

Lecture 21

EE 421 / CS 425

Digital System Design

Fall 2025

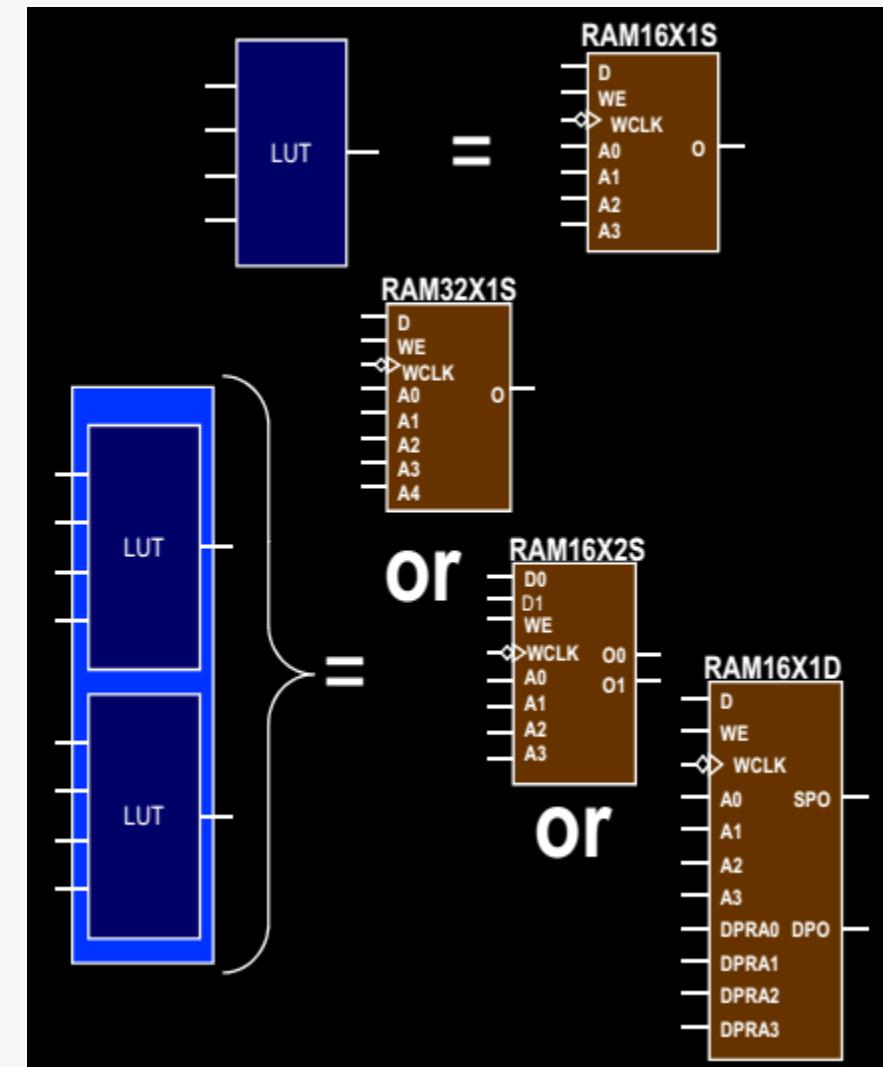
Shahid Masud

Topics

- Distributed RAM and Block RAM in FPGA (Recap)
- Special Features in FPGA
- Sequential Implementation on CLB
- Memory
- Multipliers
- DSP Slices
- FIR and Symmetric Filters
- **QUIZ 4 TODAY**

Distributed RAM

- Distributed RAM:
- CLB LUT configurable as Distributed RAM
- A LUT equals 16×1 RAM
- Implements Single and DualPorts
- Cascade LUTs to increase RAM size
- Synchronous write and Synchronous/Asynchronous read
- Comparison:
 - Block Ram is a dedicated Ram that does not consume any additional LUT in your design whereas distributed Ram is built up with LUT.
 - In terms of speed the distributed RAM is faster than Block Rams.
 - Generally speaking, if not much Ram is needed you can consider to implement it as a distributed Ram.



Single Port Distributed RAM from LUT based CLB

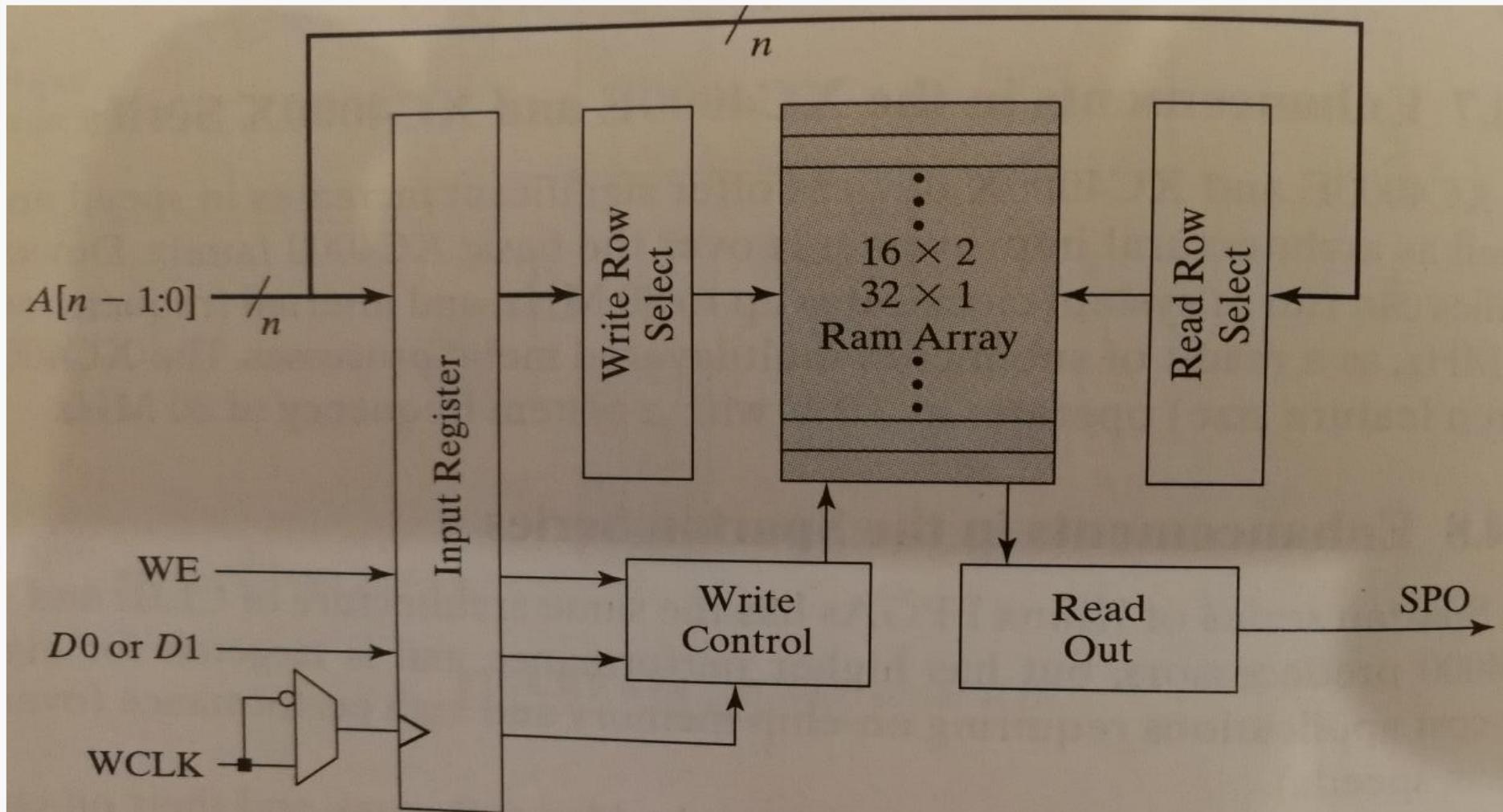


FIGURE 8-68 Single-port distributed RAM formed from an LUT.

Block RAM

- Block RAM:
- Xilinx FPGA Consist of 2 columns of memory called Block RAM or BRAM.
- It is a Dual port memory with separate Read/Write port.
- It can be configured as different data width 16Kx1, 8Kx8, 4Kx4 and so on.
- BRAM can be excellent for FIFO implementation.
- Multiple blocks can be cascaded to create still larger memory.
- The block RAM functions as dual or single-port memory.
- The maximum data path width of the block RAM is 18 bits.

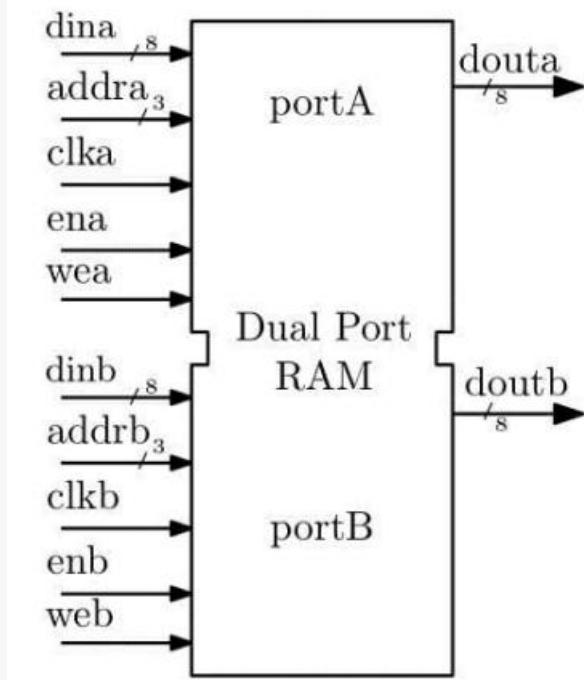


Fig. 4: Dual Port RAM

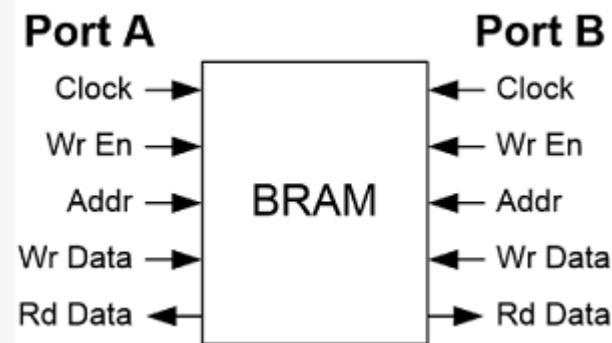


Table 1: Modes of Dual Port RAM

modes	ena	wea	enb	web	portA	portB
1	1	1	1	1	write	write
2	1	1	1	0	write	read
3	1	0	1	1	read	write
4	1	0	1	0	read	read

FIFO BRAM Configuration

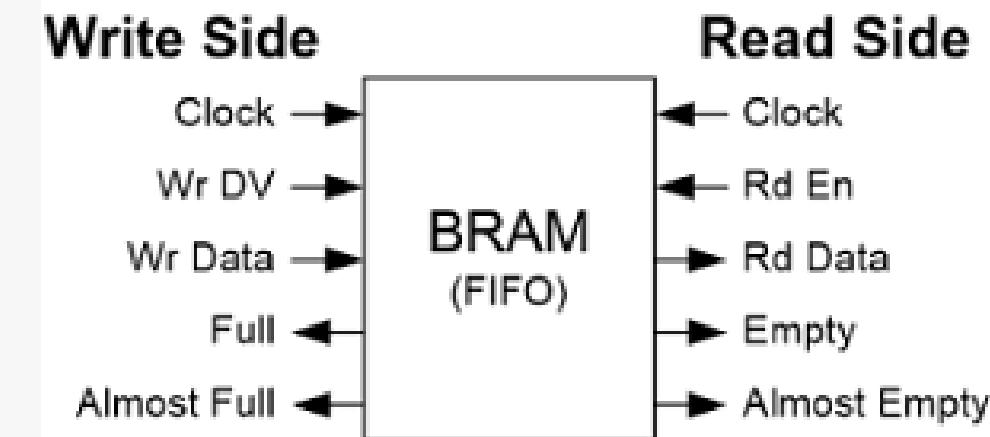
FIFO means First In First Out and they are frequently used in FPGA design.

