

Parallel and Reconfigurable VLSI Computing (7)

Practical RTL Design

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Outline

- Practical RTL design methodology
 - From behavior (C/C++ code) to HDL one
- Interface co-design
 - Control a hardware from an ARM processor
- RTL design optimization

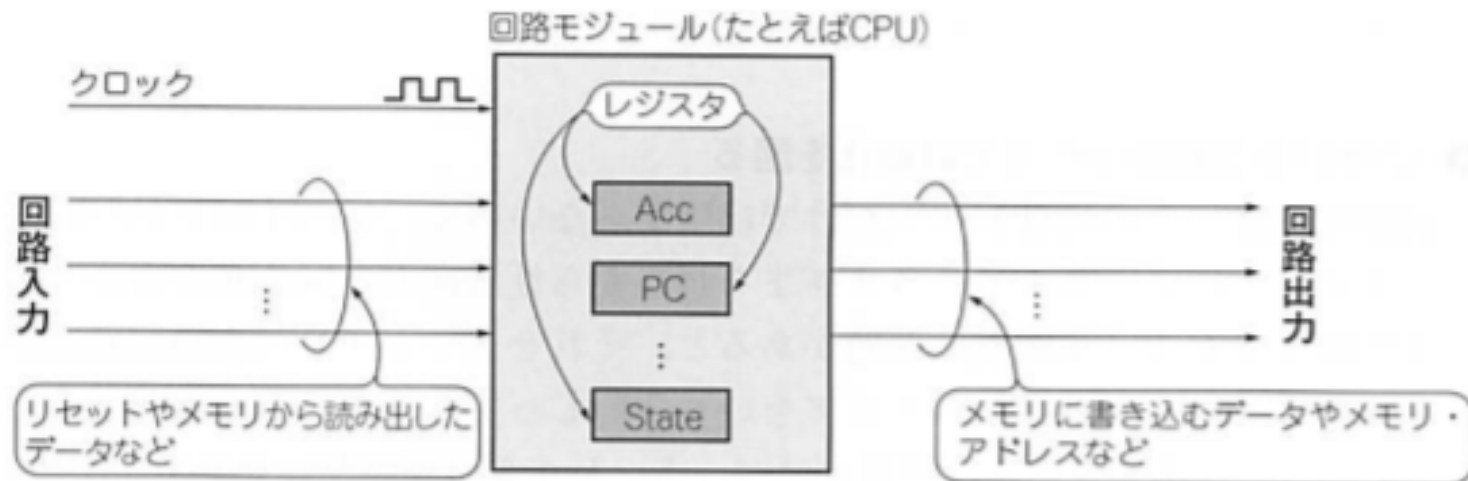
Practical RTL Design Methodology

C/C++ to RTL

- Determine the specifications of the circuit
 - Timing chart, state transition diagram, performance, block diagram
- Consider the configuration of the module
 - Design and combine for each IP core
- Function assigned to each core and its resource
 - Including a consideration of interface
 - Often written in C/C++
 - It becomes a testbench for a verification
- Convert C/C++ description to RTL
- Optimize behaviors (pipelining and parallelization)
 - Automation by the remaining work with CAD

C/C++ Description for a Concept of Module

- Approximate ~300 lines for single function
- Data input/output (Interface)
- Data processing



Case Study: FIR Filter

- x_n : N sampling signals and y_n : Output signal, then

$$y_n = \sum_{k=0}^{N-1} h_k x_{n-k}$$

, where a filter coefficient h_n is given by

$$h_n = \frac{\rho_n}{2\pi} \int_0^{2\pi} d\tilde{\omega} e^{i\tilde{\omega}(n-\tilde{\tau})} H_0(\tilde{\omega}).$$

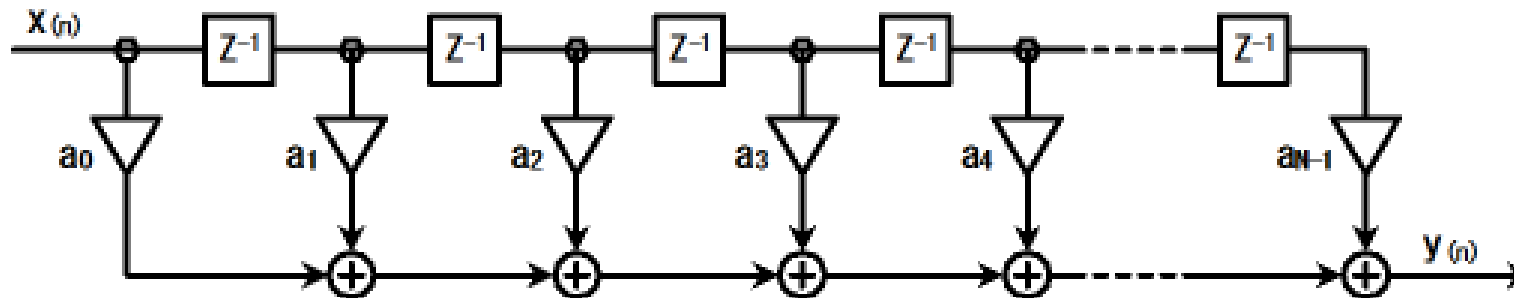
, where $\tilde{\omega} = 2\pi\omega / \omega_s$ denotes normalized freq., ω_s denotes sampling freq., $H_0(\tilde{\omega}) \in \mathbb{R}$ denotes frequency characteristic, ρ_n denotes window function, and $\tilde{\Gamma} = (N-1)/2$.

Cont'd

- Deference equation for a FIR filter:

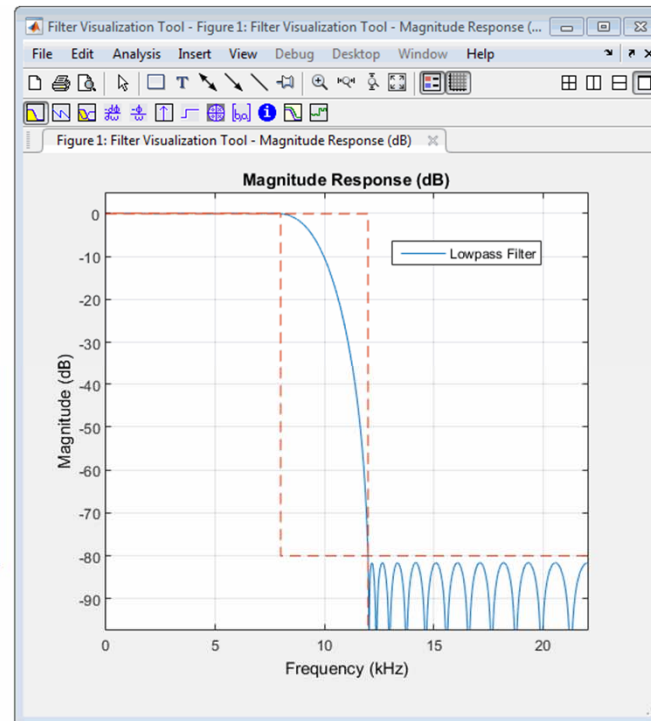
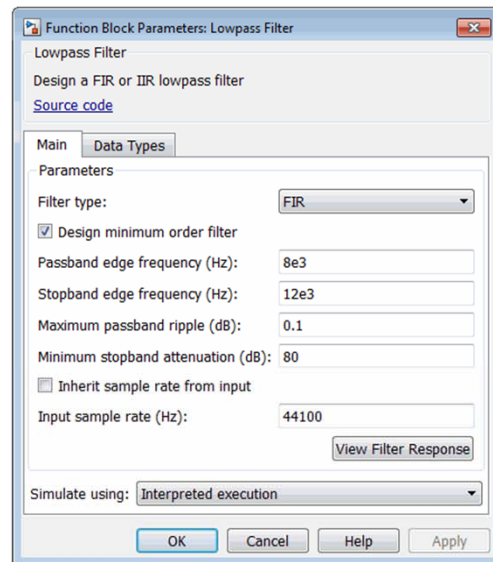
$$y[n] = a_0x[n] + a_1x[n-1] + a_2x[n-2] + a_3x[n-3] + a_4x[n-4] + \cdots + a_{N-1}x[n-(N-1)]$$

- Diagram for a FIR filter:



FIR Filter Coefficient Design

- MathWorks Matlab with DSP System Toolbox
 - Sampling Freq.: 44.1 kHz
 - LPF for 20 kHz → Normalized cut-off freq.
 - #Taps: 11
 - Window function: Hamming



C Behavior for a FIR Filter

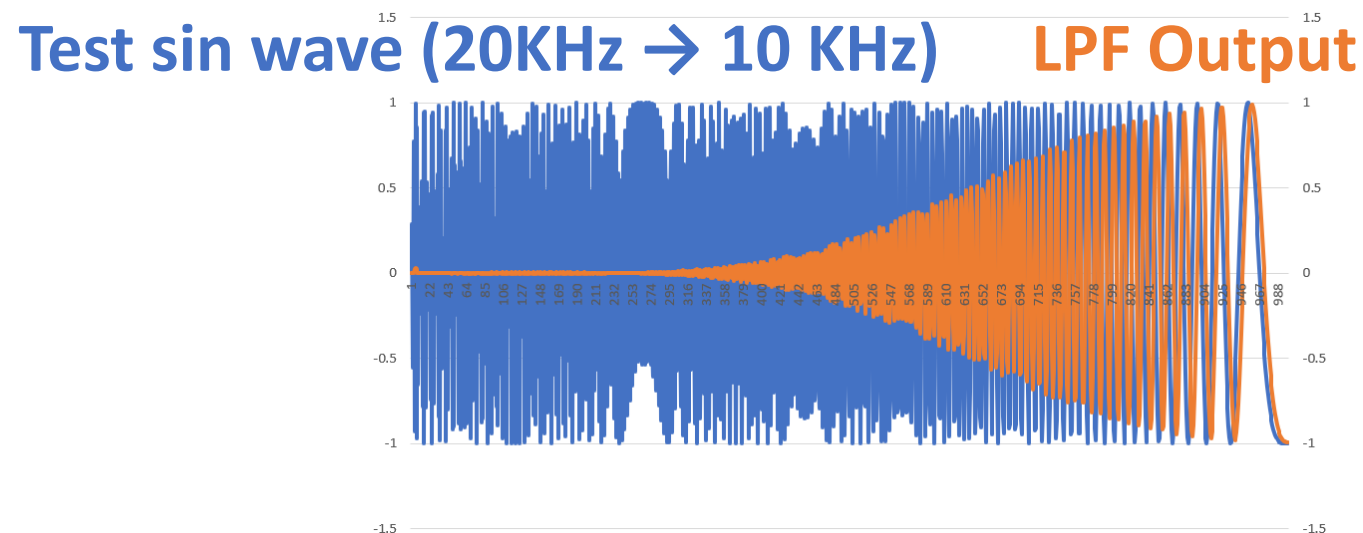
https://github.com/HirokiNakahara/FPGA_lecture/tree/master/Lec7_Practical_RTL_design/fir.c

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <math.h>
4
5  #define N 11
6
7  void fir(float *y, float x)
8  {
9      float c[N] = { // 0.17 = 20KHz/44.1KHz, LPF, Hamming Window
10         -4.120289718403869e-03, -1.208600321298122e-02,
11         -2.650603053411641e-03,  9.166631627169690e-02,
12         2.544318483405623e-01,  3.400000000000001e-01,
13         2.544318483405623e-01,  9.166631627169690e-02,
14         -2.650603053411641e-03, -1.208600321298122e-02,
15         -4.120289718403869e-03, };
16
17     static float shift_reg[N];
18     float acc;
19     int i;
20
21     acc = 0.0;
22     for (i = N - 1; i >= 0; i--) {
23         if (i == 0) {
24             acc += x * c[0];
25             shift_reg[0] = x;
26         } else {
27             shift_reg[i] = shift_reg[i - 1];
28             acc += shift_reg[i] * c[i];
29         }
30     }
31     *y = acc;
32 }
```

