

A Proposed Implementation of a 16 Bit ALU

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High Level Description:

Our decided implementation of the bit slice for this 8 bit ALU attempted to target minimizing the energy delay product while keeping the overall design as intuitive and readable as possible. Our decided upon implementation was a reasonably modular slice comprised of a combination of simpler gates with varying numbers of inputs. Our solution to minimizing the energy product delay of the whole slice was to limit the number of transistors used in the circuit. However, in some cases extra transistors were added simply to either:

(a) Keep the design more readable / maintainable.

or

(b) Allow a particular component of the circuit to be self-restoring.

These tradeoffs were determined as acceptable since they would simplify some of the development process moving forward and would ensure that we did not experience any unexpected signal degradation.

Using this approach, we began constructing some basic gates at the transistor level. The most basic gates constructed were the following:

- Inverter
- 2-input NAND
- 3-input NAND
- 2-input NOR
- 3-input XOR

- Transmission Gate
- 2-input MUX
- 8-input MUX
- 2-output DEMUX

All other components of the circuit were more or less assembled from these basic building blocks. These included:

- 2-input AND
- 3-input AND
- 2-input OR
- Logical Shift (left or right)
- Adder

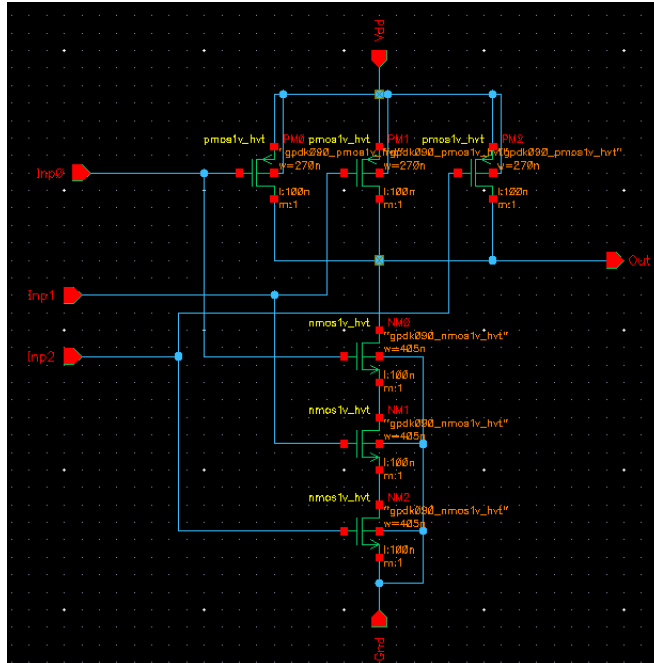
Finally, using these higher level building blocks, we constructed the "Master" high level schematic to serve as our control for the overall slice. Using our master schematic as the control and the components as the actual operations of the ALU, we constructed our overall single bit slice.

More Detailed Breakdowns:

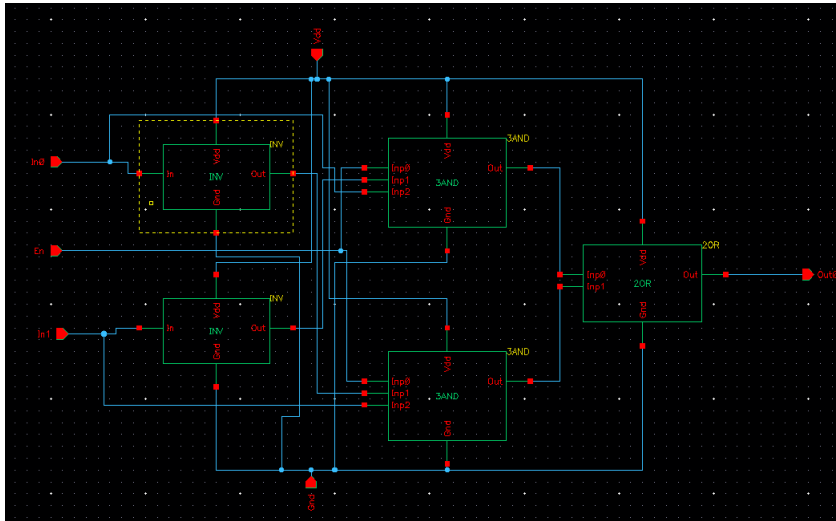
OR-NOR-AND etc. Implementation and Uses:

Each of these gates was constructed using a static CMOS layout, with the PMOS pull-up network being complementary to the NMOS pull-down network. Each gate was driven by its own voltage supply and was connected to ground to ensure that it could drive itself and not be dependent on the input. Some of these gates were used as final outputs of the ALU, while others were used to build more complex modules or serve as control blocks. The transistors were sized such that both the pull-up and the pull-down network both resulted in an ultimate unity resistance, using a base unit of 3λ . For reference, see some samples below:

3-input and:



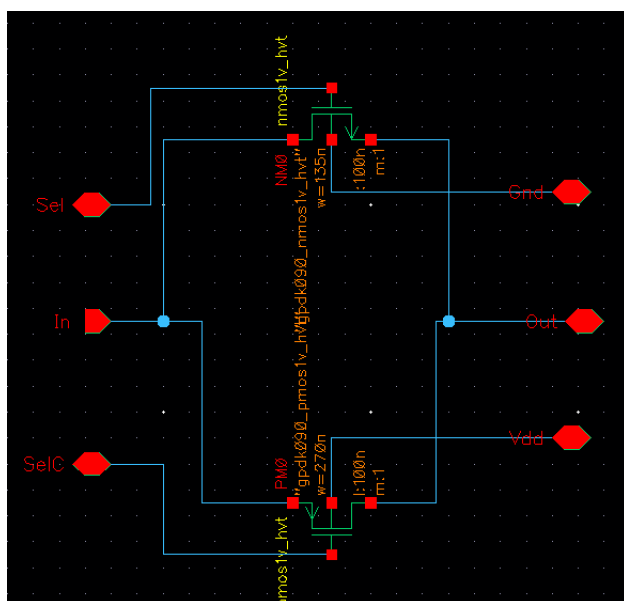
3-input xor:



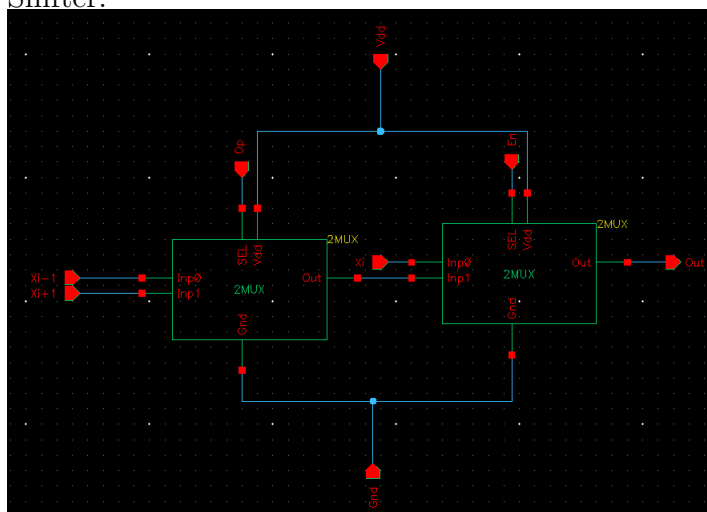
MUX / DEMUX Implementation and Uses:

The primary building blocks for each of these gates were transmission gates, with each T-Gate having a 3λ NMOS and a 6λ PMOS. These gates primarily served as control logic for the circuit (our master schematic heavily relies on DEMUX gates), allowing us to handle multiple input modules and granting us the ability to selectively activate only certain portions of the ALU during any particular OpCode in order to minimize power consumption. They also served very crucial roles in allowing us to compress the left and right shift modules into one by cleverly mapping the input and easily implement the clear operation. The implementation of these gates are pictured below:

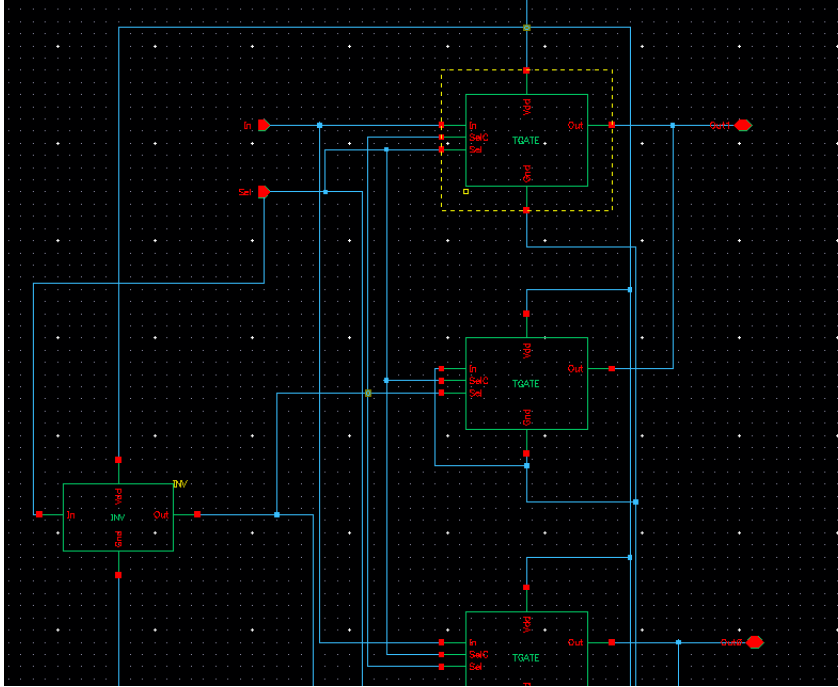
Transmission gate:



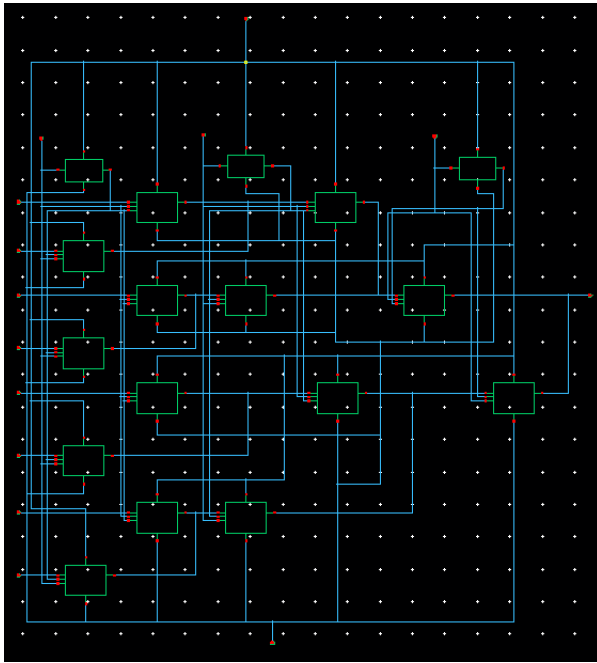
Shifter:



Partial Demux:

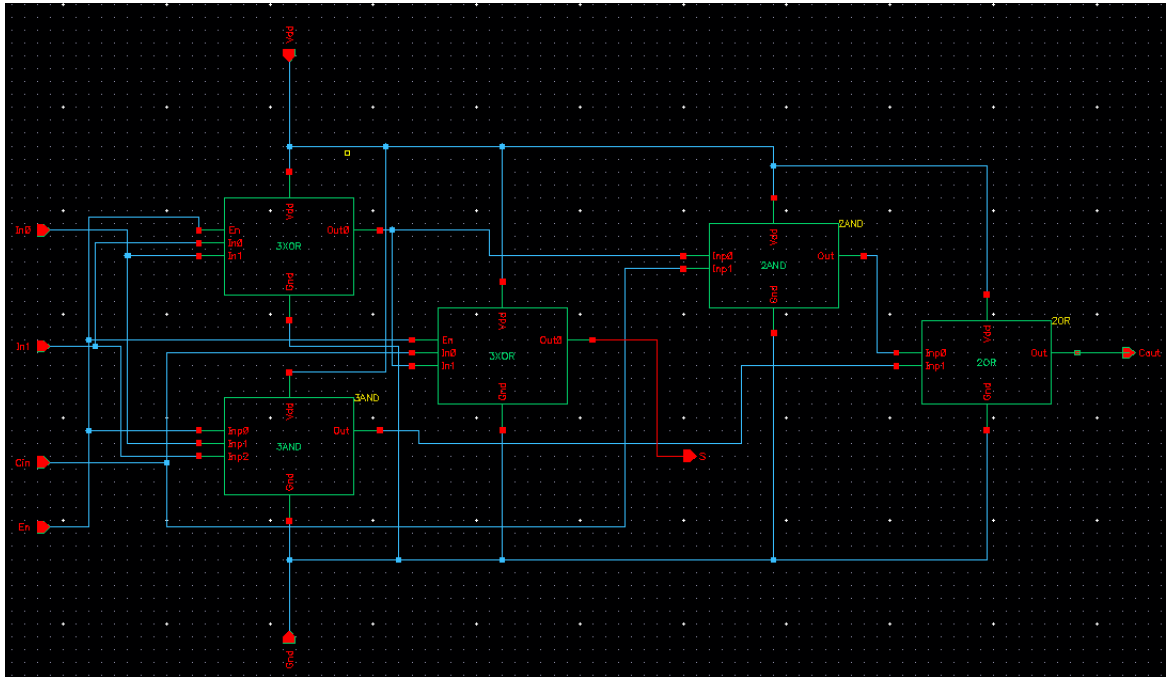


A final large 8-input MUX was then used to serve as the final channel to the ultimate output bit for the slice. Though each OpCode is 4 bits in length, we managed to come up with an interesting mapping such that only the 3 least significant bits are used:



Adder Implementation:

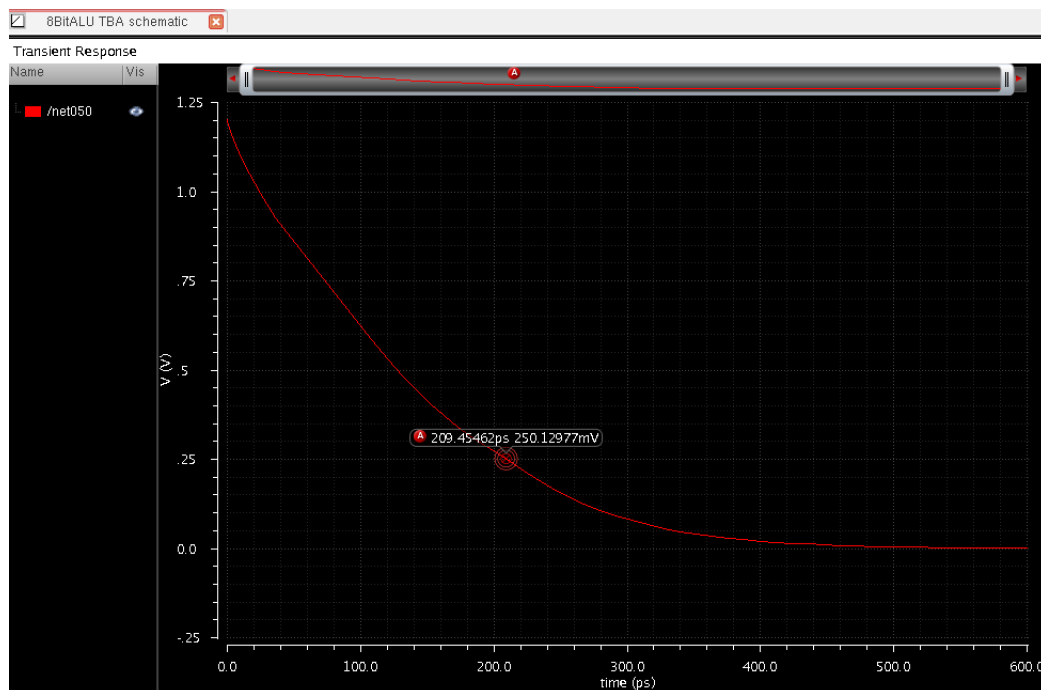
We chose to go with a Carry Look-Ahead adder implementation using a combination of AND, OR, and XOR gates, as shown below:



The Look-Ahead implementation would allow for the parallel computation of the Carry-Out and Sum quantities, which would allow us to quickly send the carry-out number on the look-ahead bus for other bit slices to absorb. In this regard, we would be significantly reducing the delay of the adder module and a reasonable amount of power consumption as well. This minimization is further supported by the fact that the adder does not even activate unless the enable bit is activated (controlled via a combination of DEMUX gates). Future iterations of the project may include changing this implementation, but for now the attempt seemed good enough to suffice.

Ending Remarks:

All components were tested individually for correct functionality before being incorporated into other blocks of the circuit.



This demonstrates the delay from the Bitwise AND instruction in the ALU. While not the worst delay path in the ALU, it does a reasonable approximation of the work that must be done, since it travels along the farthest path (besides adder instructions). The propagation delay here is about 209 ps.

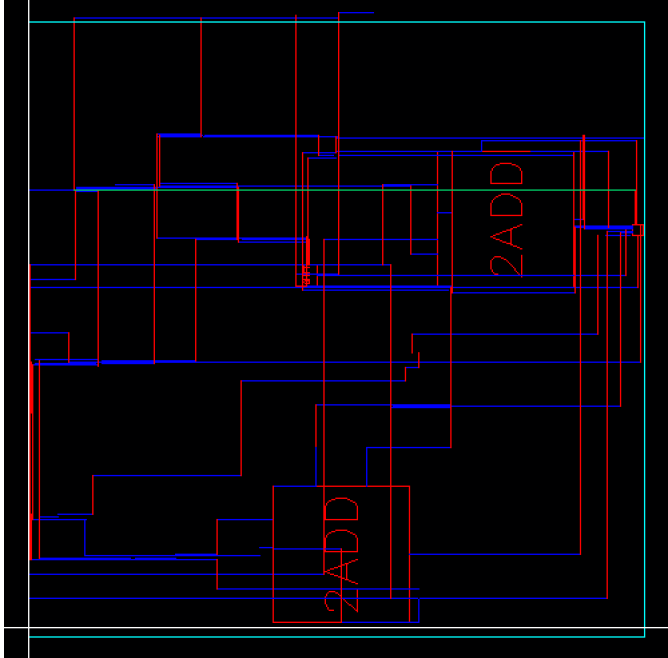
After trying a variety of OpCodes, we found that the slice worked as far as functionality is concerned. For this stage of the project, this was a reasonable testament of our progress and hard work.

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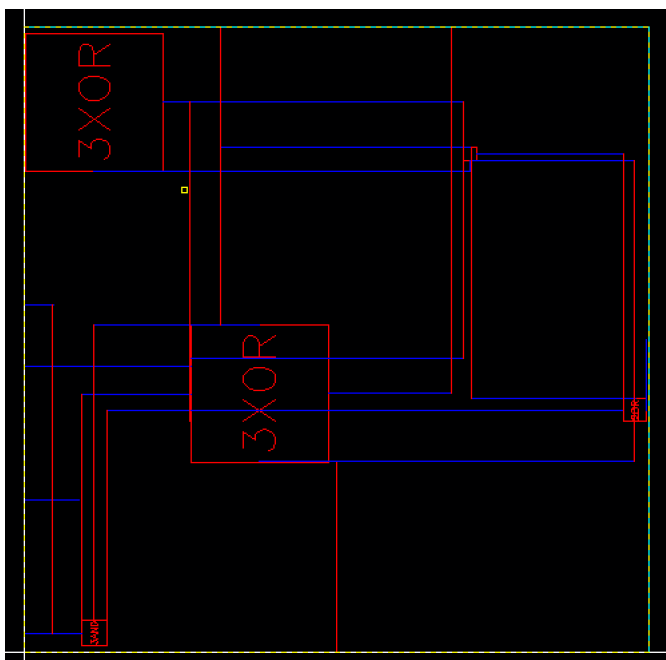
Layouts

The layouts werw a semi-complicated beast. Once we got the hang of creating the module layouts and have them be in the larger circuits, the process got easier. However, every time an LVS failed somewhere lower down, each higher circuit needed to be redone to accomadate for said changes.

