

Description:

MACs for 2D Image Processing

Specification:

Input: Pixel_in(Input pixel value) size 8 bits, clk - 100 MHz, rst_n, rst_clk

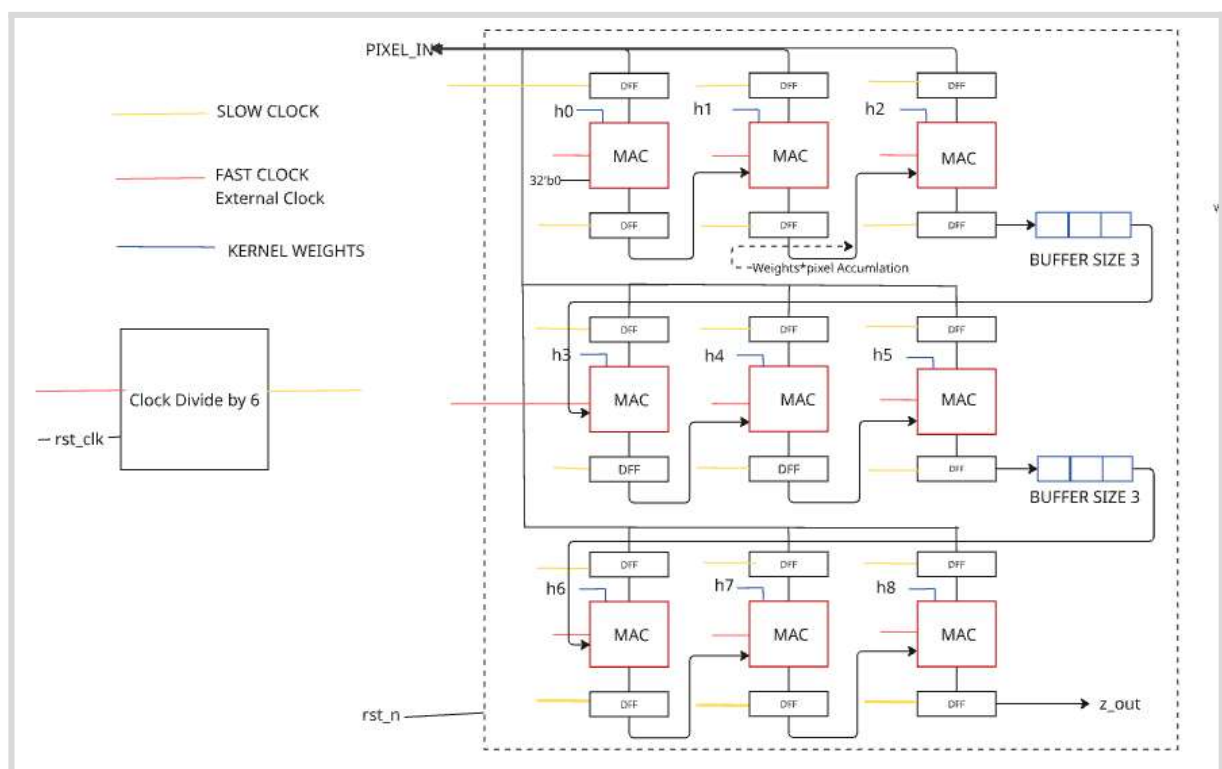
Output: z_out of size 32 bits, slow clock for control of input flow

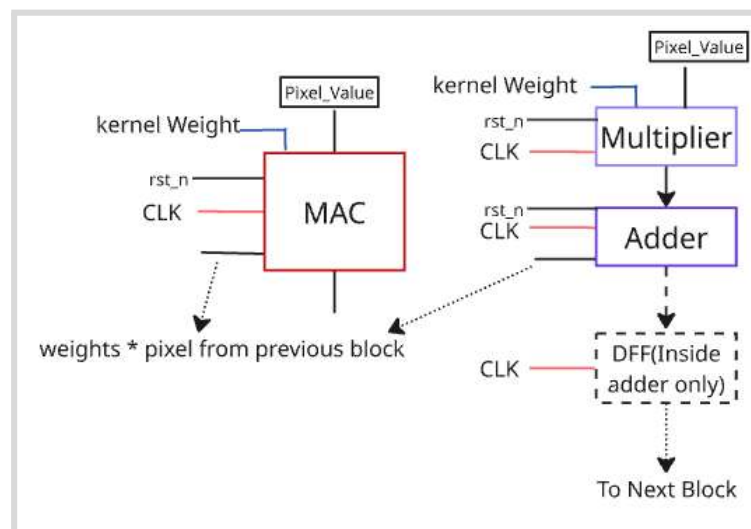
Kernel size: 3 x 3

Note: Input image width should be 6.

In the project, MAC units are implemented and used to form a Kernel for the convolution operation on an image.

Architecture of Kernel :





Adder is a 32-bit Kogge Stone adder.

Multiplier:

We implemented an 8-bit × 8-bit pipelined multiplier to reduce the combinational delay between the stages of the multiplier for operation at a higher frequency.

Let's take two 8-bit numbers A and B. We decompose $A \times B$ as:

$$(A_{high} \ll 4 + A_{low}) (B_{high} \ll 4 + B_{low})$$

We computed these four partial products and then shifted them properly to align their values corresponding to the places in the final multiplication.

Pipeline Stages:

Design has three pipeline stages:

1st Stage: Break the input into a 4-bit combination, do the product, and load it into the register.

$$P1 = (A3A2A1A0) \times (B3B2B1B0)$$

$$P2 = (A7A6A5A4) \times (B3B2B1B0)$$

$$P3 = (A3A2A1A0) \times (B7B6B5B4)$$

$$P4 = (A7A6A5A4) \times (B7B6B5B4)$$

All 8 bits.

2nd Stage: Sum of P2 and P3. Shifted the P1 and P4 products.

$P2+P3 = S1(9\text{bits})$ and shift it 4 bits left. After the shift, there will be a total of 13 bits.

Add eight zero bits before P1. After the addition of zero bits, P1 will be 16 bits.

Shift P4 eight bits towards the left. After the shift, it will also become 16 bits.

Shift to get the magnitude of the P1, P2, P3, and P4.

