PINBALL MACHINE
DEVELOPMENT NOTES

EPIC Robotz, Fall 2022 Project

AC Wiring

Otherwise known as “Mains” Wiring

110 Volt AC Line Items

- Power to the main 20-48 Adjustable Supply for Magnets and Coils
- Power to 12 Volt Supply for high powered LEDs
- Power to 5 Volt Supply for Raspberry, Logic, and NeoPixel LEDs
- Power to 17” Monitor used as the Score Board

Questions to Resolve

Requirements:
- One ON/OFF switch for entire machine.
- One AC power cord to outlet on a wall to power entire machine.

Questions:
- Where should the On/Off switch be mounted?
- Do we need a fuse? If so, where should it be mounted?
- How should the power be routed to various components?
  - Use Power Strip and Multiple AC cords inside of machine?
  - Or use terminal screw strip and route AC power over custom wires?

Controlling Magnets and Coils

List of High Voltage Magnets and Coils

Feature	Number	Coil Resistance	Coil Windings	Amps @ 48v
Flippers	3	3.3 / 350	25-500 / 34-4500	14.5
Bumpers	3	11.2	26-1200	4.2
Kickers	3	4	023-800	12
New Ball Kicker	1	4	023-800	12
Dropped Ball Kicker	1	4	023-800	12
Replacement	0	14.25	26-1500	3.4
Total Circuits	**11**			

Direct Control vs Computer Control

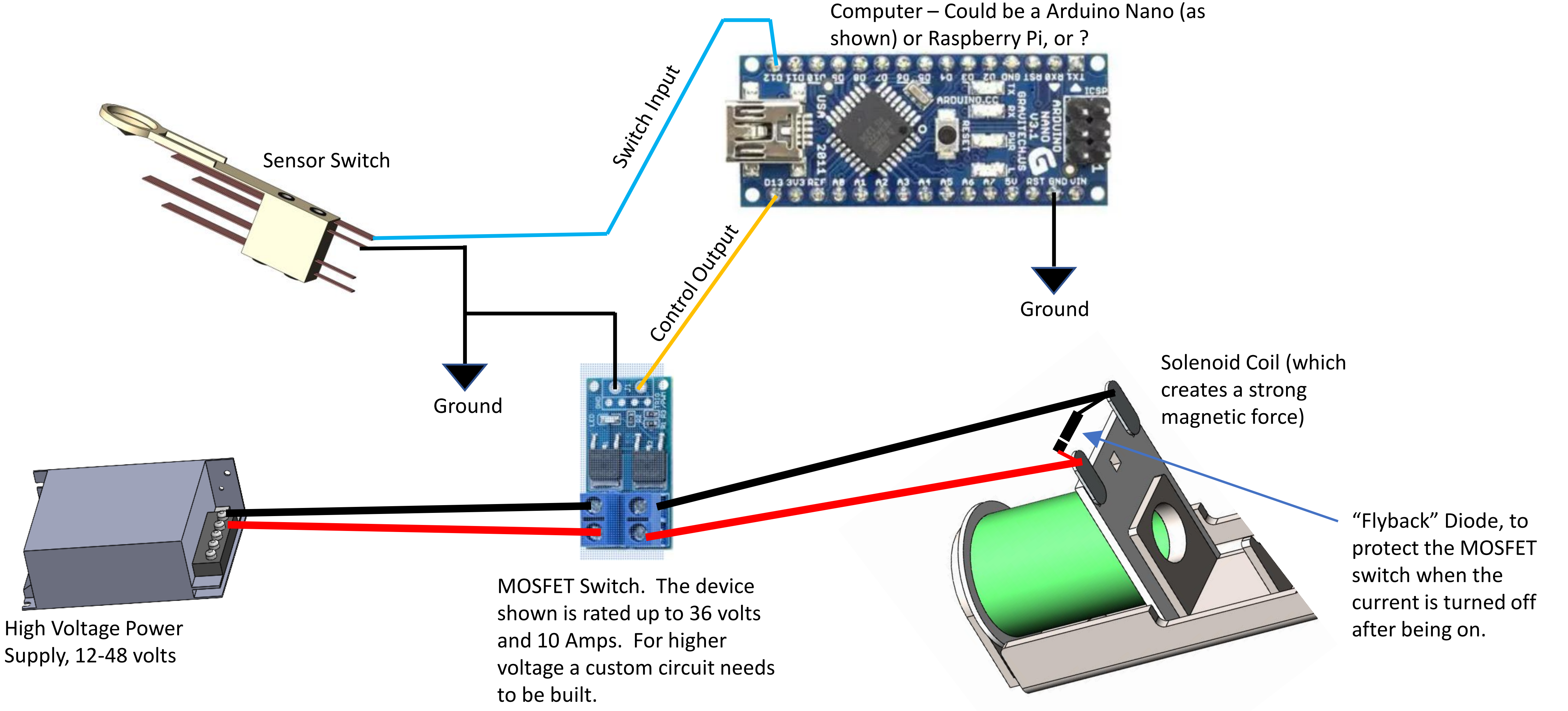
Direct Control:

- Current runs though “switch” directly to Coil.
- Switch is physically closed by human or pinball
- Switch must be rated for high current
- By itself, computer does not know about switch closure, and therefore cannot score or make sounds
- High current must be limited by circuit design
- In old pinball machines, this design was only choice since there were no computers.

Computer Control:

- The computer has ability to fire the coil anytime it wants
- The computer reads switch inputs and decides when the coil should be fired.
- Using PWM, the computer can change the strength of the coil magnet, and limit current.
- The sensing switches can be driven with very low current and voltage, so they can be much smaller.
- Scoring is easy, just becomes a software issue
- Downsides:
  - The computer must respond fast enough so that any delay in coil activation does not change gameplay. (Flippers, Kickers, Bumpers, etc)
  - A special computer-controlled switch is needed for each coil. (We use MOSFET switches)

Typical Coil Wiring



MOSFET for Coil Switch: FQP30N06L

Important Parameters:

- 60 Volts
- 32 Amps
- .045 ohm On State Resistance
- About $1.00 each

FAIRCHILD SEMICONDUCTOR®

November 2013

FQP30N06L

N-Channel QFET® MOSFET

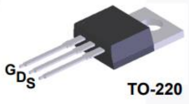
60 V, 32 A, 35 mΩ

Description

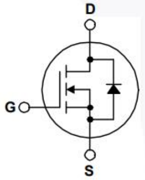
This N-Channel enhancement mode power MOSFET is produced using Fairchild Semiconductor's proprietary planar stripe and DMOS technology. This advanced MOSFET technology has been especially tailored to reduce on-state resistance, and to provide superior switching performance and high avalanche energy strength. These devices are suitable for switched mode power supplies, audio amplifier, DC motor control, and variable switching power applications.

Features

- 32 A, 60 V, $R_{DS(on)}$ = 35 mΩ (Max.) @ V_{GS} = 10 V, I_D = 16 A
- Low Gate Charge (Typ. 15 nC)
- Low Crss (Typ. 50 pF)
- 100% Avalanche Tested
- 175°C Maximum Junction Temperature Rating



TO-220



Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

Symbol	Parameter		FQP30N06L	Unit
V_{DSS}	Drain-Source Voltage		60	V
I_D	Drain Current - Continuous (T_C = 25°C)		32	A
	- Continuous (T_C = 100°C)		22.6	A
I_{DM}	Drain Current - Pulsed	(Note 1)	128	A
V_{GSS}	Gate-Source Voltage		± 20	V
E_{AS}	Single Pulsed Avalanche Energy	(Note 2)	350	mJ
I_{AR}	Avalanche Current	(Note 1)	32	A
E_{AR}	Repetitive Avalanche Energy	(Note 1)	7.9	mJ
dv/dt	Peak Diode Recovery dv/dt	(Note 3)	7.0	V/ns
P_D	Power Dissipation (T_C = 25°C)		79	W
	- Derate above 25°C		0.53	W/°C
T_J, T_{STG}	Operating and Storage Temperature Range		-55 to +175	°C
T_L	Maximum Lead Temperature for Soldering, 1/8" from Case for 5 seconds		300	°C

FQP30N06L — N-Channel QFET® MOSFET

Package Marking and Ordering Information

Part Number	Top Mark	Package	Packing Method	Reel Size	Tape Width	Quantity
FQP30N06L	FQP30N06L	TO-220	Tube	N/A	N/A	50 units

