

Circuit Schematic, building instructions, and parts list

Here, we show the circuit schematic. We first discuss why we chose to use breadboards as our permanent circuits instead of printed circuit boards (PCBs) before explaining how to wire the circuit and how the circuit operates.

PCB vs breadboards:

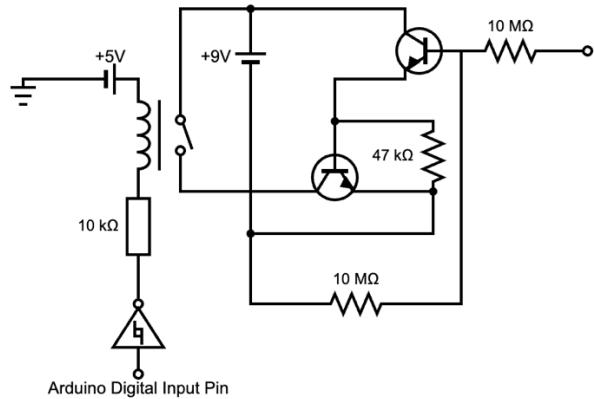
Our primary design goal for the circuit was for it to be stable, yet flexible enough that hardware components can be easily added, removed, or replaced. For this reason, we decided to build a permanent solution using breadboards. The choice of breadboards for a permanent circuit may be non-intuitive. Hence, we explain this choice here.

1. PCBs are fantastic when a circuit is fully stable and no change in hardware configuration will be necessary in the future. However, when the hardware configuration changes, a PCB needs to be redesigned, which requires time, effort, and money. Since we would like the hardware in our system to be quickly modifiable, we resort to using breadboards, wherein changes are easy to make.
2. Though circuits on breadboards can be unstable when assembled with poor quality boards, or with inappropriate wires, they can be highly stable when made appropriately (good quality boards, solid core wires and leads with appropriate thickness).
3. When circuit components fail, they can be quickly replaced from a breadboard. This is much harder with fully assembled PCBs, especially those with built-in small form factor chips.
4. Making this circuit on a breadboard allows other labs to potentially modify the circuit to add their own hardware. A fully assembled PCB would not easily allow such modification.
5. Despite these advantages, breadboards have a major disadvantage due to stray capacitances. These capacitances slow signal processing and this is a major reason why breadboards are not used for applications requiring sub-microsecond clocking. However, for controlling animal behavior, the highest signal frequencies of interest are only over millisecond timescales. Thus, in this frequency space, breadboards are fully functional. Indeed, one can make a functional computer on breadboards despite the constraints on processing speed (<https://eater.net/8bit/>)

How this circuit works:

The general principle of design for this circuit is simple. For any hardware component, we allocate one of the IO pins on the Arduino Mega as an input or an output. Since in our case, all such connections are digital, we use the digital pins of the Arduino Mega. In our case, the inputs are lick measurements for the three lick tubes (left, right and center). The outputs are one to four fluid delivery solenoids, two lick tube retraction solenoids, two buzzers, and two LEDs. The fluid delivery solenoids can be hooked up to the three lick tubes, with one each for the left and right tube and two for the two separate electrically connected tubes in the center lick tube. In practice, for most simple experiments, one would only need a single fluid delivery solenoid for one of the center tubes. In the behavioral tasks shown in Zhou et al., we use only one fluid delivery solenoid to deliver sucrose, except for the experiment in which quinine is also delivered (two total fluid delivery solenoids in this case). Each of these connection types (lick detection, buzzer, LED, fluid delivery solenoid, lick tube retraction solenoid) has its own circuit motif that is repeated for the desired number of hardware components. These are described below.

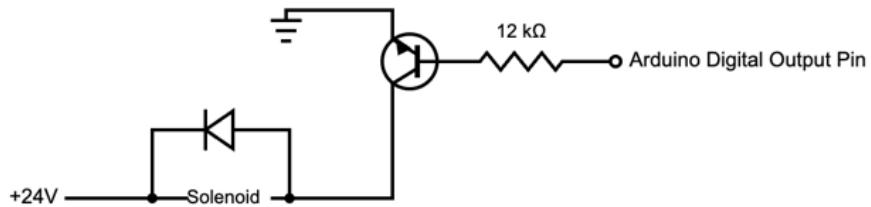
Lick detection: We used a previously published circuit for detecting licks (Slotnick 2009). The only two changes we made are to add a Schmitt trigger to debounce the detected licks, and to use a 9V power supply instead of a battery.



Buzzers and LEDs: This circuit simply connects one lead of the buzzer/LED to an Arduino digital output pin through a resistor, with the other lead connected to ground.



Fluid delivery solenoid: We used a power transistor (TIP120) as a switch to drive a 24V supply through the solenoid whenever the base of the transistor was turned to a high voltage by the Arduino output pin. Thus, the Arduino output pin was connected to the base of TIP120 through a resistor (to limit current) and the solenoid was connected on a path from a 24V supply to the collector of the TIP120. The emitter was connected to ground. In effect, this circuit operates as a switch, with the Arduino output either causing flow of current to the solenoid thereby turning it on, or preventing flow of current, thereby turning it off.



Lick tube retraction solenoid: This uses a similar circuit as the fluid delivery circuit, but with a MOSFET instead of TIP120. The MOSFET is more power efficient, thereby reducing any concerns of heating when the solenoid is turned on for longer durations. A MOSFET could also be used for the fluid delivery solenoid circuit.