Any time there is a need to buffer some data between two interfaces we need a FIFO.

if we want to cross clock domains,

if we want to buffer a row of image data and manipulate it,

if we want to send data off-chip to a DDR memory, these all require the use of a Block RAM FIFO.



Conceptual Dual Port RAM

Simple Dual Port RAM

A general question arises in mind that how the dual port RAMs are realized. A conceptual diagram of a simple Dual Port RAM having only 4-bit memory is shown below.

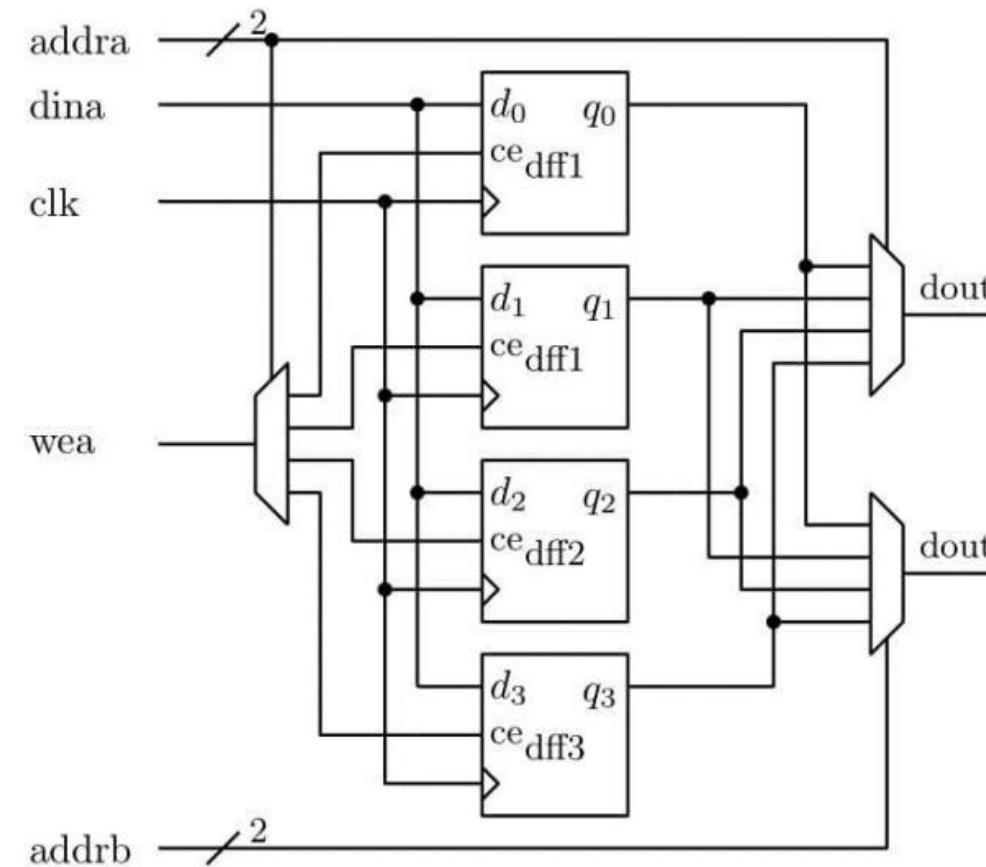


Fig. 7: Conceptual Diagram of a Simple Dual Port RAM

In a true Dual Port RAM writing can be done through both the ports. Also it has separate clock, en and we signals for separate port. In case of simple Dual Port RAM writing is done through port A and reading can be done through both the ports.

Dual Port RAM in Xilinx Spartan FPGA

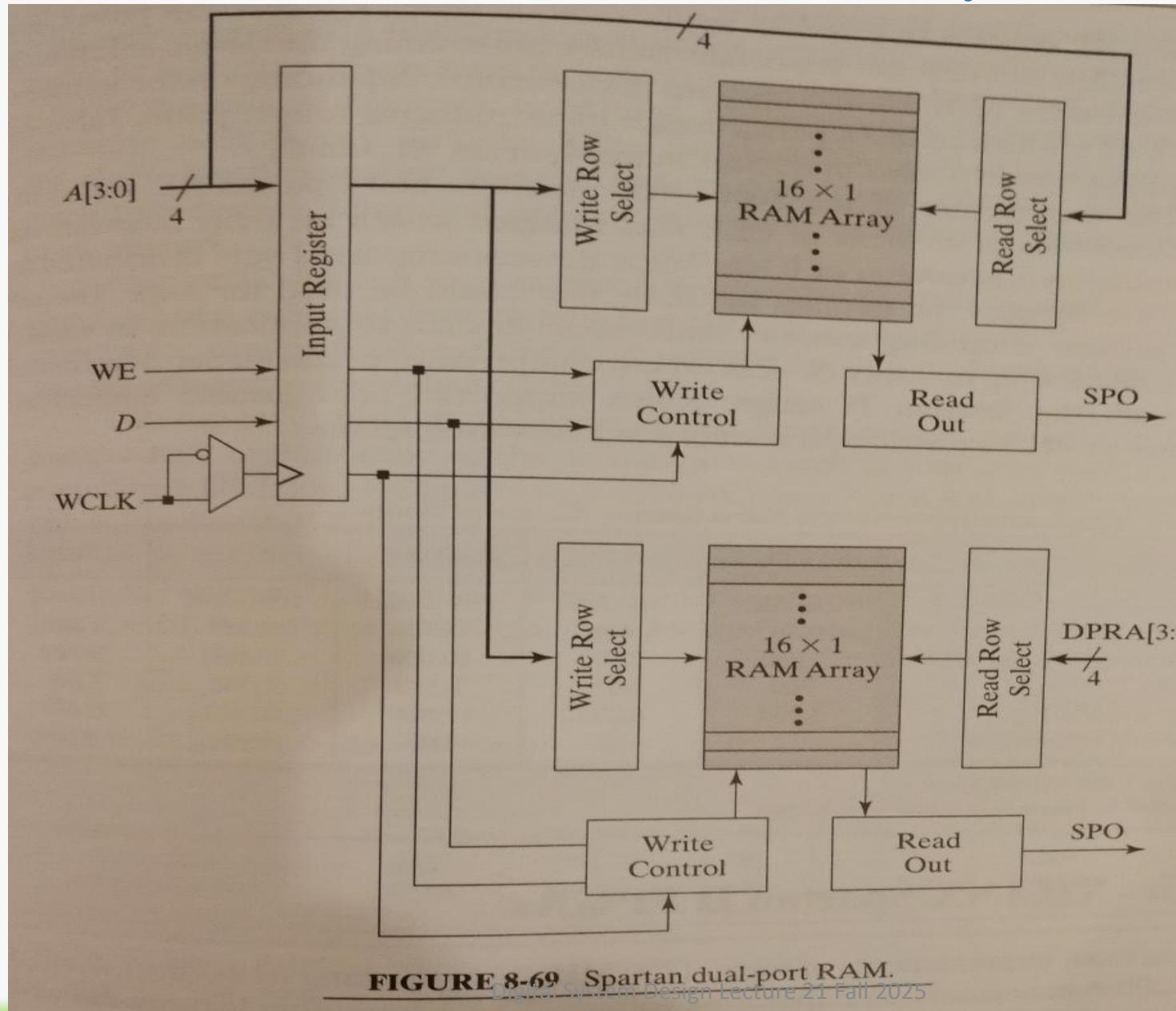
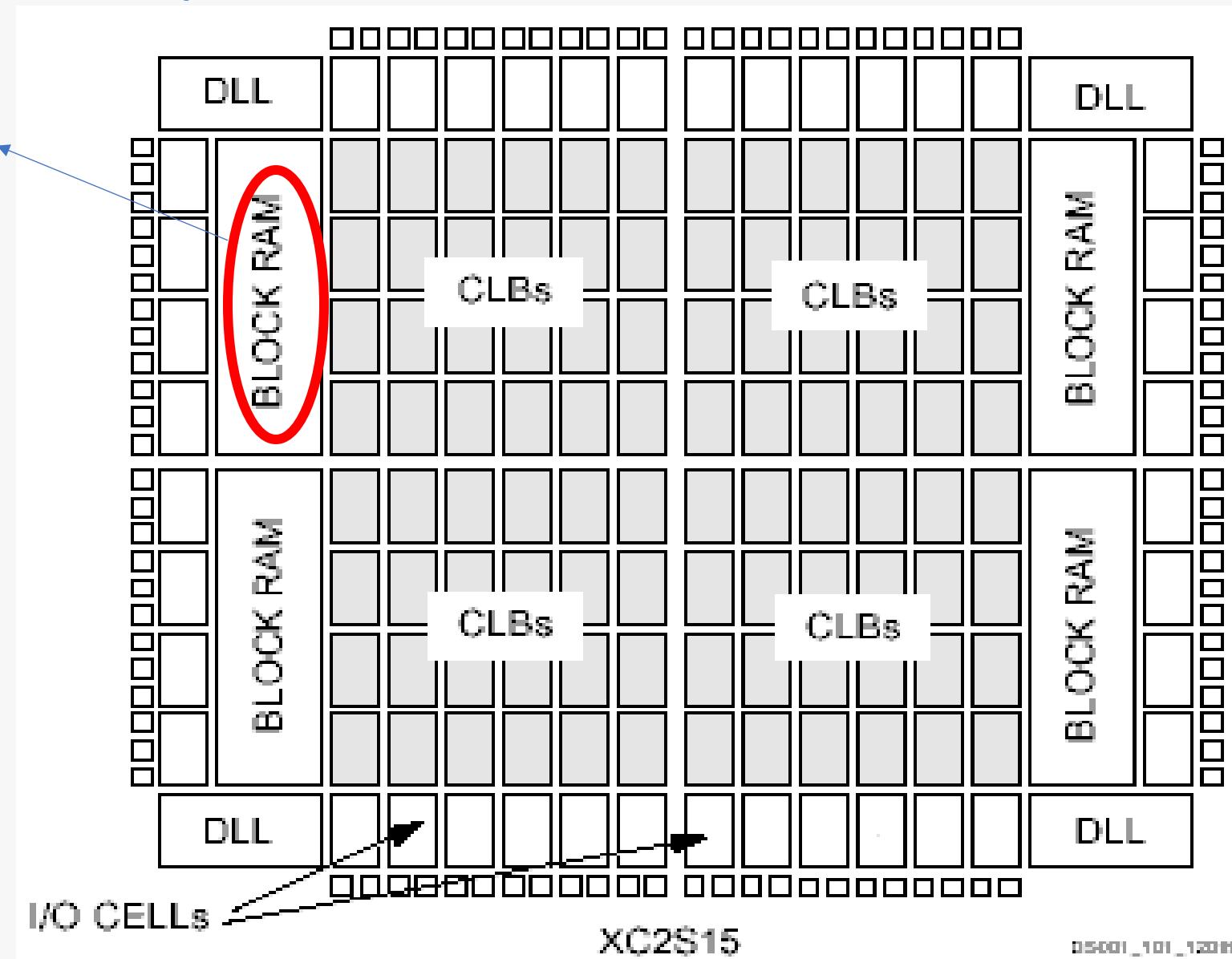


FIGURE 8-69 Spartan dual-port RAM.

