Step-By-Step Lab1: FIR

Yuan-teng Chang, Catapult HLS AE
yuan-teng.chang@siemens.com

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Objectives

- Learn the Catapult HLS C++ flow
- Understand the loop unrolling and pipelining
- Understand the memory interface
- Learn how to design with multiple blocks

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Environment Variables

To run Catapult HLS and QuestaSim, a few environment variables are required to be defined

- Define them in a shell script like setup-catapult.csh and source it
- Modify the path depending on the tool install path in your workstation

```
 2 echo "Catapult setup"
 3 setenv MGC_HOME /usr/local/bin/Siemens_EDA/Catapult_Synthesis_2022.2_1-1019737/Mgc_home
 4
 5 setenv CXX_HOME $MGC_HOME
 6 setenv SYSTEMC_INCDIR $MGC_HOME/shared/include
 7 setenv SYSTEMC_LIBDIR $MGC_HOME/shared/lib
 8 set path = ($path ${MGC_HOME}/bin)
 9
10 setenv LD_LIBRARY_PATH $SYSTEMC_LIBDIR
11 setenv LD_LIBRARY_PATH ${MGC_HOME}/lib:$LD_LIBRARY_PATH
12
13 echo "QuestaSim setup"
14 setenv MODEL_TECH /usr/local/bin/Siemens_EDA/Questa_Sim_2022_4/questasim/bin
15 setenv QUESTA_HOME /usr/local/bin/Siemens_EDA/Questa_Sim_2022_4/questasim
16 set path = ($path ${MODEL_TECH})
```


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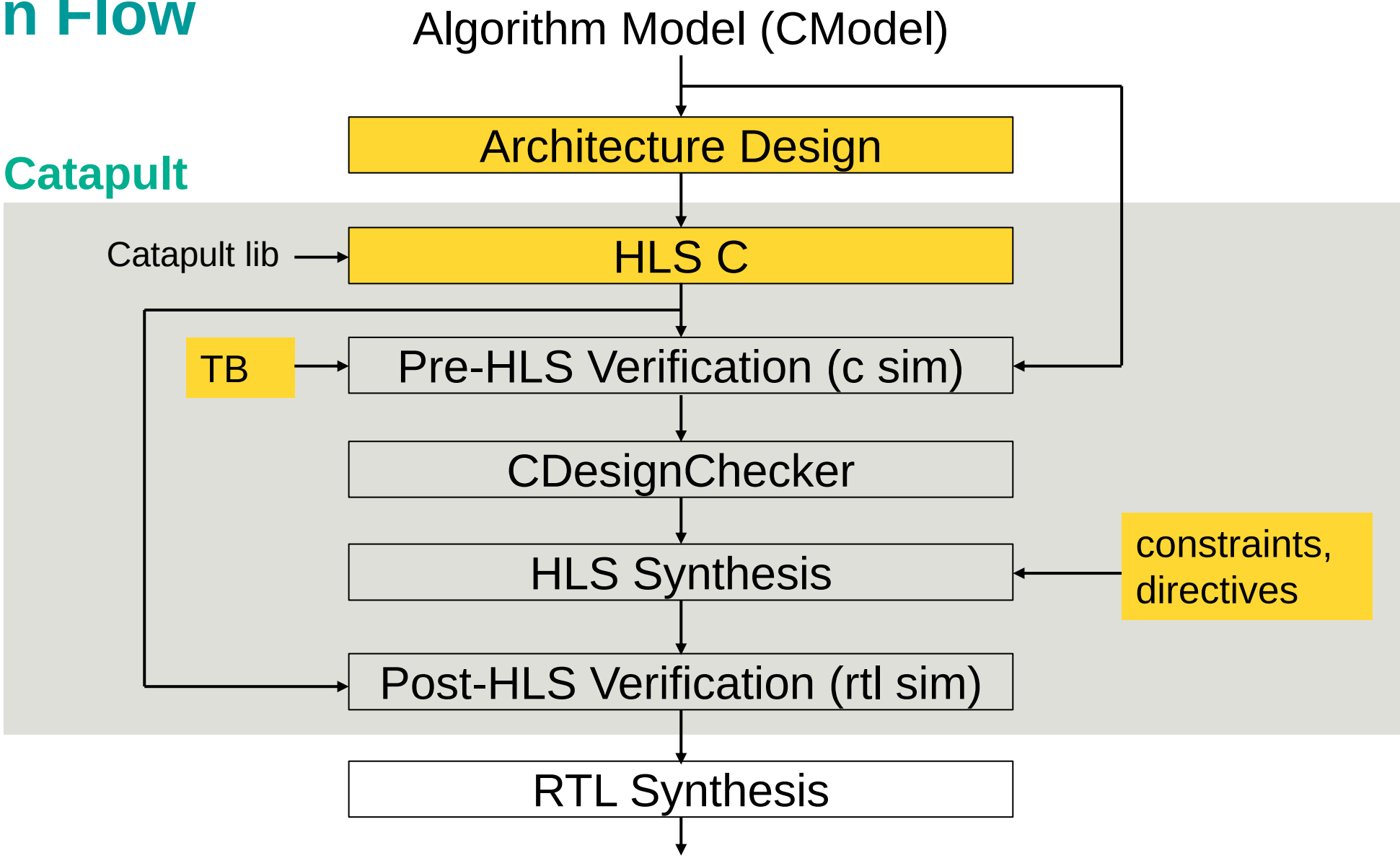
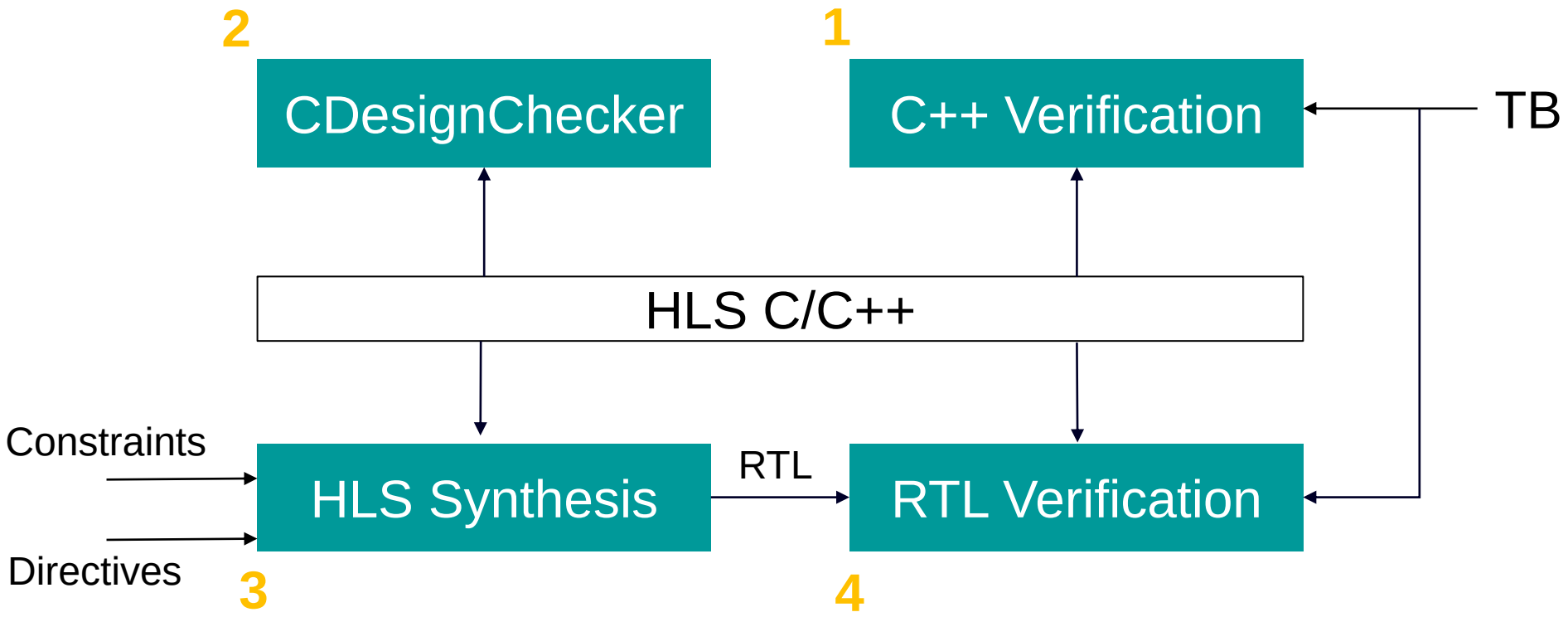
Design Flow



Catapult Flow



Walkthrough of Catapult C++ Flow

An 8-tap FIR

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fir_ref.h (Reference model)

$$y = \sum_{i=0}^{7} c_i \cdot r[i]$$
$$= c_0 r[0] + c_1 r[1] + \ldots + c_7 r[7]$$

```
class fir_ref {
  private:
  int regs[8];

  public:
  fir_ref() {
    for (int i = 7; i>=0; i--)
    { regs[i] = 0; }
  }
  …
```

```
void run(int input, int coeffs[8], int &output)
{
    int temp = 0;

    for (int i = 7; i>=0; i--) {
      if ( i == 0 ) {
        regs[i] = input;
      } else {
        regs[i] = regs[i-1];
      }
    }

    for(int i = 0; i < 8; i++)
      temp += regs[i] * coeffs[i];

    output = temp >> 11;
};
```

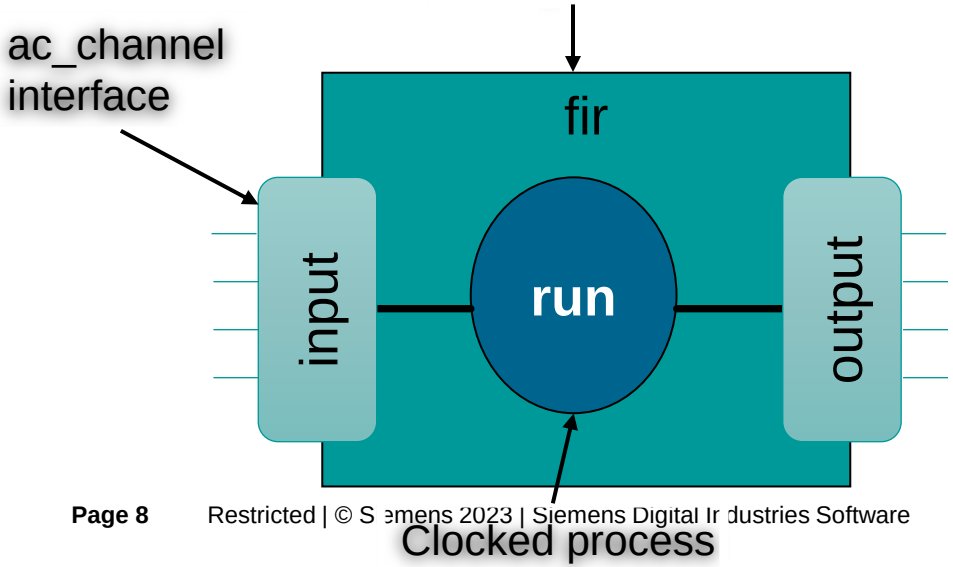
fir.h (HLS C)

```
#include <ac_int.h>
#include <ac_channel.h>
#include <mc_scverify.h>

class fir {
  private:
  int8 regs[8];
  public:
  fir() {
    for (int i = 7; i>=0; i--)
    { regs[i] = 0; }
  }
```

Required

Design block



label

```
#pragma hls_design interface
 void CCS_BLOCK(run)(ac_channel<int8> &input,
                     int8 coeffs[8],
                     ac_channel<int8> &output)
{
    int19 temp = 0;

    SHIFT:for (int i = 7; i>=0; i--) {
      if ( i == 0 ) {
        regs[i] = input.read();
      } else {
        regs[i] = regs[i-1];
      }
    }
    MAC:for (int i = 7; i>=0; i--) {
      temp += coeffs[i]*regs[i];
    }
    output.write(temp>>11);

};
```

Required

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fir_tb.cpp (TB)

```
#include "fir_ref.h"
#include "fir.h"
CCS_MAIN(int argc, char *argv[])
{
  int8 coeffs[8];
  ac_channel<int8> in_chn;
  ac_channel<int8> out_chn;
  int8 din ,dout;
  int coeffs_ref[8];
  int din_ref;
  int dout_ref;
  fir      dut;
  fir_ref ref_model;
  int pass_cnt = 0;
  int fail_cnt = 0;
  // Test Impulse
  for (int i=0; i < 8; i++)
    coeffs_ref[i]=coeffs[i]=-128+rand()%256;
  …
```

```
 for (int i = 0; i < 100; i++ ) {
    din_ref = din = -128 + rand()%256;
    in_chn.write(din);
    dut.run(in_chn, coeffs, out_chn);
    ref_model.run(din_ref, coeffs_ref,
dout_ref);
    dout = out_chn.read();
    if (dout.to_int()!=dout_ref) {
      printf("fail @ %3d: %4d != %4d \n", i,
dout.to_int(), dout_ref);
      fail_cnt ++;
    } else {
      printf("pass @ %3d: %4d == %4d \n", i,
dout.to_int(), dout_ref);
      pass_cnt ++;
    }
  }
  printf("\n");
  printf("total pass count %d\n", pass_cnt);
  printf("total fail count %d\n", fail_cnt);
  CCS_RETURN(0);
}
```

Pre-HLS Verification by gcc (C Sim)

Build with gcc

- g++ -o3 -std=c++11 -I $MGC_HOME/shared/include fir_tb.cpp -o SCVerify_fir.exe

```
[mentor@RHEL74 01_walkthrough_loops]$ make
/usr/local/bin/Siemens_EDA/Catapult_Synthesis_2023.2_1-1065141/Mgc_home/bin/g++ -g -o3 -std=c++11 -Wall -Wno-unknown-pragmas -Wno-unused-variable -Wno-unused-label -I./ -I/usr/local/bin/Siemens_EDA/Catapult_Synthesis_2023.2_1-1065141/Mgc_home/shared/include ./fir_tb.cpp -o bin/SCVerify_fir.exe
[mentor@RHEL74 01_walkthrough_loops]$
```

Run execution file

- ./SCVerify_fir.exe

```
pass @  89:    3 ==    3
pass @  90:  -18 ==  -18
pass @  91:   21 ==   21
pass @  92:  -12 ==  -12
pass @  93:    2 ==    2
pass @  94:   -6 ==   -6
pass @  95:    5 ==    5
pass @  96:  -21 ==  -21
pass @  97:   18 ==   18
pass @  98:   -5 ==   -5
pass @  99:    9 ==    9

total pass count 100
total fail count 0
```


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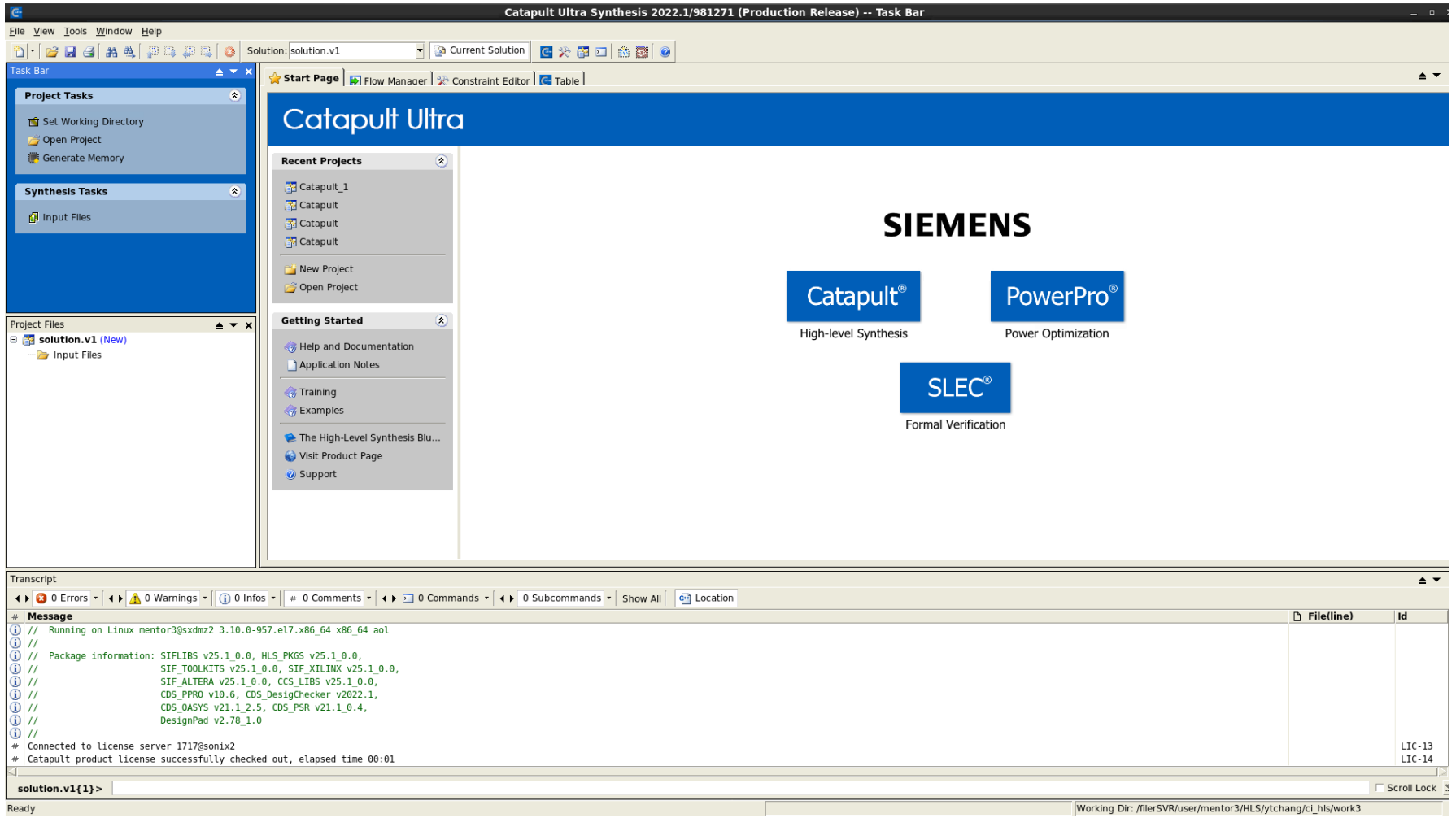
Launch Catapult

catapult &



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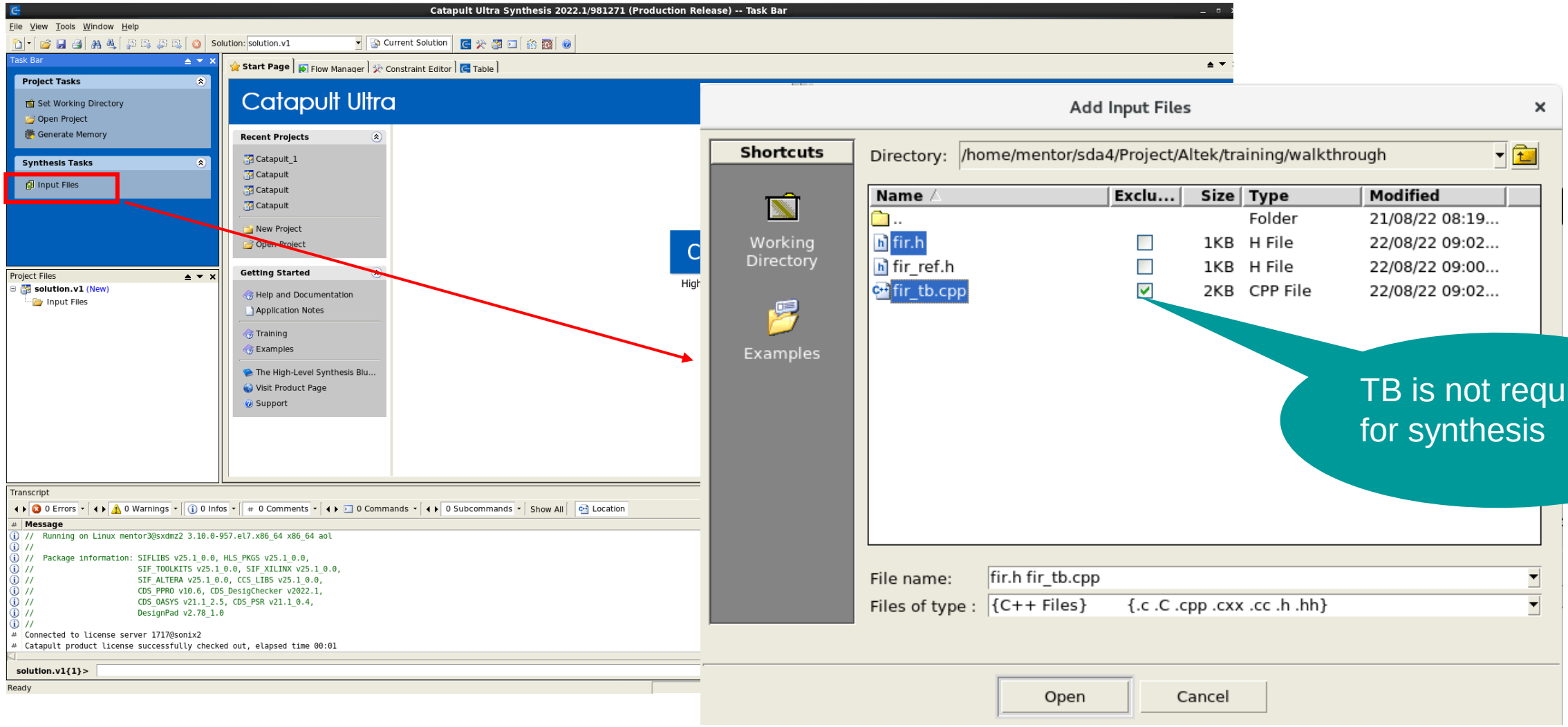
Add input file