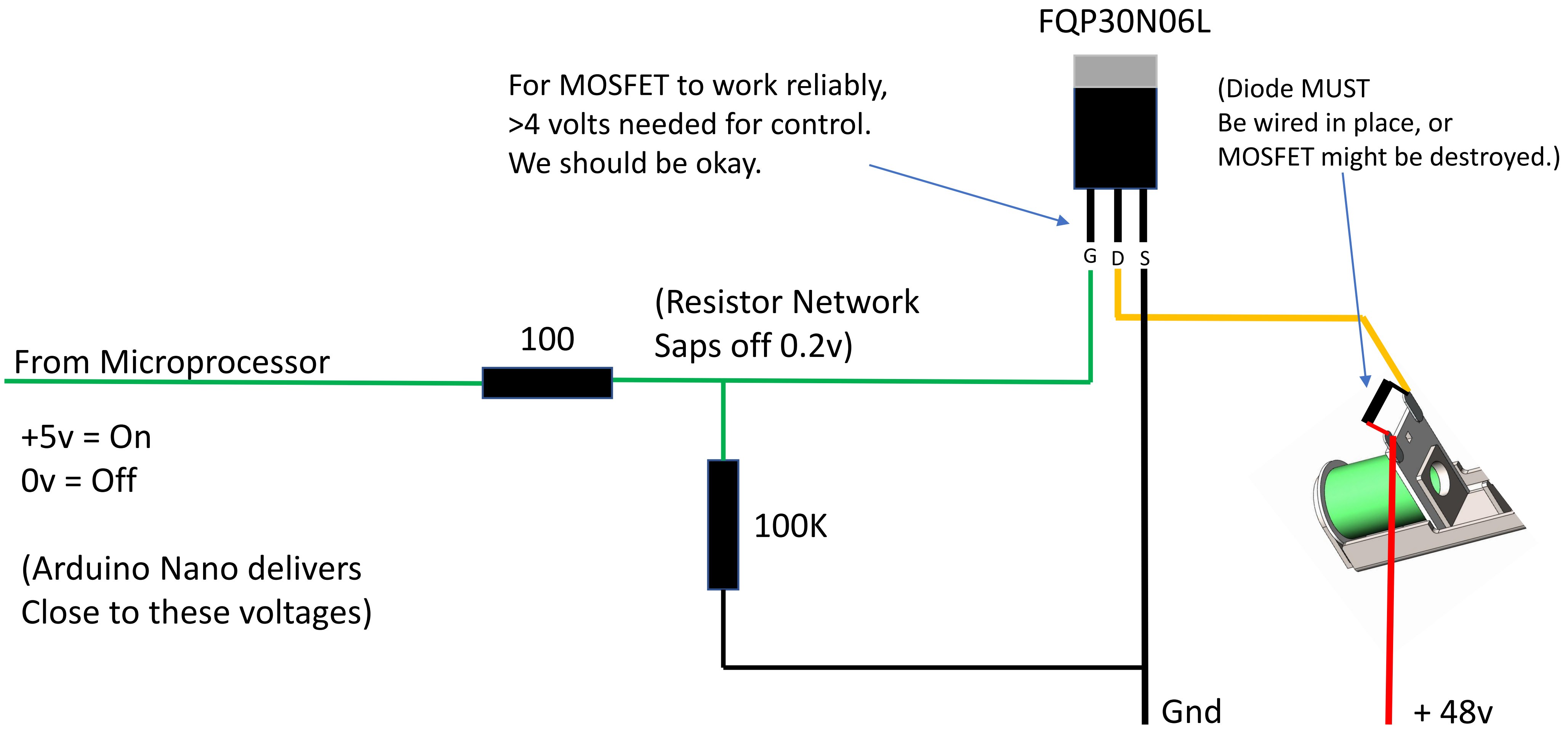
Electrical Characteristics T_C = 25°C unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
Off Characteristics						
BV_{DSS}	Drain-Source Breakdown Voltage	V_{GS} = 0 V, I_D = 250 μA	60	--	--	V
ΔBV_{DSS} / ΔT_J	Breakdown Voltage Temperature Coefficient	I_D = 250 μA, Referenced to 25°C	--	0.06	--	V/°C
I_{DSS}	Zero Gate Voltage Drain Current	V_{DS} = 60 V, V_{GS} = 0 V	--	--	1	μA
		V_{DS} = 48 V, T_C = 150°C	--	--	10	μA
I_{GSSF}	Gate-Body Leakage Current, Forward	V_{GS} = 20 V, V_{DS} = 0 V	--	--	100	nA
I_{GSSR}	Gate-Body Leakage Current, Reverse	V_{GS} = -20 V, V_{DS} = 0 V	--	--	-100	nA
On Characteristics						
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS} = V_{GS}, I_D = 250 μA	1.0	--	2.5	V
$R_{DS(on)}$	Static Drain-Source On-Resistance	V_{GS} = 10 V, I_D = 16 A V_{GS} = 5 V, I_D = 16 A	-- --	0.027 0.035	0.035 0.045	Ω
g_{FS}	Forward Transconductance	V_{DS} = 25 V, I_D = 16 A	--	24	--	S
Dynamic Characteristics						
C_{iss}	Input Capacitance	V_{DS} = 25 V, V_{GS} = 0 V, f = 1.0 MHz	--	800	1040	pF
C_{oss}	Output Capacitance		--	270	350	pF
C_{rss}	Reverse Transfer Capacitance		--	50	65	pF
Switching Characteristics						
$t_{d(on)}$	Turn-On Delay Time	V_{DD} = 30 V, I_D = 16 A, R_G = 25 Ω (Note 4)	--	15	40	ns
t_r	Turn-On Rise Time		--	210	430	ns
$t_{d(off)}$	Turn-Off Delay Time		--	60	130	ns
t_f	Turn-Off Fall Time		--	110	230	ns
Q_g	Total Gate Charge	V_{DS} = 48 V, I_D = 32 A, V_{GS} = 5 V (Note 4)	--	15	20	nC
Q_{gs}	Gate-Source Charge		--	3.5	--	nC
Q_{gd}	Gate-Drain Charge		--	8.5	--	nC
Drain-Source Diode Characteristics and Maximum Ratings						
I_S	Maximum Continuous Drain-Source Diode Forward Current		--	--	32	A
I_{SM}	Maximum Pulsed Drain-Source Diode Forward Current		--	--	128	A
V_{SD}	Drain-Source Diode Forward Voltage	V_{GS} = 0 V, I_S = 32 A	--	--	1.5	V
t_{rr}	Reverse Recovery Time	V_{GS} = 0 V, I_S = 32 A, dI_F / dt = 100 A/μs	--	60	--	ns
Q_{rr}	Reverse Recovery Charge		--	90	--	nC

Notes:
1. Repetitive Rating : Pulse width limited by maximum junction temperature.
2. L = 400 μH, I_{AS} = 32 A, V_{DD} = 25 V, R_G = 25 Ω, starting T_J = 25°C.
3. I_{SD} ≤ 32 A, di/dt ≤ 300 A/us, V_{DD} ≤ $BV_{DSS,}$ starting T_J = 25°C.
4. Essentially independent of operating temperature.

FQP30N06L — N-Channel QFET® MOSFET

Building a MOSFET Switch



Experiments for Computer Control

Control Questions

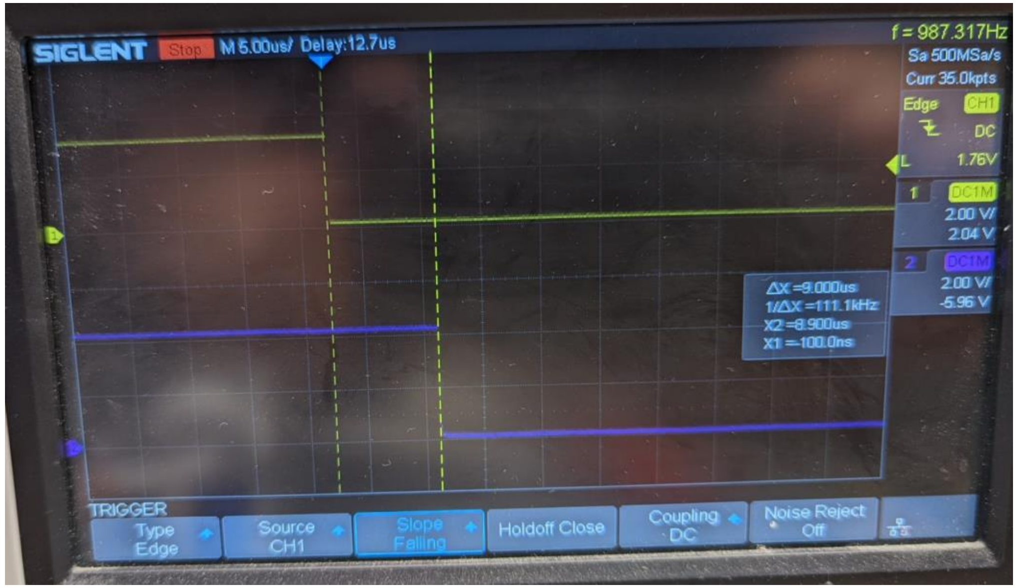
- What Electrical Architecture should be used to respond quickly to sensor inputs?
- It a cheap Arduino Nano ($2.00 each) fast enough for our needs?

Computerized Control Test

- Testing ability of microprocessor to be in full control of solenoid
- Wrote NanoMagTest
- Had following states:
  - READY – fires the solenoid on switch closure
  - FIRING – Holds the solenoid down for 100 msec
  - STUCK – Comes here after FIRING if switch is still closed. Waits for switch to open.
  - RESTING – comes here after FIRING or STUCK to “rest” before allowing another cycle… Rest time was 80ms
- Observations:
  - Seems to work.
  - Sometimes gets untriggered double strikes
  - Shaking and vibration of table is causes fires… Solve that with sturdy table?

Response Time Test

- Measure time to respond to interrupt on Pin 3 of NANO
- Looks like about 9 uses.

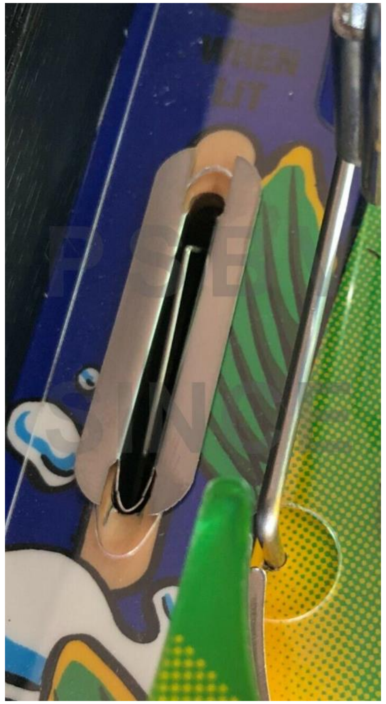



```
#define PIN_SQ 3  // Input Square Wave
#define PIN_OUT 4 // Output flasher

// the setup function runs once when you press reset or power the board
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(PIN_SQ, INPUT_PULLUP);
  pinMode(PIN_OUT, OUTPUT);
  attachInterrupt(digitalPinToInterrupt(PIN_SQ), sq_ISR, FALLING);
  Serial.begin(115200);
}
long volatile counter = 0;
long last_counter = 0;
int volatile iled = 0;

void sq_ISR() {
    counter++;
    iled++;
    if (iled > 1) iled = 0;
    if (iled == 0) digitalWrite(PIN_OUT, LOW);
    else digitalWrite(PIN_OUT, HIGH);
}
```

Notes on Ardunio NANO @ 16 MHz

- Max out square wave: 113 Khz, 8.8us
  - Two Digital Write Calls in a while(true) loop.
  - A NANO should execute 16 instructions every 1us.
  - The argues that the C loop generated about 8.8*16 = 140 Instructions!
  - (Same code should be about 10 instructions in assembly language, or over 1MHz square wave).

Slot Switches



Senses when ball rolls through a slot

Force Calculation

Assume Best Case: weight of entire ball presses down at right angle to flat, horizontal surface where the switch is located.

