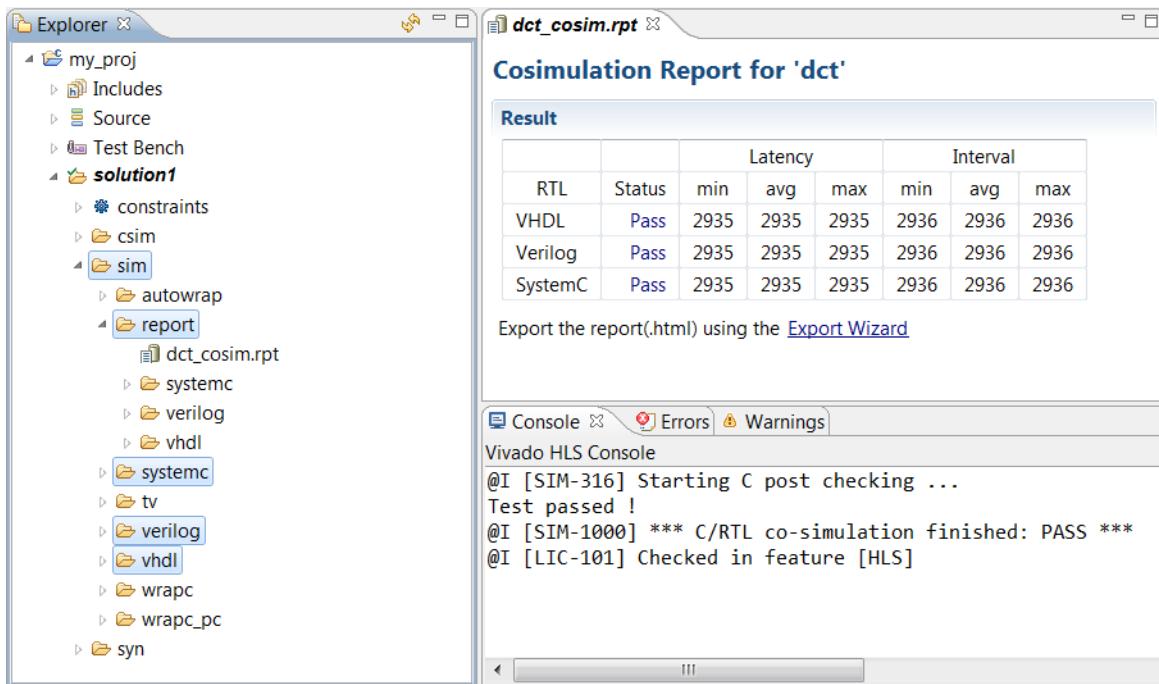


Figure 1-32: RTL Verification Output

Packaging the IP

The final step in the Vivado HLS design flow is to package the RTL output as IP. Use the **Export RTL** toolbar button or the menu **Solution > Export RTL** to open the Export RTL dialog box shown in the following figure.

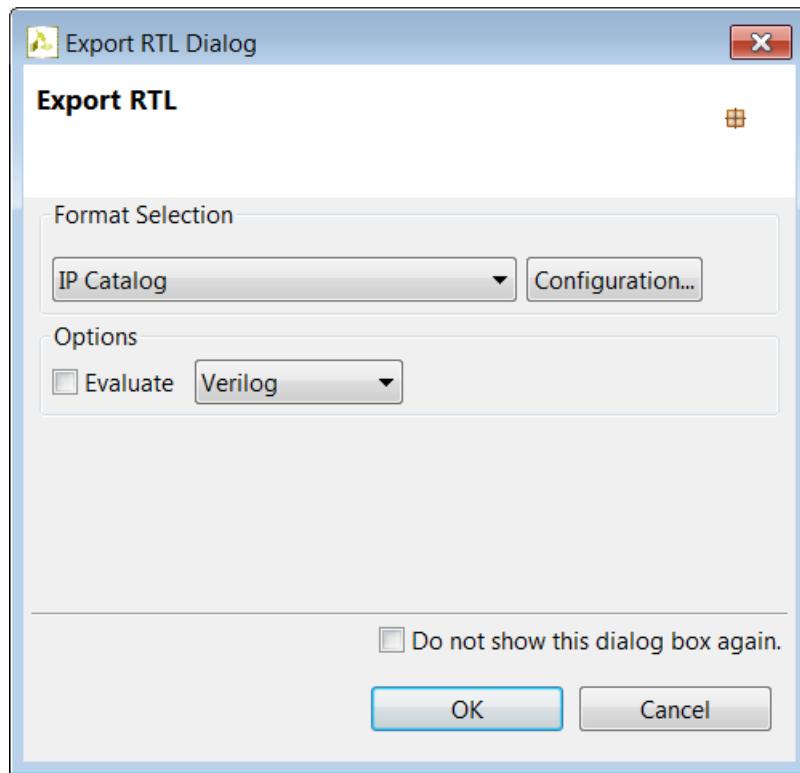


Figure 1-33: RTL Export Dialog Box

The selections available in the drop-down Format Selection menu depend on the FPGA device targeted for synthesis. More details on the IP packaging options is provided in [Exporting the RTL Design](#).

Reviewing the Output of IP Packaging

The folder `impl` is created in the solution folder when the Export RTL process completes.

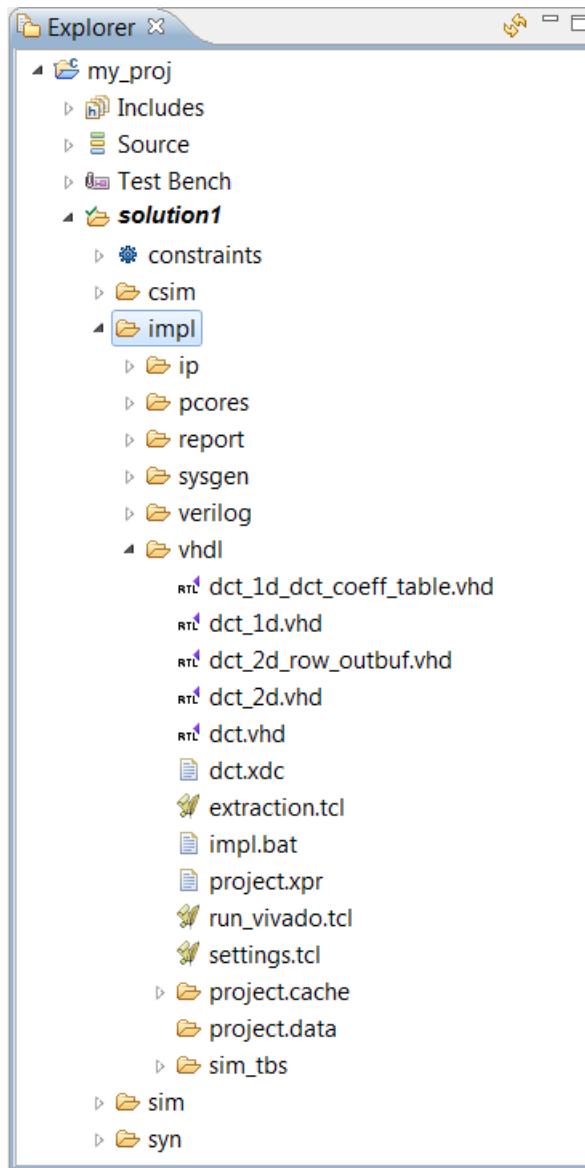


Figure 1-34: Export RTL Output

In all cases the output includes:

- The **report** folder. If the evaluate option is selected, the synthesis report for Verilog and VHDL synthesis is placed in this folder.
- The **verilog** folder. This contains the Verilog format RTL output files. If the evaluate option is selected, RTL synthesis is performed in this folder.
- The **vhdl** folder. This contains the VHDL format RTL output files. If the evaluate option is selected, RTL synthesis is performed in this folder.



IMPORTANT: *It is not recommended to directly use the files in the verilog or vhdl folders for your own RTL synthesis project. Instead, it is recommended to use the packaged IP output files discussed next. Please, carefully read the text which immediately follows this note.*

In cases where Vivado HLS uses Xilinx IP in the design, such as with floating point designs, the RTL directory includes a script to create the IP during RTL synthesis. If the files in the verilog or vhdl folders copied out and used for RTL synthesis, it is your responsibility to correctly use any script files present in those folders. If the package IP is used, this process is performed automatically by the design Xilinx tools.

The Format Selection drop-down determines which other folders are created. The following table details the folder created and their content.

Table 1-3: RTL Export Selections

Format Selection	Sub-Folder	Comments
IP Catalog	ip	Contains a ZIP file which can be added to the Vivado IP Catalog. The ip folder also contains the contents of the ZIP file (unzipped). This option is not available for FPGA devices older than 7 series or Zynq-7000 AP SoC.
System Generator for DSP	sysgen	This output can be added to the Vivado edition of System Generator for DSP. This option is not available for FPGA devices older than 7 series or Zynq-7000 AP SoC.
System Generator for DSP (ISE)	sysgen	This output can be added to the ISE edition of System Generator for DSP.
Pcore for EDK	pcore	This output can be added to Xilinx Platform Studio.
Synthesized Checkpoint (.dcp)	ip	This option creates Vivado checkpoint files which can be added directly into a design in the Vivado Design Suite. This option requires RTL synthesis to be performed. When this option is selected, the evaluate option is automatically selected. This option is not available for FPGA devices older than 7 series or Zynq-7000 AP SoC.

Example Vivado RTL Project

The Export RTL process automatically creates a Vivado RTL project. For hardware designers more familiar with RTL design and working in the Vivado RTL environment, this provides a convenient way to analyze the RTL.

As shown in [Figure 1-34](#) a project.xpr file is created in the verilog and vhdl folders. This file can be used to directly open the RTL output inside the Vivado Design Suite.

If C/RTL co-simulation has been executed in Vivado HLS, the Vivado project contains an RTL test bench and the design can be simulated.

Note: The Vivado RTL project has the RTL output from Vivado HLS as the top-level design. Typically, this design should be incorporated as IP into a larger Vivado RTL project. This Vivado project is provided solely as a means for design analysis and is not intended as a path to implementation.

Example IP Integrator Project

If IP Catalog is selected as the output format, the output folder `impl/ip/example` is created. This folder contains an executable (`ipi_example.bat` or `ipi_example.csh`) which can be used to create a project for IP Integrator.

To create the IP Integrator project, execute the `ipi_example.*` file at the command prompt then open the Vivado IPI project file which is created.

Archiving the Project

To archive the Vivado HLS project to an industry-standard ZIP file, select **File > Archive**. Use the **Archive Name** option to name the specified ZIP file. You can modify the default settings as follows:

- By default, only the current active solution is archived. To ensure all solutions are archived, deselect the **Active Solution Only** option.
- By default, the archive contains all of the output results from the archived solutions. If you want to archive the input files only, deselect the **Include Run Results** option.

Using the Command Prompt and Tcl Interface

On Windows the Vivado HLS Command Prompt can be invoked from the start menu:
`Xilinx Design Tools > Vivado 2014.x > Vivado HLS > Vivado HLS 2014.x Command Prompt`.

On Windows and Linux, using the `-i` option with the `vivado_hls` command opens Vivado HLS in interactive mode. Vivado HLS then waits for Tcl commands to be entered.

```
$ vivado_hls -i [-l <log_file>]  
vivado_hls>
```

By default, Vivado HLS creates a `vivado_hls.log` file in the current directory. To specify a different name for the log file, the `-l <log_file>` option can be used.

The `help` command is used to access documentation on the commands. A complete list of all commands is provided using:

```
vivado_hls> help
```

Help on any individual command is provided by using the command name.

```
vivado_hls> help <command>
```

Any command or command option can be completed using the auto-complete feature. After a single character has been specified, pressing the tab key causes Vivado HLS to list the possible options to complete the command or command option. Entering more characters improves the filtering of the possible options. For example, pressing the tab key after typing "open" lists all commands that start with "open".

```
vivado_hls> open <press tab key>
open
open_project
open_solution
```

Selecting the Tab Key after typing `open_p` auto-completes the command `open_project`, because there are no other possible options.

Type the `exit` command to quit interactive mode and return to the shell prompt:

```
vivado_hls> exit
```

Additional options for Vivado HLS are:

- `vivado_hls -p`: open the specified project
- `vivado_hls -nosplash`: open the GUI without the Vivado HLS splash screen
- `vivado_hls -r`: return the path to the installation root directory
- `vivado_hls -s`: return the type of system (for example: Linux, Win)
- `vivado_hls -v`: return the release version number.

Commands embedded in a Tcl script are executed in batch mode with the `-f <script_file>` option.

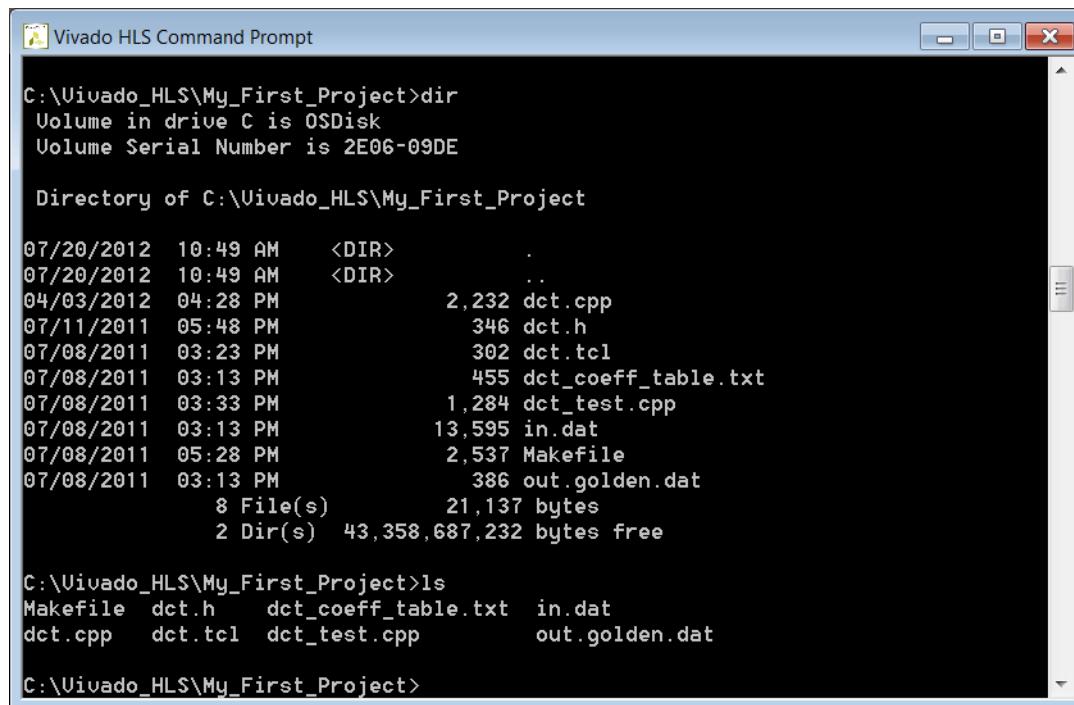
```
$ vivado_hls -f script.tcl
```

All the Tcl commands for creating a project in GUI are stored in the `script.tcl` file within the solution. If you wish to develop Tcl batch scripts, the `script.tcl` file is an ideal starting point.

Understanding the Windows Command Prompt

On the Windows OS, the Vivado HLS Command prompt is implemented using the Minimalist GNU for Windows (minGW) environment, that allows both standard Windows DOS commands to be used and/or a subset of Linux commands.

The following figure shows that both (or either) the Linux `ls` command and the DOS `dir` command is used to list the contents of a directory.



```
Vivado HLS Command Prompt

C:\Uvadado_HLS\My_First_Project>dir
Volume in drive C is OSDisk
Volume Serial Number is 2E06-09DE

Directory of C:\Uvadado_HLS\My_First_Project

07/20/2012 10:49 AM <DIR> .
07/20/2012 10:49 AM <DIR> ..
04/03/2012 04:28 PM 2,232 dct.cpp
07/11/2011 05:48 PM 346 dct.h
07/08/2011 03:23 PM 302 dct.tcl
07/08/2011 03:13 PM 455 dct_coeff_table.txt
07/08/2011 03:33 PM 1,284 dct_test.cpp
07/08/2011 03:13 PM 13,595 in.dat
07/08/2011 05:28 PM 2,537 Makefile
07/08/2011 03:13 PM 386 out.golden.dat
               8 File(s)    21,137 bytes
               2 Dir(s) 43,358,687,232 bytes free

C:\Uvadado_HLS\My_First_Project>ls
Makefile  dct.h    dct_coeff_table.txt  in.dat
dct.cpp   dct.tcl  dct_test.cpp       out.golden.dat

C:\Uvadado_HLS\My_First_Project>
```

Figure 1-35: High-Level Synthesis CLI Icon

Be aware that not all Linux commands and behaviors are supported in the minGW environment. The following represent some known common differences in support:

- The Linux `which` command is not supported.
- Linux paths in a Makefile expand into minGW paths. In all Makefile files, replace any Linux style pathname assignments such as `FOO := :/` with versions in which the pathname is quoted such as `FOO := ":"` to prevent any path substitutions.

Design Examples and References

Vivado HLS provides many tutorials and design examples.

Tutorials

Tutorials are available in the *Vivado Design Suite Tutorial: High-Level Synthesis* (UG871) [Ref 2]. The following table shows a list of the tutorial exercises.

Table 1-4: Vivado HLS Tutorial Exercises

Tutorial Exercise	Description
High-Level Synthesis Introductory Tutorial	An introduction to the operation and primary features of Vivado HLS using an FIR design.
C Validation	This tutorial uses a Hamming window design to explain C simulation and using the C debug environment to validate your C algorithm.
Interface Synthesis	Exercises on how to create various types of RTL interface ports using interface synthesis.
Arbitrary Precision Types	Shows how a floating-point winding function is implemented using fixed-point arbitrary precision types to produce more optimal hardware.
Design Analysis	Shows how the Analysis perspective is used to improve the performance of a DCT block.
Design Optimization	Uses a matrix multiplication example to show how an algorithm is optimized. This tutorial demonstrates how changes to the initial might be required for a specific hardware implementation.
RTL Verification	How to use the RTL verification features and analyze the RTL signals waveforms.
Using HLS IP in IP Integrator	Shows how two HLS pre and post processing blocks for an FFT can be connected to an FFT IP block using IP integrator.
Using HLS IP in a Zynq-7000 AP SoC Processor Design	Shows how the CPU can be used to control a Vivado HLS block through the AXI4-Lite interface and DMA streaming data from DDR memory to and from a Vivado HLS block. Includes the CPU source code and required steps in SDK.
Using HLS IP in System Generator for DSP	A tutorial on how to use an HLS block and inside a System Generator for DSP design.

Design Examples

The Vivado HLS design examples can be accessed from the GUI Welcome screen by selecting **Open Example Project** and expanding the design folder. The GUI Welcome screen appears when the Vivado HLS GUI is invoked and can be accessed at any time using **Help > Welcome**.

The design examples can be accessed directly in the Vivado installation area in directory `Vivado_HLS\2014.x\examples\design`.

The following table provides an explanation of the design examples.

Table 1-5: Vivado HLS Design Examples

Design Example	Description
2D_convolution_with_linebuffer	2D convolution implemented using hls::streams and a line buffer to conserve resources.
FFT > fft_ifft	Using the FFT IP for an inverse FFT.
FFT > fft_single	Single 1024 point forward FFT with pipelined streaming I/O.
FIR > fir_2ch_int	FIR filter 2 interleaved channels.
FIR > fir_3stage	A FIR chain with 3 FIRs connected in series: Half band FIR to Half band FIR to an SRRC (Square Root Raise Cosine) FIR.
FIR > fir_config	Example showing how to update coefficients using FIR CONFIG channel.
FIR > fir_srrc	SRRC (Square Root Raise Cosine) FIR filter.
_builtin_ctz	Using gcc built-in 'count trailing zero' function to implement a priority encoder (32- and 64-bit versions).
axi_lite	Using an AXI4-Lite interface.
axi_master	Using an AXI4 master interface.
axi_stream_no_side_channel_data	Using an AXI4-Stream interface with no side-channel data in the C code.
axi_stream_side_channel_data	AXI4-Stream interfaces using side-channel data.
fp_mul_pow2	Implementing efficient (area and timing) floating point multiplication by power-of-two, which uses no floating-point core and no DSP resources; just a small adder and some optional limit checks
fpx_sqrt	A square-root implementation for ap_fixed types; bit-serial fully pipelineable. This is provided as an example. The HLS math library provides an implementation of the sqrt function using ap_fixed types.
hls_stream	Multirate dataflow (8-bit I/O, 32-bit data processing and decimation) design using hls::stream
Linear_Algebra > cholesky	Basic test-bench demonstrating how to parameterize and instantiate the Cholesky function.
Linear_Algebra > cholesky_alt	Demonstrates how to select the alternative Cholesky implementation.
Linear_Algebra > cholesky_complex	Demonstrates how to use the Cholesky function with a complex data type.
Linear_Algebra > cholesky_inverse	Basic test-bench demonstrating how to parameterize and instantiate the Cholesky Inverse function.
Linear_Algebra > matrix_multiply	Basic test-bench demonstrating how to parameterize and instantiate the matrix multiply function.
Linear_Algebra > matrix_multiply_alt	Demonstrates how to select the one of the alternative multiplier implementations.

Table 1-5: Vivado HLS Design Examples (Cont'd)

Design Example	Description
Linear_Algebra > qr_inverse	Basic test-bench demonstrating how to parameterize and instantiate the QR Inverse function.
Linear_Algebra > qrf	Basic test-bench demonstrating how to parameterize and instantiate the QRF function.
Linear_Algebra > svd	Basic test-bench demonstrating how to parameterize and instantiate the SVD function.
Linear_Algebra > svd_pairs	Demonstrates how to select the alternative, "pairs", SVD implementation.
Loop_Label > loop_label	Using a loop with a label.
Loop_Label > no_loop_label	Using a loop without a label shows Vivado HLS adds a label when you place any optimization on the loop.
memory_porting_and_ii	Highlights how array partitioning directives are used to improve initiation interval
Perfect_Loop > perfect	Example of a perfect loop
Perfect_Loop > semi_perfect	Example of a semi-perfect loop
rom_init_c	Using an array in a sub-function to guarantee a ROM implementation of the array.
window_fn_float	Single-precision floating point windowing function; C++ template class example with compile time selection between Rectangular (none), Hann, Hamming, or Gaussian windows.
window_fn_fxpt	Fixed-point windowing function. Uses the same C++ class as example window_fn_float and shows an easy migration from using float types to ap_fixed types.

Coding Examples

Examples of various coding techniques are provided with the coding examples. These are small examples intended to highlight the results of Vivado HLS synthesis on various C, C++ and SystemC constructs.

The Vivado HLS coding examples can be accessed from the GUI Welcome screen by selecting Open Example Project and expanding the coding folder. The GUI Welcome screen appears when the Vivado HLS GUI is invoked and can be accessed at any time using **Help > Welcome**.

The coding examples can be accessed directly in the Vivado installation area in directory Vivado_HLS\2014.x\examples\coding.

The following table provides an explanation of the design examples.

Table 1-6: Vivado HLS Coding Examples

Coding Example	Description
apint_arith	Using C ap_cint types.
apint_promotion	Highlights the casting required to avoid integer promotion issues with C ap_cint types.
array_arith	Using arithmetic in interface arrays.
array_FIFO	Implementing a FIFO interface.
array_mem_bottleneck	Demonstrates how access to arrays can create a performance bottleneck.
array_mem_perform	A solution for the performance bottleneck shown by example array_mem_bottleneck.
array_RAM	Implementing a block RAM interface.
array_ROM	Example demonstrating how a ROM is automatically inferred.
array_ROM_math_init	Example demonstrating how to infer a ROM in more complex cases.
cpp_ap_fixed	Using C++ ap_int types.
cpp_ap_int_arith	Using C++ ap_int types for arithmetic.
cpp_FIR	An example C++ design using object orientated coding style.
cpp_math	An example floating point math design that shows how to use a tolerance in the test bench when comparing results for operations that are not IEEE exact.
cpp_template	C++ template example.
func_sized	Fixing the size of operation by defining the data widths at the interface.
hier_func	An example of adding files as test bench and design files.
hier_func2	An example of adding files as test bench and design files. An example of synthesizing a lower-level block in the hierarchy.
hier_func3	An example of combining test bench and design functions into the same file.
hier_func4	Using the pre-defined macro __SYNTHESIS__ to prevent code being synthesized.
loop_functions	Converting loops into functions for parallel execution.
loop_imperfect	An imperfect loop example.
loop_max_bounds	Using a maximum bounds to allow loops be unrolled.
loop_perfect	An perfect loop example.
loop_pipeline	Example of loop pipelining.
loop_sequential	Sequential loops.
loop_sequential_assert	Using assert statements.
loop_var	A loop with variable bounds.
malloc_removed	Example on removing mallocs from the code.
pointer_arith	Pointer arithmetic example.

Table 1-6: Vivado HLS Coding Examples (Cont'd)

Coding Example	Description
pointer_array	An array of pointers.
pointer_basic	Basic pointer example.
pointer_cast_native	Pointer casting between native C types.
pointer_double	Pointer-to-Pointer example.
pointer_multi	An example of using multiple pointer targets.
pointer_stream_better	Example showing how the volatile keyword is used on interfaces.
pointer_stream_good	Multi-read pointer example using explicit pointer arithmetic.
sc_combo_method	SystemC combinational design example.
sc_FIFO_port	SystemC FIFO port example.
sc_multi_clock	SystemC example with multiple clocks.
sc_RAM_port	SystemC block RAM port example.
sc_sequ_cthread	SystemC sequential design example.
struct_port	Using structs on the interface.
sum_io	Example of top-level interface ports.
types_composite	Composite types.
types_float_double	Float types to double type conversion.
types_global	Using global variables.
types_standard	Example with standard C types.
types_union	Example with unions.

HLS UltraFast Design Methodology

A key component in using a High-Level Synthesis design flow is to follow a good design methodology. The HLS UltraFast Design Methodology allows designers to quickly achieve results and accelerate time to market.

This HLS UltraFast Design Methodology section is a collection of good practices covering aspects of High-Level Synthesis using Vivado HLS: design validation, hardware efficient C code, synthesis strategies, design analysis, optimization and verification.

Subsequent sections explain all of the features and uses of Vivado HLS. However, before diving into the details, it is worthwhile to appreciate how these features are applied.

C Test Bench: Required for Productivity

The single biggest mistake made by users new to a High-Level Synthesis design flow is to proceed to synthesize their C code without using a C test bench and performing C

simulation. This can be highlighted by the following code. What is wrong with this example of nested loops?

```
#include Nested_Loops.h

void Nested_Loops(din_t A[N], dout_t B[N]) {
    int i,j;
    dint_t acc;

    LOOP_I:for(i=0; i < 20; i++) {
        LOOP_J: for(j=0; j < 20; j++) {
            if(j==0) acc = 0;
            acc += A[i] * j;
            if(j==19) B[i] = acc / 20;
        }
    }
}
```

This code fails to synthesize into the expected result because the conditional statements evaluate as FALSE and J set to 19 at the end of the first iteration of LOOP_J. The conditional statements should be `j==0` and `j==19` (using `==` instead of just `=`). The code above compiles, executes and can be synthesized without any issue. It will not do what is expected by a cursory visual evaluation of the code.

In an era where developers consistently use one or more of C/C++, Perl, Tcl, Python, Verilog and VHDL on a daily basis, it is hard to catch such trivial mistakes, more difficult still to catch functional mistakes and extremely difficult and time consuming to uncover either after synthesis.

A C test bench is nothing more than a program which calls the C function to be synthesized, provides it test data and tests the correctness of its output; the `main()` function is the top-level of the C test bench. C code such as this can be compiled and run prior to synthesis and the expected results validated before synthesis. The term used throughout this guide to validate the algorithm is functionally correct is "C simulation".

The Vivado HLS examples described in [Design Examples and References](#) are all provided with a C, C++ or SystemC test bench. These examples can be copied and modified to create a C test bench.

You initially feel you are saving time by going directly to synthesis but the benefits of using a C test bench in your design methodology are worth a lot more than the time it takes to create one.

Checking the Results: A Productivity Boost

The HLS UltraFast Design Methodology supports C simulation prior to synthesis to validate the C algorithm and C/RTL co-simulation after synthesis to verify the RTL implementation. In both cases Vivado HLS uses the `return` value of function `main()` to confirm the results are correct.

An ideal C test bench has the result checking attribute shown in this code example. The outputs from the function for synthesis are saved into file `results.dat` and compared to the correct and expected results, which are referred to as the "golden" results in this example.

```

int main () {
    ...
    int retval=0;
    fp=fopen("result.dat", "w");
    ...
    // Call the function for synthesis
    loop_perfect(A,B);
    // Save the output results
    for(i=0; i<N;++i) {
        fprintf(fp, "%d \n", B[i]);
    }
    ...
    // Compare the results file with the golden results
    retval = system("diff --brief -w result.dat result.golden.dat");
    if (retval != 0) {
        printf("Test failed !!!\n");
        retval=1;
    } else {
        printf("Test passed !\n");
    }

    // Expect to return 0 if the results are correct
    return retval;
}

```

In the Vivado HLS design flow, the `return` value to function `main()` indicates the following:

- Zero: Results are correct.
- Non-zero value: Results are incorrect.

Note: The test bench can return any non-zero value. A complex test bench can return different values depending on the type of difference or failure. If the test bench returns a non-zero value after C simulation or C/RTL co-simulation, Vivado HLS reports an error and simulation fails.



RECOMMENDED: Because the system environment (for example, Linux, Windows, or Tcl) interprets the return value of the `main()` function, it is recommended that you constrain the return value to an 8-bit range for portability and safety.

By using a self-checking test bench, you are not required to create an RTL test bench to verify the output from Vivado HLS is correct. The same test bench used for the C simulation is automatically used during C/RTL co-simulation and the post-synthesis results verified by the test bench.

There are many ways in C to check the results are valid. In the above example, the output from the function for synthesis is saved to file `result.dat` and compared to a file with the expected results. The results could also be compared to an identical function not marked for

synthesis (which executes in software when the test bench runs) or compared to values calculated by the test bench.



IMPORTANT: *If there is no return statement in function main() of the test bench, the C standard dictates the return value is zero. Thus, C and C/RTL co-simulation always reports the simulation as passing, even if the results are incorrect. Check the results and return zero only if they are correct.*

The time spent to create a self-checking test bench ensures there are no obvious errors in the C code and no requirement to create RTL test benches to verify the output from synthesis is correct.

C Simulation Benefits: Speed, Speed, and Speed

Simulating an algorithm in C can be orders of magnitude faster than simulating the same algorithm in RTL. It of course depends on the algorithm but take the example of a standard video algorithm.

A typical video algorithm in C processes a complete frame of video data and compares the output image against a reference image to confirm the results are correct. The C simulation for this typically take 10-20 seconds. A simulation of the RTL implementation typically takes 2-3 days. The difference in the run time between C simulation and C/RTL co-simulation depends on the algorithm but these are very typical numbers for a video algorithm.

The more development performed at the C level, using the simulation speed of software, the more productive you will be. The productivity benefits of C simulation can only be realized when a C test bench is used as part of your design methodology.

Migrating to Hardware Efficient Data Types

Later sections in this [HLS UltraFast Design Methodology](#) section review the benefit of using Vivado HLS arbitrary precision data types.

Arbitrary precision data types allow variables to be specified using any width. For example, variables might be defined as 12-bit, 22-bit or 34-bits wide. Using standard C data types, these variables are required to be 16-bit, 32-bit and 64-bit respectively. Using the standard C data types often results in unnecessary hardware to implement the required accuracy, for example, 64-bit hardware when only 34-bit is required.

There is a great benefit in providing arbitrary precision data types in C (and C++) rather than using optimization directives to control the data width: the C algorithm can be simulated using these new bit-widths and the output analyzed. For example, to confirm the signal-to-noise ratio is still acceptable when using smaller bit-widths or verify using a smaller more efficient accumulator does not limit the accuracy of the output.

This migration to more hardware efficient data types can only be performed safely and productively if there is a C test bench allowing you to quickly verify the smaller more efficient data types are adequate.

The benefits of using a C test bench, and the loss of productivity in not using one as part of your design methodology, cannot be overstated.

[C Test Bench in Chapter 3](#) contains more details on using C test benches.

Language Support

Understanding what is supported for synthesis is important part of the HLS UltraFast Design Methodology. Vivado HLS provides comprehensive support for C, C++ and SystemC. Everything is supported for C simulation, however, it is not possible to synthesize every description into an equivalent RTL implementation.

The two key principles to keep in mind when reviewing the code for implementation in an FPGA are:

- An FPGA is a fixed size resource. The functionality must be fixed at compile time. Objects in hardware cannot be dynamically created and destroyed.
- All communication with the FPGA must be performed through the input and output ports. There is no underlying Operating System (OS) or OS resources in an FPGA.

Unsupported Constructs

System Calls

System calls are not supported for synthesis. These calls are used to interact with the OS upon which the C program executes. In an FPGA there is no underlying OS to communicate with. Examples of this are `time()` and `printf()`.

Some commonly used functions are automatically ignored by Vivado HLS and there is no requirement to remove them from the code:

- `abort()`
- `atexit()`
- `exit()`
- `fprintf()`
- `printf()`
- `perror()`
- `putchar()`
- `puts()`

An alternative to removing any unsupported code is to guard it from synthesis. The `__SYNTHESIS__` macro is automatically defined by Vivado HLS when synthesis is

performed. This macro can be used to include code when C simulation is run, but exclude the code when synthesis is performed.

```
#ifndef __SYNTHESIS__
    // The following code is ignored for synthesis
    FILE *fp1;
    char filename[255];
    sprintf(filename,Out_apb_%03d.dat,apb);
    fp1=fopen(filename,w);
    fprintf(fp1, %d \n, apb);
    fclose(fp1);
#endif
```

If information is required from the OS, the data must be passed into the top-level function for synthesis as an argument. It is then the task of the remaining system to provide this information to the FPGA. This can typically be done by implementing the data port as an AXI4-Lite interface connected to a CPU.

Dynamic Objects

Dynamic objects cannot be synthesized. The function calls `malloc()`, `alloc()`, pre-processor `free()` and C++ `new` and `delete` dynamically create or destroy memory resources which exist in the OS memory map. The only memory resources available in an FPGA are block RAMs and registers. Block RAMs are created when arrays are synthesized and the values in the array must be maintained over one or more clock cycles. Registers are created when the value stored by a variable must be maintained over one or more clock cycle. Arrays of a fixed size or variables must be used in place of any dynamic memory allocation.

As with restrictions on dynamic memory usage, Vivado HLS does not support (for synthesis) C++ objects that are dynamically created or destroyed. This includes dynamic polymorphism and dynamic virtual function calls. New functions, which would result in new hardware, cannot be dynamically created at run time.

For similar reasons, recursion is not supported for synthesis. All objects must be of a known size at compile time. Limited support for recursion is provided when using templates.

Finally, the C++ Standard Template Libraries (STLs) are not supported. These libraries contain functions which make extensive use of dynamic memory allocation and recursion.

SystemC Constructs

An `SC_MODULE` cannot be nested inside, or derived from, another `SC_MODULE`.

The `SC_THREAD` construct is not supported (`SC_CTHREAD` is).

Constructs with Limited Support

Top-Level Function

Templates are supported for synthesis but are not supported for use on the top-level function.

A C++ class object cannot be to top-level for synthesis. The class must be instantiated into a top-level function.

Pointers to pointers are supported for synthesis but not when used as a argument to the top-level function.

Pointer Support

Vivado HLS supports pointer casting between native C types but does not support general pointer casting, for example. casting between pointers to differing structure types.

Vivado HLS supports pointer arrays provided each pointer points to a scalar or an array of scalars. Arrays of pointers cannot point to additional pointers.

Recursion

Recursion in an FPGA is only supported through the use of templates. The key to performing recursion in synthesis is the use of a termination class, with a size of one, to implement the final call in the recursion.

Memory Functions

The `memcpy()` and `memset()` are both supported with the limitation that `const` values must be used.

- `memcpy()`: used for bus burst operation or array initialization with `const` values. The `memcpy` function can only be used to copy values to or from arguments to the top-level function.
- `memset()`: used for aggregate initialization with constant set value.

Any code which is not supported for synthesis, or for which only limited support is provided, must be modified before it can be synthesized. More complete details on language support and are provided in the [Impact of Coding Style in Chapter 3](#).

Understanding Concurrent Hardware

An FPGA can implement each operations in the C code using unique hardware. This allows operations to be executed concurrently (at the same time), enabling higher performance operation.

Parallel Operation

The following code performs some simple multiplication operations and can be used to highlight the benefits of concurrent hardware. In this example, the clock frequency is specified to ensure there is only enough time to perform one, and only one, multiplication in each clock cycle.

This example also contains an INTERFACE optimization directive: this is to simplify the interface and facilitate an easier explanation of the hardware. Interface optimizations are discussed later.

```
#include "foo.h"

int foo(char a, char b, char c, char d) {

#pragma HLS INTERFACE ap_ctrl_none register=return

    int y0,y1,y2;
    y0 = a * b;
    y1 = c * y0;
    y2 = d * y1;
    return y2;
}
```

Generally, this guide will not review hardware diagrams. It is important to review the details as a means of reviewing some fundamental aspects of hardware operation. The implementation after synthesis is shown in the following figure.

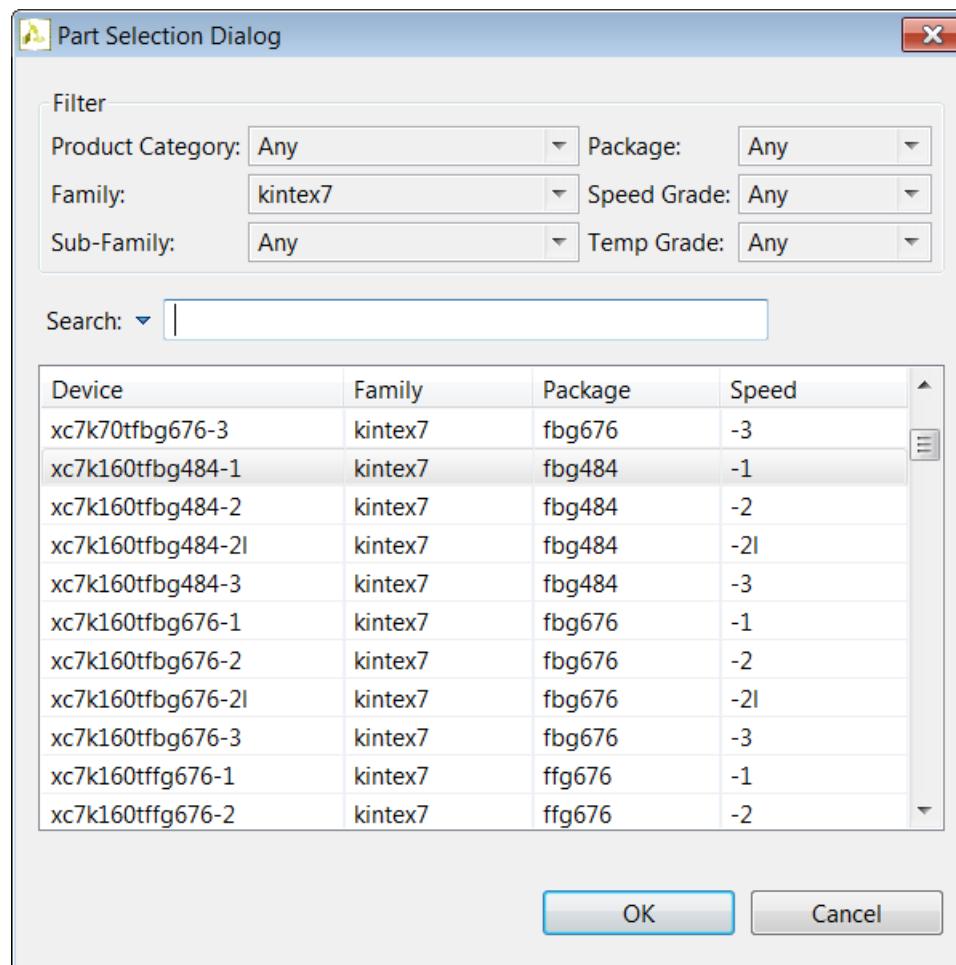


Figure 1-36: Simple Multiplier

Following are key features:

- The logic shown in the lower-half of the figure is used to sequence the design. This is discussed shortly and can be ignored for now.
- The function arguments a, b, c and d are now input ports, shown on the top-half part of the diagram. The data enters through the ports, is multiplied and the results saved into the registers on the next rising edge of the clock.
- The final multiplication is performed in the next clock cycle, registered and then output through port ap_return.
- There are 3 multipliers. The same as in the C code: dedicated resources are used for each operation. If synthesis determines there is no benefit in using dedicated resources it automatically seeks to share the resources.
- Synthesis is able to perform two of the multiplications in parallel.

Here you can see the first benefit of hardware concurrency: parallel operations. The design does not simply calculate y0, then y1 and then y2 in the sequence they appear in the C

code. By re-ordering the operations it is able to perform two of the multiplications in parallel and complete all operations in 2 clock cycles, rather than 3.

After synthesis Vivado HLS reports the results for this design as follows:

```
+ Latency (clock cycles):
 * Summary:
 +-----+-----+-----+
 | Latency | Interval | Pipeline|
 | min | max | min | max | Type |
 +-----+-----+-----+
 | 2 | 2 | 3 | 3 | none |
 +-----+-----+
```

The design requires 2 clock cycles to output the results and new inputs can be processed every 3 clock cycles. These results can be improved using an optimization directive.

Pipelined Operation

During the time the two input multiplications in the previous example are performed, the multiplier on the output side is doing nothing. Conversely, while the output multiplication is being performed, the input multipliers are doing nothing. Another benefit of concurrent hardware is pipelined operation: using all resources at the same time.

The following figure shows a conceptual explanation of pipelining. Without pipelining, the operations execute sequentially until the function completes the first transaction. Then the next set transaction is performed. With pipelining, the next 2nd transaction starts as soon as the hardware resource becomes available.

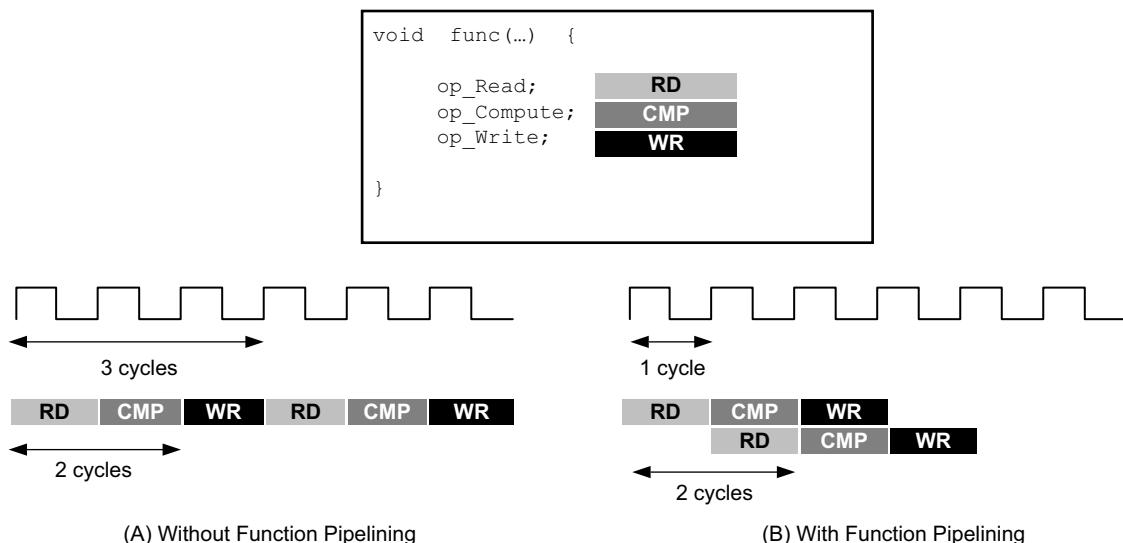


Figure 1-37: Pipelining Behavior

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If the previous example is updated to pipeline the function:

```
#include "foo.h"

#pragma HLS INTERFACE ap_ctrl_none register=return
#pragma HLS PIPELINE

int foo(char a, char b, char c, char d) {
    int y0,y1,y2;
    y0 = a * b;
    y1 = c * y0;
    y2 = d * y1;
    return y2;
}
```

The performance is reported as:

```
+ Latency (clock cycles):
 * Summary:
 +-----+-----+-----+
 | Latency | Interval | Pipeline |
 | min | max | min | max | Type |
 +-----+-----+-----+
 | 2 | 2 | 1 | 1 | function |
 +-----+-----+-----+
```

The latency remains the same but the function can now process a new set of data every clock cycle. This is the ideal case for high performance design.

Vivado HLS can pipeline both functions and loops. The advantage of pipelining loops can be seen with a small example

```
for(i=0; i<N;++i) {
    temp=input_read;
    ..Logic with Latency = L;
}
```

Without pipelining, a new input read can only be performed every L cycles and it will take $L \times N$ cycles to complete all the operations in the loop.

- For $L=7$ and $N=1024$
- A new read (or write) every 7 clock cycles
- Total number of clock cycles to complete is $7 \times 1024 = 7168$.

If the loop is pipelined with an initiation interval of II, a new read operation can occur every II cycles and it will take $L+(N-1) \times II$ to complete all the operations in the loop.

- For $L=7$ and $N=1024$ and $II=1$
- A new read every 1 clock cycle
- Total number of clock cycles to complete is $7+(1024-1) \times 1 = 1030$

If the II is 2 in this example, the total time to complete the loop is 2053. This highlights the benefit in a design with a low initiation interval.

In addition to pipelining the operations within functions and loops, Vivado HLS can pipeline tasks.

Pipelined Tasks

The following figure shows a conceptual view of task pipelining, which is the ability to execute tasks in parallel. After synthesis, the default behavior is to execute and complete func_A, then func_B, and finally func_C. However, you can use the Vivado HLS DATAFLOW optimization directive to schedule each function to execute as soon as data is available.

In this example, the original function has a latency and interval of 8 clock cycles. When you use dataflow optimization, the interval is reduced to only 3 clock cycles. The tasks shown in this example are functions, but you can perform dataflow optimization between functions, between functions and loops, and between loops.

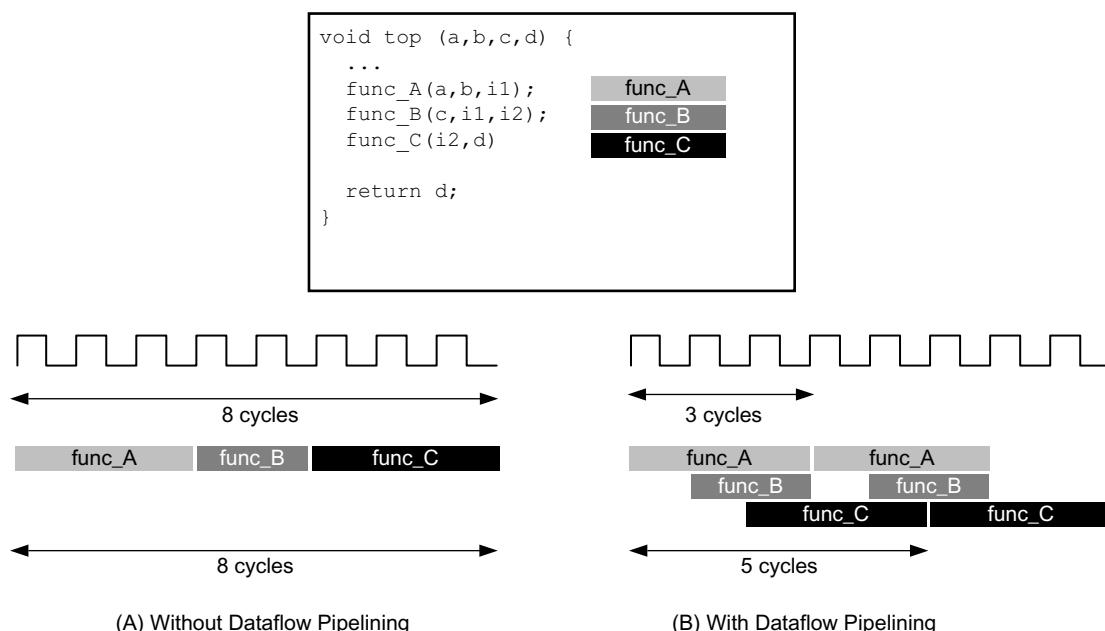


Figure 1-38: Dataflow Optimization

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Memory Channels

Dataflow optimization inserts memory channels between tasks. You can use the following buffer types to implement the memory channel:

- Ping-pong buffers

Ping-pong buffers store two copies of the data passed between the tasks. For example, if the `My_Array[1024]` variable is passed between a function or loop in a dataflow region, the ping-pong buffer is two block RAMs of size 1024. The first task writes data into one of the block RAMs. When all of the data is available, the second task starts to consume the data. At the same time, the first task writes the next set of data into the other half of the memory channel. From this point on, both tasks are constantly processing data. The advantage of using ping-pong buffers is that Vivado HLS can read and write data in any order. The trade-off is increased buffer size.

- FIFO buffers

FIFO buffers store only one copy of the data, and you can configure the size of the buffer. For example, if `func_A` is pipelined with an interval of 1, it outputs a new value every clock cycle. If `func_B` is pipelined with an interval of 1, it accepts a new value every clock cycle. In this case, you can reduce the size of the FIFO to a single element. The advantage of using FIFO buffers is reduced buffer size. The trade-off is that Vivado HLS must read and write data in sequential order.

Note: FIFO buffers work well in a typical high-performance system where data streams from one task to the next.

By default, if Vivado HLS determines that the data flow between the tasks is streaming, it implements the memory channel as a FIFO buffer of size 1. If Vivado HLS cannot determine if the data is streaming between the tasks, it implements the memory channel as a ping-pong buffer.

Using the dataflow configuration settings, you can specify the type of buffer to use in the memory channels. To set the dataflow configuration settings, select **Solution > Solution Settings**, click **General**, and add **config_dataflow**. Alternatively, you can use the `config_dataflow` Tcl command. This is a global setting that is applied to all channels between all tasks.



IMPORTANT: If you use a FIFO to implement the memory channel and set the depth too small, the design might stall and wait.

Based on the type of system you are working with, use the following recommendations to set the size of memory channels:

- Systems with arbitrary or non-streaming accesses

Use the default memory channel, because Vivado HLS does not automatically implement FIFO buffers. This is the safest configuration and guarantees that all samples can safely pass between tasks.

- Systems with streaming data that is not automatically detected by Vivado HLS

Change the memory channel to a FIFO implementation, and initially set the depth of the FIFO at a higher level than the required minimum data rate. Synthesize the design, and confirm that C/RTL co-simulation passes. This ensures that the FIFO size does not stall the design. Then, reduce the size of the memory channel, re-synthesize the design, and re-confirm the C/RTL co-simulation passes. Repeat this process until you implement the minimum sized buffer.

- Complex systems with both arbitrary and streaming data or systems where decimation and interpolation might change the rate at which tasks produce and consume data

Use the STREAM directive to specify individual memory channels between tasks. For example, you can set the default to a ping-pong channel and specify individual channels as FIFO implementations or vice versa.

Summary of Concurrent Hardware Advantages

Using dedicated hardware resources to implemented the operations specified in the C code allows those operations to be performed in parallel and be executed in a pipelined manner. This ensures the highest performance.

The next stage of the HLS UltraFast Design Methodology is to understand what optimizations are performed by default by Vivado HLS and what optimizations may be specified.

Synthesis Strategies

The first step in defining a strategy to synthesize any design is to appreciate what optimizations are automatically performed by Vivado HLS and what optional optimizations are available.

Default Optimization Strategy

Vivado HLS quickly creates the most optimum implementation based on its own default behavior and constraints. The clock is the primary constraint and Vivado HLS uses this along with the target device specifications to determine how many operations can be

performed within a clock cycle. After satisfying the clock frequency constraint, the performance goals for Vivado HLS, in order of importance, are:

- **Interval:** Minimize the interval between new inputs and maximize the data throughput rate.
- **Latency:** After the minimum interval has been achieved, or if no internal target has been specified, minimize the latency.
- **Area:** After the minimum latency has been achieved, minimize the area.

In the absence of any optimization directives, Vivado HLS uses these goals and the default synthesis behavior outlined below to create the initial design.

Synthesis of Top-Level Function Arguments

The arguments to the top-level function are synthesized into data ports with an optional IO protocol. An IO protocol is one or more signals associated with the data port to automatically synchronize data communication between the data port and other hardware blocks in the system.

For example, in an handshake protocol, the data port is accompanied by a valid port to indicate when the data is valid for reading or writing and an acknowledge port to indicate the data has been read or written.

The types of IO protocol which can be used depends upon the type of C argument.

- Pass-By-Value scalar arguments default to data ports with no IO protocol.
- Pass-By-Reference inputs default to a data port with no IO protocol.
- Pass-By-Reference outputs default to a data output port with an associated output valid port.
- Pass-By-Reference arguments which are both read from and written to are partitioned into separate input and output ports, with the defaults as noted above.
- Arrays arguments are implemented as block RAM memory ports.

By default, structs in the top-level function argument list are decomposed into their separate member elements. Each element is synthesized into an IO port as described above.

In addition, an IO protocol is by default implemented for the top-level function itself. This protocol allows the function to start operation and indicates when the function has completed its operation or ready for new input data. This IO protocol is associated with the function return. (This is true, even if the C program has no explicit return value).

Synthesis of Sub-Functions

Functions are synthesized into hierarchical blocks in the final RTL design. Each function in the C code will be represented in the final RTL by a unique block. In general, optimizations

stop at function boundaries - some optimization directives have a recursive option or behavior which allows the directive to take effect across function boundaries.

Functions can be inlined using an optimization directive. This removes the function hierarchy permanently and can lead to better optimization of the logic. Vivado HLS may automatically inline small functions in order to improve the quality of results. The optimization directive `INLINE` can be used with the `-off` option to prevent automatic inlining.

Functions are scheduled to execute as early as possible. The following examples shows two functions, `foo_1` and `foo_2`.

```
void foo_1 (a,b,c,d,*x,*y) {
    ...
    func_A(a,b,&x);
    func_B(c,d,&y);
}
```

In function `foo_1`, there is no data dependency between functions `func_A` and `func_B`. Even though they appear serially in the code, Vivado HLS will implement an architecture where both functions start to process data at the same time in the first clock cycle.

```
void foo_2 (a,b,c,*x,*y) {
    int inter1;
    ...
    func_A(a,b,inter1,&x);
    func_B(c,d,inter1,&y)
}
```

In function `foo_2`, there is a data dependency between the functions. Internal variable `inter1` is passed from `func_A` to `func_B`. In this case, Vivado HLS must schedule function `func_B` to start only after function `func_A` is finished.

Synthesis of Loops

Loops by default are left "rolled". This means Vivado HLS synthesizes the logic in the loop body once and then executes this logic serially until the loop termination limit is reached. It typically cost 1 clock cycle to enter a loop and 1 clock cycle to exit a loop. Sometimes the loop entry or exit cycle can be merged with operations in the clock cycle before or after the loop.

Loops are always scheduled to execute in order. In the following example, there is no dependency between loop `SUM_X` and `SUM_Y`, however they will always be scheduled in the order they appear in the code.

```
#include loop_sequential.h

void loop_sequential(din_t A[N], din_t B[N], dout_t X[N], dout_t Y[N],
                      dsel_t xlimit, dsel_t ylimit) {

    dout_t X_accum=0;
    dout_t Y_accum=0;
    int i,j;

    SUM_X:for (i=0;i<xlimit; i++) {
        X_accum += A[i];
        X[i] = X_accum;
    }

    SUM_Y:for (i=0;i<ylimit; i++) {
        Y_accum += B[i];
        Y[i] = Y_accum;
    }
}
```

Example 1-1: Sequential Loops

Synthesis of Arrays

By default, Vivado HLS synthesizes arrays into block RAM. In an FPGA, block RAM is provided in blocks of 18K-bit primitive elements. Each block RAM uses as many 18K primitives elements as required to implement the array. For example, an array of 1024 `int` types, requires $1024 * 32\text{-bit} = 32768$ bits of block RAM, which requires $32768/18000 = 1.8$ 18K block RAM primitives to implement the block RAM. Although Vivado HLS reports that each array is synthesized into one block RAM, the block RAM might contain multiple 18K primitive block RAM elements.

By default, Vivado HLS makes no attempt to group smaller block RAMs into a single large block RAM or partition large block RAM into smaller block RAMs. However, this is possible using optimization directives. Vivado HLS might automatically partition small arrays into individual registers to improve the quality of results. To control the size at which arrays are automatically partitioned, select the **Solution > Solution Settings**, click **General**, and add the `config_array_partition` command.

Vivado HLS automatically determines whether to use a single or dual-port block RAM based on the synthesis goals. For example, Vivado HLS uses a dual-port block RAM if this helps to minimize the interval or latency. To explicitly specify whether to use a single or dual-port block RAM, you can use the `RESOURCE` optimization directive.

By default, the latency of a block RAM is 1 clock cycle. That is, 1 cycle after the address is supplied, the data is ready to be read. You can use the RESOURCE directive to specify the latency of a block RAM as follows:

- For arrays on the top-level function interface, a latency greater than 1 allows Vivado HLS to model RAMs external to the FPGA. For example, if the latency is set to 3, the design waits 3 clock cycles before reading data from the RAM data input port.
- For internal arrays, a latency of greater than 1 allows Vivado HLS to add register pipeline stages to the block RAM. For details on how Vivado HLS adds these registers, see [Controlling Operator Pipelining](#).

Synthesis of Structs

Structs by default, are decomposed into their member elements. Each member element is implemented as a separate element. An array of structs, where each struct has M elements, is decomposed into M arrays. The DATA_PACK directive is used to flatten structs into a single wide-vector.

Synthesis of Operators

Operators in the C code, such as +, * and / are synthesized into hardware cores. Vivado HLS will automatically select the most appropriate core to achieve the synthesis goals. The optimization directive RESOURCE can be used to explicitly specify which hardware core is used to implement the operation.

General Optimization Strategy for Performance

In addition to the default synthesis behavior discussed in the previous section, Vivado HLS provides a number of optimization directives and configurations which are used to direct synthesis towards a desired outcome.

Following is a complete list of optimization directives. This list shows the Tcl commands on the left side and the equivalent pragma directives on the right:

set_directive_allocation	- Directive ALLOCATION
set_directive_array_map	- Directive ARRAY_MAP
set_directive_array_partition	- Directive ARRAY_PARTITION
set_directive_array_reshape	- Directive ARRAY重塑
set_directive_data_pack	- Directive DATA_PACK
set_directive_dataflow	- Directive DATAFLOW
set_directive_dependence	- Directive DEPENDENCE
set_directive_expression_balance	- Directive EXPRESSION_BALANCE
set_directive_function_instantiate	- Directive FUNCTION_INSTANTIMATE
set_directive_inline	- Directive INLINE
set_directive_interface	- Directive INTERFACE
set_directive_latency	- Directive LATENCY
set_directive_loop_flatten	- Directive LOOP_FLATTEN
set_directive_loop_merge	- Directive LOOP_MERGE
set_directive_loop_tripcount	- Directive LOOP_TRIPCOUNT
set_directive_occurrence	- Directive OCCURRENCE
set_directive_pipeline	- Directive PIPELINE
set_directive_protocol	- Directive PROTOCOL
set_directive_reset	- Directive RESET
set_directive_resource	- Directive RESOURCE
set_directive_stream	- Directive STREAM
set_directive_top	- Directive TOP
set_directive_unroll	- Directive UNROLL

Configurations modify the default synthesis behavior. There are no pragma equivalents for the configurations. In the GUI, configurations are set using the menu **Solution > Solution Settings > General**. A complete list of the available configurations is:

config_array_partition	- Config the array partition
config_bind	- Config the options for binding
config_compile	- Config the optimization
config_dataflow	- Config the dataflow pipeline
config_interface	- Config command for io mode
config_rtl	- Config the options for RTL generation
config_schedule	- Config scheduler options

Having a list of all the optimization directives and synthesis configurations is good. Having a strategy to use them is better.

There are many possible goals when trying to optimize a design using Vivado HLS. The HLS UltraFast Design Methodology assumes you want to create a design with the highest possible performance, processing one sample of new input data every clock cycle.

If this is not your goal, it is still very worthwhile understanding the strategy for performance. This performance optimization strategy will discuss and briefly explain each of the optimizations listed above.

Detailed explanations of the optimizations discussed here are provided in [Managing Interfaces](#) and [Design Optimization](#). It is highly recommended to review the methodology and obtain a global perspective of High-Level Synthesis optimization before reviewing the details of specific optimization.

Initial Optimizations

The following table shows the first directives you should think about adding to your design.

Table 1-7: Optimization Strategy Step 1

Directives and Configurations	Description
INTERFACE	Specifies how RTL ports are created from the function description.
DATA_PACK	Packs the data fields of a struct into a single scalar with a wider word width.
LOOP_TRIPCOUNT	Used for loops which have variables bounds. Provides an estimate for the loop iteration count. This has no impact on synthesis, only on reporting.
Config Interface	This configuration controls IO ports not associated with the top-level function arguments and allows unused ports to be eliminated from the final RTL.

The design interface is typically defined by the other blocks in the system. Since the type of IO protocol helps determine what can be achieved by synthesis it is recommended to use the INTERFACE directive to specify this before proceeding to optimize the design.

If the algorithm accesses data in a streaming manner, you may want to consider using one of the streaming protocols to ensure high performance operation.



TIP: *If the I/O protocol is completely fixed by the external blocks and will never change, consider inserting the INTERFACE directives directly into the C code as pragmas.*

When structs are used in the top-level argument list they are decomposed into separate elements and each element in the struct is implemented as a separate port. In some case it is useful to use the DATA_PACK optimization to implement the entire port as a single data word. Care should be taken if the struct contains large arrays. Each element of the array is implemented in the data word and this may results in a very wide data port.

A common issue when designs are first synthesized is report files showing the latency and interval as a question mark "?" rather than as numerical values. If the design has loops with variable loop bounds Vivado HLS cannot determine the latency.

Use the analysis perspective or the synthesis report to locate the lowest level loop for which synthesis fails to report a numerical value and use the LOOP_TRIPCOUNT directive to apply an estimated tripcount. This allows values for latency and interval to be reported and allows solutions with different optimizations to be compared.

Note: Loops with variable bounds cannot be unrolled completely and prevent the functions and loops above them in the hierarchy from being pipelined. This is discussed in the next section.

Finally, global variables are generally written to and read from, within the scope of the function for synthesis and are not required to be IO ports in the final RTL design. If a global

variable is used to bring information into or out of the design you may wish to expose them as an IO port using the interface configuration.

Pipeline for Performance

The next stage in creating a high performance design is to pipeline the functions, loops, and tasks. The following table shows the directives you can use for pipelining.

Table 1-8: Optimization Strategy Step 2

Directives and Configurations	Description
PIPELINE	Reduces the initiation interval by allowing the concurrent execution of operations within a loop or function.
DATAFLOW	Enables task level pipelining, allowing functions and loops to execute concurrently. Used to minimize interval.
RESOURCE	Specify a resource (core) to use to implement a variable (array, arithmetic operation, or function argument) in the RTL.

At this stage of the optimization process you want to create as much concurrent operation as possible. You can apply the PIPELINE directive to functions and loops. You can use the DATAFLOW directive at the level that contains the functions and loops to make them work in parallel.

A recommended strategy is to work from the bottom up and be aware of the following:

- Some functions and loops contain sub-functions. If the sub-function is not pipelined, the function above it might show limited improvement when it is pipelined. However, it is the non-pipelined sub-function that is the limiting factor.
- Some functions and loops contain sub-loops. When you use the PIPELINE directive, the directive automatically unrolls all loops in the hierarchy below. This can create a great deal of logic. It might make more sense to pipeline the loops in the hierarchy below.
- Loops with variable bounds cannot be unrolled, and the loops and function above these loops cannot be pipelined. To address this issue, pipeline these loops, and use DATAFLOW optimization to maximize the performance of the function that contains the loop. Alternatively, rewrite the loop to remove the variable bound.

The basic strategy at this point in the optimization process is to pipeline the tasks (functions and loops) and as much as possible. For detailed information on which functions and loops to pipeline and where to apply the DATAFLOW directive, see [Strategies for Applying Pipelining](#).

Although not commonly used, you can also apply pipelining at the operator level. For example, wire routing in the FPGA can introduce large and unanticipated delays that make it difficult for the design to be implemented at the required clock frequency. In this case, you can use the RESOURCE directive to pipeline specific operations.

The RESOURCE directive specifies which hardware cores to use to implement the operations in the C code. Specifying that a resource is implemented with a latency greater than 1 causes Vivado HLS to uses additional pipeline stages for the operation. RTL synthesis can use these additional pipeline stages to improve the overall timing.

The following operations support pipelined implementations:

- Standard arithmetic operations for which there is a multi-stage (*nS) core available, as shown in [Table 1-26](#)
- Floating-point operations, as shown in [Table 1-27](#)
- Arrays implemented with a block RAM, as shown in [Table 1-28](#)

Directives to Enable Pipelined Performance

C code can contain descriptions which prevent a function or loop from being pipelined or from prevent it being pipelined with the required performance. In some cases, this may require the a code modification but in most cases these issues can be address using other optimization directives.

The following example shows a case where an optimization directive improves the performance of pipelining.

```
#include "bottleneck.h"

dout_t bottleneck(din_t mem[N]) {

    dout_t sum=0;
    int i;

    SUM_LOOP: for(i=3;i<N;i=i+4)
#pragma HLS PIPELINE
        sum += mem[i] + mem[i-1] + mem[i-2] + mem[i-3];

    return sum;
}
```

When the code above is synthesized the following message is output:

```
@I [SCHED-61] Pipelining loop 'SUM_LOOP'.
@W [SCHED-69] Unable to schedule 'load' operation ('mem_load_2', bottleneck.c:57) on
array 'mem' due to limited memory ports.
@I [SCHED-61] Pipelining result: Target II: 1, Final II: 2, Depth: 3.
```

When pipelining fails to meet the required performance, the key to addressing the issue is to examine the design in the analysis perspective. The view of this design in the analysis perspective is shown in the figure below.

- The memory accesses are highlighted in the figure.
- Each takes two cycles: one to generate the address and one to read the data.
- Only two memory reads can start in cycle C1 because a block RAM only has a maximum of two data ports.
- The third and forth memory reads can only start in cycle C2.
- The earliest the next set of memory reads can occur is starting in cycle C3: hence an II=2.

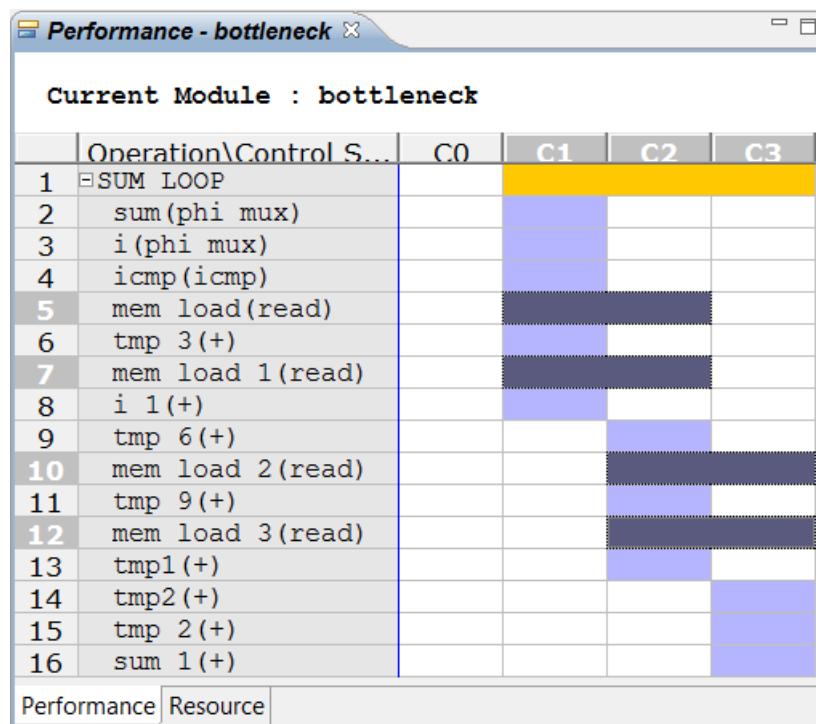


Figure 1-39: Pipelining Fails Due to Too Few Ports

This issue can be solved by using the ARRAY_PARTITION directive. This directive partitions arrays into smaller arrays providing more data ports. With the additional directive shown below, array `mem` is partitioned in 2 memories and all four reads can occur in one clock cycle. (Cyclic partitioning with a factor of 2 partitions the first array to contain elements 0,2,4 etc. from the original array and the second array to contain elements 1,3,5, etc.)

```
#include "bottleneck.h"

dout_t bottleneck(din_t mem[N]) {
    #pragma HLS ARRAY_PARTITION variable=mem cyclic factor=2 dim=1

    dout_t sum=0;
    int i;

    SUM_LOOP: for(i=3;i<N;i=i+4)
    #pragma HLS PIPELINE
        sum += mem[i] + mem[i-1] + mem[i-2] + mem[i-3];

    return sum;
}
```

Other such issues may be encountered when trying to pipeline loops and functions. The following table lists the directives which are likely to address these issues.

Table 1-9: Optimization Strategy Step 3

Directives and Configurations	Description
ARRAY_PARTITION	Partitions large arrays into multiple smaller arrays or into individual registers, to improve access to data and remove block RAM bottlenecks.
DEPENDENCE	Used to provide additional information that can overcome loop-carry dependencies and allow loops to be pipelined (or pipelined with lower intervals).
INLINE	Inlines a function, removing all function hierarchy. Used to enable logic optimization across function boundaries and improve latency/interval by reducing function call overhead.
UNROLL	Unroll for-loops to create multiple independent operations rather than a single collection of operations.
Config Array Partition	This configuration determines how arrays are partitioned, including global arrays and if the partitioning impacts array ports.
Config Compile	Controls synthesis specific optimizations such as the automatic loop pipelining and floating point math optimizations.
Config Schedule	Determines the effort level to use during the synthesis scheduling phase and the verbosity of the output messages

In addition to the ARRAY_PARTITION directive, the configuration for array partitioning can be used to automatically partition arrays.

The configuration for compile is used to automatically pipeline loop hierarchies. The DEPENDENCE directive may be required to remove implied dependencies when pipelining loops. Such dependencies will be reported by message SCHED-68.

```
@W [SCHED-68] Target II not met due to carried dependence(s)
```

The INLINE directive removes function boundaries. This can be used to bring logic or loops up one level of hierarchy. It may be more efficient to pipeline the logic in a function by including the logic in the function above it and it may be easier to dataflow a series of loops with other loops by raising them up the hierarchy.

The UNROLL directive may be required for cases where a loop cannot be pipelined with the required initiation interval. If loop can only be pipelined with II=4 it will constrain the other loops and functions in the system to be limited to II=4. In some cases, it may be worth unrolling the loop and creating more logic.

The schedule configuration is to increase the verbosity of the message and to control the effort levels in scheduling. When the verbose option is used Vivado HLS lists the critical path when scheduling is unable to meet the constraints.

In general, there are few cases where increasing the schedule effort improves the scheduling but the option is provided.

If optimization directives and configurations cannot be used to improve the initiation interval it may require changes to the code. Example of this are discussed later in [Writing Hardware Efficient C Code](#).

Improving the Area

After meeting the required initiation interval, the next step is to reduce the area while maintaining the same performance.

If you used the DATAFLOW optimization and Vivado HLS cannot determine whether the tasks in the design are streaming data, Vivado HLS implements the memory channels using ping-pong buffers. In this case, you can greatly reduce the area by using the dataflow configuration config_dataflow to convert the ping-pong buffers used in the default memory channels into FIFO buffers. You can then set the FIFO depth to the minimum required size. For example, if a design streams with II=1, it only requires a FIFO depth of 1 or 2 not a block RAM of size 1024.

The dataflow configuration config_dataflow specifies the default implementation for all memory channels. You can use the STREAM directive to specify which arrays to implement as block RAM and which to implement as FIFOs. If the design is implemented using an `hls::stream`, the memory channels default to FIFOs with a depth of 1, and the dataflow configuration is not required.

The following table lists the other directives to consider when attempting to minimize the resources used to implement the design.

Table 1-10: Optimization Strategy Step 4

Directive	Description
ALLOCATION	Specify a limit for the number of operations, cores or functions used. This can force the sharing of hardware resources and might increase latency
ARRAY_MAP	Combines multiple smaller arrays into a single large array to help reduce block RAM resources.
ARRAY_RESHAPE	Reshape an array from one with many elements to one with greater word-width. Useful for improving block RAM accesses without using more block RAM.
LOOP_MERGE	Merge consecutive loops to reduce overall latency, increase sharing and improve logic optimization.
OCCURRENCE	Used when pipelining functions or loops, to specify that the code in a location is executed at a lesser rate than the code in the enclosing function or loop.
RESOURCE	Specify that a specific library resource (core) is used to implement a variable (array, arithmetic operation or function argument) in the RTL.
STREAM	Specifies that a specific memory channel is to be implemented as a FIFO or RAM during dataflow optimization.
Config Bind	Determines the effort level to use during the synthesis binding phase and can be used to globally minimize the number of operations used.
Config Dataflow	This configuration specifies the default memory channel and FIFO depth in dataflow optimization.

The ALLOCATION and RESOURCE directives are used to limit the number of operations and to select which cores (or resources) are used to implement the operations. For example, you could limit the function or loop to using only 1 multiplier and specify it to be implemented using a pipelined multiplier. The binding configuration is used to globally limit the use of a particular operation.



IMPORTANT: *Optimization directives are only applied within the scope in which they are specified.*

If the ARRAY_PARTITION directive is used to improve the initiation interval you may want to consider using the ARRAY_RESHAPE directive instead. The ARRAY_RESHAPE optimization performs a similar task to array partitioning however the reshape optimization re-combines the elements created by partitioning into a single block RAM with wider data ports.

If the C code contains a series of loops with similar indexing, merging the loops with the LOOP_MERGE directive may allow some optimizations to occur.

Finally, in cases where a section of code in a pipeline region is only required to operate at an initiation interval lower than the rest of the region, the OCCURENCE directive is used to indicate this logic may be optimized to execute at a lower rate.

Reducing Latency

When Vivado HLS finishes minimizing the initiation interval it automatically seeks to minimize the latency. The optimization directives listed in the following table can help reduce or specify a particular latency.

These are generally not required when the loops and function are pipelined but are covered here for completeness.

Table 1-11: Optimization Strategy Step 5

Directive	Description
LATENCY	Allows a minimum and maximum latency constraint to be specified.
LOOP_FLATTEN	Allows nested loops to be collapsed into a single loop with improved latency.
LOOP_MERGE	Merge consecutive loops to reduce overall latency, increase sharing and improve logic optimization.

The LATENCY directive is used to specify the required latency. The loop optimization directives can be used to flatten a loop hierarchy or merge serial loops together. The benefit to the latency is due to the fact that it typically costs a clock cycle to enter and leave a loop. The fewer the number of transitions between loops, the less number of clock cycles a design will take to complete.

Strategies for Applying Pipelining

[General Optimization Strategy for Performance](#) describes how to start with an un-optimized design and proceed by adding optimizations to create a high-performance design.

The key optimization directives for obtaining a high-performance design are the PIPELINE and DATAFLOW directives. This section discusses in detail how to apply these directives for various architectures of C code.

The following code shows an example of C code to perform a matrix multiplication.

```
void matrixmul(
    mat_a_t a[MAT_A_ROWS] [MAT_A_COLS],
    mat_b_t b[MAT_B_ROWS] [MAT_B_COLS],
    result_t res[MAT_A_ROWS] [MAT_B_COLS]) {

    // Iterate over the rows of the A matrix
    Row: for(int i = 0; i < MAT_A_ROWS; i++) {
        // Iterate over the columns of the B matrix
        Col: for(int j = 0; j < MAT_B_COLS; j++) {
            res[i][j] = 0;
            // Do the inner product of a row of A and col of B
            Product: for(int k = 0; k < MAT_B_ROWS; k++) {
                res[i][j] += a[i][k] * b[k][j];
            }
        }
    }
}
```

The architecture of this code can be summarized as:

- The input and output data is in an array.
- The function processes blocks of data.
- The values in the array are processed by loops.
- For multi-dimensional arrays, and to perform calculations, there are typically nested loops.

The following code example shows an abstracted version of the attributes in the preceding code example. This concise version of the code shows only the function, loops, and data input and output:

```
void matrixmul(
    data_t a[MAT_A_ROWS] [MAT_A_COLS],
    data_t b[MAT_B_ROWS] [MAT_B_COLS],
    data_t res[MAT_A_ROWS] [MAT_B_COLS]) {

Loop1: for(int i = 0; i < MAT_A_ROWS; i++) {
    Loop2: for(int j = 0; j < MAT_B_COLS; j++) {
        Loop3: for(int k = 0; k < MAT_B_ROWS; k++) {
            res[i][j] += a[i][k] * b[k][j];
        }
    }
}
```

This representation of the code suffices for the purposes of this discussion on optimization strategies.

The following sections present a number of C code architectures and explain the best strategy to optimize the code for high-performance operation.

Function with a Top-Level Loop Processing Blocks

The following code processes blocks of data and has a top-level loop with multiple nested loops.

```
void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT][WIDTH]) {

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            out[i][j] = in1[i][j] * in2[i][j];
            Loop3: for(int k = 0; k < NUM_CALC; k++) {
            }
        }
    }
}
```

Since the data is processed in a sequential manner the interface arrays can be implemented with a streaming type interface using the INTERFACE directive.

Applying the PIPELINE directive to the top-level function will automatically unroll all the loops in the hierarchy. This will be a simple solution to execute but it will result in the logic in Loop2 being replicated $HEIGHT*WIDTH$ times.

Scheduling is then required re-assemble all the operations in a pipelined manner. Even in this small example, this results in:

- HEIGHT*WIDTH read operations on input in1.
- HEIGHT*WIDTH read operations on input in2.
- HEIGHT*WIDTH write operations on input out.
- HEIGHT*WIDTH multiplication operations.

This increases run time and since one of the goals of scheduling is to also minimize latency it will seek to execute operations as early as possible and will likely create a design with more than 1 multiplier.

The key strategy when working with C code which processes blocks of data is to focus on pipelining the loops. It is possible to pipeline the function and simply unroll all the loops but this typically creates designs with more resources than is required.

The best strategy here is to pipeline one of the loops. This keeps the operations grouped in a well defined structure and increases the likelihood of balancing high-performance with minimal resources while allowing Vivado HLS to schedule everything quickly.



TIP: *The most optimum loop to pipeline is the lowest loop in the loop hierarchy which operates on a data sample.*

In this code, there are `HEIGHT*WIDTH` data samples to process. If `Loop2` is pipelined with `II=1` the design will complete in `HEIGHT*WIDTH` clock cycles: the design will process one sample per clock.

If you selected `Loop1` to pipeline, the design would complete in `HEIGHT` clock cycles but is required to read and write `WIDTH` samples per clock cycle and use `WIDTH` multipliers. It will complete faster than one sample per clock but will require more resources and data ports.

An additional issue to address when pipelining loops are loop transition cycles. It typically cost 1 clock cycle to enter a loop and 1 clock cycle to exit a loop. Sometimes the loop entry or exit cycle can be merged with operations in the clock cycle before or after the loop.

When nested loops are pipelined the `LOOP_FLATTEN` optimization is automatically applied to the nested loops. This automatically removes any additional cycle between `Loop1` and `Loop2`.

There is still an issue transitioning between the newly flattened `Loop_1_2` and the function. In the above example:

- The function will start to execute.
- Since there are no logic operations before `Loop1_2`, the loop will execute immediately.
- When the loop completes, it will take one clock cycle to exit the loop.
- The function will then start to execute again.

While the loop exits and returns to the start of the function, none of the operations in the loop body are executed. There will be a pause in the reading, processing and writing of data.

If a loop is the top-level loop in a function, the `rewind` option may be used when pipelining the loop. The `rewind` option informs Vivado HLS that this loop will always jump back to the start of the loop when it completes. The `rewind` option can only be used if:

- The loop is the top-level loop in a function and there are no logic operations before the loop starts or after the loop ends.
- Note:** The function must have the same operation if either it is executed multiple times or the loop was to execute in an infinite manner, which can be coded but cannot be simulated.
- The loop is pipelined in a region which uses the `DATAFLOW` optimization.

The solution here is to use streaming interfaces, pipeline Loop2, the loop which operates at the sample level and use the pipeline `rewind` option.

```
void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT][WIDTH]) {
    #pragma HLS INTERFACE axis port=in1
    #pragma HLS INTERFACE axis port=in2
    #pragma HLS INTERFACE axis port=out

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            #pragma HLS PIPELINE rewind
            out[i][j] = in1[i][j] * in2[i][j];
        }
    }
}
```

Doing so results in a design which processes one sample per clock and immediately starts to execute the next set of samples, without pause.

Function with a Top-Level Loop Processing Samples

The following code processes samples of data and has a top-level loop.

```
void foo (data_t x) {

    temp = x;
    Loop1: for (int i=N-1;i>=0;i--) {
        acc+= ..some calculation..
    }
}
```

Since the data is inherently sequential, the function reads one value of `x` after the next, the interface arrays can be implemented with a streaming type interface using the `INTERFACE` directive.

To achieve an interval of 1, reading one data value each time the function is called, the function must be pipelined with `II=1`. This will unroll the loop and create additional logic but there is no way around this. If `Loop1` is pipelined, it will take a minimum of `N` clock cycles to complete. Only then can the function read the next `x` input value.

When dealing with C code which processes at the sample level, where the function processes a single sample each time it executes, the strategy is always to pipeline the function. Since loops in a sample based design are typically operating on arrays of data it is not uncommon to partition these arrays to ensure an `II=1` is achieved,

The solution here is to pipeline function `foo`. Doing so results in a design which processes one sample per clock.

Function with Nested Operations

The following code has a top-level loop with multiple nested loops but the inner loop Loop3 performs multiple operations.

```

void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT][WIDTH]) {

    data_t int1[HEIGHT][WIDTH];
    data_t int2[HEIGHT][WIDTH];

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            int1[i][j] += in1[i][j] * in2[i][j];
            Loop3: for(int k = 0; k < NUM_CALC; k++) {
                int2[k] = ..some calculations ...
            }
            out[i][j] += int2[i][j];
        }
    }
}

```

This is similar to the previous block code example but this time, if the inner loop, loop Loop3, is pipelined the design will execute for a minimum of $HEIGHT*WIDTH*NUM_CALC$ clock cycles. There are only $HEIGHT*WIDTH$ data samples to process. This will result in a design which requires multiple clock cycles to process each data sample.

This is a common feature, where the lowest level loop is sometimes performing calculations on the data and pipelining the lowest level loop would result in many additional cycles. The key point made in the earlier example is to pipeline the lowest loop which processes a data sample.

The solution here is to pipeline Loop2, the loop which operates at the sample level and use the pipeline rewind option. Doing so results in a design which processes one sample per clock and immediately starts to execute the next set of samples, without pause.

Function with Serial Loops and Sub-Functions

The following function executes a number of functions and loops in series.

```

void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT*WIDTH]) {
    data_t int1[HEIGHT][WIDTH];
    data_t int2[HEIGHT*WIDTH];

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            int1[i][j] = in1[i][k] * in2[k][j];
        }
    }
    fool(int1, int2);

    Loop3: for(int k = 0; k < HEIGHT*WIDTH; k++) {
        out[k] = int2[k];
    }
}

```

The strategy with this type of code structure is to pipeline each of the loops and the sub-functions and then use the DATAFLOW optimization in function `foo` to allow the loops and sub-function to execute in parallel.

It is recommended to start by optimizing the sub-functions. If a sub-function is not pipelined before synthesis, the optimization achieved at this level of hierarchy will be limited by the performance of the sub-function. Optimize the sub-function using any one of the strategies for optimizing a function.

Then pipeline `Loop2` and `Loop3`. Since the loops are implemented in a dataflow region, the pipeline rewind option can be applied to the loops.

The solution here is to pipeline all the tasks: the sub-function and the loops. Then apply the dataflow optimization to function `foo` and use the dataflow configuration to minimize the size of the memory channels between the tasks.

Function with Task Fanout

The following function executes a number of functions and loops in series but this time the flow of data is not a point-to-point connection.

```

void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT*WIDTH]) {

    data_t int1[HEIGHT][WIDTH];
    data_t int2[HEIGHT*WIDTH];

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            int1[i][j] = in1[i][k] * in2[k][j];
        }
    }
    foo1(int1, int2);
    foo2(int1, int3);

    Loop3: for(int k = 0; k < HEIGHT*WIDTH; k++) {
        out[k] = int2[k] + int3[k];
    }
}

```

This is similar to the previous example, and a similar strategy of pipelining the individual tasks can be used. However, in this case the internal array `int1` is used as an input to both sub-functions `foo1` and `foo2`. The DATAFLOW optimization can only be used when there is a single producer and single consumer.

The strategy with this type of code structure is split the fanout of `int1` into two separate paths. In this case, an additional copy of `int1` is created as `int11` in Loop2.

```

void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT*WIDTH]) {

    data_t int1[HEIGHT][WIDTH];
data_t int11[HEIGHT][WIDTH];
    data_t int2[HEIGHT*WIDTH];

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            int1[i][j] = in1[i][k] * in2[k][j];
            int11[i][j] = in1[i][k] * in2[k][j];
        }
    }
    foo1(int1, int2);
    foo2(int11, int3);

    Loop3: for(int k = 0; k < HEIGHT*WIDTH; k++) {
        out[k] = int2[k] + int3[k];
    }
}

```

An alternative option is to create a new sub-function and use the new sub-function to replicate the data path. The new sub-function is optimized in the same manner as any other function or if it simply contains a pipelined loop, the `INLINE` directive can be used to raise the loop to this level of hierarchy where it will be included the in dataflow region.

The solution here is to first modify the code to allow a single-producer and single-consumer model to exist between the tasks. Then pipeline all the tasks: the sub-function and the loops. Finally, apply the dataflow optimization to function `foo` and use the dataflow configuration to minimize the size of the memory channels between the tasks.

Function with Complex Loop Hierarchy

The following function contains a loop which itself contains loops and functions in series.

```
void foo(
    data_t in1[HEIGHT][WIDTH],
    data_t in2[HEIGHT][WIDTH],
    data_t out[HEIGHT*WIDTH]) {

    data_t int1[WIDTH];
    data_t int2[WIDTH];

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            int1[j] = in1[i][j] * in2[i][j];
        }
    }

    foo1(int1, int2);

    Loop3: for(int k = 0; k < WIDTH; k++) {
        out[i][k] = int2[k];
    }
}
```

From the previous examples it should be clear the strategy is to pipeline the individual tasks (loops and sub-functions) and then apply the DATAFLOW optimizations to have the loops and sub-function execute in parallel.

Unfortunately the DATAFLOW optimization cannot be used inside a loop. There are three alternatives here and the solution depends on how much logic will be created.

- Pipeline `Loop1` and sub-function `foo1`. This will unroll all the loops in the hierarchy: `Loop2`, `Loop3` and any loops in sub-function `foo1`.
- Unroll `Loop1` and pipeline the remaining loops and function. This will create multiple copies of the logic in `Loop1` (multiple instances of `Loop2`, `foo1` and `Loop3`).
- Capture `Loop2`, `foo` and `Loop3` into a new sub-function. Inside the new sub-function, pipeline each task individually and use DATAFLOW to maximize the parallelism. This will provide an overall performance improvement without the additional area of the first two options.

The solution here depends on the size of the loop indexes and how much logic will be created by unrolling the loops.

Writing Hardware Efficient C Code

When C code is compiled for a CPU, the compiler transforms and optimizes the C code into a set of CPU machine instructions. In many cases, the developer's work is done at this stage. If however, there is a need for performance the developer will seek to perform some or all of the following:

- Understand if any additional optimizations can be performed by the compiler.
- Seek to better understand the processor architecture and modify the code to take advantage of any architecture specific behaviors (for example, reducing conditional branching to improve instruction pipelining)
- Modify the C code to use CPU-specific intrinsics to perform key operations in parallel. (for example, ARM NEON intrinsics)

The same methodology applies to code written for a DSP or a GPU, and when using an FPGA: an FPGA device is simply another target.

C code synthesized by Vivado HLS will execute on an FPGA and provide the same functionality as the C simulation. In some cases, the developer's work is done at this stage.

Typically however, an FPGA is selected to implement the C code due to the superior performance of the FPGA device - the massively parallel architecture of an FPGA allows it to perform operations much faster than the inherently sequential operations of a processor - and users typically wish to take advantage of that performance.

The keys to creating a high performance FPGA design are:

- Understanding the inherent concurrency of hardware.
- Understanding the default optimizations of Vivado HLS.
- Understanding the optional optimizations of Vivado HLS.
- Understanding how the C code impacts the performance of the design.

The first of these topics is addressed in [Understanding Concurrent Hardware](#). The second and third are addressed in [Synthesis Strategies](#). The focus here is on understanding the impact of the C code on the results which can be achieved and how modifications to the C code can be used to extract the maximum advantage from the first three items in this list.

Typical C Code for a Convolution Function

A standard convolution function applied to an image is used here to demonstrate how the C code can negatively impact the performance which is possible from an FPGA. In this example, a horizontal and then vertical convolution is performed on the data. Since the data at edge of the image lies outside the convolution windows, the final step is to address the data around the border.

The algorithm structure can be summarized as follows:

```

template<typename T, int K>
static void convolution_orig(
    int width,
    int height,
    const T *src,
    T *dst,
    const T *hcoeff,
    const T *vcoeff) {

    T local[MAX_IMG_ROWS*MAX_IMG_COLS];

    // Horizontal convolution
    HconvH:for(int col = 0; col < height; col++) {
        HconvW:for(int row = border_width; row < width - border_width; row++) {
            Hconv:for(int i = - border_width; i <= border_width; i++) {
            }
        }
    }
    // Vertical convolution
    VconvH:for(int col = border_width; col < height - border_width; col++) {
        VconvW:for(int row = 0; row < width; row++) {
            Vconv:for(int i = - border_width; i <= border_width; i++) {
            }
        }
    }
    // Border pixels
    Top_Border:for(int col = 0; col < border_width; col++) {
    }
    Side_Border:for(int col = border_width; col < height - border_width; col++) {
    }
    Bottom_Border:for(int col = height - border_width; col < height; col++) {
    }
}

```

Horizontal Convolution

The first step in this is to perform the convolution in the horizontal direction as shown in the following figure.

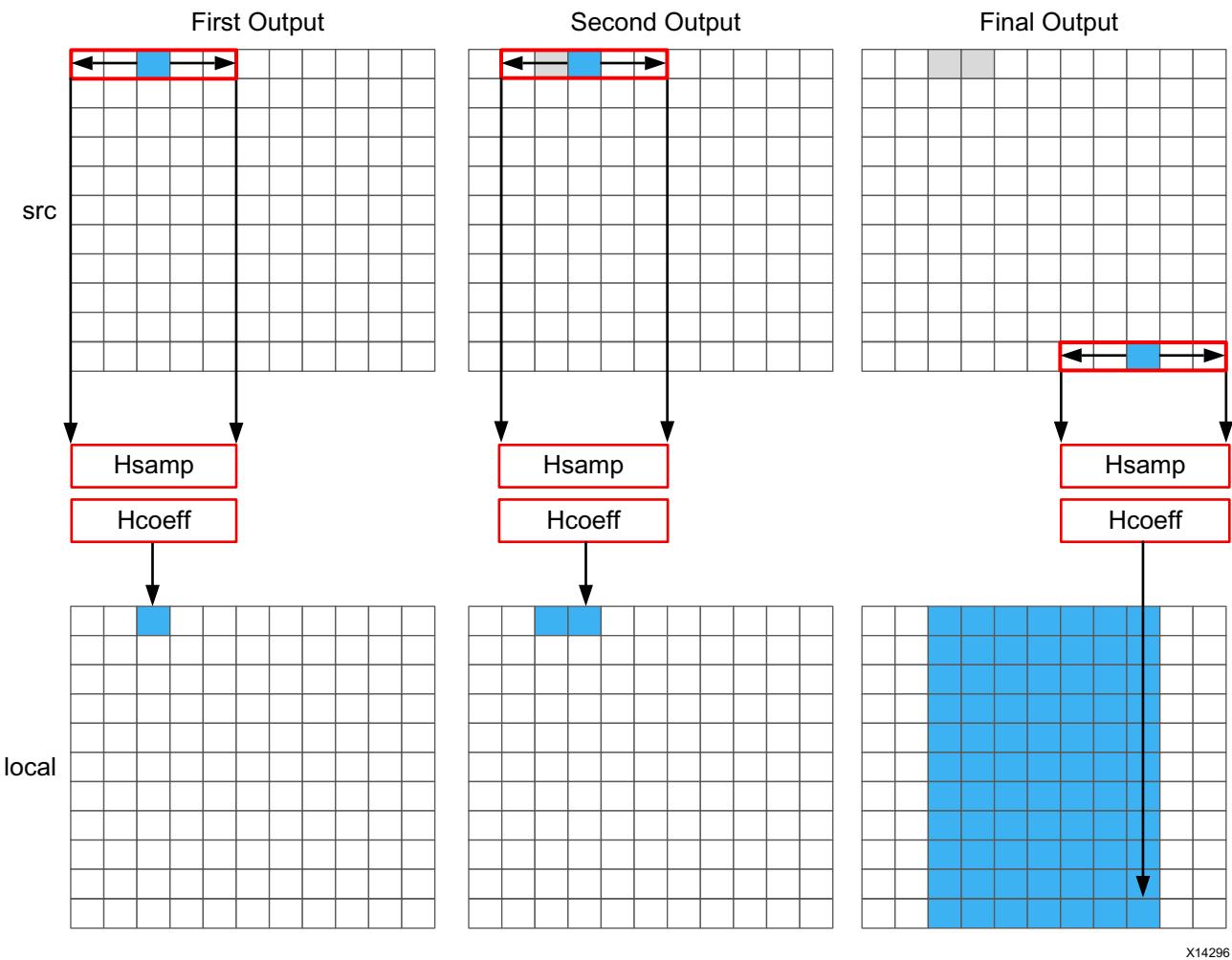


Figure 1-40: Horizontal Convolution

The convolution is performed using K samples of data and K convolution coefficients. In the figure above, K is shown as 5 however the value of K is defined in the code. To perform the convolution, a minimum of K data samples are required. The convolution window cannot start at the first pixel, since the window would need to include pixels which are outside the image.

By performing a symmetric convolution, the first K data samples from input `src` can be convolved with the horizontal coefficients and the first output calculated. To calculate the second output, the next set of K data samples are used. This calculation proceeds along each row until the final output is written.

The final result is a smaller image, shown above in blue. The pixels along the vertical border are addressed later.

The C code for performing this operation is shown below.

```

const int conv_size = K;
const int border_width = int(conv_size / 2);

#ifndef __SYNTHESIS__
T * const local = new T[MAX_IMG_ROWS*MAX_IMG_COLS];
#else // Static storage allocation for HLS, dynamic otherwise
T local[MAX_IMG_ROWS*MAX_IMG_COLS];
#endif

Clear_Local:for(int i = 0; i < height * width; i++) {
    local[i]=0;
}
// Horizontal convolution
HconvH:for(int col = 0; col < height; col++) {
    HconvWfor(int row = border_width; row < width - border_width; row++) {
        int pixel = col * width + row;
        Hconv:for(int i = - border_width; i <= border_width; i++) {
            local[pixel] += src[pixel + i] * hcoeff[i + border_width];
        }
    }
}

```

The code is straight forward and intuitive. There are already however some issues with this C code and three which will negatively impact the quality of the hardware results.

First issue is the requirement for two separate storage requirements. The results are stored in an internal `local` array. This requires an array of `HEIGHT*WIDTH` which for a standard video image of `1920*1080` will hold 2,073,600 values. On some windows systems it is not uncommon for this amount of local storage to give problems. The data for a local array is placed on the stack and not the heap which is managed by the OS.

A useful way to avoid such problems is to use the `__SYNTHESIS__` macro. This macro is automatically defined when synthesis is executed. The code shown above will use the dynamic memory allocation during C simulation to avoid any compilation issues and only use the static storage during synthesis. A downside of using this macro is the code verified by C simulation is not the same code which is synthesized. In this case however, the code is not complex and the behavior will be the same.

The first issue for the quality of the FPGA implementation is the array `local`. Since this is an array it will be implemented using internal FPGA block RAM. This is a very large memory to implement inside the FPGA. It may require a larger and more costly FPGA device. The use of block RAM can be minimized by using the DATAFLOW optimization and streaming the data through small efficient FIFOs, but this will require the data to be used in a streaming manner.

The next issue is the initialization for array `local`. The loop `Clear_Local` is used to set the values in array `local` to zero. Even if this loop is pipelined, this operation will require approximately 2 million clock cycles ($HEIGHT*WIDTH$) to implement. This same initialization of the data could be performed using a temporary variable inside loop `HConv` to initialize the accumulation before the write.

Finally, the throughput of the data is limited by the data access pattern.

- For the first output, the first K values are read from the input.
- To calculate the second output, the same K-1 values are re-read through the data input port.
- This process of re-reading the data is repeated for the entire image.

One of the keys to a high-performance FPGA is to minimize the access to and from the top-level function arguments. The top-level function arguments become the data ports on the RTL block. With the code shown above, the data cannot be streamed directly from a processor using a DMA operation, since the data is required to be re-read time and again. Re-reading inputs also limits the rate at which the FPGA can process samples.

Vertical Convolution

The next step is to perform the vertical convolution shown in the following figure.

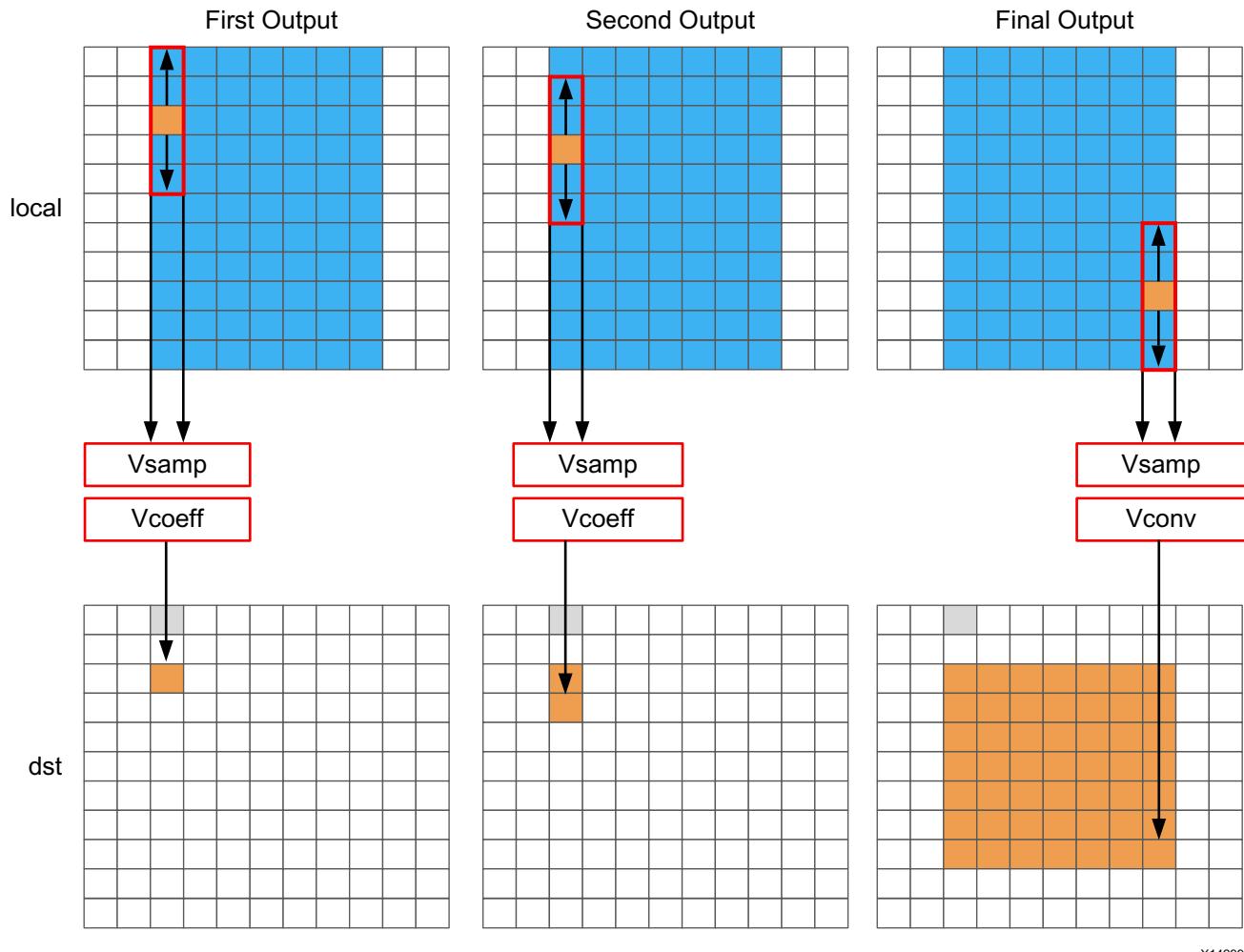


Figure 1-41: Vertical Convolution

The process for the vertical convolution is similar to the horizontal convolution. A set of K data samples is required to convolve with the convolution coefficients, Vcoeff in this case. After the first output is created using the first K samples in the vertical direction, the next set K values are used to create the second output. The process continues down through each column until the final output is created.

After the vertical convolution, the image is now smaller than the source image src due to both the horizontal and vertical border effect.

The code for performing these operations is:

```

Clear_Dst:for(int i = 0; i < height * width; i++){
    dst[i]=0;
}
// Vertical convolution
VconvH:for(int col = border_width; col < height - border_width; col++) {
    VconvW:for(int row = 0; row < width; row++) {
        int pixel = col * width + row;
        Vconv:for(int i = - border_width; i <= border_width; i++) {
            int offset = i * width;
            dst[pixel] += local[pixel + offset] * vcoeff[i + border_width];
        }
    }
}

```

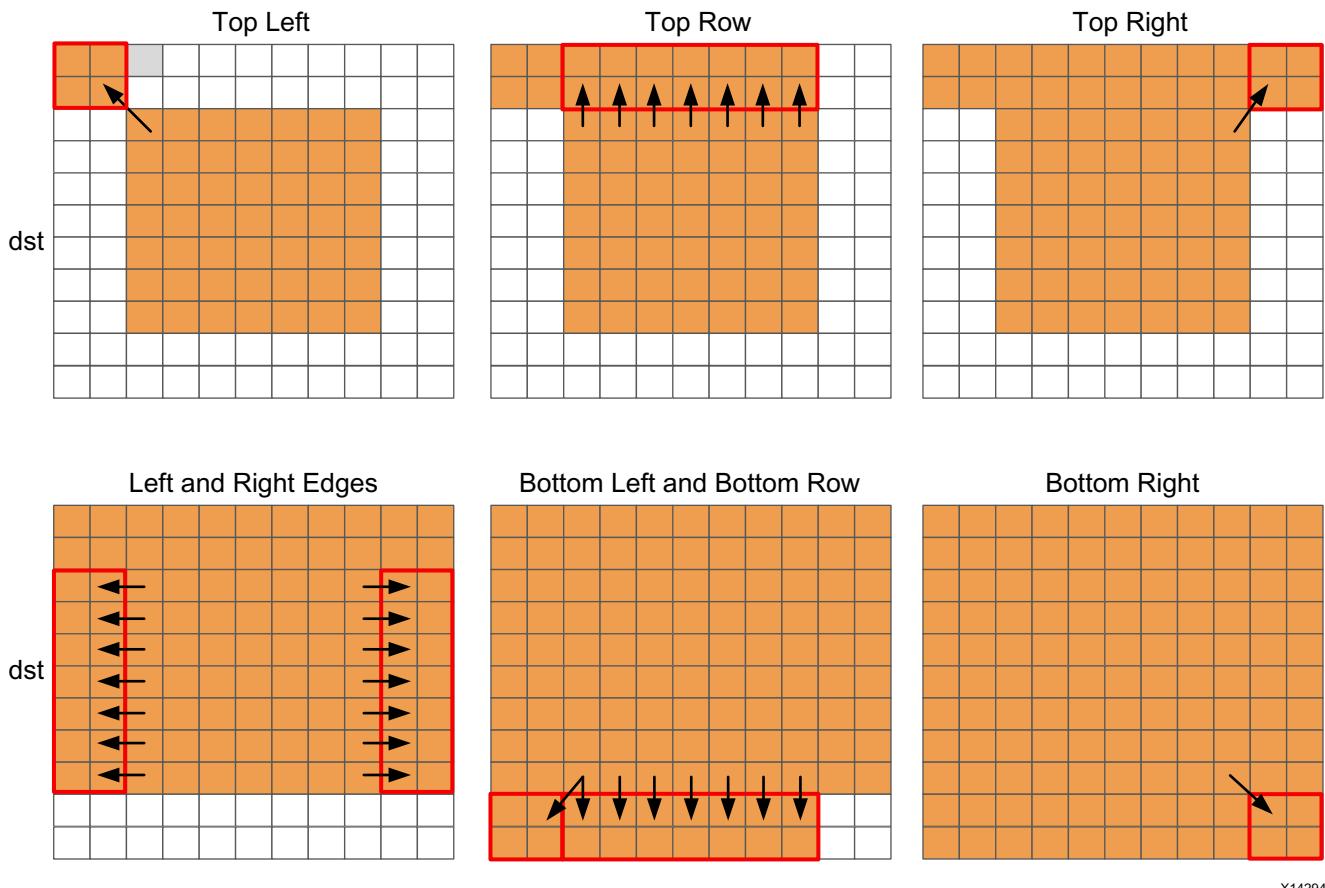
This code highlights similar issues to those already discussed with the horizontal convolution code.

- Many clock cycles are spent to set the values in the output image `dst` to zero. In this case, approximately another 2 million cycles for a 1920*1080 image size.
- There are multiple accesses per pixel to re-read data stored in array `local`.
- There are multiple writes per pixel to the output array/port `dst`.

Another issue with the code above is the access pattern into array `local`. The algorithm requires the data on row K to be available to perform the first calculation. Processing data down the rows before proceeding to the next column requires the entire image to be stored locally. In addition, because the data is not streamed out of array `local`, a FIFO cannot be used to implement the memory channels created by DATAFLOW optimization. If DATAFLOW optimization is used on this design, this memory channel requires a ping-pong buffer: this doubles the memory requirements for the implementation to approximately 4 million data samples all stored locally on the FPGA.

Border Pixels

The final step in performing the convolution is to create the data around the border. These pixels can be created by simply re-using the nearest pixel in the convolved output. The following figures shows how this is achieved.



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Figure 1-42: Convolution Border Samples

The border region is populated with the nearest valid value. The following code performs the operations shown in the figure.

```

int border_width_offset = border_width * width;
int border_height_offset = (height - border_width - 1) * width;
// Border pixels
Top_Border:for(int col = 0; col < border_width; col++) {
    int offset = col * width;
    for(int row = 0; row < border_width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_width_offset + border_width];
    }
    for(int row = border_width; row < width - border_width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_width_offset + row];
    }
    for(int row = width - border_width; row < width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_width_offset + width - border_width - 1];
    }
}

Side_Border:for(int col = border_width; col < height - border_width; col++) {
    int offset = col * width;
    for(int row = 0; row < border_width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[offset + border_width];
    }
    for(int row = width - border_width; row < width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[offset + width - border_width - 1];
    }
}

Bottom_Border:for(int col = height - border_width; col < height; col++) {
    int offset = col * width;
    for(int row = 0; row < border_width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_height_offset + border_width];
    }
    for(int row = border_width; row < width - border_width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_height_offset + row];
    }
    for(int row = width - border_width; row < width; row++) {
        int pixel = offset + row;
        dst[pixel] = dst[border_height_offset + width - border_width - 1];
    }
}

```

The code suffers from the same repeated access for data. The data stored outside the FPGA in array dst must now be available to be read as input data re-read multiple time. Even in the first loop, `dst[border_width_offset + border_width]` is read multiple times but the values of `border_width_offset` and `border_width` do not change.

The final aspect where this coding style negatively impact the performance and quality of the FPGA implementation is the structure of how the different conditions is address. A

for-loop processes the operations for each condition: top-left, top-row, etc. The optimization choice here is to:

Pipelining the top-level loops, (Top_Border, Side_Border, Bottom_Border) is not possible in this case because some of the sub-loops have variable bounds (based on the value of input width). In this case you must pipeline the sub-loops and execute each set of pipelined loops serially.

Even if the loop bounds are not variable, remember, the DATAFLOW optimization cannot be applied inside loops. The question of whether to pipeline the top-level loop and unroll the sub-loops or pipeline the sub-loops individually is determined by the loop limits and how many resources are available on the FPGA device. If the top-level loop limit is small, unroll the loops to replicate the hardware and meet performance. If the top-level loop limit is large, pipeline the lower level loops and lose some performance by executing them sequentially in a loop (Top_Border, Side_Border, Bottom_Border).

As shown in this review of a standard convolution algorithm, the following coding styles negatively impact the performance and size of the FPGA implementation:

- Setting default values in arrays costs clock cycles and performance.
- Multiple accesses to read and then re-read data costs clock cycles and performance.
- Accessing data in an arbitrary or random access manner requires the data to be stored locally in arrays and costs resources.

Ensuring the Continuous Flow of Data and Data Reuse

The key to implementing the convolution example reviewed in the previous section as a high-performance design with minimal resources is to consider how the FPGA implementation will be used in the overall system. The ideal behavior is to have the data samples constantly flow through the FPGA.

- Maximize the flow of data through the system. Refrain from using any coding techniques or algorithm behavior which limits the flow of data.
- Maximize the reuse of data. Use local caches to ensure there are no requirements to re-read data and the incoming data can keep flowing.

The first step is to ensure you perform optimal I/O operations into and out of the FPGA. The convolution algorithm is performed on an image. When data from an image is produced and consumed, it is transferred in a standard raster-scan manner as shown in the following figure.

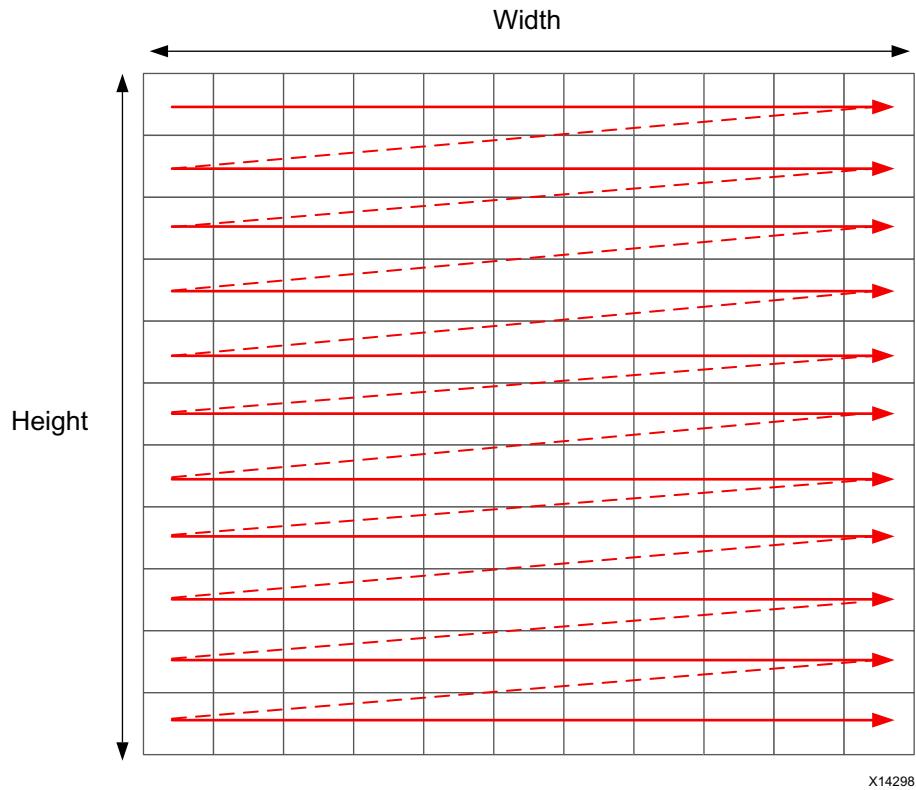


Figure 1-43: Raster Scan Order

If the data is transferred from the CPU or system memory to the FPGA it will typically be transferred in this streaming manner. The data transferred from the FPGA back to the system should also be performed in this manner.

Using HLS Streams for Streaming Data

One of the first enhancements which can be made to the earlier code is to use the HLS stream construct, typically referred to as an `hls::stream`. An `hls::stream` object can be used to store data samples in the same manner as an array. The data in an `hls::stream` can only be accessed sequentially. In the C code, the `hls::stream` behaves like a FIFO of infinite depth.

Code written using `hls::streams` will generally create designs in an FPGA which have high-performance and use few resources because an `hls::stream` enforces a coding style which is ideal for implementation in an FPGA.

Multiple reads of the same data from an `hls::stream` are impossible. Once the data has been read from an `hls::stream` it no longer exists in the stream. This helps remove this coding practice.

If the data from an `hls::stream` is required again, it must be cached. This is another good practice when writing code to be synthesized on an FPGA.

The `hls::stream` forces the C code to be developed in a manner which is ideal for an FPGA implementation.

When an `hls::stream` is synthesized it is automatically implemented as a FIFO channel which is 1 element deep. This is the ideal hardware for connecting pipelined tasks.

There is no requirement to use `hls::streams` and the same implementation can be performed using arrays in the C code. The `hls::stream` construct does help enforce good coding practices. More details on `hls::streams` are provided in [HLS Stream Library in Chapter 2](#).

With an `hls::stream` construct the outline of the new optimized code is as follows:

```
template<typename T, int K>
static void convolution_strm(
    int width,
    int height,
    hls::stream<T> &src,
    hls::stream<T> &dst,
    const T *hcoeff,
    const T *vcoeff)
{
    hls::stream<T> hconv("hconv");
    hls::stream<T> vconv("vconv");
    // These assertions let HLS know the upper bounds of loops
    assert(height < MAX_IMG_ROWS);
    assert(width < MAX_IMG_COLS);
    assert(vconv_xlim < MAX_IMG_COLS - (K - 1));

    // Horizontal convolution
    HConvH:for(int col = 0; col < height; col++) {
        HConvW:for(int row = 0; row < width; row++) {
            HConv:for(int i = 0; i < K; i++) {
            }
        }
    }
    // Vertical convolution
    VConvH:for(int col = 0; col < height; col++) {
        VConvW:for(int row = 0; row < vconv_xlim; row++) {
            VConv:for(int i = 0; i < K; i++) {
            }
        }
    }

    Border:for (int i = 0; i < height; i++) {
        for (int j = 0; j < width; j++) {
        }
    }
}
```

Some noticeable differences compared to the earlier code are:

- The input and output data is now modelled as `hls::streams`.
- Instead of a single local array of size `HEIGHT*WDITH` there are two internal `hls::streams` used to save the output of the horizontal and vertical convolutions.