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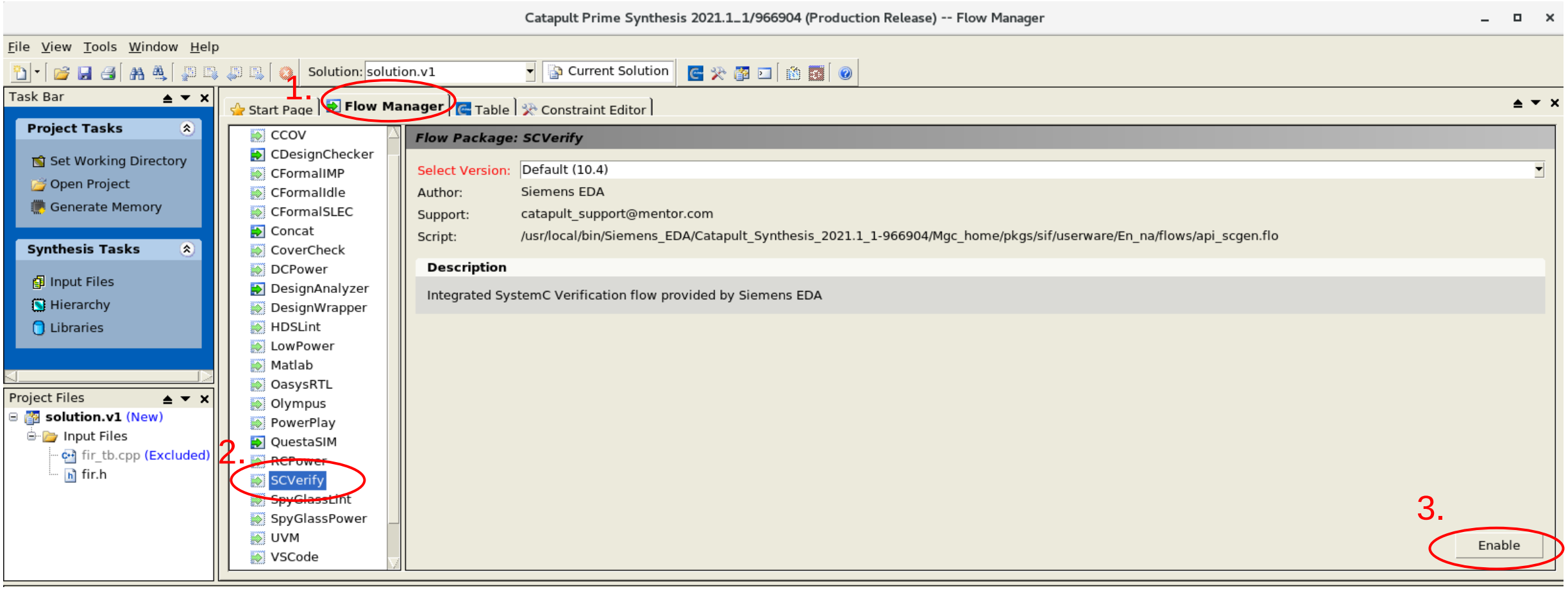
Enable SCVerify



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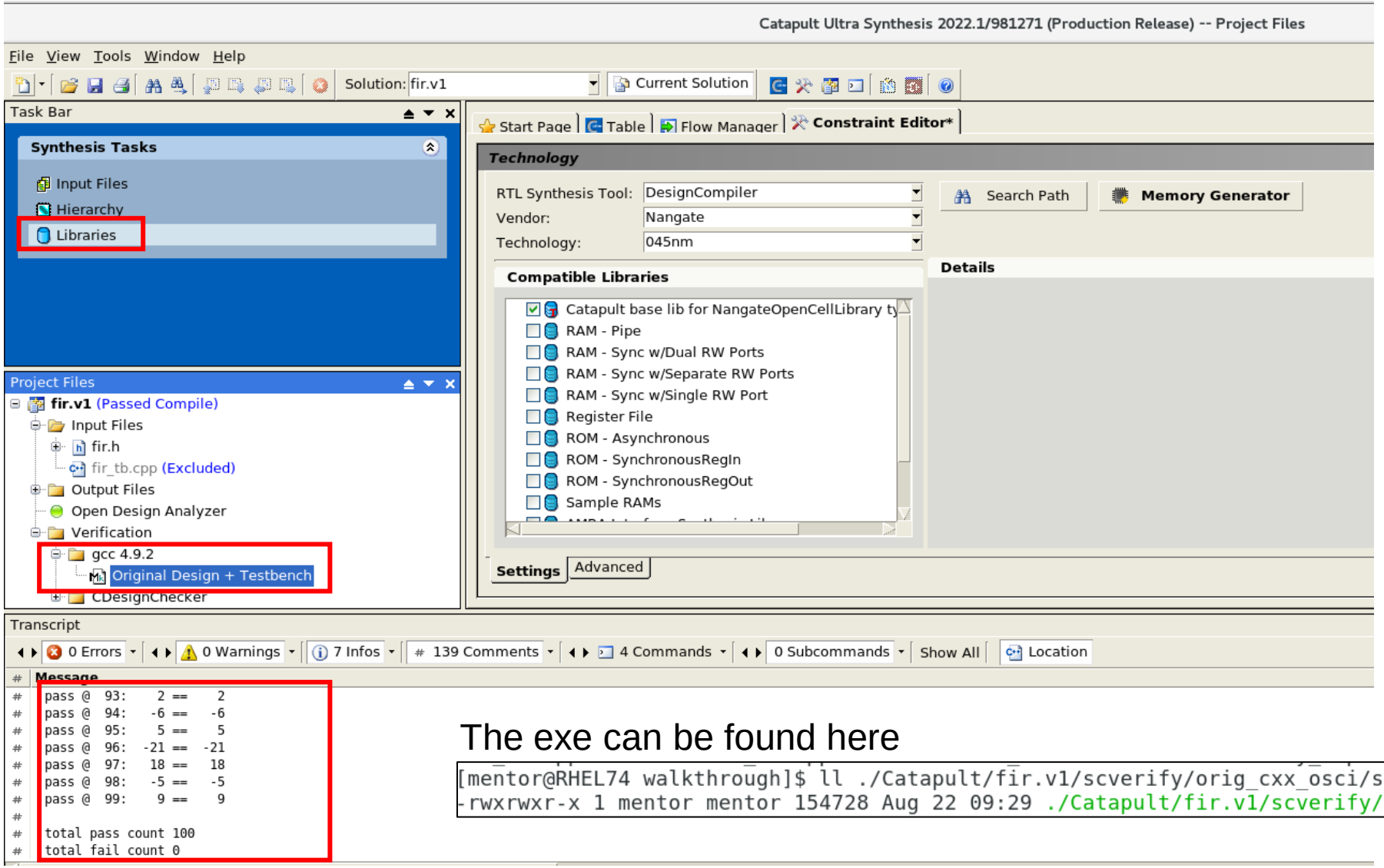
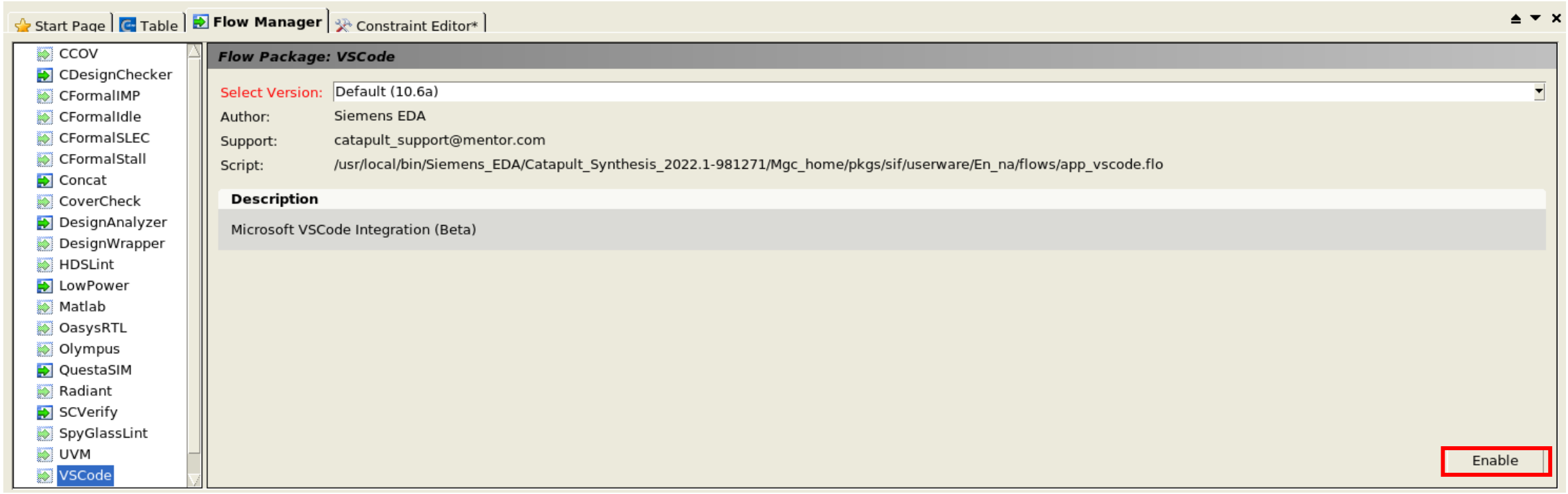
Pre-HLS (C++) Verification by gcc



The exe can be found here

```
[mentor@RHEL74 walkthrough]$ ll ./Catapult/fir.v1/scverify/orig_cxx_osci/scverify_top
-rwxrwxr-x 1 mentor mentor 154728 Aug 22 09:29 ./Catapult/fir.v1/scverify/orig_cxx_osci/scverify_top
```

Build VSCode Environment



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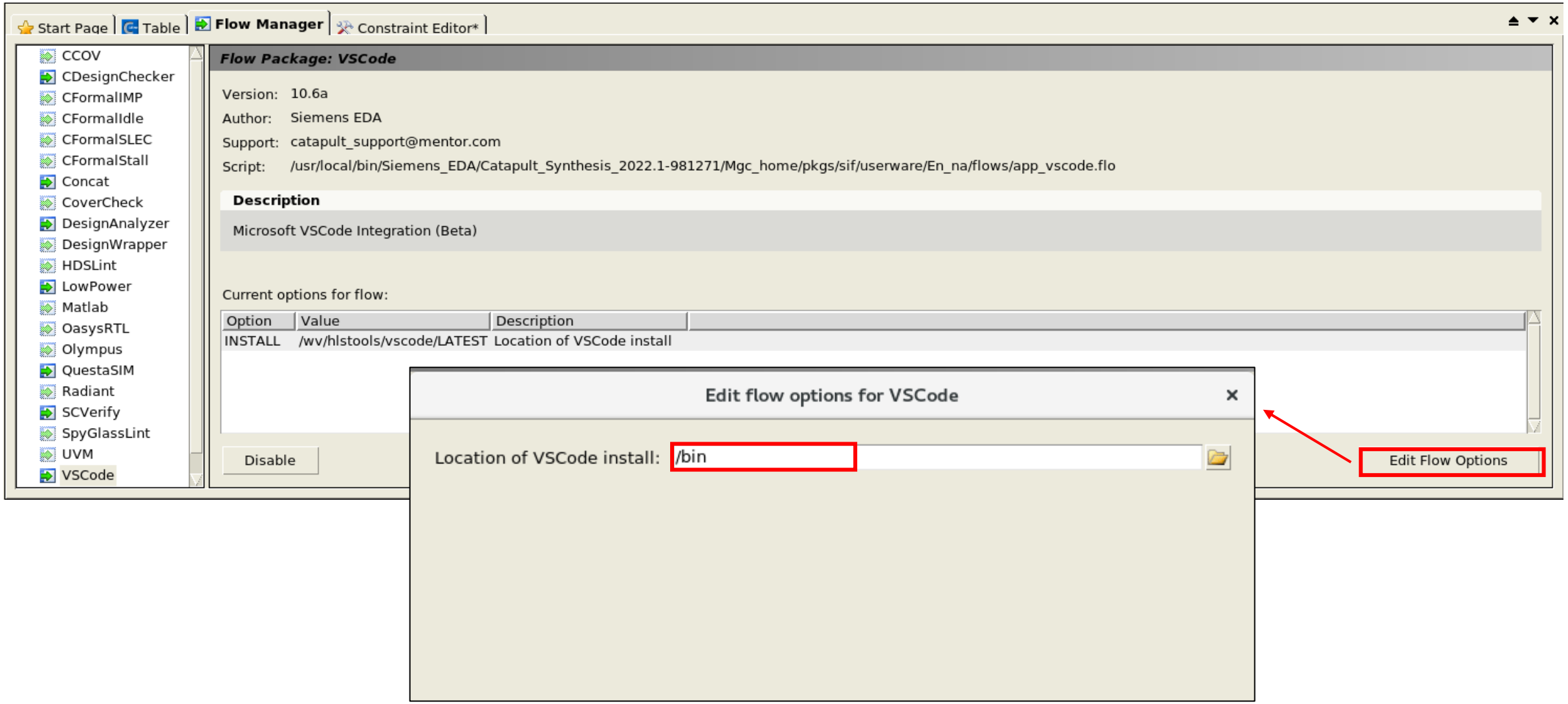
Build VSCode Environment (Cont.)



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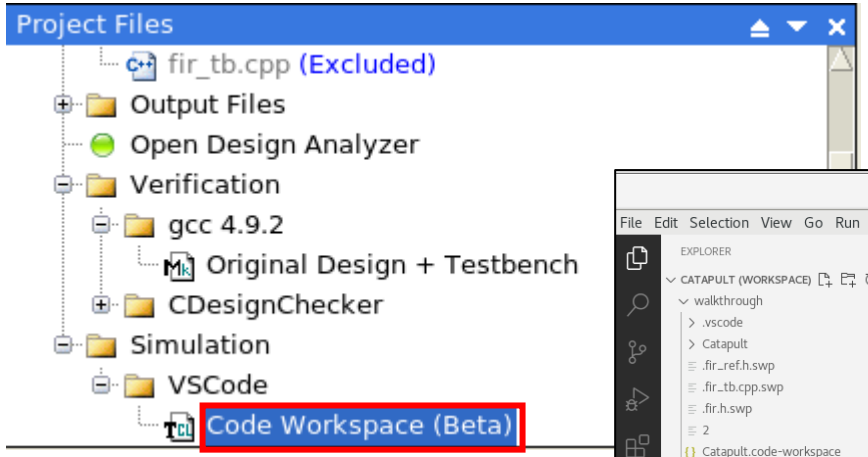
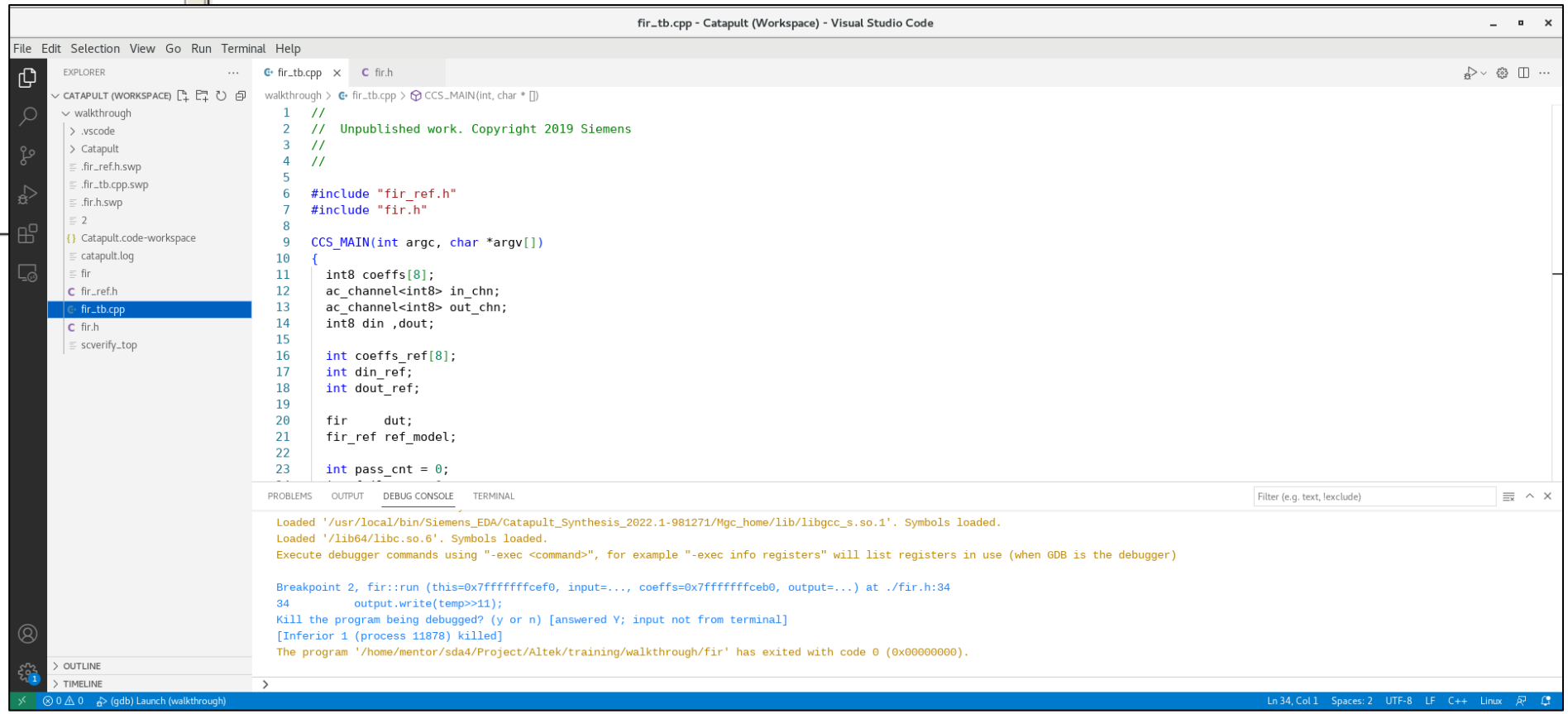
Build VSCode Environment (Cont.)