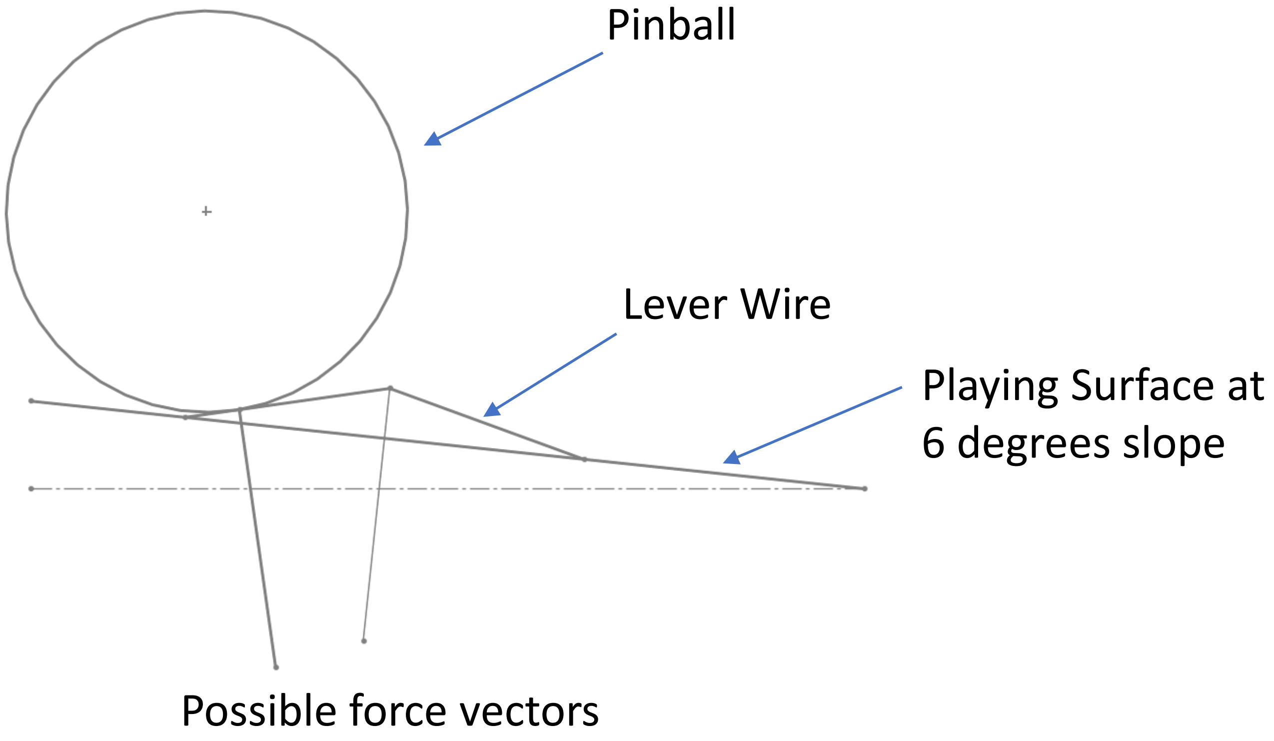
Weight of ball is about 0.15 pounds, or about 2.4 oz, or about 68 grams

Therefore, to account for misalignment, slope of table, and angle to where the force will be applied, assume we want an activating force of about half the weight of the ball, or about 34 grams, or 0.034 kg.

1 Newton of Force is 9.8 kg of mass.

Our Max Force = 0.034 * 9.8 = 0.33 Netwons

Note, also, we don’t want to slow the ball down or change its direction to activate the switch.

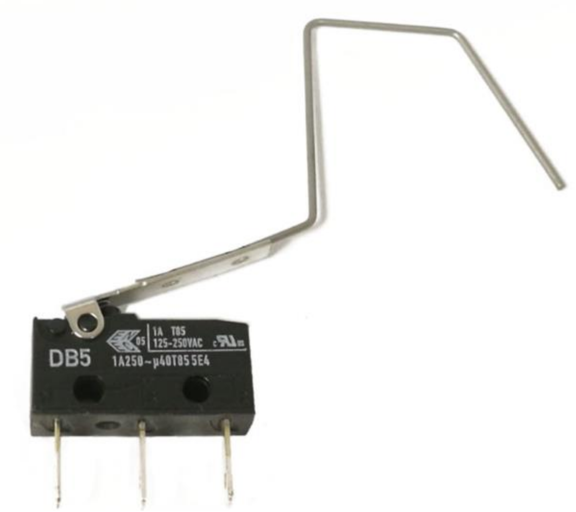


Old Machines, How They Did It

Williams/Bally Sub-Microswitch

About $5.00 each

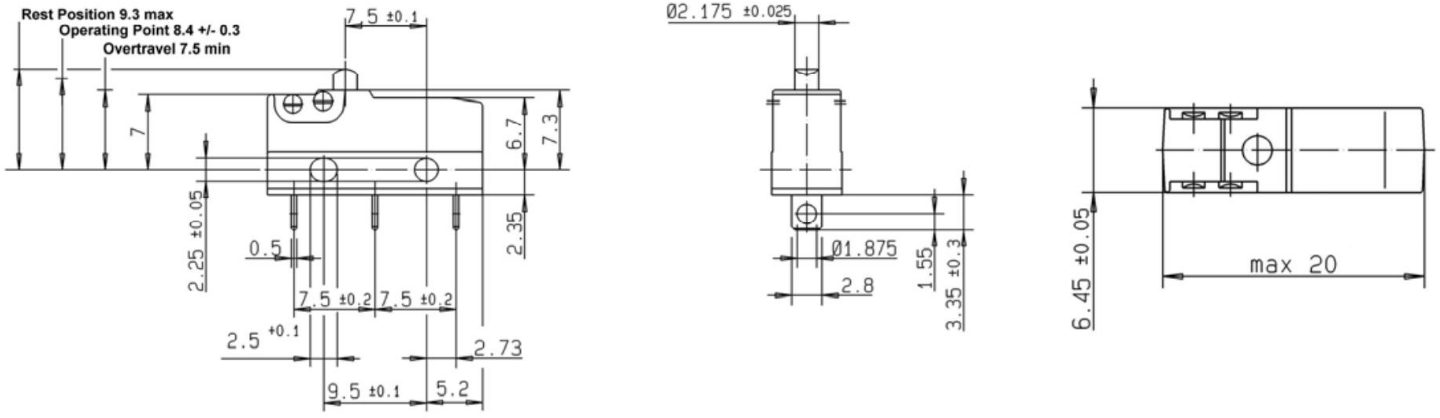
Appears to have spot welded paper clip wire



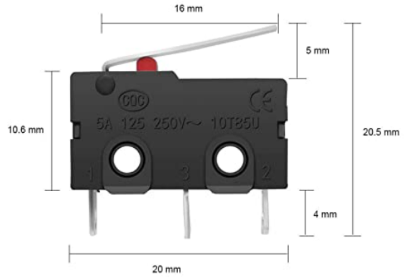
More Info on DB5 Switch

- Made by CHERRY
- Datasheet: https://www.farnell.com/datasheets/1641341.pdf
- Hard to Tell, but Operating Force seems to be about 0.50 N

Dimensions - millimeter



Possible Substitute Switches



MUZHI SPDT 1NO 1NC Hinge Lever Momentary Push Button Micro Limit Switch AC 5A 125V 250V 3 Pins 12 Pcs

Brand: MXRS

785 ratings | 30 answered questions

#1 Best Seller in Limit Switches

-33% $6.69 ($0.56 / Count)

List Price: ~~$9.99~~

prime

FREE Returns

Save 5% at checkout Terms

Style: 4

1	2	3	4
$6.99 ($0.58 / Count) prime	$6.99 ($0.58 / Count) prime	$6.99 ($0.58 / Count) prime	$6.69 ($0.56 / Count) prime

4 out of 5
Rated By 12 Customers

CHERRY SUB-MINIATURE SWITCH 1 AMP 125/ 250V .110" TERMINAL DB5G-B1AA 70 GRAM

Part # 95-1807-00

$4.00 ea.
$2.58 ea. L/ 100

Out of Stock, please contact your sales rep for updated ETA information

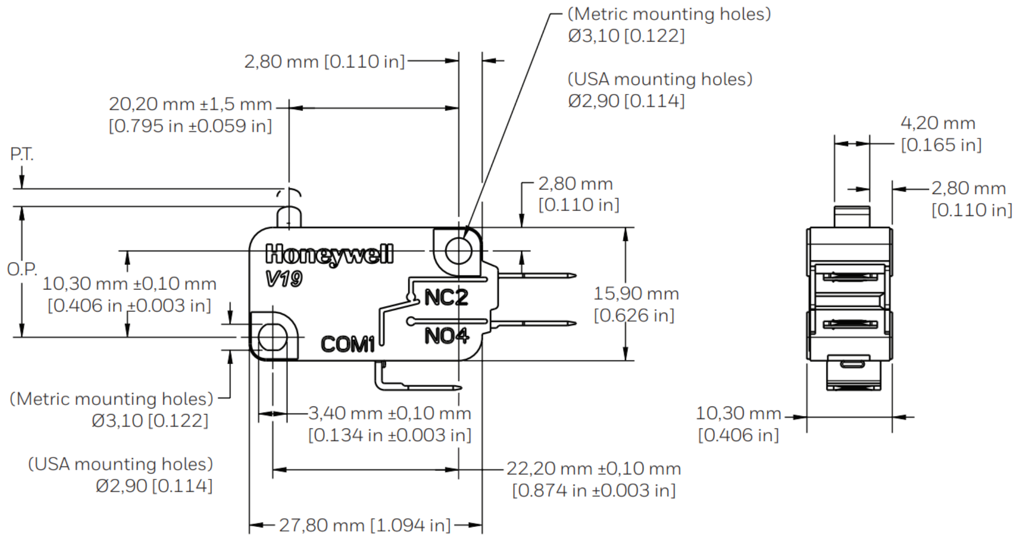
QTY: 1 ADD TO CART

I believe that this is the present-day raw switch that the original pinball machines used.

DigiKey Switches

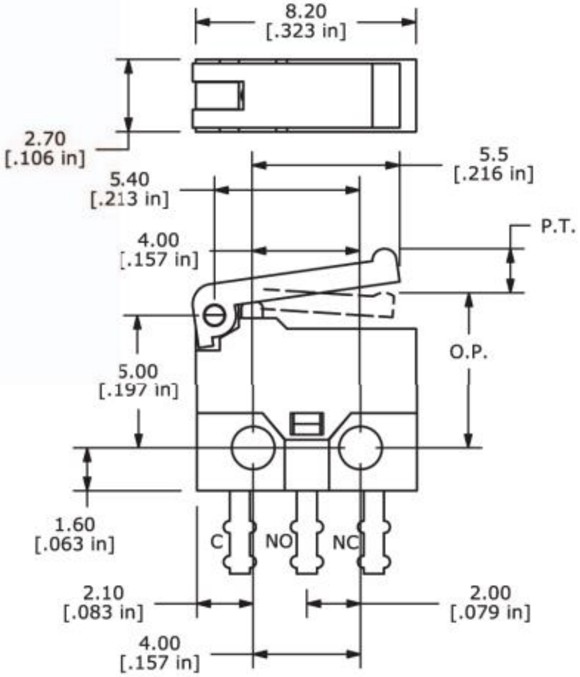
V19S05-HZ015A03

- 0.15 Netwons of force, or 15 grams of force
- Lever Far from Plunger
- 3.1mm Mounting Holes
- $1.93 each
- Plunger Travel: 9 + 3.8 + 2.0 mm