```
34 void main()
35 {
36     float fs = 44100.0;
37     int len = 1000;
38
39     float f0 = 20000.0;
40     float sin_wave;
41     float fir_out;
42
43     int i;
44
45     for( i = 0; i < len; i++){
46         sin_wave = sin( 2.0 * M_PI * f0 * i / fs);
47
48         fir( &fir_out, sin_wave);
49
50         printf("%d %f %f\n", i, sin_wave, fir_out);
51         f0 = f0 - 10.0;
52     }
53 }
```

Debug for C Description

- Confirm the operation of FIR
- In/Out are reused as a testbench for HDL simulation
- Note, a parallel operation cannot be verified
- Area and speed of the circuit can not be estimated



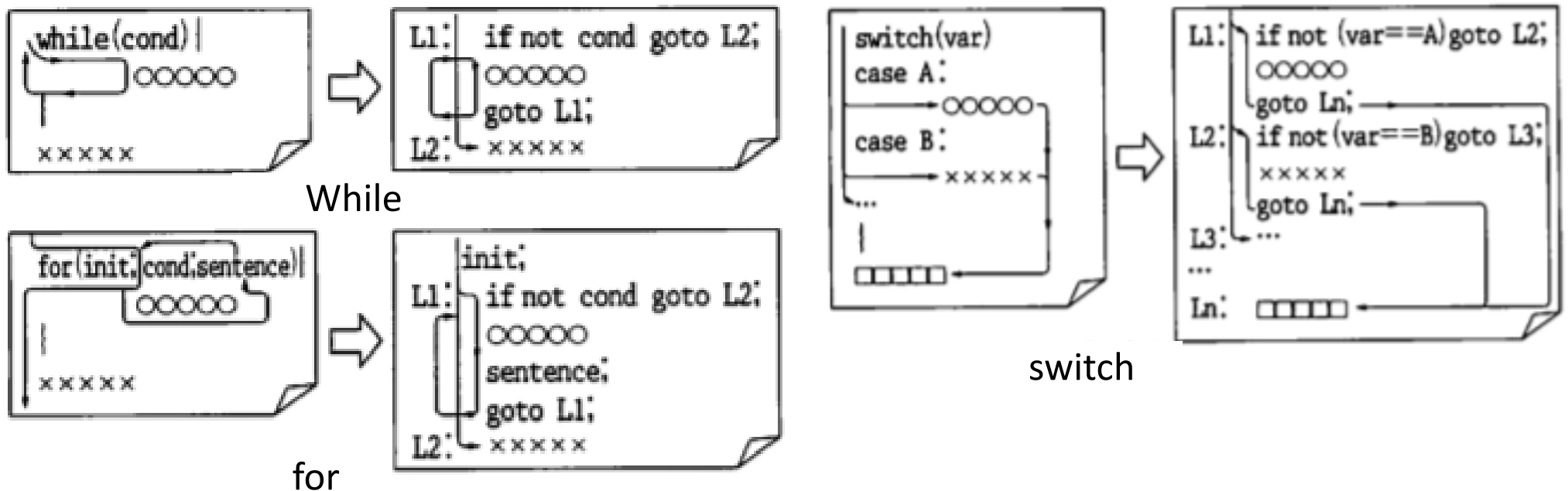
Convert to Fixed Point Precision

https://github.com/HirokiNakahara/FPGA_lecture/tree/master/Lec7_Practical_RTL_design/fir_int.c

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <math.h>
4
5  #define N 11
6  #define PREC 65536 // 2**16 sign + 15bit precision
7
8  void fir(int *y, int x)
9  {
10     int c[N] = { // 0.17 = 20KHz/44.1KHz, LPF, Hamming Window
11                 -136, -397, -87, 3004, 8338, 11142, 8338,
12                 3004, -87, -397, -136, };
13
14     static int shift_reg[N];
15     int acc;
16     int i;
17
18     acc = 0;
19     for (i = N - 1; i >= 0; i--) {
20         if (i == 0) {
21             acc += x * c[0];
22             shift_reg[0] = x;
23         } else {
24             shift_reg[i] = shift_reg[i - 1];
25             acc += shift_reg[i] * c[i];
26         }
27     }
28     *y = acc;
29 }
30
31 void main()
32 {
33     float fs = 44100.0;
34     int len = 1000;
35
36     float f0 = 20000.0;
37     float sin_wave;
38     int fir_out;
39
40     int i;
41
42     for( i = 0; i < len; i++){
43         sin_wave = sin( 2.0 * M_PI * f0 * i / fs);
44
45         fir( &fir_out, (int)(sin_wave * PREC));
46
47         printf("%d %f %f\n", i, sin_wave, (float)fir_out / PREC);
48         f0 = f0 - 10.0;
49     }
50 }
```

C Behavior to RTL

- RTL → Data path + FSM
- Re-write control *while*, *for*, *switch* statements to *if-then*, *goto* statements, then convert FSM
- Assign label to each statement → FSM state number



Example

```
L1: acc = 0;
L2: for (i = N - 1; i >= 0; i--) {
L3: if (i == 0) {
L3_1:  acc += x * c[0];
L3_2:  shift_reg[0] = x;
      } else {
L3_3:  shift_reg[i] = shift_reg[i - 1];
L3_4:  acc += shift_reg[i] * c[i];
      }
}
L4: *y = acc;
```



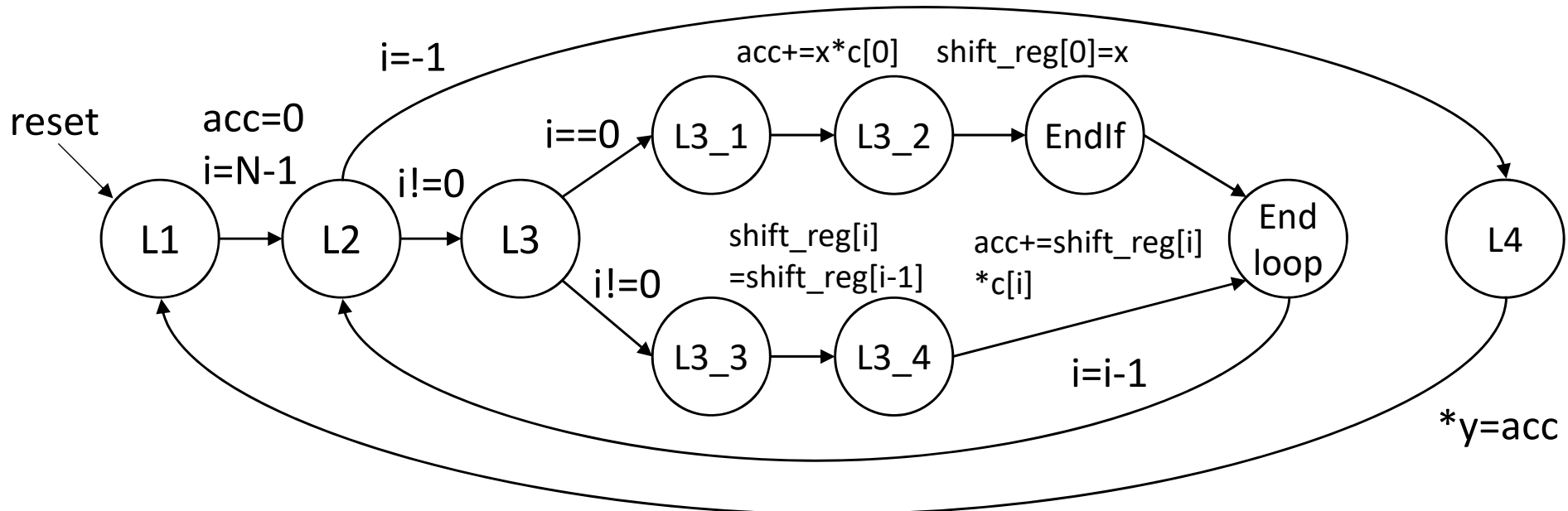
```
L1: acc = 0, i = N - 1;
L2: if i == -1 then goto L4:
L3:  if i != 0 then goto L3_3:
L3_1:  acc += x * c[0];
L3_2:  shift_reg[0] = x;
EndIf: goto Endloop:
L3_3:  shift_reg[i] = shift_reg[i - 1];
L3_4:  acc += shift_reg[i] * c[i];
Endloop: i = i - 1, goto L2:
L4: *y = acc;
```

Write FSM

- Convert *if-then goto* statement to FSM
 - Writing an FSM until you get used to it!
- Add an initialization processing (register value after resetting)
- Make the whole process an infinite loop
 - Generally, return to the initial state after finished all processing

Example

```
L1: acc = 0, i = N - 1;  
L2: if i == -1 then goto L4:  
L3:   if i != 0 then goto L3_3:  
L3_1:     acc += x * c[0];  
L3_2:     shift_reg[0] = x;  
EndIf:   goto Endloop:  
L3_3:     shift_reg[i] = shift_reg[i - 1];  
L3_4:     acc += shift_reg[i] * c[i];  
Endloop: i = i - 1, goto L2:  
L4: *y = acc;
```



Parallel Processing

- Concurrent assignment

tmp=A; A<=B;

A = B; B<=A;

B = tmp;

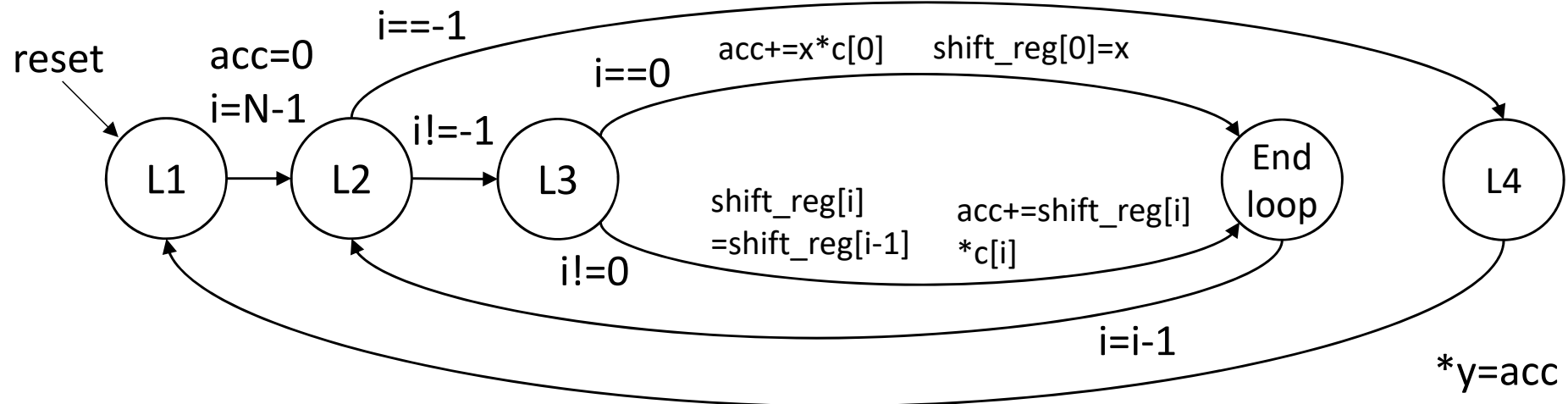
- Continuous assignments

A=B; B=C; $\rightarrow$ A=C;

- Reduce number of states by parallel processing
- Considering simultaneous assignment from the starting FSM description

More Simplify

```
L1: acc = 0, i = N - 1;  
L2: if i == -1 then goto L4:  
L3:   if i == 0 then  
      acc += x * c[0];  
      shift_reg[0] = x;  
      goto Endloop  
    else  
      shift_reg[i] = shift_reg[i - 1];  
      acc += shift_reg[i] * c[i];  
Endloop: i = i - 1, goto L2:  
L4: *y = acc;
```



RTL Simulation for an FIR Filter

See, https://github.com/HirokiNakahara/FPGA_lecture/tree/master/Lec7_Practical_RTL_design/

