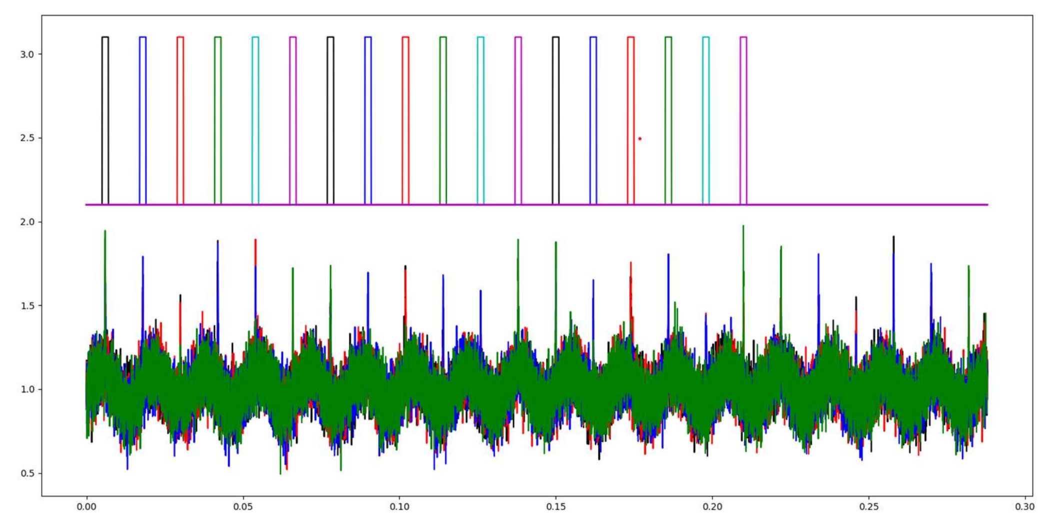
ENEE 611 – Fall 2024 – Class Project: Neural Spike Detection/Sorting

Introduction/Motivation: To support research in a neural recording laboratory, you are being asked to develop a custom VLSI chip that can take multiple analog voltage signals from a recording device and detect the occurrence of a limited class of 'events'. The design is intended to be a stepping stone towards automating the process of recording from 1000s of microelectrodes that might be used in future neural prostheses.

Problem Statement: You will be given simultaneous voltage recordings from an array of ***four*** electrodes (i.e., a tetrode). The relative positioning of the four electrodes is unknown due to imprecise manufacturing and to physical distortion when the array was implanted into the brain tissue. The electrodes are there to record the occurrence of neural "spikes". These voltage spikes will appear in the recording as a bipolar voltage event whose amplitude varies with the physical distance of the neuron to a given electrode. *These voltage events will typically appear on three to four electrodes simultaneously (no delay).* The amplitudes will be your only cue for identifying which neuron fired the spike. For this project, the amplitudes of the neural spike are unchanging. It has been determined that (in the recordings you will be given) there are 6 different neurons and stationary background noise.



Example starting dataset: Top: 6 digital signals that switch between 0V and 5V (shifted and scaled for clarity) indicating which neuron is producing a spike and when. This "teacher" signal should be used to trigger a memory circuit capturing the amplitudes of the spikes on each channel. Bottom: 4 (overlaid) electrode channels with noise. There is a "training" phase where neuron spikes are repeatedly presented, followed by a "test" phase where your circuit should indicate which neurons are firing and when.

Project Goal: Based on the "teacher" signal in the beginning of the recording (which indicate which neuron is firing when) your circuit must identify and store the characteristics of each neuron's spike to recognize it in the later part of the recording. Success is measured by how many neurons you can correctly recognize in the "test" portion of the file.

You will be given several data sets (4-analog signals + 6 digital teacher signal recordings) that contain different neuron signatures. Your circuit should be able to "learn" to recognize these neurons without changes in the circuit between datasets.

To use these files in your ngspice simulation, you will use the technique demonstrated in the files_test.sch example provided in UbuntuLab. Be sure that the datafiles are stored in the correct directory.

Around two weeks before the end of classes, a final test dataset will be given to run in your project simulation. While your written report will be used to describe your approach and the circuits you used to implement it, an electronic submission of your circuit output using this final data set will be used to verify the correctness of your solution. Note that the evaluation data set will be longer (in time) than the starting data sets. Anticipate up to 600 ms.

