Electronics & Signal Processing for Experimental Rigs

Day 1: Basic Electronics

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Goals for the Course

Experimental Rigs are used to:

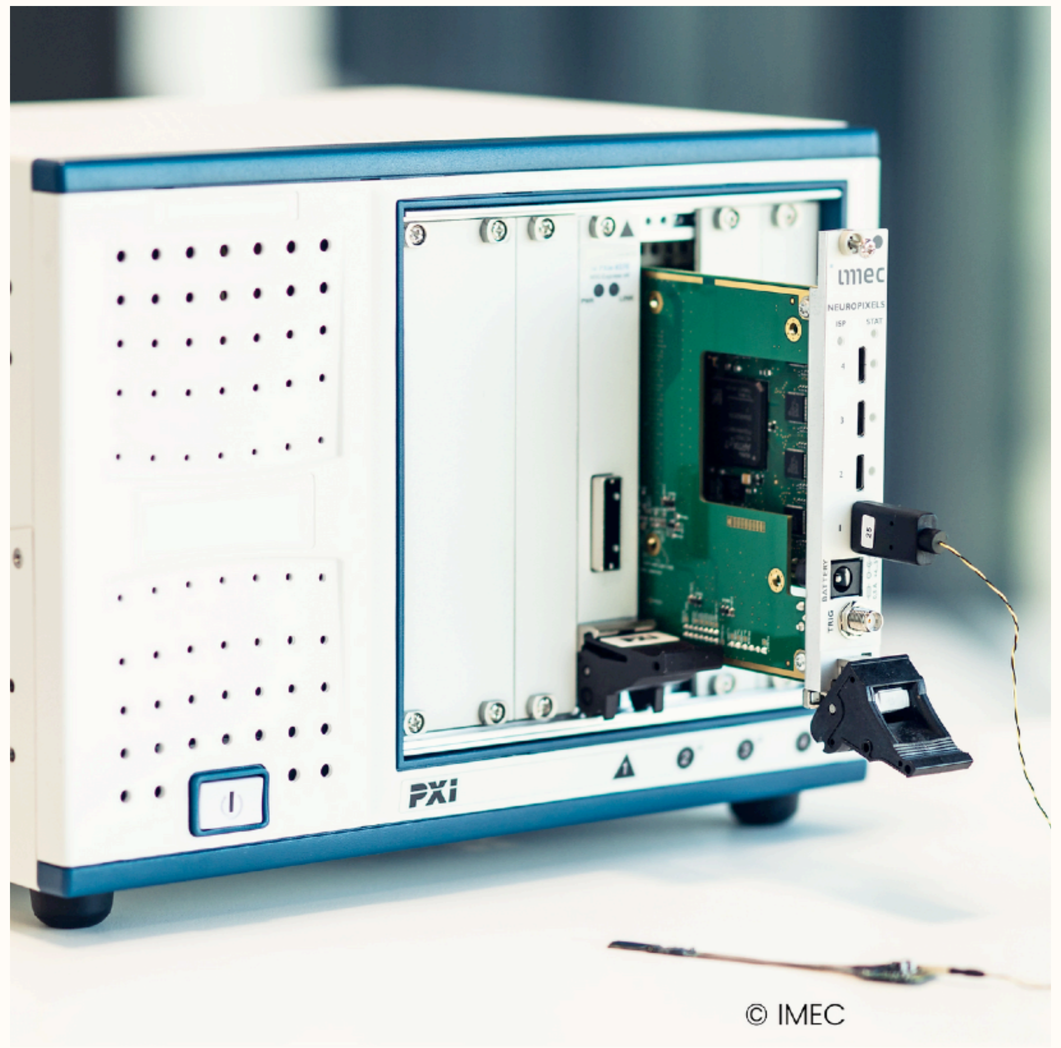
- Measure small signals (neurons, photons, force, temperature, etc)
- Generate precise stimuli
- Maintain signal fidelity (high signal-to-noise ratio)
- Minimize noise
- Keep accurate timing (between different channels of input & output)

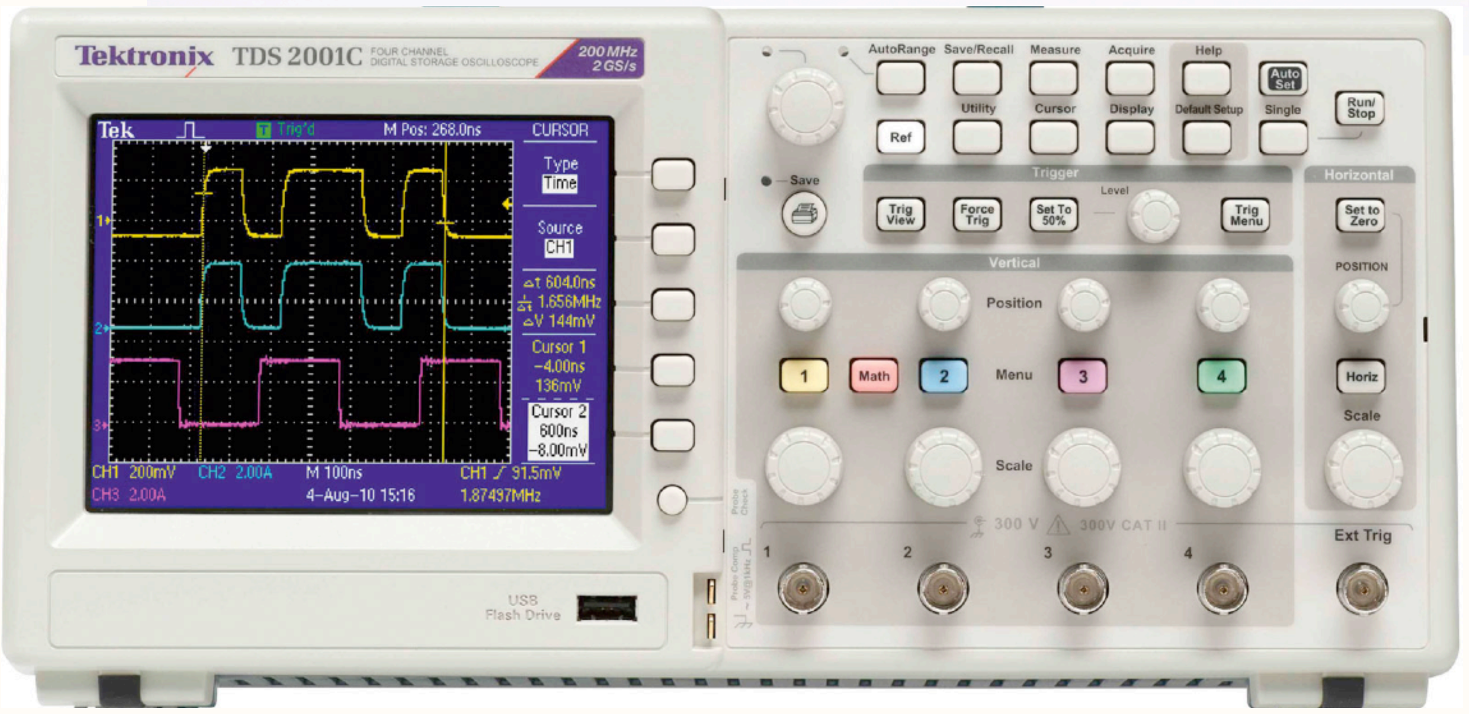
Goal for the course is to better understand:

- Mechanisms of noise & signal degradation
- Techniques and equipment to avoid noise & degradation

- Key topics from Electronics and Signal Processing
  - Focus on concepts & intuition (not too many formulas)
  - Both theory & practical skills

What does all the equipment on my rig do?

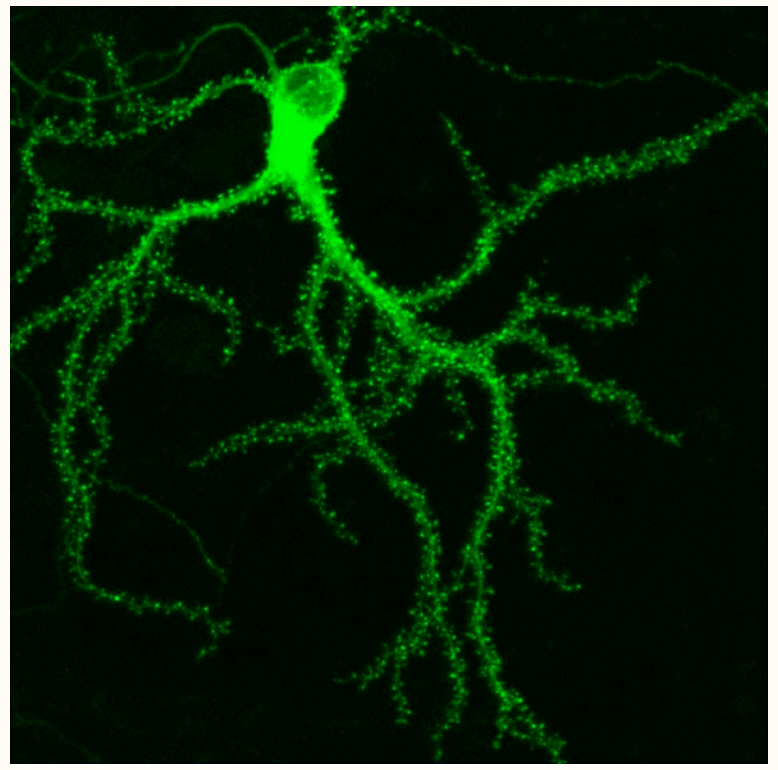




(Is all of it really necessary?)

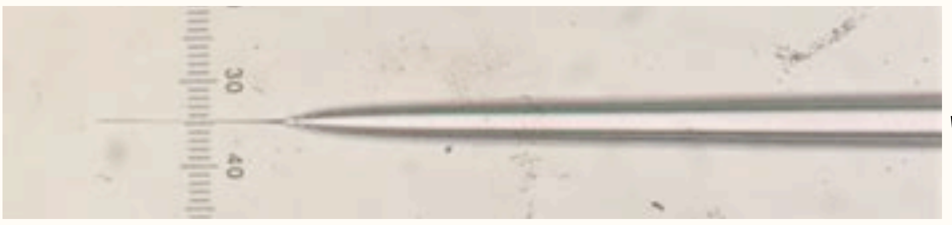
Idealized signaling

Physical Quantity to be Measured

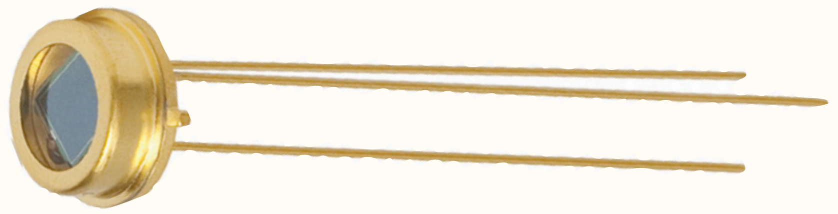


- Membrane Voltage
- Light Intensity (Fluorescence)

Sensor/ Electrode



Electrode



Photodiode / PMT

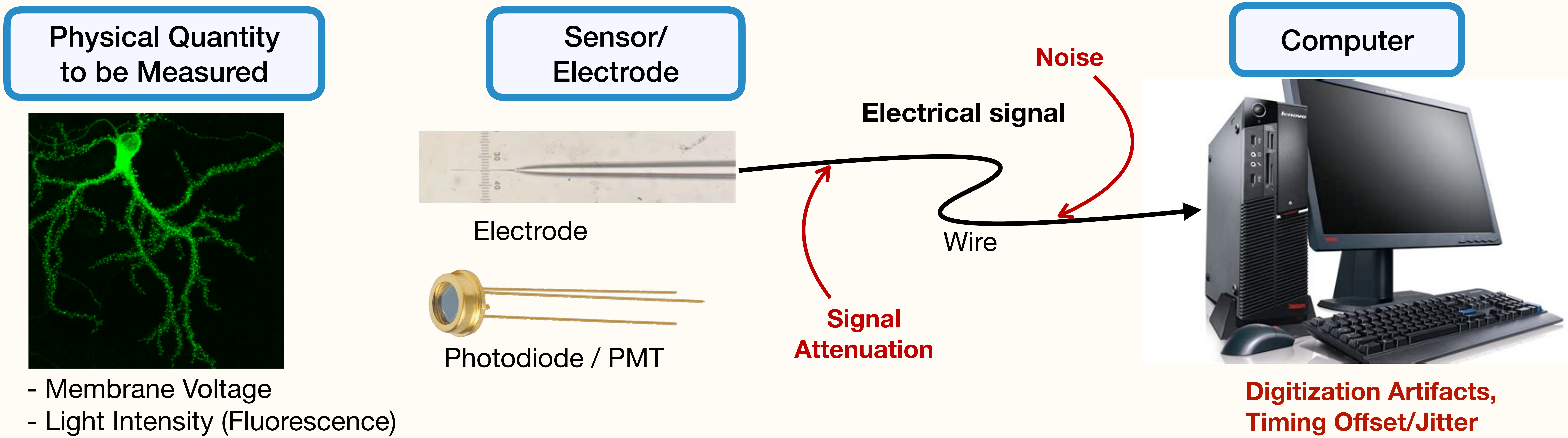
Electrical signal

Wire

Computer

Why can’t I just send my sensor signal straight to the computer?