- FIR Filter module: fir_1.v
- Testbench for FIR Filter: testbench_fir_1.v

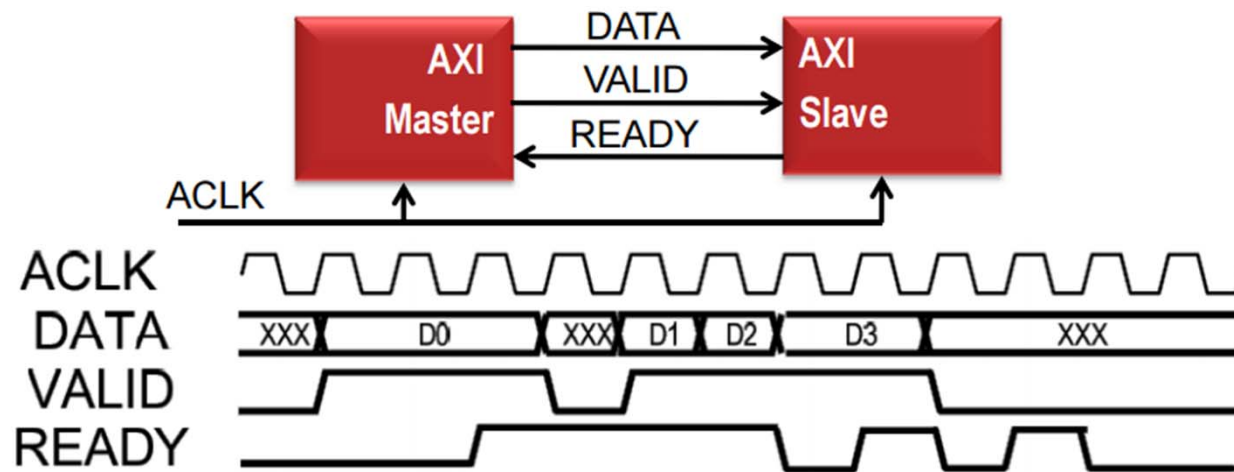
1 Add internal signals to wave viewer

2 Then, reset simulation "restart", and simulation again "run 1000ns"

Interface Co-Design

Interface

- Data Transfer/Receive between modules



Streaming



Burst



Irregular interval



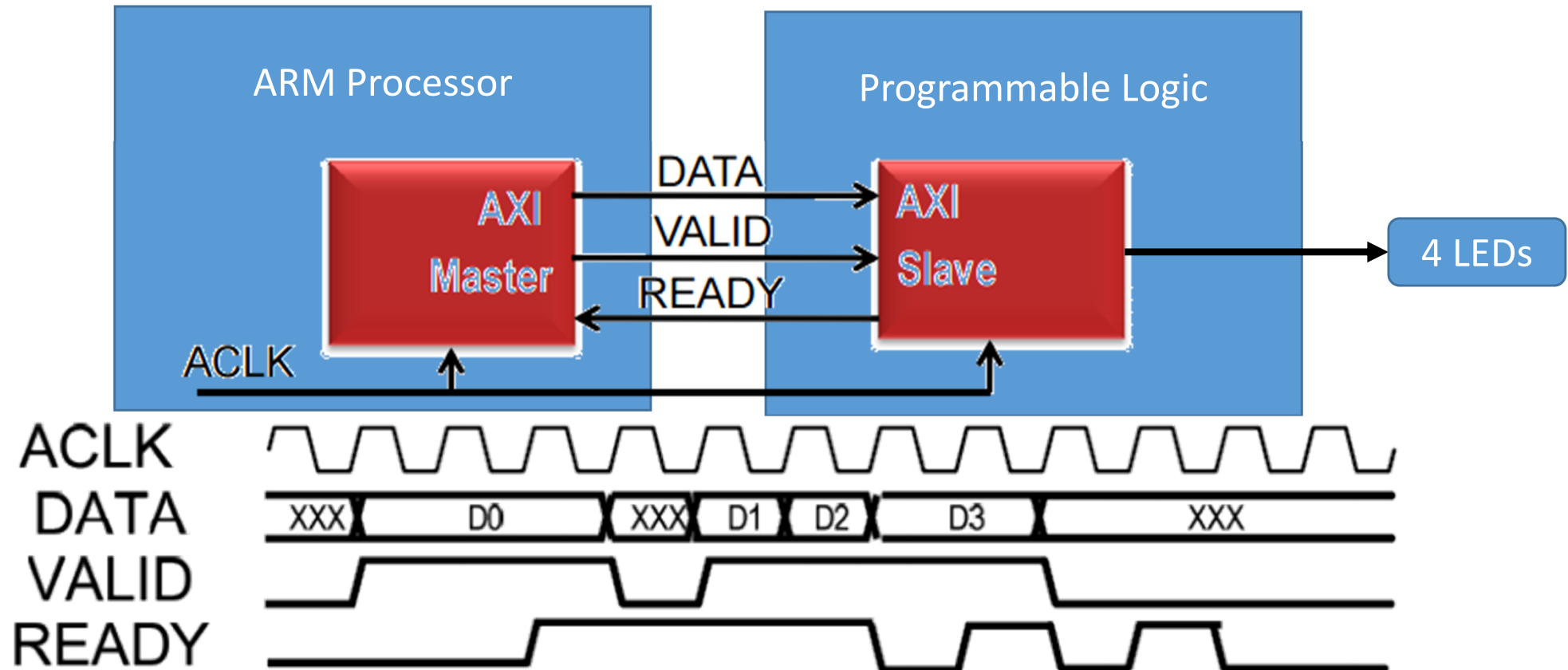
AXI 4 bus: General Interface of ARM Embedded FPGA

- Complex protocols
 - High-level synthesis (HLS) can be easily generated with Directive
 - System design tool (SDSoC) automatically selects the best protocol

	AXI4	AXI4-Lite	AXI4-Stream
Dedicated for	high-performance and memory mapped systems	register-style interfaces (area efficient implementation)	non-address based IP (PCIe, Filters, etc.)
Burst (data beta)	up to 256	1	Unlimited
Data width	32 to 1024 bits	32 or 64 bits	any number of bytes
Applications (examples)	Embedded, memory	Small footprint control logic	DSP, video, communication

Case Study: AXI4 Bus Connection

- Led blinking via AXI-lite bus



Create a New Project

Project location: C:\FPGA\lect7_2\led_axi_lite_1

Target FPGA: Zybo-Z7-10 or (Z7-20)

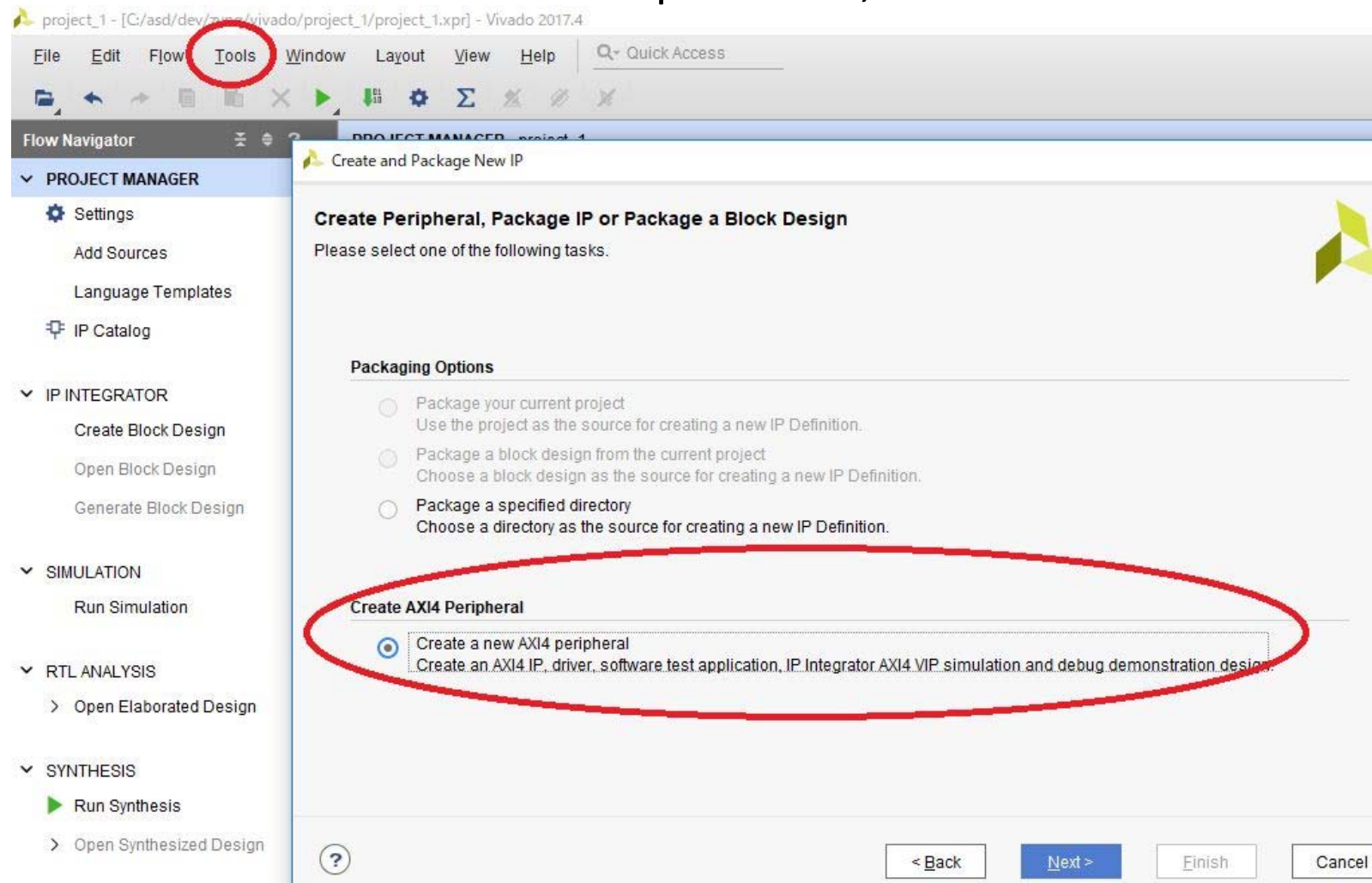
Design Sources: None

Constraints: Zybo-Z7-Master.xdc

Simulation Sources: None

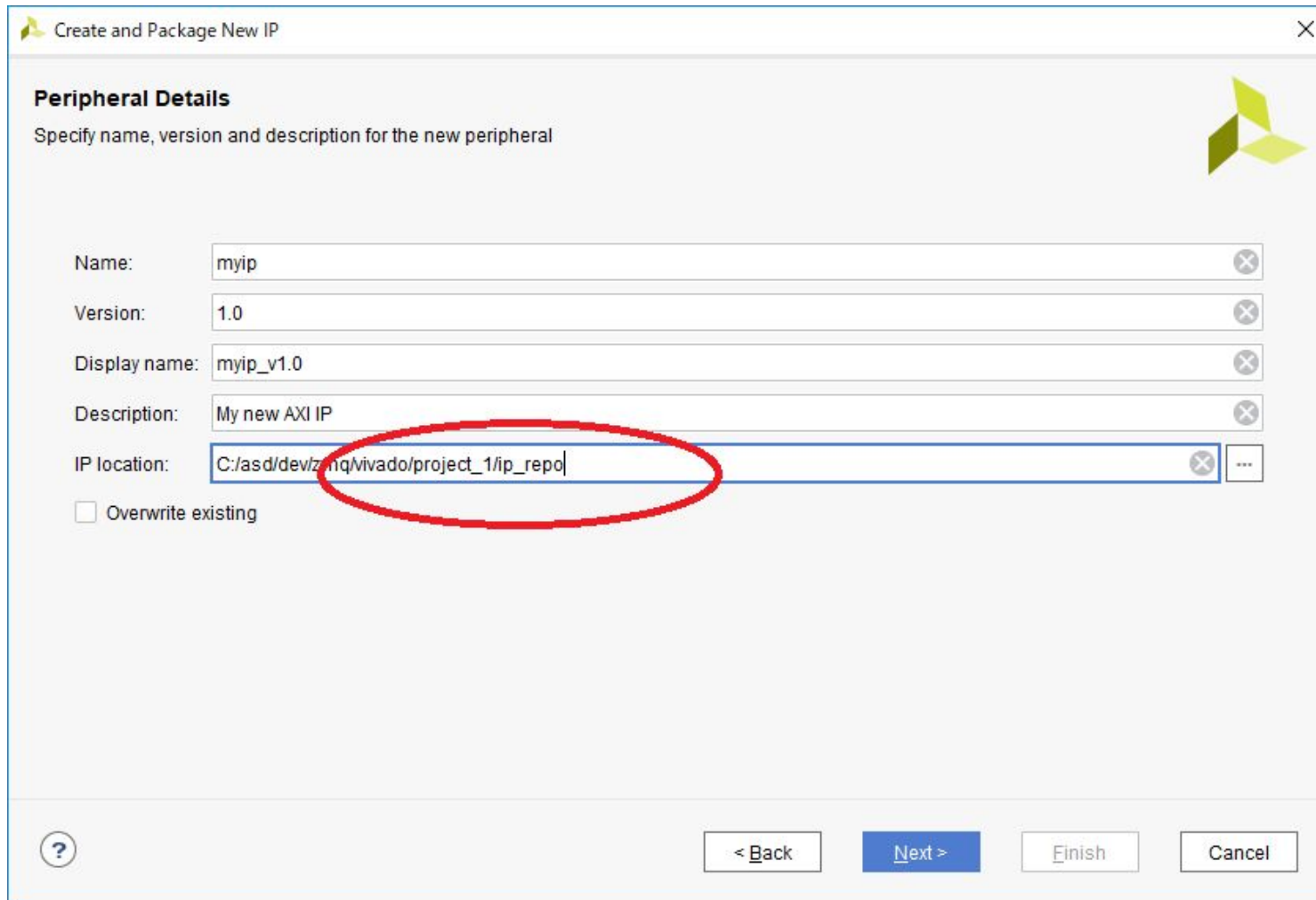
Create AXI4 Peripheral

- Select "Tools->Create and Package New IP", then check "Create AXI4 Peripheral", and "Next"



