

EECS 151/251A ASIC Lab 3: Logic Synthesis

Prof. John Wawrzynek
TAs: Quincy Huynh, Tan Nguyen

Overview

For this lab, you will learn how to translate RTL code into a gate-level netlist in a process called synthesis. In order to successfully synthesize your design, you will need to understand how to constrain your design, learn how the tools optimize logic and estimate timing, analyze the critical path of your design, and simulate the gate-level netlist.

To begin this lab, get the project files by typing the following commands:

```
git clone /home/ff/eecs151/labs/lab3.git
cd lab3
```

You should add the following lines to the `.bashrc` file in your home folder.¹ so that every time you open a new terminal you have the paths for the tools setup properly.

```
source /home/ff/eecs151/tutorials/eecs151.bashrc
source HAMMER_HOME=/home/ff/eecs151/hammer
source ${HAMMER_HOME}/sourceme.sh
```

Type

```
which genus
```

to see if the shell prints out the path to the Cadence Genus Synthesis program (which we will be using for this lab). If it does not work, add the lines to your `.bash_profile` in your home folder as well. Try log in or open a new terminal to see if it works. The file `eecs151.bashrc` sets various environment variables in your system such as where to find the CAD programs or license servers.

Throughout the rest of the semester, we will be using **ASAP7** (Arizona State Predictive PDK), a 7nm predictive design kit. This is an educational kit developed to mimic how a 7nm technology node might behave.

Synthesis Environment

To perform synthesis, we will be using Cadence Genus. However, we will not be interfacing with Genus directly, we will rather use HAMMER (Highly Agile Masks Made Effortlessly from RTL), a

¹For more information on what `.bashrc` does, see <https://www.tldp.org/LDP/abs/html/sample-bashrc.html>.

digital back-end tool developed in Berkeley that performs most of the interfacing with ASIC design tools. HAMMER provides tool (Cadence vs. Synopsys vs. Mentor...) and technology-agnostic (TSMC x nm, Intel y nm...) synthesis and place-and-route. Such an approach highly eases reuse of modules between projects with vastly different tool and technology infrastructures. We have set up the basic HAMMER flow for your lab exercises using Makefile, but for additional reference please read the HAMMER Documentation. You might also be interested in Chipyard ASAP7 Tutorial which provides some examples of how to set up a VLSI project using HAMMER.

HAMMER needs several input files to perform its operation. These are provided in the lab structure, but you may need to modify some of them to synthesize other designs for lab reports and eventually the lab project. The first set of files are the source codes for our design that you will explore in the next section. The second set of files are some YAML files (`inst-env.yml`, `asap7.yml`, `design.yml`, `design_gl.yml`) that configure the HAMMER flow. Of these YAML files, you should only need to modify `design.yml` and `design_gl.yml` in order to configure to the synthesis and simulation for your design.

HAMMER is already setup at `/home/ff/eecs151/hammer` with all the required plugins for Cadence Synthesis (Genus) and Place-and-Route (Innovus), Synopsys Simulator (VCS), Mentor Graphics DRC and LVS (Calibre). You should not need to install it on your own home directory. **These HAMMER plugins are under NDA. They are provided to us for educational purpose. They should never be copied outside of instructional machines under any circumstances or else we are at risk of unable to get access to the tools in the future!**

Let us take a look at some parts of `design.yml` file:

```
gcd.clockPeriod: &CLK_PERIOD "1ns"
gcd.simClockPeriod : &SIM_CLK_PERIOD "CLOCK_PERIOD=1.00"
```

The first option sets the target clock speed for our design. A more stringent target (a lower clock period) will make the tool work harder and use more power consuming gates to meet the clock period. A lower target lets the tool focus on reducing area and/or power. The second option sets the clock period used during simulation. It is generally useful to separate the two as you might want to see how the circuit performs under different clock frequencies without changing the design constraints. Continuing from `design.yml`:

```
gcd.verilogSrc: &VERILOG_SRC
- "src/gcd.v"
- "src/gcd_datapath.v"
- "src/gcd_control.v"
gcd.simVerilogSrc: &SIM_VERILOG_SRC
- "<YOUR_LAB_ROOT_DIRECTORY>/src/gcd.v"
- "<YOUR_LAB_ROOT_DIRECTORY>/src/gcd_datapath.v"
- "<YOUR_LAB_ROOT_DIRECTORY>/src/gcd_control.v"
- "<YOUR_LAB_ROOT_DIRECTORY>/src/gcd_testbench.v"
```