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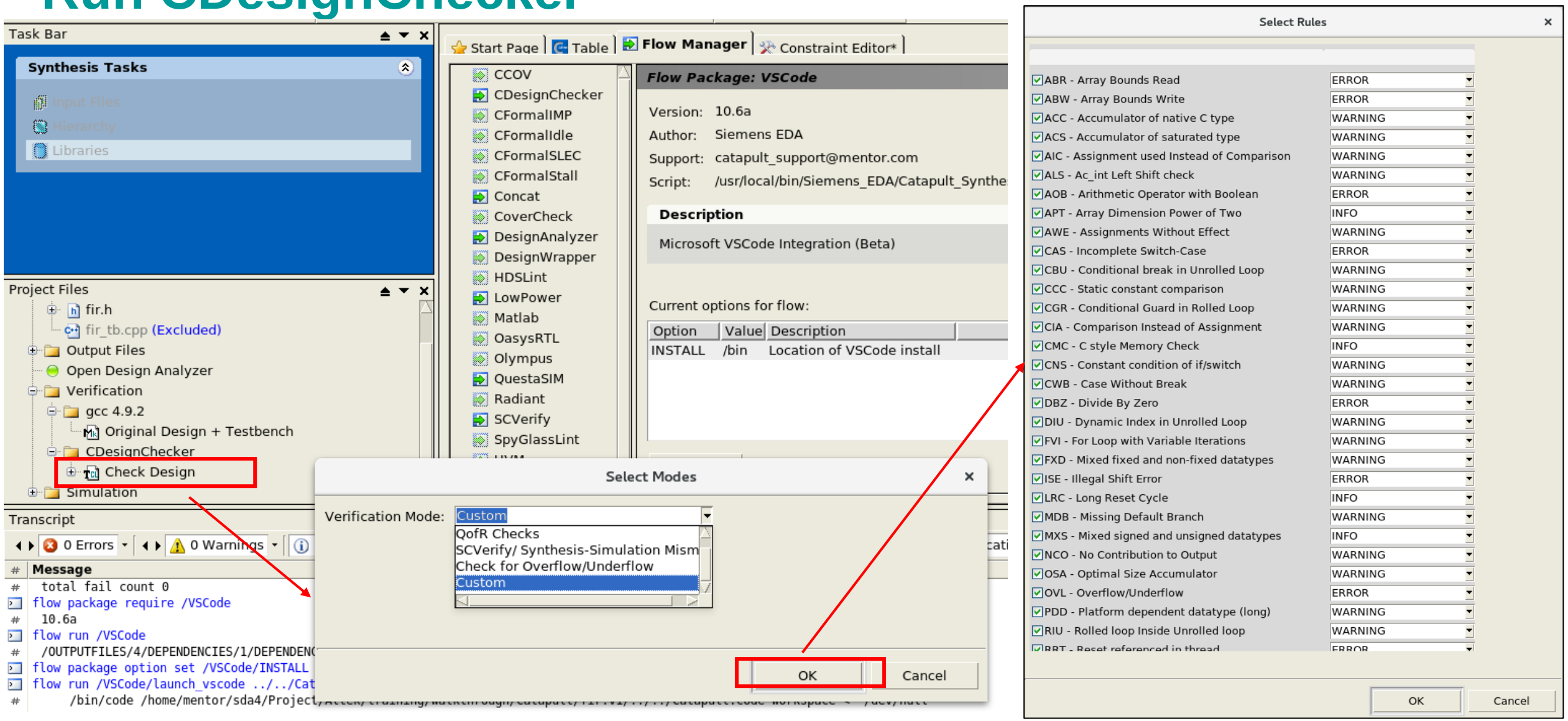
Run CDesignChecker



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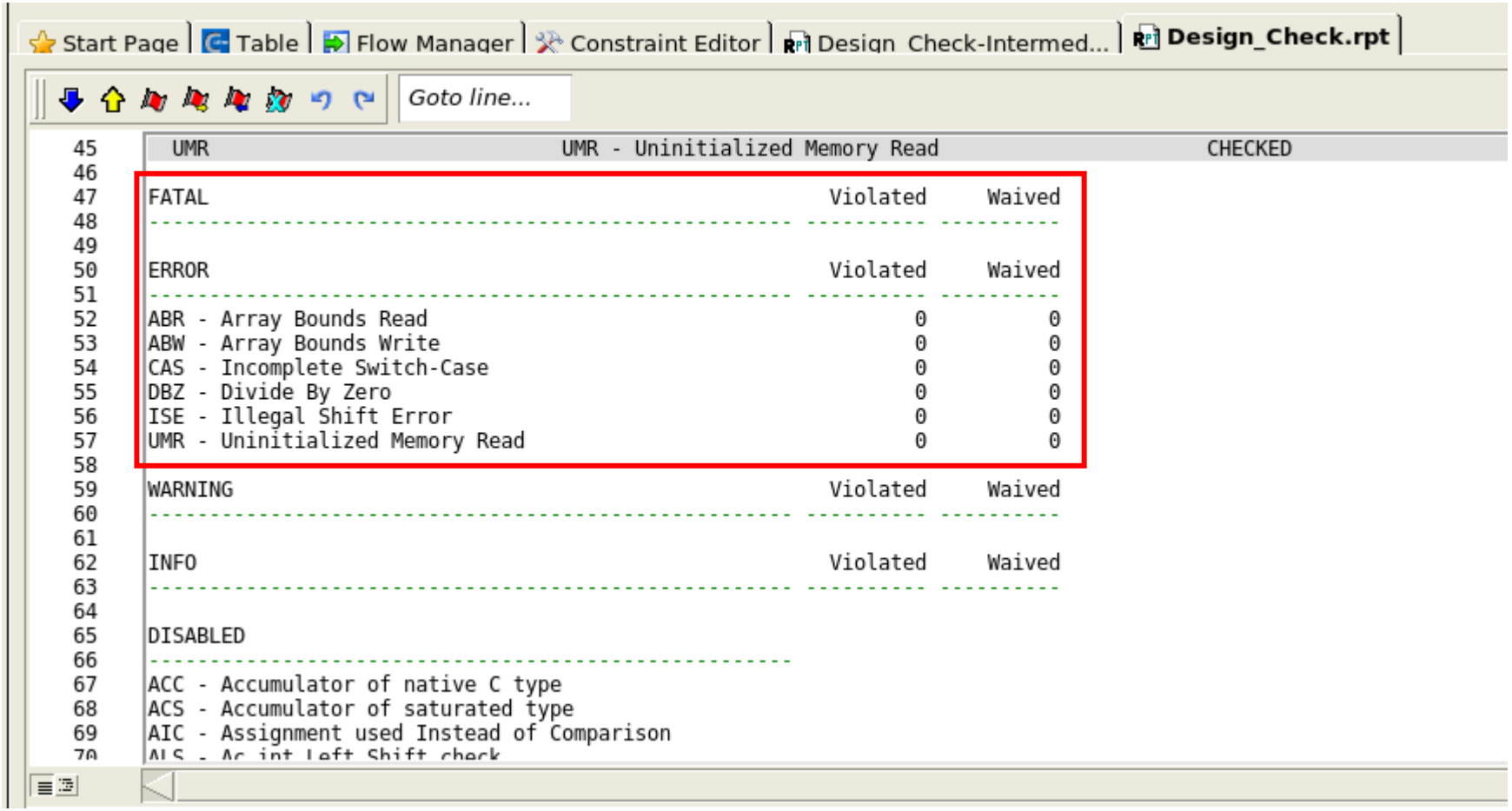
Run CDesignChecker (Cont.)



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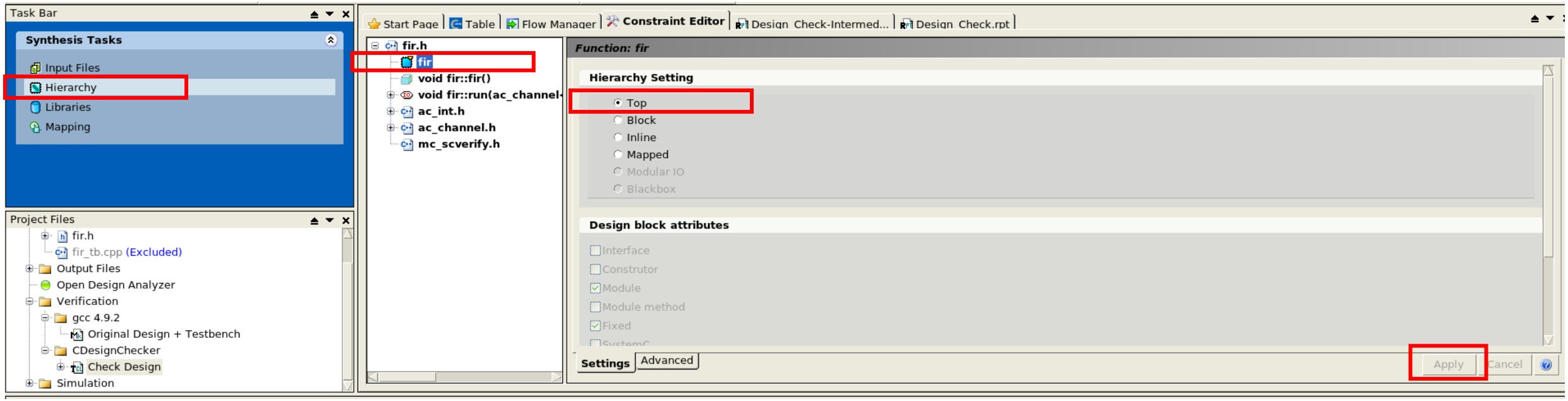
HLS Synthesis – Set Top Design



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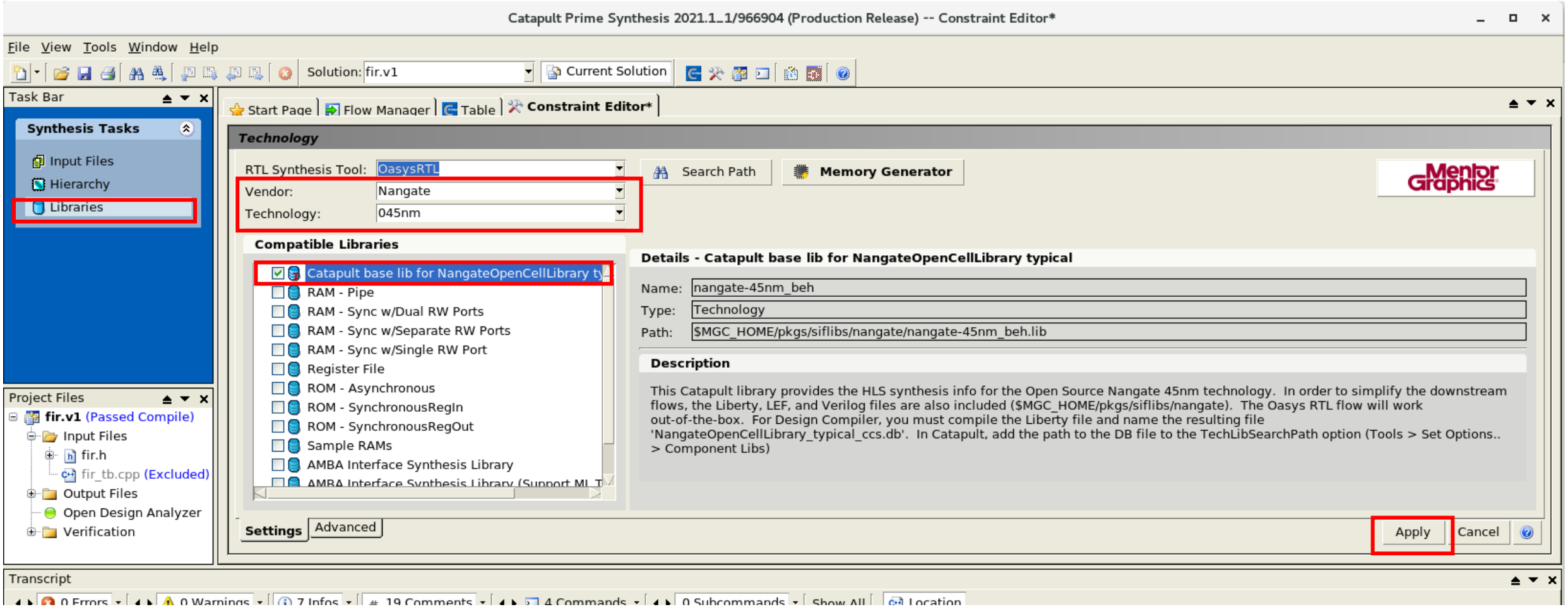
HLS Synthesis – Library Setup



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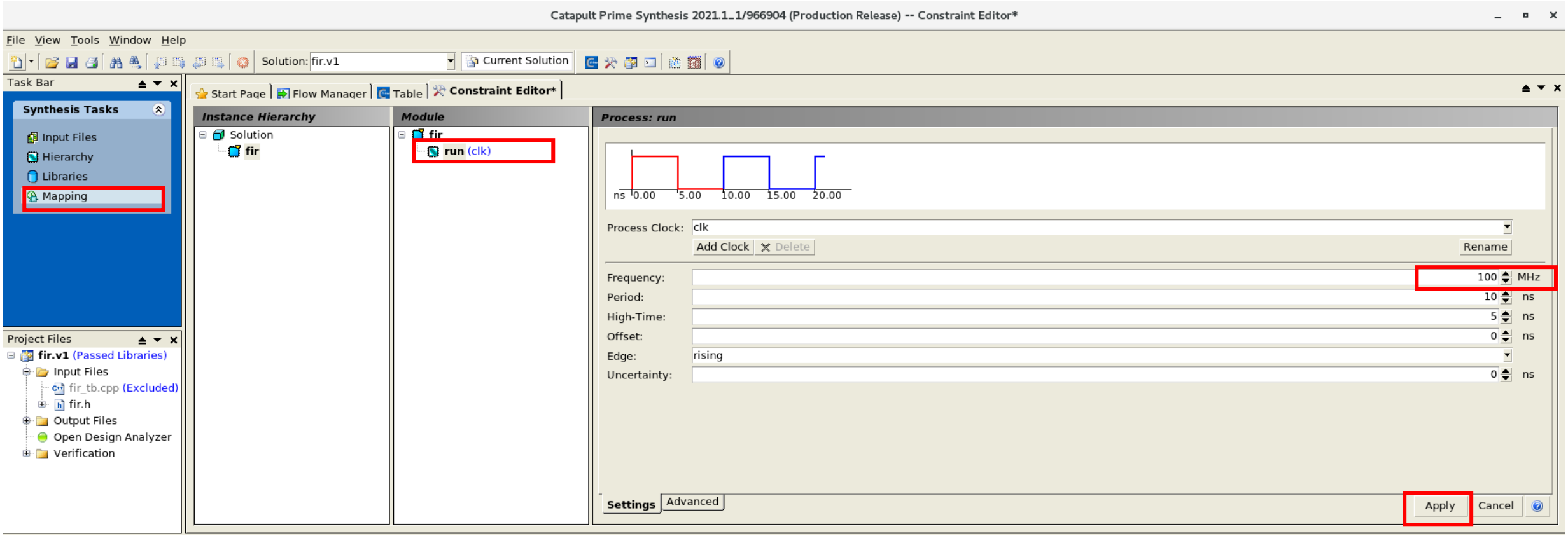
HLS Synthesis – Mapping

Frequency



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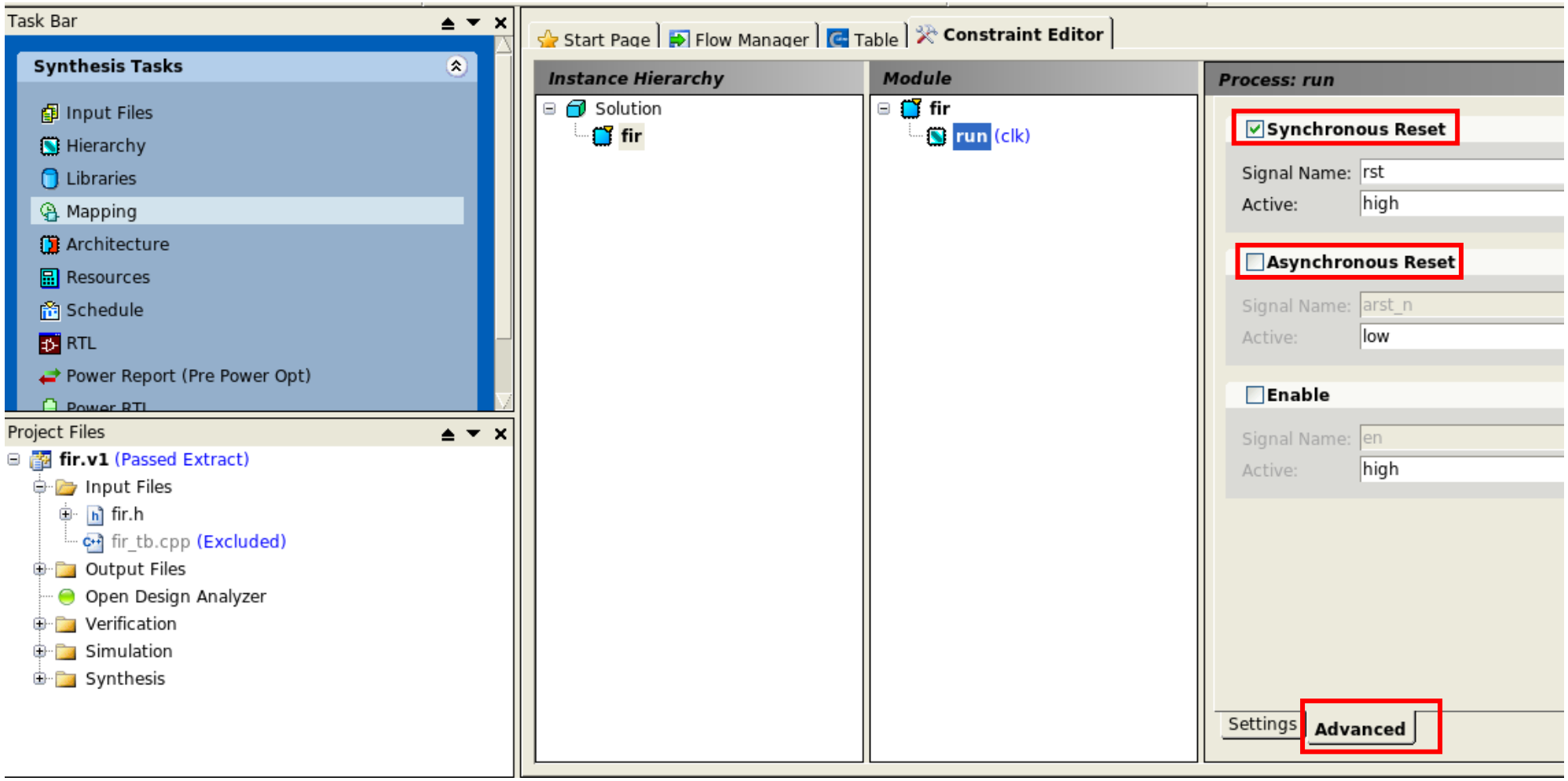
HLS Synthesis – Mapping