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Xilinx Spartan Architecture

Block RAM ?

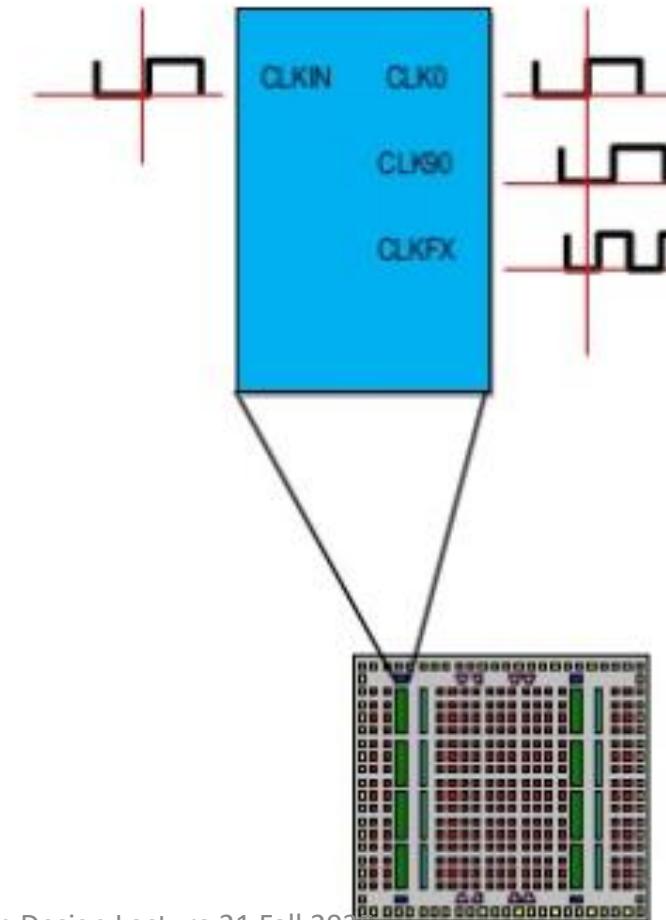


DLL = Delay Locked Loop
For Clock Management

Digital Clock Module in Xilinx FPGA

Clock Management

- Digital Clock Managers (DCMs)
 - Clock de-skew
 - Phase shifting
 - Clock multiplication
 - Clock division
 - Frequency synthesis

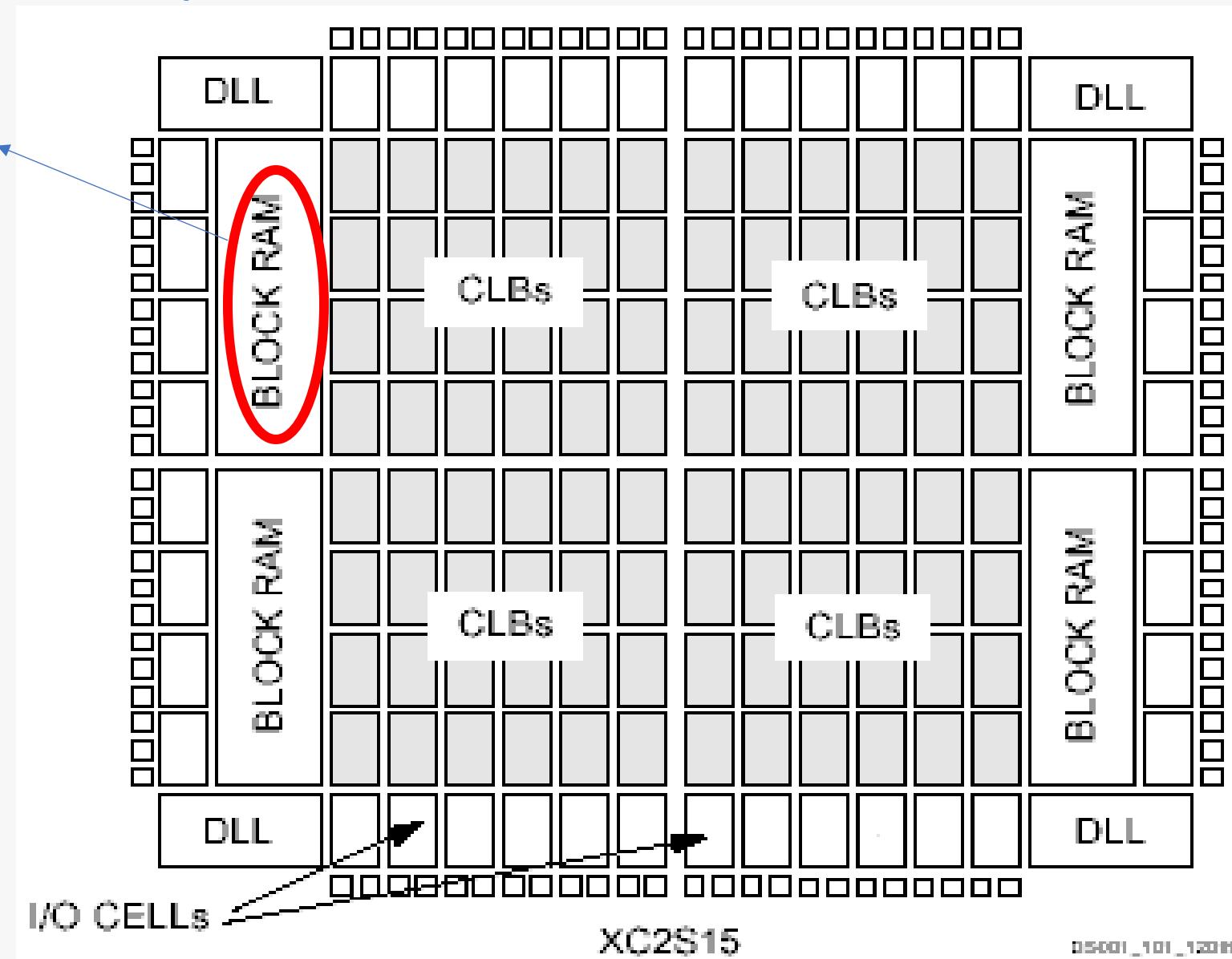


Specialized Modules in FPGAs

- Dedicated Memory
 - Single Port and Dual Port Embedded Memory Blocks – Block RAM
- Dedicated Arithmetic Units
 - Adders, Multipliers, Multipliers – Accumulators, Fast Carry Logic
- Digital Signal Processing Blocks – DSP Slice
 - FFT Butterfly Modules, FIR / IIR Filters,
 - IP Core Libraries for Encryption, Video Compression, Cloud Applications, etc.
- Embedded Processors
 - PowerPC, Microblaze, NIOS, ARM, MIPS, etc.
- Content Addressable Memory (CAM)
 - used in Branch Prediction, Caches inside CPU
- More and more features keep appearing in new FPGA devices
 - High Speed Interfaces, Security Features, RISC-V Support, etc.

Xilinx Spartan Architecture

Block RAM ?