Specify IP Location

Type "ip_repo" on your project directory, then "Next"



Create and Package New IP

Peripheral Details
Specify name, version and description for the new peripheral

Name: myip

Version: 1.0

Display name: myip_v1.0

Description: My new AXI IP

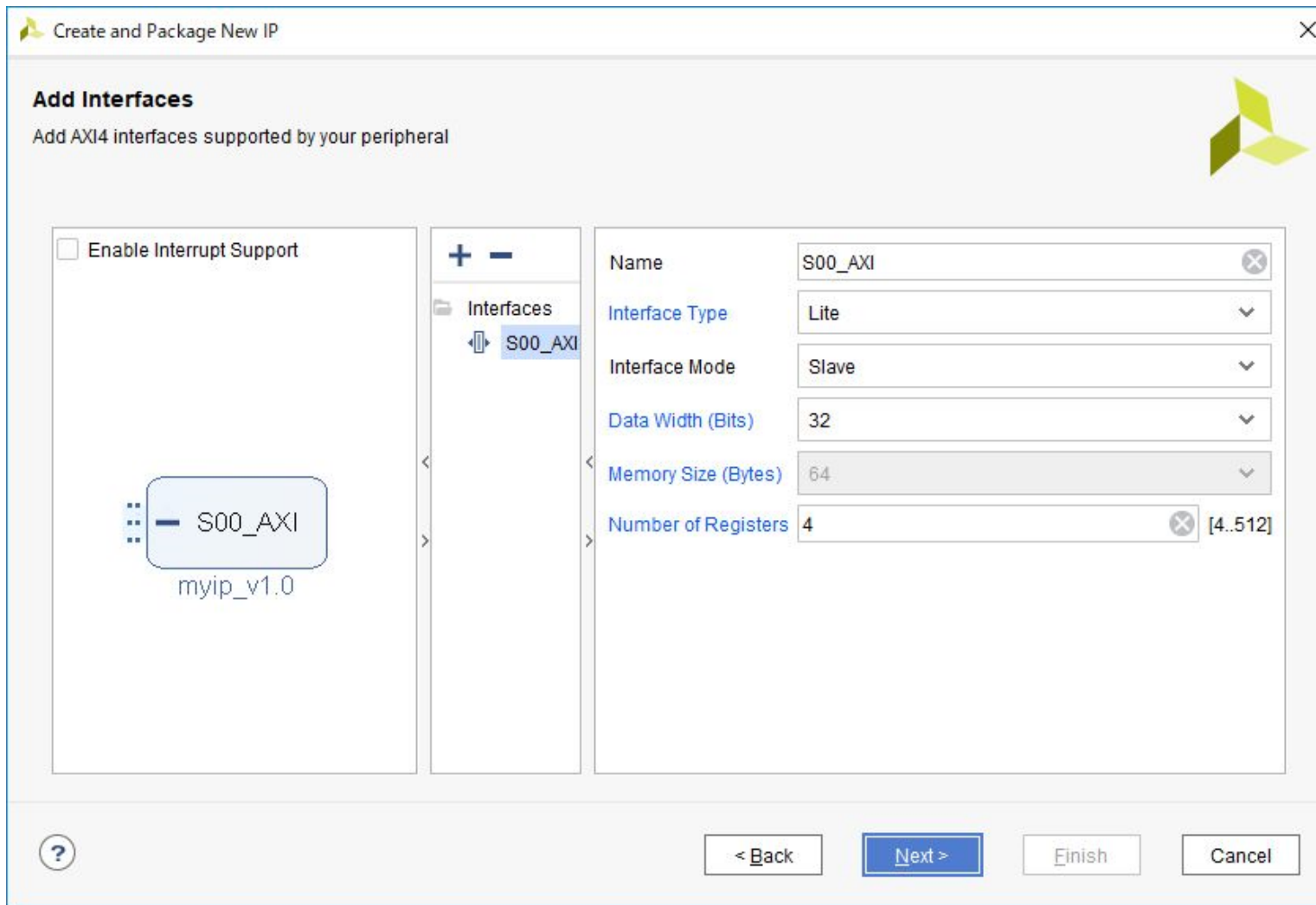
IP location: C:/asd/dev/znq/vivado/project_1/ip_repo

☐ Overwrite existing

< Back Next > Finish Cancel

Edit Interface

- Set the default "AXI4-Lite Slave (four 32-bit registers)", and "OK", then "Finish"



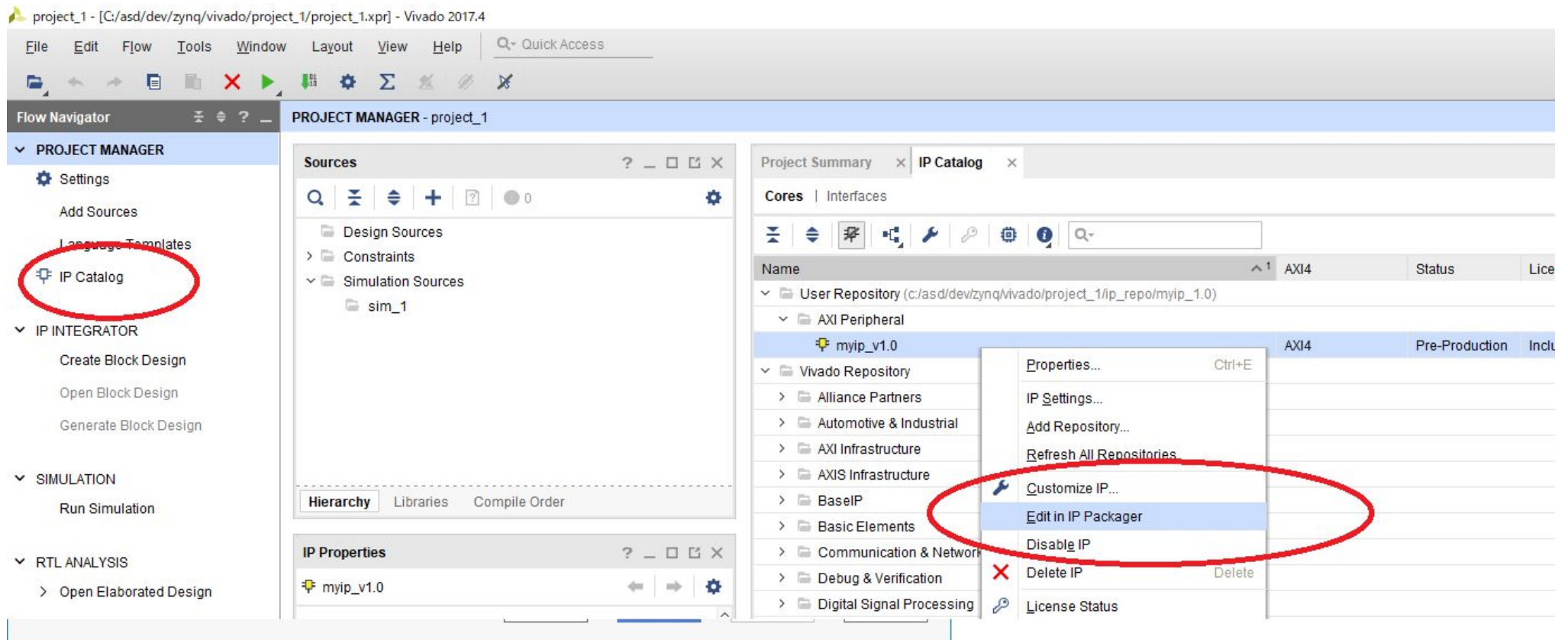
The screenshot shows the 'Create and Package New IP' dialog box, specifically the 'Add Interfaces' tab. The dialog has a title bar with a yellow triangle icon and the text 'Create and Package New IP'. The main area is titled 'Add Interfaces' with the subtitle 'Add AXI4 interfaces supported by your peripheral'. On the left, there is a checkbox for 'Enable Interrupt Support' which is unchecked. Below it, there is a diagram showing a block labeled 'S00_AXI' with 'myip_v1.0' underneath it. In the center, there is a list of interfaces under the heading 'Interfaces', with 'S00_AXI' selected. On the right, there is a configuration table for the selected interface.

Property	Value
Name	S00_AXI
Interface Type	Lite
Interface Mode	Slave
Data Width (Bits)	32
Memory Size (Bytes)	64
Number of Registers	4 [4..512]

At the bottom of the dialog, there are four buttons: '?', '< Back', 'Next >', and 'Cancel'. The 'Next >' button is highlighted in blue.

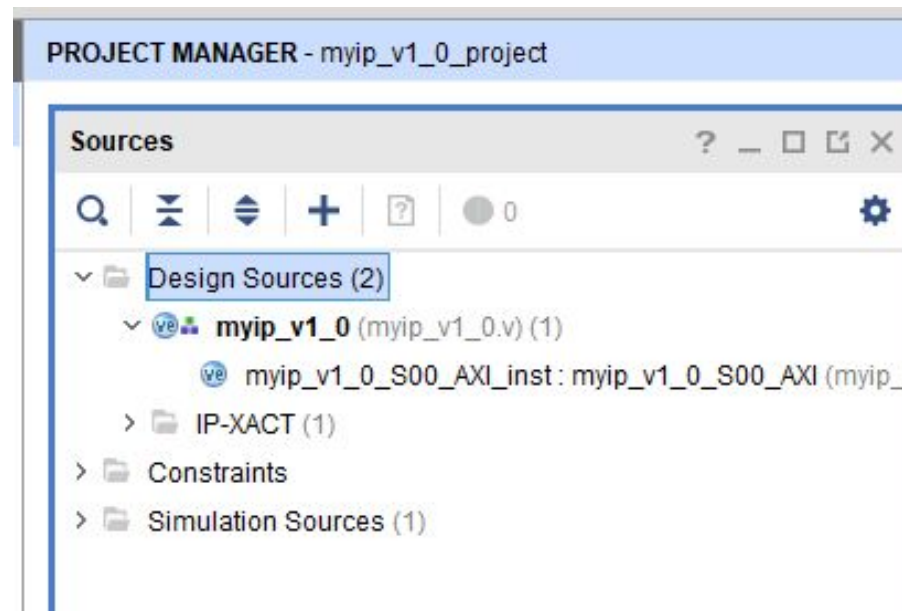
Edit "myip_v1.0"

- Click Flow Navigator->PROJECT MANAGER -> IP Catalog
- Make sure "myip_v1.0" under "User Repository" on "IP Catalog"
- Right click on "myip_v1.0", then select "Edit in IP Packager"
 - Click "OK" to save the project location