Real-world signaling

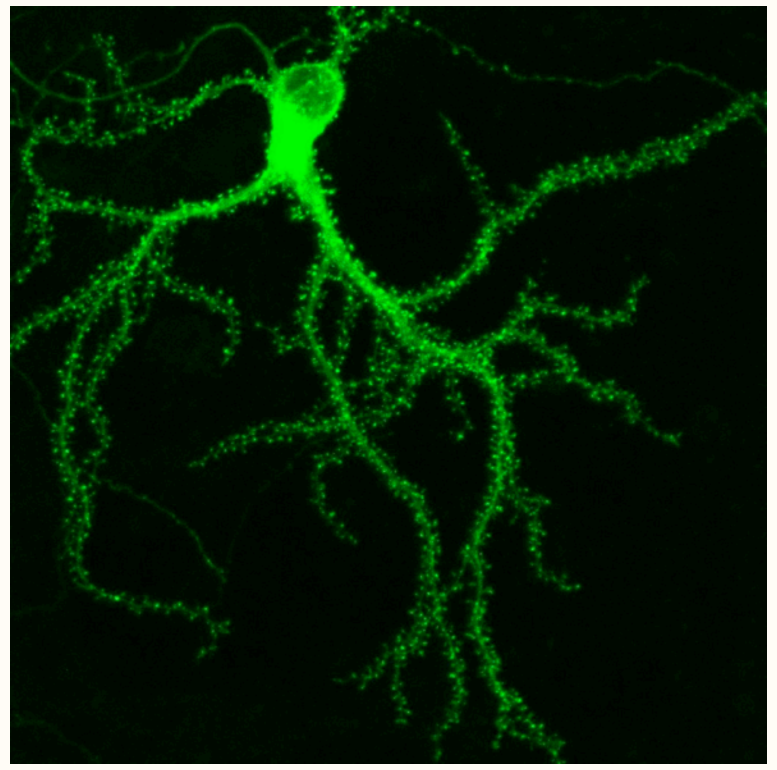


Three Problems to be Addressed:

- **Signal loss/attenuation:** Signals must be transmitted with negligible attenuation
- **Noise:** Signals must travel up to several meters without picking up appreciable noise
- **Digitization:** Analog real-world signals must be converted to/from a digital representation to work with our computers & software

Real-world signaling

Physical Quantity to be Measured → Sensor/ Electrode → Signal Amplification and Conditioning → Digitization → Computer



Membrane Voltage

Electrode

Ephys Headstage & Amplifier
- Minimize attenuation and noise

DAQ Board
- **D**ata **AQ**uisition board
- Convert analog signal to digital
- Must be tuned to minimize artifacts

Three Problems to be Addressed:

- **Signal loss/attenuation**
- **Noise**
- **Digitization**

These are **not** rig-specific problems. They are present in consumer devices as well, but those have been engineered to minimize these effects.

Lecture 1: Fundamentals of Electronics

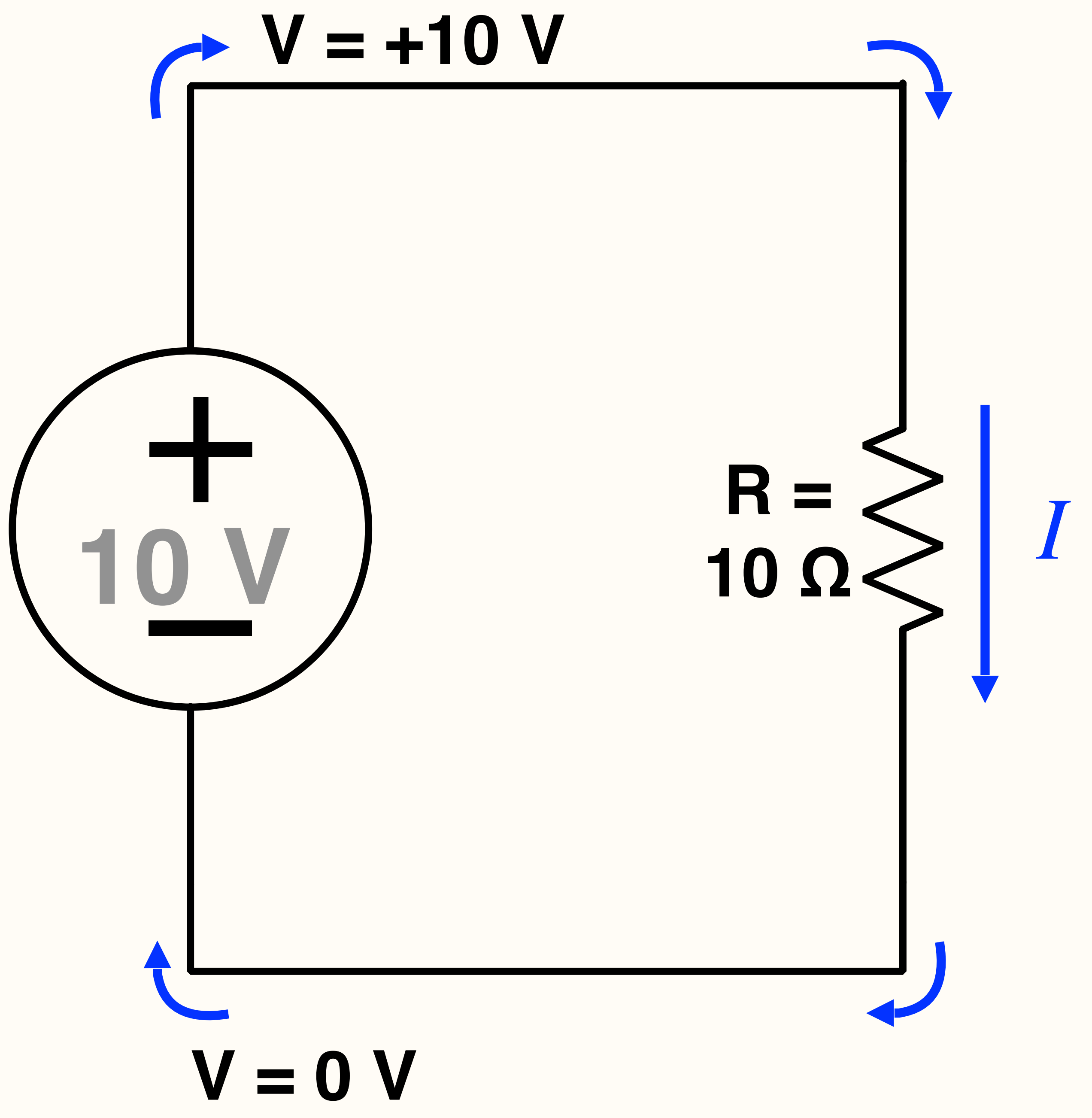
- Basic concepts (R, I, V), Ohm's Law
- Voltage divider: a fundamental circuit motif
- Output & Input Impedance = Voltage divider
  - Explains why, e.g., we need amplifiers for audio speaker or neural recordings
- Capacitance
- RC Filters = Frequency-dependent (voltage) dividers
  - Can be used to filter out unwanted frequencies

Lecture 2: Noise Sources & Amplifiers

Lecture 3: Digitization & Filtering

Lab Electronics Basics

Electricity (Symbol)	Units	Definition
Current (I)	Amp (A)	Flow of charge
Voltage (V)	Volt (V)	Potential Difference (Driving force for current)
Resistance (R)	Ohm (Ω)	Resistance to flow
Power (P)	Watt (W)	Rate of work $P = VI$