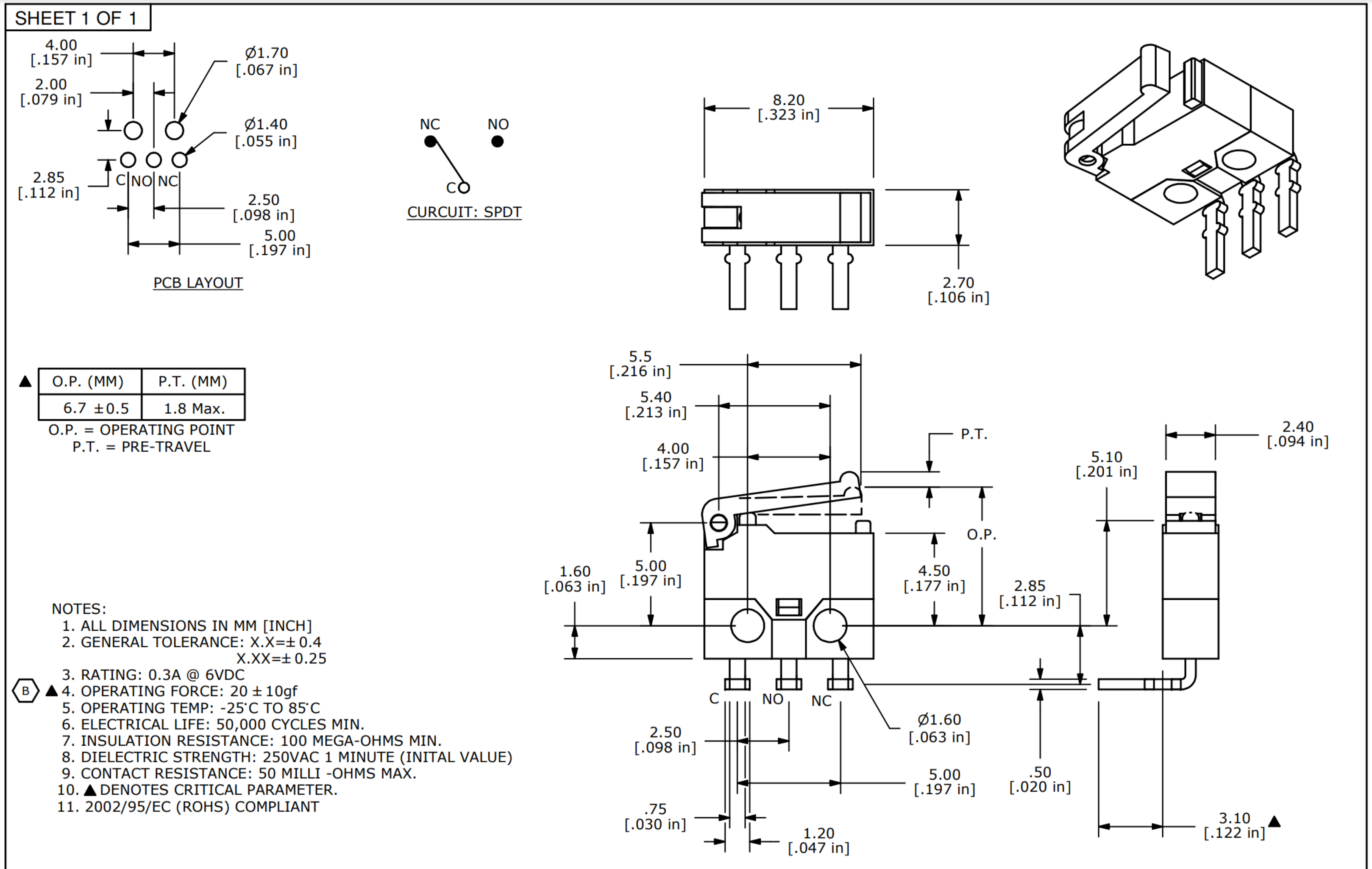


TS0101F020V3

- Made by E-Switch
- Only rated for 6v @ 0.3 amps
- 20 grams (+/- 10g) operating force
- PCB terminals – must be soldered
- About $1.00 each



Micro Switch: **TS0101F020V3**



REV	PCR NO	DESCRIPTION	DATE	BY
D	18561	BODY CHANGED TO ADD STOP	6/18/09	BLR
C	18269	TITLE CHANGE FROM TS0101F030V3	10/6/08	BLR
B	17974	CHANGE OPERATING FORCE SPEC	2/15/08	BLR
A	17918	New Product Release	1/8/08	rc

E-SWITCH™

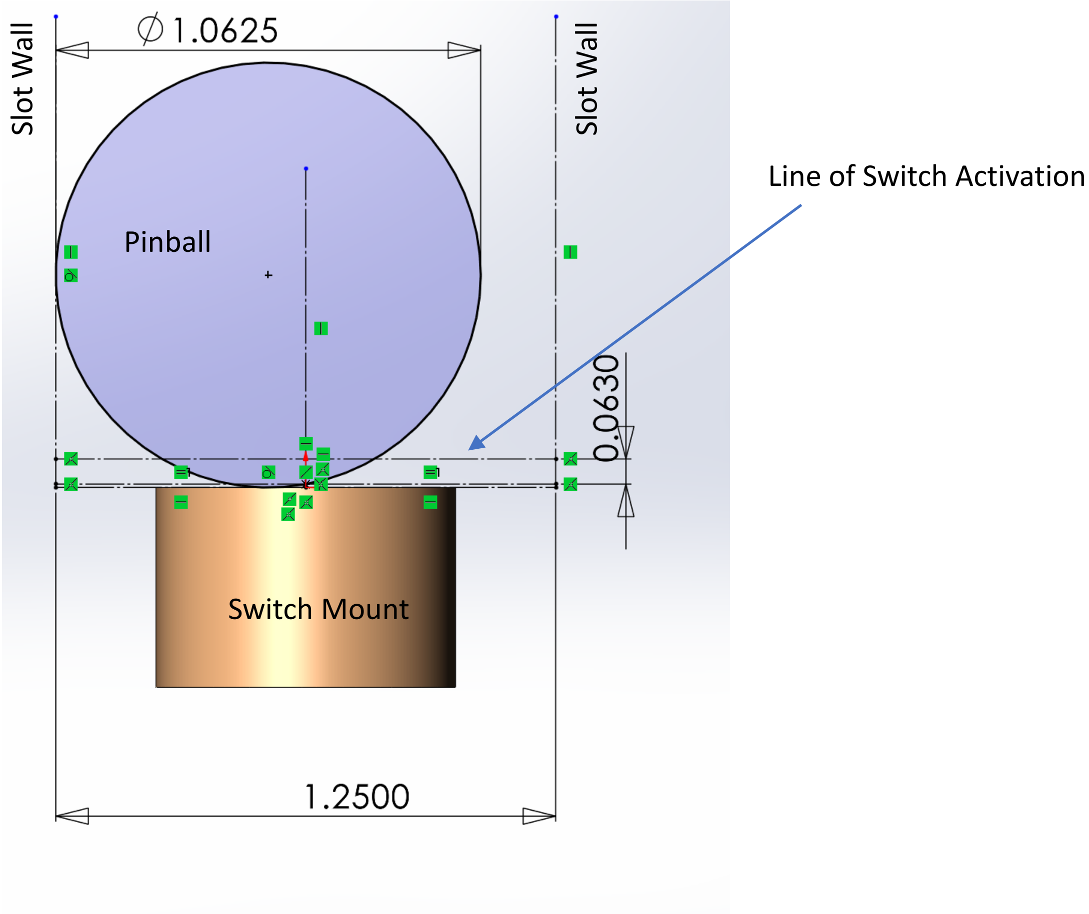
TITLE TS0101F020V3

SCALE	DATE	DR	DWG	REV
4=1	6/18/2009	BLR	Q980001	D

Most Promising

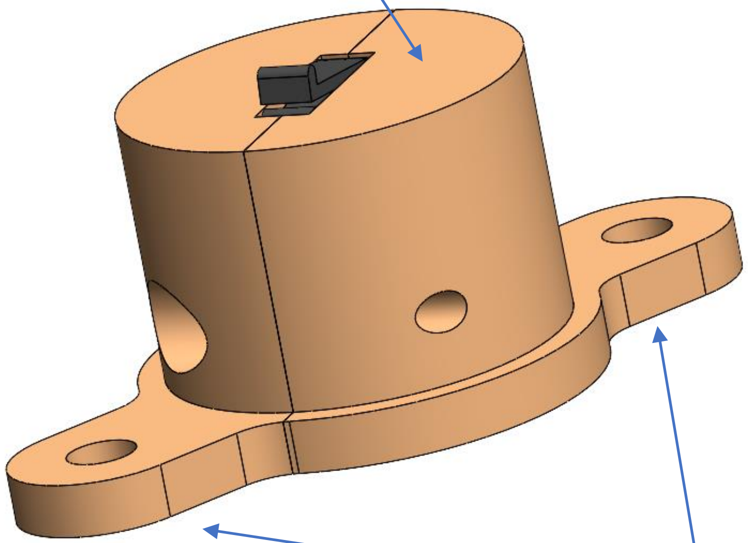
Drawing Showing that TS Micro Switch can Work

This shows that the switch should be activated even when the pinball is traveling against the slot side wall.

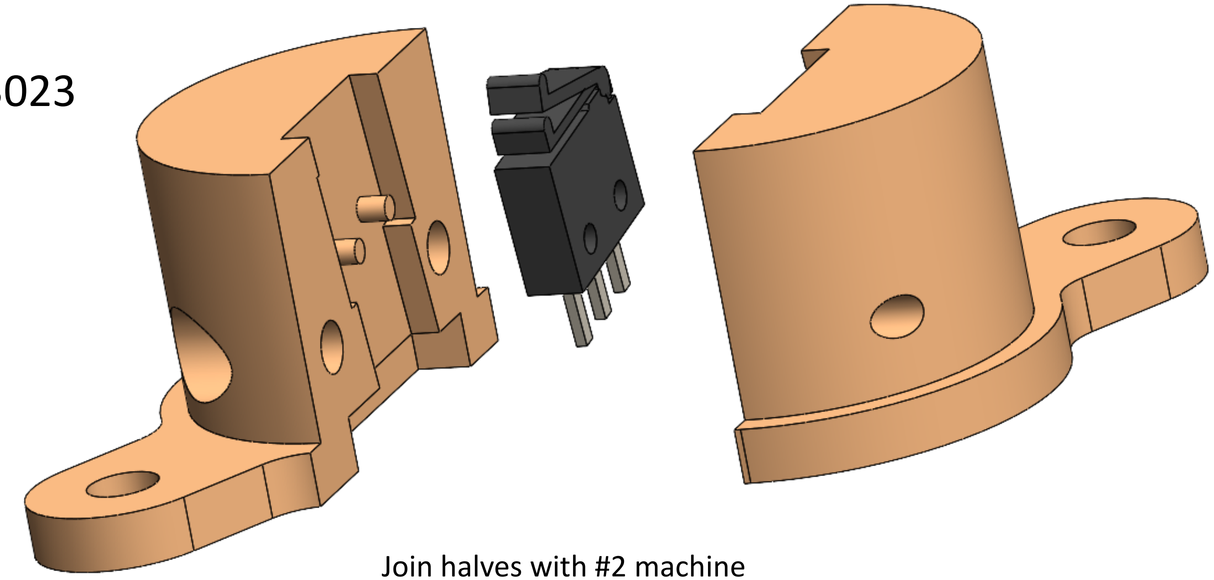


Micro-switch Mount for Slot Switches

Drill 0.75 inch hole in playing surface. Insert Part, making this surface flush with playing surface