3rd Stage: Add as below to get the final product

Product = $(8b'0P1)+(3b'0S14b'0)+(P48b'0)$

Example:

$11010011 * 10100110 = 211 * 166 = 35026$ (1000100011010010)

$P1 = 0011 * 0110 = 00010010$ ($3 * 6 = 18$)

$P2 = 1101 * 0110 = 01001110$ ($13 * 6 = 78$)

$P3 = 0011 * 1010 = 00011110$ ($3 * 10 = 30$)

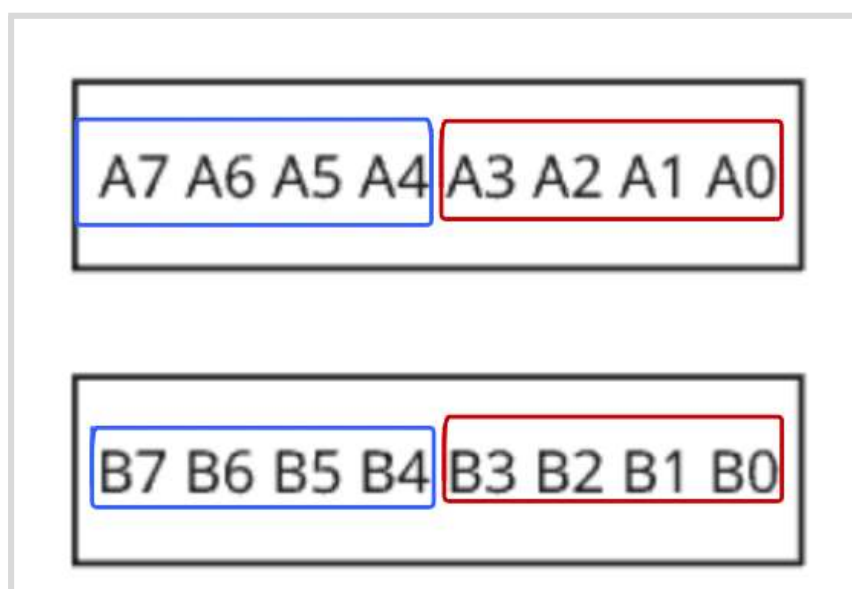
$P4 = 1101 * 1010 = 10000010$ ($13 * 10 = 130$)

$S1 = P2 + P3 = 01001110 + 00011110 = 01101100$ ($78 + 30 = 108$) in 9-bits = 001101100

Product = $(8b'0P1) + (3b'0S14b'0) + (P48b'0)$

= $0000000000010010(18) + 0000011011000000(1728) +$

$1000001000000000(33280) = 1000100011010010(35206)$



Working:

- Initially, we kept the `rst_n` and `rst_clk` low to initialize everything in the circuit to 0.
- After that, `rst_clk` followed by `rst_n` is set high after a few clock periods. Now the system starts to function.
- At the positive clock edge of the slow clock, which has 6 times the clock period of the fast clock, that is our external clock, the input pixel is sampled by DFF(D-Flip Flop) along with the propagation of $\text{weight} \times (\text{previous pixel})$ from one block to another for addition with $(\text{current pixel}) \times \text{weight}$.

Further explanation:

- At the first rising (positive) edge of the slow clock, `pixel[0]` is sampled.
- This `pixel[0]` then goes to the multiplier running on the fast clock.
- After 3 fast-clock cycles from the time the input appears, the multiplier outputs `pixel[0] * h0`.
- This product is then sampled by the adder, which adds it to 0 (since this is the first MAC unit and accumulation starts from 0).
- This result is sampled by DFF at the next positive edge of the slow clock.
- At this same slow-clock edge, `pixel[1]` is sampled by the second MAC unit.
- At this point, the second MAC has both the previous result `pixel[0]*h0` and the new pixel `pixel[1]`.
- At the next positive edge of the slow clock, `pixel[0]*h0 + pixel[1]*h1` is propagated to the third MAC.
- The third MAC then generates and forwards `pixel[0]*h0 + pixel[1]*h1 + pixel[2]*h2` to the buffer.
- The buffer is required because the upcoming pixels (`pixel[3]`, `pixel[4]`, `pixel[5]`) do not belong to the current convolution window and must not be accumulated with the current partial sum.
- Therefore, the accumulated value is held for 3 slow-clock cycles until the next valid window starts with pixels `pixel[6]`, `pixel[7]`, and `pixel[8]`.
- The 15th `z_out` value represents the final convolution result corresponding to the given kernel and the image window.

In our case, Kernel weights are stored as follows:

2	1	2
1	2	1
2	1	2

And the image from the test bench is being input as follows:

1	2	3		4	5	6
7	8	9		10	11	12
13	14	15		16	17	18

19	20	21		22	23	24
25	26	27		28	29	30
31	32	33		34	35	36

So first actual result of convolution between image and kernel in z_out will be the 15th z_out value, and the second result will be the 18th value of z_out, and then again, since the kernel changes to another set of rows again, the result will be at the 15th value from the last convoluted value, and then again at the 18th.

Expected results at 15th and 18th z_out value are

At 15th : $(2 + 2 + 6 + 7 + 16 + 9 + 26 + 14 + 30) = 112$

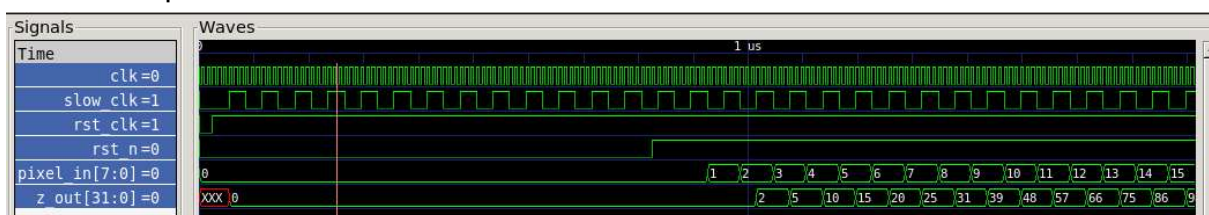
At 18th : $(8 + 5 + 12 + 10 + 22 + 12 + 32 + 17 + 36) = 154$

These values are highlighted on the simulation screenshots provided below.