In addition, some assert statements are used to specify the maximize of loop bounds. This is a good coding style which allows HLS to automatically report on the latencies of variable bounded loops and optimize the loop bounds.

Horizontal Convolution

To perform the calculation in a more efficient manner for FPGA implementation, the horizontal convolution is computed as shown in the following figure.

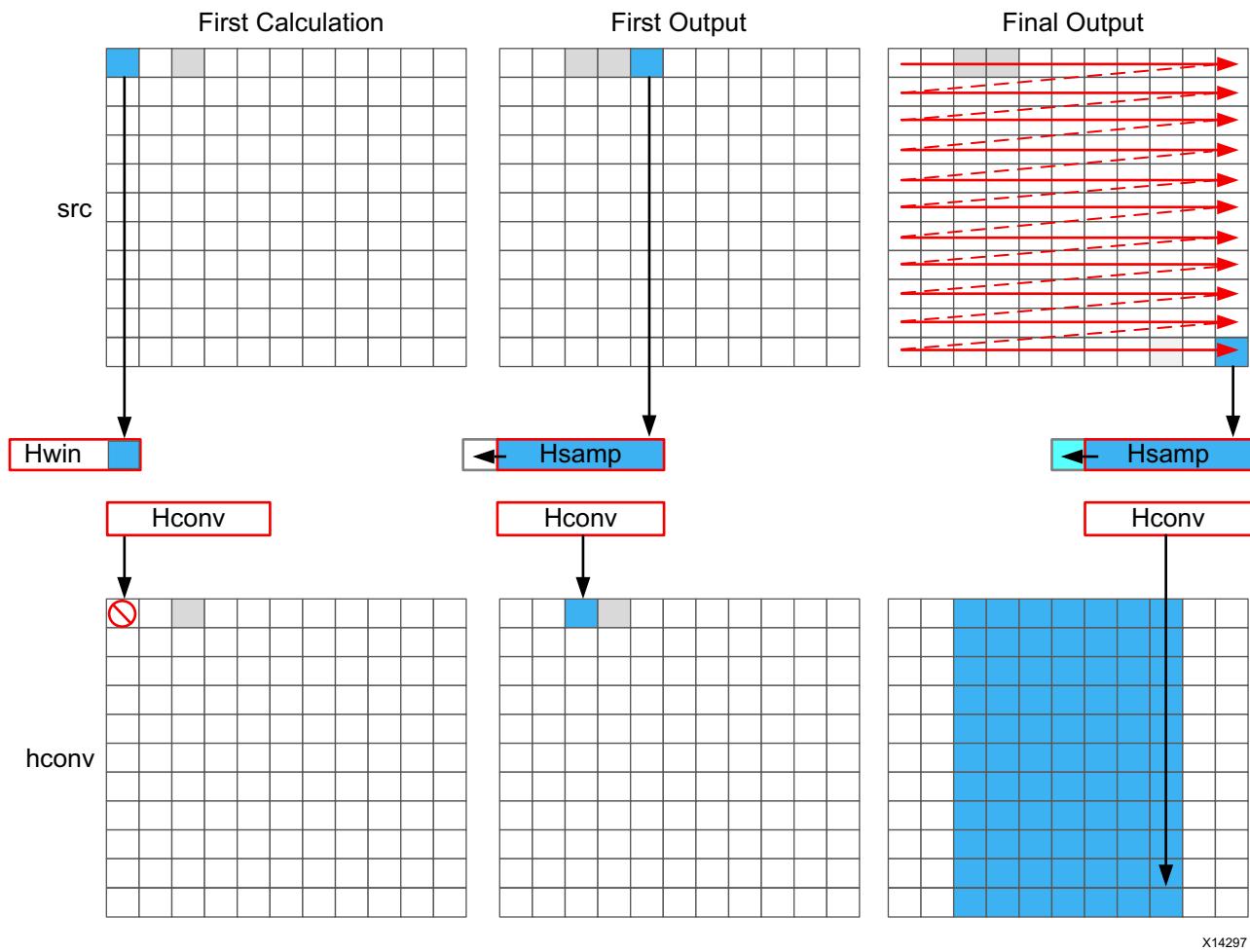


Figure 1-44: Streaming Horizontal Convolution

Using an `hls::stream` enforces the good algorithm practice of forcing you to start by reading the first sample first, as opposed to performing a random access into data. The algorithm must use the K previous samples to compute the convolution result, it therefore copies the sample into a temporary cache `hwin`. For the first calculation there are not enough values in `hwin` to compute a result, so no output values are written.

The algorithm keeps reading input samples and caching them into `hwin`. Each time it reads a new sample, it pushes an unneeded sample out of `hwin`. The first time an output value can be written is after the Kth input has been read. Now an output value can be written.

The algorithm proceeds in this manner along the rows until the final sample has been read. At point, only the last K samples are stored in `hwin`: all that is required to compute the convolution.

The code to perform these operations is shown below.

```
// Horizontal convolution
HConvW::for(int row = 0; row < width; row++) {
    HconvW::for(int row = border_width; row < width - border_width; row++) {
        T in_val = src.read();
        T out_val = 0;
        HConv::for(int i = 0; i < K; i++) {
            hwin[i] = i < K - 1 ? hwin[i + 1] : in_val;
            out_val += hwin[i] * hcoeff[i];
        }
        if (row >= K - 1)
            hconv << out_val;
    }
}
```

An interesting point to note in the code above is use of the temporary variable `out_val` to perform the convolution calculation. This variable is set to zero before the calculation is performed, negating the need to spend 2 million clocks cycle to reset the values, as in the previous example.

Throughout the entire process, the samples in the `src` input are processed in a raster-streaming manner. Every sample is read in turn. The outputs from the task are either discarded or used, but the task keeps constantly computing. This represents a difference from code written to perform on a CPU.

In a CPU architecture, conditional or branch operations are often avoided. When the program needs to branch it loses any instructions stored in the CPU fetch pipeline. In an FPGA architecture, a separate path already exists in the hardware for each conditional branch and there is no performance penalty associated with branching inside a pipelined task. It is simply a case of selecting which branch to use.

The outputs are stored in the `hls::stream` `hconv` for use by the vertical convolution loop.

Vertical Convolution

The vertical convolution represents a challenge to the streaming data model preferred by an FPGA. The data must be accessed by column but you do not wish to store the entire image. The solution is to use line buffers, as shown in the following figure.

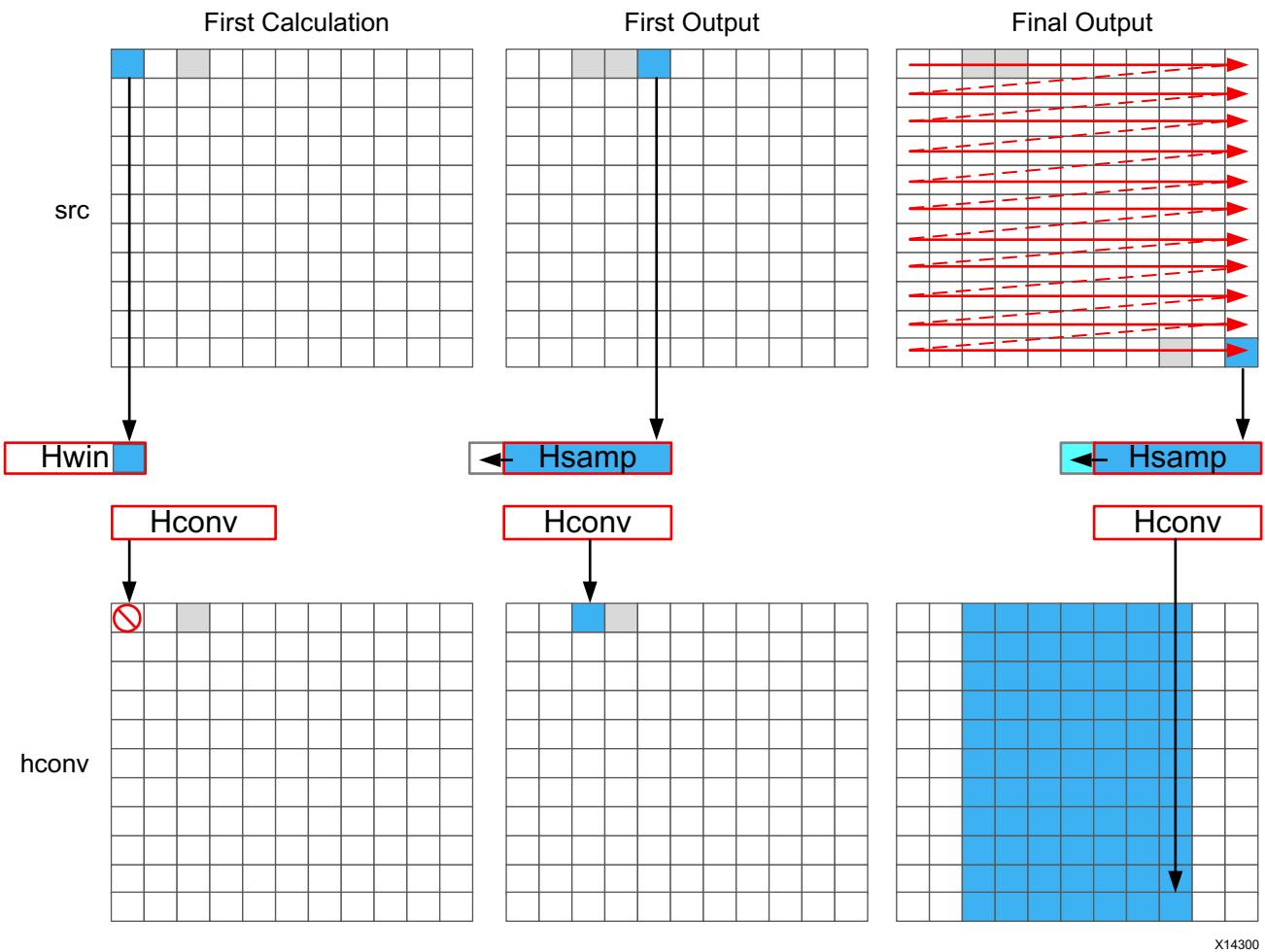


Figure 1-45: Streaming Vertical Convolution

Once again, the samples are read in a streaming manner, this time from the `hls::stream` `hconv`. The algorithm requires at least $K-1$ lines of data before it can process the first sample. All the calculations performed before this are discarded.

A line buffer allows $K-1$ lines of data to be stored. Each time a new sample is read, another sample is pushed out the line buffer. An interesting point to note here is that the newest sample is used in the calculation and then the sample is stored into the line buffer and the old sample ejected out. This ensures only $K-1$ lines are required to be cached, rather than K lines. Although a line buffer does require multiple lines to be stored locally, the convolution kernel size K is always much less than the 1080 lines in a full video image.

The first calculation can be performed when the first sample on the Kth line is read. The algorithm then proceeds to output values until the final pixel is read.

```
// Vertical convolution
VConvH:for(int col = 0; col < height; col++) {
    VConvW:for(int row = 0; row < vconv_xlim; row++) {
#pragma HLS DEPENDENCE variable=linebuf inter false
#pragma HLS PIPELINE
        T in_val = hconv.read();
        T out_val = 0;
        VConv:for(int i = 0; i < K; i++) {
            T vwin_val = i < K - 1 ? linebuf[i][row] : in_val;
            out_val += vwin_val * vcoeff[i];
            if (i > 0)
                linebuf[i - 1][row] = vwin_val;
        }
        if (col >= K - 1)
            vconv << out_val;
    }
}
```

The code above once again process all the samples in the design in a streaming manner. The task is constantly running. The use of the `hls::stream` construct forces you to cache the data locally. This is an ideal strategy when targeting an FPGA.

Border Pixels

The final step in the algorithm is to replicate the edge pixels into the border region. Once again, to ensure the constant flow or data and data reuse the algorithm makes use of an `hls::stream` and caching.

The following figure shows how the border samples are aligned into the image.

- Each sample is read from the `vconv` output from the vertical convolution.
- The sample is then cached as one of 4 possible pixel types.
- The sample is then written to the output stream.

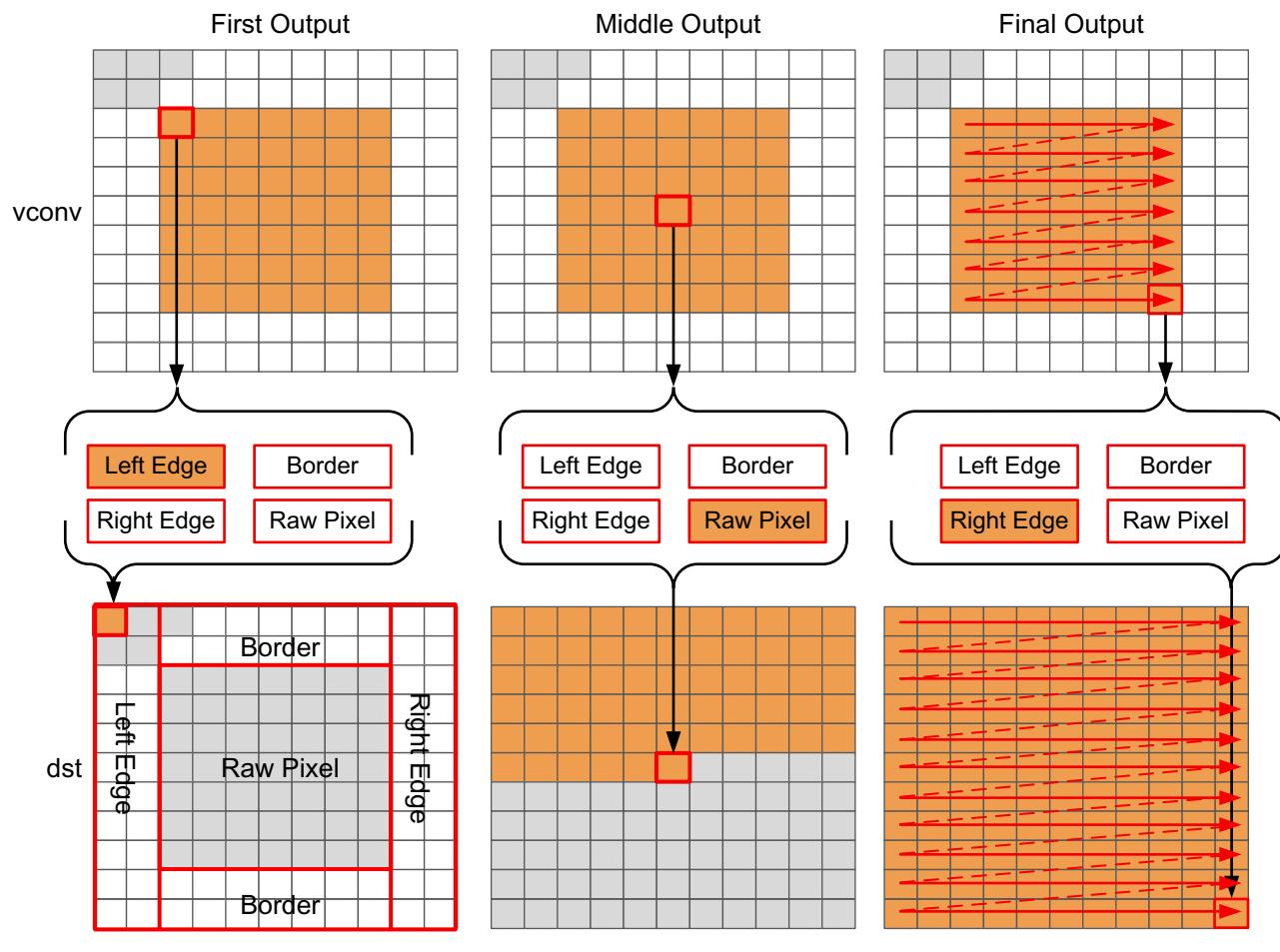


Figure 1-46: Streaming Border Samples

The code for determining the location of the border pixels is:

```

Border:for (int i = 0; i < height; i++) {
    for (int j = 0; j < width; j++) {
        T pix_in, l_edge_pix, r_edge_pix, pix_out;
#pragma HLS PIPELINE
        if (i == 0 || (i > border_width && i < height - border_width)) {
            if (j < width - (K - 1)) {
                pix_in = vconv.read();
                borderbuf[j] = pix_in;
            }
            if (j == 0) {
                l_edge_pix = pix_in;
            }
            if (j == width - K) {
                r_edge_pix = pix_in;
            }
        }
        if (j <= border_width) {
            pix_out = l_edge_pix;
        } else if (j >= width - border_width - 1) {
            pix_out = r_edge_pix;
        } else {
            pix_out = borderbuf[j - border_width];
        }
        dst << pix_out;
    }
}

```

A notable difference with this new code is the extensive use of conditionals inside the tasks. This allows the task, once it is pipelined, to continuously process data and the result of the conditionals does not impact the execution of the pipeline: the result will impact the output values but the pipeline will keep processing so long as input samples are available.

The final code for this FPGA-friendly algorithm has the following optimization directives used.

```

template<typename T, int K>
static void convolution_strm(
    int width,
    int height,
    hls::stream<T> &src,
    hls::stream<T> &dst,
    const T *hcoeff,
    const T *vcoeff)
{
    #pragma HLS DATAFLOW
    #pragma HLS ARRAY_PARTITION variable=linebuf dim=1 complete

    hls::stream<T> hconv("hconv");
    hls::stream<T> vconv("vconv");
    // These assertions let HLS know the upper bounds of loops
    assert(height < MAX_IMG_ROWS);
    assert(width < MAX_IMG_COLS);
    assert(vconv_xlim < MAX_IMG_COLS - (K - 1));

    // Horizontal convolution
    HConvH:for(int col = 0; col < height; col++) {
        HConvW:for(int row = 0; row < width; row++) {
            #pragma HLS PIPELINE
            HConv:for(int i = 0; i < K; i++) {
                }
            }
        }
    // Vertical convolution
    VConvH:for(int col = 0; col < height; col++) {
        VConvW:for(int row = 0; row < vconv_xlim; row++) {
            #pragma HLS PIPELINE
            #pragma HLS DEPENDENCE variable=linebuf inter false
            VConv:for(int i = 0; i < K; i++) {
                }
            }

    Border:for (int i = 0; i < height; i++) {
        for (int j = 0; j < width; j++) {
            #pragma HLS PIPELINE
            }
        }
    }
}

```

Each of the tasks are pipelined at the sample level. The line buffer is full partitioned into registers to ensure there are no read or write limitations due to insufficient block RAM ports. The line buffer also requires a dependence directive. All of the tasks execute in a dataflow region which will ensure the tasks run concurrently. The hls::streams are automatically implemented as FIFOs with 1 element.

Summary of C for Efficient Hardware

Minimize data input reads. Once data has been read into the block it can easily feed many parallel paths but the input ports can be bottlenecks to performance. Read data once and use a local cache if the data must be reused.

Minimize accesses to arrays, especially large arrays. Arrays are implemented in block RAM which like I/O ports only have a limited number of ports and can be bottlenecks to performance. Arrays can be partitioned into smaller arrays and even individual registers but partitioning large arrays will result in many registers being used. Use small localized caches to hold results such as accumulations and then write the final result to the array.

Seek to perform conditional branching inside pipelined tasks rather than conditionally execute tasks, even pipelined tasks. Conditionals will be implemented as separate paths in the pipeline. Allowing the data from one task to flow into with the conditional performed inside the next task will result in a higher performing system.

Minimize output writes for the same reason as input reads: ports are bottlenecks. Replicating addition ports simply pushes the problem further out into the system.

For C code which processes data in a streaming manner, consider using `hls::streams` as these will enforce good coding practices. It is much more productive to design an algorithm in C which will result in a high-performance FPGA implementation than debug why the FPGA is not operating at the performance required.

Use hardware efficient data types to ensure the hardware operators are the optimum size. This topic is covered next.

Data Types for Efficient Hardware

C-based native data types are all on 8-bit boundaries (8, 16, 32, 64 bits). RTL buses (corresponding to hardware) support arbitrary data lengths. Using the standard C data types can result in inefficient hardware. For example the basic multiplication unit in an FPGA is the DSP48 macro. This provides a multiplier which is 18*18-bit. If a 17-bit multiplication is required, you should not be forced to implement this with a 32-bit C data type: this would require 3 DSP48 macros to implement a multiplier when only 1 is required.

The advantage of arbitrary precision data types is that they allow the C code to be updated to use variables with smaller bit-widths and then for the C simulation to be re-executed to validate the functionality remains identical or acceptable. The smaller bit-widths result in hardware operators which are in turn smaller and faster. This in turn allows more logic to be placed in the FPGA and for the logic to execute at higher clock frequencies.

Advantages of Hardware Efficient Data Types

The following code performs some basic arithmetic operations:

```
#include "types.h"

void apint_arith(dinA_t inA, dinB_t inB, dinC_t inC, dinD_t inD,
                  dout1_t *out1, dout2_t *out2, dout3_t *out3, dout4_t *out4
) {

    // Basic arithmetic operations
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = inD % inA;

}
```

The data types `dinA_t`, `dinB_t` etc. are defined in the header file `types.h`. It is highly recommended to use a project wide header file such as `types.h` as this allows for the easy migration from standard C types to arbitrary precision types and helps in refining the arbitrary precision types to the optimal size.

If the data types in the above example are defined as:

```
typedef char dinA_t;
typedef short dinB_t;
typedef int dinC_t;
typedef long long dinD_t;
typedef int dout1_t;
typedef unsigned int dout2_t;
typedef int32_t dout3_t;
typedef int64_t dout4_t;
```

The design gives the following results after synthesis:

```
+ Timing (ns):
 * Summary:
 +-----+-----+-----+-----+
 | Clock | Target| Estimated| Uncertainty|
 +-----+-----+-----+-----+
 | default | 4.00| 3.85| 0.50|
 +-----+-----+-----+-----+

+ Latency (clock cycles):
 * Summary:
 +-----+-----+-----+-----+
 | Latency | Interval | Pipeline|
 | min | max | min | max | Type |
 +-----+-----+-----+-----+
 | 66| 66| 67| 67| none |
 +-----+-----+-----+-----+
 * Summary:
 +-----+-----+-----+-----+-----+
 | Name | BRAM_18K| DSP48E| FF | LUT |
 +-----+-----+-----+-----+
 | Expression | -| -| 0| 17|
 | FIFO | -| -| -| -|
 | Instance | -| 1| 17920| 17152|
 | Memory | -| -| -| -|
 | Multiplexer | -| -| -| -|
 | Register | -| -| 7| -|
 +-----+-----+-----+-----+
 | Total | 0| 1| 17927| 17169|
 +-----+-----+-----+-----+
 | Available | 650| 600| 202800| 101400|
 +-----+-----+-----+-----+
 | Utilization (%) | 0| ~0 | 8| 16|
 +-----+-----+-----+-----+
```

If the width of the data is not required to be implemented using standard C types but in some width which is smaller, but still greater than the next smallest standard C type, such as the following,

```
typedef int6 dinA_t;
typedef int12 dinB_t;
typedef int22 dinC_t;
typedef int33 dinD_t;
typedef int18 dout1_t;
typedef uint13 dout2_t;
typedef int22 dout3_t;
typedef int6 dout4_t;
```

The results after synthesis shown an improvement to the maximum clock frequency, the latency and a significant reduction in area of 75%.

```
+ Timing (ns):
 * Summary:
 +-----+-----+-----+
 | Clock | Target| Estimated| Uncertainty|
 +-----+-----+-----+
 | default | 4.00 | 3.49 | 0.50 |
 +-----+-----+-----+

+ Latency (clock cycles):
 * Summary:
 +-----+-----+-----+
 | Latency | Interval | Pipeline|
 | min | max | min | max | Type |
 +-----+-----+-----+
 | 35 | 35 | 36 | 36 | none |
 +-----+-----+-----+

* Summary:
 +-----+-----+-----+-----+
 | Name | BRAM_18K| DSP48E | FF | LUT |
 +-----+-----+-----+-----+
 | Expression | - | - | 0 | 13 |
 | FIFO | - | - | - | - |
 | Instance | - | 1 | 4764 | 4560 |
 | Memory | - | - | - | - |
 | Multiplexer | - | - | - | - |
 | Register | - | - | 6 | - |
 +-----+-----+-----+-----+
 | Total | 0 | 1 | 4770 | 4573 |
 +-----+-----+-----+-----+
 | Available | 650 | 600 | 202800 | 101400 |
 +-----+-----+-----+-----+
 | Utilization (%) | 0 | ~0 | 2 | 4 |
 +-----+-----+-----+-----+
```

The large difference in latency between both design is due to the division and remainder operations which take multiple cycles to complete. Using accurate data types, rather than force fitting the design into standard C data types, results in a higher quality FPGA implementation: the same accuracy, running faster with less resources.

Overview of Arbitrary Precision Integer Data Types

Vivado HLS provides integer and fixed-point arbitrary precision data types for C, C++ and supports the arbitrary precision data types that are part of SystemC.

Table 1-12: Arbitrary Precision Data Types

Language	Integer Data Type	Required Header
C	[u]int<W> (1024 bits)	#include "ap_cint.h"
C++	ap_[u]int<W> (1024 bits) Can be extended to 32K bits wide.	#include "ap_int.h"
C++	ap_[u]fixed<W,I,Q,O,N>	#include "ap_fixed.h"
System C	sc_[u]int<W> (64 bits) sc_[u]bigint<W> (512 bits)	#include "systemc.h"
System C	sc_[u]fixed<W,I,Q,O,N>	#define SC_INCLUDE_FX [#define SC_FX_EXCLUDE_OTHER] #include "systemc.h"

The header files which define the arbitrary precision types are also provided with Vivado HLS as a stand-alone package with the rights to use them in your own source code. The package, `xilinx_hls_lib_<release_number>.tgz` is provided in the include directory in the Vivado HLS installation are. The package does not include the C arbitrary precision types defined in `ap_cint.h`. These types cannot be used with standard C compilers - only with Vivado HLS.

Arbitrary Precision Integer Types with C

For the C language, the header file `ap_cint.h` defines the arbitrary precision integer data types `[u]int`. To use arbitrary precision integer data types in a C function:

- Add header file `ap_cint.h` to the source code.
- Change the bit types to `intN` or `uintN`, where N is a bit-size from 1 to 1024.

Arbitrary Precision Types with C++

For the C++ language `ap_[u]int` data types the header file `ap_int.h` defines the arbitrary precision integer data type. To use arbitrary precision integer data types in a C++ function:

- Add header file `ap_int.h` to the source code.
- Change the bit types to `ap_int<N>` or `ap_uint<N>`, where N is a bit-size from 1 to 1024.

The following example shows how the header file is added and two variables implemented to use 9-bit integer and 10-bit unsigned integer types:

```
#include ap_int.h

void foo_top (...) {
    ap_int<9> var1;           // 9-bit
    ap_uint<10> var2;         // 10-bit unsigned
```

The default maximum width allowed for `ap_[u]int` data types is 1024 bits. This default may be overridden by defining the macro `AP_INT_MAX_W` with a positive integer value less than or equal to 32768 before inclusion of the `ap_int.h` header file.



CAUTION! *Setting the value of AP_INT_MAX_W too High may cause slow software compile and run times.*

Following is an example of overriding `AP_INT_MAX_W`:

```
#define AP_INT_MAX_W 4096           // Must be defined before next line
#include "ap_int.h"

ap_int<4096> very_wide_var;
```

Arbitrary Precision Types with SystemC

The arbitrary precision types used by SystemC are defined in the `systemc.h` header file that is required to be included in all SystemC designs. The header file includes the SystemC `sc_int<>`, `sc_uint<>`, `sc_bigint<>` and `sc_bignum<>` types.

Overview of Arbitrary Precision Fixed-Point Data Types

Fixed-point data types model the data as an integer and fraction bits. In this example the Vivado HLS `ap_fixed` type is used to define an 18-bit variable with 6 bits representing the numbers above the binary point and 12-bits representing the value below the decimal point. The variable is specified as signed, the quantization mode is set to round to plus infinity. Since the overflow mode is not specified, the default wrap-around mode is used for overflow.

```
#include <ap_fixed.h>
...
ap_fixed<18, 6, AP_RND > my_type;
...
```

When performing calculations where the variables have different number of bits or different precision, the binary point is automatically aligned.

The behavior of the C++/SystemC simulations performed using fixed-point matches the resulting hardware, allowing analysis of the bit-accurate, quantization, and overflow behaviors to be analyzed with fast C-level simulation.

Fixed-point types are a useful replacement for floating point types which require many clock cycle to complete. Unless the entire range of the floating-point type is required, the same accuracy can often be implemented with a fixed-point type resulting in the same accuracy with smaller and faster hardware.

A summary of the `ap_fixed` type identifiers is provided in the following table.

Table 1-13: Fixed-Point Identifier Summary

Identifier	Description	
W	Word length in bits	
I	The number of bits used to represent the integer value (the number of bits above the binary point)	
Q	Quantization mode This dictates the behavior when greater precision is generated than can be defined by smallest fractional bit in the variable used to store the result.	
O	SystemC Types	ap_fixed Types
	SC_RND	AP_RND
	SC_RND_ZERO	AP_RND_ZERO
	SC_RND_MIN_INF	AP_RND_MIN_INF
	AP_RND_INF	AP_RND_INF
	AP_RND_CONV	AP_RND_CONV
	AP_TRN	AP_TRN
	AP_TRN_ZERO	AP_TRN_ZERO
	Truncation to zero (default)	
N	Overflow mode. This dictates the behavior when the result of an operation exceeds the maximum (or minimum in the case of negative numbers) value which can be stored in the result variable.	
	SystemC Types	ap_fixed Types
	SC_SAT	AP_SAT
	SC_SAT_ZERO	AP_SAT_ZERO
	SC_SAT_SYM	AP_SAT_SYM
	SC_WRAP	AP_WRAP
	SC_WRAP_SM	AP_WRAP_SM
Sign magnitude wrap around		

The default maximum width allowed for `ap_[u]fixed` data types is 1024 bits. This default may be overridden by defining the macro `AP_INT_MAX_W` with a positive integer value less than or equal to 32768 before inclusion of the `ap_int.h` header file.



CAUTION! *Setting the value of AP_INT_MAX_W too High may cause slow software compile and run times.*

Following is an example of overriding AP_INT_MAX_W:

```
#define AP_INT_MAX_W 4096           // Must be defined before next line
#include "ap_fixed.h"

ap_fixed<4096> very_wide_var;
```

Arbitrary precision data types are highly recommended when using High-Level Synthesis. As shown in the earlier example, they typically have a significant positive benefit on the quality of the hardware implementation. Complete details on the Vivado HLS arbitrary precision data types are provided in the [Chapter 4, High-Level Synthesis Reference Guide](#).

Using Hardware Optimized C Libraries

Vivado HLS provides a number of C libraries for commonly used C functions. The functions provided in the C libraries are generally pre-optimized to ensure high-performance and result in an efficient implementation for when synthesized.

[Chapter 2, High-Level Synthesis C Libraries](#) provides extensive details on all the C libraries provided with Vivado HLS, however it is highly recommended to have an appreciation of what C functions are available in the C libraries as part of your methodology.

The following C Libraries are provided with Vivado HLS:

- Arbitrary Precision Data Types.
- HLS Stream Library
- Math Functions
- Linear Algebra Functions
- Video Functions
- IP Library

Arbitrary Precision Data Type Libraries

Three C libraries are provided for modelling data types with of any arbitrary width from 1-bit to 1024-bits (and beyond for C++ types). The benefits and uses of these data types are discussed in the previous section. The table below summarizes the libraries provided.

Table 1-14: Arbitrary Precision Data Type Libraries

Library Header File	Description
ap_cin.h	A library of data types for use with C functions which allow variables to be defined using any arbitrary bit size from 1 to 1024.
ap_int.h	A library of data types for use with C++ functions which allow variables to be defined using any arbitrary bit size from 1 to 1024. (And optionally to 32768).
ap_fixeddt.h	A library of data types for use with C++ functions which allow fixed-point variables to be defined using any arbitrary bit size from 1 to 1024. (And optionally to 32768). Fixed-point numbers include a range of integer bits and fractional bits. This data type supports a number of quantization and overflow modes to determine the behavior when for overflow and rounding.

HLS Stream Library

Vivado HLS provides a C++ template class (`hls::stream<>`) for modeling streaming data structures. The streams implemented with the `hls::stream<>` class have the following attributes.

- The values are written or read in strictly sequential order.
- Streams are automatically implemented as efficient internal FIFOs (the default depth of 1 can be over-ridden) or FIFO ports.
- Both block and non-blocking accesses are supported.

Table 1-15: HLS Stream Data Type Libraries

Library Header File	Description
<code>hls_stream.h</code>	Defines the <code>hls::stream</code> C++ class used to model streaming data.

An HLS stream variable is referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "ap_int.h"
#include "hls_stream.h"

typedef ap_uint<128> uint128_t; // 128-bit user defined type
hls::stream<uint128_t> my_wide_stream; // A stream declaration
```

- Using scoped naming:

```
#include "ap_int.h"
#include "hls_stream.h"
using namespace hls; // Namespace specified after the header files

typedef ap_uint<128> uint128_t; // 128-bit user defined type
stream<uint128_t> my_wide_stream; // A stream declaration
```



RECOMMENDED: The recommended coding style is to use the `hls` namespace.

For the purposes of clarity, this document refers to HLS stream objects using the `hls` namespace format. For example, "an `hls::stream` called `stream_in` is used to implement the input data stream".

Details on the advantages of `hls::stream` variables are provided in [Writing Hardware Efficient C Code](#).

Math Functions

Math functions are provided for both floating and fixed-point data types. The key issue to be aware when using math functions is the potential difference in accuracy between the C code and the RTL implementation.

All standard arithmetic operations and some math functions are available as Xilinx IP blocks. Operations which can be synthesized directly into a Xilinx IP block match the C simulation results exactly over the entire dynamic range. For math functions which cannot be directly implemented using a Xilinx IP block, the C Math Library provides a synthesizable implementation of the function. In this case there may be a difference between the C simulation and the RTL implementation. Any difference is noted in the table below in Units of Least Precision (ULP) which specifies the maximum difference in the bits.

When using functions which have a ULP greater than zero, you are highly encouraged to use a smart C test bench which uses an error range to verify the results. Without such a test bench, the results of the C and RTL simulations may differ. Refer to [HLS Math Library in Chapter 2](#).

Not every function supported by the standard C math libraries is provided in the HLS Math Library. Only the math functions shown in the table below are supported for synthesis.

Table 1-16: HLS Math Library

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

Table 1-16: HLS Math Library (Cont'd)

Function	Data Type	Accuracy (ULP)	Implementation Style
copysignf	float	Exact	Synthesized
cos	float	10	Synthesized
	double ap_fixed<32,I>	28-29	Synthesized
cosf	float	1	Synthesized
coshf	float	4	Synthesized
exp	float	Exact	LogiCORE™ IP
	double		
expf	float	Exact	LogiCORE IP
fabs	float	Exact	Synthesized
	double		
fabsf	float	Exact	Synthesized
floorf	float	Exact	Synthesized
fmax	float	Exact	Synthesized
	double		
fmin	float	Exact	Synthesized
	double		
logf	float	1	Synthesized
floor	float	Exact	Synthesized
	double		
fpclassify	float	Exact	Synthesized
	double		
isfinite	float	Exact	Synthesized
	double		
isnan	float	Exact	Synthesized
	double		
isnormal	float	Exact	Synthesized
	double		
log	float	1	Synthesized
	double	16	Synthesized
log10	float	2	Synthesized
	double	3	Synthesized
modf	float	Exact	Synthesized
	double		
modff	float	Exact	Synthesized

Table 1-16: HLS Math Library (Cont'd)

Function	Data Type	Accuracy (ULP)	Implementation Style
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
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

The HLS math functions are referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "hls_math.h"  
  
data_t s = hls::sinf(angle);  
  
• Using scoped naming:  
  
#include "hls_math.h"  
using namespace hls; // Namespace specified after the header files  
  
data_t s = sinf(angle);
```



RECOMMENDED: *The recommended coding style is to use the `hls` namespace.*

Linear Algebra Functions

The HLS Linear Algebra Library provides a number of commonly used linear algebra functions. Since linear algebra functions are used in a wide variety of designs, from those which require high-performance to low throughput designs which require an area efficient implementation, the linear algebra library functions are not pre-optimized for high-performance.

Details on adding performance directives functions from the HLS Linear Algebra Library are provided in [HLS Linear Algebra Library in Chapter 2](#).

The functions in the HLS Linear Algebra Library all use two-dimensional arrays to represent matrices and are listed in the following table.

Table 1-17: HLS Linear Algebra Library

Function	Data Type	Implementation Style
cholesky	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
cholesky_inverse	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
matrix_multiply	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
qrf	float x_complex<float>	Synthesized
qr_inverse	float x_complex<float>	Synthesized
svd	float x_complex<float>	Synthesized

The HLS linear algebra functions are referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "hls_linear_algebra.h"

hls::cholesky(In_Array,Out_Array);
```

- Using scoped naming:

```
#include "hls_linear_algebra.h"
using namespace hls;// Namespace specified after the header files

cholesky(In_Array,Out_Array);
```



RECOMMENDED: *The recommended coding style is to use the `hls` namespace.*

Video Functions

The HLS Video Library provides:

- Xilinx Video data types.
- Data types for creating line buffers and memory windows.
- Video functions compatible with OpenCV library functions.
- Format translation functions for use with the video library functions.

The data types provided in the HLS Video Library are used to ensure the output RTL created by synthesis can be seamlessly integrated with any Xilinx Video IP blocks used in the system. When using any Xilinx Video IP in your system, refer to the IP data sheet and determine the format used to send or receive the video data. Use the appropriate video data type in the C code and the RTL created by synthesis can connect to the Xilinx Video IP. The following data types are provided in the HLS Video Library.

The following table summarizes the data types provided in the HLS Video Library.

Table 1-18: HLS Video Library Data Types

Data Type	Description
yuv422_8	Provides 8-bit Y and U fields
yuv444_8	Provides 8-bit Y, U, and V fields
rgb_8	Provides 8-bit R, G, and B fields
yuva422_8	Provides 8-bit Y, UV, and A fields
yuva444_8	Provides 8-bit Y, U, V, and A fields
rgba_8	Provides 8-bit R, G, B, and A fields
yuva420_8	Provides 8-bit Y and AUV fields
yuvd422_8	Provides 8-bit Y, UV, and D fields
yuvd444_8	Provides 8-bit Y, U, V, and D fields
rgbd_8	Provides 8-bit R, G, B, and D fields
bayer_8	Provides 8-bit RGB field
luma_8	Provides 8-bit Y field
LineBuffer<type,rows,cols>	Defines a line buffer of the specified data type with methods for data access
Window<type,rows,cols>	Defines a two dimensional memory window of the specified data type with methods for data access

The video processing functions included in the HLS Video library are compatible with existing OpenCV functions and are similarly named. They do not directly replace existing OpenCV video library functions. The video processing functions use a data type `hls::Mat`. This data type allows the functions to be synthesized and implemented as high performance hardware.

Three types of functions are provided in the HLS Video Library:

- Video Processing Functions: Compatible with standard OpenCV functions for manipulating and processing video images. These functions use the `hls::mat` data type and are synthesized by Vivado HLS.
- AXI4-Stream Functions: These functions are used to convert the video data specified in `hls::mat` data types into an AXI4 streaming data type. This AXI4 streaming data type is used as arguments to the function to be synthesized, to ensure a high-performance interface is synthesized.
- OpenCV Interface Functions: Converts data to and from the AXI4 streaming data type to and from the standard OpenCV data types. These functions allow any OpenCV functions executed in software to transfer data, via the AXI4 streaming functions, to and from the hardware block created by HLS.

All three function types allow the seamless transfer of data between a CPU and the synthesized hardware. The table below summarizes the functions provided in the HLS Video Library.

Table 1-19: HLS Video Library

Function Type	Function	Accuracy (ULP)
OpenCV Interface	<code>AXIvideo2cvMat</code>	Converts data from AXI4 video stream (<code>hls::stream</code>) format to OpenCV <code>cv::Mat</code> format
OpenCV Interface	<code>AXIvideo2CvMat</code>	Converts data from AXI4 video stream (<code>hls::stream</code>) format to OpenCV <code>CvMat</code> format
OpenCV Interface	<code>AXIvideo2IplImage</code>	Converts data from AXI4 video stream (<code>hls::stream</code>) format to OpenCV <code>IplImage</code> format
OpenCV Interface	<code>cvMat2AXIvideo</code>	Converts data from OpenCV <code>cv::Mat</code> format to AXI4 video stream (<code>hls::stream</code>) format
OpenCV Interface	<code>CvMat2AXIvideo</code>	Converts data from OpenCV <code>CvMat</code> format to AXI4 video stream (<code>hls::stream</code>) format
OpenCV Interface	<code>cvMat2hlsMat</code>	Converts data from OpenCV <code>cv::Mat</code> format to <code>hls::Mat</code> format
OpenCV Interface	<code>CvMat2hlsMat</code>	Converts data from OpenCV <code>CvMat</code> format to <code>hls::Mat</code> format
OpenCV Interface	<code>CvMat2hlsWindow</code>	Converts data from OpenCV <code>CvMat</code> format to <code>hls::Window</code> format
OpenCV Interface	<code>hlsMat2cvMat</code>	Converts data from <code>hls::Mat</code> format to OpenCV <code>cv::Mat</code> format
OpenCV Interface	<code>hlsMat2CvMat</code>	Converts data from <code>hls::Mat</code> format to OpenCV <code>CvMat</code> format
OpenCV Interface	<code>hlsMat2IplImage</code>	Converts data from <code>hls::Mat</code> format to OpenCV <code>IplImage</code> format
OpenCV Interface	<code>hlsWindow2CvMat</code>	Converts data from <code>hls::Window</code> format to OpenCV <code>CvMat</code> format

Table 1-19: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
OpenCV Interface	IplImage2AXIvideo	Converts data from OpenCV IplImage format to AXI4 video stream (hls::stream) format
OpenCV Interface	IplImage2hlsMat	Converts data from OpenCV IplImage format to hls::Mat format
AXI4-Stream	AXIvideo2Mat	Converts image data stored in hls::Mat format to an AXI4 video stream (hls::stream) format
AXI4-Stream	Mat2AXIvideo	Converts image data stored in AXI4 video stream (hls::stream) format to an image of hls::Mat format
Video Processing	AbsDiff	Computes the absolute difference between two input images src1 and src2 and saves the result in dst
Video Processing	AddS	Computes the per-element sum of an image src and a scalar scl
Video Processing	AddWeighted	Computes the weighted per-element sum of two image src1 and src2
Video Processing	And	Calculates the per-element bit-wise logical conjunction of two images src1 and src2
Video Processing	Avg	Calculates an average of elements in image src
Video Processing	AvgSdv	Calculates an average of elements in image src
Video Processing	Cmp	Performs the per-element comparison of two input images src1 and src2
Video Processing	CmpS	Performs the comparison between the elements of input images src and the input value and saves the result in dst
Video Processing	CornerHarris	This function implements a Harris edge/corner detector
Video Processing	CvtColor	Converts a color image from or to a grayscale image
Video Processing	Dilate	Dilates the image src using the specified structuring element constructed within the kernel
Video Processing	Duplicate	Copies the input image src to two output images dst1 and dst2, for divergent point of two data paths
Video Processing	EqualizeHist	Computes a histogram of each frame and uses it to normalize the range of the following frame
Video Processing	Erode	Erodes the image src using the specified structuring element constructed within kernel
Video Processing	FASTX	Implements the FAST corner detector, generating either a mask of corners, or an array of coordinates
Video Processing	Filter2D	Applies an arbitrary linear filter to the image src using the specified kernel
Video Processing	GaussianBlur	Applies a normalized 2D Gaussian Blur filter to the input

Table 1-19: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
Video Processing	Harris	This function implements a Harris edge or corner detector
Video Processing	HoughLines2	Implements the Hough line transform
Video Processing	Integral	Implements the computation of an integral image
Video Processing	InitUndistortRectifyMap	Generates map1 and map2, based on a set of parameters, where map1 and map2 are suitable inputs for hls::Remap()
Video Processing	Max	Calculates per-element maximum of two input images src1 and src2 and saves the result in dst
Video Processing	MaxS	Calculates the maximum between the elements of input images src and the input value and saves the result in dst
Video Processing	Mean	Calculates an average of elements in image src, and return the value of first channel of result scalar
Video Processing	Merge	Composes a multi-channel image dst from several single-channel images
Video Processing	Min	Calculates per-element minimum of two input images src1 and src2 and saves the result in dst
Video Processing	MinMaxLoc	Finds the global minimum and maximum and their locations in input image src
Video Processing	MinS	Calculates the minimum between the elements of input images src and the input value and saves the result in dst
Video Processing	Mul	Calculates the per-element product of two input images src1 and src2
Video Processing	Not	Performs per-element bit-wise inversion of image src
Video Processing	PaintMask	Each pixel of the destination image is either set to color (if mask is not zero) or the corresponding pixel from the input image
Video Processing	PyrDown	Blurs the image and then reduces the size by a factor of 2.
Video Processing	PyrUp	Upsamples the image by a factor of 2 and then blurs the image.
Video Processing	Range	Sets all value in image src by the following rule and return the result as image dst
Video Processing	Remap	Remaps the source image src to the destination image dst according to the given remapping
Video Processing	Reduce	Reduces 2D image src along dimension dim to a vector dst
Video Processing	Resize	Resizes the input image to the size of the output image using bilinear interpolation

Table 1-19: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
Video Processing	Set	Sets elements in image src to a given scalar value scl
Video Processing	Scale	Converts an input image src with optional linear transformation
Video Processing	Sobel	Computes a horizontal or vertical Sobel filter, returning an estimate of the horizontal or vertical derivative, using a filter
Video Processing	Split	Divides a multi-channel image src from several single-channel images
Video Processing	SubRS	Computes the differences between scalar value scl and elements of image src
Video Processing	SubS	Computes the differences between elements of image src and scalar value scl
Video Processing	Sum	Sums the elements of an image
Video Processing	Threshold	Performs a fixed-level threshold to each element in a single-channel image
Video Processing	Zero	Sets elements in image src to 0

The HLS video data types and functions are referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "hls_video.h"

hls::rgb_8 video_data[1920][1080]
hls::LineBuffer<char,3,5> Buff_A;
hls::Scale(img_2, img_3, 2, 0);

• Using scoped naming:

#include "hls_linear_algebra.h"
using namespace hls; // Namespace specified after the header files

rgb_8 video_data[1920][1080]
LineBuffer<char,3,5> Buff_A;
Scale(img_2, img_3, 2, 0);
```



RECOMMENDED: *The recommended coding style is to use the `hls` namespace.*

IP Library

Vivado HLS can take advantage of the high-performance Xilinx IP when synthesizing into an FPGA. The table below lists the C libraries and Xilinx IP which can be directly inferred from C code.

The following table summarizes the libraries provided.

Table 1-20: Arbitrary Precision Data Type Libraries

Library Header File	Description
<code>hls_fft.h</code>	Allows the Xilinx LogiCORE IP FFT to be simulated in C and implemented using the Xilinx LogiCORE block.
<code>hls_fir.h</code>	Allows the Xilinx LogiCORE IP FIR to be simulated in C and implemented using the Xilinx LogiCORE block.
<code>ap_shift_reg.h</code>	Provides a C++ class to implement a shift register which is implemented directly using a Xilinx SRL primitive.

The Xilinx FFT and FIR IP are referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "hls_fft.h"
#include "hls_fir.h"

//Call the FFT Function
hls::fft<param1> (xn1, xk1, &fft_status1, &fft_config1);
// Create an instance of the FIR
static hls::FIR<STATIC_PARAM> fir1;
```

- Using scoped naming:

```
#include "hls_fft.h"
#include "hls_fir.h"
using namespace hls;// Namespace specified after the header files

//Call the FFT Function
fft<param1> (xn1, xk1, &fft_status1, &fft_config1);
// Create an instance of the FIR
static FIR<STATIC_PARAM> fir1;
```



RECOMMENDED: *The recommended coding style is to use the `hls` namespace.*

The shift register class can be directly used without reference to the `hls` namespace.

Design Analysis and Optimization

The final part of any design methodology is using a productive process for design analysis and improvement. The process for using Vivado HLS for C simulation, C debug, synthesis, analysis, RTL verification and IP packaging is described in [Using Vivado HLS](#). The process for creating and improving the design performance can be summarized as:

- Simulate the C code and validate the algorithm is correct.
- Synthesize an initial design.
- Analyze the design performance.
- Create a new solution and add optimization directives.
- Analyze the performance of the new solution
- Continue creating new solutions and optimization directives until the requirements are satisfied.
- Verify the RTL is correct.
- Package the design as IP and include it into your system.

The most productive methodology is one that uses C simulation to both validate the algorithm and confirm the results are correct before synthesis. The benefit of C simulation

speed is one of the major advantages of a High-Level Synthesis design flow. Confirming the correctness of the C design is a much more productive use of your time than debugging performance issues which turn out to be due an incorrect specification.

Ensuring Useful Reports

After the initial synthesis results are achieved, the first step is to review the results. If the synthesis report contains any unknown values (shown as a question mark "?") they must be addressed. To determine if optimization directives improve the design performance, it is crucial to be able to compare the solutions: the latency must have known values for comparison.

If a loop has variable bounds, Vivado HLS cannot determine the number of iterations for the loop to complete. Even if the latency of one iteration of the loop is known, it cannot determine the latency to complete all iterations of the loop due to the variable bounds.

Review the loops in the design. In the synthesis report, review the loops in the **Latency > Details > Loops** section. Start with the lowest level loop in the loop hierarchy which reports an unknown latency as this unknown propagates up the hierarchy. The loop or loops may be in lower levels of hierarchy. Review the **Latency > Details > Instance** section of the report to determine if any sub-functions shown unknown values. Open the report for any functions which show an unknown latency values and repeat the process until the loop or loops have been identified.

An alternative to the synthesis report is to use the Analysis perspective.

After you identify the variable bound loops, add a LOOP_TRIPCOUNT directive to specify the loop iteration count, or use assertions in the C code to specify the limits. For more information, see [Assertions in Chapter 3](#). If you are using the LOOP_TRIPCOUNT directive, consider adding the directive to the source code as a pragma, because this directive is required in every solution.

If you are aware of other loops with variables bounds, provide iteration limits for these loops, otherwise repeat synthesis and use the same bottom up process until the top-level report contains real numbers.

Design Analysis

Design analysis can be performed using three different techniques.

- The synthesis reports.
- The analysis perspective.
- RTL simulation waveforms.



TIP: Before analyzing the results, review the console window or log file to see what optimizations where performed, skipped or failed.

The synthesis reports and analysis perspective can be used to analyze the latency, interval and resource estimates. If there is now more than one solution, use the compare reports button in the GUI to compare the solutions side-by-side. This feature, like the analysis perspective, is only available in the GUI but remember that projects created using batch-mode can be opened for analysis in the GUI using `vivado_hls -p project_name`.

Again, a hierarchical approach is useful. Start at the top-level and determine which tasks contribute the most to either then latency, interval or area and examine those tasks in more detail. Recursively move down the hierarchy until you find a loop or function which you think could or should be performing better to achieve your goals. When these function or loops are improved, the improvements will ripple up the hierarchy.

The analysis perspective allows for much easier migration up and down the design hierarchy than the synthesis reports. In addition the analysis perspective provides a detailed view of the scheduled operations and resource usage which can be cross-correlated with the C code. Refer to the Design Analysis and Design Optimization tutorials in [Table 1-4](#) for more details on using the analysis perspective.

It can be useful when using the detailed schedule views in the analysis perspective to first look at the macro-level behavior before diving into the details. The operations are typically listed in the order the code executes. Keep in mind, Vivado HLS will try to schedule everything into clock cycle 1 and be finished in 1 clock cycle if it can.

- If you see a general drift in the operations from the top-left to the bottom-right, it is probably due to data dependencies or the execution of tasks inherent in the code. Each needs the operation before to complete before it can start.
- If you see operations scheduled one after then other, then the sudden execution of many items in parallel, or vice-versa, it probably indicates a bottleneck (such as I/O ports or RAM ports) where the design has to wait, and wait, then everything can execute in parallel.

In addition to the synthesis reports and analysis perspective, the RTL simulation waveforms can be used to help analyze the design. During RTL verification the trace files can be saved and viewed using an appropriate viewer. Refer to the tutorial on RTL verification in [Table 1-4](#) for more details. Alternatively, export the IP package and open the Vivado RTL project in the `project_name/solution_name/impl/ip/verilog` or `vhdl` folder. If C/RTL co-simulation has been executed, this project will contain an RTL test bench.

Be very careful investing time in using the RTL for design analysis. If you change the C code or add an optimization directive you will likely get a very different RTL design with very different names when synthesize is re-executed. Any time spent in understanding the RTL details will likely need repeated every time a new design is generated and very different names and structures are used.

In summary, work down the hierarchy to identify tasks which could be further optimized.

Design Optimizations

Before performing any optimizations it is recommended to create a new solution within the project. Solutions allow one set of results to be compared against a different set of results. They allow you to compare not only the results, but also the log files and even output RTL files.

The basic optimization strategy for a high-performance design is:

- Create an initial or baseline design.
- Pipeline the loops and functions.
- Address any issues which limit pipelining, such as array bottlenecks and loop dependencies (with ARRAY_PARTITION and DEPENDENCE directives).
- Apply the DATAFLOW optimization to execute loops and functions concurrently.
- It may sometimes be necessary to make adjustments to the code to meet performance.
- Reduce the size of the dataflow memory channels and use the ALLOCATION and RESOURCES directives to further reduce area.

In summary, the goal is to always meet performance first, before reducing area. If the strategy is to create a design with fewer resources, then simply omit the steps to improving performance.

Throughout the optimization process it is highly recommended to review the console output (or log file) after synthesis. When Vivado HLS cannot reach the specified performance goals of an optimization, it will automatically relax the goals (except the clock frequency) and create a design with the goals which can be satisfied. It is important to review the output from the synthesis to understand what optimizations have been performed.

For specific details on applying optimizations, refer to the following:

- Details on applying optimizations and using Tcl directives or C code pragmas are provided in [Applying Optimization Directives](#).
- Details on where to apply optimization directives to achieve performance are provided in [Synthesis Strategies](#).
- Detailed explanations of the optimizations are provided in [Design Optimization](#).

Improving Run-Time and Capacity

If the issue is with C/RTL co-simulation, refer to the `reduce_diskspace` option discussed in [RTL Verification](#). The remainder of this section reviews issues with synthesis run-time.

Vivado HLS schedules operations hierarchically. The operations within a loop are scheduled, then the loop, the sub-functions and operations with a function are scheduled. Run time for High-Level Synthesis increases when:

- There are more objects to schedule.
- There is more freedom and more possibilities to explore.

Vivado HLS schedules objects. Whether the object is a floating-point multiply operation or a single register, it is still an object to be scheduled. The floating-point multiply may take multiple cycles to complete and use many resources to implement but at the level of scheduling it is still one object.

Unrolling loops and partitioning arrays creates more objects to schedule and potentially increases the run time. Inlining functions creates more objects to schedule at this level of hierarchy and also increases run time. These optimizations may be required to meet performance but be very careful about simply partitioning all arrays, unrolling all loops and inlining all functions: you can expect a run time increase. Use the optimization strategies provided earlier and judiciously apply these optimizations.

If the arrays must be partitioned to achieve performance, consider using the `throughput_driven` option for `config_array_partition` to only partition the arrays based on throughput requirements.

If the loops must be unrolled, or if the use of the `PIPELINE` directive in the hierarchy above has automatically unrolled the loops, consider capturing the loop body as a separate function. This will capture all the logic into one function instead of creating multiple copies of the logic when the loop is unrolled: one set of objects in a defined hierarchy will be scheduled faster. Remember to pipeline this function if the unrolled loop is used in pipelined region.

The degrees of freedom in the code can also impact run time. Consider Vivado HLS to be an expert designer who by default is given the task of finding the design with the highest throughput, lowest latency and minimum area. The more constrained High-Level Synthesis is, the fewer options it has to explore and the faster it will run. Consider using latency constraints over scopes within the code: loops, functions or regions. Setting a `LATENCY` directive with the same minimum and maximum values reduces the possible optimization searches within that scope.

Finally, the `config_schedule` configuration controls the effort level used during scheduling. This generally has less impact than the techniques mentioned above, but it is worth considering. The default strategy is set to `Medium`.

If this setting is set to `Low`, Vivado HLS will reduce the amount of time it spends on trying to improve on the initial result. In some cases, especially if there are many operations and hence combinations to explore, it may be worth using the low setting. The design may not be ideal but it may satisfy the requirements and be very close to the ideal. You can proceed

to make progress with the low setting and then use the default setting before you create your final result.

With a run strategy set to High, High-Level Synthesis uses additional CPU cycles and memory, even after satisfying the constraints, to determine if it can create an even smaller or faster design. This exploration may, or may not, result in a better quality design but it does take more time and memory to complete. For designs that are just failing to meet their goals or for designs where many different optimization combinations are possible, this could be a useful strategy. In general, it is a better practice to leave the run strategies at the Medium default setting.

Managing Interfaces

In C based design, all input and output operations are performed, in zero time, through formal function arguments. In an RTL design these same input and output operations must be performed through a port in the design interface and typically operates using a specific I/O (input-output) protocol.

Vivado HLS supports two solutions for specifying the type of I/O protocol used:

- Interface Synthesis, where the port interface is created based on efficient industry standard interfaces.
- Manual interface specification where the interface behavior is explicitly described in the input source code. This allows any arbitrary I/O protocol to be used.
 - This solution is provided through SystemC designs, where the I/O control signals are specified in the interface declaration and their behavior specified in the code.
 - Vivado HLS also supports this mode of interface specification for C and C++ designs.

Interface Synthesis

When the top-level function is synthesized, the arguments (or parameters) to the function are synthesized into RTL ports. This process is called *interface synthesis*.

Interface Synthesis Overview

The following code provides a comprehensive overview of interface synthesis. #include sum_io.h

```
dout_t sum_io(din_t in1, din_t in2, dio_t *sum) {
    dout_t temp;
    *sum = in1 + in2 + *sum;
    temp = in1 + in2;
    return temp;
}
```

This example above includes:

- Two pass-by-value inputs `in1` and `in2`.
- A pointer `sum` that is both read from and written to.
- A function `return`, the value of `temp`.

With the default interface synthesis settings, the design is synthesized into an RTL block with the ports shown in the following figure.

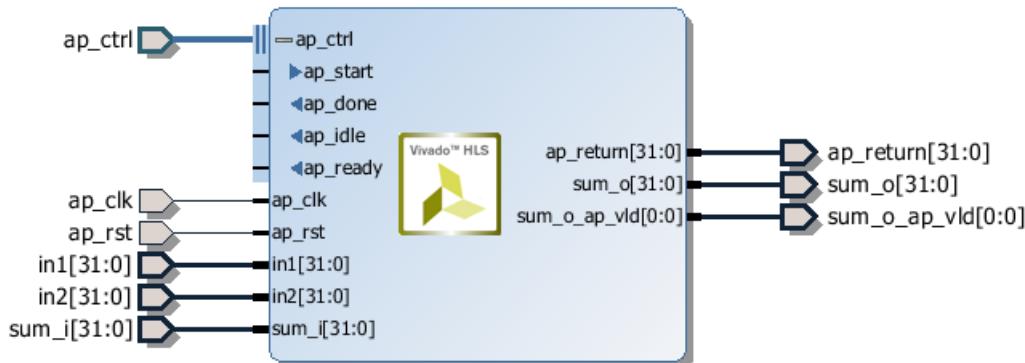


Figure 1-47: RTL Ports After Default Interface Synthesis

Vivado HLS creates three types of ports on the RTL design:

- Clock and Reset ports: `ap_clk` and `ap_rst`.
- Block-Level interface protocol. These are shown expanded in the preceding figure: `ap_start`, `ap_done`, `ap_ready`, and `ap_idle`.
- Port Level interface protocols. These are created for each argument in the top-level function and the function return (if the function returns a value). In this example, these ports are: `in1`, `in2`, `sum_i`, `sum_o`, `sum_o_ap_vld`, and `ap_return`.

Clock and Reset Ports

If the design takes more than 1 cycle to complete operation.

A chip-enable port can optionally be added to the entire block using **Solution > Solution Settings > General** and `config_interface` configuration.

The operation of the reset is controlled by the `config_rtl` configuration. More details on the reset configuration are provided in [Clock, Reset, and RTL Output](#).

Block-Level Interface Protocol

By default, a block-level interface protocol is added to the design. These signal control the block, independently of any port-level I/O protocols. These ports control when the block can start processing data (`ap_start`), indicate when it is ready to accept new inputs (`ap_ready`) and indicate if the design is idle (`ap_idle`) or has completed operation (`ap_done`).

Port-Level Interface Protocol

The final group of signals are the data ports. The I/O protocol created depends on the type of C argument and on the default. A complete list of all possible I/O protocols is shown in [Figure 1-49](#). After the block-level protocol has been used to start the operation of the block, the port-level IO protocols are used to sequence data into and out of the block.

By default input pass-by-value arguments and pointers are implemented as simple wire ports with no associated handshaking signal. In the above example, the input ports are therefore implemented without an I/O protocol, only a data port. If the port has no I/O protocol, (by default or by design) the input data must be held stable until it is read.

By default output pointers are implemented with an associated output valid signal to indicate when the output data is valid. In the above example, the output port is implemented with an associated output valid port (`sum_o_ap_vld`) which indicates when the data on the port is valid and can be read. If there is no I/O protocol associated with the output port, it is difficult to know when to read the data. It is always a good idea to use an I/O protocol on an output.

Function arguments which are both read from and writes to are split into separate input and output ports. In the above example, `sum` is implemented as input port `sum_i` and output port `sum_o` with associated I/O protocol port `sum_o_ap_vld`.

If the function has a return value, an output port `ap_return` is implemented to provide the return value. When the design completes one transaction - this is equivalent to one execution of the C function - the block-level protocols indicate the function is complete with the `ap_done` signal. This also indicates the data on port `ap_return` is valid and can be read.

Note: The return value to the top-level function cannot be a pointer.

For the example code shown the timing behavior is shown in the following figure (assuming that the target technology and clock frequency allow a single addition per clock cycle).

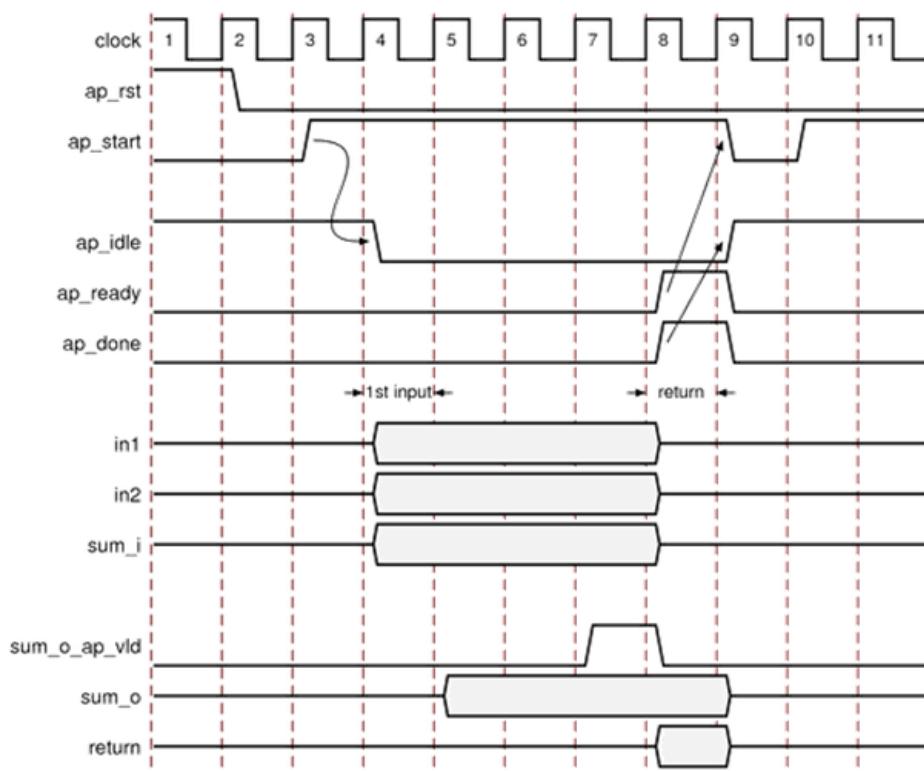


Figure 1-48: RTL Port Timing with Default Synthesis

- The design starts when `ap_start` is asserted High.
- The `ap_idle` signal is asserted Low to indicate the design is operating.
- The input data is read at any clock after the first cycle. Vivado HLS schedules when the reads occur. The `ap_ready` signal is asserted high when all inputs have been read.
- When output `sum` is calculated, the associated output handshake (`sum_o_ap_vld`) indicates that the data is valid.
- When the function completes, `ap_done` is asserted. This also indicates that the data on `ap_return` is valid.
- Port `ap_idle` is asserted High to indicate that the design is waiting start again.

Interface Synthesis I/O Protocols

The type of interfaces that are created by interface synthesis depend on the type of C argument, the default interface mode, and the INTERFACE optimization directive. The following figure shows the interface protocol mode you can specify on each type of C argument. This figure uses the following abbreviations:

- **D**: Default interface mode for each type.
Note: If you specify an illegal interface, Vivado HLS issues a message and implements the default interface mode.
- **I**: Input arguments, which are only read.
- **O**: Output arguments, which are only written to.
- **I/O**: Input/Output arguments, which are both read and written.

Argument Type	Scalar		Array			Pointer or Reference		
	Input	Return	I	I/O	O	I	I/O	O
Interface Mode								
ap_ctrl_none								
ap_ctrl_hs		D						
ap_ctrl_chain								
axis								
s_axilite								
m_axi								
ap_none	D					D		
ap_stable								
ap_ack								
ap_vld							D	
ap_ovld							D	
ap_hs								
ap_memory			D	D	D			
bram								
ap_fifo								
ap_bus								

Supported D = Default Interface
 Not Supported

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Figure 1-49: Data Type and Interface Synthesis Support

Full details on the interfaces protocols, including waveform diagrams, are included in [Interface Synthesis Reference in Chapter 4](#). The following provides an overview of each interface mode.

Block-Level Interface Protocols

The block-level interface protocols are ap_ctrl_none, ap_ctrl_hs, and ap_ctrl_chain. These are specified, and can only be specified, on the function or the function return. When the directive is specified in the GUI it will apply these protocols to the function return. Even if the function does not use a return value, the block-level protocol may be specified on the function return.

The ap_ctrl_hs mode described in the previous example is the default protocol. The ap_ctrl_chain protocol is similar to ap_ctrl_hs but has an additional input port ap_continue which provides back-pressure from blocks consuming the data from this block. If the ap_continue port is logic 0 when the function completes, the block will halt

operation and the next transaction will not proceed. The next transaction will only proceed when the `ap_continue` is asserted to logic 1.

The `ap_ctrl_none` mode implements the design without any block-level I/O protocol.

If the function return is also specified as an AXI4-Lite interface (`s_axilite`) all the ports in the block-level interface are grouped into the AXI4-Lite interface. This is a common practice when another device, such as a CPU, is used to configure and control when this block starts and stops operation.

Port-Level Interface Protocols: AXI4 Interfaces

The AXI4 interfaces supported by Vivado HLS include the AXI4-Stream (`axis`), AXI4-Lite (`s_axilite`), and AXI4 master (`m_axi`) interfaces, which you can specify as follows:

- AXI4-Stream interface: Specify on input arguments or output arguments only, not on input/output arguments.
- AXI4-Lite interface: Specify on any type of argument except arrays. You can group multiple arguments into the same AXI4-Lite interface.
- AXI4 master interface: Specify on arrays and pointers (and references in C++) only. You can group multiple arguments into the same AXI4-Lite interface.

For information on additional functionality provided by the AXI4 interface, see [Using AXI4 Interfaces](#).

Port-Level Interface Protocols: No I/O Protocol

The `ap_none` and `ap_stable` modes specify that no I/O protocol be added to the port. When these modes are specified the argument is implemented as a data port with no other associated signals. The `ap_none` mode is the default for scalar inputs. The `ap_stable` mode is intended for configuration inputs which only change when the device is in reset mode.

Port-Level Interface Protocols: Wire Handshakes

Interface mode `ap_hs` includes a two-way handshake signal with the data port. The handshake is an industry standard valid and acknowledge handshake. Mode `ap_vld` is the same but only has a valid port and `ap_ack` only has a acknowledge port.

Mode `ap_ovld` is for use with in-out arguments. When the in-out is split into separate input and output ports, mode `ap_none` is applied to the input port and `ap_vld` applied to the output port. This is the default for pointer arguments which are both read and written.

The `ap_hs` mode can be applied to arrays which are read or written in sequential order. If Vivado HLS can determine the read or write accesses are not sequential it will halt synthesis with an error. If the access order cannot be determined Vivado HLS will issue a warning.

Port-Level Interface Protocols: Memory Interfaces

Array arguments are implemented by default as an `ap_memory` interface. This is a standard block RAM interface with data, address, chip-enable and write-enable ports.

An `ap_memory` interface may be implemented as a single-port or dual-port interface. If Vivado HLS can determine that using a dual-port interface will reduce the initial interval it will automatically implement a dual-port interface. The `RESOURC` directive is used to specify the memory resource and if this directive is specified on the array with a single-port block RAM, a single-port interface will be implemented. Conversely, if a dual-port interface is specified using the `RESOURCE` directive and Vivado HLS determines this interface provides no benefit it will automatically implement a single-port interface.

The `bram` interface mode is functional identical to the `ap_memory` interface. The only difference is how the ports are implemented when the design is used in Vivado IP Integrator:

- An `ap_memory` interface is displayed as multiple and separate ports.
- A `bram` interface is displayed as a single grouped port which can be connected to a Xilinx block RAM using a single point-to-point connection.

If the array is accessed in a sequential manner an `ap_fifo` interface can be used. As with the `ap_hs` interface, Vivado HLS will halt if determines the data access is not sequential, report a warning if it cannot determine if the access is sequential or issue no message if it determines the access is sequential. The `ap_fifo` interface can only be used for reading or writing, not both.

The `ap_bus` interface can communicate with a bus bridge. The interface does not adhere to any specific bus standard but is generic enough to be used with a bus bridge that in-turn arbitrates with the system bus. The bus bridge must be able to cache all burst writes.

Interface Synthesis and Structs

Structs on the interface are by default de-composed into their member elements and ports are implemented separately for each member element. Each member element of the struct will be implemented, in the absence of any INTERFACE directive, as shown in [Figure 1-49](#).

Arrays of structs are implemented as multiple arrays, with a separate array for each member of the struct.

The DATA_PACK optimization directive is used for packing all the elements of a struct into a single wide vector. This allows all members of the struct to be read and written to simultaneously. The member elements of the struct are placed into the vector in the order they appear in the C code: the first element of the struct is aligned on the LSB of the vector and the final element of the struct is aligned with the MSB of the vector. Any arrays in the struct are partitioned into individual array elements and placed in the vector from lowest to highest, in order.

Care should be taken when using the DATA_PACK optimization on structs with large arrays. If an array has 4096 elements of type `int`, this will result in a vector (and port) of width $4096 \times 32 = 131072$ bits. Vivado HLS can create this RTL design, however it is very unlikely logic synthesis will be able to route this during the FPGA implementation.

If a struct port using DATA_PACK is to be implemented with an AXI4 interface you may wish to consider using the DATA_PACK byte_pad option. The byte_pad option is used to automatically align the member elements to 8-bit boundaries. This alignment is sometimes required by Xilinx IP. If an AXI4 port using DATA_PACK is to be implemented, refer to the documentation for the Xilinx IP it will connect to and determine if byte alignment is required.

For the following example code, the options for implementing a struct port are shown in the following figure.

```
typedef struct{
    int12 A;
    int18 B[4];
    int6 C;
} my_data;

void foo(my_data *a)
```

- By default, the members are implemented as individual ports. The array has multiple ports (data, addr, etc.)
- Using DATA_PACK results in a single wide port.
- Using DATA_PACK with `struct_level` byte padding aligns entire struct to the next 8-bit boundary.
- Using DATA_PACK with `field_level` byte padding aligns each struct member to the next 8-bit boundary.

Note: The maximum bit-width of any port or bus created by data packing is 8192 bits.

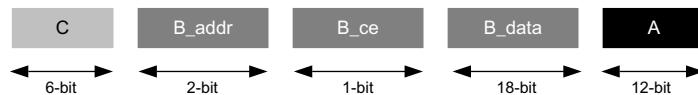
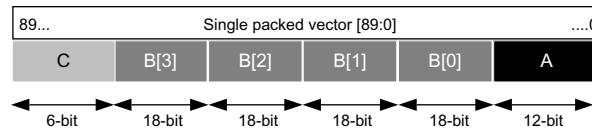
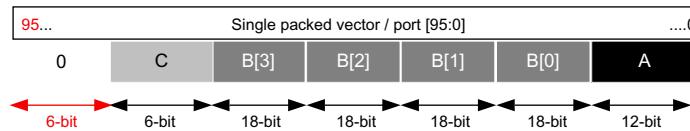
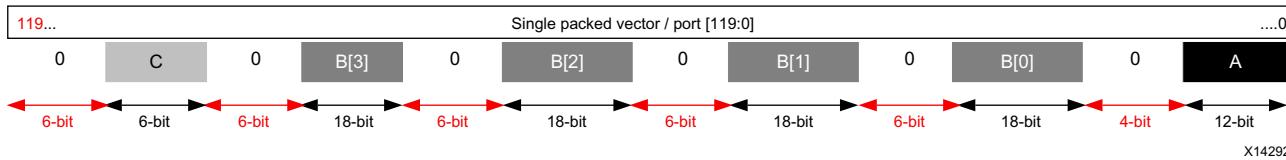
Struct Port Implementation

DATA_PACK optimization

DATA_PACK optimization with byte_pad on the struct_level

DATA_PACK optimization with byte_pad on the field_level


Figure 1-50: DATA_PACK byte_pad Alignment Options

If a struct contains arrays, those arrays can be optimized using the ARRAY_PARTITION directive to partition the array or the ARRAY_RESHAPE directive to partition the array and re-combine the partitioned elements into a wider array. The DATA_PACK directive performs the same operation as ARRAY_RESHAPE and combines the reshaped array with the other elements in the struct.

A struct cannot be optimized with DATA_PACK and then partitioned or reshaped. The DATA_PACK, ARRAY_PARTITION and ARRAY_RESHAPE directives are mutually exclusive.

Interface Synthesis and Multi-Access Pointers

Using pointers which are accessed multiple times can introduce unexpected behavior after synthesis. In the following example pointer `d_i` is read four times and pointer `d_o` is written to twice: the pointers perform multiple accesses.

```
#include pointer_stream_bad.h

void pointer_stream_bad ( dout_t *d_o, din_t *d_i) {
    din_t acc = 0;

    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
}
```

After synthesis this code will result in an RTL design which reads the input port once and writes to the output port once. As with any standard C compiler, Vivado HLS will optimize away the redundant pointer accesses. To implement the above code with the "anticipated" 4 reads on `d_i` and 2 writes to the `d_o` the pointers must be specified as `volatile` as shown in the next example.

```
#include pointer_stream_better.h

void pointer_stream_better ( volatile dout_t *d_o, volatile din_t *d_i) {
    din_t acc = 0;

    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
}
```

Even this C code is problematic. Using a test bench, there is no way to supply anything but a single value to `d_i` or verify any write to `d_o` other than the final write. Although multi-access pointers are supported, it is highly recommended to implement the behavior required using the `hls::stream` class. Details on the `hls::stream` class are in [HLS Stream Library in Chapter 2](#).

Specifying Interfaces

Interface synthesis is controlled by the `INTERFACE` directive or by using a configuration setting. To specify the interface mode on ports, select the port in the GUI directives tab and right-click the mouse to open the directives menu as shown in the following figure.

For the block-level I/O protocols, select the function.

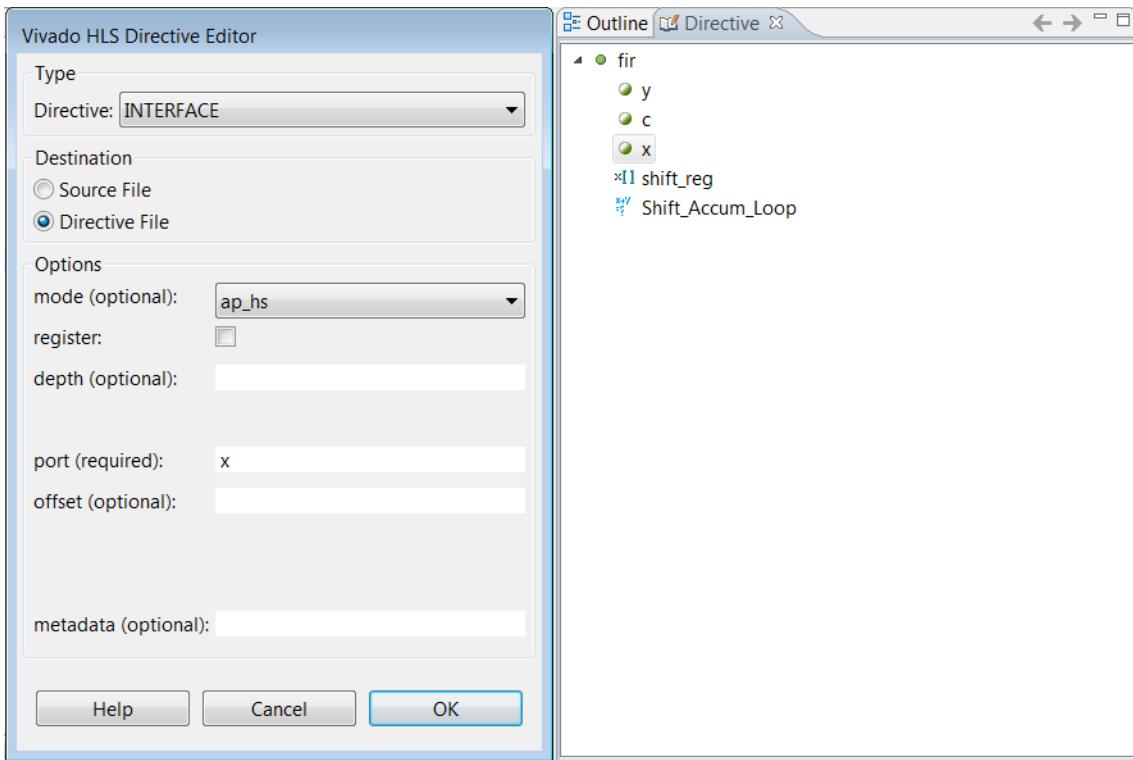


Figure 1-51: Specifying Port Interfaces

The interface mode is selected from the drop-down menu. The port option is required. By default Vivado HLS does not register ports. If the register option is selected all pass-by-value reads are performed in the first cycle of operation. For output ports, the register option guarantees the output is registered. For memory, FIFO and AXI4 interfaces the register option has no effect.

The offset option is used for AXI4 interfaces and is discussed in [Using AXI4 Interfaces](#). For cases in which a pointer is read from or written to multiple times within a single transaction, the depth option is required for C/RTL co-simulation. This option specifies how many samples will be provided to the design by the test bench and how many output values the test bench must store. Use whichever number is greater.

If the depth option is set too small, the C/RTL co-simulation might deadlock:

- The input reads may stall waiting for data and the test bench cannot provide.
- The output writes may stall when trying to write data as the storage is full.

The offset option is used for AXI4 interfaces and is discussed in [Using AXI4 Interfaces](#).

An interface protocol can be applied to the top-level function. The register option can be applied to any function in the design.

The interface configuration can be set using the menu **Solution > Solution Settings > General > config_interface**. Configuration settings can be used to:

- Add a global clock enable to the RTL design.
- Remove dangling ports, such as those created by elements of a struct that are not used in the design.
- Create RTL ports for any global variables.

Any C function can use global variables: those variables defined outside the scope of any function. By default, global variables do not result in the creation of RTL ports: Vivado HLS assumes the global variable is inside the final design. The `config_interface` configuration setting `expose_global` instructs Vivado HLS to create a ports for global variables. For more information on the synthesis of global variables, see [Global Variables in Chapter 3](#).

Interface Synthesis for SystemC

In general, interface synthesis is not supported for SystemC designs. The I/O ports for SystemC designs are fully specified in the SC_MODULE interface and the behavior of the ports fully described in the source code. Interface synthesis is provided to support:

- Memory block RAM interfaces
- AXI4-Stream interfaces
- AXI4-Lite interfaces
- AXI4 master interfaces

The processes for performing interface synthesis on a SystemC design is different from adding the same interfaces to C or C++ designs.

- Memory block RAM and AXI4 master interfaces require the SystemC data port is replaced with a Vivado HLS port.
- AXI4-Stream and AXI4-Lite slave interfaces only require directives but there is a different process for adding directives to a SystemC design.

Applying Interface Directives with SystemC

When adding directives as pragmas to SystemC source code, the pragma directives cannot be added where the ports are specified in the SC_MODULE declaration, they must be added inside a function called by the SC_MODULE.

When adding directives using the GUI:

- Open the C source code and directives tab.
- Select the function which requires a directive.
- Right-click with the mouse and the INTERFACE directive to the function.

The directives can be applied to any member function of the SC_MODULE, however it is a good design practice to add them to the function where the variables are used.

Block RAM Memory Ports

Given a SystemC design with an array port on the interface:

```
SC_MODULE(my_design) {
    // "RAM" Port
    sc_uint<20> my_array[256];
    ...
}
```

The port `my_array` is synthesized into an internal block RAM, not a block RAM interface port.

Including the Vivado HLS header file `ap_mem_if.h` allows the same port to be specified as an `ap_mem_port<data_width, address_bits>` port. The `ap_mem_port` data type is synthesized into a standard block RAM interface with the specified data and address bus-widths and using the `ap_memory` port protocol.

```
#include "ap_mem_if.h"
SC_MODULE(my_design) {
    // "RAM" Port
    ap_mem_port<sc_uint<20>, sc_uint<8>, 256> my_array;
    ...
}
```

When an `ap_mem_port` is added to a SystemC design, an associated `ap_mem_chn` must be added to the SystemC test bench to drive the `ap_mem_port`. In the test bench, an `ap_mem_chn` is defined and attached to the instance as shown:

```
#include "ap_mem_if.h"
ap_mem_chn<int, int, 68> bus_mem;
...
// Instantiate the top-level module
my_design U_dut ("U_dut")
U_dut.my_array.bind(bus_mem);
...
```

The header file `ap_mem_if.h` is located in the include directory located in the Vivado HLS installation area and must be included if simulation is performed outside Vivado HLS.

SystemC AXI4-Stream Interface

An AXI4-Stream interface can be added to any SystemC ports that are of the `sc_fifo_in` or `sc_fifo_out` type. The following shows the top-level of a typical SystemC design. As is typical, the SC_MODULE and ports are defined in a header file:

```
SC_MODULE(sc_FIFO_port)
{
    //Ports
    sc_in <bool> clock;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_out<bool> done;
    sc_fifo_out<int> dout;
    sc_fifo_in<int> din;

    //Variables
    int share_mem[100];
    bool write_done;

    //Process Declaration
    void Prc1();
    void Prc2();

    //Constructor
    SC_CTOR(sc_FIFO_port)
    {
        //Process Registration
        SC_CTHREAD(Prc1,clock.pos());
        reset_signal_is(reset,true);

        SC_CTHREAD(Prc2,clock.pos());
        reset_signal_is(reset,true);
    }
};
```

To create an AXI4-Stream interface the RESOURCE directive must be used to specify the ports are connected an AXI4-Stream resource. For the example interface shown above, the directives are shown added in the function called by the SC_MODULE: ports `din` and `dout` are specified to have an AXI4-Stream resource.

```
#include "sc_FIFO_port.h"

void sc_FIFO_port::Prc1()
{
    //Initialization
    write_done = false;

    wait();
    while(true)
    {
        while (!start.read()) wait();
        write_done = false;

        for(int i=0;i<100; i++)
            share_mem[i] = i;

        write_done = true;
        wait();
    } //end of while(true)
}

void sc_FIFO_port::Prc2()
{
    #pragma HLS resource core=AXI4Stream variable=din
    #pragma HLS resource core=AXI4Stream variable=dout
    //Initialization
    done = false;

    wait();

    while(true)
    {
        while (!start.read()) wait();
        wait();
        while (!write_done) wait();
        for(int i=0;i<100; i++)
        {
            dout.write(share_mem[i]+din.read());
        }

        done = true;
        wait();
    } //end of while(true)
}
```

When the SystemC design is synthesized, it results in an RTL design with standard RTL FIFO ports. When the design is packaged as IP using the **Export RTL** toolbar button , the output is a design with an AXI4-Stream interfaces.

SystemC AXI4-Lite Interface

An AXI4-Lite slave interface can be added to any SystemC ports of type `sc_in` or `sc_out`. The following example shows the top-level of a typical SystemC design. In this case, as is typical, the SC_MODULE and ports are defined in a header file:

```
SC_MODULE(sc_sequ_cthread) {
    //Ports
    sc_in <bool> clk;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_in<sc_uint<16> > a;
    sc_in<bool> en;
    sc_out<sc_uint<16> > sum;
    sc_out<bool> vld;

    //Variables
    sc_uint<16> acc;

    //Process Declaration
    void accum();

    //Constructor
    SC_CTOR(sc_sequ_cthread) {

        //Process Registration
        SC_CTHREAD(accum,clk.pos());
        reset_signal_is(reset,true);
    }
};
```

To create an AXI4-Lite interface the RESOURCE directive must be used to specify the ports are connected to an AXI4-Lite resource. For the example interface shown above, the following example shows how ports `start`, `a`, `en`, `sum` and `vld` are grouped into the same AXI4-Lite interface `slv0`: all the ports are specified with the same `bus_bundle` name and are grouped into the same AXI4-Lite interface.

```
=#include "sc_sequ_cthread.h"

void sc_sequ_cthread::accum(){
    //Group ports into AXI4 slave slv0
    #pragma HLS resource core=AXI4Lites metadata="-bus_bundle slv0" variable=start
    #pragma HLS resource core=AXI4Lites metadata="-bus_bundle slv0" variable=a
    #pragma HLS resource core=AXI4Lites metadata="-bus_bundle slv0" variable=en
    #pragma HLS resource core=AXI4Lites metadata="-bus_bundle slv0" variable=sum
    #pragma HLS resource core=AXI4Lites metadata="-bus_bundle slv0" variable=vld

    //Initialization
    acc=0;
    sum.write(0);
    vld.write(false);
    wait();

    // Process the data
    while(true) {
        // Wait for start
        wait();
        while (!start.read()) wait();

        // Read if valid input available
        if (en) {
            acc = acc + a.read();
            sum.write(acc);
            vld.write(true);
        } else {
            vld.write(false);
        }
    }
}
```

When the SystemC design is synthesized, it results in an RTL design with standard RTL ports. When the design is packaged as IP using **Export RTL** toolbar button , the output is a design with an AXI4-Lite interface.

SystemC AXI4 Master Interface

In most standard SystemC designs, you have no need to specify a port with the behavior of the Vivado HLS ap_bus I/O protocol. However, if the design requires an AXI4 master bus interface the ap_bus I/O protocol is required.

To specify an AXI4 master interface on a SystemC design:

- Use the Vivado HLS type `AXI4M_bus_port` to create an interface with the `ap_bus` I/O protocol.
- Assign an `AXI4M` resource to the port.

The following example shows how an `AXI4M_bus_port` called `bus_if` is added to a SystemC design.

- The header file `AXI4_if.h` must be added to the design.
- The port is defined as `AXI4M_bus_port<type>`, where `type` specifies the data type to be used (in this example, an `sc_fixed` type is used).

Note: The data type used in the `AXI4M_bus_port` must be multiples of 8-bit. In addition, structs are not supported for this data type.

```
#include "systemc.h"
#include "AXI4_if.h"
#include "tlm.h"
using namespace tlm;

#define DT sc_fixed<32, 8>

SC_MODULE(dut)
{
    //Ports
    sc_in<bool> clock; //clock input
    sc_in<bool> reset;
    sc_in<bool> start;
    sc_out<int> dout;
    AXI4M_bus_port<sc_fixed<32, 8> > bus_if;

    //Variables

    //Constructor
    SC_CTOR(dut)
    //:bus_if ("bus_if")
    {
        //Process Registration
        SC_CTHREAD(P1,clock.pos());
        reset_signal_is(reset,true);
    }
}
```

The following shows how the variable `bus_if` can be accessed in the SystemC function to produce standard or burst read and write operations.

```

//Process Declaration
void P1()
{
    //Initialization
    dout.write(10);
    int addr = 10;
    DT tmp[10];
    wait();
    while(1)
    {
        tmp[0]=10;
        tmp[1]=11;
        tmp[2]=12;

        while (!start.read()) wait();

        // Port read
        tmp[0] = bus_if->read(addr);

        // Port burst read
        bus_if->burst_read(addr, 2, tmp);

        // Port write
        bus_if->write(addr, tmp);

        // Port burst write
        bus_if->burst_write(addr, 2, tmp);

        dout.write(tmp[0].to_int());
        addr+=2;
        wait();
    }
}

```

When the port class `AXI4M_bus_port` is used in a design, it must have a matching HLS bus interface channel `hls_bus_chn<start_addr >` in the test bench, as shown in the following example:

```

#include <systemc.h>
#include "tlm.h"
using namespace tlm;

#include "hls_bus_if.h"
#include "AE_clock.h"
#include "driver.h"
#ifndef __RTL_SIMULATION__
#include "dut_rtl_wrapper.h"
#define dut dut_rtl_wrapper
#else
#include "dut.h"
#endif

int sc_main (int argc , char *argv[])

```

```
{
    sc_report_handler::set_actions("/IEEE_Std_1666/deprecated", SC_DO_NOTHING);
    sc_report_handler::set_actions( SC_ID_LOGIC_X_TO_BOOL_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_VECTOR_CONTAINS_LOGIC_VALUE_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_OBJECT_EXISTS_, SC_LOG);

    // hls_bus_chan<type>
    // bus_variable("name", start_addr, end_addr)
    //
    hls_bus_chn<sc_fixed<32, 8>> bus_mem("bus_mem", 0, 1024);

    sc_signal<bool>           s_clk;
    sc_signal<bool>           reset;
    sc_signal<bool>           start;
    sc_signal<int>            dout;

    AE_Clock     U_AE_Clock("U_AE_Clock", 10);
    dut         U_dut("U_dut");
    driver      U_driver("U_driver");

    U_AE_Clock.reset(reset);
    U_AE_Clock.clk(s_clk);

    U_dut.clock(s_clk);
    U_dut.reset(reset);
    U_dut.start(start);
    U_dut.dout(dout);
    U_dut.bus_if(bus_mem);

    U_driver.clk(s_clk);
    U_driver.start(start);
    U_driver.dout(dout);

    int end_time = 8000;

    cout << "INFO: Simulating " << endl;

    // start simulation
    sc_start(end_time, SC_NS);

    return U_driver.ret;
};
```

The synthesized RTL design contains an interface with the ap_bus I/O protocol.

When the AXI4M_bus_port class is used, it results in an RTL design with an ap_bus interface. When the design is packaged as IP using Export RTL the output is a design with an AXI4 master port.

Manual Interface Specification

Vivado HLS has the ability to identify blocks of code that defines a specific I/O protocol. This allows an I/O protocol to be specified without using Interface Synthesis or SystemC (the protocol directive explained below can also be used with SystemC designs to provide greater I/O control).

In following example code:

- input "response[0]" is read
- output "request" is written
- input "response[1]" is read.
- AND it is necessary that the final design perform the I/O accesses in this order

```
void test (
    int      *z1,
    int      a,
    int      b,
    int      *mode,
    volatile int  *request,
    volatile int  response[2],
    int      *z2
) {

    int    read1, read2;
    int    opcode;
    int    i;

    P1: {
        read1      = response[0];
        opcode     = 5;
        *request   = opcode;
        read2      = response[1];
    }
    C1: {
        *z1      = a + b;
        *z2      = read1 + read2;
    }
}
```

When Vivado HLS implements this code there is no reason the "request" write should be between the two reads on "response". The code is written with this I/O behavior but there are no dependencies in the code that enforce it. High-Level Synthesis may schedule the I/O accesses in the same manner or choose some other access pattern.

In this case the use of a protocol block can enforce a specific I/O protocol behavior. Because the accesses occur in the scope defined by block "P1", a protocol can be applied to this block as follows:

- Include "ap_utils.h" header file that defines applet().
- Place an ap_wait() statement after the write to "request", but before the read on "response[1]".
 - The ap_wait() statement does not cause the simulation to behave any differently, but it instructs High-Level Synthesis to insert a clock here during synthesis.
- Specify that block P1 is a protocol region.
 - This instructs High-Level Synthesis that the code within this region is to be scheduled as is: no re-ordering of the I/O or ap_wait() statements.

Applying the directive as shown:

```
set_directive_protocol test P1 -mode floating
```

To the modified code:

```
#include "ap_utils.h" // Added include file

void test (
    int *z1,
    int a,
    int b,
    int *mode,
    volatile int *request,
    volatile int response[2],
    int *z2
) {

    int read1, read2;
    int opcode;
    int i;

    P1: {
        read1 = response[0];
        opcode = 5;
        ap_wait(); // Added ap_wait statement
        *request = opcode;
        read2 = response[1];
    }
    C1: {
        *z1 = a + b;
        *z2 = read1 + read2;
    }
}
```

Results in exact I/O behavior specified in the code:

- input "response[0]" is read
- output "request" is written
- input "response[1]" is read.

The -mode floating option allows other code to execute in parallel with this block, if allowed by data dependencies. The fixed mode would prevent this.

Using AXI4 Interfaces

AXI4-Stream Interfaces

An AXI4-Stream interface can be applied to any input argument and any array or pointer output argument. Since an AXI4-Stream interface transfers data in a sequential streaming manner it cannot be used with arguments which are both read and written.

There are two basic ways to use an AXI4-Stream in your design.

- Use an AXI4-Stream without side-channels.
- Use an AXI4-Stream with side-channels.

This second use model provides additional functionality, allowing the optional side-channels which are part of the AXI4-Stream standard, to be used directly in the C code.

AXI4-Stream Interfaces without Side-Channels

An AXI4-Stream is used without side-channels when the data type does not contain any AXI4 side-channel elements. The following example shows a design where the data type is a standard C int type. In this example, both interfaces are implemented using an AXI4-Stream.

```
void example(int A[50], int B[50]) {
    //Set the HLS native interface types
    #pragma HLS INTERFACE axis port=A
    #pragma HLS INTERFACE axis port=B

    int i;

    for(i = 0; i < 50; i++){
        B[i] = A[i] + 5;
    }
}
```

After synthesis, both arguments are implemented with a data port and the standard AXI4-Stream TVALID and TREADY protocol ports as shown in the following figure.

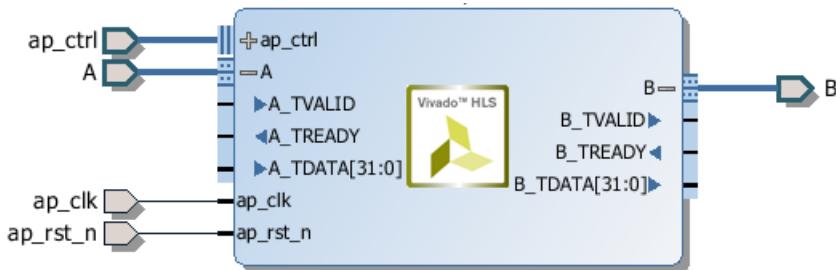


Figure 1-52: AXI4-Stream Interfaces Without Side-Channels

AXI4-Stream Interfaces with Side-Channels

Side-channels are optional signals which are part of the AXI4-Stream standard. The side-channel signals may be directly referenced and controlled in the C code. The Vivado HLS include directory contains the file `ap_axi_sdata.h`. This header file contains the following structs.,.

```
#include "ap_int.h"

template<int D,int U,int TI,int TD>
struct ap_axis{
    ap_int<D>    data;
    ap_uint<D/8>  keep;
    ap_uint<D/8>  strb;
    ap_uint<U>    user;
    ap_uint<1>    last;
    ap_uint<TI>   id;
    ap_uint<TD>   dest;
};

template<int D,int U,int TI,int TD>
struct ap_axiu{
    ap_uint<D>    data;
    ap_uint<D/8>  keep;
    ap_uint<D/8>  strb;
    ap_uint<U>    user;
    ap_uint<1>    last;
    ap_uint<TI>   id;
    ap_uint<TD>   dest;
};
```

Both structs contain as top-level members, variables whose names match those of the optional AXI4-Stream side-channel signals. Provided the struct contains elements with these names, there is no requirement to use the header file provided. You can create your own user defined structs. Since the structs shown above use `ap_int` types and templates, this header file is only for use in C++ designs.

Note: The valid and ready signals are mandatory signals in an AXI4-Stream and will always be implemented by Vivado HLS. These cannot be controlled using a struct.

The following example shows how the side-channels can be used directly in the C code and implemented on the interface. In this example a signed 32-bit data type is used.

```
#include "ap_axi_sdata.h"

void example(ap_axis<32,2,5,6> A[50], ap_axis<32,2,5,6> B[50]){
    //Map ports to Vivado HLS interfaces
    #pragma HLS INTERFACE axis port=A
    #pragma HLS INTERFACE axis port=B

    int i;

    for(i = 0; i < 50; i++){
        B[i].data = A[i].data.to_int() + 5;
        B[i].keep = A[i].keep;
        B[i].strb = A[i].strb;
        B[i].user = A[i].user;
        B[i].last = A[i].last;
        B[i].id = A[i].id;
        B[i].dest = A[i].dest;
    }
}
```

After synthesis, both arguments are implemented with data ports, the standard AXI4-Stream TVALID and TREADY protocol ports and all of the optional ports described in the struct.

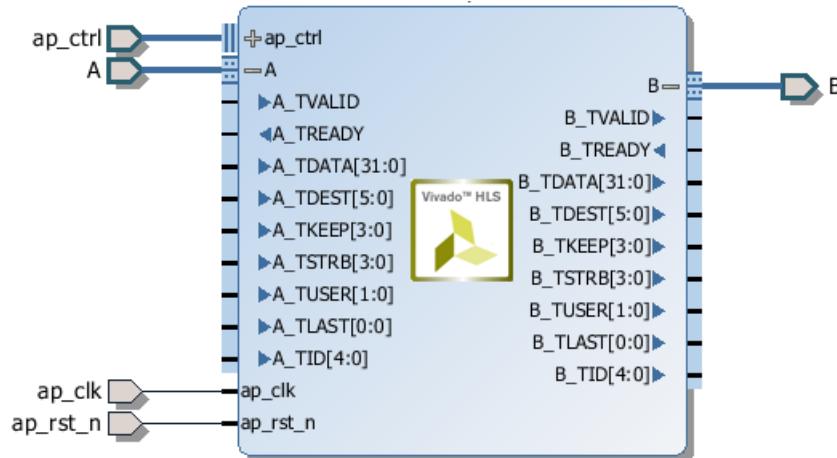


Figure 1-53: **Pcore: AXI4-Stream Interfaces**

Packing Structs into AXI4-Stream Interfaces

Xilinx IP that use AXI4-Stream interfaces typically use a single-wide vector with various fields of the vector representing different data. You can easily represent this data structure in C using a struct.

If an argument to the top-level function is a struct, Vivado HLS partitions the struct into separate elements by default and implements each member of the struct as a separate port.

If you want to apply an AXI4-Stream interface to a struct, the struct must meet one of the following criteria:

- The struct must contain only a single data member, and all other struct members must be side-band channels.
- If the struct contains multiple data members, all data members must be grouped into a single word using the DATA_PACK directive. In this case, the struct can optionally have side-band channels.

It is not uncommon when using structs and AXI4-Stream interfaces to want to pack all the elements of the struct into a single wide vector or in the case of arrays, into an array of wide-vectors and to align that data to the fields required by Xilinx IP.

The DATA_PACK optimization directive is used to pack the elements of a struct into a single wide-vector. Complete details on packing structs and using the byte padding option to align the data fields in the wide-vector are provided in [Interface Synthesis and Structs](#).

There is no requirement to use the DATA_PACK directive to pack structs using the AXI4-Stream side-channel signals. These signals are automatically packed in the struct.

AXI4-Lite Interface

You can use an AXI4-Lite interface to allow the design to be controlled by a CPU or microcontroller. Using the Vivado HLS AXI4-Lite interface, you can:

- Group multiple ports into the same AXI4-Lite interface.
- Output C driver files for use with the code running on a processor.

Note: This provides a set of C API functions, which allows you to easily control the hardware from the software. This is useful when the design is exported to the IP Catalog or as a Pcore for the EDK environment.

The following example shows how Vivado HLS implements multiple arguments, including the function return, as an AXI4-Lite interface. Because each directive uses the same name for the bundle option, each of the ports is grouped into the same AXI4-Lite interface.

```
void example(char *a, char *b, char *c)
{
#pragma HLS INTERFACE s_axilite port=return bundle=BUS_A
#pragma HLS INTERFACE s_axilite port=a          bundle=BUS_A
#pragma HLS INTERFACE s_axilite port=b          bundle=BUS_A
#pragma HLS INTERFACE s_axilite port=c          bundle=BUS_A offset=0x0400
#pragma HLS INTERFACE ap_vld port=b

    *c += *a + *b;
}
```

Note: If you do not use the bundle option, Vivado HLS groups all arguments specified with an AXI4-Lite interface into the same default bundle and automatically names the port.

You can also assign an I/O protocol to ports grouped into an AXI4-Lite interface. In the example above, Vivado HLS implements port `b` as an `ap_vld` interface and groups port `b` into the AXI4-Lite interface. As a result, the AXI4-Lite interface contains a register for the port `b` data, a register for the output to acknowledge that port `b` was read, and a register for the port `b` input valid signal.

Each time port `b` is read, Vivado HLS automatically clears the input valid register and resets the register to logic 0. If the input valid register is not set to logic 1, the data in the `b` data register is not considered valid, and the design stalls and waits for the valid register to be set.



RECOMMENDED: *For ease of use during the operation of the design, it is recommended that you do not include additional I/O protocol in all ports grouped into an AXI4-Lite interface. It is recommended that the AXI4-Lite interface only includes the block-level I/O protocol associated with the return port.*



IMPORTANT: *You cannot assign arrays to an AXI4-Lite interface using the `bram` interface. You can only assign arrays to an AXI4-Lite interface using the default `ap_memory` interface.*

By default, Vivado HLS automatically assigns the address for each port that is grouped into an AXI4-Lite interface. Vivado HLS provides the assigned addresses in the C driver files. For more information, see [C Driver Files](#).

Note: To explicitly define the address, you can use the `offset` option, as shown for argument `c` in the example above.



IMPORTANT: *In an AXI4-Lite interface, Vivado HLS reserves addresses 0x0000 through 0x000C for the block-level I/O protocol signals and interrupt controls.*

After synthesis, Vivado HLS implements the ports in the AXI4-Lite port, as shown in the following figure. Vivado HLS creates the interrupt port by including the function return in the AXI4-Lite interface. You can program the interrupt through the AXI4-Lite interface. You can also drive the interrupt from the following block-level protocols:

- `ap_done`: Indicates when the function completes all operations.
- `ap_ready`: Indicates when the function is ready for new input data.

You can program the interface using the C driver files.

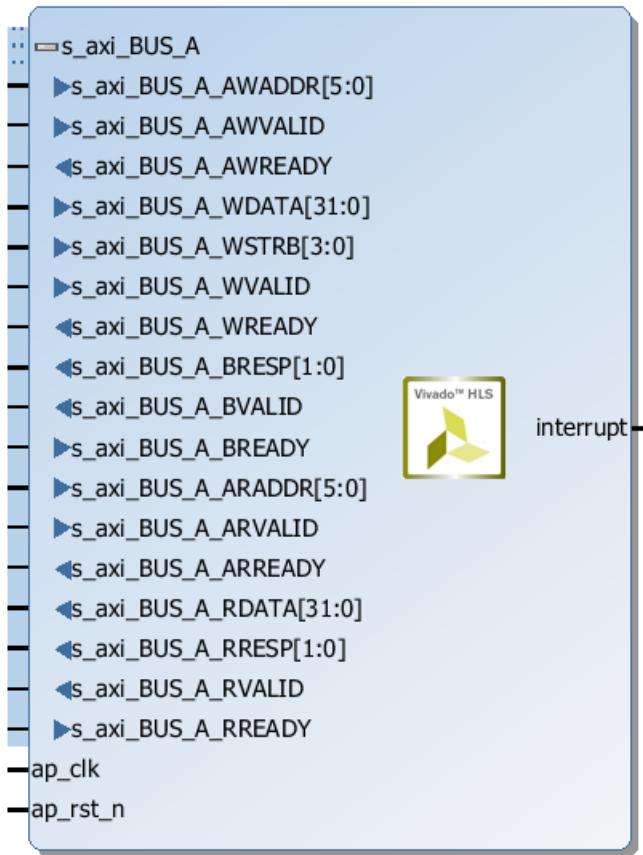


Figure 1-54: AXI4-Lite Slave Interfaces with Grouped RTL Ports

C Driver Files

When an AXI4-Lite slave interface is implemented, a set of C driver files are automatically created. These C driver files provide a set of APIs that can be integrated into any software running on a CPU and used to communicate with the device via the AXI4-Lite slave interface.

The C driver files are created when the design is packaged as IP in either the IP Catalog or Pcore format. For more details on packing IP, see [Exporting the RTL Design](#).

Driver files are created for standalone and Linux modes. In standalone mode the drivers are used in the same way as any other Xilinx standalone drivers. In Linux mode, copy all the C files (.c) and header files (.h) files into the software project.

The driver files and API functions derive their name from the top-level function for synthesis. In the above example, the top-level function is called “example”. If the top-level function was named “DUT” the name “example” would be replaced by “DUT” in the following description. The driver files are created in the packaged IP (located in the `impl` directory inside the solution).

Table 1-21: C Driver Files for a Design Named `example`

File Path	Usage Mode	Description
data/example.mdd	Standalone	Driver definition file. When exporting a Pcore, this file is named example_top_v2_1_0.mdd.
data/example.tcl	Standalone	Used by SDK to integrate the software into an SDK project. When exporting a Pcore, this file is named example_top_v2_1_0.tcl.
src/xexample_hw.h	Both	Defines address offsets for all internal registers.
src/xexample.h	Both	API definitions
src/xexample.c	Both	Standard API implementations
src/xexample_sinit.c	Standalone	Initialization API implementations
src/xexample_linux.c	Linux	Initialization API implementations
src/Makefile	Standalone	Makefile

In file `xexample.h`, two structs are defined.

- **XExample_Config:** This is used to hold the configuration information (base address of each AXI4-Lite slave interface) of the IP instance.
- **XExample:** This is used to hold the IP instance pointer. Most APIs take this instance pointer as the first argument.

The standard API implementations are provided in files `xexample.c`, `xexample_sinit.c`, `xexample_linux.c`, and provide functions to perform the following operations.

- Initialize the device
- Control the device and query its status
- Read/write to the registers
- Set up, monitor, and control the interrupts

The following table lists each of the API function provided in the C driver files.

Table 1-22: C Driver API Functions

API Function	Description
XExample_Initialize	This API will write value to InstancePtr which then can be used in other APIs. It is recommended to call this API to initialize a device except when an MMU is used in the system.
XExample_CfgInitialize	Initialize a device configuration. When a MMU is used in the system, replace the base address in the XDut_Config variable with virtual base address before calling this function. Not for use on Linux systems.
XExample_LookupConfig	Used to obtain the configuration information of the device by ID. The configuration information contain the physical base address. Not for user on Linux.
XExample_Release	Release the uio device in linux. Delete the mappings by munmap: the mapping will automatically be deleted if the process terminated. Only for use on Linux systems.
XExample_Start	Start the device. This function will assert the ap_start port on the device. Available only if there is ap_start port on the device.
XExample_IsDone	Check if the device has finished the previous execution: this function will return the value of the ap_done port on the device. Available only if there is an ap_done port on the device.
XExample_IsIdle	Check if the device is in idle state: this function will return the value of the ap_idle port. Available only if there is an ap_idle port on the device.
XExample_IsReady	Check if the device is ready for the next input: this function will return the value of the ap_ready port. Available only if there is an ap_ready port on the device.
XExample_Continue	Assert port ap_continue. Available only if there is an ap_continue port on the device.
XExample_EnableAutoRestart	Enables “auto restart” on device. When this is set the device will automatically start the next transaction when the current transaction completes.
XExample_DisableAutoRestart	Disable the “auto restart” function.
XExample_Set_ARG	Write a value to port ARG (a scalar argument of the top function). Available only if ARG is input port.
XExample_Set_ARG_vld	Assert port ARG_vld. Available only if ARG is an input port and implemented with an ap_hs or ap_vld interface protocol.
XExample_Set_ARG_ack	Assert port ARG_ack. Available only if ARG is an output port and implemented with an ap_hs or ap_ack interface protocol.
XExample_Get_ARG	Read a value from ARG. Only available if port ARG is an output port on the device.
XExample_Get_ARG_vld	Read a value from ARG_vld. Only available if port ARG is an output port on the device and implemented with an ap_hs or ap_vld interface protocol.

Table 1-22: C Driver API Functions (Cont'd)

API Function	Description
XExample_Get_ARG_ack	Read a value from ARG_ack. Only available if port ARG is an input port on the device and implemented with an ap_hs or ap_ack interface protocol.
XExample_Get_ARG_BaseAddress	Return the base address of the array inside the interface. Only available when ARG is an array grouped into the AXI4-Lite interface.
XExample_Get_ARG_HighAddress	Return the address of the uppermost element of the array. Only available when ARG is an array grouped into the AXI4-Lite interface.
XExample_Get_ARG_TotalBytes	<p>Return the total number of bytes used to store the array. Only available when ARG is an array grouped into the AXI4-Lite interface.</p> <p>Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.</p>
XExample_Get_ARG_BitWidth	<p>Return the bit width of each element in the array. Only available when ARG is an array grouped into the AXI4-Lite interface.</p> <p>Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.</p>
XExample_Get_ARG_Depth	<p>Return the total number of elements in the array. Only available when ARG is an array grouped into the AXI4-Lite interface.</p> <p>Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.</p>
XExample_Write_ARG_Words	Write the length of a 32-bit word into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XExample_Read_ARG_Words	Read the length of a 32-bit word from the array. This API requires the data target, the offset address from BaseAddress, and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XExample_Write_ARG_Bytes	Write the length of bytes into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XExample_Read_ARG_Bytes	Read the length of bytes from the array. This API requires the data target, the offset address from BaseAddress, and the length of data to be loaded. Only available when ARG is an array grouped into the AXI4-Lite interface.

Table 1-22: C Driver API Functions (Cont'd)

API Function	Description
XExample_InterruptGlobalEnable	Enable the interrupt output. Interrupt functions are available only if there is ap_start.
XExample_InterruptGlobalDisable	Disable the interrupt output.
XExample_InterruptEnable	Enable the interrupt source. There may be at most 2 interrupt sources (source 0 for ap_done and source 1 for ap_ready)
XExample_InterruptDisable	Disable the interrupt source.
XExample_InterruptClear	Clear the interrupt status.
XExample_InterruptGetEnabled	Check which interrupt sources are enabled.
XExample_InterruptGetStatus	Check which interrupt sources are triggered.

For a complete description of the API functions, see [AXI4-Lite Slave C Driver Reference in Chapter 4](#).

Hardware Control

The hardware header file `xexample_hw.h` (in this example) provides a complete list of the memory mapped locations for the ports grouped into the AXI4-Lite slave interface.

```

// 0x00 : Control signals
//      bit 0 - ap_start (Read/Write/SC)
//      bit 1 - ap_done (Read/COR)
//      bit 2 - ap_idle (Read)
//      bit 3 - ap_ready (Read)
//      bit 7 - auto_restart (Read/Write)
//      others - reserved
// 0x04 : Global Interrupt Enable Register
//      bit 0 - Global Interrupt Enable (Read/Write)
//      others - reserved
// 0x08 : IP Interrupt Enable Register (Read/Write)
//      bit 0 - Channel 0 (ap_done)
//      bit 1 - Channel 1 (ap_ready)
// 0x0c : IP Interrupt Status Register (Read/TOW)
//      bit 0 - Channel 0 (ap_done)
//      others - reserved
// 0x10 : Data signal of a
//      bit 7~0 - a[7:0] (Read/Write)
//      others - reserved
// 0x14 : reserved
// 0x18 : Data signal of b
//      bit 7~0 - b[7:0] (Read/Write)
//      others - reserved
// 0x1c : reserved
// 0x20 : Data signal of c_i
//      bit 7~0 - c_i[7:0] (Read/Write)
//      others - reserved
// 0x24 : reserved
// 0x28 : Data signal of c_o
//      bit 7~0 - c_o[7:0] (Read)
//      others - reserved
// 0x2c : Control signal of c_o

```

```

//      bit 0 - c_o_ap_vld (Read/COR)
//      others - reserved
// (SC = Self Clear, COR = Clear on Read, TOW = Toggle on Write, COH = Clear on
// Handshake)

```

To correctly program the registers in the AXI4-Lite slave interface, there is some requirement to understand how the hardware ports operate. The block will operate with the same port protocols described in [Interface Synthesis](#).

For example, to start the block operation the `ap_start` register must be set to 1. The device will then proceed and read any inputs grouped into the AXI4-Lite slave interface from the register in the interface. When the block completes operation, the `ap_done`, `ap_idle` and `ap_ready` registers will be set by the hardware output ports and the results for any output ports grouped into the AXI4-Lite slave interface read from the appropriate register. This is the same operation described in [Figure 1-48](#).

The implementation of function argument `c` in the example above also highlights the importance of some understanding how the hardware ports are operate. Function argument `c` is both read and written to, and is therefore implemented as separate input and output ports `c_i` and `c_o`, as explained in [Interface Synthesis](#).

The first recommended flow for programming the AXI4-Lite slave interface is for a one-time execution of the function:

- Use the interrupt function to determine how you wish the interrupt to operate.
 - Load the register values for the block input ports. In the above example this is performed using API functions `XExample_Set_a`, `XExample_Set_b`, and `XExample_Set_c_i`.
 - Set the `ap_start` bit to 1 using `XExample_Start` to start executing the function. This register is self-clearing as noted in the header file above. After one transaction, the block will suspend operation.
 - Allow the function to execute. Address any interrupts which are generated.
 - Read the output registers. In the above example this is performed using API functions `XExample_Get_c_o_vld`, to confirm the data is valid, and `XExample_Get_c_o`.
- Note:** The registers in the AXI4-Lite slave interface obey the same I/O protocol as the ports. In this case, the output valid is set to logic 1 to indicate if the data is valid.
- Repeat for the next transaction.

The second recommended flow is for continuous execution of the block. In this mode, the input ports included in the AXI4-Lite slave interface should only be ports which perform configuration. The block will typically run much faster than a CPU. If the block must wait for inputs, the block will spend most of its time waiting:

- Use the interrupt function to determine how you wish the interrupt to operate.
- Load the register values for the block input ports. In the above example this is performed using API functions `XExample_Set_a`, `XExample_Set_a` and `XExample_Set_c_i`.
- Set the auto-start function using API `XExample_EnableAutoRestart`
- Allow the function to execute. The individual port I/O protocols will synchronize the data being processed through the block.
- Address any interrupts which are generated. The output registers could be accessed during this operation but the data may change often.
- Use the API function `XExample_DisableAutoRestart` to prevent any more executions.
- Read the output registers. In the above example this is performed using API functions `XExample_Get_c_o` and `XExample_Set_c_o_vld`.

Software Control

The API functions can be used in the software running on the CPU to control the hardware block. An overview of the process is:

- Create an instance of the HW instance
- Look Up the device configuration
- Initialize the Device
- Set the input parameters of the HLS block
- Start the device and read the results

An abstracted version of this process is shown below. Complete examples of the software control are provided in the Zynq-7000 AP SoC tutorials noted in [Table 1-4](#).

