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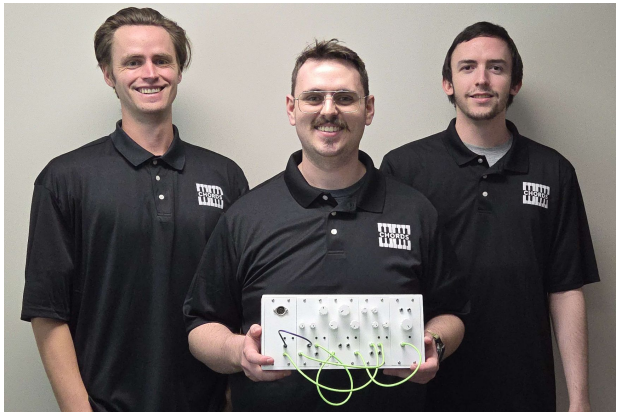
CHORDS

Customizable Hardware-based Open-source Real-time Digital Synthesizer



Senior Design Technical Report
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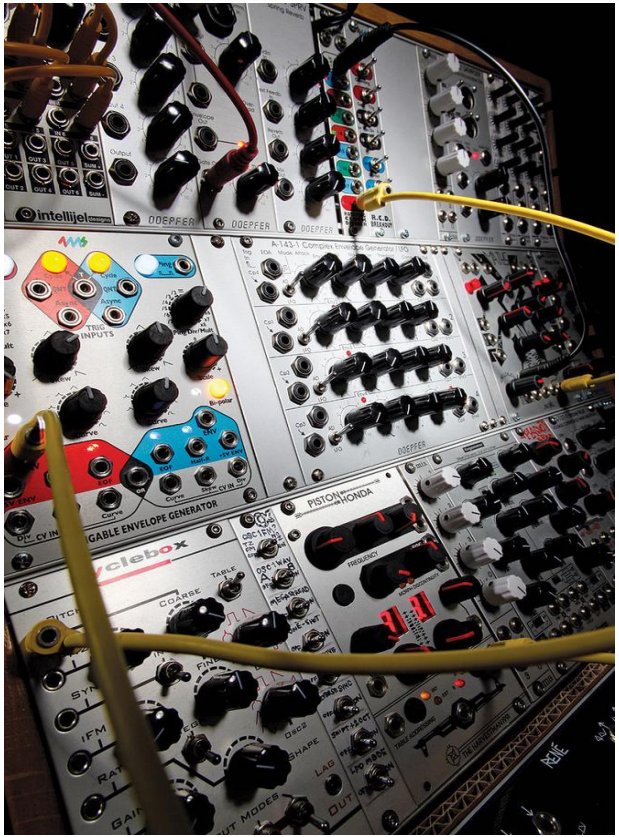
Overview

- Modular Synthesizer background and Terminology
- Problem Statement, Existing and Proposed Solutions
- Value Proposition and Comparison
- Marketing and Engineering Requirements
- System Overview
- Digital Modular Synth Protocol (DMSP) and Software Design
- Hardware Development
- Challenges
- Tests and Results
- List of Components
- Future Work
- Supporting Courses
- Demonstration

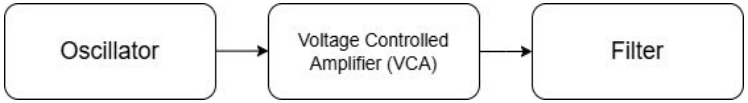
Modular Synthesis



Flexibility & Creativity

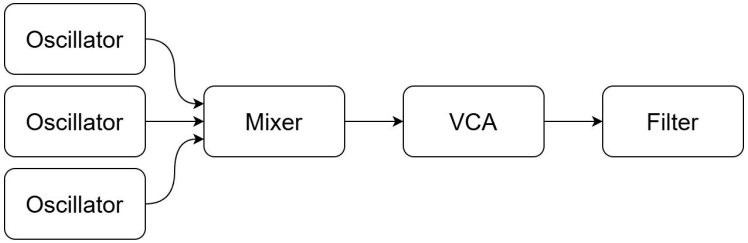
- Allows for unique signal paths & limitless scalability
- Modules are dedicated to different aspects of audio synthesis
- Ideal for experimental sound design and live performances
- For Real-time manipulation and musical expression

Terminology



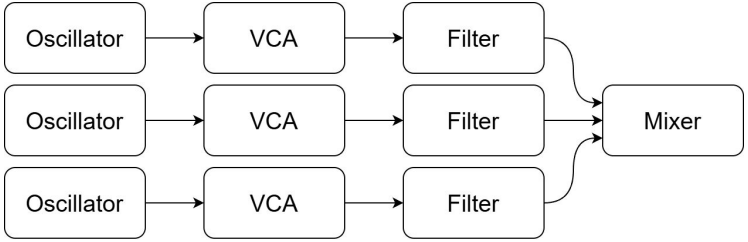
Monophonic

One frequency, One signal path



Paraphonic

Multiple frequencies, Shared signal path



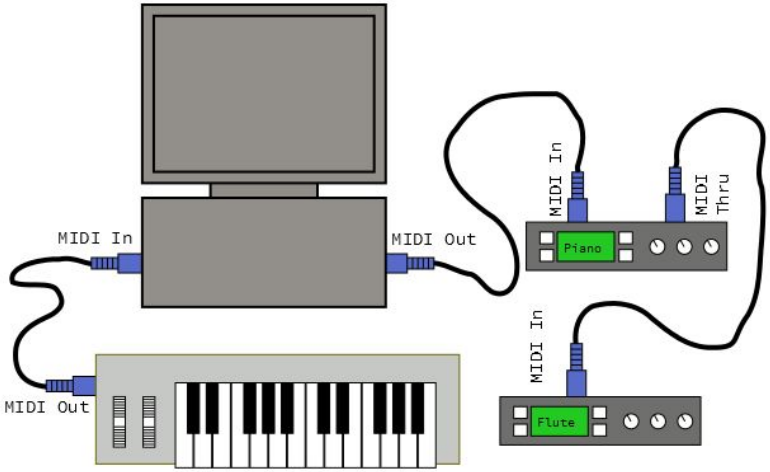
Polyphonic

Multiple frequencies, Separate signal path

Terminology

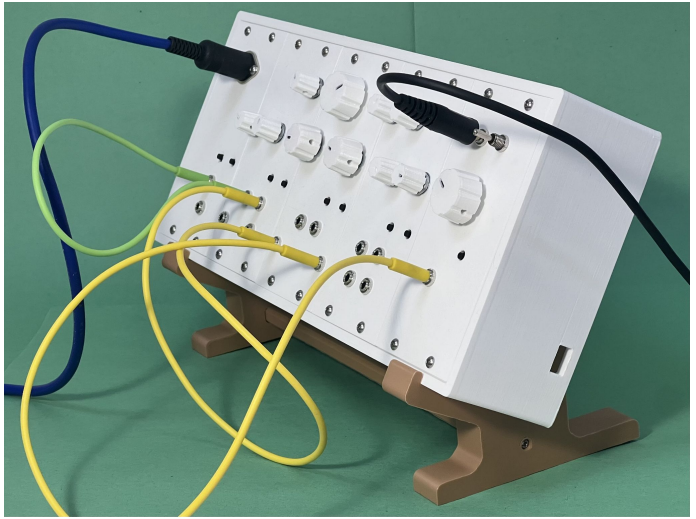
MIDI

Musical Instrument Digital Interface



DMSP

Digital Modular Synth Protocol



Problem Statement

Who: Musicians and sound designers who use hardware modular synthesizers

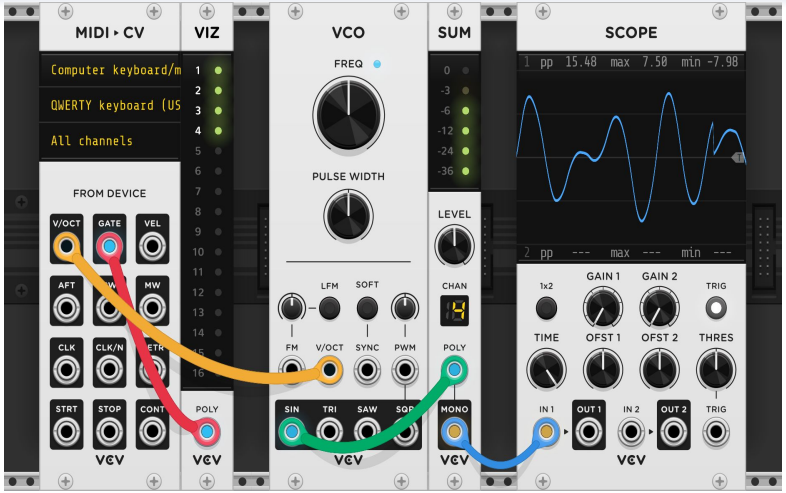
What: Traditional modular synthesizers do not support polyphony.

Why: Lack of polyphony restricts musical freedom. This contradicts the core philosophy of modular synthesis, which emphasizes complete control and flexibility in patching and sound design.

Existing Solutions

Multi Oscillators

- Control of analog waveforms at industry standard
- Complex & Expensive, *i.e.* Quad VCO = $419.99



Virtual Racks

- Lower cost than Hardware & Support Polyphony
- Lack Physical Control & Increased screen time

Proposed Solution

CHORDS

Advantages:

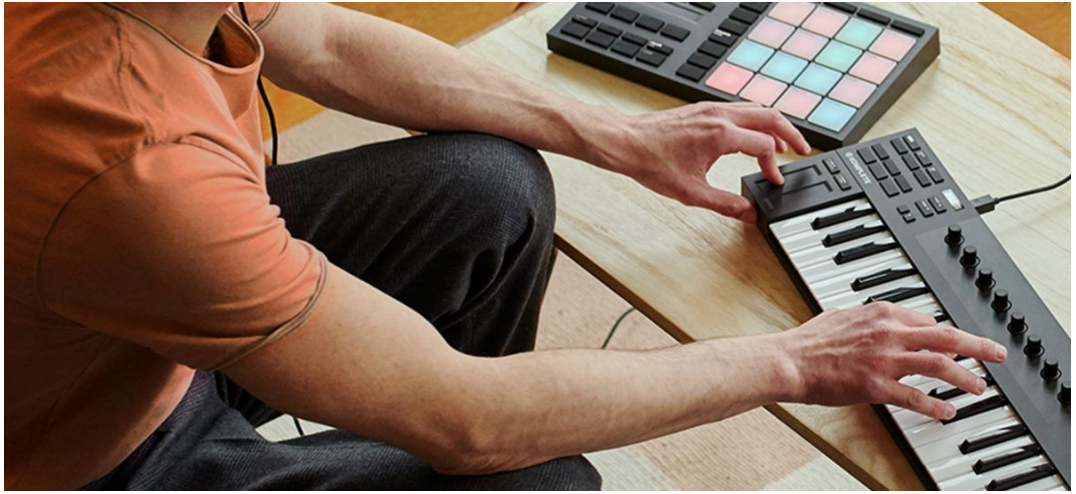
- Supports Polyphony
- Physical Controls
- Lower cost per module
- Customizable Hardware and Software

Disadvantages:

- Difficult to create Analog Modules
- Higher Latency than Eurorack

Value Proposition

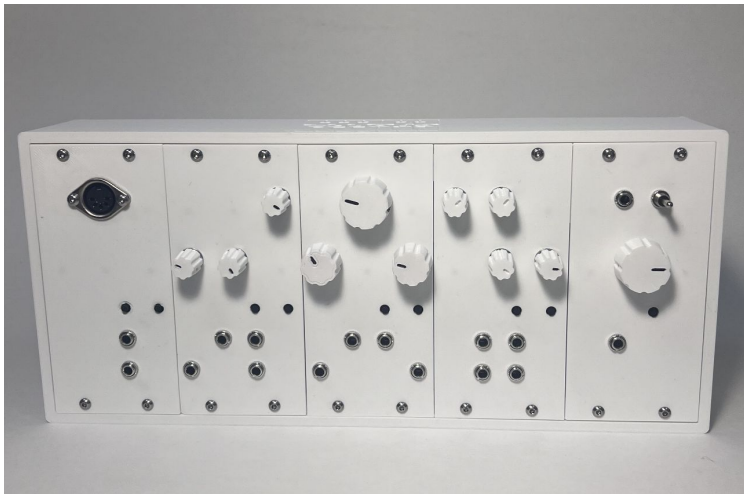
The CHORDS synthesizer helps musicians who want to make polyphonic sounds by providing a hardware modular synthesizer option with a low cost and physical controls.



Comparison

Doepfer Eurorack 4 Voice Synth
40+ patch cables

CHORDS 4 Voice Synth
6 Patch Cables



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Marketing Requirements

1. CHORDS is a hardware synthesizer, utilizing a new digital communication protocol
2. CHORDS will have polyphonic capabilities, with a minimum of 4 voice channels
3. CHORDS and the DMSP will be compatible with MIDI commands for versatile user control
4. CHORDS is modular, and comes equipped with an Lookup Table Oscillator, Biquad Filter, ADSR, Line-Out, and MIDI in modules
    a. CHORDS oscillator module is a Lookup Table Oscillator
    b. The CHORDS Line-Out module will utilize a ¼” audio jack to send a Line-Out signal at to the user's audio interface or speaker system
    c. The CHORDS Biquad Filter module will have a control knobs for the musician to change cutoff frequency, Q, and morph between low and high pass
    d. The CHORDS ADSR modules will allow the musician to set Attack, Decay, Sustain, and Release time with the control knobs
5. CHORDS will have a durable custom case
6. CHORDS is a portable system that operates on battery power.
7. CHORDS will have low latency, ensuring that each musical note or control input is reflected quickly for a responsive playing experience.
8. CHORDS provides a more versatile musical experience at an affordable price

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Engineering Requirements

1. CHORDS modules will have knobs, switches, and buttons, to control parameters (MR 1)
2. CHORDS will be Polyphonic, allowing for a minimum of 4 voice channels to be played at one time. DMSP has 3 channel bits, which supports a maximum of 8 voice channels (MR 2)
3. Each CHORDS Module shall introduce a maximum latency of no more than 5 milliseconds and system latency shall scale linearly with the number of modules in the signal chain (MR 7)
4. CHORDS will be controllable with a standard MIDI controller. Using the IC (6N138) MIDI information will be converted into DMSP signals containing pitch and gate data (MR 3)
5. CHORDS oscillator module will be tuned to 440 Hz for the A4 note on MIDI keyboard (MR 4a)
6. CHORDS Inter-Integrated Circuit Sound (I2S) module will run at a sample rate of 40 kHz at 24-bits and Total Harmonic Distortion (THD) shall be no higher than 1%, ensuring high audio fidelity with minimal distortion.(MR 4b)
7. CHORDS Biquad Filter will operate from 15 Hz-20 kHz (MR 4c)
8. CHORDS case will be 3d printed in PETG (MR 5)
9. CHORDS will utilize a 5 V supply powered by a rechargeable battery for portability and shall last at least 8 hours on one charge(MR 6)
10. Utilizing the RP 2350 Microcontroller, CHORDS is estimated to cost $200 or less (MR 8)

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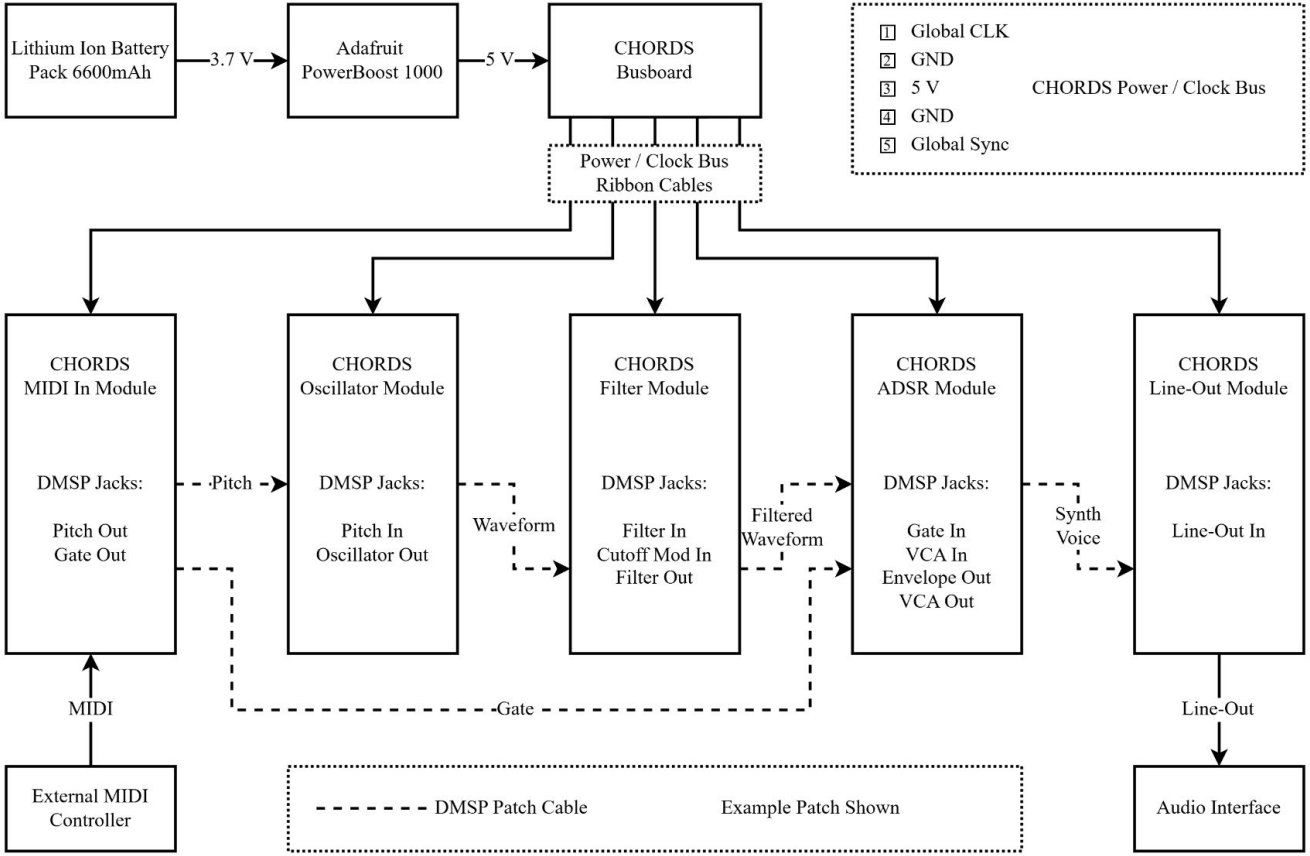
System Overview



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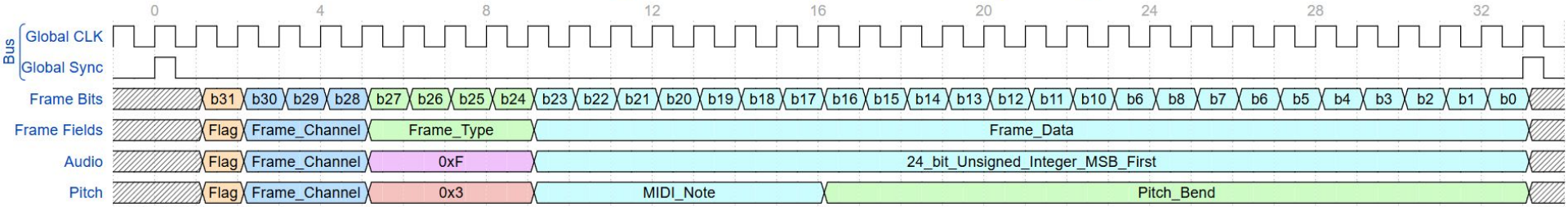
Digital Modular Synth Protocol



Global CLK Frequency = Frame Length × Number of Channels × Sampling Frequency

= 33 × 4 × 40,000 = **5.28 MHz** (For Current 4 Channel System)

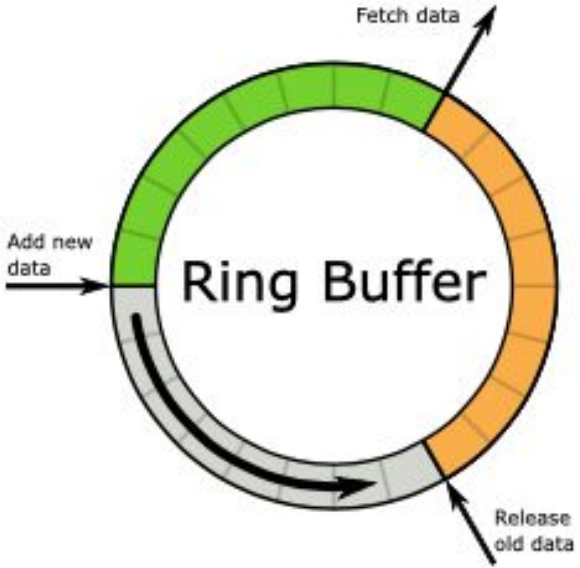
Global Sync Frequency = Number of Channels × Sampling Frequency