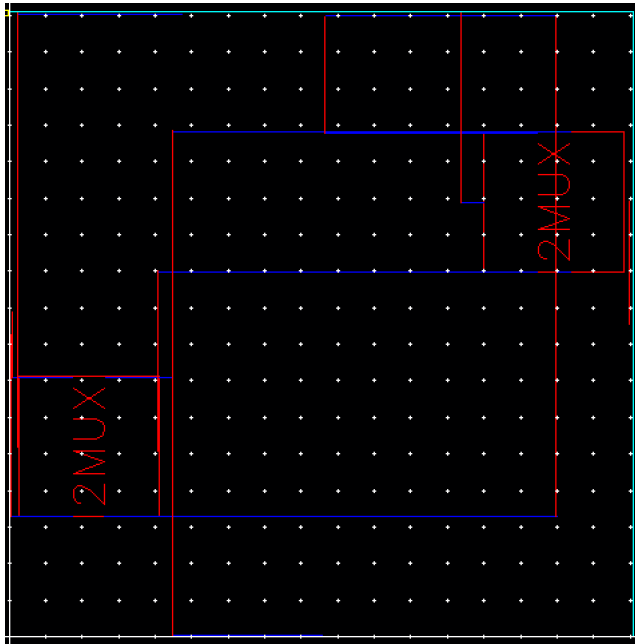
The master layout:



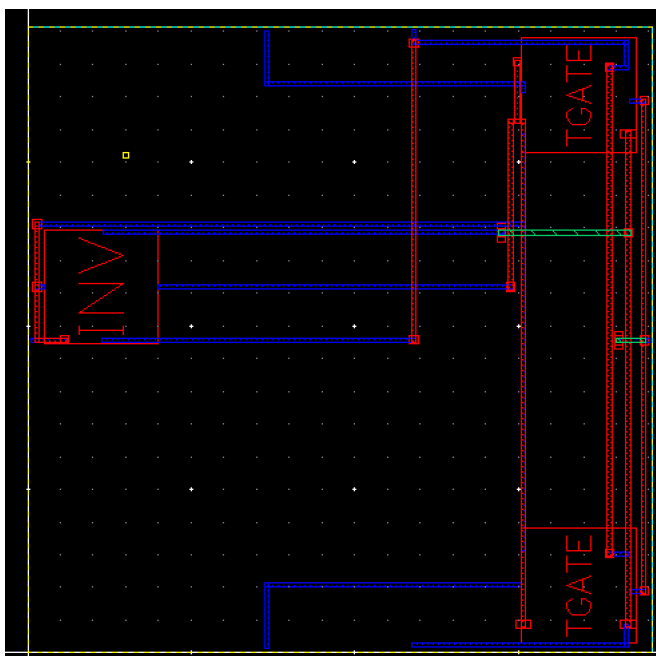
As you can see, the adder is easily the largest module in the layout.



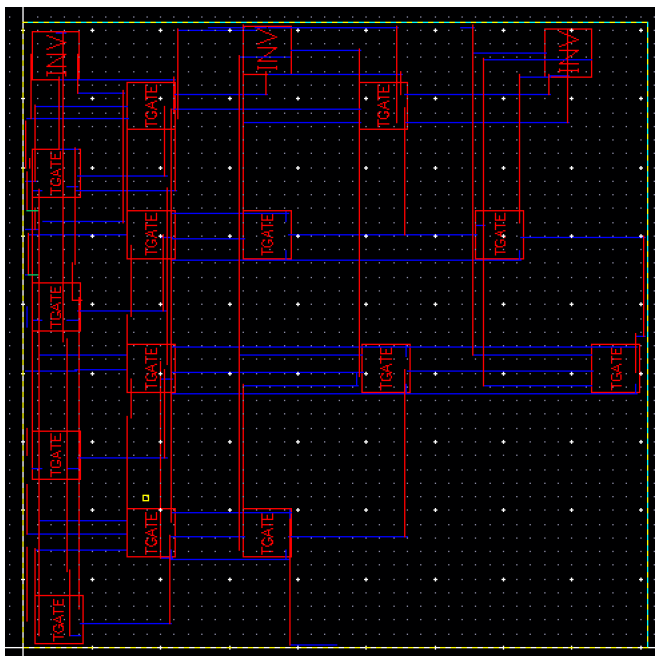
Which, in turn, has XOR's and AND's. Obviously, the XOR is bigger than the AND.



The shifter, made of 2MUX's is relatively straightforward when moving from schematic to layout.



And the mux has 2TGATE's and an INVERTER. Simple, straightforward compared to the master.