These specify the files for synthesis and simulation. While synthesis part uses a relative pathing, simulation requires the absolute paths to the verilog files. You should replace `<YOUR_LAB_ROOT_`

DIRECTORY> part with the absolute path to this lab, including the lab3 directory. `design_gl.yml` also has a similar field which you must replace with your absolute path. Moving on, we have:

```
vlsi.inputs.clocks: [
{name: "clk", period: *CLK_PERIOD, uncertainty: "0.1ns"}
]
```

This is where we specify to HAMMER that we intend on using the `CLK_PERIOD` we defined earlier as the constraint for our design. We will see more detailed constraints in the later labs.

Understanding the example design

We have provided a circuit described in Verilog that computes the greatest common divisor (GCD) of two numbers. Unlike the FIR filter from the last lab where the testbench constantly provided stimuli, the GCD algorithm takes a variable number of cycles, so the testbench needs to know when the circuit is done to check the output. This is accomplished through a “ready/valid” handshake protocol. This protocol is very ubiquitous and a flavor of it will appear both in the class project and later on in other blocks you will encounter throughout your career. The block diagram is shown in Figure 1.

```
module gcd#( parameter W = 16 )
(
    input clk, reset,

    input [W-1:0] operands_bits_A, // Operand A
    input [W-1:0] operands_bits_B, // Operand B
    input          operands_val,   // Are operands valid?
    output         operands_rdy,   // ready to take operands

    output [W-1:0] result_bits_data, // GCD
    output         result_val,      // Is the result valid?
    input          result_rdy       // ready to take the result
);
```

On the `operands` boundary, nothing will happen until GCD is ready to receive data (`operands_rdy`). When this happens, the testbench will place data on the operands (`operands_bits_A` and `operands_bits_B`), but GCD will not start until the testbench declares that these operands are valid (`operands_val`). Then GCD will start.

The testbench needs to know that GCD is not done. This will be true as long as `result_val` is 0 (the results are not valid). Also, even if GCD is finished, it will hold the result until the testbench is prepared to receive the data (`result_rdy`). The testbench will check the data when GCD declares the results are valid by setting `result_val` to 1.

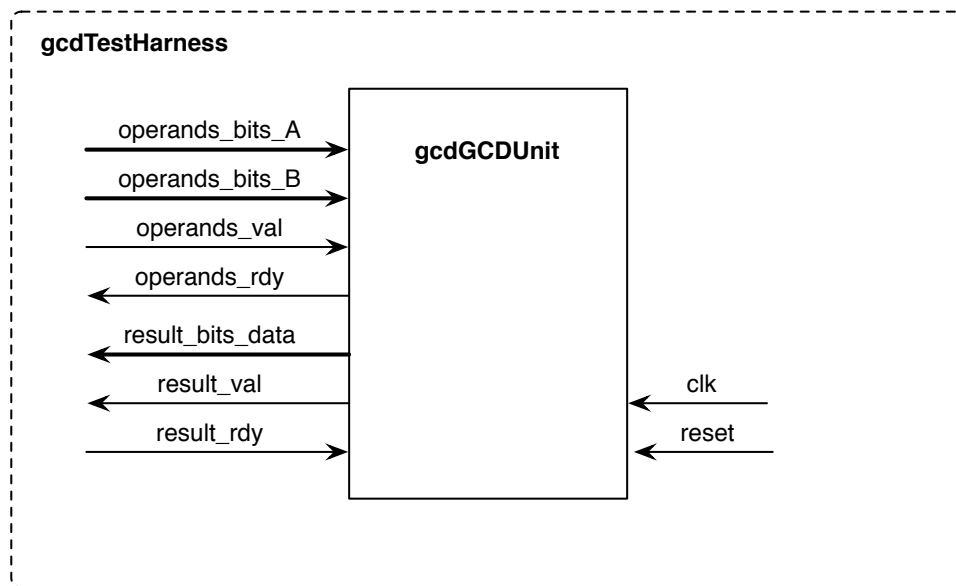


Figure 1: Block diagram for GCD Test Harness

The main contract is that if the interface declares it is ready, and the other side declares valid, the information must be transferred.