= 4 × 40,000 = **160 kHz**

Digital Modular Synth Protocol

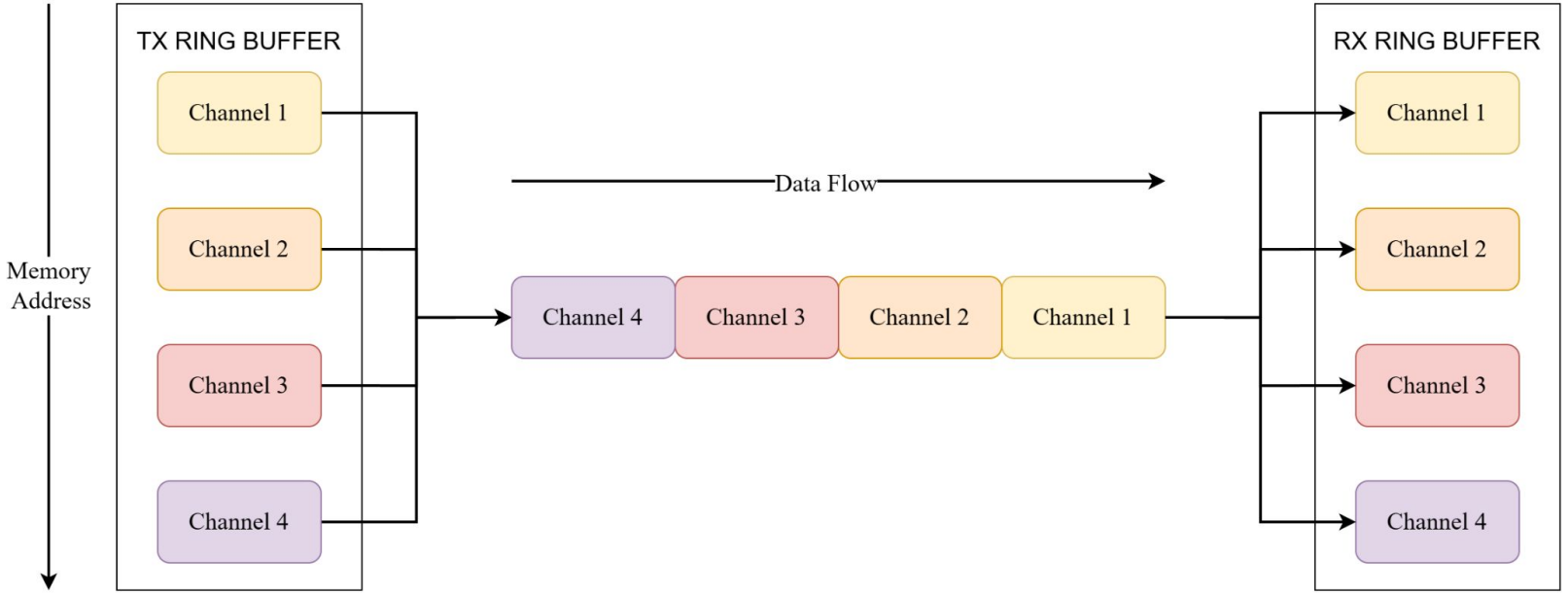
CHORDS Utilizes DMA Ring Buffers on All DMSP

Transmitters and Receivers



Digital Modular Synth Protocol

DMSP Buffers must cycle through the channels in order



Buffer Latency

- **Sample Rate:** $f_s = 40\,\text{kHz}$ (1 sample every $25\,\mu\text{s}$)
- **Buffer Size:** 256 frames (64 samples/channel)
- **DMSP Channels:** 4

$$\text{Samples per channel per buffer} = \frac{256}{4} = 64$$

$$\text{Buffer duration per channel} = 64 \times 25\,\mu\text{s} = 1.6\,\text{ms}$$

$$\text{Per-module latency (worst-case)} = \text{RX buffer} + \text{TX buffer}$$

$$= 1.6\,\text{ms} + 1.6\,\text{ms} = \boxed{3.2\,\text{ms}}$$

Buffer Latency

Ring Buffer Role:

- Ring buffer size = 1024 frames (4× headroom)
- Helps absorb timing jitter, interrupts, or control processing spikes
- **Does not increase latency unless full**

DSP Time

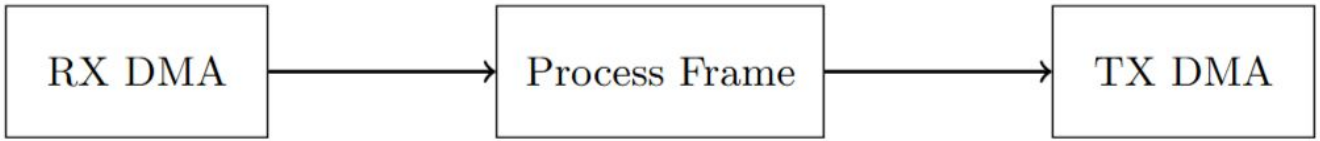
- CPU clock: $f_{\text{CPU}} = 150\,\text{MHz}$
- Sample rate: $f_s = 40\,\text{kHz}$ ($25\,\mu\text{s}$ per sample)
- Channels: 4 (each channel updated once every $25\,\mu\text{s}$)

Time Budget Per Channel:

$$T_{\text{frame}} = \frac{25\,\mu\text{s}}{4} = 6.25\,\mu\text{s}$$

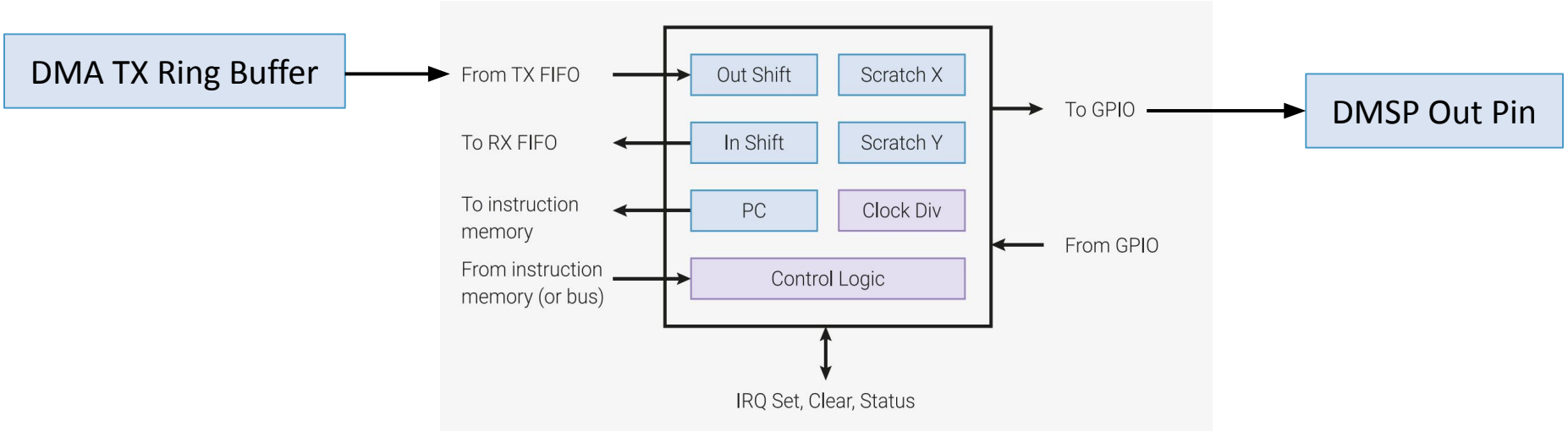
$$\text{Cycles per frame} = f_{\text{CPU}} \times T_{\text{frame}} = 150\,\text{MHz} \times 6.25\,\mu\text{s}$$

$$= 150 \times 10^6 \times 6.25 \times 10^{-6} = \boxed{937.5 \text{ cycles}}$$



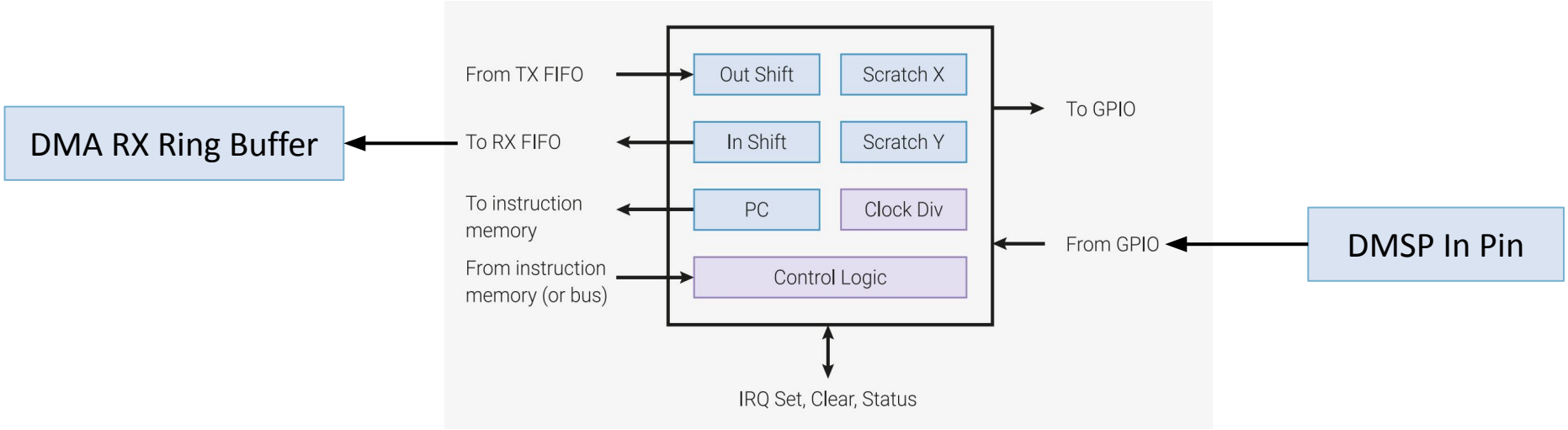
DMSP Transmitter

RP 2350 PIO State Machine



DMSP Receiver

RP 2350 PIO State Machine



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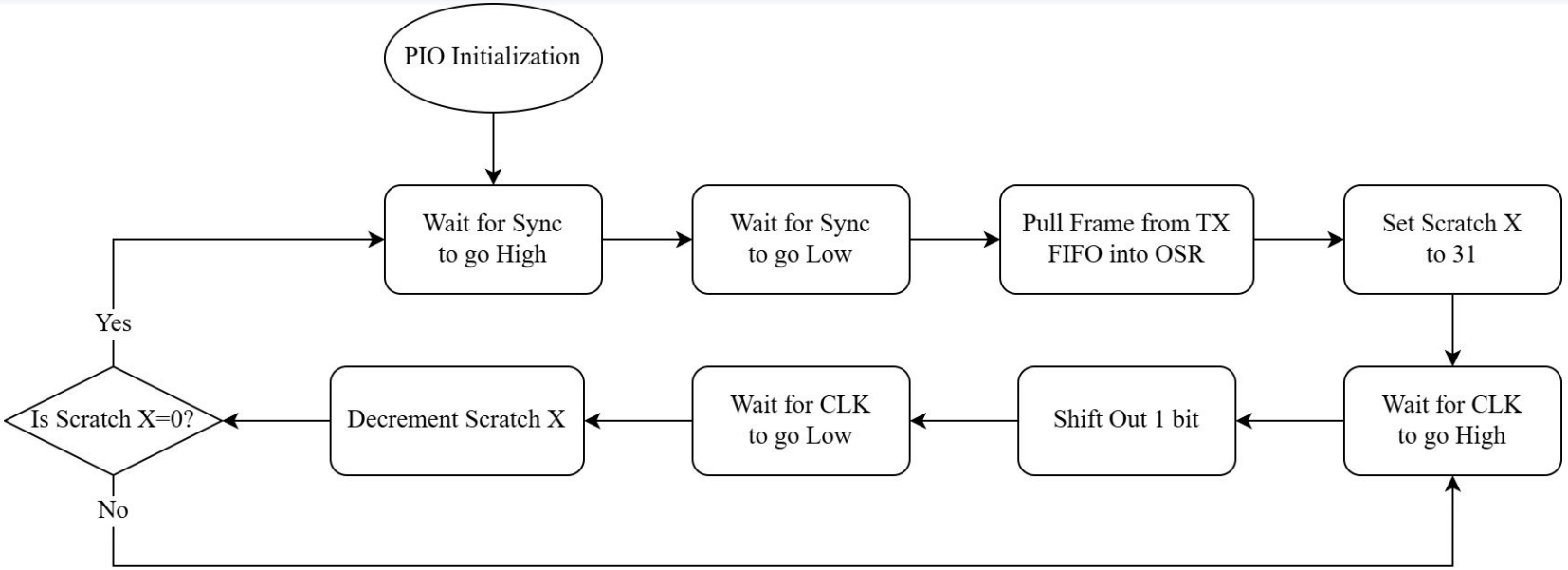
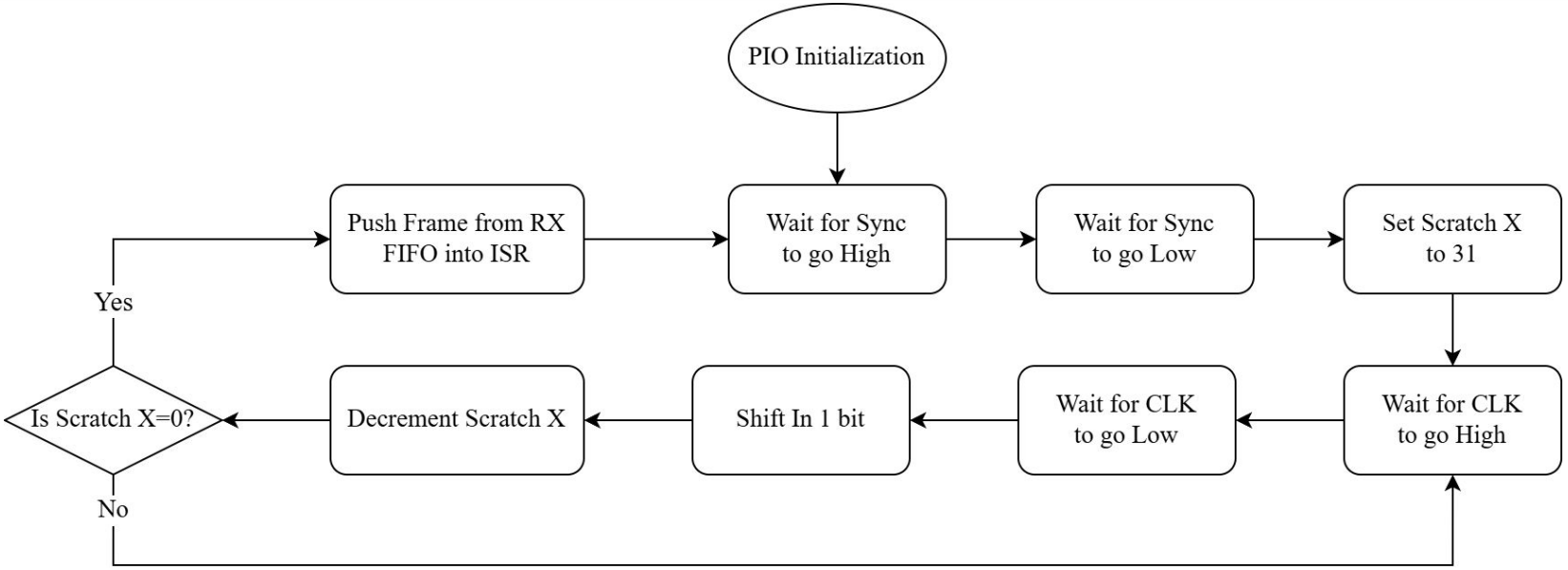
DMSP Transmitter Flowchart



Runs at RP 2350 Clock Speed (150 MHz)

DMSP Receiver Flowchart



Runs at RP 2350 Clock Speed (150 MHz)

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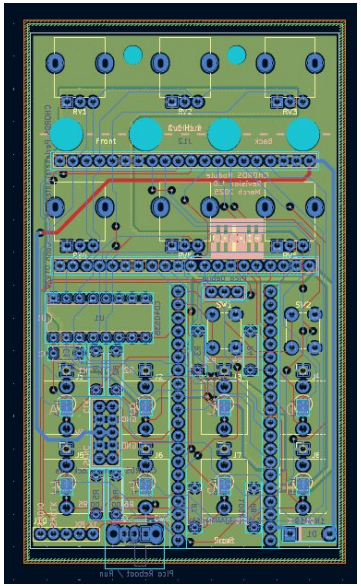
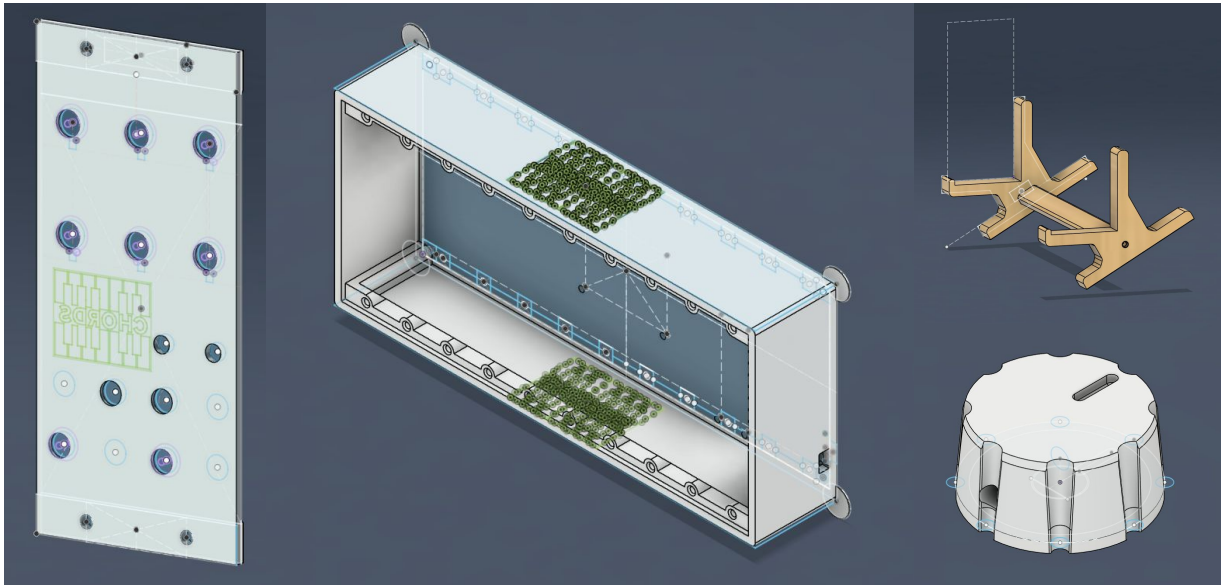
CHORDS Modular Ecosystem



PCB Module schematic
Prototype *via* KiCAD



3D printed Case, Knobs, Faceplate, and Stand Prototype *via* Fusion 360

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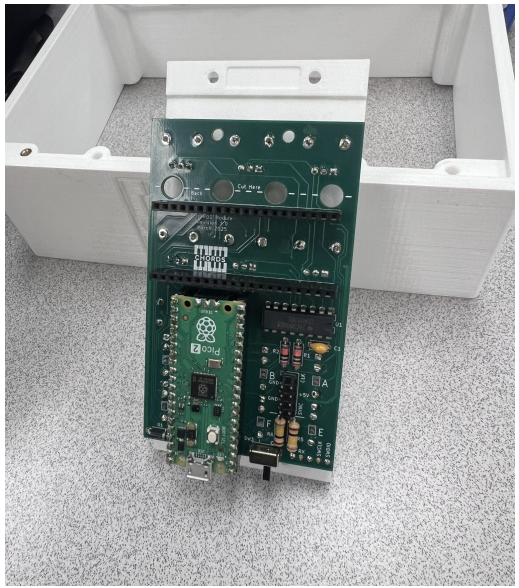
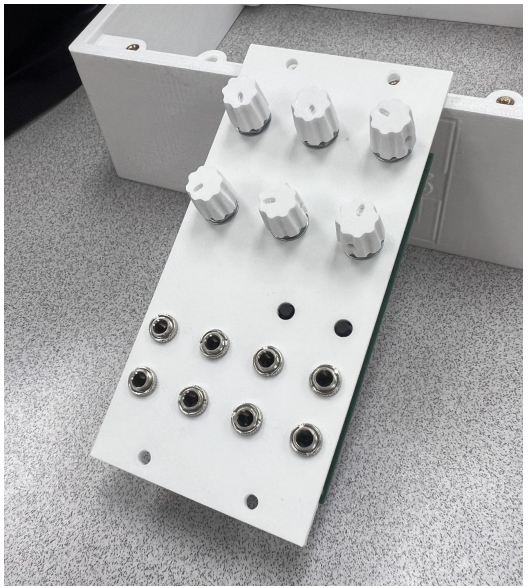
CHORDS Modular Ecosystem



