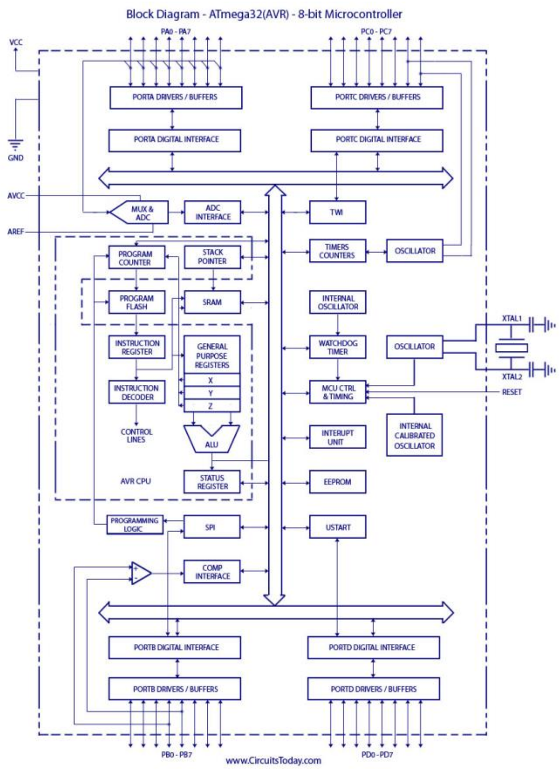
Arduino for (Neuro)Biologists

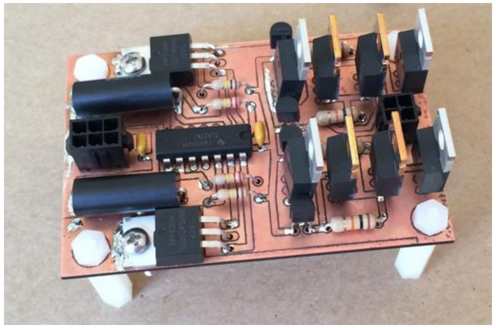
Day 2: Electronic Hardware for Microcontrollers

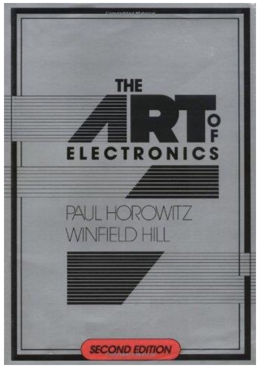
Outline

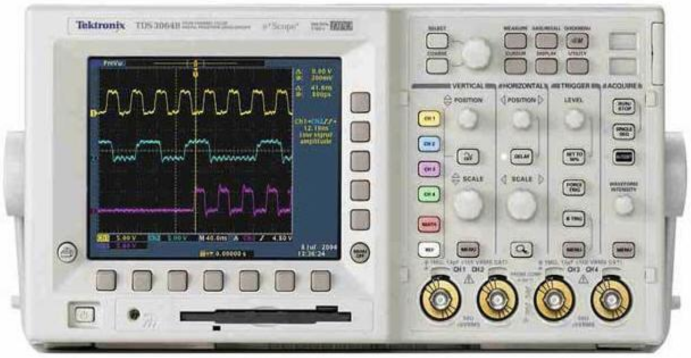
- Strategies for building and debugging
- Voltage, current and resistance
- Sources
- Power and I/O
- Interfacing circuit fragments
- Building circuits in the real world

Hardware is Hard







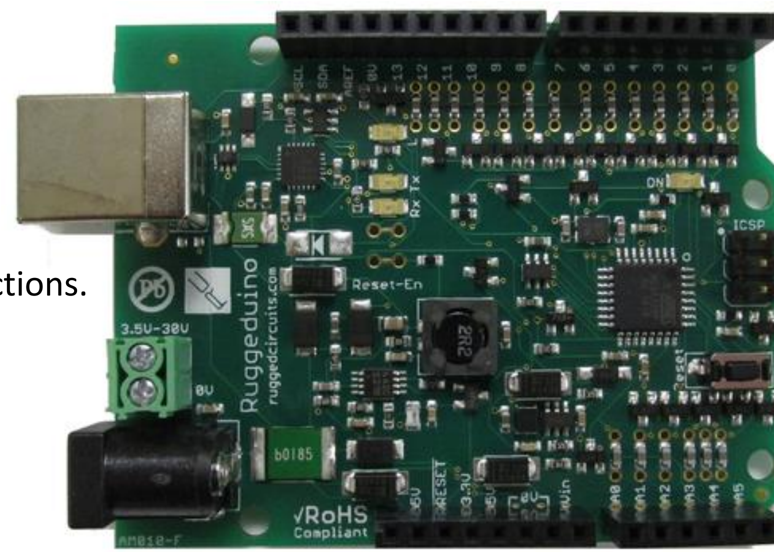


- Hardware takes work to make modifications.
- You can't see what it's doing just by looking.
- Non-linear interactions (and unintentional coupling) can make behavior hard to intuit.

Debugging

When building new systems, much of the time will be spent debugging. Plan for it when designing and assembling.

- Don’t design from scratch.
- During Assembly
  - Build in stages, confirm no power to ground shorts before power-on.
  - Test as you go.
  - Tidy wiring.
- When things break
  - Have a mental model of the circuit.
  - Localize the problem: LEDs, Serial monitor, measurement equipment.
- Common hardware mistakes:
  - Shorts (especially power to ground) and bad connections.
  - Polarity reversal.
  - No power.
- Consider using a “ruggedized” board.*



*Ruggeduinos from rugged-circuits.com can tolerate many types of errors.

Safety

Pay Special Attention To:

- Shock (> 50 V)
- Fire (currents > 1A, heating elements)
- Mess (liquids)
- Collimated light (esp. IR lasers)
- Motors
- Connection to dangerous (or expensive) instruments

Safety Practices:

- Don’t let homemade circuits run unattended without special care.
- Design for component failures.
- Document what you build in case something bad does happen.
- Physically isolate and clearly label dangerous stuff.
- Peer review complex or potentially dangerous systems.

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Voltage, Current and Resistance

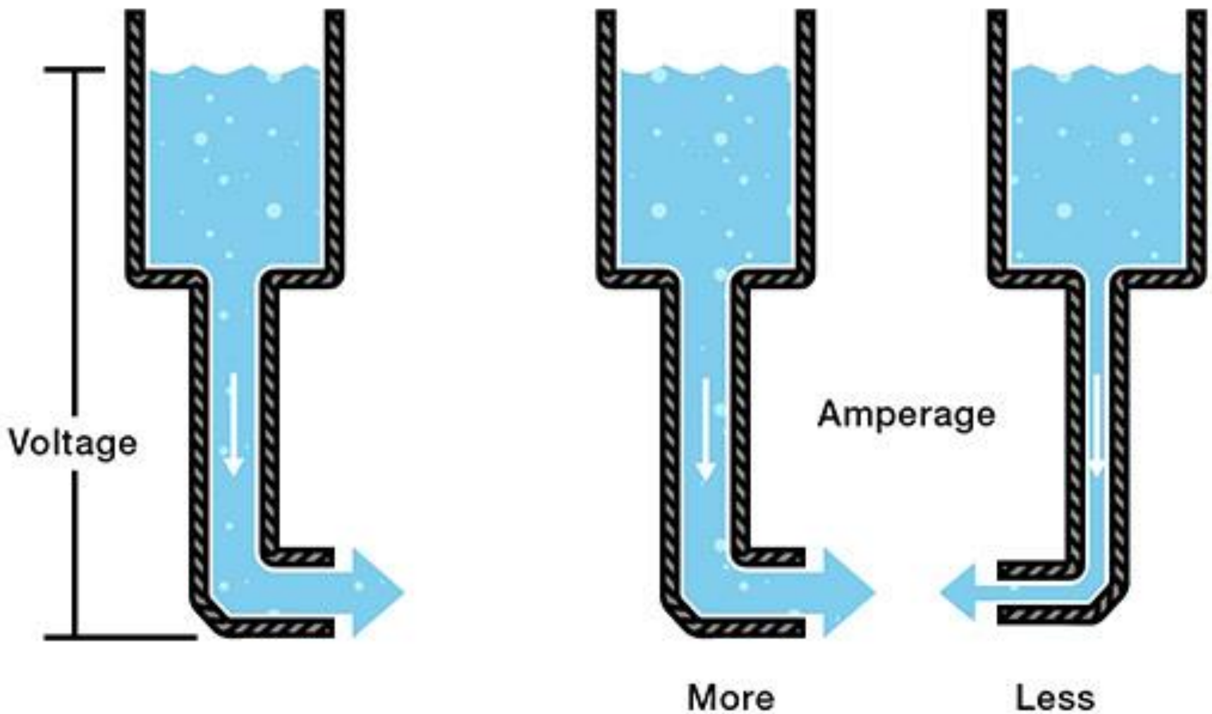
Electricity (Symbol)	Units	Definition
Voltage (V)	Volt (V)	Electrical potential[1] difference between two nodes.[2]
Current (I)	Amp (A)	Flow of charge.[3]
Resistance (R)	Ohm (Ω)	Material property that opposes flow of charge. Results in energy dissipation due to heat.