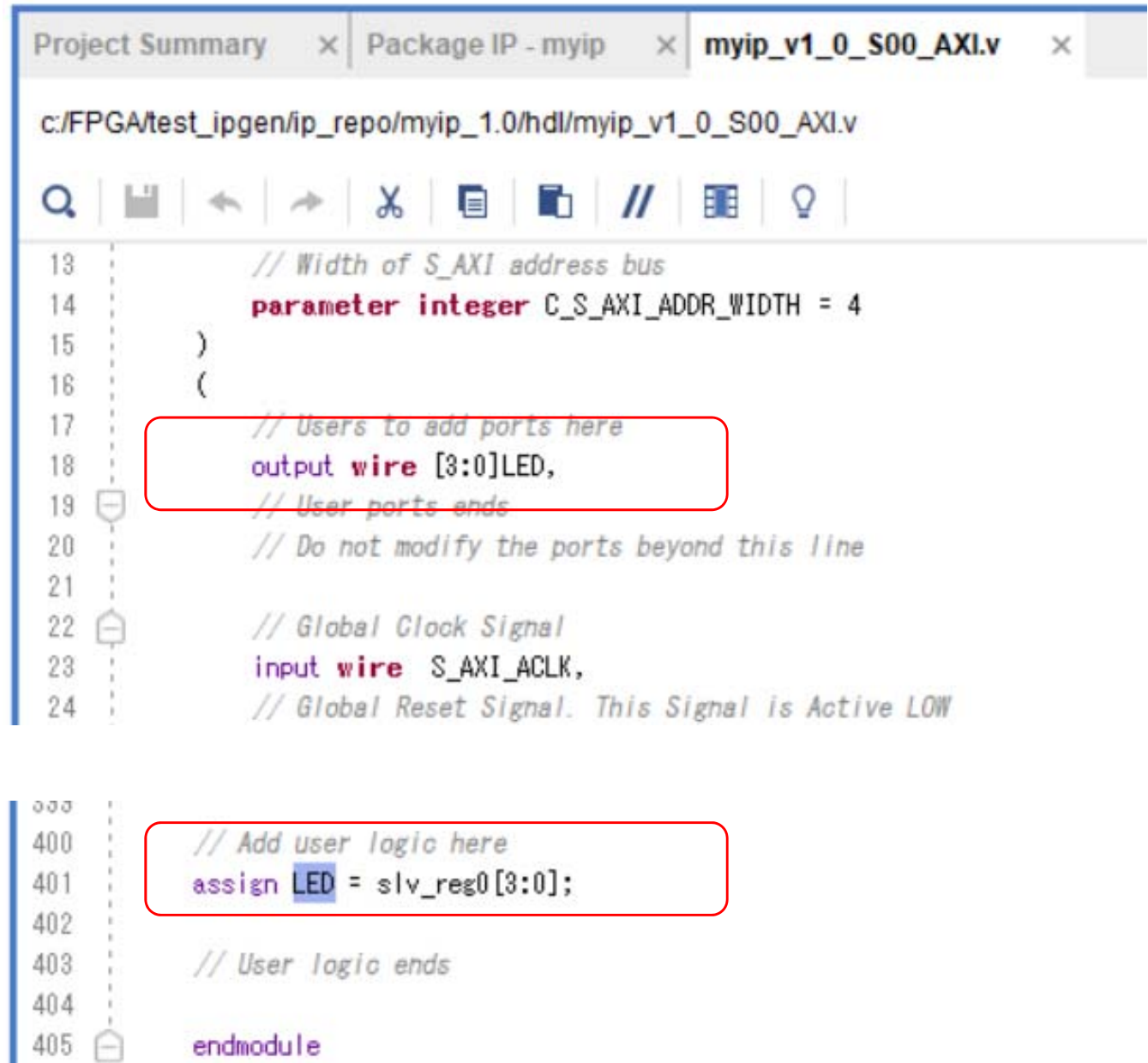


Synthesis "myip" on a New Vivado

- Make sure "myip_v1_0.v" as a wrapper and "myip_v1_0_S00_AXI.v" as a top module



Edit "myip_v1_0_S00_AXI.v"



```
Project Summary x Package IP - myip x myip_v1_0_S00_AXI.v x
c:/FPGA/test_ipgen/ip_repo/myip_1.0/hdl/myip_v1_0_S00_AXI.v

13 // Width of S_AXI address bus
14 parameter integer C_S_AXI_ADDR_WIDTH = 4
15 )
16 (
17 // Users to add ports here
18 output wire [3:0]LED,
19 // User ports ends
20 // Do not modify the ports beyond this line
21
22 // Global Clock Signal
23 input wire S_AXI_ACLK,
24 // Global Reset Signal. This Signal is Active LOW

333
400 // Add user logic here
401 assign LED = slv_reg0[3:0];
402
403 // User logic ends
404
405 endmodule
```

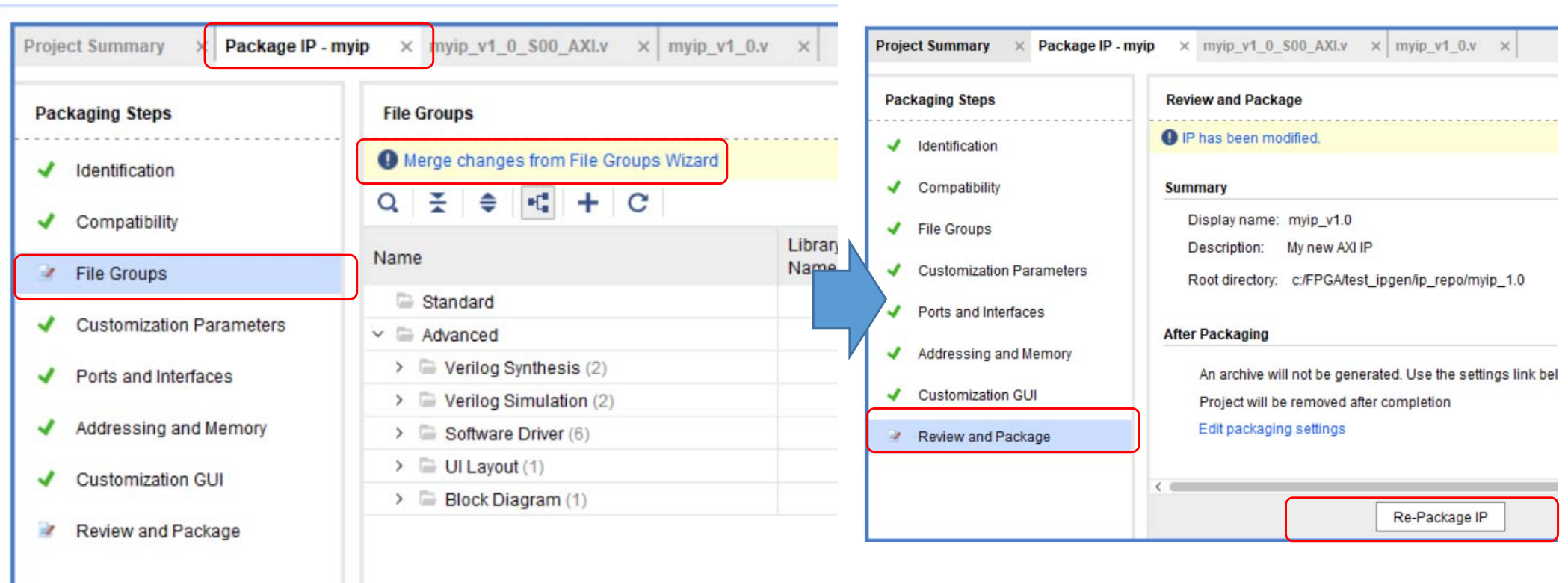
Edit "myip_v1_0.v"

```
12 // Parameters of Axi Slave Bus Interface S00_AXI
13 parameter integer C_S00_AXI_DATA_WIDTH  = 32,
14 parameter integer C_S00_AXI_ADDR_WIDTH  = 4
15 )
16 (
17 // Users to add ports here
18 output wire [3:0]LED,
19 // User ports ends
20 // Do not modify the ports beyond this line
21
```

```
44 input wire s00_axi_rready
45 );
46 // Instantiation of Axi Bus Interface S00_AXI
47 myip_v1_0_S00_AXI # (
48     .C_S_AXI_DATA_WIDTH(C_S00_AXI_DATA_WIDTH),
49     .C_S_AXI_ADDR_WIDTH(C_S00_AXI_ADDR_WIDTH)
50 ) myip_v1_0_S00_AXI_inst (
51     .LED( LED),
52     .S_AXI_ACLK(s00_axi_aclk),
53     .S_AXI_ARESETN(s00_axi_aresetn),
54     .S_AXI_M00ANDP(s00_axi_m00andp)
```

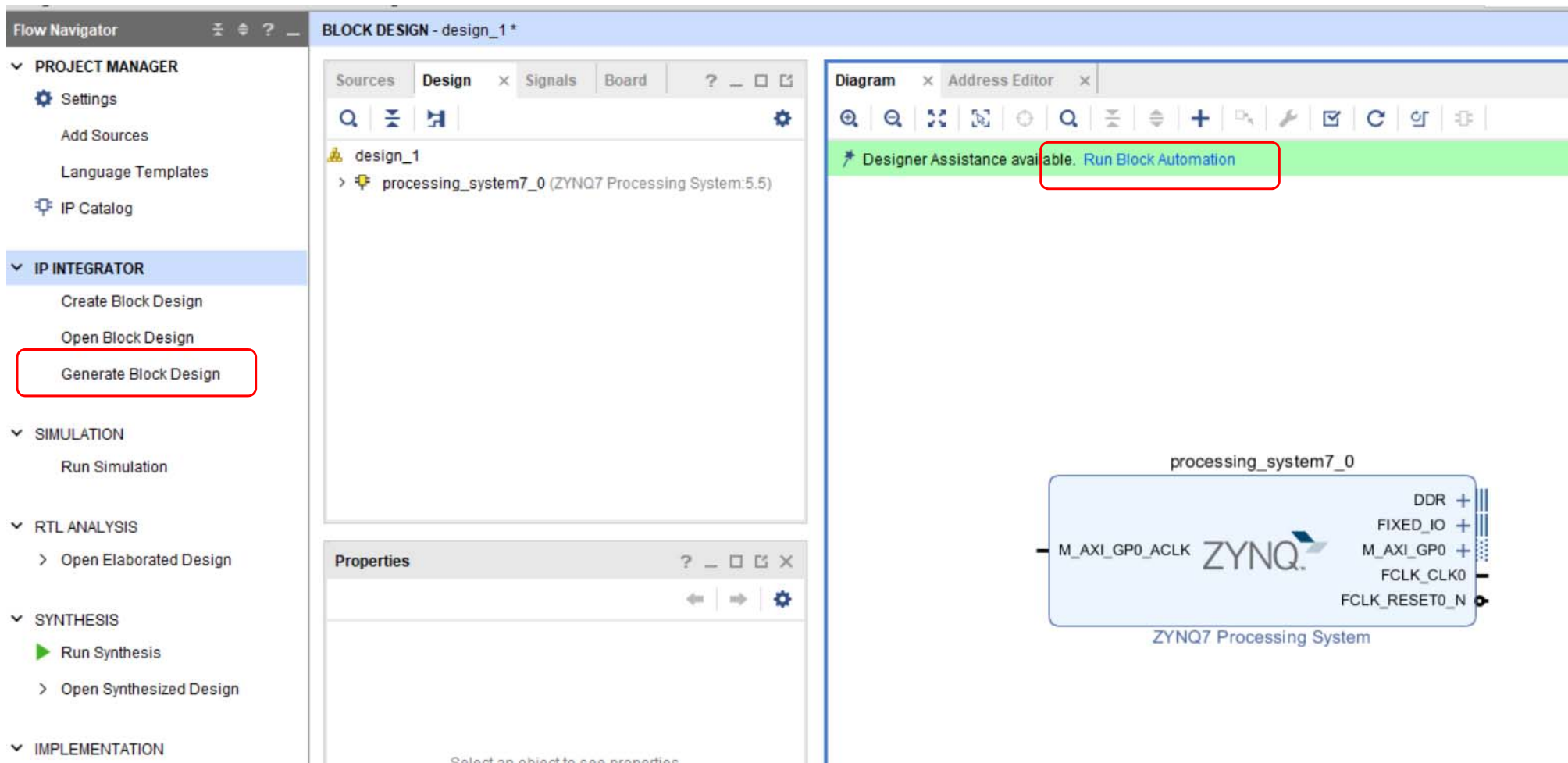
Re-Package IP

- Switch to "Package IP" tab, then "Re-Package IP"