Sync / async reset



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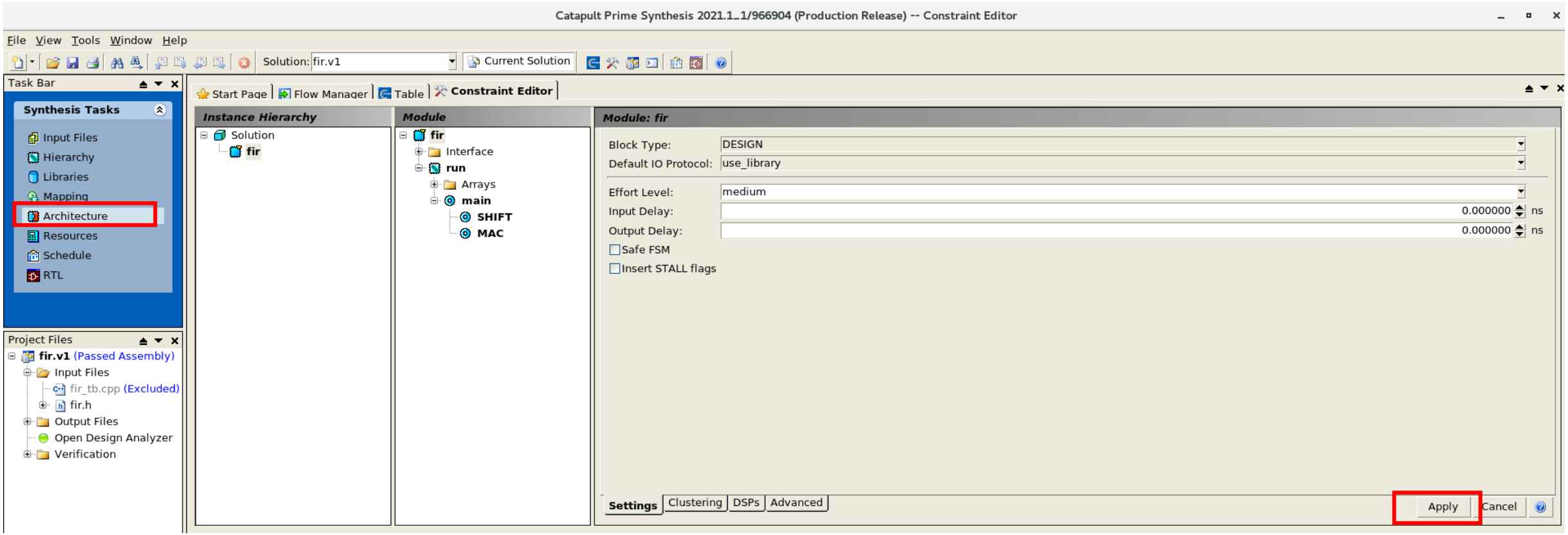
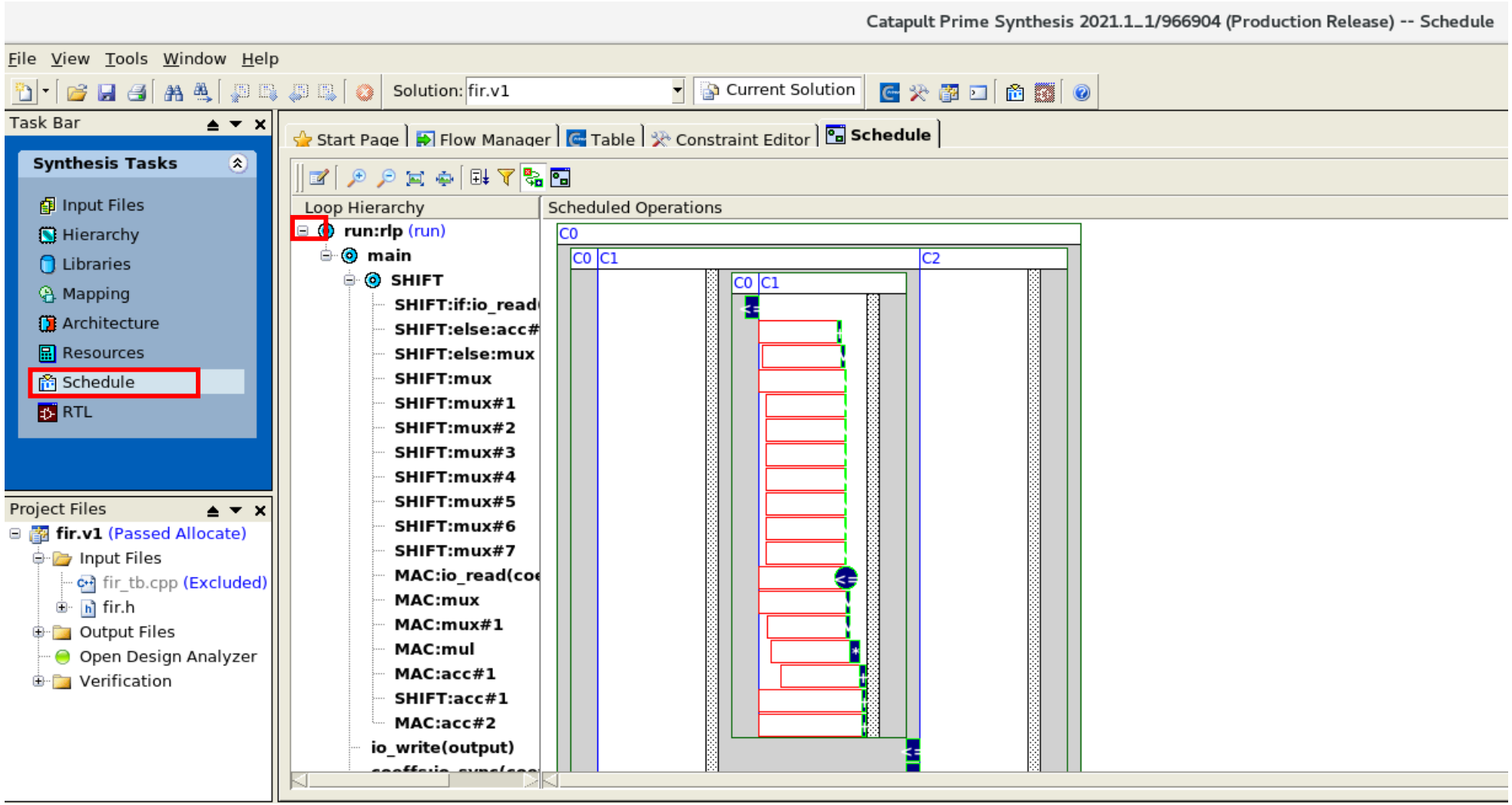
HLS Synthesis – Architecture



HLS Synthesis – Scheduling



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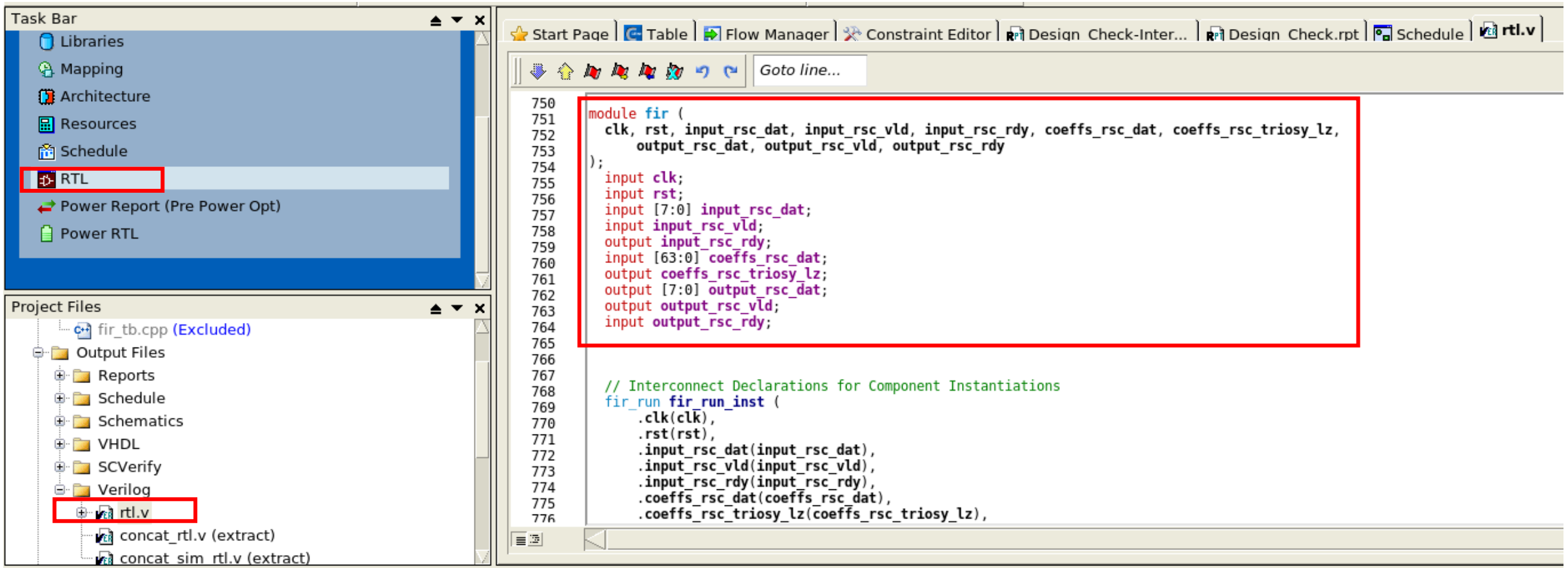
HLS Synthesis – RTL



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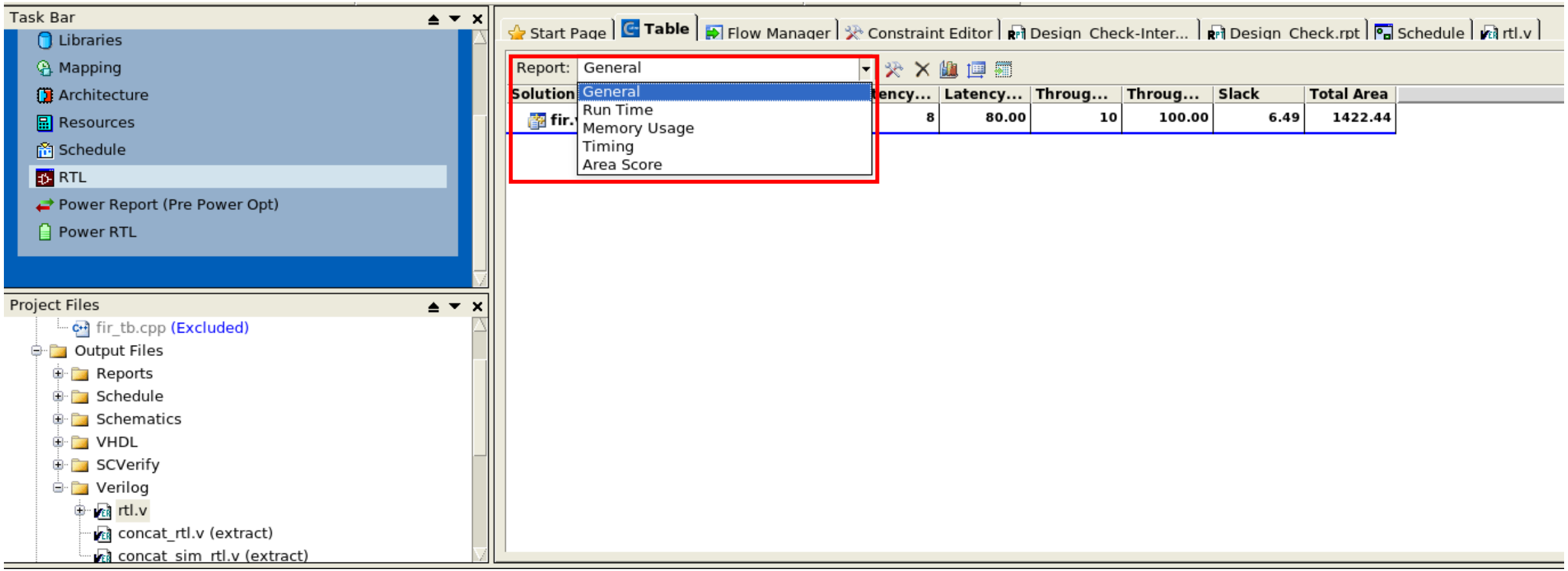
HLS Synthesis – Report



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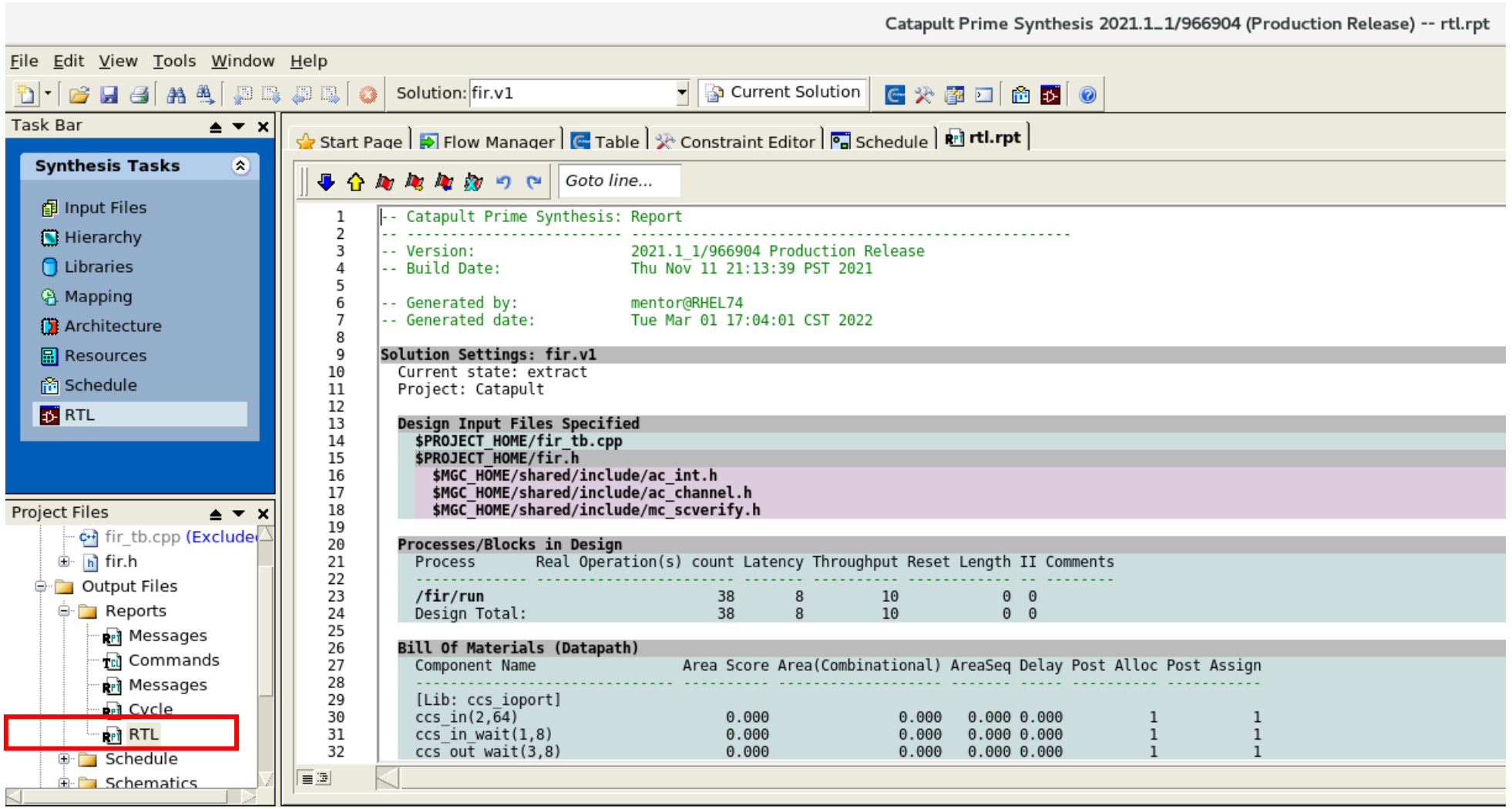
HLS Synthesis – Report (Cont.)



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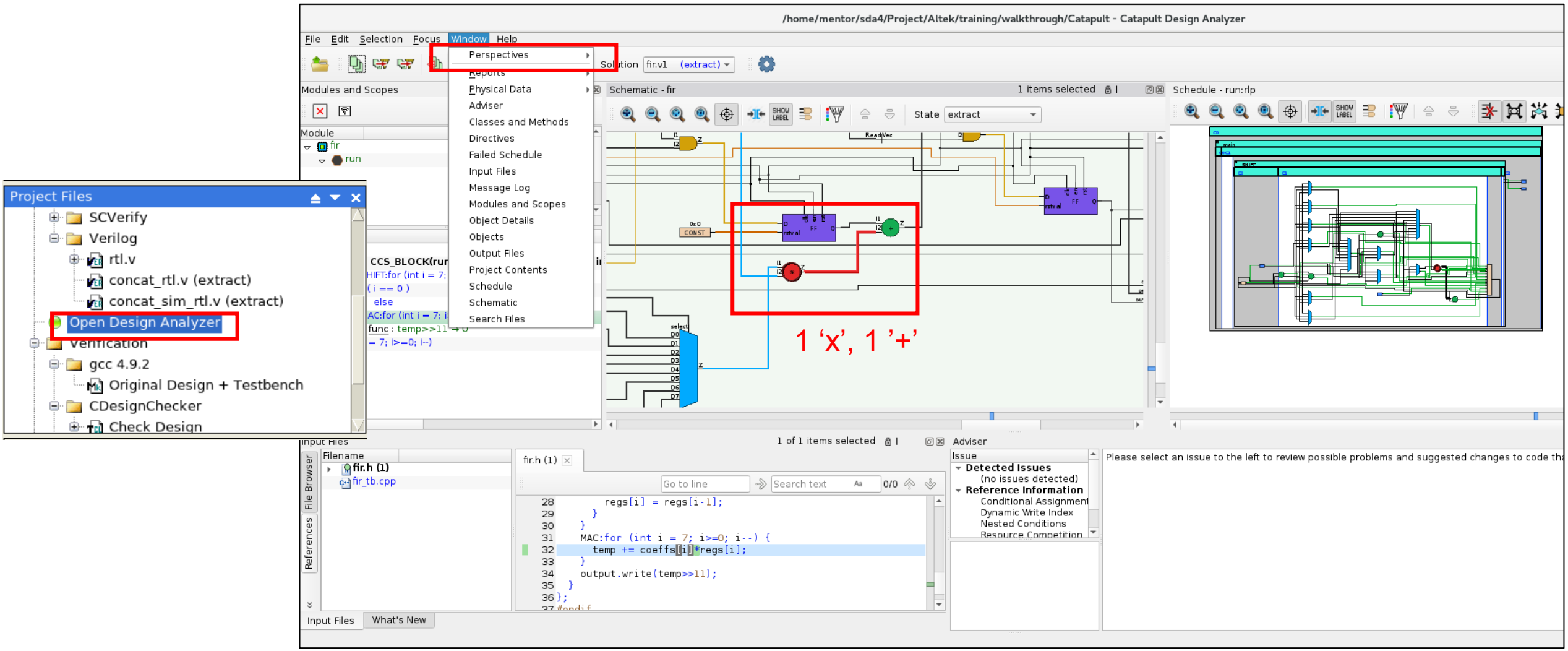
Design Analyzer