F22-PM-3023



Join halves with #2 machine screws, 0.25 inches long

Mount with 2 #4 Pan Head Wood Screws, 0.5 inches long

Score Board

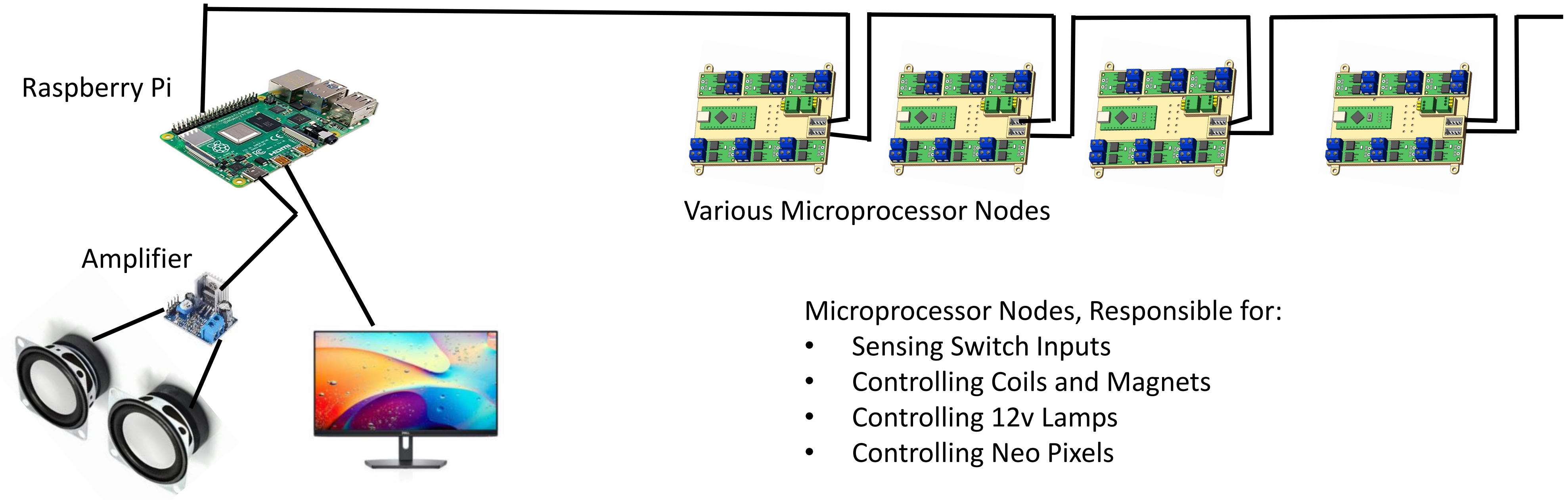
Requirements and Ideas

- Scoreboard Attached to rear of machine on pivots for transport
- Scoreboard houses Monitor and Speakers
- Scoreboard may house AC system, on/off switch, computers?
- Scoreboard has bright lights and Neo Pixels
- Must provide Disconnect of wires between scoreboard and rest of machine

Wires in Scoreboard Disconnect

Purpose	Conductor	Max Current	Plug Type
48 Volt Supply	12 AWG	20 Amps	Anderson
12 Volt Supply	12 AWG	15 Amps	Anderson
5 Volt Supply	12 AWG	15 Amps	Anderson
Ground	12 AWG x 3	50 Amps	Anderson
Computer Control	24 AWG Stranded, x4	I2C + Logic Power	MicroFit-4Pin

Block Diagram of Control Circuitry



Control Cable

- 2 wires for the RS-485 Bus
- 2 wires to carry +7 volt power

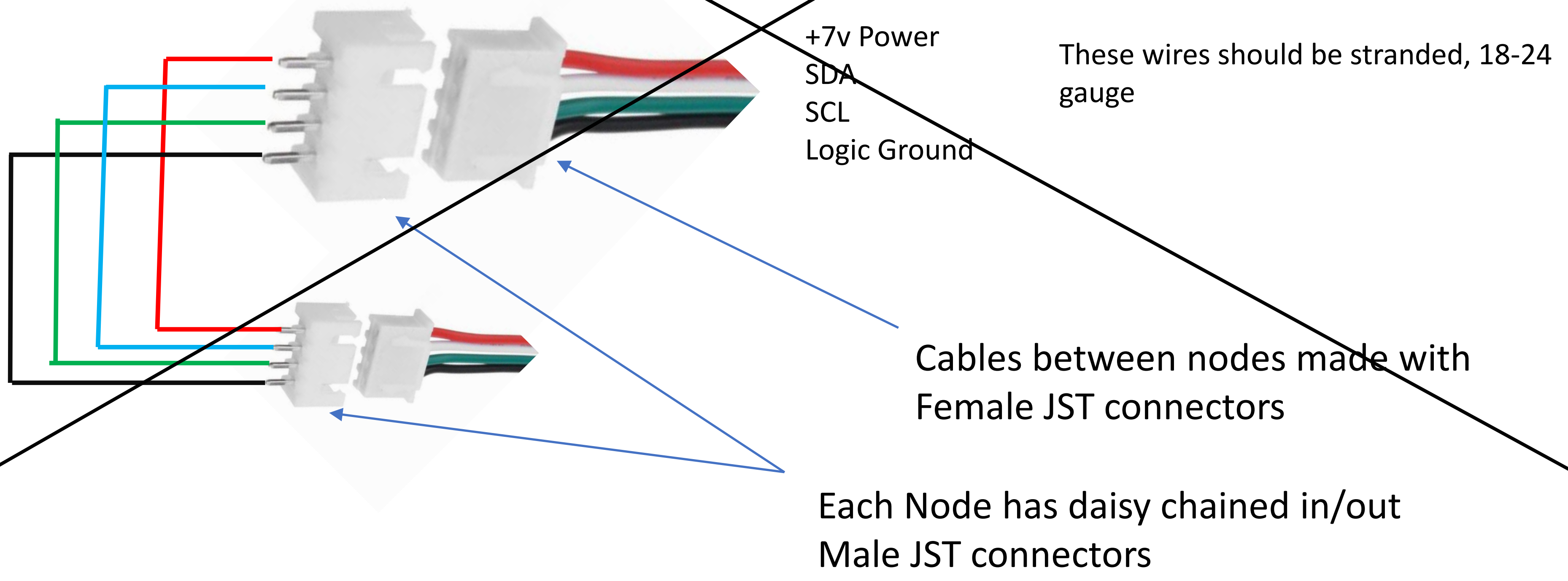
Microprocessor Nodes, Responsible for:

- Sensing Switch Inputs
- Controlling Coils and Magnets
- Controlling 12v Lamps
- Controlling Neo Pixels

Control Signal Wiring to all Microprocessor Nodes

- Use I2C bus -- Later can use CAN physical layer for increased robustness
- Send Logic Power (+7 volts) with Data Signals
- Use JST connectors…
- Each Node does a pass through for all signals and power

Superseded cause I2C Sucks!



Implementing a Robust Comm Bus

- Use RS-485
    - According to Wikipedia, good to 50 meters at 2 Mbits/s, and up to 10 Mbits/s at shorter distances, such at 2 meters in the pinball machine. We only need about 100 KHz.
    - Uses differential signaling over twisted pair
    - One twisted pair means half duplex communication.
    - Can be implemented with the MAX485 chip for less than $1/node

Data on MAX485 chip

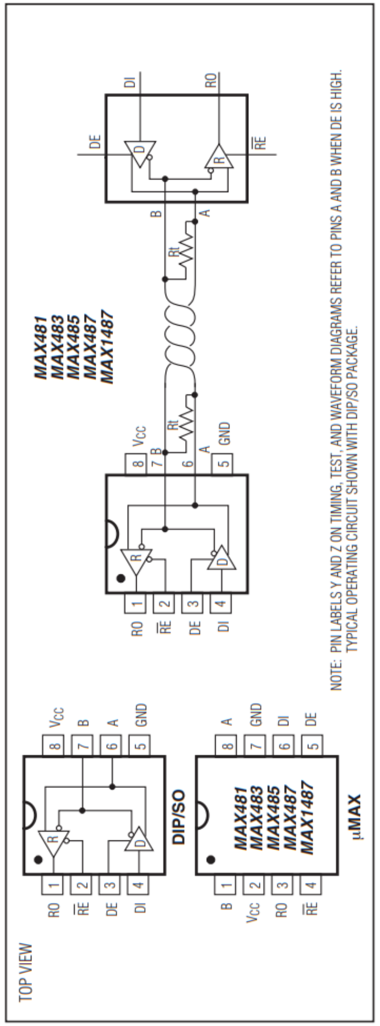


Figure 1. MAX481/MAX483/MAX485/MAX487/MAX1487 Pin Configuration and Typical Operating Circuit

MAX481/MAX483/MAX485/ MAX487–MAX491/MAX1487

Low-Power, Slew-Rate-Limited RS-485/RS-422 Transceivers

Pin Description

PIN					NAME	FUNCTION
MAX481/MAX483/ MAX485/MAX487/ MAX1487		MAX488/ MAX490		MAX489/ MAX491		
DIP/SO	µMAX	DIP/SO	µMAX	DIP/SO		
1	3	2	4	2	RO	Receiver Output: If A > B by 200mV, RO will be high; If A < B by 200mV, RO will be low.
2	4	—	—	3	$\overline{RE}$	Receiver Output Enable. RO is enabled when $\overline{RE}$ is low; RO is high impedance when $\overline{RE}$ is high.
3	5	—	—	4	DE	Driver Output Enable. The driver outputs, Y and Z, are enabled by bringing DE high. They are high impedance when DE is low. If the driver outputs are enabled, the parts function as line drivers. While they are high impedance, they function as line receivers if $\overline{RE}$ is low.
4	6	3	5	5	DI	Driver Input. A low on DI forces output Y low and output Z high. Similarly, a high on DI forces output Y high and output Z low.
5	7	4	6	6, 7	GND	Ground
—	—	5	7	9	Y	Noninverting Driver Output
—	—	6	8	10	Z	Inverting Driver Output
6	8	—	—	—	A	Noninverting Receiver Input and Noninverting Driver Output
—	—	8	2	12	A	Noninverting Receiver Input
7	1	—	—	—	B	Inverting Receiver Input and Inverting Driver Output
—	—	7	1	11	B	Inverting Receiver Input
8	2	1	3	14	V_{CC}	Positive Supply: $4.75V \leq V_{CC} \leq 5.25V$
—	—	—	—	1, 8, 13	N.C.	No Connect—not internally connected