Full PCB Module Prototype (Back)

3D printed Case, Knobs, Faceplate, and Stand *via* SSU Makerspace



Full PCB Module Prototype (Front)

Challenges

1. **Noise:** CHORDS is intended to provide clean digital waveforms for the Musician
   Factors: Signal being sent to separated modules, cheap components
   Outcome: SNR = -43.28dBV. Harmonics were lost in the noise floor raising total harmonic distortion (THD)

2. **Clock Distribution:** All of the modules need to be synchronized
   Factors: Improper clock frequency, inconsistent distribution of DMSP
   Outcome: Global Clock was synced ever 32 bits with no measurable drift after 2 hours

3. **Module Latency:** Latency is a major concern for all digital audio systems
   Factors: Each CHORDS module will introduce latency into the patch
   Outcome: Our DMSP helped sync the modules with an average system latency of 13.02ms

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List of Tests

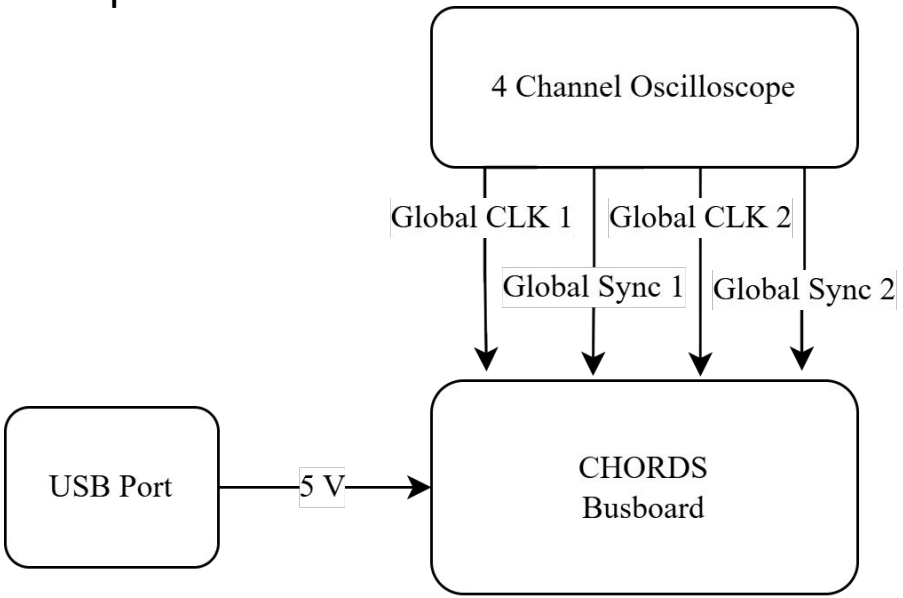
Test Number	Objective	ER to address	Status	Notes
ST. 1	Global CLK and Sync Alignment Over Time	ER. 2, 3	Pass	CLK = 5.28 +/- 0.01 MHz
ST. 2	Full System Test on Breadboards	ER. 1, 2, 3, 4, 5, 6, 7	Pass	Recorded Demo
ST. 3	Average Power Draw	ER. 9	Pass	Average current = 180.60mA, Calculated 25.7 hours of battery life
ST. 4	Full System Latency	ER. 3	Pass	Average system latency of 13.40ms
FT. 1	Oscillator Output	ER. 2, 5	Pass	Tuned to A= 440.32 Hz
FT. 2	MIDI Input	ER. 1, 2, 3, 5	Pass	< 5ms of Latency
FT. 3	Total Harmonic Distortion	ER. 6	Fail	THD 5.93%
FT. 4	Filter Module	ER. 1, 3, 7	Pass	Filter from 15 Hz - 20 kHz, with resonance knob
FT. 5	I2S Module	ER. 3, 6	Pass	40 kHz sample rate at 24-bit

Global CLK and Sync Alignment Over Time

Purpose:

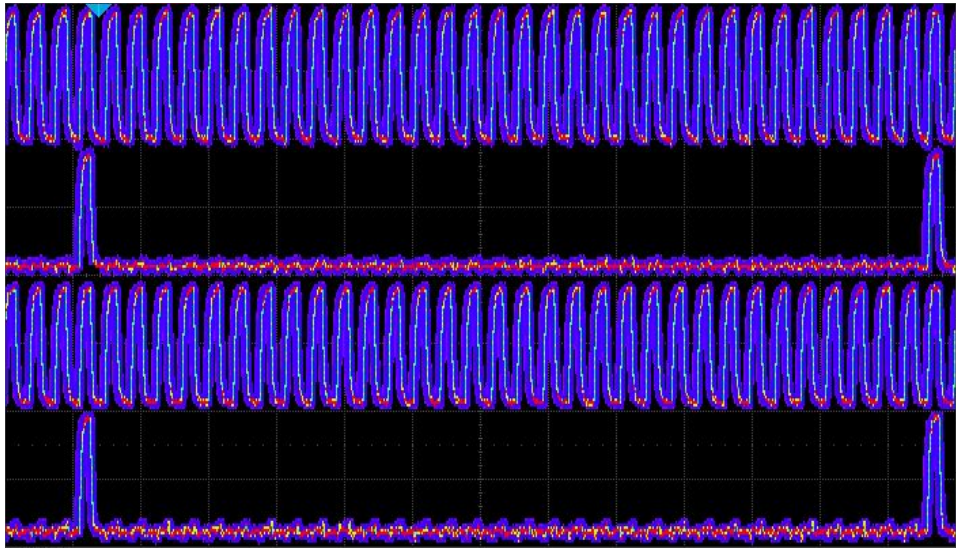
- To verify long-term timing consistency between Global CLK and Sync and signals distributed via the CHORDS Busboard. The test focuses on detecting gradual drift in phase alignment rather than short-term jitter.

Setup:



Global CLK and Sync Alignment Over Time

Results:



Conclusion:

- No measurable drift in Global CLK and Sync signals over 2 hours
- Signals generated via PIO state machines (RP2350)
- Flag pin ensures simultaneous signal start on power-up
- Confirms long-term timing stability across all Power / Clock Bus connections

System Test 2

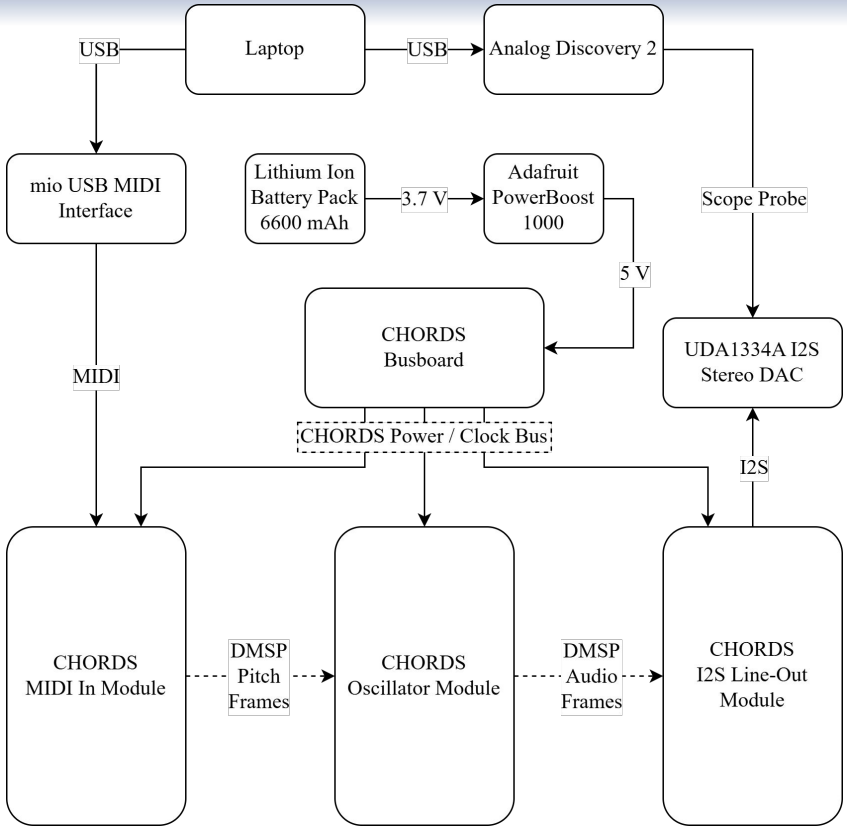
Total Harmonic Distortion

Purpose:

- To evaluate the system's ability to produce a low-distortion sine wave by measuring total harmonic distortion (THD) across the oscillator and output modules.

- Our THD target < 1%, corresponding to harmonic content at least 40 dB below the fundamental, as a benchmark for waveform purity and output linearity.

Setup:



System Test 2

Total Harmonic Distortion

Results:

- THD = 5.93%

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

	root	1st	2nd	3rd	4th	5th
Freq	440 Hz	880 Hz	1,320 Hz	1,760 Hz	2,200 Hz	2,660 Hz
dBV	-16.72	-65.13	-45.18	-61.49	-44.88	-59.18
Volts	0.146	0.001	0.006	0.001	0.006	0.001

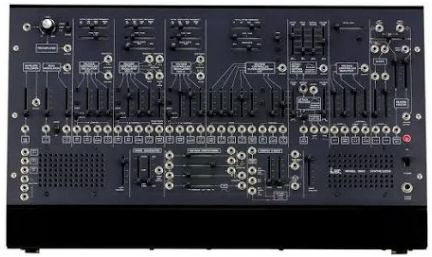
Conclusion:

- Our synthesizer did **NOT** meet our THD requirement of less than 1%.

System Test 2

Compared to Commercial Synthesizers

Arturia MiniBrute
THD = 2.23%



Korg Arp 2600
THD = 5.14%

Erebus Dreadbox
THD = 22.11%

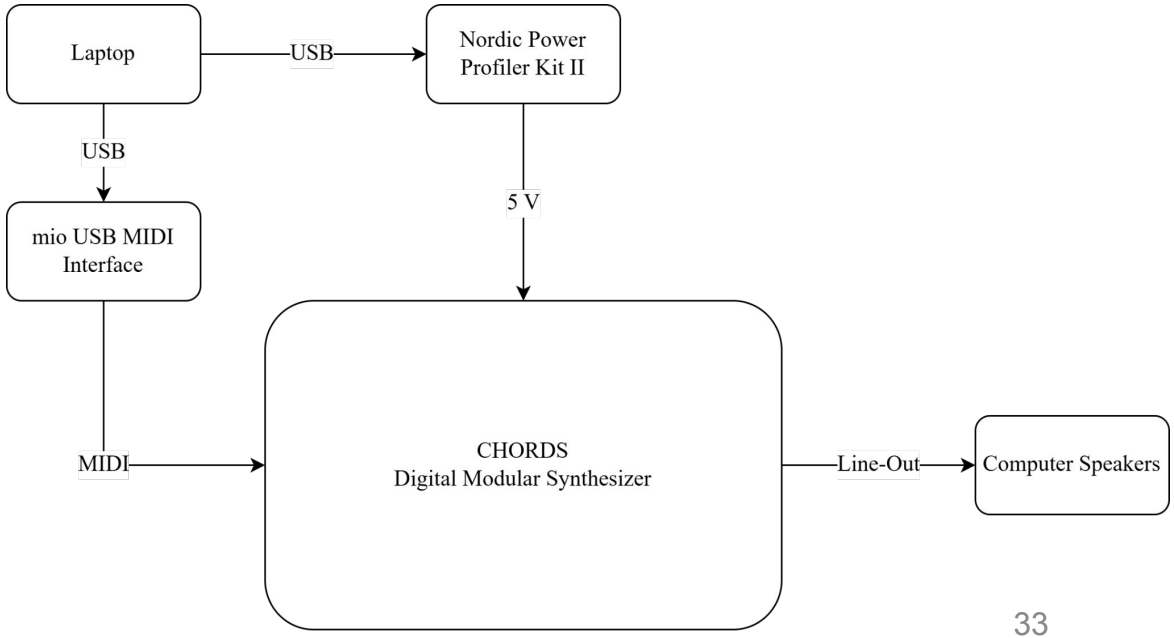
CHORDS
THD = 5.93%

Average Power Draw

Purpose:

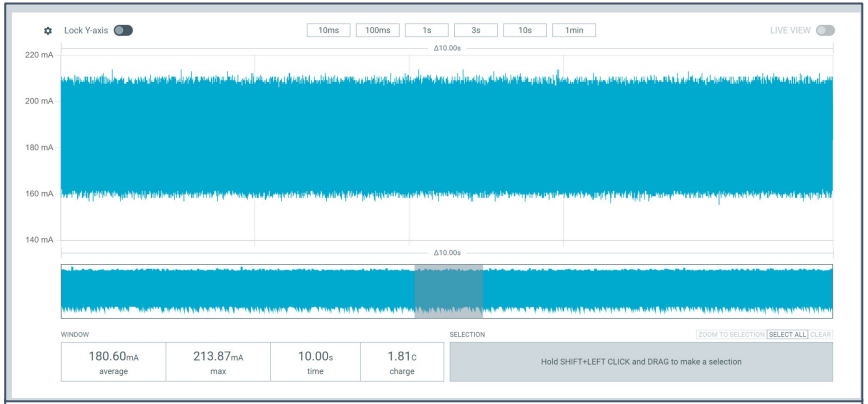
- To characterize the power consumption CHORDS during typical operation. The system was allowed to run continuously while playing music, and current draw was measured using the Nordic Power Profiler Kit II over several minutes to capture steady-state and dynamic behavior.

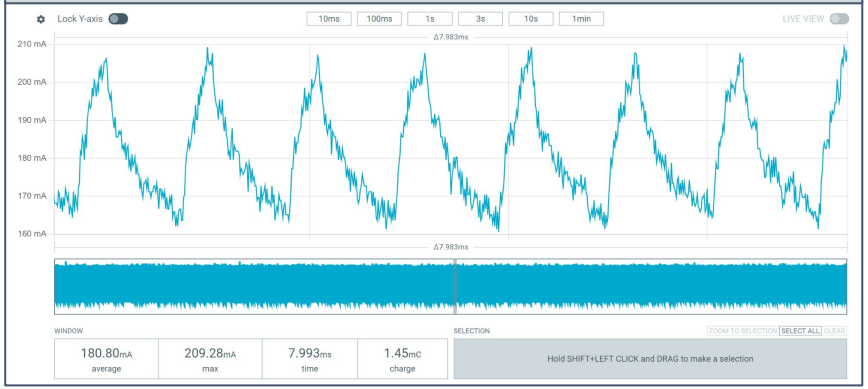
Setup:



System Test 3

Average Power Draw





Results:

- The Power Profiler read a consistent average current draw of 180.60 mA
- With this average current draw we calculate the system will be able to run for approximately 24 hours on its battery

$$\text{Battery Life} = \frac{6600\ \text{mAhr} \times 3.7\ \text{V} \times 0.95}{180.60\ \text{mA} \times 5\ \text{V}} = 25.7\ \text{hr}$$

Conclusion:

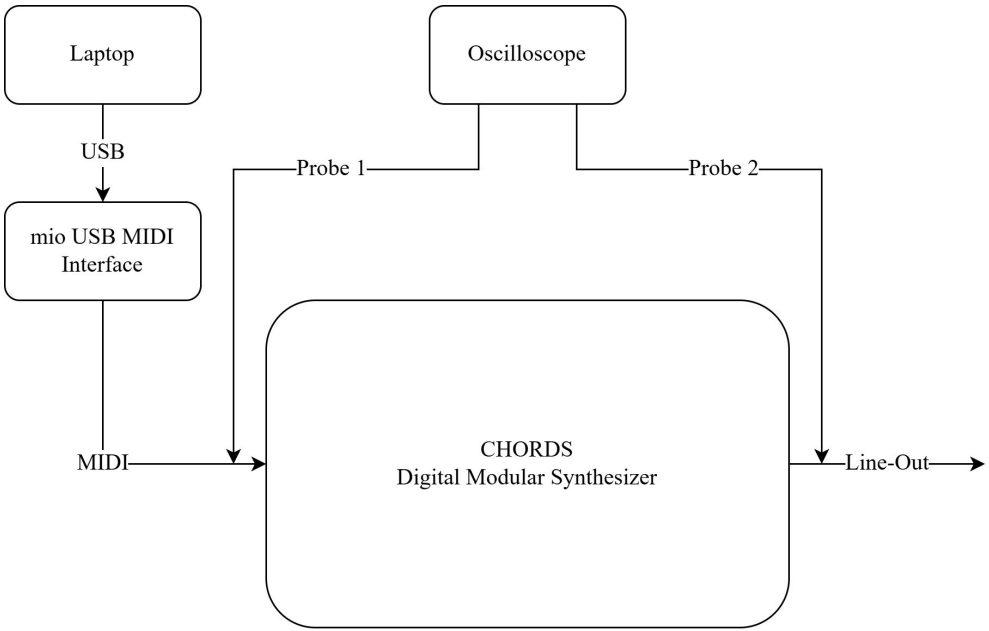
- ~25 hours of running time on battery power exceeds our goal time of 8 hours (ER 9)

Full System Latency Test

Purpose:

- To measure the end-to-end latency introduced by CHORDS. Each Module used introduced frame processing time. The patch included 8 total DMSP TX and RX ports, each introducing latency by buffering.