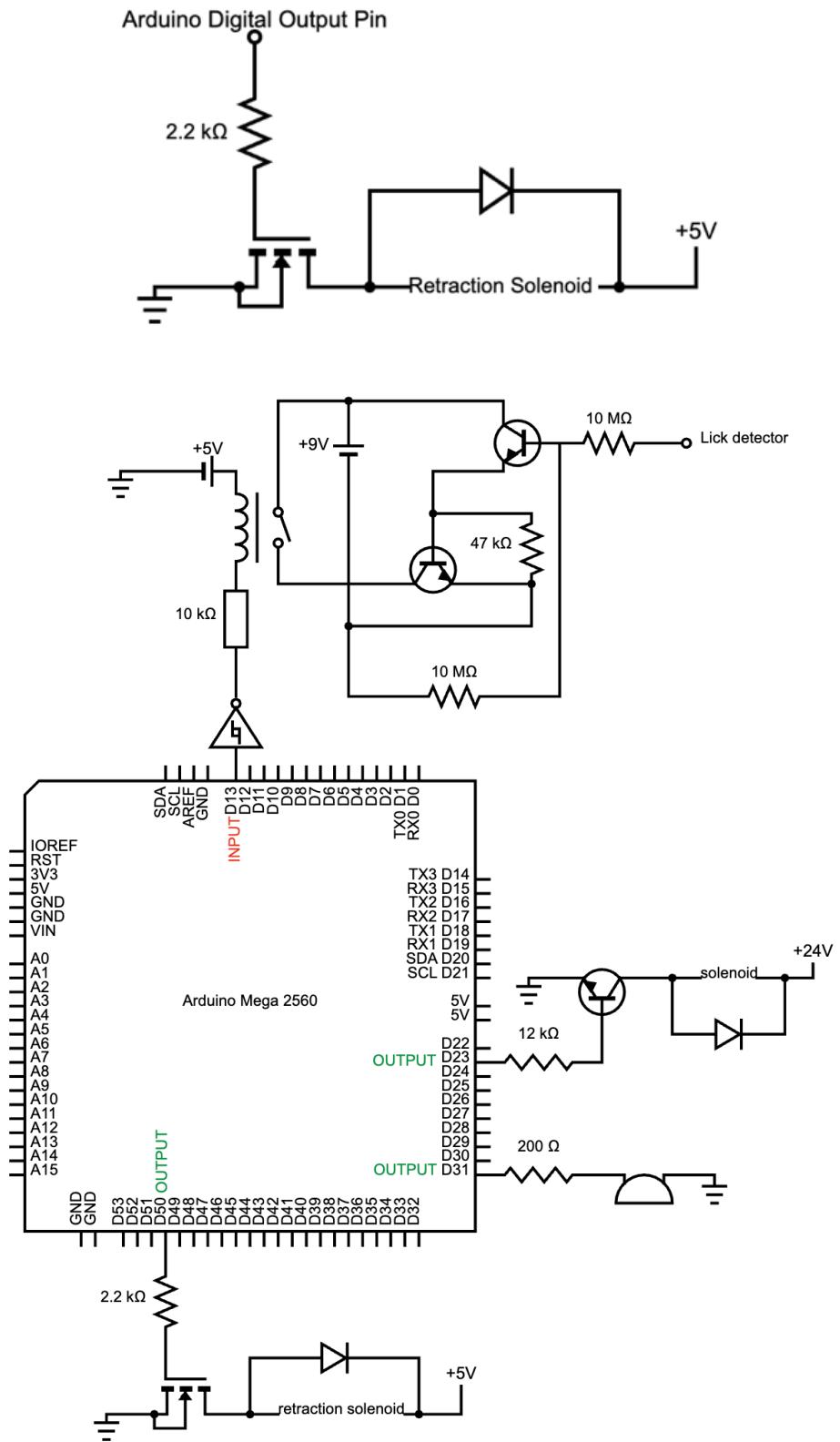


Figure 1 Circuit schematic with one each of the external hardware components. Full circuits are shown below

Why we show a hand-drawn schematic (in addition to the electronically generated schematic):

Here, we show both an electronic schematic of the circuit (**Fig 4**) and our original hand-drawn design (**Fig 2**) that was used to conceptualize the circuit. The electronic circuit was designed using PICAXE Electronic Bread Board Layout Emulator (PEBBLE). We show the hand-drawn design since in personal communication with others, we have found that it provides a lower barrier to entry to understand the circuit and to make modifications. The electronic schematic provides the exact breadboard locations in which we wire our circuit and thus, can be mimicked without any understanding of the circuit function.

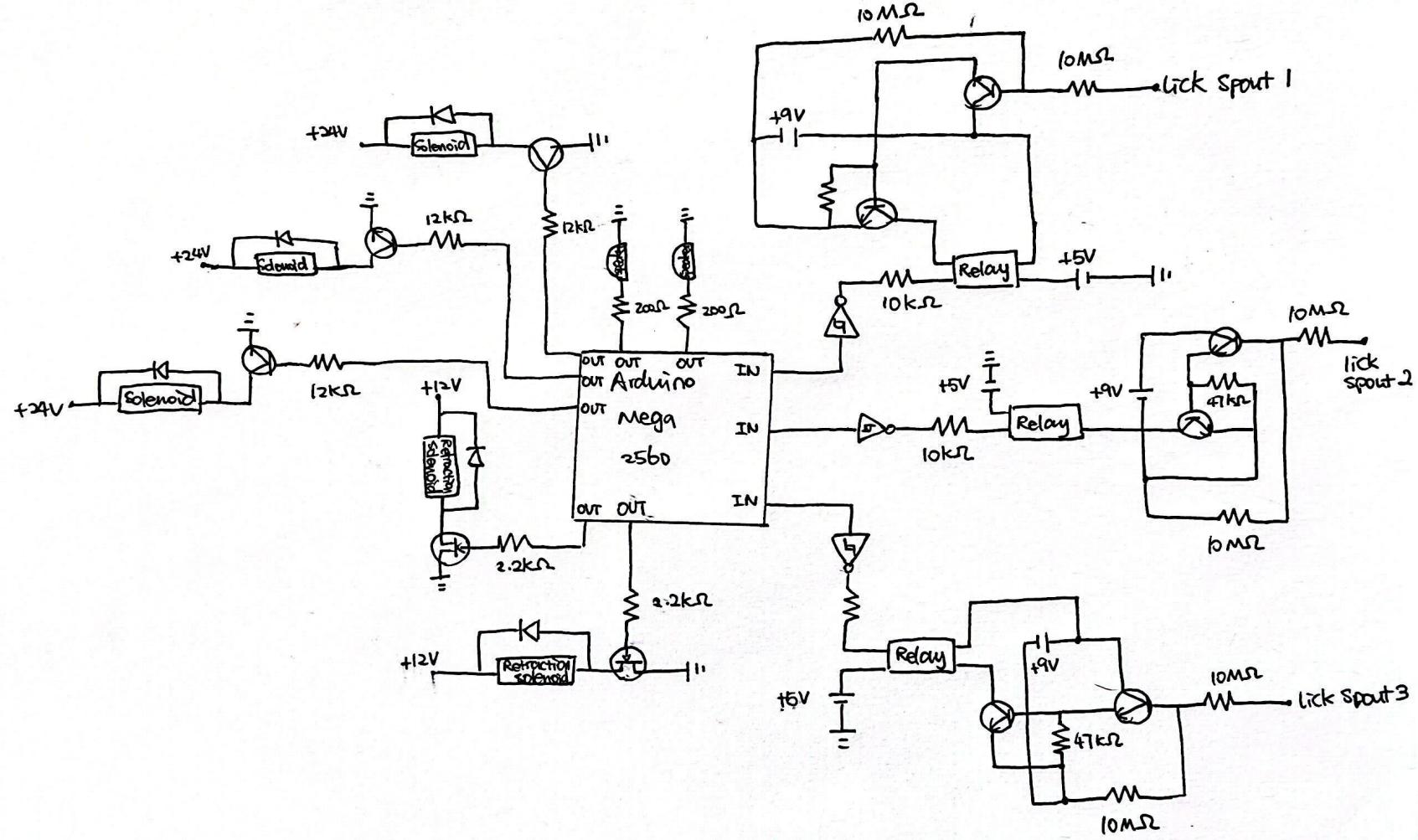


Figure 2 Hand-drawn full circuit schematic

Parallel running:

Our system can support multiple Arduino boards and behavioral box setups using a single computer. Separate behavioral setups are connected to the computer via USB connection. Each separate MATLAB window can control one setup and multiple setups can be executed simultaneously.

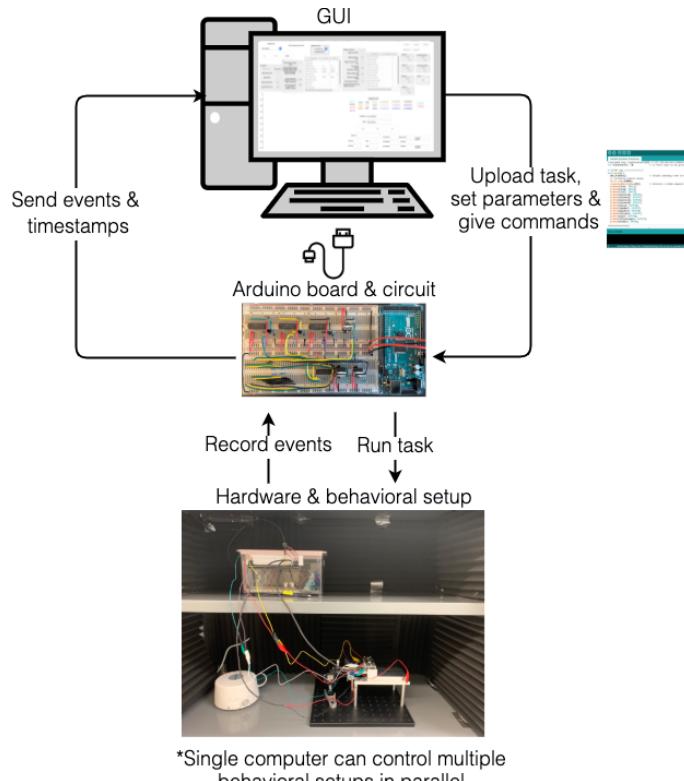


Figure 3 System overview

Building Instructions:

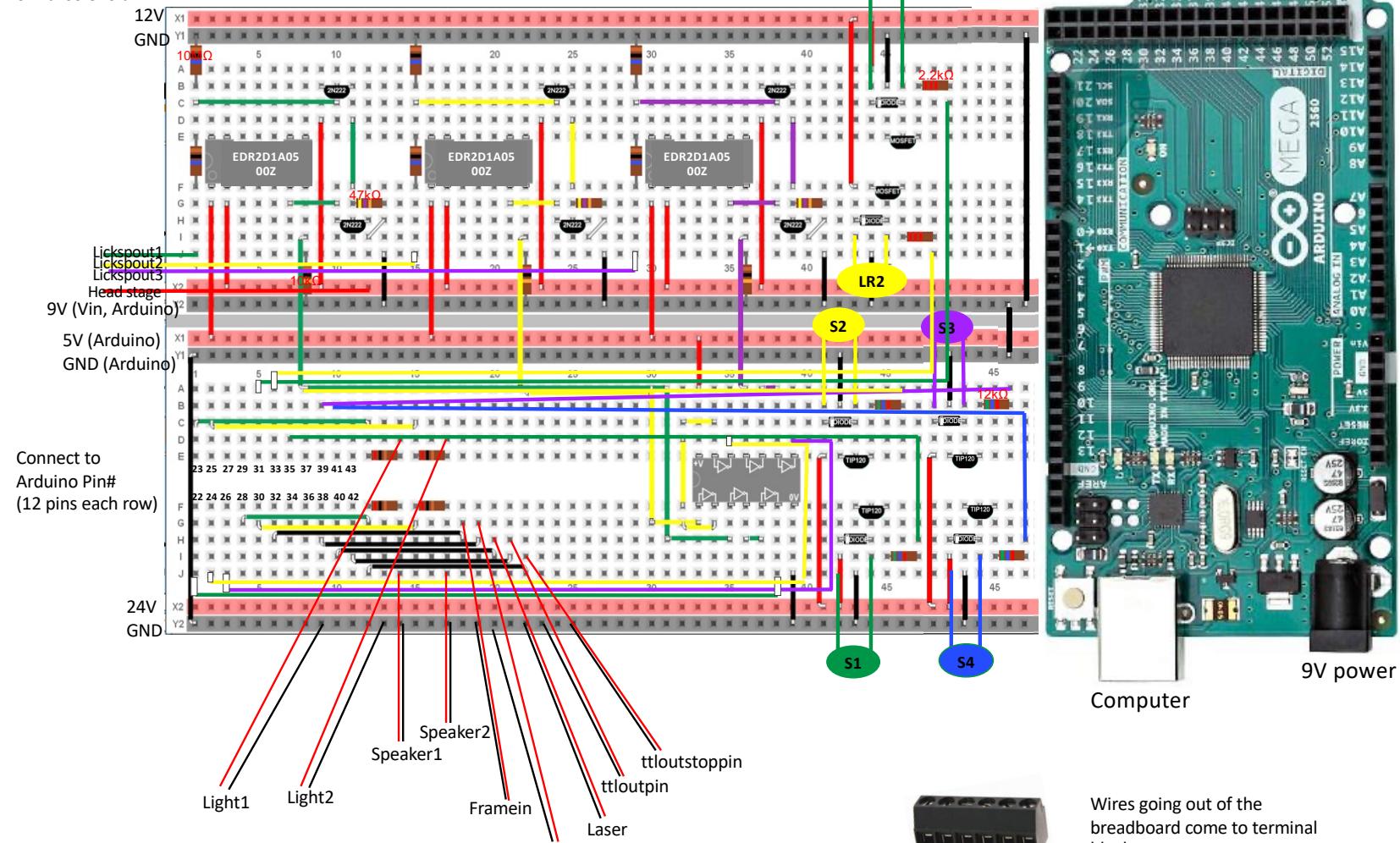
1. Please refer to the following photos attached for the complete circuit. All parts needed to complete the circuit is listed here. Please follow the same schematic for circuit layout.

Parts needed:

- i. Lickometer systems: 10 M Ω resistors x 6, 47 k Ω resistors x 3, 10 k Ω resistors x 3, reed relay x 3, 2N222 transistor x 3, Schmitt trigger x 1, solid core wires
- ii. Linear actuator system: 2.2 k Ω resistors x 2, Power MOSFET x 2, solid core wires
- iii. Speakers & lights: 200 Ω resistors x 4 (speaker resistors vary, please use the resistor kit to test the best value)
- iv. Solenoids: 5.6 k Ω resistors x 4, TIP120 x 4, single diode x 4, solid core wire