Similarly, at the next 15th and 18th values from the last correct z_out will be 364 and 406, respectively.

Pre-Synthesis Simulation

Initial Setup

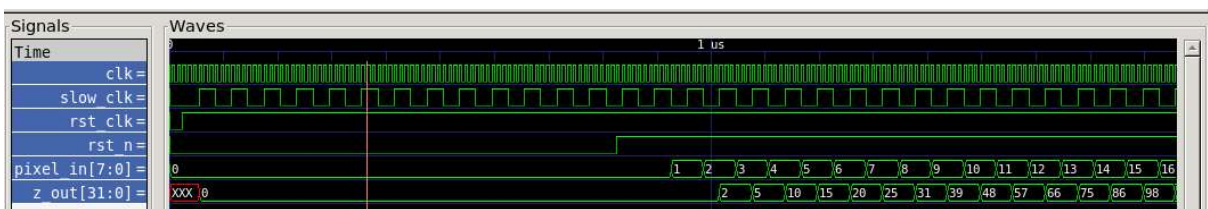


Convolution highlighted Result



Post Synthesis Simulation

Initial Setup

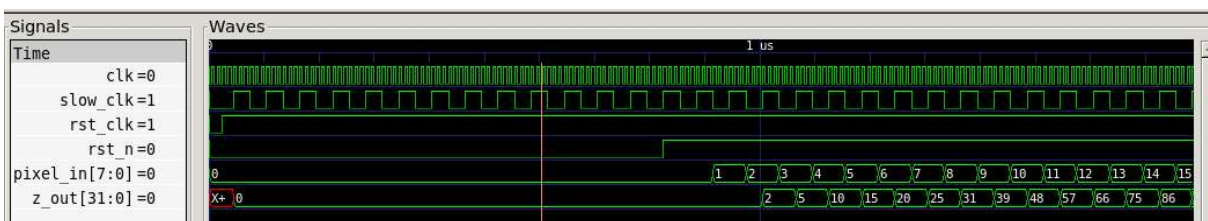


Convolution highlighted Result



Post Physical Design Simulation

Initial setup

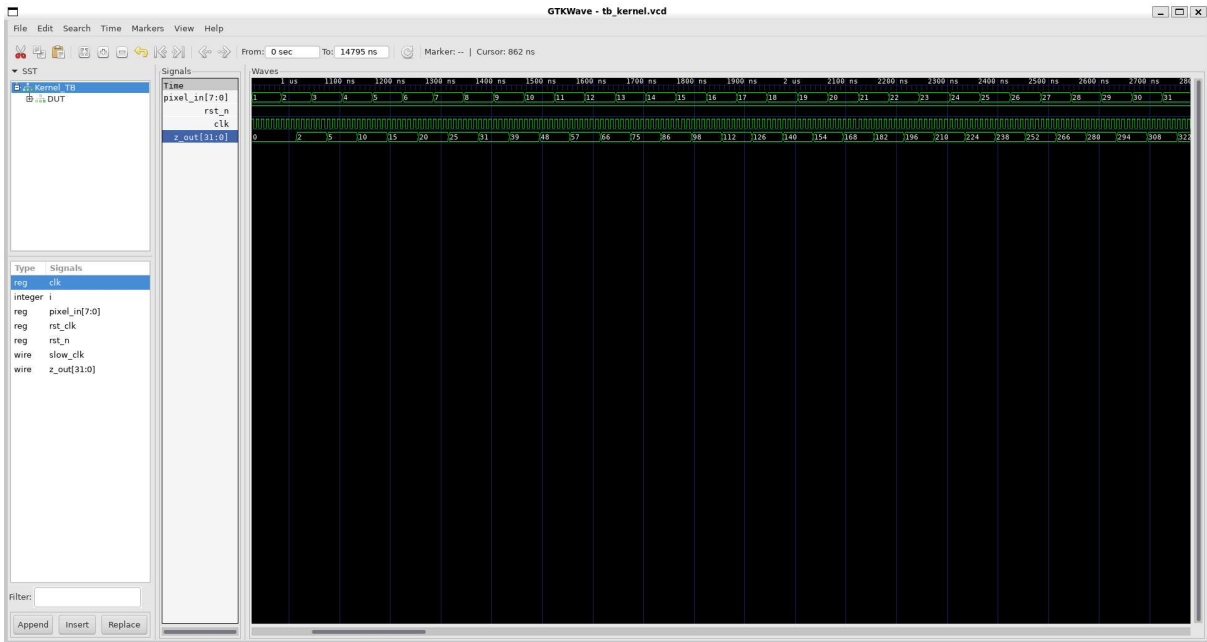


Result Highlighted Screenshot



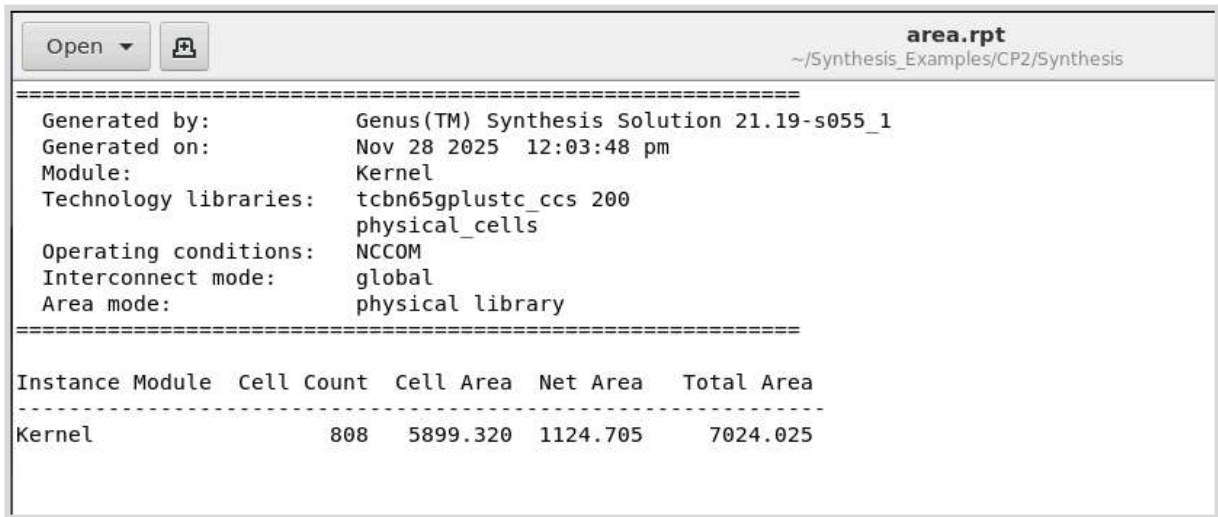
Note: Here, screen screenshots of gtkwave are the same as above. So, for understanding purposes, refer above.