Data on MAX485 chip

Vcc is 5v

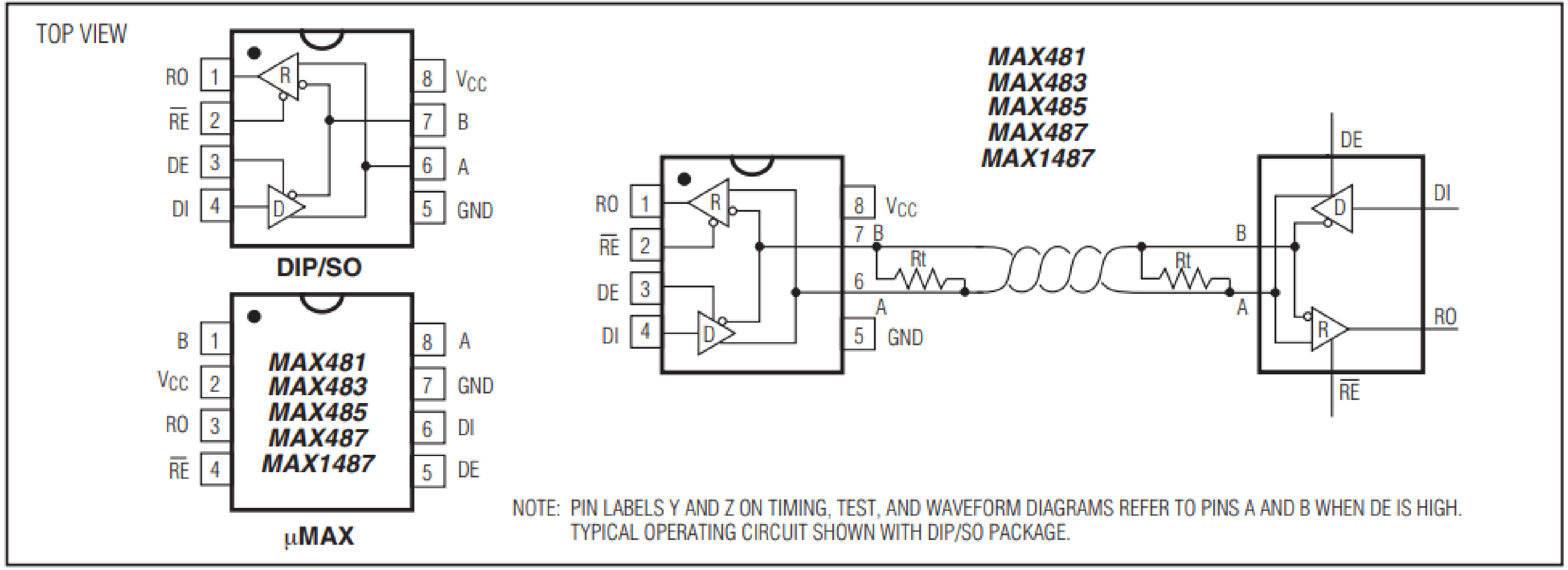


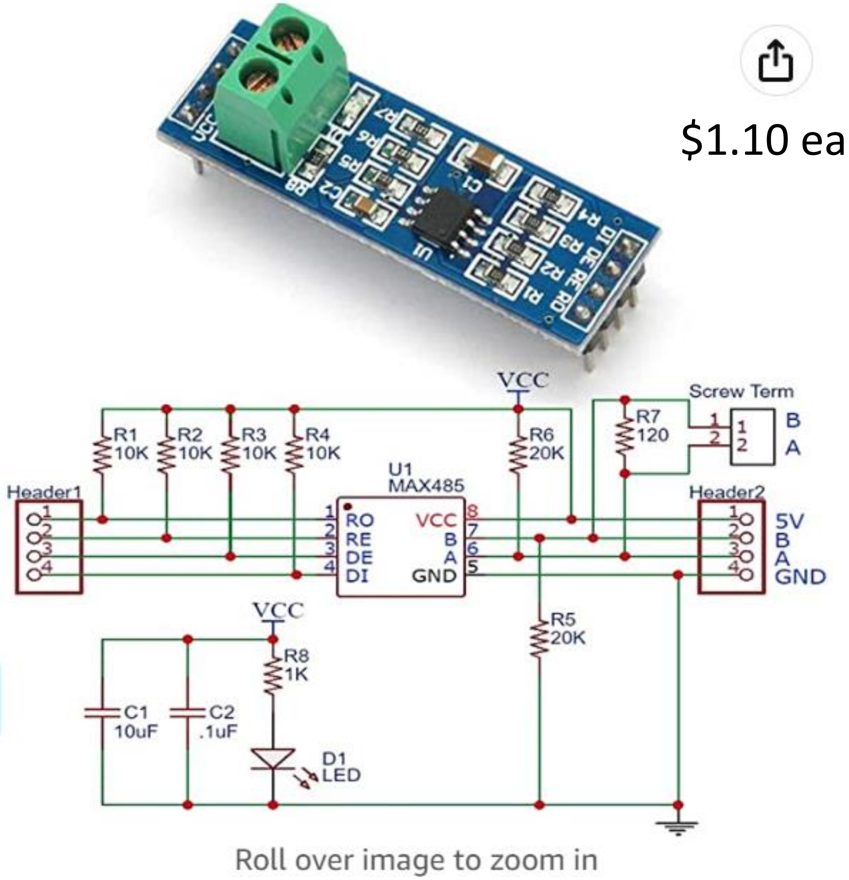
Figure 1. MAX481/MAX483/MAX485/MAX487/MAX1487 Pin Configuration and Typical Operating Circuit

We need to terminal the twisted pair at each end with a 120 ohm resistor.
Vcc is 5 volts, so we need to level shift for Raspberry Pi on R0.
However, V-high is 2 volts, so Pi can drive DI direct.

MAX485 Module from Amazon

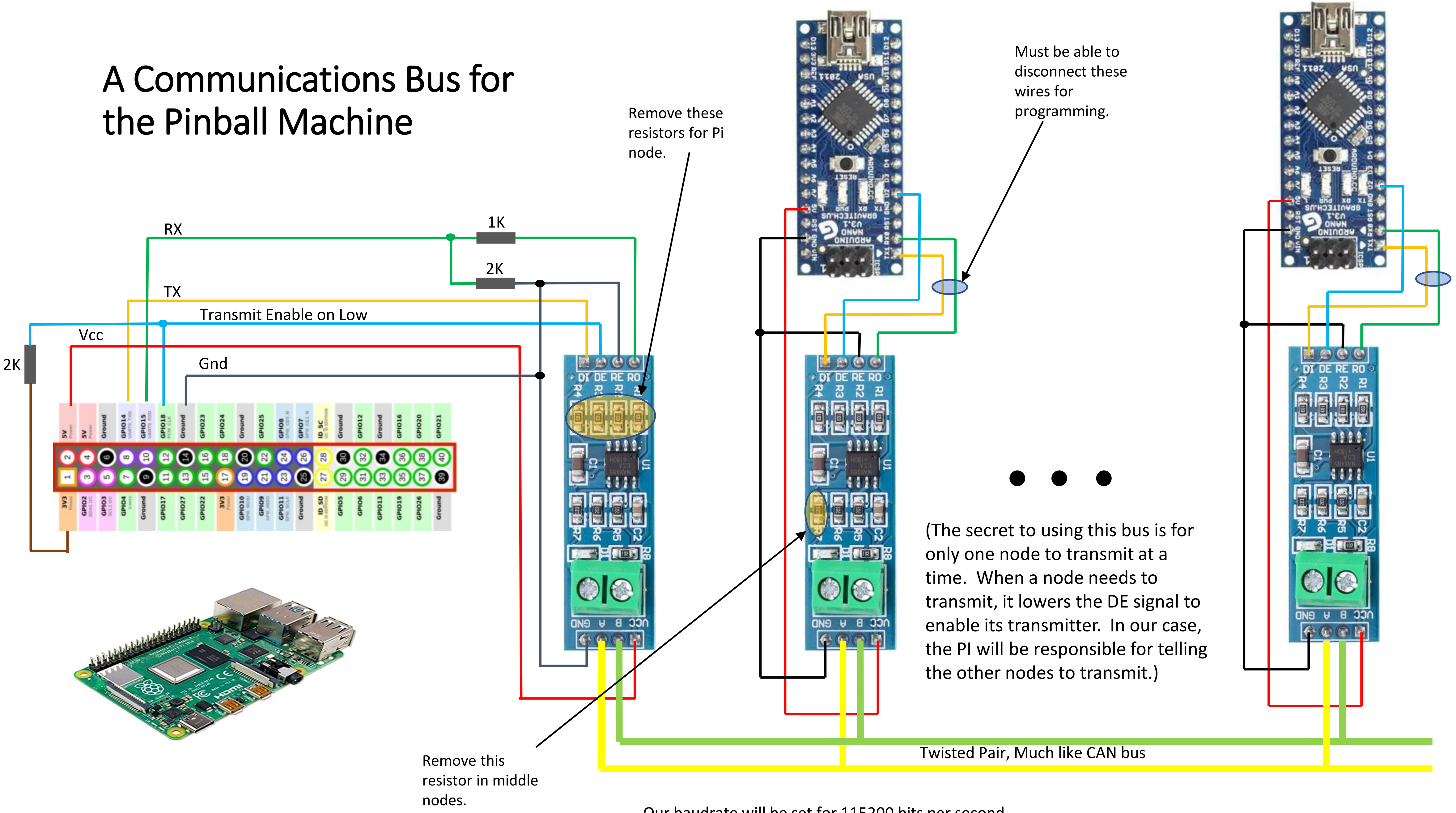
Vcc = 5 volts
V-high on DI, DE, and RE >= 2.0 so Pi Logic levels will be okay.
Possible Modifications:

- Note there is a 120 ohm resister already across the A and B lines. This resistor should be removed on all nodes except the Pi and the last node.
- For the Pi Node, the pullups may interfere with the level shifting needed. Therefore, remove them all (R1-R4).



$1.10 each

A Communications Bus for the Pinball Machine



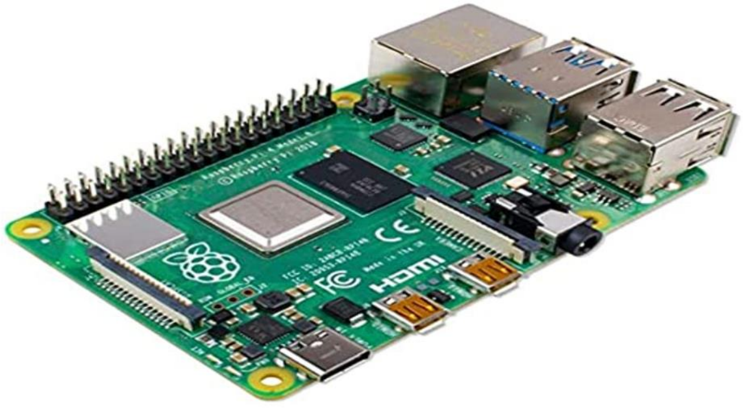
(The secret to using this bus is for only one node to transmit at a time. When a node needs to transmit, it lowers the DE signal to enable its transmitter. In our case, the PI will be responsible for telling the other nodes to transmit.)

Our baudrate will be set for 115200 bits per second.