LR – lick retraction solenoid

S – normal solenoid



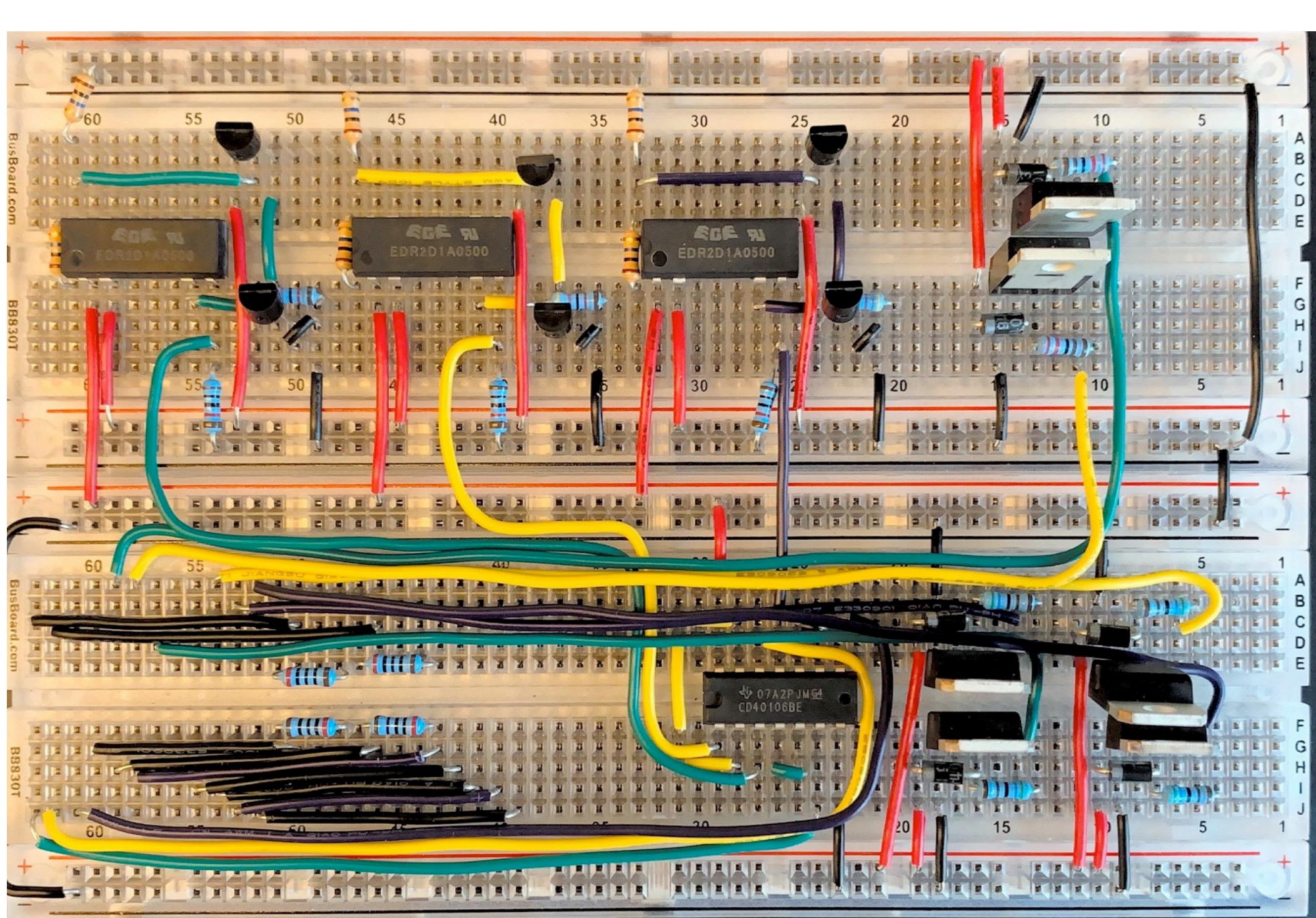


Figure 5 Breadboard circuit reference

2. Dremel one rectangular opening of 15×0.6 cm (150×6 mm) on one long side (horizontal), roughly 3 cm from the top edge of the box. Dremel two square openings with length of 16 mm and 11 mm at the right bottom corner of the plastic box (Amazon 14090MDT). The distance between the two squares is around 10 mm, the distance from the bottom edge of the box to the bottom side of the squares is also around 10 mm, and the distance from the right side of the box to the right square is roughly 1.5cm. The two square openings are for putting the USB cord and 9V power to the Arduino board.

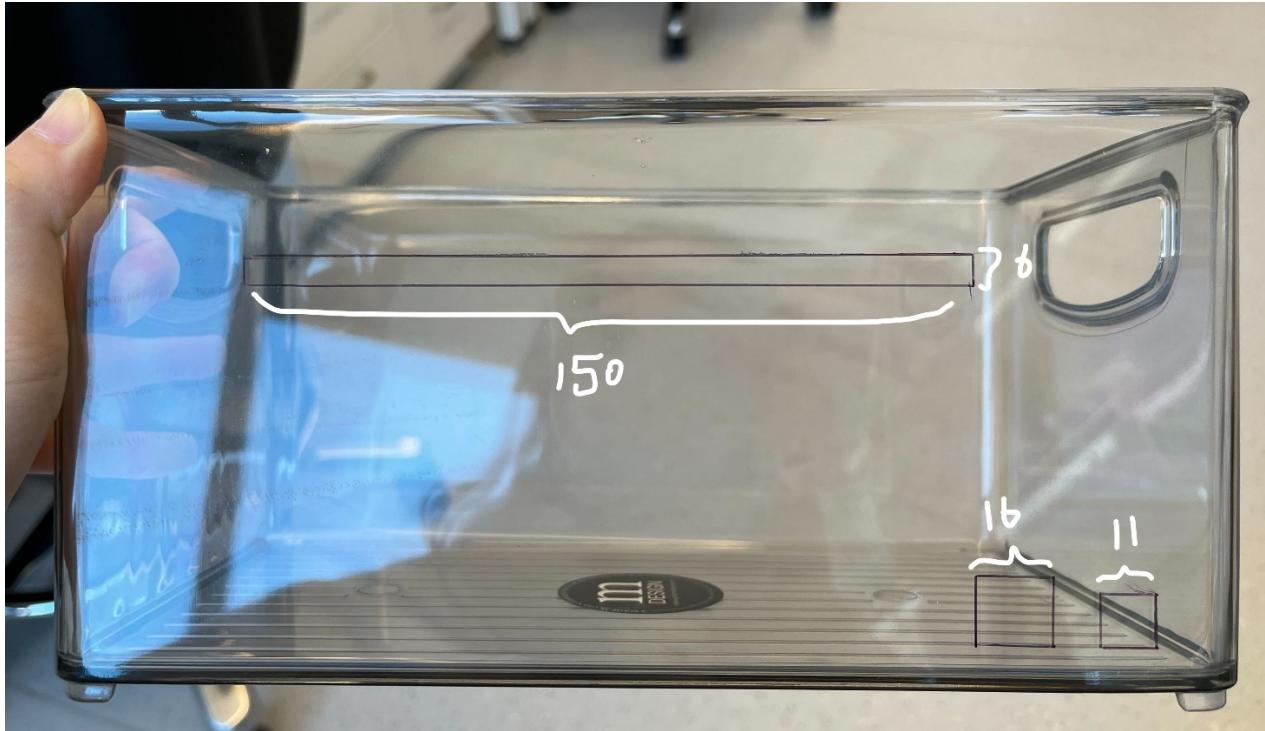


Figure 6 Plastic box openings size

3. Use super glue to glue 7 terminal blocks (Molex 0393570006) together. Make sure the opening slots are all facing the same way.



Figure 7 Glued terminal block

4. Place the glued terminal block into the plastic box opening with the screw slots side facing upwards. Use a hot glue gun to glue the bottom of the terminal block body onto

the plastic box (front and back side reference photo attached). Make sure the terminal block pins are in the center of the hole, not touching the sides.

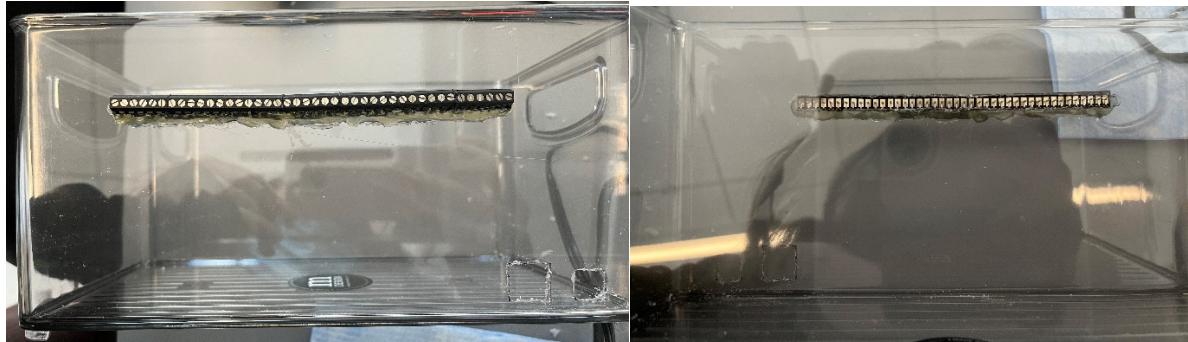


Figure 8 Terminal block glued on the opening of the plastic box

- Print the breakout pin label slip (see below) and glue it on top of the terminal blocks to reference the breadboard pin locations.

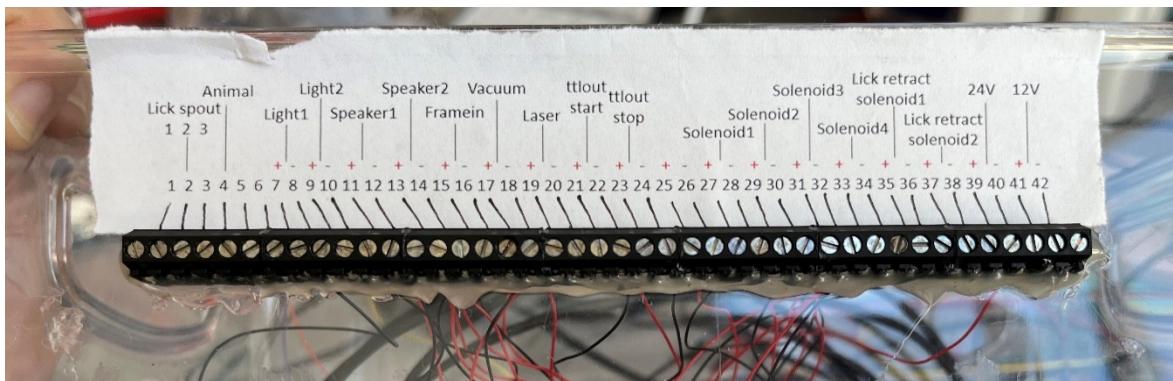
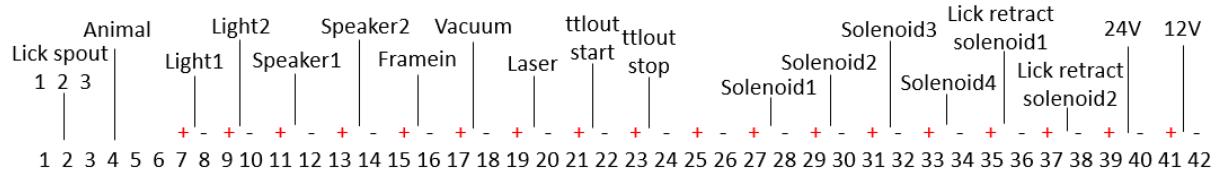


Figure 9 Breakout pin label

- Wrap six 30cm wire-wrapping wires onto one header pin strip.