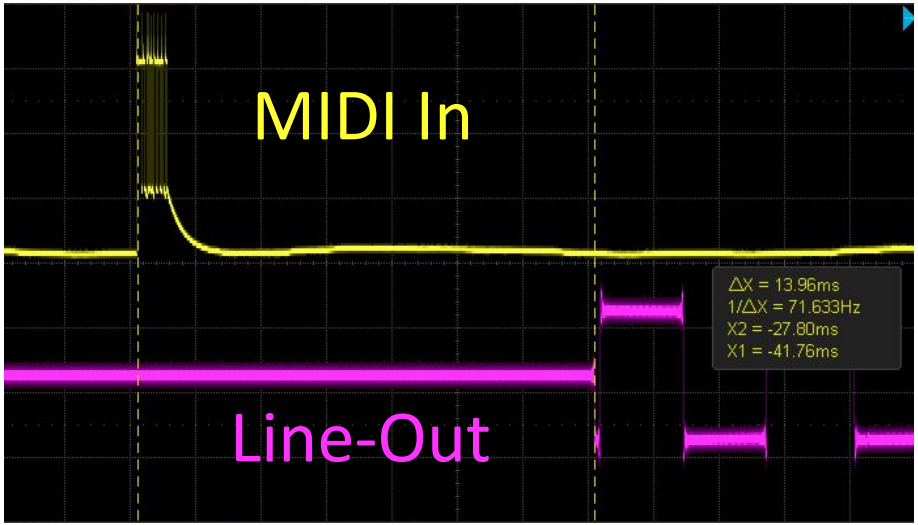
Setup:



System Test 4

Full System Latency Test

Results:



Test Number:	1	2	3	4	5	6	7	8	9
Latency (ms):	15.48	10.22	13.96	13.04	15.32	10.88	16.20	12.24	13.28

Conclusion:

Each TX or RX stage introduces:

$$\text{Latency}_{\text{per DMSP}} = \frac{256}{4} \times 25\,\mu\text{s} = 1.6\,\text{ms}$$

Configuration:

- 3 full modules (TX+RX): $3 \times 3.2 = 9.6$ ms
- 1 TX-only module (MIDI): 1.6 ms
- 1 RX-only module (Line-Out): 1.6 ms

Total theoretical latency: $9.6 + 1.6 + 1.6 = \boxed{12.8\,\text{ms}}$

Measured latency: 10.2 ms to 16.2 ms | Average = 13.40 ms

List of Components

Part/ Quantity	Price	Description	Link
⅛” Acrylic sheet	$8.25	Clear backplate for the synthesizer	https://www.amazon.com/dp/B0BBQ8B41F?ref=fed_asin_title
3D printing	$9	For Case, knobs, and sliders	https://library.sonoma.edu/create/makerspace
Adafruit power supply	$20	Board used to power modules from both battery and usb	https://www.adafruit.com/product/2465
Audio jacks	$0.60(x14)	Custom busboard PCB	
Busboard PCB	$2.73	Custom busboard PCB	https://cart.jlcpcb.com/quote?spm=Jlcpcb.Homepage.1006
I2S output Board	$7	Audio output module	https://www.adafruit.com/product/3678
IC (6N138)	$0.96	MIDI Input module	https://www.digikey.com/en/products/detail/lite-on-inc./6N138/1969179
Subtotal:	$87.34		

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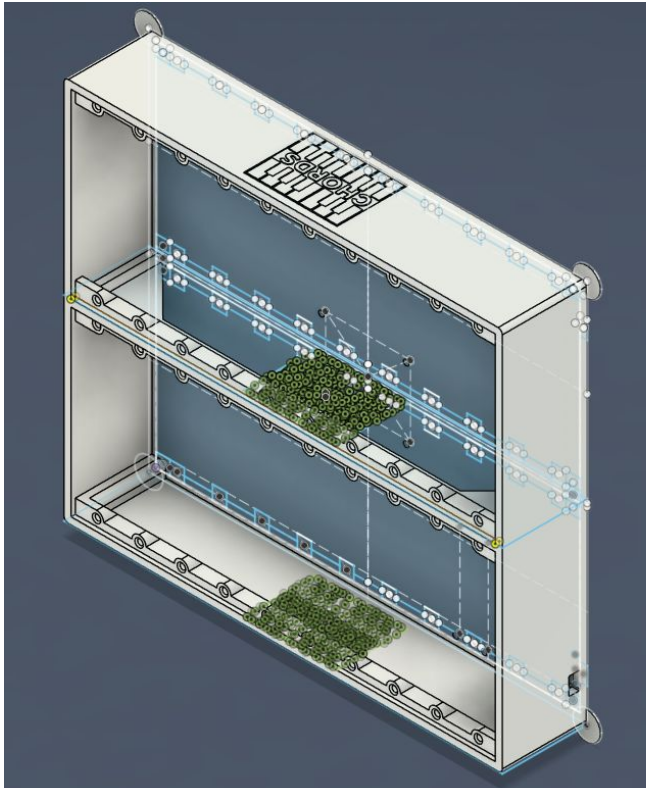
List of Components

Part/ Quantity	Price	Description	Link
Lithium Ion battery	$24.50	Battery to power the project	https://www.adafruit.com/product/353
M3 Heat Inserts	$7.39	Heat inserts for Screwing Modules to Case	https://www.amazon.com/dp/B01DBOBRHQ?ref=ppx_yo2ov_dt_b_fed_asin_title
M3 x 10mm Screws	$8.76	Securing Modules to Case	https://www.amazon.com/dp/B08H2HSPQD?ref=ppx_yo2ov_dt_b_fed_asin_title
Module PCBs	$2.05(x5)	Custom module PCBs	https://cart.jlcpcb.com/quote?spm=Jlcpcb.Homepage.1006
MIDI Socket	$1.33	Socket to plug in MIDI controller	https://www.amazon.com/dp/B0978STN2X?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1
PICO-2 (RP 2350)	$5 (x6)	Board used for all modules	https://www.adafruit.com/product/6006
Potentiometers	$1 (x11)	Potentiometers used for knobs to control modules	
Total cost:	$169.57		

Future Work



- 10 Module Case
- FM Modulation
- Develop CHORDS Header/Library
  - Optimize Code
- Addition modules
  - Audio FX
  - Step Sequencer
  - Dedicated VCA
  - Control
  - Noise Source
  - ADC
  - High Quality DAC
- Lower Noise Floor

Supporting Courses

- EE 210 Digital Circuits and Design
- EE 310/310L Microprocessors and System Design
- EE 334/334L Microelectronic Circuits
- EE 400 Linear Systems Theory
- EE 410 Advanced Digital System Design
- EE 442/442L Analog And Digital Communications

Demo

Questions

Thank You

Questions/Comments

CHORDS LUT Oscillator

$$\Delta\phi = \frac{f \times N}{f_s}$$

f: Desired oscillator frequency (Hz)

N: Table size = 1024 samples

f_s: Sample rate = 40 kHz

Phase increment (Δφ) controls how quickly an oscillator moves through a waveform stored in memory. A larger phase increment results in higher frequency output, while a smaller increment gives a lower frequency.

CHORDS Biquad Filter

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2] - a_1 y[n-1] - a_2 y[n-2]$$

Explanation of Terms

- $x[n]$: Current input sample at discrete time step n.
- $y[n]$: Current output sample at discrete time step n.
- $x[n-1], x[n-2]$: Previous input samples.
- $y[n-1], y[n-2]$: Previous output samples.

Filter Coefficients

- b_0, b_1, b_2: Feed-forward coefficients computed from cutoff frequency and resonance, determining how current and past inputs shape the filter's response.
- a_1, a_2: Feedback coefficients, normalized by a_0, influencing how previous outputs affect the current output.

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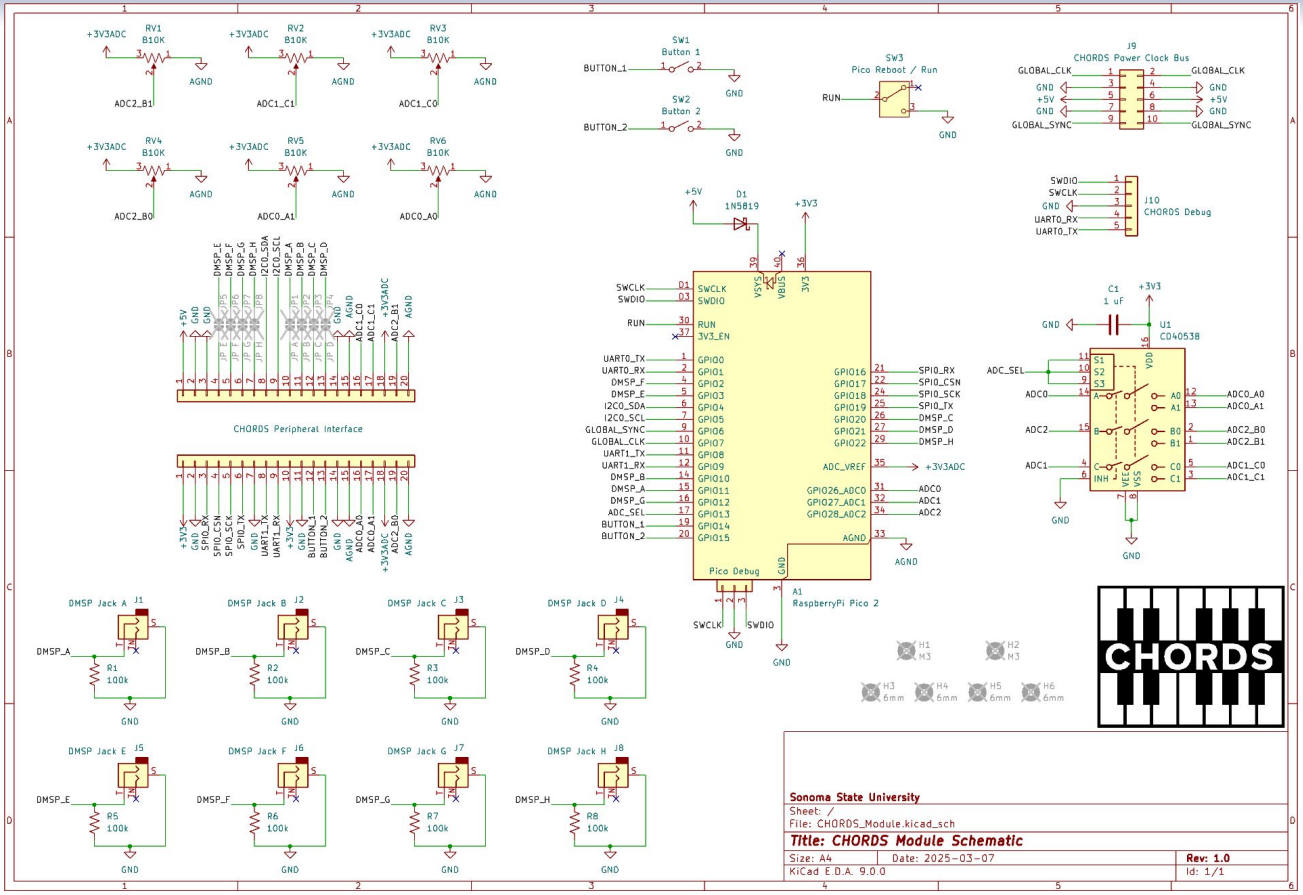
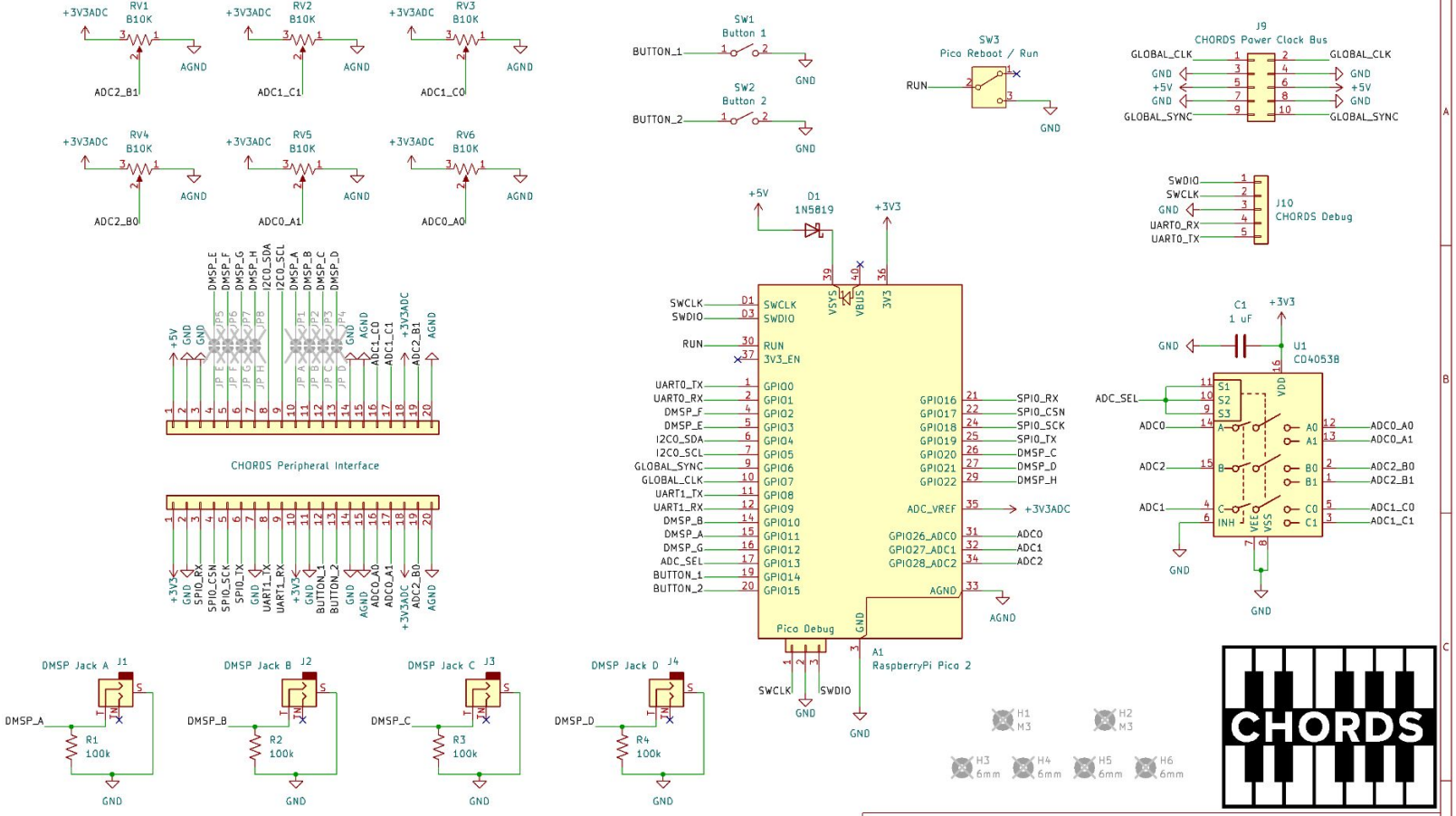
CHORDS Module Schematic





Sonoma State University		
Sheet: /		
File: CHORDS_Module.kicad_sch		
Title: CHORDS Module Schematic		
Size: A4	Date: 2025-03-07	**Rev: 1.0**
KiCad E.D.A. 9.0.0		Id: 1/1

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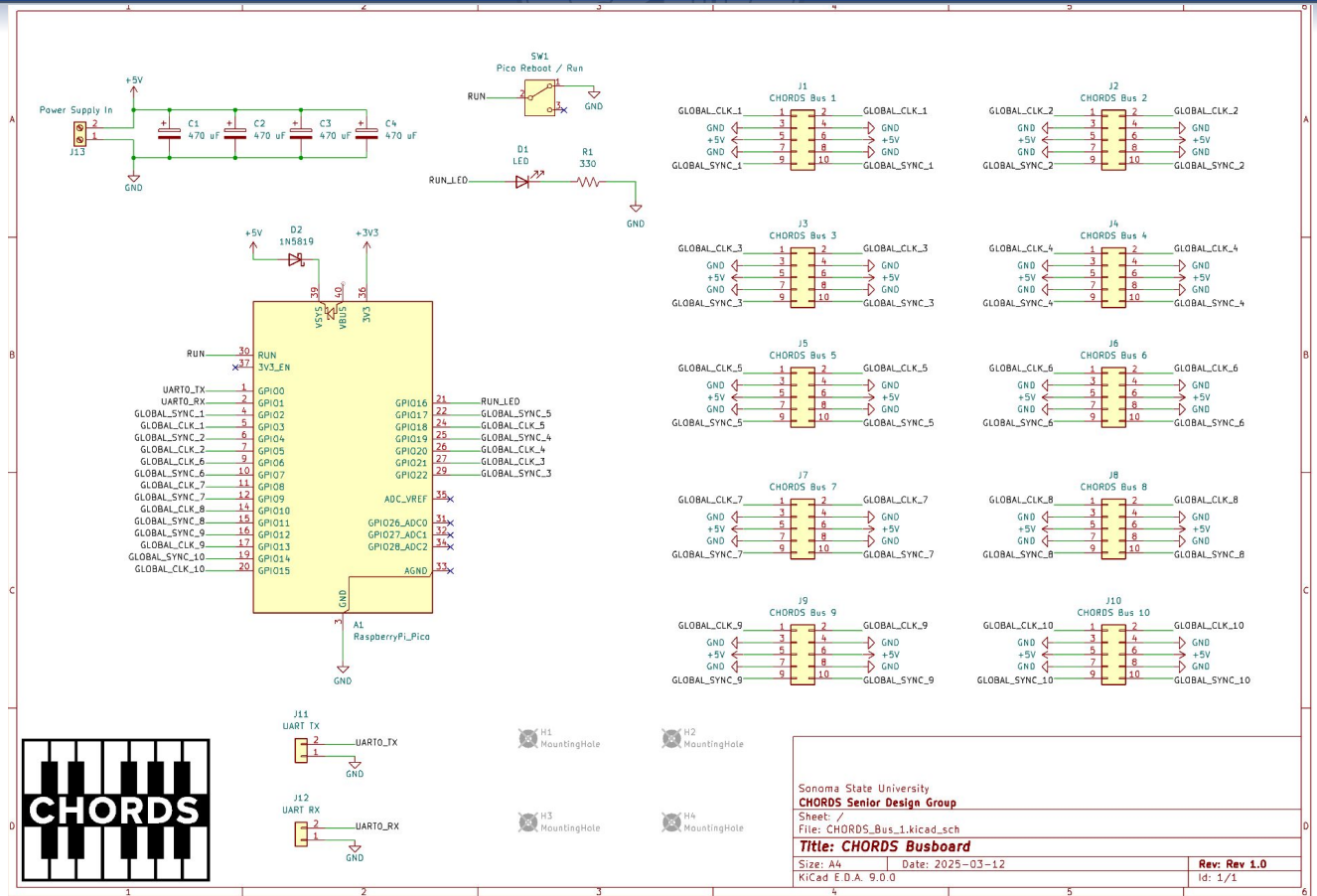
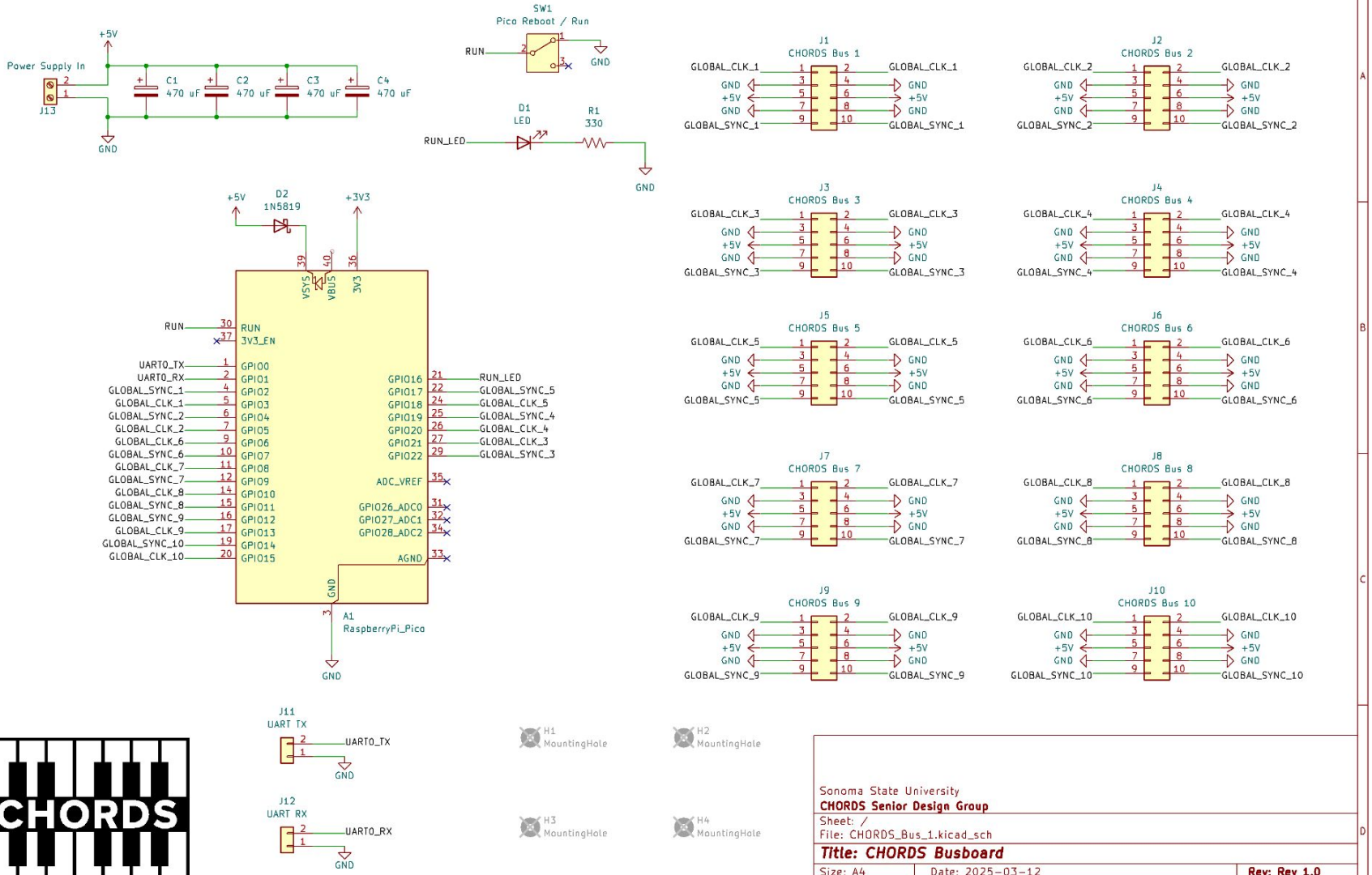
CHORDS Busboard Schematic