Analyze the design in various perspectives



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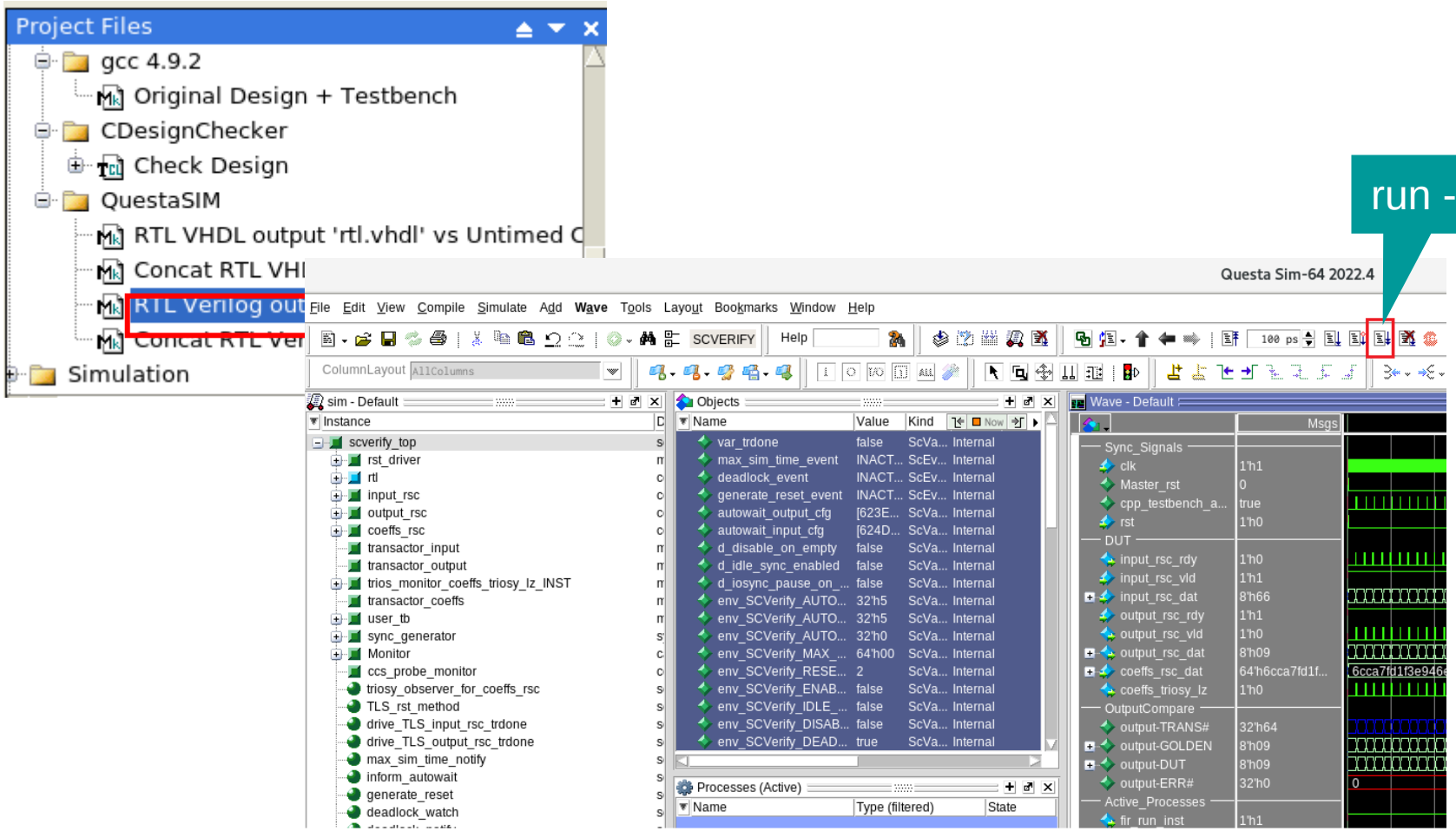
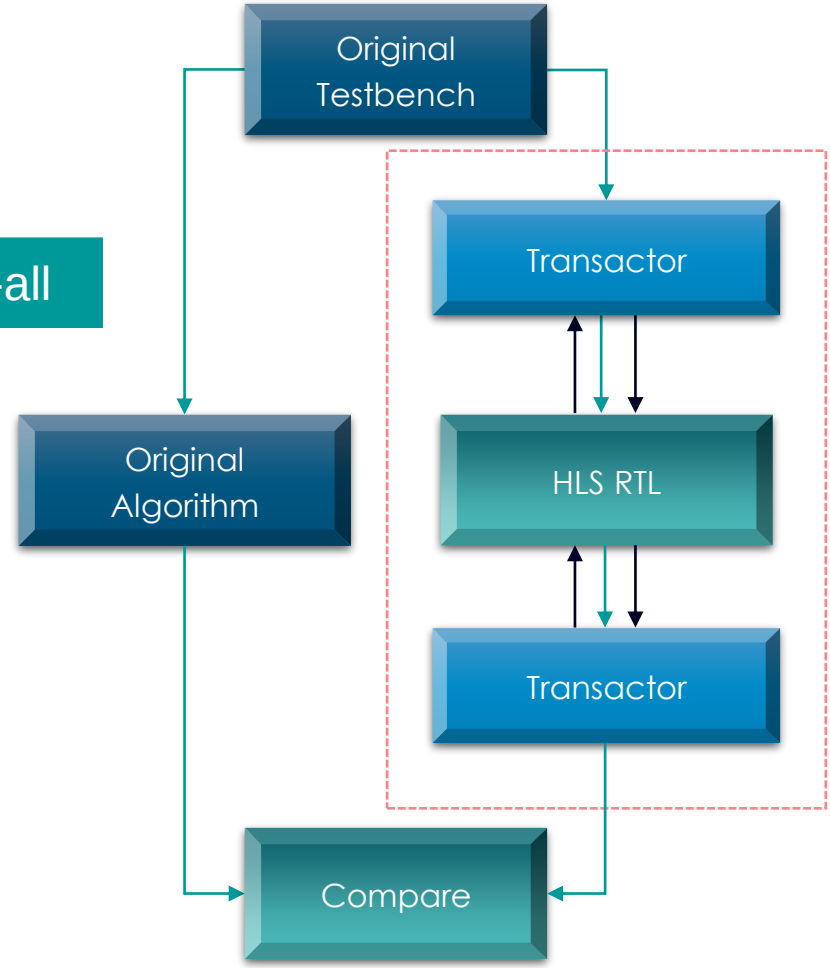
RTL Verification

Automatically compare the outputs of HLC C and RTL





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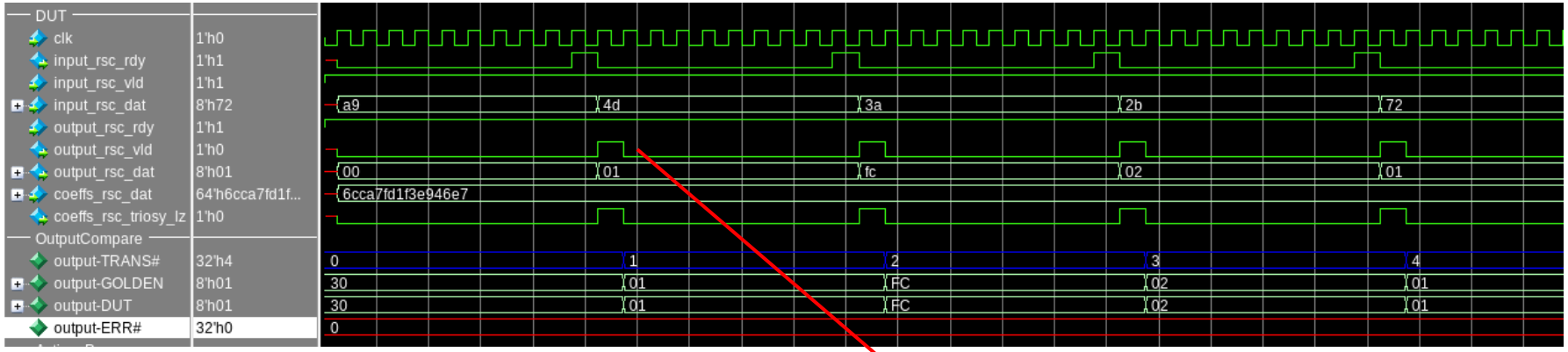
RTL Verification

Automatically compare the outputs of HLC C and RTL

```
Transcript
#    captured 100 values of output
# Info: scverify_top/user_tb: Simulation completed
#
# Checking results
# 'output'
#    capture count        = 100
#    comparison count     = 100
#    ignore count         = 0
#    error count          = 0
#    stuck in dut fifo    = 0
#    stuck in golden fifo = 0
#
# Info: scverify_top/user_tb: Simulation PASSED @ 10016 ns
# ** Note: (vsim-6574) SystemC simulation stopped by user.
# 1
#

VSIM 3>
```



Throughput = 10

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Loop Unrolling and Pipelining

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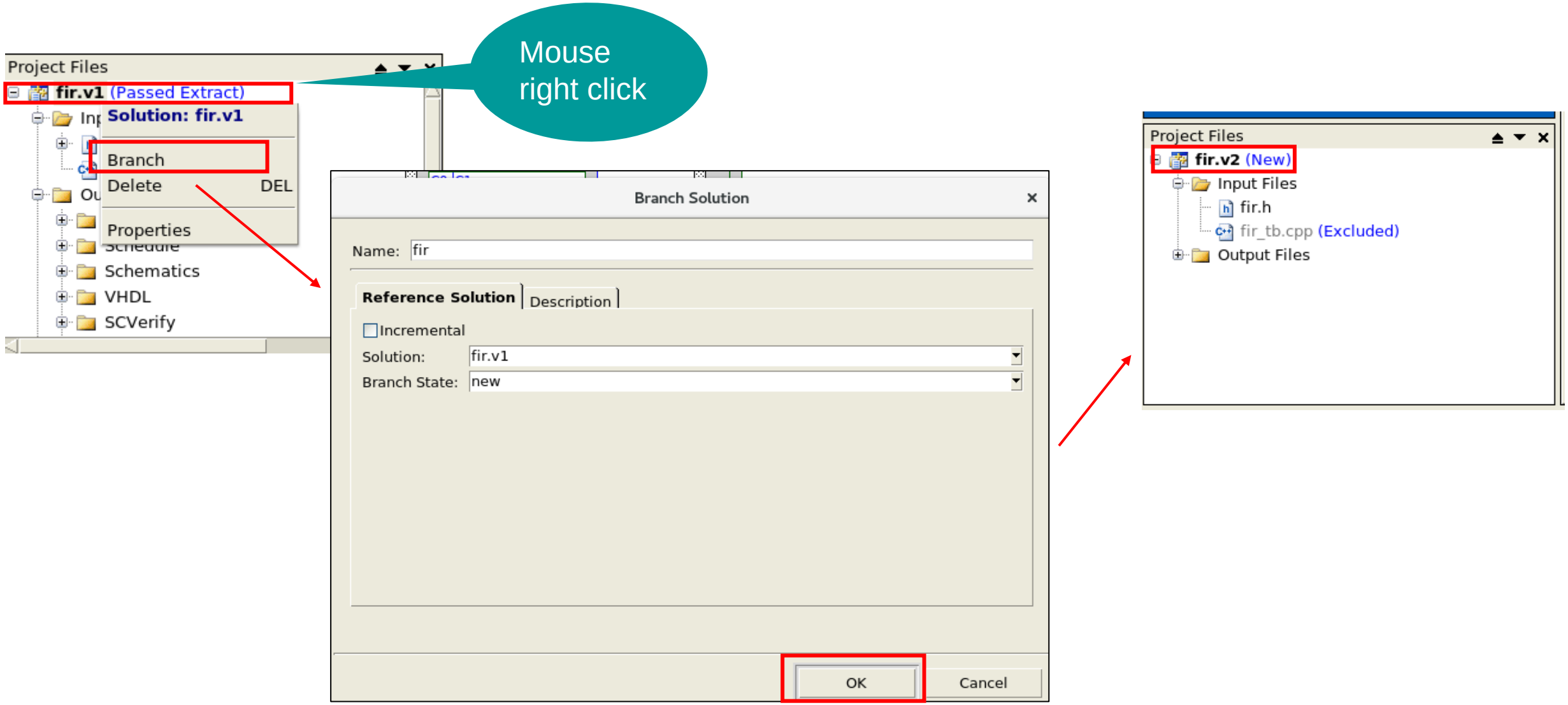
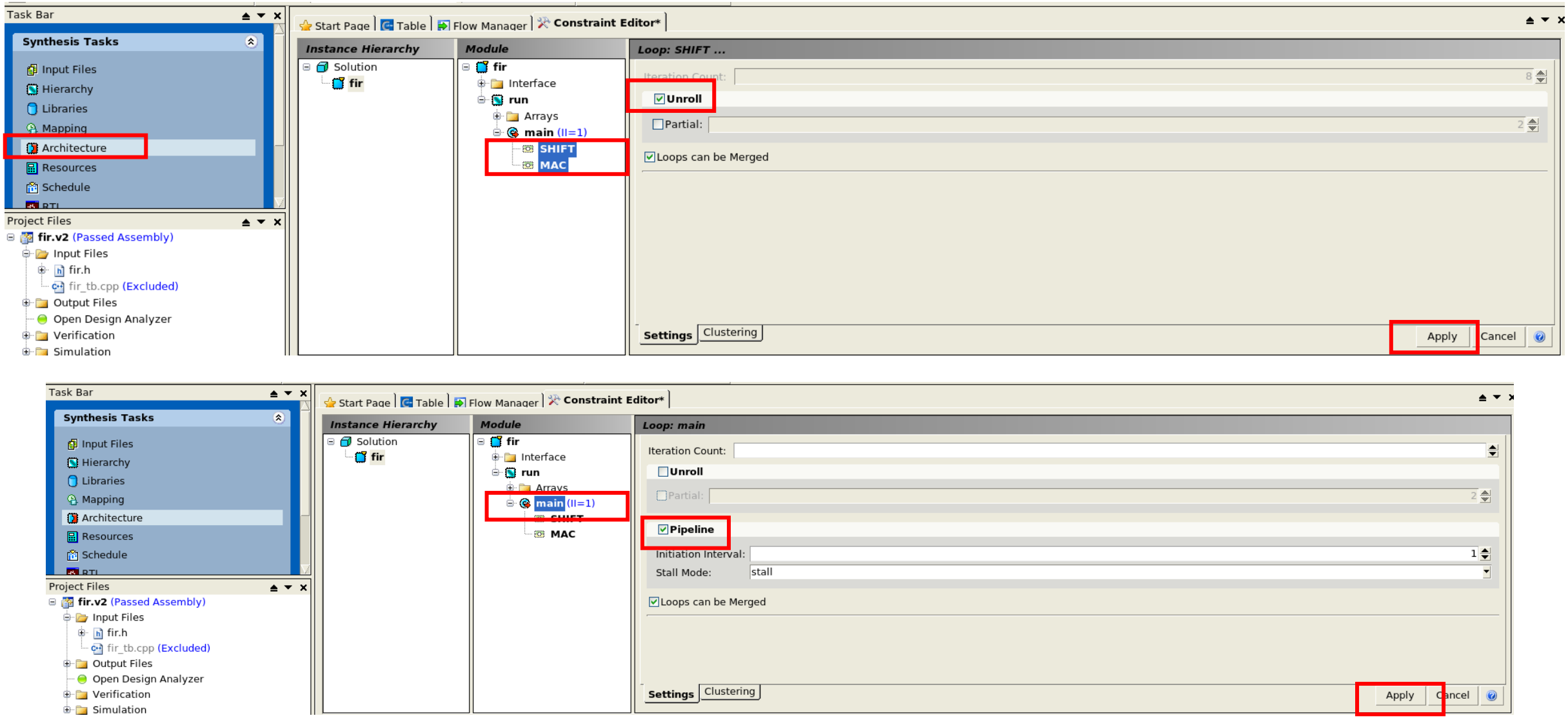
Branch a New Solution



HLS Synthesis – Architecture



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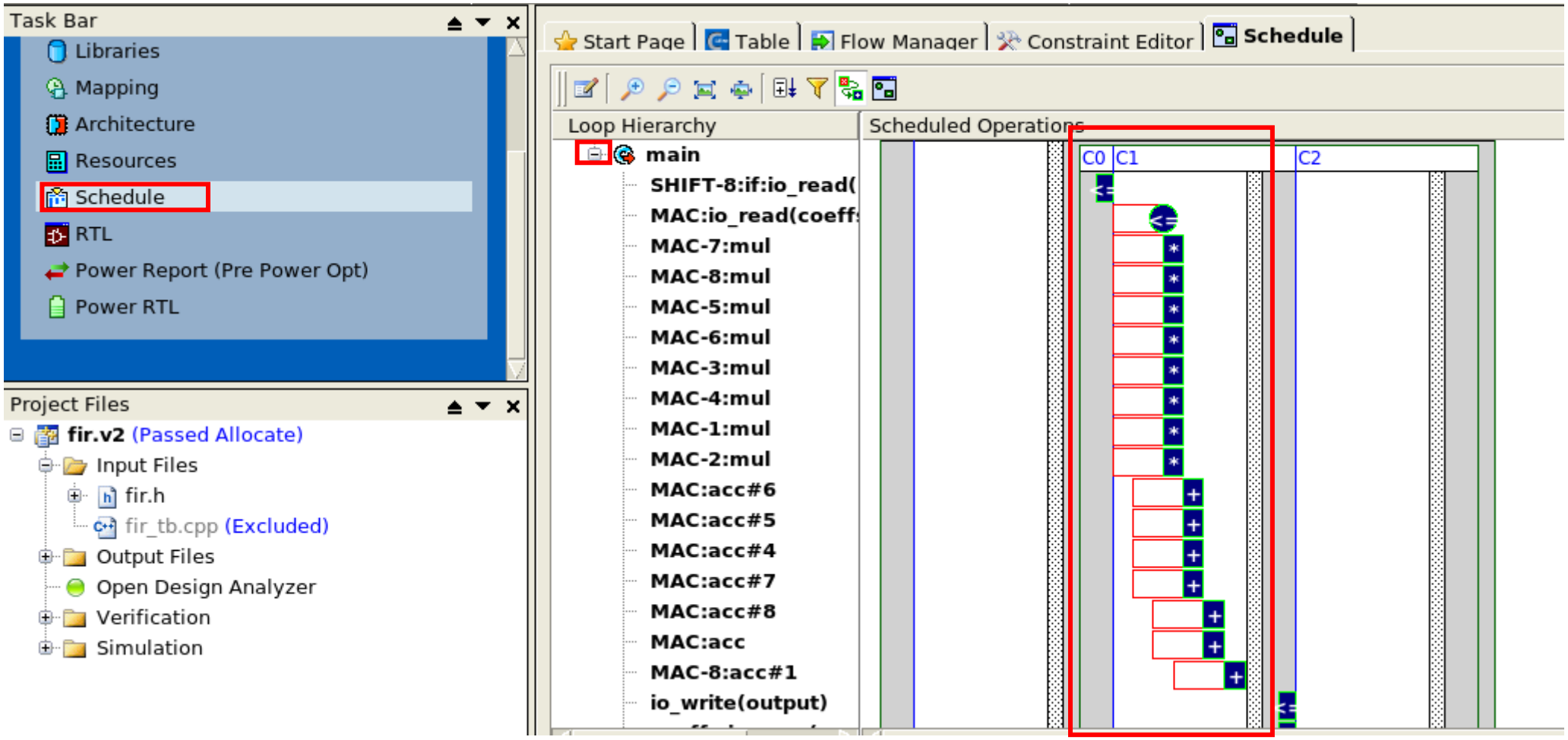
HLS Synthesis – Scheduling