1 Electrical potential is the potential energy per unit charge.

2 Voltage is usually (but not always) measured relative to ground potential.

3 By convention, current is defined as flow of positive charge. In most simple circuits the charge carriers are negative electrons. Semiconductors have both negative and positive charge carriers.

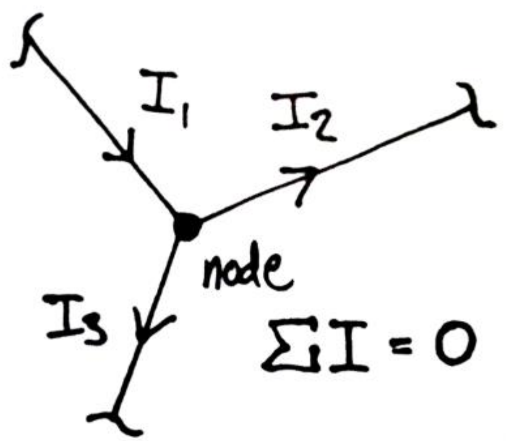
Water Analogy



Sparkfun.com

Conservation Laws

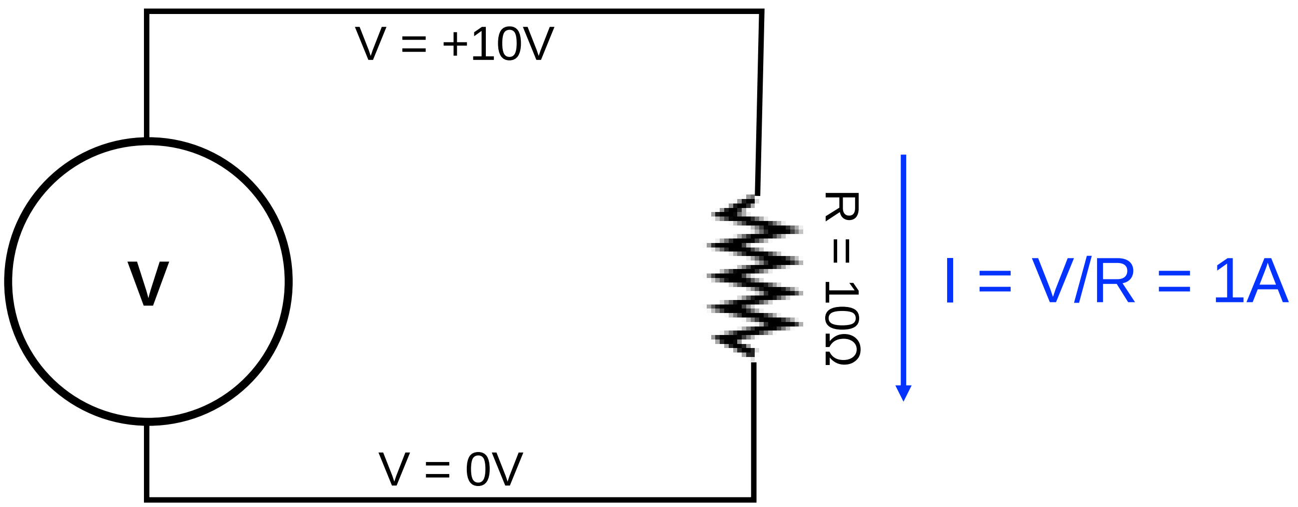
- Points connected by zero-resistance conductors are at the same voltage. All such points are called a *node.*
- Sum of all currents into a node is zero; i.e. charge does not disappear.

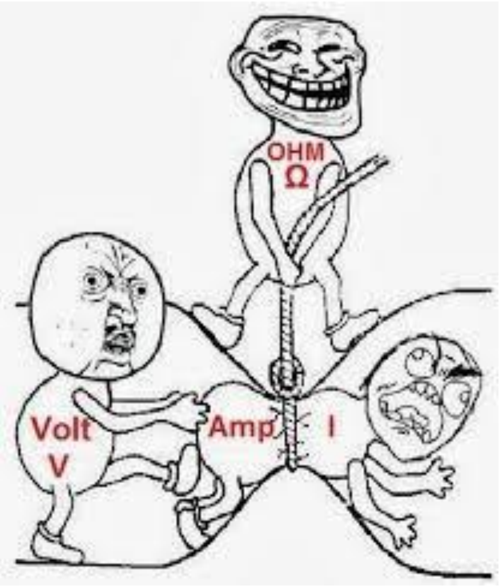


Ohm's Law

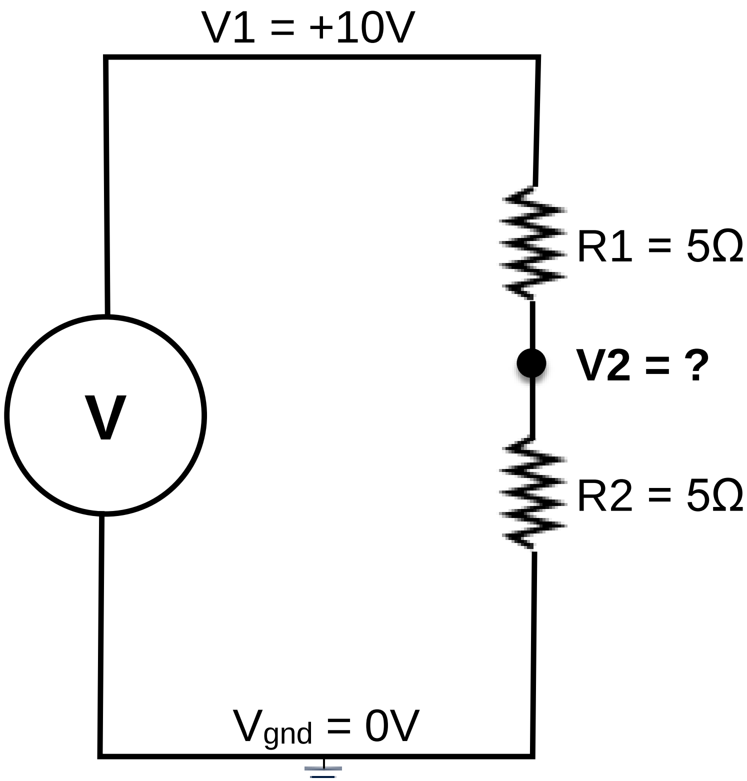
Describes the relationship between current and voltage across an ideal resistor.