Advice and troubleshooting information for XSchem/NGSpice can be found on the class website

(Mandatory) Digital and Analog Output Format:

Your circuit output should consist of 6 digital lines, one for each of the neuron detectors. The signal should be logic HIGH (>= 5V) when a given neuron's spike has been detected. ONLY ONE detector output should be HIGH at any time.

Circuit Specifics:

I am expecting you to be using the nFET from the Skywater 130nm process that we have been using in the homework assignments.

Drawings: It is important that you present neat circuit schematics! Points will be taken off for extremely messy schematics, ambiguously or inadequately labeled. ALL information about each transistor must be in your report somewhere. I should be able to reproduce your circuit exactly from your documentation.

Your circuit should be reasonable from the point of view of fabrication. This means:

Transistors: Transistors should not be super long or wide. For the purposes of this class project, neither the length nor the width of a single transistor should exceed 30 um. The *minimum* width is: 0.39 um and the minimum length is: 0.26 um

Capacitances: You are allowed up to 24 capacitors as large as 10pF (useful for storing the 4 amplitude values for 6 neurons), but no other capacitors should not exceed 1pF (neglecting parasitic capacitances). You may NOT put 1pF capacitors in parallel to obtain something higher.

Resistances: Resistors with a value less than (or equal to) 500 Ohms may be used.

Current Sources: Ideal current sources are NOT allowed in your project. All current sources should be implemented using transistors.

Voltage sources and VDD: Aside from the inputs signal sources, you can only use fixed voltage sources (i.e., no pulse generators, sinewaves, etc.) Your voltage sources must all stay at or below 6V. While you do not need to operate in subthreshold, your average power consumption should be below 50mW. Subthreshold circuits will help you stay below both the voltage and power limits.

Your circuit should be designed such that a fabricated chip can be used for completely new experiments with different neurons and different coupling strengths. In other words, do not encode the specifics of the dataset into the widths and lengths of the transistors.

Project REPORT and Final Electronic Submission

Write your report in a way that you would be proud to show to a future employer during an interview to show them what you are capable of in a circuit design project. They don't know anything about the project, so you need to explain at least a little of this in the introduction.

Your report should consist of:

1) A minimum 1-page description of the overall strategy and high-level system block diagram of your approach to solving the problem. Describe your design choices and any obvious limitations that you recognize before getting into the details.
2) A full set of clear and details schematics of all circuits used. I should be able to replicate your simulations from these. None of the parameters or labels should be obscured. Individual module testing results are highly desirable and an important design step. If equations or special numerical analysis was necessary or used in the design, please describe this as well. If circuits were used that were described in class, you must supply the schematic, but you do not need to go into depth about its operation.
3) An ordered list of neuron spike occurrences that you detected: e.g., 1, 2, 2, 6, 6, 4, 1, 4, 3, …..
4) A clearly documented ***transistor count*** so that I can verify your counting procedure. I should be able to replicate your answer from the schematics. Included with this transistor count, a ***total transistor area*** measurement. To do this, simply compute the square microns using WL for each transistor and add them up. Using a table is handy for this purpose.
5) Energy consumption: Provide a plot of total power supply current during the entire period of the file.

6) If you used filtering, you need to use ngspice to obtain a frequency response plot of your filtering (ac analysis).
7) If any circuits were used from outside the material presented in class, please provide suitable academic references (similar to what you see in conference papers) at the end in a References section.

Electronic Submission:

In addition to the project report, to verify your final filtering and spike detection/classification results, you need to send me two files: 1) the (analog) filtered signals you are using to begin the detection/classification process, and 2) the 6 digital outputs of the detectors. Both files should have time and voltage labels for the axes. There should be a plot of these signals in your report. I should be able to take these plots and line them up (literally hold them up to the light) to check the relative timing of the analog signal and the detector outputs.

Grading Plan:

Your project will be given a score out of 100 points.

20 pts : Successful detection and classification of all neuron spikes from the evaluation files

20 pts: Clear and scholarly description of the approach (i.e., algorithm)

20 pts: Clear documentation and explanation/demonstration/testing of the specific circuits (modules) used, analyses performed, and/or equations.

20 pts: Clear documentation of all relevant internal signals from input to output. Labels, axes, explanations.

20 pts: "The 10,000 foot view": Did you calculate the area of the transistors? Did you estimate power consumption? Did you describe the efficacy of your design? – How would you have done things differently? – Was the circuit designed according to the project requirements?

Extra pts: (up to 5) Points for anything (that I find) exceptional, original, or interesting about your design or efforts