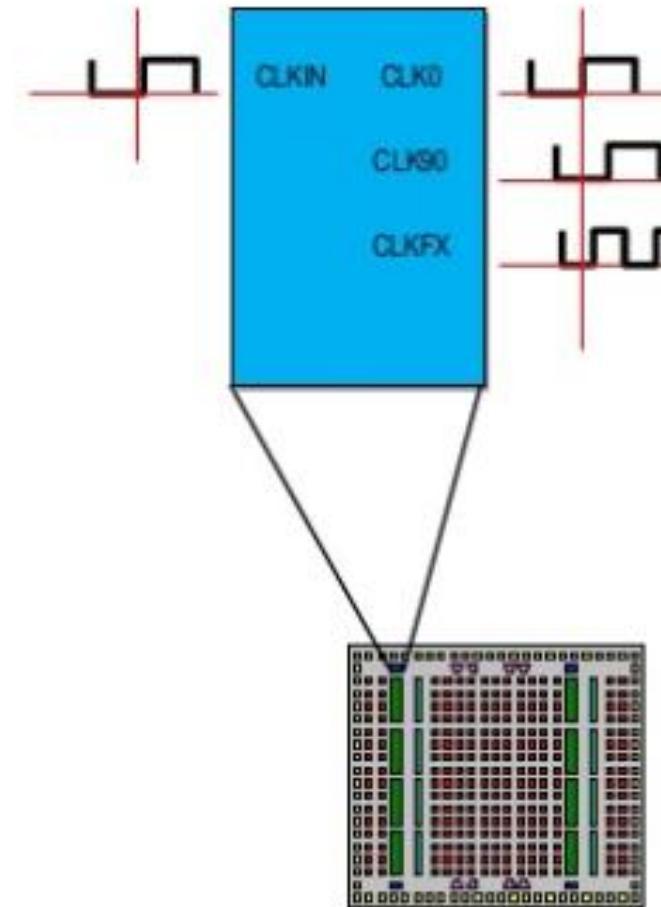


DLL = Delay Locked Loop
For Clock Management

Digital Clock Module in Xilinx FPGA

Clock Management

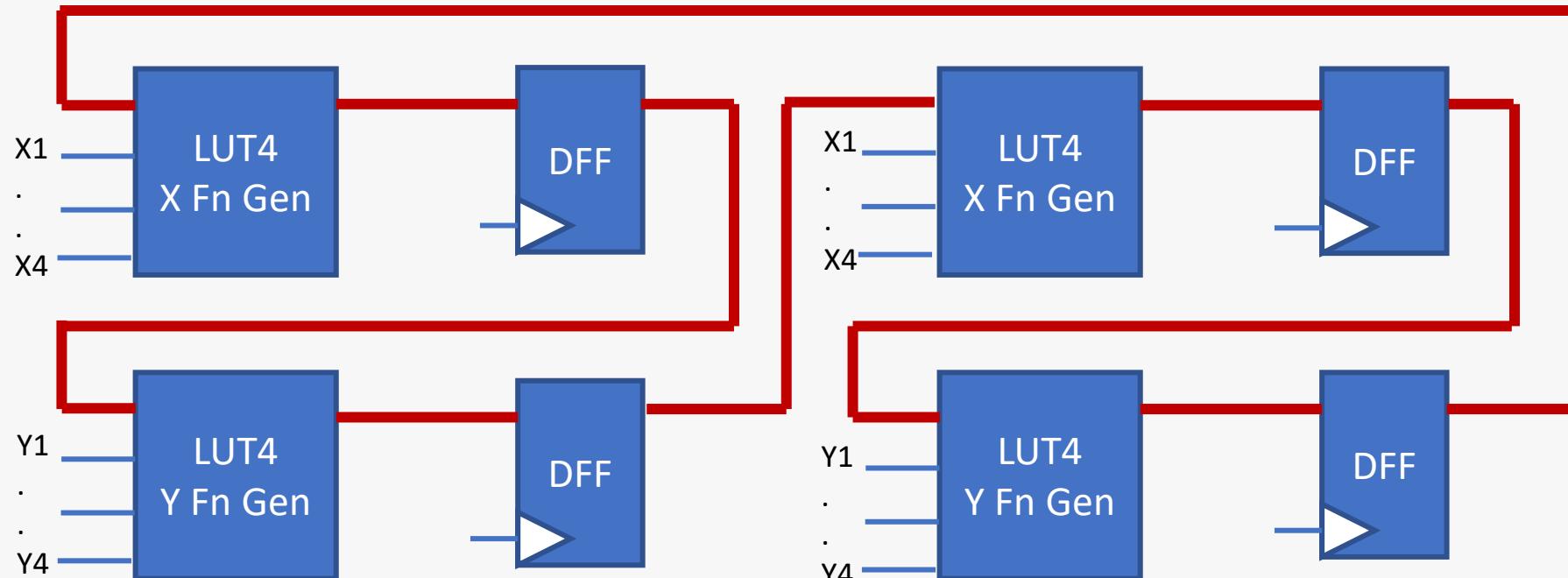
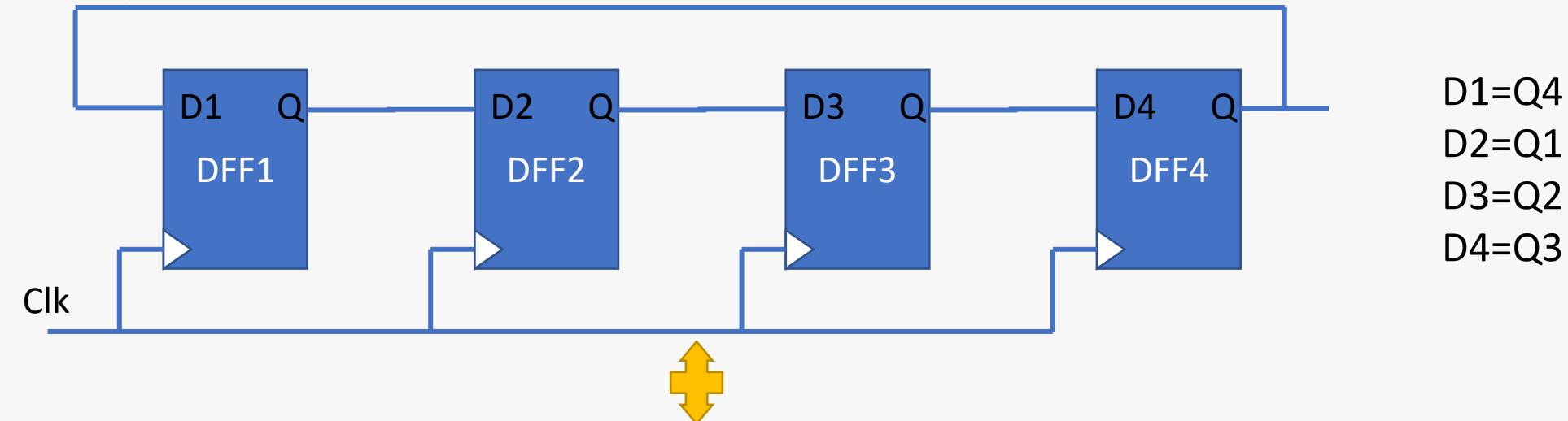
- Digital Clock Managers (DCMs)
 - Clock de-skew
 - Phase shifting
 - Clock multiplication
 - Clock division
 - Frequency synthesis



Implementation of Memory in FPGA

- Using LUT in CLBs – **Distributed RAM**
- Instantiating **Block RAMs**
- Provision of **Dual port memory** in modern FPGA

Sequential Circuits in FPGA



Multiplier Blocks – Xilinx Spartan-3AN



Spartan-3AN FPGA Family: Introduction and Ordering Information

Architectural Overview

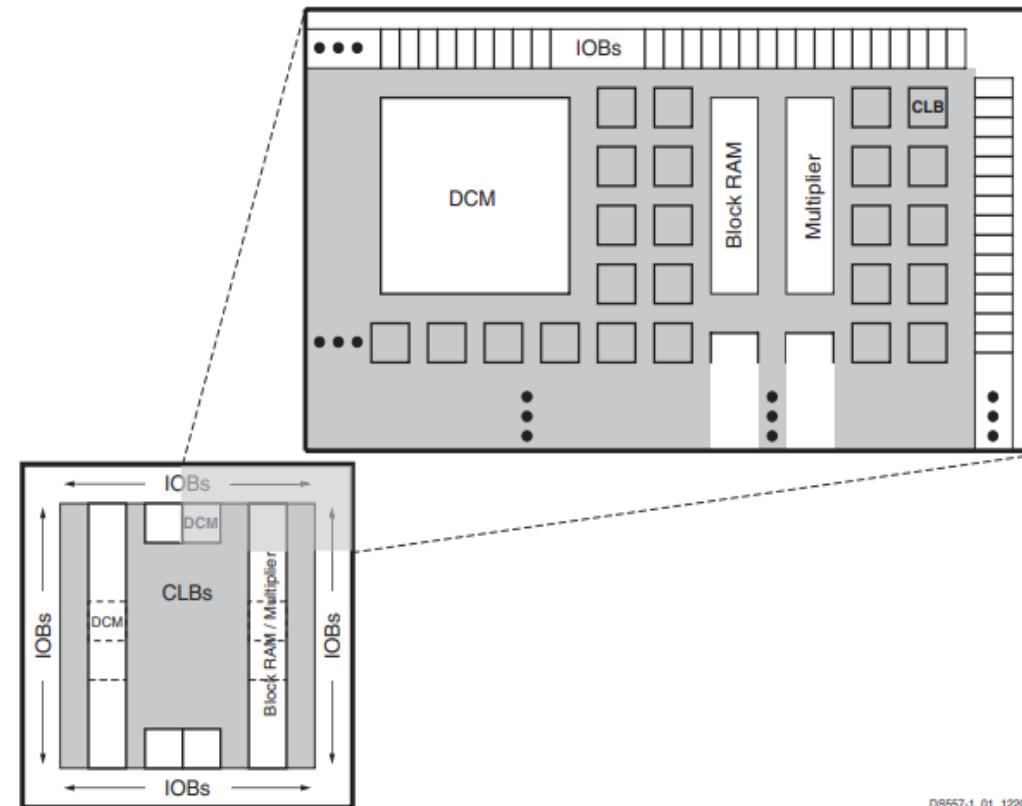
The Spartan-3AN FPGA architecture is compatible with that of the Spartan-3A FPGA. The architecture consists of five fundamental programmable functional elements:

- **Configurable Logic Blocks (CLBs)** contain flexible Look-Up Tables (LUTs) that implement logic plus storage elements used as flip-flops or latches.
- **Input/Output Blocks (IOBs)** control the flow of data between the I/O pins and the internal logic of the device. IOBs support bidirectional data flow plus 3-state operation. They support a variety of signal standards, including several high-performance differential standards. Double Data-Rate (DDR) registers are included.
- **Block RAM** provides data storage in the form of 18-Kbit dual-port blocks.
- **Multiplier Blocks** accept two 18-bit binary numbers as inputs and calculate the product.

- **Digital Clock Manager (DCM) Blocks** provide self-calibrating, fully digital solutions for distributing, delaying, multiplying, dividing, and phase-shifting clock signals.

These elements are organized as shown in [Figure 1](#). A dual ring of staggered IOBs surrounds a regular array of CLBs. Each device has two columns of block RAM except for the XC3S50AN, which has one column. Each RAM column consists of several 18-Kbit RAM blocks. Each block RAM is associated with a dedicated multiplier. The DCMS are positioned in the center with two at the top and two at the bottom of the device. The XC3S50AN has DCMs only at the top, while the XC3S700AN and XC3S1400AN add two DCMs in the middle of the two columns of block RAM and multipliers.

The Spartan-3AN FPGA features a rich network of traces that interconnect all five functional elements, transmitting signals among them. Each functional element has an associated switch matrix that permits multiple connections to the routing.



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Notes:

1. The XC3S700AN and XC3S1400AN have two additional DCMs on both the left and right sides as indicated by the dashed lines. The XC3S50AN has only two DCMs at the top and only one Block RAM/Multiplier column.

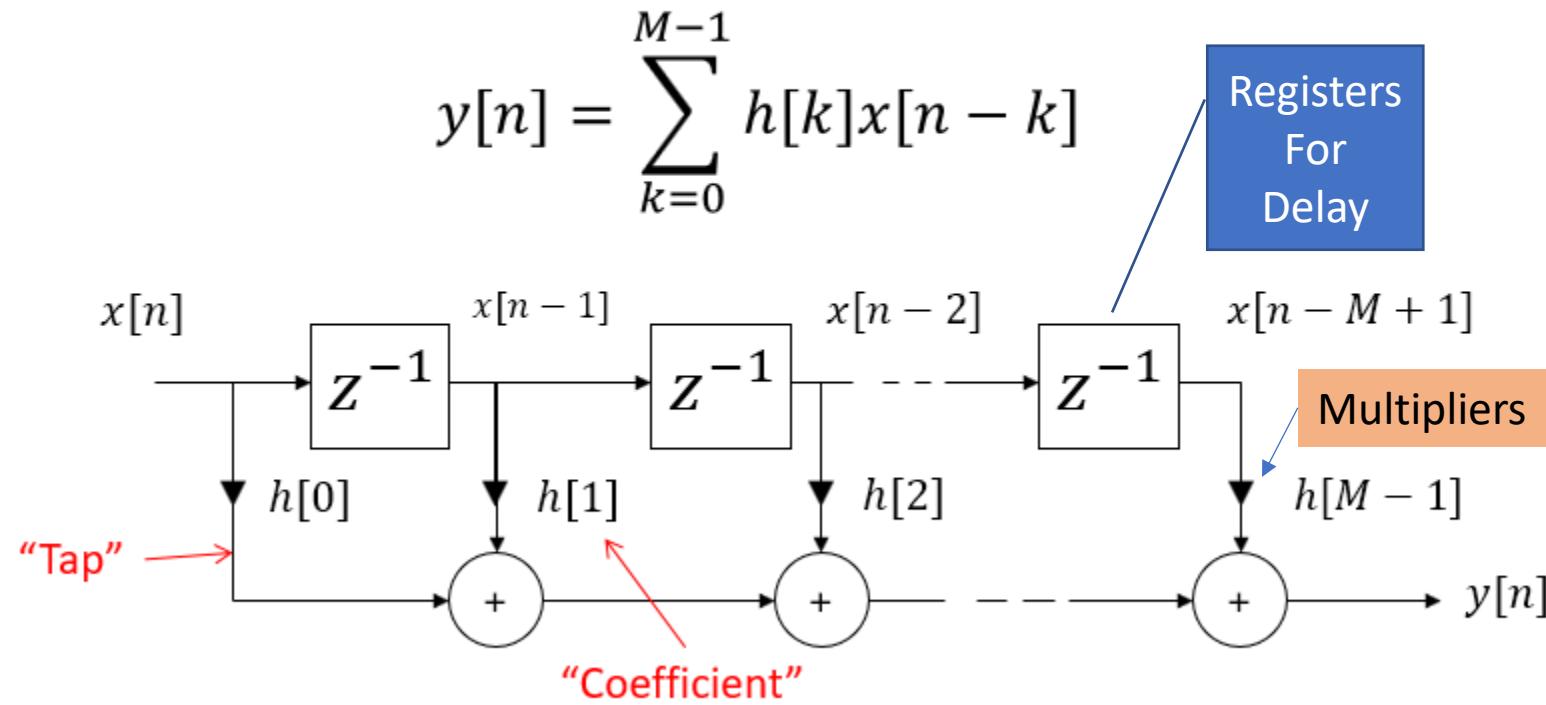
Figure 1: Spartan-3AN Family Architecture