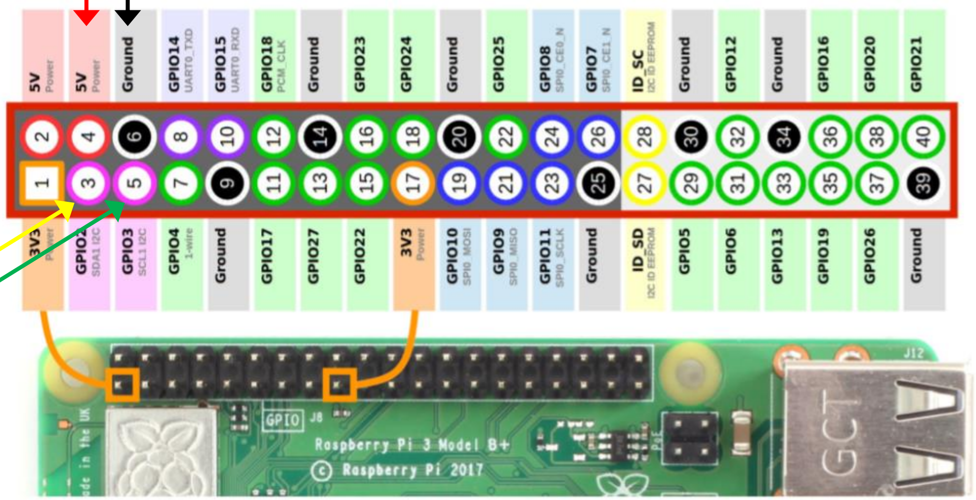
Estimate of Nodes Needed

Node Name	Inputs	Outputs	Comments
Light Control Unit	None	NeoPixels, 6x Lamps	To be used in the Scoring Box for Lights
Light Control Unit	None	NeoPixels, 6x Lamps	To be used under playfield to control all NeoPixels, Panic Light, And Other Decorative Lights
Bumper Control Unit	Bumper Contacts (x3)	Bumper Coils (x3) Bumper Lamps (x3)	Controls all aspects of the three round bumpers in the center of the board
Flipper Control Unit	Flipper Switches (x2) Game Start Button (x1)	Flipper Coils (x3)	Controls all aspects of the flippers
Kicker Control Unit	Kicker Switches (x3) Hole Senser Switch (x1) Ball Ready for Load (x1)	Kicker Coils (x3) Drop Hole Coil (x1) Ball Load Coil (x1)	Controls Kickers, Drop Ball and Coils for returning the ball into play
Switch Input Unit	Micro Switches (Approx x20)	None	Senses all remaining micro switches.

Heart of Control System: Raspberry Pi



Power with these two pins.
Be sure to get polarity correct!
Pin 4 = + 5 Volts, Regulated, at least > 2 Amps
Pin 6 = Logic Ground, 0 volts

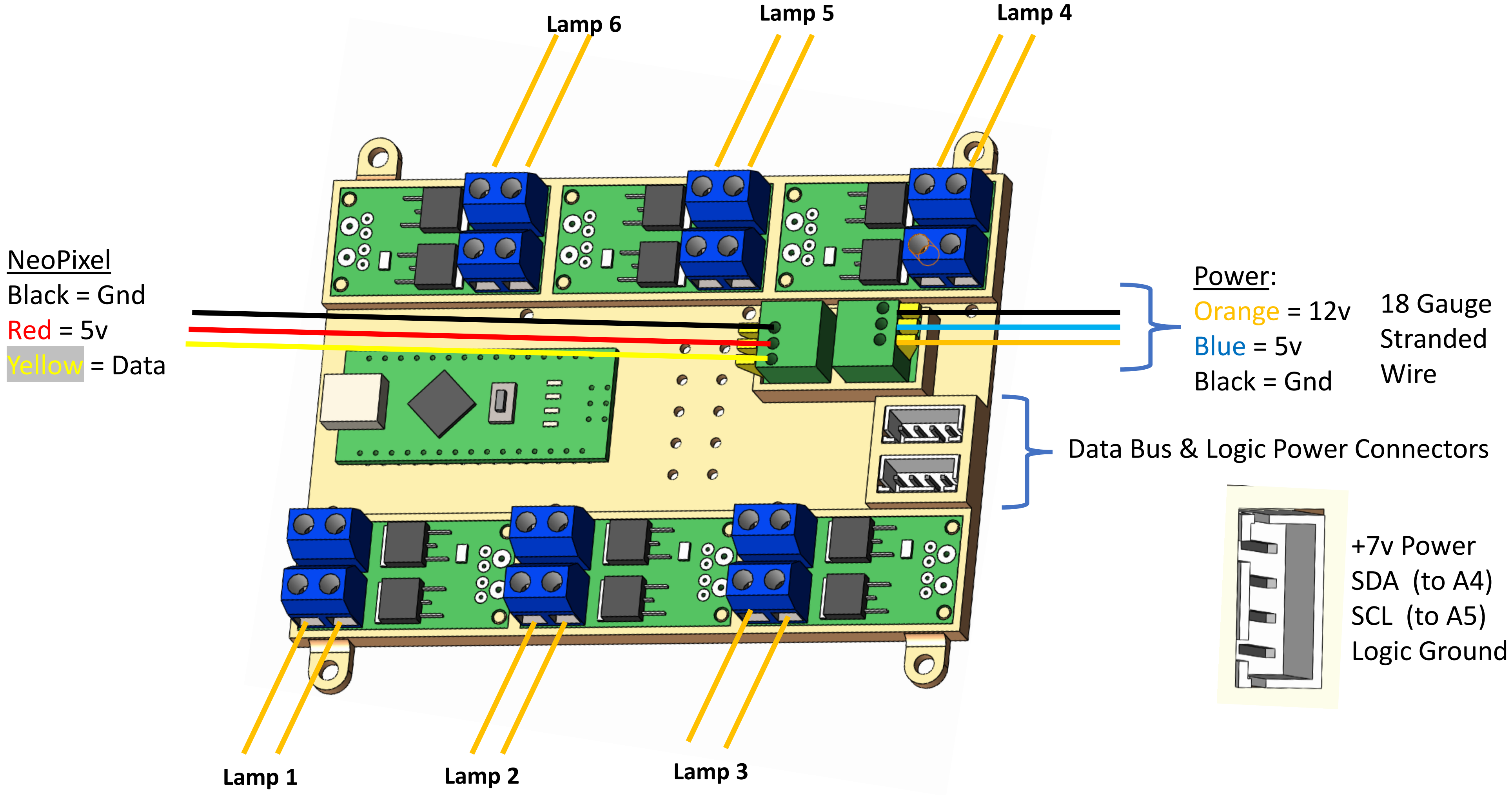


SDA = Pin 3 = Yellow or White
SCL = Pin 5 = Green or Blue

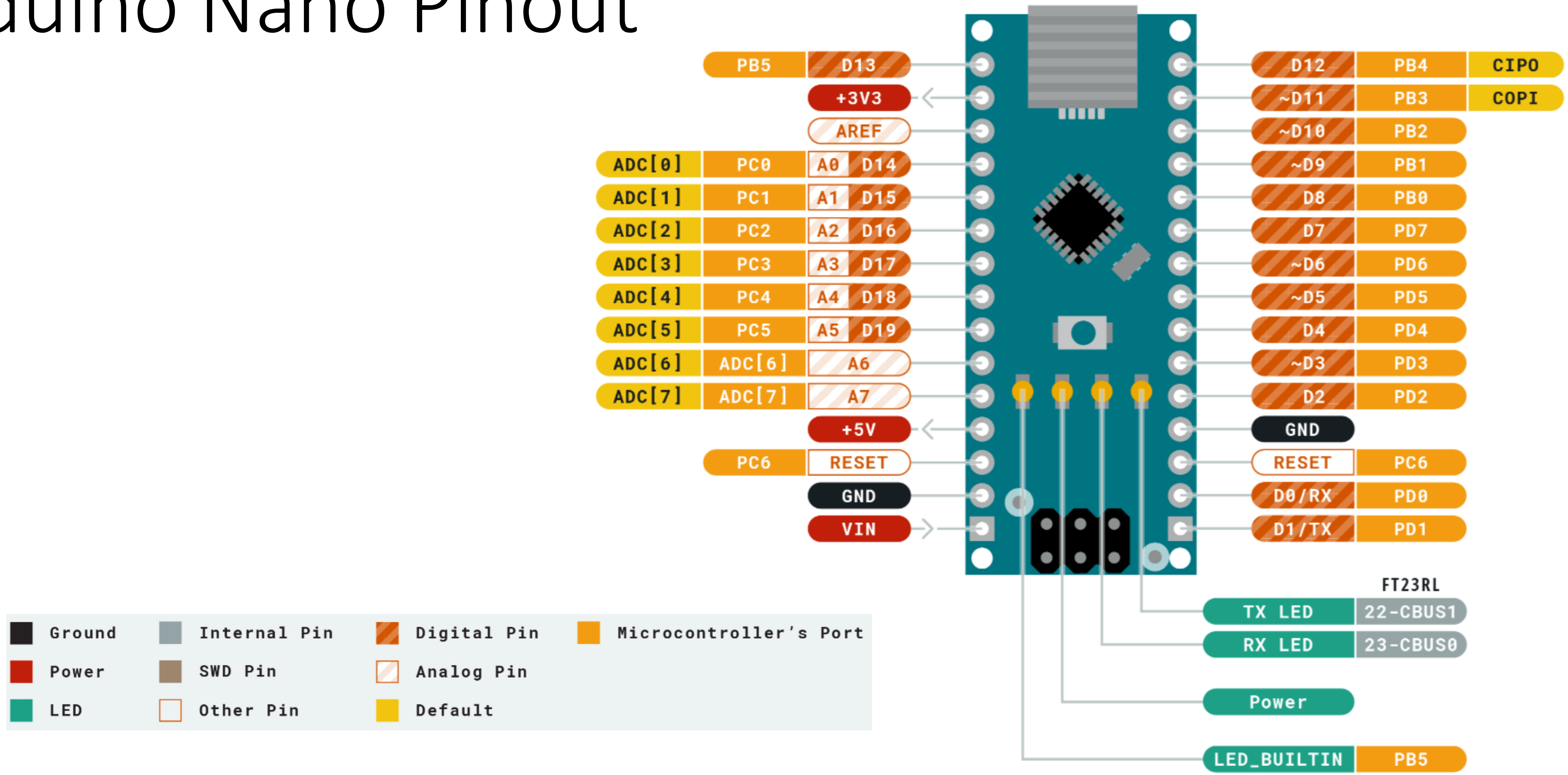
Light Controller Unit -- Requirements

- Two similar units needed: Scoreboard and Playfield
- Features: Controls 6x 12v LED lamps, and one Neo-Pixel Strand
- Inputs:
  - 12v, 5v, GND -- Spring Terminals
  - I2C in (4 Conductors) JST
- Outputs:
  - I2C out (4 conductors) JST
  - Pos, Neg x6 for Lamps – Screw Terminals
  - Neo Out (3 conductors) – Spring Terminals