Lab Electronics Basics

Ohm's Law: $V = IR$

or $I = V/R$

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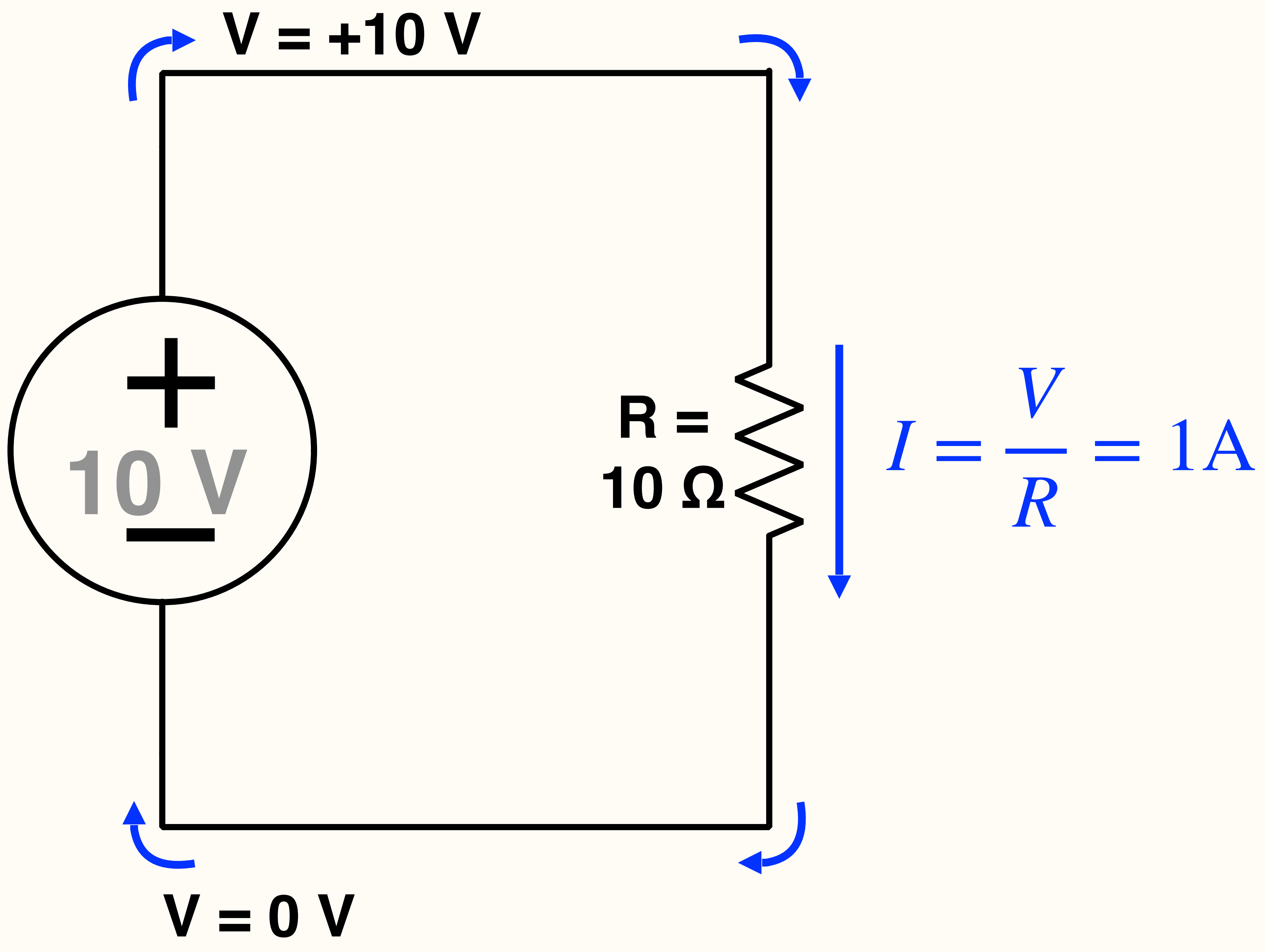
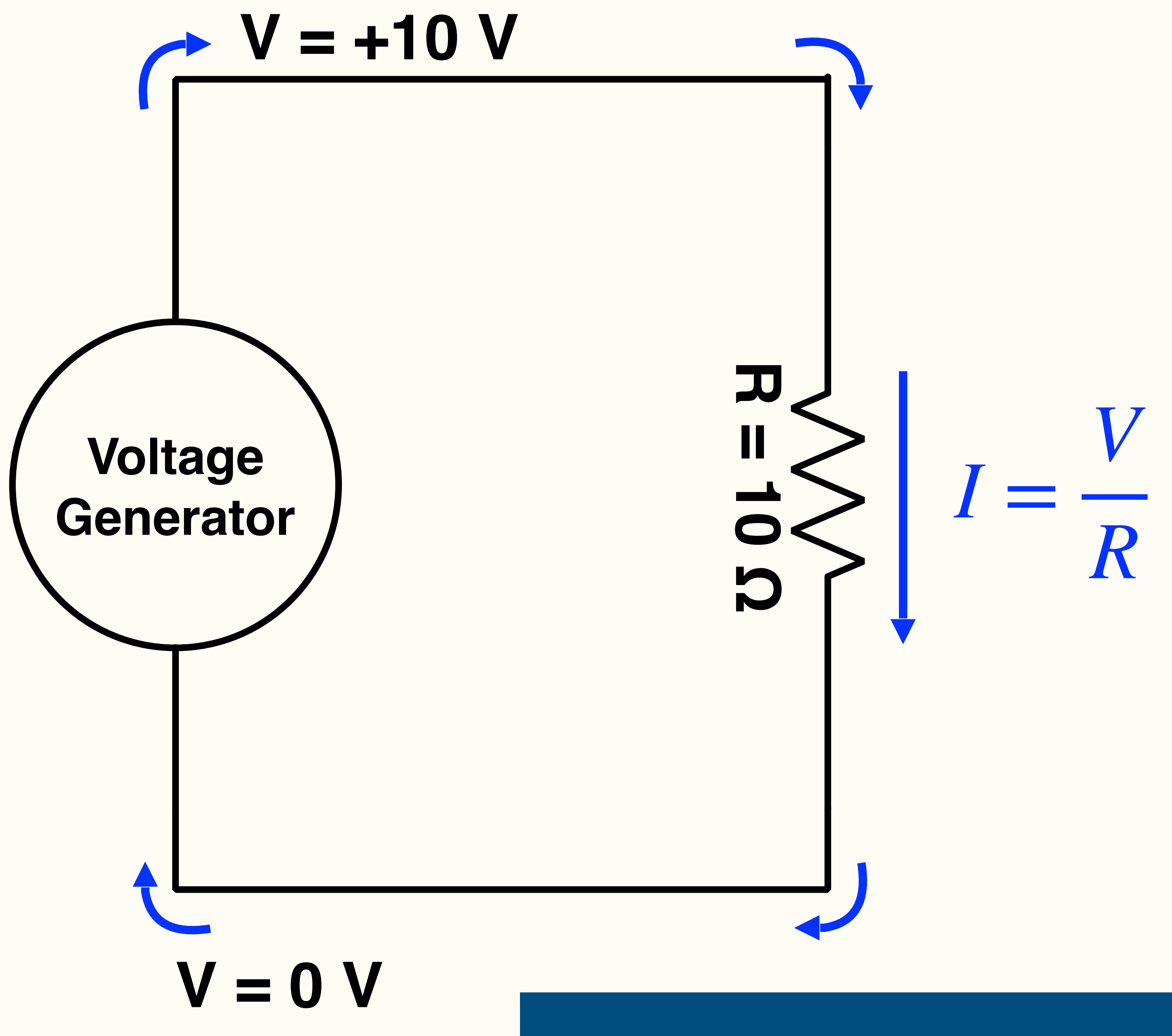
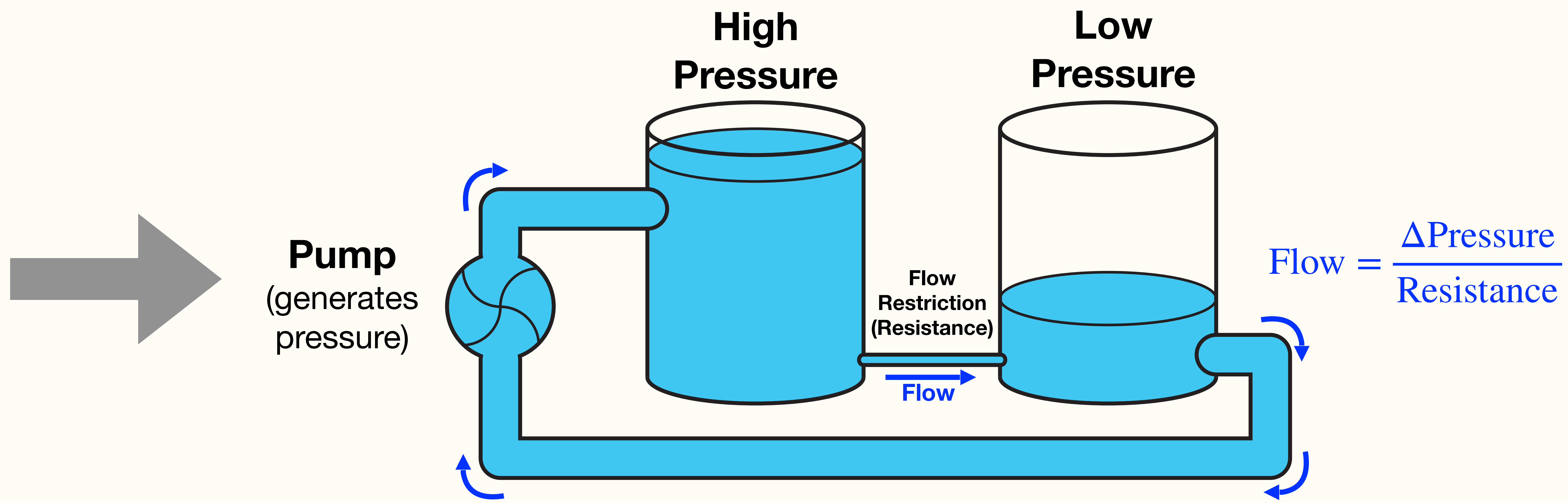


Electricity: Water analogy

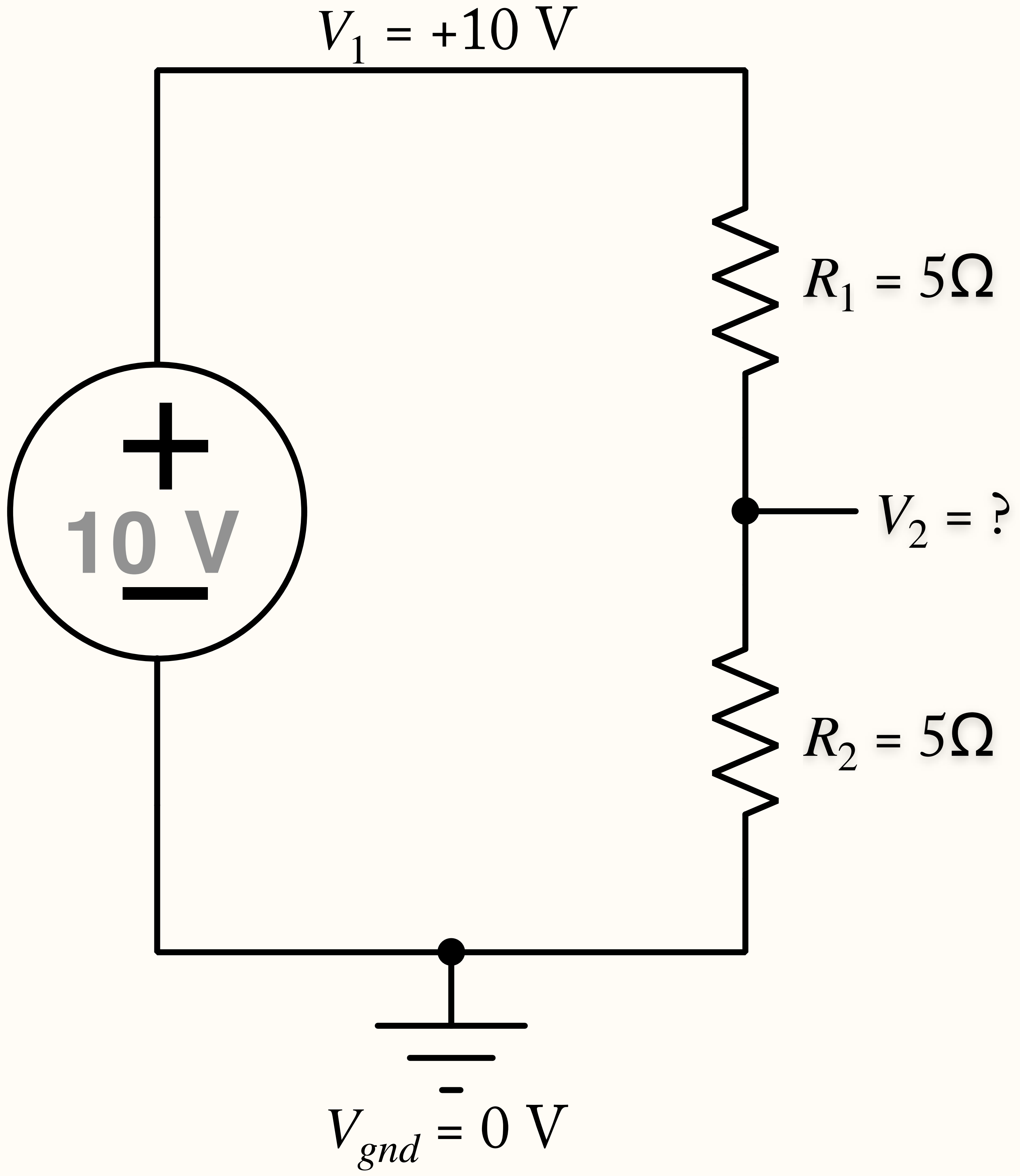




General Concept	Electricity (Units)	Water
Flow	Electric Current (Amps)	Flow of Water
Potential Difference	Voltage (Volts)	Pressure / Height
Resistance	Resistance (Ohms)	Restriction

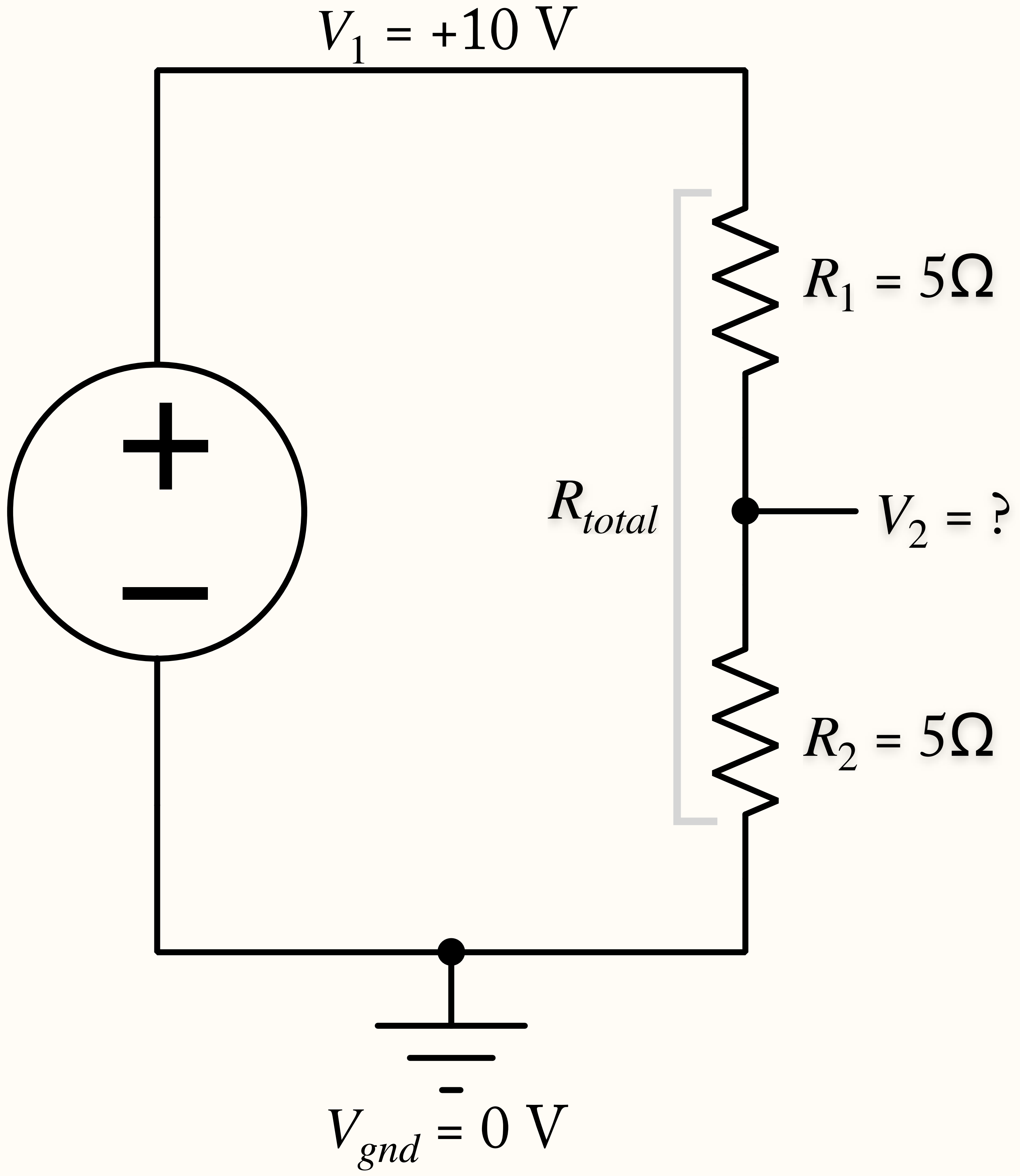
Simulation
https://tinyurl.com/y7jl6nnh

Voltage Divider



- Fundamental circuit motif
- Key to understanding many concepts:
  - Impedance, RC Filters, etc