```
#include "xexample.h"      // Device driver for HLS HW block
#include "xparameters.h"

// HLS HW instance
XExample_HlsExample;
XExample_Config *ExamplePtr

int main() {
    int res_hw;

    // Look Up the device configuration
    ExamplePtr = XExample_LookupConfig(XPAR_XEXAMPLE_0_DEVICE_ID);
```

```

if (!ExamplePtr) {
    print("ERROR: Lookup of accelerator configuration failed.\n\r");
    return XST_FAILURE;
}

// Initialize the Device
status = XExample_CfgInitialize(&HlsExample, ExamplePtr);
if (status != XST_SUCCESS) {
    print("ERROR: Could not initialize accelerator.\n\r");
    exit(-1);
}

//Set the input parameters of the HLS block
XExample_Set_a(&HlsExample, 42);
XExample_Set_b(&HlsExample, 12);
XExample_Set_c_i(&HlsExample, 1);

// Start the device and read the results
XExample_Start(&HlsExample);
do {
    res_hw = XExample_Get_c_o(&HlsExample);
} while (XExample_Get_c_o(&HlsExample) == 0); // wait for valid data output
print("Detected HLS peripheral complete. Result received.\n\r");
}

```

Customizing AXI4-Lite Slave Interfaces in IP Integrator

When an HLS RTL design using an AXI4-Lite slave interface is incorporated into a design in Vivado IP Integrator, you can customize the block. From the block diagram in IP Integrator, select the HLS block, right-click with the mouse button and select Customize Block.

The address width is by default configured to the minimum required size. Modify this to connect to blocks with address sizes less than 32-bit.

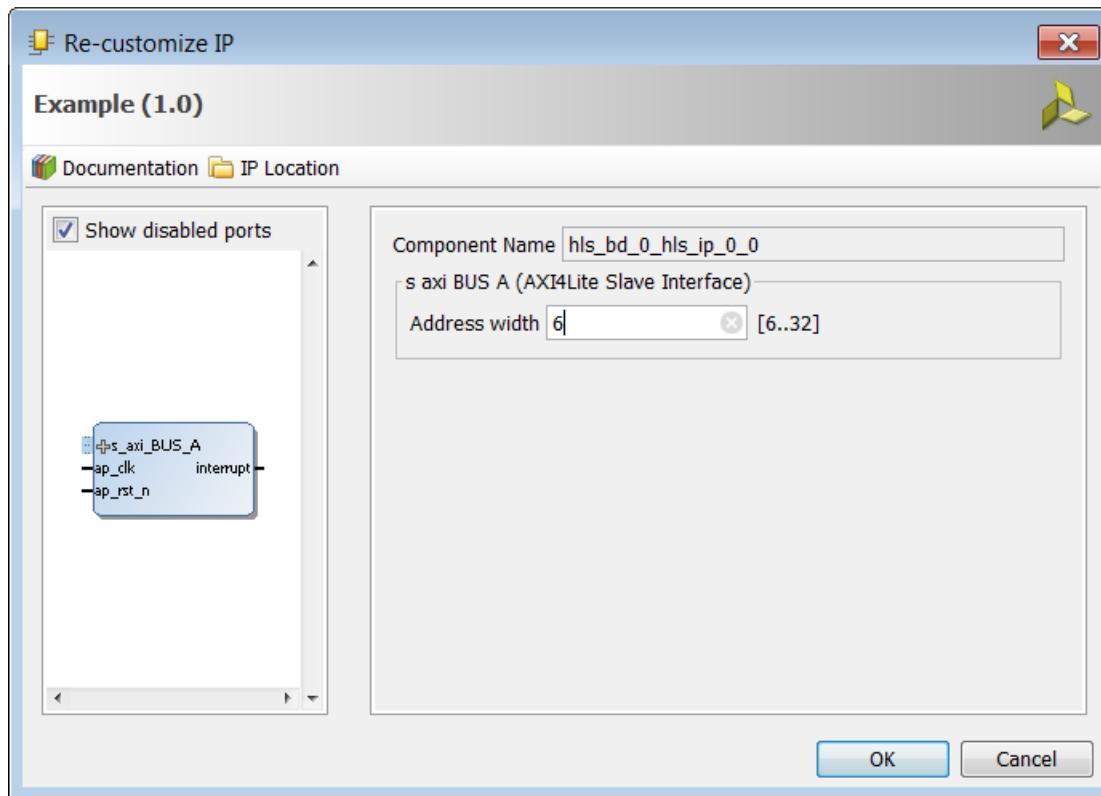


Figure 1-55: Customizing AXI4-Lite Slave Interfaces in IP Integrator

Using the AXI4 Master Interface

An AXI4 master interface is used on any array or pointer/reference arguments and is used two mode:

- Individual data transfers.
- Burst mode data transfers using the C `memcpy` function.

Individual data transfers are those with the characteristics shown in the following examples, where a data is read or written to the top-level function argument.

```
void bus (int *d) {
    static int acc = 0;

    acc += *d;
    *d = acc;
}
```

Or,

```
void bus (int *d) {
    static int acc = 0;
    int i;

    for (i=0;i<4;i++) {
        acc += d[i];
        d[i] = acc;
    }
}
```

In both cases, the data is transferred over the AXI4 master interface as simple read or write operation: one address, one data values at a time.

Burst transfer mode transfers data using a single base address followed by multiple sequential data samples and is capable of higher data throughput. Burst mode of operation is possible only when the C `memcpy` function is used to read data into or out of the top-level function for synthesis.

Note: The C `memcpy` function is only supported for synthesis when used to transfer data to or from a top-level function argument specified with an AXI4 master interface.

The following example shows a copy of burst mode. The top-level function argument `a` is specified as an AXI4 master interface.



IMPORTANT: When using the AXI4 master interface, the block-level I/O protocol signals must be grouped into an AXI4-Lite slave interface as shown for C/RTL co-simulation to be used.

```
void example(volatile int *a){

#pragma HLS INTERFACE m_axi depth=50 port=a
#pragma HLS INTERFACE s_axilite port=return bundle=AXILites

//Port a is assigned to an AXI4 master interface

int i;
int buff[50];

//memcpy creates a burst access to memory
memcpy(buff,(const int*)a,50*sizeof(int));

for(i=0; i < 50; i++){
    buff[i] = buff[i] + 100;
}

memcpy((int *)a,buff,50*sizeof(int));
}
```

When this example is synthesized it results in the following interface (the AXI4 interfaces are shown collapsed).

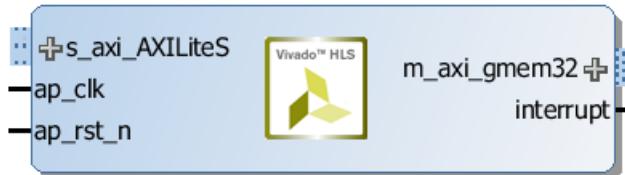


Figure 1-56: Customizing AXI4-Lite Slave Interfaces in IP Integrator

Controlling the Address Offset in an AXI4 Master Interface

By default, the AXI4 master interface starts all read and write operations from address 0x00000000. For example, given the following code, the design reads data from addresses 0x00000000 to 0x00000032, which represents a range of 50 address values. The design then writes data back to the same addresses.

```
void example(volatile int *a) {

    #pragma HLS INTERFACE m_axi depth=50 port=a
    #pragma HLS INTERFACE s_axilite port=return bundle=AXILites

    int i;
    int buff[50];

    memcpy(buff, (const int*)a, 50*sizeof(int));

    for(i=0; i < 50; i++){
        buff[i] = buff[i] + 100;
    }
    memcpy((int *)a,buff,50*sizeof(int));
}
```

To apply an address offset, use the `-offset` option with the `INTERFACE` directive, and specify one of the following options:

- `off`: Does not apply an offset address. This is the default.
- `direct`: Adds a 32-bit port to the design for applying an address offset.
- `slave`: Adds a 32-bit register inside the AXI4-Lite interface for applying an address offset.

In the final RTL, the address offset is applied directly to any read or write address generated by the AXI4 master interface, which allows the design to access any address location in the system.

Customizing AXI4 Master Interfaces in IP Integrator

When an HLS RTL design using an AXI4 master interface is incorporated into a design in Vivado IP Integrator, the block may be customized. From the block diagram in IP Integrator, select the HLS block, right-click with the mouse button and select `Customize Block`.

The following figure shows the Re-Customize IP dialog box for the design shown above. This design also includes an AXI4-Lite slave interface.

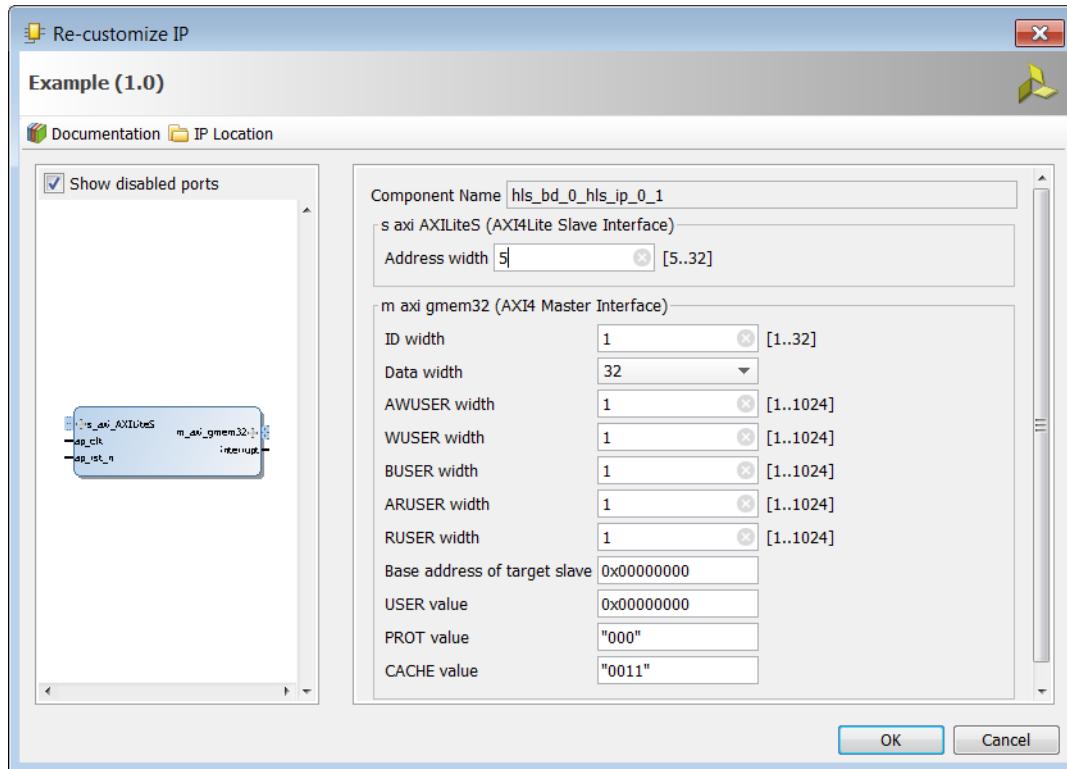


Figure 1-57: Customizing AXI4 Master Interfaces in IP Integrator

Design Optimization

This chapter outlines the various optimizations and techniques that can be employed to direct Vivado HLS to produce a micro-architecture that satisfies the desired performance, and area goals.

A complete list of the optimization directives provided by Vivado HLS is provided in The following table.

Table 1-23: Vivado HLS Optimization Directives

Directive	Description
ALLOCATION	Specify a limit for the number of operations, cores or functions used. This can force the sharing or hardware resources and may increase latency
ARRAY_MAP	Combines multiple smaller arrays into a single large array to help reduce block RAM resources.
ARRAY_PARTITION	Partitions large arrays into multiple smaller arrays or into individual registers, to improve access to data and remove block RAM bottlenecks.
ARRAY_RESHAPE	Reshape an array from one with many elements to one with greater word-width. Useful for improving block RAM accesses without using more block RAM.
DATA_PACK	Packs the data fields of a struct into a single scalar with a wider word width.
DATAFLOW	Enables task level pipelining, allowing functions and loops to execute concurrently. Used to minimize interval.
DEPENDENCE	Used to provide additional information that can overcome loop-carry dependencies and allow loops to be pipelined (or pipelined with lower intervals).
EXPRESSION_BALANCE	Allows automatic expression balancing to be turned off.
FUNCTION_INSTANTIATE	Allows different instances of the same function to be locally optimized.
INLINE	Inlines a function, removing all function hierarchy. Used to enable logic optimization across function boundaries and improve latency/interval by reducing function call overhead.
INTERFACE	Specifies how RTL ports are created from the function description.
LATENCY	Allows a minimum and maximum latency constraint to be specified.
LOOP_FLATTEN	Allows nested loops to be collapsed into a single loop with improved latency.
LOOP_MERGE	Merge consecutive loops to reduce overall latency, increase sharing and improve logic optimization.
LOOP_TRIPCOUNT	Used for loops which have variables bounds. Provides an estimate for the loop iteration count. This has no impact on synthesis, only on reporting.
OCCURRENCE	Used when pipelining functions or loops, to specify that the code in a location is executed at a lesser rate than the code in the enclosing function or loop.
PIPELINE	Reduces the initiation interval by allowing the concurrent execution of operations within a loop or function.

Table 1-23: Vivado HLS Optimization Directives (Cont'd)

Directive	Description
PROTOCOL	This command specifies a region of the code to be a protocol region. A protocol region can be used to manually specify an interface protocol.
RESET	This directive is used to add or remove reset on a specific state variable (global or static).
RESOURCE	Specify that a specific library resource (core) is used to implement a variable (array, arithmetic operation or function argument) in the RTL.
STREAM	Specifies that a specific array is to be implemented as a FIFO or RAM memory channel during dataflow optimization.
UNROLL	Unroll for-loops to create multiple independent operations rather than a single collection of operations.

In addition to the optimization directives, Vivado HLS provides a number of configuration settings. Configuration settings are used to change the default behavior of synthesis. The configuration settings are shown in the following table.

Table 1-24: Vivado HLS Configurations

GUI Directive	Description
Config Array Partition	This configuration determines how arrays are partitioned, including global arrays and if the partitioning impacts array ports.
Config Bind	Determines the effort level to use during the synthesis binding phase and can be used to globally minimize the number of operations used.
Config Compile	Controls synthesis specific optimizations such as the automatic loop pipelining and floating point math optimizations.
Config Dataflow	This configuration specifies the default memory channel and FIFO depth in dataflow optimization.
Config Interface	This configuration controls I/O ports not associated with the top-level function arguments and allows unused ports to be eliminated from the final RTL.
Config RTL	Provides control over the output RTL including file and module naming, reset style and FSM encoding.
Config Schedule	Determines the effort level to use during the synthesis scheduling phase and the verbosity of the output messages

Details on how to apply the optimizations and configurations is provided in [Applying Optimization Directives](#). The configurations are accessed using the menu **Solution** > **Solution Settings** > **General** and selecting the configuration using the **Add** button.

The optimizations are presented in the context of how they are typically applied on a design.

The Clock, Reset and RTL output are discussed together. The clock frequency along with the target device is the primary constraint which drives optimization. High-Level Synthesis seeks to place as many operations from the target device into each clock cycle. The reset style used in the final RTL is controlled, along setting such as the FSM encoding style, using the config_rtl configuration.

The primary optimizations for Optimizing for Throughput are presented together in the manner in which they are typically used: pipeline the tasks to improve performance, improve the data flow between tasks and optimize structures to improve address issues which may limit performance.

Optimizing for Latency uses the techniques of latency constraints and the removal of loop transitions to reduce the number of clock cycles required to complete.

A focus on how operations are implemented - controlling the number of operations and how those operations are implemented in hardware - is the principal technique for improving the area.

Clock, Reset, and RTL Output

Specifying the Clock Frequency

For C and C++ designs only a single clock is supported. The same clock is applied to all functions in the design.

For SystemC designs, each SC_MODULE may be specified with a different clock. To specify multiple clocks in a SystemC design, use the -name option of the `create_clock` command to create multiple named clocks and use the CLOCK directive or pragma to specify which function contains the SC_MODULE to be synthesized with the specified clock. Each SC_MODULE can only be synthesized using a single clock: clocks may be distributed through functions, such as when multiple clocks are connected from the top-level ports to individual blocks, but each SC_MODULE can only be sensitive to a single clock.

The clock period, in ns, is set in the **Solutions > Solutions Setting**. Vivado HLS uses the concept of a clock uncertainty to provide a user defined timing margin. Using the clock frequency and device target information Vivado HLS estimates the timing of operations in the design but it cannot know the final component placement and net routing: these operations are performed by logic synthesis of the output RTL. As such, Vivado HLS cannot know the exact delays.

To calculate the clock period used for synthesis, Vivado HLS subtracts the clock uncertainty from the clock period, as shown in the following figure.

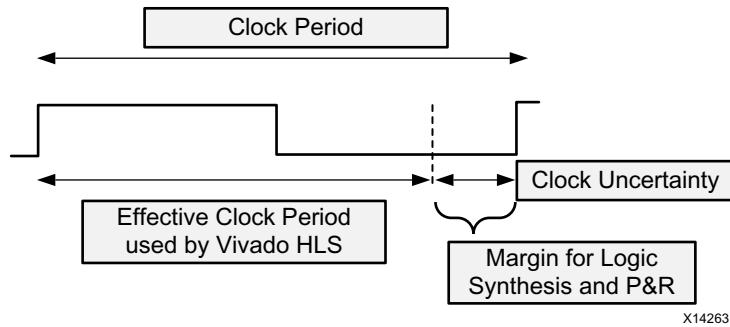


Figure 1-58: Clock Period and Margin

This provides a user specified margin to ensure downstream processes, such as logic synthesis and place & route, have enough timing margin to complete their operations. If the FPGA device is mostly utilized the placement of cells and routing of nets to connect the cells might not be ideal and might result in a design with larger than expected timing delays. For a situation such as this, an increased timing margin ensures Vivado HLS does not create a design with too much logic packed into each clock cycle and allows RTL synthesis to satisfy timing in cases with less than ideal placement and routing options.

By default, the clock uncertainty is 12.5% of the cycle time. The value can be explicitly specified beside the clock period.

Vivado HLS aims to satisfy all constraints: timing, throughput, latency. However, if a constraints cannot be satisfied, Vivado HLS always outputs an RTL design.

If the timing constraints inferred by the clock period cannot be met Vivado HLS issues message SCED-644, as shown below, and creates a design with the best achievable performance.

```
@W [SCED-644] Max operation delay (<operation_name> 2.39ns) exceeds the effective
cycle time
```

Even if Vivado HLS cannot satisfy the timing requirements for a particular path, it still achieves timing on all other paths. This behavior allows you to evaluate if higher optimization levels or special handling of those failing paths by downstream logic syntheses can pull-in and ultimately satisfy the timing.



IMPORTANT: *It is important to review the constraint report after synthesis to determine if all constraints is met: the fact that High-Level Synthesis produces an output design does not guarantee the design meets all performance constraints. Review the "Performance Estimates" section of the design report.*

A design report is generated for each function in the hierarchy when synthesis completes and can be viewed in the solution reports folder. The worse case timing for the entire design is reported as the worst case in each function report. There is no need to review every report in the hierarchy.

If the timing violations are too severe to be further optimized and corrected by downstream processes, review the techniques for specifying an exact latency and specifying exact implementation cores before considering a faster target technology.

Specifying the Reset

Typically the most important aspect of RTL configuration is selecting the reset behavior. When discussing reset behavior it is important to understand the difference between initialization and reset.

Initialization Behavior

In C, variables defined with the static qualifier and those defined in the global scope, are by default initialized to zero. Optionally, these variables may be assigned a specific initial value. For these type of variables, the initial value in the C code is assigned at compile time (at time zero) and never again. In both cases, the same initial value is implemented in the RTL.

- During RTL simulation the variables are initialized with the same values as the C code.
- The same variables are initialized in the bitstream used to program the FPGA. When the device powers up, the variables will start in their initialized state.

The variables start with the same initial state as the C code. However, there is no way to force a return to this initial state. To return to their initial state the variables must be implemented with a reset.

Controlling the Reset Behavior

The reset port is used in an FPGA to return the registers and block RAM connected to the reset port to an initial value any time the reset signal is applied. The presence and behavior of the RTL reset port is controlled using the `config_rtl` configuration shown in the following figure. To access this configuration, select **Solution > Solution Settings > General > Add > config_rtl**.

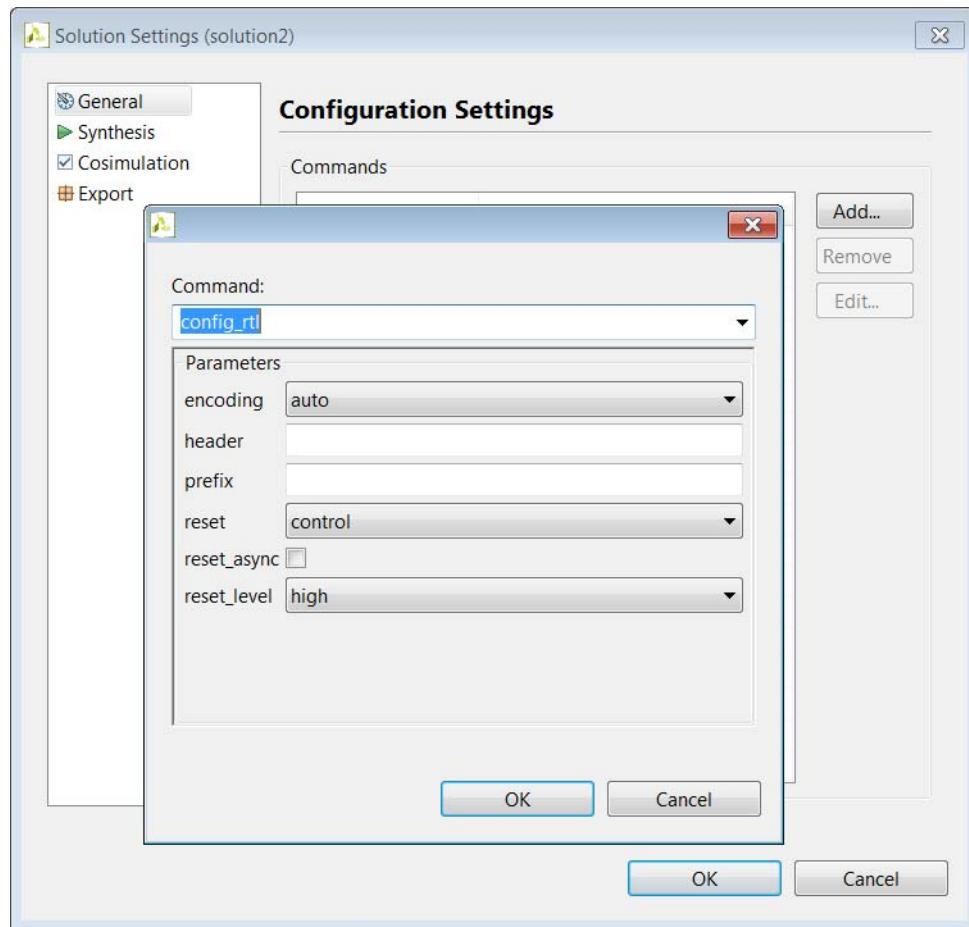


Figure 1-59: RTL Configurations

The reset settings include the ability to set the polarity of the reset and whether the reset is synchronous or asynchronous but more importantly it controls, through the reset option, which registers are reset when the reset signal is applied.



IMPORTANT: When AXI4 interfaces are used on a design the reset polarity is automatically changed to active-low irrespective of the setting in the config_rtl configuration. This is required by the AXI4 standard.

The reset option has four settings:

- **none**: No reset is added to the design.
- **control**: This is the default and ensures all control registers are reset. Control registers are those used in state machines and to generate I/O protocol signals. This setting ensures the design can immediately start its operation state.
- **state**: This option adds a reset to control registers (as in the control setting) plus any registers or memories derived from static and global variables in the C code. This setting ensures static and global variable initialized in the C code are reset to their initialized value after the reset is applied.
- **all**: This adds a reset to all registers and memories in the design.

Finer grain control over reset is provided through the RESET directive. If a variable is a static or global, the RESET directive is used to explicitly add a reset, or the variable can be removed from those being reset by using the RESET directive's `off` option. This can be particularly useful when static or global arrays are present in the design.



IMPORTANT: It is important when using the `reset state` or `all` option to consider the effect on arrays.

Array Initialization and Reset

Arrays are often defined as static variables, which implies all elements be initialized to zero, and arrays are typically implemented as block RAM. When reset options `state` or `all` are used, it forces all arrays implemented as block RAM to be returned to their initialized state after reset. This may result in two very undesirable attributes in the RTL design:

- Unlike a power-up initialization, an explicit reset requires the RTL design iterate through each address in the block RAM to set the value: this can take many clock cycles if N is large and require more area resources to implement.
- A reset is added to every array in the design.

To prevent placing reset logic onto every such block RAM and incurring the cycle overhead to reset all elements in the RAM:

- Use the default `control` reset mode and use the RESET directive to specify individual static or global variables to be reset.
- Alternatively, use reset mode `state` and remove the reset from specific static or global variables using the `off` option to the RESET directive.

RTL Output

Various characteristics of the RTL output by Vivado HLS can be controlled using the config_rtl configuration shown in [Figure 1-59](#).

- Specify the type of FSM encoding used in the RTL state machines.
- Add an arbitrary comment string, such as a copyright notice, to all RTL files using the -header option.
- Specify a unique name with the prefix option which is added to all RTL output files.

The default FSM coding is style is auto. With auto encoding Vivado HLS determines the style of encoding however the Xilinx logic synthesis tools (Vivado and ISE) can extract and re-implement the FSM style during logic synthesis. If any other encoding style is selected (bin, onehot), the encoding style cannot be re-optimized by Xilinx logic synthesis tools.

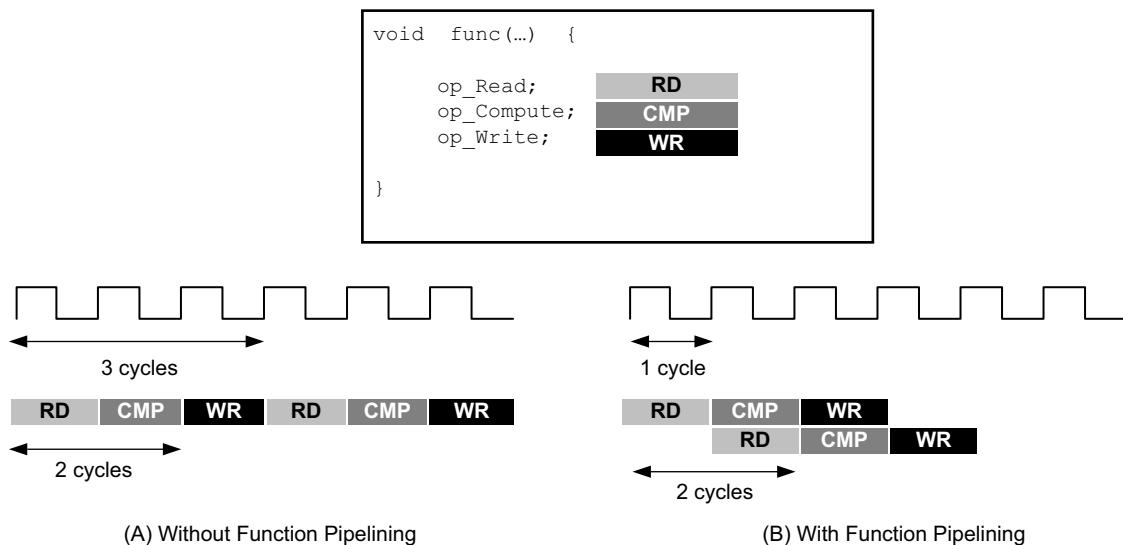
The name of the RTL output files is derived from the name of the top-level function for synthesis. If different RTL blocks are created from the same top-level function, the RTL files will have the same name and cannot be combined in the same RTL project. The prefix option allows RTL files generated from the same top-level function (and which by default have the same name as the top-level function) to be easily combined in the same directory.

Optimizing for Throughput

The flow for optimizing a design to improve throughput, or reduce the initiation interval, is discussed in [Synthesis Strategies](#). The optimizations used to perform this type of optimization are reviewed in detail here.

Task Pipelining

Pipelining allows operations to happen concurrently: the task does not have to complete all operations before it begin the next operation. Pipelining is applied to functions and loops. The throughput improvements in function pipelining are shown in the following figure.



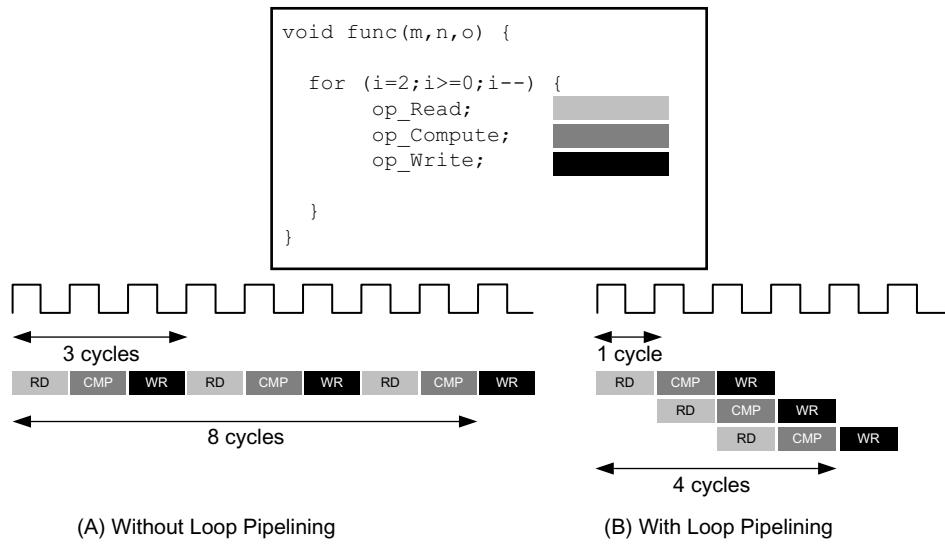
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Figure 1-60: Function Pipelining Behavior

Without pipelining the function reads an input every 3 clock cycles and outputs a value every 2 clock cycles. The function has an Initiation Interval (II) of 3 and a latency of 2. With pipelining, a new input is read every cycle (II=1) with no change to the output latency or resources used.

Loop pipelining allows the operations in a loop to be implemented in a concurrent manner as shown in the following figure. In this figure, (A) shows the default sequential operation where there are 3 clock cycles between each input read (II=3), and it requires 8 clock cycles before the last output write is performed.

In the pipelined version of the loop shown in (B), a new input sample is read every cycle (II=1) and the final output is written after only 4 clock cycles: substantially improving both the II and latency while using the same hardware resources.



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Figure 1-61: Loop Pipelining

Tasks are pipelined using the PIPELINE directive. The initiation interval defaults to 1 if not specified but may be explicitly specified.

Pipelining is applied to the specified task not to the hierarchy below: all loops in the hierarchy below are automatically unrolled. Any sub-functions in the hierarchy below the specified task must be pipelined individually. If the sub-functions are pipelined, the pipelined tasks above it can take advantage of the pipeline performance. Conversely, any sub-function below the pipelined task that is not pipelined, may be the limiting factor in the performance of the pipeline.

There is a difference in how pipelined functions and loops behave.

- In the case of functions, the pipeline runs forever and never ends.
- In the case of loops, the pipeline executes until all iterations of the loop are completed.

This difference in behavior is summarized in the following figure.

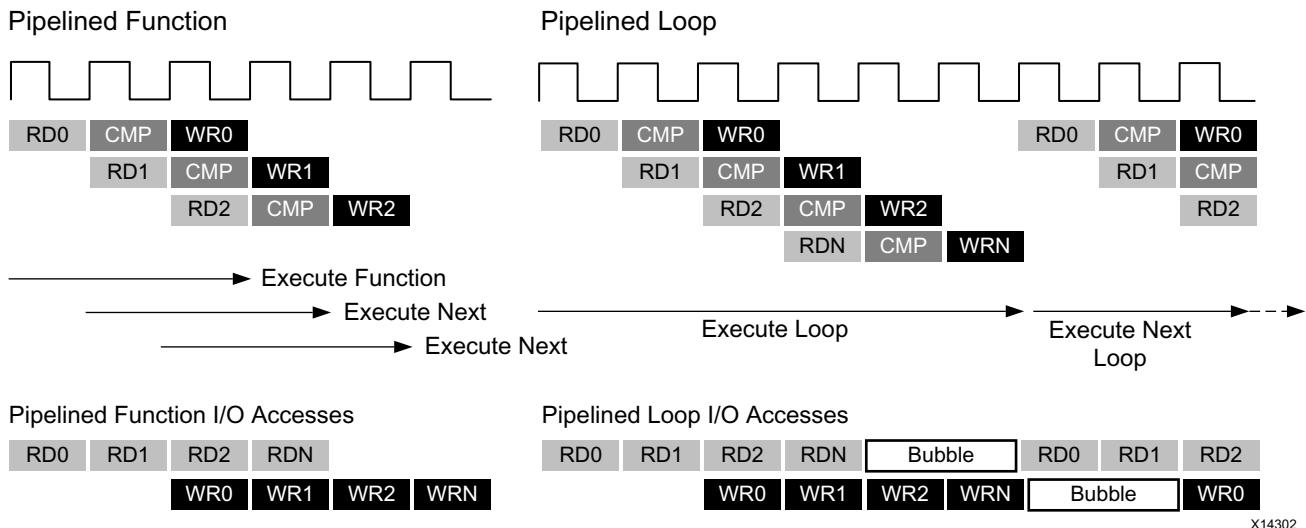


Figure 1-62: Function and Loop Pipelining Behavior

An implication from the difference in behavior is the difference in how inputs and outputs to the pipeline are processed. As seen the figure above, a pipelined function will continuously read new inputs and write new outputs. By contrast, because a loop must first finish all operations in the loop before starting the next loop, a pipelined loop causes a “bubble” in the data stream: a point when no new inputs are read as the loop completes the execution of the final iterations, and a point when no new outputs are written as the loop starts new loop iterations.

Rewinding Pipelined Loops for Performance

Loops which are the top-level loop in a function or are used in a region where the DATAFLOW optimization is used can be made to continuously execute using the PIPELINE directive with the `rewind` option.

The following figure shows the operation when the `rewind` option is used when pipelining a loop. At the end of the loop iteration count, the loop immediately starts to re-execute.

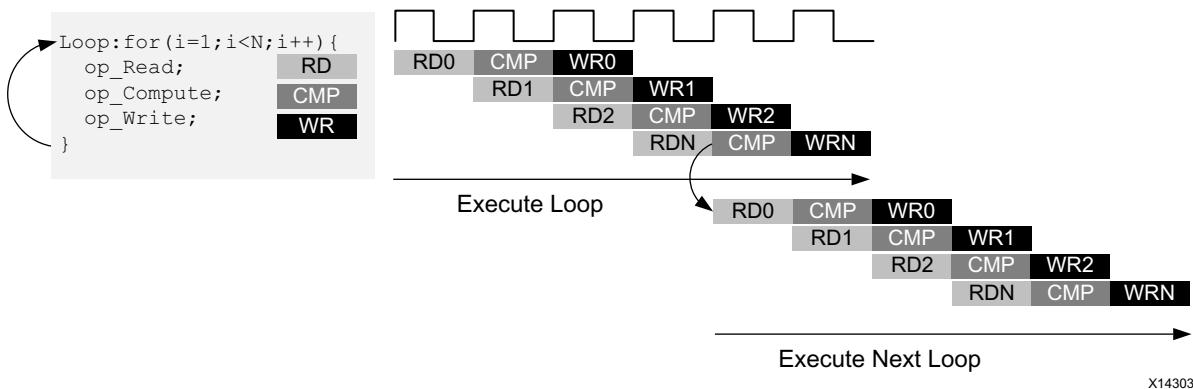


Figure 1-63: Loop Pipelining with Rewind Option

If the loop is the top-level loop in a function, the C code before the loop cannot perform any operations on the data. The result of the function must be the same if the function is executed again or if the loop immediately re-executes.

If the loop is used in a region with the DATAFLOW optimization, Vivado HLS automatically implements the loop as if it is in a function hierarchy.

Flushing Pipelines

Pipelines continue to execute as long as data is available at the input of the pipeline. If there is no data available to process, the pipeline will stall. This is shown in the following figure, where the input data valid signal goes low to indicate there is no more data. Once there is new data available to process, the pipeline will continue operation.

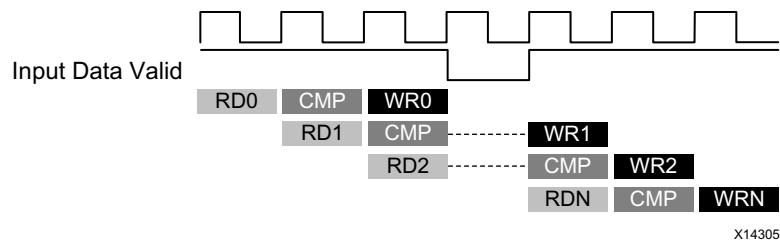


Figure 1-64: Loop Pipelining with Stall

In some cases, it is desirable to have a pipeline that can be “emptied” or “flushed”. The `flush` option is provided to perform this. When a pipeline is “flushed” the pipeline stops reading new inputs when none are available (as determined by a data valid signal at the start of the pipeline) but continues processing, shutting down each successive pipeline stage, until the final input has been processed through to the output of the pipeline.



IMPORTANT: The pipeline flush feature is only supported for pipelined functions.

Automatic Loop Pipelining

The `config_compile` configuration enables loops to be pipelined automatically based on the iteration count. This configuration is accessed through the menu **Solution > Solution Settings > General > Add > config_compile**.

The `pipeline_loops` option set the iteration limit. All loops with an iteration count below this limit are automatically pipelined. The default is 0: no automatic loop pipelining is performed.

Given the following example code:

```
for (y = 0; y < 480; y++) {
    for (x = 0; x < 640; x++) {
        for (i = 0; i < 5; i++) {
            // do something 5 times
            ...
        }
    }
}
```

If the `pipeline_loops` option is set to 10 - a value above 5 but below 5×640 - the following pipelining will be performed automatically:

```
for (y = 0; y < 480; y++) {
    for (x = 0; x < 640; x++) {
#pragma HLS PIPELINE II=1
        for (i = 0; i < 5; i++) {
            // This loop will be automatically unrolled
            // do something 5 times in parallel
            ...
        }
    }
}
```

If there are loops in the design which you do not wish automatic pipelining to be applied to, the `PIPELINE` directive with the `off` option can be applied to that loop. The `off` option prevents automatic loop pipelining.

Addressing Failure to Pipeline

When a task is pipelined, all loops in the hierarchy are automatically unrolled. This is a requirement for pipelining to proceed. If a loop has variables bounds it cannot be unrolled. This will prevent the task from being pipelined. Refer to [Variable Loop Bounds in Chapter 3](#) for techniques to remove such loops from the design.

Partitioning Arrays to Improve Pipelining

A common issue when pipelining tasks is the following message:

```
@I [SCHED-61] Pipelining loop 'SUM_LOOP'.
@W [SCHED-69] Unable to schedule 'load' operation ('mem_load_2', bottleneck.c:57) on
array 'mem' due to limited memory ports.
@I [SCHED-61] Pipelining result: Target II: 1, Final II: 2, Depth: 3.
```

In this example, Vivado HLS states it cannot reach the specified initiation interval (II) of 1 because it cannot schedule a load (write) operation onto the memory because of limited memory ports. It reports a final II of 2 instead of the desired 1.

This problem is typically caused by arrays. Arrays are implemented as block RAM which only has a maximum of two data ports. This can limit the throughput of a read/write (or load/store) intensive algorithm. The bandwidth can be improved by splitting the array (a single block RAM resource) into multiple smaller arrays (multiple block RAMs), effectively increasing the number of ports.

Arrays are partitioned using the `ARRAY_PARTITION` directive. Vivado HLS provides three types of array partitioning, as shown in the following figure. The three styles of partitioning are:

- **block**: the original array is split into equally sized blocks of consecutive elements of the original array.
- **cyclic**: the original array is split into equally sized blocks interleaving the elements of the original array.
- **complete**: the default operation is to split the array into its individual elements. This corresponds to resolving a memory into registers.

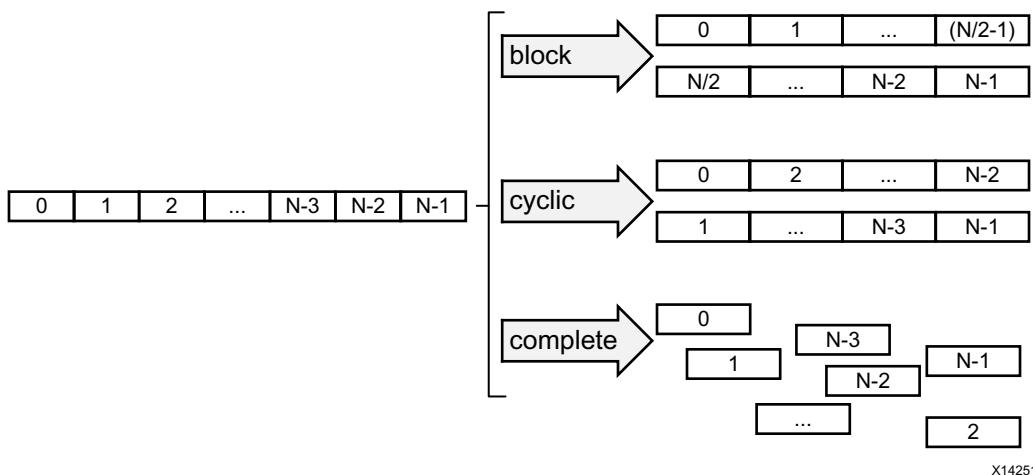


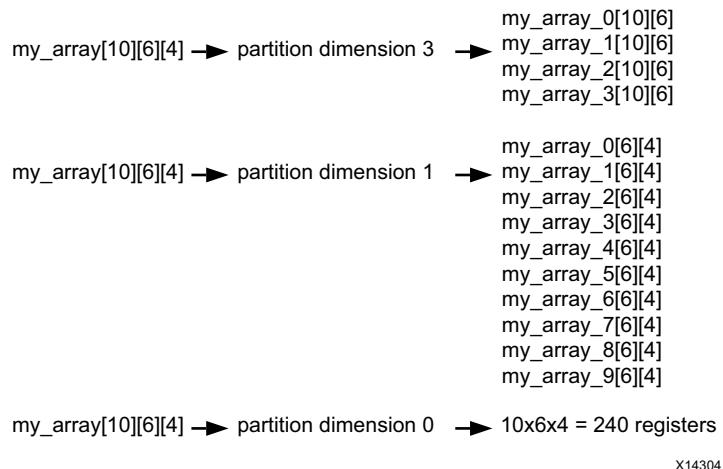
Figure 1-65: Array Partitioning

For block and cyclic partitioning the `factor` option specifies the number of arrays that are created. In the preceding figure, a factor of 2 is used, that is, the array is divided into two smaller arrays. If the number of elements in the array is not an integer multiple of the factor, the final array has fewer elements.

When partitioning multi-dimensional arrays, the `dimension` option is used to specify which dimension is partitioned. The following figure shows how the `dimension` option is used to partition the following example code:

```
void foo (...) {
    int my_array[10][6][4];
    ...
}
```

The examples in the figure demonstrate how partitioning dimension 3 results in 4 separate arrays and partitioning dimension 1 results in 10 separate arrays. If zero is specified as the dimension, all dimensions are partitioned.



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Figure 1-66: Partitioning Array Dimensions

Automatic Array Partitioning

The `config_array_partition` configuration determines how arrays are automatically partitioned based on the number of elements. This configuration is accessed through the menu **Solution > Solution Settings > General > Add > config_array_partition**.

The partition thresholds can be adjusted and partitioning can be fully automated with the `throughput_driven` option. When the `throughput_driven` option is selected Vivado HLS automatically partitions arrays to achieve the specified throughput.

Removing False Dependencies to Improve Loop Pipelining

Loop pipelining can be prevented by loop carry dependencies. Under certain complex scenarios automatic dependence analysis can be too conservative and fail to filter out false dependencies.

In this example, the Vivado HLS does not have any knowledge about the value of `cols` and conservatively assumes that there is always a dependence between the write to `buff_A[1][cols]` and the read from `buff_A[1][cols]`.

```
void foo(int rows, int cols, ...)

for (row = 0; row < rows + 1; row++) {
    for (col = 0; col < cols + 1; col++) {
#pragma HLS PIPELINE II=1
        if (col < cols) {
            buff_A[2][col] = buff_A[1][col]; // read from buff_A[1][col]
            buff_A[1][col] = buff_A[0][col]; // write to buff_A[1][col]
            buff_B[1][col] = buff_B[0][col];
            temp = buff_A[0][col];
        }
    }
}
```

The issue is highlighted in the following figure. If `cols=0`, the next iteration of the rows loop starts immediately, and the read from `buff_A[0][cols]` cannot happen at the same time as the write.

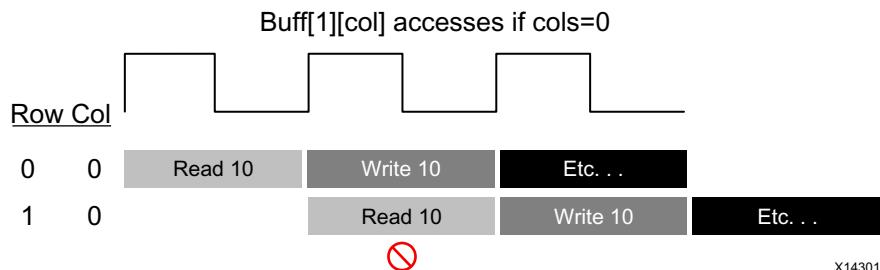


Figure 1-67: Partitioning Array Dimensions

In an algorithm such as this, it is unlikely `cols` will ever be zero but Vivado HLS cannot make assumptions about data dependencies. To overcome this deficiency, you can use the `DEPENDENCE` directive to provide Vivado HLS with additional information about the dependencies. In this case, state there is no dependence between loop iterations (in this case, for both `buff_A` and `buff_B`).

```
void foo(int rows, int cols, ...)

for (row = 0; row < rows + 1; row++) {
    for (col = 0; col < cols + 1; col++) {
        #pragma HLS PIPELINE II=1
        #pragma AP dependence variable=buf_A inter false
        #pragma AP dependence variable=buf_B inter false
        if (col < cols) {
            buf_A[2][col] = buf_A[1][col]; // read from buf_A[1][col]
            buf_A[1][col] = buf_A[0][col]; // write to buf_A[1][col]
            buf_B[1][col] = buf_B[0][col];
            temp = buf_A[0][col];
        }
    }
}
```

Note: Specifying a false dependency, when in fact the dependency is not false, can result in incorrect hardware. Be sure dependencies are correct (true or false) before specifying them.

When specifying dependencies there are two main types:

- **Inter:** Specifies the dependency is between different iterations of the same loop.

If this is specified as false it allows Vivado HLS to perform operations in parallel if the pipelined or loop is unrolled or partially unrolled and prevents such concurrent operation when specified as true.

- **Intra:** Specifies dependence within the same iteration of a loop, for example an array being accessed at the start and end of the same iteration.

When intra dependencies are specified as false Vivado HLS may move operations freely within the loop, increasing their mobility and potentially improving performance or area. When the dependency is specified as true, the operations must be performed in the order specified.

Data dependencies are a much harder issues to resolve and often require changes to the source code. A scalar data dependency could look like the following:

```
while (a != b) {
    if (a > b) a -= b;
    else b -= a;
}
```

The next iteration of this loop cannot start until the current iteration has calculated the updated values of `a` and `b`, as shown in the following figure.

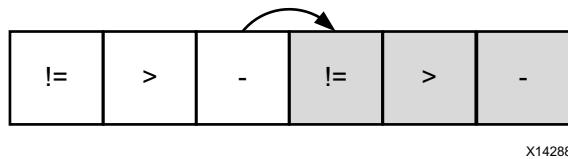


Figure 1-68: Scalar Dependency

If the result of the previous loop iteration must be available before the current iteration can begin, loop pipelining is not possible. If Vivado HLS cannot pipeline with the specified initiation interval it increases the initiation interval. If it cannot pipeline at all, as shown by the above example, it halts pipelining and proceeds to output a non-pipelined design.

Optimal Loop Unrolling to Improve Pipelining

By default loops are kept rolled in Vivado HLS. That is to say that the loops are treated as a single entity: all operations in the loop are implemented using the same hardware resources for iteration of the loop.

Vivado HLS provides the ability to unroll or partially unroll for-loops using the UNROLL directive.

The following figure shows both the powerful advantages of loop unrolling and the implications that must be considered when unrolling loops. This example assumes the arrays `a[i]`, `b[i]` and `c[i]` are mapped to block RAMs. This example shows how easy it is to create many different implementations by the simple application of loop unrolling.

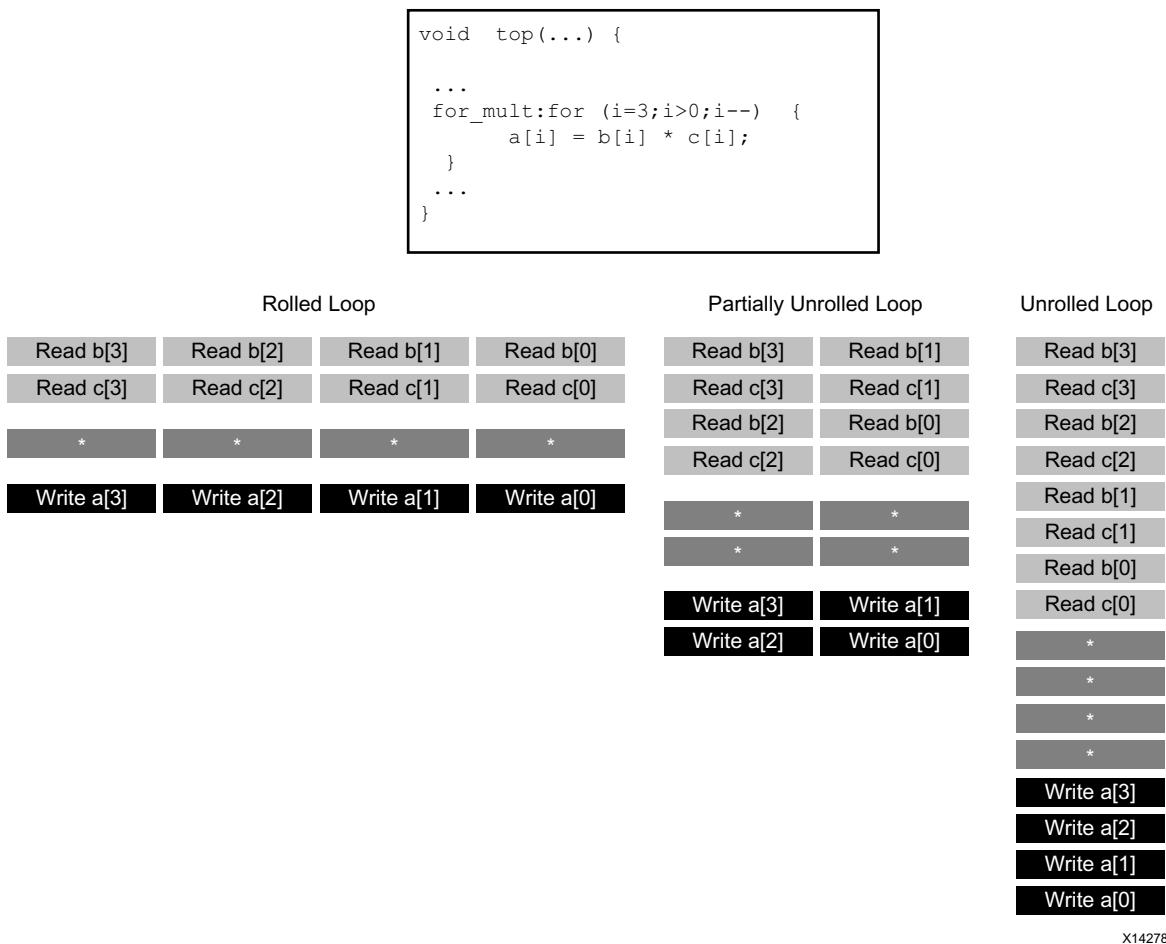


Figure 1-69: Loop Unrolling Details

- **Rolled Loop:** When the loop is rolled, each iteration is performed in a separate clock cycle. This implementation takes four clock cycles, only requires one multiplier and each block RAM can be a single-port block RAM.
- **Partially Unrolled Loop:** In this example, the loop is partially unrolled by a factor of 2. This implementation required two multipliers and dual-port RAMs to support two reads or writes to each RAM in the same clock cycle. This implementation does however only take 2 clock cycles to complete: half the initiation interval and half the latency of the rolled loop version.
- **Unrolled loop:** In the fully unrolled version all loop operation can be performed in a single clock cycle. This implementation however requires four multipliers. More importantly, this implementation requires the ability to perform 4 reads and 4 write operations in the same clock cycle. Because a block RAM only has a maximum of two ports, this implementation requires the arrays be partitioned.

To perform loop unrolling, you can apply the UNROLL directives to individual loops in the design. Alternatively, you can apply the UNROLL directive to a function, which unrolls all loops within the scope of the function.

If a loop is completely unrolled, all operations will be performed in parallel: if data dependencies allow. If operations in one iteration of the loop require the result from a previous iteration, they cannot execute in parallel but will execute as soon as the data is available. A completely unrolled loop will mean multiple copies of the logic in the loop body.

The following example code demonstrates how loop unrolling can be used to create an optimal design. In this example, the data is stored in the arrays as interleaved channels. If the loop is pipelined with II=1 each channel is only read and written every 8th block cycle.

```

// Array Order :  0   1   2   3   4   5   6   7   8      9      10      etc. 16      etc...
// Sample Order: A0  B0  C0  D0  E0  F0  G0  H0  A1      B1      C2      etc. A2      etc...
// Output Order: A0  B0  C0  D0  E0  F0  G0  H0  A0+A1  B0+B1  C0+C2  etc. A0+A1+A2 etc...

#define CHANNELS 8
#define SAMPLES 400
#define N CHANNELS * SAMPLES

void foo (dout_t d_o[N], din_t d_i[N]) {
    int i, rem;

    // Store accumulated data
    static dacc_t acc[CHANNELS];

    // Accumulate each channel
    For_Loop: for (i=0;i<N;i++) {
        rem=i%CHANNELS;
        acc[rem] = acc[rem] + d_i[i];
        d_o[i] = acc[rem];
    }
}

```

Partially unrolling the loop by a factor of 8 will allow each of the channels (every 8th sample) to be processed in parallel (if the input and output arrays are also partitioned in a cyclic manner to allow multiple accesses per clock cycle). If the loop is also pipelined with the rewind option, this design will continuously process all 8 channels in parallel.

```
void foo (dout_t d_o[N], din_t d_i[N]) {
    #pragma HLS ARRAY_PARTITION variable=d_i cyclic factor=8 dim=1 partition
    #pragma HLS ARRAY_PARTITION variable=d_o cyclic factor=8 dim=1 partition

    int i, rem;

    // Store accumulated data
    static dacc_t acc[CHANNELS];

    // Accumulate each channel
    For_Loop: for (i=0;i<N;i++) {
        #pragma HLS PIPELINE rewind
        #pragma HLS UNROLL factor=8

        rem=i%CHANNELS;
        acc[rem] = acc[rem] + d_i[i];
        d_o[i] = acc[rem];
    }
}
```

Partial loop unrolling does not require the unroll factor to be an integer multiple of the maximum iteration count. Vivado HLS adds an exit checks to ensure partially unrolled loops are functionally identical to the original loop. For example, given the following code:

```
for(int i = 0; i < N; i++) {
    a[i] = b[i] + c[i];
}
```

Loop unrolling by a factor of 2 effectively transforms the code to look like the following example where the `break` construct is used to ensure the functionality remains the same:

```
for(int i = 0; i < N; i += 2) {
    a[i] = b[i] + c[i];
    if (i+1 >= N) break;
    a[i+1] = b[i+1] + c[i+1];
}
```

Because N is a variable, Vivado HLS may not be able to determine its maximum value (it could be driven from an input port). If you know the unrolling factor, 2 in this case, is an integer factor of the maximum iteration count N, the `skip_exit_check` option removes the exit check and associated logic. The effect of unrolling can now be represented as:

```
for(int i = 0; i < N; i += 2) {
    a[i] = b[i] + c[i];
    a[i+1] = b[i+1] + c[i+1];
}
```

This helps minimize the area and simplify the control logic.

Task Level Pipelining: Data Flow Optimization

The DATAFLOW optimization starts with a series of sequential tasks (functions, loops, or both) as shown in the following figure.

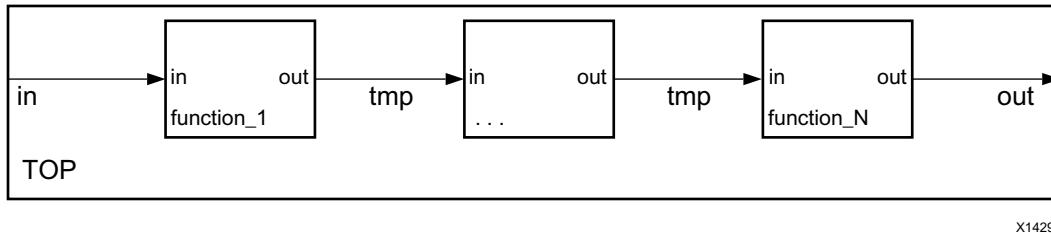


Figure 1-70: Sequential Functional Description

Using this series of sequential tasks, DATAFLOW optimization creates a parallel process architecture as shown in the following figure. Dataflow optimization is a powerful method for improving design throughput.

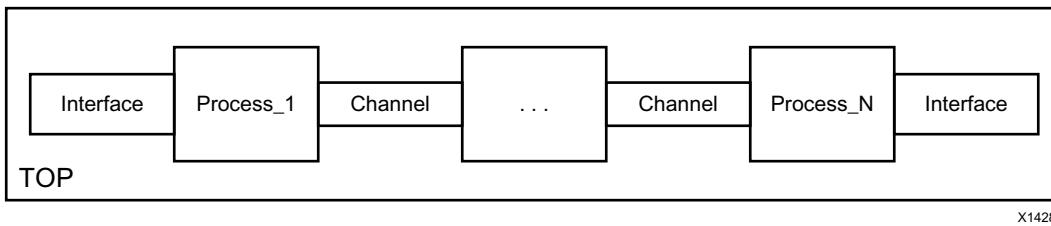
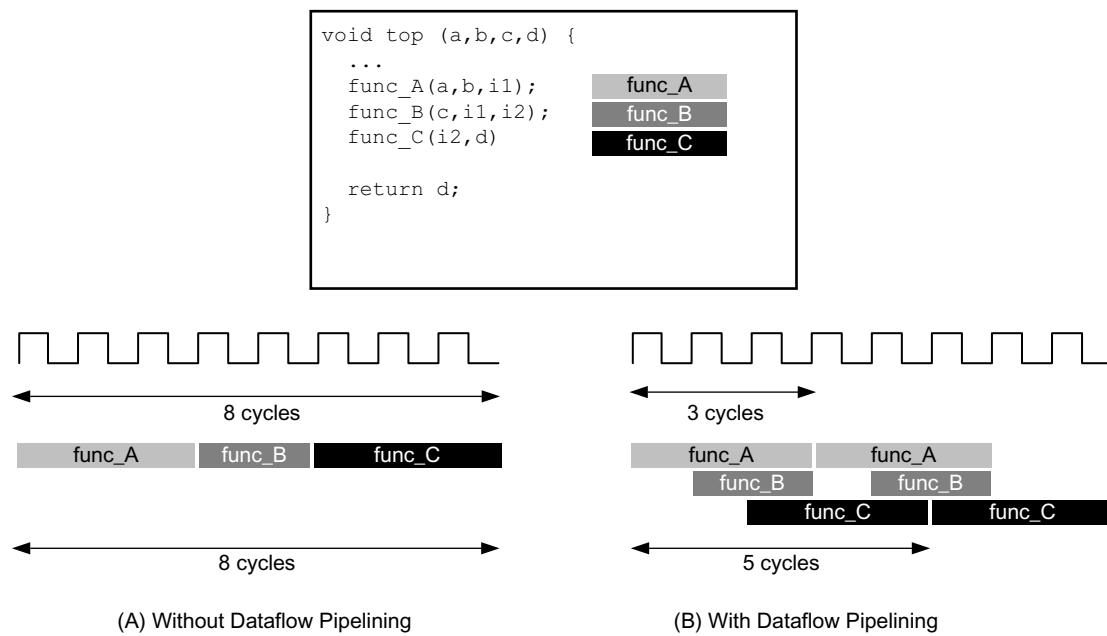


Figure 1-71: Parallel Process Architecture

The channels shown in the preceding figure ensure a task is not required to wait until the previous task has completed all operations before it can begin. The following figure shows how DATAFLOW optimization allows the execution of tasks to overlap, increasing the overall throughput of the design and reducing latency.

In the example without dataflow pipelining (A) in the following figure, the implementation requires 8 cycles before a new input can be processed by func_A and 8 cycles before an output is written by func_C .

In the example with dataflow pipelining (B) in the following figure, func_A can begin processing a new input every 3 clock cycles (lower initiation interval) and it now only requires 5 clocks to output a final value (shorter latency).



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Figure 1-72: Dataflow Optimization

The DATAFLOW optimization does not optimize tasks that are conditionally executed. The following example highlights this limitation:

```

void foo(boolean cond) {

    if (cond)
        Loop1: for(int i = 0; i < HEIGHT; i++) {
            ...Loop1 Body
        }
    } else {
        Loop2: for(int j = 0; j < WIDTH; j++) {
            ...Loop2 Body
        }
    }
    Loop3: for(int k = 0; k < NUM_CALC; k++) {
        ...Loop3 Body
    }
}
  
```

The conditional execution of Loop1 and Loop2 prevents the data flow between these loops from being optimized. Each loop only starts executing when the previous loop completes all operations. To use the DATAFLOW optimization, you must transform the code into the following:

```
void foo(boolean cond) {
    #pragma HLS DATAFLOW

    Loop1: for(int i = 0; i < HEIGHT; i++) {
        if (cond) {
            ...Loop1 Body
        }
    }
    Loop2: for(int j = 0; j < WIDTH; j++) {
        if (!cond){
            ...Loop2 Body
        }
    }
    Loop3: for(int k = 0; k < NUM_CALC; k++) {
        ...Loop3 Body
    }
}
```

The DATAFLOW optimization then ensures that each loop starts processing data as soon as data is available to enable the maximum possible throughput.



IMPORTANT: *To use dataflow optimization, the arguments in each task must appear only twice: once as the producer of a task and once as the consumer of another task. This includes return arguments. In addition, all data or variables must flow from one task (loop or function) to the next. For example, all inputs must be consumed by the first task. All outputs from the first task must be consumed by the second task and so forth until the final task in the dataflow region produces all outputs.*

The DATAFLOW optimization can only be applied to function scopes. The DATAFLOW optimization cannot be applied inside loops. The optimization is only applied to the tasks within the scope. If a sub-function contains additional tasks which could also benefit from the DATAFLOW optimization, the DATAFLOW optimization must be applied to the sub-function of the sub-function should be inlined.

Configuring Dataflow Memory Channels

Vivado HLS implements channels between the tasks as either ping-pong or FIFO buffers, depending on the access patterns of the producer and the consumer of the data:

- For scalar, pointer, and reference parameters as well as the function return, Vivado HLS implements the channel as a FIFO.
- Note:** For scalar values, the maximum channel size is one, that is, only one value is passed from one function to another.
- If the parameter (producer or consumer) is an array, Vivado HLS implements the channel as a ping-pong buffer or a FIFO as follows:
 - If Vivado HLS determines the data is accessed in sequential order, Vivado HLS implements the memory channel as a FIFO channel of depth 1.
 - If Vivado HLS is unable to determine that the data is accessed in sequential order or determines the data is accessed in an arbitrary manner, Vivado HLS implements the memory channel as a ping-pong buffer, that is, as two block RAMs each defined by the maximum size of the consumer or producer array.

Note: A ping-pong buffer ensures that the channel always has the capacity to hold all samples without a loss. However, this might be an overly conservative approach in some cases. For example, if tasks are pipelined with an interval of 1 and use data in a streaming, sequential manner but Vivado HLS is unable to automatically determine the sequential data usage, Vivado HLS implements a ping-pong buffer. In this case, the channel only requires a single register and not 2 block RAM defined by the size of the array.

To explicitly specify the default channel used between tasks, use the `config_dataflow` configuration. This configuration sets the default channel for all channels in a design. To reduce the size of the memory used in the channel, you can use a FIFO. To explicitly set the depth or number of elements in the FIFO, use the `fifo_depth` option.

Specifying the size of the FIFO channels overrides the default safe approach. If any task in the design can produce or consume samples at a greater rate than the specified size of the FIFO, the FIFOs might become empty (or full). In this case, the design halts operation, because it is unable to read (or write). This might result in a stalled, unrecoverable state.

Note: This issue only appears when executing C/RTL co-simulation or when the block is used in a complete system.

When setting the depth of the FIFOs, it is recommended that you use FIFOs with the default depth, confirm the design passes C/RTL co-simulation, and then reduce the size of the FIFOs and confirm C/RTL co-simulation still completes without issues. If RTL co-simulation fails, the size of the FIFO is likely too small to prevent stalling.

Specifying Arrays as Block RAM or FIFOs

By default all arrays are implemented as block RAM elements, unless complete partitioning reduces them to individual registers. To use a FIFO instead of a block RAM, the array must be specified as streaming using the STREAM directive.

The following arrays are automatically specified as streaming:

- If an array on the top-level function interface is set as interface type ap_fifo, axis or ap_hs it is automatically set as streaming.
- The arrays used in a region where the DATAFLOW optimization is applied are automatically set to streaming if Vivado HLS determines the data is streaming between the tasks or if the config_dataflow configuration sets the default memory channel as FIFO.

All other arrays must be specified as streaming using the STREAM directive if a FIFO is required for the implementation.

The STREAM directive is also used to change any arrays in a DATAFLOW region from the default implementation specified by the config_dataflow configuration.

- If the config_dataflow default_channel is set as ping-pong, any array can be implemented as a FIFO by applying the STREAM directive to the array.
 - To use a FIFO implementation, the array must be accessed in a streaming manner.
- If the config_dataflow default_channel is set to FIFO or Vivado HLS has automatically determined the data in a dataflow region is accessed in a streaming manner, any array can be implemented as a ping-pong implementation by applying the STREAM directive to the array with the off option.

Optimizing for Latency

Using Latency Constraints

Vivado HLS supports the use of a latency constraint on any scope. Latency constraints are specified using the LATENCY directive.

When a maximum and/or minimum LATENCY constraint is placed on a scope, Vivado HLS tries to ensure all operations in the function complete within the range of clock cycles specified.

The latency directive applied to a loop specifies the required latency for a single iteration of the loop: it specifies the latency for the loop body, as the following examples shows:

```
Loop_A: for (i=0; i<N; i++) {
  #pragma HLS latency max=10
  ..Loop Body...
}
```

If the intention is to limit the total latency of all loop iterations, the latency directive should be applied to a region that encompasses the entire loop, as in this example:

```
Region_All_Loop_A: {
    #pragma HLS latency max=10
    Loop_A: for (i=0; i<N; i++)
    {
        ...
        ..Loop Body...
    }
}
```

In this case, even if the loop is unrolled, the latency directive sets a maximum limit on all loop operations.

If Vivado HLS cannot meet a maximum latency constraint it relaxes the latency constraint and tries to achieve the best possible result.

If a minimum latency constraint is set and Vivado HLS can produce a design with a lower latency than the minimum required it inserts dummy clock cycles to meet the minimum latency.

Merging Sequential Loops to Reduce Latency

All rolled loops imply and create at least one state in the design FSM. When there are multiple sequential loops it can create additional unnecessary clock cycles and prevent further optimizations.

The following figure shows a simple example where a seemingly intuitive coding style has a negative impact on the performance of the RTL design.

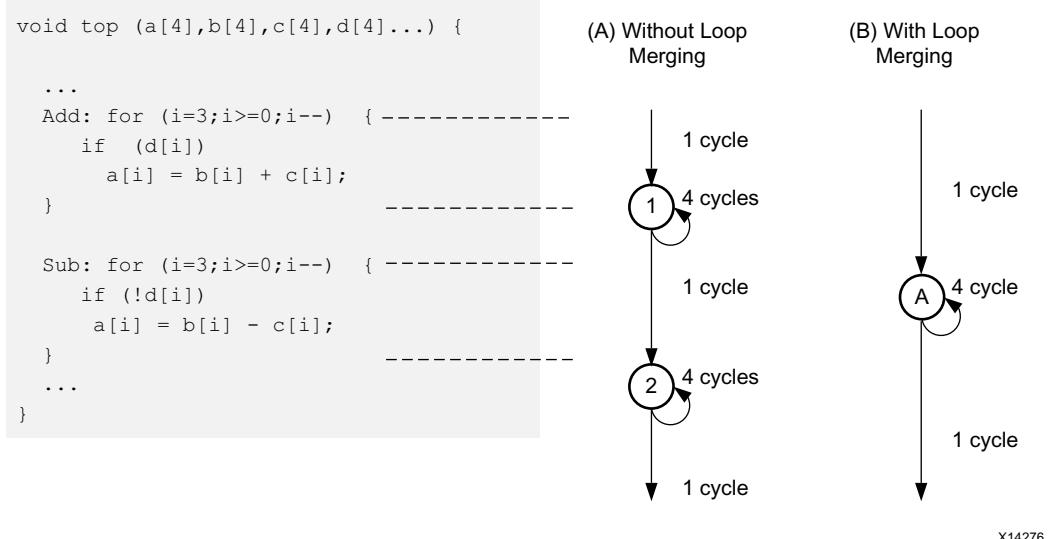


Figure 1-73: Loop Directives

In the preceding figure, (A) shows how, by default, each rolled loop in the design creates at least one state in the FSM. Moving between those states costs clock cycles: assuming each loop iteration requires one clock cycle, it take a total of 11 cycles to execute both loops:

- 1 clock cycle to enter the ADD loop.
- 4 clock cycles to execute the add loop.
- 1 clock cycle to exit ADD and enter SUB.
- 4 clock cycles to execute the SUB loop.
- 1 clock cycle to exit the SUB loop.
- For a total of 11 clock cycles.

In this simple example it is obvious that an else branch in the ADD loop would also solve the issue but in a more complex example it may be less obvious and the more intuitive coding style may have greater advantages.

The LOOP_MERGE optimization directive is used to automatically merge loops. The LOOP_MERGE directive will seek so to merge all loops within the scope it is placed. In the above example, merging the loops creates a control structure similar to that shown in (B) in the preceding figure, which requires only 6 clocks to complete.

Merging loops allows the logic within the loops to be optimized together. In the example above, using a dual-port block RAM allows the add and subtraction operations to be performed in parallel.

Currently, loop merging in Vivado HLS has the following restrictions:

- If loop bounds are all variables, they must have the same value.
- If loops bounds are constants, the maximum constant value is used as the bound of the merged loop.
- Loops with both variable bound and constant bound cannot be merged.
- The code between loops to be merged cannot have side effects: multiple execution of this code should generate the same results ($a=b$ is allowed, $a=a+1$ is not).
- Loops cannot be merged when they contain FIFO accesses: merging would change the order of the reads and writes from a FIFO: these must always occur in sequence.

Flattening Nested Loops to Improve Latency

In a similar manner to the consecutive loops discussed in the previous section, it requires additional clock cycles to move between rolled nested loops. It requires one clock cycle to move from an outer loop to an inner loop and from an inner loop to an outer loop.

In the small example shown here, this implies 200 extra clock cycles to execute loop Outer.

```

void foo_top { a, b, c, d} {
    ...
    Outer: while(j<100)
        Inner: while(i<6)// 1 cycle to enter inner
        ...
        LOOP_BODY
        ...
    } // 1 cycle to exit inner
}
...
}

```

Vivado HLS provides the `set_directive_loop_flatten` command to allow labeled perfect and semi-perfect nested loops to be flattened, removing the need to re-code for optimal hardware performance and reducing the number of cycles it takes to perform the operations in the loop.

- **Perfect loop nest:** only the innermost loop has loop body content, there is no logic specified between the loop statements and all the loop bounds are constant.
- **Semi-perfect loop nest:** only the innermost loop has loop body content, there is no logic specified between the loop statements but the outermost loop bound can be a variable.

For imperfect loop nests, where the inner loop has variables bounds or the loop body is not exclusively inside the inner loop, designers should try to restructure the code, or unroll the loops in the loop body to create a perfect loop nest.

When the directive is applied to a set of nested loops it should be applied to the inner most loop that contains the loop body.

```
set_directive_loop_flatten top/Inner
```

Loop flattening can also be performed using the directive tab in the GUI, either by applying it to individual loops or applying it to all loops in a function by applying the directive at the function level.

Optimizing for Area

Data Types and Bit-Widths

The bit-widths of the variables in the C function directly impact the size of the storage elements and operators used in the RTL implementation. If a variable only requires 12-bits but is specified as an integer type (32-bit) it will result in larger and slower 32-bit operators being used, reducing the number of operations that can be performed in a clock cycle and potentially increasing initiation interval and latency.

- Use the appropriate precision for the data types. Refer to [Data Types for Efficient Hardware](#).
- Confirm the size of any arrays that are to be implemented as RAMs or registers. The area impact of any over-sized elements is wasteful in hardware resources.
- Pay special attention to multiplications, divisions, modulus or other complex arithmetic operations. If these variables are larger than they need to be, they negatively impact both area and performance.

Function Inlining

Function inlining removes the function hierarchy. A function is inlined using the `INLINE` directive.

Inlining a function may improve area by allowing the components within the function to be better shared or optimized with the logic in the calling function. This type of function inlining is also performed automatically by Vivado HLS. Small functions are automatically inlined.

Inlining allows functions sharing to be better controlled. For functions to be shared they must be used within the same level of hierarchy. In this code example, function `foo_top` calls `foo` twice and function `foo_sub`.

```

foo_sub (p, q) {
    int q1 = q + 10;
    foo(p1,q); // foo_3
    ...
}
void foo_top { a, b, c, d} {
    ...
    foo(a,b); //foo_1
    foo(a,c); //foo_2
    foo_sub(a,d);
    ...
}

```

Inlining function `foo_sub` and using the `ALLOCATION` directive to specify only 1 instance of function `foo` is used, results in a design which only has one instance of function `foo`: one-third the area of the example above.

```

foo_sub (p, q) {
    #pragma HLS INLINE
    int q1 = q + 10;
    foo(p1,q); // foo_3
    ...
}
void foo_top { a, b, c, d} {
    #pragma HLS ALLOCATION instances=foo limit=1 function
    ...
    foo(a,b); //foo_1
    foo(a,c); //foo_2
    foo_sub(a,d);
    ...
}

```

The `INLINE` directive optionally allows all functions below the specified function to be recursively inlined by using the `recursive` option. If the `recursive` option is used on the top-level function, all function hierarchy in the design is removed.

The `INLINE off` option can optionally be applied to functions to prevent them being inlined. This option may be used to prevent Vivado HLS from automatically inlining a function.

The `INLINE` directive is a powerful way to substantially modify the structure of the code without actually performing any modifications to the source code and provides a very powerful method for architectural exploration.

Mapping Many Arrays into One Large Array

When there are many small arrays in the C Code, mapping them into a single larger array typically reduces the number of block RAM required.

Each array is mapped into a block RAM. The basic block RAM unit provide in an FPGA is 18K. If many small arrays do not use the full 18K, a better use of the block RAM resources is map many of the small arrays into a larger array. If a block RAM is larger than 18K, they are automatically mapped into multiple 18K units. In the synthesis report, review **Utilization Report > Details > Memory** for a complete understanding of the block RAMs in your design.

The `ARRAY_MAP` directive supports two ways of mapping small arrays into a larger one:

- **Horizontal mapping:** this corresponds to creating a new array by concatenating the original arrays. Physically, this gets implemented as a single array with more elements.
- **Vertical mapping:** this corresponds to creating a new array by concatenating the original words in the array. Physically, this gets implemented by a single array with a larger bit-width.

Horizontal Array Mapping

The following code example has two arrays that would result in two RAM components.

```
void foo (...) {
    int8 array1[M];
    int12 array2[N];
    ...
loop_1: for(i=0;i<M;i++) {
    array1[i] = ...;
    array2[i] = ...;
    ...
}
...
}
```

Arrays `array1` and `array2` can be combined into a single array, specified as `array3` in the following example:

```
void foo (...) {
    int8 array1[M];
    int12 array2[N];
#pragma HLS ARRAY_MAP variable=array1 instance=array3 horizontal
#pragma HLS ARRAY_MAP variable=array2 instance=array3 horizontal
    ...
loop_1: for(i=0;i<M;i++) {
    array1[i] = ...;
    array2[i] = ...;
    ...
}
...
}
```

In this example, the `ARRAY_MAP` directive transforms the arrays as shown in the following figure.



Figure 1-74: Horizontal Mapping

When using horizontal mapping the smaller arrays are mapped into a larger array, starting at location 0 in the larger array, and in the order the commands are specified (In the Vivado HLS GUI it is the order the arrays are specified using the menu. In the Tcl environment it is the order the commands are issued).

The `offset` option to the `ARRAY_MAP` directive is used to specify at which location subsequent arrays are added when using the `horizontal` option. Repeating the previous example, but reversing the order of the commands (specifying `array2` then `array1`) and adding an `offset`, as shown below,

```
void foo (...) {
    int8 array1[M];
    int12 array2[N];
#pragma HLS ARRAY_MAP variable=array2 instance=array3 horizontal
#pragma HLS ARRAY_MAP variable=array1 instance=array3 horizontal offset=2
    ...
loop_1: for(i=0;i<M;i++) {
    array1[i] = ...;
    array2[i] = ...;
    ...
}
...
}
```

results in the transformation shown in the following figure.

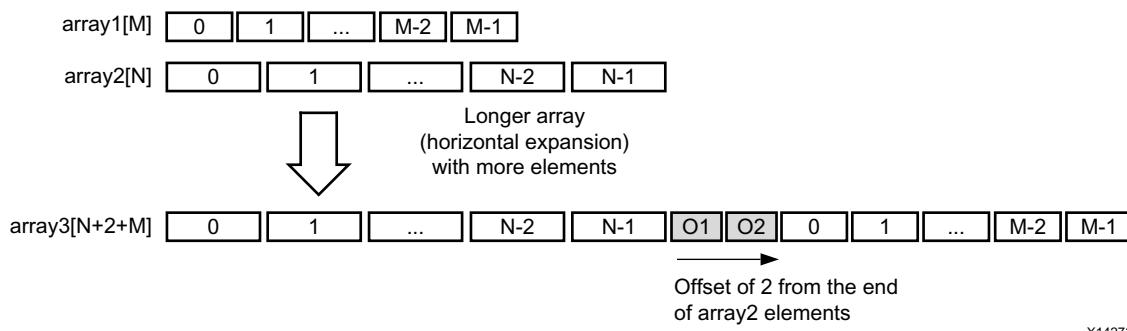


Figure 1-75: Horizontal Mapping with Offset

After mapping, the newly formed array, `array3` in the above examples, can be targeted into a specific block RAM by applying the `RESOURCE` directive to any of the variables mapped into the new instance.

The block RAM implementation shown in the following figure corresponds to the mapping in the following figure (no offset is used).

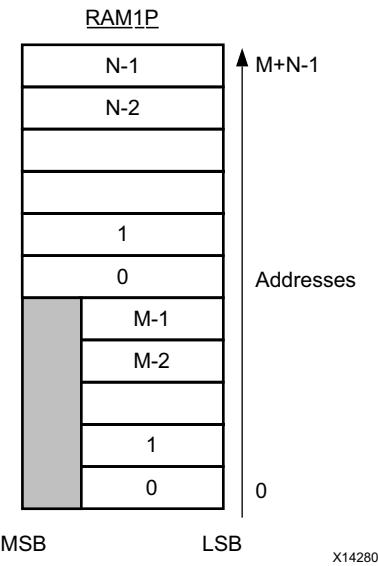


Figure 1-76: Memory for Horizontal Mapping

Although horizontal mapping can result in using less block RAM components and therefore improve area, it does have an impact on the throughput and performance as there are now fewer block RAM ports. To overcome this limitation, Vivado HLS also provides vertical mapping mode.

Vertical Mapping

In vertical mapping, arrays are concatenated by to produce an array with higher bit-widths. Vertical mapping is applied using the `vertical` option to the `INLINE` directive. The following figure shows how the same example as before transformed when vertical mapping mode is applied.

```
void foo (...) {
    int8  array1[M];
    int12 array2[N];
#pragma HLS ARRAY_MAP variable=array2 instance=array3 horizontal
#pragma HLS ARRAY_MAP variable=array1 instance=array3 horizontal
    ...
loop_1: for(i=0;i<M;i++) {
    array1[i] = ...;
    array2[i] = ...;
    ...
}
...
}
```

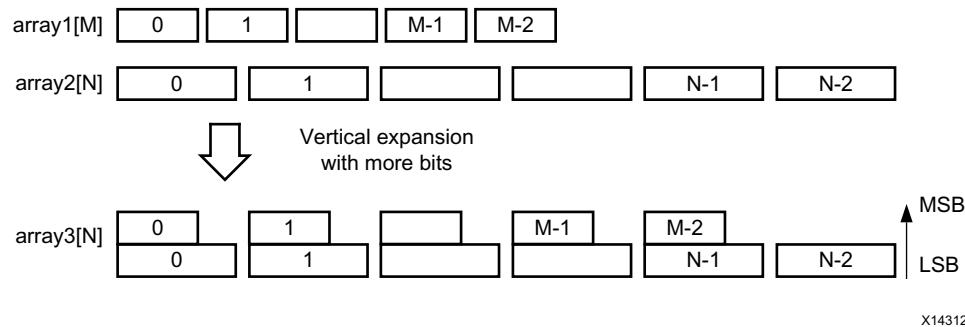


Figure 1-77: Vertical Mapping

In vertical mapping the arrays are concatenated in the order specified by the command, with the first arrays starting at the LSB and the last array specified ending at the MSB. After vertical mapping the newly formed array, is implemented in a single block RAM component as shown in the following figure.

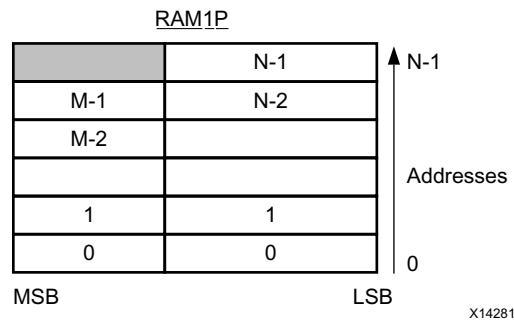


Figure 1-78: Memory for Vertical Mapping

Array Mapping and Special Considerations



IMPORTANT: The object for an array transformation must be in the source code prior to any other directives being applied.

To map elements from a partitioned array into a single array with horizontal mapping, the individual elements of the array to be partitioned must be specified in the ARRAY_MAP directive. For example, the following Tcl commands partition array accum and map the resulting elements back together.

```
#pragma HLS array_partition variable=m_accum cyclic factor=2 dim=1
#pragma HLS array_partition variable=v_accum cyclic factor=2 dim=1
#pragma HLS array_map variable=m_accum[0] instance=mv_accum horizontal
#pragma HLS array_map variable=v_accum[0] instance=mv_accum horizontal
#pragma HLS array_map variable=m_accum[1] instance=mv_accum_1 horizontal
#pragma HLS array_map variable=v_accum[1] instance=mv_accum_1 horizontal
```

It is possible to map a global array. However, the resulting array instance is global and any local arrays mapped onto this same array instance become global. When local arrays of different functions get mapped onto the same target array, then the target array instance becomes global.

Array function arguments may only be mapped if they are arguments to the same function.

Array Reshaping

The ARRAY_RESHAPE directive combines ARRAY_PARTITIONING with the vertical mode of ARRAY_MAP and is used to reduce the number of block RAM while still allowing the beneficial attributes of partitioning: parallel access to the data.

Given the following example code:

```
void foo (...) {
    int array1[N];
    int array2[N];
    int array3[N];
    #pragma HLS ARRAY_RESHAPE variable=array1 block factor=2 dim=1
    #pragma HLS ARRAY_RESHAPE variable=array2 cycle factor=2 dim=1
    #pragma HLS ARRAY_RESHAPE variable=array3 complete dim=1
    ...
}
```

The ARRAY_RESHAPE directive transforms the arrays into the form shown in the following figure.

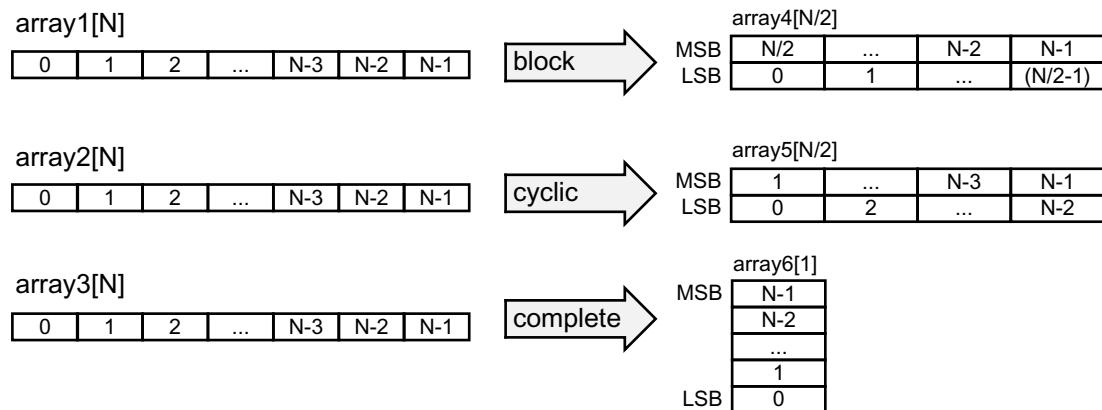


Figure 1-79: Array Reshaping

Function Instantiation

Function instantiation is an optimization technique that has the area benefits of maintaining the function hierarchy but provides an additional powerful option: performing targeted local optimizations on specific instances of a function. This can simplify the control logic around the function call and potentially improve latency and throughput.

The FUNCTION_INSTANTIATE directive exploits the fact that some inputs to a function may be a constant value when the function is called and uses this to both simplify the surrounding control structures and produce smaller more optimized function blocks. This is best explained by example.

Given the following code:

```
void foo_sub(bool mode) {
    #pragma HLS FUNCTION_INSTANTIATE variable=mode
    if (mode) {
        // code segment 1
    } else {
        // code segment 2
    }
}

void foo(){
    #pragma HLS FUNCTION_INSTANTIATE variable=select
    foo_sub(true);
    foo_sub(false);
}
```

It is clear that function `foo_sub` has been written to perform multiple but exclusive operations (depending on whether `mode` is true or not). Each instance of function `foo_sub` is implemented in an identical manner: this is great for function reuse and area optimization but means that the control logic inside the function must be more complex.

The FUNCTION_INSTANTIATE optimization allows each instance to be independently optimized, reducing the functionality and area. After FUNCTION_INSTANTIATE optimization, the code above can effectively be transformed to have two separate functions, each optimized for different possible values of `mode`, as shown:

```
void foo_sub1() {
    // code segment 1
}

void foo_sub2() {
    // code segment 2
}

void A(){
    B1();
    B2();
}
```

If the function is used at different levels of hierarchy such that function sharing is difficult without extensive inlining or code modifications, function instantiation can provide the best means of improving area: many small locally optimized copies are better than many large copies that cannot be shared.

Controlling Hardware Resources

During synthesis Vivado HLS performs the following basic tasks:

- First, elaborates the C, C++ or SystemC source code into an internal database containing operators.

The operators represent operations in the C code such as additions, multiplications, array reads, and writes.

- Then, maps the operators on to cores which implement the hardware operations.

Cores are the specific hardware components used to create the design (such as adders, multipliers, pipelined multipliers, and block RAM).

Control is provided over each of these steps, allowing you to control the hardware implementation at a fine level of granularity.

Limiting the Number of Operators

Explicitly limiting the number of operators to reduce area may be required in some cases: the default operation of Vivado HLS is to first maximize performance. Limiting the number of operators in a design is a useful technique to reduce the area: it helps reduce area by forcing sharing of the operations.

The ALLOCATION directive allows you to limit how many operators, or cores or functions are used in a design. For example, if a design called `foo` has 317 multiplications but the FPGA only has 256 multiplier resources (DSP48s). The ALLOCATION directive shown below directs Vivado HLS to create a design with maximum of 256 multiplication (`mul`) operators:

```
dout_t array_arith (dio_t d[317]) {
    static int acc;
    int i;
#pragma HLS ALLOCATION instances=mul limit=256 operation

    for (i=0;i<317;i++) {
#pragma HLS UNROLL
        acc += acc * d[i];
    }
    rerun acc;
}
```

Note: If you specify an ALLOCATION limit that is greater than needed, Vivado HLS attempts to use the number of resources specified by the limit, which reduces the amount of sharing.

You can use the type option to specify if the ALLOCATION directives limits operations, cores, or functions. The following table lists all the operations that can be controlled using the ALLOCATION directive.

Table 1-25: Vivado HLS Operators

Operator	Description
add	Integer Addition
ashr	Arithmetic Shift-Right
dadd	Double-precision floating point addition
dcmp	Double -precision floating point comparison
ddiv	Double -precision floating point division
dmul	Double -precision floating point multiplication
drecip	Double -precision floating point reciprocal
drem	Double -precision floating point remainder
drsqrt	Double -precision floating point reciprocal square root
dsub	Double -precision floating point subtraction
dsqrt	Double -precision floating point square root
fadd	Single-precision floating point addition
fcmp	Single-precision floating point comparison
fdiv	Single-precision floating point division
fmul	Single-precision floating point multiplication
frecip	Single-precision floating point reciprocal
frem	Single-precision floating point remainder
frsqrt	Single-precision floating point reciprocal square root
fsub	Single-precision floating point subtraction
fsqrt	Single-precision floating point square root
icmp	Integer Compare
lshr	Logical Shift-Right
mul	Multiplication
sdiv	Signed Divider
shl	Shift-Left
srem	Signed Remainder
sub	Subtraction
udiv	Unsigned Division
urem	Unsigned Remainder

Global Minimization of Operators

The ALLOCATION directive, like all directives, is specified inside a scope: a function, a loop or a region. The config_bind configuration allows the operators to be minimized throughout the entire design.

The minimization of operators through the design is performed using the min_op option in the config_bind configuration. An any of the operators listed in [Table 1-25](#) can be limited in this fashion.

After the configuration is applied it applies to all synthesis operations performed in the solution: if the solution is closed and re-opened the specified configuration still applies to any new synthesis operations.

Any configurations applied with the config_bind configuration can be removed by using the reset option or by using open_solution -reset to open the solution.

Controlling the Hardware Cores

When synthesis is performed, Vivado HLS uses the timing constraints specified by the clock, the delays specified by the target device together with any directives specified by you, to determine which core is used to implement the operators. For example, to implement a multiplier operation Vivado HLS could use the combinational multiplier core or use a pipeline multiplier core.

The cores which are mapped to operators during synthesis can be limited in the same manner as the operators. Instead of limiting the total number of multiplication operations, you can choose to limit the number of combinational multiplier cores, forcing any remaining multiplications to be performed using pipelined multipliers (or vice versa). This is performed by specifying the ALLOCATION directive type option to be core.

The RESOURCE directive is used to explicitly specify which core to use for specific operations. In the following example, a 2-stage pipelined multiplier is specified to implement the multiplication for variable c. The following command informs Vivado HLS to use a 2-stage pipelined multiplier for variable c. It is left to Vivado HLS which core to use for variable d.

```
int foo (int a, int b) {
    int c, d;
    #pragma HLS RESOURCE variable=c core=MultiS latency=2
    c = a*b;
    d = a*c;

    return d;
}
```

In the following example, the RESOURCE directives specify that the add operation for variable temp and is implemented using the AddSub_DSP core. This ensures that the

operation is implemented using a DSP48 primitive in the final design - by default, add operations are implemented using LUTs.

```

void apint_arith(dinA_t  inA, dinB_t  inB,
                  dout1_t *out1
) {

    dout2_t temp;
#pragma HLS RESOURCE variable=temp core=AddSub_DSP

    temp = inB + inA;
    *out1 = temp;

}

```

The `list_core` command is used to obtain details on the cores available in the library. The `list_core` can only be used in the Tcl command interface and a device must be specified using the `set_part` command. If a device has not been selected, the command does not have any effect.

The `-operation` option of the `list_core` command lists all the cores in the library that can be implemented with the specified operation.

The following table lists the cores used to implement standard RTL logic operations (such as add, multiply, and compare).

Table 1-26: Functional Cores

Core	Description
AddSub	This core is used to implement both adders and subtractors.
AddSubnS	N-stage pipelined adder or subtractor. Vivado HLS determines how many pipeline stages are required.
AddSub_DSP	This core ensures that the add or sub operation is implemented using a DSP48 (Using the adder or subtractor inside the DSP48).
DivnS	N-stage pipelined divider.
Mul	Combinational multiplier.
MulnS	N-stage pipelined multiplier.

In addition to the standard cores, the following floating point cores are used when the operation uses floating-point types. Refer to the documentation for each device to determine if the floating-point core is supported in the device.

Table 1-27: 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 without any 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.

Table 1-27: Floating Point Cores (Cont'd)

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.

The following table lists the cores used to implement storage elements, such as registers or memories.

Table 1-28: Storage Cores

Core	Description
FIFO	A FIFO. Vivado HLS determines whether to implement this in the RTL with a block RAM or as distributed RAM.
FIFO_BRAM	A FIFO implemented with a block RAM.
FIFO_LUTRAM	A FIFO implemented as distributed RAM.
FIFO_SRL	A FIFO implemented as with an SRL.
RAM_1P	A single-port RAM. Vivado HLS determines whether to implement this in the RTL with a block RAM or as distributed RAM.
RAM_1P_BRAM	A single-port RAM, implemented with a block RAM.
RAM_1P_LUTRAM	A single-port RAM, implemented as distributed RAM.
RAM_2P	A dual-port RAM, using separate read and write ports. Vivado HLS determines whether to implement this in the RTL with a block RAM or as distributed RAM.
RAM_2P_BRAM	A dual-port RAM, using separate read and write ports, implemented with a block RAM.
RAM_2P_LUTRAM	A dual-port RAM, using separate read and write ports, implemented as distributed RAM.
RAM_T2P_BRAM	A true dual-port RAM, with support for both read and write on both the input and output side, implemented with a block RAM.
ROM_1P	A single-port ROM. Vivado HLS determines whether to implement this in the RTL with a block RAM or with LUTs.
ROM_1P_BRAM	A single-port ROM, implemented with a block RAM.
ROM_1P_LUTRAM	A single-port ROM, implemented as distributed ROM.
ROM_2P	A dual-port ROM. Vivado HLS determines whether to implement this in the RTL with a block RAM or as distributed ROM.
ROM_2P_BRAM	A dual-port ROM implemented with a block RAM.
ROM_2P_LUTRAM	A dual-port ROM implemented as distributed ROM.

The resource directives uses the assigned variable as the target for the resource. Given the code, the RESOURCE directive specifies the multiplication for `out1` is implemented with a 3-stage pipelined multiplier.

```
void foo(...) {
    #pragma HLS RESOURCE variable=out1 core=MultiS latency=4

    // Basic arithmetic operations
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = inD % inA;

}
```

If the assignment specifies multiple identical operators, the code must be modified to ensure there is a single variable for each operator to be controlled. For example if only the first multiplication in this example (`inA * inB`) is to be implemented with a pipelined multiplier:

```
*out1 = inA * inB * inC;
```

The code should be changed to the following with the directive specified on the `Result_tmp` variable:

```
#pragma HLS RESOURCE variable=out1 core=Mul4S
Result_tmp = inA * inB;
*out1 = Result_tmp * inC;
```

Global Optimization of Hardware Cores

The `config_bind` configuration provides control over the binding process. The configuration allows you to direct how much effort is spent when binding cores to operators. By default Vivado HLS chooses cores which are the best balance between timing and area. The `config_bind` influences which operators are used.

```
config_bind -effort [low | medium | high] -min_op <list> -reset
```

The `config_bind` command can only be issued inside an active solution. The default run strategies for the binding operation is medium.

- **Low Effort:** Spend less timing sharing, run time is faster but the final RTL may be larger. Useful for cases when the designer knows there is little sharing possible or desirable and does not wish to waste CPU cycles exploring possibilities.
- **Medium Effort:** The default, where Vivado HLS tries to share operations but endeavors to finish in a reasonable time.
- **High Effort:** Try to maximize sharing and do not limit run time. Vivado HLS keeps trying until all possible combinations of sharing is explored.

Logic Optimization

Controlling Operator Pipelining

Vivado HLS automatically determines the level of pipelining to use for internal operations. You can use the `RESOURCE` directive with the `-latency` option to explicitly specify the number of pipeline stages and override the number determined by Vivado HLS.

RTL synthesis might use the additional pipeline registers to help improve timing issues that might result after place and route. Registers added to the output of the operation typically help improve timing in the output data path. Registers added to the input of the operation typically help improve timing in both the input data path and the control logic from the FSM.

The rules for adding these additional pipeline stages are:

- If the latency is specified as 1 cycle more than the latency decided by Vivado HLS, Vivado HLS adds new output registers to the output of the operator.
- If the latency is specified as 2 more than the latency decided by Vivado HLS, Vivado HLS adds registers to the output of the operation and to the input side of the operation.
- If the latency is specified as 3 or more cycles than the latency decided by Vivado HLS, Vivado HLS adds registers to the output of the operation and to the input side of the operation. Vivado HLS automatically determines the location of any additional registers.

Optimizing Logic Expressions

During synthesis several optimizations, such as strength reduction and bit-width minimization are performed. Included in the list of automatic optimizations is expression balancing.

Expression balancing rearranges operators to construct a balanced tree and reduce latency.

- For integer operations expression balancing is on by default but may be disabled.
- For floating-point operations, expression balancing is off by default but may be enabled.

Given the highly sequential code using assignment operators such as `+=` and `*=` in the following example:

```
data_t foo_top (data_t a, data_t b, data_t c, data_t d)
{
    data_t sum;

    sum = 0;
    sum += a;
    sum += b;
    sum += c;
    sum += d;
    return sum;
}
```

Without expression balancing, and assuming each addition requires one clock cycle, the complete computation for `sum` requires four clock cycles shown in the following figure.

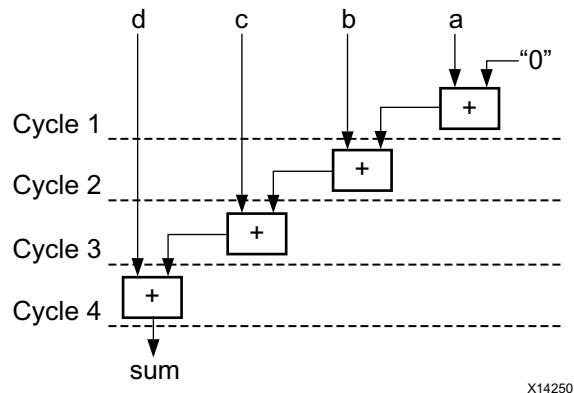


Figure 1-80: Adder Tree

However additions $a+b$ and $c+d$ can be executed in parallel allowing the latency to be reduced. After balancing the computation completes in two clock cycles as shown in the following figure. Expression balancing prohibits sharing and results in increased area.

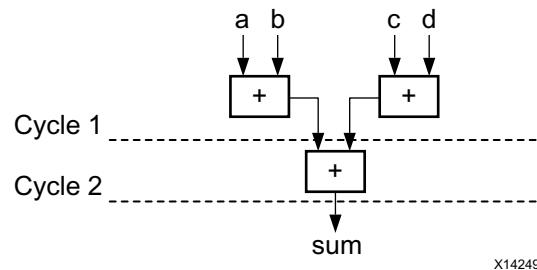


Figure 1-81: Adder Tree After Balancing

For integers expression balancing can be disabled using the `EXPRESSION_BALANCE` optimization directive with the `off` option.

When synthesizing float and double types, Vivado HLS maintains the order of operations performed in the C code to ensure that the results are the same as the C simulation. Due to saturation and truncation, the `O1` and `O2` are not guaranteed to be the same in the following example code.

```
A=B*C;           A=B*F;
D=E*F;           D=E*C;
O1=A*D;          O2=A*D;
```

To enable expression balancing with `float` and `double` types the configuration `config_compile` is used. Use the menu **Solution > Solution Settings > General > Add > config_compile** and enable `unsafe_math_operations`.

The `unsafe_math_operations` feature also enables the `no_signed_zeros` optimization.

The `no_signed_zeros` optimization ensure the following expressions used with float and double types are identical

```
x - 0.0 = x;
x + 0.0 = x;
0.0 - x = -x;
x - x = 0.0;
x*0.0 = 0.0;
```

Without the `no_signed_zeros` optimization the expressions above would not be equivalent due to rounding. The optimization may be optionally used without expression balancing by selecting only this option in the `config_compile` configuration.



TIP: When the `unsafe_math_operations` and `no_signed_zero` optimizations are used, the RTL implementation will have different results than the C simulation. The test bench should be capable of ignoring minor differences in the result: check for a range, do not perform an exact comparison.

RTL Verification

Post-synthesis verification is automated through the C/RTL co-simulation feature which reuses the pre-synthesis C test bench to perform verification on the output RTL.

Automatic Verification of the RTL

C/RTL co-simulation uses the C test bench to automatically verify the RTL design. The verification process consists of three phases, shown in [Figure 1-82](#).

- The C simulation is executed and the inputs to the top-level function, or the Device-Under-Test (DUT), are saved as “input vectors”.
- The “input vectors” are used in an RTL simulation using the RTL created by Vivado HLS. The outputs from the RTL are save as “output vectors”.
- The “output vectors” from the RTL simulation are applied to C test bench, after the function for synthesis, to verify the results are correct. The C test bench performs the verification of the results.

The following messages are output by Vivado HLS to show the progress of the verification.

C simulation:

```
[SIM-14] Instrumenting C test bench (wrapc)
[SIM-302] Generating test vectors (wrapc)
```

At this stage, since the C simulation was executed, any messages written by the C test bench will be output in console window or log file.

RTL simulation:

```
[SIM-333] Generating C post check test bench
[SIM-12] Generating RTL test bench
[SIM-323] Starting Verilog simulation (Issued when Verilog is the RTL verified)
[SIM-322] Starting VHDL simulation (Issued when VHDL is the RTL verified)
[SIM-11] Starting SystemC simulation (Issued when SystemC is the verified RTL)
```

At this stage, any messages from the RTL simulation are output in console window or log file.

C test bench results checking:

```
[SIM-316] Starting C post checking
[SIM-1000] C/RTL co-simulation finished: PASS (If test bench returns a 0)
[SIM-4] C/RTL co-simulation finished: FAIL (If the test bench returns non-zero)
```

The importance of the C test bench in the C/RTL co-simulation flow is discussed below.

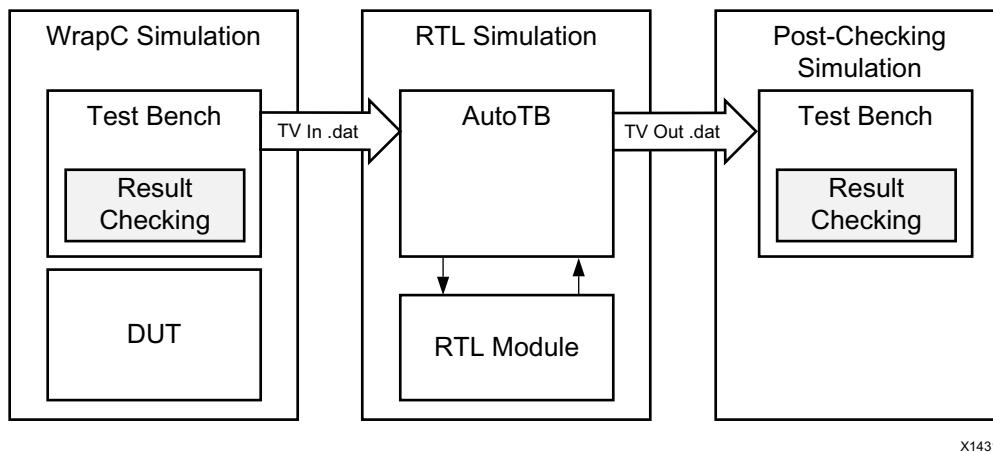


Figure 1-82: RTL Verification Flow

The following is required to use C/RTL co-simulation feature successfully:

- The test bench must be self-checking and return a value of 0 if the test passes or returns a non-zero value if the test fails.
- The correct interface synthesis options must be selected.
- Any 3rd-party simulators must be available in the search path.
- Any arrays or structs on the design interface cannot use the optimization directives or combinations of optimization directives listed in [Unsupported Optimizations for Co-Simulation](#).

Test Bench Requirements

To verify the RTL design produces the same results as the original C code, use a self-checking test bench to execute the verification. The following code example shows the important features of a self-checking test bench:

```
int main () {
    int ret=0;
    ...
    // Execute (DUT) Function
    ...

    // Write the output results to a file
    ...