$$\boxed{V = I\,R}$$

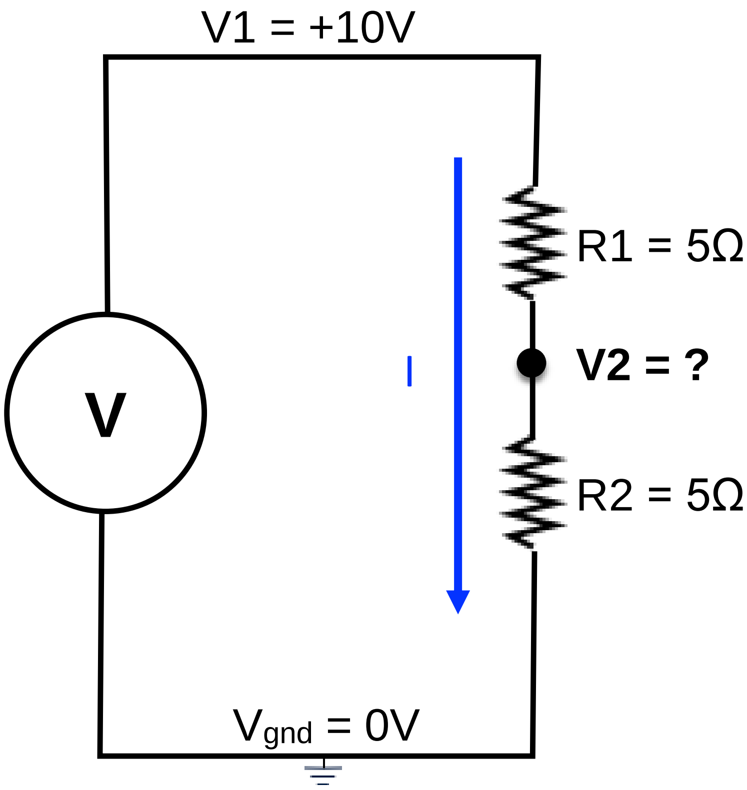




Resistive Divider



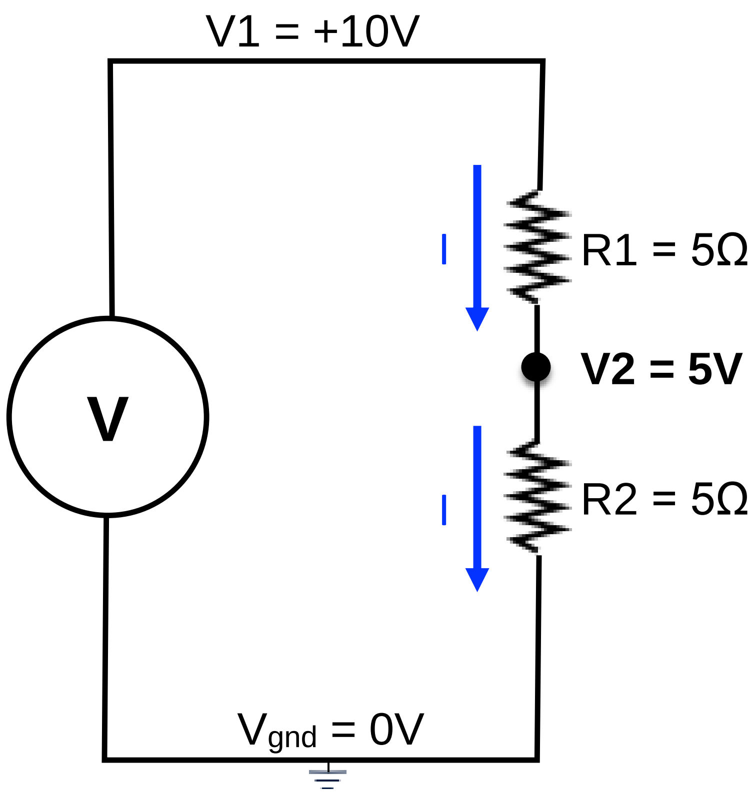
Resistive Divider



(1)

$$I = V_1/(R_1 + R_2)$$
$$I = 10V/10\Omega = 1A$$

Resistive Divider



(1)

$$I = V_1/(R_1 + R_2)$$

$$I = 10V/10\Omega = 1A$$

(2)

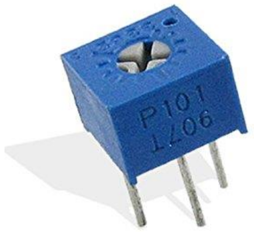
$$V_2 = IR_2$$

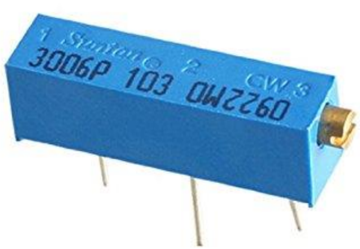
$$V_2 = 1A \times 5\Omega = 5V$$

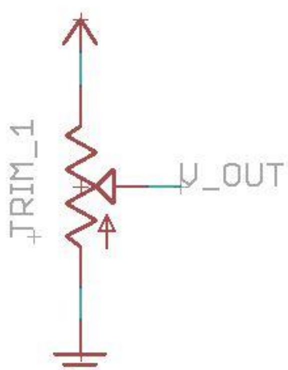
$$\boxed{V_2 = V_1 \frac{R_2}{R_1 + R_2}}$$

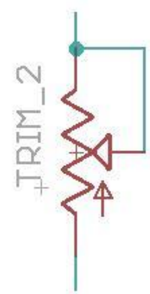
Potentiometer Demo

- A potentiometer is an adjustable voltage divider.
- Output voltage takes on a value between the two inputs.
- Can be connected as a variable resistor.









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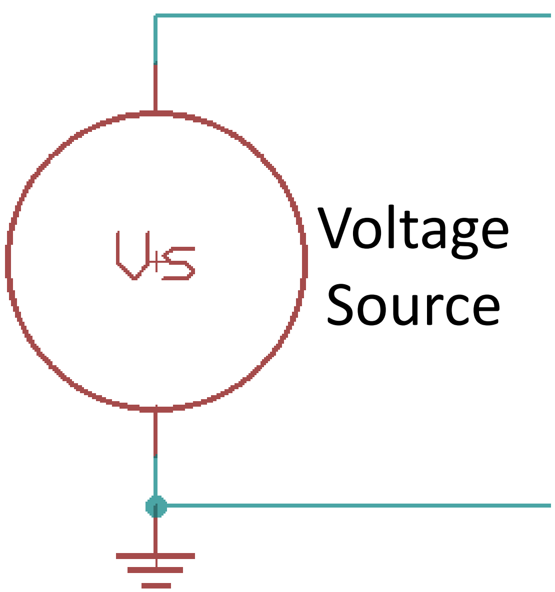
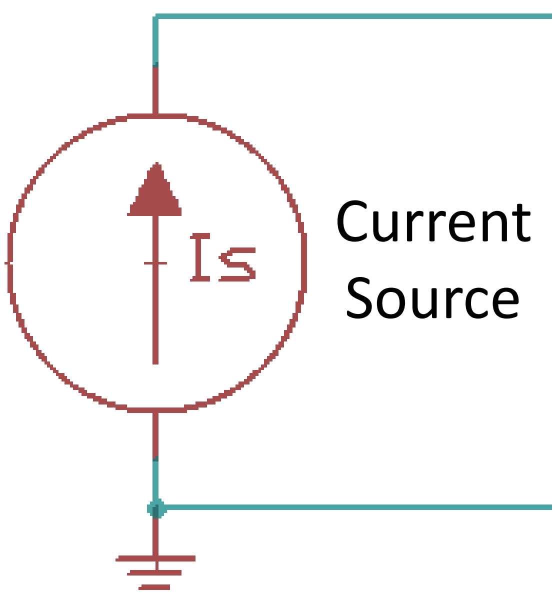
Ideal Sources

- A perfect voltage source maintains its voltage regardless of load.
- A perfect current source supplies a fixed current regardless of load.