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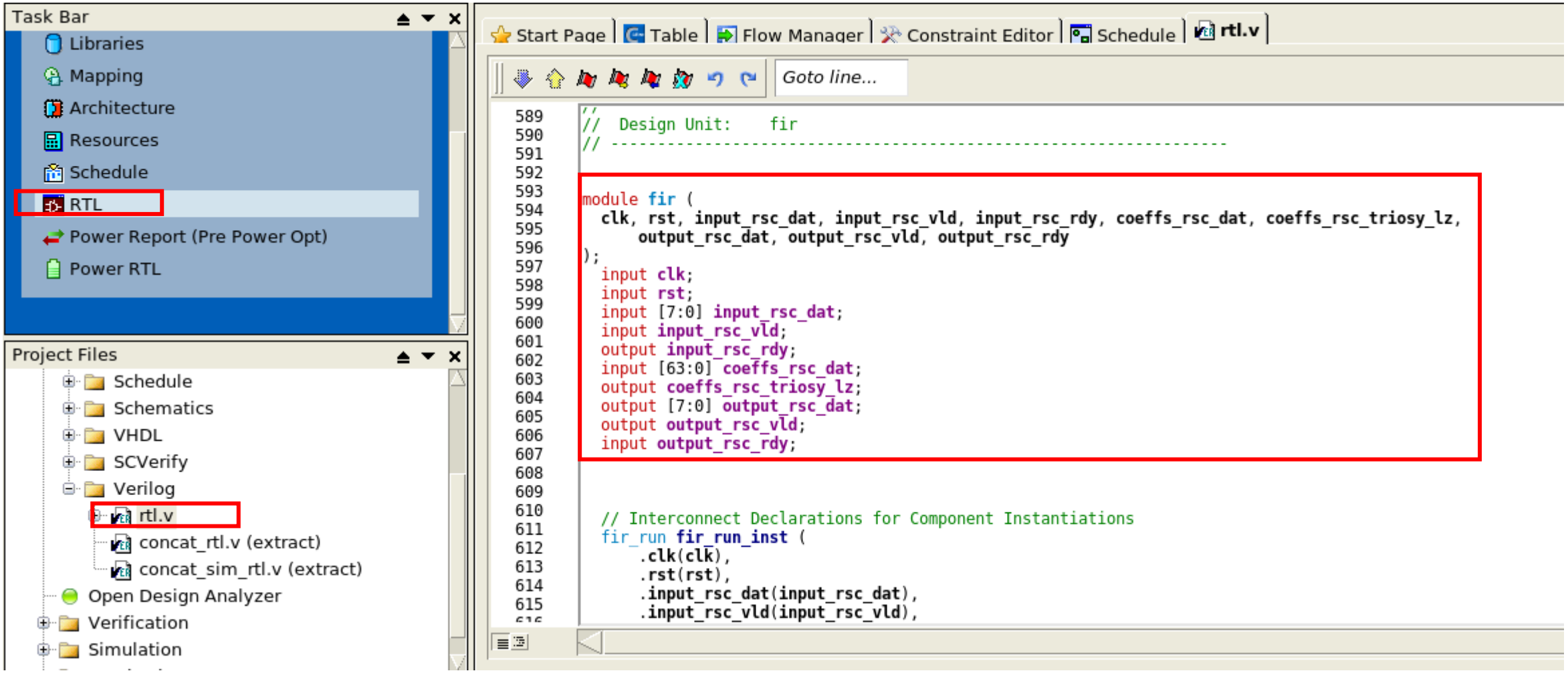
HLS Synthesis – RTL



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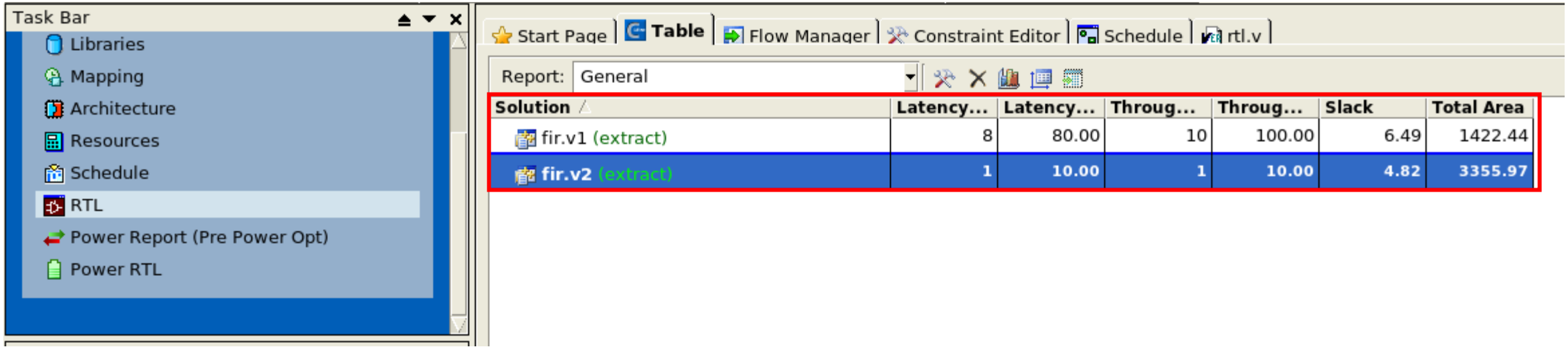
HLS Synthesis – Report



Solution	Latency...	Latency...	Throug...	Throug...	Slack	Total Area
fir.v1 (extract)	8	80.00	10	100.00	6.49	1422.44
fir.v2 (extract)	**1**	**10.00**	**1**	**10.00**	**4.82**	**3355.97**

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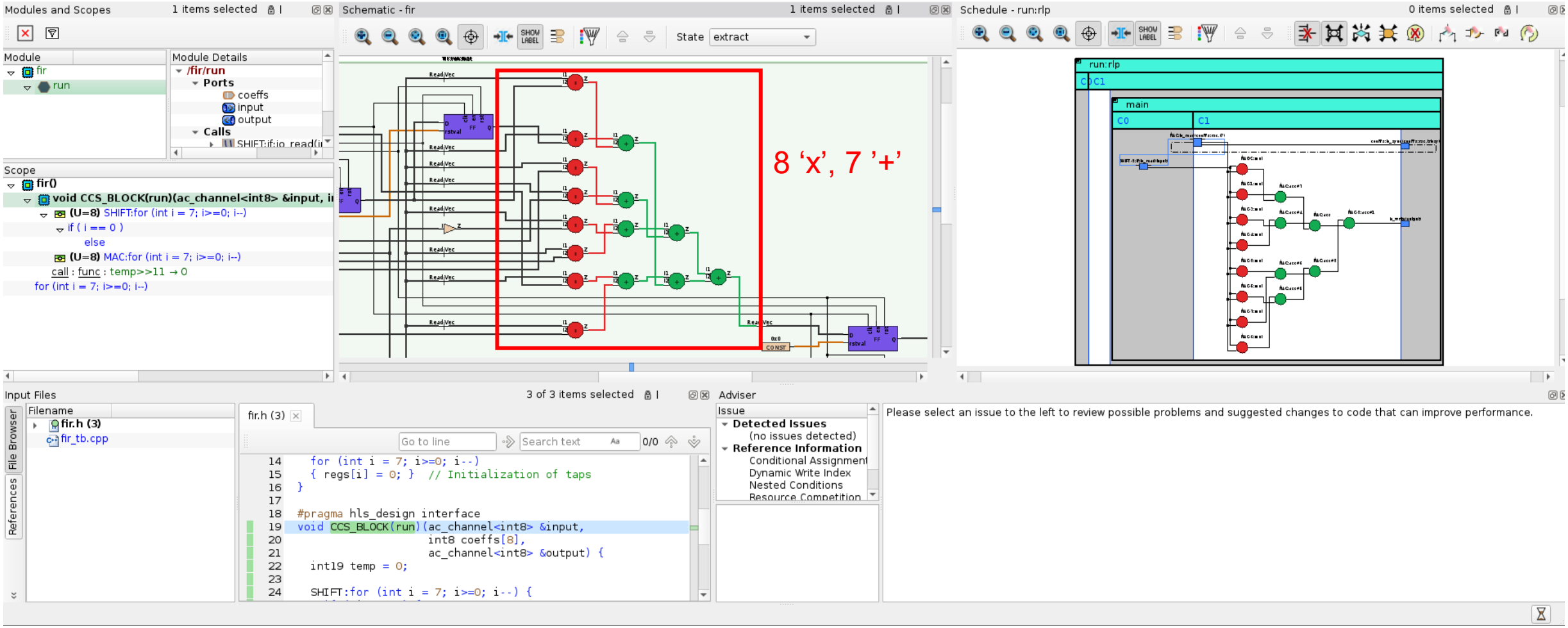
Design Analyzer

Analyze the design in various perspectives



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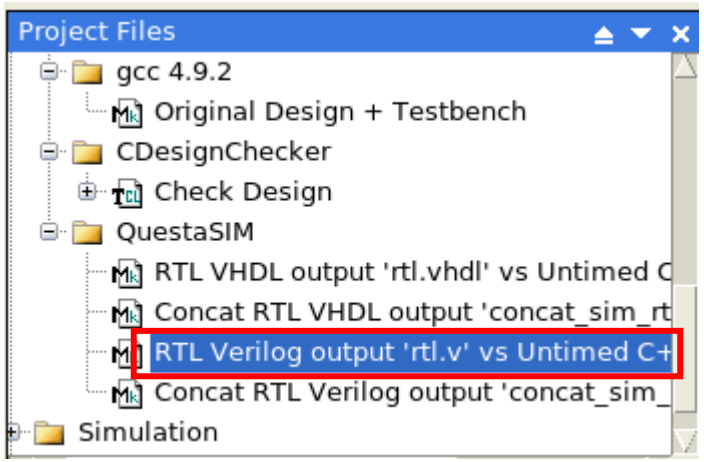
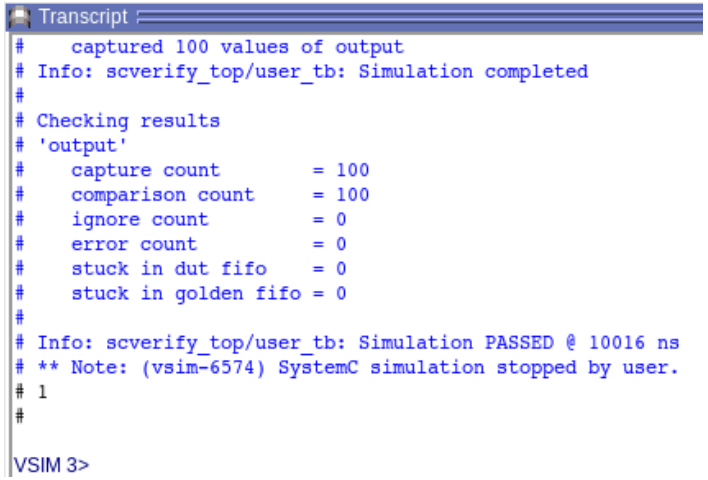
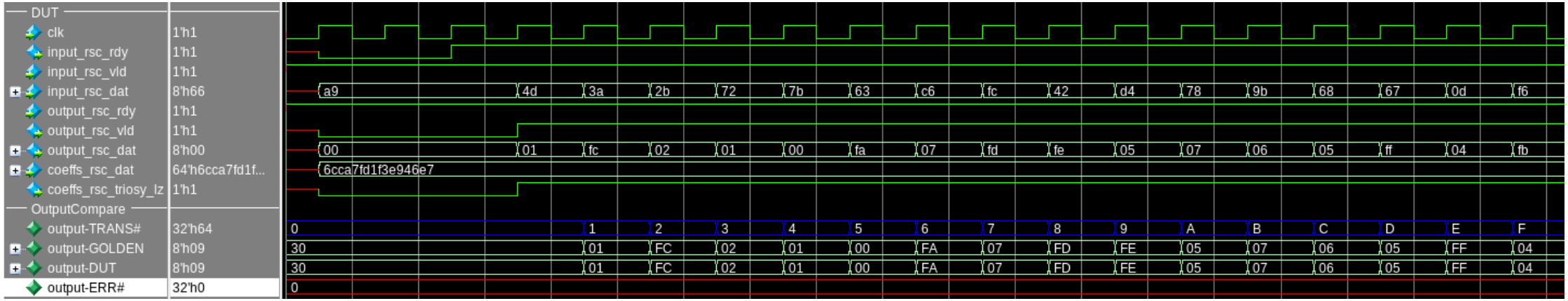
RTL Verification

Automatically compare the outputs of HLC C and RTL







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Reproduce the Solution

All command has been recorded in a tcl script

```
[mentor@RHEL74 walkthrough]$ ll ./Catapult/fir.v2/directives.tcl
-rw-rw-r-- 1 mentor mentor 3531 Aug 22 11:45 ./Catapult/fir.v2/directives.tcl

go new
go compile
solution library add nangate-45nm_beh -- -rtlsyntool DesignCompiler -vendor Nangate -technology 045nm
go libraries
directive set -CLOCKS {clk {-CLOCK_PERIOD 10.0 -CLOCK_EDGE rising -CLOCK_UNCERTAINTY 0.0 -CLOCK_HIGH_TI
go assembly
directive set /fir/run/main -PIPELINE_INIT_INTERVAL 1
directive set /fir/run/SHIFT -UNROLL yes
directive set /fir/run/MAC -UNROLL yes
go architect
```

The same result can be produced with this .tcl

- catapult –f ./Catapult/fir.v2/directives.tcl &

Memory Interface

Source Code (fir.h)

```
void CCS_BLOCK(run)(ac_channel<ac_int<8>> &input,
                    ac_int<8> coeffs[32][8],
                    ac_channel<ac_int<5,false>> &coeff_addr,
                    ac_channel<ac_int<8>> &output) {
  ac_int<19> temp = 0;
  ac_int<5,false> addr = coeff_addr.read();

  SHIFT:for (int i = 7; i>=0; i--) {
    if ( i == 0 ) {
      regs[i] = input.read();
    } else {
      regs[i] = regs[i-1];
    }
  }
  MAC:for (int i = 7; i>=0; i--) {
    temp += coeffs[addr][i]*regs[i];
  }
  output.write(temp>>11);
}
```


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TestBench (fir_tb.cpp)

```
#include "fir.h"

CCS_MAIN(int argc, char *argv[])
{
  ac_int<8> coeffs[32][8];
  ac_channel<ac_int<8>> input;
  ac_channel<ac_int<5,false>> coeff_addr;
  ac_channel<ac_int<8>> output;
  ac_int<8> data;
  ac_int<5,false> addr;
  fir inst;
  …
```

```
  …
  // Test Impulse
  for (int j=0; j < 32; j++)
    for (int i=0; i < 8; i++)
      coeffs[j][i] = rand();
  for (int i = 0; i < 10; i++ ) {
    data = rand();
    input.write(data);
    addr = rand();
    coeff_addr.write(addr);
    inst.run(input, coeffs, coeff_addr, output);
  }
  while (output.available(1))
    printf("Output = %3d\n",output.read().to_int());
  CCS_RETURN(0);
}
```


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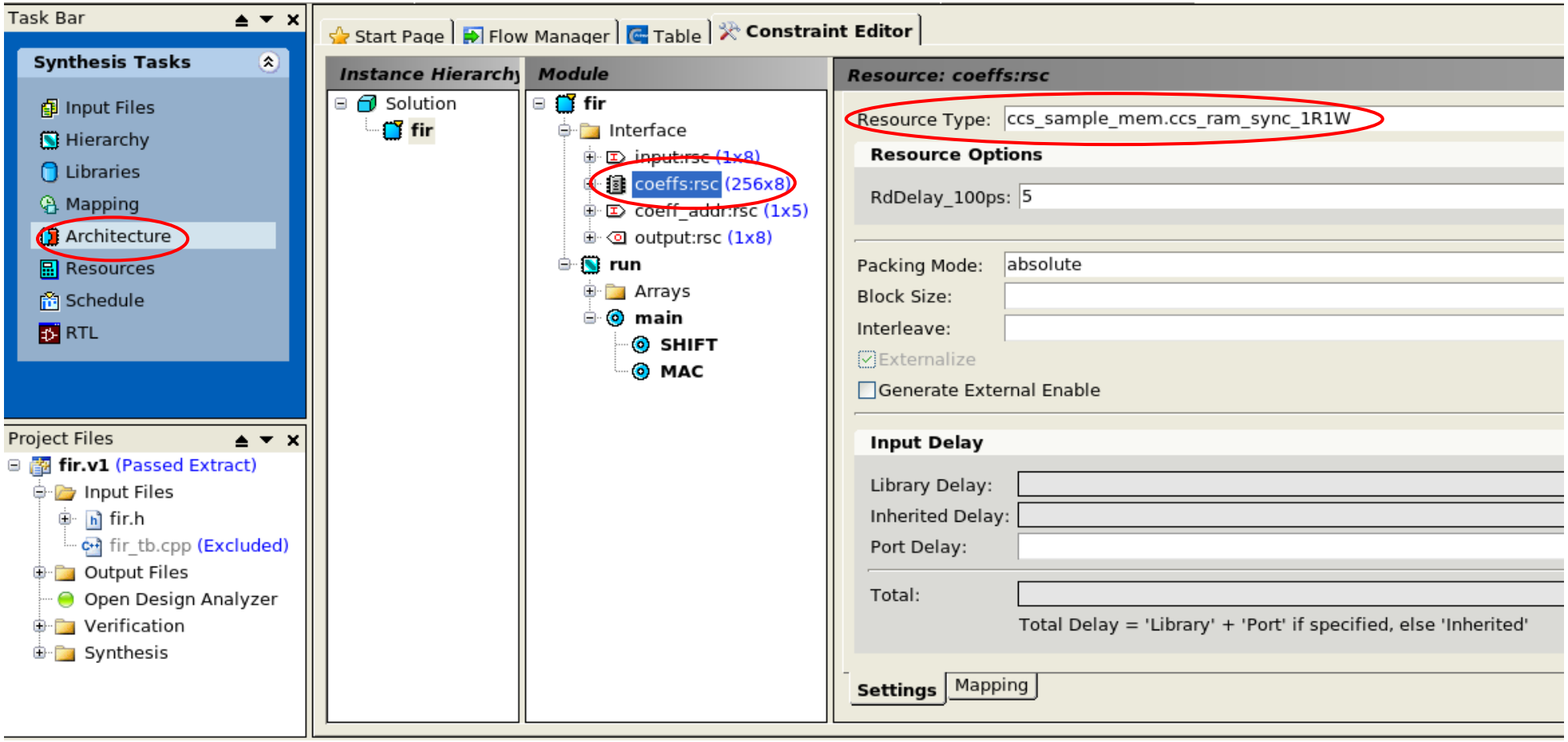
Start with running directives.tcl