Add a ZYNQ Processor

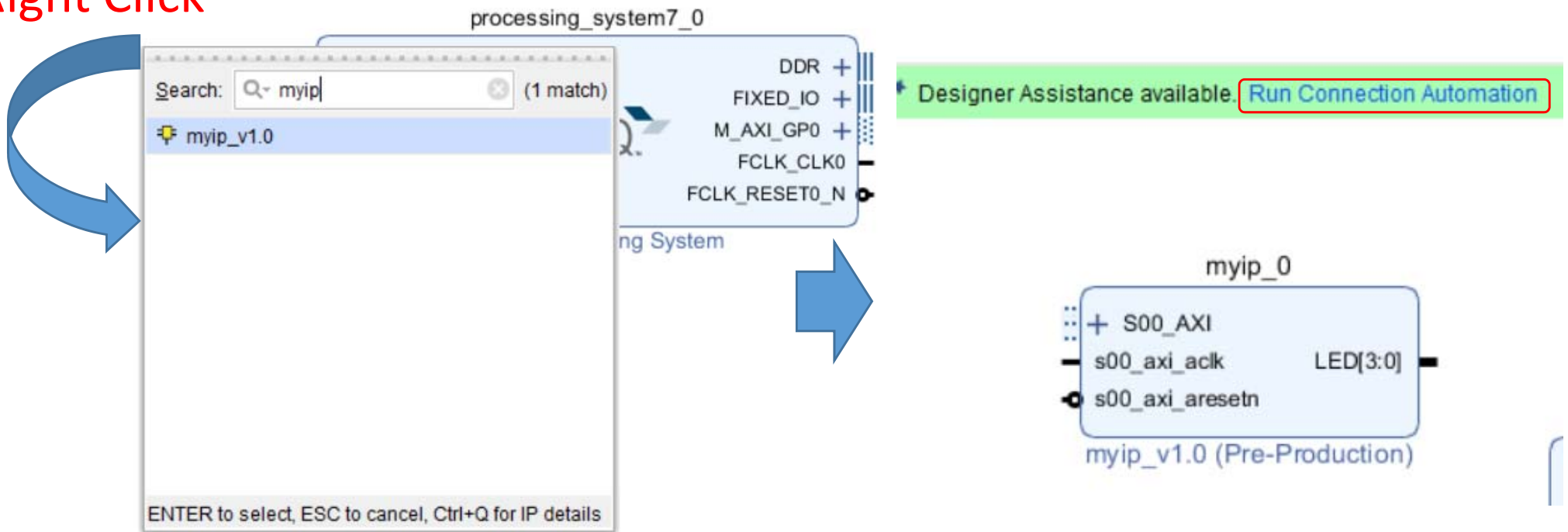
- In the initial Vivado, Flow Navigator -> IP INTEGRATOR -> Create Block Design, then add a ZYNQ Processor, and "Run Block Automation"



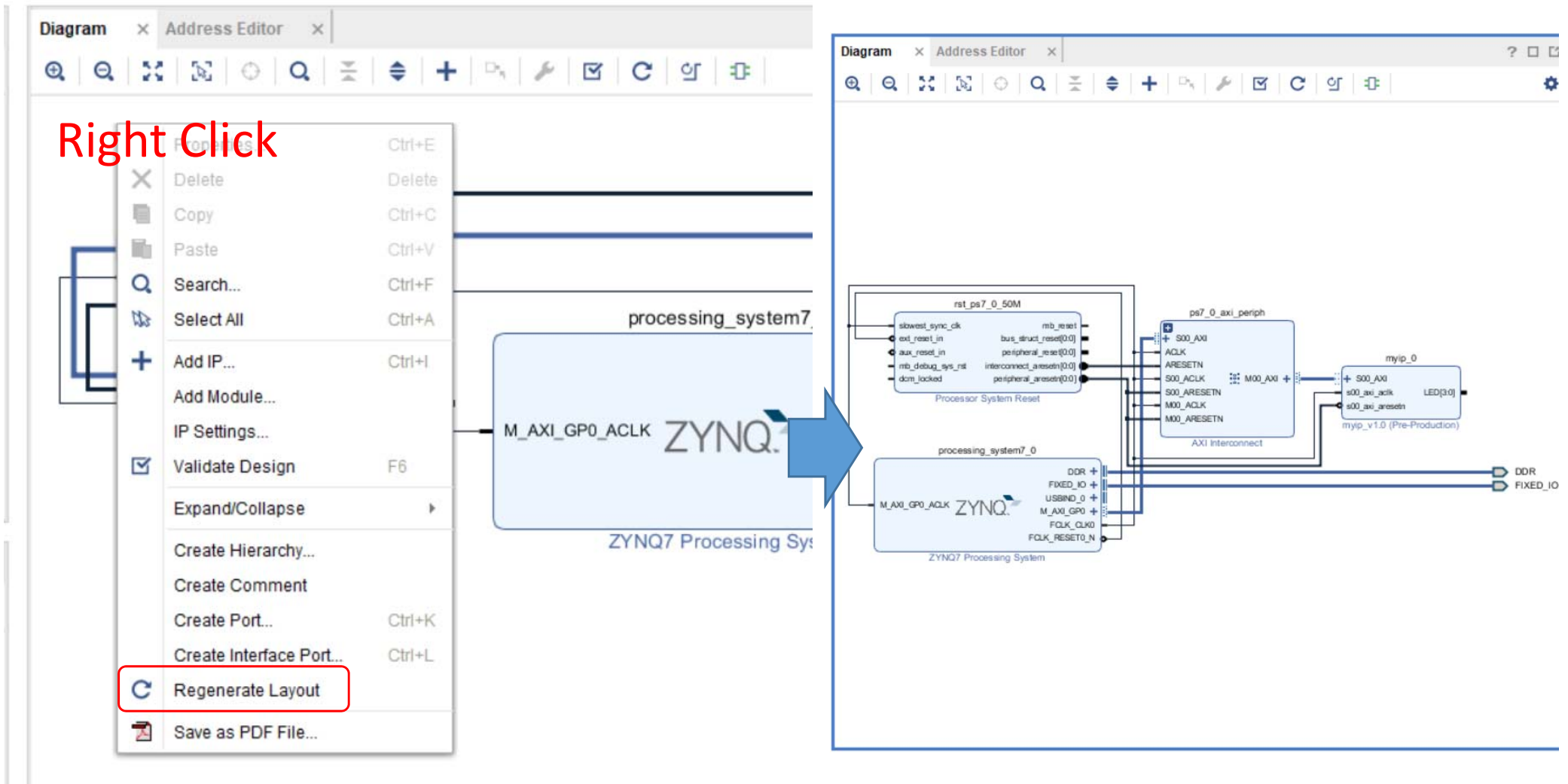
Add a "myip" IP

- Place your "myip" on the Block Design View, then click "Run Connection Automation", and "OK"

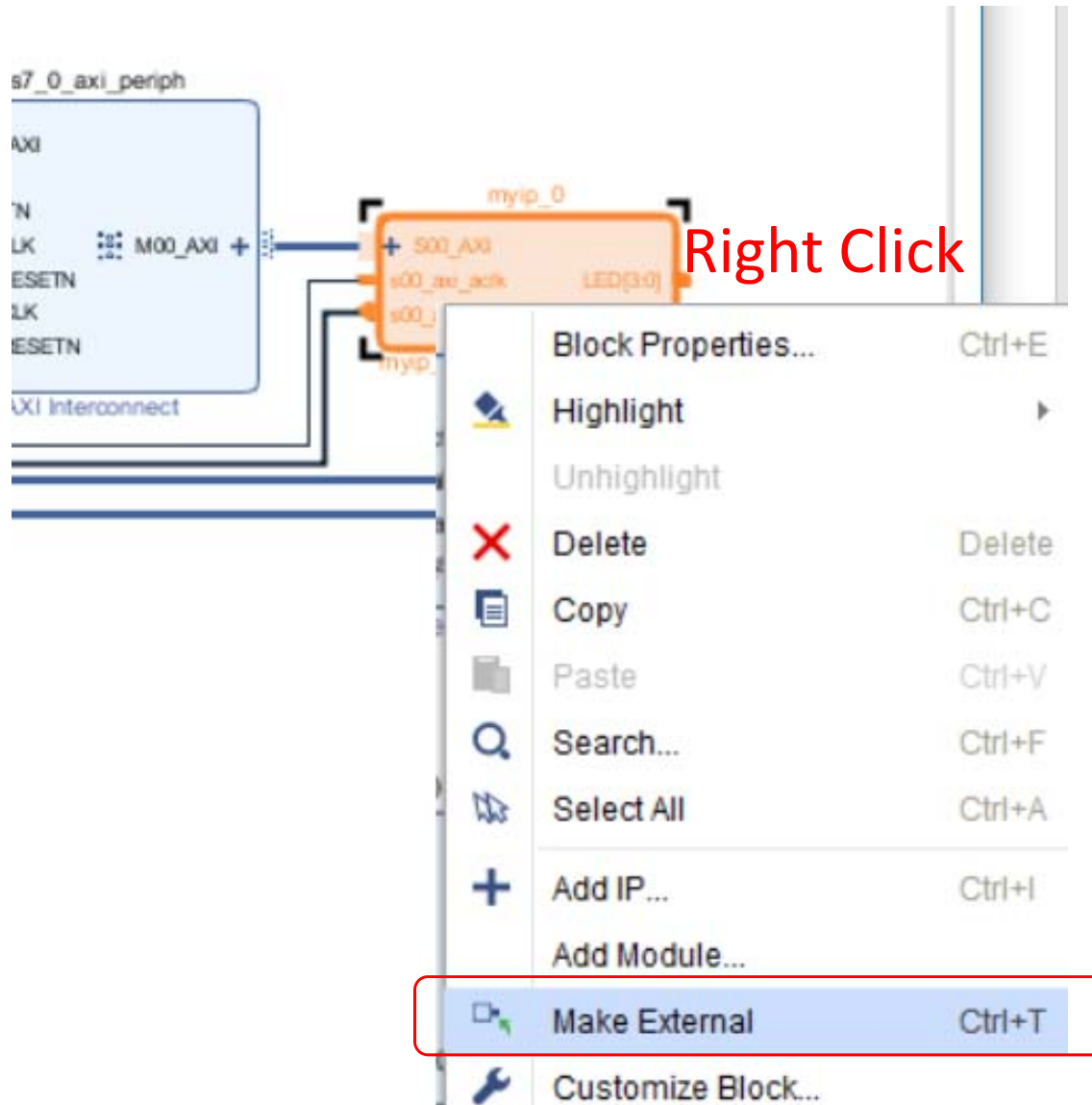
Right Click



Regenerate Layout



Make External



Specify an External Port Name

The screenshot displays the Xilinx Block Design tool interface for a design named "design_1". The left sidebar shows the project hierarchy, including "design_1_wrapper", "design_1_i: design_1", and "design_1". The main diagram area shows a block design with components like "rst_ps7_0_50M", "processing_system7_0", "ps7_0_axi_periph", and "myip_0". A red arrow points from the "myip_0" block to the "External Port Properties" dialog box, which is open. In this dialog, the "Name" field is set to "led", and the "Net" field is set to "myip_0_LED". A red box highlights the "Name" field with the text "set 'led'". Another red box highlights the "External Port Properties" dialog with the text "Right Click". A context menu is visible on the right side of the diagram, showing options like "Highlight", "Unhighlight", "Delete", "Copy", "Paste", "Search...", "Select All", "Add IP...", and "Add Module...".