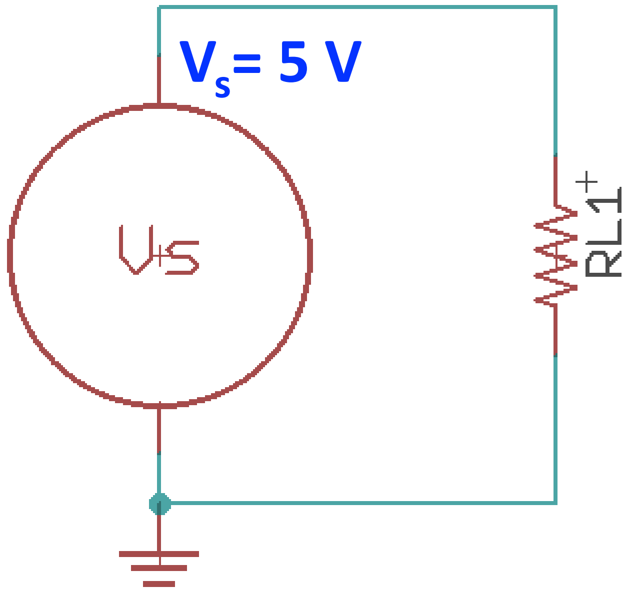


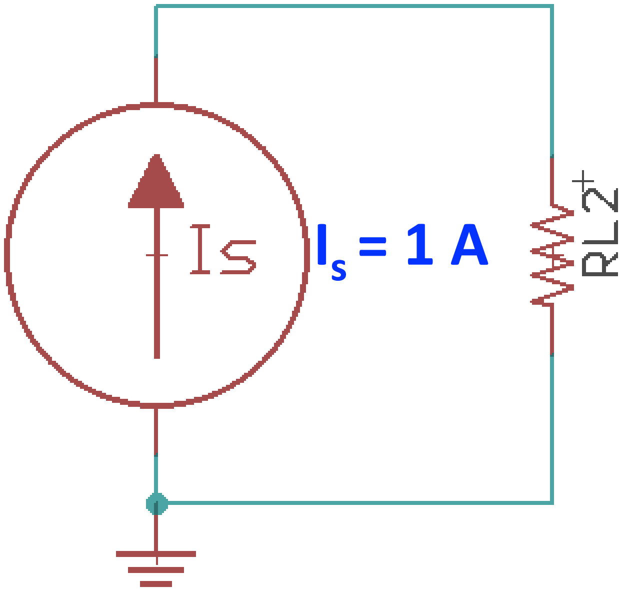


Ideal Sources with Loads

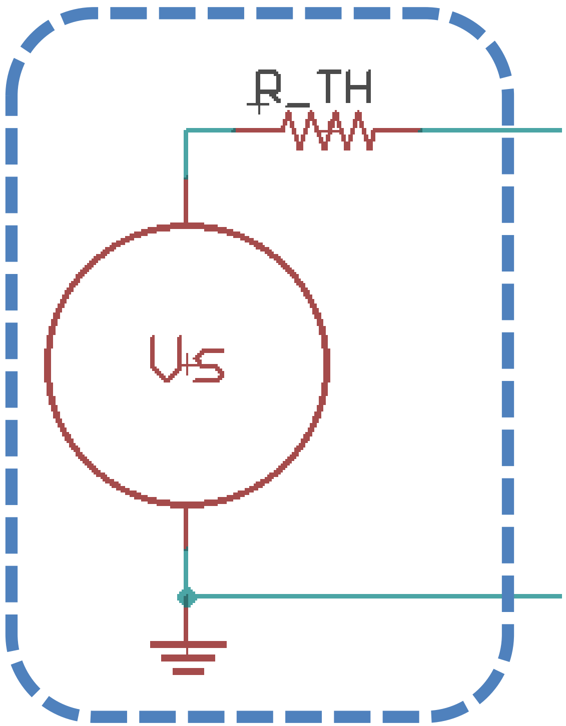
R_L	Current
1 Ω	5 A
.1 Ω	50 A
.01 Ω	500 A
0 Ω	∞

R_L	Voltage
1 Ω	1 V
10 Ω	10 V
100 Ω	100 V
∞	∞

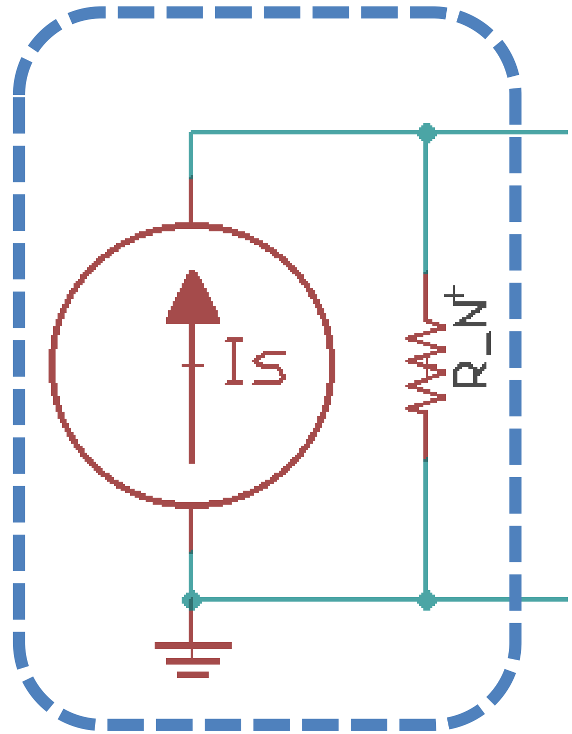




Model of Real Sources



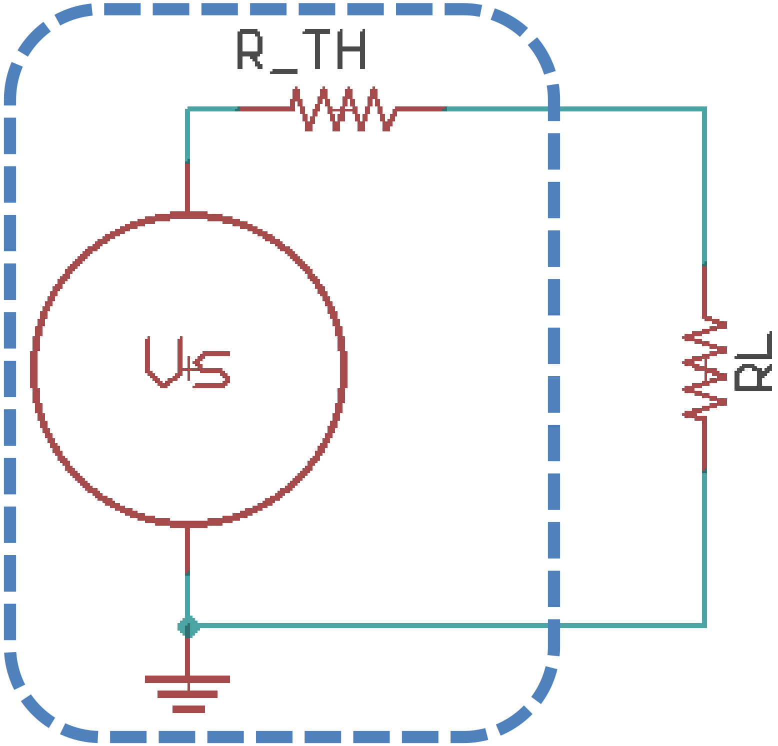
A good **voltage** source has very **small** $\mathbf{R_{Th}}$



A good **current** source has very **large** $\mathbf{R_N}$

Modern electronics signal with voltage, but they must supply sufficient current to maintain signal integrity. We will focus on voltage signaling.

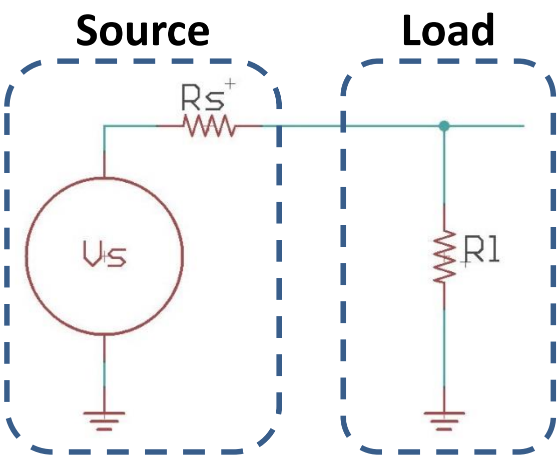
Voltage Source with Load



Voltage divider!

Voltage across R_L is close to V_s if $R_{Th} << R_L$

Input and Output Impedance



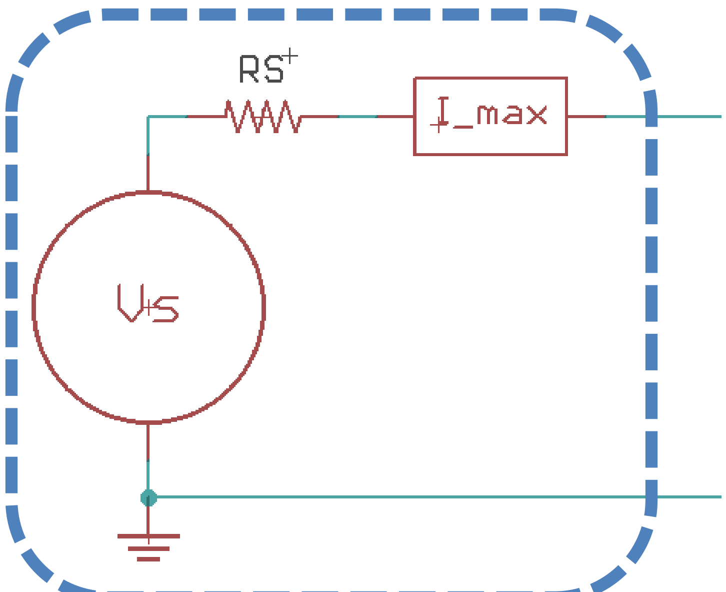
Circuit fragments that play well with others are characterized by:

Low output impedances that can supply plenty of current.

High input impedances that don’t require a lot of current.

Output Compliance

- Voltage sources can maintain predictable output up to a specified maximum current.
- If I_{max} is exceeded, voltage is not guaranteed, and the source may be damaged.



Examples of Real Sources

- A fresh battery is a good voltage source. As it ages, its internal series resistance increases.
- Wall outlet.
- NI DAQ.
- Photo-multiplier tube or a photo-diode is a current source.

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Powering the Arduino

- 5 V internal circuitry.
- Can be powered directly from the USB connection.
- 5 V and 3.3 V outputs to power external components.
- 7-20 V can be applied to the barrel connector or the Vin pin. Built in voltage regulator provides 5 V.
- Vin pin can be used to pass through up to 20V and ~1 A.

Image from Sparkfun.com.