Sonoma State University
CHORDS Senior Design Group
Sheet: /
File: CHORDS_Bus_1.kicad_sch

Title: CHORDS Busboard

Size: A4	Date: 2025-03-12	**Rev: Rev 1.0**

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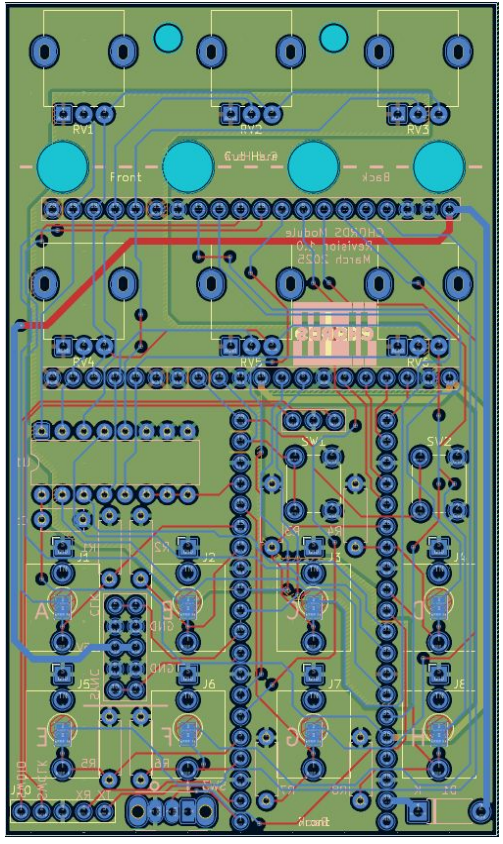
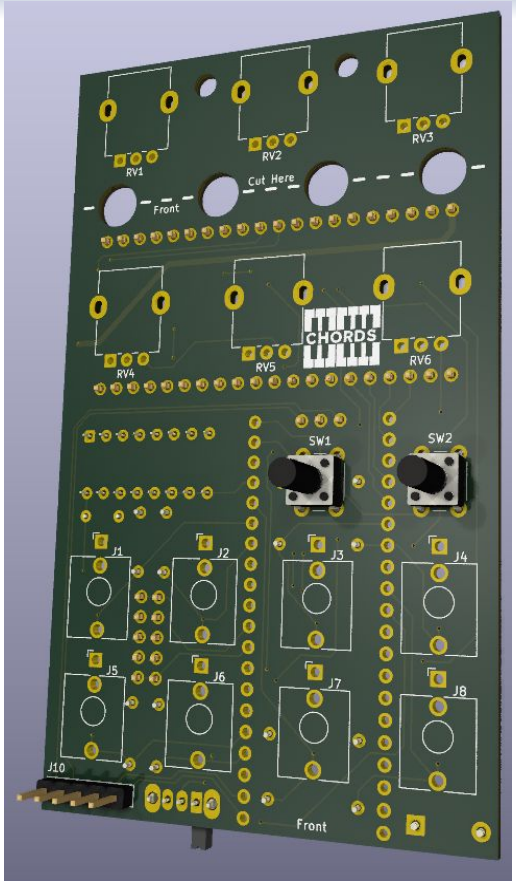
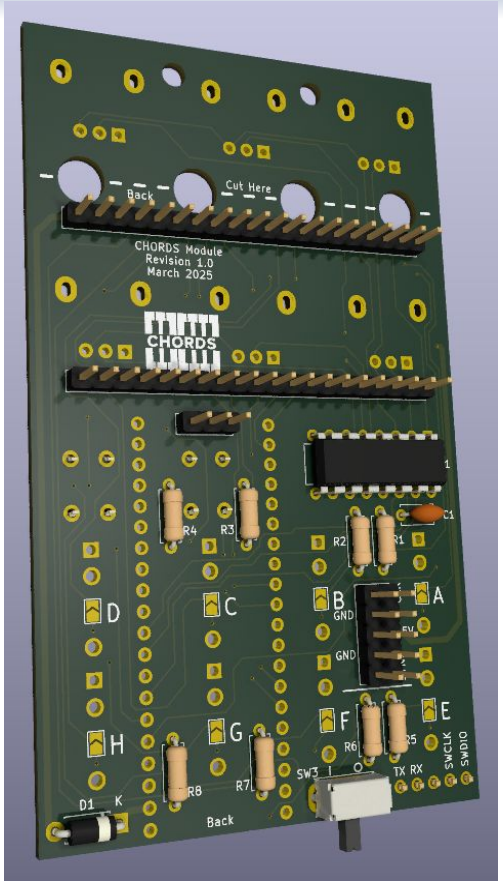
CHORDS Module PCB

60 mm x 100 mm







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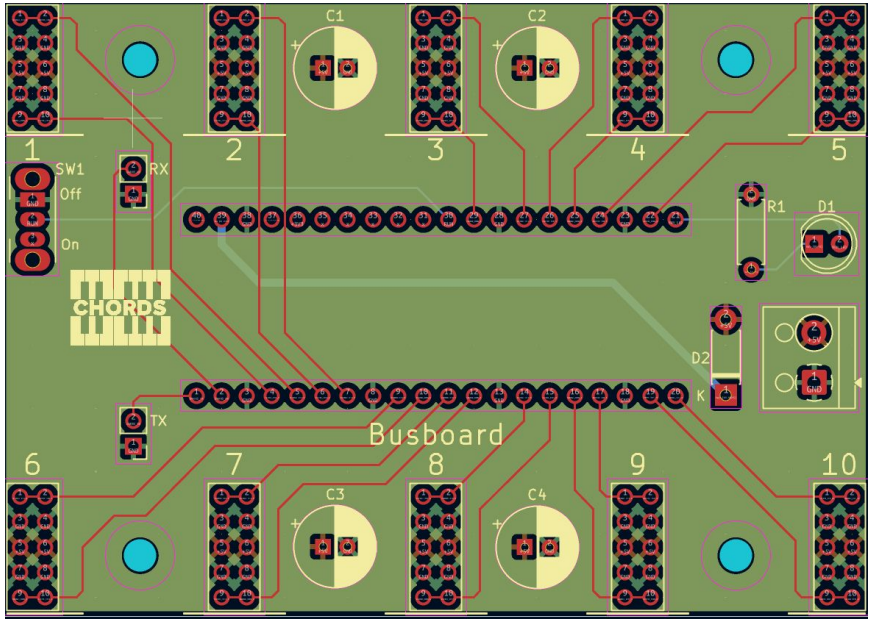
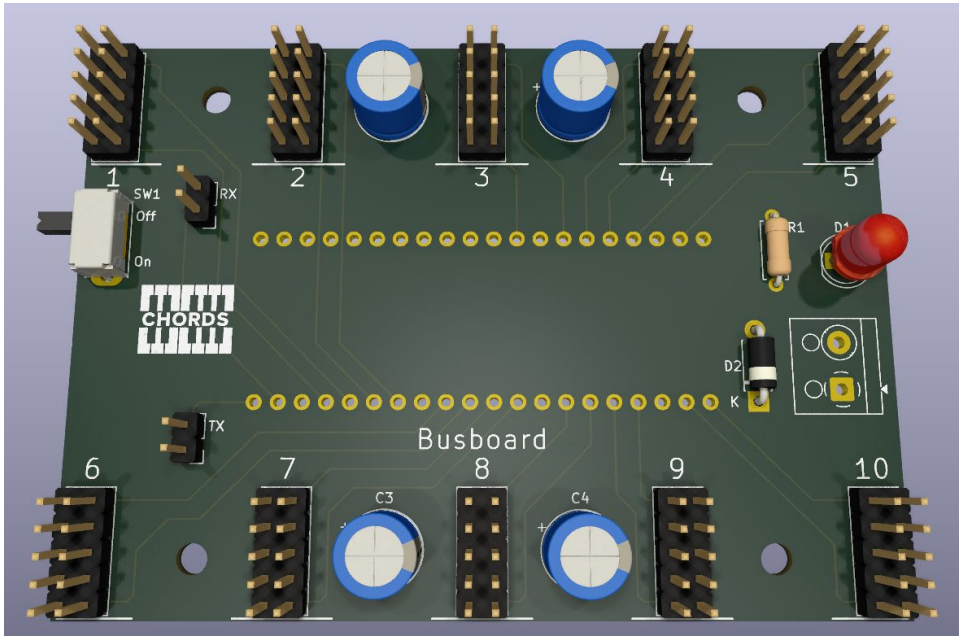
CHORDS Busboard PCB

88 mm x 62 mm





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Customizable Hardware-based Open-source Real-time Digital Synthesizer

Madison McIntyre
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Bjorn Lavik
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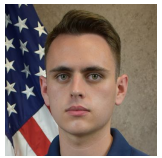

Julius Faller
fallerj@sonoma.edu

Senior Design Technical Report

Sonoma State University Department of Engineering Science

Advisor: Farid Farahmand

Client: Cameron Bartoloma, https://www.logica1err0r.com

Date 4/25/2025

Website: https://chordsynthesizer.com

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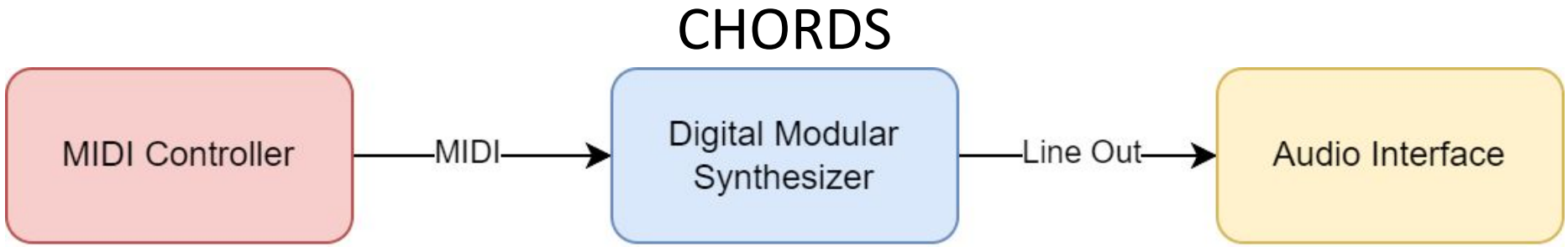
System Overview



Challenges and Risks

Risks

1. **Latency between input and output:** Rating = 15; Consequence = 3, Likelihood = 5
   a. Factors: Too many modules and Inefficient implementation of DMSP or DSP algorithms
   b. Contingency Plan: Optimize each module to reduce latency added to patch, Ensure Modules meet ER 4.

2. **Signal Integrity of DMSP and Global CLK Bus:** Rating = 15; Consequence = 5, Likelihood = 3
   a. Factors: cable type and length, distances between modules or latency causing synchronization issues
   b. Contingency Plan: consistent hardware implementation for bus and DMSP connections

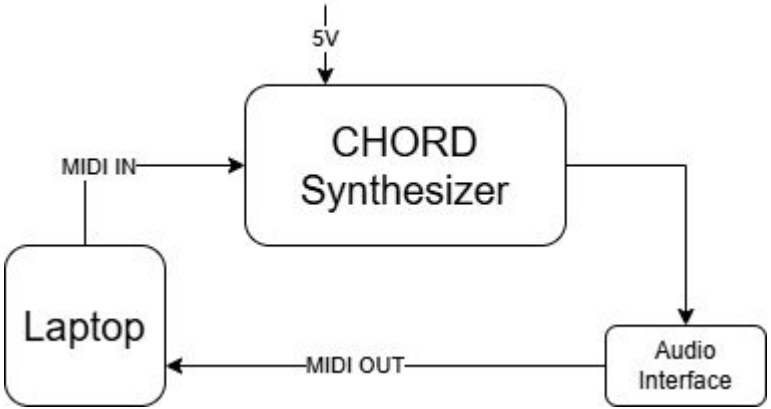
3. **Running out of RAM or ARM Core overload:** Rating = 10; Consequence = 5, Likelihood = 2
   a. Factors: Buffer size, DSP Algorithm implementation,
   b. Contingency Plan: Reduce buffer size and optimize code, or reduce module feature

Full System test on Breadboards

Purpose:

- Test the current system on breadboard
- Be able to record the output into a Digital Audio Workstation (DAW)

Setup:



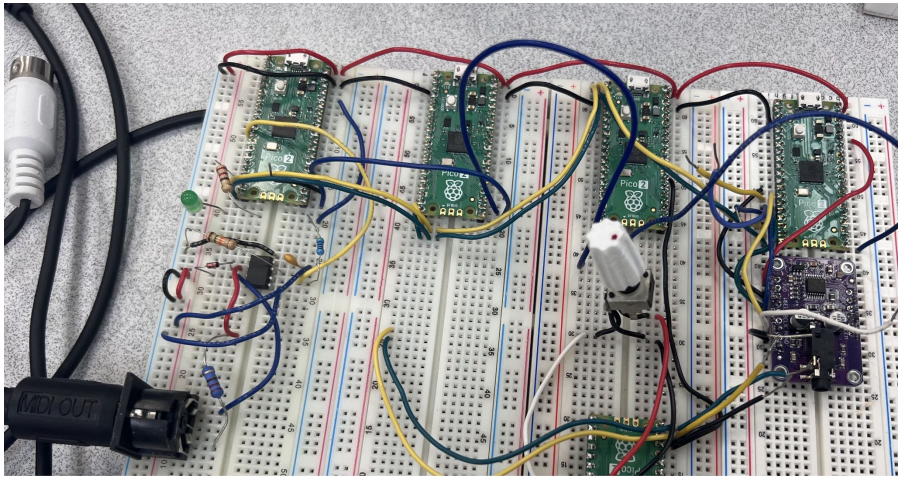
Full System Test on Breadboards

Results:

- Audio was recorded into our DAW
- Frequency was tuned to 440 Hz

Conclusion:

- Our system will be able to operate as intended with the musician easily able to hook up and record their music



Demo

MSO-X 2002A, MY53040558: Tue Dec 03 04:19:36 2024
1 500mV/ 2
0.0s
20.00ms/
Stop
1 43.8mV
KEYSIGHT TECHNOLOGIES
Acquisition
Normal
250kSa/s
Channels
DC 10.0:1
DC 10.0:1
Measurements
Freq(1):
54.71Hz
Pk-Pk(1):
2.63V
Max(M):
-2.8dBV
Min(M):
-110.4dBV
Measurement Menu
Source Math
Type: Min
Add Measurement
Settings
Clear Meas

Global CLK and Channel Control Test 1

Purpose:

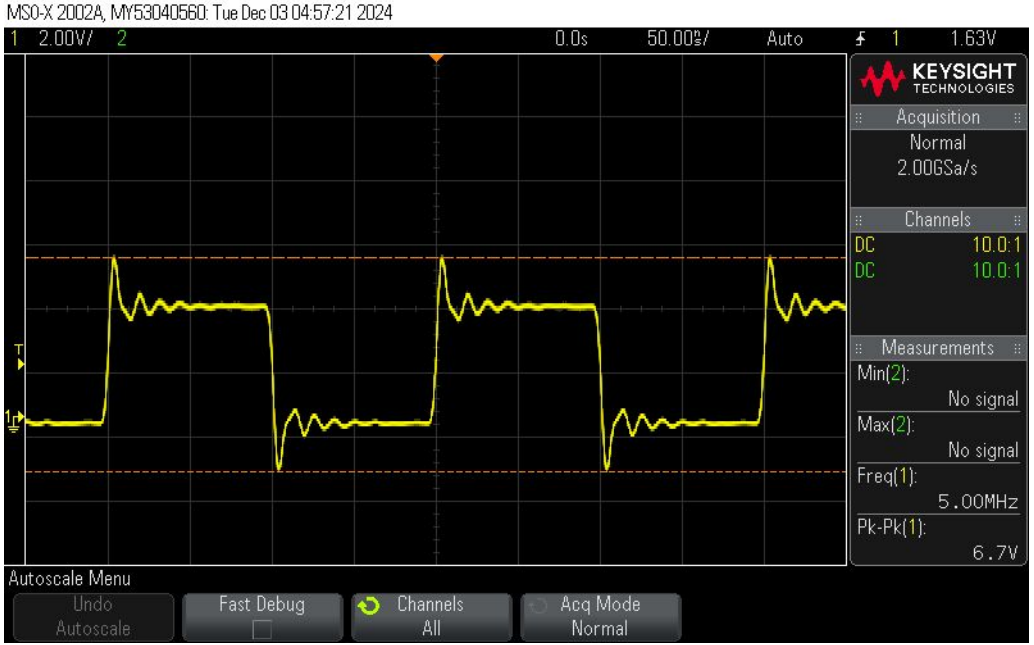
- To test the frequency of the clock and its synchronization with the channel control signal.
- Clock will ideally be within 1% of the 5 Mhz desired frequency
- The time between the rising edges of the CLK and Channel Control signal should be within 0.1% of the period of the CLK

Setup:

- RP 2350 powered by a laptop via micro usb
- Oscilloscope probe connected to gpio pin 1 for the global CLK
- Probe connected to pin 3 for the channel control signal

System Test 1

Global CLK and Channel Control Test 1



Results:

- Global CLK at 5.01 +/- 0.01 MHz
- No channel control signal received

Conclusion:

- Global CLK frequency test passed
  - 5 MHz is an integer division of the 150 MHz CLK
- Channel control test failed
  - No channel control signal picked up by the oscilloscope
  - Likely a software issue; will require further development

Challenges and Risks

Challenges *re-draft

- Clock Distribution
- through research we will know which microcontroller are best for our project
  - testing early we should give us time to troubleshoot this problem
  - using high quality connections to ensure less resistance
- Noise
  - Designing our communication protocol around polyphony will ensure we can successfully implement it
  - Through research we have found source on round robin protocols to cycle notes, as well as multiple frequencies channels to be sent from the input to the output.
  - We can change the number of channels to retain polyphony without sacrificing audio quality
- Ensuring a clean audio output
  - Testing sound quality through each module will ensure we find any generated noise
  - Ensuring our audio output is converting the signal at the highest quality possible
  - Testing connections will point out any faulty wires that may deteriorate the sound quality

Problem Statement

Who: ***Re-draft**

Musicians and sound designers who use hardware modular synthesizers

What problem do they face:

Musicians are limited to monophonic sound production, meaning they can only play one voice at a time. Traditional modular synths, don't fully support polyphony or multiple voices being played simultaneously. Workarounds to simulate polyphony, such as using multiple oscillators, arpeggiators, or delay lines, are cumbersome and require complex patching. These methods typically address only part of the problem, without providing a comprehensive solution. As a result, musicians are forced to compromise flexibility and usability, making it difficult to achieve full, multi-voiced polyphony in a modular setup.

Why this is a problem:

The lack of polyphony restricts creative freedom and limits the musicality of modular synthesizers. Users are unable to layer sounds, play chords, or sequence multiple voices in real time, leading to frustration in their creative process. This directly contradicts the core philosophy of modular synthesis, which emphasizes complete control and flexibility in patching and sound design.

Proposed Solution

CHORDS

Modules communicate with, and generate **Digital** signals.

All Modules are **Digital**

Module cost is based on processor

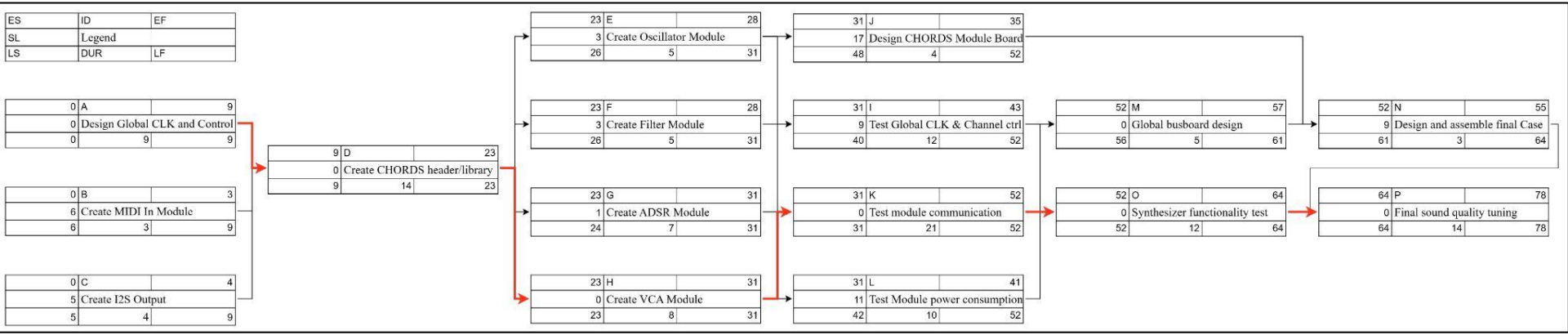
Eurorack

Modules communicate with, and generate **Analog** signals.