Screenshot of the gtkwave waveforms (pre-synthesis)



Screenshot of the various reports after synthesis

Area report



Timing report

Open

timing.rpt
~/Synthesis_Examples/CP2/Synthesis

Generated by: Genus(TM) Synthesis Solution 21.19-s055_1
Generated on: Nov 28 2025 12:03:48 pm
Module: Kernel
Technology libraries: tcbn65gplustc_ccs 200
physical_cells
Operating conditions: NCCOM
Interconnect mode: global
Area mode: physical library

Pin	Type	Fanout	Load (fF)	Slew (ps)	Delay (ps)	Arrival (ps)
(clock clk)	launch					0 R
M8_original_u_adder_b_reg_reg[0]/CP				0	+0	0 R
M8_original_u_adder_b_reg_reg[0]/Q	DFCNQD1	1	4.5	34	+93	93 R
g3920__1617/B					+0	93
g3920__1617/C0	HA1D0	1	2.8	40	+53	146 R
g3827__9945/CI					+0	146
g3827__9945/C0	FA1D0	1	2.8	41	+64	210 R
g3781__5115/CI					+0	210
g3781__5115/C0	FA1D0	1	2.8	41	+64	273 R
g3757__5122/CI					+0	273
g3757__5122/C0	FA1D0	1	2.8	41	+64	337 R
g3728__6783/CI					+0	337
g3728__6783/C0	FA1D0	1	2.8	41	+64	401 R
g3706__5107/CI					+0	401
g3706__5107/C0	FA1D0	1	2.8	41	+64	465 R
g3682__7410/CI					+0	465
g3682__7410/C0	FA1D0	1	2.8	41	+64	529 R
g3661__9945/CI					+0	529
g3661__9945/C0	FA1D0	1	4.5	58	+74	603 R
g3651__4733/B					+0	603
g3651__4733/C0	HA1D0	1	4.5	58	+67	670 R
g3641__5115/B					+0	670
g3641__5115/C0	HA1D0	1	4.5	58	+67	737 R
g3632__7098/B					+0	737
g3632__7098/C0	HA1D0	1	4.5	58	+67	804 R
g3620__1705/B					+0	804
g3620__1705/C0	HA1D0	1	4.5	58	+67	870 R
g3610__1617/B					+0	870
g3610__1617/C0	HA1D0	1	4.5	58	+67	937 R
g3603__6783/B					+0	937
g3603__6783/C0	HA1D0	1	4.5	58	+67	1004 R
g3596__8428/B					+0	1004
g3596__8428/S	HA1D0	1	2.7	38	+70	1074 R
M8_original_u_adder_sum_reg[14]/D	<<< DFCNQD1				+0	1074
M8_original_u_adder_sum_reg[14]/CP	setup			0	+24	1098 R
(clock clk)	capture					10000 R

Music

Power report

Open

power.rpt
~/Synthesis_Examples/CP2/Synthesis

Instance: /Kernel
Power Unit: W
PDB Frames: /stim#0/frame#0

Category	Leakage	Internal	Switching	Total	Row%
memory	0.00000e+00	0.00000e+00	0.00000e+00	0.00000e+00	0.00%
register	2.40884e-05	5.40610e-04	8.58522e-06	5.73283e-04	91.72%
latch	0.00000e+00	0.00000e+00	0.00000e+00	0.00000e+00	0.00%
logic	4.87989e-06	1.13296e-05	4.66415e-06	2.08736e-05	3.34%
bbox	0.00000e+00	0.00000e+00	0.00000e+00	0.00000e+00	0.00%
clock	0.00000e+00	0.00000e+00	3.08700e-05	3.08700e-05	4.94%
pad	0.00000e+00	0.00000e+00	0.00000e+00	0.00000e+00	0.00%
pm	0.00000e+00	0.00000e+00	0.00000e+00	0.00000e+00	0.00%
Subtotal	2.89683e-05	5.51939e-04	4.41194e-05	6.25027e-04	100.00%
Percentage	4.63%	88.31%	7.06%	100.00%	100.00%

Gates report

Open

gates.rpt
~/Synthesis_Examples/CP2/Synthesis

Generated by: Genus(TM) Synthesis Solution 21.19-s055_1
Generated on: Nov 28 2025 12:03:48 pm
Module: Kernel
Technology libraries: tcbn65gplustc_ccs 200
physical_cells
Operating conditions: NCCOM
Interconnect mode: global
Area mode: physical library

Gate	Instances	Area	Library
AN3XD1	1	2.520	tcbn65gplustc_ccs
A022D0	11	31.680	tcbn65gplustc_ccs
CKX0R2D1	11	39.600	tcbn65gplustc_ccs
DFCND1	1	8.640	tcbn65gplustc_ccs
DFCNQD1	270	2138.400	tcbn65gplustc_ccs
DFKCNQD1	414	2980.800	tcbn65gplustc_ccs
EDFCND1	2	22.320	tcbn65gplustc_ccs
FA1D0	44	396.000	tcbn65gplustc_ccs
HA1D0	41	236.160	tcbn65gplustc_ccs
INR2XD0	1	2.160	tcbn65gplustc_ccs
NR2XD0	1	1.440	tcbn65gplustc_ccs
XOR2D1	11	39.600	tcbn65gplustc_ccs
total	808	5899.320	

Type	Instances	Area	Area %
sequential	687	5150.160	87.3
logic	121	749.160	12.7
physical_cells	0	0.000	0.0
total	808	5899.320	100.0