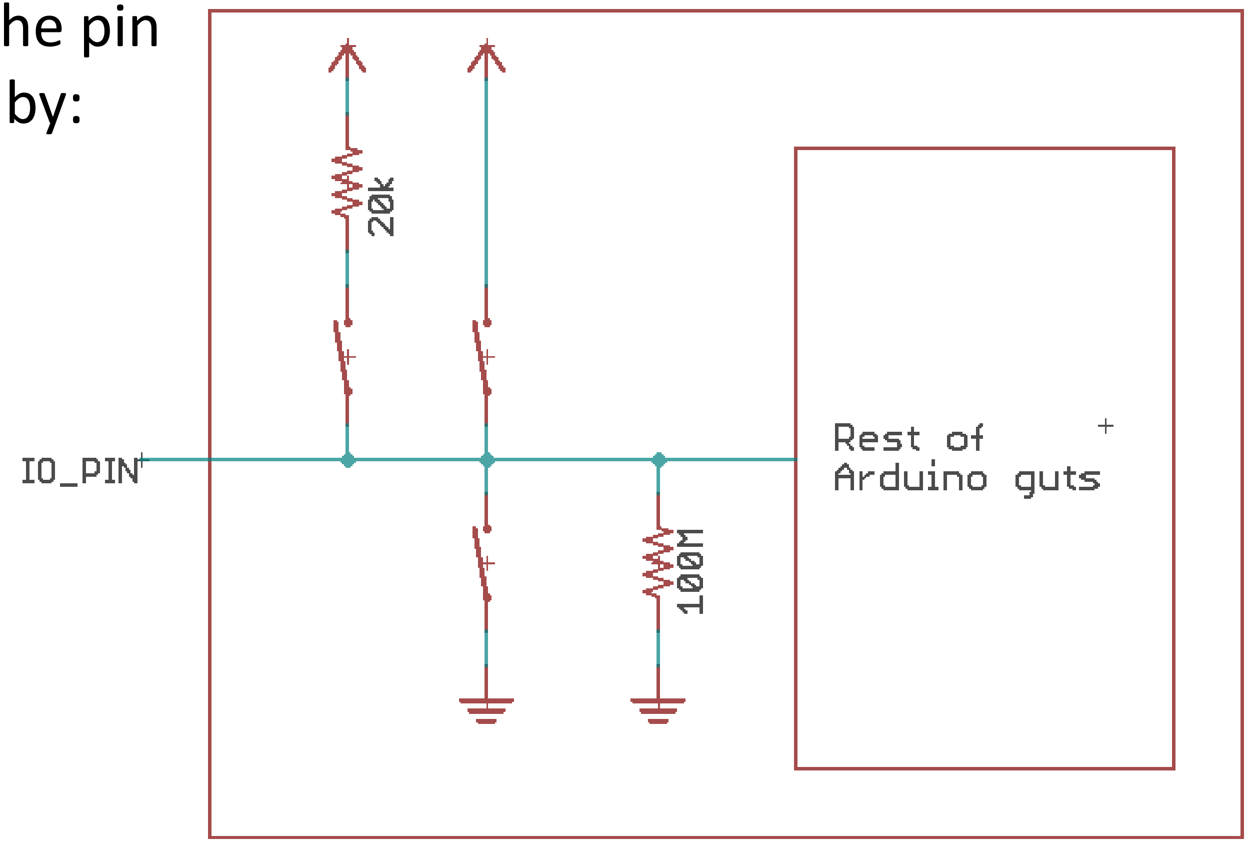
Input and Output with Arduino

- Pins can be configured (by software) as inputs or outputs.
- Connecting *input* pins to voltages <0 V or >5 V can damage the Arduino.
- Shorting *output* pins to power, ground or other pins can damage the Arduino.

Input and Output with Arduino

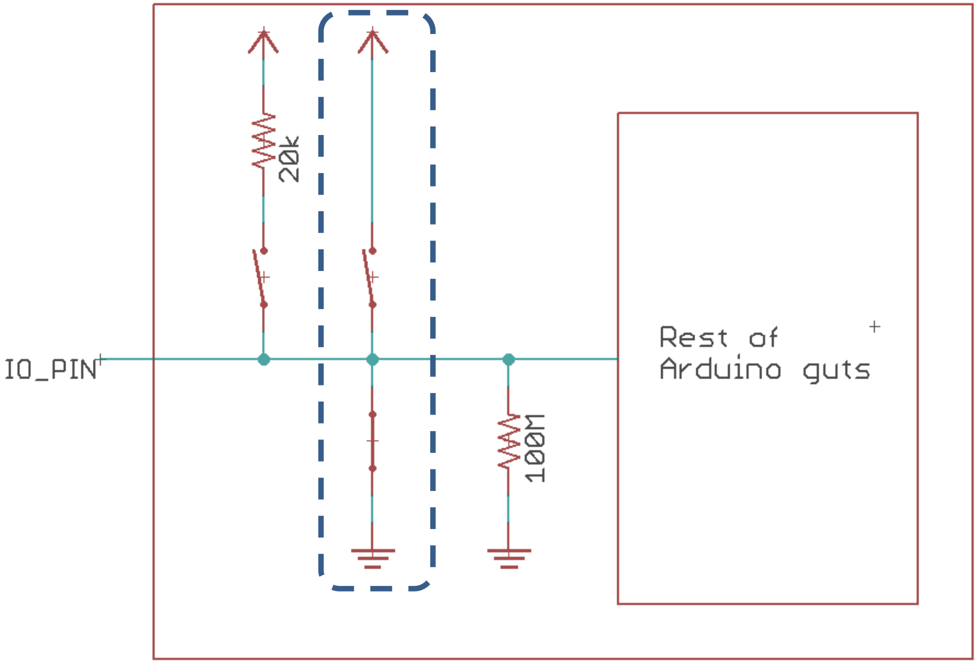
Hardware switches change the functionality of the pin circuitry. Controlled by:

```
void setup()
{
  pinMode();
}
```



pinMode(OUTPUT);

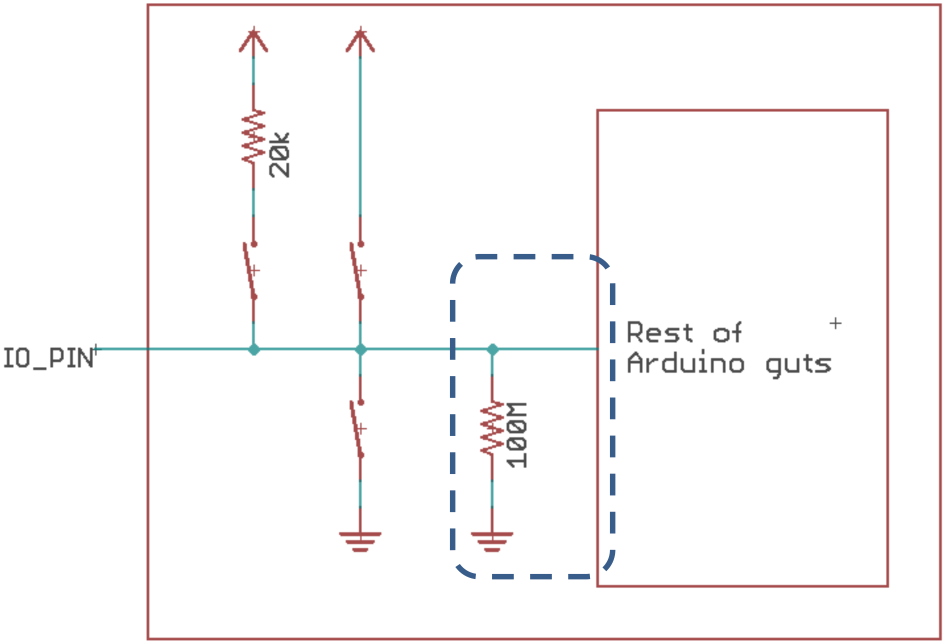
- Sink, or source, up to 20 mA.
- Enough to power a small LED or buzzer.
- Be careful not to short to power or ground.



digitalWrite(pin, LOW);