    // Check the results
    ret = system("diff --brief -w output.dat output.golden.dat");

    if (ret != 0) {
        printf("Test failed !!!\n");
        ret=1;
    } else {
        printf("Test passed !\n");
    }
    ...
    return ret;
}
```

This self-checking test bench compares the results against known good results in the `output.golden.dat` file.

Note: There are many ways to perform this checking. This is just one example.

In the Vivado HLS design flow, the return value to function `main()` indicates the following:

- Zero: Results are correct.
- Non-zero value: Results are incorrect.

Note: The test bench can return any non-zero value. A complex test bench can return different values depending on the type of difference or failure. If the test bench returns a non-zero value after C simulation or C/RTL co-simulation, Vivado HLS reports an error and simulation fails.



RECOMMENDED: Because the system environment (for example, Linux, Windows, or Tcl) interprets the return value of the `main()` function, it is recommended that you constrain the return value to an 8-bit range for portability and safety.



CAUTION! You are responsible for ensuring that the test bench checks the results. If the test bench does not check the results but returns zero, Vivado HLS indicates that the simulation test passed even though the results were not actually checked.

Interface Synthesis Requirements

To use the C/RTL co-simulation feature to verify the RTL design, one or more of the following conditions must be true.

- The top-level function must be synthesized using an ap_ctrl_hs or ap_ctrl_chain function-level interface.
- Or the design must be purely combinational.
- Or the top-level function must have an initiation interval of 1.
- Or the interface must be all arrays that are streaming and implemented with ap_fifo, ap_hs, or axis interface modes.

Note: - hls::stream variables are automatically implemented as ap_fifo interfaces.

If one of these conditions is not met, C/RTL co-simulation halts with the following message:

```
@E [SIM-345] Cosim only supports the following 'ap_ctrl_none' designs: (1)
combinational designs; (2) pipelined design with task interval of 1; (3) designs with
array streaming or hls_stream ports.
@E [SIM-4] *** C/RTL co-simulation finished: FAIL ***
```

RTL Simulator Support

With the above requirements in place, C/RTL co-simulation can verify the RTL design using any of the RTL types and simulator combinations shown in the following table.

Table 1-29: Cosim_design Simulation Support

RTL	SystemC OSCI	Vivado Simulator (Xsim)	ISE Simulator (ISim)	ModelSim	VCS (Linux only)	NC-Sim (Linux only)	Riviera (PC only)
SystemC	Supported	Not Supported	Not Supported	Not Supported	Not Supported	Not Supported	Not Supported
Verilog	Not Supported	Supported	Supported	Supported	Supported	Supported	Supported
VHDL	Not Supported	Supported	Supported	Supported	Supported	Supported	Supported



IMPORTANT: To verify an RTL design using the third-party simulators shown in [Table 1-29](#) (ModelSim, VCS, Riviera), you must include the executable to the simulator in the system search path, and the appropriate license must be available. See the third-party vendor documentation for details on configuring these simulators.

The default simulator is:

- Vivado Simulator (XSim) for 7-series, Zynq-7000 AP SoC, and later devices
- ISE Simulator (ISim) for earlier devices

The default simulation language is Verilog. However, you can also specify VHDL or SystemC. For information on changing these defaults, see [Using C/RTL Co-Simulation](#).

When verifying the SystemC RTL output, Vivado HLS uses the built-in SystemC kernel to execute the RTL simulation. No HDL simulator is required.

Note: If the input source code to Vivado HLS is SystemC, Vivado HLS performs the RTL verification using concurrent co-simulation, that is, Vivado HLS compiles the SystemC test bench with the output RTL. If you want to simulate using Verilog or VHDL RTL, you must use the ModelSim simulator with C compiler capabilities.

Unsupported Optimizations for Co-Simulation

The automatic RTL verification does not support cases in multiple transformations that are performed upon arrays or arrays within structs on the interface.

In order for automatic verification to be performed, arrays on the function interface, or array inside structs on the function interface, can use any of the following optimizations, but not two or more:

- Vertical mapping on arrays of the same size
- Reshape
- Partition
- Data Pack on structs

Verification by C/RTL co-simulation cannot be performed when the following optimizations are used on top-level function interface.

- Horizontal Mapping
- Vertical Mapping of arrays of different sizes
- Data Pack on structs containing other structs as members

Simulation of Floating-Point Cores

When the design is implemented with floating-point cores bit accurate models of the floating-point cores must be made available to the RTL simulator. This is automatically accomplished if the RTL simulation is performed using the following:

- SystemC RTL
- Verilog and VHDL using the Xilinx Vivado Simulator
- Verilog and VHDL using the Xilinx ISE Simulator
- Verilog and VHDL using the Mentor Graphics QuestaSim Simulator

For other supported HDL simulators the Xilinx floating point library must be pre-compiled and added to the simulator libraries. Details on how to compile floating point simulation libraries are available in the Vivado Design Suite documentation and within the online help (of the Vivado Design Suite, not Vivado HLS). Open the Vivado Design Suite GUI or the Vivado Tcl shell and type `compile_simlib -help` at the Tcl command prompt.

Using C/RTL Co-Simulation

To perform C/RTL co-simulation from the GUI, click the **C/RTL Cosimulation** toolbar button  . This opens the simulation wizard window shown in the following figure.

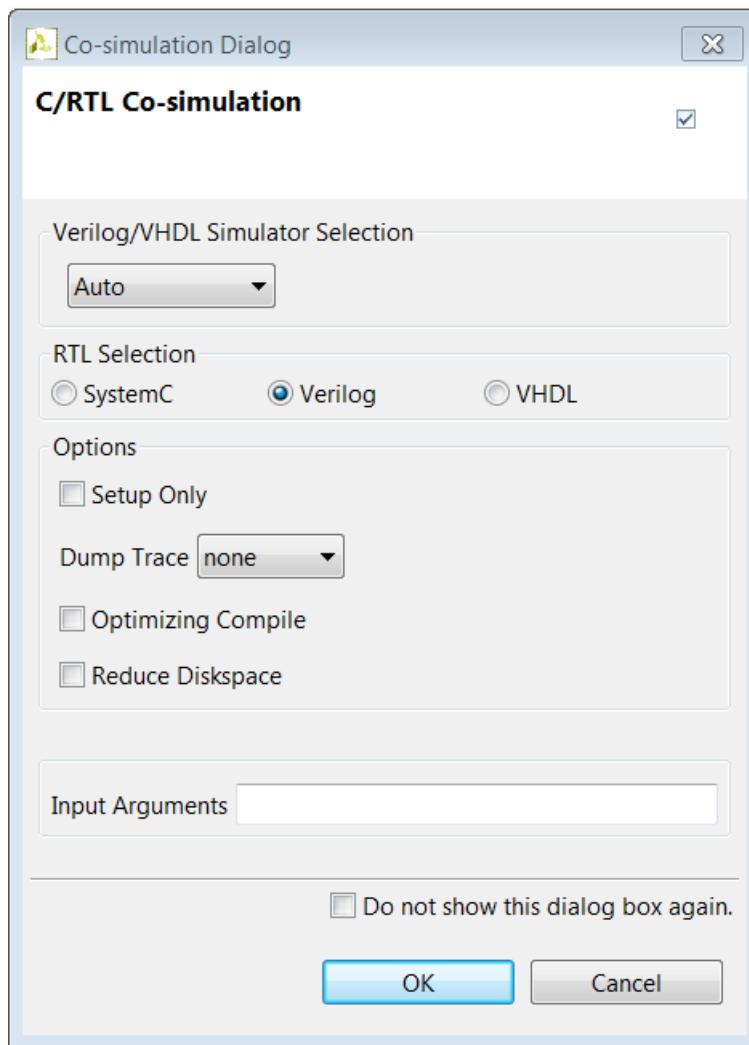


Figure 1-83: C/RTL Co-Simulation Wizard

Select the RTL that is simulated (SystemC, Verilog or VHDL). If Verilog or VHDL is selected, the drop-down menu allows the simulator to be selected. The defaults and possible selections are noted above in [RTL Simulator Support](#).

The options are as follows:

- **Setup Only:** This creates all the files (wrappers, adapters, and scripts) required to run the simulation but does not execute the simulator. The simulation can be run in the command shell from within the appropriate RTL simulation folder `<solution_name>/sim/<RTL>`.
- **Dump Trace:** This generates a trace file for every function. This is saved to the `<solution>/sim/<RTL>` folder. Refer to the documentation for the RTL simulator selected for details on using the trace file. The drop-down menu allows you to select which signals are saved to the trace file: all, only the top-level ports or the ports for every function in the hierarchy.

- Optimize Compile: This option ensures a high level of optimization is used to compile the C test bench. If SystemC is selected, the RTL design is also compiled using this higher level of optimization. Using this option increases the compile time but the simulation executes faster.
- Reduce Disk Space: The flow shown [Figure 1-82](#) saves the results for all transactions before executing RTL simulation. In some cases, this can result in large data files. The `reduce_diskspace` option can be used to execute one transaction at a time and reduce the amount of disk space required for the file. If the function is executed N times in the C test bench, the `reduce_diskspace` option ensures N separate RTL simulations are performed. This will cause the simulation to run slower.

The Input Arguments allows the specification of any arguments required by the test bench.

RTL Simulation Execution

Vivado HLS executes the RTL simulation in the project sub-directory:

<SOLUTION>/sim/<RTL>

where

- SOLUTION is the name of the solution.
- RTL is the RTL type chosen for simulation.

Any files written by the C test bench during co-simulation and any trace files generated by the simulator are written to this directory. For example, if the C test bench save the output results for comparison, review the output file in this directory and compare it with the expected results.

Exporting the RTL Design

The final step in the Vivado HLS flow is to export the RTL design as a block of Intellectual Property (IP) which can be used by other tools in the Xilinx design flow. The RTL design can be packaged into the following output formats:

- IP Catalog formatted IP for use with the Vivado Design Suite
- System Generator for DSP IP for use with Vivado System Generator for DSP
- System Generator for DSP (ISE Design Suite) IP for use with ISE System Generator for DSP
- Pcore for EDK IP for use with EDK
- Synthesized Checkpoint (.dcp)

Table 1-30: RTL Export Selections

Format Selection	Sub-Folder	Comments
IP Catalog	ip	<p>Contains a ZIP file which can be added to the Vivado IP Catalog. The <code>ip</code> folder also contains the contents of the ZIP file (unzipped).</p> <p>This option is not available for FPGA devices older than 7-series or Zynq-7000 AP SoC.</p>
System Generator for DSP	sysgen	<p>This output can be added to the Vivado edition of System Generator for DSP.</p> <p>This option is not available for FPGA devices older than 7-series or Zynq-7000 AP SoC.</p>
System Generator for DSP (ISE)	sysgen	This output can be added to the ISE edition of System Generator for DSP.
Pcore for EDK	pcore	This output can be added to Xilinx Platform Studio.
Synthesized Checkpoint (.dcp)	ip	<p>This option creates Vivado checkpoint files which can be added directly into a design in the Vivado Design Suite.</p> <p>This option requires RTL synthesis to be performed. When this option is selected, the evaluate option is automatically selected.</p> <p>This option is not available for FPGA devices older than 7-series or Zynq-7000 AP SoC.</p>

Only designs targeted to 7 series and Zynq-7000 AP SoC can be exported to the Vivado design flows. For example, if the target is a Virtex®-6 device, the options for packing as the Vivado IP Catalog, System Generator for DSP (Vivado) or Synthesis Checkpoint (.dsp) will not be available as these IP package formats are only for use in the Vivado design flow.

In addition to the packaged output formats, the RTL files are available as stand-alone files (not part of a packaged format) in the `verilog` and `vhd1` directories located within the implementation directory `<project_name>/<solution_name>/impl`.

In addition to the RTL files, these directories also contain project files for the Vivado Design Suite. Opening the file `project.xpr` causes the design (Verilog or VHDL) to be opened in a Vivado project where the design may be analyzed. If co-simulation was executed in the Vivado HLS project, the C/RTL co-simulation files are available inside the Vivado project.

RTL Synthesis

When Vivado HLS reports on the results of synthesis, it provides an estimation of the results expected after RTL synthesis: the expected clock frequency, the expected number of registers, LUTs and block RAMs. These results are estimations because Vivado HLS cannot know what exact optimizations RTL synthesis performs or what the actual routing delays will be, and hence cannot know the final area and timing values.

Before exporting a design, you have the opportunity to execute logic synthesis and confirm the accuracy of the estimates. The evaluate option shown the following figure invokes RTL synthesis during the export process and synthesizes the RTL design to gates.

Note: The RTL synthesis option is provided to confirm the reported estimates. In most cases, these RTL results are not included in the packaged IP.

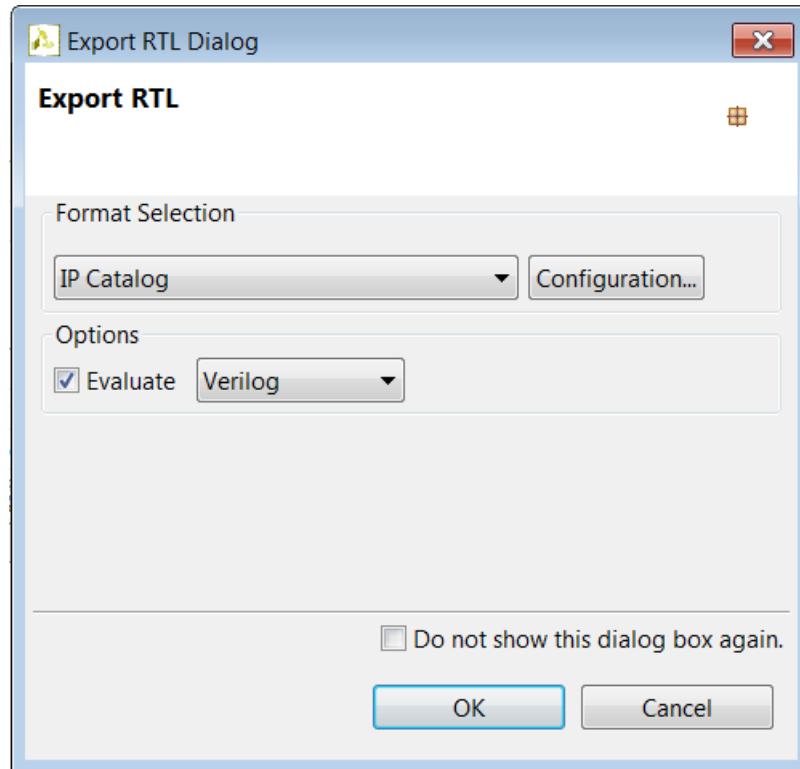


Figure 1-84: Export RTL Dialog Box

For most export formats, the RTL synthesis is executed in the verilog or vhdl directories, whichever HDL was chosen for RTL synthesis using the drop-down menu in the preceding figure, but the results of RTL synthesis are not included in the packaged IP.

The following export formats do include the synthesized RTL in the packaged IP:

- Pcore for EDK: Part or all of the design can be exported as the synthesized RTL. Refer to the options in the section Exporting in PCore format below.
- Synthesized Checkpoint (.dcp): A design checkpoint is always exported as synthesized RTL. The evaluate option is not available when using this format: RTL synthesis is always run.

Packaging IP Catalog Format

Upon completion of synthesis and RTL verification, open the **Export RTL** dialog box by clicking the **Export RTL** toolbar button .

Select the `IP Catalog` format in the `Format Selection` section.

The configuration options allow the following identification tags to be embedded in the exported package. These fields can be used to help identify the packaged RTL inside the Vivado IP Catalog.

The configuration information is used to differentiate between multiple instances of the same design when the design is loaded into the IP Catalog. For example, if an implementation is packaged for the IP Catalog and then a new solution is created and packaged as IP, the new solution by default has the same name and configuration information. If the new solution is also added to the IP Catalog, the IP Catalog will identify it as an updated version of the same IP and the last version added to the IP Catalog will be used.

An alternative method is to use the `prefix` option in the `config_rtl` configuration to rename the output design and files with a unique prefix.

If no values are provided in the configuration setting the following values are used:

- Vendor: xilinx.com
- Library: hls
- Version: 1.0
- Description: An IP generated by Vivado HLS
- Display Name: This field is left blank by default
- Taxonomy: This field is left blank by default

After the packaging process is complete, the.zip file archive in directory
`<project_name>/<solution_name>/impl/ip` can be imported into the Vivado IP catalog and used in any Vivado design (RTL or IP Integrator).

Software Driver Files

For designs that include AXI4-Lite slave interfaces, a set of software driver files is created during the export process. These C driver files can be included in an SDK C project and used to access the AXI4-Lite slave port.

The software driver files are written to directory
`<project_name>/<solution_name>/impl/ip/drivers` and are included in the package .zip archive. Refer to [AXI4-Lite Interface](#) for details on the C driver files.

Exporting IP to System Generator

Upon completion of synthesis and RTL verification, open the Export RTL dialog box by clicking the **Export RTL** toolbar button .

The process of exporting to System Generator for DSP depends on whether the ISE or Vivado version of System Generator for DSP is used. Select the appropriate option for your design flow. In the following example, the Vivado version is used as shown in the following figure.

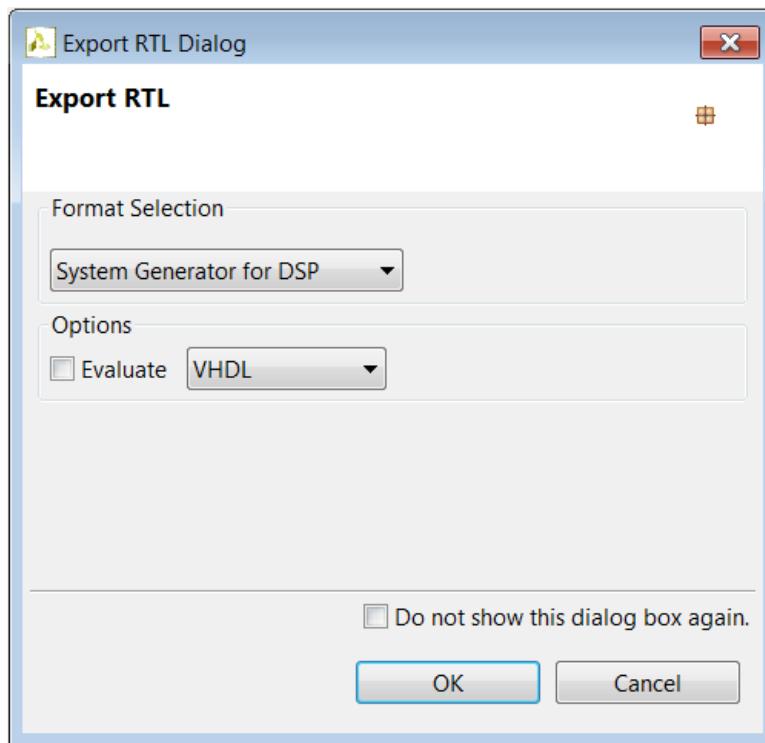


Figure 1-85: Export RTL to System Generator

If post-place-and-route resource and timing statistic for the IP block are desired then select the `Evaluate` option and select the desired RTL language.

Pressing `OK` generates the IP package. This package is written to the `<project_name>/<solution_name>/impl/sysgen` directory. And contains everything need to import the design to System Generator.

If the `Evaluate` option was selected, RTL synthesis is executed and the final timing and resources reported but not included in the IP package. See the RTL synthesis section above for more details on this process.

Importing the RTL into System Generator

A Vivado HLS generated System Generator package may be imported into System Generator using the following steps:

1. Inside the System Generator design, right-click and use option `XilinxBlockAdd` to instantiate new block.
2. Scroll down the list in dialog box and select Vivado HLS.
3. Double-click on the newly instantiated Vivado HLS block to open the Block Parameters dialog box.

4. Browse to the solution directory where the Vivado HLS block was exported. Using the example, <project_name>/<solution_name>/impl/sysgen, browse to the <project_name>/<solution_name> directory and select apply.

Port Optimizations

If any top-level function arguments are transformed during the synthesis process into a composite port, the type information for that port cannot be determined and included in the System Generator IP block.

The implication for this limitation is that any design that uses the reshape, mapping or data packing optimization on ports must have the port type information, for these composite ports, manually specified in System Generator.

To manually specify the type information in System Generator, you should know how the composite ports were created and then use slice and reinterpretation blocks inside System Generator when connecting the Vivado HLS block to other blocks in the system.

For example:

- If three 8-bit in-out ports R, G and B are packed into a 24-bit input port (RGB_in) and a 24-bit output port (RGB_out) ports.

After the IP block has been included in System Generator:

- The 24-bit input port (RGB_in) would need to be driven by a System Generator block that correctly groups three 8-bit input signals (Rin, Gin and Bin) into a 24-bit input bus.
- The 24-bit output bus (RGB_out) would need to be correctly split into three 8-bit signals (Rout, Bout and Gout).

See the System Generator documentation for details on how to use the slice and reinterpretation blocks for connecting to composite type ports.

Exporting in Pcore Format

Upon completion of synthesis and RTL verification, open the Export RTL dialog box by clicking the **Export RTL** toolbar button .

Select Pcore for EDK in the Format Selection section, as shown in the following figure.

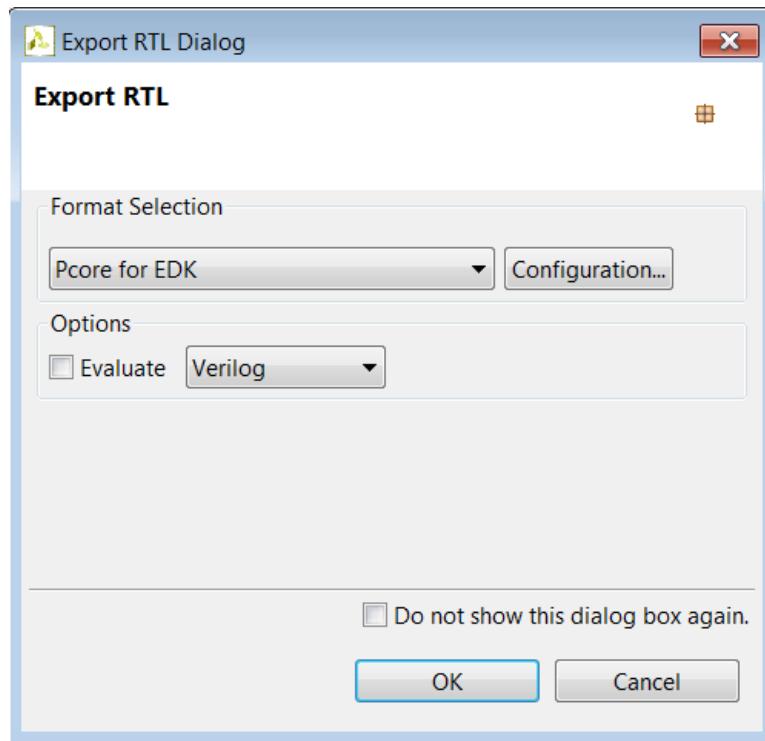


Figure 1-86: Export RTL as Pcore

The Configuration dialog box can be used to customize the IP settings and implementation. The version information field for the Pcore package may be customized. A default value of 1.00.a is used if none is specified.

The Configuration dialog box also allows a netlist (.ngc file) to be generated for parts or all of the pcore. The advantage of generating a netlist for the design is that the same netlist is then used when the design is elaborated inside XPS. The following netlist options are provided:

- none: This is the default and ensures no netlists are generated for the design. The IP only includes RTL files.
- ip: Generate a netlist for any Xilinx IP (if any). This includes any floating-point cores. This causes all Xilinx IP to be synthesized and included in the IP package.
- top: Generate a netlist for the top-level design. The entire design will be synthesized and the result included in the packaged IP.



IMPORTANT: NGC format files are not supported in the Vivado Design Suite for UltraScale™ devices. It is recommended that you regenerate the IP using the Vivado Design Suite IP customization tools with native output products. Alternatively, you can use the NGC2EDIF command to migrate the NGC file to EDIF format for importing, as described in the ISE to Vivado Design Suite Migration Guide (UG911) [Ref 4]. However, Xilinx recommends using native Vivado IP rather than XST-generated NGC format files going forward.

If post-place-and-route resource and timing statistics for the IP block are desired then select the Evaluate option and select the desired RTL language. Pressing OK generates the Pcore package. This package is written to the `<project_name>/<solution_name>/impl/pcores` directory.

If the Evaluate option was selected, RTL synthesis is executed and the final timing and resources reported but not included in the IP package. See [RTL Synthesis](#) for more details on this process.

A Vivado HLS generated Pcore package might be imported into the EDK environment by copying the contents of the pcores directory to the pcores directory in the EDK project.

Software Driver Files

For designs which include AXI4-Lite slave interfaces, a set of software driver files is created during the export process. These C driver files can be included in an SDK C project and used to access the AXI4-Lite slave port.

The software driver files are written to the include directory inside the pcore, for example, `<project_name>/<solution_name>/impl/pcores/<design_name_version>/include`. See [Specifying Interfaces](#) for details on how these files are used.

Exporting a Synthesized Checkpoint

Upon completion of synthesis and RTL verification, open the Export RTL dialog box by clicking the **Export RTL** toolbar button .

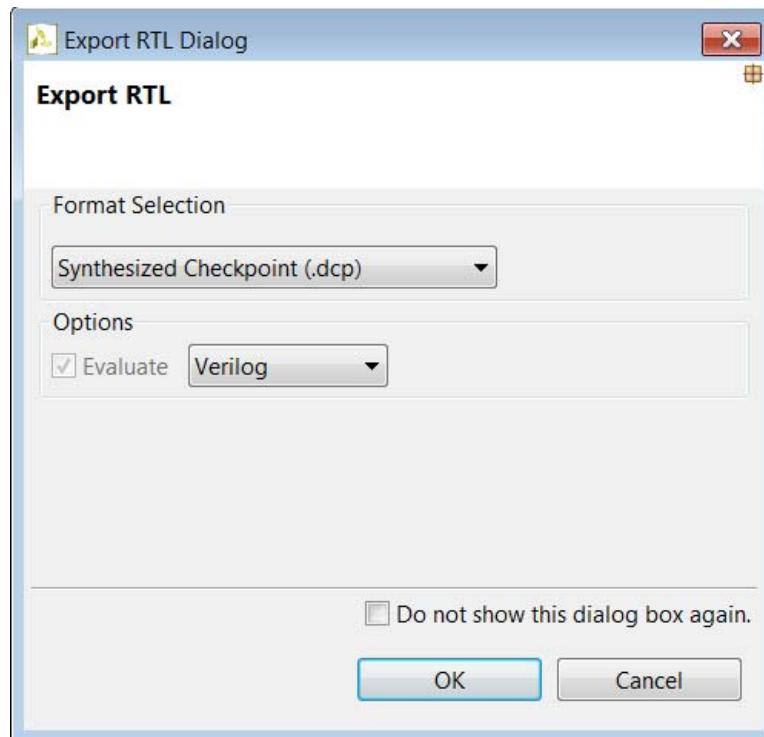


Figure 1-87: Export RTL to Synthesized Checkpoint

When the design is packaged as a design checkpoint IP, the design is first synthesized before being packaged. The evaluate option () is disabled when packaging the IP.

Selecting **OK** generates the design checkpoint package. This package is written to the <project_name>/<solution_name>/impl/ip directory. The design checkpoint files can be used in a Vivado Design Suite project in the same manner as any other design checkpoint.

High-Level Synthesis C Libraries

Introduction to the Vivado HLS C Libraries

Vivado® HLS C libraries allow common hardware design constructs and function to be easily modeled in C and synthesized to RTL. The following C libraries are provided with Vivado HLS:

- Arbitrary Precision Data Types Library
- HLS Stream Library
- HLS Math Library
- HLS Video Library
- HLS IP Library
- HLS Linear Algebra Library

You can use each of the C libraries in your design by including the library header file. These header files are located in the `include` directory in the Vivado HLS installation area.



IMPORTANT: *The header files for the Vivado HLS C libraries do not have to be in the include path if the design is used in Vivado HLS. The paths to the library header files are automatically added.*

Arbitrary Precision Data Types Library

C-based native data types are on 8-bit boundaries (8, 16, 32, 64 bits). RTL buses (corresponding to hardware) support arbitrary lengths. HLS needs a mechanism to allow the specification of arbitrary precision bit-width and not rely on the artificial boundaries of native C data types: if a 17-bit multiplier is required, you should not be forced to implement this with a 32-bit multiplier.

Vivado HLS provides both integer and fixed-point arbitrary precision data types for C, C++ and supports the arbitrary precision data types which are part of SystemC.

The advantage of arbitrary precision data types is that they allow the C code to be updated to use variables with smaller bit-widths and then for the C simulation to be re-executed to validate the functionality remains identical or acceptable.

Using Arbitrary Precision Data Types

Vivado HLS provides arbitrary precision integer data types that manage the value of the integer numbers within the boundaries of the specified width, as shown in the following table.

Table 2-1: Integer Data Types

Language	Integer Data Type	Required Header
C	[u]int<precision> (1024 bits)	gcc #include "ap_cin.h"
C++	ap_[u]int<W> (1024 bits)	#include "ap_int.h"
System C	sc_[u]int<W> (64 bits) sc_[u]bigint<W> (512 bits)	#include "systemc.h"

Note: The header files define the arbitrary precision types are also provided with Vivado HLS as a stand-alone package with the rights to use them in your own source code. The package, `xilinx_hls_lib_<release_number>.tgz` is provided in the include directory in the Vivado HLS installation area.

Arbitrary Integer Precision Types with C

For the C language, the header file `ap_cint.h` defines the arbitrary precision integer data types `[u]int`.

Note: The package `xilinx_hls_lib_<release_number>.tgz` does not include the C arbitrary precision types defined in `ap_cint.h`. These types cannot be used with standard C compilers, only with the Vivado HLS `cpcc` compiler. More details on this are provided in [Validating Arbitrary Precision Types in C](#).

To use arbitrary precision integer data types in a C function:

- Add header file `ap_cint.h` to the source code.
- Change the bit types to `intN` for signed types or `uintN` for unsigned types, where N is a bit-size from 1 to 1024.

The following example shows how the header file is added and two variables implemented to use 9-bit integer and 10-bit unsigned integer types:

```
#include ap_cint.h

void foo_top (...) {
    int9 var1;           // 9-bit
    uint10 var2;         // 10-bit unsigned
```

Arbitrary Integer Precision Types with C++

The header file `ap_int.h` defines the arbitrary precision integer data type for the C++ `ap_[u]int` data types listed in [Table 2-2](#). To use arbitrary precision integer data types in a C++ function:

- Add header file `ap_int.h` to the source code.
- Change the bit types to `ap_int<N>` for signed types or `ap_uint<N>` for unsigned types, where N is a bit-size from 1 to 1024.

The following example shows how the header file is added and two variables implemented to use 9-bit integer and 10-bit unsigned integer types:

```
#include ap_int.h

void foo_top (...) {
    ap_int<9> var1;           // 9-bit
    ap_uint<10> var2;         // 10-bit unsigned
```

Arbitrary Precision Integer Types with SystemC

The arbitrary precision types used by SystemC are defined in the `systemc.h` header file that is required to be included in all SystemC designs. The header file includes the SystemC `sc_int<>`, `sc_uint<>`, `sc_bigint<>` and `sc_bignum<>` types.

Arbitrary Precision Fixed-Point Data Types

The use of fixed-point types is of particular importance when using HLS because the behavior of the C++/SystemC simulations performed using fixed-point data types match that of the resulting hardware created by synthesis, allowing analysis of the effects of bit-accuracy, quantization, and overflow to be analyzed with fast C-level simulation.

Vivado HLS offers arbitrary precision fixed-point data types for use with C++ and SystemC functions, as shown in the following table.

Table 2-2: Fixed-Point Data Types

Language	Fixed-Point Data Type	Required Header
C	-- Not Applicable --	-- Not Applicable --
C++	<code>ap_[u]fixed<W,I,Q,O,N></code>	<code>#include "ap_fixed.h"</code>
System C	<code>sc_[u]fixed<W,I,Q,O,N></code>	<code>#define SC_INCLUDE_FX</code> <code>[#define SC_FX_EXCLUDE_OTHER]</code> <code>#include "systemc.h"</code>

These data types manage the value of floating point numbers within the boundaries of a specified total width and integer width, as shown in the following figure.

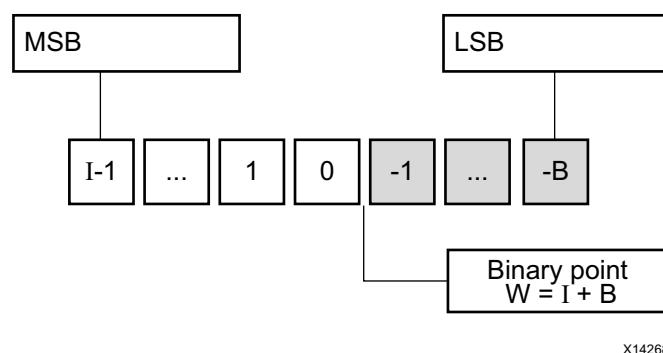


Figure 2-1: Fixed-Point Data Type

The following table provides a brief overview of operations supported by fixed-point types.

Table 2-3: Fixed-Point Identifier Summary

Identifier	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 This dictates the behavior when greater precision is generated than can be defined by smallest fractional bit in the variable used to store the result.	
SystemC Types	ap_fixed Types	Description
SC_RND	AP_RND	Round to plus infinity
SC_RND_ZERO	AP_RND_ZERO	Round to zero
SC_RND_MIN_INF	AP_RND_MIN_INF	Round to minus infinity
AP_RND_INF	AP_RND_INF	Round to infinity
AP_RND_CONV	AP_RND_CONV	Convergent rounding
AP_TRN	AP_TRN	Truncation to minus infinity
AP_TRN_ZERO	AP_TRN_ZERO	Truncation to zero (default)

Table 2-3: Fixed-Point Identifier Summary (Cont'd)

Identifier	Description	
O	Overflow mode. This dictates the behavior when the result of an operation exceeds the maximum (or minimum in the case of negative numbers) possible value that can be stored in the variable used to store the result.	
SystemC Types	ap_fixed Types	Description
SC_SAT	AP_SAT	Saturation
SC_SAT_ZERO	AP_SAT_ZERO	Saturation to zero
SC_SAT_SYM	AP_SAT_SYM	Symmetrical saturation
SC_WRAP	AP_WRAP	Wrap around (default)
SC_WRAP_SM	AP_WRAP_SM	Sign magnitude wrap around
N	This defines the number of saturation bits in overflow wrap modes.	

Example Using ap_fixed

In this example the Vivado HLS ap_fixed type is used to define an 18-bit variable with 6 bits representing the numbers above the decimal point and 12-bits representing the value below the decimal point. The variable is specified as signed, the quantization mode is set to round to plus infinity and the default wrap-around mode is used for overflow.

```
#include <ap_fixed.h>
...
ap_fixed<18, 6, AP_RND> my_type;
...
```

Example Using sc_fixed

In this sc_fixed example a 22-bit variable is shown with 21 bits representing the numbers above the decimal point: enabling only a minimum accuracy of 0.5. Rounding to zero is used, such that any result less than 0.5 rounds to 0 and saturation is specified.

```
#define SC_INCLUDE_FX
#define SC_FX_EXCLUDE_OTHER
#include <systemc.h>
...
sc_fixed<22, 21, SC_RND_ZERO, SC_SAT> my_type;
...
```

C Arbitrary Precision Integer Data Types

The native data types in C are on 8-bit boundaries (8, 16, 32 and 64 bits). RTL signals and operations support arbitrary bit-lengths. Vivado HLS provides arbitrary precision data types for C to allow variables and operations in the C code to be specified with any arbitrary bit-widths: for example, 6-bit, 17-bit, and 234-bit, up to 1024 bits.

Vivado HLS also provides arbitrary precision data types in C++ and supports the arbitrary precision data types that are part of SystemC. These types are discussed in the respective C++ and SystemC coding.

Advantages of C Arbitrary Precision Data Types

The primary advantages of arbitrary precision data types are:

- Better quality hardware

If, for example, a 17-bit multiplier is required, you can use arbitrary precision types to require exactly 17 bits in the calculation.

Without arbitrary precision data types, a multiplication such as 17 bits must be implemented using 32-bit integer data types. This results in the multiplication being implemented with multiple DSP48 components.

- Accurate C simulation and analysis

Arbitrary precision data types in the C code allows the C simulation to be executed using accurate bit-widths and for the C simulation to validate the functionality (and accuracy) of the algorithm before synthesis.

For the C language, the header file `ap_cint.h` defines the arbitrary precision integer data types `[u]int#W`. For example:

- `int8` represents an 8-bit signed integer data type.
- `uint234` represents a 234-bit unsigned integer type.

The `ap_cint.h` file is located in the directory:

`$HLS_ROOT/include`

where

- `$HLS_ROOT` is the Vivado HLS installation directory.

The code shown in the following example is a repeat of the code shown in the [Example 3-22](#) on basic arithmetic. In both examples, the data types in the top-level function to be synthesized are specified as `dinA_t`, `dinB_t`, and so forth.

```
#include apint_arith.h

void apint_arith(din_A  inA, din_B  inB, din_C  inC, din_D  inD,
                  out_1 *out1, dout_2 *out2, dout_3 *out3, dout_4 *out4
) {

    // Basic arithmetic operations
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = inD % inA;

}
```

Example 2-1: Basic Arithmetic Revisited

The real difference between the two examples is in how the data types are defined. To use arbitrary precision integer data types in a C function:

- Add header file `ap_cint.h` to the source code.
- Change the native C types to arbitrary precision types:
 - `intN`

or

- `uintN`

where

- `N` is a bit size from 1 to 1024.

The data types are defined in the header `apint_arith.h`. See the following example compared with [Example 3-22](#):

- The input data types have been reduced to represent the maximum size of the real input data. For example, 8-bit input `inA` is reduced to 6-bit input.
- The output types have been refined to be more accurate. For example, `out2` (the sum of `inA` and `inB`) needs to be only 13-bit, not 32-bit.

```
#include <stdio.h>
#include ap_cint.h

// Previous data types
//typedef char dinA_t;
//typedef short dinB_t;
//typedef int dinC_t;
//typedef long long dinD_t;
//typedef int dout1_t;
//typedef unsigned int dout2_t;
//typedef int32_t dout3_t;
//typedef int64_t dout4_t;

typedef int6 dinA_t;
typedef int12 dinB_t;
typedef int22 dinC_t;
typedef int33 dinD_t;

typedef int18 dout1_t;
typedef uint13 dout2_t;
typedef int22 dout3_t;
typedef int6 dout4_t;

void apint_arith(dinA_t inA,dinB_t inB,dinC_t inC,dinD_t inD,dout1_t
    *out1,dout2_t *out2,dout3_t *out3,dout4_t *out4);
```

Example 2-2: Basic Arithmetic apint Types

Synthesizing the preceding example results in a design that is functionally identical to [Example 3-22](#) (given data in the range specified by the preceding example). The final RTL design is smaller in area and has a faster clock speed, because smaller bit-widths result in reduced logic.

The function must be compiled and validated before synthesis.

Validating Arbitrary Precision Types in C

To create arbitrary precision types, attributes are added to define the bit-sizes in file `ap_cint.h`. Standard C compilers such as `gcc` compile the attributes used in the header file, but they do not know what the attributes mean. This results in computations that do not reflect the bit-accurate behavior of the code. For example, a 3-bit integer value with binary representation 100 is treated by `gcc` (or any other third-party C compiler) as having a decimal value 4 and not -4.

Note: This issue is only present when using C arbitrary precision types. There are no such issues with C++ or SystemC arbitrary precision types.

Vivado HLS solves this issue by automatically using its own built-in C compiler `apcc`, when it recognizes arbitrary precision C types are being used. This compiler is `gcc` compatible but correctly interprets arbitrary precision types and arithmetic. You can invoke the `apcc` compiler at the command prompt by replacing "gcc" by "apcc".

```
$ apcc -o foo_top foo_top.c tb_foo_top.c
$ ./foo_top
```

When arbitrary precision types are used in C, the design can no longer be analyzed using the Vivado HLS C debugger. If it is necessary to debug the design, Xilinx recommends one of the following methodologies:

- Use the `printf` or `fprintf` functions to output the data values for analysis.
- Replace the arbitrary precision types with native C types (int, char, short, etc). This approach helps debug the operation of the algorithm itself but does not help when you must analyze the bit-accurate results of the algorithm.
- Change the C function to C++ and use C++ arbitrary precision types for which there are no debugger limitations.

Integer Promotion

Take care when the result of arbitrary precision operations crosses the native 8, 16, 32 and 64-bit boundaries. In the following example, the intent is that two 18-bit values are multiplied and the result stored in a 36-bit number:

```
#include ap_cint.h

int18 a,b;
int36 tmp;

tmp = a * b;
```

Integer promotion occurs when using this method. The result might not be as expected.

In integer promotion, the C compiler:

- Promotes the result of the multiplication operator from 18-bit to the next native bit size (32-bit).
- Assigns the result to the 36-bit variable `tmp`.

This results in the behavior and incorrect result shown in the following figure.

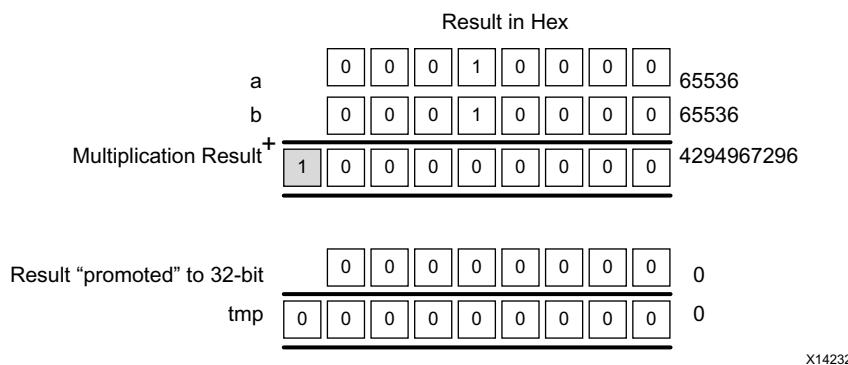


Figure 2-2: Integer Promotion

Because Vivado HLS produces the same results as C simulation, Vivado HLS creates hardware in which a 32-bit multiplier result is sign-extended to a 36-bit result.

To overcome the integer promotion issue, cast operator inputs to the output size. The following example shows where the inputs to the multiplier are cast to 36-bit value before the multiplication. This results in the correct (expected) results during C simulation and the expected 36-bit multiplication in the RTL.

```
#include ap_cint.h

typedef int18 din_t;
typedef int36 dout_t;

dout_t apint_promotion(din_t a,din_t b) {
    dout_t tmp;

    tmp = (dout_t)a * (dout_t)b;
    return tmp;
}
```

Example 2-3: Cast to Avoid Integer Promotion

Casting to avoid integer promotion issue is required only when the result of an operation is greater than the next native boundary (8, 16, 32, or 64). This behavior is more typical with multipliers than with addition and subtraction operations.

There are no integer promotion issues when using C++ or SystemC arbitrary precision types.

C Arbitrary Precision Integer Types: Reference Information

The information in [C Arbitrary Precision Types in Chapter 4](#) provides information on:

- Techniques for assigning constant and initialization values to arbitrary precision integers (including values greater than 64-bit).
- A description of Vivado HLS helper functions, such as printing, concatenating, bit-slicing and range selection functions.
- A description of operator behavior, including a description of shift operations (a negative shift values, results in a shift in the opposite direction).

C++ Arbitrary Precision Integer Types

The native data types in C++ are on 8-bit boundaries (8, 16, 32 and 64 bits). RTL signals and operations support arbitrary bit-lengths.

Vivado HLS provides arbitrary precision data types for C++ to allow variables and operations in the C++ code to be specified with any arbitrary bit-widths: 6-bit, 17-bit, 234-bit, up to 1024 bits.



TIP: *The default maximum width allowed is 1024 bits. You can override this default by defining the macro AP_INT_MAX_W with a positive integer value less than or equal to 32768 before inclusion of the ap_int.h header file.*

C++ supports use of the arbitrary precision types defined in the SystemC standard. Include the SystemC header file systemc.h, and use SystemC data types. For more information on SystemC types, see [SystemC Synthesis in Chapter 3](#).

Arbitrary precision data types have two primary advantages over the native C++ types:

- Better quality hardware: If for example, a 17-bit multiplier is required, arbitrary precision types can specify that exactly 17-bit are used in the calculation.

Without arbitrary precision data types, such a multiplication (17-bit) must be implemented using 32-bit integer data types and result in the multiplication being implemented with multiple DSP48 components.
- Accurate C++ simulation/analysis: Arbitrary precision data types in the C++ code allows the C++ simulation to be performed using accurate bit-widths and for the C++ simulation to validate the functionality (and accuracy) of the algorithm before synthesis.

The arbitrary precision types in C++ have none of the disadvantages of those in C:

- C++ arbitrary types can be compiled with standard C++ compilers (there is no C++ equivalent of apcc, as discussed in [Validating Arbitrary Precision Types in C](#)).
- C++ arbitrary precision types do not suffer from Integer Promotion Issues.

It is not uncommon for users to change a file extension from .c to .cpp so the file can be compiled as C++, where neither of these issues are present.

For the C++ language, the header file ap_int.h defines the arbitrary precision integer data types ap_(u)int<W>. For example, ap_int<8> represents an 8-bit signed integer data type and ap_uint<234> represents a 234-bit unsigned integer type.

The ap_int.h file is located in the directory \$HLS_ROOT/include, where \$HLS_ROOT is the Vivado HLS installation directory.

The code shown in the following example, is a repeat of the code shown in the earlier example on basic arithmetic ([Example 3-22](#) and again in [Example 2-1](#)). In this example the data types in the top-level function to be synthesized are specified as dinA_t, dinB_t ...

```
#include cpp_ap_int_arith.h

void cpp_ap_int_arith(din_A inA, din_B inB, din_C inC, din_D inD,
                      dout_1 *out1, dout_2 *out2, dout_3 *out3, dout_4 *out4)
{
    // Basic arithmetic operations
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = inD % inA;
}
```

Example 2-4: Basic Arithmetic Revisited with C++ Types

In this latest update to this example, the C++ arbitrary precision types are used:

- Add header file ap_int.h to the source code.
- Change the native C++ types to arbitrary precision types ap_int<N> or ap_uint<N>, where N is a bit-size from 1 to 1024 (as noted above, this can be extended to 32K-bits if required).

The data types are defined in the header cpp_ap_int_arith.h as shown in [Example 2-2](#).

Compared with [Example 3-22](#), the input data types have simply been reduced to represent the maximum size of the real input data (for example, 8-bit input inA is reduced to 6-bit input). The output types have been refined to be more accurate, for example, out2, the sum of inA and inB, need only be 13-bit and not 32-bit.

```

#ifndef _CPP_AP_INT_ARITH_H_
#define _CPP_AP_INT_ARITH_H_

#include <stdio.h>
#include ap_int.h

#define N 9

// Old data types
//typedef char dinA_t;
//typedef short dinB_t;
//typedef int dinC_t;
//typedef long long dinD_t;
//typedef int dout1_t;
//typedef unsigned int dout2_t;
//typedef int32_t dout3_t;
//typedef int64_t dout4_t;

typedef ap_int<6> dinA_t;
typedef ap_int<12> dinB_t;
typedef ap_int<22> dinC_t;
typedef ap_int<33> dinD_t;

typedef ap_int<18> dout1_t;
typedef ap_uint<13> dout2_t;
typedef ap_int<22> dout3_t;
typedef ap_int<6> dout4_t;

void cpp_ap_int_arith(dinA_t inA,dinB_t inB,dinC_t inC,dinD_t inD,dout1_t
                      *out1,dout2_t *out2,dout3_t *out3,dout4_t *out4);

#endif

```

Example 2-5: Basic Arithmetic with C++ Arbitrary Precision Types

If [Example 2-4](#) is synthesized, it results in a design that is functionally identical to [Example 3-22](#) and [Example 2-2](#). It keeps the test bench as similar as possible to [Example 2-2](#), rather than use the C++ cout operator to output the results to a file, the built-in ap_int method .to_int() is used to convert the ap_int results to integer types used with the standard fprintf function.

```

fprintf(fp, %d*%d=%d; %d+%d=%d; %d/%d=%d; %d mod %d=%d;\n,
        inA.to_int(), inB.to_int(), out1.to_int(),
        inB.to_int(), inA.to_int(), out2.to_int(),
        inC.to_int(), inA.to_int(), out3.to_int(),
        inD.to_int(), inA.to_int(), out4.to_int());

```

C++ Arbitrary Precision Integer Types: Reference Information

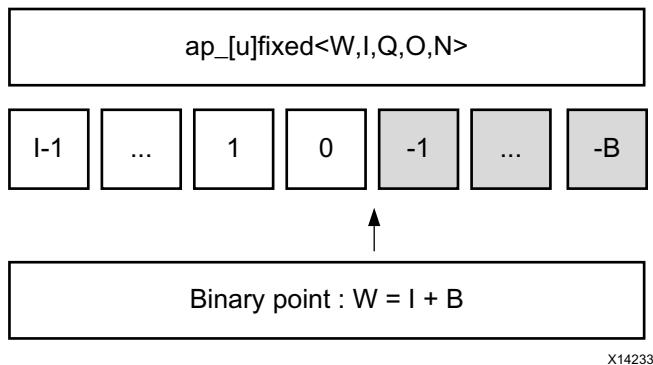
For comprehensive information on the methods, synthesis behavior, and all aspects of using the `ap_(u)int<N>` arbitrary precision data types, see [C++ Arbitrary Precision Types in Chapter 4](#). This section includes:

- Techniques for assigning constant and initialization values to arbitrary precision integers (including values greater than 1024-bit).
- A description of Vivado HLS helper methods, such as printing, concatenating, bit-slicing and range selection functions.
- A description of operator behavior, including a description of shift operations (a negative shift values, results in a shift in the opposite direction).

C++ Arbitrary Precision Fixed-Point Types

C++ functions can take advantage of the arbitrary precision fixed-point types included with Vivado HLS. The following figure summarizes the basic features of these fixed-point types:

- The word can be signed (`ap_fixed`) or unsigned (`ap_ufixed`).
- A word with of any arbitrary size W can be defined.
- The number of places above the decimal point I , also defines the number of decimal places in the word, $W-I$ (represented by B in the following figure).
- The type of rounding or quantization (Q) can be selected.
- The overflow behavior (O and N) can be selected.



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Figure 2-3: Arbitrary Precision Fixed-Point Types

The arbitrary precision fixed-point types can be used when header file `ap_fixed.h` is included in the code.



TIP: *Arbitrary precision fixed-point types use more memory during C simulation. If using very large arrays of `ap_[u]fixed` types, refer to the discussion of C simulation in [Arrays in Chapter 3](#).*

The advantages of using fixed-point types are:

- They allow fractional number to be easily represented.
- When variables have a different number of integer and decimal place bits, the alignment of the decimal point is handled.
- There are numerous options to handle how rounding should happen: when there are too few decimal bits to represent the precision of the result.
- There are numerous options to handle how variables should overflow: when the result is greater than the number of integer bits can represent.

These attributes are summarized by examining the code in [Example 2-6](#). First, the header file `ap_fixed.h` is included. The `ap_fixed` types are then defined using the `typedef` statement:

- A 10-bit input: 8-bit integer value with 2 decimal places.
- A 6-bit input: 3-bit integer value with 3 decimal places.
- A 22-bit variable for the accumulation: 17-bit integer value with 5 decimal places.
- A 36-bit variable for the result: 30-bit integer value with 6 decimal places.

The function contains no code to manage the alignment of the decimal point after operations are performed. The alignment is done automatically.

```
#include ap_fixed.h

typedef ap_ufixed<10,8, AP_RND, AP_SAT> din1_t;
typedef ap_fixed<6,3, AP_RND, AP_WRAP> din2_t;
typedef ap_fixed<22,17, AP_TRN, AP_SAT> dint_t;
typedef ap_fixed<36,30> dout_t;

dout_t cpp_ap_fixed(din1_t d_in1, din2_t d_in2) {

    static dint_t sum;
    sum += d_in1;
    return sum * d_in2;
}
```

Example 2-6: ap_fixed Type Example

The following table shows the quantization and overflow modes. For detailed information, see [C++ Arbitrary Precision Fixed-Point Types in Chapter 4](#).



TIP: Quantization and overflow modes that do more than the default behavior of standard hardware arithmetic (wrap and truncate) result in operators with more associated hardware. It costs logic (LUTs) to implement the more advanced modes, such as round to minus infinity or saturate symmetrically.

Table 2-4: Fixed-Point Identifier Summary

Identifier	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 dictates the behavior when greater precision is generated than can be defined by smallest fractional bit in the variable used to store the result.	
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 dictates the behavior when more bits are generated than the variable to store the result contains.	
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.	

Using `ap_(u)fixed` types, the C++ simulation is bit accurate. Fast simulation can validate the algorithm and its accuracy. After synthesis, the RTL exhibits the identical bit-accurate behavior.

Arbitrary precision fixed-point types can be freely assigned literal values in the code. See [shown the test bench \(Example 2-7\)](#) used with [Example 2-6](#), in which the values of `in1` and `in2` are declared and assigned constant values.

When assigning literal values involving operators, the literal values must first be cast to ap_(u)fixed types. Otherwise, the C compiler and Vivado HLS interpret the literal as an integer or float/double type and may fail to find a suitable operator. As shown in the following example, in the assignment of `in1 = in1 + din1_t(0.25)`, the literal 0.25 is cast an ap_fixed type.

```
#include <cmath>
#include <fstream>
#include <iostream>
#include <iomanip>
#include <cstdlib>
using namespace std;
#include ap_fixed.h

typedef ap_ufixed<10,8, AP_RND, AP_SAT> din1_t;
typedef ap_fixed<6,3, AP_RND, AP_WRAP> din2_t;
typedef ap_fixed<22,17, AP_TRN, AP_SAT> dint_t;
typedef ap_fixed<36,30> dout_t;

dout_t cpp_ap_fixed(din1_t d_in1, din2_t d_in2);

int main()
{
    ofstream result;
    din1_t in1 = 0.25;
    din2_t in2 = 2.125;
    dout_t output;
    int retval=0;

    result.open(result.dat);
    // Persistent manipulators
    result << right << fixed << setbase(10) << setprecision(15);

    for (int i = 0; i <= 250; i++)
    {
        output = cpp_ap_fixed(in1,in2);

        result << setw(10) << i;
        result << setw(20) << in1;
        result << setw(20) << in2;
        result << setw(20) << output;
        result << endl;

        in1 = in1 + din1_t(0.25);
        in2 = in2 - din2_t(0.125);
    }
    result.close();

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed !!!\n);
        retval=1;
    } else {
        printf(Test passed !\n);
    }
}
```

```

    // Return 0 if the test passes
    return retval;
}

```

Example 2-7: ap_fixed Type Test Bench Coding Example

C++ Arbitrary Precision Fixed-Point Types: Reference Information

For comprehensive information on the methods, synthesis behavior, and all aspects of using the `ap_(u)fixed<N>` arbitrary precision fixed-point data types, see [C++ Arbitrary Precision Fixed-Point Types in Chapter 4](#). This section includes:

- Techniques for assigning constant and initialization values to arbitrary precision integers (including values greater than 1024-bit).
 - A detailed description of the overflow and saturation modes.
 - A description of Vivado HLS helper methods, such as printing, concatenating, bit-slicing and range selection functions.
 - A description of operator behavior, including a description of shift operations (a negative shift values, results in a shift in the opposite direction).
-

HLS Stream Library

Streaming data is a type of data transfer in which data samples are sent in sequential order starting from the first sample. Streaming requires no address management.

Modeling designs that use streaming data can be difficult in C. As discussed in [Multi-Access Pointer Interfaces: Streaming Data in Chapter 3](#), the approach of using pointers to perform multiple read and/or write accesses can introduce problems, because there are implications for the type qualifier and how the test bench is constructed.

Vivado HLS provides a C++ template class `hls::stream<>` for modeling streaming data structures. The streams implemented with the `hls::stream<>` class have the following attributes.

- In the C code, an `hls::stream<>` behaves like a FIFO of infinite depth. There is no requirement to define the size of an `hls::stream<>`.
- They are read from and written to sequentially. That is, after data is read from an `hls::stream<>`, it cannot be read again.
- An `hls::stream<>` on the top-level interface is by default implemented with an `ap_fifo` interface.
- An `hls::stream<>` is implemented in synthesis as a FIFO with a depth of 1. The optimization directive `STREAM` is used to change this default size.

This section shows how the `hls::stream<>` class can more easily model designs with streaming data. The topics in this section provide:

- An overview of modeling with streams and the RTL implementation of streams.
- Rules for global stream variables.
- How to use streams.
- Blocking reads and writes.
- Non-Blocking Reads and writes.
- Controlling the FIFO depth.

Note: The `hls::stream` class should always be passed between functions as a C++ reference argument. For example, `&my_stream`.



IMPORTANT: *The `hls::stream` class is only used in C++ designs.*

C Modeling and RTL Implementation

Streams are modeled as infinite queue in software (and in the test bench during RTL co-simulation). There is no need to specify any depth to simulate streams in C++. Streams can be used inside functions and on the interface to functions. Internal streams may be passed as function parameters.

Streams can be used only in C++ based designs. Each `hls::stream<>` object must be written by a single process and read by a single process. For example, in a DATAFLOW design each stream can have only one producer and one consumer process.

In the RTL, streams are implemented as FIFO interface but can optionally be implemented using a full handshake interface port (`ap_hs`). The default interface port is an `ap_fifo` port. The depth of the FIFO optionally can be using the STREAM directive.

Global and Local Streams

Streams may be defined either locally or globally. Local streams are always implemented as internal FIFOs. Global streams can be implemented as internal FIFOs or ports:

- Globally-defined streams that are only read from, or only written to, are inferred as external ports of the top-level RTL block.
- Globally-defined streams that are both read from and written to (in the hierarchy below the top-level function) are implemented as internal FIFOs.

Streams defined in the global scope follow the same rules as any other global variables. For more information on the synthesis of global variables, see [Data Types and Bit-Widths in Chapter 1](#).

Using HLS Streams

To use `hls::stream<>` objects, include the header file `hls_stream.h`. Streaming data objects are defined by specifying the type and variable name. In this example, a 128-bit unsigned integer type is defined and used to create a stream variable called `my_wide_stream`.

```
#include "ap_int.h"
#include "hls_stream.h"

typedef ap_uint<128> uint128_t; // 128-bit user defined type
hls::stream<uint128_t> my_wide_stream; // A stream declaration
```

Streams must use scoped naming. It is recommended to use the scoped `hls::` naming shown in the example above. However, if the `hls` namespace is used, the above example can be rewritten as:

```
#include <ap_int.h>
#include <hls_stream.h>
using namespace hls;

typedef ap_uint<128> uint128_t; // 128-bit user defined type
stream<uint128_t> my_wide_stream; // hls:: no longer required
```

Given a stream specified as `hls::stream<T>`, the type `T` may be:

- Any C++ native data type
- A Vivado HLS arbitrary precision type (for example, `ap_int<>`, `ap_ufixed<>`)
- A user-defined struct containing either of the above types

Note: General user-defined classes (or structures) that contain methods (member functions) should not be used as the type (`T`) for a stream variable.

Streams may be optional named. Providing a name for the stream allows the name to be used in reporting. For example, Vivado HLS automatically checks to ensure all elements from an input stream are read during simulation. Given the following two streams:

```
stream<uint8_t> bytestr_in1;
stream<uint8_t> bytestr_in2("input_stream2");
```

Any warning on elements left in the streams are reported as follows, where it is clear which message relates to `bytetr_in2`:

```
WARNING: Hls::stream 'hls::stream<unsigned char>.1' contains leftover data, which
may result in RTL simulation hanging.
WARNING: Hls::stream 'input_stream2' contains leftover data, which may result in RTL
simulation hanging.
```

When streams are passed into and out of functions, they must be passed-by-reference as in the following example:

```
void stream_function (
    hls::stream<uint8_t> &strm_out,
    hls::stream<uint8_t> &strm_in,
    uint16_t strm_len
)
```

Vivado HLS supports both blocking and non-blocking access methods.

- Non-blocking accesses can be implemented only as FIFO interfaces.
- Streaming ports that are implemented as `ap_fifo` ports and that are defined with an AXI4-Stream resource must not use non-blocking accesses.

A complete design example using streams is provided in the Vivado HLS examples. Refer to the `hls_stream` example in the design examples available from the GUI welcome screen.

Blocking Reads and Writes

The basic accesses to an `hls::stream<>` object are blocking reads and writes. These are accomplished using class methods. These methods stall (block) execution if a read is attempted on an empty stream FIFO, a write is attempted to a full stream FIFO, or until a full handshake is accomplished for a stream mapped to an `ap_hs` interface protocol.

Blocking Write Methods

In this example, the value of variable `src_var` is pushed into the stream.

```
// Usage of void write(const T & wdata)

hls::stream<int> my_stream;
int src_var = 42;

my_stream.write(src_var);
```

The `<<` operator is overloaded such that it may be used in a similar fashion to the stream insertion operators for C++ stream (for example, `iostreams` and `filestreams`). The `hls::stream<>` object to be written to is supplied as the left-hand side argument and the value to be written as the right-hand side.

```
// Usage of void operator << (T & wdata)

hls::stream<int> my_stream;
int src_var = 42;

my_stream << src_var;
```

Blocking Read Methods

This method reads from the head of the stream and assigns the values to the variable `dst_var`.

```
// Usage of void read(T &rdata)

hls::stream<int> my_stream;
int dst_var;

my_stream.read(dst_var);
```

Alternatively, the next object in the stream can be read by assigning (using for example `=`, `+=`) the stream to an object on the left-hand side:

```
// Usage of T read(void)

hls::stream<int> my_stream;

int dst_var = my_stream.read();
```

The '`>>`' operator is overloaded to allow use similar to the stream extraction operator for C++ stream (for example, iostreams and filestreams). The `hls::stream` is supplied as the LHS argument and the destination variable the RHS.

```
// Usage of void operator >> (T & rdata)

hls::stream<int> my_stream;
int dst_var;

my_stream >> dst_var;
```

Non-Blocking Reads and Writes

Non-blocking write and read methods are also provided. These allow execution to continue even when a read is attempted on an empty stream FIFO or a write to a full stream FIFO.

These methods return a Boolean value indicating the status of the access (`true` if successful, `false` otherwise). Additional methods are included for testing the status of an `hls::stream<>` stream.



TIP: *None of the methods discussed for non-blocking accesses can be used on an `hls::stream<>` interface for which the `ap_hs` protocol has been selected.*

During C simulation, streams have an infinite size. It is therefore not possible to validate with C simulation if the stream is full. These methods can be verified only during RTL simulation when the FIFO sizes are defined (either the default size of 1, or an arbitrary size defined with the STREAM directive).

Non-Blocking Writes

This method attempts to push variable `src_var` into the stream `my_stream`, returning a boolean `true` if successful. Otherwise, `false` is returned and the queue is unaffected.

```
// Usage of void write_nb(const T & wdata)

hls::stream<int> my_stream;
int src_var = 42;

if (my_stream.write_nb(src_var)) {
    // Perform standard operations
    ...
} else {
    // Write did not occur
    return;
}
```

Fullness Test

```
bool full(void)
```

Returns `true`, if and only if the `hls::stream<>` object is full.

```
// Usage of bool full(void)

hls::stream<int> my_stream;
int src_var = 42;
bool stream_full;

stream_full = my_stream.full();
```

Non-Blocking Read

```
bool read_nb(T & rdata)
```

This method attempts to read a value from the stream, returning `true` if successful. Otherwise, `false` is returned and the queue is unaffected.

```
// Usage of void read_nb(const T & wdata)

hls::stream<int> my_stream;
int dst_var;

if (my_stream.read_nb(dst_var)) {
    // Perform standard operations
    ...
} else {
    // Read did not occur
    return;
}
```

Emptiness Test

```
bool empty(void)
```

Returns true if the `hls::stream<>` is empty.

```
// Usage of bool empty(void)

hls::stream<int> my_stream;
int dst_var;
bool stream_empty;

fifo_empty = my_stream.empty();
```

The following example shows how a combination of non-blocking accesses and full/empty tests can provide error handling functionality when the RTL FIFOs are full or empty:

```
#include hls_stream.h
using namespace hls;

typedef struct {
    short    data;
    bool     valid;
    bool     invert;
} input_interface;

bool invert(stream<input_interface>& in_data_1,
            stream<input_interface>& in_data_2,
            stream<short>& output
        ) {
    input_interface in;
    bool full_n;

    // Read an input value or return
    if (!in_data_1.read_nb(in))
        if (!in_data_2.read_nb(in))
            return false;

    // If the valid data is written, return not-full (full_n) as true
    if (in.valid) {
        if (in.invert)
            full_n = output.write_nb(~in.data);
        else
            full_n = output.write_nb(in.data);
    }
    return full_n;
}
```

Controlling the RTL FIFO Depth

For most designs using streaming data, the default RTL FIFO depth of 1 is sufficient. Streaming data is generally processed one sample at a time.

For multirate designs in which the implementation requires a FIFO with a depth greater than 1, you must determine (and set using the STREAM directive) the depth necessary for the RTL simulation to complete. If the FIFO depth is insufficient, RTL co-simulation stalls.

Because stream objects cannot be viewed in the GUI directives pane, the STREAM directive cannot be applied directly in that pane.

Right-click the function in which an `hls::stream<>` object is declared (or is used, or exists in the argument list) to:

- Select the STREAM directive.
- Populate the variable field manually with name of the stream variable.

Alternatively, you can:

- Specify the STREAM directive manually in the `directives.tcl` file, or
- Add it as a pragma in source.

C/RTL Co-Simulation Support

The Vivado HLS C/RTL co-simulation feature does not support structures or classes containing `hls::stream<>` members in the top-level interface. Vivado HLS supports these structures or classes for synthesis.

```
typedef struct {
    hls::stream<uint8_t> a;
    hls::stream<uint16_t> b;
} strm_strct_t;

void dut_top(strm_strct_t indata, strm_strct_t outdata) { ... }
```

These restrictions apply to both top-level function arguments and globally declared objects. If structs of streams are used for synthesis, the design must be verified using an external RTL simulator and user-created HDL test bench. There are no such restrictions on `hls::stream<>` objects with strictly internal linkage.

HLS Math Library

The Vivado HLS Math Library (`hls_math.h`) provides extensive support for the synthesis of the standard C (`math.h`) and C++ (`cmath.h`) libraries. The support includes floating point and fixed-point functions.

Not every function supported by the standard C math libraries is provided in the HLS Math Library. Only the math functions shown in the following table are supported for synthesis.

Table 2-5: HLS Math Library

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

Table 2-5: HLS Math Library (Cont'd)

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

Table 2-5: HLS Math Library (Cont'd)

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

Using the HLS Math Library

The `hls_math.h` library is used automatically when synthesis is performed. It can optionally be included in the C source. The only difference between using the standard C math library or using the `hls_math.h` math library in the C source is the results for C simulation and C/RTL co-simulation.

This is related to the accuracy of the implemented functions, as listed in the preceding table.

HLS Math Library Accuracy

Some of the HLS math functions are implemented using a floating point LogiCORE IP. These functions are always an exact match to the functions in the standard C libraries over the entire range of operation. Others math functions are implemented as synthesizable bit-approximate functions from the `hls_math.h` library. In some cases, the bit-approximate HLS math library function does not provide the same accuracy as the standard C function. To achieve the desired result, a bit-approximate implementation may use a different underlying algorithm than the C or C++ version.

The accuracy of the function is specified in terms of ULP (Unit of Least Precision). With floating point numbers, the least significant binary bit does not always represent the value 1 or 0. The exact representation of the LSB depends on the value of the exponent. The ULP is a measure of how accurate the implementation is over the entire range of operation. An accuracy of 1 ULP means that, over the entire range of operation the result might differ from the mathematically exact answer by 1 LSB: in this case, the relative error is extremely small.

This difference in accuracy has implications, discussed later, for both C simulation and C/RTL co-simulation.

In addition, the following seven functions might show some differences, depending on the C standard used to compile and run the C simulation:

- `copysign`
- `fpclassify`
- `isinf`
- `isfinite`
- `isnan`
- `isnormal`
- `signbit`

C90 mode

Only `isinf`, `isnan`, and `copysign` are usually provided by the system header files, and they operate on doubles. In particular, `copysign` always returns a double result. This might result in unexpected results after synthesis, if it must be returned to a float, because a double-to-float conversion block is introduced into the hardware.

C99 mode (-std=c99)

All seven functions are usually provided under the expectation that the system header files will redirect them to `__isnan(double)` and `__isnan(float)`. The usual GCC header files do not redirect `isnormal`, but implement it in terms of `fpclassify`.

C++ Using math.h

All seven are provided by the system header files, and they operate on doubles.

`copysign` always returns a double result. This might cause unexpected results after synthesis if it must be returned to a float, because a double-to-float conversion block is introduced into the hardware.

C++ Using cmath

Similar to C99 mode (`-std=c99`) except that:

- The system header files are usually different.
- The functions are properly overloaded for:
 - `float().snan(double)`
 - `isinf(double)`

`copysign` and `copysignf` are handled as built-ins even when using namespace `std`;

C++ Using cmath and namespace std

No issues. Xilinx recommends using the following for best results:

- `-std=c99` for C
- `-fno-builtin` for C and C++

Note: To specify the C compile options, such as `-std=c99`, use the Tcl command `add_files` with the `-cflags` option. Alternatively, use the **Edit CFLAGs** button in the Project Settings dialog box.

Verification and Math Functions

If the standard C math library is used in the C source code, the C simulation results and the C/RTL co-simulation results are different: if any of the math functions in the source code have an accuracy other than exact (as stated in the table of math functions above), it results in differences when the RTL is simulated.

If the `hls_math.h` library is used in the C source code, the C simulation and C/RTL co-simulation results are identical. However, the results of C simulation using `hls_math.h` are not the same as those using the standard C libraries. The `hls_math.h` library simply ensures the C simulation matches the C/RTL co-simulation results.

In both cases, the same RTL implementation is created.

The following explains each of the possible options which are used to perform verification when using math functions.

Verification Option 1: Standard Math Library and Verify Differences

In this option, the standard C math libraries are used in the source code. If any of the functions synthesized do have exact accuracy the C/RTL co-simulation is different than the C simulation. The following example highlights this approach.

```
#include <cmath>
#include <fstream>
#include <iostream>
#include <iomanip>
#include <cstdlib>
using namespace std;

typedef float data_t;

data_t cpp_math(data_t angle) {
    data_t s = sinf(angle);
    data_t c = cosf(angle);
    return sqrtf(s*s+c*c);
}
```

Example 2-8: Standard C Math Library Example

In this case, the results between C simulation and C/RTL co-simulation are different. Keep in mind when comparing the outputs of simulation, any results written from the test bench are written to the working directory where the simulation executes:

- C simulation: Folder <project>/<solution>/csim/build
- C/RTL co-simulation: Folder <project>/<solution>/sim/<RTL>

where <project> is the project folder, <solution> is the name of the solution folder and <RTL> is the type of RTL verified (verilog, vhdl or systemc). The following figure shows a typical comparison of the pre-synthesis results file on the left-hand side and the post-synthesis RTL results file on the right-hand side. The output is shown in the third column.

	result.dat			proj_cpp_math.prj/solution1/sim/systemc/result.dat		
1	0.000000000000000	0.00999999776483	1.000000000000000	0.009999997776483	1.000000000000000	
2	1.000000000000000	0.10999999403954	1.000000000000000	1.000000000000000	1.000000000000000	
3	2.000000000000000	0.20999993443489	1.000000000000000	2.00999993443489	1.000000000000000	
4	3.000000000000000	0.31000002384186	1.000000000000000	3.01000002384186	1.000000000000000	
5	4.000000000000000	0.40999995423721	1.000000000000000	4.040999996423721	1.000000000000000	
6	5.000000000000000	0.50999990463257	1.000000000000000	5.05099990463257	1.000000000000000	
7	6.000000000000000	0.61000014305115	1.000000000000000	6.16000014305115	1.000000000000000	
8	7.000000000000000	0.71000038146973	1.000000000000000	7.071000038146973	1.000000000000000	
9	8.000000000000000	0.81000061988831	1.000000000000000	8.081000061988831	1.000000000000000	
10	9.000000000000000	0.91000085830688	1.000000000000000	9.091000085830688	1.000000000000000	
11	10.000000000000000	1.010000109672546	1.000000000000000	10.1010000109672546	1.000000000000000	
12	11.000000000000000	1.110000132514404	1.000000000000000	11.1110000132514404	0.999999940395355	
13	12.000000000000000	1.210000157356262	1.000000000000000	12.1210000157356262	1.000000000000000	
14	13.000000000000000	1.310000181198120	0.999999940395355	13.1310000181198120	0.999999940395355	
15	14.000000000000000	1.410000205039978	1.000000000000000	14.1410000205039978	1.000000000000000	
16	15.000000000000000	1.510000228881836	1.000000000000000	15.1510000228881836	1.000000000000000	
17	16.000000000000000	1.610000252723694	1.000000000000000	16.1610000252723694	1.000000000000000	
18	17.000000000000000	1.710000276565552	1.000000000000000	17.1710000276565552	1.000000000000000	
19	18.000000000000000	1.810000300407410	1.000000000000000	18.1810000300407410	1.000000000000000	
20	19.000000000000000	1.910000324249268	0.999999940395355	19.1910000324249268	1.000000000000000	
21	20.000000000000000	2.010000228881836	0.999999940395355	20.2010000228881836	0.999999940395355	
22	21.000000000000000	2.110000133514404	1.000000000000000	21.2110000133514404	1.000000000000000	
23	22.000000000000000	2.21000038146973	1.000000000000000	22.221000038146973	1.000000000000000	
24	23.000000000000000	2.30999942779541	1.000000000000000	23.230999942779541	1.000000000000000	
25	24.000000000000000	2.40999847412109	1.000000000000000	24.240999847412109	1.000000000000000	
26	25.000000000000000	2.50999752044678	1.000000000000000	25.250999752044678	1.000000000000000	
27	26.000000000000000	2.60999656677246	1.000000000000000	26.260999656677246	1.000000000000000	
28	27.000000000000000	2.709999561309814	0.999999940395355	27.2709999561309814	1.000000000000000	
29	28.000000000000000	2.80999465942383	1.000000000000000	28.280999465942383	1.000000000000000	
30	29.000000000000000	2.90999370574951	1.000000000000000	29.290999370574951	1.000000000000000	

Figure 2-4: Pre-Synthesis and Post-Synthesis Simulation Differences

The results of pre-synthesis simulation and post-synthesis simulation differ by fractional amounts. You must decide whether these fractional amounts are acceptable in the final RTL implementation.

The recommended flow for handling these differences is using a test bench that checks the results to ensure that they lie within an acceptable error range. This can be accomplished by creating two versions of the same function, one for synthesis and one as a reference version. In this example, only function `cpp_math` is synthesized.

```
#include <cmath>
#include <fstream>
#include <iostream>
#include <iomanip>
#include <cstdlib>
using namespace std;

typedef float data_t;

data_t cpp_math(data_t angle) {
    data_t s = sinf(angle);
```

```

    data_t c = cosf(angle);
    return sqrtf(s*s+c*c);
}

data_t cpp_math_sw(data_t angle) {
    data_t s = sinf(angle);
    data_t c = cosf(angle);
    return sqrtf(s*s+c*c);
}

```

The test bench to verify the design compares the outputs of both functions to determine the difference, using variable `diff` in the following example. During C simulation both functions produce identical outputs. During C/RTL co-simulation function `cpp_math` produces different results and the difference in results are checked.

```

int main() {
    data_t angle = 0.01;
    data_t output, exp_output, diff;
    int retval=0;

    for (data_t i = 0; i <= 250; i++) {
        output = cpp_math(angle);
        exp_output = cpp_math_sw(angle);

        // Check for differences
        diff = ( (exp_output > output) ? exp_output - output : output - exp_output);
        if (diff > 0.0000005) {
            printf("Difference %.10f exceeds tolerance at angle %.10f \n", diff, angle);
            retval=1;
        }

        angle = angle + .1;
    }

    if (retval != 0) {
        printf("Test failed !!!\n");
        retval=1;
    } else {
        printf("Test passed !\n");
    }
    // Return 0 if the test passes
    return retval;
}

```

If the margin of difference is lowered to 0.00000005, this test bench highlights the margin of error during C/RTL co-simulation:

```

Difference 0.0000000596 at angle 1.1100001335
Difference 0.0000000596 at angle 1.2100001574
Difference 0.0000000596 at angle 1.5100002289
Difference 0.0000000596 at angle 1.6100002527
etc..

```

When using the standard C math libraries (`math.h` and `cmath.h`) create a "smart" test bench to verify any differences in accuracy are acceptable.

Verification Option 2: HLS Math Library and Validate Differences

An alternative verification option is to convert the source code to use the HLS math library. With this option, there are no differences between the C simulation and C/RTL co-simulation results. The following example shows how the code above is modified to use the `hls_math.h` library.

Note: This option is only available in C++.

- Include the `hls_math.h` header file.
- Replace the math functions with the equivalent `hls::` function.

```
#include <cmath>
#include "hls_math.h"
#include <fstream>
#include <iostream>
#include <iomanip>
#include <cstdlib>
using namespace std;

typedef float data_t;

data_t cpp_math(data_t angle) {
    data_t s = hls::sinf(angle);
    data_t c = hls::cosf(angle);
    return hls::sqrtf(s*s+c*c);
}
```

There is a difference between the C simulation results using the HLS math library and those previously obtained using the standard C math libraries. These difference should be validated with C simulation using a “smart” test bench similar to option 1.

In cases where there are many math functions and updating the code is painful, a third option can be used.

Verification Option 3: HLS Math Library File and Validate Differences

Including the HLS math library file `lib_hlsm.cpp` as a design file ensures Vivado HLS uses the HLS math library for C simulation. This option is identical to option2 however it does not require the C code to be modified.

The HLS math library file is located in the `src` directory in the Vivado HLS installation area. Simply copy the file to your local folder and add the file as a standard design file.

Note: This option is only available in C++.

There is a difference between the C simulation results using the HLS math library file and those previously obtained without adding this file. These difference should be validated with C simulation using a “smart” test bench similar to option 1.

Verification Option 4: HLS Math Macros and Validate Differences

A final verification option is to use the HLS math macros defined in header file `hls_fpo.h`. This header file is located in the include directory in the Vivado HLS installation area. This solution, like options 2 and 3, ensures the results of C simulation uses the HLS math library and has identical results to the C/RTL cosimulation but does not require the design to be C++.

- Include the `hls_fpo.h` header file.
- Replace the math functions with their equivalent `HLS_FPO_` macro.

Fixed-Point Math Functions

Fixed-point math functions are also provided. Fixed-point implementations can be called using the same `hls_math.h` library as those used with float or double types. The fixed-point type provides a slightly-less accurate version of the function value, but a smaller and faster RTL implementation.

The fixed-point type functions are intended as replacements for functions using float type variables and are therefore fixed to 32-bit input and return. The number of integer bits can be any value up to 32.

The HLS math library provides fixed-point implementations for some of the most common math functions. The methodology for using these functions is:

- Review [Table 2-5](#) to determine if a fixed-point implementation is supported.
- Update the math functions to use `ap_fixed` types.
- Perform C simulation to validate the design still operates with the required precision. The C simulation is performed using the same bit-accurate types as the RTL implementation.
- Synthesize the design.

When using fixed-point math functions, the input type must include the decimal point ($W \geq I, I >= 0$ if unsigned, $I \geq 1$ if signed). The result type has the same width and integer bits as the input (although some of the leading bits are likely to be zero).

The `sqrt()` of a negative number returns zero.

Common Synthesis Errors

The following are common use errors when synthesizing math functions. These are often (but not exclusively) caused by converting C functions to C++ to take advantage of synthesis for math functions.

C++ cmath.h

If the C++ `cmath.h` header file is used, the floating point functions (for example, `sinf` and `cosf`) can be used. These result in 32-bit operations in hardware. The `cmath.h` header file also overloads the standard functions (for example, `sin` and `cos`) so they can be used for float and double types.

C math.h

If the C `math.h` library is used, the floating point functions (for example, `sinf` and `cosf`) are required to synthesize 32-bit floating point operations. All standard function calls (for example, `sin` and `cos`) result in doubles and 64-bit double-precision operations being synthesized.

Cautions

When converting C functions to C++ to take advantage of `math.h` support, be sure that the new C++ code compiles correctly before synthesizing with Vivado HLS. For example, if `sqrtf()` is used in the code with `math.h`, it requires the following code `extern` added to the C++ code to support it:

```
#include <math.h>
extern "C" float sqrtf(float);
```

To avoid unnecessary hardware caused by type conversion, follow the warnings on mixing double and float types discussed in [Floats and Doubles in Chapter 3](#).

Vivado HLS Video Library

The video library contains functions to help address several aspects of modeling video design in C++. The following topics are addressed in this section:

- Data Types
- Memory Line Buffer
- Memory Window
- Video Functions

Using the Video Library

The Vivado HLS video library requires the `hls_video.h` header file. This file includes all image and video processing specific video types and functions provided by Vivado HLS.

When using the Vivado HLS video library, the only additional usage requirement is as follows.

The design is written in C++ and uses the `hls` namespace:

```
#include <hls_video.h>

hls::rgb_8 video_data[1920][1080]
```

You can use alternatively scoped naming as shown in the following example. However, the recommended coding style is to use the `hls` namespace.

```
#include <hls_video.h>
using namespace hls;

rgb_8 video_data[1920][1080]
```

Video Data Types

The data types provided in the HLS Video Library are used to ensure the output RTL created by synthesis can be seamlessly integrated with any Xilinx® Video IP blocks used in the system.

When using any Xilinx Video IP in your system, refer to the IP data sheet and determine the format used to send or receive the video data. Use the appropriate video data type in the C code and the RTL created by synthesis may be connected to the Xilinx Video IP.

The library includes the following data types. All data types support 8-bit data only.

Table 2-6: Video Data Types

Data Type Name	Field 0 (8 bits)	Field 1 (8 bits)	Field 2 (8 bits)	Field 3 (8 bits)
yuv422_8	Y	UV	Not Used	Not Used
yuv444_8	Y	U	V	Not Used
rgb_8	G	B	R	Not Used
yuva422_8	Y	UV	A	Not Used
yuva444_8	Y	U	V	A
rgba_8	G	B	R	A
yuva420_8	Y	AUV	Not Used	Not Used
yuvd422_8	U	UV	D	Not Used
yuvd444_8	Y	U	V	D
rgbd_8	G	B	R	D
bayer_8	RGB	Not Used	Not Used	Not Used
luma_8	Y	Not Used	Not Used	Not Used

After the `hls_video.h` library is included, the data types can be freely used in the source code.

```
#include "hls_video.h"
hls::rgb_8 video_data[1920][1080]
```

Memory Line Buffer

The LineBuffer class is a C++ class that allows you to easily declare and manage line buffers within your algorithmic code. This class provides all the methods required for instantiating and working with line buffers. The LineBuffer class works with all data types.

The main features of the LineBuffer class are:

- Support for all data types through parameterization
- User-defined number of rows and columns
- Automatic banking of rows into separate memory banks for increased memory bandwidth
- Provides all the methods for using and debugging line buffers in an algorithmic design

The LineBuffer class has the following methods, explained below:

- `shift_up();`
- `shift_down()`
- `insert_bottom()`
- `insert_top()`
- `getval(row,column)`

To illustrate the usage of the LineBuffer class, the following data set is assumed at the start of all examples.

Table 2-7: Data Set for LineBuffer Examples

Row	Column 0	Column 1	Column 2	Column 3	Column 4
Row 2	1	2	3	4	5
Row 1	6	7	8	9	10
Row 0	11	12	13	14	15

A line buffer can be instantiated in an algorithm by using the `LineBuffer` data type, shown in this example specifying a LineBuffer variable for the data in the table above:

```
// hls::LineBuffer<type, rows, columns> variable;
hls::LineBuffer<char,3,5> Buff_A;
```

The LineBuffer class assumes the data entering the block instantiating the line buffer is arranged in raster scan order. Each new data item is therefore stored in a different column than the previous data item.

Inserting new values, while preserving a finite number of previous values in a column, requires a vertical shift between rows for a given column. After the shift is complete, a new data value can be inserted at either the top or the bottom of the column.

For example, to insert the value 100 to the top of column 2 of the line buffer set:

```
Buff_A.shift_down(2);
Buff_A.insert_top(100,2);
```

This results in the new data set shown in the following table.

Table 2-8: Data Set After Shift Down and Insert Top Classes Used

Line	Column 0	Column 1	Column 2	Column 3	Column 4
Line 2	1	2	100	4	5
Line 1	6	7	3	9	10
Line 0	11	12	8	14	15

To insert the value 100 to the bottom of column 2 of the line buffer set in [Table 2-7](#) use of the following:

```
Buff_A.shift_up(2);
Buff_A.insert_bottom(100,2);
```

This results in the new data set shown in the following table.

Table 2-9: Data Set After Shift Up and Insert Bottom Classes Used

Line	Column 0	Column 1	Column 2	Column 3	Column 4
Line 2	1	2	8	4	5
Line 1	6	7	13	9	10
Line 0	11	12	100	14	15

The shift and insert methods both require the column value on which to operate.

All values stored by a LineBuffer instance are available using the `getval(row, column)` method. Returns the value of any location inside the line buffer. For example, the following results in variable `Value` being assigned the value 9:

```
Value = Buff_A.getval(1,3);
```

Memory Window Buffer

The memory window C++ class allows you to declare and manage two-dimensional memory windows. The main features of this class are:

- Support for all data types through parametrization
- User-defined number of rows and columns
- Automatic partitioning into individual registers for maximum bandwidth
- Provides all the methods to use and debug memory windows in the context of an algorithm

The memory window class is supported by the following methods, explained below:

- `shift_up();`
- `shift_down()`
- `shift_left()`
- `shift_right()`
- `insert(value, row, column)`
- `insert_bottom()`
- `insert_top()`
- `insert_left()`
- `insert_right()`
- `getval(row, column)`

You can instantiate a memory window in an algorithm by specifying a `Window` variable for the following data type:

```
// hls::Window<type, rows, columns> variable;
hls::Window<char, 3, 3> Buff_B;
```

The memory window class examples in this section use the data set in the following table.

Table 2-10: Data Set for Memory Window Examples

Row	Column 0	Column 1	Column 2
Row 2	1	2	3
Row 1	6	7	8
Row 0	11	12	13

The `Window` class provides methods for moving data stored within the memory window up, down, left, and right. Each shift operation clears space in the memory window for new data.

Buff_B.shift_up() ; produces the following results.

Table 2-11: Memory Window Data Set After Shift Up

Row	Column 0	Column 1	Column 2
Row 2	6	7	8
Row 1	11	12	13
Row 0	New	New	New

Note: The New data has undefined, arbitrary values.

Buff_B.shift_down() ; produces the following results.

Table 2-12: Memory Window Data Set After Shift Down

Row	Column 0	Column 1	Column 2
Row 2	New	New	New
Row 1	1	2	3
Row 0	6	7	8

Note: The New data has undefined, arbitrary values.

Buff_B.shift_left() ; produces the following results.

Table 2-13: Memory Window Data Set After Shift Left

Row	Column 0	Column 1	Column 2
Row 2	2	3	New
Row 1	7	8	New
Row 0	12	13	New

Note: The New data has undefined, arbitrary values.

Buff_B.shift_right() ; produces the following results.

Table 2-14: Memory Window Data Set After Shift Right

Row	Column 0	Column 1	Column 2
Row 2	New	1	2
Row 1	New	6	7
Row 0	New	11	12

Note: The New data has undefined, arbitrary values.

The Window class allows you to insert and retrieve data from any location within the memory window. It also supports block insertion of data on the boundaries of the memory window.

To insert data into any location of the memory window, use the following:

```
insert(value, row, column);
```

For example, you can place the value 100 into row 1, column 1 of the memory window using:

```
Buff_B.insert(100,1,1);
```

This operation produces the following results.

Table 2-15: Memory Window Data Set After Insertion Operation at Location 1,1

Row	Column 0	Column 1	Column 2
Row 2	1	2	3
Row 1	6	100	8
Row 0	11	12	13

Block level insertion requires that you provide an array of data elements to insert on a boundary. The methods provided by the window class are:

- `insert_bottom`
- `insert_top`
- `insert_left`
- `insert_right`

For example, when C is an array of three elements in which each element has the value of 50, you can insert the value 50 across the bottom boundary of the memory window using the following operation:

```
char C[3] = {50, 50, 50};  
Buff_B.insert_bottom(C);
```

This operation produces the following results.

Table 2-16: Memory Window Data Set After Insert Bottom Operation Using an Array

Row	Column 0	Column 1	Column 2
Row 2	1	2	3
Row 1	6	7	8
Row 0	50	50	50

The other edge insertion methods for the window class work in the same way as the `insert_bottom()` method.

To retrieve data can from a memory window, use:

```
getval(row,column)
```

For example:

```
A = Buff_B.getval(0,1);
```

results in:

```
A = 50
```

Video Functions

The video processing functions included in the HLS Video library are compatible with existing OpenCV functions and are similarly named. They do not directly replace existing OpenCV video library functions. The video processing functions use a data type `hls::Mat`. This data type allows the functions to be synthesized and implemented as high performance hardware.

Three types of functions are provided in the HLS Video Library:

- OpenCV Interface Functions: Converts data to and from the AXI4 streaming data type and the standard OpenCV data types. These functions allow any OpenCV functions executed in software to transfer data, via the AXI4 streaming functions, to and from the hardware block created by HLS.
- AXI4-Stream Functions: These functions are used to convert the video data specified in `hls::mat` data types into an AXI4 streaming data type. This AXI4 streaming data type is used as an argument to the function to be synthesized, ensuring a high-performance interface is synthesized.
- Video Processing Functions: Compatible with standard OpenCV functions for manipulating and processing video images. These functions use the `hls::mat` data type and are synthesized by Vivado HLS.

OpenCV Interface Functions

In a typical video system using OpenCV functions, most of the algorithm remains on the CPU using OpenCV functions. Only those parts of the algorithm that require acceleration in the FPGA fabric are synthesized and therefore updated to use the Vivado HLS video functions.

Because the AXI4 streaming protocol is commonly used as the interface between the code that remains on the CPU and the functions to be synthesized, the OpenCV interface functions are provided to enable the data transfer between the OpenCV code running on the CPU and the synthesized hardware function running on FPGA fabric.

Using the interface functions to transform the data before passing it to the function to be synthesized ensures a high-performance system. In addition to transforming the data, the functions also include the means of converting OpenCV data formats to and from the Vivado HLS Video Library data types, for example `hls::Mat`.

To use the OpenCV interface functions, you must include the header file `hls_opencv.h`. These functions are used in the code that remains on the CPU.

AXI4-Stream Functions

The AXI4-Stream functions are used to transfer data into and out of the function to be synthesized. The video functions to be synthesized use the `hls::Mat` data type for an image.

The AXI4-Stream I/O functions discussed below allow you to convert the `hls::Mat` data type to or from the AXI4-Stream data type (`hls::stream`) used in the OpenCV Interface functions.

Video Processing Functions

The video processing functions included in the Vivado HLS Video Library are specifically for manipulating video images. Most of these functions are designed for accelerating corresponding OpenCV functions, which have a similar signature and usage.

Using Video Functions

The following example demonstrates how each of three types of video functions are used. In the test bench shown below:

- The data starts as standard OpenCV image data.
- This is converted to AXI4-Stream format using one of the OpenCV Interface Functions.
- The AXI4-Stream format is used for the input and output to the function for synthesis.
- Finally, the data is converted back into standard OpenCV formatted data.

This process ensures the test bench operates using the standard OpenCV functions used in many software applications. The test bench may be executed on a CPU with the following:

```
#include "hls_video.h"

int main (int argc, char** argv) {

    // Load data in OpenCV image format
    IplImage* src = cvLoadImage(INPUT_IMAGE);
    IplImage* dst = cvCreateImage(cvGetSize(src), src->depth, src->nChannels);
    AXI_STREAM src_axi, dst_axi;

    // Convert OpenCV format to AXI4 Stream format
    IplImage2AXIvideo(src, src_axi);
    // Call the function to be synthesized
    image_filter(src_axi, dst_axi, src->height, src->width);
    // Convert the AXI4 Stream data to OpenCV format
    AXIvideo2IplImage(dst_axi, dst);

    // Standard OpenCV image functions
    cvSaveImage(OUTPUT_IMAGE, dst);
    opencv_image_filter(src, dst);
    cvSaveImage(OUTPUT_IMAGE_GOLDEN, dst);
    cvReleaseImage(&src);
    cvReleaseImage(&dst);

    char tempbuf[2000];
    sprintf(tempbuf, "diff --brief -w %s %s", OUTPUT_IMAGE, OUTPUT_IMAGE_GOLDEN);
    int ret = system(tempbuf);
    if (ret != 0) {
        printf("Test Failed!\n");
        ret = 1;
    } else {
        printf("Test Passed!\n");
    }
    return ret;
}
```

The function to be synthesized, `image_filter`, is shown below. The characteristics of this function are:

- The input data type is the AXI4-Stream formatted data.
- The AXI4-Stream formatted data is converted to `hls::mat` format using an the AXI4-Stream function.
- The Video Processing Functions, named in a similar manner to their equivalent OpenCV functions, process the image and will synthesize into a high-quality FPGA implementation.
- The data is converted back to AXI4-Stream format and output.

```
#include "hls_video.h"
typedef hls::stream<ap_axiu<32,1,1,1> > AXI_STREAM;
typedef hls::Scalar<3, unsigned char> RGB_PIXEL;
typedef hls::Mat<MAX_HEIGHT, MAX_WIDTH, HLS_8UC3> RGB_IMAGE;

void image_filter(AXI_STREAM& INPUT_STREAM, AXI_STREAM& OUTPUT_STREAM, int rows, int
cols) {

    //Create AXI streaming interfaces for the core
    RGB_IMAGE img_0(rows, cols);
    RGB_IMAGE img_1(rows, cols);
    RGB_IMAGE img_2(rows, cols);
    RGB_IMAGE img_3(rows, cols);
    RGB_IMAGE img_4(rows, cols);
    RGB_IMAGE img_5(rows, cols);
    RGB_PIXEL pix(50, 50, 50);

    // Convert AXI4 Stream data to hls::mat format
    hls::AXIVideo2Mat(INPUT_STREAM, img_0);

    // Execute the video pipelines
    hls::Sobel<1,0,3>(img_0, img_1);
    hls::SubS(img_1, pix, img_2);
    hls::Scale(img_2, img_3, 2, 0);
    hls::Erode(img_3, img_4);
    hls::Dilate(img_4, img_5);

    // Convert the hls::mat format to AXI4 Stream format
    hls::Mat2AXIVideo(img_5, OUTPUT_STREAM);
}
```

Using all three types of functions allows you to implement video functions on an FPGA and maintain a seamless transfer of data between the video functions optimized for synthesis and the OpenCV functions and data which remain in the test bench (executing on the CPU).

The following table summarizes the functions provided in the HLS Video Library.

Table 2-17: HLS Video Library

Function Type	Function	Accuracy (ULP)
OpenCV Interface	AXIvideo2cvMat	Converts data from AXI4 video stream (hls::stream) format to OpenCV cv::Mat format
OpenCV Interface	AXIvideo2CvMat	Converts data from AXI4 video stream (hls::stream) format to OpenCV CvMat format2
OpenCV Interface	AXIvideo2IplImage	Converts data from AXI4 video stream (hls::stream) format to OpenCV IplImage format
OpenCV Interface	cvMat2AXIvideo	Converts data from OpenCV cv::Mat format to AXI4 video stream (hls::stream) format
OpenCV Interface	CvMat2AXIvideo	Converts data from OpenCV CvMat format to AXI4 video stream (hls::stream) format
OpenCV Interface	cvMat2hlsMat	Converts data from OpenCV cv::Mat format to hls::Mat format
OpenCV Interface	CvMat2hlsMat	Converts data from OpenCV CvMat format to hls::Mat format
OpenCV Interface	CvMat2hlsWindow	Converts data from OpenCV CvMat format to hls::Window format
OpenCV Interface	hlsMat2cvMat	Converts data from hls::Mat format to OpenCV cv::Mat format
OpenCV Interface	hlsMat2CvMat	Converts data from hls::Mat format to OpenCV CvMat format
OpenCV Interface	hlsMat2IplImage	Converts data from hls::Mat format to OpenCV IplImage format
OpenCV Interface	hlsWindow2CvMat	Converts data from hls::Window format to OpenCV CvMat format
OpenCV Interface	IplImage2AXIvideo	Converts data from OpenCV IplImage format to AXI4 video stream (hls::stream) format
OpenCV Interface	IplImage2hlsMat	Converts data from OpenCV IplImage format to hls::Mat format
AXI4-Stream	AXIvideo2Mat	Converts image data stored in hls::Mat format to an AXI4 video stream (hls::stream) format
AXI4-Stream	Mat2AXIvideo	Converts image data stored in AXI4 video stream (hls::stream) format to an image of hls::Mat format
Video Processing	AbsDiff	Computes the absolute difference between two input images src1 and src2 and saves the result in dst
Video Processing	AddS	Computes the per-element sum of an image src and a scalar scl
Video Processing	AddWeighted	Computes the weighted per-element sum of two image src1 and src2
Video Processing	And	Calculates the per-element bit-wise logical conjunction of two images src1 and src2

Table 2-17: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
Video Processing	Avg	Calculates an average of elements in image src
Video Processing	AvgSdv	Calculates an average of elements in image src
Video Processing	Cmp	Performs the per-element comparison of two input images src1 and src2
Video Processing	CmpS	Performs the comparison between the elements of input images src and the input value and saves the result in dst
Video Processing	CornerHarris	This function implements a Harris edge/corner detector
Video Processing	CvtColor	Converts a color image from or to a grayscale image
Video Processing	Dilate	Dilates the image src using the specified structuring element constructed within the kernel
Video Processing	Duplicate	Copies the input image src to two output images dst1 and dst2, for divergent point of two data paths
Video Processing	EqualizeHist	Computes a histogram of each frame and uses it to normalize the range of the following frame
Video Processing	Erode	Erodes the image src using the specified structuring element constructed within kernel
Video Processing	FASTX	Implements the FAST corner detector, generating either a mask of corners, or an array of coordinates
Video Processing	Filter2D	Applies an arbitrary linear filter to the image src using the specified kernel
Video Processing	GaussianBlur	Applies a normalized 2D Gaussian Blur filter to the input
Video Processing	Harris	This function implements a Harris edge or corner detector
Video Processing	HoughLines2	Implements the Hough line transform
Video Processing	Integral	Implements the computation of an integral image
Video Processing	InitUndistortRectifyMap	Generates map1 and map2, based on a set of parameters, where map1 and map2 are suitable inputs for hls::Remap()
Video Processing	Max	Calculates per-element maximum of two input images src1 and src2 and saves the result in dst
Video Processing	MaxS	Calculates the maximum between the elements of input images src and the input value and saves the result in dst
Video Processing	Mean	Calculates an average of elements in image src, and return the value of first channel of result scalar

Table 2-17: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
Video Processing	Merge	Composes a multi-channel image dst from several single-channel images
Video Processing	Min	Calculates per-element minimum of two input images src1 and src2 and saves the result in dst
Video Processing	MinMaxLoc	Finds the global minimum and maximum and their locations in input image src
Video Processing	MinS	Calculates the minimum between the elements of input images src and the input value and saves the result in dst
Video Processing	Mul	Calculates the per-element product of two input images src1 and src2
Video Processing	Not	Performs per-element bit-wise inversion of image src
Video Processing	PaintMask	Each pixel of the destination image is either set to color (if mask is not zero) or the corresponding pixel from the input image
Video Processing	PyrDown	Blurs the image and then reduces the size by a factor of 2.
Video Processing	PyrUp	Upsamples the image by a factor of 2 and then blurs the image.
Video Processing	Range	Sets all value in image src by the following rule and return the result as image dst
Video Processing	Remap	Remaps the source image src to the destination image dst according to the given remapping
Video Processing	Reduce	Reduces 2D image src along dimension dim to a vector dst
Video Processing	Resize	Resizes the input image to the size of the output image using bilinear interpolation
Video Processing	Set	Sets elements in image src to a given scalar value scl
Video Processing	Scale	Converts an input image src with optional linear transformation
Video Processing	Sobel	Computes a horizontal or vertical Sobel filter, returning an estimate of the horizontal or vertical derivative, using a filter
Video Processing	Split	Divides a multi-channel image src from several single-channel images
Video Processing	SubRS	Computes the differences between scalar value scl and elements of image src
Video Processing	SubS	Computes the differences between elements of image src and scalar value scl
Video Processing	Sum	Sums the elements of an image

Table 2-17: HLS Video Library (Cont'd)

Function Type	Function	Accuracy (ULP)
Video Processing	Threshold	Performs a fixed-level threshold to each element in a single-channel image
Video Processing	Zero	Sets elements in image src to 0

As shown in the example above, the video functions are not direct replacements for OpenCV functions. They use input and output arrays to process the data and typically use template parameters.

A complete description of all functions in the HLS video library is provided in [Chapter 4, High-Level Synthesis Reference Guide](#).

Optimizing Video Functions for Performance

The HLS video functions are pre-optimized to ensure a high-quality and high-performance implementation. The functions already include the optimization directives required to process data at a rate of one sample per clock.

The exact performance metrics of the video functions depends upon the clock rate and the target device specifications. Refer to the synthesis report for complete details on the final performance achieved after synthesis.

The previous example is repeated below to highlight the only optimizations required to achieve a complete high-performance design.

- Since the functions are already pipelined, adding the DATAFLOW optimization ensures the pipelined functions will execute in parallel.
- In this example, the data type is an `hls::stream` which is automatically implemented as a FIFO of depth 1: there is no requirement to use the `config_dataflow` configuration to control the size of the dataflow memory channels.
- Implementing the input and output ports with an AXI4-Stream interface (axis) ensures a high-performance streaming interface.
- Optionally, implementing the block-level protocol with an AXI4-Lite slave interface would allow the synthesized block to be controlled from a CPU.

```
#include "hls_video.h"
typedef hls::stream<ap_axiu<32,1,1,1> > AXI_STREAM;
typedef hls::Scalar<3, unsigned char> RGB_PIXEL;
typedef hls::Mat<MAX_HEIGHT, MAX_WIDTH, HLS_8UC3> RGB_IMAGE;

void image_filter(AXI_STREAM& INPUT_STREAM, AXI_STREAM& OUTPUT_STREAM, int rows, int
cols) {

#pragma HLS INTERFACE axis port=INPUT_STREAM
#pragma HLS INTERFACE axis port=OUTPUT_STREAM
#pragma HLS dataflow
```

```

//Create AXI streaming interfaces for the core
RGB_IMAGE img_0(rows, cols);
RGB_IMAGE img_1(rows, cols);
RGB_IMAGE img_2(rows, cols);
RGB_IMAGE img_3(rows, cols);
RGB_IMAGE img_4(rows, cols);
RGB_IMAGE img_5(rows, cols);
RGB_PIXEL pix(50, 50, 50);

// Convert AXI4 Stream data to hls::mat format
hls::AXIVideo2Mat(INPUT_STREAM, img_0);

// Execute the video pipelines
hls::Sobel<1,0,3>(img_0, img_1);
hls::SubS(img_1, pix, img_2);
hls::Scale(img_2, img_3, 2, 0);
hls::Erode(img_3, img_4);
hls::Dilate(img_4, img_5);

// Convert the hls::mat format to AXI4 Stream format
hls::Mat2AXIVideo(img_5, OUTPUT_STREAM);
}

```

HLS IP Libraries

Vivado HLS provides C libraries to implement a number of Xilinx IP blocks. The C libraries allow the following Xilinx IP blocks to be directly inferred from the C source code ensuring a high-quality implementation in the FPGA.

Table 2-18: HLS IP Libraries

Library Header File	Description
hls_fft.h	Allows the Xilinx LogiCORE IP FFT to be simulated in C and implemented using the Xilinx LogiCORE block.
hls_fir.h	Allows the Xilinx LogiCORE IP FIR to be simulated in C and implemented using the Xilinx LogiCORE block.
ap_shift_reg.h	Provides a C++ class to implement a shift register which is implemented directly using a Xilinx SRL primitive.

FFT IP Library

The Xilinx FFT IP block can be called within a C++ design using the library `hls_fft.h`. This section explains how the FFT can be configured in your C++ code.



RECOMMENDED: It is highly recommended that you review the LogiCORE IP Fast Fourier Transform v9.0 Product Guide (PG109) [\[Ref 5\]](#) to understand how to implement the IP using its many features. This user guide only describes how to use and implement the C model using Vivado HLS.

There are five steps to using the FFT in your C++ code:

- Include the `hls_fft.h` library in the code
- Set the default parameters using the pre-defined struct `hls::ip_fft::params_t`
- Define the run time configuration
- Call the FFT function
- Optionally check the run time status

The following code examples provide a summary of how each of these steps is performed. Each step is discussed in more detail below.

First, include the FFT library in the source code. This header file resides in the include directory in the Vivado HLS installation area which is automatically searched when Vivado HLS executes.

```
#include "hls_fft.h"
```

Define the static parameters of the FFT. This includes such things as input width, number of channels, type of architecture, which do not change dynamically. The FFT library includes a parameterization struct `hls::ip_fft::params_t`, which can be used to initialize all static parameters with default values.

In this example, the default values for output ordering and the widths of the configuration and status ports are over-ridden using a user-defined struct `param1` based on the pre-defined struct.

```
struct param1 : hls::ip_fft::params_t {
    static const unsigned ordering_opt = hls::ip_fft::natural_order;
    static const unsigned config_width = FFT_CONFIG_WIDTH;
    static const unsigned status_width = FFT_STATUS_WIDTH;
};
```

Define types and variables for both the run time configuration and run time status. These values can be dynamic and are therefore defined as variables in the C code which can change and are accessed through APIs.

```
typedef hls::ip_fft::config_t<param1> config_t;
typedef hls::ip_fft::status_t<param1> status_t;
config_t fft_config1;
status_t fft_status1;
```

Next, set the run time configuration. This example sets the direction of the FFT (Forward or Inverse) based on the value of variable “direction” and also set the value of the scaling schedule.

```
fft_config1->setDir(direction);
fft_config1->setSch(0x2AB);
```

Call the FFT function using the HLS namespace with the defined static configuration (param1 in this example). The function parameters are, in order, input data, output data, output status and input configuration.

```
hls::fft<param1> (xn1, xk1, &fft_status1, &fft_config1);
```

Finally, check the output status. This example checks the overflow flag and stores the results in variable "ovflo".

```
*ovflo = fft_status1->getOvflo();
```

Design examples using the FFT C library are provided in the Vivado HLS examples and can be accessed using menu option **Help > Welcome > Open Example Project > Design Examples > FFT**.

FFT Static Parameters

The static parameters of the FFT define how the FFT is configured and specifies the fixed parameters such as the size of the FFT, whether the size can be changed dynamically, whether the implementation is pipelined or radix_4_burst_io.

The `hls_fft.h` header file defines a struct `hls::ip_fft::params_t` which can be used to set default values for the static parameters. If the default values are to be used, the parameterization struct can be used directly with the FFT function.

```
hls::fft<hls::ip_fft::params_t >
    (xn1, xk1, &fft_status1, &fft_config1);
```

A more typical use is to change some of the parameters to non-default values. This is performed by creating a new user-defined parameterization struct based on the default parameterization struct and changing some of the default values.

In this example, a new user struct `my_fft_config` is defined and with a new value for the output ordering (changed to `natural_order`). All other static parameters to the FFT use the default values (shown below in [Table 2-20](#)).

```
struct my_fft_config : hls::ip_fft::params_t {
    static const unsigned ordering_opt = hls::ip_fft::natural_order;
};

hls::fft<my_fft_config >
    (xn1, xk1, &fft_status1, &fft_config1);
```

The values used for the parameterization struct `hls::ip_fft::params_t` are explained in the following table. The default values for the parameters and a list of possible values is provided in [Table 2-20](#).



RECOMMENDED: It is highly recommended that you refer to the LogiCORE IP Fast Fourier Transform v9.0 Product Guide (PG109) [\[Ref 5\]](#) for details on the parameters and the implication for their settings.

Table 2-19: FTT Struct Parameters

Parameter	Description
input_width	Data input port width.
output_width	Data output port width.
status_width	Output status port width.
config_width	Input configuration port width.
max_nfft	The size of the FFT data set is specified as <code>1 << max_nfft</code> .
has_nfft	Determines if the size of the FFT can be run time configurable.
channels	Number of channels.
arch_opt	The implementation architecture.
phase_factor_width	Configure the internal phase factor precision.
ordering_opt	The output ordering mode.
ovflo	Enable overflow mode.
scaling_opt	Define the scaling options.
rounding_opt	Define the rounding modes.
mem_data	Specify using block or distributed RAM for data memory.
mem_phase_factors	Specify using block or distributed RAM for phase factors memory.
mem_reorder	Specify using block or distributed RAM for output reorder memory.
stages_block_ram	Defines the number of block RAM stages used in the implementation.
mem_hybrid	When block RAMs are specified for data, phase factor, or reorder buffer, mem_hybrid specifies where or not to use a hybrid of block and distributed RAMs to reduce block RAM count in certain configurations.
complex_mult_type	Defines the types of multiplier to use for complex multiplications.
butterfly_type	Defines the implementation used for the FFT butterfly.

When specifying parameter values which are not integer or boolean, the HLS FFT namespace should be used.

For example the possible values for parameter `butterfly_type` in the following table are `use_luts` and `use_xtremedsp_slices`. The values used in the C program should be `butterfly_type = hls::ip_fft::use_luts` and `butterfly_type = hls::ip_fft::use_xtremedsp_slices`.

The following table covers all features and functionality of the FFT IP. Features and functionality not described in this table are not supported in the Vivado HLS implementation.

Table 2-20: FTT Struct Parameters Values

Parameter	C Type	Default Value	Valid Values
input_width	unsigned	16	8-34
output_width	unsigned	16	input_width to (input_width + max_nfft + 1)
status_width	unsigned	8	Depends on FFT configuration
config_width	unsigned	16	Depends on FFT configuration
max_nfft	unsigned	10	3-16
has_nfft	bool	false	True, False
channels	unsigned	1	1-12
arch_opt	unsigned	pipelined_streaming_io	automatically_select pipelined_streaming_io radix_4_burst_io radix_2_burst_io radix_2_lite_burst_io
phase_factor_width	unsigned	16	8-34
ordering_opt	unsigned	bit_reversed_order	bit_reversed_order natural_order
ovflo	bool	true	false true
scaling_opt	unsigned	scaled	scaled unscaled block_floating_point
rounding_opt	unsigned	truncation	truncation convergent_rounding
mem_data	unsigned	block_ram	block_ram distributed_ram
mem_phase_factors	unsigned	block_ram	block_ram distributed_ram
mem_reorder	unsigned	block_ram	block_ram distributed_ram
stages_block_ram	unsigned	(max_nfft < 10) ? 0 : (max_nfft - 9)	0-11
mem_hybrid	bool	false	false true
complex_mult_type	unsigned	use_mults_resources	use_luts use_mults_resources use_mults_performance
butterfly_type	unsigned	use_luts	use_luts use_xtremedsp_slices

FFT Run Time Configuration and Status

The FFT supports run time configuration and run time status monitoring through the configuration and status ports. These ports are defined as arguments to the FFT function, shown here as variables `fft_status1` and `fft_config1`:

```
hls::fft<param1> (xn1, xk1, &fft_status1, &fft_config1);
```

The run time configuration and status can be accessed using the predefined structs from the FFT C library:

- `hls::ip_fft::config_t<param1>`
- `hls::ip_fft::status_t<param1>`

Note: In both cases, the struct requires the name of the static parameterization struct, shown in these examples as `param1`. Refer to the previous section for details on defining the static parameterization struct.

The run time configuration struct allows the following actions to be performed in the C code:

- Set the FFT length, if run time configuration is enabled
- Set the FFT direction as forward or inverse
- Set the scaling schedule

The FFT length can be set as follows:

```
typedef hls::ip_fft::config_t<param1> config_t;
config_t fft_config1;
// Set FFT length to 512 => log2(512) =>9
fft_config1-> setNfft(9);
```

The FFT direction can be set as follows:

```
typedef hls::ip_fft::config_t<param1> config_t;
config_t fft_config1;
// Forward FFT
fft_config1->setDir(1);
// Inverse FFT
fft_config1->setDir(0);
```

The FFT scaling schedule can be set as follows:

```
typedef hls::ip_fft::config_t<param1> config_t;
config_t fft_config1;
fft_config1->setSch(0x2AB);
```

The output status port can be accessed using the pre-defined struct to determine:

- If any overflow occurred during the FFT
- The value of the block exponent

The FFT overflow mode can be checked as follows:

```
typedef hls::ip_fft::status_t<param1> status_t;
status_t fft_status1;
// Check the overflow flag
bool *ovflo = fft_status1->getOvflo();
```

And the block exponent value can be obtained using:

```
typedef hls::ip_fft::status_t<param1> status_t;
status_t fft_status1;
// Obtain the block exponent
unsigned int *blk_exp = fft_status1-> getBlkExp();
```

Using the FFT Function

The FFT function is defined in the HLS namespace and can be called as follows:

```
hls::fft<STATIC_PARAM> (
    INPUT_DATA_ARRAY,
    OUTPUT_DATA_ARRAY,
    OUTPUT_STATUS,
    INPUT_RUN_TIME_CONFIGURATION);
```

The STATIC_PARAM is the static parameterization struct discussed in the earlier section FFT Static Parameters. This defines the static parameters for the FFT.

Both the input and output data are supplied to the function as arrays (INPUT_DATA_ARRAY and OUTPUT_DATA_ARRAY). In the final implementation, the ports on the FFT RTL block will be implemented as AXI4-Stream ports. It is recommended to always use the FFT function in a region using dataflow optimization (set_directive_dataflow) as this will ensure the arrays are implemented as streaming arrays. An alternative is to specify both arrays as streaming using the set_directive_stream command.



IMPORTANT: *The FFT cannot be used in a region which is pipelined. If high-performance operation is required, pipeline the loops or functions before and after the FFT then use dataflow optimization on all loops and functions in the region.*

The data types for the arrays can be float or ap_fixed.

```
typedef float data_t;
complex<data_t> xn[FFT_LENGTH];
complex<data_t> xk[FFT_LENGTH];
```

To use fixed-point data types, the Vivado HLS arbitrary precision type ap_fixed should be used.

```
#include "ap_fixed.h"
typedef ap_fixed<FFT_INPUT_WIDTH,1> data_in_t;
typedef ap_fixed<FFT_OUTPUT_WIDTH,FFT_OUTPUT_WIDTH-FFT_INPUT_WIDTH+1> data_out_t;
#include <complex>
typedef std::complex<data_in_t> cmplxData;
typedef std::complex<data_out_t> cmplxDataOut;
```

In both cases, the FFT should be parameterized with the same correct data sizes. In the case of floating point data, the data widths will always be 32-bit and any other specified size will be considered invalid.



TIP: *The input and output width of the FFT can be configured to any arbitrary value within the supported range. The variables which connect to the input and output parameters must be defined in increments of 8-bit. For example, if the output width is configured as 33-bit, the output variable must be defined as a 40-bit variable.*

The multi-channel functionality of the FFT can be used by using two-dimensional arrays for the input and output data. In this case, the array data should be configured with the first dimension representing each channel and the second dimension representing the FFT data.

```
typedef float data_t;
static complex<data_t> xn[CHANNEL][FFT_LENGTH];
static complex<data_t> xk[CHANELL][FFT_LENGTH];
```

The OUTPUT_STATUS and INPUT_RUN_TIME_CONFIGURATION are the structs discussed in the earlier section FFT Run Time Configuration.

Note: Any design using the FFT can only be verified using HDL (Verilog or VHDL). RTL co-simulation using SystemC RTL is not supported for design using the FFT.

Design examples using the FFT C library are provided in the Vivado HLS examples and can be accessed using menu option **Help > Welcome > Open Example Project > Design Examples > FFT**.

FIR Filter IP Library

The Xilinx FIR IP block can be called within a C++ design using the library `hls_fir.h`. This section explains how the FIR can be configured in your C++ code.



RECOMMENDED: *It is highly recommended that you review the LogiCORE IP FIR Compiler v7.1 Product Guide (PG149) [Ref 6] to understand how to implement the IP using its many features. This user guide only describes how the C model can be used and implemented using Vivado HLS.*

There are four steps to use the FIR in your C++ code:

- Include the `hls_fir.h` library in the code.
- Set the default parameters using the pre-defined struct `hls::ip_fir::params_t`.
- Call the FIR function.
- Optionally, define a run time input configuration.

The following code examples provide a summary of how each of these steps is performed. Each step is discussed in more detail below.

First, include the FIR library in the source code. This header file resides in the include directory in the Vivado HLS installation area. This directory is automatically searched when Vivado HLS executes. There is no need to specify the path to this directory if compiling inside Vivado HLS.

```
#include "hls_fir.h"
```

Define the static parameters of the FIR. This includes such static attributes such as the input width, the coefficients, the filter rate (single, decimation, hilbert). The FIR library includes a parameterization struct `hls::ip_fir::params_t` which can be used to initialize all static parameters with default values.

In this example, the coefficients are defined as residing in array `coeff_vec` and the default values for the number of coefficients, the input width and the quantization mode are over-ridden using a user a user-defined struct `myconfig` based on the pre-defined struct.

```
struct myconfig : hls::ip_fir::params_t {
    static const double coeff_vec[sg_fir_srrc_coeffs_len];
    static const unsigned num_coeffs = sg_fir_srrc_coeffs_len;
    static const unsigned input_width = INPUT_WIDTH;
    static const unsigned quantization = hls::ip_fir::quantize_only;
};
```

Create an instance of the FIR function using the HLS namespace with the defined static parameters (`myconfig` in this example) and then call the function with the `run` method to execute the function. The function arguments are, in order, input data and output data.

```
static hls::FIR<param1> fir1;
fir1.run(fir_in, fir_out);
```

Optionally, a run time input configuration can be used. In some modes of the FIR, the data on this input determines how the coefficients are used during interleaved channels or when coefficient reloading is required. This configuration can be dynamic and is therefore defined as a variable. For a complete description of which modes require this input configuration, refer to the *LogiCORE IP FIR Compiler v7.1 Product Guide (PG149)* [Ref 6].

When the run time input configuration is used, the FIR function is called with three arguments: input data, output data and input configuration.

```
// Define the configuration type
typedef ap_uint<8> config_t;
// Define the configuration variable
config_t fir_config = 8;
// Use the configuration in the FFT
static hls::FIR<param1> fir1;
fir1.run(fir_in, fir_out, &fir_config);
```

Design examples using the FIR C library are provided in the Vivado HLS examples and can be accessed using menu option **Help > Welcome > Open Example Project > Design Examples > FIR**.

FIR Static Parameters

The static parameters of the FIR define how the FIR IP is parameterized and specifies non-dynamic items such as the input and output widths, the number of fractional bits, the coefficient values, the interpolation and decimation rates. Most of these configurations have default values: there are no default values for the coefficients.

The `hls_fir.h` header file defines a struct `hls::ip_fir::params_t` that can be used to set the default values for most of the static parameters.



IMPORTANT: *There are no defaults defined for the coefficients. It is therefore not recommended to use the pre-defined struct to directly initialize the FIR. A new user defined struct which specifies the coefficients should always be used to perform the static parameterization.*

In this example, a new user struct `my_config` is defined and with a new value for the coefficients. The coefficients are specified as residing in array `coeff_vec`. All other parameters to the FIR will use the default values (shown below in [Table 2-22](#)).

```
struct myconfig : hls::ip_fir::params_t {
    static const double coeff_vec[sg_fir_srrc_coeffs_len];
};

static hls::FIR<myconfig> fir1;
fir1.run(fir_in, fir_out);
```

The following table describes the parameters used for the parametrization struct `hls::ip_fir::params_t`. [Table 2-22](#) provides the default values for the parameters and a list of possible values.



RECOMMENDED: *It is highly recommended that you refer to the LogiCORE IP FIR Compiler v7.1 Product Guide (PG149) [Ref 6] for details on the parameters and the implication for their settings.*

Table 2-21: FIR Struct Parameters

Parameter	Description
input_width	Data input port width
input_fractional_bits	Number of fractional bits on the input port
output_width	Data output port width
output_fractional_bits	Number of fractional bits on the output port
coeff_width	Bit-width of the coefficients
coeff_fractional_bits	Number of fractional bits in the coefficients
num_coeffs	Number of coefficients
coeff_sets	Number of coefficient sets
input_length	Number of samples in the input data
output_length	Number of samples in the output data
num_channels	Specify the number of channels of data to process
total_number_coeff	Total number of coefficients
coeff_vec[total_num_coeff]	The coefficient array
filter_type	The type implementation used for the filter
rate_change	Specifies integer or fractional rate changes
interp_rate	The interpolation rate
decim_rate	The decimation rate
zero_pack_factor	Number of zero coefficients used in interpolation
rate_specification	Specify the rate as frequency or period
hardware_oversampling_rate	Specify the rate of over-sampling
sample_period	The hardware oversample period
sample_frequency	The hardware oversample frequency
quantization	The quantization method to be used
best_precision	Enable or disable the best precision
coeff_structure	The type of coefficient structure to be used
output_rounding_mode	Type of rounding used on the output
filter_arch	Selects a systolic or transposed architecture
optimization_goal	Specify a speed or area goal for optimization
inter_column_pipe_length	The pipeline length required between DSP columns
column_config	Specifies the number of DSP48 column
config_method	Specifies how the DSP48 columns are configured
coeff_padding	Number of zero padding added to the front of the filter

When specifying parameter values that are not integer or boolean, the HLS FIR namespace should be used.

For example the possible values for `rate_change` are shown in the following table to be `integer` and `fixed_fractional`. The values used in the C program should be `rate_change = hls::ip_fir::integer` and `rate_change = hls::ip_fir::fixed_fractional`.

The following table covers all features and functionality of the FIR IP. Features and functionality not described in this table are not supported in the Vivado HLS implementation.

Table 2-22: FIR Struct Parameters Values

Parameter	C Type	Default Value	Valid Values
input_width	unsigned	16	No limitation
input_fractional_bits	unsigned	0	Limited by size of input_width
output_width	unsigned	24	No limitation
output_fractional_bits	unsigned	0	Limited by size of output_width
coeff_width	unsigned	16	No limitation
coeff_fractional_bits	unsigned	0	Limited by size of coeff_width
num_coeffs	bool	21	Full
coeff_sets	unsigned	1	1-1024
input_length	unsigned	21	No limitation
output_length	unsigned	21	No limitation
num_channels	unsigned	1	1-1024
total_number_coeff	unsigned	21	num_coeffs * coeff_sets
coeff_vec[total_num_coeff]	double array	None	Not applicable
filter_type	unsigned	single_rate	single_rate, interpolation, decimation, hilbert, interpolated
rate_change	unsigned	integer	integer, fixed_fractional
interp_rate	unsigned	1	2-1024
decim_rate	unsigned	1	2-1024
zero_pack_factor	unsigned	1	2-8
rate_specification	unsigned	period	frequency, period
hardware_oversampling_rate	unsigned	1	No Limitation
sample_period	bool	1	No Limitation
sample_frequency	unsigned	0.001	No Limitation
quantization	unsigned	integer_coefficients	integer_coefficients, quantize_only, maximize_dynamic_range

Table 2-22: FIR Struct Parameters Values (Cont'd)

best_precision	unsigned	false	false true
coeff_structure	unsigned	non_symmetric	inferred, non_symmetric, symmetric, negative_symmetric, half_band, hilbert
output_rounding_mode	unsigned	full_precision	full_precision, truncate_lsbs, non_symmetric_rounding_down ,
			non_symmetric_rounding_up, symmetric_rounding_to_zero, symmetric_rounding_to_infinity, convergent_rounding_to_even, convergent_rounding_to_odd
filter_arch	unsigned	systolic_multiply_accumulate	systolic_multiply_accumulate, transpose_multiply_accumulate
optimization_goal	unsigned	area	area, speed
inter_column_pipe_length	unsigned	4	1-16
column_config	unsigned	1	Limited by number of DSP48s used
config_method	unsigned	single	single, by_channel
coeff_padding	bool	false	false true

Using the FIR Function

The FIR function is defined in the HLS namespace and can be called as follows:

```
// Create an instance of the FIR
static hls::FIR<STATIC_PARAM> fir1;
// Execute the FIR instance fir1
fir1.run(INPUT_DATA_ARRAY, OUTPUT_DATA_ARRAY);
```

The STATIC_PARAM is the static parameterization struct discussed in the earlier section FIR Static Parameters. This defines most static parameters for the FIR.

Both the input and output data are supplied to the function as arrays (INPUT_DATA_ARRAY and OUTPUT_DATA_ARRAY). In the final implementation, these ports on the FIR IP will be implemented as AXI4-Stream ports. It is recommended to always use the FIR function in a region using the dataflow optimization (set_directive_dataflow) as this ensures the arrays are implemented as streaming arrays. An alternative is to specify both arrays as streaming using the set_directive_stream command.



IMPORTANT: *The FIR cannot be used in a region which is pipelined. If high-performance operation is required, pipeline the loops or functions before and after the FIR then use dataflow optimization on all loops and functions in the region.*

The multichannel functionality of the FIR is supported through interleaving the data in a single input and single output array.

- The size of the input array should be large enough to accommodate all samples: num_channels * input_length.
- The output array size should be specified to contain all output samples: num_channels * output_length.

The following code example demonstrates, for two channels, how the data is interleaved. In this example, the top-level function has two channels of input data (`din_i`, `din_q`) and two channels of output data (`dout_i`, `dout_q`). Two functions, at the front-end (fe) and back-end (be) are used to correctly order the data in the FIR input array and extract it from the FIR output array.