Open `src/gcd.v`. This is the top-level of GCD and just instantiates `gcd_control` and `gcd_datapath`. Separating files into control and datapath is generally a good idea. Open `src/gcd_datapath.v`. This file stores the operands, and contains the logic necessary to implement the algorithm (subtraction and comparison). Open `src/gcd_control.v`. This file contains a state machine that handles the ready-valid interface and controls the mux selects in the datapath. Open `src/gcd_testbench.v`. This file sends different operands to GCD, and checks to see if the correct GCD was found. Make sure you understand how this file works. Note that the inputs are changed on the negative edge of the clock. This will prevent hold time violations for gate-level simulation, because once a clock tree has been added, the input flops will register data at a time later than the testbench's rising edge of the clock.

Now simulate the design by running `make sim-rtl`. The waveform is located under `build/sim-rundir/`. Open the waveform in DVE (you may need to scroll down in DVE to find the testbench) and try to understand how the code works by comparing the waveforms with the Verilog code. It might help to sketch out a state machine diagram and draw the datapath.

Question 1: Understanding the algorithm

By reading the provided Verilog code and/or viewing the RTL level simulations, demonstrate that you understand the provided code:

- Draw a table with 5 columns (cycle number, value of A_reg, value of B_reg, next value of A_reg, next value of B_reg) and fill in all of the rows for the first test vector (GCD of 27 and 15)
- In `src/gcd_testbench.v`, the inputs are changed on the negative edge of the clock to prevent hold time violations. Is the output checked on the positive edge of the clock or the negative edge of the clock? Why?
- In `src/gcd_testbench.v`, what will happen if you change `result_rdy = 1;` to `result_rdy = 0;`? What state will `gcd_control.v` state machine be in?

Question 2: Testbenches

- Modify `src/gcd_testbench.v` so that intermediate steps are displayed in the format below. Include a copy of the code you wrote in your writeup (this should be approximately 3-4 lines).

```

0: [ ..... ] Test (  x ), [  x ==  x ] (decimal)
1: [ ..... ] Test (  x ), [  x ==  0 ] (decimal)
2: [ ..... ] Test (  x ), [  x ==  0 ] (decimal)
3: [ ..... ] Test (  x ), [  x ==  0 ] (decimal)
4: [ ..... ] Test (  x ), [  x ==  0 ] (decimal)
5: [ ..... ] Test (  x ), [  x ==  0 ] (decimal)
6: [ ..... ] Test (  0 ), [  3 ==  0 ] (decimal)
7: [ ..... ] Test (  0 ), [  3 ==  0 ] (decimal)
8: [ ..... ] Test (  0 ), [  3 == 27 ] (decimal)
9: [ ..... ] Test (  0 ), [  3 == 12 ] (decimal)
10: [ ..... ] Test (  0 ), [  3 == 15 ] (decimal)
11: [ ..... ] Test (  0 ), [  3 ==  3 ] (decimal)
12: [ ..... ] Test (  0 ), [  3 == 12 ] (decimal)
13: [ ..... ] Test (  0 ), [  3 ==  9 ] (decimal)
14: [ ..... ] Test (  0 ), [  3 ==  6 ] (decimal)
15: [ ..... ] Test (  0 ), [  3 ==  3 ] (decimal)
16: [ ..... ] Test (  0 ), [  3 ==  0 ] (decimal)
17: [ ..... ] Test (  0 ), [  3 ==  3 ] (decimal)
18: [ passed ] Test (  0 ), [  3 ==  3 ] (decimal)
19: [ ..... ] Test (  1 ), [  7 ==  3 ] (decimal)