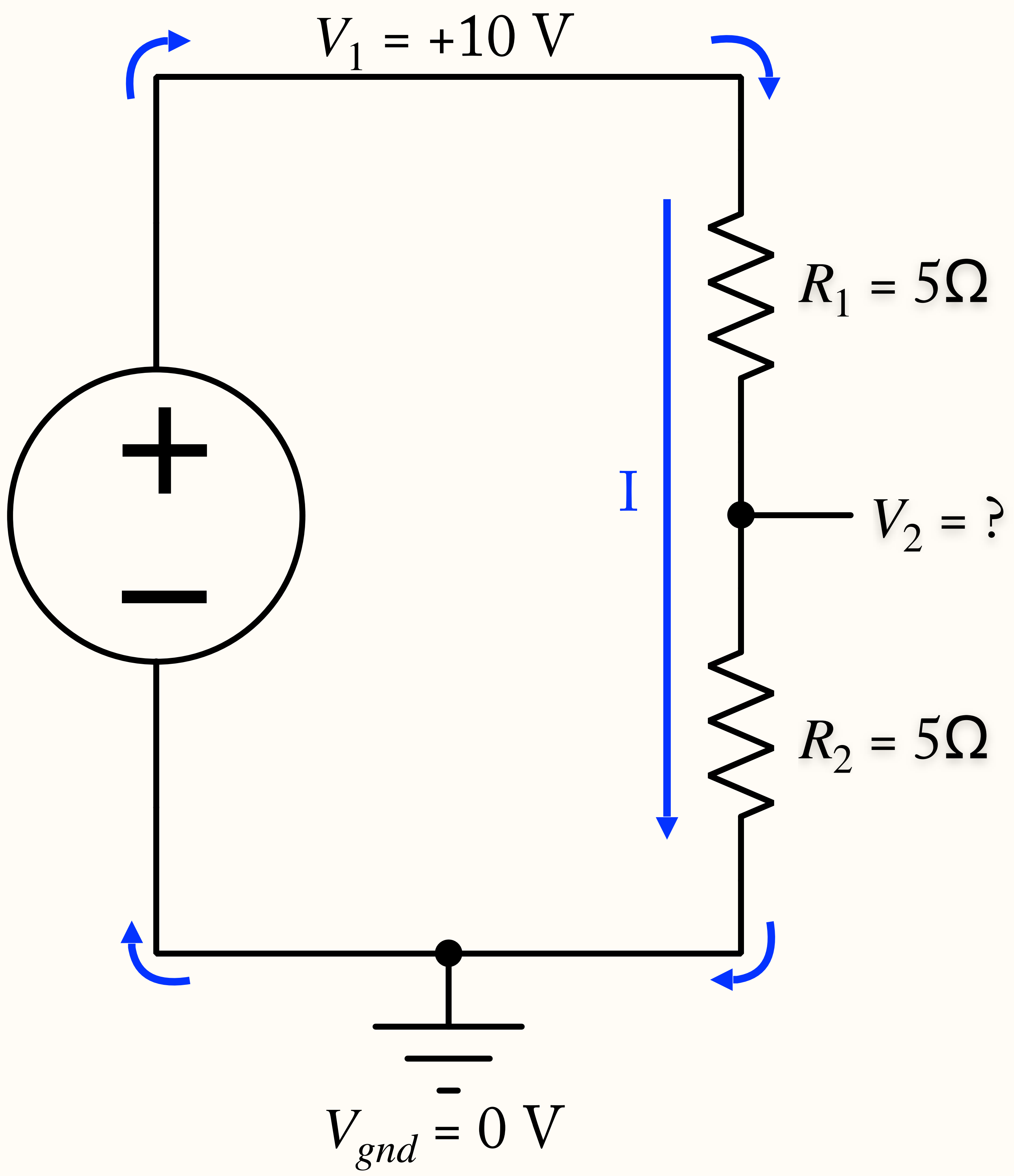
Voltage Divider



1. Compute the combined resistance of the two resistors in series:

$$R_{total} = R_1 + R_2 = 10\Omega$$

Voltage Divider

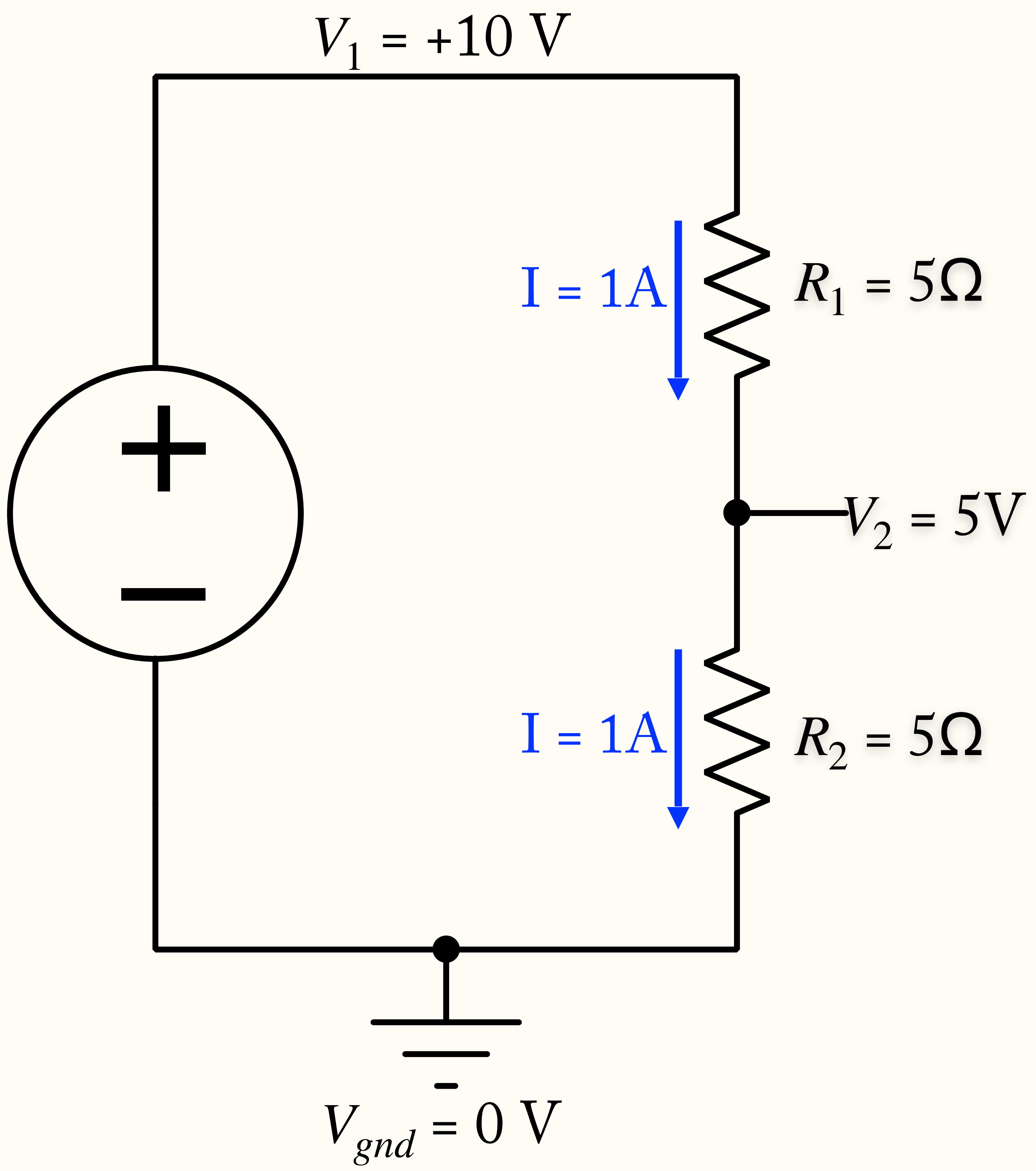


1. $R_{total} = R_1 + R_2 = 10\Omega$

2. Determine the current flowing through the circuit:

$$I = \frac{V}{R_{total}} = \frac{10V}{10\Omega} = 1A$$