```

void dummy_fe(din_t din_i[LENGTH], din_t din_q[LENGTH], din_t out[FIR_LENGTH]) {
    for (unsigned i = 0; i < LENGTH; ++i) {
        out[2*i] = din_i[i];
        out[2*i + 1] = din_q[i];
    }
}
void dummy_be(dout_t in[FIR_LENGTH], dout_t dout_i[LENGTH], dout_t dout_q[LENGTH]) {
    for(unsigned i = 0; i < LENGTH; ++i) {
        dout_i[i] = in[2*i];
        dout_q[i] = in[2*i+1];
    }
}
void fir_top(din_t din_i[LENGTH], din_t din_q[LENGTH],
             dout_t dout_i[LENGTH], dout_t dout_q[LENGTH]) {

    din_t fir_in[FIR_LENGTH];
    dout_t fir_out[FIR_LENGTH];
    static hls::FIR<myconfig> fir1;

    dummy_fe(din_i, din_q, fir_in);
    fir1.run(fir_in, fir_out);
    dummy_be(fir_out, dout_i, dout_q);
}

```

Note: Any design using the FIR can only be verified using HDL (Verilog or VHDL). RTL co-simulation using SystemC RTL is not supported for design using the FIR.

Optional FIR Run Time Configuration

In some modes of operation, the FIR requires an additional input to configure how the coefficients are used. For a complete description of which modes require this input configuration, refer to the *LogiCORE IP FIR Compiler v7.1 Product Guide* (PG149) [Ref 6].

This input configuration can be performed in the C code using a standard ap_int.h 8-bit data type. In this example, the header file fir_top.h specifies the use of the FIR and ap_fixed libraries, defines a number of the design parameter values and then defines some fixed-point types based on these:

```
#include "ap_fixed.h"
#include "hls_fir.h"

const unsigned FIR_LENGTH    = 21;
const unsigned INPUT_WIDTH   = 16;
const unsigned INPUT_FRACTIONAL_BITS = 0;
const unsigned OUTPUT_WIDTH  = 24;
const unsigned OUTPUT_FRACTIONAL_BITS = 0;
const unsigned COEFF_WIDTH   = 16;
const unsigned COEFF_FRACTIONAL_BITS = 0;
const unsigned COEFF_NUM     = 7;
const unsigned COEFF_SETS    = 3;
const unsigned INPUT_LENGTH  = FIR_LENGTH;
const unsigned OUTPUT_LENGTH = FIR_LENGTH;
const unsigned CHAN_NUM      = 1;
typedef ap_fixed<INPUT_WIDTH, INPUT_WIDTH - INPUT_FRACTIONAL_BITS> s_data_t;
typedef ap_fixed<OUTPUT_WIDTH, OUTPUT_WIDTH - OUTPUT_FRACTIONAL_BITS> m_data_t;
typedef ap_uint<8> config_t;
```

In the top-level code, the information in the header file is included, the static parameterization struct is created using the same constant values used to specify the bit-widths, ensuring the C code and FIR configuration match, and the coefficients are specified. At the top-level, an input configuration, defined in the header file as 8-bit data, is passed into the FIR.

```
#include "fir_top.h"

struct param1 : hls::ip_fir::params_t {
    static const double coeff_vec[total_num_coeff];
    static const unsigned input_length = INPUT_LENGTH;
    static const unsigned output_length = OUTPUT_LENGTH;
    static const unsigned num_coeffs = COEFF_NUM;
    static const unsigned coeff_sets = COEFF_SETS;
};

const double param1::coeff_vec[total_num_coeff] =
{6,0,-4,-3,5,6,-6,-13,7,44,64,44,7,-13,-6,6,5,-3,-4,0,6};

void dummy_fe(s_data_t in[INPUT_LENGTH], s_data_t out[INPUT_LENGTH],
              config_t* config_in, config_t* config_out)
{
    *config_out = *config_in;
    for(unsigned i = 0; i < INPUT_LENGTH; ++i)
        out[i] = in[i];
}

void dummy_be(m_data_t in[OUTPUT_LENGTH], m_data_t out[OUTPUT_LENGTH])
{
    for(unsigned i = 0; i < OUTPUT_LENGTH; ++i)
        out[i] = in[i];
}
```

```

// DUT
void fir_top(s_data_t in[INPUT_LENGTH],
             m_data_t out[OUTPUT_LENGTH],
             config_t* config)
{
    s_data_t fir_in[INPUT_LENGTH];
    m_data_t fir_out[OUTPUT_LENGTH];
    config_t fir_config;
    // Create struct for config
    static hls::FIR<param1> fir1;

    //=====
    // Dataflow process
    dummy_fe(in, fir_in, config, &fir_config);
    fir1.run(fir_in, fir_out, &fir_config);
    dummy_be(fir_out, out);
    //=====
}

```

Design examples using the FIR C library are provided in the Vivado HLS examples and can be accessed using menu option **Help > Welcome > Open Example Project > Design Examples > FIR**.

SRL IP Library

C code is written to satisfy several different requirements: reuse, readability, and performance. Until now, it is unlikely that the C code was written to result in the most ideal hardware after High-Level Synthesis.

Like the requirements for reuse, readability, and performance, certain coding techniques or pre-defined constructs can ensure that the synthesis output results in more optimal hardware or to better model hardware in C for easier validation of the algorithm.

Mapping Directly into SRL Resources

Many C algorithms sequentially shift data through arrays. They add a new value to the start of the array, shift the existing data through array, and drop the oldest data value. This operation is implemented in hardware as a shift register.

This most common way to implement a shift register from C into hardware is to completely partition the array into individual elements, and allow the data dependencies between the elements in the RTL to imply a shift register.

Logic synthesis typically implements the RTL shift register into a Xilinx SRL resource, which efficiently implements shift registers. The problem is that sometimes logic synthesis does not implement the RTL shift register using an SRL component:

- When data is accessed in the middle of the shift register, logic synthesis cannot directly infer an SRL.
- Sometimes, even when the SRL is ideal, logic synthesis may implement the shift-register in flip-flops, due to other factors. (Logic synthesis is also a complex process).

Vivado HLS provides a C++ class (`ap_shift_reg`) to ensure that the shift register defined in the C code is always implemented using an SRL resource. The `ap_shift_reg` class has two methods to perform the various read and write accesses supported by an SRL component.

Read from the Shifter

The read method allows a specified location to be read from the shifter register.

The `ap_shift_reg.h` header file that defines the `ap_shift_reg` class is also included with Vivado HLS as a stand-alone package. You have the right to use it in your own source code. The package `xilinx_hls_lib_<release_number>.tgz` is located in the include directory in the Vivado HLS installation area.

```
// Include the Class
#include ap_shift_reg.h

// Define a variable of type ap_shift_reg<type, depth>
// - Sreg must use the static qualifier
// - Sreg will hold integer data types
// - Sreg will hold 4 data values
static ap_shift_reg<int, 4> Sreg;
int var1;

// Read location 2 of Sreg into var1
var1 = Sreg.read(2);
```

Read, Write, and Shift Data

A shift method allows a read, write, and shift operation to be performed.

```
// Include the Class
#include ap_shift_reg.h

// Define a variable of type ap_shift_reg<type, depth>
// - Sreg must use the static qualifier
// - Sreg will hold integer data types
// - Sreg will hold 4 data values
static ap_shift_reg<int, 4> Sreg;
int var1;

// Read location 3 of Sreg into var1
// THEN shift all values up one and load In1 into location 0
var1 = Sreg.shift(In1,3);
```

Read, Write, and Enable-Shift

The shift method also supports an enabled input, allowing the shift process to be controlled and enabled by a variable.

```
// Include the Class
#include ap_shift_reg.h

// Define a variable of type ap_shift_reg<type, depth>
// - Sreg must use the static qualifier
// - Sreg will hold integer data types
// - Sreg will hold 4 data values
static ap_shift_reg<int, 4> Sreg;
int var1, In1;
bool En;

// Read location 3 of Sreg into var1
// THEN if En=1
// Shift all values up one and load In1 into location 0
var1 = Sreg.shift(In1,3,En);
```

When using the `ap_shift_reg` class, Vivado HLS creates a unique RTL component for each shifter. When logic synthesis is performed, this component is synthesized into an SRL resource.

HLS Linear Algebra Library

The HLS Linear Algebra Library provides a number of commonly used linear algebra functions. The functions in the HLS Linear Algebra Library all use two-dimensional arrays to represent matrices and are listed in the following table.

Table 2-23: HLS Linear Algebra Library

Function	Data Type	Implementation Style
cholesky	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
cholesky_inverse	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
matrix_multiply	float ap_fixed x_complex<float> x_complex<ap_fixed>	Synthesized
qrf	float x_complex<float>	Synthesized
qr_inverse	float x_complex<float>	Synthesized
svd	float x_complex<float>	Synthesized

The linear algebra functions all use two-dimensional arrays to represent matrices. All functions support float (single precision) inputs, for real and complex data. A subset of the functions support `ap_fixed` (fixed-point) inputs, for real and complex data. The precision and rounding behavior of the `ap_fixed` types may be user defined, if desired.

A complete description of all linear algebra functions is provided in the [HLS Linear Algebra Library in Chapter 4](#).

Using the Linear Algebra Library

The HLS linear algebra functions are referenced using the `hls` namespace or using scoped naming.

- Using the `hls` namespace:

```
#include "hls_linear_algebra.h"

hls::cholesky(In_Array,Out_Array);
```

- Using scoped naming:

```
#include "hls_linear_algebra.h"
using namespace hls; // Namespace specified after the header files

cholesky(In_Array,Out_Array);
```

Because linear algebra functions are used in a wide variety of designs, from those which require high-performance to low throughput designs which require an area efficient implementation, the linear algebra library functions are not pre-optimized for high-performance.

To apply optimizations on the linear algebra functions, open the header file `hls_linear_algebra.h` in the GUI:

- Press the Control key and click on "#include "hls_linear_algebra.h"
- Or use the Explorer Pane and navigate to the file using the Includes folder.

With the header file open in the information pane, use the directives tab to add any optimization as a Directive: if the optimization is added as a pragma it will be placed in the library (file write permissions may be required) and it will be applied every time the header file is added to a design.

High-Level Synthesis Coding Styles

Introduction to Coding Styles

This chapter explains how various constructs of C, C++ and SystemC are synthesized into an FPGA hardware implementation.



IMPORTANT: The term "C code" as used in this guide refers to code written in C, C++, or SystemC, unless otherwise specifically noted.

The coding examples in this guide are part of the Vivado® HLS release. Access the coding examples using one of the following methods:

- From the Welcome screen, click **Open Example Project**.
Note: To view the Welcome screen at any time, select **Help > Welcome**.
- In the examples/coding directory in the Vivado HLS installation area.

For more information, see [Coding Examples in Chapter 1](#).

Unsupported C Constructs

While Vivado HLS supports a wide range of the C language, some constructs are not synthesizable, or can result in errors further down the design flow. This section discusses areas in which coding changes must be made for the function to be synthesized and implemented in a device.

To be synthesized:

- The C function must contain the entire functionality of the design.
- None of the functionality can be performed by system calls to the operating system.
- The C constructs must be of a fixed or bounded size.
- The implementation of those constructs must be unambiguous.

System Calls

System calls cannot be synthesized because they are actions that relate to performing some task upon the operating system in which the C program is running.

Vivado HLS ignores commonly-used system calls that display only data and that have no impact on the execution of the algorithm, such as `printf()` and `fprintf(stdout,)`. In general, calls to the system cannot be synthesized and should be removed from the function before synthesis. Other examples of such calls are `getc()`, `time()`, `sleep()`, all of which make calls to the operating system.

Vivado HLS defines the macro `__SYNTHESIS__` when synthesis is performed. This allows the `__SYNTHESIS__` macro to exclude non-synthesizable code from the design.

In the following code example, the intermediate results from a sub-function are saved to a file on the hard drive. The macro `__SYNTHESIS__` is used to ensure the non-synthesizable writes are ignored during synthesis.

```
#include hier_func4.h

int sumsub_func(din_t *in1, din_t *in2, dint_t *outSum, dint_t *outSub)
{
    *outSum = *in1 + *in2;
    *outSub = *in1 - *in2;
}

int shift_func(dint_t *in1, dint_t *in2, dout_t *outA, dout_t *outB)
{
    *outA = *in1 >> 1;
    *outB = *in2 >> 2;
}

void hier_func4(din_t A, din_t B, dout_t *C, dout_t *D)
{
    dint_t apb, amb;

    sumsub_func(&A,&B,&apb,&amb);
#ifndef __SYNTHESIS__
    FILE *fp1;// The following code is ignored for synthesis
    char filename[255];
    sprintf(filename,Out_apb_%03d.dat,apb);
    fp1=fopen(filename,w);
    fprintf(fp1, %d \n, apb);
    fclose(fp1);
#endif
    shift_func(&apb,&amb,C,D);
}
```

Example 3-1: File Writes for Debug

The `__SYNTHESIS__` macro is a convenient way to exclude non-synthesizable code without removing the code itself from the C function. Using such a macro does mean that the C code for simulation and the C code for synthesis are now different.



CAUTION! If the `__SYNTHESIS__` macro is used to change the functionality of the C code, it can result in different results between C simulation and C synthesis. Errors in such code are inherently difficult to debug. Do not use the `__SYNTHESIS__` macro to change functionality.

Dynamic Memory Usage

Any system calls that manage memory allocation within the system, for example, `malloc()`, `alloc()`, and `free()` are using resources that exist in the memory of the operating system and are created and released during run time: to be able to synthesize a hardware implementation the design must be fully self-contained, specifying all required resources.

Memory allocation system calls must be removed from the design code before synthesis. Because dynamic memory operations are used to define the functionality of the design, they must be transformed into equivalent bounded representations. The following code example shows how a design using `malloc()` can be transformed into a synthesizable version and highlights two useful coding style techniques:

- The design does not use the `__SYNTHESIS__` macro.

The user-defined macro `NO_SYNTH` is used to select between the synthesizable and non-synthesizable versions. This ensures that the same code is simulated in C and synthesized in Vivado HLS.

- The pointers in the original design using `malloc()` do not need to be rewritten to work with fixed sized elements.

Fixed sized resources can be created and the existing pointer can simply be made to point to the fixed sized resource. This technique can prevent manual re-coding of the existing design.

```

#include malloc_removed.h
#include <stdlib.h>
//#define NO_SYNTH

dout_t malloc_removed(din_t din[N], dsel_t width) {

    #ifdef NO_SYNTH
        long long *out_accum = malloc (sizeof(long long));
        int* array_local = malloc (64 * sizeof(int));
    #else
        long long _out_accum;
        long long *out_accum = &_out_accum;
        int _array_local[64];
        int* array_local = &_array_local[0];
    #endif
        int i,j;

        LOOP_SHIFT:for (i=0;i<N-1; i++) {
            if (i<width)
                *(array_local+i)=din[i];
            else
                *(array_local+i)=din[i]>>2;
        }

        *out_accum=0;
        LOOP_ACCUM:for (j=0;j<N-1; j++) {
            *out_accum += *(array_local+j);
        }

        return *out_accum;
}

```

Example 3-2: Transforming malloc() to Fixed Resources

Because the coding changes here impact the functionality of the design, Xilinx does not recommend using the `__SYNTHESIS__` macro. Xilinx recommends that you:

1. Add the user-defined macro `NO_SYNTH` to the code and modify the code.
2. Enable macro `NO_SYNTH`, execute the C simulation and saves the results.
3. Disable the macro `NO_SYNTH` (for example comment out, as in Example 50), execute the C simulation to verify that the results are identical.
4. Perform synthesis with the user-defined macro disabled.

This methodology ensures that the updated code is validated with C simulation and that the identical code is then synthesized.

As with restrictions on dynamic memory usage in C, Vivado HLS does not support (for synthesis) C++ objects that are dynamically created or destroyed. This includes dynamic polymorphism and dynamic virtual function calls.

The following code cannot be synthesized because it creates a new function at run time.

```
Class A {
public:
    virtual void bar() {...};
};

void fun(A* a) {
    a->bar();
}
A* a = 0;
if (base)
    a = new A();
else
    a = new B();

foo(a);
```

Example 3-3: Unsynthesizable Code Coding Example

Pointer Limitations

General Pointer Casting

Vivado HLS does not support general pointer casting, but supports pointer casting between native C types. For more information on pointer casting, see [Example 3-36](#).

Pointer Arrays

Vivado HLS supports pointer arrays for synthesis, provided that each pointer points to a scalar or an array of scalars. Arrays of pointers cannot point to additional pointers. For more information on pointer arrays, see [Example 3-35](#).

Recursive Functions

Recursive functions cannot be synthesized. This applies to functions that can form endless recursion, where endless:

```
unsigned foo (unsigned n)
{
    if (n == 0 || n == 1) return 1;
    return (foo(n-2) + foo(n-1));
}
```

Vivado HLS does not support tail recursion in which there is a finite number of function calls.

```
unsigned foo (unsigned m, unsigned n)
{
    if (m == 0) return n;
    if (n == 0) return m;
    return foo(n, m%n);
}
```

In C++, templates can implement tail recursion. C++ is addressed next.

Standard Template Libraries

Many of the C++ Standard Template Libraries (STLs) contain function recursion and use dynamic memory allocation. For this reason, the STLs cannot be synthesized. The solution with STLs is to create a local function with identical functionality that does not exhibit these characteristics of recursion, dynamic memory allocation or the dynamic creation and destruction of objects.

C Test Bench

The first step in the synthesis of any block is to validate that the C function is correct. This step is performed by the test bench. Writing a good test bench can greatly increase your productivity.

C functions execute in orders of magnitude faster than RTL simulations. Using C to develop and validate the algorithm before synthesis is more productive than developing at the RTL.

- The key to taking advantage of C development times is to have a test bench that checks the results of the function against known good results. Because the algorithm is known to be correct, any code changes can be validated before synthesis.
- Vivado HLS reuses the C test bench to verify the RTL design. No RTL test bench needs to be created when using Vivado HLS. If the test bench checks the results from the top-level function, the RTL can be verified by simulation.

Note: To provide input arguments to the test bench, select **Project > Project Settings**, click **Simulation**, and use the **Input Arguments** option. The test bench must *not* require the execution of interactive user inputs. Vivado HLS GUI does not have a command console and cannot accept user inputs while the test bench executes.

Xilinx recommends that you separate the top-level function for synthesis from the test bench, and that you use header files. The following code example shows a design in which the function `hier_func` calls two sub-functions:

- `sumsub_func` performs addition and subtraction.
- `shift_func` performs shift.

The data types are defined in the header file (`hier_func.h`), which is also described:

```
#include hier_func.h

int sumsub_func(din_t *in1, din_t *in2, dint_t *outSum, dint_t *outSub)
{
    *outSum = *in1 + *in2;
    *outSub = *in1 - *in2;
}

int shift_func(dint_t *in1, dint_t *in2, dout_t *outA, dout_t *outB)
{
    *outA = *in1 >> 1;
    *outB = *in2 >> 2;
}

void hier_func(din_t A, din_t B, dout_t *C, dout_t *D)
{
    dint_t apb, amb;

    sumsub_func(&A,&B,&apb,&amb);
    shift_func(&apb,&amb,C,D);
}
```

Example 3-4: Hierarchical Design Coding Example

The top-level function can contain multiple sub-functions. There can be only a single top-level function for synthesis. To synthesize multiple functions, group them into a single top-level function.

To synthesize function `hier_func`:

1. Add the file shown in [Example 3-4](#) to a Vivado HLS project as a design file.
2. Specify the top-level function as `hier_func`.

After synthesis:

- The arguments to the top-level function (A, B, C, and D in [Example 3-4](#)) are synthesized into RTL ports.
- The functions within the top-level (`sumsub_func` and `shift_func` in [Example 3-4](#)) are synthesized into hierarchical blocks.

The header file (`hier_func.h`) in [Example 3-4](#) shows how to use macros and how `typedef` statements can make the code more portable and readable. Later sections show how the `typedef` statement allows the types and therefore the bit-widths of the variables to be refined for both area and performance improvements in the final FPGA implementation.

```
#ifndef _HIER_FUNC_H_
#define _HIER_FUNC_H_

#include <stdio.h>

#define NUM_TRANS 40

typedef int din_t;
typedef int dint_t;
typedef int dout_t;

void hier_func(din_t A, din_t B, dout_t *C, dout_t *D);

#endif
```

Example 3-5: Hierarchical Design Example Header File

The header file in this example includes some definitions (such as NUM_TRANS) that are not required in the design file. These definitions are used by the test bench which also includes the same header file.

The following code example shows the test bench for the design shown in [Example 3-4](#).

```
#include hier_func.h

int main() {
    // Data storage
    int a[NUM_TRANS], b[NUM_TRANS];
    int c_expected[NUM_TRANS], d_expected[NUM_TRANS];
    int c[NUM_TRANS], d[NUM_TRANS];

    // Function data (to/from function)
    int a_actual, b_actual;
    int c_actual, d_actual;

    // Misc
    int      retval=0, i, i_trans, tmp;
    FILE *fp;

    // Load input data from files
    fp=fopen(tb_data/inA.dat,r);
    for (i=0; i<NUM_TRANS; i++){
        fscanf(fp, %d, &tmp);
        a[i] = tmp;
    }
    fclose(fp);

    fp=fopen(tb_data/inB.dat,r);
    for (i=0; i<NUM_TRANS; i++){
        fscanf(fp, %d, &tmp);
        b[i] = tmp;
    }
    fclose(fp);

    // Execute the function multiple times (multiple transactions)
    for(i_trans=0; i_trans<NUM_TRANS-1; i_trans++) {
```

```

//Apply next data values
a_actual = a[i_trans];
b_actual = b[i_trans];

hier_func(a_actual, b_actual, &c_actual, &d_actual);

//Store outputs
c[i_trans] = c_actual;
d[i_trans] = d_actual;
}

// Load expected output data from files
fp=fopen(tb_data/outC.golden.dat,r);
for (i=0; i<NUM_TRANS; i++){
    fscanf(fp, %d, &tmp);
    c_expected[i] = tmp;
}
fclose(fp);

fp=fopen(tb_data/outD.golden.dat,r);
for (i=0; i<NUM_TRANS; i++){
    fscanf(fp, %d, &tmp);
    d_expected[i] = tmp;
}
fclose(fp);

// Check outputs against expected
for (i = 0; i < NUM_TRANS-1; ++i) {
    if(c[i] != c_expected[i]){
        retval = 1;
    }
    if(d[i] != d_expected[i]){
        retval = 1;
    }
}

// Print Results
if(retval == 0){
    printf(    *** *** *** *\n);
    printf(    Results are good \n);
    printf(    *** *** *** *\n);
} else {
    printf(    *** *** *** *\n);
    printf(    Mismatch: retval=%d \n, retval);
    printf(    *** *** *** *\n);
}

// Return 0 if outputs are corre
return retval;
}

```

Example 3-6: Test Bench Example

Productive Test Benches

[Example 3-6](#) highlights some of the attributes of a productive test bench, such as:

- The top-level function for synthesis (`hier_func`) is executed for multiple transactions, as defined by macro `NUM_TRANS` (specified in the header file [Example 3-5](#)). This execution allows many different data values to be applied and verified. The test bench is only as good as the variety of tests it performs.
- The function outputs are compared against known good values. The known good values are read from a file in this example, but can also be computed as part of the test bench.
- The return value of `main()` function is set to:
 - Zero: Results are correct.
 - Non-zero value: Results are incorrect.

Note: The test bench can return any non-zero value. A complex test bench can return different values depending on the type of difference or failure. If the test bench returns a non-zero value after C simulation or C/RTL co-simulation, Vivado HLS reports an error and simulation fails.



RECOMMENDED: Because the system environment (for example, Linux, Windows, or Tcl) interprets the return value of the `main()` function, Xilinx recommends that you constrain the return value to an 8-bit range for portability and safety.



CAUTION! You are responsible for ensuring that the test bench checks the results. If the test bench does not check the results but returns zero, Vivado HLS indicates that the simulation test passed even though the results were not actually checked.

A test bench that exhibits these attributes quickly tests and validates any changes made to the C functions before synthesis and is re-usable at RTL, allowing easier verification of the RTL.

Design Files and Test Bench Files

Because Vivado HLS reuses the C test bench for RTL verification, it requires that the test bench and any associated files be denoted as test bench files when they are added to the Vivado HLS project.

Files associated with the test bench are any files that are:

- Accessed by the test bench; and
- Required for the test bench to operate correctly.

Examples of such files include the data files `inA.dat` and `inB.dat` in [Example 3-6](#). You must add these to the Vivado HLS project as test bench files.

The requirement for identifying test bench files in a Vivado HLS project does not require that the design and test bench to be in separate files (although separate files are recommended).

The same design from [Example 3-4](#) is repeated in [Example 3-7](#). The only difference is that the top-level function is renamed `hier_func2`, to differentiate the examples.

Using the same header file and test bench (other than the change from `hier_func` to `hier_func2`), the only changes required in Vivado HLS to synthesize function `sumsub_func` as the top-level function are:

- Set `sumsub_func` as the top-level function in the Vivado HLS project.
- Add the file in [Example 3-7](#) as both a design file *and* project file. The level above `sumsub_func` (function `hier_func2`) is now part of the test bench. It must be included in the RTL simulation.

Even though function `sumsub_func` is not explicitly instantiated inside the `main()` function, the remainder of the functions (`hier_func2` and `shift_func`) confirm that it is operating correctly, and thus is part of the test bench.

```
#include hier_func2.h

int sumsub_func(din_t *in1, din_t *in2, dint_t *outSum, dint_t *outSub)
{
    *outSum = *in1 + *in2;
    *outSub = *in1 - *in2;
}

int shift_func(dint_t *in1, dint_t *in2, dout_t *outA, dout_t *outB)
{
    *outA = *in1 >> 1;
    *outB = *in2 >> 2;
}

void hier_func2(din_t A, din_t B, dout_t *C, dout_t *D)
{
    dint_t apb, amb;

    sumsub_func (&A,&B,&apb,&amb) ;
    shift_func(&apb,&amb,C,D) ;
}
```

Example 3-7: New Top-Level Design

Combining Test Bench and Design Files

You can also include the design and test bench into a single design file. [Example 3-8](#) has the same functionality as [Example 3-4](#) through [Example 3-6](#), except that everything is captured in a single file. Function `hier_func` is renamed `hier_func3` to ensure that the examples are unique.



IMPORTANT: If the test bench and design are in a single file, you must add the file to a Vivado HLS project as both a design file and a test bench file.

```
#include <stdio.h>

#define NUM_TRANS 40

typedef int din_t;
typedef int dint_t;
typedef int dout_t;

int sumsub_func(din_t *in1, din_t *in2, dint_t *outSum, dint_t *outSub)
{
    *outSum = *in1 + *in2;
    *outSub = *in1 - *in2;
}

int shift_func(dint_t *in1, dint_t *in2, dout_t *outA, dout_t *outB)
{
    *outA = *in1 >> 1;
    *outB = *in2 >> 2;
}

void hier_func3(din_t A, din_t B, dout_t *C, dout_t *D)
{
    dint_t apb, amb;

    sumsub_func(&A,&B,&apb,&amb);
    shift_func(&apb,&amb,C,D);
}

int main() {
    // Data storage
    int a[NUM_TRANS], b[NUM_TRANS];
    int c_expected[NUM_TRANS], d_expected[NUM_TRANS];
    int c[NUM_TRANS], d[NUM_TRANS];

    //Function data (to/from function)
    int a_actual, b_actual;
    int c_actual, d_actual;

    // Misc
    int retval=0, i, i_trans, tmp;
    FILE *fp;
    // Load input data from files
    fp=fopen(tb_data/inA.dat,r);
    for (i=0; i<NUM_TRANS; i++){
        fscanf(fp, %d, &tmp);
```

```

        a[i] = tmp;
    }
fclose(fp);

fp=fopen(tb_data/inB.dat,r);
for (i=0; i<NUM_TRANS; i++){
    fscanf(fp, %d, &tmp);
    b[i] = tmp;
}
fclose(fp);

// Execute the function multiple times (multiple transactions)
for(i_trans=0; i_trans<NUM_TRANS-1; i_trans++){

    //Apply next data values
    a_actual = a[i_trans];
    b_actual = b[i_trans];

    hier_func3(a_actual, b_actual, &c_actual, &d_actual);

    //Store outputs
    c[i_trans] = c_actual;
    d[i_trans] = d_actual;
}

// Load expected output data from files
fp=fopen(tb_data/outC.golden.dat,r);
for (i=0; i<NUM_TRANS; i++){
    fscanf(fp, %d, &tmp);
    c_expected[i] = tmp;
}
fclose(fp);

fp=fopen(tb_data/outD.golden.dat,r);
for (i=0; i<NUM_TRANS; i++){
    fscanf(fp, %d, &tmp);
    d_expected[i] = tmp;
}
fclose(fp);

// Check outputs against expected
for (i = 0; i < NUM_TRANS-1; ++i) {
    if(c[i] != c_expected[i]){
        retval = 1;
    }
    if(d[i] != d_expected[i]){
        retval = 1;
    }
}

// Print Results
if(retval == 0){
    printf( *** *** *** \n);
    printf( Results are good \n);
    printf( *** *** *** \n);
} else {
    printf( *** *** *** \n);
    printf( Mismatch: retval=%d \n, retval);
    printf( *** *** *** \n);
}

```

```

    }

    // Return 0 if outputs are correct
    return retval;
}

```

Example 3-8: Test Bench and Top-Level Design

Functions

The top-level function becomes the top level of the RTL design after synthesis. Sub-functions are synthesized into blocks in the RTL design.



IMPORTANT: *The top-level function cannot be a static function.*

After synthesis, each function in the design has its own synthesis report and RTL HDL file (Verilog, VHD, and SystemC).

Inlining functions

Sub-functions can optionally be inlined to merge their logic with the logic of the surrounding function. While inlining functions can result in better optimizations, it can also increase run time. More logic and more possibilities must be kept in memory and analyzed.



TIP: Vivado HLS may perform automatic inlining of small functions. To disable automatic inlining of a small function, set the `inline` directive to `off` for that function.

If a function is inlined, there is no report or separate RTL file for that function. The logic and loops are merged with the function above it in the hierarchy.

Impact of Coding Style

The primary impact of a coding style on functions is on the function arguments and interface.

If the arguments to a function are sized accurately, Vivado HLS can propagate this information through the design. There is no need to create arbitrary precision types for every variable. In the following example, two integers are multiplied, but only the bottom 24 bits are used for the result.

```
#include ap_cint.h

int24 foo(int x, int y) {
    int tmp;

    tmp = (x * y);
    return tmp
}
```

When this code is synthesized, the result is a 32-bit multiplier with the output truncated to 24-bit.

If the inputs are correctly sized to 12-bit types (int12) as shown in the following code example, the final RTL uses a 24-bit multiplier.

```
#include ap_cint.h
typedef int12 din_t;
typedef int24 dout_t;

dout_t func_sized(din_t x, din_t y) {
    int tmp;

    tmp = (x * y);
    return tmp
}
```

Example 3-9: Sizing Function Arguments

Using arbitrary precision types for the two function inputs is enough to ensure Vivado HLS creates a design using a 24-bit multiplier. The 12-bit types are propagated through the design. Xilinx recommends that you correctly size the arguments of all functions in the hierarchy.

In general, when variables are driven directly from the function interface, especially from the top-level function interface, they can prevent some optimizations from taking place. A typical case of this is when an input is used as the upper limit for a loop index.

Loops

Loops provide a very intuitive and concise way of capturing the behavior of an algorithm and are used often in C code. Loops are very well supported by synthesis: loops can be pipelined, unrolled, partially unrolled, merged and flattened.

The optimizations unroll, partially unroll, flatten and merge effectively make changes to the loop structure, as if the code was changed. These optimizations ensure limited coding changes are required when optimizing loops. Some optimizations can be applied only in certain conditions. Some coding changes might be required.



RECOMMENDED: *Avoid use of global variables for loop index variables, as this can inhibit some optimizations.*

Variable Loop Bounds

Some of the optimizations that Vivado HLS can apply are prevented when the loop has variable bounds. In the following code example, the loop bounds are determined by variable width, which is driven from a top-level input. In this case, the loop is considered to have variable bounds, because Vivado HLS cannot know when the loop will complete.

```
#include ap_cint.h
#define N 32

typedef int8 din_t;
typedef int13 dout_t;
typedef uint5 dsel_t;

dout_t code028(din_t A[N], dsel_t width) {
    dout_t out_accum=0;
    dsel_t x;

    LOOP_X:for (x=0;x<width; x++) {
        out_accum += A[x];
    }

    return out_accum;
}
```

Example 3-10: Variable Loop Bounds

Attempting to optimize the design in [Example 3-10](#) reveals the problems created by variable loop bounds.

The first issue with variable loop bounds is that they prevent Vivado HLS from determining the latency of the loop. Vivado HLS can determine the latency to complete one iteration of the loop, but because it cannot statically determine the exact value of variable width, it does

not know how many iteration are performed and thus cannot report the loop latency (the number of cycles to completely execute every iteration of the loop).

When variable loop bounds are present, Vivado HLS reports the latency as a question mark (?) instead of using exact values. The following shows the result after synthesis of [Example 3-10](#).

```
+ Summary of overall latency (clock cycles):
  * Best-case latency: ?
  * Average-case latency: ?
  * Worst-case latency: ?
+ Summary of loop latency (clock cycles):
  + LOOP_X:
    * Trip count: ?
    * Latency: ?
```

The first issue with variable loop bounds is that the performance of the design is unknown.

The two ways to overcome this issue are:

- Use the `Tripcount` directive. The details on this approach are explained here.
- Use an assert macro in the C code. for more information, see [C++ Classes and Templates](#).

The `tripcount` directive allows a minimum, average and/or maximum `tripcount` to be specified for the loop. The `tripcount` is the number of loop iterations. If a maximum `tripcount` of 32 is applied to `LOOP_X` in [Example 3-10](#), the report is updated to the following:

```
+ Summary of overall latency (clock cycles):
  * Best-case latency: 2
  * Average-case latency: 18
  * Worst-case latency: 34
+ Summary of loop latency (clock cycles):
  + LOOP_X:
    * Trip count: 0 ~ 32
    * Latency: 0 ~ 32
```

`Tripcount` directive has no impact on the results of synthesis, only reporting. The user-provided values for the `Tripcount` directive are used only for reporting. The `Tripcount` value allows Vivado HLS to report number in the report, allowing the reports from different solutions to be compared. To have this same loop-bound information used for synthesis, the C code must be updated. For more information, see [C++ Classes and Templates](#).

`Tripcount` directives have no impact on the results of synthesis, only reporting.

The next steps in optimizing [Example 3-10](#) for a lower initiation interval are:

- Unroll the loop and allow the accumulations to occur in parallel.
- Partition the array input, or the parallel accumulations are limited, by a single memory port.

If these optimizations are applied, the output from Vivado HLS highlights the most significant issue with variable bound loops:

```
@W [XF0RM-503] Cannot unroll loop 'LOOP_X' in function 'code028': cannot completely
unroll a loop with a variable trip count.
```

Because variable bounds loops cannot be unrolled, they not only prevent the unroll directive being applied, they also prevent pipelining of the levels above the loop.



IMPORTANT: When a loop or function is pipelined, Vivado HLS unrolls all loops in the hierarchy below the function or loop. If there is a loop with variable bounds in this hierarchy, it prevents pipelining.

The solution to loops with variable bounds is to make the number of loop iteration a fixed value with conditional executions inside the loop. The code from [Example 3-10](#) can be rewritten as shown in the following code example. Here, the loop bounds are explicitly set to the maximum value of variable width and the loop body is conditionally executed.

```
#include ap_cint.h
#define N 32

typedef int8 din_t;
typedef int13 dout_t;
typedef uint5 dsel_t;

dout_t loop_max_bounds(din_t A[N], dsel_t width) {
    dout_t out_accum=0;
    dsel_t x;

    LOOP_X:for (x=0;x<N-1; x++) {
        if (x<width) {
            out_accum += A[x];
        }
    }

    return out_accum;
}
```

Example 3-11: Variable Loop Bounds Rewritten

The for-loop (LOOP_X) in [Example 3-11](#) can be unrolled. Because the loop has fixed upper bounds, Vivado HLS knows how much hardware to create. There are N(32) copies of the loop body in the RTL design. Each copy of the loop body has conditional logic associated with it and is executed depending on the value of variable width.

Loop Pipelining

When pipelining loops, the most optimum balance between area and performance is typically found by pipelining the inner most loop. This is also results in the fastest run time. The following code example demonstrates the trade-offs when pipelining loops and functions.

```
#include loop_pipeline.h

dout_t loop_pipeline(din_t A[N]) {
    int i,j;
    static dout_t acc;

    LOOP_I:for(i=0; i < 20; i++) {
        LOOP_J: for(j=0; j < 20; j++) {
            acc += A[i] * j;
        }
    }

    return acc;
}
```

Example 3-12: Loop Pipeline

If the inner-most (LOOP_J) is pipelined, there is one copy of LOOP_J in hardware, (a single multiplier) and Vivado HLS uses the outer-loop (LOOP_I) to simply feed LOOP_J with new data. Only 1 multiplier operation and 1 array access need to be scheduled, then the loop iterations can be scheduled as single loop-body entity (20x20 loop iterations).



TIP: When a loop or function is pipelined, any loop in the hierarchy below the loop or function being pipelined must be unrolled.

If the outer-loop (LOOP_I) is pipelined, inner-loop (LOOP_J) is unrolled creating 20 copies of the loop body: 20 multipliers and 20 array accesses must now be scheduled. Then each iteration of LOOP_I can be scheduled as a single entity.

If the top-level function is pipelined, both loops must be unrolled: 400 multipliers and 400 arrays accessed must now be scheduled. It is very unlikely that Vivado HLS will produce a design with 400 multiplications because in most designs data dependencies often prevent maximal parallelism, for example, in this case, even if a dual-port RAM is used for A[N] the design can only access two values of A[N] in any clock cycle.

The concept to appreciate when selecting at which level of the hierarchy to pipeline is to understand that pipelining the inner-most loop gives the smallest hardware with generally acceptable throughput for most applications. Pipelining the upper-levels of the hierarchy unrolls all sub-loops and can create many more operations to schedule (which could impact run time and memory capacity), but typically gives the highest performance design in terms of throughput and latency.

To summarize the above options:

- **Pipeline LOOP_J**

Latency is approximately 400 cycles (20x20) and requires less than 100 LUTs and registers (the I/O control and FSM are always present).

- **Pipeline LOOP_I**

Latency is approximately 20 cycles but requires a few hundred LUTs and registers. About 20 times the logic as first option, minus any logic optimizations that can be made.

- **Pipeline function loop_pipeline**

Latency is approximately 10 (20 dual-port accesses) but requires thousands of LUTs and registers (about 400 times the logic of the first option minus any optimizations that can be made).

Imperfect Nested Loops

When the inner-loop of a loop hierarchy is pipelined, Vivado HLS flattens the nested loops, to reduce latency and improve overall throughput by removing any cycles caused by loop transitioning (the checks performed on the loop index when entering and exiting loops). Such checks can result in a clock delay when transitioning from one loop to the next (entry and/or exit). In [Example 3-12](#), pipelining the inner-most loop would result in the following message from Vivado HLS.

```
@I [XFORM-541] Flattening a loop nest 'LOOP_I' in function 'loop_pipeline'.
```

Nested loops can only be flattened if the loops are perfect or semi-perfect.

- **Perfect Loops**

- Only the inner most loop has body (contents).
- There is no logic specified between the loop statements.
- The loop bounds are constant.

- **Semi-Perfect Loops**

- Only the inner most loop has body (contents).
- There is no logic specified between the loop statements.
- The outer most loop bound can be variable.

The following code example shows a case in which the loop nest is imperfect.

```
#include loop_imperfect.h

void loop_imperfect(din_t A[N], dout_t B[N]) {

    int i,j;
    dint_t acc;

    LOOP_I:for(i=0; i < 20; i++) {
        acc = 0;
        LOOP_J: for(j=0; j < 20; j++) {
            acc += A[i] * j;
        }
        B[i] = acc / 20;
    }

}
```

Example 3-13: Imperfect Nested Loops

The assignment to `acc` and array `B[N]` inside `LOOP_I`, but outside `LOOP_J`, prevent the loops from being flattened. If `LOOP_J` in [Example 3-13](#) is pipelined, the synthesis report shows the following:

```
+ Summary of loop latency (clock cycles):
  + LOOP_I:
    * Trip count: 20
    * Latency:    480
  + LOOP_J:
    * Trip count: 20
    * Latency:    21
    * Pipeline II: 1
    * Pipeline depth: 2
```

- The pipeline depth shows it takes 2 clocks to execute one iteration of `LOOP_J`. This varies with the device technology and clock period.
- A new iteration can begin each clock cycle. Pipeline II is 1. II is the Initiation Interval: cycles between each new execution of the loop body.
- It takes 2 cycles for the first iteration to output a result. Due to pipelining each subsequent iteration executes in parallel with the previous one and outputs a value after 1 clock. The total latency of the loop is 2 plus 1 for each of the remaining 19 iterations: 21.
- `LOOP_I`, requires 480 clock cycles to perform 20 iterations, thus each iteration of `LOOP_I` is 24 clock cycles. This means there are 3 cycles of overhead to enter and exit `LOOP_J` ($24 - 21 = 3$).

Imperfect loop nests, or the inability to flatten loop them, results in additional clock cycles to enter and exit the loops. The code in [Example 3-13](#) can be rewritten to make the nested loops perfect and allow them to be flattened.

The following code example shows how conditionals can be added to loop `LOOP_J` to provide the same functionality as [Example 3-13](#) but allow the loops to be flattened.

```
#include loop_perfect.h

void loop_perfect(din_t A[N], dout_t B[N]) {

    int i,j;
    dint_t acc;

    LOOP_I:for(i=0; i < 20; i++){
        LOOP_J: for(j=0; j < 20; j++) {
            if(j==0) acc = 0;
            acc += A[i] * j;
            if(j==19) B[i] = acc / 20;
        }
    }
}
```

Example 3-14: Perfect Nested Loops

When [Example 3-14](#) is synthesized, the loops are flattened:

```
@I [XFORM-541] Flattening a loop nest 'LOOP_I' in function 'loop_perfect'.
```

The synthesis report shows an improvement in latency:

```
+ Summary of loop latency (clock cycles):
  + LOOP_I_LOOP_J:
    * Trip count:      400
    * Latency:        401
    * Pipeline II:    1
    * Pipeline depth: 2
```

When the design contains nested loops, analyze the results to ensure as many nested loops as possible have been flattened: review the log file or look in the synthesis report for cases, as shown above, where the loop labels have been merged (LOOP_I and LOOP_J are now reported as LOOP_I_LOOP_J).

Loop Parallelism

Vivado HLS schedules logic and functions as early as possible to reduce latency. To perform this, it schedules as many logic operations and functions as possible in parallel. It does not schedule loops to execute in parallel.

If the following code example is synthesized, loop SUM_X is scheduled and then loop SUM_Y is scheduled: even though loop SUM_Y does not need to wait for loop SUM_X to complete before it can begin its operation, it is scheduled after SUM_X.

```
#include loop_sequential.h

void loop_sequential(din_t A[N], din_t B[N], dout_t X[N], dout_t Y[N],
                     dsel_t xlimit, dsel_t ylimit) {

    dout_t X_accum=0;
    dout_t Y_accum=0;
    int i,j;

    SUM_X:for (i=0;i<xlimit; i++) {
        X_accum += A[i];
        X[i] = X_accum;
    }

    SUM_Y:for (i=0;i<ylimit; i++) {
        Y_accum += B[i];
        Y[i] = Y_accum;
    }
}
```

Example 3-15: Sequential Loops

Because the loops have different bounds (`xlimit` and `ylimit`), they cannot be merged. By placing the loops in separate functions, as shown in the following code example, the identical functionality can be achieved and both loops (inside the functions), can be scheduled in parallel.

```
#include loop_functions.h

void sub_func(din_t I[N], dout_t O[N], dsel_t limit) {
    int i;
    dout_t accum=0;

    SUM:for (i=0;i<limit; i++) {
        accum += I[i];
        O[i] = accum;
    }
}

void loop_functions(din_t A[N], din_t B[N], dout_t X[N], dout_t Y[N],
                    dsel_t xlimit, dsel_t ylimit) {

    dout_t X_accum=0;
    dout_t Y_accum=0;
    int i,j;

    sub_func(A,X,xlimit);
    sub_func(B,Y,ylimit);
}
```

Example 3-16: Sequential Loops as Functions

If [Example 3-16](#) is synthesized, the latency is half the latency of [Example 3-15](#) because the loops (as functions) can now execute in parallel.

The dataflow optimization could also be used in [Example 3-15](#). The principle of capturing loops in functions to exploit parallelism is presented here for cases in which dataflow optimization cannot be used. For example, in a larger example, dataflow optimization is applied to all loops and functions at the top-level and memories placed between every top-level loop and function.

Loop Dependencies

Loop dependencies are data dependencies that prevent optimization of loops, typically pipelining. They can be within a single iteration of a loop and or between different iteration of a loop.

The easiest way to understand loop dependencies is to examine an extreme example. In the following example, the result of the loop is used as the loop continuation or exit condition. Each iteration of the loop must finish before the next can start.

```
Minim_Loop: while (a != b) {
    if (a > b)
        a -= b;
    else
        b -= a;
}
```

This loop cannot be pipelined. The next iteration of the loop cannot begin until the previous iteration ends.

Not all loop dependencies are as extreme as this, but this example highlights the issue: some operation cannot begin until some other operation has completed. The solution is to try ensure the initial operation is performed as early as possible.

Loop dependencies can occur with any and all types of data. They are particularly common when using arrays, which are discussed in [Arrays](#).

Unrolling Loops in C++ Classes

When loops are used in C++ classes, care should be taken to ensure the loop induction variable is not a data member of the class as this prevents the loop from being unrolled.

In this example, loop induction variable "k" is a member of class "foo_class".

```
template <typename T0, typename T1, typename T2, typename T3, int N>
class foo_class {
private:
    pe_mac<T0, T1, T2> mac;
public:
    T0 areg;
    T0 breg;
    T2 mreg;
    T1 preg;
    T0 shift[N];
    int k; // Class Member
```

```

T0 shift_output;
void exec(T1 *pcout, T0 *dataOut, T1 pcin, T3 coeff, T0 data, int col)
{
Function_label0:;
#pragma HLS inline off
SRL:for (k = N-1; k >= 0; --k) {
#pragma HLS unroll// Loop will fail UNROLL
    if (k > 0)
        shift[k] = shift[k-1];
    else
        shift[k] = data;
}

*dataOut = shift_output;
shift_output = shift[N-1];
}

*pcout = mac.exec1(shift[4*col], coeff, pcin);
};

```

For Vivado HLS to be able to unroll the loop as specified by the UNROLL pragma directive, the code should be rewritten to remove "k" as a class member.

```

template <typename T0, typename T1, typename T2, typename T3, int N>
class foo_class {
private:
    pe_mac<T0, T1, T2> mac;
public:
    T0 areg;
    T0 breg;
    T2 mreg;
    T1 preg;
    T0 shift[N];
    T0 shift_output;
    void exec(T1 *pcout, T0 *dataOut, T1 pcin, T3 coeff, T0 data, int col)
    {
Function_label0:;
    int k;           // Local variable
#pragma HLS inline off
    SRL:for (k = N-1; k >= 0; --k) {
#pragma HLS unroll// Loop will unroll
        if (k > 0)
            shift[k] = shift[k-1];
        else
            shift[k] = data;
}

*dataOut = shift_output;
shift_output = shift[N-1];
}

*pcout = mac.exec1(shift[4*col], coeff, pcin);
};

```

Arrays

Before discussing how the coding style can impact the implementation of arrays after synthesis it is worthwhile discussing a situation where arrays can introduce issues even before synthesis is performed, for example, during C simulation.

In cases such as the following, where a very large array is specified, it might cause C simulation to run out of memory and fail. This example is not showing a function for synthesis, but simply highlighting how large arrays and large arrays with arbitrary precision types can impact the run-time memory.

```
#include ap_cint.h
int main() {

    int i, acc;
    // Use an arbitrary precision type
    int32 la0[10000000], la1[10000000];

    for (i=0 ; i < 10000000; i++) {
        acc = acc + la0[i] + la1[i];
    }

    return 0;
}
```

The simulation might fail by running out of memory, because the array is placed on the stack that exists in memory rather than the heap that is managed by the OS and can use local disk space to grow.

This might mean the design runs out of memory when running and certain issues might make this issue more likely:

- On PCs, the available memory is often less than large Linux boxes and there might be less memory available.
- Using arbitrary precision types, as shown above, could make this issue worse as they require more memory than standard C types.
- Using the more complex fixed-point arbitrary precision types found in C++ and SystemC might make the issue even more likely as they require even more memory.

A solution is to use dynamic memory allocation for simulation but a fixed sized array for synthesis, as shown in the next example. This means that the memory required for this is allocated on the heap, managed by the OS, and which can use local disk space to grow.

A change such as this to the code is not ideal, because the code simulated and the code synthesized are now different, but this might sometimes be the only way to move the design process forward. If this is done, be sure that the C test bench covers all aspects of accessing the array. The RTL simulation performed by `cosim_design` will verify that the memory accesses are correct.

```
#include ap_cint.h
int main() {

    int i, acc;
#ifndef __SYNTHESIS__
    // Use an arbitrary precision type & array for synthesis
    int32 la0[10000000], la1[10000000];
#else
    // Use an arbitrary precision type & dynamic memory for simulation
    int32 la0 = malloc(10000000 * sizeof(int32));
    int32 la1 = malloc(10000000 * sizeof(int32));
#endif
    for (i=0 ; i < 10000000; i++) {
        acc = acc + la0[i] + la1[i];
    }

    return 0;
}
```

Arrays are typically implemented as a memory (RAM, ROM or FIFO) after synthesis. As discussed in [Arrays on the Interface](#), arrays on the top-level function interface are synthesized as RTL ports that access a memory outside. Arrays internal to the design are synthesized to internal block RAM, LUTRAM or registers, depending on the optimization settings.

Like loops, arrays are an intuitive coding construct and so they are often found in C programs. Also like loops, Vivado HLS includes optimizations and directives that can be applied to optimize their implementation in RTL without any need to modify the code.

Cases in which arrays can create problems in the RTL include:

- Array accesses can often create bottlenecks to performance. When implemented as a memory, the number of memory ports limits access to the data.
- Array initialization, if not performed carefully, can result in undesirably long reset and initialization in the RTL.
- Some care must be taken to ensure arrays that only require read accesses are implemented as ROMs in the RTL.

Vivado HLS supports arrays of pointers. See [Pointers](#). Each pointer can point only to a scalar or an array of scalars.

Note: Arrays must be sized. For example, sized arrays are supported, for example: `Array[10];` However, unsized arrays are not supported, for example: `Array[];`.

Array Accesses and Performance

The following code example shows a case in which accesses to an array can limit performance in the final RTL design. In this example, there are three accesses to the array `mem[N]` to create a summed result.

```
#include array_mem_bottleneck.h

dout_t array_mem_bottleneck(din_t mem[N]) {
    dout_t sum=0;
    int i;

    SUM_LOOP:for(i=2;i<N;++i)
        sum += mem[i] + mem[i-1] + mem[i-2];

    return sum;
}
```

Example 3-17: Array-Memory Bottleneck

During synthesis, the array is implemented as a RAM. If the RAM is specified as a single-port RAM it is impossible to pipeline loop `SUM_LOOP` to process a new loop iteration every clock cycle.

Trying to pipeline `SUM_LOOP` with an initiation interval of 1 results in the following message (after failing to achieve a throughput of 1, Vivado HLS relaxes the constraint):

```
@I [SCHED-61] Pipelining loop 'SUM_LOOP'.
@W [SCHED-69] Unable to schedule 'load' operation ('mem_load_1',
array_mem_bottleneck.c:54) on array 'mem' due to limited resources (II = 1).
@W [SCHED-69] Unable to schedule 'load' operation ('mem_load_2',
array_mem_bottleneck.c:54) on array 'mem' due to limited resources (II = 2).
@I [SCHED-61] Pipelining result: Target II: 1, Final II: 3, Depth: 4.
```

The issue here is that the single-port RAM has only a single data port: only 1 read (and 1 write) can be performed in each clock cycle.

- `SUM_LOOP` Cycle1: read `mem[i]`;
- `SUM_LOOP` Cycle2: read `mem[i-1]`, sum values;
- `SUM_LOOP` Cycle3: read `mem[i-2]`, sum values;

A dual-port RAM could be used, but this allows only two accesses per clock cycle. Three reads are required to calculate the value of sum, and so three accesses per clock cycle are required to pipeline the loop with a new iteration every clock cycle.



CAUTION! *Arrays implemented as memory or memory ports, can often become bottlenecks to performance.*

The code in [Example 3-17](#) can be rewritten as shown in the following code example to allow the code to be pipelined with a throughput of 1. In the following code example, by performing pre-reads and manually pipelining the data accesses, there is only one array read specified in each iteration of the loop. This ensures that only a single-port RAM is required to achieve the performance.

```
#include array_mem_perform.h

dout_t array_mem_perform(din_t mem[N]) {
    din_t tmp0, tmp1, tmp2;
    dout_t sum=0;
    int i;

    tmp0 = mem[0];
    tmp1 = mem[1];
    SUM_LOOP:for (i = 2; i < N; i++) {
        tmp2 = mem[i];
        sum += tmp2 + tmp1 + tmp0;
        tmp0 = tmp1;
        tmp1 = tmp2;
    }

    return sum;
}
```

Example 3-18: Array-Memory with Performance Access

Vivado HLS includes optimization directives for changing how arrays are implemented and accessed. It is typically the case that directives can be used, and changes to the code are not required. Arrays can be partitioned into blocks or into their individual elements. In some cases, Vivado HLS partitions arrays into individual elements. This is controllable using the configuration settings for auto-partitioning.

When an array is partitioned into multiple blocks, the single array is implemented as multiple RTL RAM blocks. When partitioned into elements, each element is implemented as a register in the RTL. In both cases, partitioning allows more elements to be accessed in parallel and can help with performance; the design trade-off is between performance and the number of RAMs or registers required to achieve it.

FIFO Accesses

A special case of arrays accesses are when arrays are implemented as FIFOs. This is often the case when dataflow optimization is used.

Accesses to a FIFO must be in sequential order starting from location zero. In addition, if an array is read in multiple locations, the code must strictly enforce the order of the FIFO accesses. It is often the case that arrays with multiple fanout cannot be implemented as FIFOs without additional code to enforce the order of the accesses.

Arrays on the Interface

Vivado HLS synthesizes arrays into memory elements by default. When you use an array as an argument to the top-level function, Vivado HLS assumes the following:

- Memory is off-chip

Vivado HLS synthesizes interface ports to access the memory.
- Memory is standard block RAM with a latency of 1

The data is ready 1 clock cycle after the address is supplied.

To configure how Vivado HLS creates these ports:

- Specify the interface as a RAM or FIFO interface using the INTERFACE directive.
- Specify the RAM as a single or dual-port RAM using the RESOURCE directive.
- Specify the RAM latency using the RESOURCE directive.
- Use array optimization directives (`Array_Partition`, `Array_Map`, or `Array_Reshape`) to reconfigure the structure of the array and therefore, the number of I/O ports.



TIP: Because access to the data is limited through a memory (RAM or FIFO) port, arrays on the interface can create a performance bottleneck. Typically, you can overcome these bottlenecks using directives.

Arrays must be sized when using arrays in synthesizable code. If, for example, the declaration `d_i[4]` in [Example 3-19](#) is changed to `d_i[]`, Vivado HLS issues a message that the design cannot be synthesized.

```
@E [SYNCHK-61] array_RAM.c:52: unsupported memory access on
variable 'd_i' which is (or contains) an array with unknown size
at compile time.
```

Array Interfaces

The resource directive can explicitly specify which type of RAM is used, and therefore which RAM ports are created (single-port or dual-port). If no resource is specified, Vivado HLS uses:

- A single-port RAM by default.
- A dual-port RAM if it reduces the initiation interval or reduces latency.

The `partition`, `map`, and `reshape` directives can re-configure arrays on the interface. Arrays can be partitioned into multiple smaller arrays, each implemented with its own interface. This includes the ability to partition every element of the array into its own scalar

element. On the function interface, this results in a unique port for every element in the array. This provides maximum parallel access, but creates many more ports and might introduce routing issues in the hierarchy above.

Similarly, smaller arrays can be combined into a single larger array, resulting in a single interface. While this might map better to an off-chip block RAM, it might also introduce a performance bottleneck. These trade-offs can be made using Vivado HLS optimization directives and do not impact coding.

By default, the array arguments in the function shown in the following code example are synthesized into a single-port RAM interface.

```
#include array_RAM.h

void array_RAM (dout_t d_o[4], din_t d_i[4], didx_t idx[4]) {
    int i;

    For_Loop: for (i=0;i<4;i++) {
        d_o[i] = d_i[idx[i]];
    }
}
```

Example 3-19: RAM Interface

A single-port RAM interface is used because the `for-loop` ensures that only one element can be read and written in each clock cycle. There is no advantage in using a dual-port RAM interface.

If the `for-loop` is unrolled, Vivado HLS uses a dual-port. Doing so allows multiple elements to be read at the same time and improves the initiation interval. The type of RAM interface can be explicitly set by applying the resource directive.

Issues related to arrays on the interface are typically related to throughput. They can be handled with optimization directives. For example, if the arrays in [Example 3-19](#) are partitioned into individual elements and the `for-loop` unrolled, all four elements in each array are accessed simultaneously.

You can also use the `RESOURCE` directive to specify the latency of the RAM. This allows Vivado HLS to model external SRAMs with a latency of greater than 1 at the interface.

FIFO Interfaces

Vivado HLS allows array arguments to be implemented as FIFO ports in the RTL. If a FIFO port is to be used, be sure that the accesses to and from the array are sequential.

Vivado HLS determines whether the accesses are sequential.

Table 3-1: Vivado HLS Analysis of Sequential Access

Accesses Sequential?	Vivado HLS Action
Yes	<ul style="list-style-type: none"> Implements the FIFO port.
No	<ul style="list-style-type: none"> Issues an error message. Halts synthesis.
Indeterminate	<ul style="list-style-type: none"> Issues a warning. Implements the FIFO port.

Note: If the accesses are in fact not sequential, there is an RTL simulation mismatch.

The following code example shows a case in which Vivado HLS cannot determine whether the accesses are sequential. In this example, both `d_i` and `d_o` are specified to be implemented with a FIFO interface during synthesis.

```
#include array_FIFO.h

void array_FIFO (dout_t d_o[4], din_t d_i[4], didx_t idx[4]) {
    int i;

    // Breaks FIFO interface d_o[3] = d_i[2];
    For_Loop: for (i=0;i<4;i++) {
        d_o[i] = d_i[idx[i]];
    }
}
```

Example 3-20: Streaming FIFO Interface

In this case, the behavior of variable `idx` determines whether or not a FIFO interface can be successfully created.

- If `idx` is incremented sequentially, a FIFO interface can be created.
- If random values are used for `idx`, a FIFO interface fails when implemented in RTL.

Because this interface might not work, Vivado HLS issues a message during synthesis and creates a FIFO interface.

```
@W [XF0RM-124] Array 'd_i': may have improper streaming access(es).
```

If the comments in [Example 3-20](#) are removed, ("//Breaks FIFO interface"), Vivado HLS can determine that the accesses to the arrays are not sequential, and halts with an error message if a FIFO interface is specified.

Note: FIFO ports cannot be synthesized for arrays that are read from and written to. Separate input and output arrays (as in [Example 3-20](#)) must be created.

The following general rules apply to arrays that are to be streamed (implemented with a FIFO interface):

- The array must be written and read in only one loop or function. This can be transformed into a point-to-point connection that matches the characteristics of FIFO links.
- The array reads must be in the same order as the array write. Because random access is not supported for FIFO channels, the array must be used in the program following *first in, first out* semantics.
- The index used to read and write from the FIFO must be analyzable at compile time. Array addressing based on run time computations cannot be analyzed for FIFO semantics and prevent the tool from converting an array into a FIFO.

Code changes are generally not required to implement or optimize arrays in the top-level interface. The only time arrays on the interface may need coding changes is when the array is part of a struct.

Array Initialization



RECOMMENDED: As discussed in [Type Qualifiers](#), although not a requirement, Xilinx recommends specifying arrays that are to be implemented as memories with the static qualifier. This not only ensures that Vivado HLS implements the array with a memory in the RTL, it also allows the initialization behavior of static types to be used.

In the following code, an array is initialized with a set of values. Each time the function is executed, array `coeff` is assigned these values. After synthesis, each time the design executes the RAM that implements `coeff` is loaded with these values. For a single-port RAM this would take 8 clock cycles. For an array of 1024, it would of course, take 1024 clock cycles, during which time no operations depending on `coeff` could occur.

```
int coeff[8] = {-2, 8, -4, 10, 14, 10, -4, 8, -2};
```

The following code uses the `static` qualifier to define array `coeff`. The array is initialized with the specified values at start of execution. Each time the function is executed, array `coeff` remembers its values from the previous execution. A static array behaves in C code as a memory does in RTL.

```
static int coeff[8] = {-2, 8, -4, 10, 14, 10, -4, 8, -2};
```

In addition, if the variable has the `static` qualifier, Vivado HLS initializes the variable in the RTL design and in the FPGA bitstream. This removes the need for multiple clock cycles to initialize the memory and ensures that initializing large memories is not an operational overhead.

The RTL configuration command can specify if static variables return to their initial state after a reset is applied (not the default). If a memory is to be returned to its initial state after

a reset operation, this incurs an operational overhead and requires multiple cycles to reset the values. Each value must be written into each memory address.

Implementing ROMs

Vivado HLS does not require that an array be specified with the `static` qualifier to synthesize a memory or the `const` qualifier to infer that the memory should be a ROM. Vivado HLS analyzes the design and attempts to create the most optimal hardware.

Xilinx highly recommends using the `static` qualifier for arrays that are intended to be memories. As noted in [Array Initialization](#), a `static` type behaves in an almost identical manner as a memory in RTL.

The `const` qualifier is also recommended when arrays are only read, because Vivado HLS cannot always infer that a ROM should be used by analysis of the design. The general rule for the automatic inference of a ROM is that a local, static (non-global) array is written to before being read. The following practices in the code can help infer a ROM:

- Initialize the array as early as possible in the function that uses it.
- Group writes together.
- Do not interleave `array (ROM)` initialization writes with non-initialization code.
- Do not store different values to the same array element (group all writes together in the code).
- Element value computation must not depend on any non-constant (at compile-time) design variables, other than the initialization loop counter variable.

If complex assignments are used to initialize a ROM (for example, functions from the `math.h` library), placing the array initialization into a separate function allows a ROM to be inferred. In the following example, array `sin_table[256]` is inferred as a memory and implemented as a ROM after RTL synthesis.

```
#include array_ROM_math_init.h
#include <math.h>

void init_sin_table(din1_t sin_table[256])
{
    int i;
    for (i = 0; i < 256; i++) {
        dint_t real_val = sin(M_PI * (dint_t)(i - 128) / 256.0);
        sin_table[i] = (din1_t)(32768.0 * real_val);
    }
}

dout_t array_ROM_math_init(din1_t inval, din2_t idx)
{
    short sin_table[256];
    init_sin_table(sin_table);
    return (int)inval * (int)sin_table[idx];
}
```

Example 3-21: ROM Initialization with math.h



TIP: Because the result of the `sin()` function results in constant values, no core is required in the RTL design to implement the `sin()` function. The `sin()` function is not one of the cores listed in [Table 3-2](#) and is not supported for synthesis in C. See [SystemC Synthesis](#) for using `math.h` functions in C++.

Data Types

The data types used in a C function compiled into an executable impact the accuracy of the result and the memory requirements, and can impact the performance.

- A 32-bit integer `int` data type can hold more data and therefore provide more precision than an 8-bit `char` type, but it requires more storage.
- If 64-bit `long long` types are used on a 32-bit system, the run time is impacted because it typically requires multiple accesses to read and write those values.

Similarly, when the C function is to be synthesized to an RTL implementation, the types impact the precision, the area, and the performance of the RTL design. The data types used for variables determine the size of the operators required and therefore the area and performance of the RTL.

Vivado HLS supports the synthesis of all standard C types, including exact-width integer types.

- `(unsigned) char, (unsigned) short, (unsigned) int`
- `(unsigned) long, (unsigned) long long`
- `(unsigned) intN_t` (where N is 8,16,32 and 64, as defined in `stdint.h`)
- `float, double`

Exact-width integers types are useful for ensuring designs are portable across all types of system.

Integer type `(unsigned) long` is implemented as 64 bits on 64-bit operating systems and as 32 bits on 32-bit operating systems. Synthesis matches this behavior and produces different sized operators (and therefore different RTL designs), depending on the type of operating system on which Vivado HLS is run.

- Use data type `(unsigned) int` or `(unsigned) int32_t` instead of type `(unsigned) long` for 32-bit.
- Use data type `(unsigned) long long` or `(unsigned) int64_t` instead of type `(unsigned) long` for 64-bit.

It is highly recommended to define the data types for all variables in a common header file, which can be included in all source files.

- During the course of a typical High-Level Synthesis project, some of the data types might be refined, for example to reduce their size and allow a more efficient hardware implementation.
- One of the benefits of working at a higher level of abstraction is the ability to quickly create new design implementations. The same files typically are used in later projects but might use different (smaller or larger or more accurate) data types.

Both of these tasks are more easily achieved when the data types can be changed in a single location: the alternative is to edit multiple files.



TIP: When using macros in header files, always use unique names. For example, if a macro named `_TYPES_H` is defined in your header file, it is likely that such a common name might be defined in other system files, and it might enable or disable some other code, causing unforeseen side-effects.

Standard Types

The following code example shows some basic arithmetic operations being performed.

```
#include types_standard.h

void types_standard(din_A inA, din_B inB, din_C inC, din_D inD,
                     dout_1 *out1, dout_2 *out2, dout_3 *out3, dout_4 *out4
) {

    // Basic arithmetic operations
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = inD % inA;

}
```

Example 3-22: Basic Arithmetic

The data types in [Example 3-22](#) are defined in the header file `types_standard.h` shown in the following code example. They show how the following types can be used:

- Standard signed types
- Unsigned types
- Exact-width integer types (with the inclusion of header file `stdint.h`)

```
#include <stdio.h>
#include <stdint.h>

#define N 9

typedef char din_A;
typedef short din_B;
typedef int din_C;
typedef long long din_D;

typedef int dout_1;
typedef unsigned char dout_2;
typedef int32_t dout_3;
typedef int64_t dout_4;

void types_standard(din_A inA,din_B inB,din_C inC,din_D inD,dout_1
*out1,dout_2 *out2,dout_3 *out3,dout_4 *out4);
```

Example 3-23: Basic Arithmetic Type Definitions

These different types result in the following operator and port sizes after synthesis:

- The multiplier used to calculate result `out1` is a 24-bit multiplier. An 8-bit `char` type multiplied by a 16-bit `short` type requires a 24-bit multiplier. The result is sign-extended to 32-bit to match the output port width.
- The adder used for `out2` is 8-bit. Because the output is an 8-bit `unsigned char` type, only the bottom 8-bits of `inB` (a 16-bit `short`) are added to 8-bit `char` type `inA`.
- For output `out3` (32-bit exact width type), 8-bit `char` type `inA` is sign-extended to 32-bit value and a 32-bit division operation is performed with the 32-bit (`int` type) `inC` input.
- A 64-bit modulus operation is performed using the 64-bit `long long` type `inD` and 8-bit `char` type `inA` sign-extended to 64-bit, to create a 64-bit output result `out4`.

As the result of `out1` indicates, Vivado HLS uses the smallest operator it can and extends the result to match the required output bit-width. For result `out2`, even though one of the inputs is 16-bit, an 8-bit adder can be used because only an 8-bit output is required. As the results for `out3` and `out4` show, if all bits are required, a full sized operator is synthesized.

Floats and Doubles

Vivado HLS supports `float` and `double` types for synthesis. Both data types are synthesized with IEEE-754 standard compliance.

- Single-precision 32 bit
 - 24-bit fraction
 - 8-bit exponent
- Double-precision 64 bit
 - 53-bit fraction
 - 11-bit exponent

In addition to using floats and doubles for standard arithmetic operations (such as `+`, `-`, `*`) floats and doubles are commonly used with the `math.h` (and `cmath.h` for C++) . This section discusses support for standard operators. For more information on synthesizing the C and C++ math libraries, see [HLS Math Library in Chapter 2](#).

The following code example shows the header file used with [Example 3-22](#) updated to define the data types to be `double` and `float` types.

```
#include <stdio.h>
#include <stdint.h>
#include <math.h>

#define N 9

typedef double din_A;
typedef double din_B;
typedef double din_C;
typedef float din_D;

typedef double dout_1;
typedef double dout_2;
typedef double dout_3;
typedef float dout_4;

void types_float_double(din_A inA,din_B inB,din_C inC,din_D inD,dout_1
*out1,dout_2 *out2,dout_3 *out3,dout_4 *out4);
```

Example 3-24: Float and Double Types

This updated header file is used with the following code example where a `sqrtf()` function is used.

```
#include types_float_double.h

void types_float_double(
    din_A inA,
    din_B inB,
    din_C inC,
    din_D inD,
    dout_1 *out1,
    dout_2 *out2,
    dout_3 *out3,
    dout_4 *out4
) {

    // Basic arithmetic & math.h sqrtf()
    *out1 = inA * inB;
    *out2 = inB + inA;
    *out3 = inC / inA;
    *out4 = sqrtf(inD);

}
```

Example 3-25: Use of Floats and Doubles

When [Example 3-25](#) is synthesized, it results in 64-bit double-precision multiplier, adder, and divider operators. These operators are implemented by the appropriate floating-point Xilinx® CORE Generator™ tool cores.

The square-root function used `sqrtf()` is implemented using a 32-bit single-precision floating-point core.

If the double-precision square-root function `sqrt()` was used, it would result in additional logic to cast to and from the 32-bit single-precision float types used for `inD` and `out4`: `sqrt()` is a double-precision (`double`) function, while `sqrtf()` is a single precision (`float`) function.

In C functions, be careful when mixing float and double types as float-to-double and double-to-float conversion units are inferred in the hardware.

This code:

```
float foo_f      = 3.1459;
float var_f = sqrt(foo_f);
```

Results in the following hardware:

```
wire(foo_t)
→ Float-to-Double Converter unit
→ Double-Precision Square Root unit
→ Double-to-Float Converter unit
→ wire (var_f)
```

Using a `sqrtf()` function:

- Removes the need for the type converters in hardware.
- Saves area.
- Improves timing.

Operations in float and double types are synthesized to a floating-point operator LogiCORE™ IP. The following table shows the cores available for Xilinx® 7 series, Virtex®, and Spartan® devices.

The implications from the cores shown in the following table are that if the technology does not support a particular LogiCORE IP, the design cannot be synthesized. Vivado HLS halts with an error message.

Table 3-2: Floating Point Cores and Device Support

Core	7 Series	Virtex-6	Virtex-5	Virtex-4	Spartan-6	Spartan-3
FAddSub	X	X	X	X	X	X
FAddSub_nodsp	X	X	X	-	-	-
FAddSub_fulldsp	X	X	X	-	-	-
FCmp	X	X	X	X	X	X
FDiv	X	X	X	X	X	X
FMul	X	X	X	X	X	X
FExp_nodsp	X					
FExp_meddsp	X					
FExp_fulldsp	X					
FMul_nodsp	X	X	X	-	X	X
FMul_meddsp	X	X	X	-	X	X
FMul_fulldsp	X	X	X	-	X	X
FMul_maxdsp	X	X	X	-	X	X
DAddSub	X	X	X	X	X	X
DAddSub_nodsp	X	X	X	-	-	-
DAddSub_fulldsp	X	X	X	-	-	-
DCmp	X	X	X	X	X	X
DDiv	X	X	X	X	X	X
DMul	X	X	X	X	X	X
DExp_nodsp	X					
DExp_meddsp	X					
DExp_fulldsp	X					
DMul_nodsp	X	X	X	-	X	X
DMul_meddsp	X	X	X	-	-	-
DMul_fulldsp	X	X	X	-	X	X
DMul_maxdsp	X	X	X	-	X	X

The cores in the preceding table allow the operation, in some cases, to be implemented with a core in which many DSP48s are used or none (for example, DMul_nodsp and DMul_maxdsp). By default, Vivado HLS implements the operation using the core with the maximum number of DSP48s. Alternatively, the Vivado HLS resource directive can specify exactly which core to use.

When synthesizing float and double types, Vivado HLS maintains the order of operations performed in the C code to ensure that the results are the same as the C simulation. Due to saturation and truncation, the following are not guaranteed to be the same in single and double precision operations:

```
A=B*C;          A=B*F;
D=E*F;          D=E*C;
O1=A*D;         O2=A*D;
```

With float and double types, O1 and O2 are not guaranteed to be the same.



TIP: *In some cases (design dependent), optimizations such as unrolling or partial unrolling of loops, might not be able to take full advantage of parallel computations as Vivado HLS maintains the strict order of the operations when synthesizing float and double types.*

For C++ designs, Vivado HLS provides a bit-approximate implementation of the most commonly used math functions.

Composite Data Types

Vivado HLS supports composite data types for synthesis:

- struct
- enum
- union

Structs

When structs are used as arguments to the top-level function, the ports created by synthesis are a direct reflection of the struct members. Scalar members are implemented as standard scalar ports and arrays are implemented, by default, as memory ports.

In this design example, `struct data_t` is defined in the header file shown in the following code example. This struct has two data members:

- An unsigned vector A of type `short` (16-bit).
- An array B of four `unsigned char` types (8-bit).

```
typedef struct {
    unsigned short A;
    unsigned char B[4];
} data_t;

data_t struct_port(data_t i_val, data_t *i_pt, data_t *o_pt);
```

Example 3-26: Struct Declaration in Header file

In the following code example, the struct is used as both a pass-by-value argument (from `i_val` to the return of `o_val`) and as a pointer (`*i_pt` to `*o_pt`).

```
#include struct_port.h

data_t struct_port(
    data_t i_val,
    data_t *i_pt,
    data_t *o_pt
) {

    data_t o_val;
    int i;

    // Transfer pass-by-value structs
    o_val.A = i_val.A+2;
    for (i=0;i<4;i++) {
        o_val.B[i] = i_val.B[i]+2;
    }

    // Transfer pointer structs
    o_pt->A = i_pt->A+3;
    for (i=0;i<4;i++) {
        o_pt->B[i] = i_pt->B[i]+3;
    }

    return o_val;
}
```

Example 3-27: Struct as Pass-by-Value and Pointer

All function arguments and the function return are synthesized into ports as follows:

- Struct element A results in a 16-bit port.
- Struct element B results in a RAM port, accessing 4 elements.

There are no limitations in the size or complexity of structs that can be synthesized by Vivado HLS. There can be as many array dimensions and as many members in a struct as

required. The only limitation with the implementation of structs occurs when arrays are to be implemented as streaming (such as a FIFO interface). In this case, follow the same general rules that apply to arrays on the interface (FIFO Interfaces).

The elements on a struct can be packed into a single vector by the data packing optimization. For more information, see the `set_directive_data_pack` command on performing this optimization. Additionally, unused elements of a struct can be removed from the interface by the `-trim_dangling_ports` option of the `config_interface` command.

Enumerated Types

The header file in the following code example defines some `enum` types and uses them in a struct. The struct is used in turn in another struct. This allows an intuitive description of a complex type to be captured.

The following code example shows how a complex define (`MAD_NSBSAMPLES`) statement can be specified and synthesized.

```
#include <stdio.h>

enum mad_layer {
    MAD_LAYER_I    = 1,
    MAD_LAYER_II   = 2,
    MAD_LAYER_III  = 3
};

enum mad_mode {
    MAD_MODE_SINGLE_CHANNEL = 0,
    MAD_MODE_DUAL_CHANNEL  = 1,
    MAD_MODE_JOINT_STEREO   = 2,
    MAD_MODE_STEREO         = 3
};

enum mad_emphasis {
    MAD_EMPHASIS_NONE     = 0,
    MAD_EMPHASIS_50_15_US  = 1,
    MAD_EMPHASIS_CCITT_J_17 = 3
};

typedef signed int mad_fixed_t;

typedef struct mad_header {
    enum mad_layer layer;
    enum mad_mode mode;
    int mode_extension;
    enum mad_emphasis emphasis;

    unsigned long long bitrate;
    unsigned int samplerate;

    unsigned short crc_check;
    unsigned short crc_target;
}
```

```

        int flags;
        int private_bits;

    } header_t;

typedef struct mad_frame {
    header_t header;
    int options;
    mad_fixed_t sbsample[2][36][32];
} frame_t;

#define MAD_NSBSAMPLES(header) \
((header)->layer == MAD_LAYER_I ? 12 : \
((header)->layer == MAD_LAYER_III && \
((header)->flags & 17)) ? 18 : 36)

void types_composite(frame_t *frame);

```

Example 3-28: Enum, Struct, and Complex Define

The struct and enum types defined in [Example 3-28](#) are used in the following code example. If the enum is used in an argument to the top-level function, it is synthesized as a 32-bit value to comply with the standard C compilation behavior. If the enum types are internal to the design, Vivado HLS optimizes them down to the only the required number of bits.

The following code example shows how `printf` statements are ignored during synthesis.

```

#include types_composite.h

void types_composite(frame_t *frame)
{
    if (frame->header.mode != MAD_MODE_SINGLE_CHANNEL) {
        unsigned int ns, s, sb;
        mad_fixed_t left, right;

        ns = MAD_NSBSAMPLES(&frame->header);
        printf("Samples from header %d \n, ns);

        for (s = 0; s < ns; ++s) {
            for (sb = 0; sb < 32; ++sb) {
                left = frame->sbsample[0][s][sb];
                right = frame->sbsample[1][s][sb];
                frame->sbsample[0][s][sb] = (left + right) / 2;
            }
        }
        frame->header.mode = MAD_MODE_SINGLE_CHANNEL;
    }
}

```

Example 3-29: Use Complex Types

Unions

In the following code example, a union is created with a double and a struct. Unlike C compilation, synthesis does not guarantee using the same memory (in the case of synthesis, registers) for all fields in the union. Vivado HLS performs that optimization that provides the most optimal hardware.

```
#include types_union.h

dout_t types_union(din_t N, dinfp_t F)
{
    union {
        struct {int a; int b; } intval;
        double fpval;
    } intfp;
    unsigned long long one, exp;

    // Set a floating-point value in union intfp
    intfp.fpval = F;

    // Slice out lower bits and add to shifted input
    one = intfp.intval.a;
    exp = (N & 0x7FF);

    return ((exp << 52) + one) & (0x7fffffffffffffLL);
}
```

Example 3-30: Unions

Note: Vivado HLS does not support pointer reinterpretation for synthesis. Consequently, a union cannot hold pointers to different types or arrays of different types.

Vivado HLS does not support access to a union through another variable. Using the same union as the previous example, the following is not supported,

```
for (int i = 0; i < 6; ++i)
if (i<3)
    A[i] = intfp.intval.a + B[i];
else
    A[i] = intfp.intval.b + B[i];
}
```

However, it might be explicitly re-coded as:

```
A[0] = intfp.intval.a + B[0];
A[1] = intfp.intval.a + B[1];
A[2] = intfp.intval.a + B[2];
A[3] = intfp.intval.b + B[3];
A[4] = intfp.intval.b + B[4];
A[5] = intfp.intval.b + B[5];
```

The synthesis of unions does not support casting between native C types and user-defined types. The following union contains the native type `long long` and a user-defined struct.

This union cannot be synthesized because it would require casting from the native type to a user-defined type.

```
typedef union {
    long long raw[6];
    struct {
        int b;
        int c;
        int a[10];
    };
} data_t;
```

Type Qualifiers

The type qualifiers can directly impact the hardware created by high-level synthesis. In general, the qualifiers influence the synthesis results in a predictable manner, as discussed below. Vivado HLS is limited only by the interpretation of the qualifier as it affects functional behavior and can perform optimizations to create a more optimal hardware design. Examples of this are shown after an overview of each qualifier.

Volatile

The `volatile` qualifier impacts how many reads or writes are performed in the RTL when pointers are accessed multiple times on function interfaces. Although the `volatile` qualifier impacts this behavior in all functions in the hierarchy, the impact of the `volatile` qualifier is primarily discussed in the section on top-level interfaces. See [Understanding Volatile Data](#).

Arbitrary precision types do not support the `volatile` qualifier for arithmetic operations. Any arbitrary precision data types using the `volatile` qualifier must be assigned to a non-volatile data type before being used in arithmetic expression.

Statics

Static types in a function hold their value between function calls. The equivalent behavior in a hardware design is a registered variable (a flip-flop or memory). If a variable is required to be a static type for the C function to execute correctly, it will certainly be a register in the final RTL design. The value must be maintained across invocations of the function and design.

It is *not* true that *only static* types result in a register after synthesis. Vivado HLS determines which variables are required to be implemented as registers in the RTL design. For example, if a variable assignment must be held over multiple cycles, Vivado HLS creates a register to hold the value, even if the original variable in the C function was *not* a static type.

Vivado HLS obeys the initialization behavior of statics and assigns the value to zero (or any explicitly initialized value) to the register during initialization. This means that the static

variable is initialized in the RTL code and in the FPGA bitstream. It does not mean that the variable is re-initialized each time the reset signal is.

See the RTL configuration (`config_rtl` command) to determine how static initialization values are implemented with regard to the system reset.

Const

A `const` type specifies that the value of the variable is never updated. The variable is read but never written to and therefore must be initialized. For most `const` variables, this typically means that they are reduced to constants in the RTL design. Vivado HLS performs constant propagation and removes any unnecessary hardware).

In the case of arrays, the `const` variable is implemented as a ROM in the final RTL design (in the absence of any auto-partitioning performed by Vivado HLS on small arrays). Arrays specified with the `const` qualifier are (like `statics`) initialized in the RTL and in the FPGA bitstream. There is no need to reset them, because they are never written to.

Vivado HLS Optimizations

The following code example shows a case in which Vivado HLS implements a ROM even though the array is not specified with a `static` or `const` qualifier. This highlights how Vivado HLS analyzes the design and determines the most optimal implementation. The qualifiers, or lack of them, influence but do not dictate the final RTL.

```
#include array_ROM.h

dout_t array_ROM(din1_t inval, din2_t idx)
{
    din1_t lookup_table[256];
    dint_t i;

    for (i = 0; i < 256; i++) {
        lookup_table[i] = 256 * (i - 128);
    }

    return (dout_t)inval * (dout_t)lookup_table[idx];
}
```

Example 3-31: Non-Static, Non-Const ROM Implementation Coding Example

In the case of [Example 3-31](#), Vivado HLS is able to determine that the implementation is best served by having the variable `lookup_table` as a memory element in the final RTL. For more information on how this achieved for arrays, see [Implementing ROMs](#).

Global Variables

Global variables can be freely used in the code and are fully synthesizable. By default, global variables are not exposed as ports on the RTL interface.

The following code example shows the default synthesis behavior of global variables. It uses three global variables. Although this example uses arrays, Vivado HLS supports all types of global variables.

- Values are read from array `Ain`.
- Array `Aint` is used to transform and pass values from `Ain` to `Aout`.
- The outputs are written to array `Aout`.

```

din_t Ain[N];
din_t Aint[N];
dout_t Aout[N/2];

void types_global(din1_t idx) {
    int i,lidx;

    // Move elements in the input array
    for (i=0; i<N; ++i) {
        lidx=i;
        if(lidx+idx>N-1)
            lidx=i-N;
        Aint[lidx] = Ain[lidx+idx] + Ain[lidx];
    }

    // Sum to half the elements
    for (i=0; i<(N/2); i++) {
        Aout[i] = (Aint[i] + Aint[i+1])/2;
    }
}

```

Example 3-32: Global Variables Coding Example

By default, after synthesis, the only port on the RTL design is port `idx`. Global variables are not exposed as RTL ports by default. In the default case:

- Array `Ain` is an internal RAM that is *read from*.
- Array `Aout` is an internal RAM that is *written to*.

Exposing Global Variables as I/O Ports

While global variables are not exposed as I/O ports by default, they can be exposed as I/O ports by one of following three methods:

- If the global variable is defined with the external qualifier, the variable `ise` is exposed as an I/O port.
- If an I/O protocol is specified on the global variable (using the INTERFACE directive), the variable is synthesized to an I/O port with the specified interface protocol.
- The `expose_global` option in the interface configuration can expose all global variables as ports on the RTL interface. The interface configuration can be set by:

- **Solution Settings > General**, or
- The config_interface Tcl command

When global variables are exposed using the interface configuration, all global variables in the design are exposed as I/O ports, including those that are accessed exclusively inside the design.

Finally, if any global variable is specified with the static qualifier, it cannot be synthesized to an I/O port.

In summary, while Vivado HLS supports global variables for synthesis, Xilinx does not recommend a coding style that uses global variables extensively.

Pointers

Pointers are used extensively in C code and are well-supported for synthesis. Cases in which extra care must be taken when using pointers are:

- When pointers are accessed (read or written) multiple times in the same function.
For more information, see [Multi-Access Pointer Interfaces: Streaming Data](#).
- When using arrays of pointers, each pointer must point to a scalar or a scalar array (not another pointer).
- Pointer casting is supported only when casting between standard C types, as shown.

The following code example shows synthesis support for pointers that point to multiple objects.

```
#include pointer_multi.h

dout_t pointer_multi (sel_t sel, din_t pos) {
    static const dout_t a[8] = {1, 2, 3, 4, 5, 6, 7, 8};
    static const dout_t b[8] = {8, 7, 6, 5, 4, 3, 2, 1};

    dout_t* ptr;
    if (sel)
        ptr = a;
    else
        ptr = b;

    return ptr[pos];
}
```

Example 3-33: Multiple Pointer Targets

Double-pointers are also supported for synthesis but they are not supported on the top-level interface (as argument to the top-level function). If a double-pointer is used in multiple functions, Vivado HLS inlines all functions in which it is used. Inlining multiple functions can increase run time.

```

#include pointer_double.h

data_t sub(data_t ptr[10], data_t size, data_t**flagPtr)
{
    data_t x, i;

    x = 0;
    // Sum x if AND of local index and double-pointer index is true
    for(i=0; i<size; ++i)
        if (**flagPtr & i)
            x += *(ptr+i);
    return x;
}

data_t pointer_double(data_t pos, data_t x, data_t* flag)
{
    data_t array[10] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    data_t* ptrFlag;
    data_t i;

    ptrFlag = flag;

    // Write x into index position pos
    if (pos >=0 & pos < 10)
        *(array+pos) = x;

    // Pass same index (as pos) as pointer to another function
    return sub(array, 10, &ptrFlag);
}

```

Example 3-34: Double Pointers

Arrays of pointers can also be synthesized. See the following code example in which an array of pointers is used to store the start location of the second dimension of a global array. The pointers in an array of pointers can point only to a scalar or to an array of scalars. They cannot point to other pointers.

```
#include pointer_array.h

data_t A[N][10];

data_t pointer_array(data_t B[N*10]) {
    data_t i,j;
    data_t sum1;

    // Array of pointers
    data_t* PtrA[N];

    // Store global array locations in temp pointer array
    for (i=0; i<N; ++i)
        PtrA[i] = &(A[i][0]);

    // Copy input array using pointers
    for(i=0; i<N; ++i)
        for(j=0; j<10; ++j)
            *(PtrA[i]+j) = B[i*10 + j];

    // Sum input array
    sum1 = 0;
    for(i=0; i<N; ++i)
        for(j=0; j<10; ++j)
            sum1 += *(PtrA[i] + j);

    return sum1;
}
```

Example 3-35: Pointer Arrays Coding Example

Pointer casting is supported for synthesis if native C types are used. In the following code example, type int is cast to type char.

```
#define N 1024

typedef int data_t;
typedef char dint_t;

data_t pointer_cast_native (data_t index, data_t A[N]) {
    dint_t* ptr;
    data_t i =0, result = 0;
    ptr = (dint_t*)(&A[index]);

    // Sum from the indexed value as a different type
    for (i = 0; i < 4*(N/10); ++i) {
        result += *ptr;
        ptr+=1;
    }
    return result;
}
```

Example 3-36: Pointer Casting with Native Types

Vivado HLS does not support pointer casting between general types. For example, if a (struct) composite type of signed values is created, the pointer cannot be cast to assign unsigned values.

```
struct {
    short first;
    short second;
} pair;

// Not supported for synthesis
*(unsigned*)pair = -1U;
```

In such cases, the values must be assigned using the native types.

```
struct {
    short first;
    short second;
} pair;

// Assigned value
pair.first = -1U;
pair.second = -1U;
```

Pointers on the Interface

Pointers can be used as arguments to the top-level function. It is important to understand how pointers are implemented during synthesis, because they can sometimes cause problems in achieving the desired RTL interface and design after synthesis.

Basic Pointers

A function with basic pointers on the top-level interface, such as shown in the following code example, produces no issues for Vivado HLS. The pointer can be synthesized to either a simple wire interface or an interface protocol using handshakes.



TIP: *To be synthesized as a FIFO interface, a pointer must be read-only or write-only.*

```
#include pointer_basic.h

void pointer_basic (dio_t *d) {
    static dio_t acc = 0;

    acc += *d;
    *d = acc;
}
```

Example 3-37: Basic Pointer Interface

The pointer on the interface is read or written only once per function call. The test bench shown in the following code example.

```
#include pointer_basic.h

int main () {
    dio_t d;
    int i, retval=0;
    FILE *fp;

    // Save the results to a file
    fp=fopen(result.dat,w);
    printf( Din Dout\n, i, d);

    // Create input data
    // Call the function to operate on the data
    for (i=0;i<4;i++) {
        d = i;
        pointer_basic(&d);
        fprintf(fp, %d \n, d);
        printf( %d %d\n, i, d);
    }
    fclose(fp);

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed!!!\n);
        retval=1;
    } else {
        printf(Test passed!\n);
    }

    // Return 0 if the test
    return retval;
}
```

Example 3-38: Basic Pointer Interface Test Bench

C and RTL simulation verify the correct operation (although not all possible cases) with this simple data set:

```
Din Dout
0 0
1 1
2 3
3 6
Test passed!
```

Pointer Arithmetic

Introducing pointer arithmetic limits the possible interfaces that can be synthesized in RTL. The following code example shows the same code, but in this instance simple pointer arithmetic is used to accumulate the data values (starting from the second value).

```
#include pointer_arith.h

void pointer_arith (dio_t *d) {
    static int acc = 0;
    int i;

    for (i=0;i<4;i++) {
        acc += *(d+i+1);
        *(d+i) = acc;
    }
}
```

Example 3-39: Interface with Pointer Arithmetic

The following code example shows the test bench that supports this example. Because the loop to perform the accumulations is now inside function `pointer_arith`, the test bench populates the address space specified by array `d[5]` with the appropriate values.

```
#include pointer_arith.h

int main () {
    dio_t d[5], ref[5];
    int i, retval=0;
    FILE *fp;

    // Create input data
    for (i=0;i<5;i++) {
        d[i] = i;
        ref[i] = i;
    }

    // Call the function to operate on the data
    pointer_arith(d);

    // Save the results to a file
    fp=fopen(result.dat,w);
    printf( Din Dout\n, i, d);
    for (i=0;i<4;i++) {
        fprintf(fp, %d \n, d[i]);
        printf( %d %d\n, ref[i], d[i]);
    }
    fclose(fp);

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed!!!\n);
        retval=1;
    } else {
        printf(Test passed!\n);
    }

    // Return 0 if the test
    return retval;
}
```

Example 3-40: Test Bench for Pointer Arithmetic Function

When simulated, this results in the following output:

```
Din Dout
 0   1
 1   3
 2   6
 3  10
Test passed!
```

The pointer arithmetic does not access the pointer data in sequence. Wire, handshake, or FIFO interfaces have no way of accessing data out of order:

- A wire interface reads data when the design is ready to consume the data or write the data when the data is ready.
- Handshake and FIFO interfaces read and write when the control signals permit the operation to proceed.

In both cases, the data must arrive (and is written) in order, starting from element zero. In [Example 3-39](#), the code states the first data value read is from index 1 (i starts at 0, $0+1=1$). This is the second element from array `d[5]` in the test bench.

When this is implemented in hardware, some form of data indexing is required. Vivado HLS does not support this with wire, handshake, or FIFO interfaces. The code in [Example 3-39](#) can be synthesized only with an `ap_bus` interface. This interface supplies an address with which to index the data when the data is accessed (read or write).

Alternatively, the code must be modified with an array on the interface instead of a pointer. See [Example 3-41](#). This can be implemented in synthesis with a RAM (`ap_memory`) interface. This interface can index the data with an address and can perform out-of-order, or non-sequential, accesses.

Wire, handshake, or FIFO interfaces can be used only on streaming data. It cannot be used in conjunction with pointer arithmetic (unless it indexes the data starting at zero and then proceeds sequentially).

For more information on the ap_bus and ap_memory interface types, see [Chapter 1, High-Level Synthesis](#), and [Chapter 4, High-Level Synthesis Reference Guide](#).

```
#include array_arith.h

void array_arith (dio_t d[5]) {
    static int acc = 0;
    int i;

    for (i=0;i<4;i++) {
        acc += d[i+1];
        d[i] = acc;
    }
}
```

Example 3-41: Array Arithmetic

Multi-Access Pointer Interfaces: Streaming Data

Designs that use pointers in the argument list of the top-level function need special consideration when multiple accesses are performed using pointers. Multiple accesses occur when a pointer is *read from* or *written to* multiple times in the same function.

- You must use the volatile qualifier on any function argument accessed multiple times.
- On the top-level function, any such argument must have the number of accesses on the port interface specified if you are verifying the RTL using co-simulation within Vivado HLS.
- Be sure to validate the C before synthesis to confirm the intent and that the C model is correct.

If modeling the design requires that a function argument be accessed multiple times, Xilinx recommends that you model the design using streams. See [HLS Stream Library in Chapter 2](#). Use streams to ensure that you do not encounter the issues discussed in this section. The designs in the following table use the [Coding Examples in Chapter 1](#).

Table 3-3: Example Design Scenarios

Example Design	Shows
pointer_stream_bad	Why the volatile qualifier is required when accessing pointers multiple times within the same function.
pointer_stream_better	Why any design with such pointers on the top-level interface should be verified with a C test bench to ensure that the intended behavior is correctly modeled.

In the following code example, input pointer `d_i` is read from four times and output `d_o` is written to twice, with the intent that the accesses are implemented by FIFO interfaces (streaming data into and out of the final RTL implementation).

```
#include pointer_stream_bad.h

void pointer_stream_bad ( dout_t *d_o,  din_t *d_i) {
    din_t acc = 0;

    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
}
```

Example 3-42: Multi-Access Pointer Interface

The test bench to verify this design is shown in the following code example.

```
#include pointer_stream_bad.h

int main () {
    din_t d_i;
    dout_t d_o;
    int retval=0;
    FILE *fp;

    // Open a file for the output results
    fp=fopen(result.dat,w);

    // Call the function to operate on the data
    for (d_i=0;d_i<4;d_i++) {
        pointer_stream_bad(&d_o,&d_i);
        fprintf(fp, %d %d\n, d_i, d_o);
    }
    fclose(fp);

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed !!!\n);
        retval=1;
    } else {
        printf(Test passed !\n);
    }

    // Return 0 if the test
    return retval;
}
```

Example 3-43: Multi-Access Pointer Test Bench

Understanding Volatile Data

The code in [Example 3-42](#) is written with *intent* that input pointer `d_i` and output pointer `d_o` are implemented in RTL as FIFO (or handshake) interfaces to ensure that:

- Upstream producer blocks supply new data each time a read is performed on RTL port `d_i`.
- Downstream consumer blocks accept new data each time there is a write to RTL port `d_o`.

When this code is compiled by standard C compilers, the multiple accesses to each pointer is reduced to a single access. As far as the compiler is concerned, there is no indication that the data on `d_i` changes during the execution of the function and only the final write to `d_o` is relevant. The other writes are overwritten by the time the function completes.

Vivado HLS matches the behavior of the `gcc` compiler and optimizes these reads and writes into a single read operation and a single write operation. When the RTL is examined, there is only a single read and write operation on each port.

The fundamental issue with this design is that the test bench and design do not adequately model how you expect the RTL ports to be implemented:

- You expect RTL ports that read and write multiple times during a transaction (and can stream the data in and out).
- The test bench supplies only a single input value and returns only a single output value. A C simulation of [Example 3-42](#) shows the following results, which demonstrates that each input is being accumulated four times. The same value is being read once and accumulated each time. It is not four separate reads.

```
Din Dout
0    0
1    4
2    8
3   12
```

To make this design read and write to the RTL ports multiple times, use a `volatile` qualifier. See the following code example.

The `volatile` qualifier tells the C compiler (and Vivado HLS) to make no assumptions about the pointer accesses. That is, the data is volatile and might change.



TIP: *Do not optimize pointer accesses.*

```
#include pointer_stream_better.h

void pointer_stream_better ( volatile dout_t *d_o, volatile din_t *d_i) {
    din_t acc = 0;

    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
    acc += *d_i;
    acc += *d_i;
    *d_o = acc;
}
```

Example 3-44: Multi-Access Volatile Pointer Interface

Example 3-44 simulates the same as Example 3-42, but the `volatile` qualifier:

- Prevents pointer access optimizations.
- Results in an RTL design that performs the expected four reads on input port `d_i` and two writes to output port `d_o`.

Even if the `volatile` keyword is used, this coding style (accessing a pointer multiple times) still has an issue in that the function and test bench do not adequately model multiple distinct reads and writes.

In this case, four reads are performed, but the same data is read four times. There are two separate writes, each with the correct data, but the test bench captures data only for the final write.



TIP: To see the intermediate accesses, enable `cosim_design` to create a trace file during RTL simulation and view the trace file in the appropriate viewer).

Example 3-44 can be implemented with wire interfaces. If a FIFO interface is specified, Vivado HLS creates an RTL test bench to stream new data on each read. Because no new data is available from the test bench, the RTL fails to verify. The test bench does not correctly model the reads and writes.

Modeling Streaming Data Interfaces

Unlike software, the concurrent nature of hardware systems allows them to take advantage of streaming data. Data is continuously supplied to the design and the design continuously outputs data. An RTL design can accept new data before the design has finished processing the existing data.

As the Example 3-44 has shown, modeling streaming data in software is non-trivial, especially when writing software to model an existing hardware implementation (where the concurrent/streaming nature already exists and needs to be modeled).

There are several possible approaches:

- Add the `volatile` qualifier as shown in [Example 3-44](#). The test bench does not model unique reads and writes, and RTL simulation using the original C test bench might fail, but viewing the trace file waveforms shows that the correct reads and writes are being performed.
- Modify the code to model explicit unique reads and writes. See [Example 3-45](#).
- Modify the code to using a streaming data type. A streaming data type allows hardware using streaming data to be accurately modeled. See [Chapter 1, High-Level Synthesis](#).

The following code example has been updated to ensure that it reads four unique values from the test bench and write two unique values. Because the pointer accesses are sequential and start at location zero, a streaming interface type can be used during synthesis.

```
#include pointer_stream_good.h

void pointer_stream_good ( volatile dout_t *d_o,  volatile din_t *d_i) {
    din_t acc = 0;

    acc += *d_i;
    acc += *(d_i+1);
    *d_o = acc;
    acc += *(d_i+2);
    acc += *(d_i+3);
    *(d_o+1) = acc;
}
```

Example 3-45: Explicit Multi-Access Volatile Pointer Interface

The test bench is updated to model the fact that the function reads four unique values in each transaction. This new test bench models only a single transaction. To model multiple transactions, the input data set must be increased and the function called multiple times.

```
#include pointer_stream_good.h

int main () {
    din_t d_i[4];
    dout_t d_o[4];
    int i, retval=0;
    FILE *fp;

    // Create input data
    for (i=0;i<4;i++) {
        d_i[i] = i;
    }

    // Call the function to operate on the data
    pointer_stream_good(d_o,d_i);

    // Save the results to a file
    fp=fopen(result.dat,w);
    for (i=0;i<4;i++) {
        if (i<2)
            fprintf(fp, %d %d\n, d_i[i], d_o[i]);
        else
            fprintf(fp, %d \n, d_i[i]);
    }
    fclose(fp);

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed !!!\n);
        retval=1;
    } else {
        printf(Test passed !\n);
    }

    // Return 0 if the test
    return retval;
}
```

Example 3-46: Explicit Multi-Access Volatile Pointer Test Bench

The test bench validates the algorithm with the following results, showing that:

- There are two outputs from a single transaction.
- The outputs are an accumulation of the first two input reads, plus an accumulation of the next two input reads and the previous accumulation.

```
Din Dout
0   1
1   6
2
3
```

The final issue to be aware of when pointers are accessed multiple time at the function interface is RTL simulation modeling.

Multi-Access Pointers and RTL Simulation

When pointers on the interface are accessed multiple times, to read or write, Vivado HLS cannot determine from the function interface how many reads or writes are performed. Neither of the arguments in the function interface informs Vivado HLS how many values are read or written.

```
void pointer_stream_good (volatile dout_t *d_o, volatile din_t *d_i)
```

Example 3-47: Volatile Pointer Interface

Unless the interface informs Vivado HLS how many values are required (for example, the maximum size of an array), Vivado HLS assumes a single value and creates C/RTL co-simulation for only a single input and a single output.

If the RTL ports are actually reading or writing multiple values, the RTL co-simulation stalls. RTL co-simulation models the producer and consumer blocks that are connected to the RTL design. If it models requires more than a single value, the RTL design stalls when trying to read or write more than one value (because there is currently no value to read or no space to write).

When multi-access pointers are used at the interface, Vivado HLS must be informed of the maximum number of reads or writes on the interface. When specifying the interface, use the depth option on the INTERFACE directive as shown in the following figure.

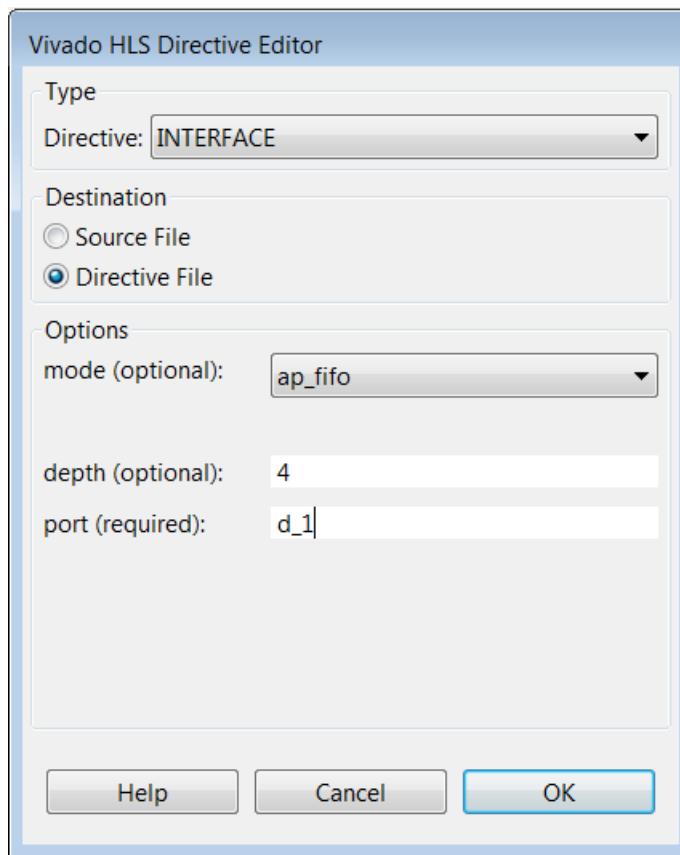


Figure 3-1: Vivado HLS Directive Editor with Depth Option

In the above example, argument or port `d_i` is set to have a FIFO interface with a depth of four. This ensures RTL co-simulation provides enough values to correctly verify the RTL.

C++ Classes and Templates

C++ classes are fully supported for synthesis with Vivado HLS. The top-level for synthesis must be a function. A class cannot be the top-level for synthesis. To synthesize a class member function, instantiate the class itself into function. Do not simply instantiate the top-level class into the test bench. The following code example shows how class `CFir` (defined in the header file discussed next) is instantiated in the top-level function `cpp_FIR` and used to implement an FIR filter.

```
#include cpp_FIR.h

// Top-level function with class instantiated
data_t cpp_FIR(data_t x)
{
    static CFir<coef_t, data_t, acc_t> fir1;

    cout << fir1;

    return fir1(x);
}
```

Example 3-48: C++ FIR Filter



IMPORTANT: *Classes and class member functions cannot be the top-level for synthesis. Instantiate the class in a top-level function.*

Before examining the class used to implement the design in [Example 3-48](#), it is worth noting Vivado HLS ignores the standard output stream cout during synthesis. When synthesized, Vivado HLS issues the following warnings:

```
@I [SYNCHK-101] Discarding unsynthesizable system call:
'std::ostream::operator<<' (cpp_FIR.h:108)
@I [SYNCHK-101] Discarding unsynthesizable system call:
'std::ostream::operator<<' (cpp_FIR.h:108)
@I [SYNCHK-101] Discarding unsynthesizable system call: 'std::operator<<
<std::char_traits<char> >' (cpp_FIR.h:110)
@
```

The following code example shows the header file `cpp_FIR.h`, including the definition of class `CFir` and its associated member functions. In this example the operator member functions () and << are overloaded operators, which are respectively used to execute the main algorithm and used with `cout` to format the data for display during C simulation.

```
#include <fstream>
#include <iostream>
#include <iomanip>
#include <cstdlib>
using namespace std;

#define N 85

typedef int coef_t;
typedef int data_t;
typedef int acc_t;

// Class CFir definition
template<class coef_T, class data_T, class acc_T>
class CFir {
protected:
    static const coef_T c[N];
    data_T shift_reg[N-1];
private:
public:
    data_T operator()(data_T x);
```

```

template<class coef_TT, class data_TT, class acc_TT>
friend ostream&
operator<<(ostream& o, const CFir<coef_TT, data_TT, acc_TT> &f);
};

// Load FIR coefficients
template<class coef_T, class data_T, class acc_T>
const coef_T CFir<coef_T, data_T, acc_T>::c[N] = {
    #include cpp_FIR.inc
};

// FIR main algorithm
template<class coef_T, class data_T, class acc_T>
data_T CFir<coef_T, data_T, acc_T>::operator()(data_T x) {
    int i;
    acc_t acc = 0;
    data_t m;

    loop: for (i = N-1; i >= 0; i--) {
        if (i == 0) {
            m = x;
            shift_reg[0] = x;
        } else {
            m = shift_reg[i-1];
            if (i != (N-1))
                shift_reg[i] = shift_reg[i - 1];
        }
        acc += m * c[i];
    }
    return acc;
}

// Operator for displaying results
template<class coef_T, class data_T, class acc_T>
ostream& operator<<(ostream& o, const CFir<coef_T, data_T, acc_T> &f) {
    for (int i = 0; i < (sizeof(f.shift_reg)/sizeof(data_T)); i++) {
        o << shift_reg[ << i << ] = << f.shift_reg[i] << endl;
    }
    o << _____ << endl;
    return o;
}

data_t cpp_FIR(data_t x);

```

Example 3-49: C++ Header File Defining Classes

The test bench Example 3-48 is shown in the following code example and demonstrates how top-level function `cpp_FIR` is called and validated. This example highlights some of the important attributes of a good test bench for Vivado HLS synthesis:

- The output results are checked against known good values.
- The test bench returns 0 if the results are confirmed to be correct.

For more information on test benches, see [Productive Test Benches](#).

```
#include cpp_FIR.h

int main() {
    ofstream result;
    data_t output;
    int retval=0;

    // Open a file to saves the results
    result.open(result.dat);

    // Apply stimuli, call the top-level function and saves the results
    for (int i = 0; i <= 250; i++)
    {
        output = cpp_FIR(i);

        result << setw(10) << i;
        result << setw(20) << output;
        result << endl;
    }
    result.close();

    // Compare the results file with the golden results
    retval = system(diff --brief -w result.dat result.golden.dat);
    if (retval != 0) {
        printf(Test failed !!!\n);
        retval=1;
    } else {
        printf(Test passed !\n);
    }

    // Return 0 if the test
    return retval;
}
```

Example 3-50: C++ Test Bench for cpp_FIR

To apply directives to objects defined in a class:

1. Open the file where the class is defined (typically a header file).
2. Apply the directive using the Directives tab.

As with functions, all instances of a class have the same optimizations applied to them.

Constructors, Destructors, and Virtual Functions

Class constructors and destructors are included and synthesized whenever a class object is declared.

Vivado HLS supports virtual functions (including abstract functions) for synthesis, provided that it can statically determine the function during elaboration. Vivado HLS does not support virtual functions for synthesis in the following cases:

- Virtual functions can be defined in a multilayer inheritance class hierarchy but only with a single inheritance.
- Dynamic polymorphism is only supported if the pointer object can be determined at compile time. For example, such pointers cannot be used in an if-else or loop constructs.
- An STL container cannot contain the pointer of an object and call the polymorphism function. For example:

```
vector<base *> base_ptrs(10);

//Push_back some base ptrs to vector.
for (int i = 0; i < base_ptrs.size(); ++i) {
    //Static elaboration cannot resolve base_ptrs[i] to actual data type.
    base_ptrs[i]->virtual_function();
}
```

- Vivado HLS does not support cases in which the base object pointer is a global variable. For example:

```
Base *base_ptr;

void func()
{
    .....
    base_ptr->virtual_function();
    .....
}
```

- The base object pointer cannot be a member variable in a class definition. For example:

```
// Static elaboration cannot bind base object pointer with correct data type.
class A
{
    .....
    Base *base_ptr;
    void set_base(Base *base_ptr);
    void some_func();
    .....
};

void A::set_base(Base *ptr)
{
    this.base_ptr = ptr;
}

void A::some_func()
{
    ...
    base_ptr->virtual_function();
    ...
}
```

- If the base object pointer or reference is in the function parameter list of constructor, Vivado HLS does not convert it. The ISO C++ standard has depicted this in section 12.7: sometimes the behavior is undefined.

```
class A {
    A(Base *b) {
        b-> virtual _ function ();
    }
};
```

Global Variables and Classes

Xilinx does not recommend using global variables in classes. They can prevent some optimizations from occurring. In the following code example, a class is used to create the component for a filter (class `polyd_cell` is used as a component that performs shift, multiply and accumulate operations).

```
typedef long long acc_t;
typedef int mult_t;
typedef char data_t;
typedef char coef_t;

#define TAPS 3
#define PHASES 4
#define DATA_SAMPLES 256
#define CELL_SAMPLES 12

// Use k on line 73 static int k;

template <typename T0, typename T1, typename T2, typename T3, int N>
class polyd_cell {
private:
public:
    T0 areg;
    T0 breg;
    T2 mreg;
    T1 preg;
    T0 shift[N];
    int k; //line 73
    T0 shift_output;
    void exec(T1 *pcout, T0 *dataOut, T1 pcin, T3 coeff, T0 data, int col)
    {
        Function_label0:

        if (col==0) {
            SHIFT:for (k = N-1; k >= 0; --k) {
                if (k > 0)
                    shift[k] = shift[k-1];
                else
                    shift[k] = data;
            }
            *dataOut = shift_output;
            shift_output = shift[N-1];
        }
        *pcout = (shift[4*col]* coeff) + pcin;
    }
};
```

```

        }

};

// Top-level function with class instantiated
void cpp_class_data (
    acc_t          *dataOut,
    coef_t         coeff1[PHASES][TAPS],
    coef_t         coeff2[PHASES][TAPS],
    data_t  dataIn[DATA_SAMPLES],
    int           row
) {

    acc_t pcin0 = 0;
    acc_t pcout0, pcout1;
    data_t dout0,  dout1;
    int col;
    static acc_t  accum=0;
    static int sample_count = 0;
    static polyd_cell<data_t, acc_t, mult_t, coef_t, CELL_SAMPLES>
polyd_cell0;
    static polyd_cell<data_t, acc_t, mult_t, coef_t, CELL_SAMPLES>
polyd_cell1;

    COL:for (col = 0; col <= TAPS-1; ++col) {

        polyd_cell0.exec(&pcout0,&dout0,pcin0,coeff1[row][col],dataIn[sample_count],
col);

        polyd_cell1.exec(&pcout1,&dout1,pcout0,coeff2[row][col],dout0,col);

        if ((row==0) && (col==2)) {
            *dataOut = accum;
            accum = pcout1;
        } else {
            accum = pcout1 + accum;
        }

    }
    sample_count++;
}

```

Example 3-51: C++ Class Data Member Used for Loop Index Coding Example

Within class `polyd_cell` there is a loop `SHIFT` used to shift data. If the loop index `k` used in loop `SHIFT` was removed and replaced with the global index for `k` (shown earlier in the example, but commented `static int k`), Vivado HLS is unable to pipeline any loop or function in which class `polyd_cell` was used. Vivado HLS would issue the following message:

```
@W [XF0RM-503] Cannot unroll loop 'SHIFT' in function 'polyd_cell<char, long long, int, char, 12>::exec' completely: variable loop bound.
```

Using local non-global variables for loop indexing ensures that Vivado HLS can perform all optimizations.

Templates

Vivado HLS supports the use of templates in C++ for synthesis. Vivado HLS does not support templates for the top-level function.



IMPORTANT: *The top-level function cannot be a template.*

In addition to the general use of templates shown in [Example 3-49](#) and [Example 3-51](#), templates can be used implement a form of recursion that is not supported in standard C synthesis (Recursive Functions).

The following code example shows a case in which a templated `struct` is used to implement a tail-recursion Fibonacci algorithm. The key to performing synthesis is that a termination class is used to implement the final call in the recursion, where a template size of one is used.