Plain 1

Summary report

Open

summary.rpt
~/Synthesis_Examples/CP2/Synthesis

=====

Generated by: Genus(TM) Synthesis Solution 21.19-s055_1
Generated on: Nov 28 2025 12:03:48 pm
Module: Kernel
Technology libraries: tcbn65gplustc_ccs 200
physical_cells
Operating conditions: NCCOM
Interconnect mode: global
Area mode: physical library

=====

Timing

Slack	Endpoint	Cost Group

+8902ps	M8_original_u_adder_sum_reg[14]/D clk	

Area

Instance	Module	Cell Count	Cell Area	Net Area	Total Area

Kernel		808	5899.320	1124.705	7024.025

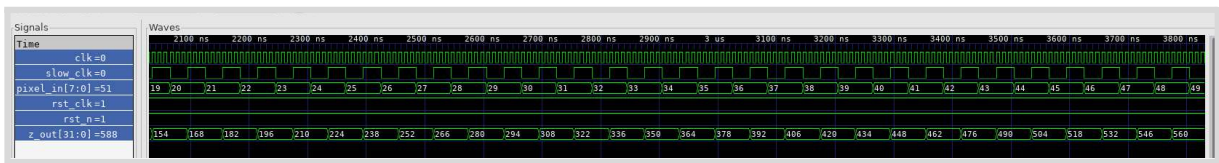
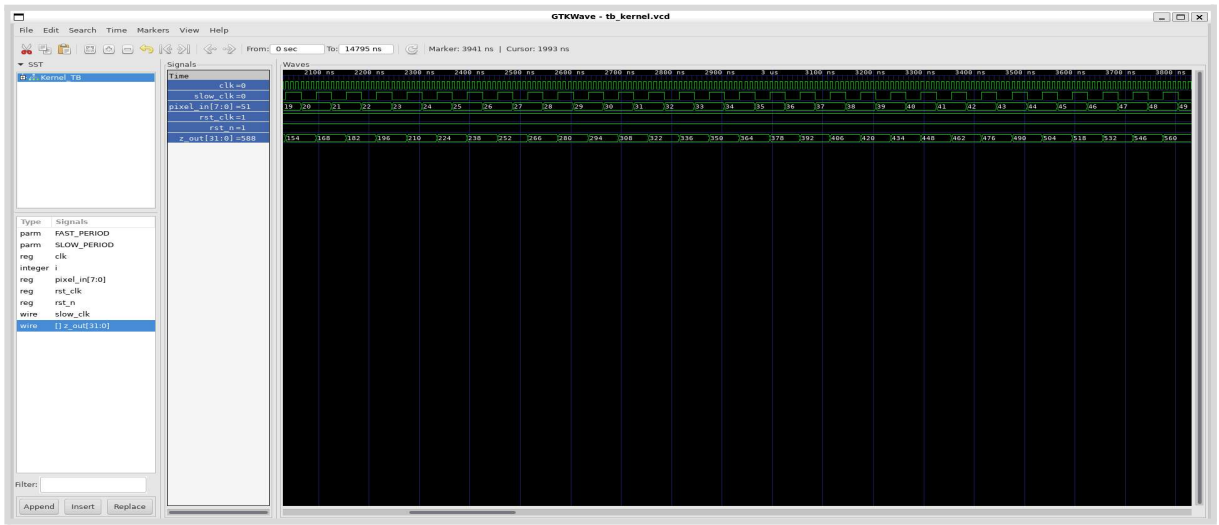
Design Rule Check

Max_transition design rule: no violations.
Max_capacitance design rule: no violations.

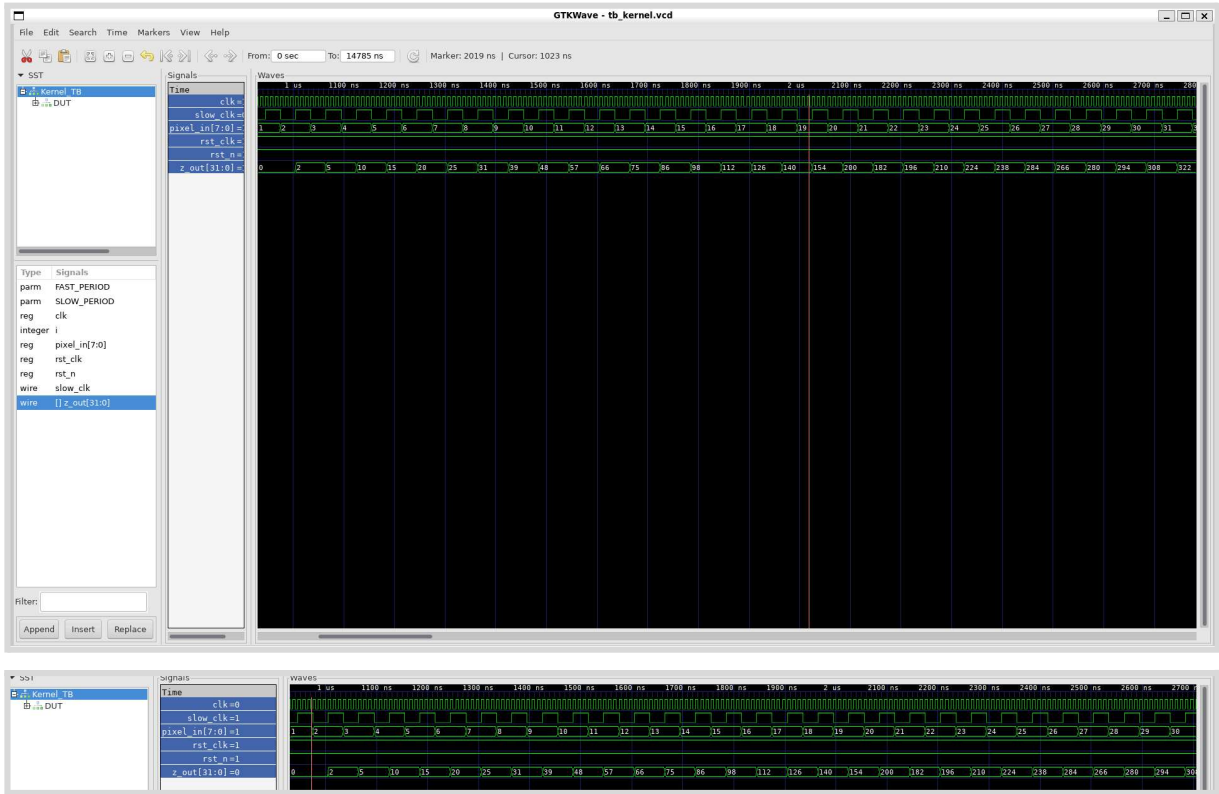
The following table is based on the above gate.rpt file:

Number of combinational cells	121
Number of sequential cells (Flip-flops)	687
Total number of cells	808

Screenshot of the gtkwave waveforms (post-synthesis)



Physical Design Post Route gtkwave



Post route reports:

Area report:

Open

area.rpt
~/PnR_Example/9.Kernel/physical_design

Hinst Name	Module Name	Inst Count	Total Area
Kernel		850	6001.920

Hold report:

Kernel_postRoute_hold.summary - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/timingReports/

File Edit Search Preferences Shell Macro Windows

1 #####

2 # Generated by: Cadence Innovus 21.12-s106_1

3 # OS: Linux x86_64(Host ID vlsi73.ee.iitb.ac.in)

4 # Generated on: Fri Nov 28 11:10:24 2025

5 # Design: Kernel

6 # Command: timeDesign -postRoute -hold

7 #####

8

9 -----

10 timeDesign Summary

11 -----

12

Hold mode	all	reg2reg	default
WNS (ns):	0.004	0.004	0.012
TNS (ns):	0.000	0.000	0.000
Violating Paths:	0	0	0
All Paths:	730	289	441

20 -----

21

22 Density: 100.000%

23 -----

24

Timing report:

Kernel_postRoute.summary - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/timingReports/

File Edit Search Preferences Shell Macro Windows

1 #####

2 # Generated by: Cadence Innovus 21.12-s106_1

3 # OS: Linux x86_64(Host ID vlsi73.ee.iitb.ac.in)

4 # Generated on: Fri Nov 28 11:10:21 2025

5 # Design: Kernel

6 # Command: timeDesign -postRoute

7 #####

8

9 -----

10 timeDesign Summary

11 -----

12

Setup mode	all	reg2reg	default
WNS (ns):	8.422	8.422	9.294
TNS (ns):	0.000	0.000	0.000
Violating Paths:	0	0	0
All Paths:	730	289	441

20 -----

21

DRVs	Real		Total
	Nr nets(terms)	Worst Vio	Nr nets(terms)
max_cap	0 (0)	0.000	0 (0)
max_tran	0 (0)	0.000	0 (0)
max_fanout	0 (0)	0	0 (0)
max_length	0 (0)	0	0 (0)

32

33 Density: 100.000%

34 -----

35

Power Report

power.rpt - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/physical_design/

File Edit Search Preferences Shell Macro Windows

1 *
2 * Innovus 21.12-s106_1 (64bit) 12/08/2021 18:19 (Linux 3.10.0-693.el7.x86_64)
3 *
4 *
5 * Date & Time: 2025-Nov-28 11:10:25 (2025-Nov-28 05:40:25 GMT)
6 *
7 *
8 *
9 * Design: Kernel
10 *
11 * Liberty Libraries used:
12 * BEST_CASE:
13 * /vlsi/pdk/course_pdk_2025/tsmc_gp_65_stdio/tc65gplus_200a/TSMCHOME/digital/Front_End/timing_power_noise/CCS/tc65gplus_200a/tc65gplusbc_ccs.lib
14 * Power Domain used:
15 * Rail: VDD Voltage: 1.1
16 *
17 * Power View : BEST_CASE
18 *
19 * User-Defined Activity : N.A.
20 *
21 * Activity File: N.A.
22 *
23 * Hierarchical Global Activity: N.A.
24 *
25 * Global Activity: N.A.
26 *
27 * Sequential Element Activity: 0.200000
28 *
29 * Primary Input Activity: 0.200000
30 *
31 * Default icg ratio: N.A.
32 *
33 * Global Comb ClockGate Ratio: N.A.
34 *
35 * Power Units = 1mW
36 *
37 * Time Units = 1e-09 secs
38 *
39 * report_power -outfile physical_design/power.rpt
40 *
41 -----
42
43
44 Total Power
45 -----
46 Total Internal Power: 0.86662250 72.5712%

power.rpt - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/physical_design/


File Edit Search Preferences Shell Macro Windows

43
44 Total Power
45 -----
46 Total Internal Power: 0.86662250 72.5712%
47 Total Switching Power: 0.10563899 8.8462%
48 Total Leakage Power: 0.22190761 18.5826%
49 Total Power: 1.19416911
50 -----
51
52
53 Group Internal Switching Leakage Total Percentage
54 Power Power Power Power (%)
55 -----
56 Sequential 0.8077 0.01411 0.1156 0.9374 78.5
57 Macro 0 0 0 0 0
58 IO 0 0 7.44e-05 7.44e-05 0.00623
59 Physical-Only 0 0 0.07719 0.07719 6.464
60 Combinational 0.03323 0.02668 0.02604 0.08595 7.198
61 Clock (Combinational) 0.0257 0.06484 0.003022 0.09357 7.835
62 Clock (Sequential) 0 0 0 0 0
63 -----
64 Total 0.8666 0.1056 0.2219 1.194 100
65 -----
66
67
68 Rail Voltage Internal Switching Leakage Total Percentage
69 Power Power Power Power (%)
70 -----
71 VDD 1.1 0.8666 0.1056 0.2219 1.194 100
72
73
74 Clock Internal Switching Leakage Total Percentage
75 Power Power Power Power (%)
76 -----
77 clk 0.0257 0.06484 0.003022 0.09357 7.835
78 -----
79 Total (excluding duplicates) 0.0257 0.06484 0.003022 0.09357 7.835
80 -----
81 Clock: clk
82 Clock Period: 0.010000 usec
83 Clock Toggle Rate: 200.0000 Mhz
84 Clock Static Probability: 0.5000
85
86
87
88
89 * Power Distribution Summary:
90 * Highest Average Power: CTS_ccl_a_buf_00001 (CKBD16): 0.01918
91 * Highest Leakage Power: CTS_ccl_a_buf_00005 (CKBD16): 0.0006045
92 * Total Cap: 3.70842e-12 F
93 * Total instances in design: 1365
94 * Total instances in design with no power: 0
95 * Total instances in design with no activity: 0
96 * Total Fillers and Decap: 515
97 -----
98
99