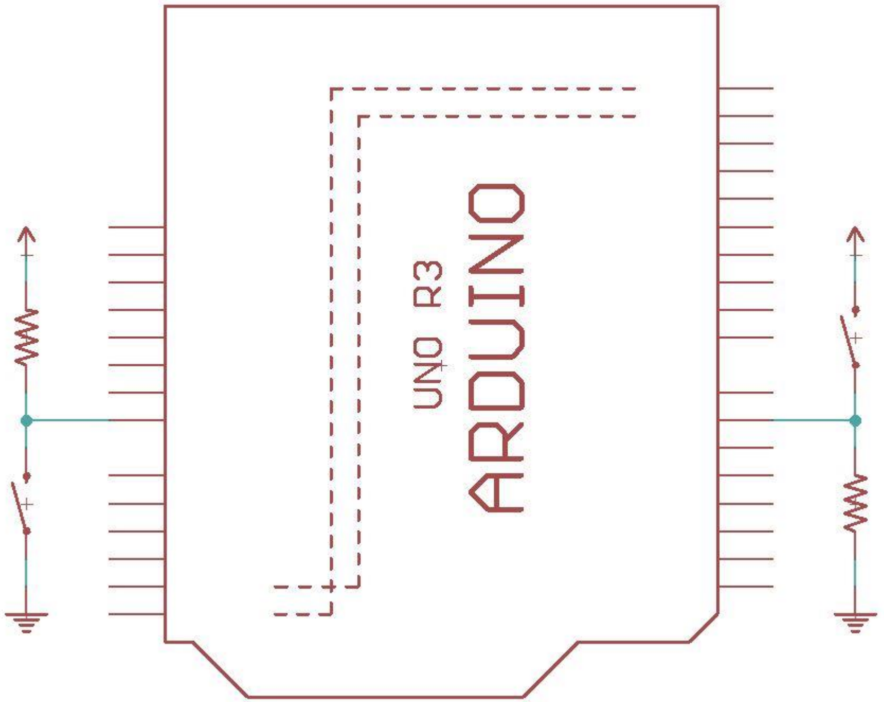
pinMode(INPUT);

- Pins are declared as INPUT by default
  - No need to explicitly declare, but good practice.
- High impedance
  - Can detect very weak signals such as from a capacitance sensor or photodiode.
  - Susceptible to noise and coupling from adjacent pins
  - May result in unexpected state changes.



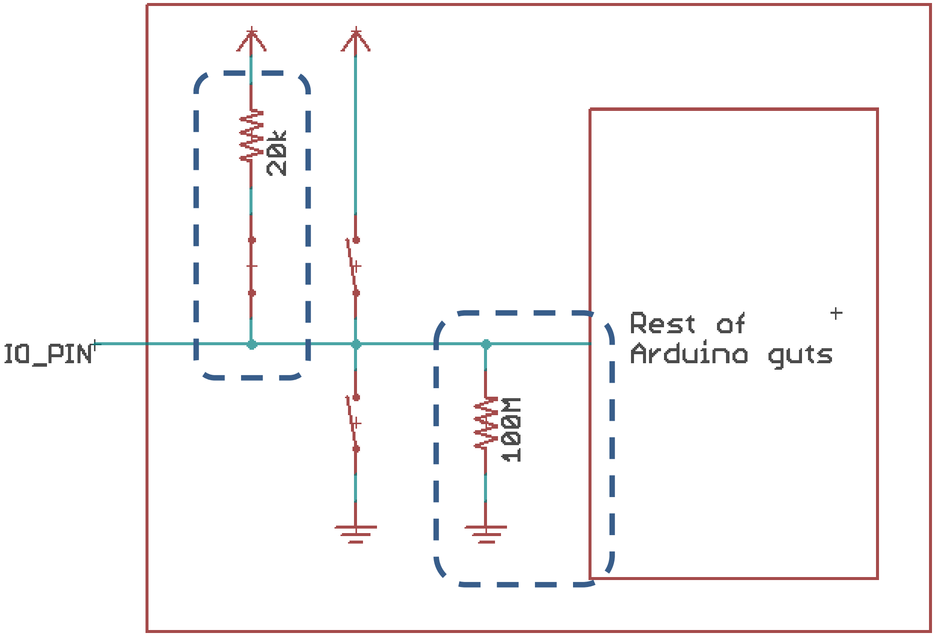
External Pull-up/Pull-down

- Pull-up or pull-down resistors “gently steer” a pin in the ‘right’ direction in the absence of other input. 10k is a reasonable external value.
- This works because input pins are high impedance.



pinMode(INPUT_PULLUP);

- Internally connects the pin to 5V with a ~20k resistor.
- Useful for connecting buttons and switches to your circuit without an external resistor.
- Provides enough power to (unintentionally) power an LED.



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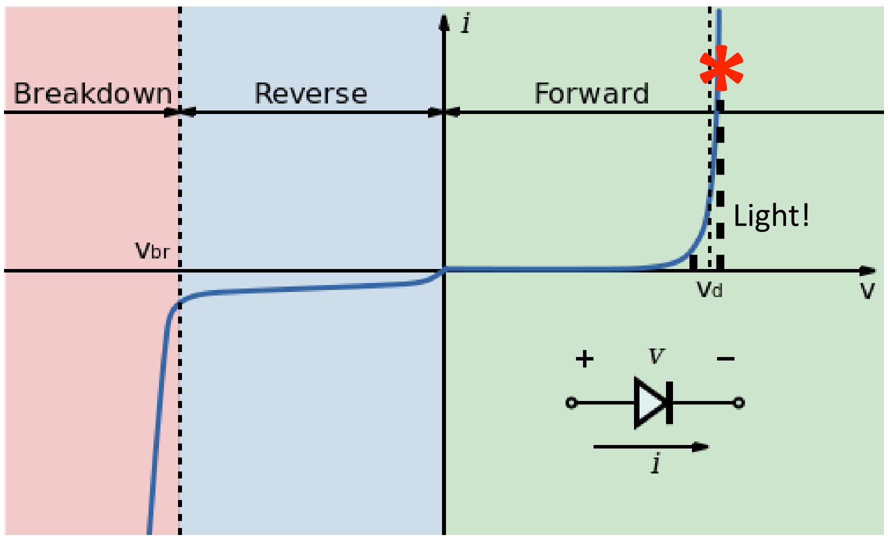
Connecting Sources to Loads

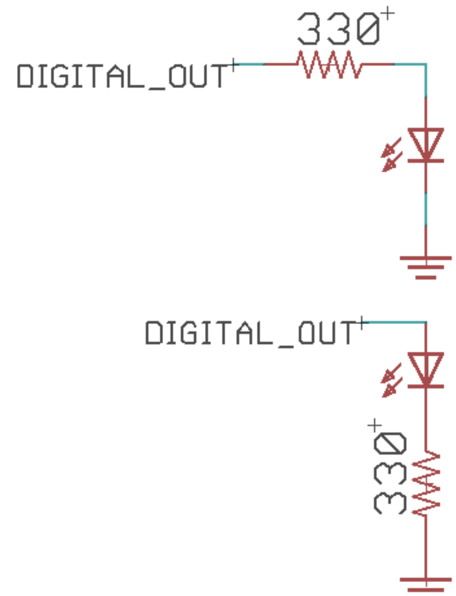
- Loads need to be appropriately matched to their sources.
- Appropriately sized loads should not modify the output of the source.

Arduino outputs 5 V at ~20 mA per pin.
Can be driven directly from Arduino output pins.
May not work as expected.
Connecting directly to Arduino can damage it.

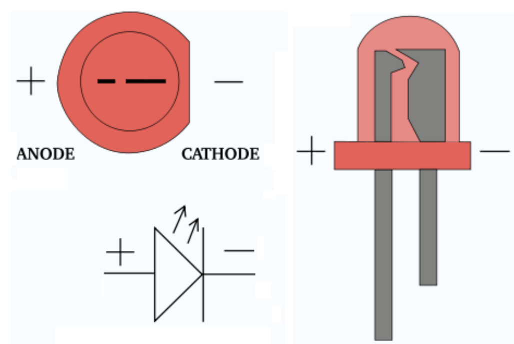
Load	Input Impedance or Drive Current
Modern Op Amp (open loop)	>10 GΩ
Acquisition System e.g. NI	>10 GΩ
Arduino inputs	100 MΩ (50 nA)
Transistor (MOSFET)	100 nA
Multimeter	>1 MΩ
Oscilloscope (configured as 1 MΩ input)	1 MΩ
Small LED	~20 mA
Small buzzer	~40 Ω
Oscilloscope (configured as 50 Ω input)	50 Ω (.1A)
Bright LED	50 mA - >10 A
Speaker	8 Ω
Solenoid or Relay	<5 Ω

Driving a Small Light Emitting Diode (LED)





- Diodes are electrical one-way valves.
- Non-linear i.e. do not obey Ohm's Law.
- Used in rectifiers, protection circuits and voltage references.
- Need current limiting circuitry.