```

Synthesis

Synthesis is the process of converting RTL Verilog files into technology (or platform, in the case of FPGAs) specific gate-level Verilog. These gates are different from the “and”, “or”, “xor” etc. primitives in Verilog. While the logic primitives correspond to gate-level operations, they do not have a physical representation outside of their symbol. A synthesized gate-level Verilog only contains cells with corresponding physical aspects: they have a transistor-level schematic with transistor sizes provided, a physical layout containing information necessary for fabrication, timing libraries providing performance specifications etc. Some synthesis tools also output **assign** statements that refer to pass-through interfaces, but no logic operation is performed in these assignments (not even simple inversion!).

Open the **Makefile** to see the available targets that you can run. You don't have to know all of these for now. The **Makefile** provides shorthands to various HAMMER commands for synthesis, placement-and-routing, or simulation. Read Hammer-Flow if you want to get more detail.

To start the synthesis process of the GCD module you just analyzed, the first step is to make HAMMER generate the necessary supplement Makefile (**build/hammer.d**). To do so, type the following command in the lab directory:

```
make buildfile
```

This generates a file with **make** targets specific to the constraints we have provided inside the YAML files. If you have not run **make clean** after simulating, this file should already be generated. **make buildfile** also copies and extracts a tarball of the ASAP7 PDK to your local workspace. It will take a while to finish if you run this command first time. The extracted PDK is not deleted when you do **make clean** to avoid unnecessarily rebuild the PDK. To explicitly remove it, you need to remove the build folder (and you should do it once you finish the lab to save your allocated disk space since the PDK is huge). To synthesize the GCD, use the following command:

```
make syn
```

This runs through all the steps necessary to generate the gate-level Verilog. The final lines of output you will see is a list of all the registers in the design. There should be all the bits of **A_reg_reg**, **B_reg_reg** and **state** registers.

By default, HAMMER puts the generated objects under the directory **build**. Go to **build/syn-rundir/reports**. There are five text files here that contain very useful information about the synthesized design that we just generated. Go through these files and familiarize yourself with these reports. One report of particular note is **final_time_PVT_0P63V_100C.setup.view.rpt**. The name of this file represents that it is a timing report, with the Process Voltage Temperature corner of 0.63 V and 100 degrees C, and that it contains the setup timing checks. Another important file is **build/syn-rundir/gcd.mapped.v**. This is your synthesized gate-level Verilog. Go through it to see what the RTL design has become to represent it in terms of technology-specific gates. Try to follow an input through these gates to see the path it takes until the output. While these files are rarely ever read by humans, you may sometimes find yourself going through these during the process of debugging.

Now open the **final_time_PVT_0P63V_100C.setup.view.rpt** file and look at the first block of text you see. It should look similar to this:

```
Path 1: MET (474 ps) Setup Check with Pin GCDdpath0/A_reg_reg[15]/CLK->D
View: PVT_0P63V_100C.setup_view
Group: clk
Startpoint: (R) GCDdpath0/B_reg_reg[5]/CLK
Clock: (R) clk
Endpoint: (F) GCDdpath0/A_reg_reg[15]/D
Clock: (R) clk

Capture      Launch
Clock Edge:+ 1000      0
```

```

Src Latency:++      0      0
Net Latency:++      0 (I)    0 (I)
Arrival:=    1000      0

Setup:-      25
Uncertainty:-      0
Required Time:=    975
Launch Clock:-      0
Data Path:-      501
Slack:=      474