Voltage Divider



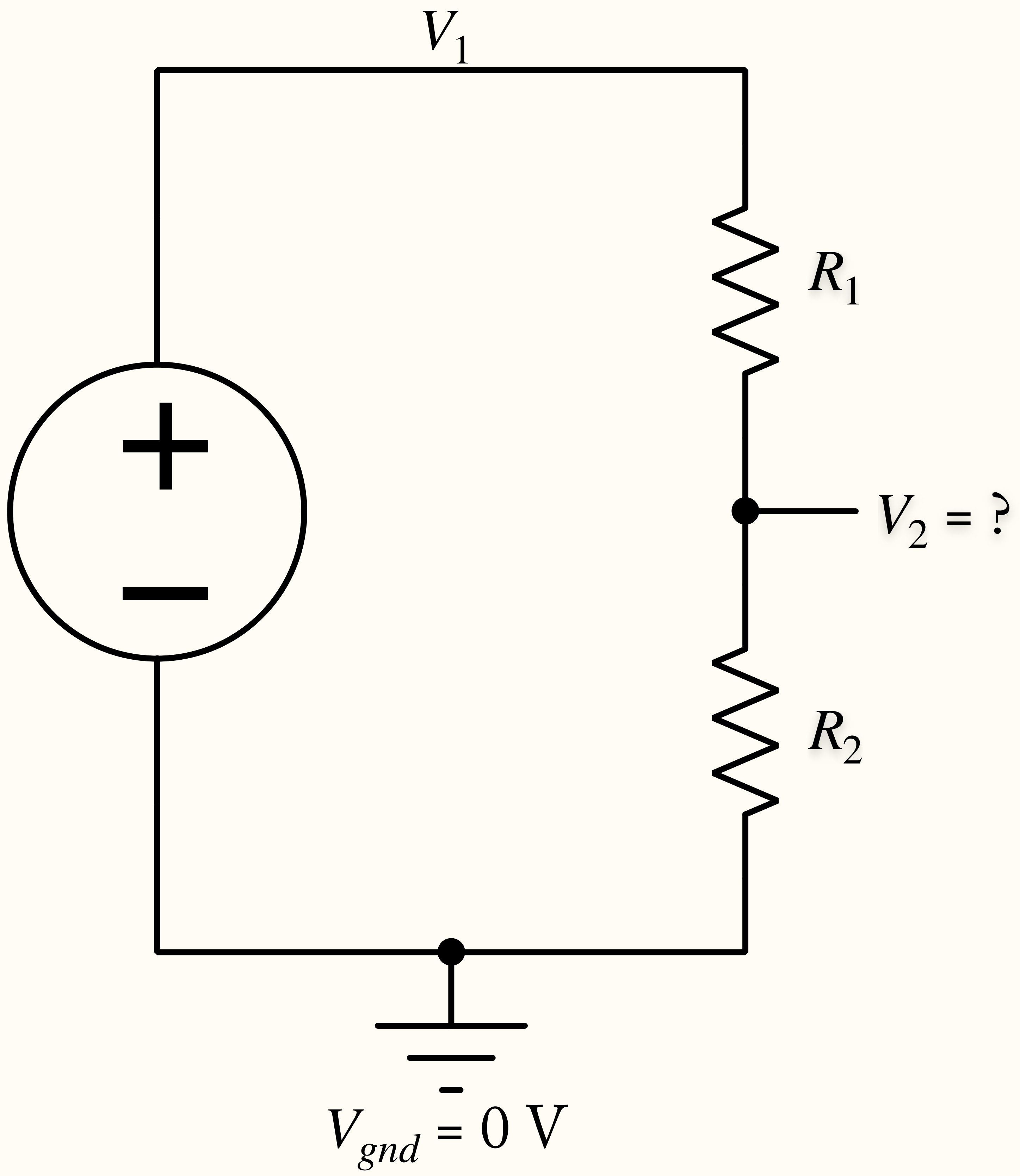
1. $R_{total} = R_1 + R_2 = 10\Omega$

2. $I = \dfrac{V}{R_{total}} = \dfrac{10\text{V}}{10\Omega} = 1\text{A}$

3. Determine the voltage across R_2:

$$V_2 = IR_2 = 5V$$

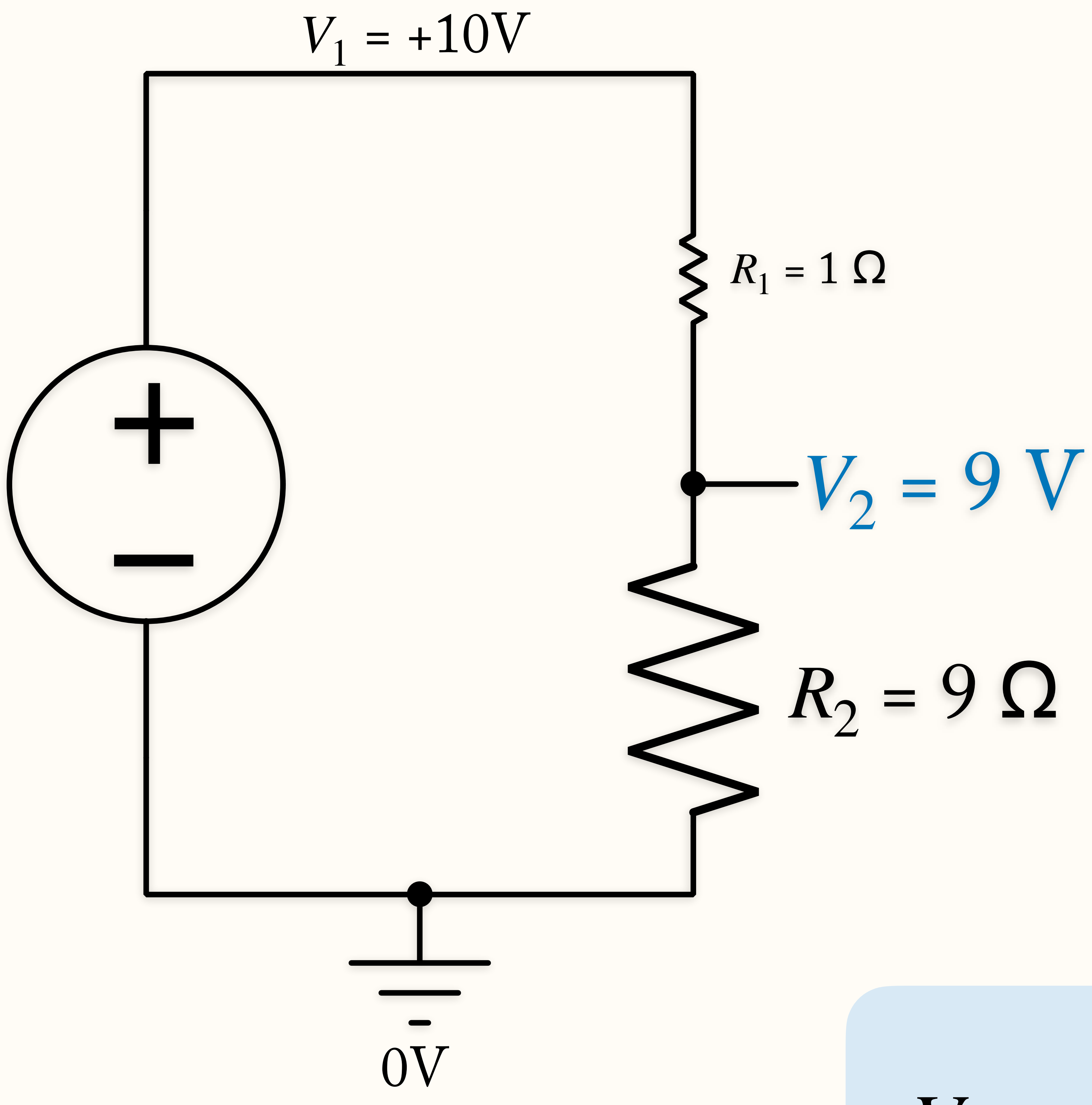
Voltage Divider

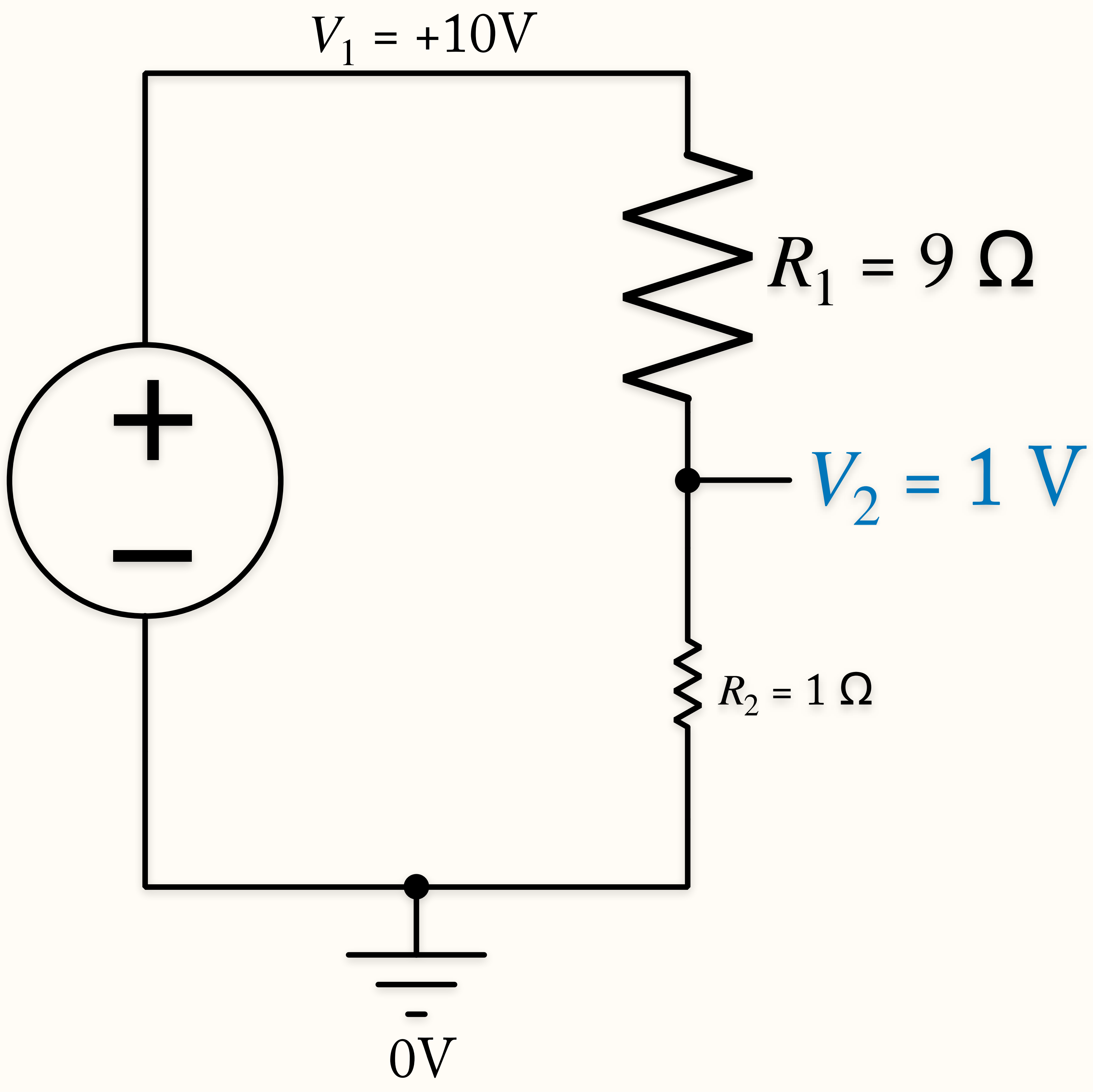


General voltage divider formula:

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

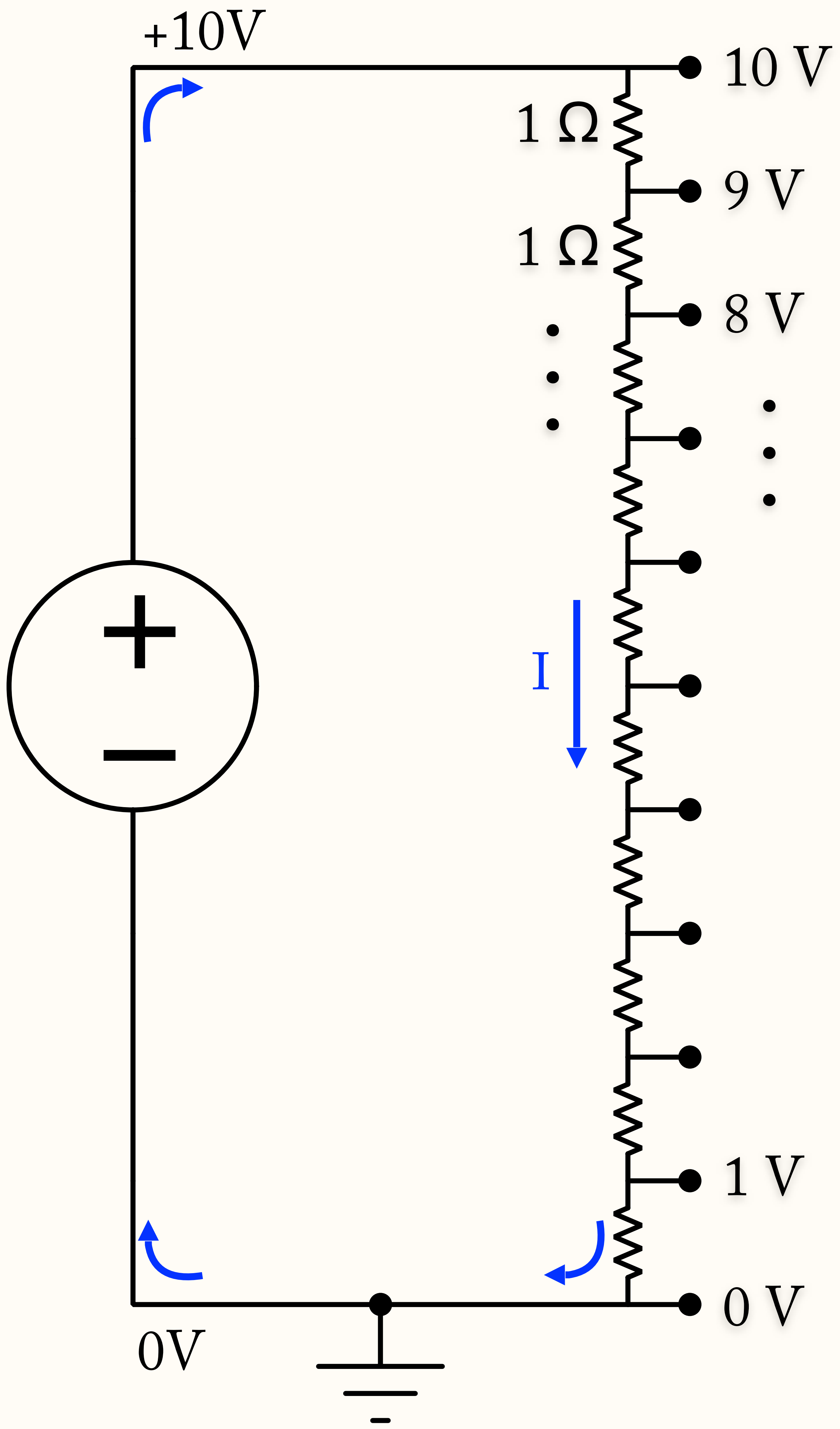
Voltage Divider





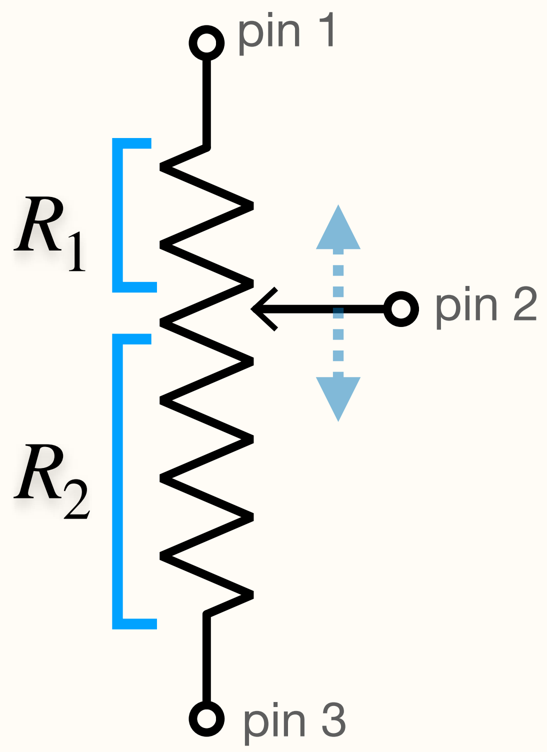
$$V_2 = V_1 \frac{R_2}{R_1 + R_2}$$

Voltage Divider



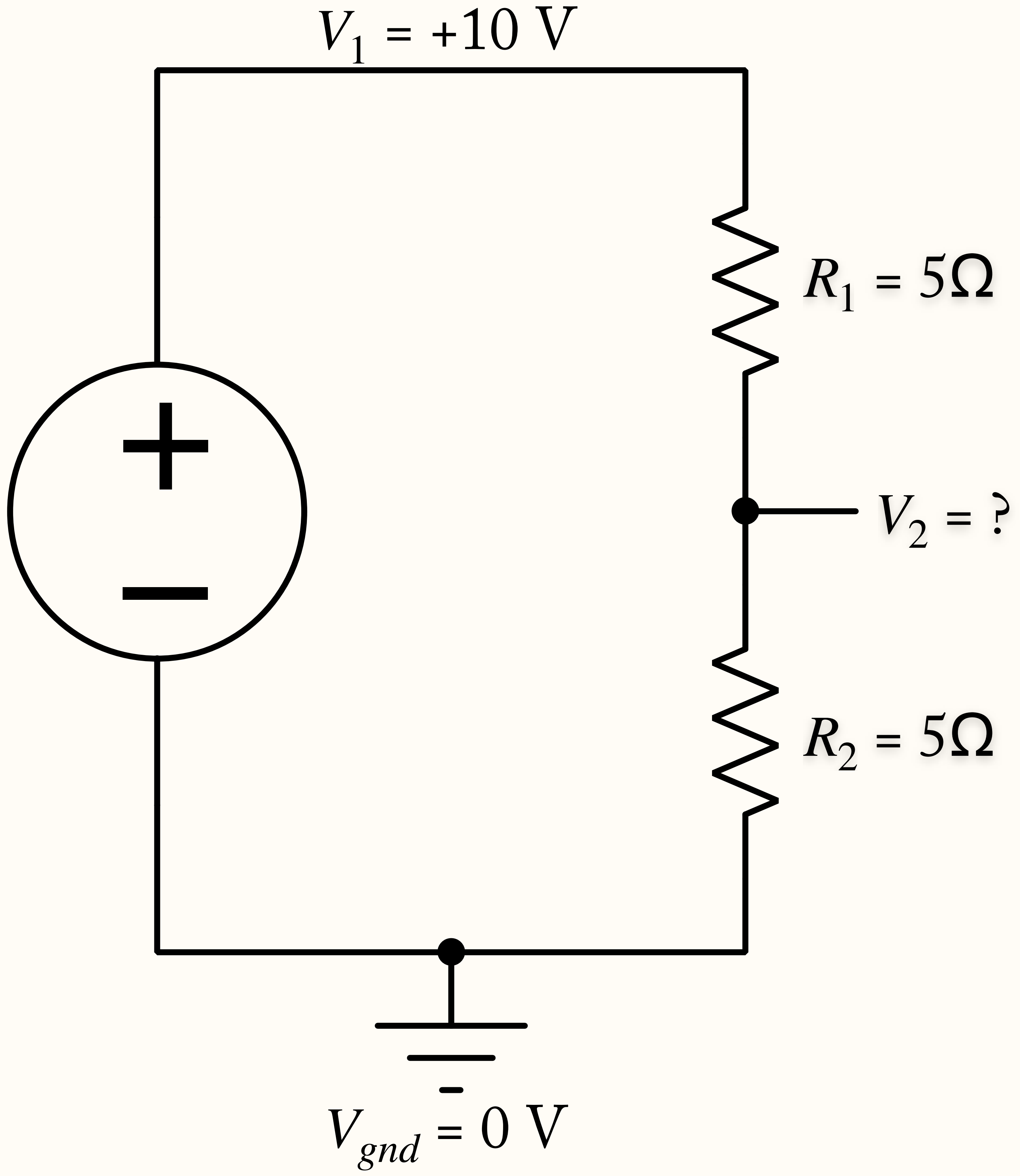
- Multi-step resistive ladders
  - Voltage gradually transitions from V_1 to V_0

- Potentiometer ("pot" for short)
  - Variable voltage divider
  - Use a knob (typically) to select ratio:



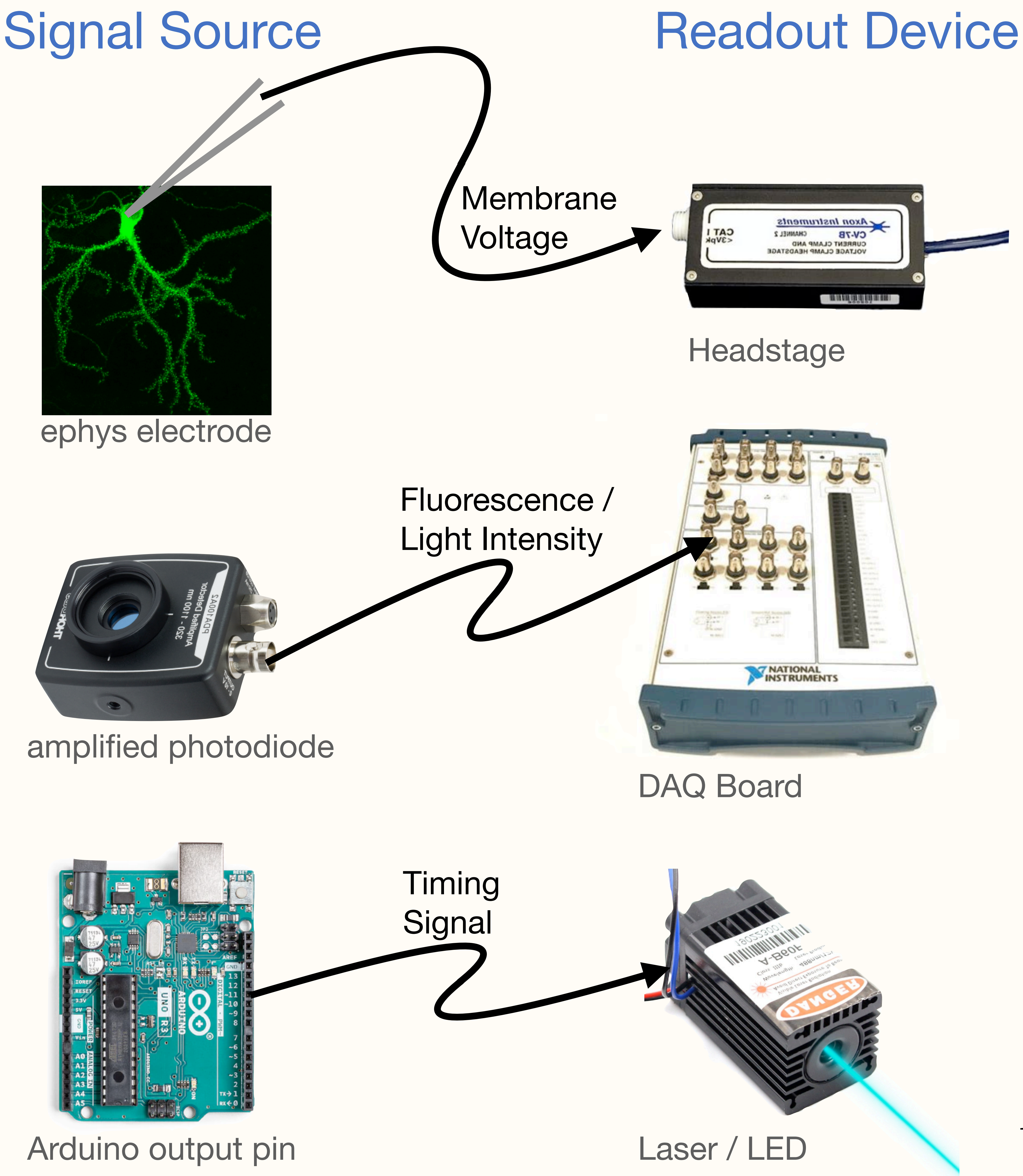
(*Pots also work as a variable resistor, by just using pins 1 and 2)

Voltage Divider



Simulation
https://tinyurl.com/ydejxeow

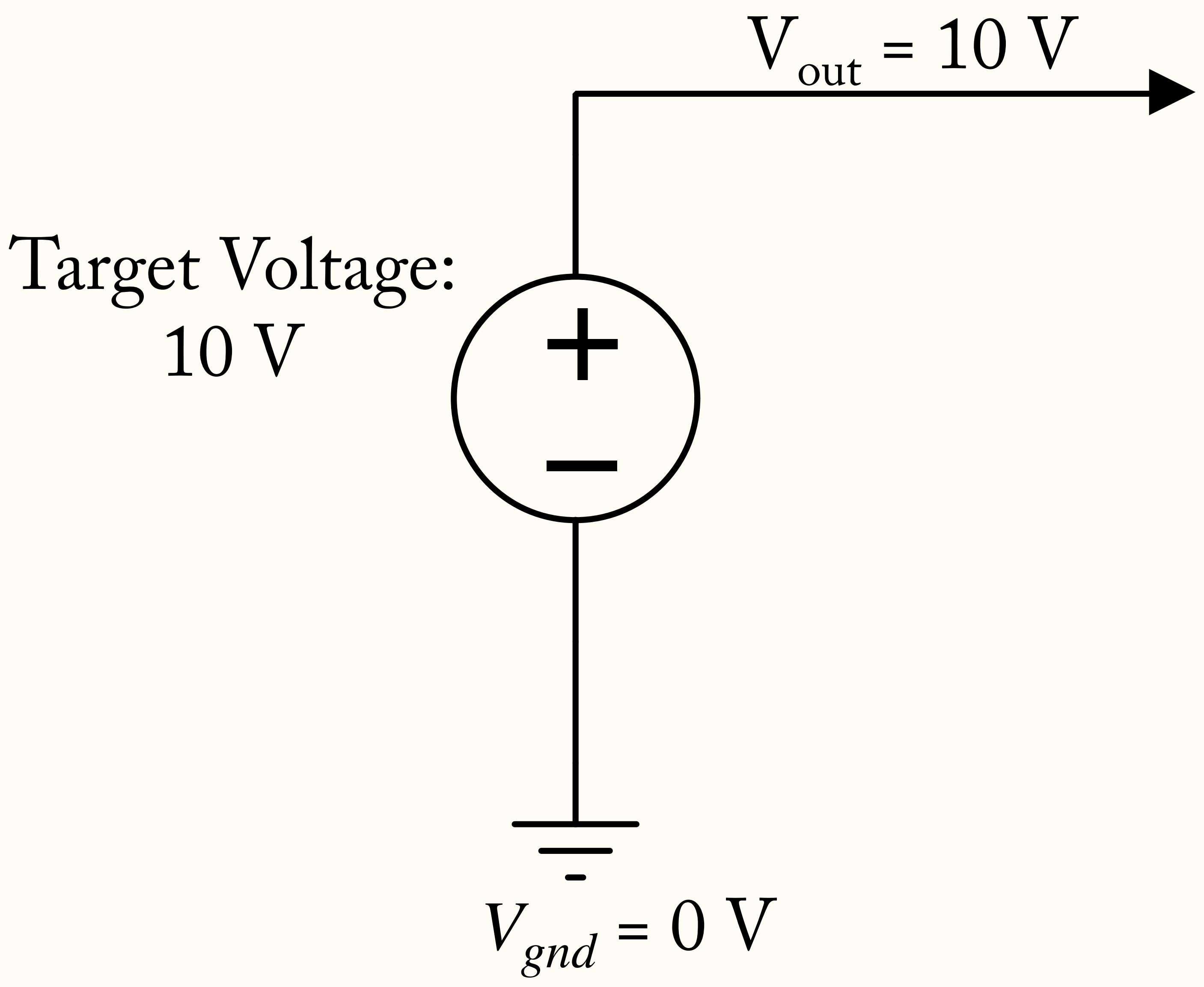
Voltage Signaling



- Most rig signals are transmitted as voltages
  - *Current signals*, like PMT outputs are typically converted to voltage signals
- But real voltage sources have limitations
  - *Voltage dividers* will help us understand….