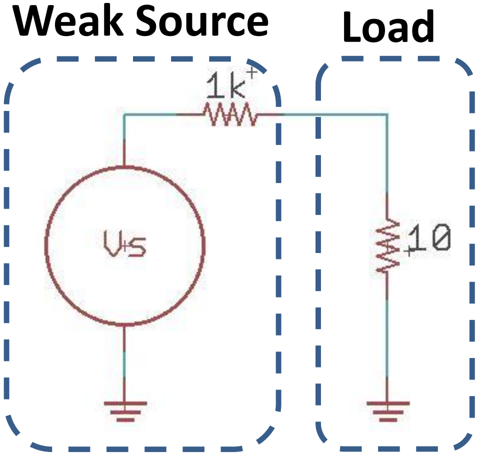


Forward Current	I_F	50 Note1	mA
Peak Forward Current Note2	I_{FP}	200	mA

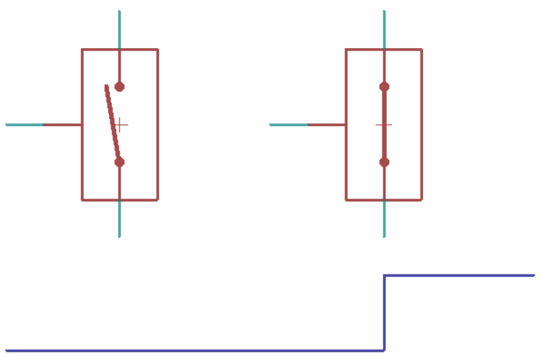
https://upload.wikimedia.org/wikipedia/commons/a/a5/Diode-IV-Curve.svg

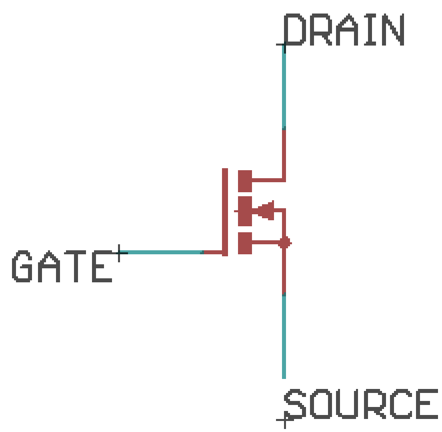
What To Do When Sources and Loads are Badly Matched?

- Driving a solenoid or a lightbulb from an Arduino.
- Source output impedance is relatively high.
- Load input impedance is relatively small.

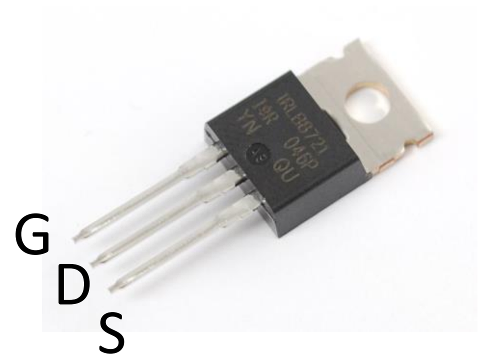


Transistor as a Switch (Demo)





- When the gate to source voltage exceeds ~1v, the transistor turns on.
- Can drive low impedance loads.
- Controls voltages higher than what the Arduino can handle.



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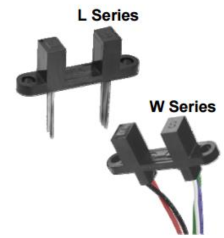


- Design starting point.
- Pay attention to *Absolute Maximum Ratings.*
- Schematics may leave out some pins for clarity.
- Application notes have useful circuit examples.
- Digikey.com

Absolute Maximum Ratings (T_A = -40°C to + 70° Unless otherwise noted)

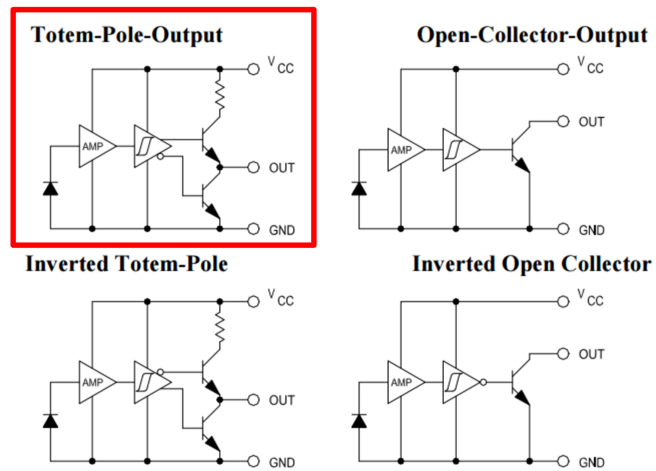
Storage Temperature	-40° C to +85° C
Operating Temperature	-40° C to +70° C
Lead Soldering Temperature (1/16" (1.6 mm) from case for 5 seconds with soldering iron)[1]	260° C

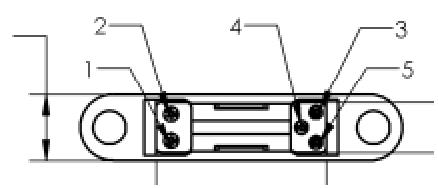
Input Infrared LED

DC Forward Diode (LED) Current	40 mA
DC Reverse Diode (LED) Voltage	2 V
Input Diode Power Dissipation[1]	100 mW

Output Photologic®

Supply Voltage, V_{CC} (not to exceed 3 seconds)	10V
Voltage at Output Lead (Open Collector Output version)	35 V
Output Photologic® Power Dissipation[2]	200 mW
Total Device Power Dissipation[3]	300 mW





1 Anode (+)
2 Cathode (-)
3 Vcc (+)
4 Out
5 Gnd

View from pin side

Output is high when beam is not broken
Output is low when beam is broken

OPB 900 Series Beam Break

Reading Datasheets

NI 625*x* Specifications

Specifications listed below are typical at 25 °C unless otherwise noted. Refer to the *M Series User Manual* for more information about NI 625*x* devices.

このドキュメントの日本語版については、ni.com/manualsを参照してください。
(For a Japanese language version, go to ni.com/manuals.)

Analog Input

Number of channels

- NI 6250/6251 .... 8 differential or 16 single ended
- NI 6254/6259 .... 16 differential or 32 single ended
- NI 6255 .... 40 differential or 80 single ended

ADC resolution .... 16 bits

DNL .... No missing codes guaranteed

INL .... Refer to the *AI Absolute Accuracy Table*

Sampling rate

- Maximum
  - NI 6250/6251/6254/6259 .... 1.25 MS/s single channel, 1.00 MS/s multi-channel

CMRR (DC to 60 Hz) .... 100 dB

Input impedance

- Device on
  - AI+ to AI GND .... >10 GΩ in parallel with 100 pF
  - AI– to AI GND .... >10 GΩ in parallel with 100 pF
- Device off
  - AI+ to AI GND .... 820 Ω
  - AI– to AI GND .... 820 Ω

Input bias current .... ±100 pA

Crosstalk (at 100 kHz)

- Adjacent channels .... –75 dB
- Non-adjacent channels .... –95 dB[1]