```

#	Timing Point	Flags	Arc	Edge	Cell	Fanout	Load	Trans	Delay	Arrival	Instance
#						(fF)	(ps)	(ps)	(ps)	(ps)	Location
#											
	GCDdpath0/B_reg_reg[5]/CLK	-	-	R	(arrival)	16	-	0	-	0	(-, -)
	GCDdpath0/B_reg_reg[5]/QN	-	CLK->QN	R	ASYNC_DFFHx1_ASAP7_75t_SL	5	3.3	42	48	48	(-, -)
	GCDdpath0/g1181/Y	-	A->Y	F	INVx1_ASAP7_75t_SL	2	1.2	20	10	58	(-, -)
	GCDdpath0/g1162__8246/Y	-	A->Y	F	OR2x2_ASAP7_75t_SL	2	1.3	12	17	76	(-, -)
	GCDdpath0/g1152__6260/Y	-	A1->Y	F	A032x1_ASAP7_75t_SL	1	0.7	13	19	95	(-, -)
	GCDdpath0/g1144__2883/Y	-	C1->Y	R	A0I322xp5_ASAP7_75t_SL	1	0.7	47	19	114	(-, -)
	GCDdpath0/g1138__5115/Y	-	B2->Y	F	A0I221xp5_ASAP7_75t_SL	1	0.7	37	14	128	(-, -)
	GCDdpath0/g1137__1881/Y	-	A2->Y	R	O2A101Ixp33_ASAP7_75t_SL	3	2.2	72	36	164	(-, -)
	GCDctrl0/g446__5526/Y	-	B->Y	F	NAND2xp5_ASAP7_75t_SL	2	1.3	36	17	182	(-, -)
	GCDctrl0/g444/Y	-	A->Y	R	INVx1_ASAP7_75t_SL	18	10.0	102	52	234	(-, -)
	GCDdpath0/g1265/Y	-	A->Y	F	INVx1_ASAP7_75t_L	17	9.4	91	63	297	(-, -)
	GCDdpath0/g1232__9945/Y	-	B->Y	R	NOR2xp33_ASAP7_75t_L	16	9.0	304	154	451	(-, -)
	GCDdpath0/g1193__6417/Y	-	C1->Y	F	A0I222xp33_ASAP7_75t_SL	1	0.7	124	51	501	(-, -)
	GCDdpath0/A_reg_reg[15]/D	-	-	F	ASYNC_DFFHx1_ASAP7_75t_SL	1	-	-	0	501	(-, -)
#											

This is one of the most common ways to assess the critical paths in your circuit. The setup timing report lists the timing checks with least “slack” (i.e. extra delay the signal can have before a setup violation occurs) to most. So the top block is generally the critical path in these kind of reports. Each row represents a timing path from a gate to the next, the whole block being the timing arc between two flip-flops (or in some cases between latches). The MET at the top of the block indicates that the timing requirements have been met and there is no violation. If there was, this indicator would have read VIOLATED. Since our critical path meets the timing requirements with a 474 ps of slack, this means we can run this synthesized design with a period equal to clock period (1000 ps) minus the critical path slack (474 ps), which is 526 ps.

Question 3: Reporting Questions

- Which report would you look at to find the total number of each different standard cell that the design contains?
- Which report contains area breakdown by modules in the design?
- What is the cell used for `A_reg_reg[7]`? How much leakage power does this contribute? How did you find this?

Question 4: Synthesis Questions

- Looking at the total number of sequential cells synthesized and the number of `reg` definitions in the Verilog files, are they consistent? If not, why?
- Modify the clock period in the `design.yml` file to make the design go faster. What is the highest clock frequency this design can operate at in this technology?

Synthesis: Step-by-step

While for the remainder of the semester we will be roughly following the above section's flow, it is useful as a digital IC design engineer to know what is going on during the process. In this section, we will look at the steps HAMMER takes to get from RTL Verilog to all the outputs we saw in the last section.

First, type `make clean` to clean the environment of previous build's files. Then, use `make buildfile` to generate the supplementary Makefile as before. Now, we will modify the `make syn` command to only run the steps we want. Go through the following commands in the given order:

```
make redo-syn HAMMER_REDO_ARGS="--only_step init_environment"
```

HAMMER flow will exit with an error. This is expected, as HAMMER looks for the final output files to gauge its success. We have not yet generated the gate-level Verilog, so we know beforehand that every step except the last one is going to end with an error. In this step, HAMMER invokes Genus to read the technology libraries and the RTL Verilog files, as well as the constraints we provided in the `design.yml` file.

```
make redo-syn HAMMER_REDO_ARGS="--only_step syn_generic"
```