Modeling Real Voltage Sources

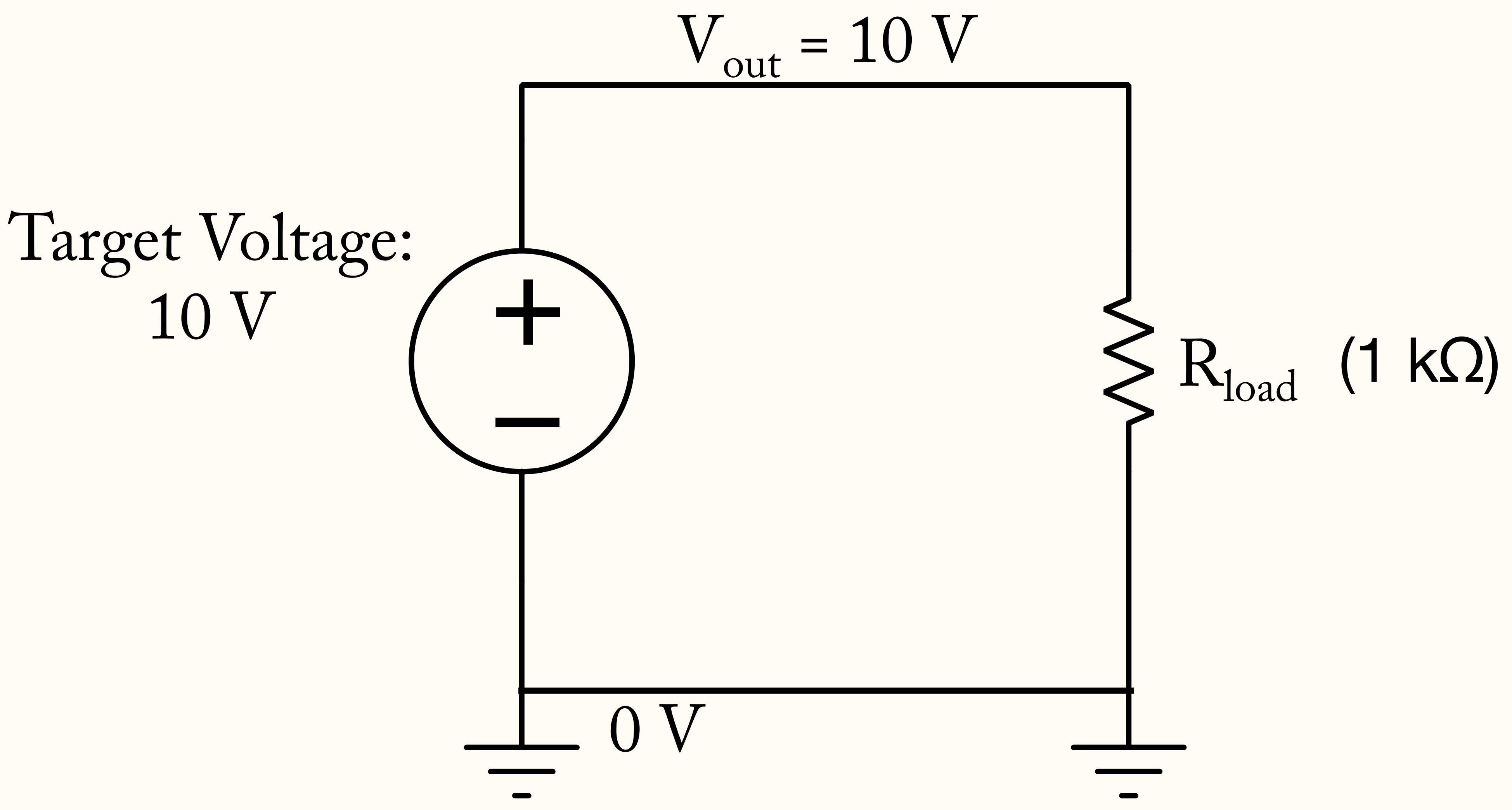
Ideal voltage source



An *Ideal Voltage Source* will output V_{out} under all conditions

Modeling Real Voltage Sources

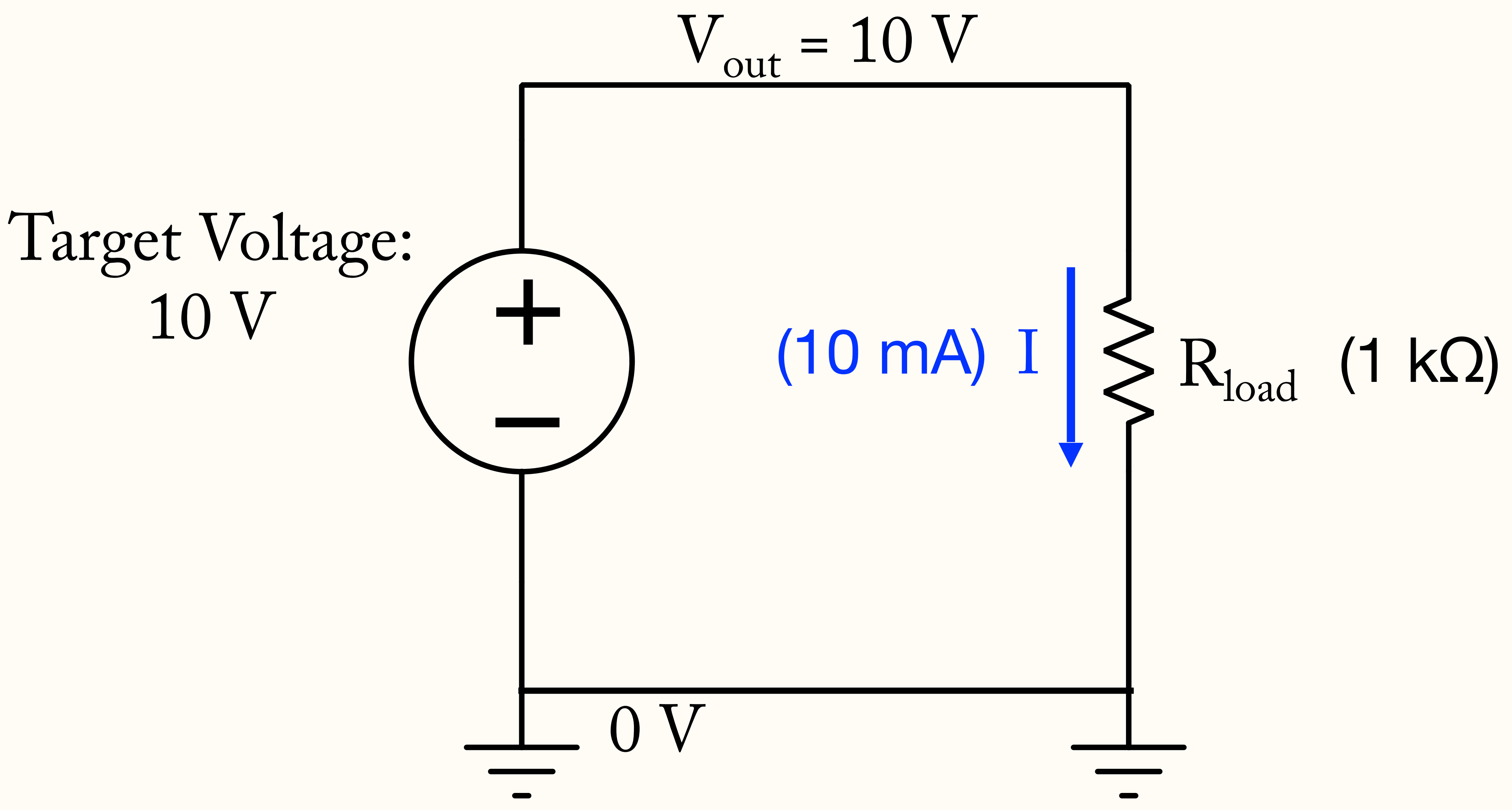
Ideal voltage source

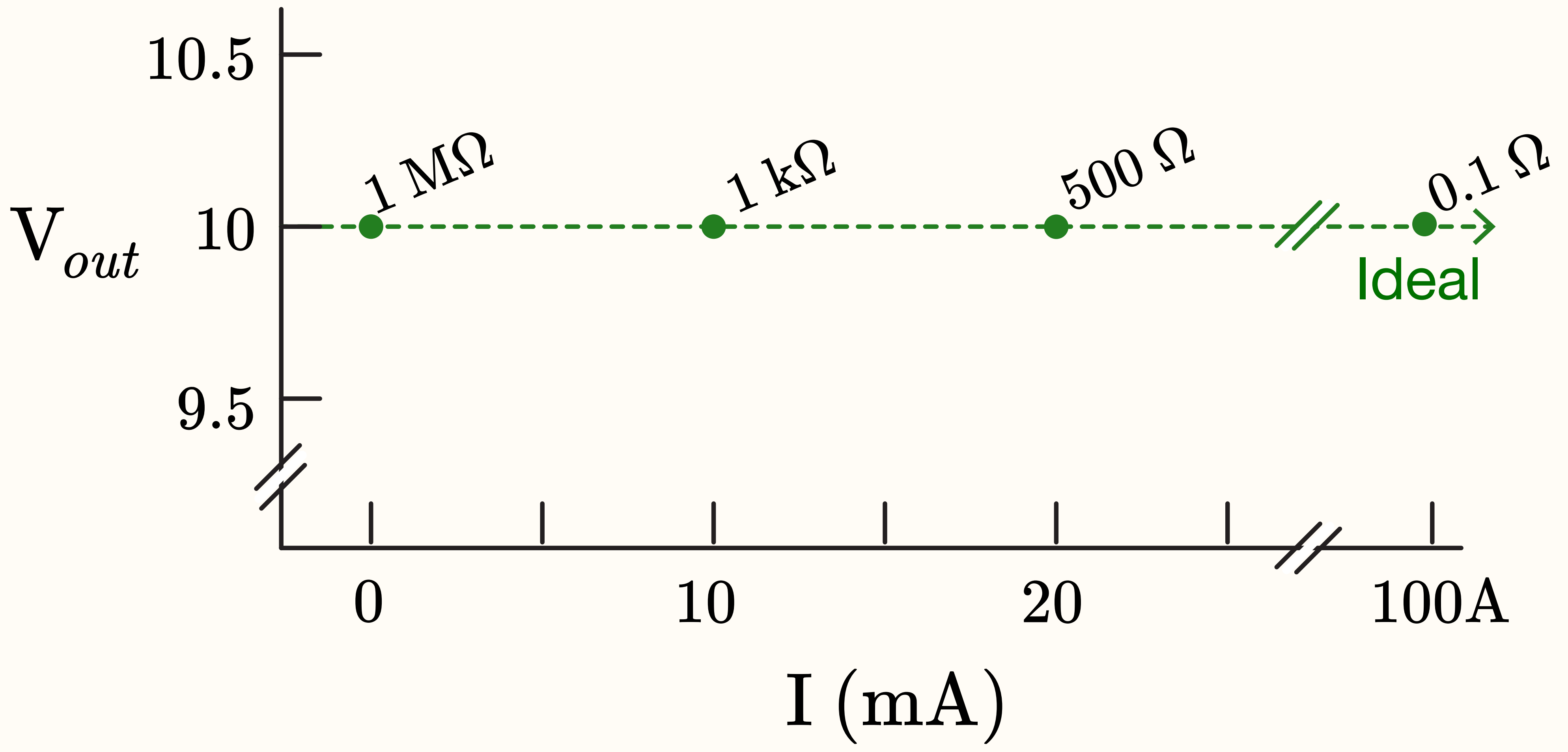


An *Ideal Voltage Source* must output as much current as needed to maintain V_{out}

Modeling Real Voltage Sources

Ideal voltage source





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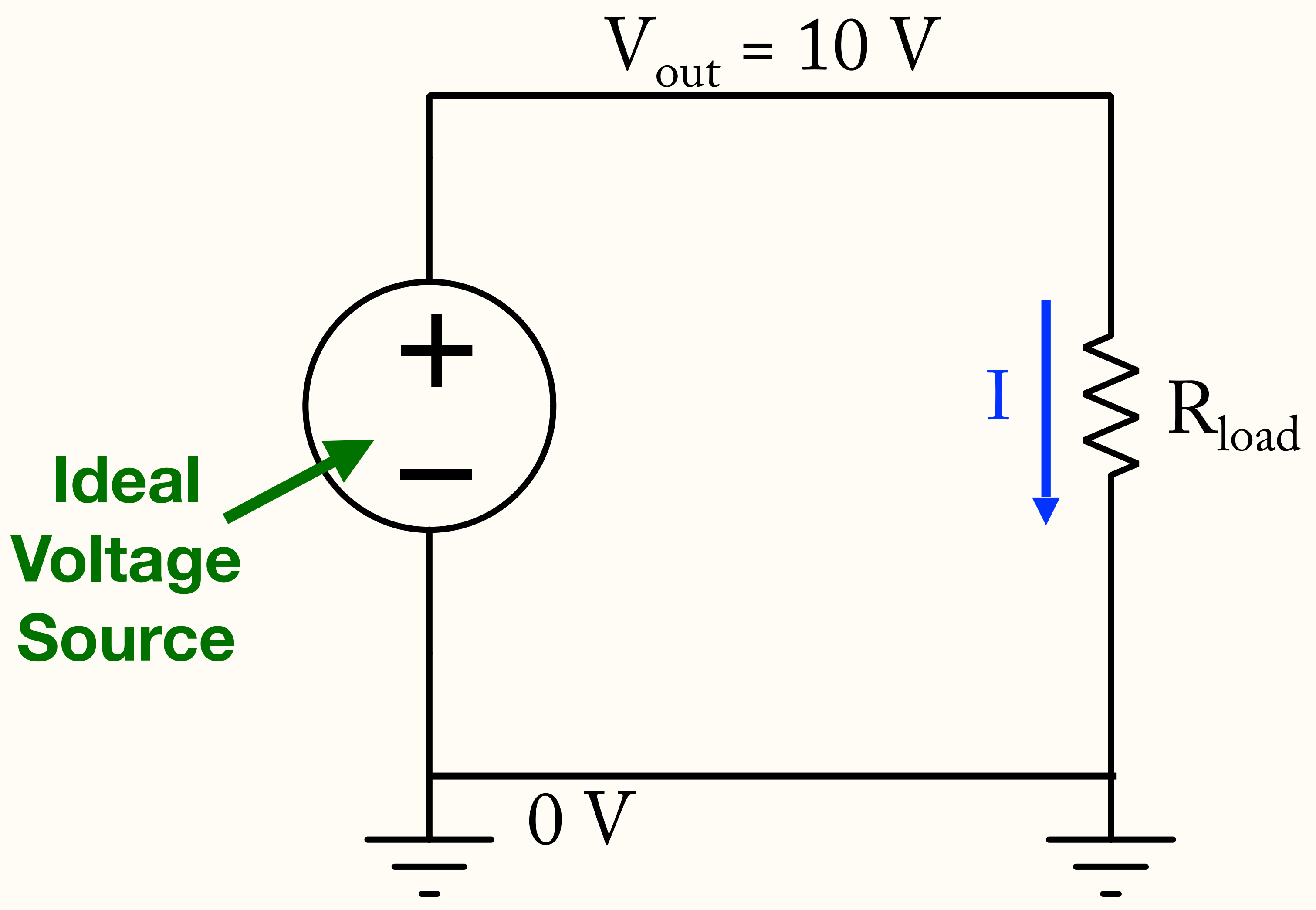