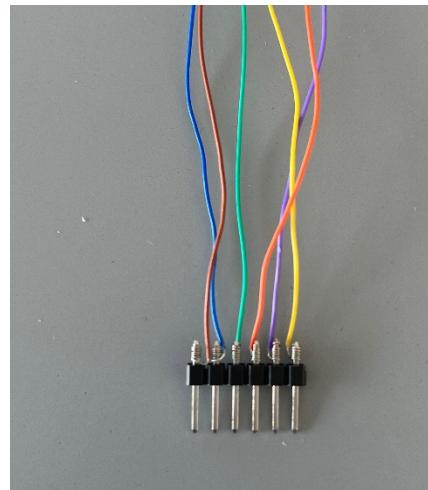


Figure 10 Wire wrapping on header pin strip

7. Add a heating shrink tubing to the six wires to secure them together. Leave some space on the other end to wrap the other end on another header pin strip. Make sure the order of the wires is the same for the two header pin strips (in this example: yellow→purple→orange→green→blue→brown). (This is inspired from <https://hackaday.com/2019/01/06/making-your-breadboard-projects-a-little-more-permanent/>).

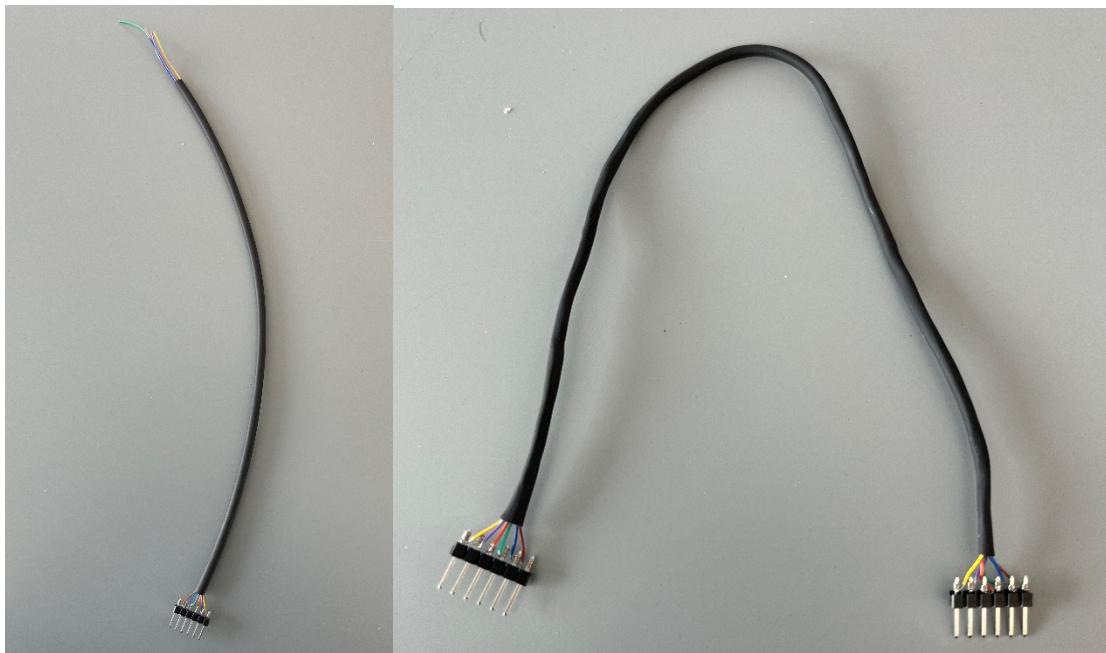


Figure 11 Make wire strip with two header pin strips

8. Use a hot glue gun to add a protective layer over the header pin strips. Repeat four times to make four wire strips total.

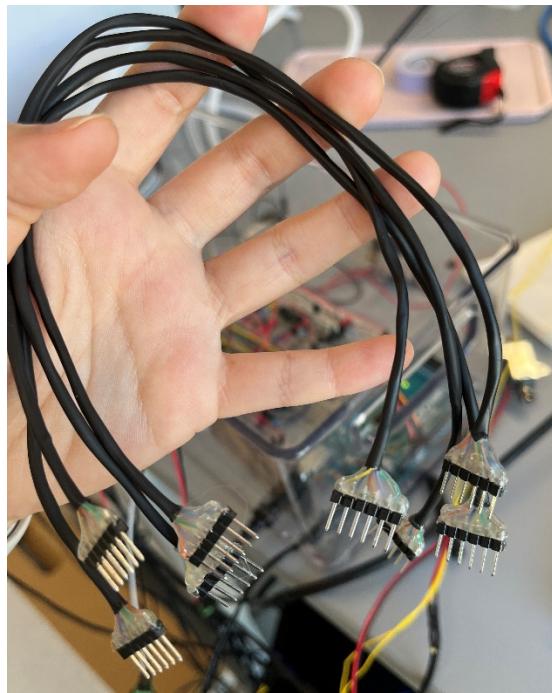


Figure 12 Make total of four wire strips

9. Place one end of the strip into the Arduino board digital I/O pins from pin 22 – 45, and the other corresponding end of the pin onto the breadboard. Please align the correct wires (see photos attached). Also refer to the Arduino pin lineup in **Figure 4**.

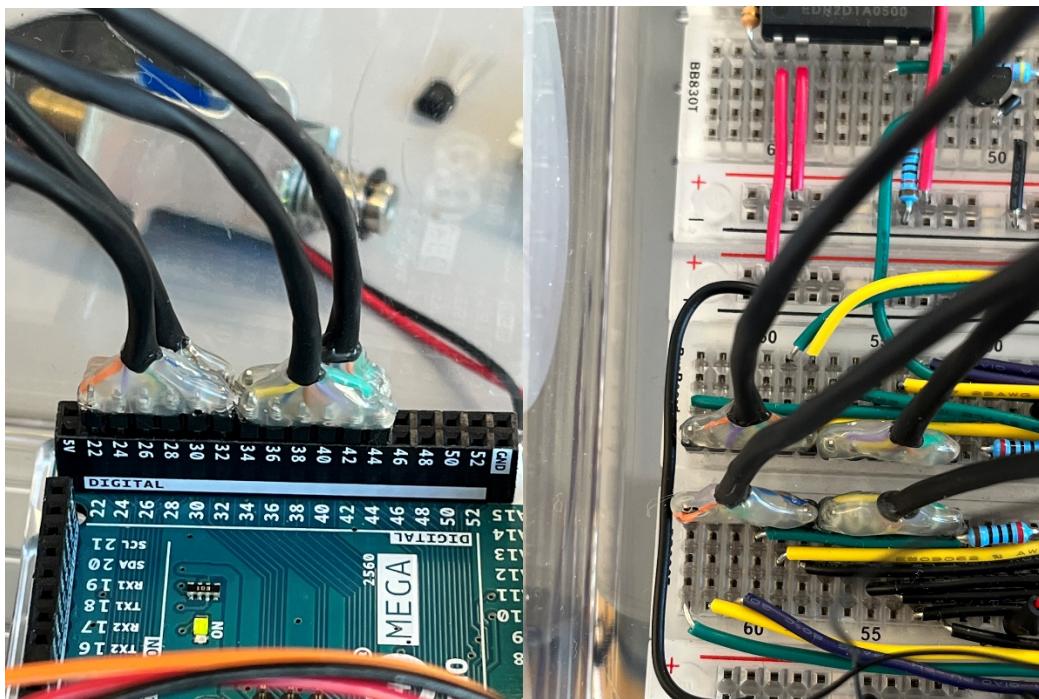


Figure 13 Connect wire strips to Arduino and breadboard pins

10. Connect the 5V pin, ground pin, and Vin pin on the Arduino board to 5V, ground, and 9V respectively on the breadboard using 10 cm jumper wires.