This step is the **generic synthesis** step. In this step, Genus converts our RTL Verilog files read in the previous step to an intermediate format, using technology-independent generic gates. These gates are purely for gate-level functional representation of the RTL we have coded, and are going to be used as an input to the next step. This step also performs logical optimizations on our design to eliminate any redundant/unused operations.

```
make redo-syn HAMMER_REDO_ARGS="--only_step syn_map"
```

This step is the **mapping** step. Genus takes its own generic gate-level output and converts it to our ASAP7-specific gates. This step further optimizes the design given the gates in our technology. That being said, this step can also increase the number of gates from the previous step as not all gates in the generic gate-level Verilog may be available for our use and they may need to be constructed using several, simpler gates.

```
make redo-syn HAMMER_REDO_ARGS="--only_step write_regs"
```

This step is purely for the benefit of the designer. For some designs, we may need to have a list of all the registers in our design. We will not use this feature in this lab, but this step still needs to be run in order for HAMMER to proceed correctly.

```
make redo-syn HAMMER_REDO_ARGS="--only_step generate_reports"
```


The reports we have seen in the previous section are generated during this step.

```
make redo-syn HAMMER_REDO_ARGS="--only_step write_outputs"
```

This step writes the outputs of the synthesis flow. This includes the gate-level .v file we looked at earlier in the lab. Other outputs include the design constraints (such as clock frequencies, output loads etc., in .sdc format) and delays between cells (in .sdf format).

Post-Synthesis Simulation

From the root folder, type the following commands:

```
make sim-gl-syn
```

This will run a post-synthesis simulation, but does not use annotated delays from the sdf file. The reason that we do this is because Genus does not create a clock tree, so you can easily have a design that contains hold time violations in it that will be fixed during place and route. The example that we used in the previous lab had a fake clock tree added to it to demonstrate part of this, but we will discuss post place and route simulations in future labs. For now, simply ensure that the design still simulates properly (passes the testbench).

Build Your Divider

Now that you understand how to use the tools to synthesize and simulate the GCD implementation. In this section, you will build a parameterized divider of unsigned integers. Some initial code has been provided to you to get started. To keep the control logic simple, the divider module uses input signal **start** to begin the computation at the next clock cycle, and asserts output signal **done** to HIGH when the division result is valid. The input **dividend** and **divisor** should be registered when **start** is HIGH. You are not required to handle corner cases such as dividing by 0. You are free to modify the skeleton code to adopt ready/valid instead, but it is not required. You are required to use the register library `/home/ff/eecs151/verilog_lib/EECS151.v` to implement any sequential circuits/registers in your design. **Please do not write any sequential always blocks or non-blocking statements in your code.** We strictly adopt the "no register inference" policy in this semester (refer to slide 18, Lecture 4). Note that this only applies to your design files. It is completely okay to use sequential always blocks or non-blocking assignments in your testbench code.

It is suggested that you implement the divide algorithm described here. Use the **Divide Algorithm Version 2** (slide 9).

A simple testbench is also provided to you. You may want to change it to add more test vectors, or test your divider with different bitwidths. You need to change the file `design.yml` to use your divider instead of the GCD module when testing.

Question 5: HAMMER your divider

1. Push your 4-bit divider design through the tools, and determine its critical path, cell area, and maximum operating frequency from the reports. You might need to rerun synthesis multiple times to determine the maximum achievable frequency.
2. Change the bitwidth of your divider to 32-bit, what is the critical path, area, and maximum operating frequency now?
3. Submit your divider code and testbench to the report. Copy-paste or screenshot is fine.

Acknowledgments

This lab is the result of the work of many EECS151/251 GSIs over the years including:

Written By:

- Nathan Narevsky (2014, 2017)
- Brian Zimmer (2014)
- Cem Yalcin (2019)

Modified By:

- John Wright (2015,2016)
- Ali Moin (2017)
- Arya Reais-Parsi (2019)
- Tan Nguyen (2020)