```
//Tail recursive call
template<data_t N> struct fibon_s {
    template<typename T>
    static T fibon_f(T a, T b) {
        return fibon_s<N-1>::fibon_f(b, (a+b));
    }
};

// Termination condition
template<> struct fibon_s<1> {
    template<typename T>
    static T fibon_f(T a, T b) {
        return b;
    }
};

void cpp_template(data_t a, data_t b, data_t &dout) {
    dout = fibon_s<FIB_N>::fibon_f(a,b);
}
```

Example 3-52: C++ Tail Recursion with Templates

Assertions

The assert macro in C is supported for synthesis when used to assert range information. For example, the upper limit of variables and loop-bounds.

As noted in [Variable Loop Bounds](#), when variable loop bounds are present, Vivado HLS cannot determine the latency for all iterations of the loop and reports the latency with a question mark. The Tripcount directive can inform High-Level Synthesis of the loop bounds, but this information is only used for reporting purposes and does not impact the result of synthesis (the same sized hardware is created, with or without the Tripcount directive).

The following code example shows how assertions can inform High-Level Synthesis about the maximum range of variables, and how those assertions are used to produce more optimal hardware.

Before using assertions, the header file that defines the assert macro must be included. In this example, this is included in the header file.

```
#ifndef _loop_sequential_assert_H_
#define _loop_sequential_assert_H_

#include <stdio.h>
#include <assert.h>
#include ap_cint.h
#define N 32

typedef int8 din_t;
typedef int13 dout_t;
typedef uint8 dsel_t;

void loop_sequential_assert(din_t A[N], din_t B[N], dout_t X[N], dout_t Y[N], dsel_t
xlimit, dsel_t ylimit);

#endif
```

Example 3-53: Variable Loop Bounds Rewritten

In the main code two assert statements are placed before each of the loops.

```
assert(xlimit<32);
...
assert(ylimit<16);
...
```

These assertions:

- Guarantee that if the assertion is false and the value is greater than that stated, the C simulation will fail. This also highlights why it is important to simulate the C code before synthesis: confirm the design is valid before synthesis.
- Inform High-Level Synthesis that the range of this variable will not exceed this value and this fact can optimize the variables size in the RTL and in this case, the loop iteration count.

The following code example shows these assertions.

```
#include loop_sequential_assert.h

void loop_sequential_assert(din_t A[N], din_t B[N], dout_t X[N], dout_t Y[N], dsel_t
xlimit, dsel_t ylimit) {

    dout_t X_accum=0;
    dout_t Y_accum=0;
    int i,j;

    assert(xlimit<32);
    SUM_X:for (i=0;i<=xlimit; i++) {
        X_accum += A[i];
        X[i] = X_accum;
    }

    assert(ylimit<16);
    SUM_Y:for (i=0;i<=ylimit; i++) {
        Y_accum += B[i];
        Y[i] = Y_accum;
    }
}
```

Example 3-54: Variable Loop Bounds Rewritten

Except for the assert macros, this code is the same as that shown in [Example 3-15](#). There are two important differences in the synthesis report after synthesis.

Without the assert macros, the report is as follows, showing that the loop tripcount can vary from 1 to 256 because the variables for the loop-bounds are of data type `d_sel` that is an 8-bit variable.

* Loop Latency:			
Target	II	Trip Count	Pipelined
- SUM_X	1 ~ 256	no	
- SUM_Y	1 ~ 256	no	

In the version with the assert macros, the report shows the loops SUM_X and SUM_Y reported Tripcount of 32 and 16. Because the assertions assert that the values will never be greater than 32 and 16, High-Level Synthesis can use this in the reporting.

* Loop Latency:

Target II	Trip Count	Pipelined
- SUM_X	1 ~ 32	no
- SUM_Y	1 ~ 16	no

In addition, and unlike using the Tripcount directive, the assert statements can provide more optimal hardware. In the case without assertions, the final hardware uses variables and counters that are sized for a maximum of 256 loop iterations.

* Expression:

Operation	Variable Name	DSP48E	FF	LUT
+	X_accum_1_fu_182_p2	0	0	13
+	Y_accum_1_fu_209_p2	0	0	13
+	indvar_next6_fu_158_p2	0	0	9
+	indvar_next_fu_194_p2	0	0	9
+	tmp1_fu_172_p2	0	0	9
+	tmp_fu_147_p2	0	0	9
icmp	exitcond1_fu_189_p2	0	0	9
icmp	exitcond_fu_153_p2	0	0	9
Total		0	0	80

The code which asserts the variable ranges are smaller than the maximum possible range results in a smaller RTL design.

* Expression:

Operation	Variable Name	DSP48E	FF	LUT
+	X_accum_1_fu_176_p2	0	0	13
+	Y_accum_1_fu_207_p2	0	0	13
+	i_2_fu_158_p2	0	0	6
+	i_3_fu_192_p2	0	0	5
icmp	tmp_2_fu_153_p2	0	0	7
icmp	tmp_9_fu_187_p2	0	0	6
Total		0	0	50

Assertions can indicate the range of any variable in the design. It is important to execute a C simulation that covers all possible cases when using assertions. This will confirm that the assertions that High-Level Synthesis uses are valid.

SystemC Synthesis

Vivado HLS supports SystemC (IEEE standard 1666), a C++ class library used to model hardware. The library is available at the Accellera website [Ref 7].

Vivado HLS supports:

- SystemC version 2.1
- SystemC Synthesizable Subset (Draft 1.3)

This section provides information on the synthesis of SystemC functions with Vivado HLS. This information is in addition to the information in the earlier chapters, C for Synthesis and C++ for Synthesis. Xilinx recommends that you read those chapters to fully understand the basic rules of coding for synthesis.



IMPORTANT: As with C and C++ designs, the top-level function for synthesis must be a function below the top-level for C compilation `sc_main()`. The `sc_main()` function cannot be the top-level function for synthesis.

Design Modeling

The top-level for synthesis must be an SC_MODULE. Designs can be synthesized if modeled using the SystemC constructor processes SC_METHOD, SC_CTHREAD and the SC_HAS_PROCESS macro or if SC_MODULES are instantiated inside other SC_MODULES.

The top-level SC_MODULE in the design cannot be a template. Templates can be used only on submodules.

The module constructor can only define or instantiate modules. It cannot contain any functionality.

An SC_MODULE cannot be defined inside another SC_MODULE. (Although they can be instantiated, as discussed later).

Using SC_MODULE

Hierarchical modules definitions are not supported. When a module is defined inside another module (SC_MODULE Example One), it must be converted into a version in which the modules are not nested (SC_MODULE Example Two).

```

SC_MODULE(nested1)
{
    SC_MODULE(nested2)
    {
        sc_in<int> in0;
        sc_out<int> out0;
        SC_CTOR(nested2)
        {
            SC_METHOD(process);
            sensitive<<in0;
        }
        void process()
        {
            int var =10;
            out0.write(in0.read()+var);
        }
    };
}

sc_in<int> in0;
sc_out<int> out0;
nested2 nd;
SC_CTOR(nested1)
:nd(nested2)
{
    nd.in0(in0);
    nd.out0(out0);
}
;
```

Example 3-55: SC_MODULE Example One

```

SC_MODULE(nested2)
{
    sc_in<int> in0;
    sc_out<int> out0;
    SC_CTOR(nested2)
    {
        SC_METHOD(process);
        sensitive<<in0;
    }
    void process()
    {
        int var =10;
        out0.write(in0.read()+var);
    }
};

SC_MODULE(nested1)
{
    sc_in<int> in0;
    sc_out<int> out0;
    nested2 nd;
    SC_CTOR(nested1)
    :nd(nested2)
    {
        nd.in0(in0);
        nd.out0(out0);
    }
};

```

Example 3-56: SC_MODULE Example Two

In addition, an SC_MODULE cannot be derived from another SC_MODULE as in the following example:

```

SC_MODULE(BASE)
{
    sc_in<bool> clock; //clock input
    sc_in<bool> reset;
    SC_CTOR(BASE) {}

};

class DUT: public BASE
{
public:
    sc_in<bool> start;
    sc_in<sc_uint<8> > din;
    ...
};

```

Example 3-57: SC_MODULE Example Three



RECOMMENDED: Define the module constructor inside the module.

Cases such as the following (SC_MODULE Example Four) should be transformed as shown in SC_MODULE Example Five.

```
SC_MODULE(dut) {
    sc_in<int> in0;
    sc_out<int>out0;
    SC_HAS_PROCESS(dut);
    dut(sc_module_name nm);
    ...
};

dut::dut(sc_module_name nm)
{
    SC_METHOD(process);
    sensitive<<in0;
}
```

Example 3-58: SC_MODULE Example Four

```
SC_MODULE(dut) {
    sc_in<int> in0;
    sc_out<int>out0;

    SC_HAS_PROCESS(dut);
    dut(sc_module_name nm)
        :sc_module(nm)
    {
        SC_METHOD(process);
        sensitive<<in0;
    }
    ...
};
```

Example 3-59: SC_MODULE Example Five

Vivado HLS does not support SC_THREADS for synthesis.

Using SC_METHOD

The following code example shows the header file (`sc_combo_method.h`) for a small combinational design modeled using an `SC_METHOD` to model a half-adder. The top-level design name (`c_combo_method`) is specified in the `SC_MODULE`.

```
#include <systemc.h>

SC_MODULE(sc_combo_method) {
    //Ports
    sc_in<sc_uint<1>> a,b;
    sc_out<sc_uint<1>> sum,carry;

    //Process Declaration
    void half_adder();

    //Constructor
    SC_CTOR(sc_combo_method) {

        //Process Registration
        SC_METHOD(half_adder);
        sensitive<<a<<b;
    }
}
```

Example 3-60: SystemC Combinational Example Header

The design has two single-bit input ports (`a` and `b`). The `SC_METHOD` is sensitive to any changes in the state of either input port and executes function `half_adder`. The function `half_adder` is specified in the file `sc_combo_method.cpp` shown in the following code example. It calculates the value for output port `carry`.

```
#include sc_combo_method.h

void sc_combo_method::half_adder(){
    bool s,c;
    s=a.read() ^ b.read();
    c=a.read() & b.read();
    sum.write(s);
    carry.write(c);

#ifndef __SYNTHESIS__
    cout << Sum is << a << ^ << b << = << s << : <<
    sc_time_stamp() << endl;
    cout << Car is << a << & << b << = << c << : <<
    sc_time_stamp() << endl;
#endif
```

Example 3-61: SystemC Combinational Example Main Function

[Example 3-61](#) shows how any `cout` statements used to display values during C simulation can be protected from synthesis using the `__SYNTHESIS__` macro.

The following code example shows the test bench for [Example 3-61](#). This test bench displays several important attributes required when using Vivado HLS.

```
#ifdef __RTL_SIMULATION__
#include sc_combo_method_rtl_wrapper.h
#define sc_combo_method sc_combo_method_RTL_wrapper
#else
#include sc_combo_method.h
#endif
#include tb_init.h
#include tb_driver.h

int sc_main (int argc , char *argv[])
{
    sc_report_handler::set_actions(/IEEE_Std_1666/deprecated, SC_DO_NOTHING);
    sc_report_handler::set_actions( SC_ID_LOGIC_X_TO_BOOL_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_VECTOR_CONTAINS_LOGIC_VALUE_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_OBJECT_EXISTS_, SC_LOG);

    sc_signal<bool>      s_reset;
    sc_signal<sc_uint<1> >      s_a;
    sc_signal<sc_uint<1> >      s_b;
    sc_signal<sc_uint<1> >      s_sum;
    sc_signal<sc_uint<1> >      s_carry;

    // Create a 10ns period clock signal
    sc_clock s_clk(s_clk,10,SC_NS);

    tb_init      U_tb_init(U_tb_init);
    sc_combo_method   U_dut(U_dut);
    tb_driver     U_tb_driver(U_tb_driver);

    // Generate a clock and reset to drive the sim
    U_tb_init.clk(s_clk);
    U_tb_init.reset(s_reset);

    // Connect the DUT
    U_dut.a(s_a);
    U_dut.b(s_b);
    U_dut.sum(s_sum);
    U_dut.carry(s_carry);

    // Drive stimuli from dat* ports
    // Capture results at out* ports
    U_tb_driver.clk(s_clk);
    U_tb_driver.reset(s_reset);
    U_tb_driver.dat_a(s_a);
    U_tb_driver.dat_b(s_b);
    U_tb_driver.out_sum(s_sum);
    U_tb_driver.out_carry(s_carry);

    // Sim for 200
    int end_time = 200;

    cout << INFO: Simulating  << endl;

    // start simulation
    sc_start(end_time, SC_NS);
```

```

if (U_tb_driver.retval != 0) {
    printf(Test failed !!!\n);
} else {
    printf(Test passed !\n);
}
return U_tb_driver.retval;
;

```

Example 3-62: SystemC Combinational Example Test Bench

To perform RTL simulation using the `cosim_design` feature in Vivado HLS, the test bench must contain the macros shown at the top of [Example 3-62](#). For a design named `DUT`, the following must be used, where `DUT` is replaced with the actual design name.

```

#ifndef __RTL_SIMULATION__
#include DUT_rtl_wrapper.h
#define DUT DUT_RTL_wrapper
#else
#include DUT.h //Original unmodified code
#endif

```

You must add this to the test bench in which the design header file is included. Otherwise, `cosim_design` RTL simulation fails.



RECOMMENDED: Add the report handler functions shown in [Example 3-62](#) to all SystemC test bench files used with Vivado HLS.

```

sc_report_handler::set_actions(/IEEE_Std_1666/deprecated, SC_DO_NOTHING);
sc_report_handler::set_actions( SC_ID_LOGIC_X_TO_BOOL_, SC_LOG);
sc_report_handler::set_actions( SC_ID_VECTOR_CONTAINS_LOGIC_VALUE_, SC_LOG);
sc_report_handler::set_actions( SC_ID_OBJECT_EXISTS_, SC_LOG);

```

These settings prevent the printing of extraneous messages during RTL simulation.

The most important of these messages are the warnings:

```
Warning: (W212) sc_logic value 'X' cannot be converted to bool
```

The adapters placed around the synthesized design start with unknown (X) values. Not all SystemC types support unknown (X) values. This warning is issued when unknown (X) values are applied to types that do not support unknown (X) values, typically before the stimuli is applied from the test bench and can generally be ignored.

Finally, the test bench in [Example 3-62](#) performs checking on the results.

Returns a value of zero if the results are correct. In this case, the results are verified inside function `tb_driver` but the return value is checked and returned in the top-level test bench.

```
if (U_tb_driver.retval != 0) {
    printf(Test failed !!!\n);
} else {
    printf(Test passed !\n);
}
return U_tb_driver.retval;
```

Instantiating SC_MODULES

Hierarchical instantiations of `SC_MODULES`s can be synthesized, as shown in the following code example. In this code example, the two instances of the half-adder design (`sc_combo_method`) from [Example 3-60](#) are instantiated to create a full-adder design.

```

#include <systemc.h>
#include sc_combo_method.h

SC_MODULE(sc_hier_inst) {
    //Ports
    sc_in<sc_uint<1>> a, b, carry_in;
    sc_out<sc_uint<1>> sum, carry_out;

    //Variables
    sc_signal<sc_uint<1>> carry1, sum_int, carry2;

    //Process Declaration
    void full_adder();

    //Half-Adder Instances
    sc_combo_methodU_1, U_2;

    //Constructor
    SC_CTOR(sc_hier_inst)
    :U_1(U_1)
    ,U_2(U_2)
    {
        // Half-adder inst 1
        U_1.a(a);
        U_1.b(b);
        U_1.sum(sum_int);
        U_1.carry(carry1);

        // Half-adder inst 2
        U_2.a(sum_int);
        U_2.b(carry_in);
        U_2.sum(sum);
        U_2.carry(carry2);

        //Process Registration
        SC_METHOD(full_adder);
        sensitive<<carry1<<carry2;
    }
}
;
```

Example 3-63: SystemC Hierarchical Example

The function `full_adder` is used to create the logic for the `carry_out` signal, as shown in the following code example.

```

#include sc_hier_inst.h

void sc_hier_inst::full_adder(){
    carry_out= carry1.read() | carry2.read();
}
```

Example 3-64: SystemC full_adder Function

Using SC_CTHREAD

The constructor process SC_CTHREAD is used to model clocked processes (threads) and is the primary way to model sequential designs. The following code example shows a case that highlights the primary attributes of a sequential design.

- The data has associated handshake signals, allowing it to operate with the same test bench before and after synthesis.
- An SC_CTHREAD sensitive on the clock is used to model when the function is executed.
- The SC_CTHREAD supports reset behavior.

```
#include <systemc.h>

SC_MODULE(sc_sequ_cthread) {
    //Ports
    sc_in <bool> clk;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_in<sc_uint<16> > a;
    sc_in<bool> en;
    sc_out<sc_uint<16> > sum;
    sc_out<bool> vld;

    //Variables
    sc_uint<16> acc;

    //Process Declaration
    void accum();

    //Constructor
    SC_CTOR(sc_sequ_cthread) {

        //Process Registration
        SC_CTHREAD(accum,clk.pos());
        reset_signal_is(reset,true);
    }
};
```

Example 3-65: SystemC SC_CTHREAD Example

Function `accum` is shown in the following code example. This example demonstrates:

- The core modeling process is an infinite `while()` loop with a `wait()` statement inside it.
- Any initialization of the variables is performed before the infinite `while()` loop. This code is executed when `reset` is recognized by the `SC_CTHREAD`.
- The data reads and writes are qualified by handshake protocols.

```
#include sc_sequ_cthread.h

void sc_sequ_cthread::accum() {

    //Initialization
    acc=0;
    sum.write(0);
    vld.write(false);
    wait();

    // Process the data
    while(true) {
        // Wait for start
        while (!start.read()) wait();

        // Read if valid input available
        if (en) {
            acc = acc + a.read();
            sum.write(acc);
            vld.write(true);
        } else {
            vld.write(false);
        }
        wait();
    }
}
```

Example 3-66: SystemC SC_CTHREAD Function

Synthesis of Loops

When coding with loops, you must account for the Vivado HLS SystemC scheduling rule in which Vivado HLS always synthesizes a loop by starting in a new state. For example, given the following design:

Note: Only a minimum amount of code is shown for this example.

```
sc_in<bool> start;
sc_in<bool> enable;

process code:
    unsigned count = 0;
    while (!start.read()) wait();
    for(int i=0;i<100; i++)
    {
        if(enable.read()) count++;
        wait();
    }
```

And the following test bench stimuli:

```
start = true;
enable=true;
wait(1);
start = false;
wait(99);
enable=false;
```

This design executes during C simulation and samples the enable signal. Then, count reaches 100. After synthesis, the SystemC loop scheduling rule requires the loop to start with a new state and any operations in the loop to be scheduled after this point. For example, the following code shows a wait statement called First Loop Clock:

```
sc_in<bool> start;
sc_in<bool> enable;

process code:
    unsigned count = 0;
    while (!start.read()) wait();
    for(int i=0;i<100; i++)
    {
        wait(); //First Loop Clock
        if(enable.read()) count++;
        wait();
    }
```

After the initial clock samples the start signal, there is a 2 clock cycle delay before the new clock samples the enable signal for the first time. This new clock occurs at the same time as the second clock in the test bench, which is the first clock in the series of 99 clocks. On the third test bench clock, which is the second clock in the series of 99 clocks, the clock samples the enable signal for the first time. In this case, the RTL design only counts to 99 before enable is set to false.



RECOMMENDED: When coding loops in SystemC, it is highly recommended that you place the `wait()` statement as the first item in a loop.

In the following example, the `wait()` statement is the first clock or state in the synthesized loop:

```
sc_in<bool> start;
sc_in<bool> enable;

process code:
    unsigned count = 0;
    while (!start.read()) wait();
    for(int i=0;i<100; i++)
    {
        wait(); // Put the 'wait()' at the beginning of the loop
        if(enable.read()) count++;
    }
```

Synthesis with Multiple Clocks

Unlike C and C++ synthesis, SystemC supports designs with multiple clocks. In a multiple clock design, the functionality associated with each clock must be captured in an SC_CTHREAD.

The following code example shows a design with two clocks (`clock` and `clock2`).

- One clock is used to activate an SC_CTHREAD executing function `Prc1`.
- The other clock is used to activate an SC_CTHREAD executing function `Prc2`.

After synthesis, all the sequential logic associated with function `Prc1` is clocked by `clock`, while `clock2` drives all the sequential logic of function `Prc2`.

```
#includesystemc.h
#includetlm.h
using namespace tlm;

SC_MODULE(sc_multi_clock)
{
    //Ports
    sc_in <bool> clock;
    sc_in <bool> clock2;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_out<bool> done;
    sc_fifo_out<int> dout;
    sc_fifo_in<int> din;

    //Variables
    int share_mem[100];
    bool write_done;

    //Process Declaration
    void Prc1();
    void Prc2();

    //Constructor
    SC_CTOR(sc_multi_clock)
    {
        //Process Registration
        SC_CTHREAD(Prc1,clock.pos());
        reset_signal_is(reset,true);

        SC_CTHREAD(Prc2,clock2.pos());
        reset_signal_is(reset,true);
    }
};
```

Example 3-67: SystemC Multiple Clock Design

Communication Channels

Communication between threads, methods, and modules (which themselves contain threads and methods) should only be performed using channels. Do not use simple variables for communication between threads.

Xilinx recommends using `sc_buffer` or `sc_signal` to communicate between different processes (thread, method). `sc_fifo` and `tlm_fifo` can be used when multiple values may be written before the first is read.

For `sc_fifo` and `tlm_fifo`, the following methods are supported for synthesis:

- Non-blocking read/write
- Blocking read/write
- `num_available()/num_free()`
- `nb_can_put()/nb_can_get()`

Top-Level SystemC Ports

The ports in a SystemC design are specified in the source code. Unlike C and C++ functions, in SystemC Vivado HLS performs interface synthesis only on supported memory interfaces. See [Arrays on the Interface](#).

All ports on the top-level interface must be one of the following types:

- `sc_in_clk`
- `sc_in`
- `sc_out`
- `sc_inout`
- `sc_fifo_in`
- `sc_fifo_out`
- `ap_mem_if`

Except for the supported memory interfaces, all handshaking between the design and the test bench must be explicitly modeled in the SystemC function. The supported memory interfaces are:

- `sc_fifo_in`
- `sc_fifo_out`
- `ap_mem_if`

Vivado HLS might add additional clock cycles to a SystemC design if required to meet timing. Because the number of clock cycles after synthesis might be different, SystemC designs should handshake all data transfers with the test bench.

Vivado HLS does not support transaction level modeling using TLM 2.0 and event-based modeling for synthesis.

SystemC Interface Synthesis

In general, Vivado HLS does not perform interface synthesis on SystemC. It does support interface synthesis for some memory interfaces, such as RAM and FIFO ports.

RAM Port Synthesis

Unlike the synthesis of C and C++, Vivado HLS does not transform array ports into RTL RAM ports. In the following SystemC code, you must use Vivado HLS directives to partition the array ports into individual elements.

Otherwise, this example code cannot be synthesized:

```
SC_MODULE(dut)
{
    sc_in<T> in0[N];
    sc_out<T>out0[N];

    ...
    SC_CTOR(dut)
    {
        ...
    }
};
```

Example 3-68: RAM Port Synthesis Coding Example

The directives to partition these arrays into individual elements are:

```
set_directive_array_partition dut in0 -type complete
set_directive_array_partition dut out0 -type complete
```

If *N* is a large number, this results in many individual scalar ports on the RTL interface.

The following code example shows how a RAM interface can be modeled in SystemC simulation and fully synthesized by Vivado HLS. In this code example, the arrays are replaced by `ap_mem_if` types that can be synthesized into RAM ports.

- To use `ap_mem_port` types, the header file `ap_mem_if.h` from the `include/ap_ssysc` directory in the Vivado HLS installation area must be included.
 - Inside the Vivado HLS environment, the directory `include/ap_ssysc` is included.
- The arrays for `din` and `dout` are replaced by `ap_mem_port` types. The fields are explained below the code example.

```

#include<systemc.h>
#include ap_mem_if.h

SC_MODULE(sc_RAM_port)
{
    //Ports
    sc_in <bool> clock;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_out<bool> done;
    //sc_out<int> dout[100];
    //sc_in<int> din[100];
    ap_mem_port<int, int, 100, RAM_2P> dout;
    ap_mem_port<int, int, 100, RAM_2P> din;

    //Variables
    int share_mem[100];
    sc_signal<bool> write_done;

    //Process Declaration
    void Prc1();
    void Prc2();

    //Constructor
    SC_CTOR(sc_RAM_port)
    : dout (dout),
    din (din)
    {
        //Process Registration
        SC_CTHREAD(Prc1,clock.pos());
        reset_signal_is(reset,true);

        SC_CTHREAD(Prc2,clock.pos());
        reset_signal_is(reset,true);
    }
};

```

Example 3-69: SystemC RAM Interface

The format of the `ap_mem_port` type is:

`ap_mem_port (<data_type>, < address_type>, <number_of_elements>, <Mem_Target>)`

- The `data_type` is the type used for the stored data elements. In [Example 3-69](#), these are standard `int` types.
- The `address_type` is the type used for the address bus. This type should have enough data bits to address all elements in the array, or C simulation fails.
- The `number_of_elements` specifies the number of elements in the array being modeled.
- The `Mem_Target` specifies the memory to which this port will connect and therefore determines the I/O ports on the final RTL. For a list of the available targets, see the following table.

The memory targets described in the following table influence both the ports created by synthesis and how the operations are scheduled in the design. For example, a dual-port RAM:

- Results in twice as many I/O ports as a single-port RAM.
- May allow internal operations to be scheduled in parallel (provided that code constructs, such as loops and data dependencies, allow it).

Table 3-4: System Cap_mem_port Memory Targets

Target RAM	Description
RAM_1P	A single-port RAM
RAM_2P	A dual-port RAM
RAM_T2P	A true dual-port RAM, with support for both read and write on both the input and output side
ROM_1P	A single-port ROM
ROM_2P	A dual-port ROM

After the ap_mem_port has been defined on the interface, the variables are accessed in the code in the same manner as any other arrays:

```
dout[i] = share_mem[i] + din[i];
```

The test bench to support [Example 3-69](#) is shown in the following code example. The ap_mem_port type must be supported by an ap_mem_chn type in the test bench. The ap_mem_chn type is defined in the header file ap_mem_if.h and supports the same fields as ap_mem_port.

```
#ifdef __RTL_SIMULATION__
#include sc_RAM_port_rtl_wrapper.h
#define sc_RAM_port sc_RAM_port_RTL_wrapper
#else
#include sc_RAM_port.h
#endif
#include tb_init.h
#include tb_driver.h
#include ap_mem_if.h

int sc_main (int argc , char *argv[])
{
    sc_report_handler::set_actions(/IEEE_Std_1666/deprecated, SC_DO_NOTHING);
    sc_report_handler::set_actions( SC_ID_LOGIC_X_TO_BOOL_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_VECTOR_CONTAINS_LOGIC_VALUE_, SC_LOG);
    sc_report_handler::set_actions( SC_ID_OBJECT_EXISTS_, SC_LOG);

    sc_signal<bool>          s_reset;
    sc_signal<bool>          s_start;
    sc_signal<bool>          s_done;
    ap_mem_chn<int,int, 100, RAM_2P> dout;
    ap_mem_chn<int,int, 100, RAM_2P> din;

    // Create a 10ns period clock signal
```

```

sc_clock s_clk(s_clk, 10, SC_NS);

tb_init      U_tb_init(U_tb_init);
sc_RAM_port  U_dut(U_dut);
tb_driver    U_tb_driver(U_tb_driver);

// Generate a clock and reset to drive the sim
U_tb_init.clk(s_clk);
U_tb_init.reset(s_reset);
U_tb_init.done(s_done);
U_tb_init.start(s_start);

// Connect the DUT
U_dut.clock(s_clk);
U_dut.reset(s_reset);
U_dut.done(s_done);
U_dut.start(s_start);
U_dut.dout(dout);
U_dut.din(din);

// Drive inputs and Capture outputs
U_tb_driver.clk(s_clk);
U_tb_driver.reset(s_reset);
U_tb_driver.start(s_start);
U_tb_driver.done(s_done);
U_tb_driver.dout(dout);
U_tb_driver.din(din);

// Sim
int end_time = 1100;

cout << INFO: Simulating  << endl;

// start simulation
sc_start(end_time, SC_NS);

if (U_tb_driver.retval != 0) {
    printf(Test failed !!!\n);
} else {
    printf(Test passed !\n);
}
return U_tb_driver.retval;
};

```

Example 3-70: SystemC RAM Interface Test Bench

FIFO Port Synthesis

FIFO ports on the top-level interface can be synthesized directly from the standard SystemC `sc_fifo_in` and `sc_fifo_out` ports. For an example of using FIFO ports on the interface, see the following code example.

After synthesis, each FIFO port has a data port and associated FIFO control signals.

- Inputs have empty and read ports.
- Outputs have full and write ports.

By using FIFO ports, the handshake required to synchronize data transfers is added in the RTL test bench.

```
#includesystemc.h
#includetlm.h
using namespace tlm;

SC_MODULE(sc_FIFO_port)
{
    //Ports
    sc_in <bool> clock;
    sc_in <bool> reset;
    sc_in <bool> start;
    sc_out<bool> done;
    sc_fifo_out<int> dout;
    sc_fifo_in<int> din;

    //Variables
    int share_mem[100];
    bool write_done;

    //Process Declaration
    void Prc1();
    void Prc2();

    //Constructor
    SC_CTOR(sc_FIFO_port)
    {
        //Process Registration
        SC_CTHREAD(Prc1,clock.pos());
        reset_signal_is(reset,true);

        SC_CTHREAD(Prc2,clock.pos());
        reset_signal_is(reset,true);
    }
};
```

Example 3-71: SystemC FIFO Interface

Unsupported SystemC Constructs

Modules and Constructors

- An SC_MODULE cannot be nested inside another SC_MODULE.
- An SC_MODULE cannot be derived from another SC_MODULE.
- Vivado HLS does not support SC_THREAD.
- Vivado HLS supports the clocked version SC_CTHREAD.

Instantiating Modules

An SC_MODULE cannot be instantiated using `new`. The code (SC_MODULE(TOP) shown in [Example 3-72](#) must be transformed as shown in [Example 3-73](#).

```
{
    sc_in<T> din;
    sc_out<T> dout;

    M1 *t0;

    SC_CTOR(TOP) {
        t0 = new M1(t0);
        t0->din(din);
        t0->dout(dout);
    }
}
```

Example 3-72: Instantiating Modules Example One

```
SC_MODULE(TOP)
{
    sc_in<T> din;
    sc_out<T> dout;

    M1 t0;

    SC_CTOR(TOP)
    : t0("t0")
    {
        t0.din(din);
        t0.dout(dout);
    }
}
```

Example 3-73: Instantiating Modules Example Two

Module Constructors

Only name parameters can be used with module constructors. Passing on variable `temp` of type `int` is not allowed. See the following example.

```
SC_MODULE(dut) {
    sc_in<int> in0;
    sc_out<int> out0;
    int var;
    SC_HAS_PROCESS(dut);
    dut(sc_module_name nm, int temp)
:sc_module(nm), var(temp)
    { ... }
};
```

Example 3-74: Module Constructors Code Example

Virtual Functions

Vivado HLS does not support virtual functions. Because the following code uses a virtual function, it cannot be synthesized.

```
SC_MODULE(DUT)
{
    sc_in<int> in0;
    sc_out<int>out0;

    virtual int foo(int var1)
    {
        return var1+10;
    }

    void process()
    {
        int var=foo(in0.read());
        out0.write(var);
    }
    ...
};


```

Example 3-75: Virtual Functions Coding Example

Top-Level Interface Ports

Vivado HLS does not support reading an `sc_out` port. The following code is not supported due to the read on `out0`.

```
SC_MODULE(DUT)
{
    sc_in<T> in0;
    sc_out<T>out0;
    ...
    void process()
    {
        int var=in0.read()+out0.read();
        out0.write(var);
    }
};


```

Example 3-76: Top-Level Interface Ports Code Example

High-Level Synthesis Reference Guide

Command Reference

add_files

Description

Adds design source files to the current project.

The tool searches the current directory for any header files included in the design source. To use header files stored in other directories, use the `-cflags` option to add those directories to the search path.

Syntax

```
add_files [OPTIONS] <src_files>
```

where

- `<src_files>` lists source files with the description of the design.

Options

`-tb`

Specifies any files used as part of the design test bench.

These files are not synthesized. They are used when post-synthesis verification is executed by the `cosim_design` command.

This option does not allow design files to be included in the list of source files. Use a separate `add_files` command to add design files and test bench files.

`-cflags <string>`

A string with any desired GCC compilation options.

Pragma

There is no pragma equivalent.

Examples

Add three design files to the project.

```
add_files a.cpp  
add_files b.cpp  
add_files c.cpp
```

Add multiple files with a single command line.

```
add_files "a.cpp b.cpp c.cpp"
```

Add a SystemC file with compiler flags to enable macro USE_RANDOM and specify an additional search path, subdirectory ./lib_functions, for header files.

```
add_files top.cpp -cflags "-DUSE_RANDOM -I./lib_functions"
```

Use the -tb option to add test bench files to the project. This example adds multiple files with a single command, including:

- The test bench a_test.cpp
- All data files read by the test bench:
 - input_stimuli.dat
 - out.gold.dat.

```
add_files -tb "a_test.cpp input_stimuli.dat out.gold.dat"
```

If the test bench data files in the previous example are stored in a separate directory (for example test_data), the directory can be added to the project in place of the individual data files.

```
add_files -tb a_test.cpp  
add_files -tb test_data
```

close_project

Description

Closes the current project. The project is no longer active in the High-Level Synthesis session.

The `close_project` command:

- Prevents you from entering any project-specific or solution-specific commands.
- Is not required. Opening or creating a new project closes the current project.

Syntax

```
close_project
```

Pragma

There is no pragma equivalent.

Examples

```
close_project
```

- Closes the current project.
- Saves all results.

close_solution

Description

Closes the current solution. The current solution is no longer active in the High-Level Synthesis session.

The `close_solution` command:

- Prevents you from entering any solution-specific commands.
- Is not required. Opening or creating a new solution closes the current solution.

Syntax

```
close_solution
```

Pragma

There is no pragma equivalent.

Examples

```
close_solution
```

- Closes the current project.
- Saves all results.

config_array_partition

Description

Specifies the default behavior for array partitioning.

Syntax

```
config_array_partition [OPTIONS]
```

Options

`-auto_partition_threshold <int>`

Sets the threshold for partitioning arrays (including those without constant indexing).

Arrays with fewer elements than the specified threshold limit are partitioned into individual elements, unless interface or core specification is applied on the array. The default is 4.

`-auto_promotion_threshold <int>`

Sets the threshold for partitioning arrays with constant-indexing.

Arrays with fewer elements than the specified threshold limit, and that have constant-indexing (the indexing is not variable), are partitioned into individual elements. The default is 64.

`-exclude_extern_globals`

Excludes external global arrays from throughput driven auto-partitioning.

By default, external global arrays are partitioned when `-throughput_driven` is specified. This option has no effect unless option `-throughput_driven` is also specified.

`-include_ports`

Enables auto-partitioning of I/O arrays.

This reduces an array I/O port into multiple ports. Each port is the size of the individual array elements.

`-scalarize_all`

Partitions all arrays in the design into their individual elements.

`-throughput_driven`

Enables auto-partitioning of arrays based on the throughput.

High-Level Synthesis determines whether partitioning the array into individual elements allows it to meet any specified throughput requirements.

Pragma

There is no pragma equivalent.

Examples

Partitions all arrays in the design with less than 12 elements (but not global arrays) into individual elements.

```
config_array_partition auto_partition_threshold 12 -exclude_extern_globals
```

Instructs High-Level Synthesis to determine which arrays to partition (including arrays on the function interface) to improve throughput.

```
config_array_partition -throughput_driven -include_ports
```

Partitions all arrays in the design (including global arrays) into individual elements.

```
config_array_partition -scalarize_all
```

config_bind

Description

Sets the default options for micro-architecture binding.

Binding is the process in which operators (such as addition, multiplication, and shift) are mapped to specific RTL implementations. For example, a **mult** operation implemented as a combinational or pipelined RTL multiplier.

Syntax

```
config_bind [OPTIONS]
```

Options

-effort (low|medium|high)

The optimizing effort level controls the trade-off between run time and optimization.

- The default is `Medium` effort.
- A `Low` effort optimization improves the run time and might be useful for cases in which little optimization is possible. For example, when all `if-else` statements have mutually exclusive operators in each branch and no operator sharing can be achieved.
- A `High` effort optimization results in increased run time, but typically gives better results.

-min_op <string>

Minimizes the number of instances of a particular operator. If there are multiple such operators in the code, they are shared onto the fewest number of RTL resources (cores).

The following operators can be specified as arguments:

- add - Addition
- sub - Subtraction
- mul - Multiplication
- icmp - Integer Compare
- sdiv - Signed Division
- udiv - Unsigned Division
- srem - Signed Remainder
- urem - Unsigned Remainder
- lshr - Logical Shift-Right
- ash - Arithmetic Shift-Right
- shl - Shift-Left

Pragma

There is no pragma equivalent.

Examples

Instructs High-Level Synthesis to:

- Spend more effort in the binding process.
- Try more options for implementing the operators.
- Try to produce a design with better resource usage.

```
config_bind -effort high
```

Minimizes the number of multiplication operators, resulting in RTL with the fewest number of multipliers.

```
config_bind -min_op mul
```

config_compile

Description

Configures the default behavior of front-end compiling.

Syntax

```
config_compile [OPTIONS]
```

Options

`-name_max_length <threshold>`

Specifies the maximum length of the function names. If the length of the name is higher than the threshold, the last part of the name is truncated. The default is 30.

`-no_signed_zeros`

Ignores the signedness of floating-point zero so that the compiler can perform aggressive optimizations on floating-point operations. The default is off.

`-pipeline_loops <threshold>`

Specifies the lower threshold used when pipelining loops automatically. The default is no automatic loop pipelining.

If the option is applied, the innermost loop with a tripcount higher than the threshold is pipelined, or if the tripcount of the innermost loop is less than or equal to the threshold, its parent loop is pipelined. If the innermost loop has no parent loop, the innermost loop is pipelined regardless of its tripcount.

The higher the threshold, the more likely it is that the parent loop is pipelined and the runtime is increased.

`-unsafe_math_optimizations`

Ignores the signedness of floating-point zero and enables associative floating-point operations so that compiler can perform aggressive optimizations on floating-point operations. The default is off.

Pragma

There is no pragma equivalent.

Examples

Pipeline the innermost loop with a tripcount higher than 30, or pipeline the parent loop of the innermost loop when its tripcount is less than or equal 30.

```
config_compile -pipeline_loops 30
```

Ignore the signedness of floating-point zero.

```
config_compile -no_signed_zeros
```

Ignore the signedness of floating-point zero and enable the associative floating-point operations.

```
config_compile -unsafe_math_optimizations
```

config_dataflow

Description

- Specifies the default behavior of dataflow pipelining (implemented by the `set_directive_dataflow` command).
- Allows you to specify the default channel memory type and depth.

Syntax

```
config_dataflow [OPTIONS]
```

Options

`-default_channel (fifo|pingpong)`

By default, a RAM memory, configured in pingpong fashion, is used to buffer the data between functions or loops when dataflow pipelining is used. When streaming data is used (that is, the data is always read and written in consecutive order), a FIFO memory is more efficient and can be selected as the default memory type.



TIP: Set arrays to streaming using the `set_directive_stream` command to perform FIFO accesses.

`-fifo_depth <integer>`

Specifies the default depth of the FIFOs.

This option has no effect when pingpong memories are used. If not specified, the FIFOs used in the channel are set to the size of the largest producer or consumer (whichever is largest). In some cases, this might be too conservative and introduce FIFOs that are larger than necessary. Use this option when you *know* that the FIFOs are larger than required.



CAUTION! Be careful when using this option. Incorrect use might result in a design that fails to operate correctly.

Pragma

There is no pragma equivalent.

Examples

Changes the default channel from pingpong memories to a FIFO.

```
config_dataflow -default_channel
```

Changes the default channel from pingpong memories to a FIFO with a depth of 6.

```
config_dataflow -default_channel fifo -fifo_depth 6
```



CAUTION! If the design implementation requires a FIFO with greater than six elements, this setting results in a design that fails RTL verification. This option is a user override. Use care when using it.

config_interface

Description

Specifies the default interface option used to implement the RTL port of each function during interface synthesis.

Syntax

```
config_interface [OPTIONS]
```

Options

-clock_enable

Adds a clock-enable port (`ap_ce`) to the design.

The clock enable prevents all clock operations when it is active-Low. It disables all sequential operations

-expose_global

Exposes global variables as I/O ports.

If a variable is created as a global, but all read and write accesses are local to the design, the resource is created in the design. There is no need for an I/O port in the RTL.



RECOMMENDED: If you expect the global variable to be an external source or destination outside the RTL block, create ports using this option.

-trim_dangling_port

Overrides the default behavior for interfaces based on a struct.

By default, all members of an unpacked struct at the block interface become RTL ports regardless of whether they are used or not by the design block. Setting this switch to *on* removes all interface ports that are not used in some way by the block generated.

Pragma

There is no pragma equivalent.

Examples

- Exposes global variables as I/O ports.
- Adds a clock enable port.

```
config_interface -expose_global -clock_enable
```

config_rtl

Description

Configures various attributes of the output RTL, the type of reset used, and the encoding of the state machines. It also allows you to use specific identification in the RTL.

By default, these options are applied to the top-level design and all RTL blocks within the design. You can optionally specify a specific RTL model.

Syntax

```
config_rtl [OPTIONS] <model_name>
```

Options

-header <string>

Places the contents of file *<string>* at the top (as comments) of all output RTL and simulation files.



TIP: Use this option to ensure that the output RTL files contain user specified identification.

-prefix <string>

Specifies a prefix to be added to all RTL entity/module names.

`-reset (none|control|state|all)`

Variables initialized in the C code are always initialized to the same value in the RTL and therefore in the bitstream. This initialization is performed only at power-on. It is not repeated when a reset is applied to the design.

The setting applied with the `-reset` option determines how registers and memories are reset.

- `none`

No reset is added to the design.

- `control` (default)

Resets control registers, such as those used in state machines and those used to generate I/O protocol signals.

- `state`

Resets control registers and registers or memories derived from static or global variables in the C code. Any static or global variable initialized in the C code is reset to its initialized value.

- `all`

Resets all registers and memories in the design. Any static or global variable initialized in the C code is reset to its initialized value.

`-reset_async`

Causes all registers to use a asynchronous reset.

If this option is not specified, a synchronous reset is used.

`-reset_level (low|high)`

Allows the polarity of the reset signal to be either active-Low or active-High.

The default is High.

`-encoding (auto|binary|onehot|gray)`

Specifies the encoding style used by the state machine of the design.

The default is auto.

With auto encoding, Vivado® HLS determines the style of encoding. However, the Xilinx® logic synthesis tools (the Vivado tools and the ISE® tools) can extract and re-implement the

FSM style during logic synthesis. If any other encoding style is selected (binary or onehot), the encoding style cannot be re-optimized by the Xilinx logic synthesis tools.

Pragma

There is no pragma equivalent.

Examples

Configures the output RTL to have all registers reset with an asynchronous active Low reset.

```
config_rtl -reset all -reset_async -reset_level low
```

Adds the contents of my_message.txt as a comment to all RTL output files.

```
config_rtl -header my_message.txt
```

config_schedule

Description

Configures the default type of scheduling performed by High-Level Synthesis.

Syntax

```
config_schedule [OPTIONS]
```

Options

-effort (high|medium|low)

Specifies the effort used during scheduling operations.

- The default is Medium effort.
- A Low effort optimization improves the run time and might be useful when there are few choices for the design implementation.
- A High effort optimization results in increased run time, but typically provides better results.

-verbose

Prints out the critical path when scheduling fails to satisfy any directives or constraints.

Pragma

There is no pragma equivalent.

Examples

Changes the default schedule effort to **Low** to reduce run time.

```
config_schedule -effort low
```

cosim_design

Description

Executes post-synthesis co-simulation of the synthesized RTL with the original C-based test bench.

To specify the files for the test bench run the following command:

```
add_files -tb
```

The simulation is run in subdirectory `sim/<HDL>` of the active solution,

where

- `<HDL>` is specified by the `-rtl` option.

For a design to be verified with `cosim_design`:

- The design must use interface mode `ap_ctrl_hs`.
- Each output port must use one of the following interface modes:
 - `ap_vld`
 - `ap_ovld`
 - `ap_hs`
 - `ap_memory`
 - `ap_fifo`
 - `ap_bus`

The interface modes use a write valid signal to specify when an output is written.

Syntax

```
cosim_design [OPTIONS]
```

Options

`-reduce_diskspace`

This option enables disk space saving flow. It helps to reduce disk space used during simulation, but with possibly larger run time and memory usage.

-rtl (`systemc` | `vhdl` | `verilog`)

Specifies which RTL to use for C/RTL co-simulation. The default is Verilog. If you select Verilog or VHDL, you can use the `-tool` option to select the HDL simulator. The default is `xsim`. If you select SystemC RTL, Vivado HLS uses the built-in SystemC kernel to perform the simulation, and no HDL simulator is required.

-setup

Creates all simulation files created in the `sim/<HDL>` directory of the active solution. The simulation is not executed.

-tool (*`auto`* | `vcs` | `modelsim` | `riviera` | `isim` | `xsim` | `ncsim`)

Specifies the simulator to use to co-simulate the RTL with the C test bench.

No tool needs to be specified for SystemC co-simulation. High-Level Synthesis uses its included SystemC kernel.

-trace_level (*`none`* | `all` | `port` | `port_hier`)

Determines the level of trace file output that is performed.

Determines the level of waveform tracing during C/RTL co-simulation. Option 'all' results in all port and signal waveforms being saved to the trace file, option 'port' only saves waveform traces for the top-level ports, and option 'port_hier' saves waveform traces for all the ports in the design hierarchy. The trace file is saved in the "sim/<RTL>" directory of the current solution when the simulation executes. The <RTL> directory depends on the selection used with the `-rtl` option: verilog, vhdl or systemc.

The default is none.

-O

Enables optimize compilation of the C test bench and RTL wrapper.

Without optimization, `cosim_design` compiles the test bench as quickly as possible.

Enable optimization to improve the run time performance, if possible, at the expense of compilation time. Although the resulting executable might potentially run much faster, the run time improvements are design-dependent. Optimizing for run time might require large amounts of memory for large functions.

-argv `<string>`

Specifies the argument list for the behavioral test bench.

The `<string>` is passed onto the main C function.

`-coverage`

Enables the coverage feature during simulation with the VCS simulator.

`-ignore_init <integer>`

Disables comparison checking for the first `<integer>` number of clock cycles.

This is useful when it is known that the RTL will initially start with unknown ('hX) values.

`-ldflags <string>`

Specifies the options passed to the linker for co-simulation.

This option is typically used to pass include path information or library information for the C test bench.

`-mflags <string>`

Specifies the options passed to the compiler for SystemC simulation.

This option is typically used to speed up compilation.

Pragma

There is no pragma equivalent.

Examples

Performs verification using the SystemC RTL.

```
cosim_design
```

Uses the VCS simulator to verify the Verilog RTL and enable saving of the waveform trace file.

```
cosim_design -tool vcs -rtl verilog -coverage -trace_level all
```

Verifies the VHDL RTL using ModelSim. Values 5 and 1 are passed to the test bench function and used in the RTL verification.

```
cosim_design -tool modelsim -rtl vhdl -argv "5 1"
```

Creates an optimized simulation model for the SystemC RTL. Does not execute the simulation. To run the simulation, execute `run.sh` in the `sim/systemc` directory of the active solution.

```
cosim_design -O -setup
```

create_clock

Description

Creates a virtual clock for the current solution.

The command can be executed only in the context of an active solution. The clock period is a constraint that drives optimization (chaining as many operations as feasible in the given clock period).

C and C++ designs support only a single clock. For SystemC designs, you can create multiple named clocks and apply them to different SC_MODULEs using the `set_directive_clock` command.

Syntax

```
create_clock -period <number> [OPTIONS]
```

Options

`-name <string>`

Specifies the clock name.

If no name is given, a default name is used.

`-period <number>`

Specifies the clock period in ns or MHz.

- If no units are specified, ns is assumed.
- If no period is specified, a default period of 10 ns is used.

Pragma

There is no pragma equivalent.

Examples

Specifies a clock period of 50 ns.

```
create_clock -period 50
```

Uses the default period of 10 ns to specify the clock.

```
create_clock
```

For a SystemC designs, multiple named clocks can be created and applied using `set_directive_clock`.

```
create_clock -period 15 fast_clk
create_clock -period 60 slow_clk
```

Specifies clock frequency in MHz.

```
create_clock -period 100MHz
```

csim_design

Description

Compiles and runs pre-synthesis C simulation using the provided C test bench.

To specify the files for the test bench, use `add_file -tb`. The simulation working directory is `csim` inside the active solution.

Syntax

```
csim_design [OPTIONS]
```

Options

-O

Enables optimizing compilation.

By default, compilation is performed in debug mode to enable debugging.

`-argv <string>`

Specifies the argument list for the C test bench.

The `<string>` is passed on the `<main>` function in the C test bench.

`-clean`

Enables a clean build.

Without this option, `csim_design` compiles incrementally.

`-ldflags <string>`

Specifies the options passed to the linker for C simulation.

This option is typically used to pass on library information for the C test bench and design.

`-mflags <string>`

Specifies the options passed to the compiler for C simulation.

This option is typically used to speed up compilation.

`-setup`

Creates the C simulation binary in the `csim` directory of the active solution. Simulation is not executed.

Pragma

There is no pragma equivalent.

Examples

Compiles and runs C simulation.

```
csim_design
```

Compiles source design and test bench to generate the simulation binary. Does not execute the binary. To run the simulation, execute `run.sh` in the `csim/build` directory of the active solution.

```
csim_design -O -setup
```

csynth_design

Description

Synthesizes the High-Level Synthesis database for the active solution.

The command can be executed only in the context of an active solution. The elaborated design in the database is scheduled and mapped onto RTL, based on any constraints that are set.

Syntax

```
csynth_design
```

Pragma

There is no pragma equivalent.

Examples

Runs High-Level Synthesis synthesis on the top-level design.

```
csynth_design
```

delete_project

Syntax

```
delete_project <project>
```

where

- <project> is the project name.

Description

Deletes the directory associated with the project.

The `delete_project` command checks the corresponding project directory `<project>` to ensure that it is a valid High-Level Synthesis project before deleting it. If no directory `<project>` exists in the current work directory, the command has no effect.

Pragma

There is no pragma equivalent.

Examples

Deletes Project_1 by removing the directory Project_1 and all its contents.

```
delete_project Project_1
```

delete_solution

Syntax

```
delete_solution <solution>
```

where

- <solution> is the solution to be deleted.

Description

Removes a solution from an active project, and deletes the `<solution>` subdirectory from the project directory.

If the solution does not exist in the project directory, the command has no effect.

Pragma

There is no pragma equivalent.

Examples

Deletes solution Solution_1 from the active project by removing the subdirectory Solution_1 from the active project directory.

```
delete_solution Solution_1
```

export_design

Description

Exports and packages the synthesized design in RTL as an IP for downstream tools.

Supported IP formats are:

- Vivado IP catalog
- Pcore
- System Generator

The packaged design is under the `impl` directory of the active solution in one of the following subdirectories:

- pcore
- ip
- sysgen

Syntax

```
export_design [OPTIONS]
```

Options

```
-description <string>
```

Provides a description for the generated IP Catalog IP.

```
-evaluate (verilog|vhdl)
```

Obtains more accurate timing and utilization data for the specified HDL using ISE or the Vivado tools depending on the format.

- If the export format is pcore, ISE tools are used.
- If the export format is *not* pcore, Vivado tools are used.

```
-format (pcore|sysgen|sysgen_ise|ip_catalog|syn_dcp)
```

Specifies the format to package the IP.

The supported formats are:

- `pcore`
 - In EDK pcore (default for 6 series and earlier devices)
- `sysgen`
 - In a format accepted by System Generator for DSP for Vivado Design Suite (Xilinx 7 series FPGA devices only)
- `sysgen_ise`
 - In a format accepted by System Generator for DSP for ISE (all devices)
- `ip_catalog`
 - In format suitable for adding to the Vivado IP Catalog (default for Xilinx 7 series devices)
- `syn_dcp`
 - Synthesized checkpoint file for the Vivado Design Suite (for Xilinx 7 series devices only). If this option is used, RTL synthesis is automatically executed.



TIP: If the format is not provided, `ip_catalog` is used if the target device is a Xilinx 7 series device or later. Otherwise, `pcore` is used.

`-library <string>`

Specifies the library name for the generated IP catalog IP.

`-use_netlist (none | ip | top)`

Directs the tool to generate a netlist (.ngc file) in place of RTL. Valid for `pcore` only.

- `none`
 - Do not generate netlist for the design.
- `ip`
 - Generate netlist for Xilinx IP (if any).
- `top`
 - Generate netlist for the top-level design.



IMPORTANT: NGC format files are not supported in the Vivado Design Suite for UltraScale™ devices. It is recommended that you regenerate the IP using the Vivado Design Suite IP customization tools with native output products. Alternatively, you can use the NGC2EDIF command to migrate the NGC file to EDIF format for importing, as described in the ISE to Vivado Design Suite Migration Guide (UG911) [Ref 4]. However, Xilinx recommends using native Vivado IP rather than XST-generated NGC format files going forward.

`-vendor <string>`

Specifies the vendor string for the generated IP catalog IP.

`-version <string>`

Specifies the version string for the generated IP catalog or pcore IP.

Pragma

There is no pragma equivalent.

Examples

Exports RTL for System Generator.

```
export_design -format sysgen
```

Exports RTL as a pcore for EDK.

```
export_design -format pcore
```

Exports RTL in IP catalog. Evaluates the VHDL to obtain better timing and utilization data (using the Vivado tools).

```
export_design -evaluate vhdl -format ip_catalog
```

help

Description

- When used without any `<cmd>` as an argument, lists all High-Level Synthesis Tcl commands.
- When used with a High-Level Synthesis Tcl command as an argument, provides information on the specified command.

For legal High-Level Synthesis commands, auto-completion using the tab key is active when typing the command argument.

Syntax

```
help [OPTIONS] <cmd>
```

where

- <cmd> is the command to display help on.

Options

This command has no options.

Pragma

There is no pragma equivalent.

Examples

Displays help for all commands and directives.

```
help
```

Displays help for the add_files command.

```
help add_files
```

list_core

Description

Lists all the cores in the currently loaded library.

Cores are the components used to implement operations in the output RTL (such as adders, multipliers, and memories).

After elaboration, the operations in the RTL are represented as operators in the internal database. During scheduling, operators are mapped to cores from the library to implement the RTL design. Multiple operators can be mapped on the same instance of a core, sharing the same RTL resource.

The list_core command allows the available operators and cores to be listed by using the relevant option:

- **Operation**

Shows which cores in the library can implement each operation.

- **Type**

Lists the available cores by type, for example those that implement functional operations, or those that implement memory or storage operations.

If no options are specified, the command lists all cores in the library.



TIP: Use the information provided by the `list_core` command with the `set_directive_resource` command to implement specific operations onto specific cores.

Syntax

```
list_core [OPTIONS]
```

Options

`-operation (opers)`

Lists the cores in the library that can implement the specified operation. The operations are:

- `add` - Addition
- `sub` - Subtraction
- `mul` - Multiplication
- `udiv` - Unsigned Division
- `urem` - Unsigned Remainder (Modulus operator)
- `srem` - Signed Remainder (Modulus operator)
- `icmp` - Integer Compare
- `shl` - Shift-Left
- `lshr` - Logical Shift-Right
- `ashr` - Arithmetic Shift-Right
- `mux` - Multiplexor
- `load` - Memory Read
- `store` - Memory Write
- `fiforead` - FIFO Read
- `fifowrite` - FIFO Write
- `fifobread` - Non-Blocking FIFO Read
- `fifobwrite` - Non-Blocking FIFO Write

`-type (functional_unit|storage|connector|adapter|ip_block)`

Lists cores only of the specified type.

- **Function Units**

Cores that implement standard RTL operations (such as add, multiply, or compare)

- **Storage**

Cores that implement storage elements such as registers or memories.

- **Connectors**

Cores used to implement connectivity within the design, including direct connections and streaming storage elements.

- **Adapter**

Cores that implement interfaces used to connect the top-level design when IP is generated. These interfaces are implemented in the RTL wrapper used in the IP generation flow (Xilinx® EDK).

- **IP Blocks**

Any IP cores that you added.

Pragma

There is no pragma equivalent.

Examples

Lists all cores in the currently loaded libraries that can implement an add operation.

```
list_core -operation add
```

Lists all available memory (storage) cores in the library.

```
list_core -type storage
```



TIP: Use the set_directive_resource command to implement an array using one of the available memories.

list_part

Description

- If a family is specified, returns the supported device families or supported parts for that family.
- If no family is specified, returns all supported families.



TIP: To return parts of a family, specify one of the supported families that was listed when no family was specified when the command was run.

Syntax

```
list_part [OPTIONS]
```

Pragma

There is no pragma equivalent.

Examples

Returns all supported families.

```
list_part
```

Returns all supported Virtex®-6 parts.

```
list_part virtex6
```

open_project

Description

Opens an existing project or creates a new one.

There can only be one project active at any given time in a High-Level Synthesis session. A project can contain multiple solutions.

To close a project:

- Use the `close_project` command, or
- Start another project with the `open_project` command.

Use the `delete_project` command to completely delete the project directory (removing it from the disk) and any solutions associated with it.

Syntax

```
open_project [OPTIONS] <project>
```

where

- `<project>` is the project name.

Options

`-reset`

- Resets the project by removing any project data that already exists.

- Removes any previous project information on design source files, header file search paths, and the top level function. The associated solution directories and files are kept, but might now have invalid results.

Note: The `delete_project` command accomplishes the same as the `-reset` option and removes all solution data).



RECOMMENDED: Use this option when executing High-Level Synthesis with Tcl scripts. Otherwise, each new `add_files` command adds additional files to the existing data.

Pragma

There is no pragma equivalent.

Examples

Opens a new or existing project named `Project_1`.

```
open_project Project_1
```

Opens a project and removes any existing data.

```
open_project -reset Project_2
```



RECOMMENDED: Use this method with Tcl scripts to prevent adding source or library files to the existing project data.

open_solution

Description

Opens an existing solution or creates a new one in the currently active project.



CAUTION! Attempting to open or create a solution when there is no active project results in an error. There can only be one solution active at any given time in an High-Level Synthesis session.

Each solution is managed in a subdirectory of the current project directory. A new solution is created if the solution does not yet exist in the current work directory.

To close a solution:

- Run the `close_solution` command, or
- Open another solution with the `open_solution` command.

Use the `delete_solution` command to remove them from the project and delete the corresponding subdirectory.

Syntax

```
open_solution [OPTIONS] <solution>
```

where

- <solution> is the solution name.

Options

-reset

- Resets the solution data if the solution already exists. Any previous solution information on libraries, constraints, and directives is removed.
- Removes synthesis, verification, and implementation.

Pragma

There is no pragma equivalent.

Examples

Opens a new or existing solution in the active project named Solution_1.

```
open_solution Solution_1
```

Opens a solution in the active project. Removes any existing data.

```
open_solution -reset Solution_2
```

 **RECOMMENDED:** Use this method with *Tcl* scripts to prevent adding to the existing solution data.

set_clock_uncertainty

Description

Sets a margin on the clock period defined by `create_clock`.

The margin is subtracted from the clock period to create an effective clock period. If the clock uncertainty is not defined, it defaults to 12.5% of the clock period.

High-Level Synthesis optimizes the design based on the effective clock period, providing a margin for downstream tools to account for logic synthesis and routing. The command can be executed only in the context of an active solution. High-Level Synthesis still uses the specified clock period in all output files for verification and implementation.

For SystemC designs in which multiple named clocks are specified by the `create_clock` command, you can specify a different clock uncertainty on each named clock by specifying the named clock.

Syntax

```
set_clock_uncertainty <uncertainty> <clock_list>
```

where

- <uncertainty> is a value, specified in ns, representing how much of the clock period is used as a margin.
- <clock_list> a list of clocks to which the uncertainty is applied. If none is provided, it is applied to all clocks.

Pragma

There is no pragma equivalent.

Examples

Specifies an uncertainty or margin of 0.5 ns on the clock. This effectively reduces the clock period that High-Level Synthesis can use by 0.5 ns.

```
set_clock_uncertainty 0.5
```

In this SystemC example, creates two clock domains. A different clock uncertainty is specified on each domain.

```
create_clock -period 15 fast_clk
create_clock -period 60 slow_clk
set_clock_uncertainty 0.5 fast_clock
set_clock_uncertainty 1.5 slow_clock
```



TIP: SystemC designs support multiple clocks. Use the `set_directive_clock` command to apply the clock to the appropriate function.

set_directive_allocation

Description

Specifies instance restrictions for resource allocation.

This defines, and can limit, the number of RTL instances used to implement specific functions or operations. For example, if the C source has four instances of a function `foo_sub`, the `set_directive_allocation` command can ensure that there is only one instance of `foo_sub` in the final RTL. All four instances are implemented using the same RTL block.

Syntax

```
set_directive_allocation [OPTIONS] <location> <instances>
```

where

- <location> is the location string in the format function[/label]
- <instances> is a function or operator.

The function can be any function in the original C code that has not been:

- Inlined by the `set_directive_inline` command, or
- Inlined automatically by High-Level Synthesis.

The list of operators is as follows (provided there is an instance of such an operation in the C source code):

- `add` - Addition
- `sub` - Subtraction
- `mul` - Multiplication
- `icmp` - Integer Compare
- `sdiv` - Signed Division
- `udiv` - Unsigned Division
- `srem` - Signed Remainder
- `urem` - Unsigned Remainder
- `lshr` - Logical Shift-Right
- `ashr` - Arithmetic Shift-Right
- `shl` - Shift-Left

Options

`-limit <integer>`

Sets a maximum limit on the number of instances (of the type defined by the `-type` option) to be used in the RTL design.

`-type (function|operation)`

The instance type can be **function** (default) or **operation**.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS allocation \
    instances=<Instance Name List> \
    limit=<Integer Value> \
    <operation, function>
```

Examples

Given a design `foo_top` with multiple instances of function `foo`, limits the number of instances of `foo` in the RTL to 2.

```
set_directive_allocation -limit 2 -type function foo_top foo
#pragma HLS allocation instances=foo limit=2 function
```

Limits the number of multipliers used in the implementation of `My_func` to 1. This limit does not apply to any multipliers that might reside in sub-functions of `My_func`. To limit the multipliers used in the implementation of any sub-functions, specify an allocation directive on the sub-functions or inline the sub-function into function `My_func`.

```
set_directive_allocation -limit 1 -type operation My_func mul
#pragma HLS allocation instances=mul limit=1 operation
```

set_directive_array_map

Description

Maps a smaller array into a larger array.

Designers typically use the `set_directive_array_map` command (with the same -instance target) to map multiple smaller arrays into a single larger array. This larger array can then be targeted to a single larger memory (RAM or FIFO) resource.

Use the `-mode` option to determine whether the new target is a concatenation of:

- Elements (horizontal mapping), or
- Bit-widths (vertical mapping)

The arrays are concatenated in the order the `set_directive_array_map` commands are issued starting at:

- Target element zero in horizontal mapping
- Bit zero in vertical mapping.

Syntax

```
set_directive_array_map [OPTIONS] <location> <array>
```

where

- <location> is the location (in the format function[/label]) which contains the array variable.
- <variable> is the array variable to be mapped into the new target array instance.

Options

-instance <string>

Specifies the new array instance name where the current array variable is to be mapped.

-mode (horizontal** | **vertical**)**

- Horizontal mapping (the default) concatenates the arrays to form a target with more elements.
- Vertical mapping concatenates the array to form a target with longer words.

-offset <integer>



IMPORTANT: *For horizontal mapping only.*

Specifies an integer value indicating the absolute offset in the target instance for current mapping operation. For example:

- Element 0 of the array variable maps to element <int> of the new target.
- Other elements map to <int+1>, <int+2>... of the new target.

If the value is not specified, High-Level Synthesis calculates the required offset automatically to avoid any overlap. Example: concatenating the arrays starting at the next unused element in the target.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS array_map \
    variable=<variable> \
    instance=<instance> \
    <horizontal, vertical> \
    offset=<int>
```

Examples

These commands map arrays A[10] and B[15] in function `foo` into a single new array AB[25].

- Element AB[0] will be the same as A[0].
- Element AB[10] will be the same as B[0] (since no `-offset` option is used).
- The bit-width of array AB[25] will be the maximum bit-width of A[10] or B[15].

```
set_directive_array_map -instance AB -mode horizontal foo A
set_directive_array_map -instance AB -mode horizontal foo B
#pragma HLS array_map variable=A instance=AB horizontal
#pragma HLS array_map variable=B instance=AB horizontal
```

Concatenates arrays C and D into a new array CD with same number of bits as C and D combined. The number of elements in CD is the maximum of C or D

```
set_directive_array_map -instance CD -mode vertical foo C
set_directive_array_map -instance CD -mode vertical foo D
#pragma HLS array_map variable=C instance=CD vertical
#pragma HLS array_map variable=D instance=CD vertical
```

set_directive_array_partition

Description

Partitions an array into smaller arrays or individual elements.

This partitioning:

- Results in RTL with multiple small memories or multiple registers instead of one large memory.
- Effectively increases the amount of read and write ports for the storage.
- Potentially improves the throughput of the design.
- Requires more memory instances or registers.

Syntax

```
set_directive_array_partition [OPTIONS] <location> <array>
```

where

- `<location>` is the location (in the format function[/label]) which contains the array variable.
- `<array>` is the array variable to be partitioned.

Options

`-dim <integer>`

Note: Relevant for multi-dimensional arrays only.

Specifies which dimension of the array is to be partitioned.

- If a value of 0 is used, all dimensions are partitioned with the specified options.
- Any other value partitions only that dimension. For example, if a value 1 is used, only the first dimension is partitioned.

`-factor <integer>`

Note: Relevant for type `block` or `cyclic` partitioning only.

Specifies the number of smaller arrays that are to be created.

`-type (block|cyclic|complete)`

- *Block* partitioning creates smaller arrays from consecutive blocks of the original array. This effectively splits the array into N equal blocks where N is the integer defined by the `-factor` option.
- *Cyclic* partitioning creates smaller arrays by interleaving elements from the original array. For example, if `-factor 3` is used:
 - Element 0 is assigned to the first new array
 - Element 1 is assigned to the second new array.
 - Element 2 is assigned to the third new array.
 - Element 3 is assigned to the first new array again.
- *Complete* partitioning decomposes the array into individual elements. For a one-dimensional array, this corresponds to resolving a memory into individual registers. For multi-dimensional arrays, specify the partitioning of each dimension, or use `-dim 0` to partition all dimensions.

The default is **complete**.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS array_partition \
    variable=<variable> \
    <block, cyclic, complete> \
    factor=<int> \
    dim=<int>
```

Examples

Partitions array AB[13] in function `foo` into four arrays. Because four is not an integer multiple of 13:

- Three arrays have three elements.
- One array has four elements (AB[9:12]).

```
set_directive_array_partition -type block -factor 4 foo AB
#pragma HLS array_partition variable=AB block factor=4
```

Partitions array AB[6][4] in function `foo` into two arrays, each of dimension [6][2].

```
set_directive_array_partition -type block -factor 2 -dim 2 foo AB
#pragma HLS array_partition variable=AB block factor=2 dim=2
```

Partitions all dimensions of AB[4][10][6] in function `foo` into individual elements.

```
set_directive_array_partition -type complete -dim 0 foo AB
#pragma HLS array_partition variable=AB complete dim=0
```

set_directive_array_reshape

Description

Combines array partitioning with vertical array mapping to create a single new array with fewer elements but wider words.

The `set_directive_array_reshape` command:

1. Splits the array into multiple arrays (in an identical manner as `set_directive_array_partition`)
2. Automatically recombine the arrays vertically (as per `set_directive_array_map -type vertical`) to create a new array with wider words.

Syntax

```
set_directive_array_reshape [OPTIONS] <location> <array>
```

where

- `<location>` is the location (in the format function[/label]) that contains the array variable.
- `<array>` is the array variable to be reshaped.

Options

`-dim <integer>`

Note: Relevant for multi-dimensional arrays only.

Specifies which dimension of the array is to be reshaped.

- If `value = 0`, all dimensions are partitioned with the specified options.
- Any other value partitions only that dimension. For example, if `value =1`, only the first dimension is partitioned.

`-factor <integer>`

Note: Relevant for type `block` or `cyclic` reshaping only.

Specifies the number of temporary smaller arrays to be created.

`-type (block|cyclic|complete)`

- *Block* reshaping creates smaller arrays from consecutive blocks of the original array. This effectively splits the array into N equal blocks where N is the integer defined by the `-factor` option and then combines the N blocks into a single array with `word-width*N`. The default is `complete`.
- *Cyclic* reshaping creates smaller arrays by interleaving elements from the original array. For example, if `-factor 3` is used, element 0 is assigned to the first new array, element 1 to the second new array, element 2 is assigned to the third new array, and then element 3 is assigned to the first new array again. The final array is a vertical concatenation (word concatenation, to create longer words) of the new arrays into a single array.
- *Complete* reshaping decomposes the array into temporary individual elements and then recombines them into an array with a wider word. For a one-dimension array this is equivalent to creating a very-wide register (if the original array was N elements of M bits, the result is a register with $N*M$ bits).

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS array_reshape \
    variable=<variable> \
    <block, cyclic, complete> \
    factor=<int> \
    dim=<int>
```

Examples

Reshapes 8-bit array `AB[17]` in function `foo`, into a new 32-bit array with five elements.

Because four is not an integer multiple of 13:

- AB[17] is in the lower eight bits of the fifth element.
- The remainder of the fifth element is unused.

```
set_directive_array_reshape -type block -factor 4 foo AB
#pragma HLS array_reshape variable=AB block factor=4
```

Partitions array AB[6][4] in function `foo`, into a new array of dimension [6][2], in which dimension 2 is twice the width.

```
set_directive_array_reshape -type block -factor 2 -dim 2 foo AB
#pragma HLS array_reshape variable=AB block factor=2 dim=2
```

Reshapes 8-bit array AB[4][2][2] in function `foo` into a new single element array (a register), 4*2*2*8(=128)-bits wide.

```
set_directive_array_reshape -type complete -dim 0 foo AB
#pragma HLS array_reshape variable=AB complete dim=0
```

set_directive_clock

Description

Applies the named clock to the specified function.

C and C++ designs support only a single clock. The clock period specified by `create_clock` is applied to all functions in the design.

SystemC designs support multiple clocks. Multiple named clocks can be specified using the `create_clock` command and applied to individual SC_MODULEs using the `set_directive_clock` command. Each SC_MODULE is synthesized using a single clock.

Syntax

```
set_directive_clock <location> <domain>
```

where

- `<location>` is the function where the named clock is to be applied.
- `<domain>` is the clock name as specified by the `-name` option of the `create_clock` command.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS clock domain=<string>
```

Examples

Assume a SystemC design in which:

- Top-level `foo_top` has clocks ports `fast_clock` and `slow_clock`.
- It uses only `fast_clock` within its function.
- Sub-block `foo` uses only `slow_clock`.

In that case, the commands shown below:

- Create both clocks.
- Apply `fast_clock` to `foo_top`.
- Apply `slow_clock` to sub-block `foo`.

```
create_clock -period 15 fast_clk
create_clock -period 60 slow_clk
set_directive_clock foo_top fast_clock
set_directive_clock foo slow_clock
#pragma HLS clock domain=fast_clock
#pragma HLS clock domain=slow_clock
```

Note: There is no pragma equivalent of `create_clock`.

set_directive_dataflow

Description

Specifies that dataflow optimization be performed on the functions or loops, improving the concurrency of the RTL implementation.

All operations are performed sequentially in a C description. In the absence of any directives that limit resources (such as `set_directive_allocation`), High-Level Synthesis seeks to minimize latency and improve concurrency.

Data dependencies can limit this. For example, functions or loops that access arrays must finish all read/write accesses to the arrays before they complete. This prevents the next function or loop that consumes the data from starting operation.

It may be possible for the operations in a function or loop to start operation before the previous function or loop completes all its operations.

When dataflow optimization is specified, High-Level Synthesis:

- Analyzes the dataflow between sequential functions or loops.
- Seeks to create channels (based on pingpong RAMs or FIFOs) that allow consumer functions or loops to start operation before the producer functions or loops have completed.

This allows functions or loops to operate in parallel, which in turn:

- Decreases the latency
- Improves the throughput of the RTL design

If no initiation interval (number of cycles between the start of one function or loop and the next) is specified, High-Level Synthesis attempts to minimize the initiation interval and start operation as soon as data is available.

Syntax

```
set_directive_dataflow <location>
```

where

- <*location*> is the location (in the format function[/label]) at which dataflow optimization is to be performed.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS dataflow
```

Examples

Specifies dataflow optimization within function foo.

```
set_directive_dataflow foo
#pragma HLS dataflow
```

set_directive_data_pack

Description

Packs the data fields of a struct into a single scalar with a wider word width.

Any arrays declared inside the struct are completely partitioned and reshaped into a wide scalar and packed with other scalar fields.

The bit alignment of the resulting new wide-word can be inferred from the declaration order of the struct fields. The first field takes the least significant sector of the word and so forth until all fields are mapped.

Syntax

```
set_directive_data_pack [OPTIONS] <location> <variable>
```

where

- <location> is the location (in the format function[/label]) which contains the variable which will be packed.
- <variable> is the variable to be packed.

Options

```
-instance <string>
```

Specifies the name of resultant variable after packing. If none is provided, the input variable is used.

```
-byte_pad ( struct_level | field_level )
```

Specify whether to pack data on 8-bit boundary:

- struct_level: Pack the struct first, then pack it on 8-bits boundary.
- field_level: Pack each individual field on 8-bits boundary first, then pack the struct.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS data_pack variable=<variable> instance=<string>
```

Examples

Packs struct array AB[17] with three 8-bit field fields (typedef struct {unsigned char R, G, B;} pixel) in function foo, into a new 17 element array of 24 bits.

```
set_directive_data_pack foo AB
#pragma HLS data_pack variable=AB
```

Packs struct pointer AB with three 8-bit fields (typedef struct {unsigned char R, G, B;} pixel) in function foo, into a new 24-bit pointer.

```
set_directive_data_pack foo AB
#pragma HLS data_pack variable=AB
```

set_directive_dependence

Description

High-Level Synthesis detects dependencies:

- Within loops (loop-independent dependency), or
- Between different iterations of a loop (loop-carry dependency).

These dependencies impact when operations can be scheduled, especially during function and loop pipelining.

- Loop-independent dependence

The same element is accessed in the same loop iteration.

```
for (i=0;i<N;i++) {
    A[i]=x;
    y=A[i];
}
```

- Loop-carry dependence

The same element is accessed in a different loop iteration.

```
for (i=0;i<N;i++) {
    A[i]=A[i-1]*2;
}
```

Under certain circumstances such as variable dependent array indexing or when an external requirement needs enforced (for example, two inputs are never the same index) the dependence analysis might be too conservative. The `set_directive_dependence` command allows you to explicitly specify the dependence and resolve a false dependence.

Syntax

```
set_directive_dependence [OPTIONS] <location>
```

where

- `<location>` is the location (in the format function[/label]) at which the dependence is to be specified.

Options

`-class (array|pointer)`

Specifies a class of variables in which the dependence needs clarification. This is mutually exclusive with the option `-variable`.

`-dependent (true | false)`

Specifies whether a dependence needs to be enforced (`true`) or removed (`false`). The default is `false`.

`-direction (RAW | WAR | WAW)`

Note: Relevant for loop-carry dependencies only.

Specifies the direction for a dependence:

- `RAW` (Read-After-Write - true dependence)

The write instruction uses a value used by the read instruction.

- `WAR` (Write-After-Read - anti dependence)

The read instruction gets a value that is overwritten by the write instruction.

- `WAW` (Write-After-Write - output dependence)

Two write instructions write to the same location, in a certain order.

`-distance <integer>`

Note: Relevant only for loop-carry dependencies where `-dependent` is set to `true`.

Specifies the inter-iteration distance for array access.

`-type (intra | inter)`

Specifies whether the dependence is:

- Within the same loop iteration (`intra`), or
- Between different loop iterations (`inter`) (default).

`-variable <variable>`

Specifies the specific variable to consider for the dependence directive. Mutually exclusive with the option `-class`.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS dependence \
    variable=<variable> \
    <array, pointer> \
    <inter, intra> \
    <RAW, WAR, WAW> \
    distance=<int> \
    <false, true>
```

Examples

Removes the dependence between Var1 in the same iterations of loop_1 in function foo.

```
set_directive_dependence -variable Var1 -type intra \
    -dependent false foo/loop_1
#pragma HLS dependence variable=Var1 intra false
```

The dependence on all arrays in loop_2 of function foo informs High-Level Synthesis that all reads must happen *after* writes in the same loop iteration.

```
set_directive_dependence -class array -type intra \
    -dependent true -direction RAW foo/loop_2
#pragma HLS dependence array inter RAW true
```

set_directive_expression_balance

Description

Sometimes a C-based specification is written with a sequence of operations. This can result in a lengthy chain of operations in RTL. With a small clock period, this can increase the design latency.

By default, High-Level Synthesis rearranges the operations through associative and commutative properties. This rearrangement creates a balanced tree that can shorten the chain, potentially reducing latency at the cost of extra hardware.

The `set_directive_expression_balance` command allows this expression balancing to be turned off or on within with a specified scope.

Syntax

```
set_directive_expression_balance [OPTIONS] <location>
```

where

- <location> is the location (in the format function[/label]) where the balancing should be enabled or disabled.

Options

-off

Turns off expression balancing at this location.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS expression_balance <off>
```

Examples

Disables expression balancing within function My_Func.

```
set_directive_expression_balance -off My_Func
#pragma HLS expression_balance off
```

Explicitly enables expression balancing in function My_Func2.

```
set_directive_expression_balance My_Func2
#pragma HLS expression_balance
```

set_directive_function_instantiate

Description

By default:

- Functions remain as separate hierarchy blocks in the RTL.
- All instances of a function, at the same level of hierarchy, uses the same RTL implementation (block).

The `set_directive_function_instantiate` command is used to create a unique RTL implementation for each instance of a function, allowing each instance to be optimized.

By default, the following code results in a single RTL implementation of function `foo_sub` for all three instances.

```
char foo_sub(char inval, char incr)
{
    return inval + incr;
}
void foo(char inval1, char inval2, char inval3,
        char *outval1, char *outval2, char *outval3)
{
    *outval1 = foo_sub(inval1, 1);
    *outval2 = foo_sub(inval2, 2);
    *outval3 = foo_sub(inval3, 3);
}
```

Using the directive as shown in the example section below results in three versions of function `foo_sub`, each independently optimized for variable `incr`.

Syntax

```
set_directive_function_instantiate <location> <variable>
```

where

- `<location>` is the location (in the format `function[/label]`) where the instances of a function are to be made unique.
- `variable <string>` specifies which function argument `<string>` is to be specified as constant.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS function_instantiate variable=<variable>
```

Examples

For the example code shown above, the following Tcl (or pragma placed in function `foo_sub`) allows each instance of function `foo_sub` to be independently optimized with respect to input `incr`.

```
set_directive_function_instantiate foo_sub incr
#pragma HLS function_instantiate variable=incr
```

set_directive_inline

Description

Removes a function as a separate entity in the hierarchy. After inlining, the function is dissolved and no longer appears as a separate level of hierarchy.

In some cases, inlining a function allows operations within the function to be shared and optimized more effectively with surrounding operations. An inlined function cannot be shared. This can increase area.

By default, inlining is only performed on the next level of function hierarchy.

Syntax

```
set_directive_inline [OPTIONS] <location>
```

where

- <location> is the location (in the format function[/label]) where inlining is to be performed.

Options

-off

Disables function inlining to prevent particular functions from being inlined. For example, if the -recursive option is used in a caller function, this option can prevent a particular called function from being inlined when all others are.

-recursive

By default, only one level of function inlining is performed. The functions within the specified function are not inlined. The -recursive option inlines all functions recursively down the hierarchy.

-region

All functions in the specified region are to be inlined.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS inline <region | recursive | off>
```

Examples

Inlines all functions in foo_top (but not any lower level functions).

```
set_directive_inline -region foo_top
#pragma HLS inline region
```

Inlines only function foo_sub1.

```
set_directive_inline foo_sub1
#pragma HLS inline
```

Inline all functions in `foo_top`, recursively down the hierarchy, except function `foo_sub2`. The first pragma is placed in function `foo_top`. The second pragma is placed in function `foo_sub2`.

```
set_directive_inline -region -recursive foo_top
set_directive_inline -off foo_sub2
#pragma HLS inline region recursive
#pragma HLS inline off
```

set_directive_interface

Description

Specifies how RTL ports are created from the function description during interface synthesis.

The ports in the RTL implementation are derived from:

- Any function-level protocol that is specified.
- Function arguments
- Global variables (accessed by the top-level function and defined outside its scope)

Function-level handshakes:

- Control when the function starts operation.
- Indicate when function operation:
 - Ends
 - Is idle
 - Is ready for new inputs

The implementation of a function-level protocol:

- Is controlled by modes `ap_ctrl_none`, `ap_ctrl_hs` or `ap_ctrl_chain`.
- Requires only the top-level function name.

Note: Specify the function `return` for the pragma.

Each function argument can be specified to have its own I/O protocol (such as valid handshake or acknowledge handshake).

If a global variable is accessed, but all read and write operations are local to the design, the resource is created in the design. There is no need for an I/O port in the RTL. If however, the global variable is expected to be an external source or destination, specify its interface in a similar manner as standard function arguments. See the examples below.

When `set_directive_interface` is used on sub-functions, only the `-register` option can be used. The `-mode` option is not supported on sub-functions.

Syntax

```
set_directive_interface [OPTIONS] <location> <port>
```

where

- `<location>` is the location (in the format function[/label]) where the function interface or registered output is to be specified.
- `<port>` is the parameter (function argument or global variable) for which the interface has to be synthesized. This is not required when modes `ap_ctrl_none` or `ap_ctrl_hs` are used.

Options

`-mode (ap_ctrl_none|ap_ctrl_hs|ap_none|ap_stable|ap_vld|ap_ovld|ap_ack|ap_hs|ap_fifo|ap_memory|ap_bus)`

Selects the appropriate protocol.

Mode Values

The function protocol is implemented by the following `-mode` values:

- `ap_ctrl_none`
No function-level handshake protocol.
- `ap_ctrl_hs`
The default behavior. Implements a function-level handshake protocol.

Input port `ap_start` must go High for the function to begin operation. (All function-level signals are active-High).

Output port `ap_done` indicates that the function is finished (and if there is a function return value, indicates when the return value is valid) and output port `ap_idle` indicates when the function is idle.

In pipelined functions, an additional output port `ap_ready` is implemented and indicates when the function is ready for new input data.
- `ap_ctrl_chain`
This function-level protocol is intended for design where multiple blocks are chained together to process a stream of data. This mode provides all the functionality of the

`ap_ctrl_hs` mode and in addition adds a new input signal `ap_continue` to the function-level protocol.

When input port `ap_continue` is asserted it low, it indicates that the downstream blocks cannot accept new data. When this occurs the block continues to process data until and the output is ready. It then asserts the done signals and halts further processing until the `ap_continue` signal is asserted high.

For function arguments and global variables, the following default protocol is used for each argument type:

- Read-only (Inputs) `ap_none`
- Write-only (Outputs) `ap_vld`
- Read-Write (Inouts) `ap_ovld`
- Arrays `ap_memory`

The RTL ports to implement function arguments and global variables are specified by the following `-mode` values:

- `ap_none`

No protocol in place. Corresponds to a simple wire.

- `ap_stable`

Applicable to input ports only. Informs High-Level Synthesis that the value on this port is stable after reset and is guaranteed not to change until the next reset. The protocol is implemented as mode `ap_none` but this allows internal optimizations to take place on the signal fanout.

Note: This is not considered a constant value, only an unchanging value.

- `ap_vld`

Creates an additional valid port (`<port_name>_vld`) to operate in conjunction with this data port.

- For *input* ports, a read stalls the function until its associated input valid port is asserted.
- An *output* port has its output valid signal asserted when it writes data.

- **ap_ack**

Creates an additional acknowledge port ($<port_name>_ack$) to operate in conjunction with this data port.

- For *input* ports, a read asserts the output acknowledge when it reads a value.
- An *output* write stalls the function until its associated input acknowledge port is asserted.

- **ap_hs**

Creates additional valid ($<port_name>_vld$) and acknowledge ($<port_name>_ack$) ports to operate in conjunction with this data port.

- For *input* ports, a read stalls the function until its input valid is asserted and asserts its output acknowledge signal when data is read.
- An *output* write asserts an output valid when it writes data and stalls the function until its associated input acknowledge port is asserted.

- **ap_ovld**

- For input signals, acts as mode **ap_none**. No protocol is added.
- For output signals, acts as mode **ap_vld**.
- For inout signals:
 - The input is implemented as mode **ap_none**.
 - The output is implemented as mode **ap_vld**.

- **ap_memory**

Implements array arguments as accesses to an external RAM.

Creates data, address and RAM control ports (such as CE, WE) to read from and write the external RAM. The specific signals and number of data ports are determined by the RAM which is being accessed.



RECOMMENDED: Target the array argument to a specific RAM in the technology library using the `set_directive_resource` command. Otherwise, High-Level Synthesis automatically determines the RAM to use.

- ap_fifo

Implements array, pointer and pass-by-reference ports as a FIFO access.

- The data input port:

- Asserts its associated output read port ($<port_name>_read$) when it is ready to read new values from the external FIFO.
- Stalls the function until its input available port ($<port_name>_empty_n$) is asserted to indicate a value is available to read.

- The output data port:

- Asserts an output write port ($<port_name>_write$) to indicate that it has written a value to the port.
- Stalls the function until its associated input available port ($<port_name>_full_n$) is asserted to indicate that there is space available in the external FIFO for new outputs. This interface mode should use the `-depth` option.

- ap_bus

Implements pointer and pass-by-reference ports as a bus interface.

Both input and output ports are synthesized with several control signals to support burst access to and from a standard FIFO bus interface.

For a detailed description of this interface, see [Chapter 1, High-Level Synthesis](#).



RECOMMENDED: *For this interface mode, use the `-depth` option.*

- `-depth`

Required for pointer interfaces using ap_fifo or ap_bus modes.

Use this option to specify the maximum number of samples to be processed by the test bench. This is required to inform High-Level Synthesis about the maximum size of FIFO needed in the verification adapter created for RTL co-simulation.

- `-register`

For the top-level function, this option:

- Is relevant for the following scalar interfaces:
 - `ap_none`
 - `ap_ack`
 - `ap_vld`
 - `ap_ovld`
 - `ap_hs`
- Causes the signal (and any relevant protocol signals) to be registered and persist until at least the last cycle of the function execution.
- Requires the `ap_ctrl_hs` function protocol to be enabled. When used with `ap_ctrl_hs`, results in the function return value being registered.
- Can be used in sub-functions to register the outputs and any control signals until the end of the function execution.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS interface <mode> register port=<string>
```

Examples

Turns off function-level handshakes for function `foo`.

```
set_directive_interface -mode ap_ctrl_none foo
#pragma HLS interface ap_ctrl_none port=return
```

Argument `InData` in function `foo` is specified to have a `ap_vld` interface and the input should be registered.

```
set_directive_interface -mode ap_vld -register foo InData
#pragma HLS interface ap_vld register port=InData
```

Expose global variable `lookup_table` used in function `foo` as a port on the RTL design, with an `ap_memory` interface.

```
set_directive_interface -mode ap_memory foo look_table
```

set_directive_latency

Description

Specifies a maximum or minimum latency value, or both, on a function, loop, or region.

High-Level Synthesis always aims for minimum latency. The behavior of High-Level Synthesis when minimum and maximum latency values are specified is as follows.

- Latency is less than the minimum.

If High-Level Synthesis can achieve less than the minimum specified latency, it extends the latency to the specified value, potentially increasing sharing.

- Latency is greater than the minimum.

The constraint is satisfied. No further optimizations are performed.

- Latency is less than the maximum.

The constraint is satisfied. No further optimizations are performed.

- Latency is greater than the maximum.

If High-Level Synthesis cannot schedule within the maximum limit, it increases effort to achieve the specified constraint. If it still fails to meet the maximum latency, it issues a warning. High-Level Synthesis then produces a design with the smallest achievable latency.

Syntax

```
set_directive_latency [OPTIONS] <location>
```

where

- <*location*> is the location (function, loop or region) (in the format function[/label]) to be constrained.

Options

-max <integer>

Specifies the maximum latency.

-min <integer>

Specifies the minimum latency.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS latency \
    min=<int> \
    max=<int>
```

Examples

Function `foo` is specified to have a minimum latency of 4 and a maximum latency of 8.

```
set_directive_latency -min=4 -max=8 foo
#pragma HLS latency min=4 max=8
```

In function `foo`, loop `loop_row` is specified to have a maximum latency of 12. Place the pragma in the loop body.

```
set_directive_latency -max=12 foo/loop_row
#pragma HLS latency max=12
```

set_directive_loop_flatten

Description

Flattens nested loops into a single loop hierarchy.

In the RTL implementation, it costs a clock cycle to move between loops in the loop hierarchy. Flattening nested loops allows them to be optimized as a single loop. This saves clock cycles, potentially allowing for greater optimization of the loop body logic.



RECOMMENDED: *Apply this directive to the inner-most loop in the loop hierarchy. Only perfect and semi-perfect loops can be flattened in this manner.*

- Perfect loop nests
 - Only the innermost loop has loop body content.
 - There is no logic specified between the loop statements.
 - All loop bounds are constant.
- Semi-perfect loop nests
 - Only the innermost loop has loop body content.
 - There is no logic specified between the loop statements.
 - The outermost loop bound can be a variable.

- Imperfect loop nests

When the inner loop has variables bounds (or the loop body is not exclusively inside the inner loop), try to restructure the code, or unroll the loops in the loop body to create a perfect loop nest.

Syntax

```
set_directive_loop_flatten [OPTIONS] <location>
```

where

- <location> is the location (inner-most loop), in the format function[/label].

Options

-off

Prevents flattening from taking place.

Can prevent some loops from being flattened while all others in the specified location are flattened.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS loop_flatten off
```

Examples

Flattens `loop_1` in function `foo` and all (perfect or semi-perfect) loops above it in the loop hierarchy, into a single loop. Place the pragma in the body of `loop_1`.

```
set_directive_loop_flatten foo/loop_1
#pragma HLS loop_flatten
```

Prevents loop flattening in `loop_2` of function `foo`. Place the pragma in the body of `loop_2`.

```
set_directive_loop_flatten -off foo/loop_2
#pragma HLS loop_flatten off
```

set_directive_loop_merge

Description

Merges all loops into a single loop.

Merging loops:

- Reduces the number of clock cycles required in the RTL to transition between the loop-body implementations.
- Allows the loops be implemented in parallel (if possible).

The rules for loop merging are:

- If the loop bounds are variables, they must have the same value (number of iterations).
- If loops bounds are constants, the maximum constant value is used as the bound of the merged loop.
- Loops with both variable bound and constant bound cannot be merged.
- The code between loops to be merged cannot have side effects. Multiple execution of this code should generate the same results.
 - $a=b$ is allowed
 - $a=a+1$ is not allowed.
- Loops cannot be merged when they contain FIFO reads. Merging changes the order of the reads. Reads from a FIFO or FIFO interface must always be in sequence.

Syntax

```
set_directive_loop_merge <location>
```

where

- <*location*> is the location (in the format function[/label]) at which the loops reside.

Options

-force

Forces loops to be merged even when High-Level Synthesis issues a warning. You must assure that the merged loop will function correctly.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS loop_merge force
```

Examples

Merges all consecutive loops in function `foo` into a single loop.

```
set_directive_loop_merge foo
#pragma HLS loop_merge
```

All loops inside `loop_2` of function `foo` (but not `loop_2` itself) are merged by using the `-force` option. Place the pragma in the body of `loop_2`.

```
set_directive_loop_merge -force foo/loop_2
#pragma HLS loop_merge force
```

set_directive_loop_tripcount

Description

The *loop tripcount* is the total number of iterations performed by a loop. High-Level Synthesis reports the total latency of each loop (the number of cycles to execute all iterations of the loop). This loop latency is therefore a function of the tripcount (number of loop iterations).

The tripcount can be a constant value. It may depend on the value of variables used in the loop expression (for example, `x < y`) or control statements used inside the loop.

High-Level Synthesis cannot determine the tripcount in some cases. These cases include, for example, those in which the variables used to determine the tripcount are:

- Input arguments, or
- Variables calculated by dynamic operation

In those cases, the loop latency might be unknown.

To help with the design analysis that drives optimization, the `set_directive_loop_tripcount` command allows you to specify minimum, average, and maximum tripcounts for a loop. This allows you to see how the loop latency contributes to the total design latency in the reports.

Syntax

```
set_directive_loop_tripcount [OPTIONS] <location>
```

where

- `<location>` is the location of the loop (in the format `function[/label]`) at which the tripcount is specified.

Options

`-avg <integer>`

Specifies the average latency.

`-max <integer>`

Specifies the maximum latency.

`-min <integer>`

Specifies the minimum latency.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS loop_tripcount \
    min=<int> \
    max=<int> \
    avg=<int>
```

Examples

`loop_1` in function `foo` is specified to have:

- A minimum tripcount of 12
- An average tripcount of 14
- A maximum tripcount of 16

```
set_directive_loop_tripcount -min 12 -max 14 -avg 16 foo/loop_1
#pragma HLS loop_tripcount min=12 max=14 avg=16
```

set_directive_occurrence

Description

When pipelining functions or loops, specifies that the code in a location is executed at a lesser rate than the code in the enclosing function or loop.

This allows the code that is executed at the lesser rate to be pipelined at a slower rate, and potentially shared within the top-level pipeline. For example:

- A loop iterates N times.
- Part of the loop is protected by a conditional statement and only executes M times, where N is an integer multiple of M .
- The code protected by the conditional is said to have an occurrence of N/M .

If N is pipelined with an initiation interval II , any function or loops protected by the conditional statement:

- May be pipelined with a higher initiation interval than II .
- Note:** At a slower rate. This code is not executed as often.
- Can potentially be shared better within the enclosing higher rate pipeline.

Identifying a region with an occurrence allows the functions and loops in this region to be pipelined with an initiation interval that is slower than the enclosing function or loop.

Syntax

```
set_directive_occurrence [OPTIONS] <location>
```

where

- $<\text{location}>$ specifies the location with a slower rate of execution.

Options

`-cycle <int>`

Specifies the occurrence N/M where:

- N is the number of times the enclosing function or loop is executed
- M is the number of times the conditional region is executed.

N must be an integer multiple of M .

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS occurrence cycle=<int>
```

Examples

Region Cond_Region in function foo has an occurrence of 4. It executes at a rate four times slower than the code that encompasses it.

```
set_directive_occurrence -cycle 4 foo/Cond_Region
#pragma HLS occurrence cycle=4
```

set_directive_pipeline

Description

Specifies the details for:

- Function pipelining
- Loop pipelining

A pipelined function or loop can process new inputs every N clock cycles, where N is the initiation interval (II). The default initiation interval is 1, which processes a new input every clock cycle, or it can be specified by the -II option.

If High-Level Synthesis cannot create a design with the specified II, it:

- Issues a warning.
- Creates a design with the lowest possible II.

You can then analyze this design with the warning message to determine what steps must be taken to create a design that satisfies the required initiation interval.

Syntax

```
set_directive_pipeline [OPTIONS] <location>
```

where

- <location> is the location (in the format function[/label]) to be pipelined.

Options

```
-II <integer>
```

Specifies the desired initiation interval for the pipeline.

High-Level Synthesis tries to meet this request. Based on data dependencies, the actual result might have a larger II.

`-enable_flush`

Implements a pipeline that can flush pipeline stages if the input of the pipeline stalls.

This feature:

- Implements additional control logic.
- Has greater area.
- Is optional.

`-rewind`

Note: Applicable only to a loop.

Enables rewinding. Rewinding enables continuous loop pipelining, with no pause between one loop iteration ending and the next starting.

Rewinding is effective only if there is one single loop (or a perfect loop nest) inside the top-level function. The code segment before the loop:

- Is considered as initialization.
- Is executed only once in the pipeline.
- Cannot contain any conditional operations (`if-else`).

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS pipeline \
    II=<int> \
    enable_flush \
    rewind
```

Examples

Function `foo` is pipelined with an initiation interval of 1.

```
set_directive_pipeline foo
#pragma HLS pipeline
```

Loop `loop_1` in function `foo` is pipelined with an initiation interval of 4. Pipelining flush is enabled.

```
set_directive_pipeline -II 4 -enable_flush foo/loop_1
#pragma HLS pipeline II=4 enable_flush
```

set_directive_protocol

Description

Specifies a region of the code (a protocol region) in which no clock operations are inserted by High-Level Synthesis unless explicitly specified in the code.

A protocol region can manually specify an interface protocol. High-Level Synthesis does not insert any clocks between any operations, including those that read from or write to function arguments. The order of read and writes are therefore obeyed at the RTL.

A clock operation may be specified:

- In C by using an `ap_wait()` statement (include `ap_utils.h`).
- In C++ and SystemC designs by using the `wait()` statement (include `systemc.h`).

The `ap_wait` and `wait` statements have no effect on the simulation of C and C++ designs respectively. They are only interpreted by High-Level Synthesis.

To create a region of C code:

1. Enclosing the region in braces {}.
2. Name it.

For example, the following defines a region called `io_section`:

```
io_section:{..lines of C code...}
```

Syntax

```
set_directive_protocol [OPTIONS] <location>
```

where

- `<location>` is the location (in the format function[/label]) to be implemented in a cycle-accurate manner, corresponding to external protocol requirements.

Options

`-mode (floating | fixed)`

The default `floating` mode allows the code corresponding to statements outside the protocol region to overlap with the statements in the protocol statements in the final RTL. The protocol region remains cycle accurate, but other operations can occur at the same time.

The `fixed` mode ensures that there is no overlap.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS protocol \
    <floating, fixed>
```

Examples

Defines region `io_section` in function `foo` as a fixed protocol region. Place the pragma inside region `io_section`.

```
set_directive_protocol -mode fixed foo/io_section
#pragma HLS protocol fixed
```

set_directive_reset

Description

Adds or removes resets for specific state variables (global or static).

Syntax

```
set_directive_reset [OPTIONS] <location> <variable>
```

Options

<location> <string>

The location (in the format `function[/label]`) at which the variable is defined.

<variable> <string>

The variable to which the directive is applied.

<variable> <string> -off

- If `-off` is specified, reset is *not* generated for the specified variable.
- If `-off` is *not* specified, reset is generated for the specified variable.

Pragma

Place the pragma in the C source within the boundaries of the variable life cycle.

```
#pragma HLS reset variable=a off
```

Examples

Adds reset to variable static int a in function foo even when the global reset setting is none or control.

```
set_directive_reset foo a
#pragma HLS reset variable=a
```

Removes reset from variable static int a in function foo even when the global reset setting is **state** or **all**.

```
set_directive_reset -off foo a
#pragma HLS reset variable=a off
```

set_directive_resource

Description

Specifies the resource (core) to implement a variable in the RTL. The variable can be any of the following:

- array
- arithmetic operation
- function argument

Vivado HLS implements the operations in the code using hardware cores. When multiple cores in the library can implement the operation, you can specify which core to use with the `set_directive_resource` command. To generate a list of cores, use the `list_core` command. If no resource is specified, Vivado HLS determines the resource to use.

To specify which memory element in the library to use to implement an array, use the `set_directive_resource` command. For example, this allows you to control whether the array is implemented as a single or a dual-port RAM. This usage is important for arrays on the top-level function interface, because the memory associated with the array determines the ports in the RTL.

You can use the `-latency` option to specify the latency of the core. For block RAMs on the interface, the `-latency` option allows you to model off-chip, non-standard SRAMs at the interface, for example to support an SRAM with a latency of 2 or 3. For internal operations, the `-latency` option allows the operation to be implemented using more pipelined stages. These additional pipeline stages can help resolve timing issues during RTL synthesis.



IMPORTANT: *To use the `-latency` option, the operation must have an available multi-stage core. Vivado HLS provides a multi-stage core for all basic arithmetic operations (add, subtract, multiply and divide), all floating-point operations, and all block RAMs.*



RECOMMENDED: For best results, it is recommended that you use `-std=c99` for C and `-fno-builtin` for C and C++. To specify the C compile options, such as `-std=c99`, use the Tcl command `add_files` with the `-cflags` option. Alternatively, use the **Edit CFLAGS** button in the Project Settings dialog box.

Syntax

```
set_directive_resource -core <string> <location> <variable>
```

where

- `<location>` is the location (in the format function[/label]) at which the variable can be found.
- `<variable>` is the variable.

Options

`-core <string>`

Specifies the core, as defined in the technology library.

`-latency <string>`

Specifies the latency of the core.

`-port_map <string>`

Specifies port mappings when using the IP generation flow to map ports on the design with ports on the adapter.

The variable `<string>` is a Tcl list of the design port and adapter ports.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS resource \
    variable=<variable> \
    core=<core>
```

Examples

Variable `coeffs[128]` is an argument to top-level function `foo_top`. This directive specifies that `coeffs` be implemented with core `RAM_1P` from the library. The ports created in the RTL to access the values of `coeffs` are those defined in the core `RAM_1P`.

```
set_directive_resource -core RAM_1P foo_top coeffs
#pragma HLS resource variable=coeffs core=RAM_1P
```

Given code `Result=A*B` in function `foo`, specifies the multiplication be implemented with two-stage pipelined multiplier core, `Mul2S`.

```
set_directive_resource -core Mul2S foo Result
#pragma HLS RESOURCE variable=Result core=Mulns latency=2
```

set_directive_stream

Description

By default, array variables are implemented as RAM:

- Top-level function array parameters are implemented as a RAM interface port.
- General arrays are implemented as RAMs for read-write access.
- In sub-functions involved in dataflow optimizations, the array arguments are implemented using a RAM pingpong buffer channel.
- Arrays involved in loop-based dataflow optimizations are implemented as a RAM pingpong buffer channel

If the data stored in the array is consumed or produced in a sequential manner, a more efficient communication mechanism is to use streaming data, where FIFOs are used instead of RAMs.

When an argument of the top-level function is specified as interface type `ap_fifo`, the array is identified as streaming.

Syntax

```
set_directive_stream [OPTIONS] <location> <variable>
```

where

- `<location>` is the location (in the format function[/label]) which contains the array variable.
- `<variable>` is the array variable to be implemented as a FIFO.

Options

`-depth <integer>`

Note: Relevant only for array streaming in dataflow channels.

Overrides the default FIFO depth specified (globally) by the `config_dataflow` command.

-off

Note: Relevant only for array streaming in dataflow channels.

The config_dataflow -default_channel fifo command globally implies a set_directive_stream on all arrays in the design. This option allows streaming to be turned off on a specific array (and default back to using a RAM pingpong buffer based channel).

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS stream
    variable=<variable> \
    off \
    depth=<int>
```

Examples

Specifies array A[10] in function foo to be streaming, and implemented as a FIFO.

```
set_directive_stream foo A
#pragma HLS STREAM variable=A
```

Array B in named loop loop_1 of function foo is set to streaming with a FIFO depth of 12. In this case, place the pragma inside loop_1.

```
set_directive_stream -depth 12 foo/loop_1 B
#pragma HLS STREAM variable=B depth=12
```

Array C has streaming disabled. It is assumed enabled by config_dataflow in this example.

```
set_directive_stream -off foo C
#pragma HLS STREAM variable=C off
```

set_directive_top

Description

Attaches a name to a function, which can then be used for the set_top command.

This is typically used to synthesize member functions of a class in C++.



RECOMMENDED: Specify the directive in an active solution. Use the set_top command with the new name.

Syntax

```
set_directive_top [OPTIONS] <location>
```

where

- <location> is the function to be renamed.

Options

```
-name <string>
```

Specifies the name to be used by the set_top command.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS top \
    name=<string>
```

Examples

Function foo_long_name is renamed to DESIGN_TOP, which is then specified as the top-level. If the pragma is placed in the code, the set_top command must still be issued in the top-level specified in the GUI project settings.

```
set_directive_top -name DESIGN_TOP foo_long_name
#pragma HLS top name=DESIGN_TOP
set_top DESIGN_TOP
```

set_directive_unroll

Description

Transforms loops by creating multiples copies of the loop body.

A loop is executed for the number of iterations specified by the loop induction variable. The number of iterations may also be impacted by logic inside the loop body (for example, break or modifications to any loop exit variable). The loop is implemented in the RTL by a block of logic representing the loop body, which is executed for the same number of iterations.

The set_directive_unroll command allows the loop to be fully unrolled. Unrolling the loop creates as many copies of the loop body in the RTL as there are loop iterations, or partially unrolled by a factor N , creating N copies of the loop body and adjusting the loop iteration accordingly.

If the factor N used for partial unrolling is not an integer multiple of the original loop iteration count, the original exit condition must be checked after each unrolled fragment of the loop body.

To unroll a loop completely, the loop bounds must be known at compile time. This is not required for partial unrolling.

Syntax

```
set_directive_unroll [OPTIONS] <location>
```

where

- $<\text{location}>$ is the location of the loop (in the format function[/label]) to be unrolled.

Options

-factor <integer>

Specifies a non-zero integer indicating that partial unrolling is requested.

The loop body is repeated this number of times. The iteration information is adjusted accordingly.

-region

Unrolls all loops within a loop without unrolling the enclosing loop itself.

Consider the following example:

- Loop `loop_1` contains multiple loops at the same level of loop hierarchy (loops `loop_2` and `loop_3`).
- A named loop (such as `loop_1`) is also a region or location in the code.
- A section of code is enclosed by braces `{ }`.
- If the unroll directive is specified on location `<function>/loop_1`, it unrolls `loop_1`.

The `-region` option specifies that the directive be applied only to the loops enclosing the named region. This results in:

- `loop_1` is left rolled.
- All loops inside `loop_1` (`loop_2` and `loop_3`) are unrolled.

-skip_exit_check

Effective only if a factor is specified (partial unrolling).

- **Fixed bounds**

No exit condition check is performed if the iteration count is a multiple of the factor.

If the iteration count is *not* an integer multiple of the factor, the tool:

- Prevents unrolling.
- Issues a warning that the exit check must be performed to proceed.

• **Variable bounds**

The exit condition check is removed. You must ensure that:

- The variable bounds is an integer multiple of the factor.
- No exit check is in fact required.

Pragma

Place the pragma in the C source within the boundaries of the required location.

```
#pragma HLS unroll \
    skip_exit_check \
    factor=<int> \
    region
```

Examples

Unrolls loop L1 in function foo. Place the pragma in the body of loop L1.

```
set_directive_unroll foo/L1
#pragma HLS unroll
```

Specifies an unroll factor of 4 on loop L2 of function foo. Removes the exit check. Place the pragma in the body of loop L2.

```
set_directive_unroll -skip_exit_check -factor 4 foo/L2
#pragma HLS unroll skip_exit_check factor=4
```

Unrolls all loops inside loop L3 in function foo, but not loop L3 itself. The -region option specifies the location be considered an enclosing region and not a loop label.

```
set_directive_unroll -region foo/L3
#pragma HLS unroll region
```

set_part

Description

Sets a target device for the current solution.

The command can be executed only in the context of an active solution.

Syntax

```
set_part <device_specification>
```

where

- <*device_specification*> is a device specification that sets the target device for High-Level Synthesis synthesis and implementation.
- <*device_family*> is the device family name, which uses the default device in the family.
- <*device*><*package*><*speed_grade*> is the target device name including device, package, and speed-grade information.

Options

```
-tool (auto|ise|vivado)
```

This command option ensures that the tool uses the correct version of Xilinx IP (such as Xilinx floating-point LogiCORE™ IP) to create the RTL. The IP version used by the High-Level Synthesis tool must match the version supported by the RTL synthesis tool.

This option has an impact on the `export_design` command. For example, a design specified for synthesis with the ISE Design Suite cannot be exported to the Vivado IP Catalog.

- If `vivado` is selected, High-Level Synthesis ensures that:
 - All IP cores match those supported by the latest Vivado Design Suite release.
 - RTL synthesis can be performed using the Vivado tools.
- If `ise` is selected, High-Level Synthesis ensures that:
 - All IP cores match those supported by the latest ISE Design Suite release.
 - ISE Design Suite can be used for RTL synthesis.
- If `auto` (the default) is selected:
 - Vivado tools are used for Zynq®-7000 AP SoC and Xilinx 7 series and later devices.
 - ISE tools are used for Virtex-6 series and earlier devices.



IMPORTANT: This option influences the IP packaging. A design targeted for the Vivado Design Suite cannot be exported as a Pcore or ISE Design Suite System Generator IP.

Pragma

There is no pragma equivalent.

Examples

The FPGA libraries provided with High-Level Synthesis can be added to the current solution by providing the device family name as shown below. In this case, the default device, package, and speed-grade specified in the High-Level Synthesis FPGA library for this device family are used.

```
set_part virtex6
```

The FPGA libraries provided with High-Level Synthesis can optionally specify the specific device with package and speed-grade information.

```
set_part xc6vlx240tff1156-1
```

set_top

Description

Defines the top-level function to be synthesized.

Any functions called from this function will also be part of the design.

Syntax

```
set_top <top>
```

where

- <*top*> is the function to be synthesized.

Pragma

There is no pragma equivalent.

Examples

Sets the top-level function as `foo_top`.

```
set_top foo_top
```

GUI Reference

This reference section explains how to use, control and customize the Vivado HLS GUI.

Monitoring Variables

You can view the values of variables and expressions directly in the Debug perspective. The following figure shows how you can monitor the value of individual variables.

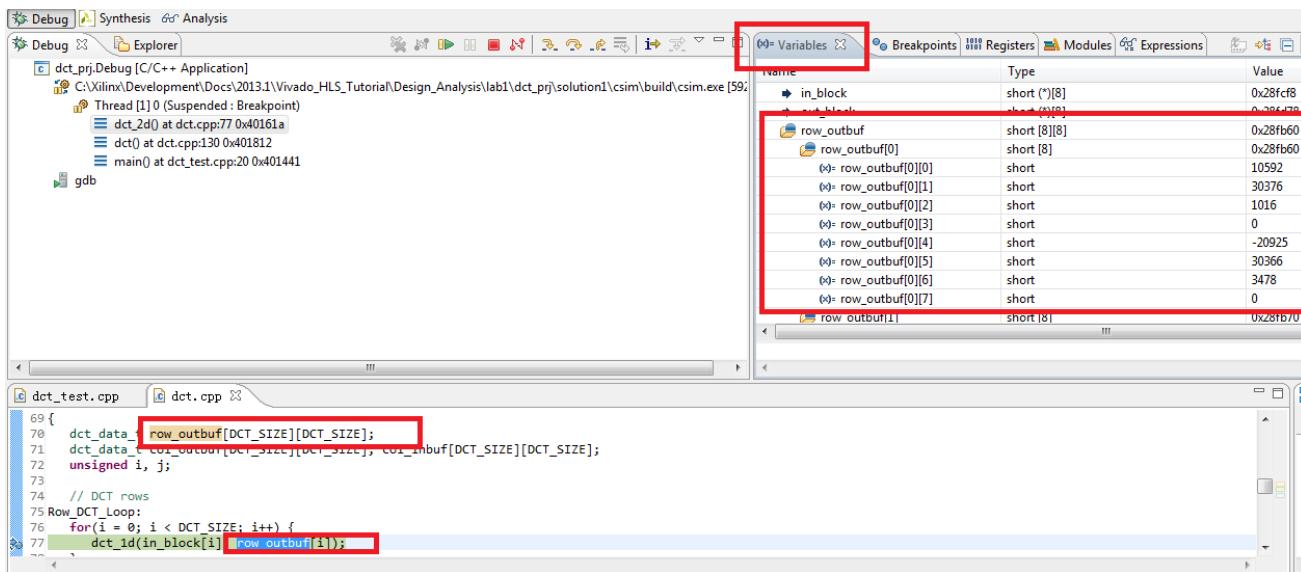


Figure 4-1: Monitoring Variables

You can monitor the value of expressions using the Expressions tab.

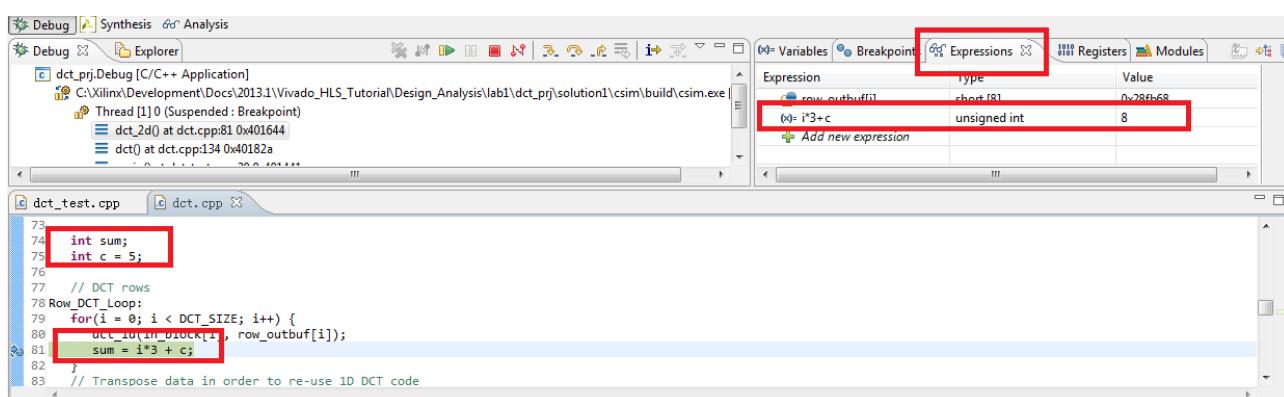
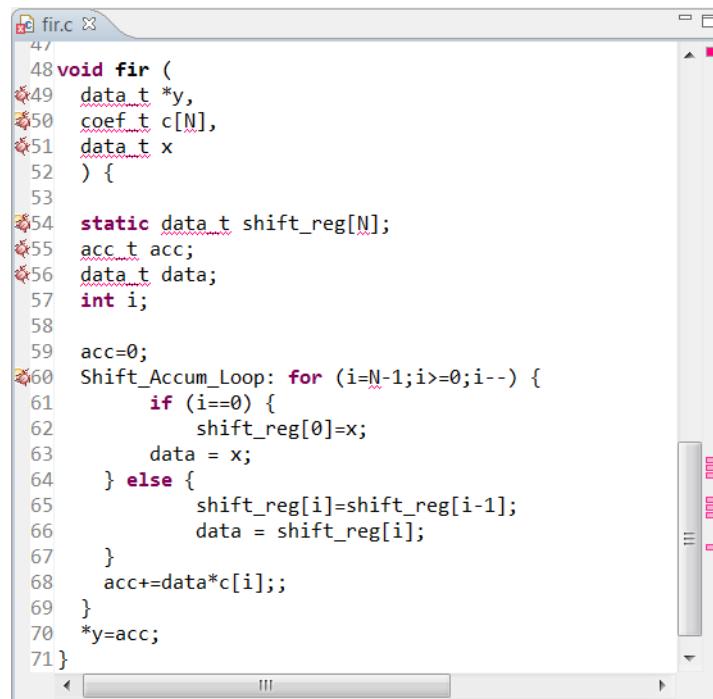


Figure 4-2: Monitoring Expressions

Resolving Header File Information

By default, the Vivado HLS GUI continually parses all header files to resolve coding references. The GUI highlights unresolved references, as shown in the following figure:

- Left sidebar: Highlights undefined references in the current view.
- Right sidebar: Highlights unresolved references throughout the file.