Small signal bandwidth (–3 dB) ...... 1.7 MHz

Analog Output

Number of channels

- NI 6250/6254 0
- NI 6251/6255 2
- NI 6259 4

DAC resolution .... 16 bits

Timing accuracy .... 50 ppm of sample rate

Timing resolution .... 50 ns

Output range .... ±10 V, ±5 V, ±external reference on APFI <0..1>

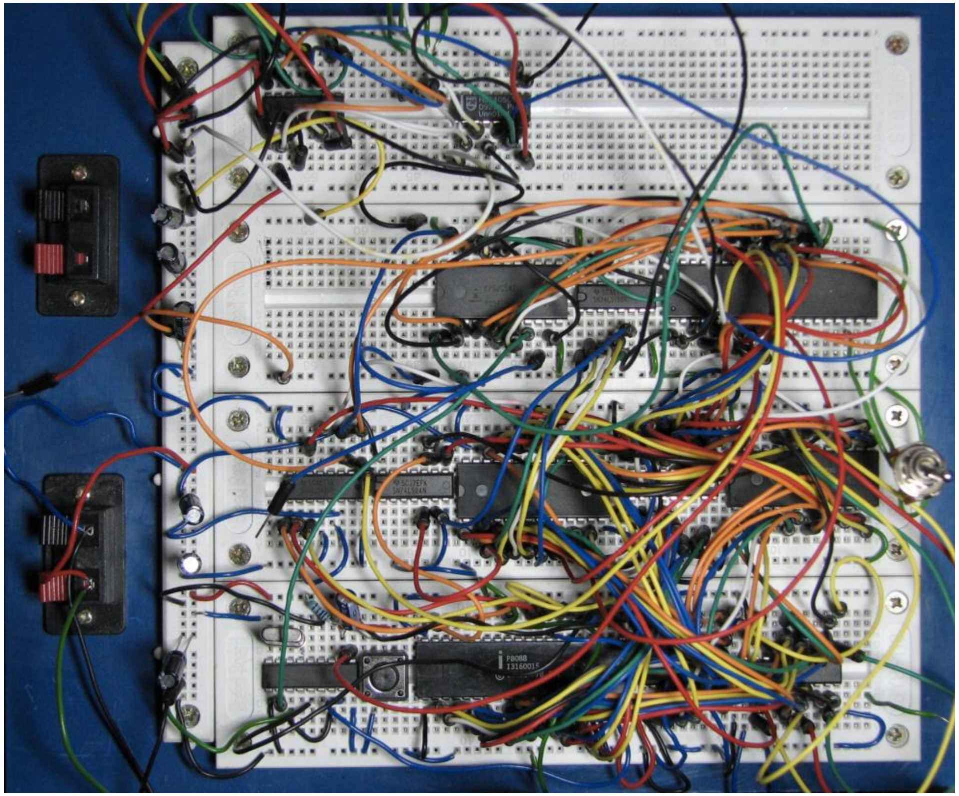
Output coupling .... DC

Output impedance .... 0.2 Ω

Output current drive .... ±5 mA

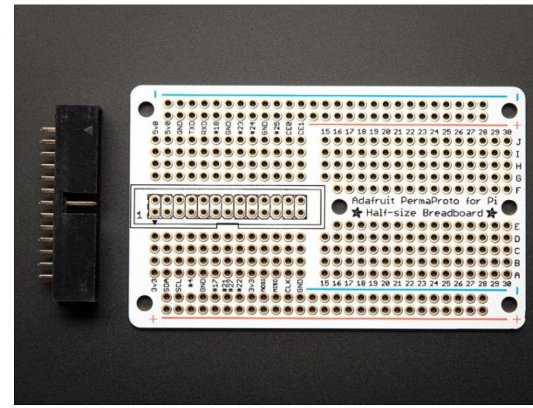
Solderless Breadboard

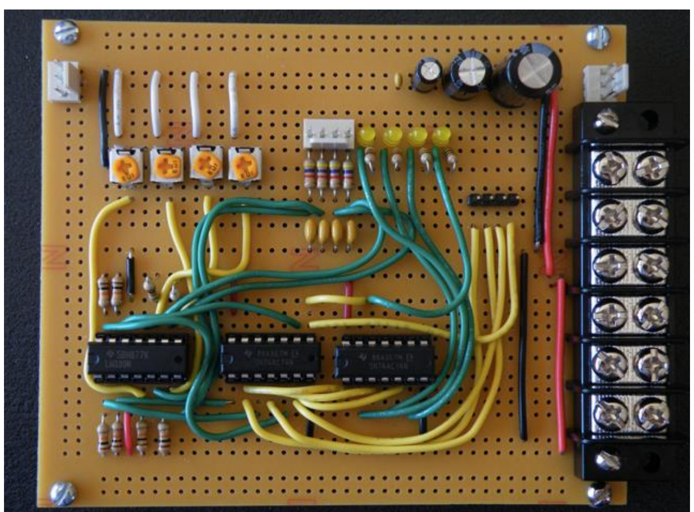
- Fast and easy for small prototypes.
- Easy to debug simple circuits.
- Contact resistance (and other pathology).
- Does not scale.
- Not durable.

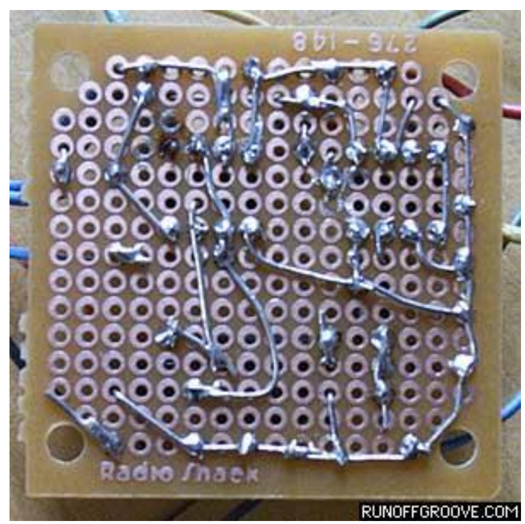


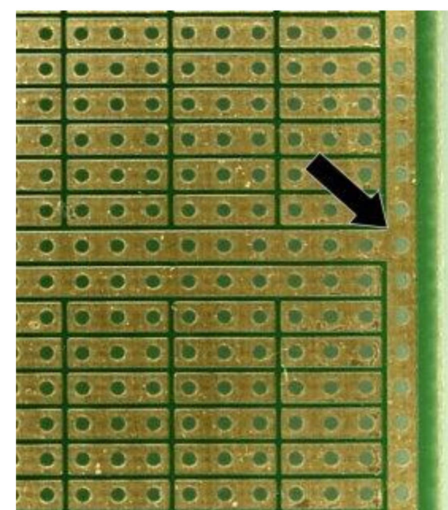
Perfboard or Protoboard

- Same-day hand-made circuits with point-to-point wiring.
- Painstaking wiring and soldering.
- Changes more difficult, but possible.
- Better performance and durability than breadboards.
- But wires aren’t mechanically fixed.



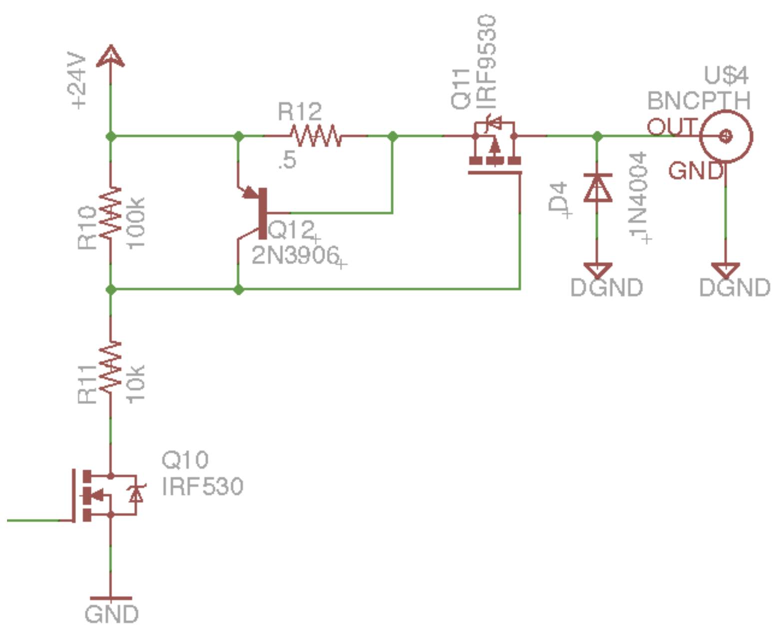


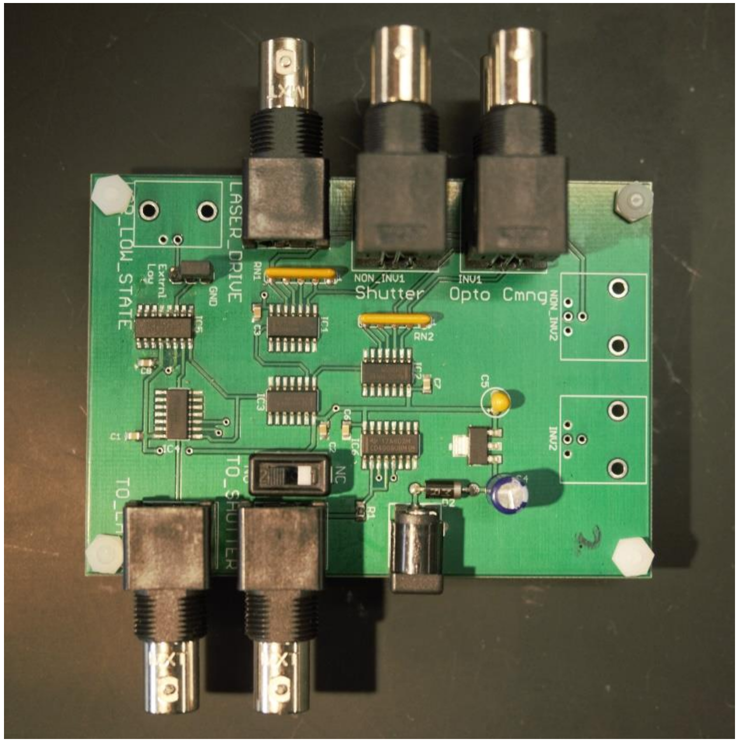




Printed circuit board (PCB)

- Higher design overhead: Requires CAD layout (eg. EagleCAD)
- Much easier to solder (esp. with complex designs)
- Cost ~$100 for a few boards, price falls dramatically with #
- Turn-around time ~2 days to ~2 weeks





Class Projects:

- Finish project #1?
- Rodent nose-poke behavior controller.