DSP Features in modern FPGA

Example FIR Filter Implementation

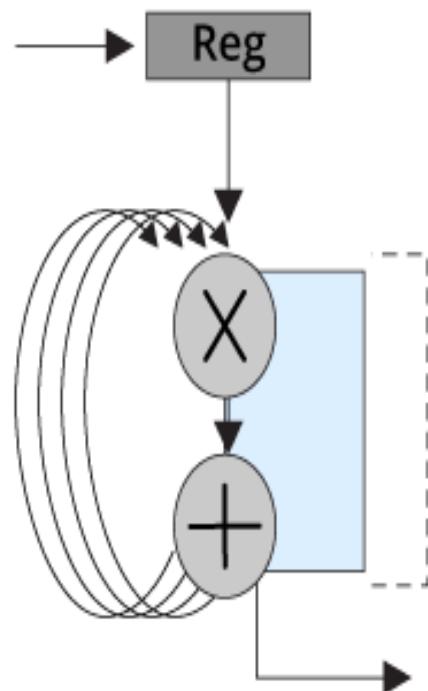
FIR Filter Design

- FIR system is easily implemented directly from convolution summation



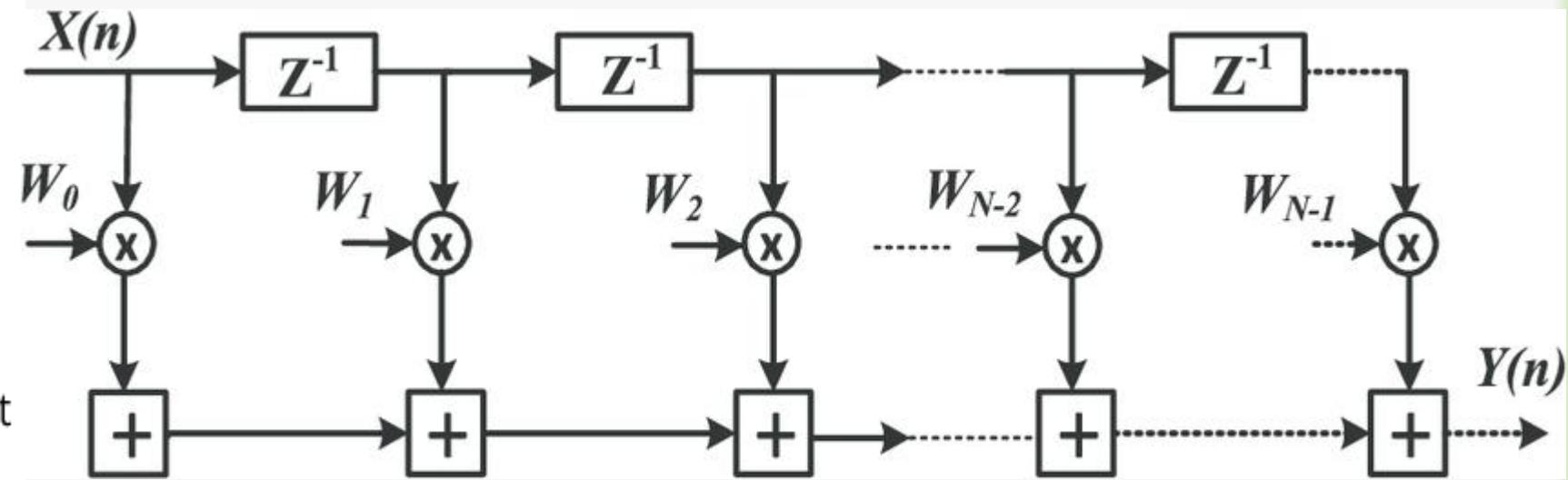
Implementation of DSP Filters

Conventional DSP Device
(Von Neumann Architecture)



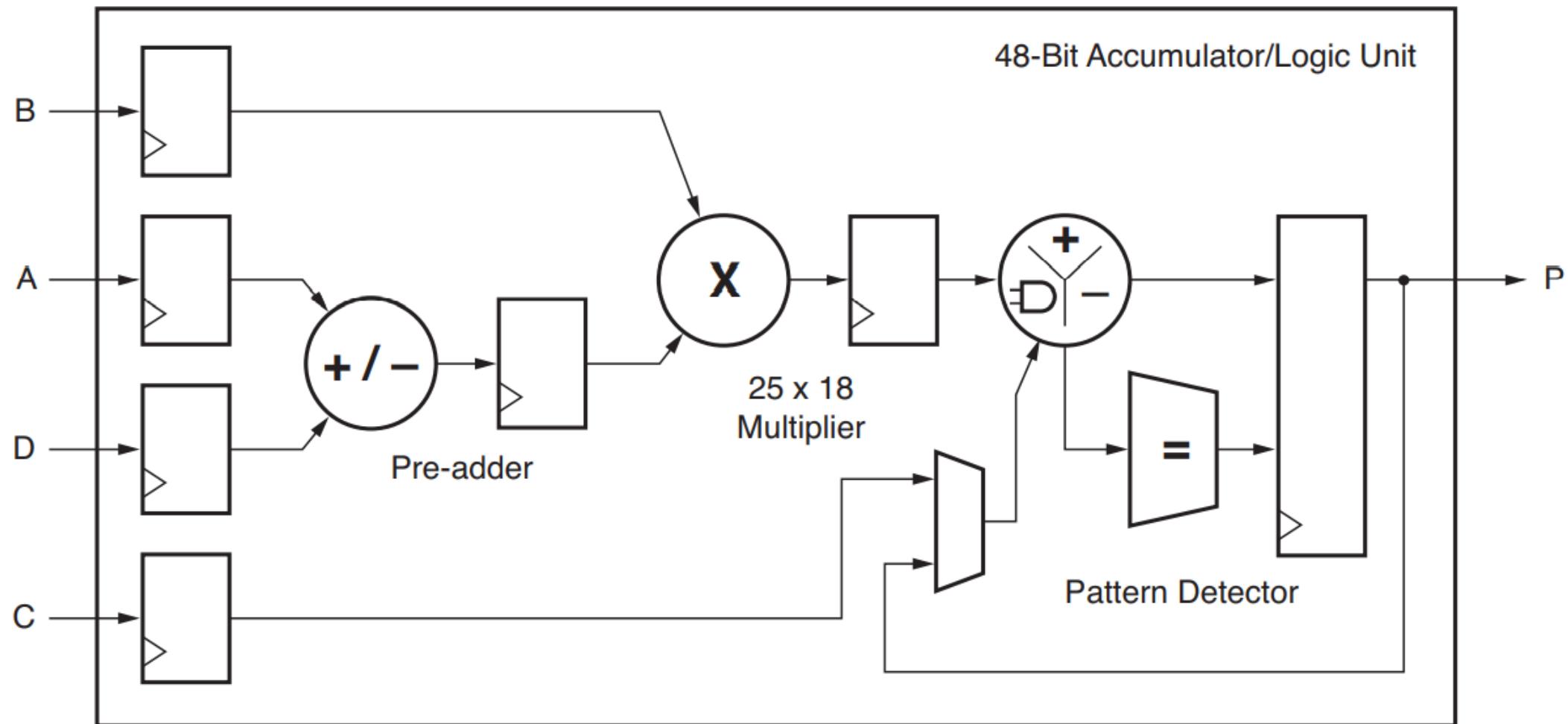
FIR filter mapping on
Software Programmable Device

Implementation of FIR filters in Digital Signal Processing



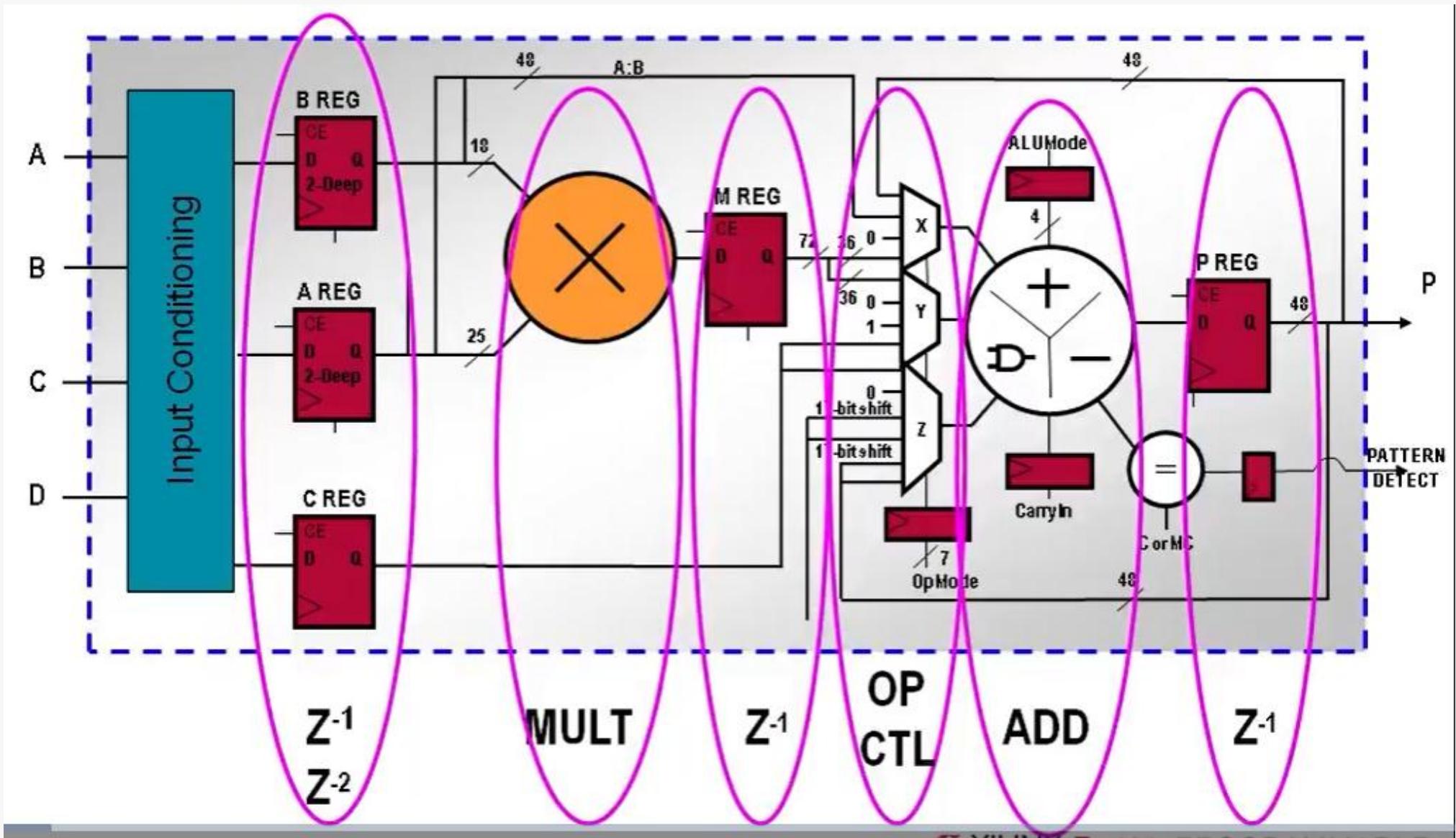
FIR filter mapping on
a configurable Hardware Device