Modules can be both **Analog** and **Digital**,

Digital modules require ADCs, DACs, and level shifting.

Critical Path



*update for readability

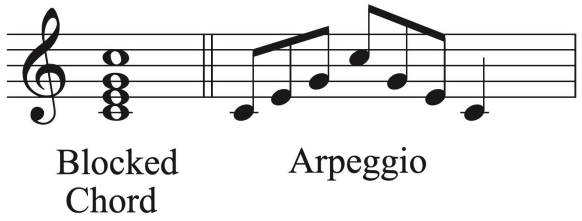
Existing Solutions

*remove slide Other Approximations

Voice Modules

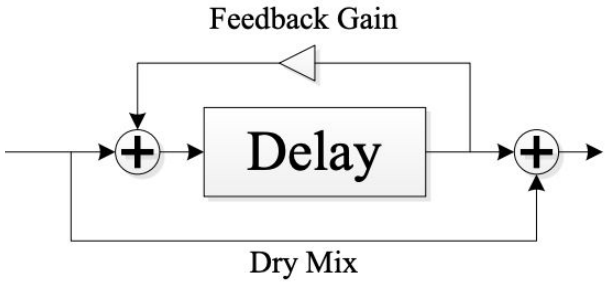
Arpeggio:

Can sound mechanical, no overlap between notes



Delay:

Control over timing is limited, sounds muddy if overused



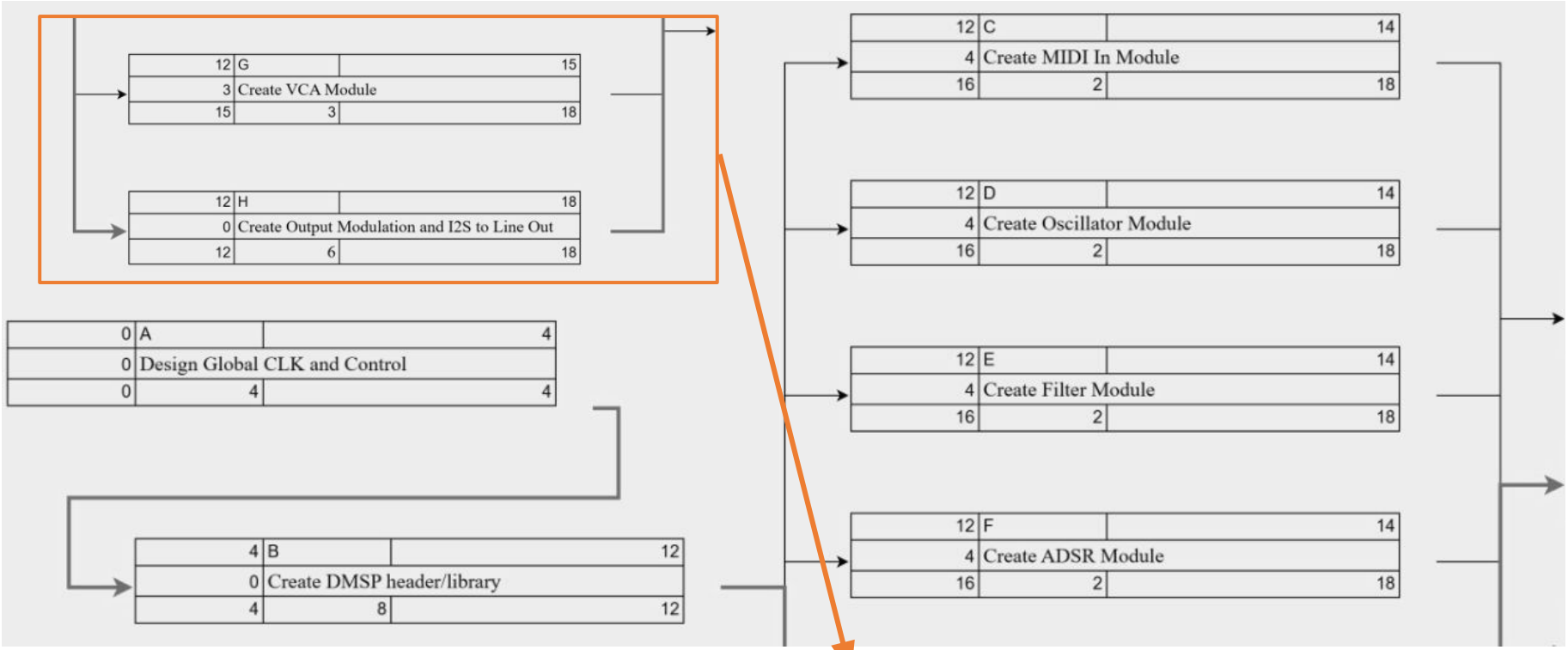
Voice Modules:

Limited CV control and patchability because of predefined signal flow.

Value Proposition

The Cost-effective Hardware Oriented Real-time Digital Synthesizer (CHORDS) empowers musicians and sound designers who seek polyphonic capabilities in a hardware modular synthesizer by implementing the Digital Modular Synth Protocol (DMSP) that allows for serial signals over patch cables. We enable users to create and manipulate multiple voices in real time, enhancing their creative freedom. Unlike existing solutions that only partially address polyphony and compromise flexibility, our system supports full customization through a modular architecture, allowing for an intuitive and seamless patching experience that aligns with the core philosophy of modular synthesis.

Critical Path



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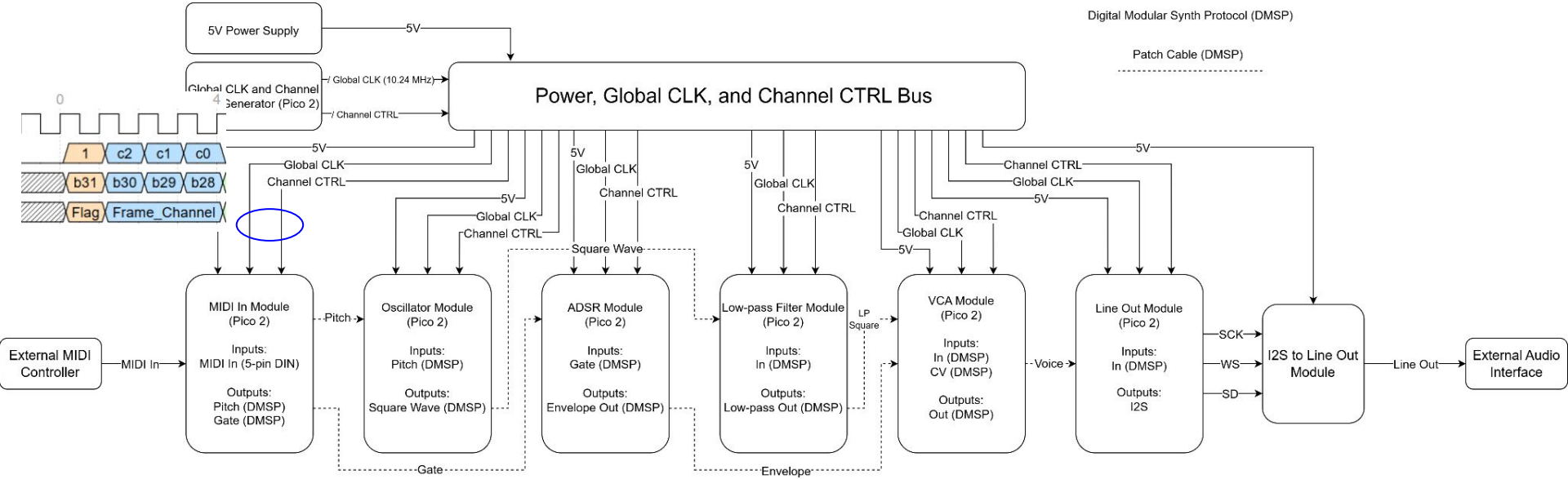
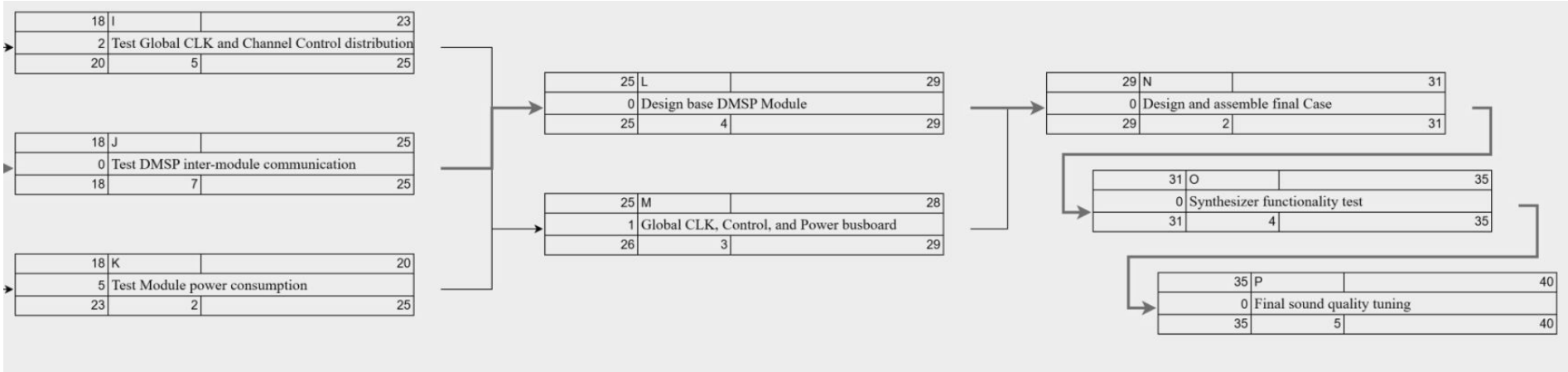
System Overview



Critical Path



Cost-effective Hardware Oriented Real-time Digital Synthesizer

C.H.O.R.D.S.

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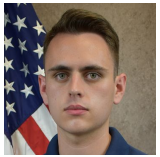
Bjorn Lavik
lavikb@sonoma.edu



Julius Faller
fallerj@sonoma.edu

Senior Design Project Proposal
Sonoma State University Department of Engineering Science
Advisor: Farid Farahmand
Client: Cameron Bartoloma, https://www.logica1err0r.com
Date 12/6/2024

Website: https://chordsynthesizer.com

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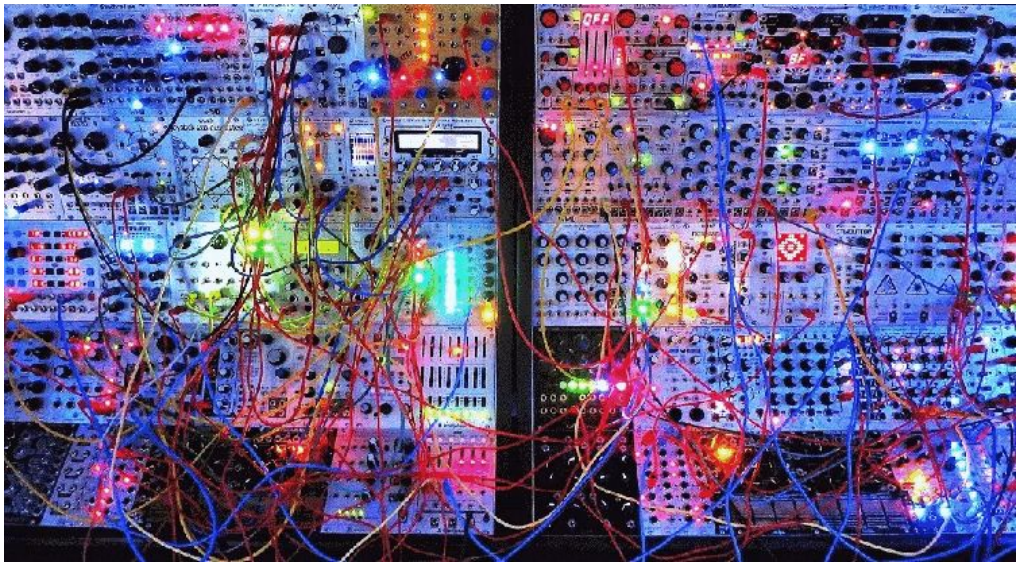
What is Modular Synthesis?

A Flexible Approach to Sound Design in a Module-Rack Format.

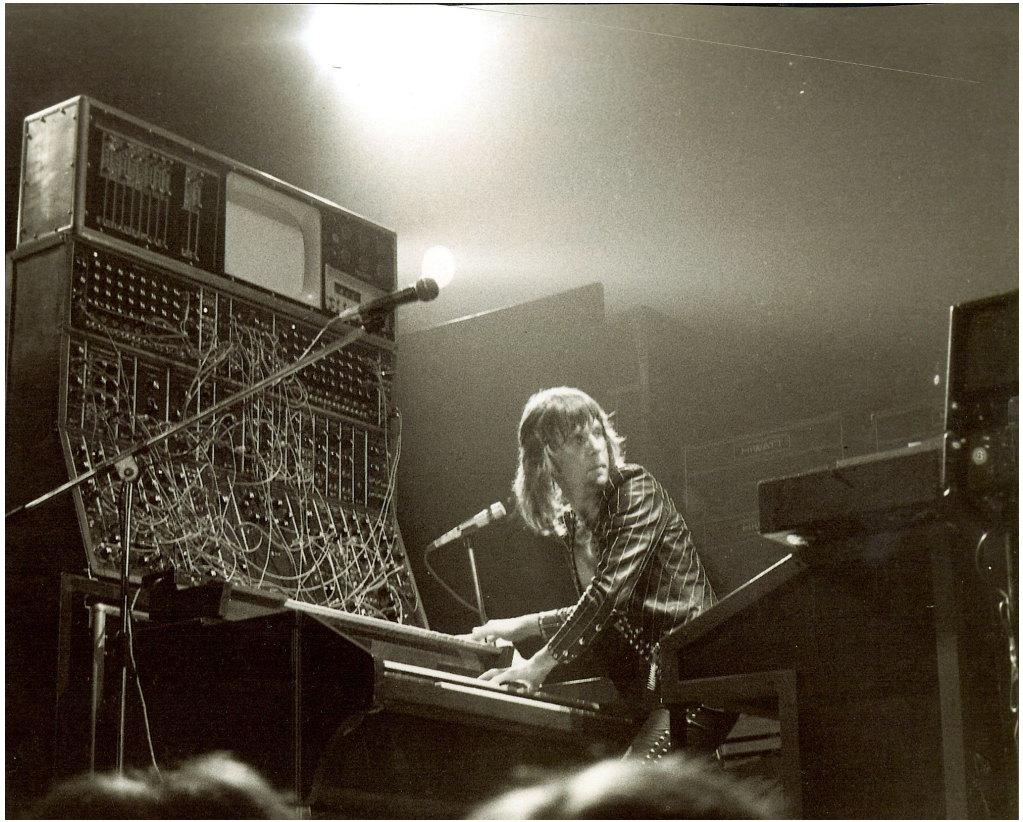
- No Fixed Architecture, Users design the signal path with patches.
- Easily scalable by adding new modules.
- Modules provide specific functions and can control aspects of others via control signals.



Types of Modules:

Signal Generator, Signal Modifier, Control.

Why Modular Synthesis?



Unmatched Flexibility

Ideal for experimental sound design and live performances.

Hands-On Control

For Real-time manipulation and musical expression.

Scalability

Start small and expand as needed.

Existing Solutions

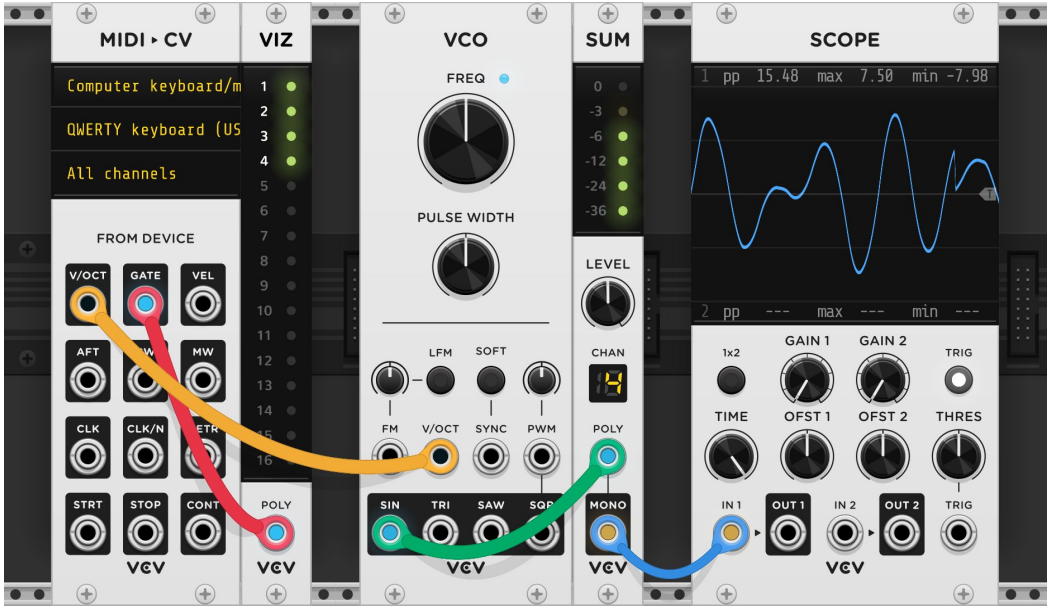
Virtual Racks

Advantages:

- Lower Cost than Hardware
- Supports Polyphony
- Accessible for Beginners

Disadvantages:

- Lack of Physical Control
- Latency Issues
- Increased Screen Time



Example: Virtual Rack Modules

Eurorack Multi Oscillators

Advantages:

- Analog Oscillators
- Physical Controls
- Industry Standard

Disadvantages:

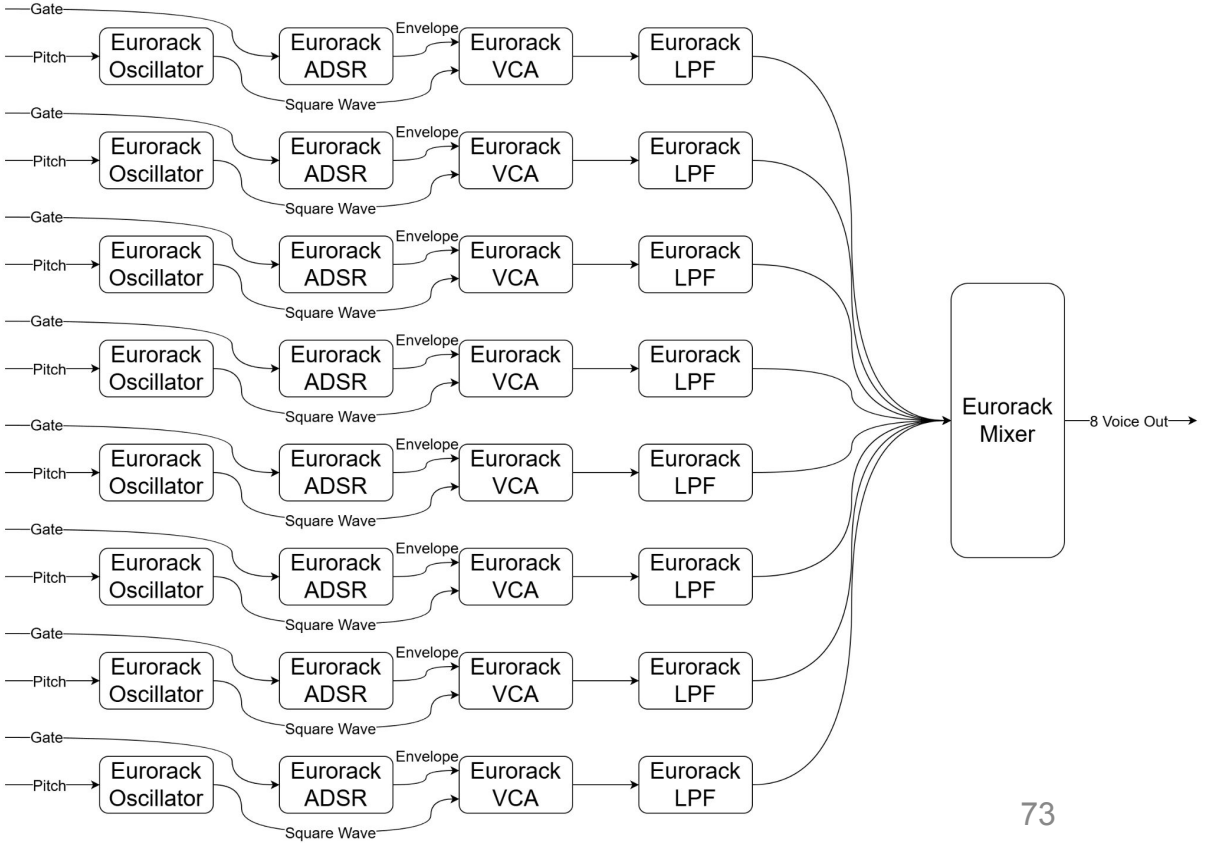
- Paraphonic
- Complex: Non-Standardized CV Limits Control
- Expensive: Quad VCO = $419.99