```

47
48 void fir (
49     data_t *y,
50     coef_t c[N],
51     data_t x
52 ) {
53
54     static data_t shift_reg[N];
55     acc_t acc;
56     data_t data;
57     int i;
58
59     acc=0;
60     Shift_Accum_Loop: for (i=N-1;i>=0;i--) {
61         if (i==0) {
62             shift_reg[0]=x;
63             data = x;
64         } else {
65             shift_reg[i]=shift_reg[i-1];
66             data = shift_reg[i];
67         }
68         acc+=data*c[i];
69     }
70     *y=acc;
71 }
```

Figure 4-3: Index C Files



IMPORTANT: It is important to remove undefined references in the code before performing C simulation or synthesis. To check for undefined references, see the annotations in the code viewer that indicate a variable or value is unknown or cannot be defined. Undefined references do not appear in the directives window.

Undefined references occur when code defined in a header file (.h or .hpp extension) cannot be resolved. The primary causes of undefined references are:

- The code was recently added to the file.

If the code is new, ensure the header file is saved. After saving the header file, Vivado HLS automatically indexes the header files and updates the coding references.

- The header file is not in the search path.

Ensure the header file is included in the C code using an `include` statement, the location to the header file is in the search path, and the header file is in the same directory as the C files added to the project.

Note: To explicitly add the search path, select **Solution > Solution Settings**, click **Synthesis** or **Simulation**, and use the **Edit CFLAGS** button. For more information, see [Creating a New Synthesis Project in Chapter 1](#).

- Automatic indexing is disabled.

Ensure that Vivado HLS is parsing all header files automatically. Select **Project > Project Settings** to open the Project Settings dialog box. Click **General**, and make sure **Disable Parsing All Header Files** is deselected, as shown in the following figure. This might result in a reduced GUI response time, because Vivado HLS uses CPU cycles to automatically check the header files.

Note: To manually force Vivado HLS to index all C files, click the **Index C files** toolbar button .

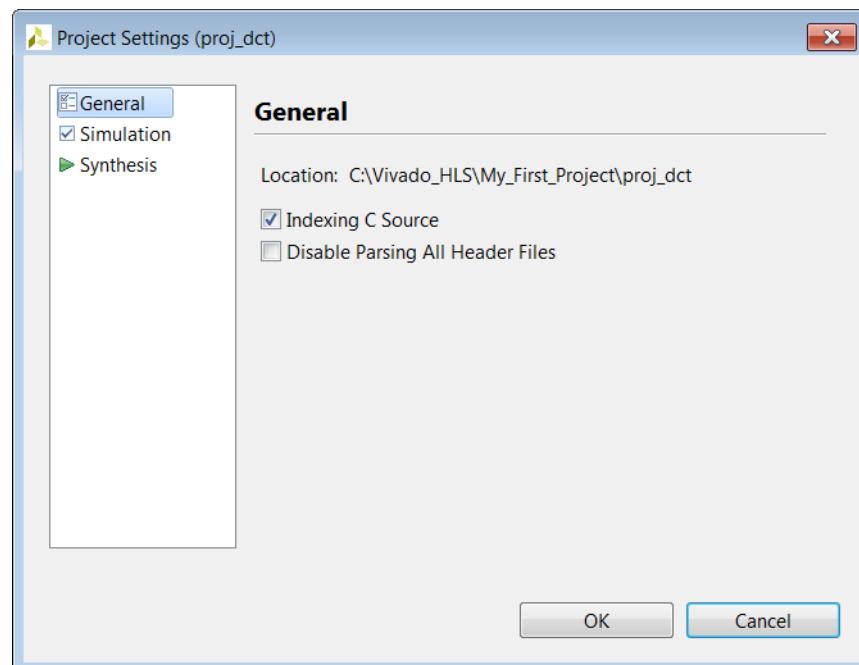


Figure 4-4: Controlling Header File Parsing

Resolving Comments in the Source Code

In some localizations, non-English comments in the source file appears as strange characters. This can be corrected by:

1. Selecting the project in the Explorer Pane.
2. Right-click and select the appropriate language encoding using **Properties > Resource**. In the section titled Text File Encoding select Other and choose appropriate encoding from the drop-down menu.

Customizing the GUI Behavior

In some cases the default setting of the Vivado HLS GUI prevents certain information from being shown or the defaults that are not suitable for you. This sections explains how the following can be customized:

- Console window buffer size.
- Default key behaviors.

Customizing the Console Window

The console windows displays the messages issued during operations such as synthesize and verification.

The default buffer size for this windows is 80,000 characters and can be changed, or the limit can be removed, to ensure all messages can be reviewed, by using menu **Window > Preferences > Run/Debug > Console**.

Customizing the Key Behavior

The behavior of the GUI can be customized using the menu **Windows > Preferences** and new user-defined tool settings saved.

The default setting for the key combination **Ctrl+Tab**, is to make the active tab in the Information Pane toggle between the source code and the header file. This is changed to make the **Ctrl+Tab** combination make each tab in turn the active tab.

- In the Preferences menu, sub-menu **General > Keys** allows the Command value Toggle Source/Header to be selected and the CTRL-TAB combination removed by using the Unbind Command key.
- Selecting Next Tab in the Command column, placing the cursor in the Binding dialog box and pressing the **Ctrl** key and then the **Tab** key, that causes the operation **Ctrl+Tab** to be associated with making the next tab active.

A find-next hot key can be implemented by using the Microsoft Visual Studio scheme. This can be performed using the menu **Window > Preference > General > Keys** and replace the Default scheme with the Microsoft Visual Studio scheme.

Reviewing the sub-menus in the Preferences menu allows every aspect of the GUI environment to be customized to ensure the highest levels of productivity.

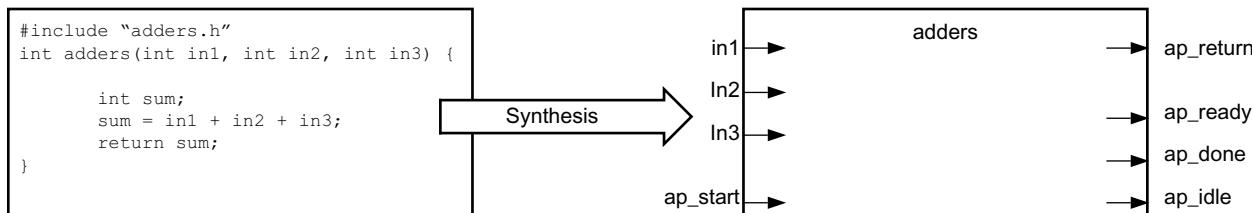
Interface Synthesis Reference

This reference section explains each of the Vivado HLS interface protocol modes.

Block-Level I/O Protocols

Interface types `ap_ctrl_none`, `ap_ctrl_hs` and `ap_ctrl_chain` are used to specify if the RTL is implemented with block-level handshake signals or not. Block-level handshake signals specify when the design can start to perform its standard operation and when that operation ends. These interface types are specified on the function or the function return.

The following figure shows the resulting RTL ports and behavior when `ap_ctrl_hs` is specified on a function, which is the default operation. In this example, the function returns a value using the `return` statement and thus output port `ap_return` is created in the RTL design: if there is no function `return` statement this port is not created.



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Figure 4-5: Example ap_ctrl_hs Interface

The `ap_ctrl_chain` interface mode is similar to `ap_ctrl_hs` but provide an additional input signal `ap_continue` to apply "back-pressure" and is recommend when chaining Vivado HLS blocks together. The protocols for `ap_ctrl_hs` and `ap_ctrl_chain` are explained below.

ap_ctrl_none

If `ap_ctrl_none` is specified, none of the handshake signal ports ("`ap_start`", "`ap_idle`" and "`ap_done`") shown in [Figure 4-5](#) are created, and the block cannot be verified with the C/RTL co-simulation.

ap_ctrl_hs

The behavior of the block level handshake signals created by interface mode ap_ctrl_hs are shown in the following figure and summarized below.

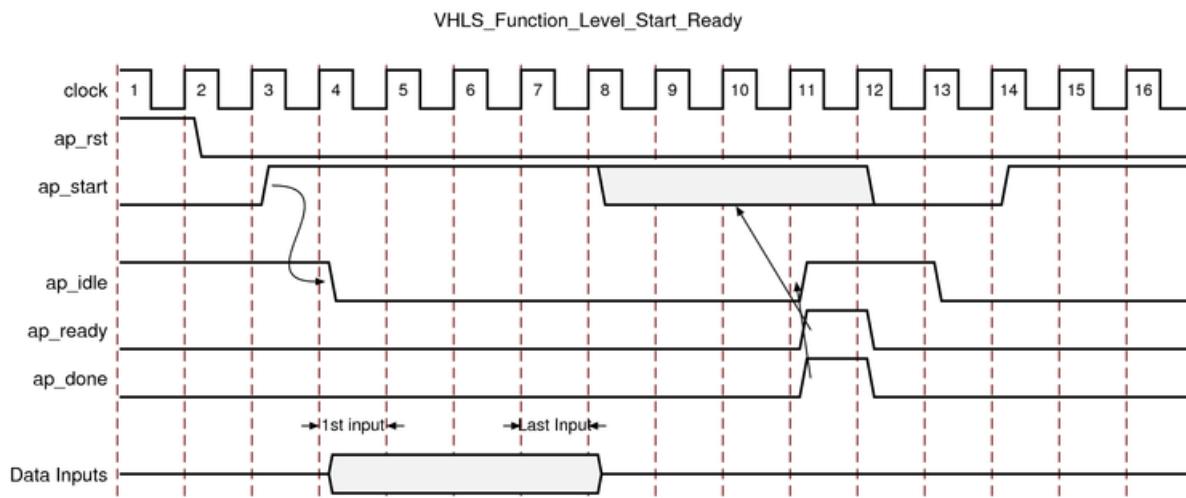


Figure 4-6: Behavior of ap_ctrl_hs Interface

After reset:

- The block waits for "ap_start" to go High before it begins operation.
- The ap_start signal should remain High until ap_ready signal indicates that the design is ready for new inputs: ap_start can be taken Low or remain High to start another transaction.
- Output "ap_idle" goes Low when "ap_start" is sampled High.
- Data can now be read on the input ports.
 - The first input data can be sampled on the first clock edge after "ap_idle" goes Low.
- When the block completes all operations, any return value is written to port ap_return.
 - If there was no function return, there is no ap_return port on the RTL block.
 - Other outputs may be written to at any time until the block completes and are independent of this I/O protocol.

- Output "ap_done" goes High when the block completes operation.
 - When the design is ready to accept new inputs, the ap_ready signal goes High. In non-pipelined designs this signal is asserted at the same time as ap_done. Now the ap_start can be taken Low or remain High to start a new transaction.
 - If there is an ap_return port, the data on this port is valid when "ap_done" is High.
 - The "ap_done" signal can therefore used to validate when the function return value (output on port ap_return) is valid.
- The idle signal goes High one cycle after "ap_done" and remains High until the next time "ap_start" is sampled High (indicating the block should begin operation).

If the "ap_start" signal is High when "ap_done" goes High:

- The "ap_idle" signal remains Low.
- The block immediately starts its next execution (or next transaction).
- The next input can be read on the next clock edge.

Vivado HLS supports pipelining, allowing the next transaction to begin before the current one ends. In this case, the block can accept new inputs before the first transaction completes and output port "ap_done" is asserted High.

If the function is pipelined, or if the top-level loop is pipelined with the -rewind option the ap_ready signal goes High before the ap_done signal and the decision on whether to start the next transaction or not must be made before the current transaction has completed. To obtain data already in the pipeline now, use the -enable_flush option with the pipeline directive.

ap_ctrl_chain

The ap_ctrl_chain interface protocol is similar to the ap_ctrl_hs protocol but provides an additional input port ap_continue. Asserting the ap_continue signal Low informs the design that the downstream block that consumes the data is not ready to accept new data.

When ap_continue is asserted Low, the design stalls when it reaches the final state of the current transaction: the output data is presented on the interface, the ap_done signal can be asserted High and the design remains in this state until ap_continue is asserted High. This is shown in the following figure.

Note: In a pipelined design, keep in mind the end of the current transaction might occur in the very next clock cycle after ap_continue goes Low (if the design is pipelined with a throughput of one).

This "back-pressure" signal allows downstream blocks to prevent any more data being generated.

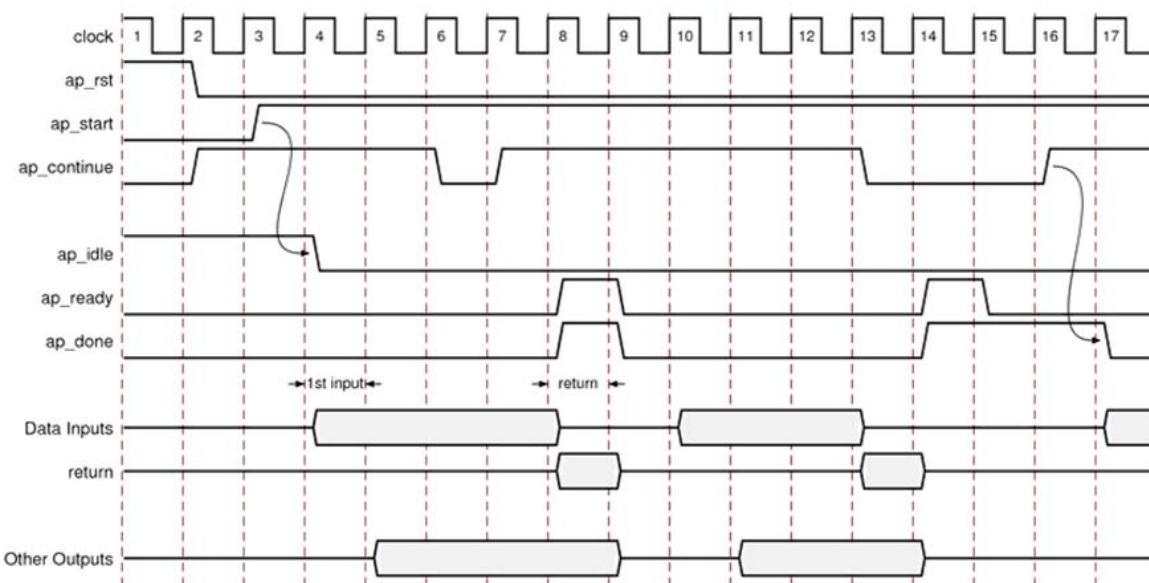


Figure 4-7: Behavior of ap_ctrl_chain Interface

Note: The only data that is guaranteed to be valid when “ap_done” is asserted is the data on the optional ap_return port (this port only exists if a value is returned from the function using the return statement).

The other outputs in the design can be valid at this time, the end of the transaction when “ap_done” is asserted, but that is not guaranteed. If it is a requirement that an output port must have an associated valid signal, it should be specified with one of the port-level I/O protocols discussed in the remainder of this section.

ap_none

The ap_none interface type is the simplest interface and has no other signals associated with it. Neither the input nor output signals have any associated control ports indicating when data is read or written. The only ports in the RTL design are those specified in the source code.

An ap_none interface requires no additional hardware overhead but does require that producer blocks provide data to the input port at the correct time or hold it for the length of a transaction (until the design completes) and consumer blocks are required to read output ports at the correct time: as such, a design with interface mode ap_none specified on an output cannot be verified using the cosim_design feature.

The ap_none interface cannot be used with array arguments.

ap_stable

The ap_stable interface type, like type ap_none, does not add any interface control ports to the design. The ap_stable type informs High-Level Synthesis that the data applied to this port remains stable during normal operation, but is not a constant value that could be optimized, and the port is not required to be registered.

The ap_stable type is typically used for ports that provide configuration data. Data that can change but remains stable during normal operation (configuration data is typically only changed during or before a reset).

The ap_stable type can only be applied to input ports. When applied to inout ports, only the input part of the port is considered to be stable.

ap_hs (ap_ack, ap_vld, and ap_ovld)

An ap_hs interface provides both an acknowledge signal to say when data has been consumed and a valid signal to indicate when data can be read. This interface type is a superset of types ap_ack, ap_vld and ap_ovld.

- Interface type ap_ack only provides an acknowledge signal.
- Interface type ap_vld only provides a valid signal.
- Interface type ap_ovld only provides a valid signal and only applies to output ports or the output half of an inout pair.

The following figure shows how an ap_hs interface behaves for both an input and output port. In this example the input port is named "in" and the output port named "out".

Note: The control signals are named, based on the original port name (For example, the valid port for input "in" is added and named "in_vld").

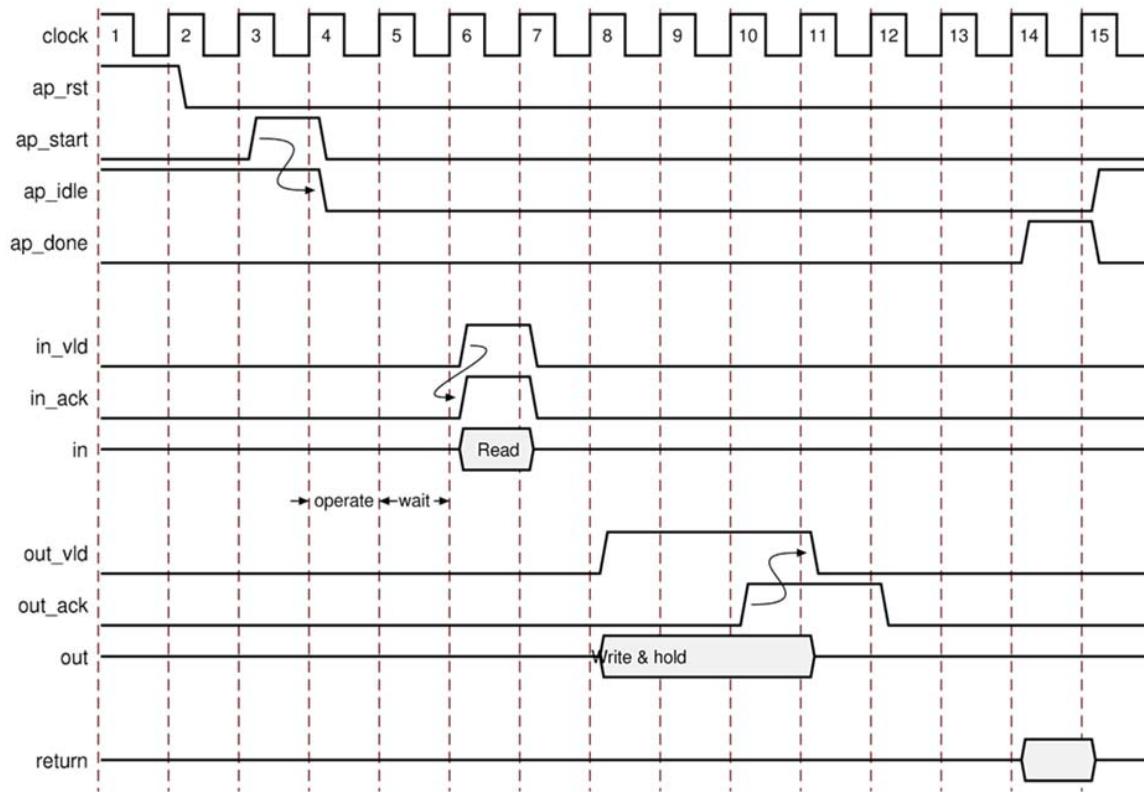


Figure 4-8: Behavior of ap_hs Interface

For inputs:

- After reset and start is applied, the block begins normal operation.
- If the input port is to be read but the input valid is Low, the design stalls and waits for the input valid to be asserted; indicating a new input value is present.
- As soon as the input valid is asserted High, an output acknowledge is asserted High to indicate the data was read.

For outputs:

- After reset and start is applied, the block begins normal operation.
- When an output port is written to, its associated output valid signal is simultaneously asserted to indicate valid data is present on the port.
- If the associated input acknowledge is Low, the design stalls and waits for the input acknowledge to be asserted.
- When the input acknowledge is asserted, the output valid is deasserted on the next clock edge.

Designs that use ap_hs interfaces can be verified with cosim_design and provide the greatest flexibility in the development process, allowing both bottom-up and top-down design flows: all intra-block communication is safely performed by two-way handshakes, with no manual intervention or assumptions required for correct operation.

The ap_hs interface is a safe interface protocol, but requires a two-port overhead, with associated control logic.

With an ap_ack interface, only an acknowledge port is synthesized.

- For input arguments, this results in an output acknowledge port that is active-High in the cycle the input read.
- For output arguments, this results in an input acknowledge port.
 - After a write operation, the design stalls and wait until the input acknowledge has been asserted High, indicating the output has been read by a consumer block.
 - However, there is no associated output port to indicate when the data can be consumed.

Care should be taken when specifying output ports with ap_ack interface types. Designs that use ap_ack on an output port cannot be verified by cosim_design.

Specifying interface type ap_vld results in a single associated valid port in the RTL design.

- For output arguments this results in an output valid port, indicating when the data on the output port is valid.
- Note:** For input arguments this valid port behaves in a different manner than the valid port implemented with ap_hs.
- If ap_vld is used on an input port (there is no associated output acknowledge signal), the input port is read as soon as the valid is active: even if the design is not ready to read the port, the data port is sampled and held internally until needed.
 - The input data reads each cycle the input valid is active.

An ap_ovld interface type is the same an ap_vld but can only be specified on output ports. This is a useful type for ensuring pointers that are both read from and written to, can only be implemented with an output valid port (and the input half defaults to type ap_none).

ap_memory, bram

Array arguments are typically implemented using the ap_memory interface. This type of port interface is used to communicate with memory elements (RAMs, ROMs) when the implementation requires random accesses to the memory address locations. Array arguments are the only arguments that support a random access memory interface.

If sequential access to the memory element is all that is required, the ap_fifo interface discussed next can reduce the hardware overhead: no address generation is performed in an ap_fifo interface.

The ap_memory and bram interfaces are identical. The only difference is when the block is used inside Vivado IP integrator:

- The ap_memory interface is shown as discrete ports.
- The bram interface is shown as a single grouped port. Connections to all ports can be performed inside IP integrator using a single connection.

When using an ap_memory interface, the array targets should be specified using the set_directive_resource command. If no target is specified for the arrays, High-Level Synthesis determines if a single or dual-port RAM interface is used.



TIP: Ensure array arguments are targeted to the correct memory type using RESOURCE directive before synthesis as re-synthesizing with new, correct, memories can result in a different schedule and RTL.

The following figure shows an example where an array named "d" has the resource specified as a single-port block RAM.

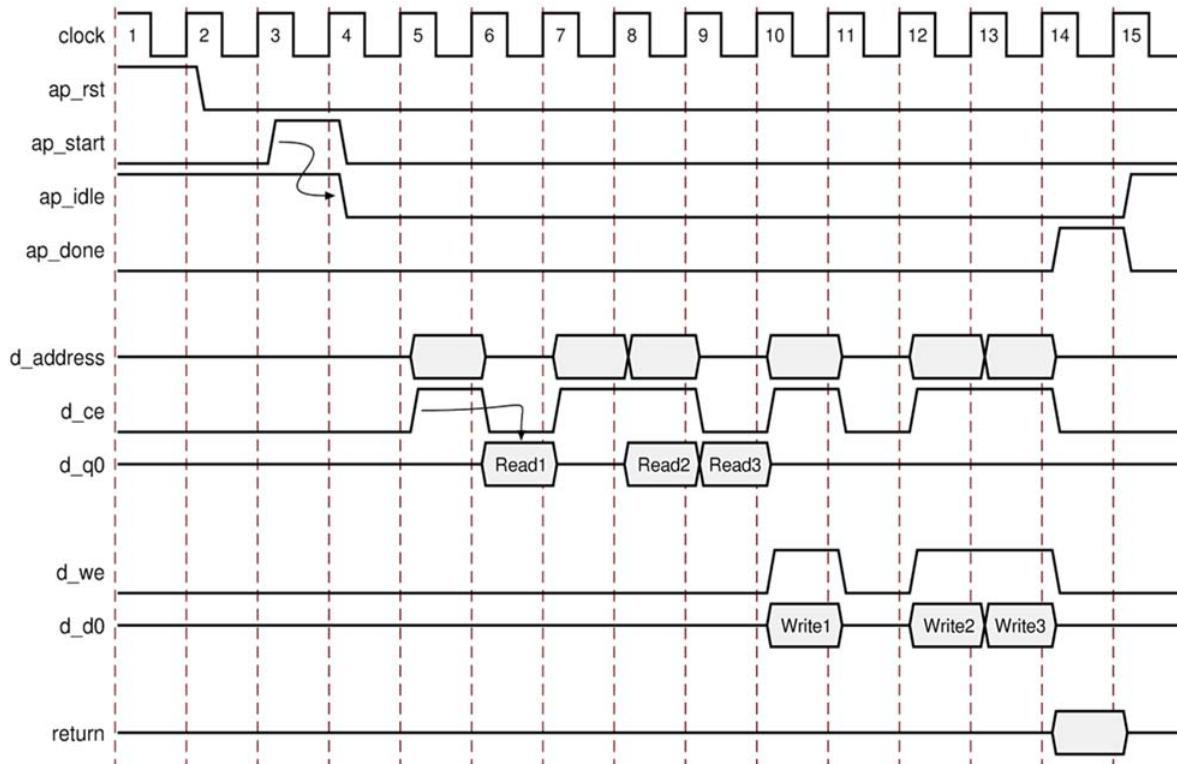


Figure 4-9: Behavior of ap_memory Interface

After reset:

- After reset and start is applied, the block begins normal operation.
- Reads are performed by applying an address on the output address ports while asserting the output signal "d_ce".
 - For this block RAM target, the design expects the input data to be available in the next clock cycle.
- Write operations are performed by asserting output ports "d_ce" and "d_we" while simultaneously applying the address and data.

A memory interface cannot be stalled by external signals, provides an indication of when output data is valid and can therefore be verified using C/RTL co-simulation.

ap_fifo

If access to a memory element is required and the access is only ever performed in a sequential manner (no random access required) an ap_fifo interface is the most hardware efficient. The ap_fifo interface allows the port to be connected to a FIFO, supports full two-way empty-full communication and can be specified for array, pointer and pass-by-reference argument types.

Functions that can use an ap_fifo interface often use pointers and may access the same variable multiple times. See [Multi-Access Pointer Interfaces: Streaming Data in Chapter 3](#) to understand the importance of the volatile qualifier when this coding style is used.

Note: An ap_fifo interface assumes that all reads and writes are sequential in nature. If Vivado HLS can determine this is not the case, it issues an error and halts. If Vivado HLS cannot determine that the accesses are always sequential, it issues a warning that it is unable to confirm this and proceed.

In the following example "in1" is a pointer that accesses the current address, then two addresses above the current address and finally one address below.

```
void foo(int* in1, ...) {
    int data1, data2, data3;
    ...
    data1= *in1;
    data2= *(in1+2);
    data3= *(in1-1);
    ...
}
```

If "in1" is specified as an ap_fifo interface, High-Level Synthesis checks the accesses and determine the accesses are not in sequential order, issue an error and halt. To read from non-sequential address locations use an ap_memory interface as this random accessed or use an ap_bus interface.

An ap_fifo interface cannot be specified on an argument that is both read from and written to (an inout port). Only input and output arguments can be specified with an ap_fifo

interface. An interface with input argument "in" and output argument "out" specified as ap_fifo interfaces behaves as follows:

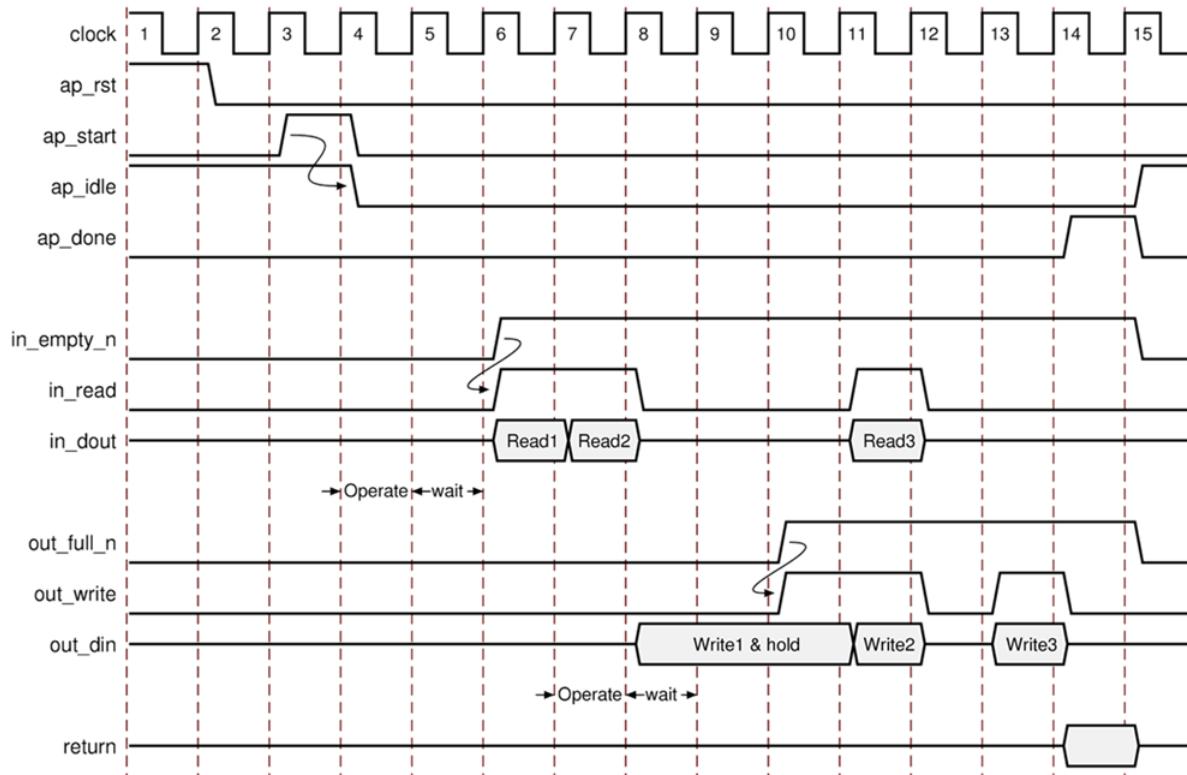


Figure 4-10: Behavior of ap_fifo Interface

After reset and start is applied, the block begins normal operation.

For reads:

- If the input port is to be read but the FIFO is empty, as indicated by input port "in_empty_n" Low, the design stalls and waits for data to become available.
- As soon as the input port "in_empty_n" is asserted High to indicate data is available, an output acknowledge ("in_read") is asserted High to indicate the data was read in this cycle.
- If data is available in the FIFO when a port read is required, the output acknowledge is asserted to acknowledge data was read in this cycle.

For outputs:

- If an output port is to written to but the FIFO is full, as indicated by "out_full_n" Low, the data is placed on the output port but the design stalls and waits for the space to become available in the FIFO.
- When space becomes available in the FIFO (input "out_full_n" goes High) the output acknowledge signal "out_write" is asserted to indicate the output data is valid.
- If there is space available in the FIFO when an output is written to, the output valid signal is asserted to indicate the data is valid in this cycle.

In an ap_fifo interface the output data port has an associated write signal: ports with an ap_fifo interface can be verified using cosim_design.

If top-level function is pipelined or if the top-level loop is pipelined with -rewind option, an additional out port with the suffix _lwr is created. This port is active-High when the last write to the FIFO interface is performed.

ap_bus

An ap_bus interface can communicate with a bus bridge. The interface does not adhere to any specific bus standard but is generic enough to be used with a bus bridge that in-turn arbitrates with the system bus. The bus bridge must be able to cache all burst writes.

Functions that can employ an ap_bus interface use pointers and may access the same variable multiple times. See [Multi-Access Pointer Interfaces: Streaming Data in Chapter 3](#) to understand the importance of the volatile qualifier when this coding style is used.

An ap_bus interface can be used in two specific ways.

- Standard Mode: The standard mode of operation is to perform individual read and write operations, specifying the address of each.
- Burst Mode: If the C function memcpy is used in the C source code, burst mode is used for data transfers. In burst mode, the base address and the size of the transfer is indicated by the interface: the data samples are then quickly transferred in consecutive cycles.
- Arrays accessed by the memcpy function cannot be partitioned into registers.

[Figure 4-11](#) and [Figure 4-12](#) show the behavior for read and write operations in standard mode, when an ap_bus interface is applied to argument "d" in the following example:

```
void foo (int *d) {
    static int acc = 0;
    int i;

    for (i=0;i<4;i++) {
        acc += d[i+1];
        d[i] = acc;
    }
}
```

[Figure 4-13](#) and [Figure 4-14](#) show the behaviors when the C memcpy function and burst mode is used, as in this example code:

```
void bus (int *d) {
    int buf1[4], buf2[4];
    int i;

    memcpy(buf1,d,4*sizeof(int));

    for (i=0;i<4;i++) {
        buf2[i] = buf1[3-i];
    }

    memcpy(d,buf2,4*sizeof(int));
}
```

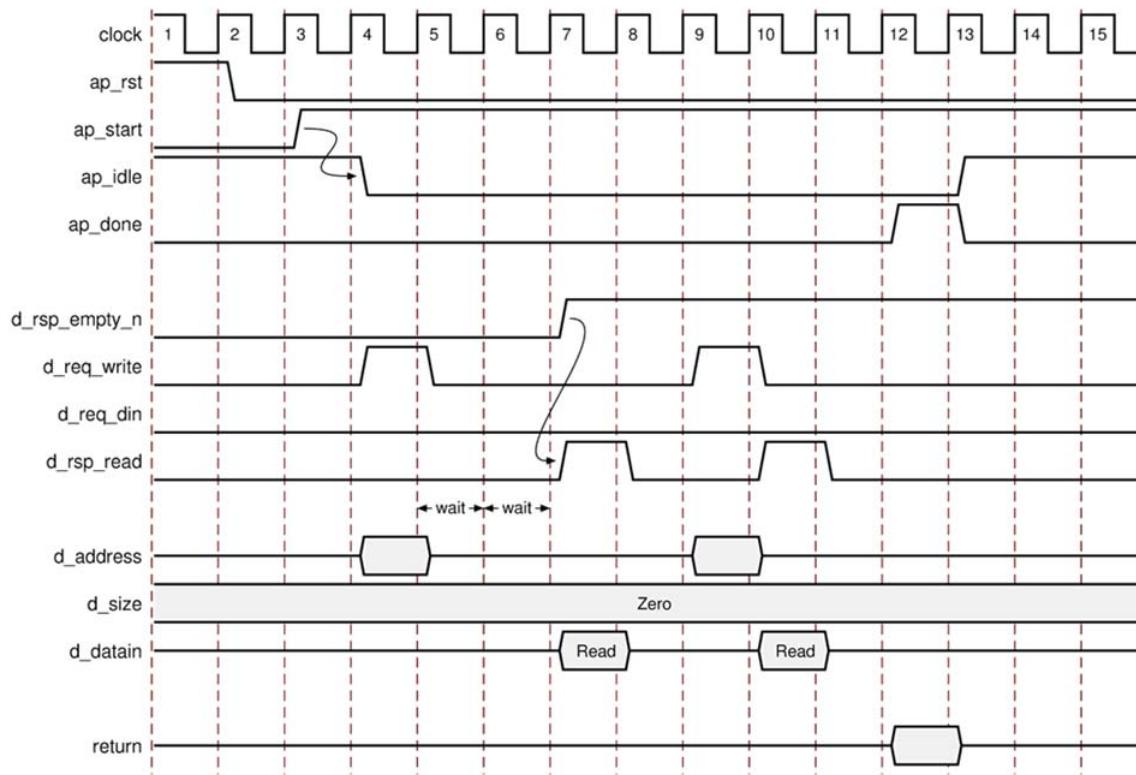


Figure 4-11: Behavior of ap_bus Interface: Standard Read

After reset:

- After reset and start is applied, the block begins normal operation.
- If a read is to be performed, but there is no data in the bus bridge FIFO ("d_rsp_empty_n" is Low):
 - Output port "d_req_write" is asserted with port "d_req_din" deasserted, to indicate a read operation.
 - The address is output.
 - The design stalls and wait for data to become available.
- When data becomes available for reading the output signal "d_rsp_read" is immediately asserted and data is read at the next clock edge.

- If a read is to be performed, and data is available in the bus bridge FIFO ("d_rsp_empty_n" is High):
 - Output port "d_req_write" is asserted and port "d_req_din" is deasserted, to indicate a read operation.
 - The address is output.
 - "d_rsp_read" is asserted in the next clock cycle and data is read at the next clock edge.

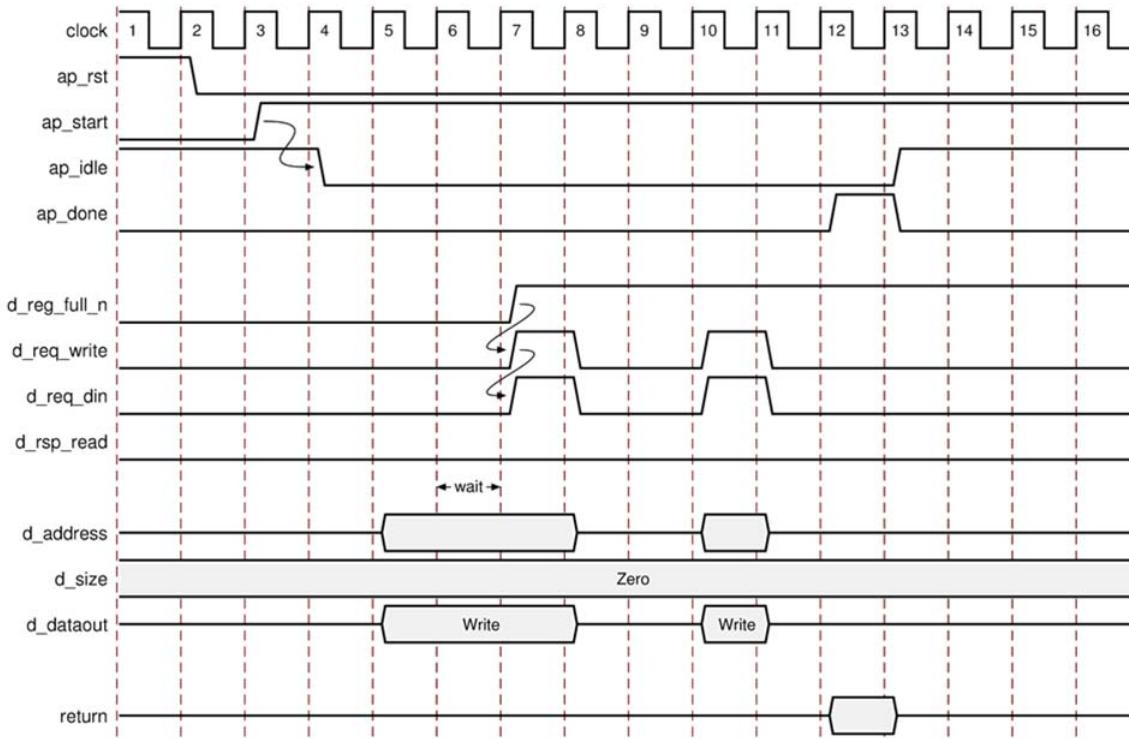


Figure 4-12: Behavior of ap_bus Interface: Standard Write

After reset:

- After reset and start is applied, the block begins normal operation.
- If a write is to be performed, but there is no space in the bus bridge FIFO ("d_req_full_n" is Low):
 - The address and data are output.
 - The design stalls and waits for space to become available.

- When space becomes available for writing:
 - Output ports “d_req_write” and “d_req_din” are asserted, to indicate a write operation.
 - The output signal “d_req_din” is immediately asserted to indicate the data is valid at the next clock edge.
- If a write is to be performed, and space is available in the bus bridge FIFO (“d_req_full_n” is High):
 - Output ports “d_req_write” and “d_req_din” are asserted, to indicate a write operation.
 - The address and data are output.
 - “d_req_din” is asserted to indicate the data is valid at the next clock edge.

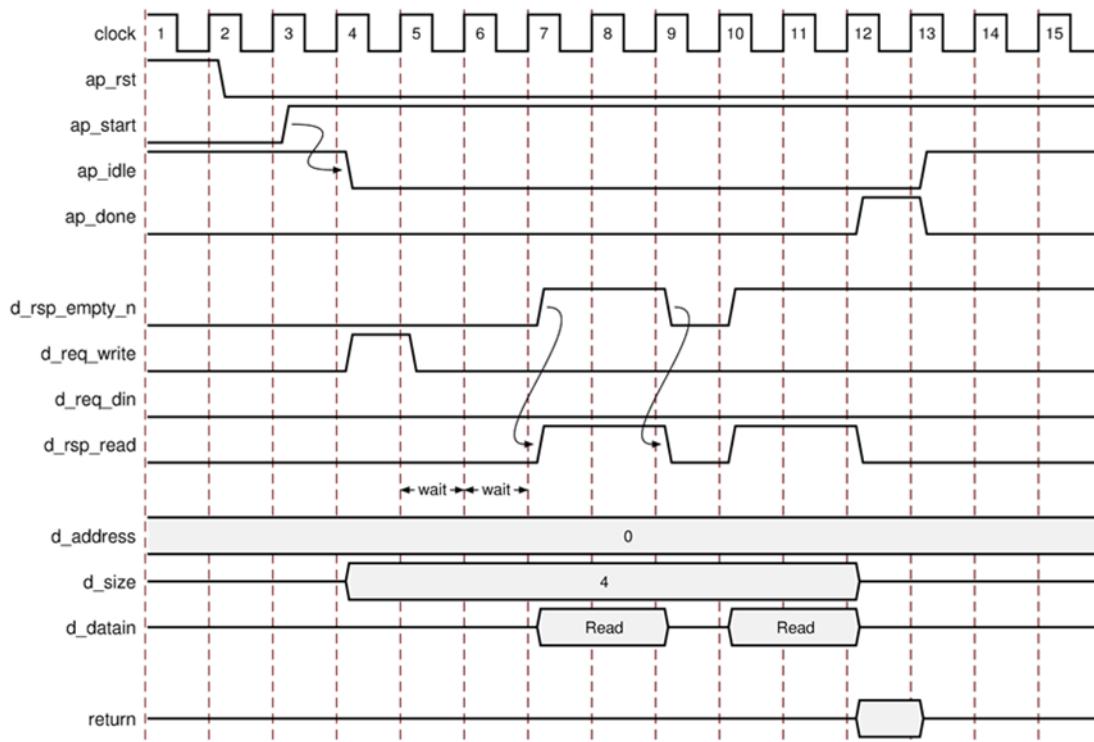


Figure 4-13: Behavior of ap_bus Interface: Burst Read

After reset:

- After reset and start is applied, the block begins normal operation.
- If a read is to be performed, but there is no data in the bus bridge FIFO ("d_rsp_empty_n" is Low):
 - Output port "d_req_write" is asserted with port "d_req_din" deasserted, to indicate a read operation.
 - The base address for the transfer and the size are output.
 - The design stalls and waits for data to become available.
- When data becomes available for reading the output signal "d_rsp_read" is immediately asserted and data is read at the next N clock edges, where N is the value on output port size.
- If the bus bridge FIFO runs empty of values, the data transfers stop immediately and wait until data is available before continuing where it left off.
- If a read is to be performed, and data is available in the bus bridge FIFO
 - Transfer begin and the design stalls and waits if the FIFO empties

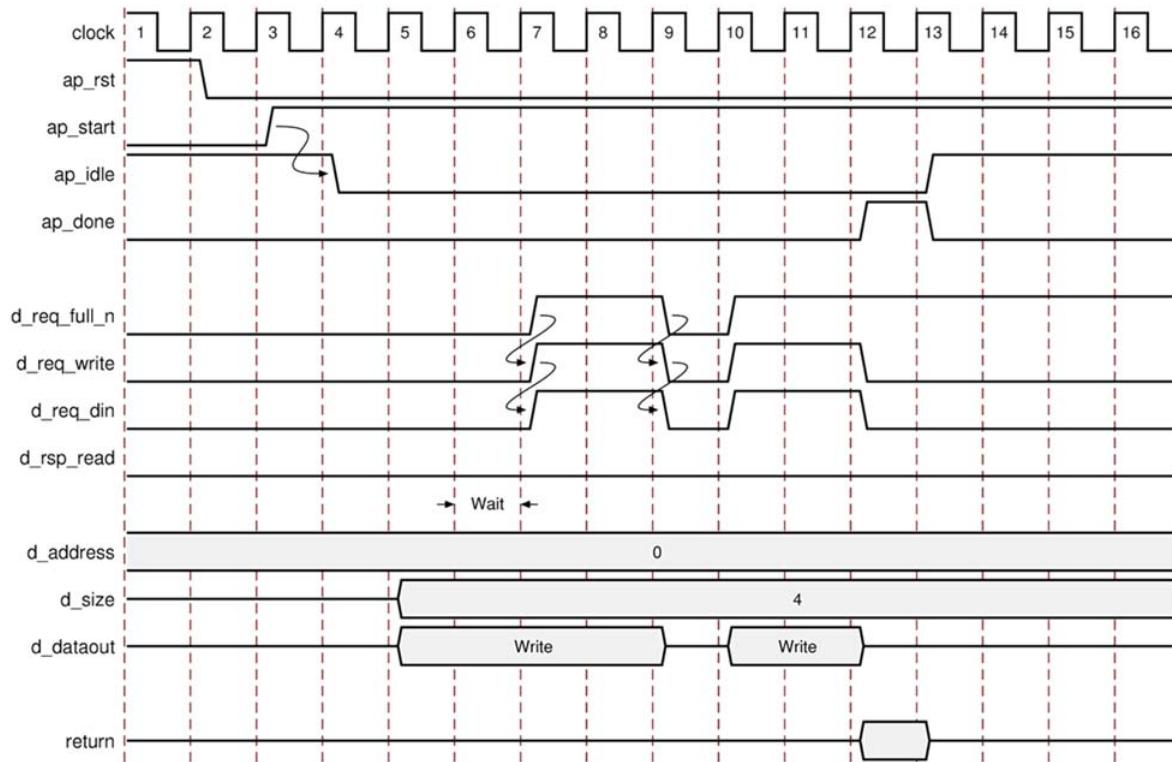


Figure 4-14: Behavior of ap_bus Interface: Burst Write

After reset:

- After reset and start is applied, the block begins normal operation.
- If a write is to be performed, but there is no space in the bus bridge FIFO ("d_req_full_n" is Low):
 - The base address, transfer size and data are output.
 - The design stalls and waits for space to become available.
- When space becomes available for writing:
 - Output ports "d_req_write" and "d_req_din" are asserted, to indicate a write operation.
 - The output signal "d_req_din" is immediately asserted to indicate the data is valid at the next clock edge.
 - Output signal "d_req_din" is immediately deasserted if the FIFO becomes full and re-asserted when space is available.
 - The transfer stops after N data values is transferred, where N is the value on the size output port.
- If a write is to be performed, and space is available in the bus bridge FIFO ("d_rsp_full_n" is High):
 - Transfer begins and the design stalls and waits when the FIFO is full.

The ap_bus interface can be verified by cosim_design.

axis

An AXI4-Stream I/O protocol can be specified as the I/O protocol using mode `axis`. For a complete description of the AXI4-Stream interface including timing and ports, see the *Vivado Design Suite AXI Reference Guide* (UG1037) [Ref 8]. For details on using the full capabilities of this I/O protocol, see [Using AXI4 Interfaces in Chapter 1](#).

s_axilite

An AXI4-Lite slave I/O protocol can be specified as one of the I/O protocol using mode `s_axilite`. For a complete description of the AXI4-Lite slave interface including timing and ports, see the *Vivado Design Suite AXI Reference Guide* (UG1037) [Ref 8]. For details on using the full capabilities of this I/O protocol, see [Using AXI4 Interfaces in Chapter 1](#).

m_axi

An AXI4 master I/O protocol can be specified as one of the I/O protocols using mode `m_axi`. For a complete description of the AXI4 master interface including timing and ports, see the *Vivado Design Suite AXI Reference Guide* (UG1037) [Ref 8]. For details on using the full capabilities of this I/O protocol, see [Using AXI4 Interfaces in Chapter 1](#).

AXI4-Lite Slave C Driver Reference

When an AXI4-Lite slave interface is added to the design, a set of C driver files are automatically created. These C driver files provide a set of APIs that can be integrated into any software running on a CPU and used to communicate with the device using the AXI4-Lite interface.

The API functions derive their name from the top-level function for synthesis. This reference section assumes the top-level function is called DUT. The following table lists each of the API function provided in the C driver files.

Table 4-1: C Driver API Functions

API Function	Description
<code>XDut_Initialize</code>	This API will write value to InstancePtr which then can be used in other APIs. Xilinx recommends calling this API to initialize a device except when an MMU is used in the system.
<code>XDut_CfgInitialize</code>	Initialize a device configuration. When a MMU is used in the system, replace the base address in the <code>XDut_Config</code> variable with virtual base address before calling this function. Not for use on Linux systems.
<code>XDut_LookupConfig</code>	Used to obtain the configuration information of the device by ID. The configuration information contain the physical base address. Not for user on Linux.
<code>XDut_Release</code>	Release the uio device in linux. Delete the mappings by munmap: the mapping will automatically be deleted if the process terminated. Only for use on Linux systems.
<code>XDut_Start</code>	Start the device. This function will assert the <code>ap_start</code> port on the device. Available only if there is <code>ap_start</code> port on the device.
<code>XDut_IsDone</code>	Check if the device has finished the previous execution: this function will return the value of the <code>ap_done</code> port on the device. Available only if there is an <code>ap_done</code> port on the device.
<code>XDut_IsIdle</code>	Check if the device is in idle state: this function will return the value of the <code>ap_idle</code> port. Available only if there is an <code>ap_idle</code> port on the device.
<code>XDut_IsReady</code>	Check if the device is ready for the next input: this function will return the value of the <code>ap_ready</code> port. Available only if there is an <code>ap_ready</code> port on the device.

Table 4-1: C Driver API Functions (Cont'd)

API Function	Description
XDut_Continue	Assert port ap_continue. Available only if there is an ap_continue port on the device.
XDut_EnableAutoRestart	Enables "auto restart" on device. When this is set the device will automatically start the next transaction when the current transaction completes.
XDut_DisableAutoRestart	Disable the "auto restart" function.
XDut_Set_ARG	Write a value to port ARG (a scalar argument of the top function). Available only if ARG is input port.
XDut_Set_ARG_vld	Assert port ARG_vld. Available only if ARG is an input port and implemented with an ap_hs or ap_vld interface protocol.
XDut_Set_ARG_ack	Assert port ARG_ack. Available only if ARG is an output port and implemented with an ap_hs or ap_ack interface protocol.
XDut_Get_ARG	Read a value from ARG. Only available if port ARG is an output port on the device.
XDut_Get_ARg_vld	Read a value from ARG_vld. Only available if port ARG is an output port on the device and implemented with an ap_hs or ap_vld interface protocol.
XDut_Get_ARg_ack	Read a value from ARG_ack. Only available if port ARG is an input port on the device and implemented with an ap_hs or ap_ack interface protocol.
XDut_Get_ARG_BaseAddress	Return the base address of the array inside the interface. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_Get_ARG_HighAddress	Return the address of the uppermost element of the array. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_Get_ARG_TotalBytes	Return the total number of bytes used to store the array. Only available when ARG is an array grouped into the AXI4-Lite interface. Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.
XDut_Get_ARG_BitWidth	Return the bit width of each element in the array. Only available when ARG is an array grouped into the AXI4-Lite interface. Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.
XDut_Get_ARG_Depth	Return the total number of elements in the array. Only available when ARG is an array grouped into the AXI4-Lite interface. Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.

Table 4-1: C Driver API Functions (Cont'd)

API Function	Description
XDut_Write_ARG_Words	Write the length of a 32-bit word into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_Read_ARG_Words	Read the length of a 32-bit word from the array. This API requires the data target, the offset address from BaseAddress, and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_Write_ARG_Bytes	Write the length of bytes into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_Read_ARG_Bytes	Read the length of bytes from the array. This API requires the data target, the offset address from BaseAddress, and the length of data to be loaded. Only available when ARG is an array grouped into the AXI4-Lite interface.
XDut_InterruptGlobalEnable	Enable the interrupt output. Interrupt functions are available only if there is ap_start.
XDut_InterruptGlobalDisable	Disable the interrupt output.
XDut_InterruptEnable	Enable the interrupt source. There may be at most 2 interrupt sources (source 0 for ap_done and source 1 for ap_ready)
XDut_InterruptDisable	Disable the interrupt source.
XDut_InterruptClear	Clear the interrupt status.
XDut_InterruptGetEnabled	Check which interrupt sources are enabled.
XDut_InterruptGetStatus	Check which interrupt sources are triggered.

The details on the API functions are provided below.

XDut_Initialize

Synopsis

```
int XDut_Initialize(XDut *InstancePtr, u16 DeviceId);  
  
int XDut_Initialize(XDut *InstancePtr, const char* InstanceName);
```

Description

int XDut_Initialize(XDut *InstancePtr, u16 DeviceId): For use on standalone systems, initialize a device. This API will write a proper value to InstancePtr which then can be used in other APIs. It is recommended to call this API to initialize a device except when an MMU is used in the system, in which case refer to function XDut_CfgInitialize.

int XDut_Initialize(XDut *InstancePtr, const char* InstanceName): For use on Linux systems, initialize a specifically named uio device. Create up to 5 memory mappings and assign the slave base addresses by mmap, utilizing the uio device information in sysfs.

- **InstancePtr:** A pointer to the device instance.
- **DeviceId:** Device ID as defined in xparameters.h.
- **InstanceName:** The name of the uio device.
- **Return:** XST_SUCCESS indicates success, otherwise fail.

XDut_CfgInitialize

Synopsis

```
XDut_CfgInitializeint XDut_CfgInitialize(XDut *InstancePtr, XDut_Config *ConfigPtr);
```

Description

Initialize a device when an MMU is used in the system. In such a case the effective address of the AXI4-Lite slave is different from that defined in xparameters.h and API is required to initialize the device.

- **InstancePtr:** A pointer to the device instance.
- **DeviceId:** A pointer to a XDut_Config.
- **Return:** XST_SUCCESS indicates success, otherwise fail.

XDut_LookupConfig

Synopsis

```
XDut_Config* XDut_LookupConfig(u16 DeviceId);
```

Description

This function is used to obtain the configuration information of the device by ID.

- **DeviceId:** Device ID as defined in xparameters.h.
- **Return:** A pointer to a XDut_LookupConfig variable that holds the configuration information of the device whose ID is DeviceId. NULL if no matching Deviceid is found.

XDut_Release

Synopsis

```
int XDut_Release(XDut *InstancePtr);
```

Description

Release the uio device. Delete the mappings by munmap. (The mapping will automatically be deleted if the process terminated)

- **InstanceName:** The name of the uio device.
- **Return:** XST_SUCCESS indicates success, otherwise fail.

XDut_Start

Synopsis

```
void XDut_Start(XDut *InstancePtr);
```

Description

Start the device. This function will assert the ap_start port on the device. Available only if there is ap_start port on the device.

- **InstancePtr:** A pointer to the device instance.

XDut_IsDone

Synopsis

```
void XDut_IsDone(XDut *InstancePtr);
```

Description

Check if the device has finished the previous execution: this function will return the value of the ap_done port on the device. Available only if there is an ap_done port on the device.

- **InstancePtr:** A pointer to the device instance.

XDut_IsIdle

Synopsis

```
void XDut_IsIdle(XDut *InstancePtr);
```

Description

Check if the device is in idle state: this function will return the value of the ap_idle port. Available only if there is an ap_idle port on the device.

- **InstancePtr:** A pointer to the device instance.

XDut_IsReady

Synopsis

```
void XDut_IsReady(XDut *InstancePtr);
```

Description

Check if the device is ready for the next input: this function will return the value of the ap_ready port. Available only if there is an ap_ready port on the device.

- **InstancePtr:** A pointer to the device instance.

XDut_Continue

Synopsis

```
void XExample_Continue(XExample *InstancePtr);
```

Description

Assert port ap_continue. Available only if there is an ap_continue port on the device.

- **InstancePtr:** A pointer to the device instance.

XDut_EnableAutoRestart

Synopsis

```
void XDut_EnableAutoRestart(XDut *InstancePtr);
```

Description

Enables “auto restart” on device. When this is enabled,

- Port ap_start will be asserted as soon as ap_done is asserted by the device and the device will auto-start the next transaction.
- Alternatively, if the block-level I/O protocol ap_ctrl_chain is implemented on the device, the next transaction will auto-restart (ap_start will be asserted) when ap_ready is asserted by the device and if ap_continue is asserted when ap_done is asserted by the device.

Available only if there is an ap_start port.

- **InstancePtr:** A pointer to the device instance.

XDut_DisableAutoRestart

Synopsis

```
void XDut_DisableAutoRestart(XDut *InstancePtr);
```

Description

Disable the “auto restart” function. Available only if there is an ap_start port.

- **InstancePtr:** A pointer to the device instance.

XDut_Set_ARG

Synopsis

```
void XDut_Set_ARG(XDut *InstancePtr, u32 Data);
```

Description

Write a value to port ARG (a scalar argument of the top-level function). Available only if ARG is an input port.

- **InstancePtr:** A pointer to the device instance.
- **Data:** Value to write.

XDut_Set_ARG_vld

Synopsis

```
void XDut_Set_ARG_vld(XDut *InstancePtr);
```

Description

Assert port ARG_vld. Available only if ARG is an input port and implemented with an ap_hs or ap_vld interface protocol.

- **InstancePtr:** A pointer to the device instance.

XDut_Set_ARG_ack

Synopsis

```
void XDut_Set_ARG_ack(XDut *InstancePtr);
```

Description

Assert port ARG_ack. Available only if ARG is an output port and implemented with an ap_hs or ap_ack interface protocol.

- **InstancePtr:** A pointer to the device instance.

XDut_Get_ARG

Synopsis

```
u32 XDut_Get_ARG(XDut *InstancePtr);
```

Description

Read a value from ARG. Only available if port ARG is an output port on the device.

- **InstancePtr:** A pointer to the device instance.

Return: Value of ARG.

XDut_Get_ARG_vld

Synopsis

```
u32 XDut_Get_ARG_vld(XDut *InstancePtr);
```

Description

Read a value from ARG_vld. Only available if port ARG is an output port on the device and implemented with an ap_hs or ap_vld interface protocol.

- **InstancePtr:** A pointer to the device instance.

Return: Value of ARG_vld.

XDut_Get_ARG_ack

Synopsis

```
u32 XDut_Get_ARG_ack(XDut *InstancePtr);
```

Description

Read a value from ARG_ack. Only available if port ARG is an input port on the device and implemented with an ap_hs or ap_ack interface protocol.

- **InstancePtr:** A pointer to the device instance.

Return: Value of ARG_ack.

XDut_Get_ARG_BaseAddress

Synopsis

```
u32 XDut_Get_ARG_BaseAddress(XDut *InstancePtr);
```

Description

Return the base address of the array inside the interface. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.

Return: Base address of the array.

XDut_Get_ARG_HighAddress

Synopsis

```
u32 XDut_Get_ARG_HighAddress(XDut *InstancePtr);
```

Description

Return the address of the uppermost element of the array. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.

Return: Address of the uppermost element of the array.

XDut_Get_ARG_TotalBytes

Synopsis

```
u32 XDut_Get_ARG_TotalBytes(XDut *InstancePtr);
```

Description

Return the total number of bytes used to store the array. Only available when ARG is an array grouped into the AXI4-Lite interface.

Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.

- **InstancePtr:** A pointer to the device instance.

Return: The total number of bytes used to store the array.

XDut_Get_ARG_BitWidth

Synopsis

```
u32 XDut_Get_ARG_BitWidth(XDut *InstancePtr);
```

Description

Return the bit width of each element in the array. Only available when ARG is an array grouped into the AXI4-Lite interface.

Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.

- **InstancePtr:** A pointer to the device instance.

Return: The bit-width of each element in the array.

XDut_Get_ARG_Depth

Synopsis

```
u32 XDut_Get_ARG_Depth(XDut *InstancePtr);
```

Description

Return the total number of elements in the array. Only available when ARG is an array grouped into the AXI4-Lite interface.

Note: If the elements in the array are less than 16-bit, Vivado HLS groups multiple elements into the 32-bit data width of the AXI4-Lite interface. If the bit width of the elements exceeds 32-bit, Vivado HLS stores each element over multiple consecutive addresses.

- **InstancePtr:** A pointer to the device instance.

Return: The total number of elements in the array.

XDut_Write_ARG_Words

Synopsis

```
u32 XDut_Write_ARG_Words(XDut *InstancePtr, int offset, int *data, int length);
```

Description

Write the length of a 32-bit word into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.
- **offset:** The address in the AXI4-Lite interface.
- **data:** A pointer to the data value to be stored.
- **length:** The length of the data to be stored.

Return: Write length of data from the specified address.

XDut_Read_ARG_Words

Synopsis

```
u32 XDut_Read_ARG_Words(XDut *InstancePtr, int offset, int *data, int length);
```

Description

Read the length of a 32-bit word from the array. This API requires the data target, the offset address from BaseAddress, and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.
- **offset:** The address in the ARG.
- **data:** A pointer to the data buffer.
- **length:** The length of the data to be stored.

Return: Read length of data from the specified address.

XDut_Write_ARG_Bytes

Synopsis

```
u32 XDut_Write_ARG_Bytes(XDut *InstancePtr, int offset, char *data, int length);
```

Description

Write the length of bytes into the specified address of the AXI4-Lite interface. This API requires the offset address from BaseAddress and the length of the data to be stored. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.
- **offset:** The address in the ARG.
- **data:** A pointer to the data value to be stored.
- **length:** The length of data to be stored.

Return: Write length of data from the specified address.

XDut_Read_ARG_Bytes

Synopsis

```
u32 XDut_Read_ARG_Bytes(XDut *InstancePtr, int offset, char *data, int length);
```

Description

Read the length of bytes from the array. This API requires the data target, the offset address from BaseAddress, and the length of data to be loaded. Only available when ARG is an array grouped into the AXI4-Lite interface.

- **InstancePtr:** A pointer to the device instance.
- **offset:** The address in the ARG.
- **data:** A pointer to the data buffer.
- **length:** The length of data to be loaded.

Return: Read length of data from the specified address.

XDut_InterruptGlobalEnable

Synopsis

```
void XDut_InterruptGlobalEnable(XDut *InstancePtr);
```

Description

Enable the interrupt output. Interrupt functions are available only if there is ap_start.

- **InstancePtr:** A pointer to the device instance.

XDut_InterruptGlobalDisable

Synopsis

```
void XDut_InterruptGlobalDisable(XDut *InstancePtr);
```

Description

Disable the interrupt output.

- **InstancePtr:** A pointer to the device instance.

XDut_InterruptEnable

Synopsis

```
void XDut_InterruptEnable(XDut *InstancePtr, u32 Mask);
```

Description

Enable the interrupt source. There may be at most 2 interrupt sources (source 0 for ap_done and source 1 for ap_ready).

- **InstancePtr:** A pointer to the device instance.
- **Mask:** Bit mask.
 - **Bit n = 1:** enable interrupt source n.
 - **Bit n = 0:** no change.

XDut_InterruptDisable

Synopsis

```
void XDut_InterruptDisable(XDut *InstancePtr, u32 Mask);
```

Description

Disable the interrupt source.

- **InstancePtr:** A pointer to the device instance.
- **Mask:** Bit mask.
 - **Bit n = 1:** disable interrupt source n.
 - **Bit n = 0:** no change.

XDut_InterruptClear

Synopsis

```
void XDut_InterruptClear(XDut *InstancePtr, u32 Mask);
```

Description

Clear the interrupt status.

- **InstancePtr:** A pointer to the device instance.
- **Mask:** Bit mask.
 - **Bit n = 1:** toggle interrupt status n.
 - **Bit n = 0:** no change.

XDut_InterruptGetEnabled

Synopsis

```
u32 XDut_InterruptGetEnabled(XDut *InstancePtr);
```

Description

Check which interrupt sources are enabled.

- **InstancePtr:** A pointer to the device instance.
- **Return:** Bit mask.
 - **Bit n = 1:** enabled.
 - **Bit n = 0:** disabled.

XDut_InterruptGetStatus

Synopsis

```
u32 XDut_InterruptGetStatus(XDut *InstancePtr);
```

Description

Check which interrupt sources are triggered.

- **InstancePtr:** A pointer to the device instance.
- **Return:** Bit mask.
 - **Bit n = 1:** triggered.
 - **Bit n = 0:** not triggered.

Video Functions Reference

This section explains the following Vivado HLS video functions.

- **OpenCV Interface Functions**

Converts data to and from the standard OpenCV data types to AXI4 streaming protocol.

- **AXI4-Stream I/O Functions**

Allows the AXI4 streaming protocol to be converted into the `hsl::Mat` data types used by the video processing functions.

- **Video Processing Functions**

Compatible with standard OpenCV functions for manipulating and processing video images.

For more information and a complete methodology for working with the video functions in the context of an existing OpenCV design, see *Accelerating OpenCV Applications with Zynq-7000 All Programmable SoC Using Vivado HLS Video Libraries* (XAPP1167) [Ref 9].

OpenCV Interface Functions

IplImage2AXIvideo

Synopsis

```
template<int W> void IplImage2AXIvideo (
    IplImage* img,
    hls::stream<ap_axiu<W,1,1,1> >& AXI_video_strm);
```

Parameters

Table 4-2: Parameters

Parameter	Description
img	Input image header in OpenCV IplImage format
AXI_video_strm	Output AXI4 video stream in hls::stream format, compatible with AXI4-Stream protocol

Description

- Converts data from OpenCV IplImage format to AXI4 video stream (hls::stream) format.
- Image data must be stored in img.
- AXI_video_strm must be empty before invoking.
- The data width (in bits) of a pixel in img must be no greater than W, the data width of TDATA in AXI4-Stream protocol.

AXIvideo2IplImage

Synopsis

```
template<int W> void AXIvideo2IplImage (
    hls::stream<ap_axiu<W,1,1,1> >& AXI_video_strm,
    IplImage* img);
```

Parameters

Table 4-3: Parameters

Parameter	Description
AXI_video_strm	Input AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol
img	Output image header in OpenCV <code>IplImage</code> format

Description

- Converts data from AXI4 video stream (`hls::stream`) format to OpenCV `IplImage` format.
- Image data must be stored in `AXI_video_strm`.
- Invoking this function consumes the data in `AXI_video_strm`.
- The data width of a pixel in `img` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

cvMat2AXIvideo

Synopsis

```
template<int W> void cvMat2AXIvideo (
    cv::Mat& cv_mat,
    hls::stream<ap_axiu<W,1,1,1> >& AXI_video_strm);
```

Parameters

Table 4-4: Parameters

Parameter	Description
<code>cv_mat</code>	Input image in OpenCV <code>cv::Mat</code> format
<code>AXI_video_strm</code>	Output AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol

Description

- Converts data from OpenCV `cv::Mat` format to AXI4 video stream (`hls::stream`) format.
- Image data must be stored in `cv_mat`.
- `AXI_video_strm` must be empty before invoking.
- The data width (in bits) of a pixel in `cv_mat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

AXIvideo2cvMat

Synopsis

```
template<int W> void AXIvideo2cvMat (
    hls::stream<ap_axiu<W,1,1,1> >& AXI_video_strm,
    cv::Mat& cv_mat);
```

Parameters

- Converts data from AXI4 video stream (`hls::stream`) format to OpenCV `cv::Mat` format.
- Image data must be stored in `AXI_video_strm`.
- Invoking this function consumes the data in `AXI_video_strm`.
- The data width of a pixel in `cv_mat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

Description

- Converts data from OpenCV `cv::Mat` format to AXI4 video stream (`hls::stream`) format.
- Image data must be stored in `cv_mat`.
- `AXI_video_strm` must be empty before invoking.
- The data width (in bits) of a pixel in `cv_mat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

CvMat2AXIvideo

Synopsis

```
template<int W> void CvMat2AXIvideo (
    CvMat* cvmat,
    hls::stream<ap_axiu<W,1,1,1> >& AXI_video_strm);
```

Parameters

Table 4-5: Parameters

Parameter	Description
<code>cvmat</code>	Input image pointer to OpenCV <code>CvMat</code> format
<code>AXI_video_strm</code>	Output AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol

Description

- Converts data from OpenCV CvMat format to AXI4 video stream (`hls::stream`) format.
- Image data must be stored in `cvmat`.
- `AXI_video_strm` must be empty before invoking.
- The data width (in bits) of a pixel in `cvmat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

AXIvideo2CvMat

Synopsis

```
template<int W> void AXIvideo2CvMat (
    hls::stream<ap_axiu<W,1,1,1>>& AXI_video_strm,
    CvMat* cvmat);
```

Parameters

Table 4-6: Parameters

Parameter	Description
<code>AXI_video_strm</code>	Input AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol
<code>cvmat</code>	Output image pointer to OpenCV CvMat format

Description

- Converts data from AXI4 video stream (`hls::stream`) format to OpenCV CvMat format.
- Image data must be stored in `AXI_video_strm`.
- Invoking this function consumes the data in `AXI_video_strm`.
- The data width of a pixel in `cvmat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.

IplImage2hlsMat

Synopsis

```
template<int ROWS, int COLS, int T> void IplImage2hlsMat (
    IplImage* img,
    hls::Mat<ROWS, COLS, T>& mat);
```

Parameters

Table 4-7: Parameters

Parameter	Description
img	Input image header in OpenCV IplImage format
mat	Output image in hls::Mat format

Description

- Converts data from OpenCV IplImage format to hls::Mat format.
- Image data must be stored in img.
- mat must be empty before invoking.
- Arguments img and mat must have the same size and number of channels.

hlsMat2IplImage

Synopsis

```
template<int ROWS, int COLS, int T> void hlsMat2IplImage (
    hls::Mat<ROWS, COLS, T>& mat,
    IplImage* img);
```

Parameters

Table 4-8: Parameters

Parameter	Description
mat	Input image in hls::Mat format
img	Output image header in OpenCV IplImage format

Description

- Converts data from hls::Mat format to OpenCV IplImage format.
- Image data must be stored in mat.
- Invoking this function consumes the data in mat.
- Arguments mat and img must have the same size and number of channels.

cvMat2hlsMat

Synopsis

```
template<int ROWS, int COLS, int T> void cvMat2hlsMat (
    cv::Mat* cv_mat,
    hls::Mat<ROWS, COLS, T>& mat);
```

Parameters

Table 4-9: Parameters

Parameter	Description
cv_mat	Input image in OpenCV cv::Mat format
mat	Output image in hls::Mat format

Description

- Converts data from OpenCV cv::Mat format to hls::Mat format.
- Image data must be stored in cv_mat.
- mat must be empty before invoking.
- Arguments cv_mat and mat must have the same size and number of channels.

hlsMat2cvMat

Synopsis

```
template<int ROWS, int COLS, int T> void hlsMat2cvMat (
    hls::Mat<ROWS, COLS, T>& mat,
    cv::Mat& cv_mat);
```

Parameters

Table 4-10: Parameters

Parameter	Description
mat	Input image in hls::Mat format
cv_mat	Output image in OpenCV cv::Mat format

Description

- Converts data from hls::Mat format to OpenCV cv::Mat format.
- Image data must be stored in mat.
- Invoking this function consumes the data in mat.
- Arguments mat and cv_mat must have the same size and number of channels.

CvMat2hlsMat

Synopsis

```
template<int ROWS, int COLS, int T> void CvMat2hlsMat (
    CvMat* cvmat,
    hls::Mat<ROWS, COLS, T>& mat);
```

Parameters

Table 4-11: Parameters

Parameter	Description
cvmat	Input image pointer to OpenCV CvMat format
mat	Output image in hls::Mat format

Description

- Converts data from OpenCV CvMat format to hls::Mat format.
- Image data must be stored in cvmat.
- mat must be empty before invoking.
- Arguments cvmat and mat must have the same size and number of channels.

hlsMat2CvMat

Synopsis

```
template<int ROWS, int COLS, int T> void hlsMat2CvMat (
    hls::Mat<ROWS, COLS, T>& mat,
    CvMat* cvmat);
```

Parameters

Table 4-12: Parameters

Parameter	Description
mat	Input image in hls::Mat format
cvmat	Output image pointer in OpenCV cv::Mat format

Description

- Converts data from hls::Mat format to OpenCV CvMat format.
- Image data must be stored in mat.
- Invoking this function consumes the data in mat.
- Arguments mat and cvmat must have the same size and number of channels.

CvMat2hlsWindow

Synopsis

```
template<int ROWS, int COLS, typename T> void CvMat2hlsWindow (
    CvMat* cvmat,
    hls::Window<ROWS, COLS, T>& window);
```

Parameters

Table 4-13: Parameters

Parameter	Description
cvmat	Input 2D window pointer to OpenCV CvMat format
window	Output 2D window in hls::Window format

Description

- Converts data from OpenCV CvMat format to hls::Window format.
- Image data must be stored in cvmat.
- window must be empty before invoking.
- Arguments cvmat and window must be single-channel, and have the same size. This function is mainly for converting image processing kernels.

hlsWindow2CvMat

Synopsis

```
template<int ROWS, int COLS, typename T> void hlsWindow2hlsCvMat (
    hls::Window<ROWS, COLS, T>& window,
    CvMat* cvmat);
```

Parameters

Table 4-14: Parameters

Parameter	Description
window	Input 2D window in hls::Window format
cvmat	Output 2D window pointer to OpenCV CvMat format

Description

- Converts data from hls::Window format to OpenCV CvMat format.
- Image data must be stored in window.
- Invoking this function consumes the data in window.
- Arguments mat and window must be single-channel, and have the same size. This function is mainly for converting image processing kernels.

AXI4-Stream I/O Functions

hls::AXIvideo2Mat

Synopsis

```
template<int W, int ROWS, int COLS, int T> int hls::AXIvideo2Mat (
    hls::stream<ap_axiu<W,1,1,1>>& AXI_video_strm,
    hls::Mat<ROWS, COLS, T>& mat);
```

Parameters

Table 4-15: Parameters

Parameter	Description
AXI_video_strm	Input AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol
mat	Output image in <code>hls::Mat</code> format

Description

- Converts image data stored in `hls::Mat` format to an AXI4 video stream (`hls::stream`) format.
- Image data must be stored in `AXI_video_strm`.
- The data field of `mat` must be empty before invoking.
- Invoking this function consumes the data in `AXI_video_strm` and fills the image data of `mat`.
- The data width of a pixel in `mat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.
- This function is able to perform frame sync for the input video stream, by detecting the TUSER bit to mark the top-left pixel of an input frame. It returns a bit error of `ERROR_IO_EOL_EARLY` or `ERROR_IO_EOL_LATE` to indicate an unexpected line length, by detecting the TLAST input.

hls::Mat2AXIvideo

Synopsis

```
template<int W, int ROWS, int COLS, int T> int hls::AXIvideo2Mat (
    hls::Mat<ROWS, COLS, T>& mat,
    hls::stream<ap_axiu<W,1,1,1>>& AXI_video_strm);
```

Parameters

Table 4-16: Parameters

Parameter	Description
mat	Input image in <code>hls::Mat</code> format
AXI_video_strm	Output AXI4 video stream in <code>hls::stream</code> format, compatible with AXI4-Stream protocol

Description

- Converts image data stored in AXI4 video stream (`hls::stream`) format to an image of `hls::Mat` format.
- Image data must be stored in `mat`.
- The data field of `AXI_video_strm` must be empty before invoking.
- Invoking this function consumes the data in `mat` and fills the image data of `AXI_video_strm`.
- The data width of a pixel in `mat` must be no greater than `W`, the data width of TDATA in AXI4-Stream protocol.
- To fill image data to AXI4 video stream, this function also sets TUSER bit of stream element for indicating the top-left pixel, as well as setting TLAST bit in the last pixel of each line to indicate the end of line.

Video Processing Functions

hls::AbsDiff

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::AbsDiff (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-17: Parameters

Parameter	Description
src1	First input image
src2	Second input image
dst	Output image

Description

- Computes the absolute difference between two input images `src1` and `src2` and saves the result in `dst`.
- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- `src1` and `src2` must have the same size and number of channels.
- `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- `cvAbsDiff`
- `cv::absdiff`

hls::AddS

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::AddS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::AddS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask,
    hls::Mat<ROWS, COLS, DST_T>& dst_ref);
```

Parameters

Table 4-18: Parameters

Parameter	Description
src	Input image
scl	Input scalar
dst	Output image
mask	Operation mask, an 8-bit single channel image that specifies elements of the dst image to be computed.
dst_ref	Reference image that stores the elements for output image when <code>mask(I) = 0</code>

Description

- Computes the per-element sum of an image `src` and a scalar `scl`.
- Saves the result in `dst`.
- If computed with `mask`:

$$dst(I) = \begin{cases} src(I) + scl & \text{if } mask(I) \neq 0 \\ dst_ref(I) & \text{if } mask(I) = 0 \end{cases}$$

- Image data must be stored in `src` (if computed with `mask`, `mask` and `dst_ref` must have data stored), and the image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` (if computed with `mask`. The data of `mask` and `dst_ref` are also consumed) and fills the image data of `dst`.
- `src` and `scl` must have the same number of channels. `dst` and `dst_ref` must have the same size and number of channels as `src`. `mask` must have the same size as the `src`.

OpenCV Reference

- `cvAddS`
- `cv::add`

hls::AddWeighted

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T, typename P_T>
void hls::AddWeighted (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    P_T alpha,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    P_T beta,
    P_T gamma,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-19: Parameters

Parameter	Description
src1	First input image
alpha	Weight for the first image elements
src2	Second input image
beta	Weight for the second image elements
gamma	Scalar added to each sum
dst	Output image

Description

- Computes the weighted per-element sum of two image `src1` and `src2`.
- Saves the result in `dst`.
- The weighted sum computes as follows:

`dst(I)=src1(I)*alpha+src2(I)*beta+gamma`

- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- The three parameters (`alpha`, `beta` and `gamma`) must have the same datatypes.
- `src1` and `src2` must have the same size and number of channels.
- `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- `cvAddWeighted`
- `cv::addWeighted`

hls::And

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::And (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

With Mask:

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::And (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask,
    hls::Mat<ROWS, COLS, DST_T>& dst_ref);
```

Parameters

Table 4-20: Parameters

Parameter	Description
src1	First input image
src2	Second input scalar
dst	Output image
mask	Operation mask, an 8-bit single channel image that specifies elements of the dst image to be computed
dst_ref	Reference image that stores the elements for output image when mask(I) = 0

Description

- Calculates the per-element bitwise logical conjunction of two images `src1` and `src2`.
- Returns the result as image `dst`.
- If computed with `mask`:

$$dst(I) = \begin{cases} src1(I) \wedge src2(I) & \text{if } mask(I) \neq 0 \\ dst_ref(I) & \text{if } mask(I) = 0 \end{cases}$$

- Image data must be stored in `src1` and `src2`.
 - The image data of `dst` must be empty before invoking.
 - If computed with `mask`, `mask` and `dst_ref` must have data stored.
 - Invoking this function:
 - Consumes the data in `src1` and `src2`
- Note:** If computed with `mask`, the data of `mask` and `dst_ref` are also consumed.
- Fills the image data of `dst`.
 - `src1` and `src2` must have the same size and number of channels.
 - `dst` and `dst_ref` must have the same size and number of channels as the inputs.
 - `mask` must have the same size as the inputs.

OpenCV Reference

- cvAnd,
- cv::bitwise_and

hls::Avg

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
hls::Scalar<HLS_MAT_CN(DST_T), DST_T> hls::Avg(
    hls::Mat<ROWS, COLS, SRC_T>& src);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
hls::Scalar<HLS_MAT_CN(DST_T), DST_T> hls::Avg(
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask);
```

Parameters

Table 4-21: Parameters

Parameter	Description
src	Input image
mask	Operation mask, an 8-bit single channel image that specifies elements of the <code>src</code> image to be computed

Description

- Calculates an average of elements in image `src`.
- Returns the result in `hls::Scalar` format.
- If computed with `mask`:

$$N = \sum_{I: \text{mask}(I) \neq 0} 1$$

$$\text{avg}(I)_c = \left(\sum_{I: \text{mask}(I) \neq 0} \text{src}(I)_c \right) / N$$

- Image data must be stored in `src`.
- If computed with `mask`, `mask` must have data stored.
- Invoking this function consumes the data in `src`.
- If computed with `mask`, the data of `mask` is also consumed).

- `src` and `mask` must have the same size.
- `mask` must have non-zero element.

OpenCV Reference

- `cvAvg`
- `cv::mean`

hls::AvgSdv

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T>
void hls::AvgSdv(
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& avg,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& sdv);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T>
void hls::AvgSdv(
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& avg,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& sdv,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask);
```

Parameters

Table 4-22: Parameters

Parameter	Description
<code>src</code>	Input image
<code>avg</code>	Output scalar of computed mean value
<code>sdv</code>	Output scalar of computed standard deviation
<code>mask</code>	Operation mask, an 8-bit single channel image that specifies elements of the <code>src</code> image to be computed

Description

- Calculates an average of elements in image `src`.
- Returns the result in `hls::Scalar` format.
- If computed with `mask`:

$$N = \sum_{I:mask(I) \neq 0} 1$$

$$\text{avg}(I)_c = \left(\sum_{I:mask(I) \neq 0} \text{src}(I)_c \right) / N$$

$$\text{sdv}(I)_c = \sqrt{\left(\sum_{I:mask(I) \neq 0} (\text{src}(I)_c - \text{avg}(I)_c)^2 \right) / N}$$

- Image data must be stored in `src`.
- If computed with `mask`, `mask` must have data stored.
- Invoking this function consumes the data in `src`.
- If computed with `mask`, the data of `mask` is also consumed.
- Arguments `src` and `mask` must have the same size.
- `mask` must have a non-zero element.

OpenCV Reference

- `cvAvgSdv`
- `cv::meanStdDev`

hls::Cmp

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::Cmp (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    int cmp_op);
```

Parameters

Table 4-23: Parameters

Parameter	Description
src1	Returns first input image
src2	Returns second input image
dst	Returns the output 8bit single channel image
cmp_op	Returns the flag specifying the relation between the elements to be checked
HLS_CMP_EQ	Equal to
HLS_CMP_GT	Greater than
HLS_CMP_GE	Greater or equal
HLS_CMP_LT	Less than
HLS_CMP_LE	Less or equal
HLS_CMP_NE	Not equal

Description

- Performs the per-element comparison of two input images `src1` and `src2`.
- Saves the result in `dst`.

`dst(I)=src1(I) cmp_op src2(I)`

- If the comparison result is true, the corresponding element of `dst` is set to 255. Otherwise, it is set to 0.
- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- `src1` and `src2` must have the same size and number of channels.
- `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- `cvCmp`
- `cv::compare`

hls::CmpS

Synopsis

```
template<int ROWS, int COLS, int SRC_T, typename P_T, int DST_T>
void hls::CmpS (
    hls::Mat<ROWS, COLS, SRC1_T>& src,
    P_T value,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    int cmp_op);
```

Parameters

Table 4-24: Parameters

Parameter	Description
src	Input image
value	Input scalar value
dst	Output 8-bit single channel image
cmp_op	Flag that specifies the relation between the elements to be checked
HLS_CMP_EQ	Equal to
HLS_CMP_GT	Greater than
HLS_CMP_GE	Greater or equal
HLS_CMP_LT	Less than
HLS_CMP_LE	Less or equal
HLS_CMP_NE	Not equal

Description

- Performs the comparison between the elements of input images `src` and the input value and saves the result in `dst`.

`dst(I)=src(I) cmp_op value`

- If the comparison result is true, the corresponding element of `dst` is set to 255. Otherwise it is set to 0.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- cvCmpS
- cv::compare

hls::CornerHarris

Synopsis

```
template<int blockSize,int Ksize,typename KT,int SRC_T,int DST_T,int ROWS,int COLS>
void CornerHarris(
    hls::Mat<ROWS, COLS, SRC_T>      &_src,
    hls::Mat<ROWS, COLS, DST_T>      &_dst,
    KT k);
```

Parameters

Table 4-25: Parameters

Parameter	Description
src	Input image
dst	Output mask of detected corners
k	Harris detector parameter
borderType	How borders are handled

Description

- This function implements a Harris edge/corner detector. The horizontal and vertical derivatives are estimated using a Ksize*Ksize Sobel filter. The local covariance matrix M of the derivatives is smoothed over a blockSize*blockSize neighborhood of each pixel (x,y). This function outputs the function.

$$dst(x,y) = \det M^{(x,y)} - k \cdot (\text{tr} M^{(x,y)})^2$$

- Only Ksize=3 is supported.

OpenCV Reference

- cvCornerHarris
- cv::cornerHarris

hls::CvtColor

Synopsis

```
template<int code, int ROWS, int COLS, int SRC_T, int DST_T>
void hls::CvtColor (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-26: Parameters

Parameter	Description
src	Input image
dst	Output image
code	Template parameter of type of color conversion

Description

- Converts a color image from or to a grayscale image. The type of conversion is defined by the value of the code:
 - HLS_RGB2GRAY converts a RGB color image to a grayscale image.
 - HLS_BGR2GRAY converts a BGR color image to a grayscale image.
 - HLS_GRAY2RGB converts a grayscale image to a RGB image.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and required number of channels.

OpenCV Reference

- `cvCvtColor`
- `cv::cvtColor`

hls::Dilate

Synopsis

Default:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Dilate (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Custom:

```
template<int ROWS, int COLS, int SRC_T, int DST_T, int K_ROWS, int K_COLS, typename
K_T, int Shape_type, int ITERATIONS>
void hls::Dilate (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    hls::Window<K_ROWS, K_COLS, K_T> & kernel);
```

Parameters

Table 4-27: Parameters

Parameter	Description
src	Input image
dst	Output image
kernel	Rectangle of structuring element used for dilation, defined by hls::Window class. Position of the anchor within the element is at (K_ROWS/2, K_COLS/2). A 3x3 rectangular structuring element is used by default.
Shape_type	Shape of structuring element
HLS_SHAPE_RECT	Rectangular structuring element
HLS_SHAPE_CROSS	Cross-shaped structuring element, cross point is at anchor
HLS_SHAPE_ELLIPSE	Elliptic structuring element, a filled ellipse inscribed into the rectangular element
ITERATIONS	Number of times dilation is applied

Description

- Dilates the image `src` using the specified structuring element constructed within the kernel.
- Saves the result in `dst`.
- The dilation determines the shape of a pixel neighborhood over which the maximum is taken.

- Each channel of image `src` is processed independently.

$$\text{dst}(x, y) = \max_{(x', y'): \text{element}(x', y') \neq 0} \text{src}(x + x', y + y')$$

- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- `cvDilate`
- `cv::dilate`

hls::Duplicate

Synopsis

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Duplicate (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst1,
    hls::Mat<ROWS, COLS, DST_T>& dst2);
```

Parameters

Table 4-28: Parameters

Parameter	Description
<code>src</code>	Input image
<code>dst1</code>	First output image
<code>dst2</code>	Second output image

Description

- Copies the input image `src` to two output images `dst1` and `dst2`, for divergent point of two data paths.
- Image data must be stored in `src`.
- The image data of `dst1` and `dst2` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst1` and `dst2`.
- `src`, `dst1`, and `dst2` must have the same size and number of channels.

OpenCV Reference

Not applicable.

hls::EqualizeHist

Synopsis

```
template<int SRC_T, int DST_T,int ROW, int COL>
void EqualizeHist(
    Mat<ROW, COL, SRC_T>&_src,
    Mat<ROW, COL, DST_T>&_dst);
```

Parameters

Table 4-29: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Computes a histogram of each frame and uses it to normalize the range of the following frame.
- The delay avoids the use of a frame buffer in the implementation.
- The histogram is stored as static data internal to this function, allowing only one call to EqualizeHist to be made.
- The input is expected to have type HLS_8UC1.

OpenCV Reference

- cvEqualizeHist
- cv::EqualizeHist

hls::Erode

Synopsis

Default:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Erode (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Custom:

```
template<int Shape_type,int ITERATIONS,int SRC_T, int DST_T,
         typename KN_T,int IMG_HEIGHT,int IMG_WIDTH,int K_HEIGHT,int K_WIDTH>
void Erode
{
    hls::Mat<IMG_HEIGHT, IMG_WIDTH, SRC_T>&_src,
    hls::Mat<IMG_HEIGHT, IMG_WIDTH, DST_T>&_dst,
    hls::Window<K_HEIGHT,K_WIDTH,KN_T>&_kernel)
}
```

Parameters

Table 4-30: Parameters

Parameter	Description
src	Input image
dst	Output image
kernel	Rectangle of structuring element used for dilation, defined by hls::Window class. Position of the anchor within the element is at (K_ROWS/2, K_COLS/2). A 3x3 rectangular structuring element is used by default.
Shape_type	Shape of structuring element
HLS_SHAPE_RECT	Rectangular structuring element
HLS_SHAPE_CROSS	Cross-shaped structuring element, cross point is at anchor
HLS_SHAPE_ELLIPSE	Elliptic structuring element, a filled ellipse inscribed into the rectangle element
ITERATIONS	Number of times erosion is applied

Description

- Erodes the image `src` using the specified structuring element constructed within `kernel`.
- Saves the result in `dst`.
- The erosion determines the shape of a pixel neighborhood over which the maximum is taken, each channel of image `src` is processed independently:

$$dst(x, y) = \min_{(x', y'): \text{element}(x', y') \neq 0} \text{src}(x + x', y + y')$$

- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- cvErode
- cv::erode

hls::FASTX

Synopsis

```
template<int SRC_T,int ROWS,int COLS>
void FASTX(
    hls::Mat<ROWS,COLS,SRC_T>      &_src,
    hls::Mat<ROWS,COLS,HLS_8UC1> &_mask,
    int      _threshold,
    bool     _nomax_supression);

template<typename T, int N, int SRC_T,int ROWS,int COLS>
void FASTX(
    hls::Mat<ROWS,COLS,SRC_T>      &_src,
    Point_<T> (&_keypoints) [N],
    int      _threshold,
    bool     _nomax_supression);
```

Parameters

Table 4-31: Parameters

Parameter	Description
src	Input image
mask	Output image with value 255 where corners are detected
keypoints	Array of the coordinates of detected corners
threshold	FAST detector threshold. If a pixel differs from the center pixel of the window by more than this threshold, then it is either a light or a dark pixel.
nomax_supression	If true, then enable suppression of non-maximal edges

Description

- Implements the FAST corner detector, generating either a `mask` of corners, or an array of coordinates.

OpenCV Reference

- cvFAST
- cv::FASTX

hls::Filter2D

Synopsis

```
template<typename BORDERMODE, int SRC_T, int DST_T, typename KN_T, typename POINT_T,
int IMG_HEIGHT,int IMG_WIDTH,int K_HEIGHT,int K_WIDTH>
void Filter2D(
    Mat<IMG_HEIGHT, IMG_WIDTH, SRC_T>&_src,
    Mat<IMG_HEIGHT, IMG_WIDTH, DST_T> &_dst,
    Window<K_HEIGHT,K_WIDTH,KN_T>&_kernel,
    Point_-<POINT_T>anchor)

template<int SRC_T, int DST_T, typename KN_T, typename POINT_T,
int IMG_HEIGHT,int IMG_WIDTH,int K_HEIGHT,int K_WIDTH>
void Filter2D(
    Mat<IMG_HEIGHT, IMG_WIDTH, SRC_T>&_src,
    Mat<IMG_HEIGHT, IMG_WIDTH, DST_T> &_dst,
    Window<K_HEIGHT,K_WIDTH,KN_T>&_kernel,
    Point_-<POINT_T>anchor);
```

Parameters

Table 4-32: Parameters

Parameter	Description
src	Input image
dst	Output image
kernel	Kernel of 2D filtering, defined by hls::Window class
anchor	Anchor of the kernel that indicates that the relative position of a filtered point within the kernel

Description

- Applies an arbitrary linear filter to the image `src` using the specified kernel.
- Saves the result to image `dst`.
- This function filters the image by computing correlation using kernel:

$$dst(x, y) = \sum_{\substack{0 \leq x' < \text{kernel.cols} \\ 0 \leq y' < \text{kernel.rows}}} \text{kernel}(x', y') * \text{src}(x + x' - \text{anchor.x}, y + y' - \text{anchor.y})$$

- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

The function can be used with or without border modes.

Usage:

```
hls::Filter2D<3,3,BORDER_CONSTANT>(src,dst)
hls::Filter2D<3,3>(src,dst)
```

- cv::filter2D
- cvFilter2D (see the note below in the discussion of border modes)

If no border mode is selected, the default mode BORDER_DEFAULT is used.

The selection for the border modes are:

- BORDER_CONSTANT: The input is extended with zeros.
- BORDER_REPLICATE: The input is extended at the boundary with the boundary value. Given the series of pixels "abcde" the boundary value at the border is completed as "abcdeeee".
- BORDER_REFLECT: The input is extended at the boundary with the edge pixel duplicated. Given the series of pixels "abcde" the boundary value at the border is completed as "abcdeedc".
- BORDER_REFLECT_101: The input is extended at the boundary with the edge pixel not duplicated. Given the series of pixels "abcde" the boundary value at the border is completed as "abcdedcb".
- BORDER_DEFAULT: Same as BORDER_REFLECT_101.

Note: For compatibility with OpenCV function cvFilter2D use the BORDER_REPLICATE mode.

hls::GaussianBlur

Synopsis

```
template<int KH,int KW,typename BORDERMODE,int SRC_T,int DST_T,int ROWS,int COLS>
void GaussianBlur(
    Mat<ROWS, COLS, SRC_T>      &_src,
    Mat<ROWS, COLS, DST_T>      &_dst,
    double sigmaX=0,
    double sigmaY=0);

template<int KH,int KW,int SRC_T,int DST_T,int ROWS,int COLS>
void GaussianBlur(
    hls::Mat<ROWS, COLS, SRC_T>      &_src,
    hls::Mat<ROWS, COLS, DST_T>      &_dst);
    double sigmaX=0,
    double sigmaY=0);
```

Parameters

Table 4-33: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Applies a normalized 2D Gaussian Blur filter to the input.
- The filter coefficients are determined by the KH and KW parameters, which must either be 3 or 5.
- The 3x3 filter taps are given by:

[1,2,1

2,4,2

1,2,1] * 1/16

- The 5x5 filter taps are given by:

[1, 2, 3, 2, 1,

2, 5, 6, 5, 2,

3, 6, 8, 6, 3,

2, 5, 6, 5, 2,

1, 2, 3, 2, 1]* 1/84

OpenCV Reference

Usage:

```
hls::GaussianBlur<3,3,BORDER_CONSTANT>(src,dst)
hls::GaussianBlur<3,3>(src,dst)
```

- cv::GaussianBlur

If no border mode is selected, the default mode BORDER_DEFAULT is used.

The selection for the border modes are:

- BORDER_CONSTANT: The input is extended with zeros.

- BORDER_REPLICATE: The input is extended at the boundary with the boundary value. Given the series of pixels "abcde" the boundary value the border is completed as "abcdeeee".
- BORDER_REFLECT: The input is extended at the boundary with the edge pixel duplicated. Given the series of pixels "abcde" the boundary value the border is completed as "abcdeedc".
- BORDER_REFLECT_101: The input is extended at the boundary with the edge pixel not duplicated. Given the series of pixels "abcde" the boundary value the border is completed as "abcdedcb".
- BORDER_DEFAULT: Same as BORDER_REFLECT_101.

hls::Harris

Synopsis

```
template<int blockSize,int Ksize,typename KT,int SRC_T,int DST_T,int ROWS,int COLS>
void Harris(
    hls::Mat<ROWS, COLS, SRC_T>      &_src,
    hls::Mat<ROWS, COLS, DST_T>      &_dst,
    KT k,
    int threshold);
```

Parameters

Table 4-34: Parameters

Parameter	Description
src	Input image
dst	Output mask of detected corners
k	Harris detector parameter
threshold	Threshold for maximum finding

Description

- This function implements a Harris edge or corner detector.
- The horizontal and vertical derivatives are estimated using a Ksize*Ksize Sobel filter.
- The local covariance matrix M of the derivatives is smoothed over a blockSize*blockSize neighborhood of each pixel (x,y).
- Points where the function

$$dst(x,y) = \det M^{(x,y)} - k \cdot (\text{tr} M^{(x,y)})^2$$

has a maximum, and is greater than the threshold are marked as corners/edges in the output image.

- Only Ksize=3 is supported.

OpenCV Reference

- cvCornerHarris
- cv::cornerHarris

hls::HoughLines2

Synopsis

```
template<typename AT, typename RT>
struct Polar_
{
    AT angle;
    RT rho;
};

template<unsigned int theta, unsigned int rho, typename AT, typename RT, int SRC_T, int
ROW, int COL, unsigned int linesMax>
void HoughLines2(
    hls::Mat<ROW,COL,SRC_T> &_src,
    Polar_<AT,RT> (&_lines)[linesMax],
    unsigned int threshold
);
```

Parameters

Table 4-35: Parameters

Parameter	Description
src	Input image
lines	Array of parameterized lines, given in polar coordinates
threshold	Number of pixels that must land on a line before it is returned

Description

- Implements the Hough line transform.

OpenCV Reference

- cvHoughLines2
- cv::HoughLines

hls::Integral

Synopsis

```
template<int SRC_T, int DST_T, int ROWS,int COLS>
void Integral(
    Mat<ROWS, COLS, SRC_T>&_src,
    Mat<ROWS+1, COLS+1, DST_T>&_sum);
template<int SRC_T, int DST_T,int DSTSQ_T, ROWS,int COLS>
void Integral(
    Mat<ROWS, COLS, SRC_T>&_src,
    Mat<ROWS+1, COLS+1, DST_T>&_sum,
    Mat<ROWS+1, COLS+1, DSTSQ_T>&_sqsum);
```

Parameters

Table 4-36: Parameters

Parameter	Description
src	Input image
sum	Sum of pixels in the input image above and to the left of the pixel
sqsum	Sum of the squares of pixels in the input image above and to the left of the pixel

Description

- Implements the computation of an integral image.

OpenCV Reference

- cvIntegral
- cv::integral

hls::InitUndistortRectifyMap

Synopsis

```
template< typename CMT, typename RT, typename DT, int ROW, int COL, int MAP1_T, int MAP2_T,
int N>
void InitUndistortRectifyMap(
    Window<3,3, CMT> cameraMatrix,
    DT (&distCoeffs)[N],
    Window<3,3, RT> R,
    Window<3,3, CMT> newcameraMatrix,
    Mat<ROW, COL, MAP1_T> &map1,
    Mat<ROW, COL, MAP2_T> &map2);

template< typename CMT, typename RT, typename DT, int ROW, int COL, int MAP1_T, int MAP2_T,
int N>
void InitUndistortRectifyMapInverse(
    Window<3,3, CMT> cameraMatrix,
    DT (&distCoeffs)[N],
    Window<3,3, ICMT> ir
    Mat<ROW, COL, MAP1_T> &map1,
    Mat<ROW, COL, MAP2_T> &map2);
```

Parameters

Table 4-37: Parameters

Parameter	Description
cameraMatrix	Input matrix representing the camera in the old coordinate system
DT	Input distortion coefficients (Generally 4, 5, or 8 distortion coefficients are provided)
R	Input rotation matrix
newCameraMatrix	Input matrix representing the camera in the new coordinate system
ir	Input transformation matrix, equal to Invert(newcameraMatrix*R)
map1, map2	Images representing the remapping

Description

- Generates `map1` and `map2`, based on a set of parameters, where `map1` and `map2` are suitable inputs for `hls::Remap()`.
- In general, `InitUndistortRectifyMapInverse()` is preferred for synthesis, because the per-frame processing to compute `ir` is performed outside of the synthesized logic. The various parameters may be floating point or fixed-point. If fixed-point inputs are used, then internal coordinate transformations are done with at least the precision given by `ICMT`.
- As the coordinate transformations implemented in this function can be hardware resource intensive, it may be preferable to compute the results of this function offline

and store `map1` and `map2` in external memory if the input parameters are fixed and sufficient external memory bandwidth is available.

Limitations

`map1` and `map2` are only supported as `HLS_16SC2`. `cameraMatrix`, and `newCameraMatrix`, are normalized in the sense that their form is:

```
[f_x,0,c_x,  
0,f_y,c_y,  
0,0,1]
```

`R` and `ir` are also normalized with the form:

```
[a,b,c,  
d,e,f,  
0,0,1]
```

OpenCV Reference

- `cv::initUndistortRectifyMap`

hls::Max

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::Max (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-38: Parameters

Parameter	Description
<code>src1</code>	First input image
<code>src2</code>	Second input image
<code>dst</code>	Output image

Description

- Calculates per-element maximum of two input images `src1` and `src2` and saves the result in `dst`.
- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- `src1` and `src2` must have the same size and number of channels. `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- `cvMax`
- `cv::max`

hls::MaxS

Synopsis

```
template<int ROWS, int COLS, int SRC_T, typename P_T, int DST_T>
void hls::MaxS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    P_T value,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-39: Parameters

Parameter	Description
<code>src</code>	Input image
<code>value</code>	Input scalar value
<code>dst</code>	Output image

Description

- Calculates the maximum between the elements of input images `src` and the input value and saves the result in `dst`.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- cvMaxS
- cv::max

hls::Mean

Synopsis

Without Mask:

```
template<typename DST_T, int ROWS, int COLS, int SRC_T>
DST_T hls::Mean(
    hls::Mat<ROWS, COLS, SRC_T>& src);
```

With Mask:

```
template<typename DST_T, int ROWS, int COLS, int SRC_T>
DST_T hls::Mean(
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask);
```

Parameters

Table 4-40: Parameters

Parameter	Description
src	Input image
mask	Operation mask, an 8-bit single channel image that specifies elements of the src image to be computed

Description

- Calculates an average of elements in image `src`, and return the value of first channel of result scalar.
- If computed with `mask`:

$$N = \sum_{I: \text{mask}(I) \neq 0} 1$$

$$\text{mean}(I) = \left(\sum_{I: \text{mask}(I) \neq 0} \text{src}(I)_0 \right) / N$$

- Image data must be stored in `src` (if computed with `mask`, `mask` must have data stored).
- Invoking this function consumes the data in `src` (if computes with `mask`. The data of `mask` is also consumed).
- `src` and `mask` must have the same size. `mask` must have non-zero element.

OpenCV Reference

- cvMean
- cv::mean

hls::Merge

Synopsis

Input of two single-channel images:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Merge (
    hls::Mat<ROWS, COLS, SRC_T>& src0,
    hls::Mat<ROWS, COLS, SRC_T>& src1,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Input of three single-channel images:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Merge (
    hls::Mat<ROWS, COLS, SRC_T>& src0,
    hls::Mat<ROWS, COLS, SRC_T>& src1,
    hls::Mat<ROWS, COLS, SRC_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Input of four single-channel images:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Merge (
    hls::Mat<ROWS, COLS, SRC_T>& src0,
    hls::Mat<ROWS, COLS, SRC_T>& src1,
    hls::Mat<ROWS, COLS, SRC_T>& src2,
    hls::Mat<ROWS, COLS, SRC_T>& src3,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-41: Parameters

Parameter	Description
src0	First single-channel input image
src1	Second single channel input image
src2	Third single channel input image
src3	Fourth single channel input image
dst	Output multichannel image

Description

- Composes a multichannel image `dst` from several single-channel images.
- Image data must be stored in input images.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in inputs and fills the image data of `dst`.
- Input images must have the same size and be single-channel. `dst` must have the same size as the inputs, the number of channels of `dst` must equal to the number of input images.

OpenCV Reference

- `cvMerge`
- `cv::merge`

hls::Min

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T>
void hls::Min (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-42: Parameters

Parameter	Description
<code>src1</code>	First input image
<code>src2</code>	Second input image
<code>dst</code>	Output image

Description

- Calculates per-element minimum of two input images `src1` and `src2` and saves the result in `dst`.
- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- `src1` and `src2` must have the same size and number of channels.
- `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- cvMin
- cv::min

hls::MinMaxLoc

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, typename P_T>
void hls::MinMaxLoc (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    P_T* min_val,
    P_T* max_val,
    hls::Point& min_loc,
    hls::Point& max_loc);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, typename P_T>
void hls::MinMaxLoc (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    P_T* min_val,
    P_T* max_val,
    hls::Point& min_loc,
    hls::Point& max_loc,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask);
```

Parameters

Table 4-43: Parameters

Parameter	Description
src	Input image
min_val	Pointer to the output minimum value
max_val	Pointer to the output maximum value
min_loc	Output point of minimum location in input image
max_loc	Output point of maximum location in input image
mask	Operation mask, an 8-bit single channel image that specifies elements of the src image to be found

Description

- Finds the global minimum and maximum and their locations in input image src.
- Image data must be stored in src (if computed with mask, mask must have data stored).

- Invoking this function consumes the data in `src` (if computed with `mask`. The data of `mask` is also consumed).
- `min_val` and `max_val` must have the same data type. `src` and `mask` must have the same size.

OpenCV Reference

- `cvMinMaxLoc`
- `cv::minMaxLoc`

hls::MinS

Synopsis

```
template<int ROWS, int COLS, int SRC_T, typename P_T, int DST_T>
void hls::MinS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    P_T value,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-44: Parameters

Parameter	Description
<code>src</code>	Input image
<code>value</code>	Input scalar value
<code>dst</code>	Output image

Description

- Calculates the minimum between the elements of input images `src` and the input value and saves the result in `dst`.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- `cvMinS`
- `cv::min`

hls::Mul

Synopsis

```
template<int ROWS, int COLS, int SRC1_T, int SRC2_T, int DST_T, typename P_T>
void hls::Mul (
    hls::Mat<ROWS, COLS, SRC1_T>& src1,
    hls::Mat<ROWS, COLS, SRC2_T>& src2,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    P_T scale=1);
```

Parameters

Table 4-45: Parameters

Parameter	Description
src1	First input image
src2	Second input image
dst	Output image
scale	Optional scale factor

Description

- Calculates the per-element product of two input images `src1` and `src2`.
- Saves the result in image `dst`. An optional scaling factor `scale` can be used.

$$\text{dst}(\mathbf{I}) = \text{scale} * \text{src}(\mathbf{I}) * \text{src2}(\mathbf{I})$$
- Image data must be stored in `src1` and `src2`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src1` and `src2` and fills the image data of `dst`.
- `src1` and `src2` must have the same size and number of channels.
- `dst` must have the same size and number of channels as the inputs.

OpenCV Reference

- `cvMul`
- `cv::multiply`

hls::Not

Synopsis

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Not (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-46: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Performs per-element bitwise inversion of image `src`.
- Outputs the result as image `dst`.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels.

OpenCV Reference

- `cvNot`
- `cv::bitwise_not`

hls::PaintMask

Synopsis

```
template<int SRC_T,int MASK_T,int ROWS,int COLS>
void PaintMask(
    hls::Mat<ROWS,COLS,SRC_T>      &_src,
    hls::Mat<ROWS,COLS,MASK_T>       &_mask,
    hls::Mat<ROWS,COLS,SRC_T>        &_dst,
    hls::Scalar<HLS_MAT_CN(SRC_T),HLS_TNAME(SRC_T)> _color);
```

Parameters

Table 4-47: Parameters

Parameter	Description
src	Input image
mask	Input mask
dst	Output image
color	Color for marking

Description

- Each pixel of the destination image is either set to color (if `mask` is not zero) or the corresponding pixel from the input image.
- `src`, `mask`, and `dst` must all be the same size.

hls::PyrDown

Synopsis

```
template<int SRC_T,int DST_T,int ROWS,int COLS, int DROWS, int DCOLS>
void PyrDown(
    Mat<ROWS, COLS, SRC_T> &_src,
    Mat<DROWS, DCOLS, DST_T> &_dst)
```

Parameters

Table 4-48: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Blurs an image by performing the Gaussian pyramid construction and then downsizes the image by a factor of 2.
- First, this function convolves the source image with the following kernel:

[1, 4, 6, 4, 1,

4, 16, 24, 16, 2,

6, 24, 36, 24, 6,

4, 16, 24, 16, 2,

1, 4, 6, 4, 1]* 1/256

- Then, this function downsamples the image by rejecting even rows and columns.

OpenCV Reference

- cvPyrDown
- cv::pyrDown

hls::PyrUp

Synopsis

```
template<int SRC_T,int DST_T,int ROWS,int COLS, int DROWS, int DCOLS>
void PyrUp(
    Mat<ROWS, COLS, SRC_T> &_src,
    Mat<DROWS, DCOLS, DST_T> &_dst)
```

Parameters

Table 4-49: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Upsamples the image by a factor of 2 and then blurs it.
- The function performs the upsampling step of the Gaussian pyramid construction, though it can actually be used to construct the Laplacian pyramid.
- First, this function upsamples the source image by injecting even zero rows and columns.
- Then, this function convolves the result with the following kernel (same as in pyrDown() but multiplied by 4).

[1, 4, 6, 4, 1,

4, 16, 24, 16, 4,

6, 24, 36, 24, 6,

4, 16, 24, 16, 4,

1, 4, 6, 4, 1]* 1/64

OpenCV Reference

- cvPyrUp
- cv::pyrUp

hls::Range

Synopsis

```
template<int ROWS, int COLS, int SRC_T, int DST_T, typename P_T>
void hls::Range (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    P_T start,
    P_T end);
```

Parameters

Table 4-50: Parameters

Parameter	Description
src	Input single-channel image
dst	Output single-channel image
start	Left boundary value of the range
end	Right boundary value of the range

Description

- Sets all value in image `src` by the following rule and return the result as image `dst`.

$$dst(i) = (end - start) * (i * dst.cols + j) / (dst.rows * dst.cols)$$

- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and be single-channel images.

OpenCV Reference

- cvRange

hls::Remap

Synopsis

```
template <int WIN_ROW, int ROW, int COL, int SRC_T, int DST_T, int MAP1_T, int
MAP2_T>
void Remap(
    hls::Mat<ROW, COL, SRC_T>      &src,
    hls::Mat<ROW, COL, DST_T>      &dst,
    hls::Mat<ROW, COL, MAP1_T>      &map1,
    hls::Mat<ROW, COL, MAP2_T>      &map2);
```

Parameters

Table 4-51: Parameters

Parameter	Description
src	Input image
dst	Output image
• map1 • map2	Remapping

Description

- Remaps the source image `src` to the destination image `dst` according to the given remapping. For each pixel in the output image, the coordinates of an input pixel are specified by `map1` and `map2`.
- This function is designed for streaming operation for cameras with small vertical disparity. It contains an internal linebuffer to enable the remapping that contains `WIN_ROW` rows of the input image. If the row `r_i` of an input pixel corresponding to an output pixel at row `r_o` is not in the range $[r_o - (WIN_ROW/2-1), r_o + (WIN_ROW/2-1)]$ then the output is black.
- In addition, because of the architecture of the line buffer, the function uses fewer resources if `WIN_ROW` and `COL` are powers of 2.

OpenCV Reference

- `cvRemap`

hls::Reduce

Synopsis

```
template<typename INTER_SUM_T, int ROWS, int COLS, int SRC_T, int DST_ROWS, int
DST_COLS, int DST_T>
void hls::Reduce (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<DST_ROWS, DST_COLS, DST_T>& dst,
    int dim,
    int reduce_op=HLS_REDUCE_SUM) ;
```

Parameters

Table 4-52: Parameters

Parameter	Description
src	Input matrix
dst	Output vector
dim	Dimension index along which the matrix is reduced. 0 means that the matrix is reduced to a single row. 1 means that the matrix is reduced to a single column.
reduce_op	Reduction operation: <ul style="list-style-type: none"> • HLS_REDUCE_SUM: Output is the sum of all of the matrix rows/columns • HLS_REDUCE_AVG: Output is the mean vector of all of the matrix rows/columns • HLS_REDUCE_MAX: Output is the maximum (column/row-wise) of all of the matrix rows/columns • HLS_REDUCE_MIN: Output is the minimum (column/row-wise) of all of the matrix rows/columns

Description

- Reduces 2D image `src` along dimension `dim` to a vector `dst`.
- Image data must be stored in `src`.
- The data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.

OpenCV Reference

- `cvReduce`,
- `cv::reduce`

hls::Resize

Synopsis

```
template<int SRC_T, int ROWS,int COLS,int DROWS,int DCOLS>
void Resize (
    Mat<ROWS, COLS, SRC_T> &_src,
    Mat<DROWS, DCOLS, SRC_T> &_dst);
```

Parameters

Table 4-53: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Resizes the input image to the size of the output image using bilinear interpolation.

OpenCV Reference

- cvResize
- cv::resize

hls::Set

Synopsis

Sets `src` image:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::Set (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(DST_T), _T> scl,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Generates `dst` image:

```
template<int ROWS, int COLS, typename _T, int DST_T>
void hls::Set (
    hls::Scalar<HLS_MAT_CN(DST_T), _T> scl,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-54: Parameters

Parameter	Description
src	Input image
scl	Scale value to be set
dst	Output image

Description

- Sets elements in image `src` to a given scalar value `scl`.
- Saves the result as image `dst`.
- Generates a `dst` image with all element has scalar value `scl` if no input image.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `scl` must have the same number of channels.
- `dst` must have the same size and number of channels as `src`.

OpenCV Reference

- `cvSet`

hls::Scale

Synopsis

```
template<int ROWS, int COLS, int SRC_T, int DST_T, typename P_T>
void hls::Scale (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    P_T scale=1.0,
    P_T shift=0.0);
```

Parameters

Table 4-55: Parameters

Parameter	Description
<code>src</code>	Input image
<code>dst</code>	Output image
<code>scale</code>	Value of scale factor
<code>shift</code>	Value added to the scaled elements

Description

- Converts an input image `src` with optional linear transformation.
- Saves the result as image `dst`.

`dst(I)=src(I)*scale+shift`

- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and number of channels. `scale` and `shift` must have the same data types.

OpenCV Reference

- `cvScale`
- `cvConvertScale`

hls::Sobel

Synopsis

```
template<int XORDER, int YORDER, int SIZE, typename BORDERMODE, int SRC_T, int DST_T,
        int ROWS,int COLS,int DROWS,int DCOLS>
void Sobel (
    Mat<ROWS, COLS, SRC_T>&_src,
    Mat<DROWS, DCOLS, DST_T>&_dst)

template<int XORDER, int YORDER, int SIZE, int SRC_T, int DST_T, int ROWS,int
        COLS,int DROWS,int DCOLS>
void Sobel (
    Mat<ROWS, COLS, SRC_T>&_src,
    Mat<DROWS, DCOLS, DST_T>&_dst)
```

Parameters

Table 4-56: Parameters

Parameter	Description
<code>src</code>	Input image
<code>dst</code>	Output image

Description

- Computes a horizontal or vertical Sobel filter, returning an estimate of the horizontal or vertical derivative, using a filter such as:

[-1,0,1]

-2,0,2,

-1,0,1]

- SIZE=3, 5, or 7 is supported. This is the same as the equivalent OpenCV function.
- Only XORDER=1 and YORDER=0 (corresponding to horizontal derivative) or XORDER=0 and YORDER=1 (corresponding to a vertical derivative) are supported.