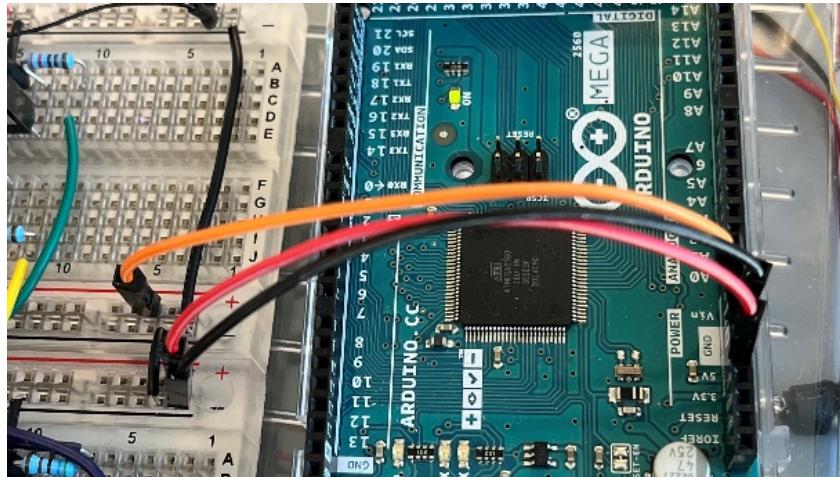


Figure 14 Connect Arduino 5V and ground to correct place on breadboard

11. Wrap one side of wire-wrapping wires onto the terminal block and the other side to a solid core wire to connect the circuit board to the terminal blocks. Location of the wires are indicated on **Figure 4**.

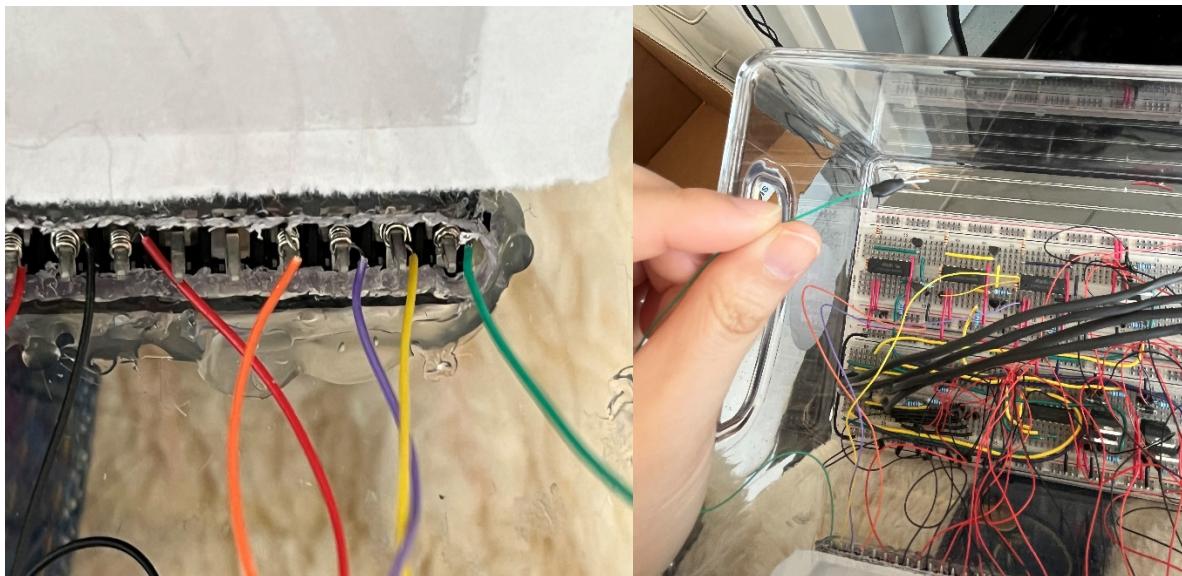


Figure 15 Use wire-wrapping wire to connect the terminal block pin and appropriate location on the breadboard

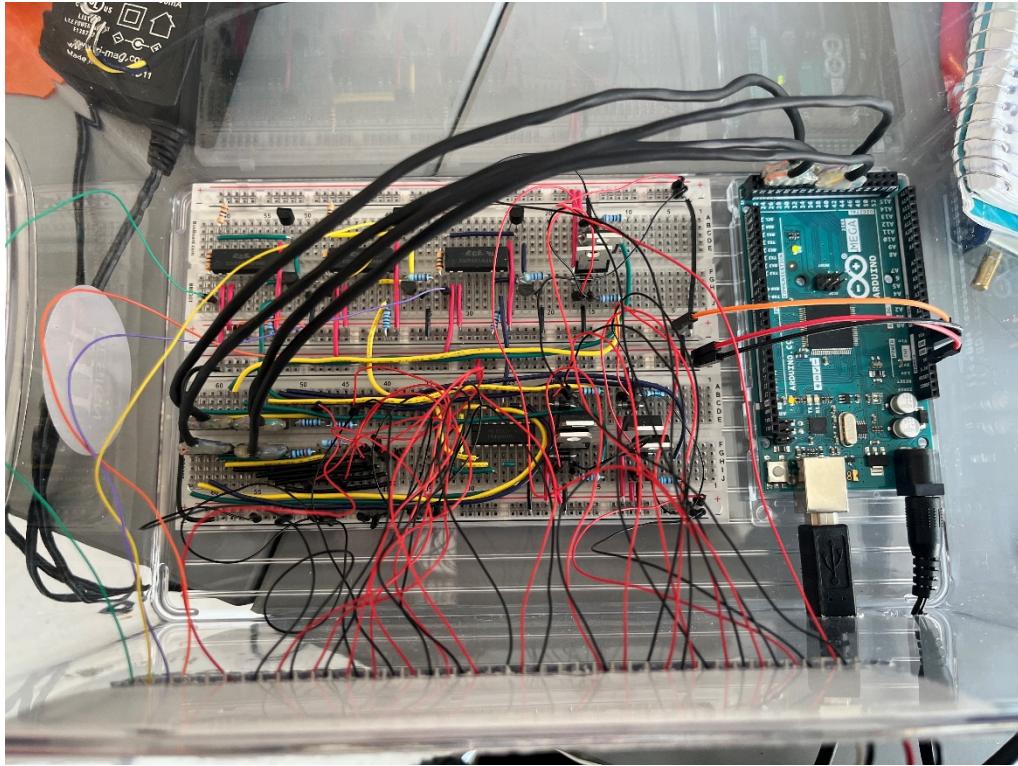


Figure 16 Wire-wrapping to connect terminal blocks and the breadboard pins

12. Use jumper wires and a female DC power adapter to connect the 12V power adapter and 24V power adapter to the corresponding breakout pins.