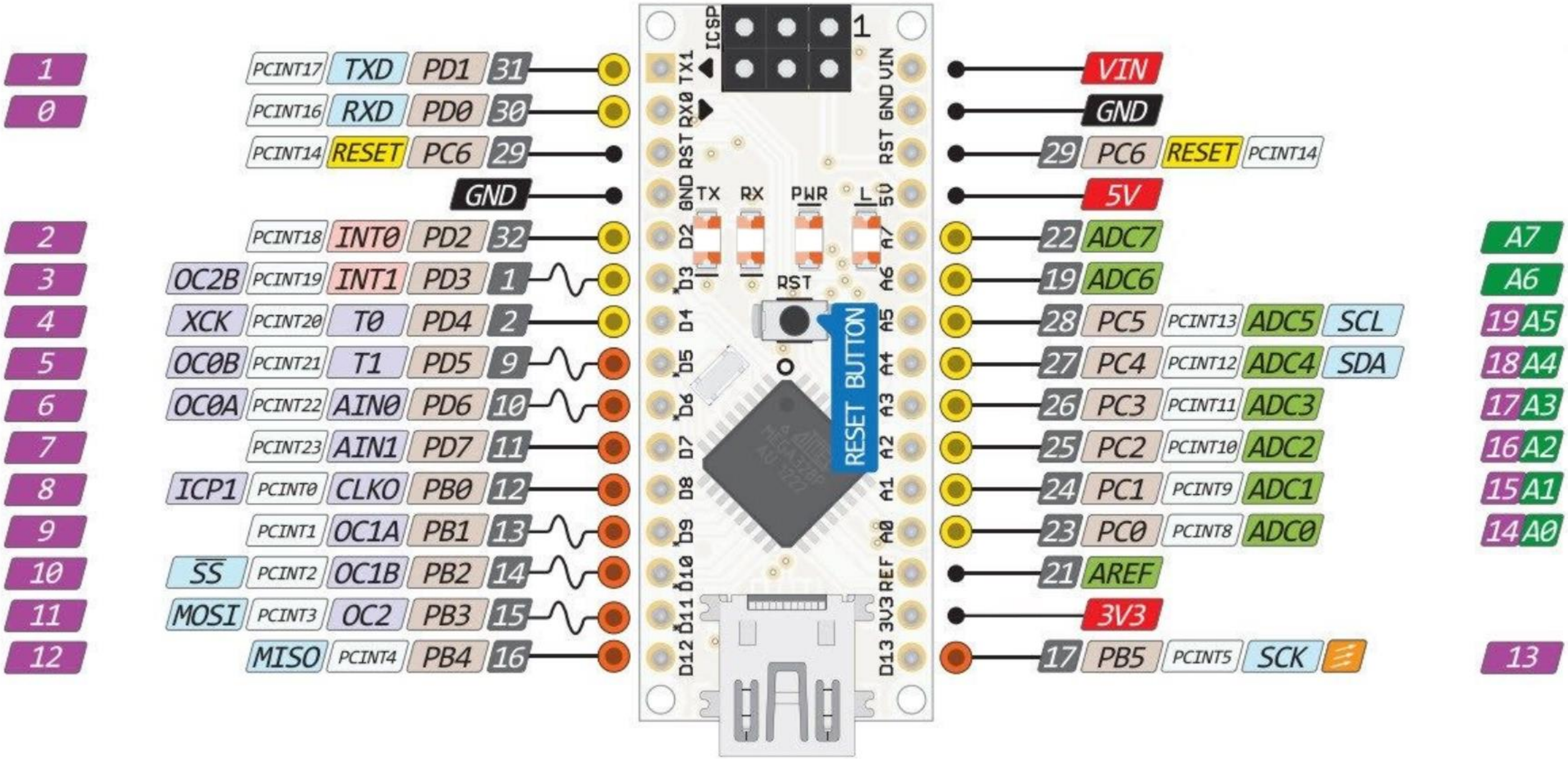
Light Controller Unit (LCU)



Arduino Nano Pinout



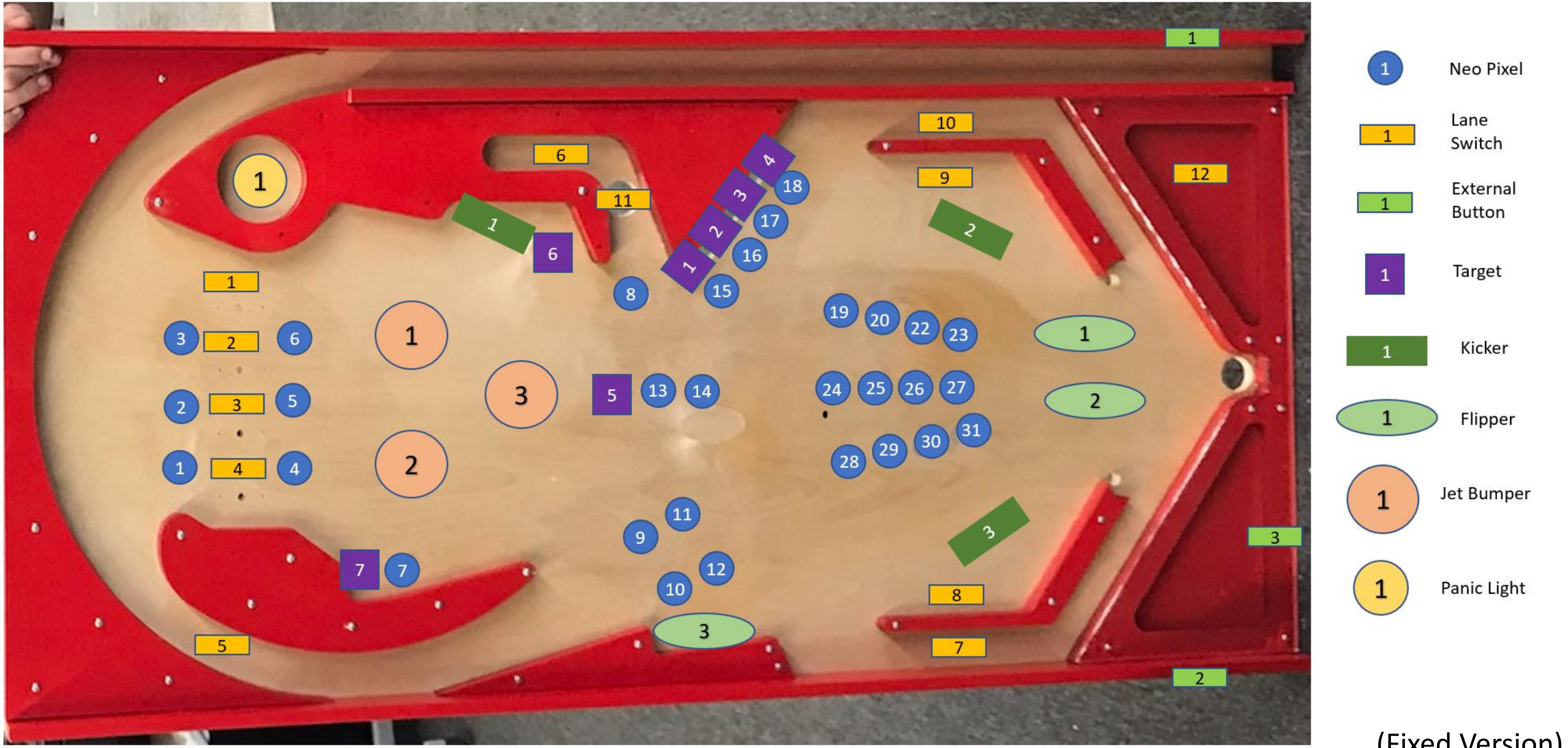
Arduino Nano Pinout



Feature Layout and Designations

(Editable Version)

Feature Layout and Designations



(Fixed Version)

Game Play Sounds

Welcome to the Game Debue – Study the Game with the Jet Bumpers
Build Season Starts! -- You have 6 Weeks!
Hit all the EPIC targets to make a better robot
Don’t Hit the Panic Button!
5 Weeks to Go. Hit the Targets in Order for the Best Robot
4 Weeks to GO! Hurry, Hurry. Hit more targets!
3 Weeks to GO! Hurry, Hurry Hurry! Hit More targets!
2 Weeks to GO! HURRY! MORE, MORE, MORE,
1 Week to GO! Your almost out of TIME. HURRY! But Don’t Panic!
Its TIME TO PANIC – Parts are out-of-stock!
Its TIME TO PANIC – CNC isn’t finished!
Its TIME TO PANIC – CAD is not ready!
Its TIME TO PANIC – Programmers are sick!
Its TIME TO PANIC – Your robot is trash!
Welcome to Competition! Cash in with your Robot!
Hit the Targets to get ranked.
Climb the Ramp for more ranking points!
You Made it to PLAYOFFS!
Get selected with the Jet Bumpers.
You are seeded #47 – Hit the PANIC or go home!
Too bad, you didn’t get selected.
You are seeded #8 – good luck!
You are seeded NUMBER ONE!

Use your scouting data at the Jet Bumpers to select your team!
FOUL! – Frame Out of Bounds
FOUL! – Illegal Contact
FOUL! – Human Player Violation
FOUL! – Overweight
RED CARD! -- (For no discernable reason!)

Nodes

Node Name	Node Function	Address	Inputs	Outputs
Lights	Lights in Score Box	2	None	Neo Pixels 6 Lamps
Flippers	Flippers	3	3 Switches	3 Coils Extra Neo Pixels
Bumpers	Jet Bumpers	4	3 Switches	3 Coils 3 Lamps
Kicker	Sling Shot Kickers	5	3 Switches	3 Coils
Lane Sensors	Lane Switches	6	15 Switches	None
Targes	Target Switches	7	8 Switches	None
Lights	Playing Surface Neo Pixels	8	None	Neo Pixels 2 Lamps
Test	Debugging Comm Bus	9	NA	NA

Node Pins VS Outputs

For the “Lights” Node

Function	IO Pin
Neo Pixels	D12
Panic Light	D6
Spare Light	D5

For the “Kickers” Node

Function	IO Pin
K1	D6
K2	D5
K3	D3
SW 1	D4
SW 2	D7
SW 3	D8

For the “Target” Node

Function	IO Pin
S1	D4
S2	D7
S3	D8
S4	A0
S5	A1
S6	A2
S7	A3
S8	A4

For the “Lane Sensor” Node

Function	IO Pin
S1	A0
S2	D11
S3	D10
S4	D9
S5	D8
S6	D7
S7	D6
S8	D5
S9	D4
S10	D3
S11	A1
S12	A2
S13	A3
S14	A4
S15	A5

Node Pins VS Outputs

For the "Jet Bumpers" Node

Function	IO Pin
B1	D6
B2	D5
B3	D3
SW 1	D4
SW 2	D7
SW 3	D8
L1	D11
L2	D10
L3	D9

For the "Flippers" Node

Function	IO Pin
F1	D6
F2	D5
F3	D3
X1	D11
X2	D10
X3	D9
EX Button 1	D8
EX Button 2	D7
EX Button 3	D4
Sensor 1	A0
Sensor 2	A1
Sensor 3	A2