OpenCV Reference

The function can be used with or without border modes.

Usage:

```
hls::Sobel<1,0,3,BORDER_CONSTANT>(src,dst)
hls::Sobel<1,0,3>(src,dst)
```

- cv::Sobel
- cvSobel (see the note below in the discussion of border modes).

If no border mode is selected, the default mode BORDER_DEFAULT is used.

The selection for the border modes are:

- BORDER_CONSTANT: The input is extended with zeros.
- BORDER_REPLICATE: The input is extended at the boundary with the boundary value. Given the series of pixels "abcde" the boundary value the border is completed as "abcdeeee".
- BORDER_REFLECT: The input is extended at the boundary with the edge pixel duplicated. Given the series of pixels "abcde" the boundary value the border is completed as "abcdeedc"
- BORDER_REFLECT_101: The input is extended at the boundary with the edge pixel not duplicated. Given the series of pixels "abcde" the boundary value the border is completed as "abcdedcb".
- BORDER_DEFAULT: Same as BORDER_REFLECT_101.

Note: For compatibility with OpenCV function cvSobel, use the BORDER_REPLICATE mode.

hls::Split

Synopsis

Input image has 2 channels:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Split (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst0,
    hls::Mat<ROWS, COLS, DST_T>& dst1);
```

Input image has 3 channels:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Split (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst0,
    hls::Mat<ROWS, COLS, DST_T>& dst1,
    hls::Mat<ROWS, COLS, DST_T>& dst2);
```

Input image has 4 channels:

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Split (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst0,
    hls::Mat<ROWS, COLS, DST_T>& dst1,
    hls::Mat<ROWS, COLS, DST_T>& dst2,
    hls::Mat<ROWS, COLS, DST_T>& dst3);
```

Parameters

Table 4-57: Parameters

Parameter	Description
src	Input multichannel image
dst0	First single channel output image
dst1	Second single channel output image
dst2	Third single channel output image
dst3	Fourth single channel output image

Description

- Divides a multichannel image `src` from several single-channel images.
- Image data must be stored in image `src`.
- The image data of outputs must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of outputs.
- Output images must have the same size and be single-channel.

- `src` must have the same size as the outputs.
- The number of channels of `src` must equal to the number of output images.

OpenCV Reference

- `cvSplit`
- `cv::split`

hls::SubRS

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::SubRS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::SubRS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask,
    hls::Mat<ROWS, COLS, DST_T>& dst_ref);
```

Parameters

Table 4-58: Parameters

Parameter	Description
<code>src</code>	Input image
<code>scl</code>	Input scalar
<code>dst</code>	Output image
<code>mask</code>	Operation mask, an 8-bit single channel image that specifies elements of the <code>dst</code> image to be computed
<code>dst_ref</code>	Reference image that stores the elements for output image when <code>mask(I) = 0</code>

Description

- Computes the differences between scalar value `scl` and elements of image `src`.
- Saves the result in `dst`.
- If computed with `mask`:

```
dst(I) = {scl-src(I)      if mask(I)≠0
          dst_ref(I)     if mask(I)=0
```

- Image data must be stored in src.
- If computed with mask, mask and dst_ref must have data stored.
- The image data of dst must be empty before invoking.
- Invoking this function consumes the data in src.
- If computed with mask, the data of mask and dst_ref are also consumed and fills the image data of dst.
- src and scl must have the same number of channels. dst and dst_ref must have the same size and number of channels as src. mask must have the same size as the src.

OpenCV Reference

- cvSubRS
- cv::subtract

hls::SubS

Synopsis

Without Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::SubRS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

With Mask:

```
template<int ROWS, int COLS, int SRC_T, typename _T, int DST_T>
void hls::SubRS (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Scalar<HLS_MAT_CN(SRC_T), _T>& scl,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    hls::Mat<ROWS, COLS, HLS_8UC1>& mask,
    hls::Mat<ROWS, COLS, DST_T>& dst_ref);
```

Parameters

Table 4-59: Parameters

Parameter	Description
src	Input image
scl	Input scalar
dst	Output image
mask	Operation mask, an 8-bit single channel image that specifies elements of the dst image to be computed
dst_ref	Reference image that stores the elements for output image when mask(I) = 0

Description

- Computes the differences between elements of image src and scalar value scl.
- Saves the result in dst.

If computed with mask:

$$dst(I) = \begin{cases} src(I)-scl & \text{if } mask(I) \neq 0 \\ dst_ref(I) & \text{if } mask(I) = 0 \end{cases}$$

- Image data must be stored in src.
- If computed with mask, mask and dst_ref must have data stored.
- The image data of dst must be empty before invoking.
- Invoking this function consumes the data in src and fills the image data of dst.
- If computed with mask, the data of mask and dst_ref are also consumed.
- src and scl must have the same number of channels.
- dst and dst_ref must have the same size and number of channels as src

OpenCV Reference

- cvSub
- cv::subtract

hls::Sum

Synopsis

```
template<typename DST_T, int ROWS, int COLS, int SRC_T>
hls::Scalar<HLS_MAT_CN(SRC_T), DST_T> hls::Sum(
    hls::Mat<ROWS, COLS, SRC_T>& src);
```

Parameters

Table 4-60: Parameters

Parameter	Description
src	Input image

Description

- Sums the elements of an image src.
- Returns the result as a scalar value.
- Image data must be stored in src
- Invoking this function consumes the data in src

OpenCV Reference

- cvSum
- cv::sum

hls::Threshold

Synopsis

```
template<int ROWS, int COLS, int SRC_T, int DST_T, typename P_T>
void hls::Threshold (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst,
    P_T thresh,
    P_T maxval,
    int thresh_type);
```

Parameters

Table 4-61: Parameters

Parameter	Description
src	Input single-channel image
dst	Output single-channel image
thresh	Threshold value
maxval	Maximum value to use with some threshold types
thresh_type	Threshold type. See details in description.

Description

Performs a fixed-level threshold to each element in a single-channel image `src` and return the result as a single-channel image `dst`. The thresholding type supported by this function are determined by `thresh_type`:

`HLS_THRESH_BINARY`

$$dst(I) = \begin{cases} maxval & \text{if } src(I) > thresh \\ 0 & \text{otherwise} \end{cases}$$

`HLS_THRESH_BINARY_INV`

$$dst(I) = \begin{cases} 0 & \text{if } src(I) > thresh \\ maxval & \text{otherwise} \end{cases}$$

`HLS_THRESH_TRUNC`

$$dst(I) = \begin{cases} thresh & \text{if } src(I) > thresh \\ src(I) & \text{otherwise} \end{cases}$$

`HLS_THRESH_TOZERO`

$$dst(I) = \begin{cases} src(I) & \text{if } src(I) > thresh \\ 0 & \text{otherwise} \end{cases}$$

`HLS_THRESH_TOZERO_INV`

$$dst(I) = \begin{cases} 0 & \text{if } src(I) > thresh \\ src(I) & \text{otherwise} \end{cases}$$

- Image data must be stored in (if computed with `src`).
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `src` and `dst` must have the same size and be single-channel images. `thresh` and `maxval` must have the same data types.

OpenCV Reference

- `cvThreshold`
- `cv::threshold`

hls::Zero

Synopsis

Set (if computed with image):

```
template<int ROWS, int COLS, int SRC_T, int DST_T>
void hls::Zero (
    hls::Mat<ROWS, COLS, SRC_T>& src,
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Generate dst image:

```
template<int ROWS, int COLS, int DST_T>
void hls::Zero (
    hls::Mat<ROWS, COLS, DST_T>& dst);
```

Parameters

Table 4-62: Parameters

Parameter	Description
src	Input image
dst	Output image

Description

- Sets elements in image `src` to 0.
- Saves the result as image `dst`.
- Generates a `dst` image with all element 0 if no input image.
- Image data must be stored in `src`.
- The image data of `dst` must be empty before invoking.
- Invoking this function consumes the data in `src` and fills the image data of `dst`.
- `dst` must have the same size and number of channels as `src`.

OpenCV Reference

- `cvSetZero`
- `cvZero`

HLS Linear Algebra Library

HLS Linear Algebra Functions

This section explains the Vivado HLS linear algebra processing functions.

hls_matrix_multiply

Synopsis

```
template<
    class TransposeFormA,
    class TransposeFormB,
    int RowsA,
    int ColsA,
    int RowsB,
    int ColsB,
    int RowsC,
    int ColsC,
    typename InputType,
    typename OutputType>
void matrix_multiply(
    const InputType A[RowsA][ColsA],
    const InputType B[RowsB][ColsB],
    OutputType C[RowsC][ColsC]);
```

Description

$C = AB$

- Computes the product of two matrices, returning a third matrix.
- Optional transposition (and conjugate transposition for complex data types) of input matrices.
- Alternative architecture provided for unrolled floating-point implementations.

Parameters

Table 4-63: Parameters

Parameter	Description
TransposeFormA	Transpose requirement for matrix A; NoTranspose, Transpose, ConjugateTranspose.
TransposeFormB	Transpose requirement for matrix B; NoTranspose, Transpose, ConjugateTranspose.
RowsA	Number of rows in matrix A
ColsA	Number of columns in matrix A
RowsB	Number of rows in matrix B
ColsB	Number of columns in matrix B
RowsC	Number of rows in matrix C
ColsC	Number of columns in matrix C
InputType	Input data type
OutputType	Output data type

The function will throw an assertion and fail to compile, or synthesize, if ColsA != RowsB.
The transpose requirements for A and B are resolved before check is made.

Arguments

Table 4-64: Arguments

Argument	Description
A	First input matrix
B	Second input matrix
C	AB product output matrix

Return Values

- Not applicable (void function)

Supported Data Types

- ap_fixed
- float
- x_complex<ap_fixed>
- x_complex<float>

Input Data Assumptions

- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

hls_cholesky

Synopsis

```
template<
    bool LowerTriangularL,
    int RowsColsA,
    typename InputType,
    typename OutputType>
int cholesky(
    const InputType A[RowsColsA][RowsColsA],
    OutputType L[RowsColsA][RowsColsA])
```

Description

$A = LL^*$

- Computes the Cholesky decomposition of input matrix A, returning matrix L.
- Output matrix L may be upper triangular or lower triangular based on parameter LowerTriangularL.
- Elements in the unused portion of matrix L are set to zero.

Parameters

Table 4-65: Parameters

Parameter	Description
RowsColsA	Row and column dimension of input and output matrices
LowerTriangularL	Selects whether lower triangular or upper triangular output is desired
InputType	Input data type
OutputType	Output data type

Arguments

Table 4-66: Arguments

Argument	Description
A	Hermitian/symmetric positive definite input matrix
L	Lower or upper triangular output matrix

Return Values

- 0 = success
- 1 = failure. The function attempted to find the square root of a negative number, that is, the input matrix A was not Hermitian/symmetric positive definite.

Supported Data Types

- ap_fixed
- float
- x_complex<ap_fixed>
- x_complex<float>

Input Data Assumptions

- The function assumes that the input matrix is symmetric positive definite (Hermitian positive definite for complex-valued inputs).
- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

hls_qrf

Synopsis

```
template<
    bool TransposeQ,
    int RowsA,
    int ColsA,
    typename InputType,
    typename OutputType>
void qrf(
    const InputType A[RowsA][ColsA],
    OutputType Q[RowsA][RowsA],
    OutputType R[RowsA][ColsA])
```

Description

A=QR

- Computes the full QR factorization (QR decomposition) of input matrix A, producing orthogonal output matrix Q and upper-triangular matrix R.
- Output matrix Q may be optionally transposed based on parameter TransposeQ.
- Lower triangular elements of output matrix R are not zeroed.
- The thin (also known as economy) QR decomposition is not implemented.

Parameters

Table 4-67: Parameters

Parameter	Description
TransposeQ	Selects whether Q matrix should be transposed or not.
RowsA	Number of rows in input matrix A
ColsA	Number of columns in input matrix A
InputType	Input data type
OutputType	Output data type

- The function will fail to compile, or synthesize, if RowsA < ColsA.

Arguments

Table 4-68: Arguments

Argument	Description
A	Input matrix
Q	Orthogonal output matrix
R	Upper triangular output matrix

Return Values

- Not applicable (void function)

Supported Data Types

- float
- x_complex<float>

Input Data Assumptions

- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

hls_cholesky_inverse

Synopsis

```
template<
    int RowsColsA,
    typename InputType,
    typename OutputType>
int cholesky_inverse(
    const InputType A[RowsColsA][RowsColsA],
    OutputType InverseA[RowsColsA][RowsColsA])
```

Description

$$AA^{-1} = I$$

- Computes the inverse of symmetric positive definite input matrix A by the Cholesky decomposition method, producing matrix InverseA.

Parameters

Table 4-69: Parameters

Parameter	Description
RowsColsA	Row and column dimension of input and output matrices
InputType	Input data type
OutputType	Output data type

Arguments

Table 4-70: Arguments

Argument	Description
A	Square Hermitian/symmetric positive definite input matrix
InverseA	Inverse of input matrix

Return Values

- 0 = success
- 1 = failure. The Cholesky function attempted to find the square root of a negative number. The input matrix A was not symmetric positive definite.

Supported Data Types

- ap_fixed
- float
- x_complex<ap_fixed>
- x_complex<float>

Input Data Assumptions

- The function assumes that the input matrix is symmetric positive definite (Hermitian positive definite for complex-valued inputs).
- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

hls_qr_inverse

Synopsis

```
template<
    int RowsColsA,
    typename InputType,
    typename OutputType>
int qr_inverse(
    const InputType A[RowsColsA][RowsColsA],
    OutputType InverseA[RowsColsA][RowsColsA])
```

Description

$$AA^{-1}=I$$

- Computes the inverse of input matrix A by the QR factorization method, producing matrix InverseA.

Parameters

Table 4-71: Parameters

Parameter	Description
RowsColsA	Row and column dimension of input and output matrices.
InputType	Input data type
OutputType	Output data type

Arguments

Table 4-72: Arguments

Argument	Description
A	Input matrix A
InverseA	Inverse of input matrix

Return Values

- 0 = success
- 1 = matrix A is singular

Supported Data Types

- float
- x_complex<float>

Input Data Assumptions

- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

hls_svd

Synopsis

```
template<
    int RowsA,
    int ColsA,
    typename InputType,
    typename OutputType>
void svd(
    const InputType A[RowsA][ColsA],
    OutputType S[RowsA][ColsA],
    OutputType U[RowsA][RowsA],
    OutputType V[ColsA][ColsA])
```

Description

A=USV*

- Computes the singular value decomposition of input matrix A, producing matrices U, S and V.
- Supports only square matrix.
- Implemented using the iterative two-sided Jacobi method.

Parameters

Table 4-73: Parameters

Parameter	Description
RowsA	Row dimension
ColsA	Column dimension
InputType	Input data type
OutputType	Output data type

- The function will throw an assertion and fail to compile, or synthesize, if RowsA != ColsA.

Arguments

Table 4-74: Arguments

Argument	Description
A	Input matrix
S	Singular values of input matrix
U	Left singular vectors of input matrix
V	Right singular vectors of input matrix

Return Values

- Not applicable (void function)

Supported Data Types

- float
- x_complex<float>

Input Data Assumptions

- For floating point types, subnormal input values are not supported. If used, the synthesized hardware will flush these to zero, and behavior will differ versus software simulation.

Examples

The examples provide a basic test-bench and demonstrate how to parameterize and instantiate each Linear Algebra function. One or more examples for each function are available in the Vivado HLS examples directory:

```
<VIVADO_HLS>/examples/design/linear_algebra
```

Each example contains the following files:

- **<example>.cpp**: Top-level synthesis wrapper instantiating the library function.
- **<example>.h**: Header file defining matrix size, data type and, where applicable, architecture selection.
- **<example>_tb.cpp**: Basic test-bench instantiating top-level synthesis wrapper.
- **run_hls.tcl**: Tcl commands to set up the example Vivado HLS project:

```
vivado_hls -f run_hls.tcl
```
- **directives.tcl**: (Optional) Additional Tcl commands applying optimization/implementation directives.

C Arbitrary Precision Types

This section discusses:

- The Arbitrary Precision (AP) types provided for C language designs by Vivado HLS.
- The associated functions for C int#W types.

Compiling [u]int#W Types

To use the [u]int#W types, you must include the ap_cint.h header file in all source files that reference [u]int#W variables.

When compiling software models that use these types, it may be necessary to specify the location of the Vivado HLS header files, for example, by adding the “-I/<HLS_HOME>/include” option for gcc compilation.



TIP: Best performance occurs for software models when compiled with gcc -O3 option.

Declaring/Defining [u]int#W Variables

There are separate signed and unsigned C types, respectively:

- int#W
- uint#W

where

- #W specifies the total width of the variable being declared.

User-defined types may be created with the C/C++ ‘typedef’ statement as shown in the following examples:

```
include "ap_cint.h"           // use [u]int#W types

typedef uint128 uint128_t;     // 128-bit user defined type
int96 my_wide_var;           // a global variable declaration
```

The maximum width allowed is 1024 bits.

Initialization and Assignment from Constants (Literals)

A [u]int#W variable can be initialized with the same integer constants that are supported for the native integer data types. The constants are zero or sign extended to the full width of the [u]int#W variable.

```
#include "ap_cint.h"

uint15    a      = 0;
uint52    b      = 1234567890U;
uint52    c      = 0o12345670UL;
uint96    d      = 0x123456789ABCDEFULL;
```

For bit-widths greater than 64-bit, the following functions can be used.

apint_string2bits()

This section also discusses use of the related functions:

- `apint_string2bits_bin()`
- `apint_string2bits_oct()`
- `apint_string2bits_hex()`

These functions convert a constant character string of digits, specified within the constraints of the radix (decimal, binary, octal, hexadecimal), into the corresponding value with the given bit-width N . For any radix, the number can be preceded with the minus sign to indicate a negative value.

```
int#W apint_string2bits[_radix] (const char*, int N)
```

This is used to construct integer constants with values that are larger than those already permitted by the C language. While smaller values also work, they are easier to specify with existing C language constant value constructs.

```
#include <stdio.h>
#include "ap_cint.h"

int128 a;

// Set a to the value hex 0000000000000000123456789ABCDF0
a = apint_string2bits_hex(-123456789ABCDEF, 128);
```

Values can also be assigned directly from a character string.

apint_vstring2bits()

This function converts a character string of digits, specified within the constraints of the hexadecimal radix, into the corresponding value with the given bit-width N . The number can be preceded with the minus sign to indicate a negative value.

This is used to construct integer constants with values that are larger than those already permitted by the C language. The function is typically used in a test bench to read information from a file.

Given file test.dat contains the following data:

```
123456789ABCDEF
-123456789ABCDEF
-5
```

The function, used in the test bench, supplies the following values:

```
#include <stdio.h>
#include "ap_cint.h"

typedef data_t;

int128 test (
    int128 t a
) {
    return a+1;
}

int main () {
    FILE *fp;
    char vstring[33];

    fp = fopen(test.dat,r);

    while (fscanf(fp,%s,vstring)==1) {

        // Supply function "test" with the following values
        // 0000000000000000123456789ABCDF0
        // FFFFFFFFFFFFFFEDCBA9876543212
        // FFFFFFFFFFFFFFEDCBA9876543212

        test(apint_vstring2bits_hex(vstring,128));
        printf(\n);
    }

    fclose(fp);
    return 0;
}
```

Support for console I/O (Printing)

A [u]int#W variable can be printed with the same conversion specifiers that are supported for the native integer data types. Only the bits that fit according to the conversion specifier are printed:

```
#include "ap_cint.h"

uint164           c = 0x123456789ABCDEFULL;

printf( d%40d\n,c);          // Signed integer in decimal format
// d                         -1985229329
printf( hd%40hd\n,c);        // Short integer
// hd                        -12817
printf( ld%40ld\n,c);        // Long integer
// ld                         81985529216486895
printf(lld%40lld\n,c);       // Long long integer
// lld                        81985529216486895

printf( u%40u\n,c);          // Unsigned integer in decimal format
// u                          2309737967
printf( hu%40hu\n,c);        // hu
// hu                        52719
printf( lu%40lu\n,c);        // lu
// lu                         81985529216486895
printf(llu%40llu\n,c);       // llu
// llu                        81985529216486895

printf( o%40o\n,c);          // Unsigned integer in octal format
// o                          21152746757
printf( ho%40ho\n,c);        // ho
// ho                        146757
printf( lo%40lo\n,c);        // lo
// lo                         4432126361152746757
printf(llo%40llo\n,c);       // llo
// llo                        4432126361152746757

printf( x%40x\n,c);          // Unsigned integer in hexadecimal format [0-9a-f]
// x                          89abcdef
printf( hx%40hx\n,c);        // hx
// hx                        cdef
printf( lx%40lx\n,c);        // lx
// lx                         123456789abcdef
printf(llx%40llx\n,c);       // llx
// llx                        123456789abcdef

printf( X%40X\n,c);          // Unsigned integer in hexadecimal format [0-9A-F]
// X                          89ABCDEF
}
```

As with initialization and assignment to [u]int#W variables, features support printing values that require more than 64 bits to represent.

apint_print()

This is used to print integers with values that are larger than those already permitted by the C language. This function prints a value to `stdout`, interpreted according to the radix (2, 8, 10, 16).

```
void apint_print(int#N value, int radix)
```

The following example shows the results when `aprintf()` is used:

apint_fprint()

This is used to print integers with values that are bigger than those already permitted by the C language. This function prints a value to a file, interpreted according to the radix (2, 8, 10, 16).

```
void apint_fprint(FILE* file, int#N value, int radix)
```

Expressions Involving [u]int#W types

Variables of `[u]int#W` types may generally be used freely in expressions involving any C operators. Some behaviors may seem unexpected and require detailed explanation.

Zero- and Sign-Extension on Assignment from Narrower to Wider Variables

When assigning the value of a narrower bit-width signed variable to a wider one, the value is sign-extended to the width of the destination variable, regardless of its signedness.

Similarly, an unsigned source variable is zero-extended before assignment.

Explicit casting of the source variable might be necessary to ensure expected behavior on assignment.

Truncation on Assignment of Wider to Narrower Variables

Assigning a wider source variables value to a narrower one leads to truncation of the value. All bits beyond the most significant bit (MSB) position of the destination variable are lost.

There is no special handling of the sign information during truncation, which may lead to unexpected behavior. Explicit casting may help avoid this unexpected behavior.

Binary Arithmetic Operators

In general, any valid operation that may be done on a native C integer data type is supported for [u]int#W types.

Standard binary integer arithmetic operators are overloaded to provide arbitrary precision arithmetic. All of the following operators take either two operands of [u]int#W or one [u]int#W type and one C/C++ fundamental integer data type, for example, char, short, int.

The width and signedness of the resulting value is determined by the width and signedness of the operands, before sign-extension, zero-padding or truncation are applied based on the width of the destination variable (or expression). Details of the return value are described for each operator.

When expressions contain a mix of ap_[u]int and C/C++ fundamental integer types, the C++ types assume the following widths:

- char: 8-bits
- short: 16-bits
- int: 32-bits
- long: 32-bits
- long long: 64-bits

Addition

```
[u]int#W::RType [u]int#W::operator + ([u]int#W op)
```

Produces the sum of two ap_[u]int or one ap_[u]int and a C/C++ integer type.

The width of the sum value is:

- One bit more than the wider of the two operands
- Two bits if and only if the wider is unsigned and the narrower is signed

The sum is treated as signed if either (or both) of the operands is of a signed type.

Subtraction

```
[u]int#W::RTType [u]int#W::operator - ([u]int#W op)
```

- Produces the difference of two integers.
- The width of the difference value is:
 - One bit more than the wider of the two operands
 - Two bits if and only if the wider is unsigned and the narrower signed
- This applies before assignment, at which point it is sign-extended, zero-padded, or truncated based on the width of the destination variable.
- The difference is treated as signed regardless of the signedness of the operands.

Multiplication

```
[u]int#W::RTType [u]int#W::operator * ([u]int#W op)
```

- Returns the product of two integer values.
- The width of the product is the sum of the widths of the operands.
- The product is treated as a signed type if either of the operands is of a signed type.

Division

```
[u]int#W::RTType [u]int#W::operator / ([u]int#W op)
```

- Returns the quotient of two integer values.
- The width of the quotient is the width of the dividend if the divisor is an unsigned type; otherwise it is the width of the dividend plus one.
- The quotient is treated as a signed type if either of the operands is of a signed type.

Note: Vivado HLS synthesis of the divide operator will lead to instantiation of appropriately parameterized Xilinx LogiCORE™ IP divider cores in the generated RTL.

Modulus

```
[u]int#W::RTType [u]int#W::operator % ([u]int#W op)
```

- Returns the modulus, or remainder of integer division, for two integer values.
- The width of the modulus is the minimum of the widths of the operands, if they are both of the same signedness; if the divisor is an unsigned type and the dividend is signed then the width is that of the divisor plus one.
- The quotient is treated as having the same signedness as the dividend.

Note: Vivado HLS synthesis of the modulus (%) operator will lead to instantiation of appropriately parameterized Xilinx LogiCORE divider cores in the generated RTL.

Bitwise Logical Operators

The bitwise logical operators all return a value with a width that is the maximum of the widths of the two operands. They are treated as unsigned if and only if both operands are unsigned. Otherwise it is of a signed type.

Sign-extension (or zero-padding) may occur, based on the signedness of the expression, not the destination variable.

Bitwise OR

```
[u]int#W::RTYPE [u]int#W::operator | ([u]int#W op)
```

Returns the bitwise OR of the two operands.

Bitwise AND

```
[u]int#W::RTYPE [u]int#W::operator & ([u]int#W op)
```

Returns the bitwise AND of the two operands.

Bitwise XOR

```
[u]int#W::RTYPE [u]int#W::operator ^ ([u]int#W op)
```

Returns the bitwise XOR of the two operands.

Shift Operators

Each shift operator comes in two versions, one for unsigned right-hand side (RHS) operands and one for signed RHS.

A negative value supplied to the signed RHS versions reverses the shift operations direction, that is, a shift by the absolute value of the RHS operand in the opposite direction occurs.

The shift operators return a value with the same width as the left-hand side (LHS) operand. As with C/C++, if the LHS operand of a shift-right is a signed type, the sign bit is copied into the most significant bit positions, maintaining the sign of the LHS operand.

Unsigned Integer Shift Right

```
[u]int#W [u]int#W::operator >>(ap_uint<int_W2> op)
```

Integer Shift Right

```
[u]int#W [u]int#W::operator >>(ap_int<int_W2> op)
```

Unsigned Integer Shift Left

```
[u]int#W [u]int#W::operator <<(ap_uint<int_W2> op)
```

Integer Shift Left

```
[u]int#W [u]int#W::operator <<(ap_int<int_W2> op)
```



CAUTION! When assigning the result of a shift-left operator to a wider destination variable, some (or all) information may be lost. Xilinx recommends that you explicitly cast the shift expression to the destination type to avoid unexpected behavior.

Compound Assignment Operators

Vivado HLS supports compound assignment operators:

- *=
- /=
- %=
- +=
- -=
- <<=
- >>=
- &=
- ^=
- =

The RHS expression is first evaluated then supplied as the RHS operand to the base operator. The result is assigned back to the LHS variable. The expression sizing, signedness, and potential sign-extension or truncation rules apply as discussed above for the relevant operations.

Relational Operators

Vivado HLS supports all relational operators. They return a Boolean value based on the result of the comparison. Variables of `ap_[u] int` types may be compared to C/C++ fundamental integer types with these operators.

Equality

```
bool [u]int#W::operator == ([u]int#W op)
```

Inequality

```
bool [u]int#W::operator != ([u]int#W op)
```

Less than

```
bool [u]int#W::operator < ([u]int#W op)
```

Greater than

```
bool [u]int#W::operator > ([u]int#W op)
```

Less than or equal to

```
bool [u]int#W::operator <= ([u]int#W op)
```

Greater than or equal to

```
bool [u]int#W::operator >= ([u]int#W op)
```

Bit-Level Operation: Support Function

The `[u]int#W` types allow variables to be expressed with bit-level accuracy. It is often desirable with hardware algorithms to perform bit-level operations. Vivado HLS provides the following functions to enable this.

Bit Manipulation

The following methods are included to facilitate common bit-level operations on the value stored in `ap_[u]int` type variables.

Length

`apint_bitwidthof()`

```
int apint_bitwidthof(type_or_value)
```

Returns an integer value that provides the number of bits in an arbitrary precision integer value. It can be used with a type or a value.

```
int5 Var1, Res1;  
  
Var1= -1;  
Res1 = apint_bitwidthof(Var1); // Res1 is assigned 5  
Res1 = apint_bitwidthof(int7); // Res1 is assigned 7
```

Concatenation

`apint_concatenate()`

```
int#(N+M) apint_concatenate(int#N first, int#M second)
```

Concatenates two `[u]int#W` variables. The width of the returned value is the sum of the widths of the operands.

The High and Low arguments are placed in the higher and lower order bits of the result respectively.



RECOMMENDED: To avoid unexpected results, explicitly cast C native types (including integer literals) to an appropriate [u]int#W type before concatenating.

Bit Selection

apint_get_bit()

```
int      apint_get_bit(int#N source, int index)
```

Selects one bit from an arbitrary precision integer value and returns it.

The source must be an [u]int#W type. The index argument must be an int value. It specifies the index of the bit to select. The least significant bit has index 0. The highest permissible index is one less than the bit-width of this [u]int#W.

Set Bit Value

apint_set_bit()

```
int#N    apint_set_bit(int#N source, int index, int value)
```

- Sets the specified bit, index, of the [u]int#W instance source to the value specified (zero or one).

Range Selection

apint_get_range()

```
int#N    apint_get_range(int#N source, int high, int low)
```

- Returns the value represented by the range of bits specified by the arguments.
- The High argument specifies the most significant bit (MSB) position of the range.
- THE Low argument specifies the least significant bit (LSB) position of the range.
- The LSB of the source variable is in position 0. If the High argument has a value less than Low, the bits are returned in reverse order.

Set Range Value

apint_set_range()

```
int#N      apint_set_range(int#N source, int high, int low, int#M part)
```

- Sets the source specified bits between High and Low to the value of the part.

Bit Reduction

AND Reduce

apint_and_reduce()

```
int          apint_and_reduce(int#N value)
```

- Applies the AND operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).

```
int5 Var1, Res1;
```

```
Var1= -1;
```

```
Res1 = apint_and_reduce(Var1); // Res1 is assigned 1
```

```
Var1= 1;
```

```
Res1 = apint_and_reduce(Var1); // Res1 is assigned 0
```

- Equivalent to comparing to -1. It returns a 1 if it matches. It returns a 0 if it does not match. Another interpretation is to check that all bits are one.

OR Reduce

apint_or_reduce()

```
int          apint_or_reduce(int#N value)
```

- Applies the XOR operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).
- Equivalent to comparing to 0, and return a 0 if it matches, 1 otherwise.

```
int5 Var1, Res1;
```

```
Var1= 1;
```

```
Res1 = apint_or_reduce(Var1); // Res1 is assigned 1
```

```
Var1= 0;
```

```
Res1 = apint_or_reduce(Var1); // Res1 is assigned 0
```

XOR Reduce

apint_xor_reduce()

```
int          apint_xor_reduce(int#N value)
```

- Applies the OR operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).
- Equivalent to counting the ones in the word. This operation:
 - Returns 0 if there is an even number.
 - Returns 1 if there is an odd number (even parity).

```

int5 Var1, Res1;

Var1= 0;
Res1 = apint_xor_reduce(Var1);           // Res1 is assigned 0

Var1= 1;
Res1 = apint_xor_reduce(Var1);           // Res1 is assigned 1

```

NAND Reduce

apint_nand_reduce()

```
int          apint_nand_reduce(int#N value)
```

- Applies the NAND operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).
- Equivalent to comparing this value against -1 (all ones) and returning false if it matches, true otherwise.

```

int5 Var1, Res1;

Var1= 1;
Res1 = apint_nand_reduce(Var1);           // Res1 is assigned 1

Var1= -1;
Res1 = apint_nand_reduce(Var1);           // Res1 is assigned 0

```

NOR Reduce

apint_nor_reduce()

```
int          apint_nor_reduce(int#N value)
```

- Applies the NOR operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).
- Equivalent to comparing this value against 0 (all zeros) and returning true if it matches, false otherwise.

```

int5 Var1, Res1;

Var1= 0;
Res1 = apint_nor_reduce(Var1);           // Res1 is assigned 1

Var1= 1;
Res1 = apint_nor_reduce(Var1);           // Res1 is assigned 0

```

XNOR Reduce

`apint_xnor_reduce()`

```
int apint_xnor_reduce(int#N value)
```

- Applies the XNOR operation on all bits in the value.
- Returns the resulting single bit as an integer value (which can be cast onto a bool).
- Equivalent to counting the ones in the word.
- This operation:
 - Returns 1 if there is an odd number.
 - Returns 0 if there is an even number (odd parity).

```
int5 Var1, Res1;

Var1= 0;
Res1 = apint_xnor_reduce(Var1);           // Res1 is assigned 1

Var1= 1;
Res1 = apint_xnor_reduce(Var1);           // Res1 is assigned 0
```

C++ Arbitrary Precision Types

Vivado HLS provides a C++ template class, `ap_[u]int<>`, that implements arbitrary precision (or bit-accurate) integer data types with consistent, bit-accurate behavior between software and hardware modeling.

This class provides all arithmetic, bitwise, logical and relational operators allowed for native C integer types. In addition, this class provides methods to handle some useful hardware operations, such as allowing initialization and conversion of variables of widths greater than 64 bits. Details for all operators and class methods are discussed below.

Compiling `ap_[u]int<>` Types

To use the `ap_[u]int<>` classes, you must include the `ap_int.h` header file in all source files that reference `ap_[u]int<>` variables.

When compiling software models that use these classes, it may be necessary to specify the location of the Vivado HLS header files, for example by adding the `-I/<HLS_HOME>/include` option for g++ compilation.



TIP: Best performance occurs for software models when compiled with `g++ -O3` option.

Declaring/Defining ap_[u] Variables

There are separate signed and unsigned classes:

- `ap_int<int_W>` (signed)
- `ap_uint<int_W>` (unsigned)

The template parameter `int_W` specifies the total width of the variable being declared.

User-defined types may be created with the C/C++ `typedef` statement as shown in the following examples:

```
include "ap_int.h"//           use ap_[u]fixed<> types
typedef ap_uint<128> uint128_t; // 128-bit user defined type
ap_int<96> my_wide_var;      // a global variable declaration
```

The default maximum width allowed is 1024 bits. This default may be overridden by defining the macro `AP_INT_MAX_W` with a positive integer value less than or equal to 32768 before inclusion of the `ap_int.h` header file.



CAUTION! *Setting the value of AP_INT_MAX_W too High may cause slow software compile and run times.*

Following is an example of overriding `AP_INT_MAX_W`:

```
#define AP_INT_MAX_W 4096          // Must be defined before next line
#include "ap_int.h"

ap_int<4096> very_wide_var;
```

Initialization and Assignment from Constants (Literals)

The class constructor and assignment operator overloads, allows initialization of and assignment to `ap_[u]fixed<>` variables using standard C/C++ integer literals.

This method of assigning values to `ap_[u]fixed<>` variables is subject to the limitations of C++ and the system upon which the software will run. This typically leads to a 64-bit limit on integer literals (for example, for those `LL` or `ULL` suffixes).

To allow assignment of values wider than 64-bits, the `ap_[u]fixed<>` classes provide constructors that allow initialization from a string of arbitrary length (less than or equal to the width of the variable).

By default, the string provided is interpreted as a hexadecimal value as long as it contains only valid hexadecimal digits (that is, 0-9 and a-f). To assign a value from such a string, an explicit C++ style cast of the string to the appropriate type must be made.

Following are examples of initialization and assignments, including for values greater than 64-bit, are:

```
ap_int<42> a_42b_var(-1424692392255LL);           // long long decimal format
a_42b_var = 0x14BB648B13FLL;                      // hexadecimal format

a_42b_var = -1;                                     // negative int literal sign-extended to full width

ap_uint<96> wide_var("76543210fedcba9876543210"); // Greater than 64-bit
wide_var = ap_int<96>("0123456789abcdef01234567");
```

The `ap_[u]<>` constructor may be explicitly instructed to interpret the string as representing the number in radix 2, 8, 10, or 16 formats. This is accomplished by adding the appropriate radix value as a second parameter to the constructor call.

A compilation error occurs if the string literal contains any characters that are invalid as digits for the radix specified.

The following examples use different radix formats:

```
ap_int<6> a_6bit_var("101010", 2);    // 42d in binary format
a_6bit_var = ap_int<6>("40", 8);      // 32d in octal format
a_6bit_var = ap_int<6>("55", 10);     // decimal format
a_6bit_var = ap_int<6>("2A", 16);     // 42d in hexadecimal format

a_6bit_var = ap_int<6>("42", 2);      // COMPILE-TIME ERROR! "42" is not binary
```

The radix of the number encoded in the string can also be inferred by the constructor, when it is prefixed with a zero (0) followed by one of the following characters: "b", "o" or "x"; the prefixes "0b", "0o" and "0x" correspond to binary, octal and hexadecimal formats respectively.

The following examples use alternate initializer string formats:

```
ap_int<6> a_6bit_var("0b101010", 2);    // 42d in binary format
a_6bit_var = ap_int<6>("0o40", 8);      // 32d in octal format
a_6bit_var = ap_int<6>("0x2A", 16);     // 42d in hexadecimal format

a_6bit_var = ap_int<6>("0b42", 2);      // COMPILE-TIME ERROR! "42" is not binary
```

If the bit-width is greater than 53-bits, the `ap_[u]fixed` value must be initialized with a string, for example:

```
ap_ufixed<72,10> Val("2460508560057040035.375");
```

Support for Console I/O (Printing)

As with initialization and assignment to `ap_[u]fixed<>` variables, Vivado HLS supports printing values that require more than 64-bits to represent.

Using the C++ Standard Output Stream

The easiest way to output any value stored in an ap_[u]int variable is to use the C++ standard output stream:

- `&std::cout` (#include <iostream> or
- <iostream.h>)

The stream insertion operator (<<) is overloaded to correctly output the full range of values possible for any given ap_[u]fixed variable. The following stream manipulators are also supported:

- dec (decimal)
- hex (hexadecimal)
- oct (octal)

These allow formatting of the value as indicated.

The following example uses cout to print values:

```
#include <iostream.h>
// Alternative: #include <iostream>

ap_ufixed<72> Val("10fedcba9876543210");

cout << Val << endl;           // Yields: "313512663723845890576"
cout << hex << val << endl; // Yields: "10fedcba9876543210"
cout << oct << val << endl; // Yields: "41773345651416625031020"
```

Using the Standard C Library

You can also use the standard C library (#include <stdio.h>) to print out values larger than 64-bits:

1. Convert the value to a C++ std::string using the ap_[u]fixed classes method `to_string()`.
2. Convert the result to a null-terminated C character string using the std::string class method `c_str()`.

Optional Argument One (Specifying the Radix)

You can pass the `ap[u]int::to_string()` method an optional argument specifying the radix of the numerical format desired. The valid radix argument values are:

- 2 (binary)
- 8 (octal)
- 10 (decimal)
- 16 (hexadecimal) (default)

Optional Argument Two (Printing as Signed Values)

A second optional argument to `ap_[u]int::to_string()` specifies whether to print the non-decimal formats as signed values. This argument is boolean. The default value is false, causing the non-decimal formats to be printed as unsigned values.

The following examples use `printf` to print values:

```
ap_int<72> Val("80fedcba9876543210");

printf("%s\n", Val.to_string().c_str());           // => "80FEDCBA9876543210"
printf("%s\n", Val.to_string(10).c_str());          // => "-2342818482890329542128"
printf("%s\n", Val.to_string(8).c_str());           // => "401773345651416625031020"
printf("%s\n", Val.to_string(16, true).c_str());    // => "-7F0123456789ABCDF0"
```

Expressions Involving `ap_[u]>` types

Variables of `ap_[u]>` types may generally be used freely in expressions involving C/C++ operators. Some behaviors may be unexpected. These are discussed in detail below.

Zero- and Sign-Extension on Assignment From Narrower to Wider Variables

When assigning the value of a narrower bit-width signed (`ap_int<>`) variable to a wider one, the value is sign-extended to the width of the destination variable, regardless of its signedness.

Similarly, an unsigned source variable is zero-extended before assignment.

Explicit casting of the source variable may be necessary to ensure expected behavior on assignment. See the following example:

```
ap_uint<10> Result;

ap_int<7> Val1 = 0x7f;
ap_uint<6> Val2 = 0x3f;

Result = Val1;           // Yields: 0x3ff (sign-extended)
Result = Val2;           // Yields: 0x03f (zero-padded)

Result = ap_uint<7>(Val1); // Yields: 0x07f (zero-padded)
Result = ap_int<6>(Val2); // Yields: 0x3ff (sign-extended)
```

Truncation on Assignment of Wider to Narrower Variables

Assigning the value of a wider source variable to a narrower one leads to truncation of the value. All bits beyond the most significant bit (MSB) position of the destination variable are lost.

There is no special handling of the sign information during truncation. This may lead to unexpected behavior. Explicit casting may help avoid this unexpected behavior.

Class Methods and Operators

The `ap_[u]int` types do not support implicit conversion from wide `ap_[u]int (>64bits)` to builtin C/C++ integer types. For example, the following code example return `s1`, because the implicit cast from `ap_int[65]` to `bool` in the if-statement returns a 0.

```
bool nonzero(ap_uint<65> data) {
    return data; // This leads to implicit truncation to 64b int
}

int main() {
    if (nonzero((ap_uint<65>)1 << 64)) {
        return 0;
    }
    printf(FAIL\n);
    return 1;
}
```

To convert wide `ap_[u]int` types to built-in integers, use the explicit conversion functions included with the `ap_[u]int` types:

- `to_int()`
- `to_long()`
- `to_bool()`

In general, any valid operation that can be done on a native C/C++ integer data type is supported using operator overloading for `ap_[u]int` types.

In addition to these overloaded operators, some class specific operators and methods are included to ease bit-level operations.

Binary Arithmetic Operators

Standard binary integer arithmetic operators are overloaded to provide arbitrary precision arithmetic. These operators take either:

- Two operands of `ap_[u]int`, or
- One `ap_[u]int` type and one C/C++ fundamental integer data type

For example:

- `char`
- `short`
- `int`

The width and signedness of the resulting value is determined by the width and signedness of the operands, before sign-extension, zero-padding or truncation are applied based on the width of the destination variable (or expression). Details of the return value are described for each operator.

When expressions contain a mix of `ap_[u]int` and C/C++ fundamental integer types, the C++ types assume the following widths:

- `char` (8-bits)
- `short` (16-bits)
- `int` (32-bits)
- `long` (32-bits)
- `long long` (64-bits)

Addition

```
ap_(u)int::RType ap_(u)int::operator + (ap_(u)int op)
```

Returns the sum of:

- Two `ap_[u]int`, or
- One `ap_[u]int` and a C/C++ integer type

The width of the sum value is:

- One bit more than the wider of the two operands, or
- Two bits if and only if the wider is unsigned and the narrower is signed

The sum is treated as signed if either (or both) of the operands is of a signed type.

Subtraction

```
ap_(u)int::RType ap_(u)int::operator - (ap_(u)int op)
```

Returns the difference of two integers.

The width of the difference value is:

- One bit more than the wider of the two operands, or
- Two bits if and only if the wider is unsigned and the narrower signed

This is true before assignment, at which point it is sign-extended, zero-padded, or truncated based on the width of the destination variable.

The difference is treated as signed regardless of the signedness of the operands.

Multiplication

```
ap_(u)int::RType ap_(u)int::operator * (ap_(u)int op)
```

Returns the product of two integer values.

The width of the product is the sum of the widths of the operands.

The product is treated as a signed type if either of the operands is of a signed type.

Division

```
ap_(u)int::RType ap_(u)int::operator / (ap_(u)int op)
```

Returns the quotient of two integer values.

The width of the quotient is the width of the dividend if the divisor is an unsigned type. Otherwise, it is the width of the dividend plus one.

The quotient is treated as a signed type if either of the operands is of a signed type.



IMPORTANT: Vivado HLS synthesis of the divide operator leads to instantiation of appropriately parameterized Xilinx LogiCORE divider cores in the generated RTL.

Modulus

```
ap_(u)int::RType ap_(u)int::operator % (ap_(u)int op)
```

Returns the modulus, or remainder of integer division, for two integer values.

The width of the modulus is the minimum of the widths of the operands, if they are both of the same signedness.

If the divisor is an unsigned type and the dividend is signed, then the width is that of the divisor plus one.

The quotient is treated as having the same signedness as the dividend.



IMPORTANT: Vivado HLS synthesis of the modulus (%) operator will lead to instantiation of appropriately parameterized Xilinx LogiCORE divider cores in the generated RTL.

Following are examples of arithmetic operators:

```
ap_uint<71> Rslt;
ap_uint<42> Val1 = 5;
ap_int<23> Val2 = -8;

Rslt = Val1 + Val2;      // Yields: -3 (43 bits) sign-extended to 71 bits
Rslt = Val1 - Val2;      // Yields: +3 sign extended to 71 bits
Rslt = Val1 * Val2;      // Yields: -40 (65 bits) sign extended to 71 bits
Rslt = 50 / Val2;        // Yields: -6 (33 bits) sign extended to 71 bits
Rslt = 50 % Val2;        // Yields: +2 (23 bits) sign extended to 71 bits
```

Bitwise Logical Operators

The bitwise logical operators all return a value with a width that is the maximum of the widths of the two operand. It is treated as unsigned if and only if both operands are unsigned. Otherwise, it is of a signed type.

Sign-extension (or zero-padding) may occur, based on the signedness of the expression, not the destination variable.

Bitwise OR

```
ap_(u)int::RTType ap_(u)int::operator | (ap_(u)int op)
```

Returns the bitwise OR of the two operands.

Bitwise AND

```
ap_(u)int::RTType ap_(u)int::operator & (ap_(u)int op)
```

Returns the bitwise AND of the two operands.

Bitwise XOR

```
ap_(u)int::RTType ap_(u)int::operator ^ (ap_(u)int op)
```

Returns the bitwise XOR of the two operands.

Unary Operators

Addition

```
ap_(u)int ap_(u)int::operator + ()
```

Returns the self copy of the `ap_[u]int` operand.

Subtraction

```
ap_(u)int::RTYPE ap_(u)int::operator - ()
```

Returns the following:

- The negated value of the operand with the same width if it is a signed type, or
- Its width plus one if it is unsigned.

The return value is always a signed type.

Bitwise Inverse

```
ap_(u)int::RTYPE ap_(u)int::operator ~ ()
```

Returns the bitwise-NOT of the operand with the same width and signedness.

Logical Invert

```
bool ap_(u)int::operator ! ()
```

Returns a Boolean `false` value if and only if the operand is *not* equal to zero (0).

Returns a Boolean `true` value if the operand is equal to zero (0).

Shift Operators

Each shift operator comes in two versions:

- One version for *unsigned* right-hand side (RHS) operands
- One version for *signed* right-hand side (RHS) operands

A negative value supplied to the signed RHS versions reverses the shift operations direction. That is, a shift by the absolute value of the RHS operand in the opposite direction occurs.

The shift operators return a value with the same width as the left-hand side (LHS) operand. As with C/C++, if the LHS operand of a shift-right is a signed type, the sign bit is copied into the most significant bit positions, maintaining the sign of the LHS operand.

Unsigned Integer Shift Right

```
ap_(u)int ap_(u)int::operator << (ap_uint<int_W2> op)
```

Integer Shift Right

```
ap_(u)int ap_(u)int::operator << (ap_int<int_W2> op)
```

Unsigned Integer Shift Left

```
ap_(u)int ap_(u)int::operator >> (ap_uint<int_W2> op)
```

Integer Shift Left

```
ap_(u)int ap_(u)int::operator >> (ap_int<int_W2> op)
```



CAUTION! When assigning the result of a shift-left operator to a wider destination variable, some or all information may be lost. Xilinx recommends that you explicitly cast the shift expression to the destination type to avoid unexpected behavior.

Following are examples of shift operations:

```
ap_uint<13> Rslt;  
  
ap_uint<7> Val1 = 0x41;  
  
Rslt = Val1 << 6;           // Yields: 0x0040, i.e. msb of Val1 is lost  
Rslt = ap_uint<13>(Val1) << 6; // Yields: 0x1040, no info lost  
  
ap_int<7> Val2 = -63;  
Rslt = Val2 >> 4;          //Yields: 0x1ffc, sign is maintained and extended
```

Compound Assignment Operators

Vivado HLS supports compound assignment operators:

- *=
- /=
- %=
- +=
- -=
- <<=
- >>=
- &=
- ^=
- |=

The RHS expression is first evaluated then supplied as the RHS operand to the base operator, the result of which is assigned back to the LHS variable. The expression sizing, signedness, and potential sign-extension or truncation rules apply as discussed above for the relevant operations.

```

ap_uint<10> Val1 = 630;
ap_int<3> Val2 = -3;
ap_uint<5> Val3 = 27;

Val1 += Val2 - Val3;           // Yields: 600 and is equivalent to:

// Val1 = ap_uint<10>(ap_int<11>(Val1) +
//           ap_int<11>((ap_int<6>(Val2) -
//           ap_int<6>(Val3))));
```

Example 4-1: Compound Assignment Statement

Increment and Decrement Operators

The increment and decrement operators are provided. All return a value of the same width as the operand and which is unsigned if and only if both operands are of unsigned types and signed otherwise.

Pre-Increment

```
ap_(u)int& ap_(u)int::operator ++ ()
```

Returns the incremented value of the operand.

Assigns the incremented value to the operand.

Post-Increment

```
const ap_(u)int ap_(u)int::operator ++ (int)
```

Returns the value of the operand before assignment of the incremented value to the operand variable.

Pre-Decrement

```
ap_(u)int& ap_(u)int::operator -- ()
```

Returns the decremented value of, as well as assigning the decremented value to, the operand.

Post-Decrement

```
const ap_(u)int ap_(u)int::operator -- (int)
```

Returns the value of the operand before assignment of the decremented value to the operand variable.

Relational Operators

Vivado HLS supports all relational operators. They return a Boolean value based on the result of the comparison. You can compare variables of ap_[u]int types to C/C++ fundamental integer types with these operators.

Equality

```
bool ap_(u)int::operator == (ap_(u)int op)
```

Inequality

```
bool ap_(u)int::operator != (ap_(u)int op)
```

Less than

```
bool ap_(u)int::operator < (ap_(u)int op)
```

Greater than

```
bool ap_(u)int::operator > (ap_(u)int op)
```

Less than or equal to

```
bool ap_(u)int::operator <= (ap_(u)int op)
```

Greater than or equal to

```
bool ap_(u)int::operator >= (ap_(u)int op)
```

Other Class Methods, Operators, and Data Members

The following sections discuss other class methods, operators, and data members.

Bit-Level Operations

The following methods facilitate common bit-level operations on the value stored in ap_[u]int type variables.

Length

```
int ap_(u)int::length ()
```

Returns an integer value providing the total number of bits in the ap_[u]int variable.

Concatenation

```
ap_concat_ref ap_(u)int::concat (ap_(u)int low)
ap_concat_ref ap_(u)int::operator , (ap_(u)int high, ap_(u)int low)
```

Concatenates two ap_[u]int variables, the width of the returned value is the sum of the widths of the operands.

The High and Low arguments are placed in the higher and lower order bits of the result respectively; the `concat()` method places the argument in the lower order bits.

When using the overloaded comma operator, the parentheses are required. The comma operator version may also appear on the LHS of assignment.



RECOMMENDED: To avoid unexpected results, explicitly cast C/C++ native types (including integer literals) to an appropriate `ap_[u]int` type before concatenating.

```
ap_uint<10> Rslt;  
  
ap_int<3> Val1 = -3;  
ap_int<7> Val2 = 54;  
  
Rslt = (Val2, Val1);           // Yields: 0x1B5  
Rslt = Val1.concat(Val2);     // Yields: 0x2B6  
(Val1, Val2) = 0xAB;          // Yields: Val1 == 1, Val2 == 43
```

Example 4-2: Concatenation Example

Bit Selection

```
ap_bit_ref ap_(u)int::operator [] (int bit)
```

Selects one bit from an arbitrary precision integer value and returns it.

The returned value is a reference value that can set or clear the corresponding bit in this `ap_[u]int`.

The bit argument must be an `int` value. It specifies the index of the bit to select. The least significant bit has index 0. The highest permissible index is one less than the bit-width of this `ap_[u]int`.

The result type `ap_bit_ref` represents the reference to one bit of this `ap_[u]int` instance specified by bit.

Range Selection

```
ap_range_ref ap_(u)int::range (unsigned Hi, unsigned Lo)  
ap_range_ref ap_(u)int::operator () (unsigned Hi, unsigned Lo)
```

Returns the value represented by the range of bits specified by the arguments.

The `Hi` argument specifies the most significant bit (MSB) position of the range, and `Lo` specifies the least significant bit (LSB).

The LSB of the source variable is in position 0. If the `Hi` argument has a value less than `Lo`, the bits are returned in reverse order.

```
ap_uint<4> Rslt;
ap_uint<8> Val1 = 0x5f;
ap_uint<8> Val2 = 0xaa;

Rslt = Val1.range(3, 0);    // Yields: 0xF
Val1(3,0) = Val2(3, 0);    // Yields: 0x5A
Val1(4,1) = Val2(4, 1);    // Yields: 0x55
Rslt = Val1.range(4, 7);    // Yields: 0xA; bit-reversed!
```

Example 4-3: Range Selection Examples

AND reduce

```
bool ap_(u)int::and_reduce ()
```

- Applies the AND operation on all bits in this `ap_(u)int`.
- Returns the resulting single bit.
- Equivalent to comparing this value against -1 (all ones) and returning `true` if it matches, `false` otherwise.

OR reduce

```
bool ap_(u)int::or_reduce ()
```

- Applies the OR operation on all bits in this `ap_(u)int`.
- Returns the resulting single bit.
- Equivalent to comparing this value against 0 (all zeros) and returning `false` if it matches, `true` otherwise.

XOR reduce

```
bool ap_(u)int::xor_reduce ()
```

- Applies the XOR operation on all bits in this `ap_int`.
- Returns the resulting single bit.
- Equivalent to counting the number of 1 bits in this value and returning `false` if the count is even or `true` if the count is odd.

NAND reduce

```
bool ap_(u)int::nand_reduce ()
```

- Applies the NAND operation on all bits in this `ap_int`.
- Returns the resulting single bit.

- Equivalent to comparing this value against -1 (all ones) and returning `false` if it matches, `true` otherwise.

NOR reduce

```
bool ap_int::nor_reduce ()
```

- Applies the NOR operation on all bits in this `ap_int`.
- Returns the resulting single bit.
- Equivalent to comparing this value against 0 (all zeros) and returning `true` if it matches, `false` otherwise.

XNOR reduce

```
bool ap_(u)int::xnor_reduce ()
```

- Applies the XNOR operation on all bits in this `ap_(u)int`.
- Returns the resulting single bit.
- Equivalent to counting the number of 1 bits in this value and returning `true` if the count is even or `false` if the count is odd.

Bit Reduction Method Examples

```
ap_uint<8> Val = 0xaa;

bool t = Val.and_reduce(); // Yields: false
t = Val.or_reduce();      // Yields: true
t = Val.xor_reduce();    // Yields: false
t = Val.nand_reduce();   // Yields: true
t = Val.nor_reduce();    // Yields: false
t = Val.xnor_reduce();   // Yields: true
```

Example 4-4: Bit Reduction Method Example

Bit Reverse

```
void ap_(u)int::reverse ()
```

Reverses the contents of `ap_[u]int` instance:

- The LSB becomes the MSB.
- The MSB becomes the LSB.

Reverse Method Example

```
ap_uint<8> Val = 0x12;

Val.reverse(); // Yields: 0x48
```

Test Bit Value

```
bool ap_(u)int::test (unsigned i)
```

Checks whether specified bit of ap_(u) int instance is 1.

Returns true if Yes, false if No.

Test Method Example

```
ap_uint<8> Val = 0x12;
bool t = Val.test(5); // Yields: true
```

Set Bit Value

```
void ap_(u)int::set (unsigned i, bool v)
void ap_(u)int::set_bit (unsigned i, bool v)
```

Sets the specified bit of the ap_(u) int instance to the value of integer v.

Set Bit (to 1)

```
void ap_(u)int::set (unsigned i)
```

Sets the specified bit of the ap_(u) int instance to the value 1 (one).

Clear Bit (to 0)

```
void ap_(u)int:: clear(unsigned i)
```

Sets the specified bit of the ap_(u) int instance to the value 0 (zero).

Invert Bit

```
void ap_(u)int:: invert(unsigned i)
```

Inverts the bit specified in the function argument of the ap_(u) int instance. The specified bit becomes 0 if its original value is 1 and vice versa.

Example of bit set, clear and invert bit methods:

```
ap_uint<8> Val = 0x12;
Val.set(0, 1);           // Yields: 0x13
Val.set_bit(5, false);  // Yields: 0x03
Val.set(7);             // Yields: 0x83
Val.clear(1);           // Yields: 0x81
Val.invert(5);          // Yields: 0x91
```

Rotate Right

```
void ap_(u)int:: rrotate(unsigned n)
```

Rotates the ap_(u) int instance *n* places to right.

Rotate Left

```
void ap_(u)int:: lrotate(unsigned n)
```

Rotates the ap_(u)int instance *n* places to left.

```
ap_uint<8> Val = 0x12;  
  
Val.rrotate(3);      // Yields: 0x42  
Val.lrotate(6);      // Yields: 0x90
```

Example 4-5: Rotate Methods Example

Bitwise NOT

```
void ap_(u)int:: b_not()
```

- Complements every bit of the ap_(u)int instance.

```
ap_uint<8> Val = 0x12;  
  
Val.b_not();    // Yields: 0xED
```

Example 4-6: Bitwise NOT Example

Test Sign

```
bool ap_int:: sign()
```

- Checks whether the ap_(u)int instance is negative.
- Returns `true` if negative.
- Returns `false` if positive.

Explicit Conversion Methods

To C/C++ “(u)int”

```
int ap_(u)int::to_int ()  
unsigned ap_(u)int::to_uint ()
```

- Returns native C/C++ (32-bit on most systems) integers with the value contained in the ap_[u]int.
- Truncation occurs if the value is greater than can be represented by an [unsigned] int.

To C/C++ 64-bit “(u)int”

```
long long ap_(u)int::to_int64 ()  
unsigned long long ap_(u)int::to_uint64 ()
```

- Returns native C/C++ 64-bit integers with the value contained in the ap_[u]int.

- Truncation occurs if the value is greater than can be represented by an [unsigned] int.

To C/C++ “double”

```
double ap_(u)int::to_double ()
```

- Returns a native C/C++ double 64-bit floating point representation of the value contained in the ap_[u]int.
- If the ap_[u]int is wider than 53 bits (the number of bits in the mantissa of a double), the resulting double may not have the exact value expected.

Sizeof

When the standard C++ `sizeof()` function is used with `ap_[u]int` types it returns the number of bytes. The following set the value of `var1` to 32.

```
int var1 = sizeof(ap_uint<256>);
```

Compile Time Access to Data Type Attributes

The `ap_[u]int<>` types are provided with a static member that allows the size of the variables to be determined at compile time. The data type is provided with the static const member `width`, which is automatically assigned the width of the data type:

```
static const int width = _AP_W;
```

You can use the `width` data member to extract the data width of an existing `ap_[u]int<>` data type to create another `ap_[u]int<>` data type at compile time. The following example shows how the size of variable `Res` is defined as 1-bit greater than variables `Val1` and `Val2`:

```
// Definition of basic data type
#define INPUT_DATA_WIDTH 8
typedef ap_int<INPUT_DATA_WIDTH> data_t;
// Definition of variables
data_t Val1, Val2;
// Res is automatically sized at run-time to be 1-bit greater than data type data_t
ap_int<data_t::width+1> Res = Val1 + Val2;
```

This ensures that Vivado HLS correctly models the bit-growth caused by the addition even if you update the value of `INPUT_DATA_WIDTH` for `data_t`.

C++ Arbitrary Precision Fixed-Point Types

Vivado HLS supports fixed-point types that allow fractional arithmetic to be easily handled. The advantage of fixed-point arithmetic is shown in the following example.

```
ap_fixed<10, 5> Var1 = 22.96875;           // 10-bit signed word, 5 fractional bits
ap_ufixed<12,11> Var2 = 512.5            // 12-bit word, 1 fractional bit
ap_fixed<13,5> Res1;                      // 13-bit signed word, 5 fractional bits

Res1 = Var1 + Var2;                        // Result is 535.46875
```

Even though `Var1` and `Var2` have different precisions, the fixed-point type ensures that the decimal point is correctly aligned before the operation (an addition in this case), is performed. You are not required to perform any operations in the C code to align the decimal point.

The type used to store the result of any fixed-point arithmetic operation must be large enough (in both the integer and fractional bits) to store the full result.

If this is not the case, the `ap_fixed` type performs:

- overflow handling (when the result has more MSBs than the assigned type supports)
- quantization (or rounding, when the result has fewer LSBs than the assigned type supports)

The `ap_[u]fixed` type provides includes various options on how the overflow and quantization are performed. The options are discussed below.

The `ap_[u]fixed` Representation

In `ap[u]fixed` types, a fixed-point value is represented as a sequence of bits with a specified position for the binary point.

- Bits to the left of the binary point represent the integer part of the value.
- Bits to the right of the binary point represent the fractional part of the value.

`ap_[u]fixed` type is defined as follows:

```
ap_[u]fixed<int W,
          int I,
          ap_q_mode Q,
          ap_o_mode O,
          ap_sat_bits N>;
```

- The `W` attribute takes one parameter, the total number of bits for the word. Only a constant integer expression can be used as the parameter value.

- The `I` attribute takes one parameter, the number of bits to represent the integer part.
 - The value of `I` must be less than or equal to `W`.
 - The number of bits to represent the fractional part is `W` minus `I`.
 - Only a constant integer expression can be used as the parameter value.
- The `Q` attribute takes one parameter, quantization mode.
 - Only a predefined enumerated value can be used as the parameter value.
 - The default value is `AP_TRN`.
- The `O` attribute takes one parameter, overflow mode.
 - Only predefined enumerated value can be used as the parameter value.
 - The default value is `AP_WRAP`.
- The `N` attribute takes one parameter, the number of saturation bits considered used in the overflow wrap modes.
 - Only a constant integer expression can be used as the parameter value.
 - The default value is zero.

Note: If the quantization, overflow and saturation parameters are not specified, as in the first example above, the default settings are used.

The quantization and overflow modes are explained below.

Quantization Modes

- Rounding to plus infinity `AP_RND`
- Rounding to zero `AP_RND_ZERO`
- Rounding to minus infinity `AP_RND_MIN_INF`
- Rounding to infinity `AP_RND_INF`
- Convergent rounding `AP_RND_CONV`
- Truncation `AP_TRUNC`
- Truncation to zero `AP_TRUNC_ZERO`

`AP_RND`

- Round the value to the nearest representable value for the specific `ap_[u]fixed` type.

```
ap_fixed<3, 2, AP_RND, AP_SAT> UAPFixed4 = 1.25;           // Yields: 1.5
ap_fixed<3, 2, AP_RND, AP_SAT> UAPFixed4 = -1.25;          // Yields: -1.0
```

Example 4-7: AP_RND Example

AP_RND_ZERO

- Round the value to the nearest representable value.
- Round towards zero.
 - For positive values, delete the redundant bits.
 - For negative values, add the least significant bits to get the nearest representable value.

```
ap_fixed<3, 2, AP_RND_ZERO, AP_SAT> UAPFixed4 = 1.25; // Yields: 1.0
ap_fixed<3, 2, AP_RND_ZERO, AP_SAT> UAPFixed4 = -1.25; // Yields: -1.0
```

Example 4-8: AP_RND_ZERO Example

AP_RND_MIN_INF

- Round the value to the nearest representable value.
- Round towards minus infinity.
 - For positive values, delete the redundant bits.
 - For negative values, add the least significant bits.

```
ap_fixed<3, 2, AP_RND_MIN_INF, AP_SAT> UAPFixed4 = 1.25; // Yields: 1.0
ap_fixed<3, 2, AP_RND_MIN_INF, AP_SAT> UAPFixed4 = -1.25; // Yields: -1.5
```

Example 4-9: AP_RND_MIN_INF Example

AP_RND_INF

- Round the value to the nearest representable value.
- The rounding depends on the least significant bit.
 - For positive values, if the least significant bit is set, round towards plus infinity. Otherwise, round towards minus infinity.
 - For negative values, if the least significant bit is set, round towards minus infinity. Otherwise, round towards plus infinity.

```
ap_fixed<3, 2, AP_RND_INF, AP_SAT> UAPFixed4 = 1.25; // Yields: 1.5
ap_fixed<3, 2, AP_RND_INF, AP_SAT> UAPFixed4 = -1.25; // Yields: -1.5
```

Example 4-10: AP_RND_INF Example

AP_RND_CONV

- Round the value to the nearest representable value.
- The rounding depends on the least significant bit.
 - If least significant bit is set, round towards plus infinity.
 - Otherwise, round towards minus infinity.

```
ap_fixed<3, 2, AP_RND_CONV, AP_SAT> UAPFixed4 = 0.75;      // Yields: 1.0
ap_fixed<3, 2, AP_RND_CONV, AP_SAT> UAPFixed4 = -1.25;     // Yields: -1.0
```

Example 4-11: AP_RND_CONV Examples

AP_TRN

- Round the value to the nearest representable value.
- Always round the value towards minus infinity.

```
ap_fixed<3, 2, AP_TRN, AP_SAT> UAPFixed4 = 1.25;      // Yields: 1.0
ap_fixed<3, 2, AP_TRN, AP_SAT> UAPFixed4 = -1.25;     // Yields: -1.5
```

Example 4-12: AP_TRN Examples

AP_TRN_ZERO

Round the value to the nearest representable value.

- * For positive values, the rounding is the same as mode AP_TRN.
- * For negative values, round towards zero.

```
ap_fixed<3, 2, AP_TRN_ZERO, AP_SAT> UAPFixed4 = 1.25;      // Yields: 1.0
ap_fixed<3, 2, AP_TRN_ZERO, AP_SAT> UAPFixed4 = -1.25;     // Yields: -1.0
```

Example 4-13: AP_TRN_ZERO Examples

Overflow Modes

- Saturation [AP_SAT](#)
- Saturation to zero [AP_SAT_ZERO](#)
- Symmetrical saturation [AP_SAT_SYM](#)
- Wrap-around [AP_WRAP](#)
- Sign magnitude wrap-around [AP_WRAP_SM](#)

AP_SAT

Saturate the value.

- To the maximum value in case of overflow.
- To the negative maximum value in case of negative overflow.

```
ap_fixed<4, 4, AP_RND, AP_SAT> UAPFixed4 = 19.0;           // Yields: 7.0
ap_fixed<4, 4, AP_RND, AP_SAT> UAPFixed4 = -19.0;          // Yields: -8.0
ap_ufixed<4, 4, AP_RND, AP_SAT> UAPFixed4 = 19.0;          // Yields: 15.0
ap_ufixed<4, 4, AP_RND, AP_SAT> UAPFixed4 = -19.0;         // Yields: 0.0
```

Example 4-14: AP_SAT Examples

AP_SAT_ZERO

Force the value to zero in case of overflow, or negative overflow.

```
ap_fixed<4, 4, AP_RND, AP_SAT_ZERO> UAPFixed4 = 19.0;        // Yields: 0.0
ap_fixed<4, 4, AP_RND, AP_SAT_ZERO> UAPFixed4 = -19.0;       // Yields: 0.0
ap_ufixed<4, 4, AP_RND, AP_SAT_ZERO> UAPFixed4 = 19.0;        // Yields: 0.0
ap_ufixed<4, 4, AP_RND, AP_SAT_ZERO> UAPFixed4 = -19.0;       // Yields: 0.0
```

Example 4-15: AP_SAT_ZERO Examples

AP_SAT_SYM

Saturate the value:

- To the maximum value in case of overflow.
- To the minimum value in case of negative overflow.
 - Negative maximum for signed `ap_fixed` types
 - Zero for unsigned `ap_ufixed` types

```
ap_fixed<4, 4, AP_RND, AP_SAT_SYM> UAPFixed4 = 19.0;        // Yields: 7.0
ap_fixed<4, 4, AP_RND, AP_SAT_SYM> UAPFixed4 = -19.0;       // Yields: -7.0
ap_ufixed<4, 4, AP_RND, AP_SAT_SYM> UAPFixed4 = 19.0;        // Yields: 15.0
ap_ufixed<4, 4, AP_RND, AP_SAT_SYM> UAPFixed4 = -19.0;       // Yields: 0.0
```

Example 4-16: AP_SAT_SYM Examples

AP_WRAP

Wrap the value around in case of overflow.

```
ap_fixed<4, 4, AP_RND, AP_WRAP> UAPFixed4 = 31.0;           // Yields: -1.0
ap_fixed<4, 4, AP_RND, AP_WRAP> UAPFixed4 = -19.0;          // Yields: -3.0
ap_ufixed<4, 4, AP_RND, AP_WRAP> UAPFixed4 = 19.0;          // Yields: 3.0
ap_ufixed<4, 4, AP_RND, AP_WRAP> UAPFixed4 = -19.0;         // Yields: 13.0
```

Example 4-17: AP_WRAP Examples

If the value of N is set to zero (the default overflow mode):

- All MSB bits outside the range are deleted.
- For unsigned numbers. After the maximum it wraps around to zero.
- For signed numbers. After the maximum, it wraps to the minimum values.

If $N > 0$:

- When $N > 0$, N MSB bits are saturated or set to 1.
- The sign bit is retained, so positive numbers remain positive and negative numbers remain negative.
- The bits that are not saturated are copied starting from the LSB side.

AP_WRAP_SM

The value should be sign-magnitude wrapped around.

```
ap_fixed<4, 4, AP_RND, AP_WRAP_SM> UAPFixed4 = 19.0;      // Yields: -4.0
ap_fixed<4, 4, AP_RND, AP_WRAP_SM> UAPFixed4 = -19.0;     // Yields: 2.0
```

Example 4-18: AP_WRAP_SM Examples

If the value of N is set to zero (the default overflow mode):

- 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.
 - a. Delete redundant MSBs.
 - b. The new sign bit is the least significant bit of the deleted bits. 0 in this case.
 - c. Compare the new sign bit with the sign of the new value.
- If different, invert all the numbers. They are different in this case.

If $N > 0$:

- Uses sign magnitude saturation
- N MSBs are saturated to 1.
- Behaves similar to a case in which $N = 0$, except that positive numbers stay positive and negative numbers stay negative.

Compiling ap_[u]fixed<> Types

To use the `ap_[u]fixed<>` classes, you must include the `ap_fixed.h` header file in all source files that reference `ap_[u]fixed<>` variables.

When compiling software models that use these classes, it may be necessary to specify the location of the Vivado HLS header files, for example by adding the `"-I/<HLS_HOME>/include"` option for g++ compilation.

TIP: *Software models perform best when compiled with the g++ -O3 option.*



Declaring and Defining ap_[u]fixed<> Variables

There are separate signed and unsigned classes:

- `ap_fixed<W, I>` (signed)
- `ap_ufixed<W, I>` (unsigned)

You can create user-defined types with the C/C++ `typedef` statement:

```
#include "ap_fixed.h"                                // use ap_[u]fixed<> types

typedef ap_ufixed<128,32> uint128_t;    // 128-bit user defined type,
                                         // 32 integer bits
```

Example 4-19: User-Defined Types Examples

Initialization and Assignment from Constants (Literals)

You can initialize `ap_[u]fixed` variable with normal floating point constants of the usual C/C++ width:

- 32 bits for type `float`
- 64 bits for type `double`

That is, typically, a floating point value that is single precision type or in the form of double precision.

Such floating point constants are interpreted and translated into the full width of the arbitrary precision fixed-point variable depending on the sign of the value (if support is also provided for using the C99 standard hexadecimal floating point constants).

```
#include <ap_fixed.h>

ap_ufixed<30, 15> my15BitInt = 3.1415;
ap_fixed<42, 23> my42BitInt = -1158.987;
ap_ufixed<99, 40> = 287432.0382911;
ap_fixed<36,30> = -0x123.456p-1;
```

The ap_[u]fixed types do not support initialization if they are used in an array of std::complex types.

```
typedef ap_fixed<DIN_W, 1, AP_TRN, AP_SAT> coeff_t; // MUST have IW >= 1
std::complex<coeff_t> twid_rom[REAL_SZ/2] = {{ 1, -0 }, { 0.9, -0.006 }, etc.}
```

The initialization values must first be cast to std::complex:

```
typedef ap_fixed<DIN_W, 1, AP_TRN, AP_SAT> coeff_t; // MUST have IW >= 1
std::complex<coeff_t> twid_rom[REAL_SZ/2] = {std::complex<coeff_t>( 1, -0 ),
std::complex<coeff_t>(0.9, -0.006 ),etc.}
```

Support for Console I/O (Printing)

As with initialization and assignment to ap_[u]fixed<> variables, Vivado HLS supports printing values that require more than 64 bits to represent.

The easiest way to output any value stored in an ap_[u]fixed variable is to use the C++ standard output stream, std::cout (#include <iostream> or <iostream.h>). The stream insertion operator, "<<", is overloaded to correctly output the full range of values possible for any given ap_[u]fixed variable. The following stream manipulators are also supported, allowing formatting of the value as shown.

- dec (decimal)
- hex (hexadecimal)
- oct (octal)

```
#include <iostream.h>
// Alternative: #include <iostream>

ap_fixed<6,3, AP_RND, AP_WRAP> Val = 3.25;

cout << Val << endl;      // Yields: 3.25
```

Example 4-20: Example Using cout to Print Values

Using the Standard C Library

You can also use the standard C library (#include <stdio.h>) to print out values larger than 64-bits:

1. Convert the value to a C++ std::string using the ap_[u]fixed classes method `to_string()`.
2. Convert the result to a null-terminated C character string using the std::string class method `c_str()`.

Optional Argument One (Specifying the Radix)

You can pass the `ap[u]int::to_string()` method an optional argument specifying the radix of the numerical format desired. The valid radix argument values are:

- 2 (binary)
- 8 (octal)
- 10 (decimal)
- 16 (hexadecimal) (default)

Optional Argument Two (Printing as Signed Values)

A second optional argument to `ap_[u]int::to_string()` specifies whether to print the non-decimal formats as signed values. This argument is boolean. The default value is false, causing the non-decimal formats to be printed as unsigned values.

```
ap_fixed<6,3, AP_RND, AP_WRAP> Val = 3.25;

printf("%s \n", in2.to_string().c_str()); // Yields: 0b011.010
printf("%s \n", in2.to_string(10).c_str()); //Yields: 3.25
```

Example 4-21: Printing Binary and Base 10

The `ap_[u]fixed` types are supported by the following C++ manipulator functions:

- `setprecision`
- `setw`
- `setfill`

The `setprecision` manipulator sets the decimal precision to be used. It takes one parameter `f` as the value of decimal precision, where `n` specifies the maximum number of meaningful digits to display in total (counting both those before and those after the decimal point).

The default value of `f` is 6, which is consistent with native `c float` type.

```
ap_fixed<64, 32> f =3.14159;
cout << setprecision (5) << f << endl;
cout << setprecision (9) << f << endl;
f = 123456;
cout << setprecision (5) << f << endl;
```

The example above displays the following results where the printed results are rounded when the actual precision exceeds the specified precision:

```
3.1416
3.14159
1.2346e+05
```

The `setw` manipulator:

- Sets the number of characters to be used for the field width.
- Takes one parameter `w` as the value of the width

where

- `w` determines the minimum number of characters to be written in some output representation.

If the standard width of the representation is shorter than the field width, the representation is padded with fill characters. Fill characters are controlled by the `setfill` manipulator which takes one parameter `f` as the padding character.

For example, given:

```
ap_fixed<65,32> aa = 123456;
int precision = 5;
cout<<setprecision(precision)<<setw(13)<<setfill('T')<<a<<endl;
```

The output is:

```
TTT1.2346e+05
```

Expressions Involving `ap_[u]fixed<>` types

Arbitrary precision fixed-point values can participate in expressions that use any operators supported by C/C++. After an arbitrary precision fixed-point type or variable is defined, their usage is the same as for any floating point type or variable in the C/C++ languages.

Observe the following caveats:

- Zero and Sign Extensions

All values of smaller bit-width are zero or sign-extended depending on the sign of the source value. You may need to insert casts to obtain alternative signs when assigning smaller bit-widths to larger.

- Truncations

Truncation occurs when you assign an arbitrary precision fixed-point of larger bit-width than the destination variable.

Class Methods, Operators, and Data Members

In general, any valid operation that can be done on a native C/C++ integer data type is supported (using operator overloading) for `ap_[u]fixed` types. In addition to these overloaded operators, some class specific operators and methods are included to ease bit-level operations.

Binary Arithmetic Operators

Addition

```
ap_[u]fixed::RType ap_[u]fixed::operator + (ap_[u]fixed op)
```

Adds an arbitrary precision fixed-point with a given operand `op`.

The operands can be any of the following integer types:

- `ap_[u]fixed`
- `ap_[u]int`
- C/C++

The result type `ap_[u]fixed::RType` depends on the type information of the two operands.

```
ap_fixed<76, 63> Result;
ap_fixed<5, 2> Val1 = 1625.153;
ap_fixed<75, 62> Val2 = 6721.355992351;

Result = Val1 + Val2; //Yields 6722.480957
```

Example 4-22: Binary Arithmetic Operator Addition Example

Because `Val2` has the larger bit-width on both integer part and fraction part, the result type has the same bit-width and plus one to be able to store all possible result values.

Subtraction

```
ap_[u]fixed::RType ap_[u]fixed::operator - (ap_[u]fixed op)
```

Subtracts an arbitrary precision fixed-point with a given operand `op`.

The result type `ap_[u]fixed::RType` depends on the type information of the two operands.

```
ap_fixed<76, 63> Result;
ap_fixed<5, 2> Val1 = 1625.153;
ap_fixed<75, 62> Val2 = 6721.355992351;

Result = Val2 - Val1; // Yields 6720.23057
```

Example 4-23: Binary Arithmetic Operator Subtraction Example

Because `Val2` has the larger bit-width on both integer part and fraction part, the result type has the same bit-width and plus one to be able to store all possible result values.

Multiplication

```
ap_[u]fixed::RType ap_[u]fixed::operator * (ap_[u]fixed op)
```

Multiplies an arbitrary precision fixed-point with a given operand op.

```
ap_fixed<80, 64> Result;  
  
ap_fixed<5, 2> Val1 = 1625.153;  
ap_fixed<75, 62> Val2 = 6721.355992351;  
  
Result = Val1 * Val2; // Yields 7561.525452
```

Example 4-24: Binary Arithmetic Operator Multiplication Example

This shows the multiplication of Val1 and Val2. The result type is the sum of their integer part bit-width and their fraction part bit width.

Division

```
ap_[u]fixed::RType ap_[u]fixed::operator / (ap_[u]fixed op)
```

Divides an arbitrary precision fixed-point by a given operand op.

```
ap_fixed<84, 66> Result;  
  
ap_fixed<5, 2> Val1 = 1625.153;  
ap_fixed<75, 62> Val2 = 6721.355992351;  
  
Result = Val2 / Val1; // Yields 5974.538628
```

Example 4-25: Binary Arithmetic Operator Division Example

This shows the division of Val1 and Val2. To preserve enough precision:

- The integer bit-width of the result type is sum of the integer = bit-width of Val1 and the fraction bit-width of Val2.
- The fraction bit-width of the result type is sum of the fraction bit-width of Val1 and the whole bit-width of Val2.

Bitwise Logical Operators

Bitwise OR

```
ap_[u]fixed::RType ap_[u]fixed::operator | (ap_[u]fixed op)
```

Applies a bitwise operation on an arbitrary precision fixed-point and a given operand `op`.

```
ap_fixed<75, 62> Result;  
  
ap_fixed<5, 2> Val1 = 1625.153;  
ap_fixed<75, 62> Val2 = 6721.355992351;  
  
Result = Val1 | Val2;           // Yields 6271.480957
```

Example 4-26: Bitwise Logical Operator Bitwise OR Example

Bitwise AND

```
ap_[u]fixed::RType ap_[u]fixed::operator & (ap_[u]fixed op)
```

Applies a bitwise operation on an arbitrary precision fixed-point and a given operand `op`.

```
ap_fixed<75, 62> Result;  
  
ap_fixed<5, 2> Val1 = 1625.153;  
ap_fixed<75, 62> Val2 = 6721.355992351;  
  
Result = Val1 & Val2;           // Yields 1.00000
```

Example 4-27: Bitwise Logical Operator Bitwise AND Example

Bitwise XOR

```
ap_[u]fixed::RType ap_[u]fixed::operator ^ (ap_[u]fixed op)
```

Applies an `xor` bitwise operation on an arbitrary precision fixed-point and a given operand `op`.

```
ap_fixed<75, 62> Result;  
  
ap_fixed<5, 2> Val1 = 1625.153;  
ap_fixed<75, 62> Val2 = 6721.355992351;  
  
Result = Val1 ^ Val2;           // Yields 6720.480957
```

Example 4-28: Bitwise Logical Operator Bitwise XOR Example

Increment and Decrement Operators

Pre-Increment

```
ap_[u]fixed ap_[u]fixed::operator ++ ()
```

This operator function prefix increases an arbitrary precision fixed-point variable by 1.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = ++Val1;           // Yields 6.125000
```

Example 4-29: Increment and Decrement Operators: Pre-Increment Example

Post-Increment

```
ap_[u]fixed ap_[u]fixed::operator ++ (int)
```

This operator function postfix:

- Increases an arbitrary precision fixed-point variable by 1.
- Returns the original val of this arbitrary precision fixed-point.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = Val1++;           // Yields 5.125000
```

Example 4-30: Increment and Decrement Operators: Post-Increment Example

Pre-Decrement

```
ap_[u]fixed ap_[u]fixed::operator -- ()
```

This operator function prefix decreases this arbitrary precision fixed-point variable by 1.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = --Val1;           // Yields 4.125000
```

Example 4-31: Increment and Decrement Operators: Pre-Decrement Example

Post-Decrement

```
ap_[u]fixed ap_[u]fixed::operator -- (int)
```

This operator function postfix:

- Decreases this arbitrary precision fixed-point variable by 1.
- Returns the original val of this arbitrary precision fixed-point.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = Val1--;           // Yields 5.125000
```

Example 4-32: Increment and Decrement Operators: Post-Decrement Example

Unary Operators

Addition

```
ap_[u]fixed ap_[u]fixed::operator + ()
```

Returns a self copy of an arbitrary precision fixed-point variable.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = +Val1;           // Yields 5.125000
```

Example 4-33: Unary Operators: Addition Example

Subtraction

```
ap_[u]fixed::RTYPE ap_[u]fixed::operator - ()
```

Returns a negative value of an arbitrary precision fixed-point variable.

```
ap_fixed<25, 8> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = -Val1;           // Yields -5.125000
```

Example 4-34: Unary Operators: Subtraction Example

Equality Zero

```
bool ap_[u]fixed::operator != ()
```

This operator function:

- Compares an arbitrary precision fixed-point variable with 0,
- Returns the result.

```
bool Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = !Val1;           // Yields false
```

Example 4-35: Unary Operators: Equality Zero Example

Bitwise Inverse

```
ap_[u]fixed::RType ap_[u]fixed::operator ~ ()
```

Returns a bitwise complement of an arbitrary precision fixed-point variable.

```
ap_fixed<25, 15> Result;
ap_fixed<8, 5> Val1 = 5.125;

Result = ~Val1;           // Yields -5.25
```

Example 4-36: Unary Operators: Bitwise Inverse Example

Shift Operators

Unsigned Shift Left

```
ap_[u]fixed ap_[u]fixed::operator << (ap_uint<_W2> op)
```

This operator function:

- Shifts left by a given integer operand.
- Returns the result.

The operand can be a C/C++ integer type:

- char
- short
- int
- long

The return type of the shift left operation is the same width as the type being shifted.

Note: Shift does not support overflow or quantization modes.

```
ap_fixed<25, 15> Result;
ap_fixed<8, 5> Val = 5.375;

ap_uint<4> sh = 2;

Result = Val << sh;           // Yields -10.5
```

Example 4-37: Shift Operators: Unsigned Shift Left Example

The bit-width of the result is ($W = 25$, $I = 15$). Because the shift left operation result type is same as the type of Val:

- The high order two bits of Val are shifted out.
- The result is -10.5.

If a result of 21.5 is required, Val must be cast to `ap_fixed<10, 7>` first -- for example, `ap_ufixed<10, 7>(Val)`.

Signed Shift Left

```
ap_[u]fixed ap_[u]fixed::operator << (ap_int<_W2> op)
```

This operator:

- Shifts left by a given integer operand.
- Returns the result.

The shift direction depends on whether the operand is positive or negative.

- If the operand is positive, a shift right is performed.
- If the operand is negative, a shift left (opposite direction) is performed.

The operand can be a C/C++ integer type:

- `char`
- `short`
- `int`
- `long`

The return type of the shift right operation is the same width as the type being shifted.

```
ap_fixed<25, 15, false> Result;
ap_uint<8, 5> Val = 5.375;

ap_int<4> Sh = 2;
Result = Val << sh;           // Shift left, yields -10.25

Sh = -2;
Result = Val << sh;           // Shift right, yields 1.25
```

Example 4-38: Shift Operators: Signed Shift Left Example

Unsigned Shift Right

```
ap_[u]fixed ap_[u]fixed::operator >> (ap_uint<_W2> op)
```

This operator function:

- Shifts right by a given integer operand.
- Returns the result.

The operand can be a C/C++ integer type:

- char
- short
- int
- long

The return type of the shift right operation is the same width as the type being shifted.

```
ap_fixed<25, 15> Result;
ap_fixed<8, 5> Val = 5.375;

ap_uint<4> sh = 2;

Result = Val >> sh;           // Yields 1.25
```

Example 4-39: Shift Operators: Unsigned Shift Right Example

If it is necessary to preserve all significant bits, extend fraction part bit-width of the Val first, for example ap_fixed<10, 5>(Val).

Signed Shift Right

```
ap_[u]fixed ap_[u]fixed::operator >> (ap_int<_W2> op)
```

This operator:

- Shifts right by a given integer operand.
- Returns the result.

The shift direction depends on whether operand is positive or negative.

- If the operand is positive, a shift right performed.
- If operand is negative, a shift left (opposite direction) is performed.

The operand can be a C/C++ integer type (char, short, int, or long).

The return type of the shift right operation is the same width as type being shifted. For example:

```
ap_fixed<25, 15, false> Result;
ap_uint<8, 5> Val = 5.375;

ap_int<4> Sh = 2;
Result = Val >> sh;           // Shift right, yields 1.25

Sh = -2;
Result = Val >> sh;           // Shift left,  yields -10.5

1.25
```

Relational Operators

Equality

```
bool ap_[u]fixed::operator == (ap_[u]fixed op)
```

This operator compares the arbitrary precision fixed-point variable with a given operand.

Returns `true` if they are equal and `false` if they are *not* equal.

The type of operand `op` can be `ap_[u]fixed`, `ap_int` or C/C++ integer types. For example:

```
bool Result;

ap_ufixed<8, 5> Val1 = 1.25;
ap_fixed<9, 4> Val2 = 17.25;
ap_fixed<10, 5> Val3 = 3.25;

Result = Val1 == Val2;           // Yields true
Result = Val1 == Val3;          // Yields false
```

Inequality

```
bool ap_[u]fixed::operator != (ap_[u]fixed op)
```

This operator compares this arbitrary precision fixed-point variable with a given operand.

Returns `true` if they are *not* equal and `false` if they are equal.

The type of operand `op` can be:

- `ap_[u]fixed`
- `ap_int`
- C or C++ integer types

For example:

```
bool Result;

ap_ufixed<8, 5> Val1 = 1.25;
ap_fixed<9, 4> Val2 = 17.25;
ap_fixed<10, 5> Val3 = 3.25;

Result = Val1 != Val2;         // Yields false
Result = Val1 != Val3;         // Yields true
```

Greater than or equal to

```
bool ap_[u]fixed::operator >= (ap_[u]fixed op)
```

This operator compares a variable with a given operand.

Returns `true` if they are equal or if the variable is greater than the operator and `false` otherwise.

The type of operand `op` can be `ap_[u]fixed`, `ap_int` or C/C++ integer types.

For example:

```
bool Result;

ap_ufixed<8, 5> Val1 = 1.25;
ap_fixed<9, 4> Val2 = 17.25;
ap_fixed<10, 5> Val3 = 3.25;

Result = Val1 >= Val2;           // Yields true
Result = Val1 >= Val3;           // Yields false
```

Less than or equal to

```
bool ap_[u]fixed::operator <= (ap_[u]fixed op)
```

This operator compares a variable with a given operand, and return `true` if it is equal to or less than the operand and `false` if not.

The type of operand `op` can be `ap_[u]fixed`, `ap_int` or C/C++ integer types.

For example:

```
bool Result;

ap_ufixed<8, 5> Val1 = 1.25;
ap_fixed<9, 4> Val2 = 17.25;
ap_fixed<10, 5> Val3 = 3.25;

Result = Val1 <= Val2;           // Yields true
Result = Val1 <= Val3;           // Yields true
```

Greater than

```
bool ap_[u]fixed::operator > (ap_[u]fixed op)
```

This operator compares a variable with a given operand, and return `true` if it is greater than the operand and `false` if not.

The type of operand `op` can be `ap_[u]fixed`, `ap_int`, or C/C++ integer types.

For example:

```
bool Result;

ap_ufixed<8, 5> Val1 = 1.25;
ap_fixed<9, 4> Val2 = 17.25;
ap_fixed<10, 5> Val3 = 3.25;

Result = Val1 > Val2;           // Yields false
Result = Val1 > Val3;           // Yields false
```

Less than

```
bool ap_[u]fixed::operator < (ap_[u]fixed op)
```

This operator compares a variable with a given operand, and return `true` if it is less than the operand and `false` if not.

The type of operand `op` can be `ap_[u]fixed`, `ap_int`, or C/C++ integer types. For example:

```
bool Result;  
  
ap_ufixed<8, 5> Val1 = 1.25;  
ap_fixed<9, 4> Val2 = 17.25;  
ap_fixed<10, 5> Val3 = 3.25;  
  
Result = Val1 < Val2;           // Yields false  
Result = Val1 < Val3;           // Yields true
```

Bit Operator

Bit-Select and Set

```
af_bit_ref ap_[u]fixed::operator [] (int bit)
```

This operator selects one bit from an arbitrary precision fixed-point value and returns it.

The returned value is a reference value that can set or clear the corresponding bit in the `ap_[u]fixed` variable. The `bit` argument must be an integer value and it specifies the index of the bit to select. The least significant bit has index 0. The highest permissible index is one less than the bit-width of this `ap_[u]fixed` variable.

The result type is `af_bit_ref` with a value of either 0 or 1. For example:

```
ap_int<8, 5> Value = 1.375;  
  
Value[3];                  // Yields 1  
Value[4];                  // Yields 0  
  
Value[2] = 1;               // Yields 1.875  
Value[3] = 0;               // Yields 0.875
```

Bit Range

```
af_range_ref af_(u)fixed::range (unsigned Hi, unsigned Lo)  
af_range_ref af_(u)fixed::operator [] (unsigned Hi, unsigned Lo)
```

This operation is similar to bit-select operator `[]` except that it operates on a range of bits instead of a single bit.

It selects a group of bits from the arbitrary precision fixed-point variable. The `Hi` argument provides the upper range of bits to be selected. The `Lo` argument provides the lowest bit to be selected. If `Lo` is larger than `Hi` the bits selected are returned in the reverse order.

The return type `af_range_ref` represents a reference in the range of the `ap_[u]fixed` variable specified by `Hi` and `Lo`. For example:

```
ap_uint<4> Result = 0;
ap_ufixed<4, 2> Value = 1.25;
ap_uint<8> Repl = 0xAA;

Result = Value.range(3, 0);           // Yields: 0x5
Value(3, 0) = Repl(3, 0);           // Yields: -1.5

// when Lo > Hi, return the reverse bits string
Result = Value.range(0, 3);           // Yields: 0xA
```

Range Select

```
af_range_ref af_(u)fixed::range()
af_range_ref af_(u)fixed::operator []
```

This operation is the special case of the range select operator `[]`. It selects all bits from this arbitrary precision fixed-point value in the normal order.

The return type `af_range_ref` represents a reference to the range specified by `Hi = W - 1` and `Lo = 0`. For example:

```
ap_uint<4> Result = 0;

ap_ufixed<4, 2> Value = 1.25;
ap_uint<8> Repl = 0xAA;

Result = Value.range();           // Yields: 0x5
Value() = Repl(3, 0);           // Yields: -1.5
```

Length

```
int ap_[u]fixed::length()
```

This function returns an integer value that provides the number of bits in an arbitrary precision fixed-point value. It can be used with a type or a value. For example:

```
ap_ufixed<128, 64> My128APFixed;

int bitwidth = My128APFixed.length();    // Yields 128
```

Explicit Conversion Methods

Fixed-to-double

```
double ap_[u]fixed::to_double ()
```

This member function returns this fixed-point value in form of IEEE double precision format. For example:

```
ap_ufixed<256, 77> MyAPFixed = 333.789;
double Result;

Result = MyAPFixed.to_double();           // Yields 333.789
```

Fixed-to-ap_int

```
ap_int ap_[u]fixed::to_ap_int ()
```

This member function explicitly converts this fixed-point value to ap_int that captures all integer bits (fraction bits are truncated). For example:

```
ap_ufixed<256, 77> MyAPFixed = 333.789;
ap_uint<77> Result;

Result = MyAPFixed.to_ap_int();      //Yields 333
```

Fixed-to-integer

```
int ap_[u]fixed::to_int ()
unsigned ap_[u]fixed::to_uint ()
ap_slong ap_[u]fixed::to_int64 ()
ap_ulong ap_[u]fixed::to_uint64 ()
```

This member function explicitly converts this fixed-point value to C built-in integer types. For example:

```
ap_ufixed<256, 77> MyAPFixed = 333.789;
unsigned int Result;

Result = MyAPFixed.to_uint();        //Yields 333

unsigned long long Result;
Result = MyAPFixed.to_uint64();      //Yields 333
```

Compile Time Access to Data Type Attributes

The `ap_[u]fixed<>` types are provided with several static members that allow the size and configuration of data types to be determined at compile time. The data type is provided with the static const members: `width`, `iwidth`, `qmode` and `omode`:

```
static const int width = _AP_W;
static const int iwidth = _AP_I;
static const ap_q_mode qmode = _AP_Q;
static const ap_o_mode omode = _AP_O;
```

You can use these data members to extract the following information from any existing `ap_[u]fixed<>` data type:

- `width`: The width of the data type.
- `iwidth`: The width of the integer part of the data type.
- `qmode`: The quantization mode of the data type.
- `omode`: The overflow mode of the data type.

For example, you can use these data members to extract the data width of an existing `ap_[u]fixed<>` data type to create another `ap_[u]fixed<>` data type at compile time.

The following example shows how the size of variable `Res` is automatically defined as 1-bit greater than variables `Val1` and `Val2` with the same quantization modes:

```
// Definition of basic data type
#define INPUT_DATA_WIDTH 12
#define IN_INTG_WIDTH 6
#define IN_QMODE AP_RND_ZERO
#define IN_OMODE AP_WRAP
typedef ap_fixed<INPUT_DATA_WIDTH, IN_INTG_WIDTH, IN_QMODE, IN_OMODE> data_t;
// Definition of variables
data_t Val1, Val2;
// Res is automatically sized at run-time to be 1-bit greater than INPUT_DATA_WIDTH
// The bit growth in Res will be in the integer bits
ap_int<data_t::width+1, data_t::iwidth+1, data_t::qmode, data_t::omode> Res = Val1 +
Val2;
```

This ensures that Vivado HLS correctly models the bit-growth caused by the addition even if you update the value of `INPUT_DATA_WIDTH`, `IN_INTG_WIDTH`, or the quantization modes for `data_t`.

Comparison of SystemC and Vivado HLS Types

The Vivado HLS types are similar and compatible the SystemC types in virtually all cases and code written using the Vivado HLS types can generally be migrated to a SystemC design and vice-versa.

There are some differences in the behavior between Vivado HLS types and SystemC types. These differences are discussed in this section and cover the following topics.

- Default constructor
- Integer division
- Integer modulus
- Negative shifts
- Over-left shift
- Range operation
- Fixed-point division
- Fixed-point right-shift
- Fixed-point left-shift

Default Constructor

In SystemC, the constructor for the following types initializes the values to zero before execution of the program:

- sc_[u]int
- sc_[u]bigint
- sc_[u]fixed

The following Vivado HLS types are not initialized by the constructor:

- ap_[u]int
- ap_[u]fixed

Vivado HLS bit-accurate data types:

- ap_[u]int
 - No default initialization
- ap_[u]fixed
 - No default initialization

SystemC bit-accurate data types:

- sc_[u]int
Default initialization to 0
- sc_big[u]int
Default initialization to 0
- sc_[u]fixed
Default initialization to 0



CAUTION! When migrating SystemC types to Vivado HLS types, be sure that no variables are read or used in conditionals until they are written to.

SystemC designs can be started showing all outputs with a default value of zero, whether or not the output has been written to. The same variables expressed as Vivado HLS types remain unknown until written to.

Integer Division

When using integer division, Vivado HLS types are consistent with sc_big[u]int types but behave differently than sc_[u]int types. The following figure shows an example.

ap_(u)int	=	sc_big(u)int	≠	sc_(u)int																																																				
<pre>#include "ap_int.h" ap_uint<15>dividend = 32757; ap_int<15>divisor = -2; ap_int<21>ret = dividend/divisor;</pre> <div style="display: flex; justify-content: space-between; align-items: center;"> <div style="text-align: center;"> <div style="border: 1px solid black; padding: 2px;">dividend</div> <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>7</td><td>F</td><td>F</td><td>F</td></tr> <tr><td>7</td><td>F</td><td>F</td><td>E</td></tr> <tr><td>1</td><td>F</td><td>C</td><td>0</td><td>0</td><td>1</td></tr> </table> 32767 </div> <div style="margin: 0 10px;">=</div> <div style="text-align: center;"> <div style="border: 1px solid black; padding: 2px;">dividend</div> <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>7</td><td>F</td><td>F</td><td>F</td></tr> <tr><td>7</td><td>F</td><td>F</td><td>E</td></tr> <tr><td>1</td><td>F</td><td>C</td><td>0</td><td>0</td><td>1</td></tr> </table> 32767 </div> <div style="margin: 0 10px;">≠</div> <div style="text-align: center;"> <div style="border: 1px solid black; padding: 2px;">dividend</div> <table border="1" style="border-collapse: collapse; text-align: center;"> <tr><td>7</td><td>F</td><td>F</td><td>F</td></tr> <tr><td>7</td><td>F</td><td>F</td><td>E</td></tr> <tr><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr> </table> -2 </div> </div>	7	F	F	F	7	F	F	E	1	F	C	0	0	1	7	F	F	F	7	F	F	E	1	F	C	0	0	1	7	F	F	F	7	F	F	E	0	0	0	0	0	0														
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Figure 4-15: Integer Division Differences

The SystemC sc_int type returns a zero value when an unsigned integer is divided by a negative signed integer. The Vivado HLS types, such as the SystemC sc_bigint type, represent the negative result.

Integer Modulus

When using the modulus operator, Vivado HLS types are consistent with `sc_big[u]int` types, but behave differently than `sc_[u]int` types. The following figure shows an example.

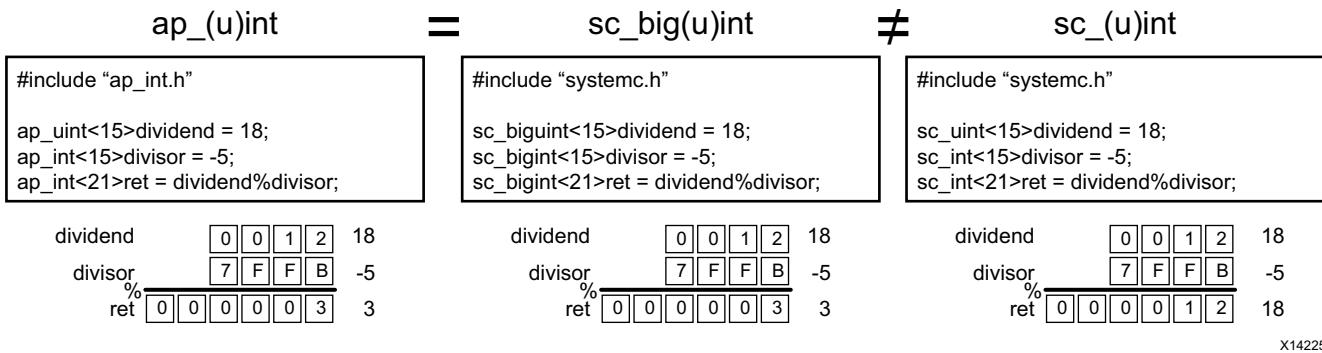


Figure 4-16: Integer Modules Differences

The SystemC `sc_int` type returns the value of the dividend of a modulus operation when:

- The dividend is an unsigned integer, and
- The divisor is a negative signed integer.

The Vivado HLS types (such as the SystemC `sc_bignum` type) returns the positive result of the modulus operation.

Negative Shifts

When the value of a shift operation is a negative number, Vivado HLS `ap_[u]int` types shift the value in the opposite direction. For example, it returns a left-shift for a right-shift operation).

The SystemC types `sc_[u]int` and `sc_bignum` behave differently in this case. The following figure shows an example of this operation for both Vivado HLS and SystemC types.

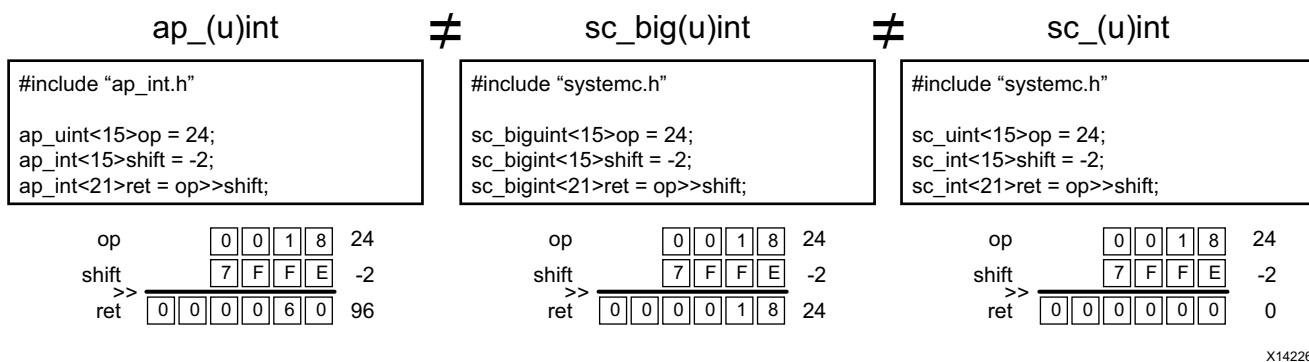


Figure 4-17: Negative Shift Differences

The following table summarizes the negative shift differences.

Table 4-75: Negative Shift Differences Summary

Type	Action
ap_[u]int	Shifts in the opposite direction.
sc_[u]int	Returns a zero
sc_big[u]int	Does not shift

Over-Shift Left

When a shift operation is performed and the result overflows the input variable but not the output or assigned variable, Vivado HLS types and SystemC types behave differently.

- Vivado HLS ap_[u]int shifts the value and then assigns meaning to the upper bits that are lost (or overflowed).
- Both SystemC sc_big(u)int and sc_(u)int types assign the result and then shift, preserving the upper bits.
- The following figure shows an example of this operation for both Vivado HLS and SystemC types.

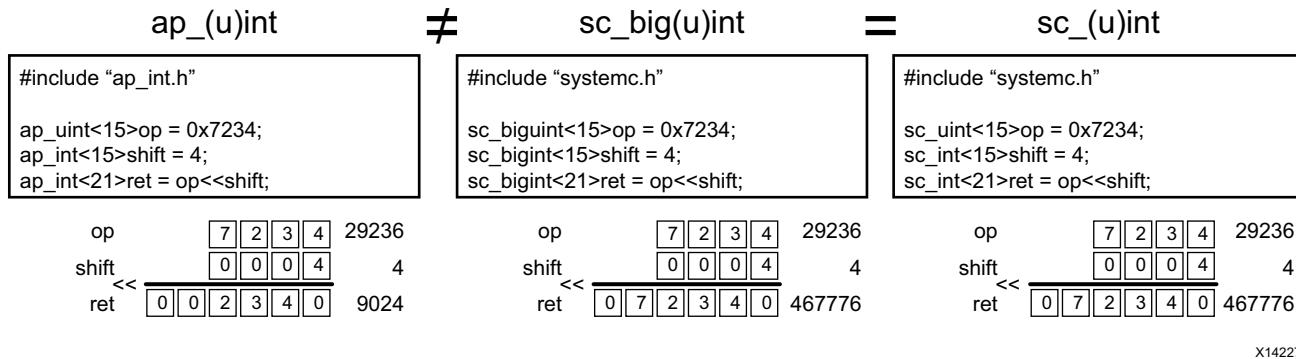


Figure 4-18: Over-Shift Left Differences

Range Operation

There are differences in behavior when the range operation is used and the size of the range is different between the source and destination. The following figure shows an example of this operation for both Vivado HLS and SystemC types. See the summary below.

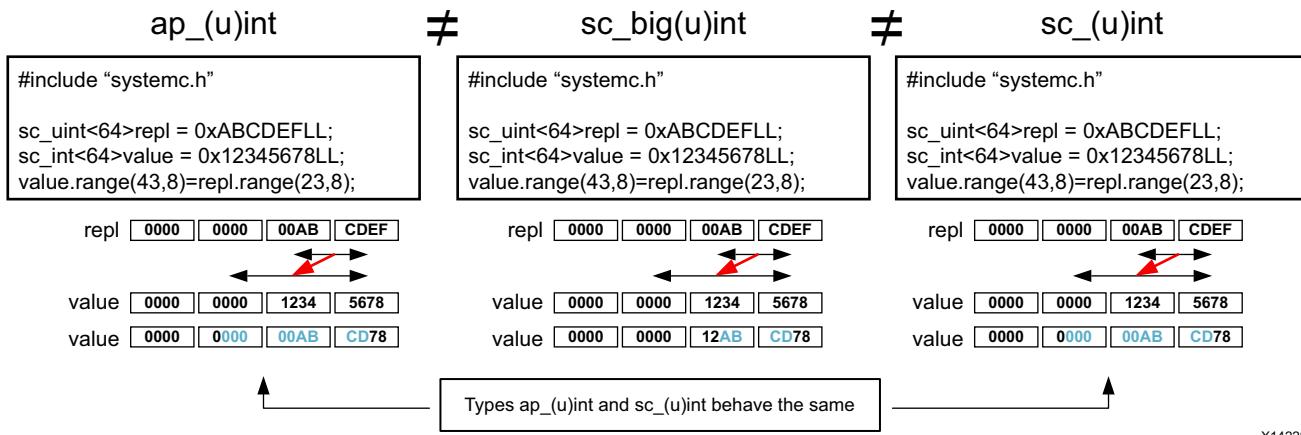


Figure 4-19: Range Operation Differences

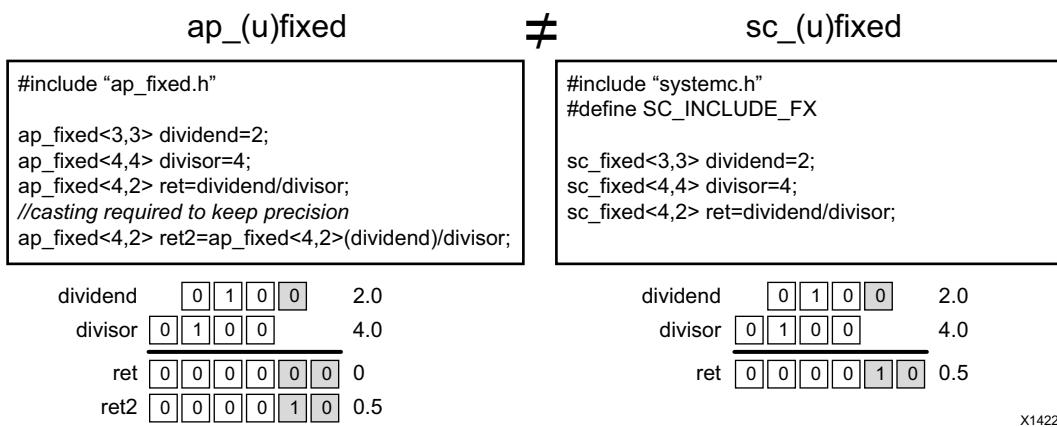
- Vivado HLS `ap_[u]int` types and SystemC `sc_big[u]int` types replace the specified range and extend to fill the target range with zeros.
- SystemC `sc_big[u]int` types update only with the range of the source.

Division and Fixed-Point Types

When performing division with fixed-point type variables of different sizes, there is a difference in how the fractional values are assigned between Vivado HLS types and SystemC types.

For `ap_[u]fixed` types, the fraction is no greater than that of the dividend. SystemC `sc_[u]fixed` types retain the fractional precision on divide. The fractional part can be retained when using the `ap_[u]fixed` type by casting to the new variable width before assignment.

The following figure shows an example of this operation for both Vivado HLS and SystemC types.



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Figure 4-20: Fixed-Point Division Differences

Right Shift and Fixed-Point Types

Vivado HLS and SystemC behave differently when a right-shift operation is performed

- With Vivado HLS fixed-point types, the shift is performed and then the value is assigned.
- With SystemC fixed-point types, the value is assigned and then the shift is performed.

When the result is a fixed-point type with more fractional bits, the SystemC type preserves the additional accuracy.

The following figure shows an example of this operation for both Vivado HLS and SystemC types.

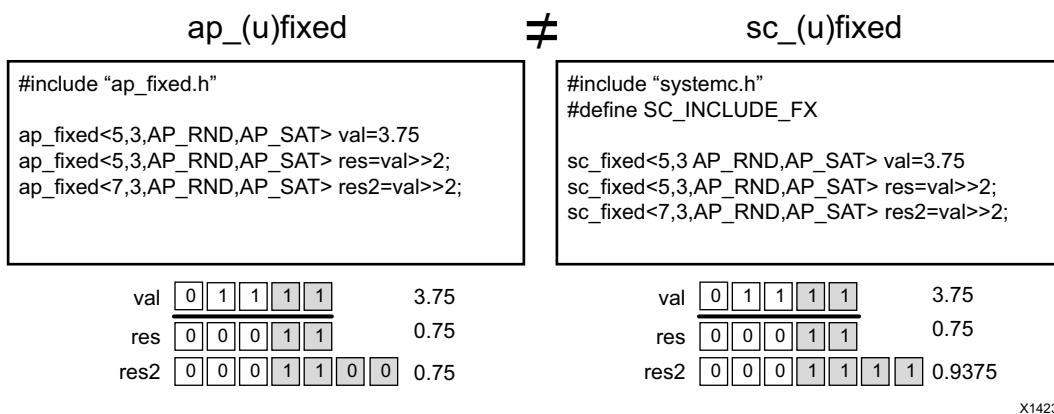


Figure 4-21: Fixed-Point Differences with Right-Shift

The type of quantization mode does not affect the result of the ap_[u]fixed right-shift. Xilinx recommends that you assign to the size of the result type before the shift operation.

Left Shift and Fixed-Point Types

When performing a left-shift operation with ap_[u]fixed types, the operand is sign-extended, then shifted and then assigned. The SystemC sc_[u]fixed types assign and then shift. In this case, the Vivado HLS types preserve any sign-intention.

The following figure shows an example of this operation for both Vivado HLS and SystemC types.

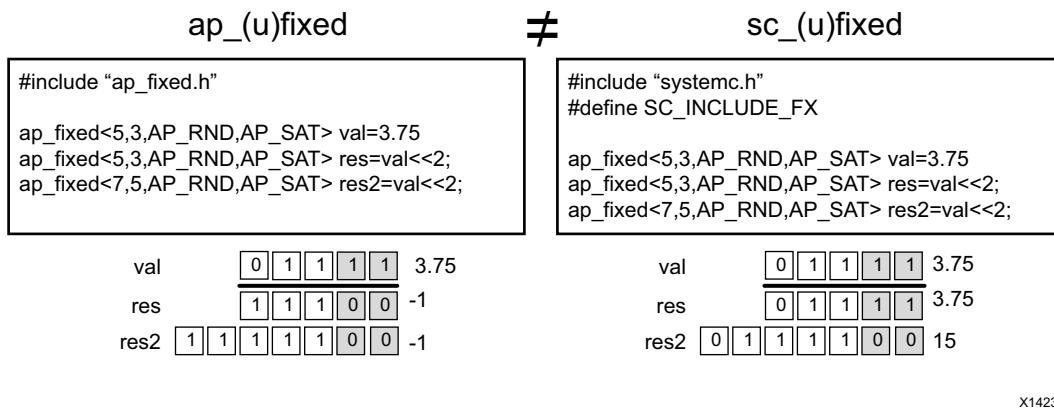


Figure 4-22: Fixed-Point Differences with Left-Shift

Additional Resources and Legal Notices

Xilinx Resources

For support resources such as Answers, Documentation, Downloads, and Forums, see [Xilinx Support](#).

Solution Centers

See the [Xilinx Solution Centers](#) for support on devices, software tools, and intellectual property at all stages of the design cycle. Topics include design assistance, advisories, and troubleshooting tips.

References

1. *Introduction to FPGA Design with Vivado High-Level Synthesis* ([UG998](#))
2. *Vivado® Design Suite Tutorial: High-Level Synthesis* ([UG871](#))
3. *Vivado Design Suite User Guide: Release Notes, Installation, and Licensing* ([UG973](#))
4. *ISE® to Vivado Design Suite Migration Guide* ([UG911](#))
5. *LogiCORE IP Fast Fourier Transform v9.0 Product Guide* ([PG109](#))
6. *LogiCORE IP FIR Compiler v7.1 Product Guide* ([PG149](#))
7. Accellera website (www.accellera.org)
8. *Vivado Design Suite AXI Reference Guide* ([UG1037](#))
9. *Accelerating OpenCV Applications with Zynq-7000 All Programmable SoC Using Vivado HLS Video Libraries* ([XAPP1167](#))
10. [Vivado Design Suite Documentation](#)

Training Resources

Xilinx provides a variety of training courses and QuickTake videos to help you learn more about the concepts presented in this document. Use these links to explore related training resources:

1. [C-based Design: High-Level Synthesis with the Vivado HLS Tool Training Course](#)
 2. [C-based HLS Coding for Hardware Designers Training Course](#)
 3. [C-based HLS Coding for Software Designers Training Course](#)
 4. [Vivado Design Suite QuickTake Video Tutorials](#)
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