Example: Eurorack Modules

Comparison

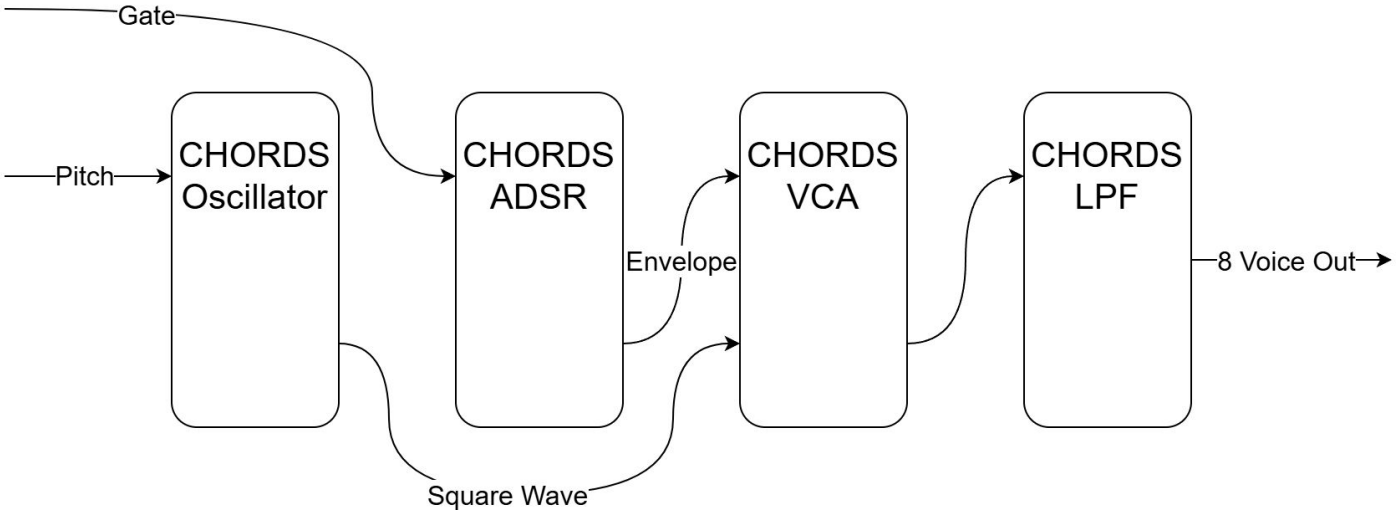
Eurorack 8 Voice Synth

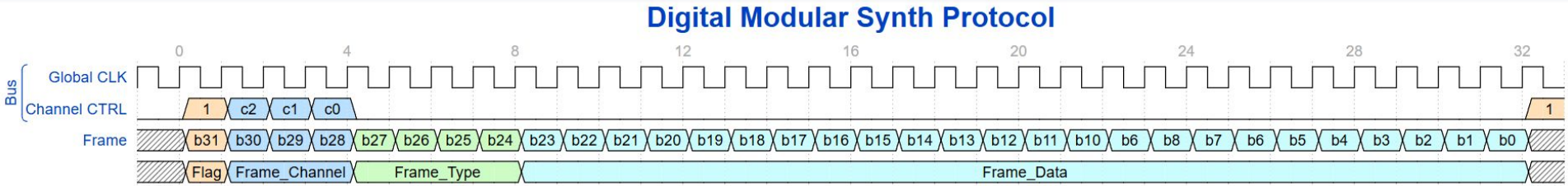
50+ Patch Cables



CHORDS 8 Voice Synth

6 Patch Cables

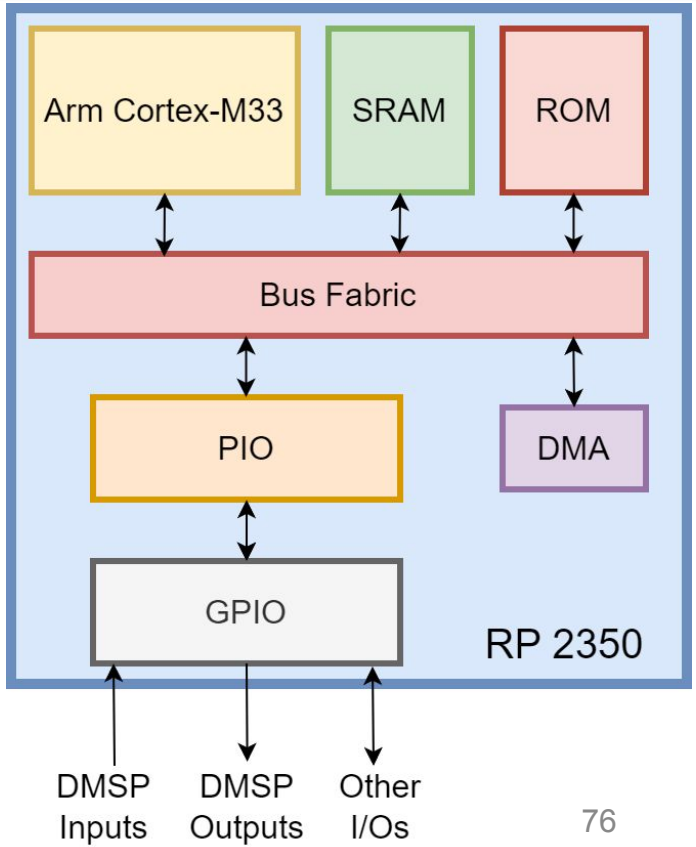




- Each frame is 32 bits:
- Channel Control Overhead 4 bits + Frame Type 4 bits + Frame Data 24 bits
- Start bit for synchronization, followed by 3 Channel Control bits allows for 8 Channels.
- 4 Frame Type bits allows for 16 frame types, eg. complete Midi messages, Control Signals, Audio.
- Each Frame contains 24 bits of Frame Data

Software Design

- DMSP utilizes PIO sm and DMA channels to minimize processor overhead
- RP 2350 Arm core runs module code, reads input buffer from SRAM and fills output buffer
- DMA transfers DMSP frames from SRAM to output PIO FIFO, vice versa
- PIO fills and empties its FIFOs in syncroniznation with Global CLK



Alternative Design Matrix for Output Module

	I2S Stereo Decoder (AdaFruit)	I2S Audio Breakout (Sparkfun)	ESP32 with I2S	DAC (HiFiBerry)
Cost (0.45)	0.45 ($6.95)	0.22 ($17.95)	0.28 ($22.99)	0.05 ($58.58)
Output Quality (Sample Rate: 24-bit 44.1KHz) (0.33)	0.175 (24-bit 44.1KHz)	0.175 (24-bit 44.1KHz)	0.20 (24-bit 44.1KHz, less noise)	0.45 (24-bit 192KHz)
Capability & Additional Features (0.22)	0.225	0.10	0.275	0.40
Score	30.975%	17.875%	25.25%	25.9%

Alternative Design Matrix for Microcontroller

	RP2350 (pico 2)	RP2040 (pico 1)	Teensy 4.0	ESP8266
Cost (0.5)	0.3243 (5.00$)	0.4054 (4.00$)	0.0676 (23.80$)	0.2027 (7.99$)
Clock Speed (0.25)	0.2442 (150 MHz)	0.1250 (100 MHz)	0.4769 (600 MHz)	0.1538 (80 MHz)
Memory (0.25)	0.2942 (520 KB)	0.1541 (264 KB)	0.4703 (1024 KB)	0.0813 (112 KB)
Score	29.68%	27.25%	27.06%	16.01%

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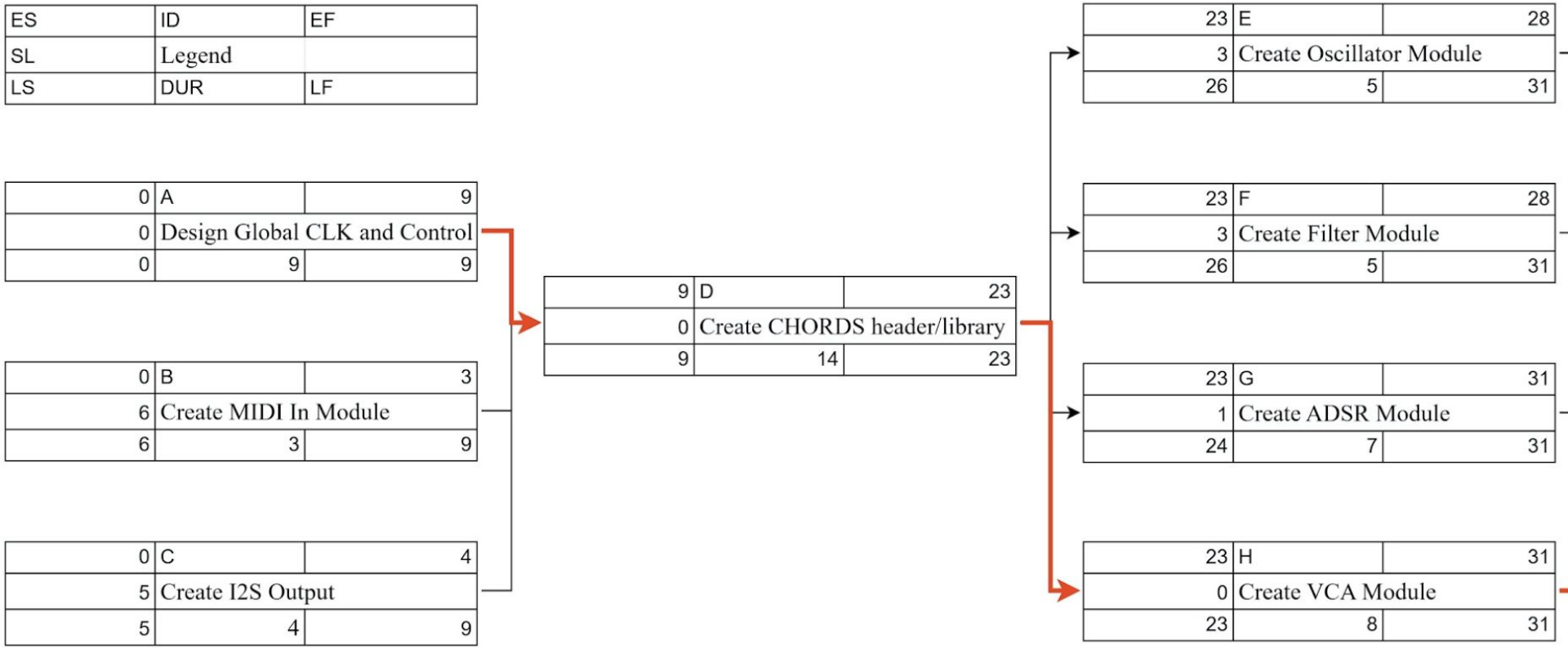
Critical Path (Winter)



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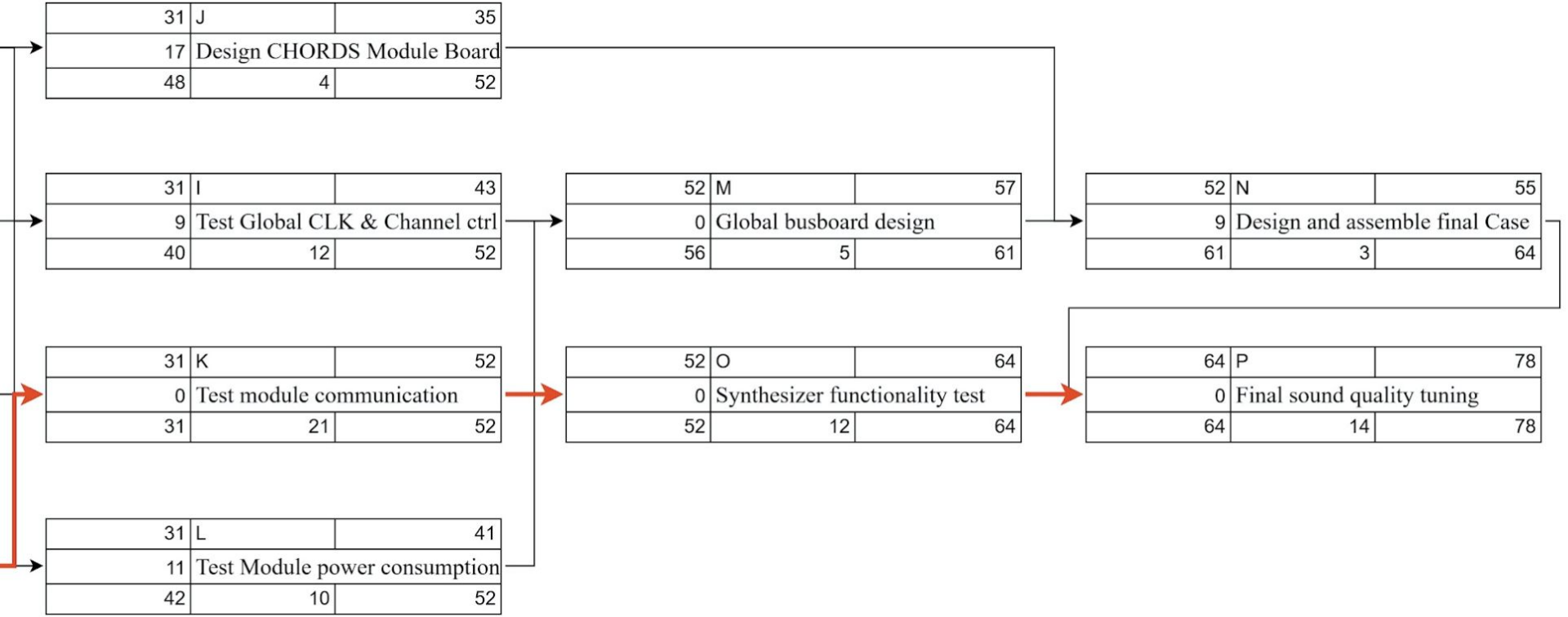
Critical Path (Spring)



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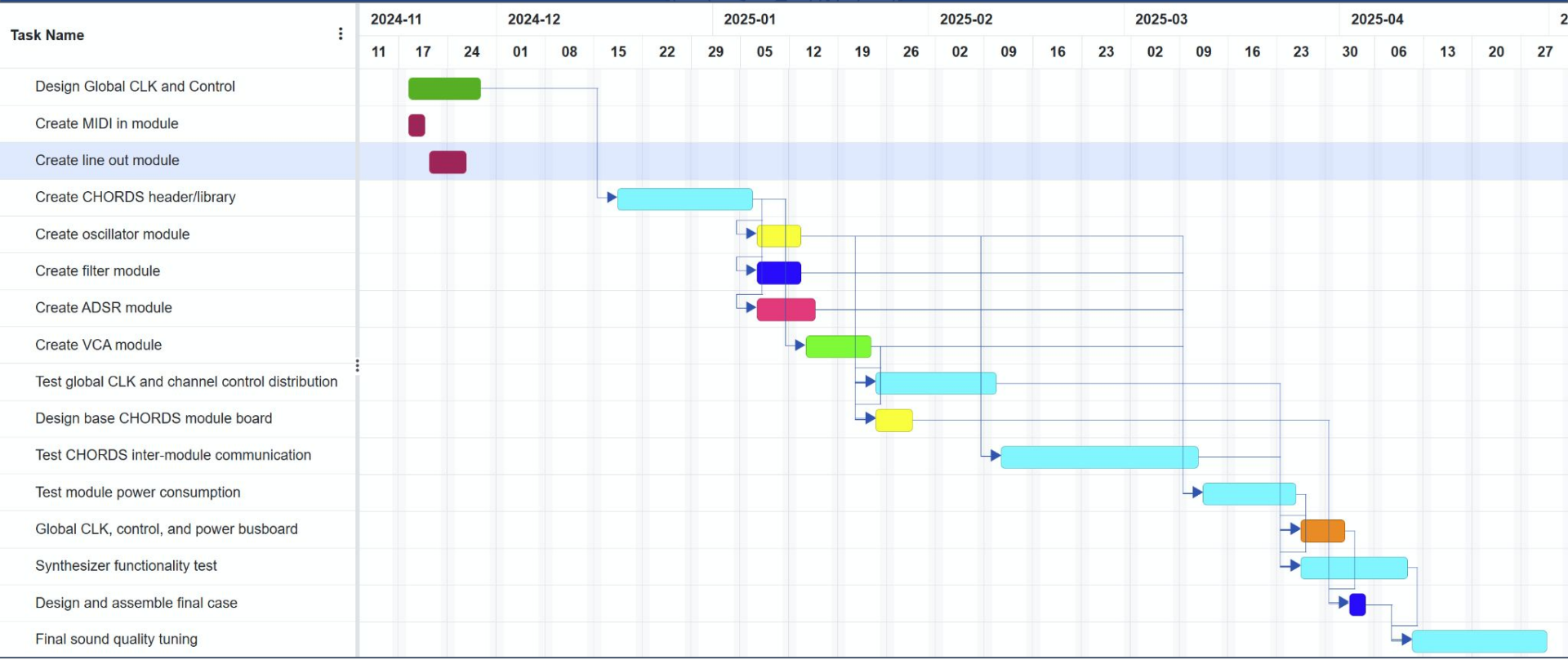
Gantt Chart



Julius: Bjorn: Madison: Everyone:

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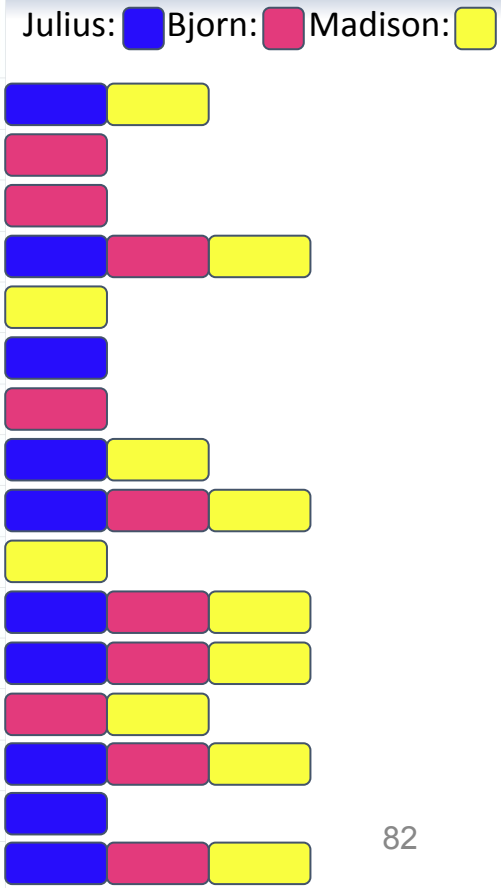
Schedule

ID	Task Name	Start	End	Duration	Progress %
1	Design Global CLK and Control	2024-11-18	2024-11-28	9 days	100
3	Create MIDI in module	2024-11-18	2024-11-20	3 days	100
8	Create line out module	2024-11-21	2024-11-26	4 days	100
2	Create CHORDS header/library	2024-12-18	2025-01-06	14 days	0
4	Create oscillator module	2025-01-07	2025-01-13	5 days	0
5	Create filter module	2025-01-07	2025-01-13	5 days	0
6	Create ADSR module	2025-01-07	2025-01-15	7 days	0
7	Create VCA module	2025-01-14	2025-01-23	8 days	0
9	Test global CLK and channel control distribution	2025-01-24	2025-02-10	12 days	0
12	Design base CHORDS module board	2025-01-24	2025-01-29	4 days	0
10	Test CHORDS inter-module communication	2025-02-11	2025-03-11	21 days	0
11	Test module power consumption	2025-03-12	2025-03-25	10 days	0
13	Global CLK, control, and power busboard	2025-03-26	2025-04-01	5 days	0
15	Synthesizer functionality test	2025-03-26	2025-04-10	12 days	0
14	Design and assemble final case	2025-04-02	2025-04-04	3 days	0
16	Final sound quality tuning	2025-04-11	2025-04-30	14 days	0