Basic Xilinx DSP48 Slice Architecture

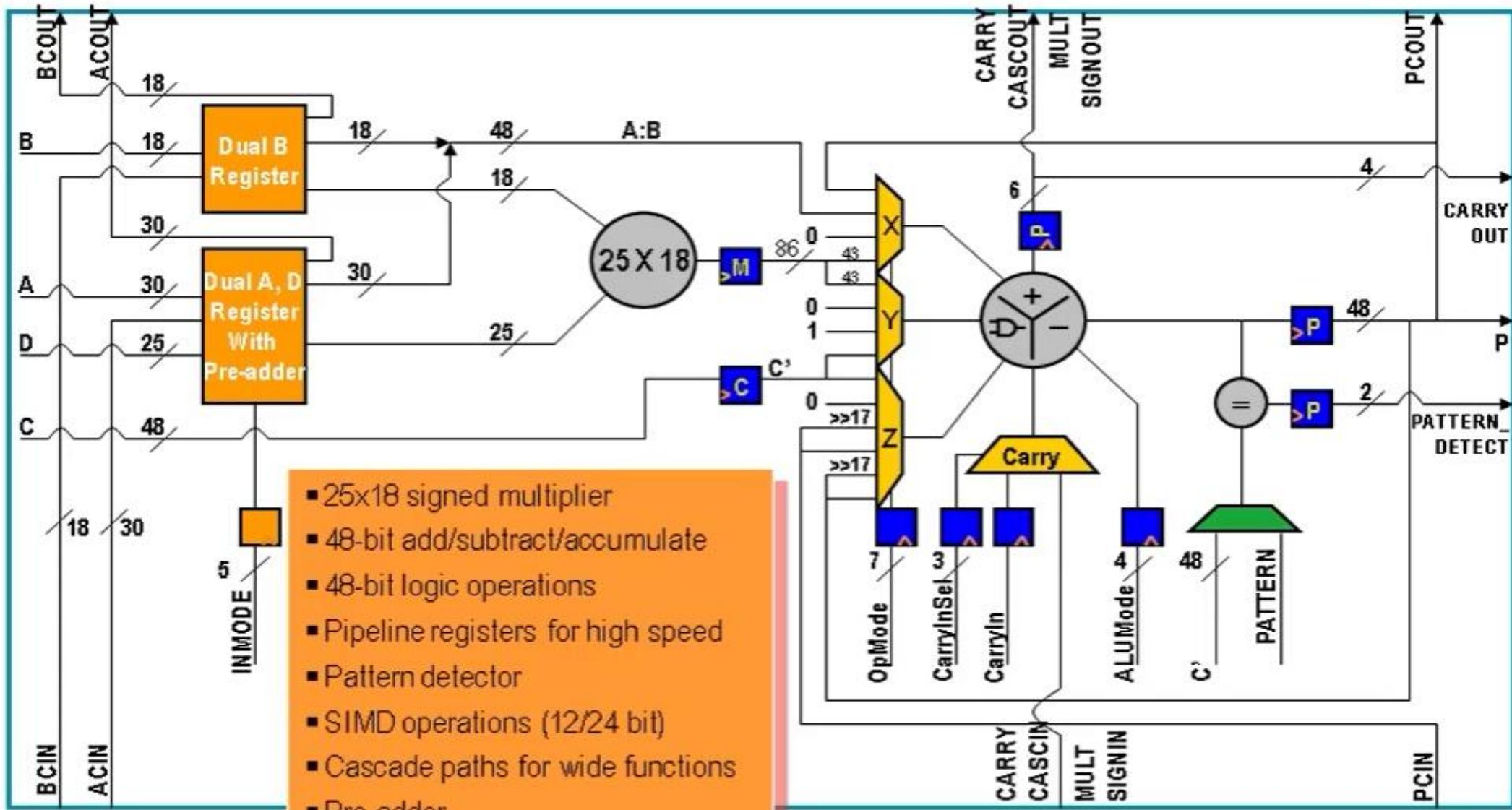


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DSP Slice Features



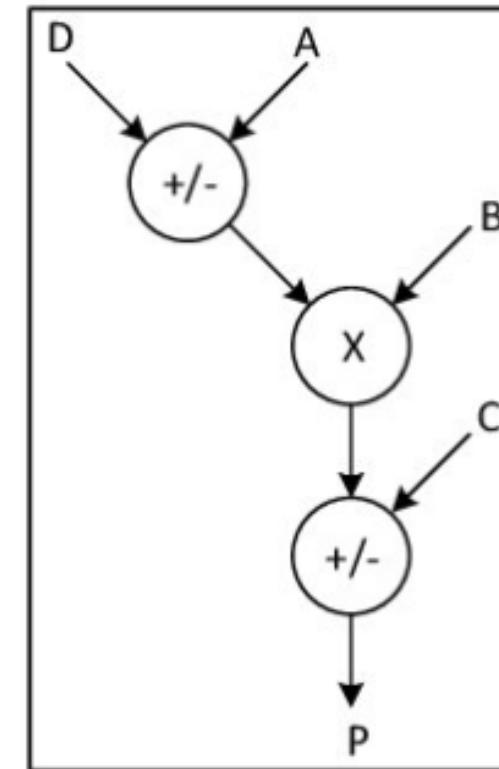
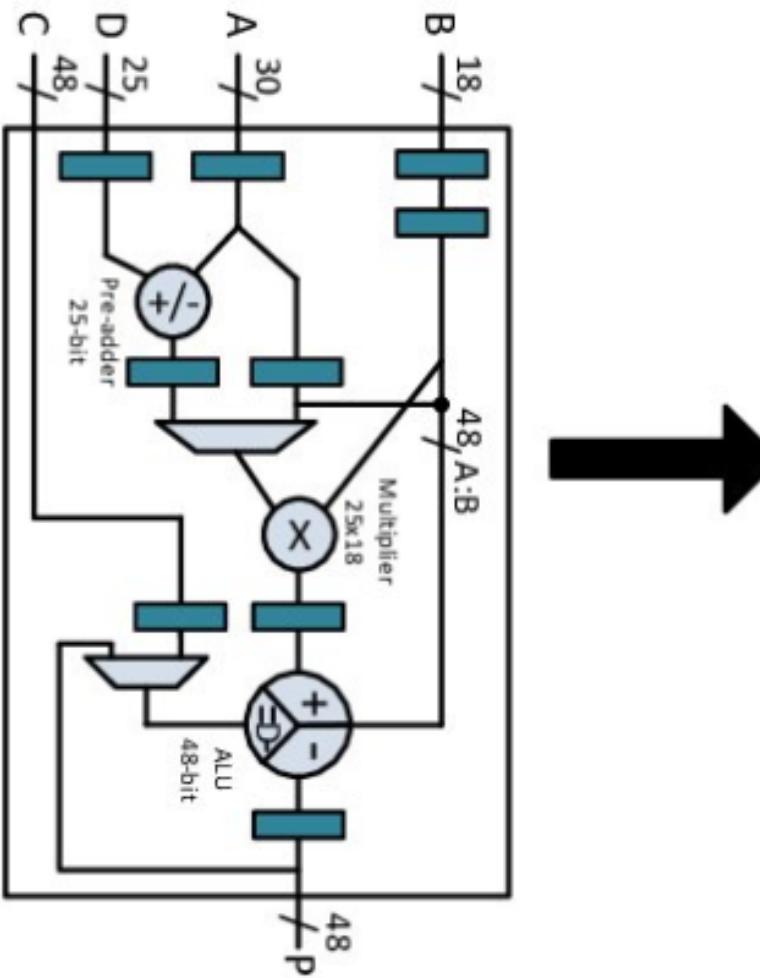
Example of DSP Slice and Features



Xilinx DSP48 Slice Functionality

- 25 x 18 two's complement multiplier
- 48-bit Accumulator
- Power saving Pre-Adder for symmetric FIR filter implementation
- Single-Instruction-Multiple-Data (SIMD) arithmetic unit
- Dual 24-bit or Quad 12-bit Add/Sub/Acc
- Optional Logic Unit with 10 different operations on two operands
- Pattern Detector for convergent or symmetric rounding
- 96-bit wide Logic functions in conjunction with Pattern Detector and Logic Unit
- Optional Pipelining and Dedicated Buses for Cascading

Mapping Add and Mult on DSP Slice



Figure

Caption

Fig. 4: Dataflow through the DSP48E1 primitive.

This figure was uploaded by Suhaib A Fahmy.

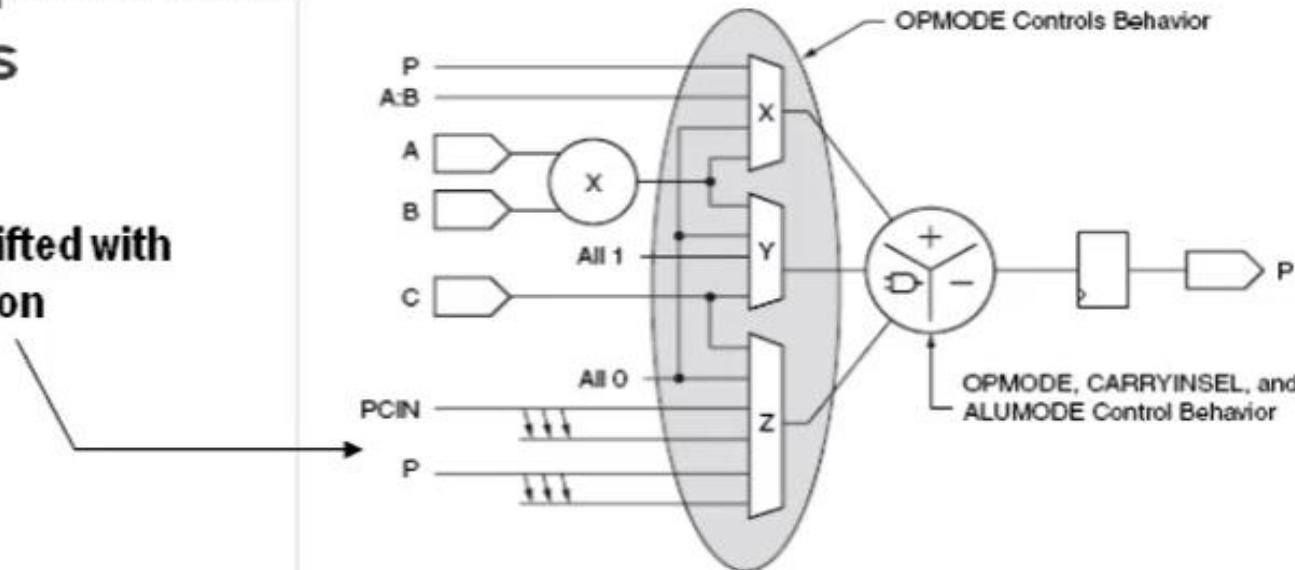
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X, Y and Z Multiplexer

- Adder/subtractor operates on X, Y, Z and CIN operands
 - Table shows basic operations
- X, Y, and Z multiplexers allow for dynamic OPMODEs
- Multiplier output requires both X and Y multiplexers