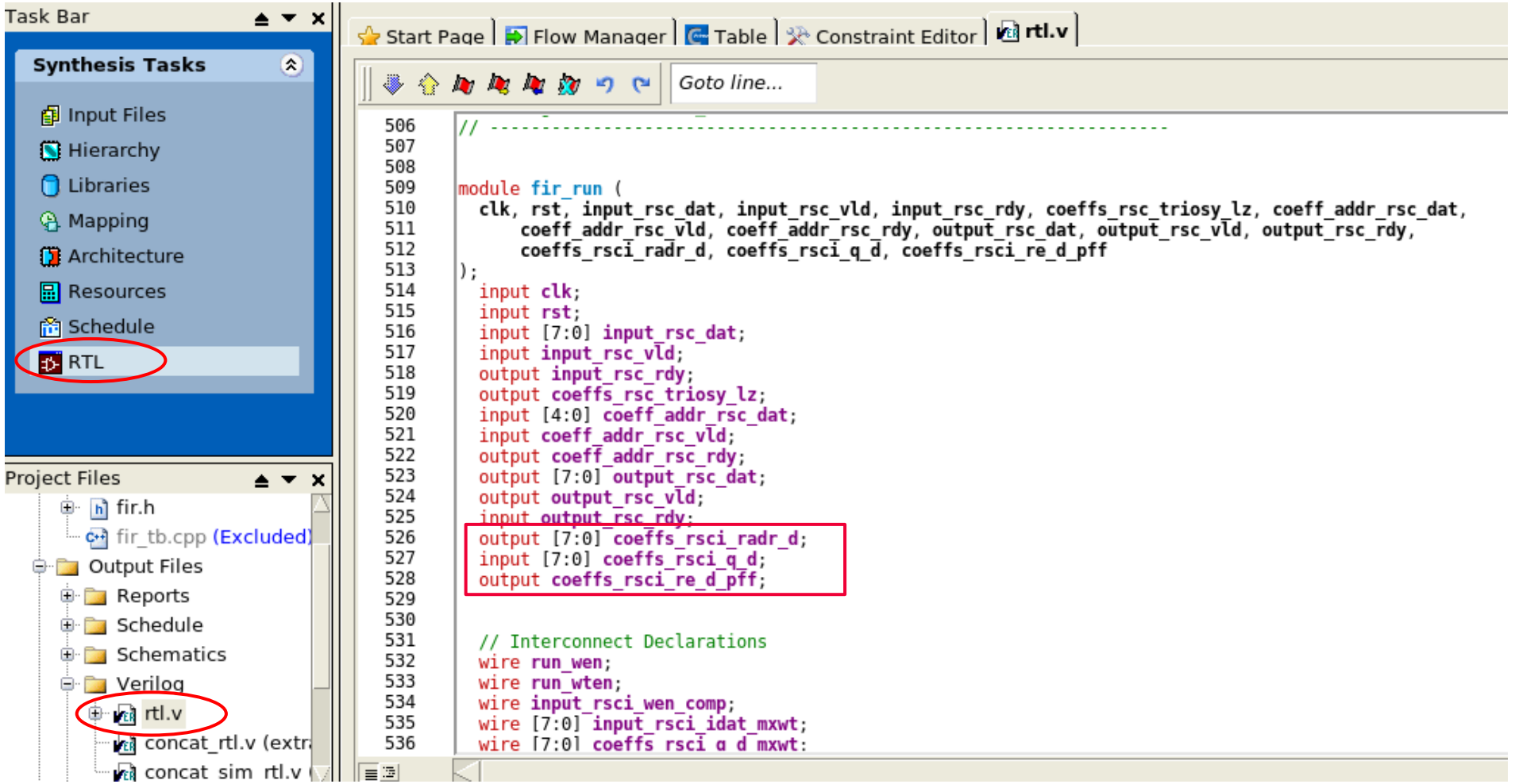
catapult –f directives.tcl

Check coeffs SRAM: (1) size: 256x8b (2) resource type: 1R1W RAM

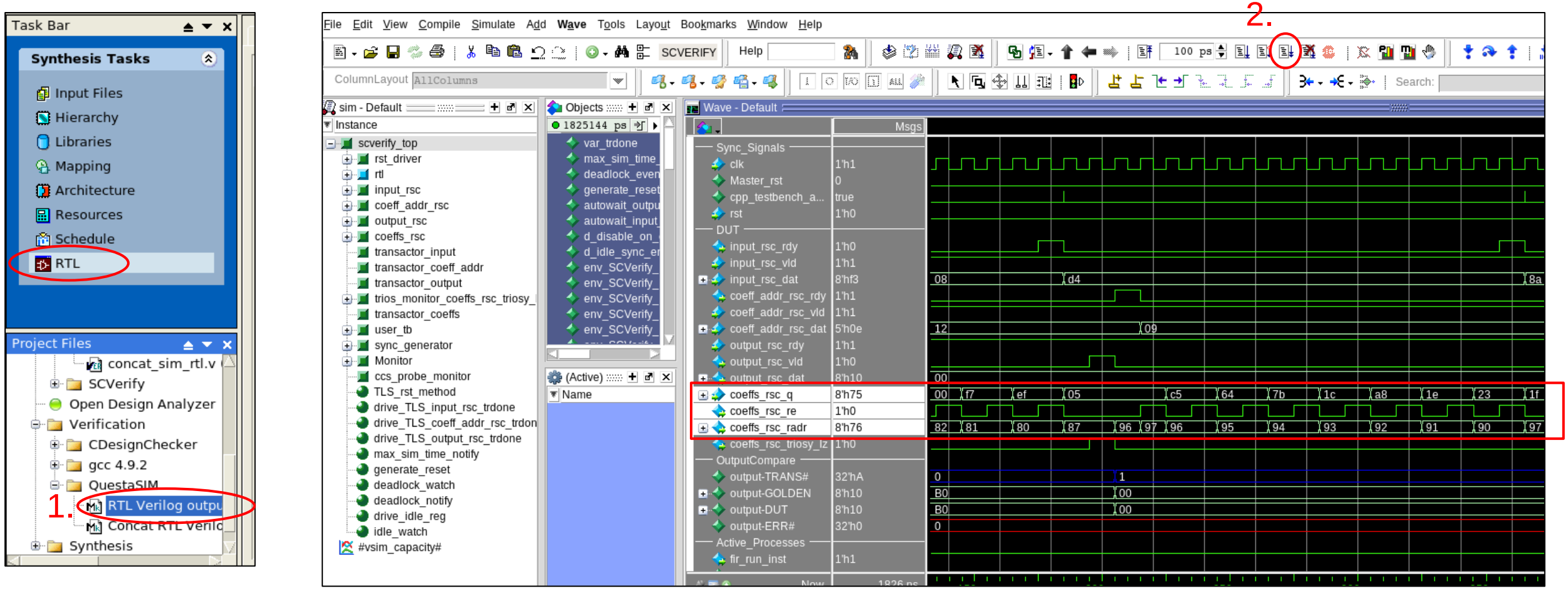


Check SRAM Interface in RTL

*_re_*: ram read enable; *_radr_*: ram read address; *_d": ram read data



Check SRAM Interface in Waveform



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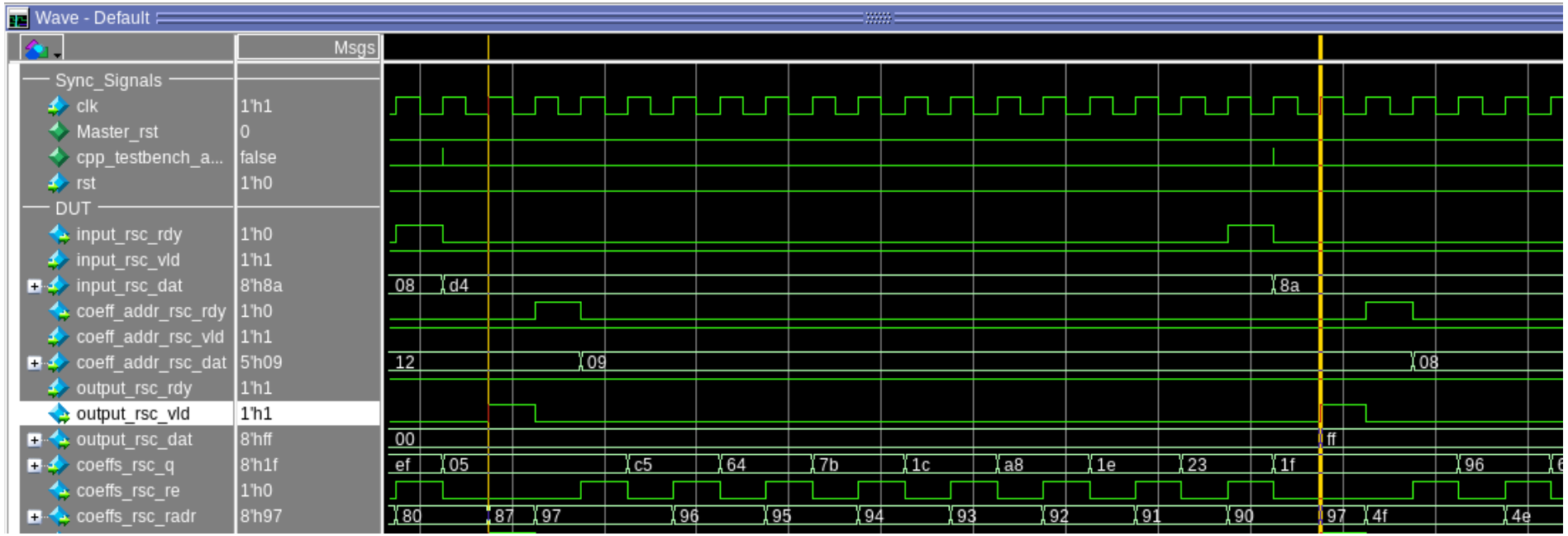
How do we improve the throughput

Current throughput is 18

Report: General

Solution	Latency...	Latency...	Throughput Cycles	Thro...	Slack	Total Area
solution.v1 (new)						
fir.v1 (extract)	**17**	**170.00**	**18**	**180.00**	**7.68**	**1461.69**



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Make convolution in parallel

```
void CCS_BLOCK(run)(ac_channel<ac_int<8>> &input,
                    ac_int<8> coeffs[32][8],
                    ac_channel<ac_int<5,false>> &coeff_addr,
                    ac_channel<ac_int<8>> &output) {
   ac_int<19> temp = 0;
   ac_int<5,false> addr = coeff_addr.read();

   SHIFT:for (int i = 7; i>=0; i--) {
     if ( i == 0 ) {
       regs[i] = input.read();
     } else {
       regs[i] = regs[i-1];
     }
   }
   MAC:for (int i = 7; i>=0; i--) {
     temp += coeffs[addr][i]*regs[i];
   }
   output.write(temp>>11);
 }
```

Make convolution parallel

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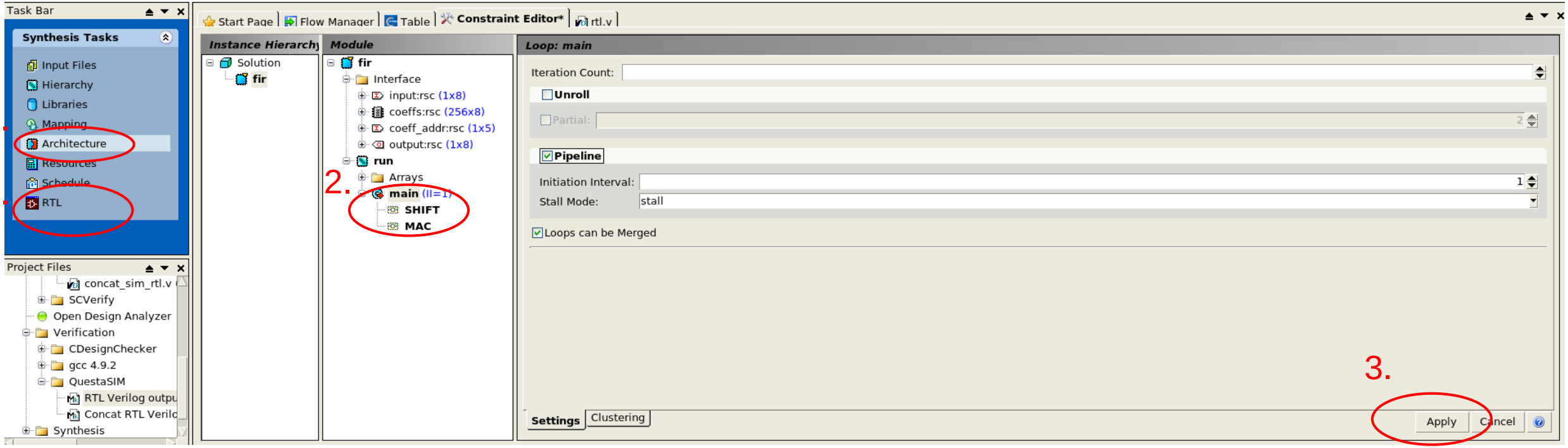
Change the Architecture

Unroll ‘SHIFT’ and ‘MAC’, and Pipeline ‘main’




```
#  Prescheduled SEQUENTIAL '/fir/run' (total length 4 c-steps)
   insufficient resources 'ccs_sample_mem.ccs_ram_sync_1R1W_rport(2,8,8,256,256,8,5)' to schedule '/fir/run'. 8 are needed, but only 1 instances are available
   please merge accesses to 'coeffs:rsc' to reduce the number of required resources
#  Netlist written to file 'schedule.gnt'
   Completed transformation 'architect' on solution 'fir.v2': elapsed time 0.25 seconds, memory usage 1364772kB, peak memory usage 1364772kB
   Design complexity at end of 'architect': Total ops = 68, Real ops = 16, Vars = 23
   Design 'fir' could not schedule partition '/fir/run' - resource competition
```

fir.h(23)	SCHD-8
	SCHD-4
fir.h(24)	SCHD-39
	NET-4
	SOL-9
	SOL-21

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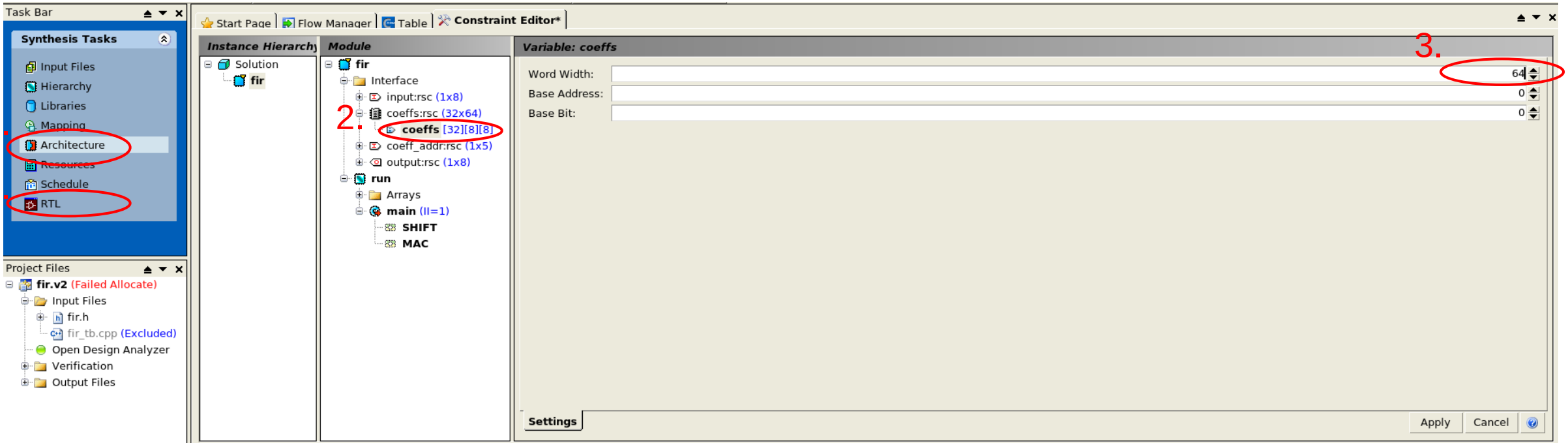
Increase Memory Data Width

Word Width = 64 (why ?)




```
#  Generating SCVerify testbench files
#  Makefile for RTL Verilog output 'rtl.v' vs Untimed C++ written to file './scverify/Verify_rtl_v_msim.mk'
#  Makefile for Concat RTL Verilog output 'concat_sim_rtl.v' vs Untimed C++ written to file './scverify/Verify_concat_sim_rtl_v_msim.mk'
(i) Completed transformation 'extract' on solution 'fir.v3': elapsed time 3.66 seconds, memory usage 1364772kB, peak memory usage 1364816kB
(i) Design complexity at end of 'extract': Total ops = 269, Real ops = 84, Vars = 199
```

SOL-9
SOL-21

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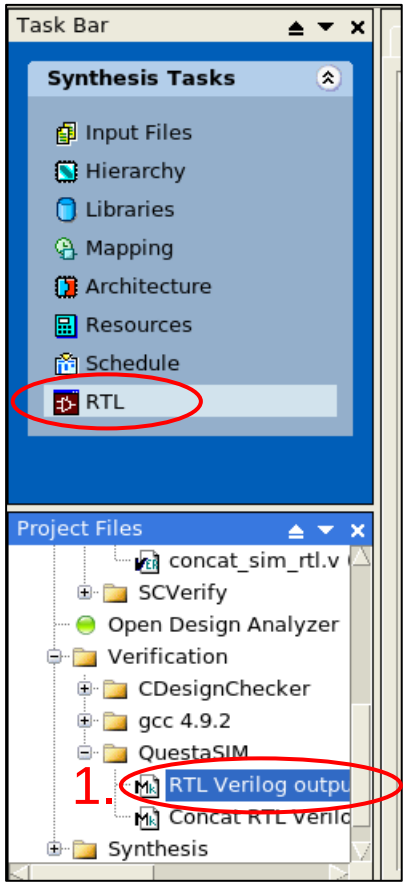
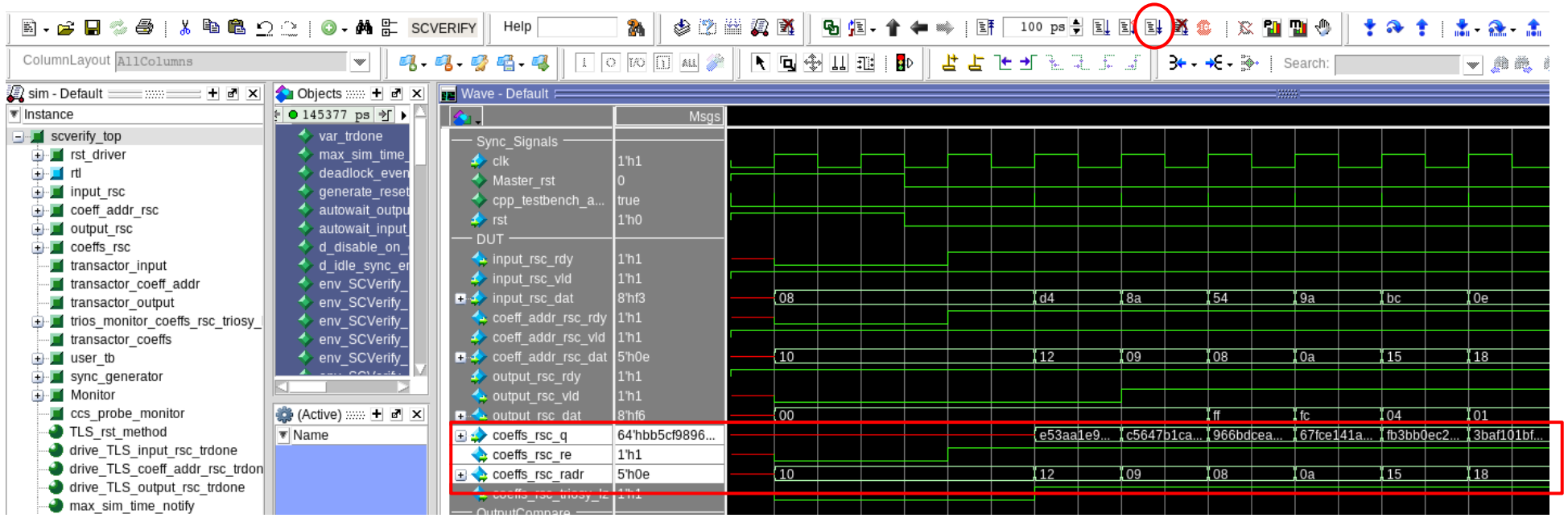
Check Waveform