Physical Verification

DRC report:


```
drc.rpt (modified) - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/
File Edit Search Preferences Shell Macro Windows
1 d#-check_same_via_cell true # bool, default=false, user setting
2 *** Starting Verify DRC (MEM: 1411.3) ***
3
4 VERIFY DRC ..... Starting Verification
5 VERIFY DRC ..... Initializing
6 VERIFY DRC ..... Deleting Existing Violations
7 VERIFY DRC ..... Creating Sub-Areas
8 VERIFY DRC ..... Using new threading
9 VERIFY DRC ..... Sub-Area: {0.000 0.000 60.480 60.480} 1 of 4
10 VERIFY DRC ..... Sub-Area : 1 complete 0 Viols.
11 VERIFY DRC ..... Sub-Area: {60.480 0.000 120.400 60.480} 2 of 4
12 VERIFY DRC ..... Sub-Area : 2 complete 0 Viols.
13 VERIFY DRC ..... Sub-Area: {0.000 60.480 60.480 120.200} 3 of 4
14 VERIFY DRC ..... Sub-Area : 3 complete 0 Viols.
15 VERIFY DRC ..... Sub-Area: {60.480 60.480 120.400 120.200} 4 of 4
16 VERIFY DRC ..... Sub-Area : 4 complete 0 Viols.
17
18 Verification Complete : 0 Viols.
19
20 *** End Verify DRC (CPU: 0:00:00.3 ELAPSED TIME: 0.00 MEM: 0.0M) ***
21
22
```

```
Open ▾  Kernel.geom.rpt
~/PnR_Example/9.Kernel

#####
# Generated by: Cadence Innovus 21.12-s106_1
# OS: Linux x86_64(Host ID vlsi73.ee.iitb.ac.in)
# Generated on: Fri Nov 28 11:41:10 2025
# Design: Kernel
# Command: verify_drc > drc.rpt
#####

No DRC violations were found
```

Antenna report:

```
Open ▾  antenna.rpt
~/PnR_Example/9.Kernel

*** Starting Verify Antenna (MEM: 1407.4) ***

Report File: Kernel.verify_antenna.rpt
VERIFY Antenna ..... Starting Verification
VERIFY Antenna ..... Using new threading
Verification Complete: 0 Violations
*** End Verify Antenna (CPU: 0:00:00.1 ELAPSED TIME: 0.00 MEM: -10.0M) ***

***** DONE VERIFY ANTENNA *****
```

```
Open [icon] Kernel.antenna.rpt
~/PnR_Example/9.Kernel

#####
# Generated by: Cadence Innovus 21.12-s106_1
# OS: Linux x86_64(Host ID vlsl73.ee.iitb.ac.in)
# Generated on: Fri Nov 28 11:36:10 2025
# Design: Kernel
# Command: saveModel -sdf -spof -dir Kernel_hier_data
#####

No Violations Found
```