Block Design - design_1*

Sources x Design Signals Board ? _ □ ✕

Design Sources (1)

- design_1_wrapper (design_1_wrapper.v) (1)
 - design_1_i: design_1 (design_1.bd) (1)
 - design_1 (design_1.v) (5)
- Constraints (1)
 - constrs_1 (1)
 - Zybo-Z7-Master.xdc
- Simulation Sources (1)

Hierarchy IP Sources Libraries Compile Order

External Port Properties

led

Name: led

Direction: Output

From: 3 To: 0

Net: myip_0_LED

Diagram x Address Editor x Zybo-Z7-Master.xdc x ? □ ✕

Processor System Reset

AXI Interconnect

ZYNQ7 Processing System

Right Click

External Port Properties...

- Highlight
- Unhighlight
- Delete
- Copy
- Paste
- Search...
- Select All
- Add IP...
- Add Module...

Write Software Code to Control "myip" from a ZYNQ Processor

- Click "Generate Bitstream", then "Export Hardware", and next, "Launch SDK"
- Create a new project as "myip_test"

Source Code

```
#include <stdio.h>
#include "platform.h"
#include "xil_printf.h"

#include "xparameters.h"

#define LED *((volatile unsigned int *) XPAR_MYIP_0_S00_AXI_BASEADDR)

int main()
{
    init_platform();

    print("Hello World\n\r");

    int i, j;

    while(1){
        for( i = 0; i < 6; i++){
            xil_printf("i=%d\n", i);
            switch(i){
                case 0: LED = 0x1; break;
                case 1: LED = 0x2; break;
                case 2: LED = 0x3; break;
                case 3: LED = 0x4; break;
                case 4: LED = 0x5; break;
                case 5: LED = 0x6; break;
                default: LED = 0x0;
            }
            for( j = 0; j < 10000000; j++);
        }
    }

    cleanup_platform();
    return 0;
}
```

Memory map is automatically generated by Vivado, and it is written in "xparameters.h"

Build the project, then "Xilinx->Program FPGA".

Next, Connect the Zybo to the PC

Run Terminal software (e.g. Tera Term for Windows, gtkterm for Unix)

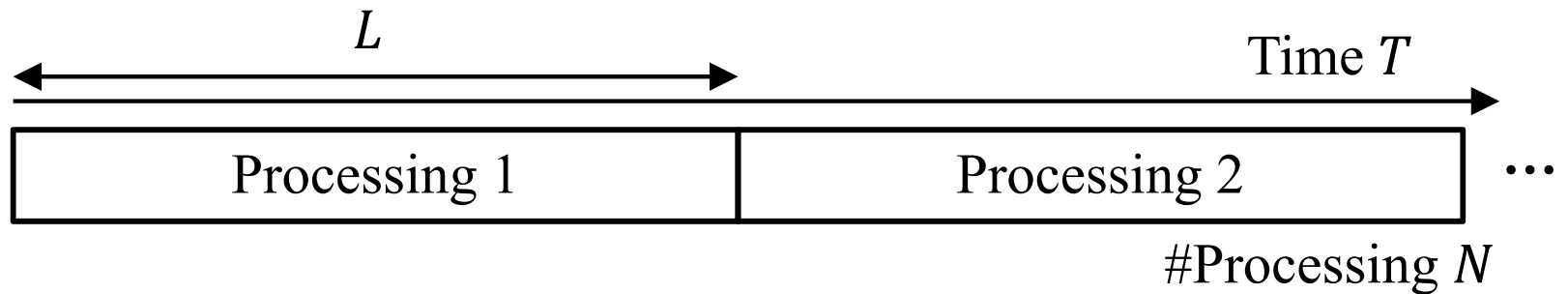
Connect "USB Serial Port" with 115200 bps
Select the project in the Project Explorer, then, in "Menu", "Run As" -> "Launch on Hardware (System Debugger)"

RTL Design Optimization

Pipelining

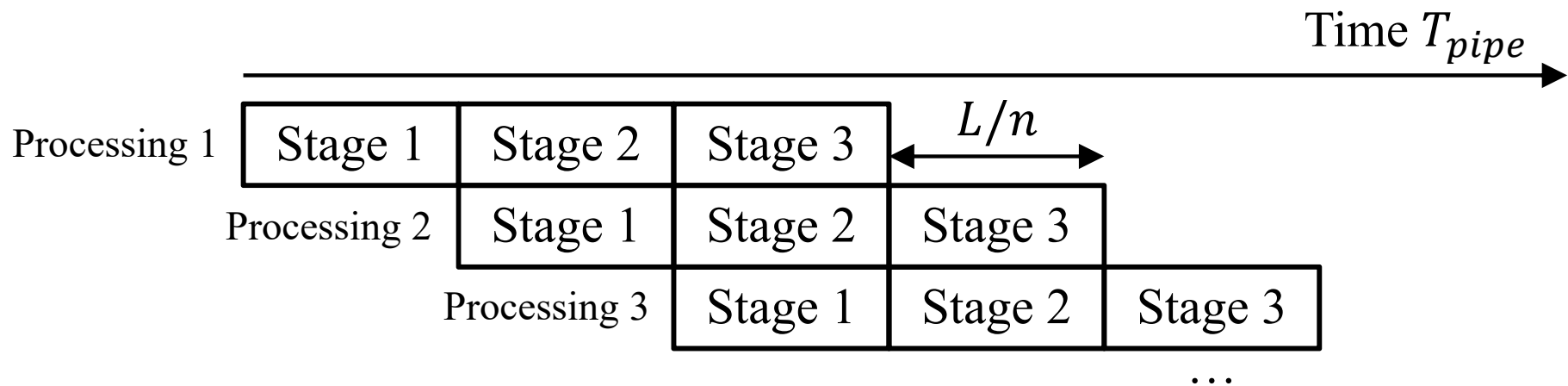
(a) Non-pipelining

Processing iteration 2 is done sequentially **after the completion of iteration 1**



(b) Pipelining ($n = 3$ stage)

Processing iteration 2 is done **after the completion of stage 1 in iteration 1**



Pipeline Efficiency

Percentage of the actually achieved speedup to the maximum

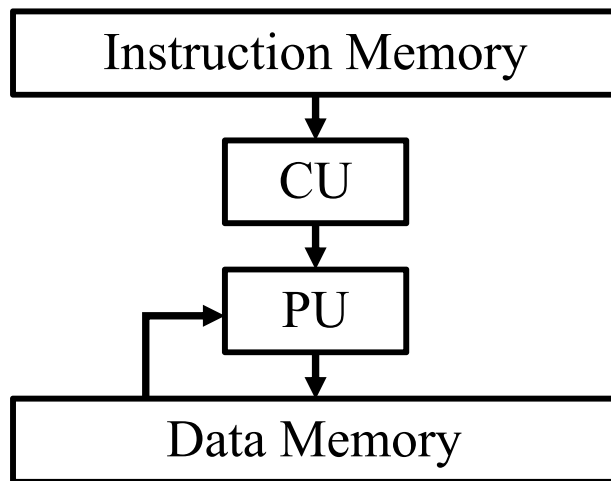
$$S_{pipe}(N) = \frac{T(N)}{T_{pipe}(N)} = \frac{nN}{n + N - 1} = \frac{n}{1 + \frac{n-1}{N}}$$

If $n \ll N$, then $S_{pipe}(N) \cong n$ and the speed-up factor over non-pipelining is n

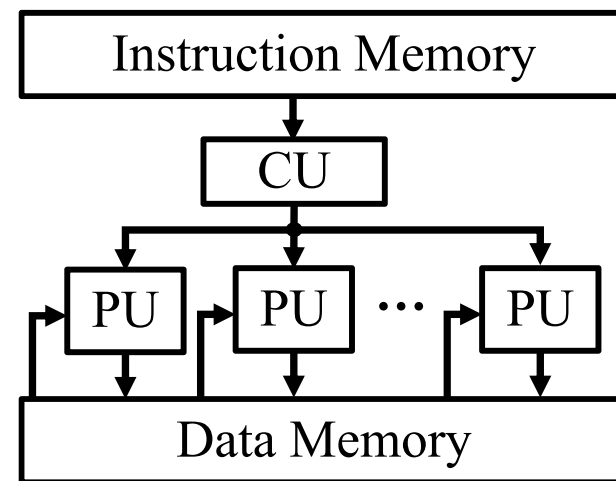
Percentage of the actually achieved speedup to the maximum

$$E_{pipe}(n, N) = \frac{S_{pipe}(N)}{n} = \frac{1}{1 + \frac{n-1}{N}} = \frac{N}{N + n - 1}$$

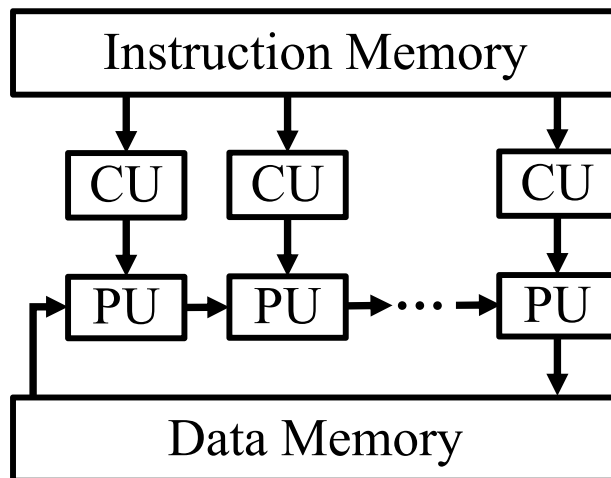
Parallel Processing and Flynn's Taxonomy



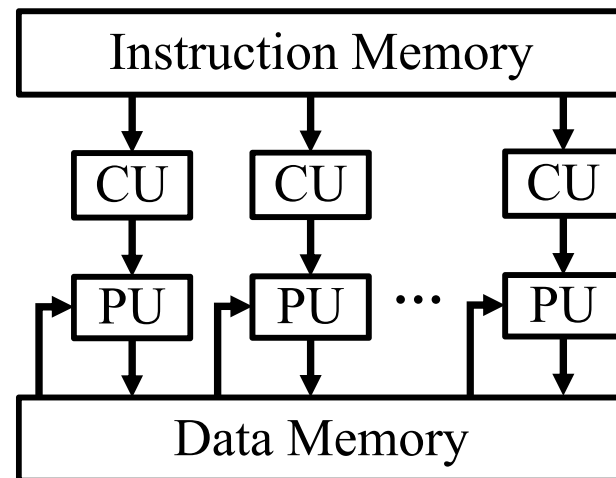
(a) SISD



(b) SIMD



(c) MISD



(d) MIMD

Loop Unrolling

- Without unrolling

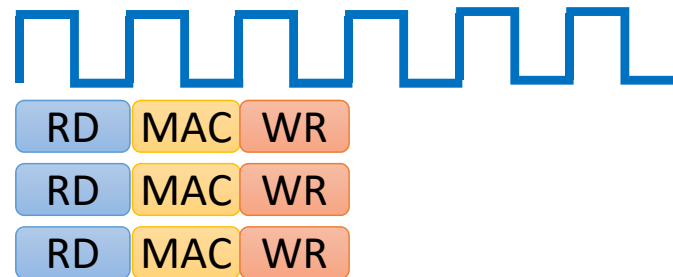
```
for ( int i = 0; i < N; i++){  
  op_Read[i];  
  op_MAC;  
  op_Write[i];  
}
```



Throughput: 3 cycles
Latency: 3 cycles
Operation: 1/3 data/cycle

- Loop Unrolling for 3 Operations

```
for ( int i = 0; i < N/3; i+=3){  
  op_Read[i*3];  
  op_MAC;  
  op_Write[i*3];  
  op_Read[i*3+1];  
  op_MAC;  
  op_Write[i*3+1];  
  op_Read[i*3+2];  
  op_MAC;  
  op_Write[i*3+2];  
}
```



Throughput: 3 cycle
Latency: 3 cycle
Operation: 1 data/cycle

Unrolling for a FIR Filter

```
int c[N] = { // 0.17 = 20KHz/44.1KHz, LPF, Hamr
    -136, -397, -87, 3004, 8338, 11142, 8338,
    3004, -87, -397, -136, };

static int shift_reg[N];
int acc;
int i;

acc = 0;
for (i = N - 1; i >= 0; i--) {
    if (i == 0) {
        acc += x * c[0];
        shift_reg[0] = x;
    } else {
        shift_reg[i] = shift_reg[i - 1];
        acc += shift_reg[i] * c[i];
    }
}
*y = acc;
```