Throughput = 1

Report: General

Solution	Latency...	Latency...	Throughput Cycles	Thro...	Slack	Total Area
solution.v1 (new)						
fir.v1 (extract)	17	170.00	18	180.00	7.68	1461.69
fir.v2 (extract)	**2**	**20.00**	**1**	**10.00**	**7.58**	**4024.42**





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Multiple Blocks

A Design with Two 8-Tap FIRs and One Decimator

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top.h

```
#include "fir.h"
#include "decimator.h"
class top {
  ac_channel<ac_int<8> > connect0;
  ac_channel<ac_int<8> > connect1;
  fir block0;
  fir block1;
  decimator block2;
  public :
  top () {}
  #pragma hls_design interface top
  void CCS_BLOCK(run) (ac_channel<ac_int<8> > &din,
                       ac_int<8> coeffs[8],
                       ac_channel<ac_int<8> > &dout)
{
    block0.run(din,coeffs,connect0);
    block1.run(connect0,coeffs,connect1);
    block2.run(connect1,dout);
  …
```


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decimator.h

```
class decimator {
  int count;
  public :
  decimator () {
    count = 0;
  }
  #pragma hls_design interface
  void CCS_BLOCK(run) (ac_channel<ac_int<8> > &din,
                       ac_channel<ac_int<8> > &dout) {
    if (count==4)
      count = 0;
    ac_int<8> temp = din.read();
    if (count==0)
      dout.write(temp);
    count++;
…
```

fir.h

```
class fir {
  ac_int<8> regs[8];
  public:
  fir() {
    for (int i = 7; i>=0; i--)
    { regs[i] = 0; }
  }
 …
```

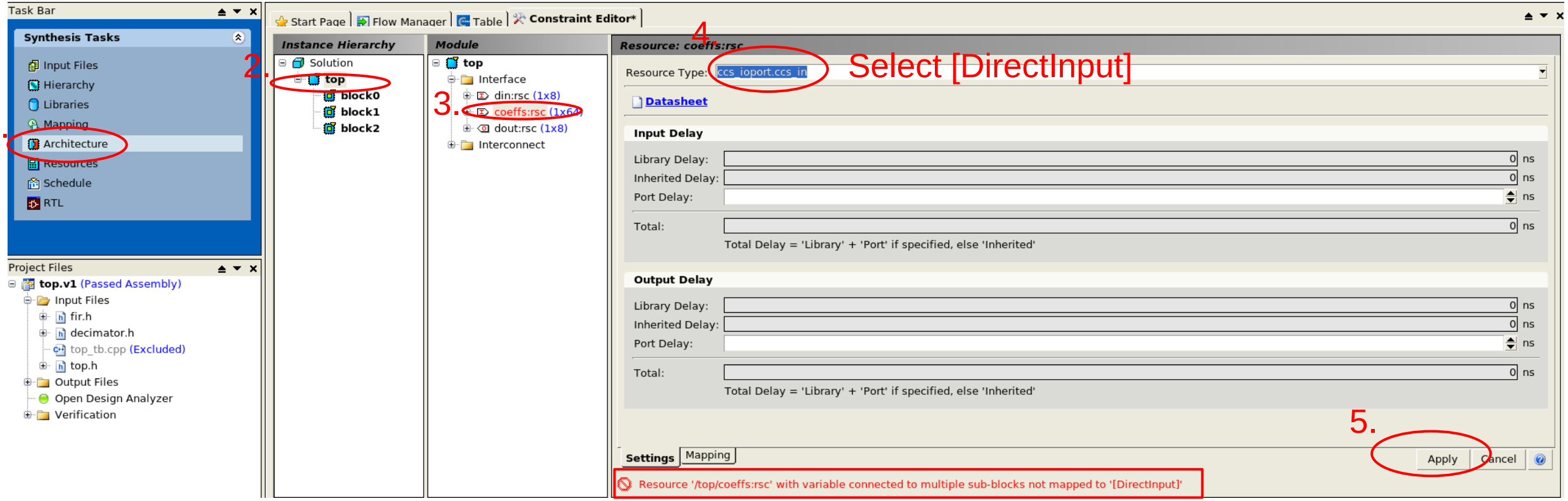
```
#pragma hls_design interface
  void CCS_BLOCK(run)(ac_channel< ac_int<8> > &input,
                      ac_int<8> coeffs[8],
                      ac_channel< ac_int<8> > &output) {
    ac_int<19> temp = 0;
    SHIFT:for (int i = 7; i>=0; i--) {
      if ( i == 0 ) {
        regs[i] = input.read();
      } else {
        regs[i] = regs[i-1];
      }
    }
    MAC:for (int i = 7; i>=0; i--) {
      temp += coeffs[i]*regs[i];
    }
    output.write(temp>>11);
…
```

Start from the ‘Architecture’ Stage

catapult -f directives.tcl &

There are three design blocks: block0, block1, block2

Set ‘DirectInput’ for the coeffs



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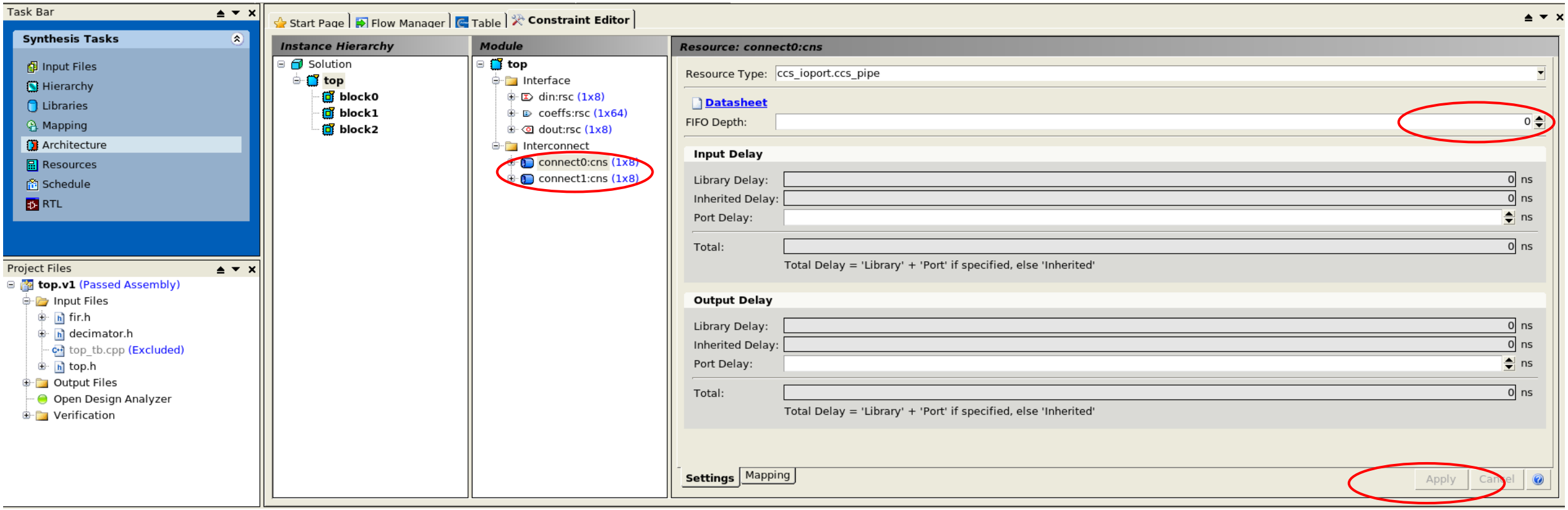
Set FIFO Depth as ‘0’

Set FIFO depth as ‘0’ for connect0 and connect1



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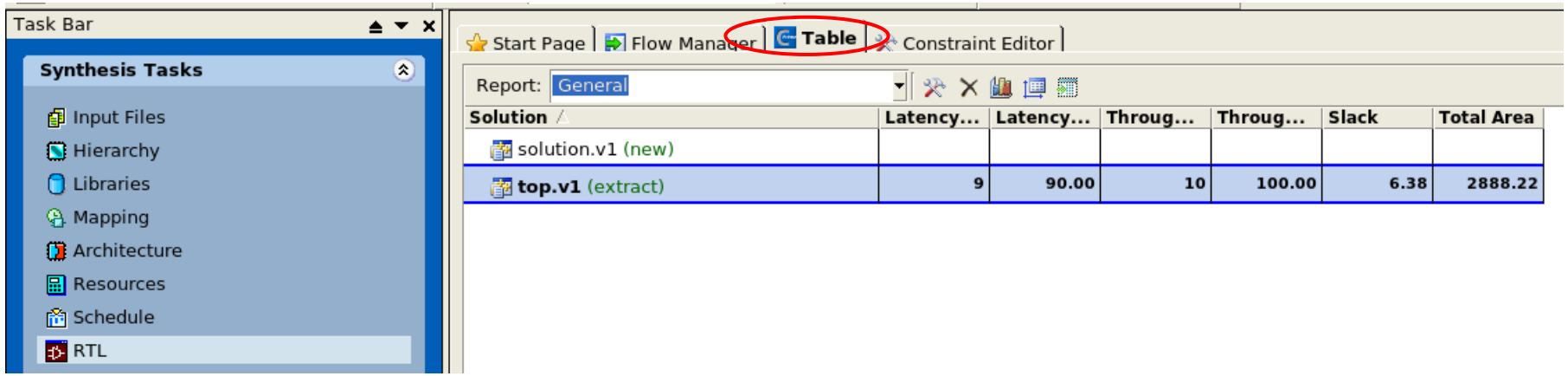
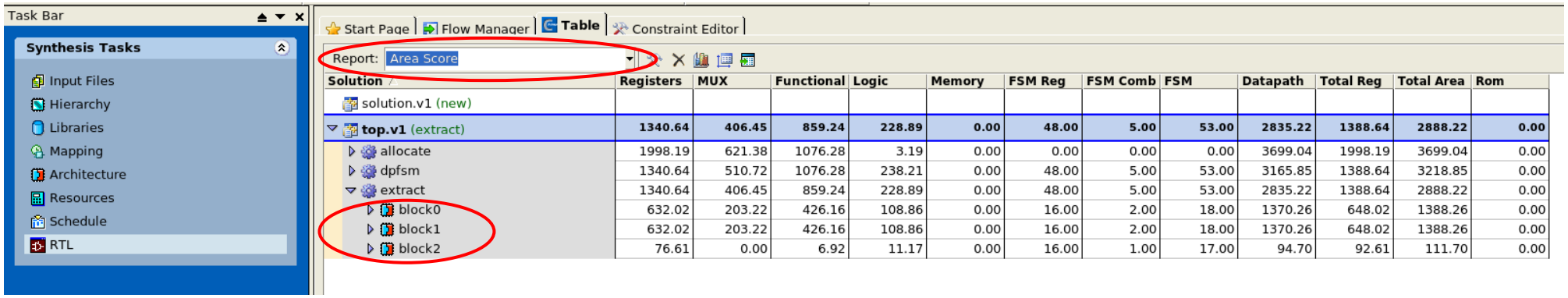
Look Report

Latency = ?, Throughput = ?

Area: block0=?, block1=?, block2=?

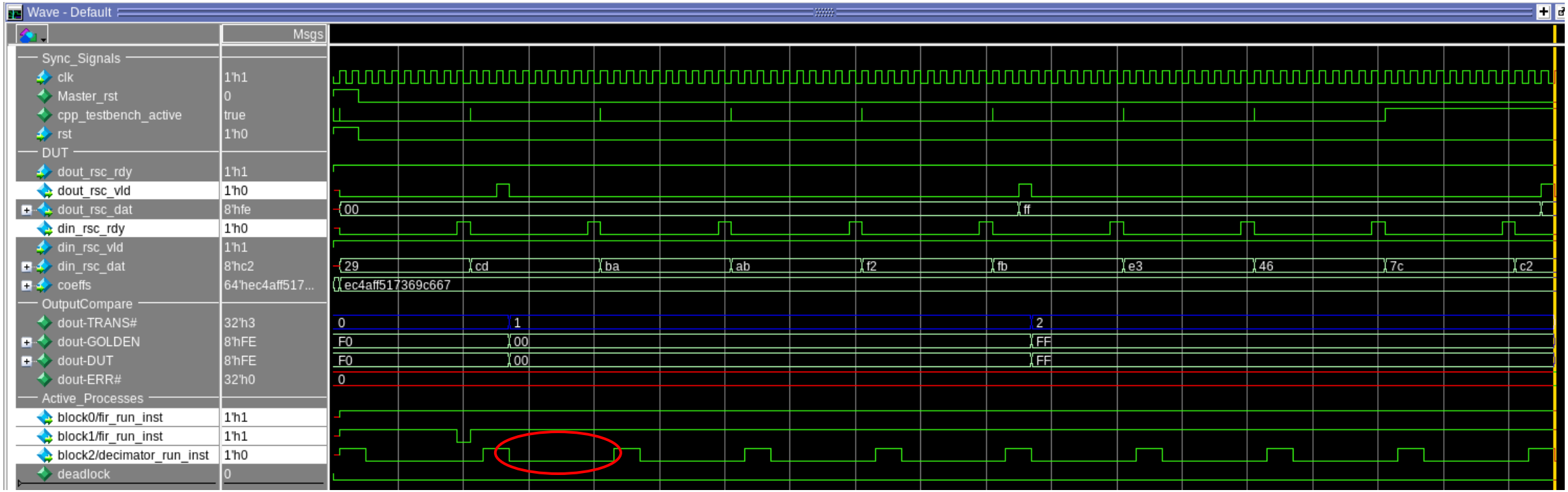


Solution	Latency...	Latency...	Throug...	Throug...	Slack	Total Area
solution.v1 (new)						
top.v1 (extract)	9	90.00	10	100.00	6.38	2888.22



Solution	Registers	MUX	Functional	Logic	Memory	FSM Reg	FSM Comb	FSM	Datapath	Total Reg	Total Area	Rom
solution.v1 (new)												
top.v1 (extract)	1340.64	406.45	859.24	228.89	0.00	48.00	5.00	53.00	2835.22	1388.64	2888.22	0.00
allocate	1998.19	621.38	1076.28	3.19	0.00	0.00	0.00	0.00	3699.04	1998.19	3699.04	0.00
dpfsm	1340.64	510.72	1076.28	238.21	0.00	48.00	5.00	53.00	3165.85	1388.64	3218.85	0.00
extract	1340.64	406.45	859.24	228.89	0.00	48.00	5.00	53.00	2835.22	1388.64	2888.22	0.00
block0	632.02	203.22	426.16	108.86	0.00	16.00	2.00	18.00	1370.26	648.02	1388.26	0.00
block1	632.02	203.22	426.16	108.86	0.00	16.00	2.00	18.00	1370.26	648.02	1388.26	0.00
block2	76.61	0.00	6.92	11.17	0.00	16.00	1.00	17.00	94.70	92.61	111.70	0.00

RTL Simulation



why idle ?

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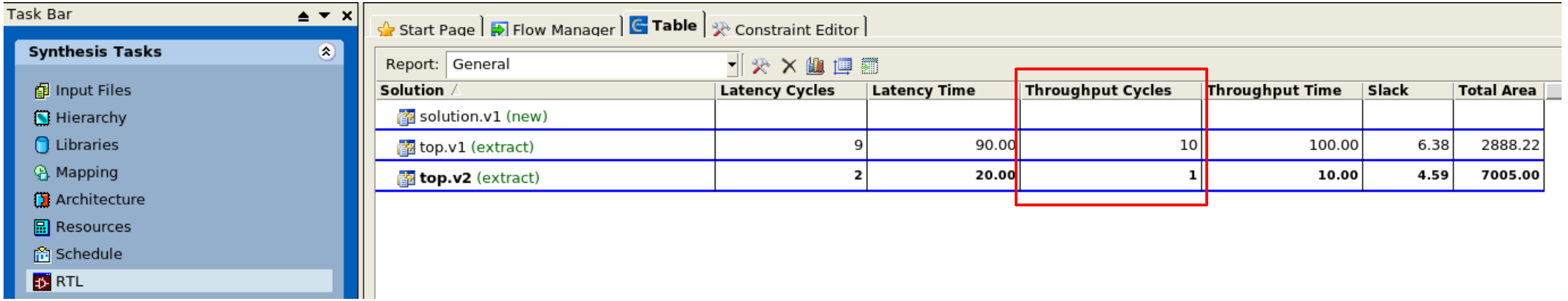
Improve Throughput

Improve the throughput from 10 to 1 by yourself



Solution	Latency Cycles	Latency Time	Throughput Cycles	Throughput Time	Slack	Total Area
solution.v1 (new)						
top.v1 (extract)	9	90.00	10	100.00	6.38	2888.22
top.v2 (extract)	**2**	**20.00**	**1**	**10.00**	**4.59**	**7005.00**

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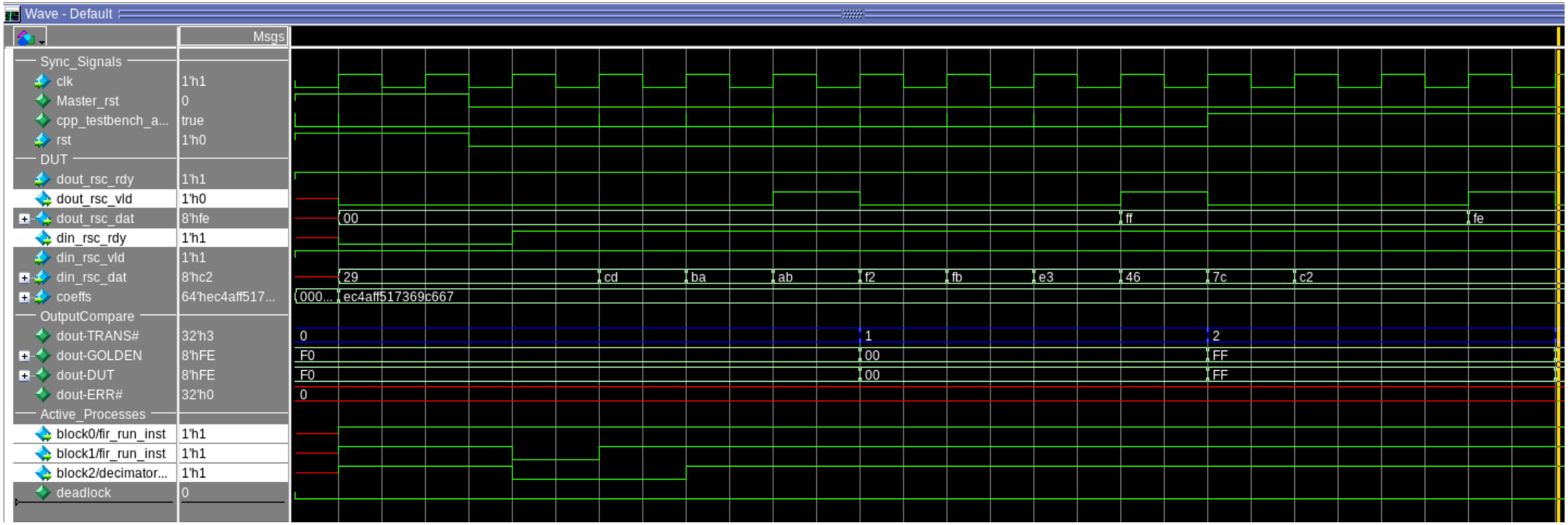
RTL Simulation (Throughput=1)

One dout every four din because of the decimation



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