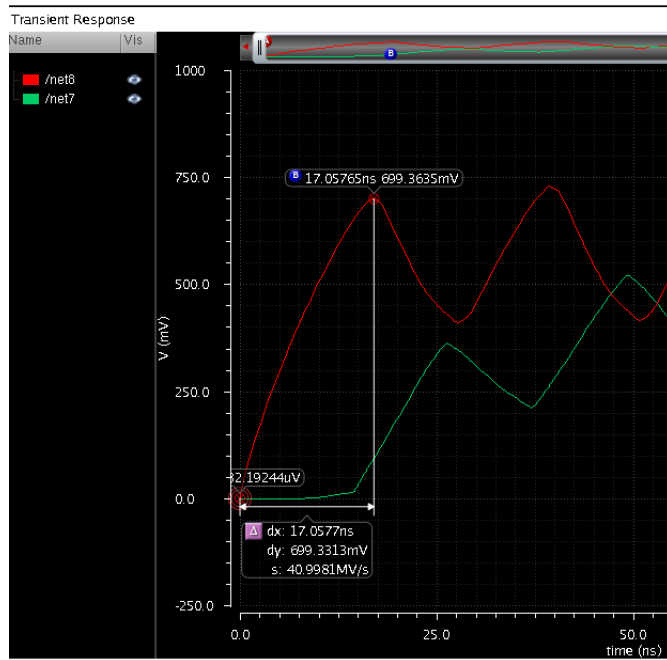
The 8 mux wasn't straightforward, however. But its layout was repetitive, which in its very nature made mistakes easier to catch.

All in all, the only headache came when, for no reason, the automatic routing would simply not the Vdd and Gnd connections, or wire the body of the transistors to the wrong placed.

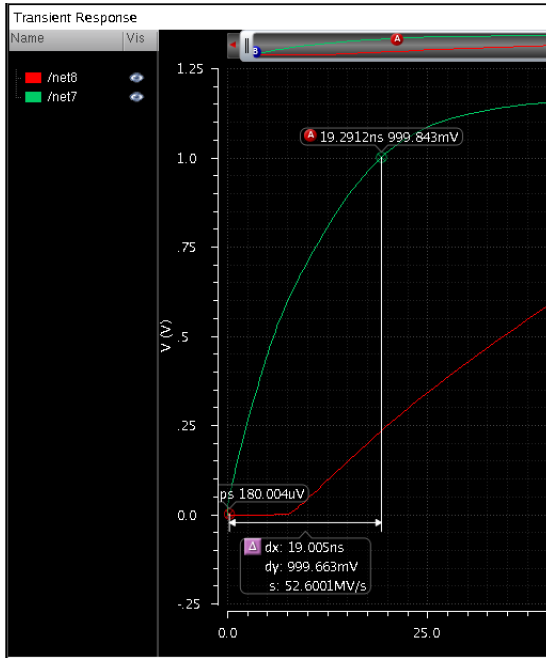
A Look at the Adder Delay

For the adder, as mentioned previously we used the carry-lookahead methodology to implement it. From there, we took two measurements: one of the propagation delay on the output, and the other on the propagation delay of the carry-out. The following graphics demonstrate the delays:

Delay of sum on the adder:



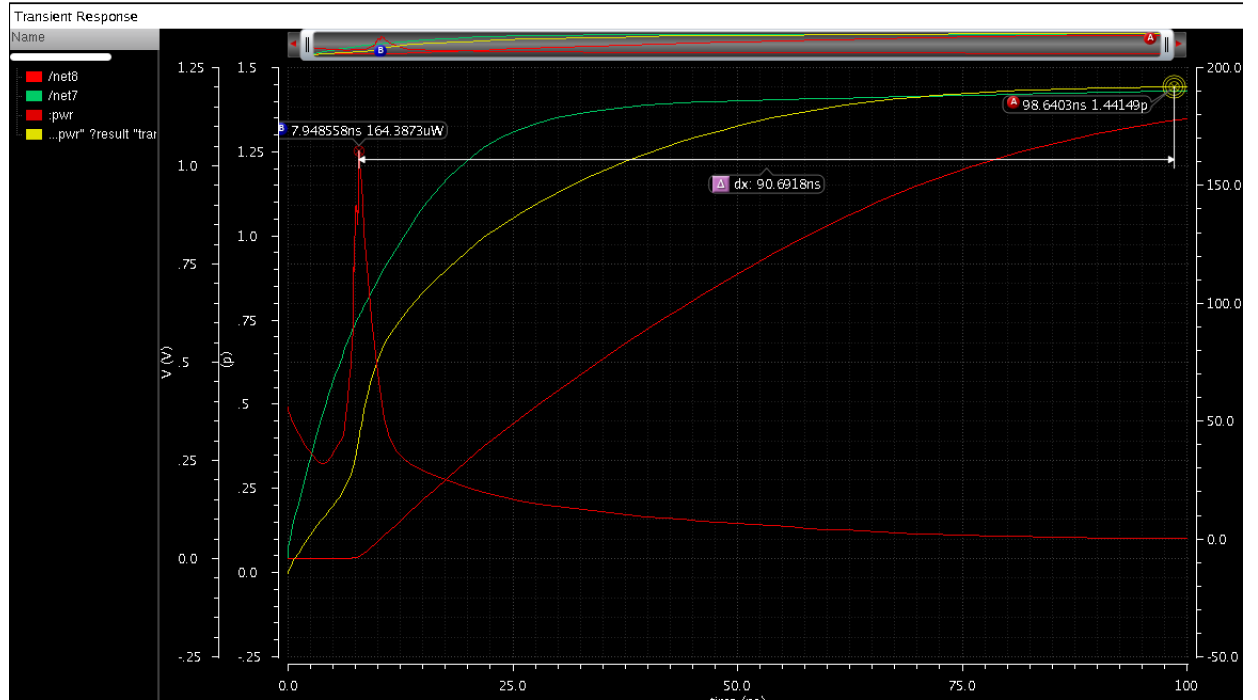
Delay of cout on the adder:



As the graphs portray, the sum takes about 17.057 ns and the cout takes about 19.29 ns. We can set the high voltage cutoff to be slightly lower to about 0.9 V to bring that number down to roughly 17.042 ns. This number is a bit higher than we expected. We attempted fix that by doing better transistors sizing to pass the constants necessary for the Cout to come faster; however, due to timing constraints and lack of access to Cadence during critical times, we were unable to properly implement and more importantly measure the delay generated by doing so. Currently, they are all of uniform size (PMOS width = 2* NMOS width), which of course is not ideal and was planned to be fixed once we learned about benefits non-uniform or unity-driven sizing. But once again, due timing constraints and the poor reliability of the Cadence software, this is the best we have in our current version. Please understand and know that we genuinely knew this would have reduced delay by several nanoseconds. There is, however, the observation that this is the time it takes to **generate** a Cout rather than propagate, and thus the total delay through the whole circuit will be much, much less than 16 times this value.

Energy Consumption

The dynamic energy consumption is a factor of the amount of switching done by the transistors due the work being done. Using the Calculator in Cadence, the graphic below demonstrates that energy consumption (and power, for that matter).



The peak power output was about $164 \mu W$, and the dynamic energy consumption is about $1.44 pJ$. This is representative of a majority of the paths in our circuit. If anything, only the subtract instruction will incur a slightly larger energy consumption. Other than that, the energy is upper-bounded by this, since use of the adder in the ALU is the most expensive procedure.

Energy Delay Product Computation

Our approach to compute the worst case energy product delay for the full ALU add operation was to first compute the product for our bit slice layout

and then extend that number to accommodate for 16 bits. As we computed the dynamic energy consumption of the add operation turned out to be 1.44 pJ, while the delay of the Cout of the add operation was roughly about 17.042 ns (generate). We believe that the Cout operation will be the limiting factor in the scenario of the worst case delay since all generates, in the worst case, will be computed as 0 while all propagates will be computed as 1. In other words, each bit slice will need to pass the Cin to the Cout and while factoring in the Cin for the sum operation. The sum operations, however, have a lot of time to compute and are thus not the critical path. The propagate signal is a 3 bit XOR operation and takes roughly 614 ps. This computation is done in parallel for all 16 bits starting at time $t = 0$, which is less time than it takes to generate the first Cout on bit slice 0. The propagation delay is thus the delay through a 2 input AND and a 2 input OR, which is roughly 209 ps and 250 ps respectively. Therefore the delay from Cin to Cout is $209 + 250 \text{ ps} = 459 \text{ ps}$. Additionally, the cost of incorporating Cin into the sum is a roughly 5.14 ns delay (this matters for the most significant bit). Therefore, the total delay in the worst case situation for the 16 bit add operation is:

$$17.042ns + 14 * 459ps + 5.14ns = 28.608ns$$

The energy consumption is roughly the same per bit slice (1.44 pJ). The total energy consumption is thus:

$$16 * 1.44pJ = 23.04pJ$$

Therefore, the worst case energy product delay is:

$$28.608 * 23.04 = \boxed{659.128}$$

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Extending to Verilog

For the Verilog bit slice implementation as well as its corresponding test-bench, please observe the attached files. All delays from the layout design were incorporated directly from the layout design into the module implementation to ensure an "as-accurate-as-possible" simulation.

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ALU Implementation

The full 16 bit ALU was implemented by wiring 16 different bit slice instantiations following a reasonably simple naming convention. All dangling input and output wires from the bit slice implementation were attached to their appropriate wires in full ALU Verilog instantiation as well, and all operations work as expected. To view the implementation, please see the attached Verilog file.

Datapath Implementation

The full datapath was implemented using the register instances specified in the project guidelines and contains an instantiation of the 16 bit ALU. The MUX gates are simulated via a series of input signals and assignment / if statements to ensure that only the proper input is written to the proper register or sent to the ALU. The OpCodes are collected and translated into the appropriate datapath signals by a module called the Control Block; the datapath itself only follows the signals it is provided and is not responsible for any kind of serialization or deserialization. It uses the same clock as the Control Block as well. The OpCode input is merely meant to be passed in to the ALU if necessary. For the full module and its corresponding testbench, please see the attached Verilog files.