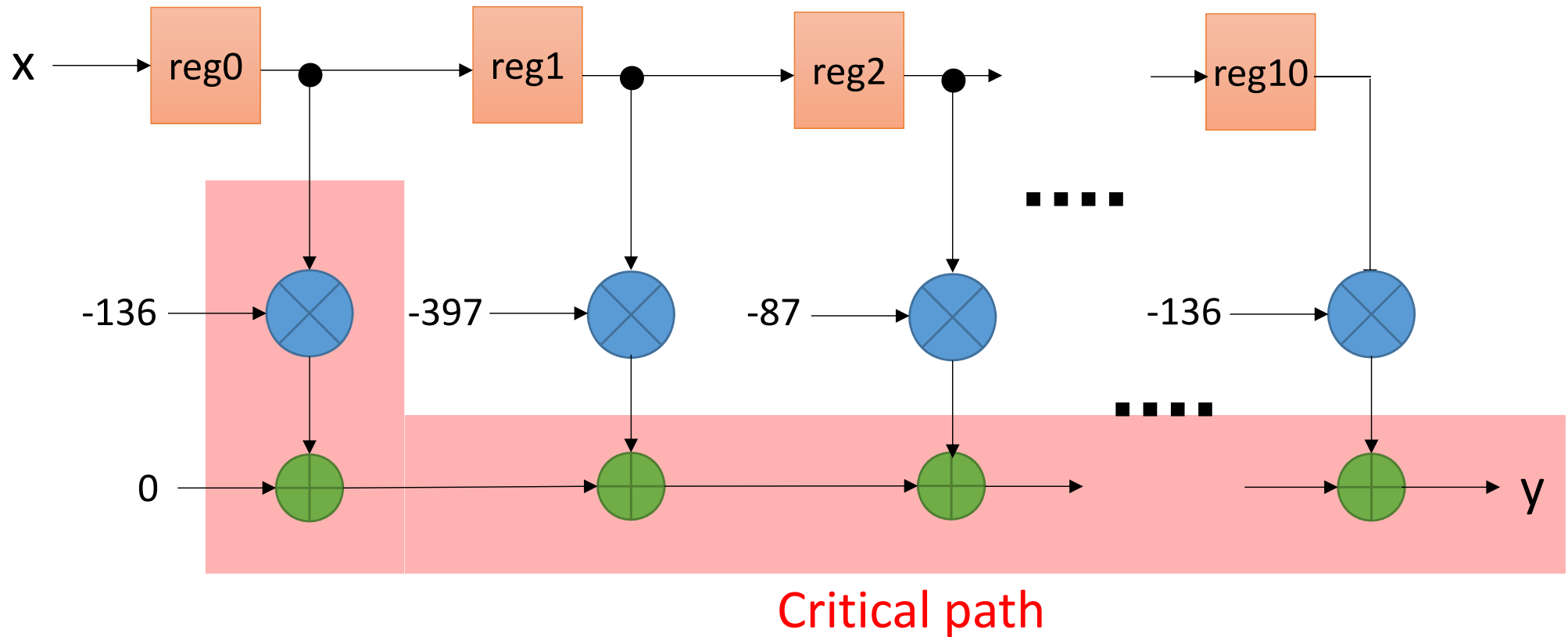


```
static int shift_reg[N];

shift_reg[10] = shift_reg[9];
shift_reg[ 9] = shift_reg[8];
shift_reg[ 8] = shift_reg[7];
shift_reg[ 7] = shift_reg[6];
shift_reg[ 6] = shift_reg[5];
shift_reg[ 5] = shift_reg[4];
shift_reg[ 4] = shift_reg[3];
shift_reg[ 3] = shift_reg[2];
shift_reg[ 2] = shift_reg[1];
shift_reg[ 1] = shift_reg[0];
shift_reg[ 0] = x;

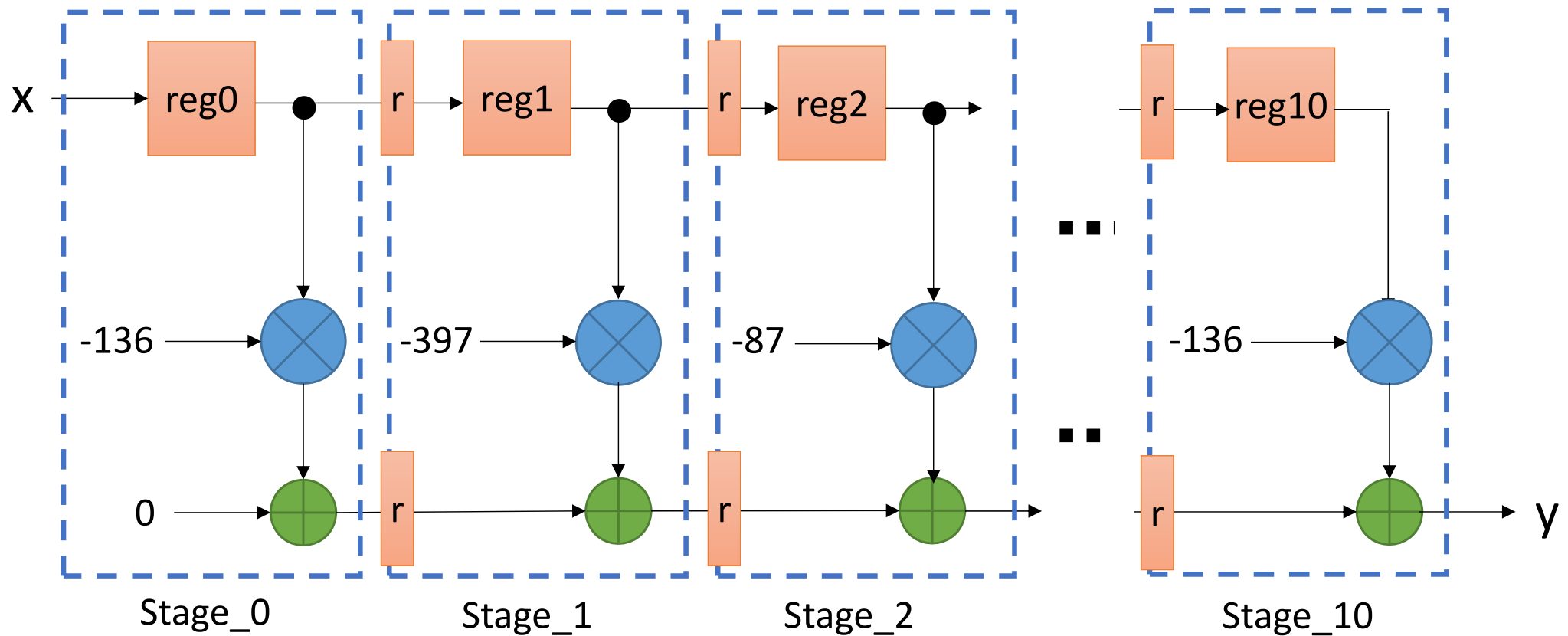
*y = shift_reg[10] * -136 + shift_reg[9] * -397
    + shift_reg[ 8] * -87 + shift_reg[7] * 3004
    + shift_reg[ 6] * 8338 + shift_reg[5] * 11142
    + shift_reg[ 4] * 8338 + shift_reg[3] * 3004
    + shift_reg[ 2] * -87 + shift_reg[1] * -397
    + shift_reg[ 0] * -136;
```

Dataflow for Unrolling FIR Filter



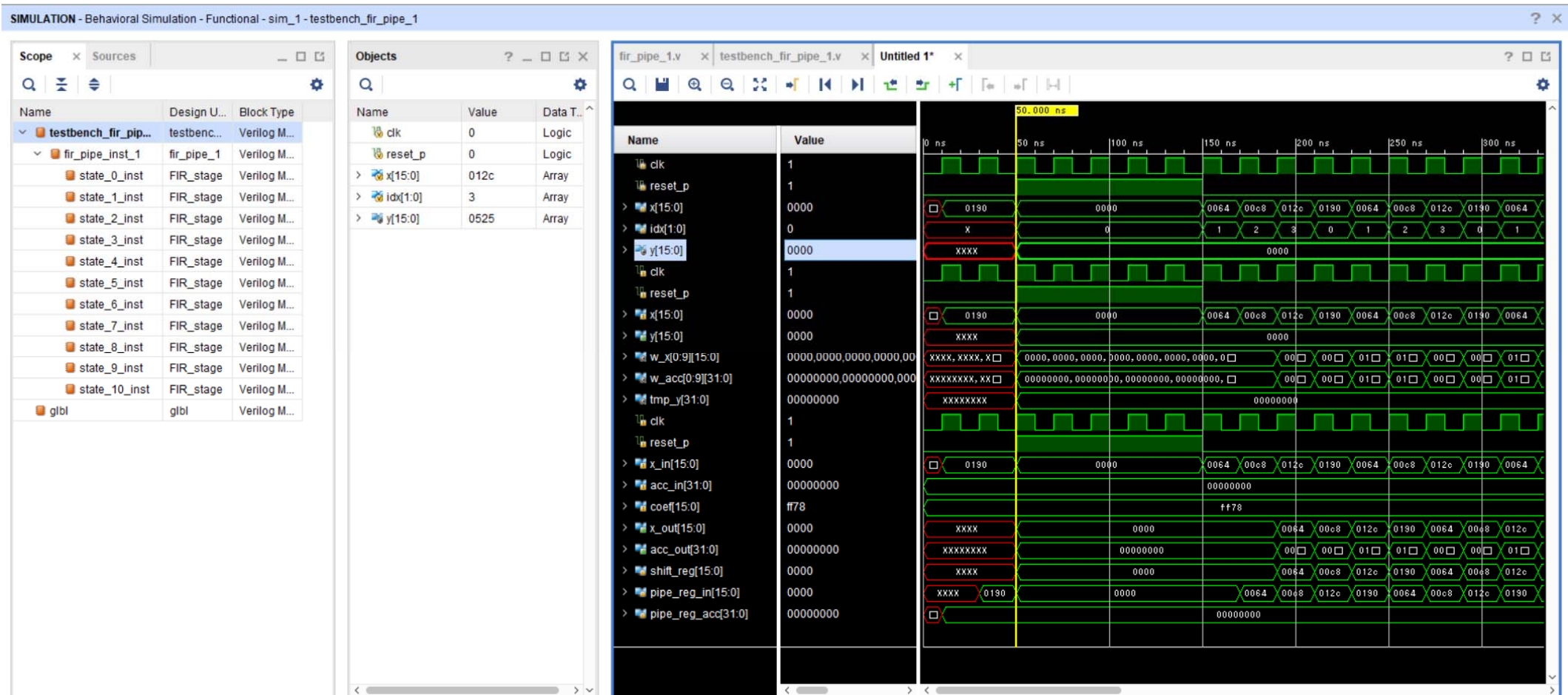
Pipelined Dataflow

- Insert a pipeline register and realized by a DSP block



RTL Simulation

- See, https://github.com/HirokiNakahara/FPGA_lecture/tree/master/Lec7_Practical_RTL_design/
- Source Code: fir_pipe_1.v, Simulation Code: testbench_fir_pipe_1.v



Conclusion

- Conversion from Behavior to RTL by C Description
- Control HW via AXI 4 bus
- Optimization method
 - Concurrent assignment
 - Parallel Processing
 - Unrolling
 - Pipelining

Exercise

- (Mandatory) Control the LED from the ARM processor via the AXI4 bus
- (Mandatory) For the FIR filter, discuss the Pros. and Cons. of pipeline version, unrolling version, sequential version by comparing latency, throughput, and multiplier
- (Optional 1) Reduce the number of multipliers by using a symmetry property for coefficients of an FIR filter
- (Optional 2) Design the RTL for above FIR filter and show the simulation result

Send a report to nakahara@ict.e.titech.ac.jp

Deadline is 17th, July, 2018 (At the beginning of the next lecture)