ND*nano* Summer Undergraduate Research
2019 Project Summary

1. Student name & home university:
Joe Carthy
University College Dublin

2. ND faculty name & department:
Prof Greg Snider
Electrical Engineering

3. Summer project title:
Energy Recovery for Low Energy Computation

4. Briefly describe new skills you acquired during your summer research:
Gained an in-depth knowledge of adiabatic circuits
Developed my ability using System Verilog to verify the operation of circuits
Learned how to design physical layouts of circuits with Cadence Virtuoso
Gained experience with lab equipment, including a semiconductor analyzer, DAAS, and assembling computers

5. Briefly share a practical application/end use of your research:
Adiabatic circuits consume less energy than conventional electronics and potentially have widespread applications across many electronic devices. Near term applications would include aiding the testing of quantum computers which require extremely low temperatures to operate. The lower heat output of adiabatic circuits could be useful in helping to retain these low operating temperatures

6. 50- to 75-word abstract of your project:
The project I worked on over the summer involved research into adiabatic circuits. Initially, it involved developing a method for simulating adiabatic circuits, that had been designed in Cadence, using SystemVerilog. Later stages involved designing adiabatic circuits in Cadence that contained temperature measurement devices, with the purpose of detecting the energy dissipated by these circuits.

7. References for papers, posters, or presentations of your research:
1. C.O. Campos-Aguillon, R. Celis-Cordova, I.K. Hanninen, C.S. Lent, A. O. Orlov, G. L. Snider, A Mini-MIPS Microprocessor for Adiabatic Computing
2. C. S. Lent, A. O. Orlov, W. Porod, G. L. Snider, Energy Limits in Computation, A Review of Landauer's Principle, Theory, and Experiments

My project involved the design and testing of adiabatic circuits. An adiabatic circuit operates using reversible logic in order to reduce the amount of heat that it dissipates. This can reduce the amount of heat dissipated due to Landauer's Principle, which states that there is no lower limit to the heat dissipated when performing reversible operations.

Adiabatic circuits can be tricky to verify because the design process is different to conventional circuits. In conventional circuit design, you write code that describes your circuit in a HDL, or hardware description language. This code is easy to test, and it is relatively simple to verify that a circuit will operate correctly. Then the tested physical layout that will be fabricated can be easily generated from this code using automated tools. These automated tools do not exist for adiabatic circuits, making the creation and testing process more complex.

In order to create adiabatic circuits, it is necessary to design the layout, that would normally be auto-generated, by hand. This is a tedious process as a simple circuit could have thousands of components that now must all be designed by hand. Once the layout is complete, testing it directly is also tedious. Tests are awkward to set up and take a long time to run compared to the tests that are run on conventional circuits designed with a HDL. The first task was to design a method for testing the layout using a HDL, SystemVerilog.

The first step in this process was to extract a "switch-level" design written in SystemVerilog. The "switch-level" design represents the circuit as a list of many switches, all interconnected. The next step involved testing this design to ensure that it functioned correctly. To this end, SystemVerilog modules were created to represent each of the switches in the extracted design file. Once these modules were created, it was possible to verify that the circuit had the correct output. However, with this simple test, it was not possible to check if the circuit was operating adiabatically.

In adiabatic operation, each switch in the design has an input that has several possible states. To check for adiabatic operation, we had to ensure that no switch in the design was powered on when its input was not in the correct state. To this end, we designed a method for representing the state in the high-level language. Using this representation, it was then possible to also test for adiabatic operation by the circuit.

After the creation of this method for testing the adiabatic circuits that the group had been designing, we began working on devices to measure the energy output of adiabatic circuits. The first task in this area was to test various types of diodes, to find the optimal type for our work. Diodes, or PN junctions, are electronic devices that pass current in one direction, but not the other. Diodes can be used for measuring the temperature in a circuit because the current that flows through them is directly related to temperature. As the energy consumed by electronic circuits is dissipated as heat energy, measuring the temperature increase after turning on the device it is possible to identify the amount of heat that a circuit is dissipating.

Diodes are created from the interface of P-type and N-type silicon. P and N type silicon are created by adding different dopants to the silicon. The diode will have different properties depending on the amount of each type of dopant that is added. In order to find the best diode for our work, we tested various combinations of P and N dopant pairs. This testing was completed using a semiconductor analyzer. This machine displayed a graph of how the current changed depending on the voltage across the diode. This curve is the reveals a lot of information about the diode. The best type of diode does not pass any current when until a certain threshold voltage is reached. After exceeding this voltage, there is a specific shape that the output current should make. This will allow the diode to be easily characterized, allowing for accurate measurements of the temperature to be taken.

Once the optimal type of diode was identified, we began to design adiabatic circuits that included these diodes as temperature measurement devices. This process involved hand designing the physical layout as described above. We developed two devices that included diodes as energy measurement devices. These were an adiabatic shift register, and an inverter chain. The structure of these two devices was similar, however the inverter chain had fewer inputs and outputs, resulting in a design that is easier to fabricate.

We were able to verify that both of these devices operated correctly using SystemVerilog, with the same method as described above. These circuits will be fabricated this Fall, and thanks to the verification method that we created, should operate both adiabatically, and correctly.