Normal or 17-bit right shifted with MSB fill for multi-precision arithmetic

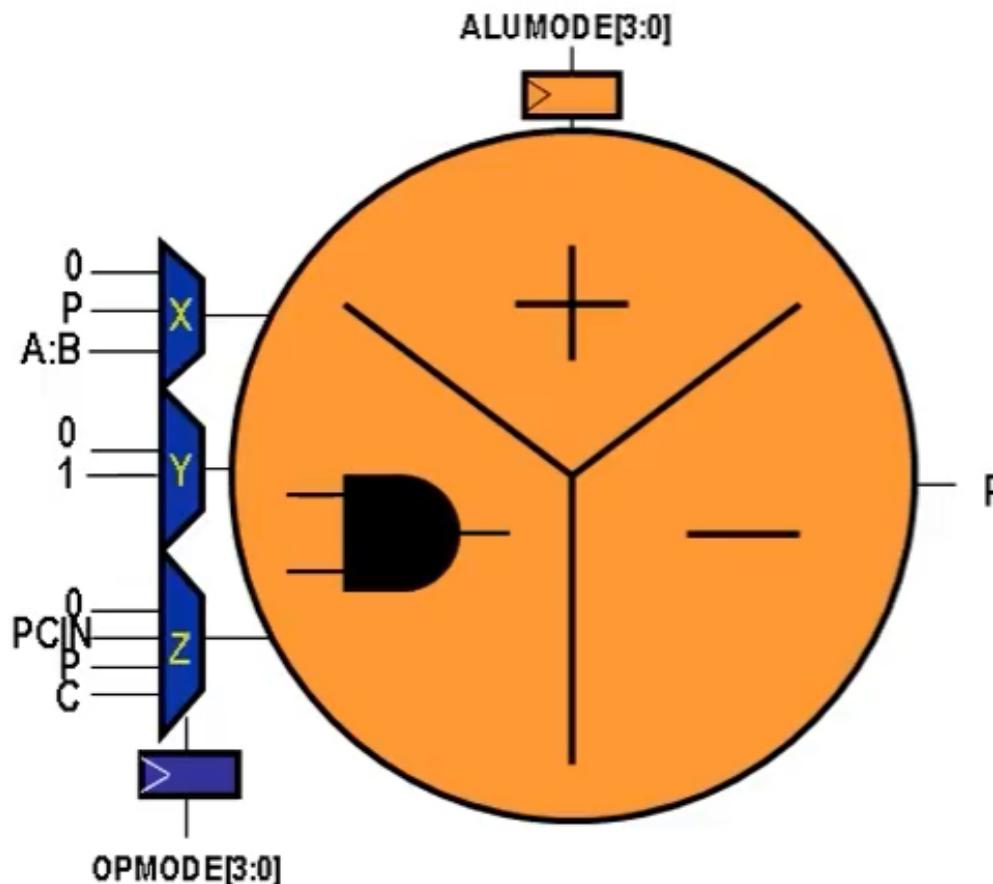
ALUMODE	Operation
0000	$Z + X + Y + \text{CIN}$
0001	$-Z + (X + Y + \text{CIN}) - 1$
0010	$-Z - X - Y - \text{CIN} - 1$
0011	$Z - (X + Y + \text{CIN})$
Others	Logic Operations



Two Input Logic Functions in DSP Slice

► 48-bit logic operations

- XOR, XNOR, AND, NAND, OR, NOR, NOT



ALUMODEs

Logic Unit Mode	OPMODE[3:2]	ALUMODE[3:0]
XXOR Z	00	0100
XXNOR Z	00	0101
XXNOR Z	00	0110
XXOR Z	00	0111
X AND Z	00	1100
X AND (NOT Z)	00	1101
X NAND Z	00	1110
(NOT X) OR Z	00	1111
XXNOR Z	10	0100
XXOR Z	10	0101
XXOR Z	10	0110
XXNOR Z	10	0111
X OR Z	10	1100
X OR (NOT Z)	10	1101
X NOR Z	10	1110
(NOT X) AND Z	10	1111