Connectivity report:

```
connectivity.rpt - /home/running_courses/EE671/EE671_24/PnR_Example/9.Kernel/
File Edit Search Preferences Shell Macro Windows
1 VERIFY_CONNECTIVITY use new engine.
2
3 ***** Start: VERIFY CONNECTIVITY *****
4 Start Time: Fri Nov 28 11:42:17 2025
5
6 Design Name: Kernel
7 Database Units: 2000
8 Design Boundary: (0.0000, 0.0000) (120.4000, 120.2000)
9 Error Limit = 1000; Warning Limit = 50
10 Check all nets
11
12 Begin Summary
13 Found no problems or warnings.
14 End Summary
15
16 End Time: Fri Nov 28 11:42:17 2025
17 Time Elapsed: 0:00:00.0
18
19 ***** End: VERIFY CONNECTIVITY *****
20 Verification Complete : 0 Viols. 0 Wrngs.
21 (CPU Time: 0:00:00.1 MEM: 0.000M)
22
23
```

```
Open [icon] Kernel.conn.rpt
~/PnR_Example/9.Kernel

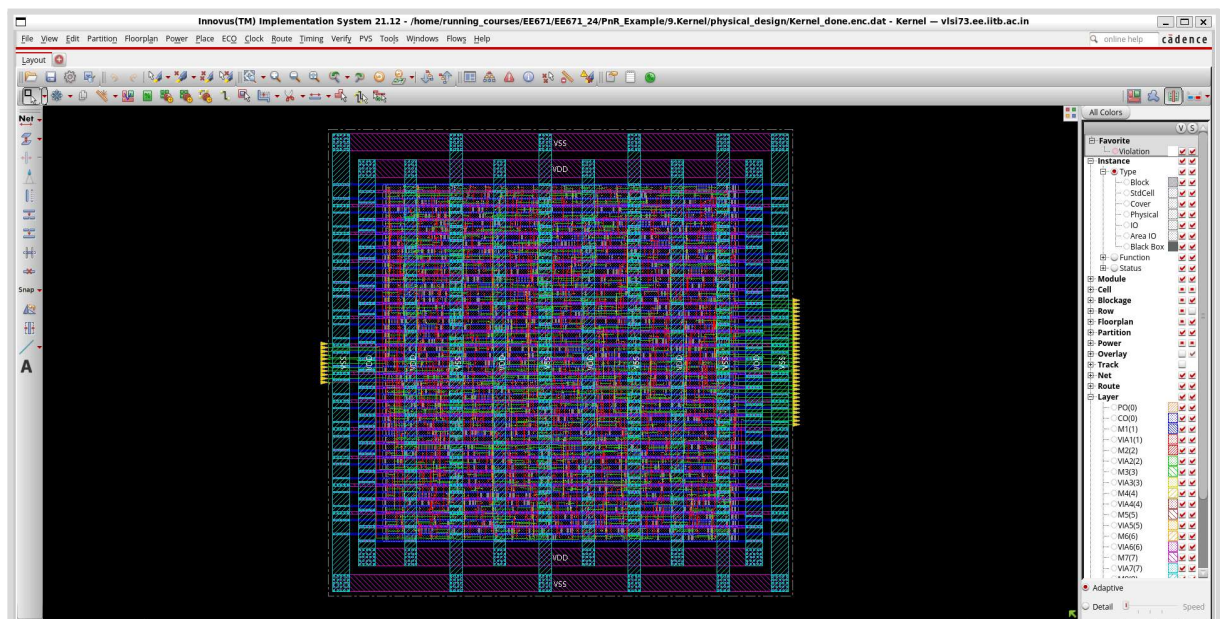
#####
# Generated by: Cadence Innovus 21.12-s106_1
# OS: Linux x86_64(Host ID vlsl73.ee.iitb.ac.in)
# Generated on: Fri Nov 28 11:42:17 2025
# Design: Kernel
# Command: verifyConnectivity > connectivity.rpt
#####
Verify Connectivity Report is created on Fri Nov 28 11:42:17 2025

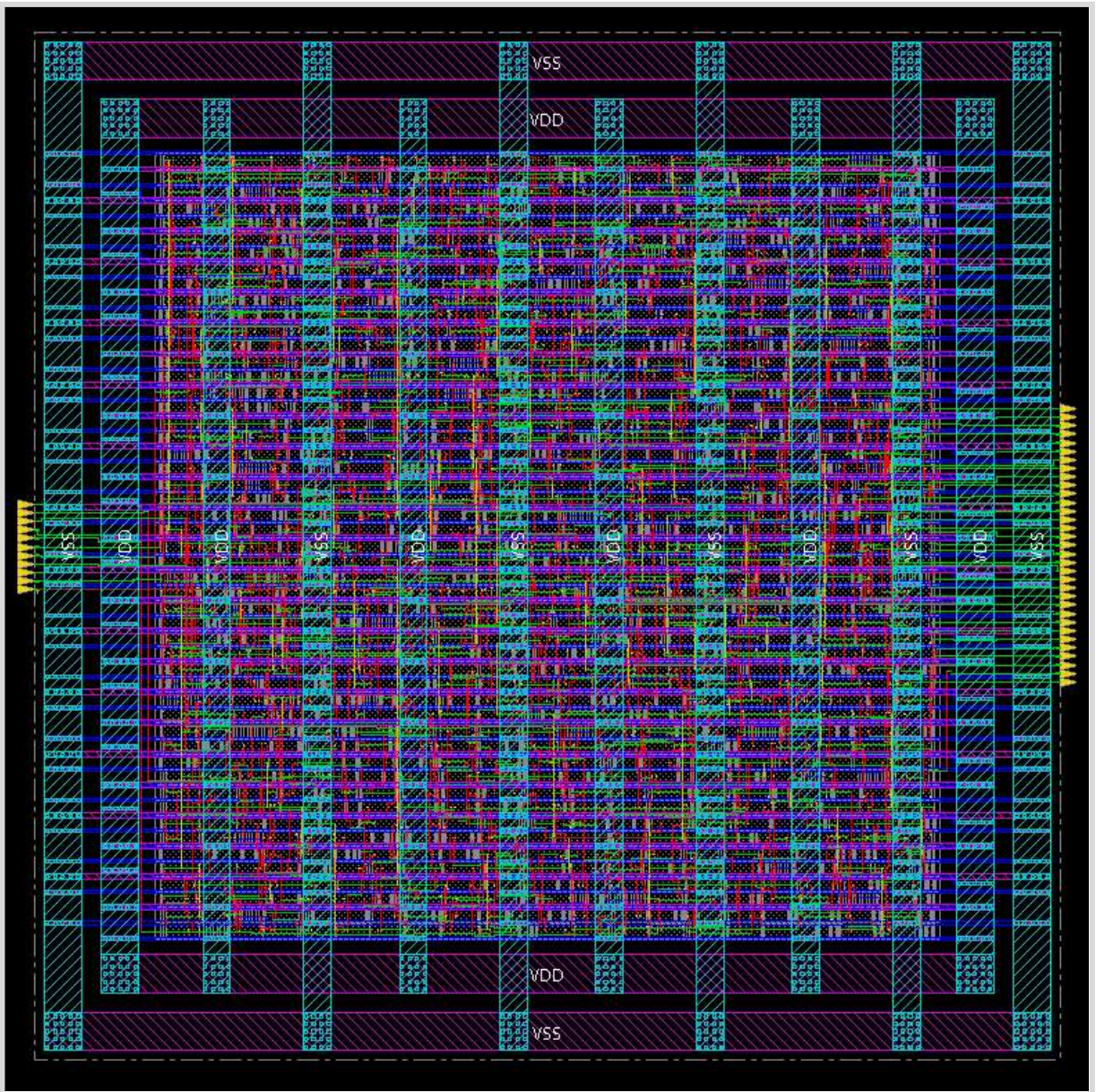
Begin Summary
Found no problems or warnings.
End Summary
```

Table containing post route timing, area, and power reports:

Clock Frequency (MHz)	100
Worst case setup slack [WNS in the report] (ns)	8.422
Worst case hold slack [WNS in the report] (ns)	0.004
Design area (μm^2)	6001.920
Power Consumption (Sequential Only) (μW)	937.4
Power Consumption (Combinational Only) (μW)	77.19
Total Power Consumption (Internal Only) (μW)	866.6225
Total Power Consumption (Switching Only) (μW)	105.6390
Total Power Consumption (Leakage Only) (μW)	221.9076
Total Power Consumption (μW)	1194.1691

Screenshot of the final Layout:





Contribution Table

Name and Roll No.	Contribution
Ankit Raj, 25M1269	Implemented the pipelined multiplier as well as did the part from verilog to synthesis of the module.
Ayush Singh, 25M1239	Implemented the part from Synthesis to physical design of the module. Log files and screenshots of the results.
Harsh Gupta, 25M1237	Implemented the complete datapath except for the multiplier block. This includes the full 32-bit Kogge Stone adder, the MAC and modified-MAC modules, the slow-clock divider, and the entire Kernel architecture.
Shubham, 25M1277	Implemented testbench for the Kernel module that includes clock generation, reset signals, pixel inputs, and waveform generation. Written report that includes description, working, waveform comparison, screenshots, and results obtained.