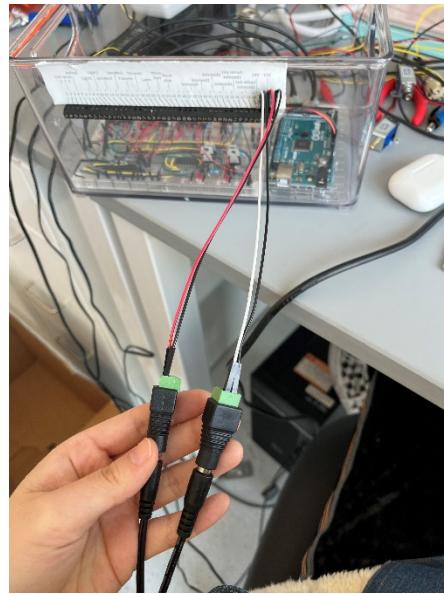


Figure 17 Use female DC power adapter to connect 12V and 24V power to the breakout pins

13. Connect a 9V power adapter to the Arduino board and use a USB A-B 2.0 cable to connect the Arduino board and computer. Both wires go through the opening holes at

the right bottom corner.



Figure 18 Connect the Arduino via USB port to the computer and power up with a 9V power adapter.

14. Solder hardware components (speakers, solenoids, linear actuators, lights etc) to desired lengths and connect them to the correct breakout pins from the outside of the box.

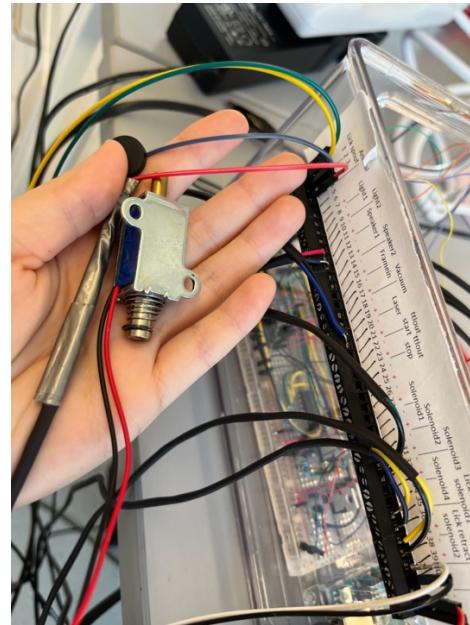


Figure 19 Connect soldered hardware to corresponding breakout pins on terminal blocks

Appendix

Circuit Parts Purchase Information

	Item Name	Function	Vendor/ manufacturer part #	Quantity per system	Unit Cost (\$)	Link
Solenoid (4)	Arduino Mega 2560 board	Runs Arduino program: triggers solenoids and speaker output and receives input from lickometer	Arduino A000067	1	40.3	https://www.digikey.com/en/products/detail/arduino/A000067/2639006?qs=N4IgjCBcoLQBxVAYygMwIYBsDOBTANCAPZQDa4ADAKwUgC6Avg4QExkgCCF3fabAOz0GQA
	Circuit breadboard	Base for wiring components	BB1660T	1	15	https://www.mouser.com/ProductDetail/BusBoard-Prototype-Systems/BB1660T?qs=l13xAFqYpRQG%252BRiHwK91ww%3D%3D
	Solenoid	Facilitates fluid delivery and vacuum function	Parker 003- 0257-900	4	108	https://ph.parker.com/us/12051/en/series-3-miniature-inert-liquid-valve/003-0257-900
	5.6 kΩ resistor	Delivers proper current to solenoid	MBB02070C560 1FCT00	4 (1 per solenoid)	0.27	https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/MBB02070C5601FCT00/5063492
Lickometer (3)	TIP120	Power transistor for switching on reward solenoid with Arduino	STMicroelectron ics TIP120	4 (1 per solenoid)	0.75	https://www.digikey.com/en/products/detail/stmicroelectronics/TIP120/603564
	Single diode	Prevent current backflow	1N4001DITR- ND	4 (1 per solenoid)	0.22	https://www.digikey.com/en/products/detail/diodes-incorporated/1N4001-T/45351?utm_adgroup=Diodes%20-%20Rectifiers%20-%20Single&utm_source=google&utm_medium=cpc&utm_campaign=Shopping_Product_Discrete%20Semiconductor%20Products_NEW&utm_term=&utm_content=Diodes%20-%20Rectifiers%20-%20Single&gclid=CjwKCAjw0On8BRAgEiwAincsHL7Hrhg3GLeSGbsyPi250ikLwQE3NXUGtQWzKWpEppk4gC_jrw0GRoCU7gQAvDBwE
Lickometer (3)	10 MΩ resistor	Delivers proper current to first transistor in lickometer	YAGEO CFR- 25JB-52-10M	6 (2 per lickometer)	0.1	https://www.digikey.com/en/products/detail/yageo/CFR-25JB-52-10M/36371?gclid=CjwKCAjwh7H7BRBBEiwAPXjadTVUweylAFOfvdibTbmy5abxGTwf8neFq2baKoy5_R3eO4NPBAdzBoC4tlQAvD_BwE
	47 kΩ resistor	Delivers proper current to second transistor in lickometer	Vishay Beyschlag/Dralo ric/BC Components MBB02070C470 2FCT00	3 (1 per lickometer)	0.27	https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/MBB02070C4702FCT00/5063436
	10 kΩ resistor	Delivers proper current to reed relay in lickometer	Vishay Beyschlag/Dralo ric/BC Components MBB02070C100 2FRP00	3 (1 per lickometer)	0.03	https://www.digikey.com/en/products/detail/vishay-beyschlag-draloric-bc-components/MBB02070C1002FRP00/338172
	Reed relay	Use to relay licks from lickometer to Schmitt	Excel Cell Electronics EDR2D1A0500Z	3 (1 per lickometer)	3.19	https://www.jameco.com/z/EDR2D1A0500Z-Excel-Cell-Electronics-Reed-Relays-SPST-NO-0-5A-5VDC-500Ohm-Thru-Hole_138431.html

		trigger for detection; gates solenoid opening				
Linear actuator (2)	2N222 transistor	Gates relay of licks from lickometer	MCIGICM 3145241	3 (1 per lickometer)	0.035	https://www.amazon.com/MclglcM-2n2222-transistor-Through-2n2222a/dp/B06XPWS52G/ref=sr_1_4?keywords=2n222%20Transistor&qid=1563393046&s=gateway&sr=8-4
	Schmitt trigger	Acts as a noise filter to detect real licks	TEXAS INSTRUMENTS CD40106BE	1 (1 per 3 lickometer)	0.933	https://www.newark.com/texas-instruments/cd40106be/ic-hex-inverter-4000-cmos-14dip/dp/33AH3784?st=schmitt%20trigger
	Linear actuator	To make retractable lick tube	Adafruit 412	2	7.5	https://www.adafruit.com/product/412
Speaker (2)	2.2 kΩ resistor	Delivers proper current to linear actuator	Vishay Beyschlag/Draloric/BC Components MBB02070C2201FCT00	2 (1 per actuator)	0.26	https://punchout.digikey.com/product-detail/en/MBB02070C2201FCT00/BC3668CT-ND/7351098/?itemSeq=343301088
	Power MOSFET	Power transistor for switching on linear actuator	Adafruit 355	2 (1 per actuator)	1.75	https://www.adafruit.com/product/355
	Resistor kit	Kit for common resistor values, mostly used for delivering proper current to speakers	E-Projects A-0005-A02	1	16.66	https://www.amazon.com/Projects-EPC-102-Value-Resistor-Kit/dp/B00E3JGGF2/ref=as_li_ss_tl?ie=UTF8&linkCode=sl1&tag=resistorkits-20&linkId=6ce7eb79349a9c9ad9cf80e3be0021e
Light (2)	Large enclosed piezo w/Wires	Large speaker for lower frequency cues	Adadruit 1739	1	0.95	https://www.adafruit.com/product/1739?gclid=Cj0KCQjwzbv7BRDIA RIaAM-A6-2am1kPGUa6JCXs49LjeeilCKSZSlu-3cUP1_4B_kfmQVM9SapoPoaAgJXEALw_wcB
	Small enclosed piezo w/Wires	Small speaker for higher frequency cues	Adadruit 1740	1	0.95	https://www.adafruit.com/product/1740#description
	200 Ω resistor	Delivers proper current to lights	From the above resistor kit	2	NA	https://www.amazon.com/Projects-EPC-102-Value-Resistor-Kit/dp/B00E3JGGF2/ref=as_li_ss_tl?ie=UTF8&linkCode=sl1&tag=resistorkits-20&linkId=6ce7eb79349a9c9ad9cf80e3be0021e
Power Supply	Pre Wired-LED Diodes Light 5mm-Blue	LED light for visual cue	ToToT PWDIODE-30-Blue	2	0.253	https://www.amazon.com/gp/product/B07QFQ24X2/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1
	24V/2A Power adapter	Delivers power to solenoids	Tri-Mag, LLC L6R48-240	1	19.11	https://www.digikey.com/en/products/detail/tri-mag-llc/L6R48-240/7682649?s=N4IgTCBcDalDIDYBKAWAHAWjCgDCAugL5A
	12V/2A power adapter	Delivers power to linear actuator	Tri-Mag, LLC L6R24-120	1	9.74	https://www.digikey.com/en/products/detail/tri-mag-llc/L6R24-120/7682639