An Implementation of FIR using RAM

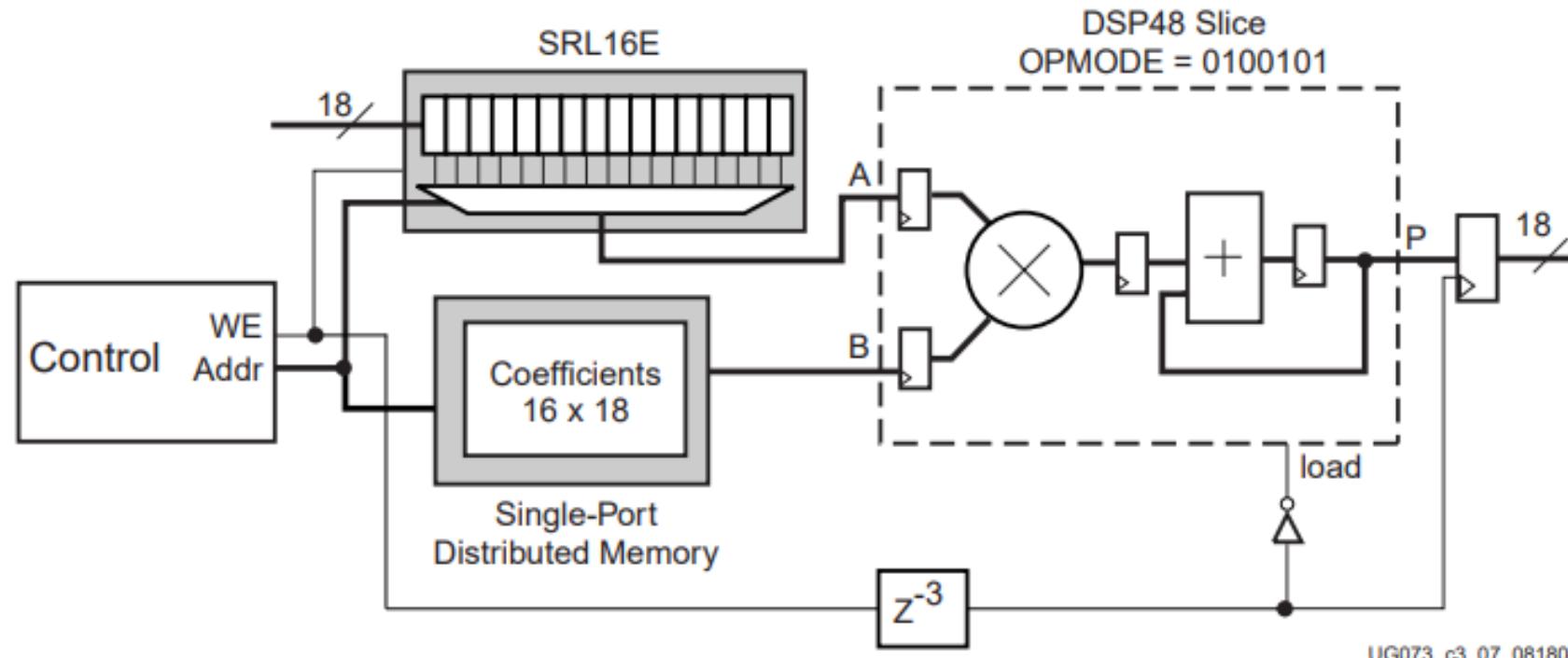


Figure 4-6: Tap-Distributed RAM MAC FIR Filter

MAC Engine for FIR Filter in FPGA

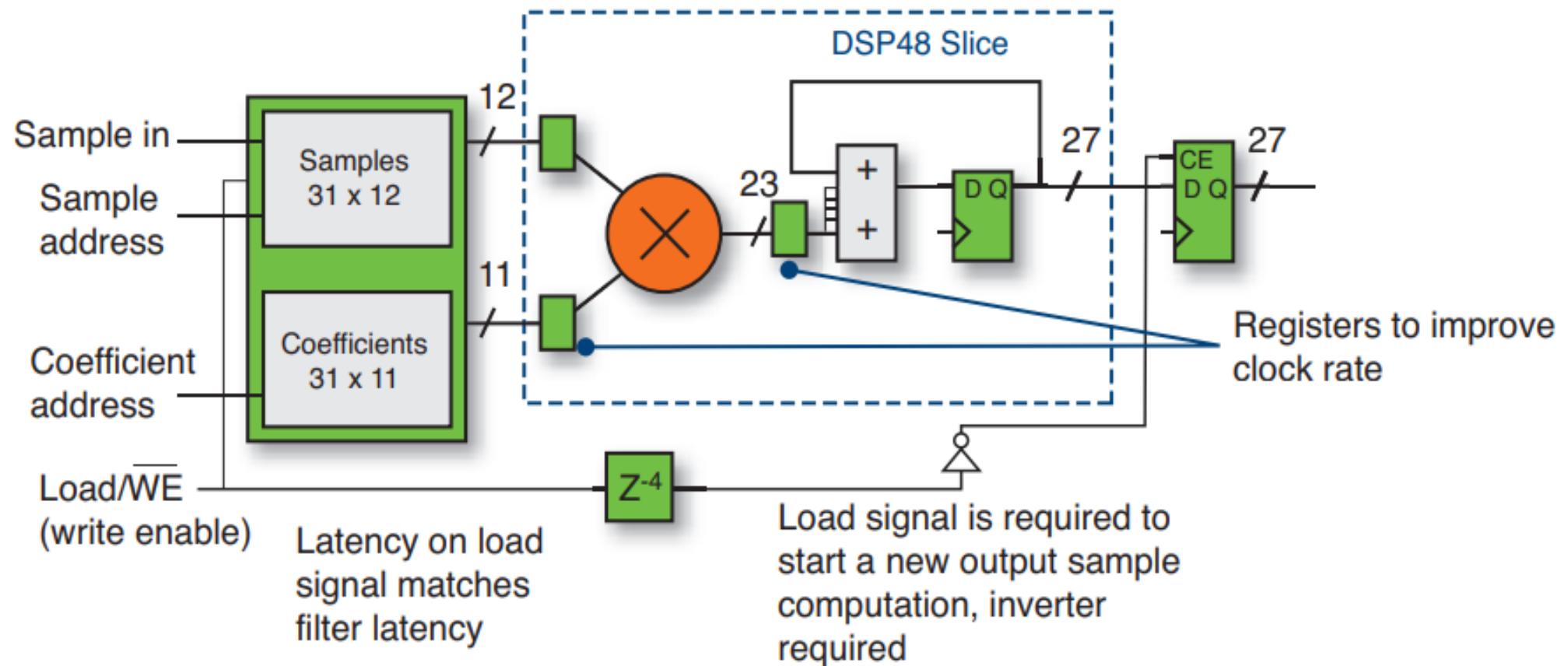


Figure 4 – MAC engine FIR filter in an FPGA

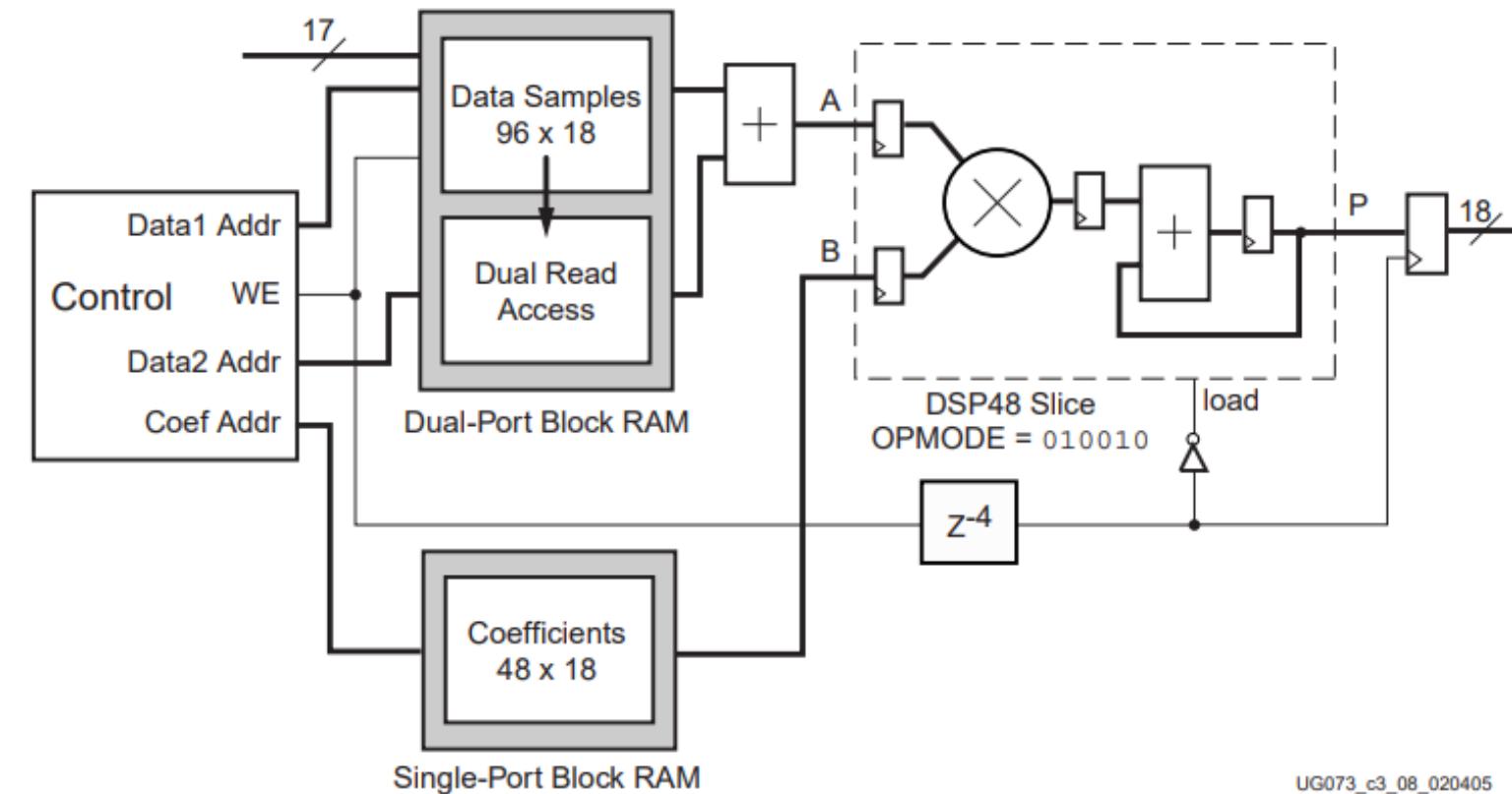
Symmetric FIR

Symmetric MAC FIR Filter

The HDL code provided in the reference design is for a single multiplier MAC FIR filter. other techniques can also be explored. This section describes how the symmetric nature of FIR filter coefficients can double the capable sample rate performance of the filter (assuming the same clock speed). By rearranging the FIR filter equation, the coefficients are exploited as follows:

$$(X_0 \times C_0) + (X_n \times C_n) \dots \rightarrow (X_0 + X_n) \times C_0 \quad (\text{if } C_0 = C_n) \quad \text{Equation 4-6}$$

Figure 4-7 shows the architecture for a symmetric MAC FIR filter.

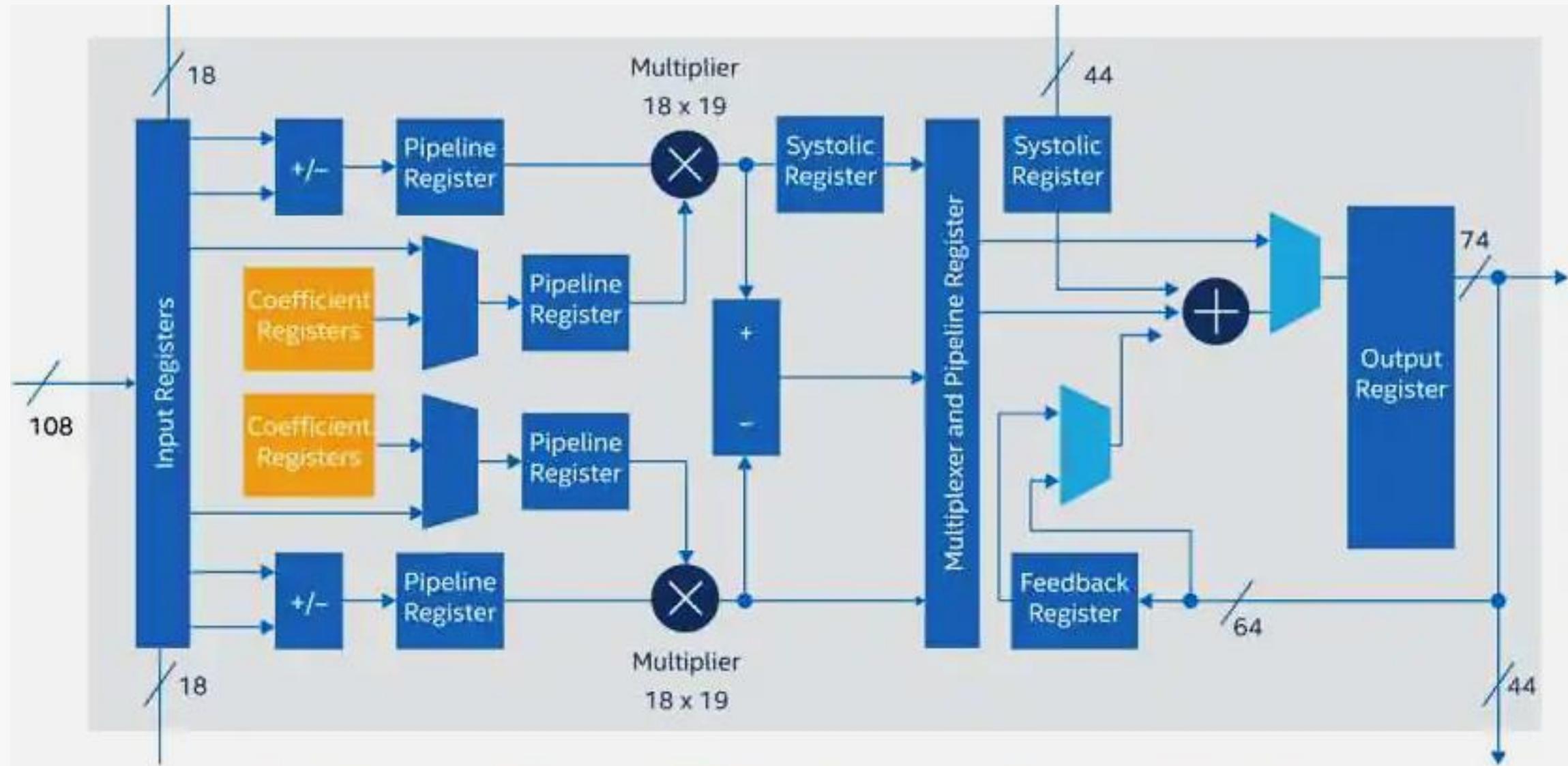


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Figure 4-7: Symmetric MAC FIR Filter

Intel Stratix Slice

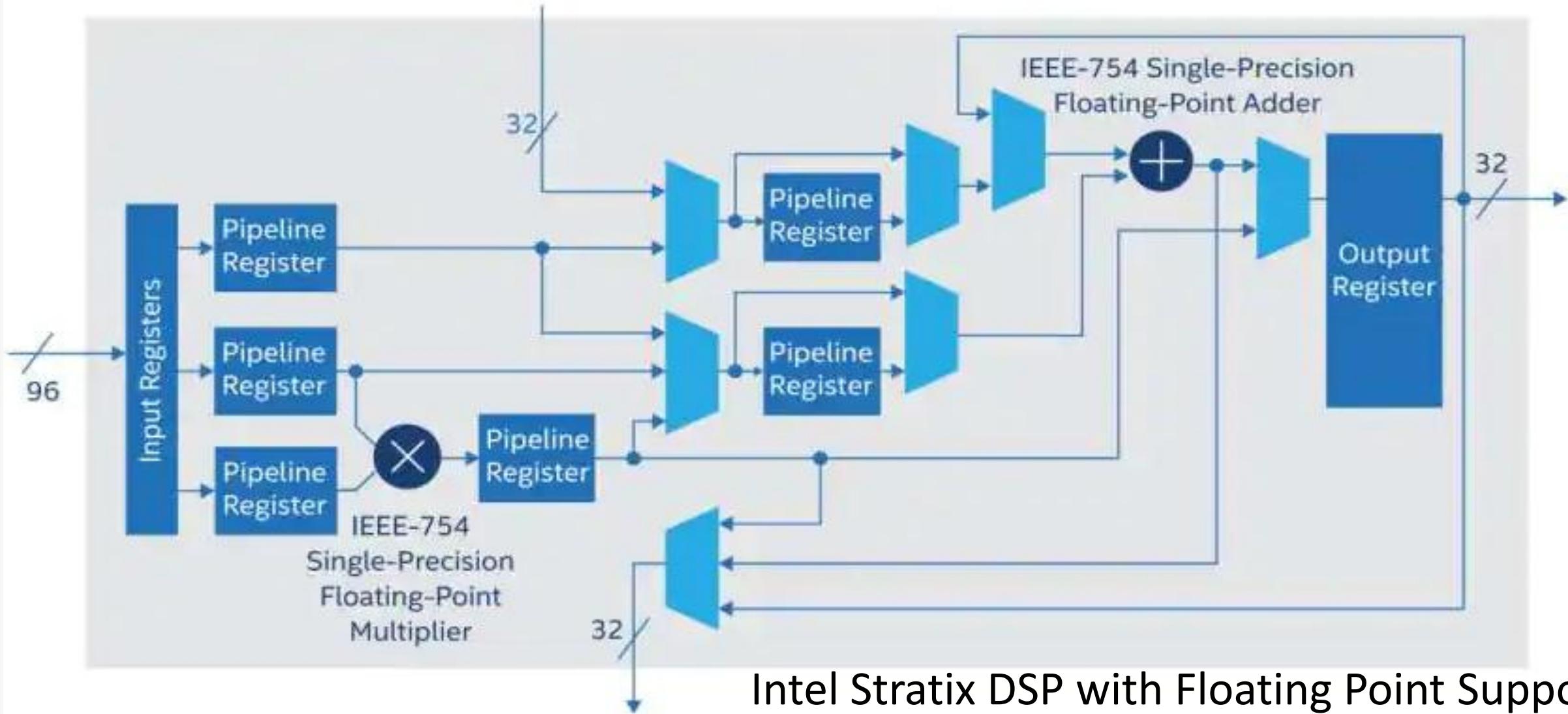
Intel Stratix DSP Block – Fixed Point



Intel® Stratix® 10 Device DSP Block: Standard-Precision Fixed Point

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Intel Stratix DSP Slice with Floating Point



Intel® Stratix® 10 Device DSP Block: Single-Precision Floating Point

Further Reading

- <https://www.xilinx.com/video/fpga/7-series-dsp-resources.html>