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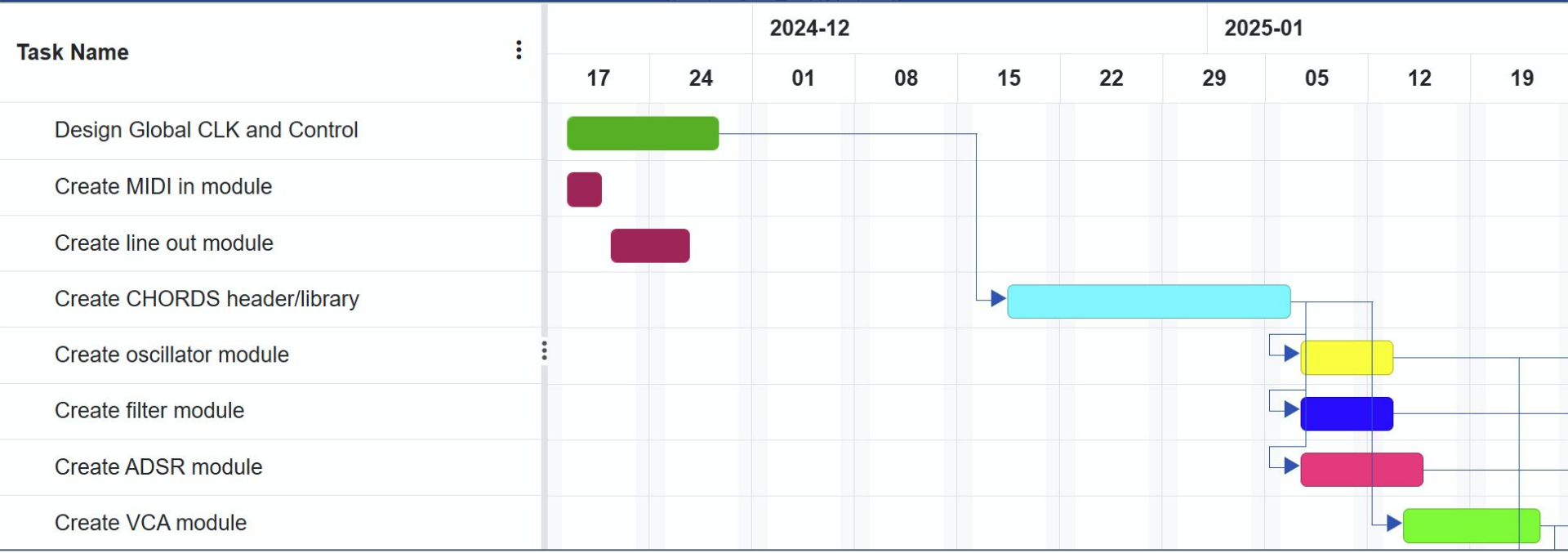
Gantt Chart



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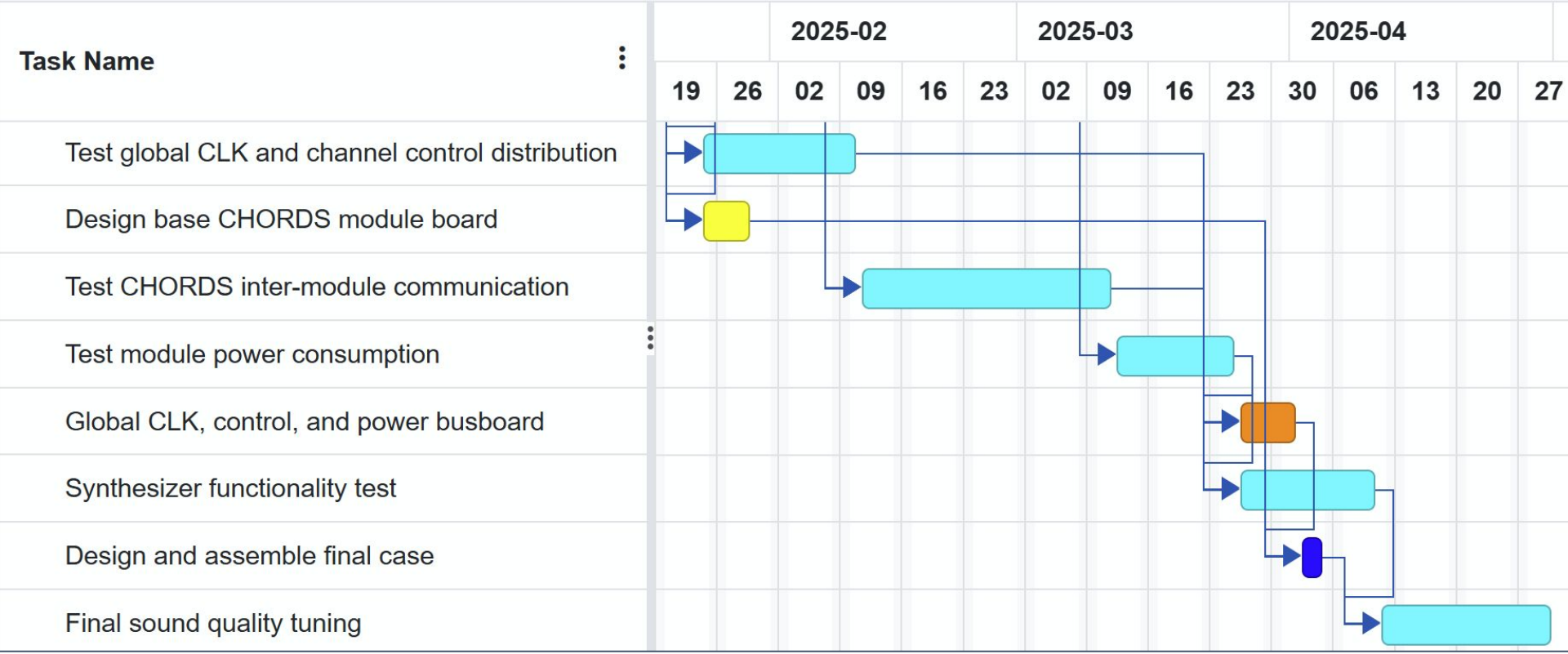
Gantt Chart



Julius: Bjorn: Madison: Everyone:

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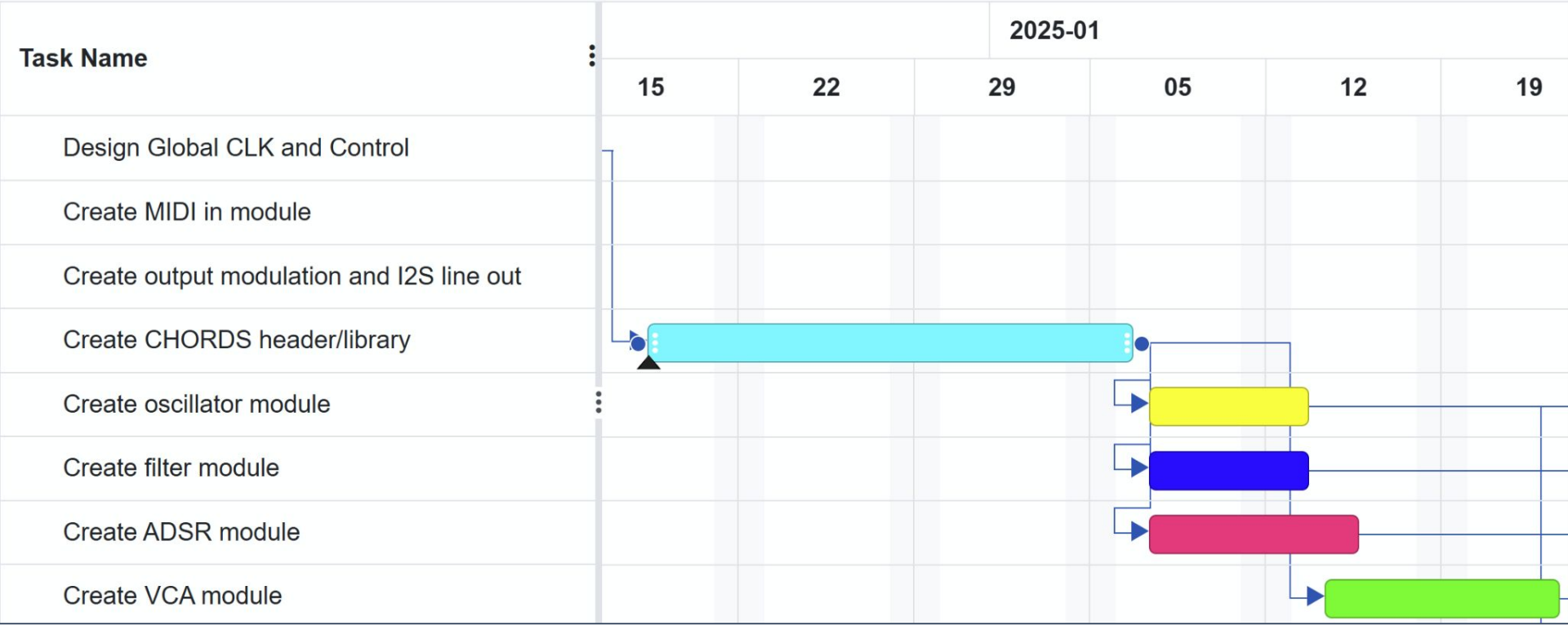
Winter Gantt Chart



Winter Schedule

2	Create CHORDS header/library		14 days	2024-12-18	2025-01-06
4	Create oscillator module		5 days	2025-01-07	2025-01-13
5	Create filter module		5 days	2025-01-07	2025-01-13
6	Create ADSR module		7 days	2025-01-07	2025-01-15
7	Create VCA module		8 days	2025-01-14	2025-01-23

Julius: Bjorn: Madison: Everyone:

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List of Tests

Test Number	Objective	ER to address	Status	Notes
ST. 1	Global Clock Accuracy and Stability	ER. 4	Complete	CLK = 10.24 +/- 0.01 MHz
FT. 1	Oscillator Output	ER. 3	Complete	
FT. 2	MIDI Input	ER.2 & ER. 6	Complete	delay < 5ms
FT. 3	Harmonic Distortion in Audio output module	ER. 6	In Progress	THD < 1%
FT. 4	Create Chords header/ library	ER. 3	Complete	
FT. 5	VCA Module	ER. 3	Complete	
FT. 6	Filter Module	ER. 3	Complete	
FT. 7	I2S Module	ER. 3	Complete	

Functional Test 1

Oscillator Module Test

Purpose:

- The objective of this test is to generate a sine wave that can later be used to capture MIDI data and send it through preceding modules. The sine wave should be tuned to A4 at 440 Hz which is standard tuning in western music.

Setup:

- Power the Oscillator module using 3.3v
- Attach test points to the output pins of the oscillator module
- Read frequency data on oscilloscope

Functional Test 1

Oscillator Module Test

Results:

-

Conclusion:

Functional Test 2

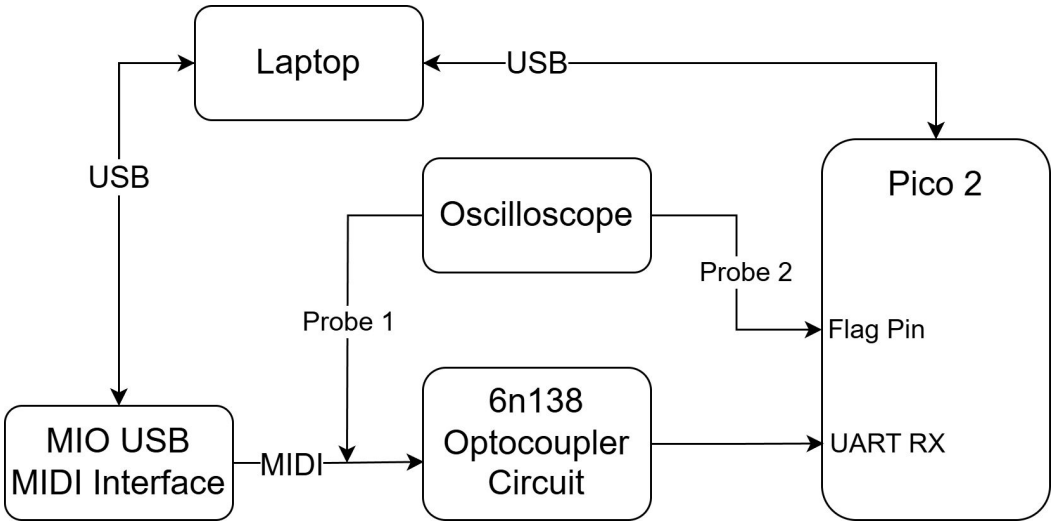
MIDI Input and Latency Test

Purpose:

- Test that the Pico 2 can receive MIDI messages and correctly interpret them within our latency requirement of 5ms (ER 4, 5)

Setup:

- Hardware UART used to receive MIDI messages
- Protection Circuit built to protect RX Pin
- MIO MIDI USB Interface to send MIDI messages
- Flag pin is set when UART has data available, cleared when MIDI is decoded
- Oscilloscope measures timing of MIDI and Flag pin signals to determine latency
- RP 2350 prints MIDI messages to USB serial monitor



Functional Test 2

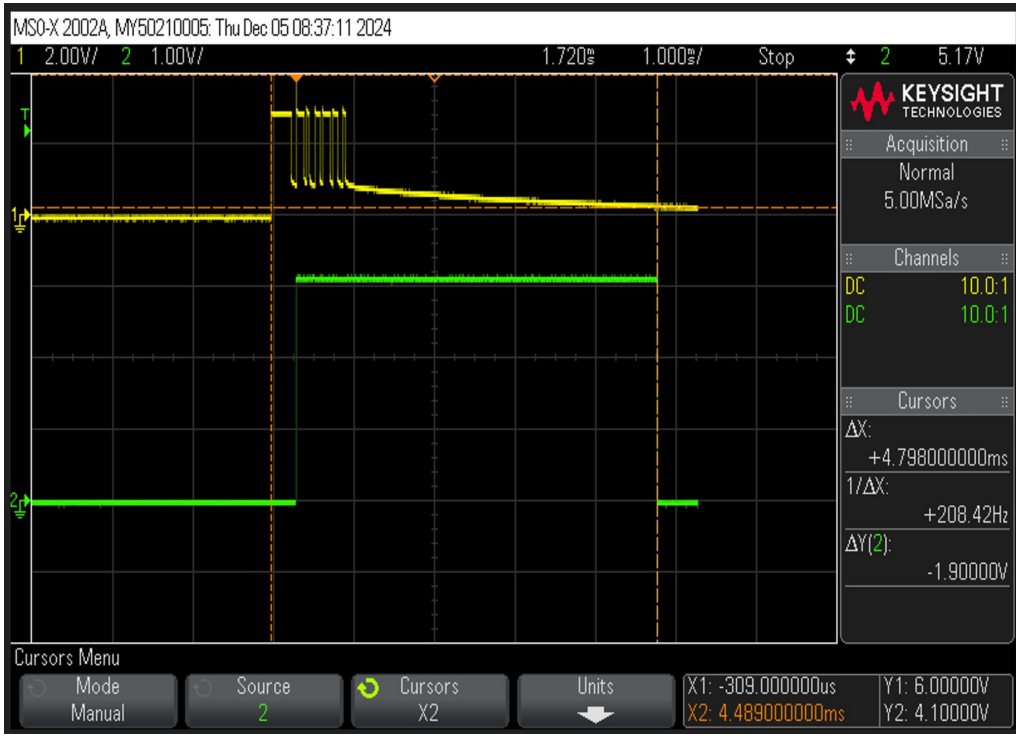
MIDI Input and Latency Test

Results:

- MIDI messages correctly interpreted
- Latency is under 5 ms goal at 4.798 ms

Conclusion:

This test was successful and satisfies our test objective. When completed, other modules will undergo latency tests with a similar setup.



Functional Test 4

CHORDS Header/Library Test

Purpose:

- The objective of this test is to develop and validate the Digital Modular Synth Protocol (DMSP) header. This includes ensuring the proper synchronization and transmission of frame data between modules in a modular synthesizer system. Key elements tested include frame synchronization, channel assignment, and data integrity for various frame types.

Setup:

- A prototype DMSP implementation loaded onto a microcontroller.
- A global clock bus operating at 10.24 MHz to synchronize data transmission.
- At least two connected modules (e.g., an oscillator module and a MIDI input module) to send and receive frame data.
- An oscilloscope to monitor the DMSP signal and verify frame timing and structure.
- A test script to generate different frame types, such as audio samples, MIDI commands, and control voltage (CV) data, and send them through the protocol.

Functional Test 4

CHORDS Header/Library Test

Results:

-

Conclusion:

Functional Test 5

VCA Module Test

Purpose:

- The goal of this test is to hear the signal generated to be attenuated as it passes through the Voltage Controlled Amplifier (VCA) module. The attenuation of the signal is controlled by a potentiometer that is connected to this module.

Setup:

- Set up the signal generator to send a waveform through the VCA module
- Ensure these modules are synced using the DMSP modules connected to each PICO-2
- Check test points as the signal is being sent into the VCA module, and at the output of the VCA module

Functional Test 5

VCA Module Test

Results:

-

Conclusion:

Functional Test 6

Filter Module Test

Purpose:

- The objective of this test is to ensure the filter module can manipulate a low pass filter to be adjusted from 20k Hz to 0 Hz. This filter will be controlled with a potentiometer attached to the module.

Setup:

- Set up the signal generator to send a waveform through the Filter module
- Ensure these modules are synced using the DMSP modules connected to each PICO-2
- Check test points as the signal is being sent into the Filter module, and at the output of the Filter module

Functional Test 6

Filter Module Test

Results:

-

Conclusion:

Functional Test 7

I2S Module Test

Purpose:

- The objective of this test is to make sure the I2S audio output module is able to generate an audible tone from the Oscillator module. This output can be observed on an oscilloscope as well to ensure there is no unwanted distortion or jitter from the output.

Setup:

- Power the modules with 3.3V
- Make sure the signal generator is connected to the I2S module.
- Plug in headphones to the mounted jack on the module board
- Attach oscilloscope to the input and output of the module

Functional Test 7

I2S Module Test

Results:

-

Conclusion:

List of Components

Part/ Quantity	Price	Description	Link	Test	ER#
PICO-2 (RP 2350)	$5 (x8)	Board used for Global Clock, DMSP, and Modules	https://www.adafruit.com/product/6006	ST.1 FT.1 FT.2	ER.1 ER.2 ER.3 ER.5
I2S output Board	~$10	Audio output module	https://www.adafruit.com/product/3678	ST.1	ER.1 ER.2 ER.3
MIDI Controller	~$100 (Provided)	MIDI keyboard that will trigger input data	https://www.amazon.com/Nektar-SE49-49-Key-Controller-Keyboard/dp/B01MF9EJPG?th=1	ST.1	ER.4
3D printing	$20	For Case, knobs, and sliders	https://library.sonoma.edu/create/makerspace	N/A	MR.6
IC (6N138)	$0.96	MIDI Input module	https://www.digikey.com/en/products/detail/lite-on-inc./6N138/1969179	ST.1 FT.1	ER.4
Total Cost					$170.96

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List of Components

Part/ Quantity	Price	Description	Link	Test	ER#
PICO-2 (RP-2350)	$70 (x14)	Board used for Global Clock, DMSP, and Modules	https://www.adafruit.com/product/6006	ST.1, FT.1, FT.2	ER.1, ER.2, ER.3, ER.5
I2S output Board	~$10	Audio output module	https://www.adafruit.com/product/3678	ST.1	ER.1, ER.2, ER.3
MIDI Controller	~$100 (Provided)	MIDI keyboard that will trigger input data	MIDI	ST.1	ER.4
3D printing	$20	For Case, knobs, and sliders	Maker Space	N/A	MR.6
IC (6N138)	$0.96	MIDI Input module	IC	ST.1 FT.1	ER.4
PCB	$39.20 (x25)	Module architecture			
¼’ Jack		Front Panel Parameter			
Potentiometers	$1.20 (x50)	Front Panel Parameter	Potentiometers		
2-1825910-7 (Button)	$5.48 (x50)	Front Panel Parameter	Button		
Switch	$10.21 (x35)	Power Control	Power Switch		
IC (CD4053BE)	$10.94 (x25)	PCB Design	https://www.digikey.com/en/products/detail/texas-instruments/CD4053BE/67309		