	9V/1A power adapter	Powers Arduino board and delivers power to lick detector circuit	Tri-Mag, LLC L6R12H-090	1	7.62	https://www.digikey.com/en/products/detail/tri-mag-llc/L6R12H-090/7682626?qs=N4IgTCBcDaIDYBKBGMAJAtABgJzZAF0BfIA
	Female DC power adapter	Connects power supply to breadboard when soldered to wires	Adafruit 368	2	2.00	https://www.adafruit.com/product/368?gclid=CjwKCAjwh7H7BRBBEiwAPXjadvcNzmKGxGlewd8k9frNSDPrIrKjcvOrcuOantF2J9L8xBGz5jd7BoCJYoQAvD_BwE
	USB A-B 2.0 Cable	Connects computer w/USB-A port to Arduino board	Qualtek 3021001-03	1	2.63	https://www.digikey.com/en/products/detail/qualtek/3021001-03/1531288?qs=N4IgTCBcDalloGYBsBGAtAOQCIGLoF8g
Necessary circuit elements	Solid-core wire spool	Connects wires for breadboard	Adafruit 290	5 colors x 25 ft (Black, Red, Green, Yellow, Purple)	2.95	https://www.adafruit.com/product/290
	Wire-Wrapping 30AWG wires	Connects circuit breadboard to terminal block	CECOMINOD03 5080	1	10.99	https://www.amazon.com/URBEST-Solder-Coated-Wire-Wrapping-Celsius/dp/B01LWI20M0/ref=pd_lpo_2?pd_rd_i=B01LWI20M0&psc=1
	Jumper wire kit (M to M)	Connect circuit elements and solder to elements to connect to board (10 cm, 15 cm, 30 cm)	EDGELEC ED-DP_L15_M-M_120pcs	1 set per length (120pcs)	7.49	https://www.amazon.com/EDGELEC-Breadboard-Optional-Assorted-Multicolored/dp/B07GD431C1/ref=sr_1_2?keywords=solderless%2Bbreadboard%2Bwires&qid=1563402097&s=gateway&sr=8-2&th=1
	Screw terminal block	Connect breadboard wires to external connections, mount directly on a plastic enclosure	Molex 0393570006	7	1.86	https://www.digikey.com/en/products/detail/molex/0393570006/1280713
	Header pin strip	Provides a wrapped wire connection to breadboard from Arduino	Harwin M20-9990646	8	0.165	mouser.com/ProductDetail/Harwin/M20-9990646?qs=Jph8NoUxlfXDcWZbabSSiw%3D%3D
	Alligator clips	Connect to lick tubes and the animal base	MCIGICM test lead-10	4	0.499	https://www.amazon.com/MCIGICM-10Pcs-Alligator-Clips-24AWG/dp/B07PHCK3VX/ref=asc_df_B07PHCK3VX/?tag=hyprod-20&linkCode=df0&hvadid=343252324310&hvpos=&hvnetw=g&hvrand=14732595993421484942&hvptone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmld=&hvlocint=&hvlocphy=9061270&hvtargid=pla-759485340661&psc=1&tag=&ref=&adgrpid=71711381880&hvpone=&hvptwo=&hvadid=343252324310&hvpos=&hvnetw=g&hvrand=14732595993421484942&hvqmt=&hvdev=c&hvdvcmld=&hvlocint=&hvlocphy=9061270&hvtargid=pla-759485340661
Enclosed Box for circuit setup	Plastic box	To place Arduino board and the breadboard	14090MDT	1	12.48	https://www.amazon.com/dp/B085LQG3TR/ref=sbl_dpx_B00F4L6L30_0

Other necessary tools	Wire wrapping tool	Wrap wire onto header pin strip and terminal block	Electronix Express 00799475033407	1	23.99	https://www.amazon.com/gp/product/B00BFYE0CY/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1
	Wire stripper	Strip wires for breadboard connections	Adafruit 147	1	6.95	https://www.adafruit.com/product/147
	Hot glue gun	To apply hot glue and provide protective coating around flimsy electronic parts for mechanical stability	Aven Tools 17621	1	29.74	https://www.digikey.com/en/products/detail/aven-tools/17621/7696004
	Hot glue sticks	Glue for the glue gun	Aven Tools 17615	1	14.51	https://www.digikey.com/en/products/detail/aven-tools/17615/7920431
	Dremel	For cutting and polishing metal, plastic parts, etc	Dremel 4300-9/64	1	199.9	https://www.digikey.com/en/products/detail/dremel/4300-9-64/9697074
	Super glue	For gluing multiple terminal blocks together	Loctite 1699233	1	3.41	https://www.amazon.com/gp/product/B01EZTPX94/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1
	Soldering iron kit	For soldering and extending wires to desired length	Plusivo	1	16.99	https://www.amazon.com/Soldering-Iron-Kit-Temperature-Desoldering/dp/B07S61WT16/ref=sr_1_2?dchild=1&keywords=soldering+kit+without+iron&qid=1600994699&s=hi&sr=1-2
	Multimeter	For measuring voltage for circuit	Triplett 2030	1	31.79	https://www.digikey.com/en/products/detail/triplett-test-equipment-and-tools/2030/11623185
	Heat shrink tubing – 1/8 in	Covers soldered connections and indicates negative current wires	Electriduct HS3-0125-100-RD; HS3-0125-100-BK	2 colors, red and black	15.8	https://www.amazon.com/Heat-Shrink-Tubing-1-100FT-Black/dp/B00FL4JO7U/ref=sr_1_8?keywords=heat%2Bshrink%2Btubing%2B1%2F8%2Bin&qid=1563401094&s=gateway&sr=8-8&th=1
	Heat gun	Use for heat shrinking	Apex Tool Group Mfr. 6966C	1	173	https://www.alliedelec.com/product/apex-tool-group-mfr-/6966c/71077034/
	Screw-driver set mini	For screwing terminal block and connecting hardware elements	Rosewill RPCT-10001	1	19.99	https://www.newegg.com/rosewill-rpct-10001/p/N82E16899261024?Description=32-Piece%20Precision%20Screwdriver&cm_re=32-Piece_Precision%20Screwdriver_-99-261-024_-Product