Remaining Components

Structure:

The layout is as follows, from top-bottom

1. main.v OR demonstrate.v (explained later)
2. control.v
3. datapath.v
4. ALU.v
5. bitslice.v

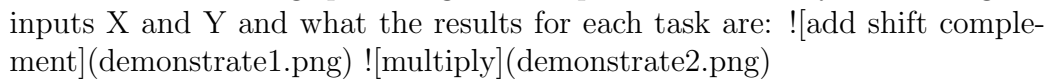
6. adder.v/subtractor.v

Main Module:

****Both main.v and demonstrate.v have testbenches, tbMain.v and tbDemonstrate.v****

For testing purposes, *main.v* should be considered the "main" module. It is left empty (other than connected to our controller), and its testbench merely shows how to multiply two numbers together.

****HOWEVER****

demonstrate.v has a nicer way of demonstrating the correctness of the routines. It has built in tasks for add, multiply, right shift, and two's complement. Those demonstrate basically all the required procedures for this protocol. *All the testbench does is provide you a place to input an X and Y*. For any new X and Y, demonstrate.v reruns all these tasks and outputs the monitor for them as well as the final values in a very human readable form. Here is an image providing an example. You can always see the original inputs X and Y and what the results for each task are: 

****We highly suggest you use demonstrate.v and tbDemonstrate.v first to get a feel for how easy it should be to test that our main functions are working**.** Only after seeing it run a couple of times, and after having read the section below on how to use our opcodes, should you add stuff to tbMain.v for testing the main function

OPCODE BREAKDOWN:

Passed to the control block is a 12 bit opcode. There are 8 prefix bits and 4 ALU bits. The meaning of each are as follows

M1 M2 M3 M4 M5 M5 RegOut RegOut ALU ALU ALU ALU

M1 through M5 are the selector bits for each of the 5 MUX's (M5 has two bits for 3 inputs)

RegOut indicates which register (X,Y,Z which correspond to Aout,Bout,Cout in the diagram provided with the spec) to write to (2 bits are needed for 3 outputs)

ALU indicates the 4 bit opcode for the ALU

If the last four bits are an actual operation in the ALU, then the following decoding is used:

1. Observe M3 to choose which register, A or B, to read from.
2. Observe M4 to choose to either read from reg C or from output registers.
3. If M4 is reading from feedback, observe M5 to see which output register to read from.
4. Compute ALU function using ALU opcode, and observe RegOut to see which register to store the data in.

If the last four bits are a datapath operation (Load into A/B/C) then the following decoding is used:

1. Observe opcode. If it is Load A/B, observe M1 to either read X or read from feedback.
2. If M1 indicates to observe from feedback, observe M5 to see which output register to read from.
3. If opcode indicates to Load C, observe M2 to either read Y or read from feedback.
4. If M2 indicates to observe from feedback, observe M5 to see which output register to read from.

For example, if we wanted to first store something from Z into B, the following opcode would handle it (spaced out for convenience):

1 0 0 0 1 0 0 0 1 0 1 1 M1 M2 M3 M4 M5 M5 RegOut RegOut ALU
 ALU ALU ALU

This means that mux-1 choses to receive input from feedback. Mux 2-4 we don't care about since the operation doesn't involve them. Mux-5 with 10 means to read from Z. RegOut is 0 0 because we are not writing to any output register. Finally, ALU code 1011 means load into B.

Then, if we want to calculate the bitwise and B with what is currently in Y and store it in Z, the following opcode would handle it:

```
0 0 1 1 0 1 1 0 0 1 1 0 M1 M2 M3 M4 M5 M5 RegOut RegOut ALU
ALU ALU ALU
```

Mux-1,2 are don't cares. Mux-3 being 1 means to read from register B, and Mux-4 being 1 means to read from feedback (from output registers). Mux-5 being 01 means to read from output register Y, and RegOut of 10 means to write to register Z. ALU opcode 0110 indicates to perform the bitwise & of the two operators.

That's all there is to it. This same documentation (minus the examples) is in control.v

Final Notes:

1. For the last few Verilog modules, they were developed locally on a Mac using [Icarus Verilog](<http://iverilog.icarus.com/>). It, for all intensive purposes, should work in ModelSim as well. However, if it doesn't work, please contact Joraaver Chahal, and don't immediately deduct points please. The connection was too slow and becoming a realy pain to work on ModelSim via ssh, and I took the initiative to find a local development environment dad the did the trick. Frankly, I think Icarus Verilog does a great, minimalist job for compiling and testing Verilog tools. It dropped support of a synthesis tool, but other open source synthesis tools exist for FPGA's, so that's not a problem.
2. I won't say this project was fun. It was a huge time commitment that I felt could have been made more manageable. However, as I always, we did learn alot about the full process in terms of laying out the ALU's bitslice and incorporating the extracted delays into the simulation, so there's always that.