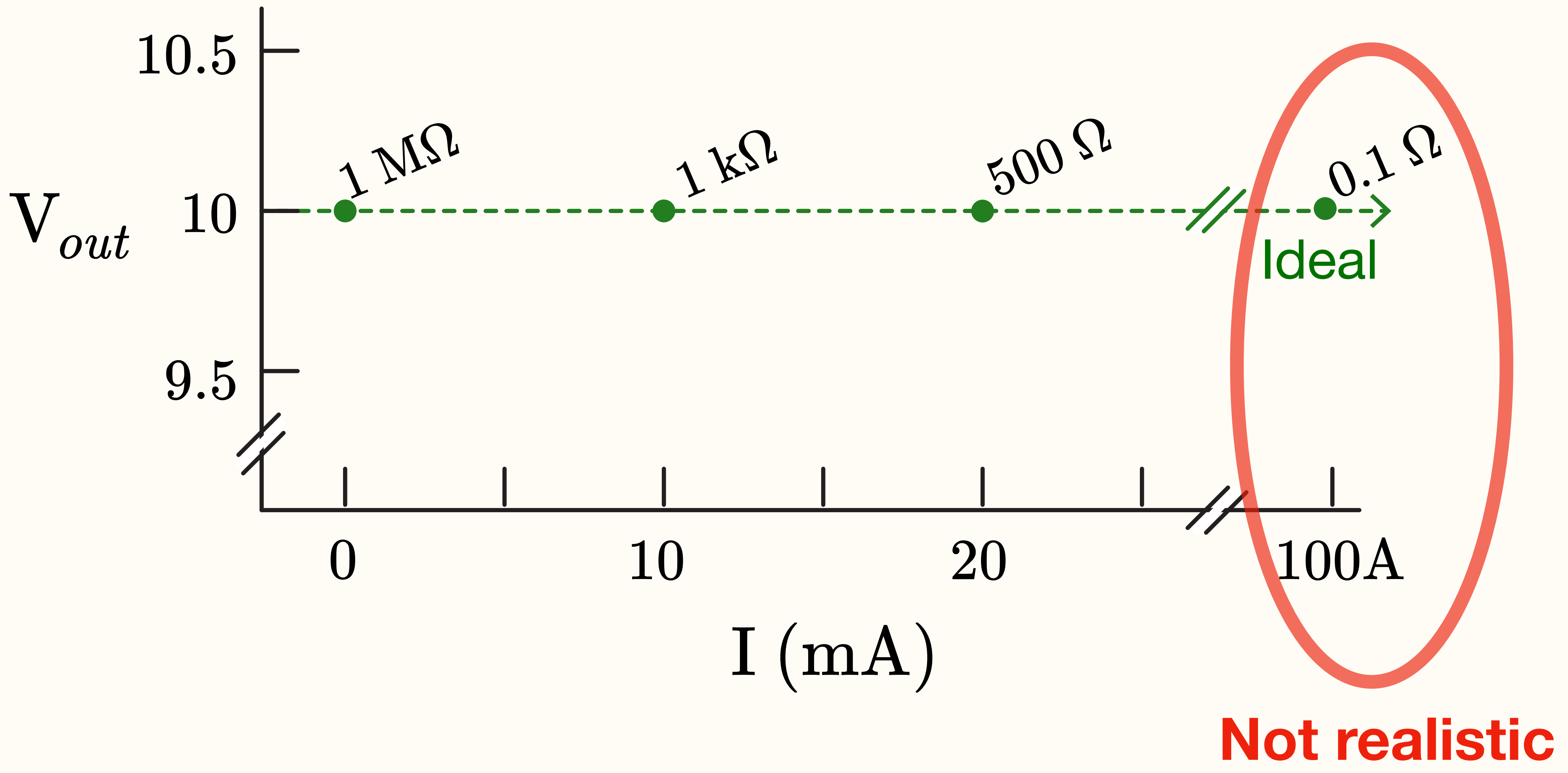

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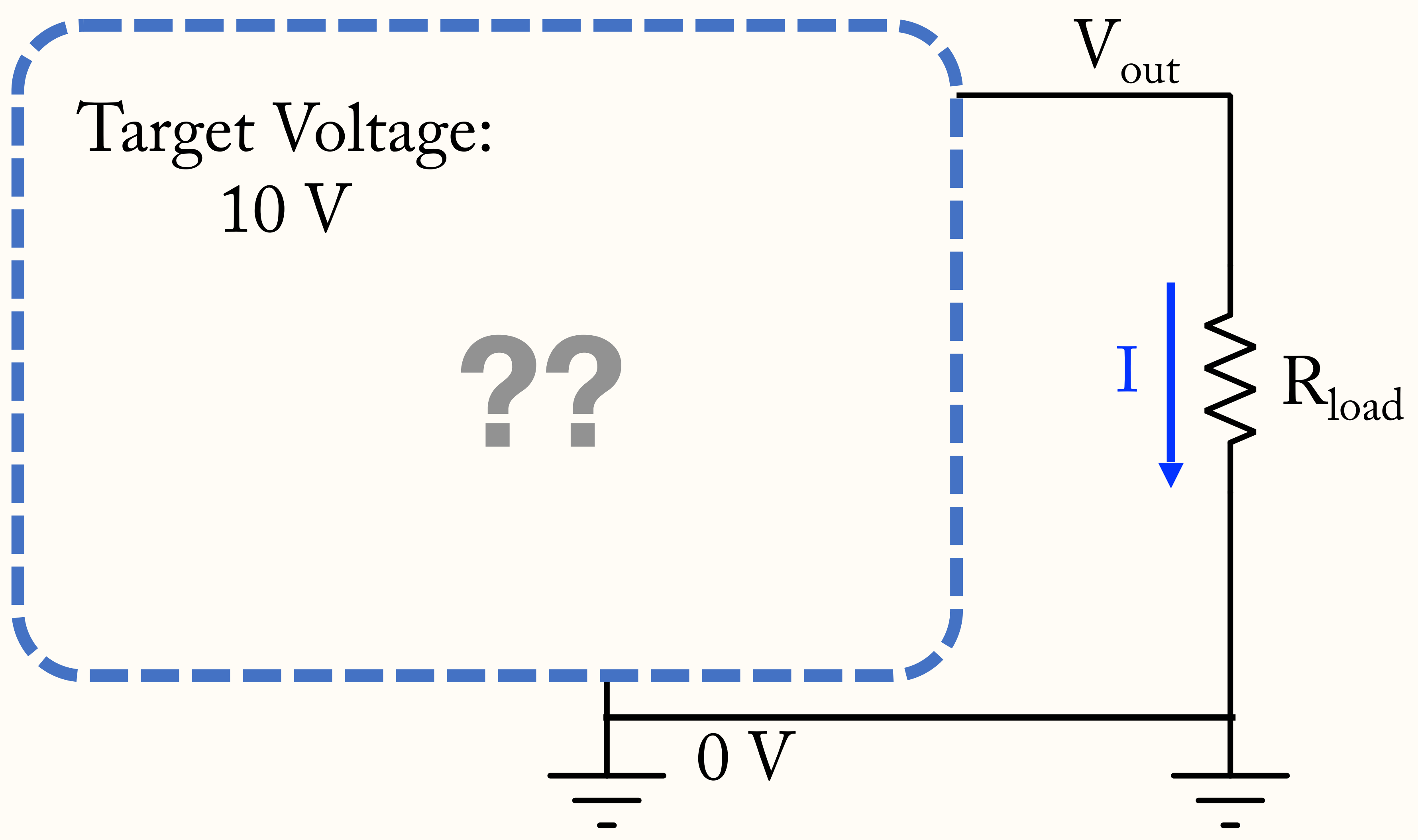
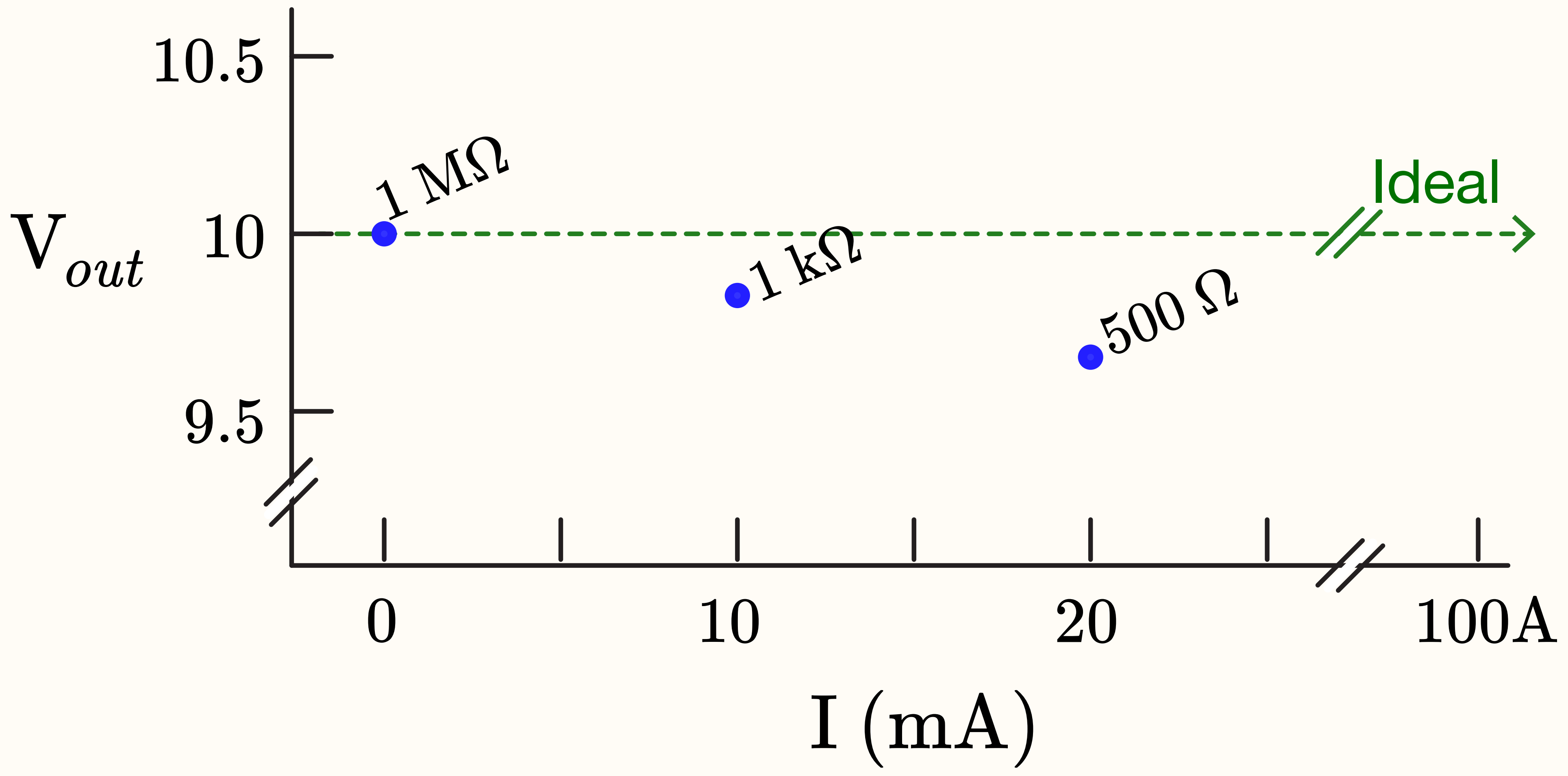
Modeling Real Voltage Sources

Real voltage source

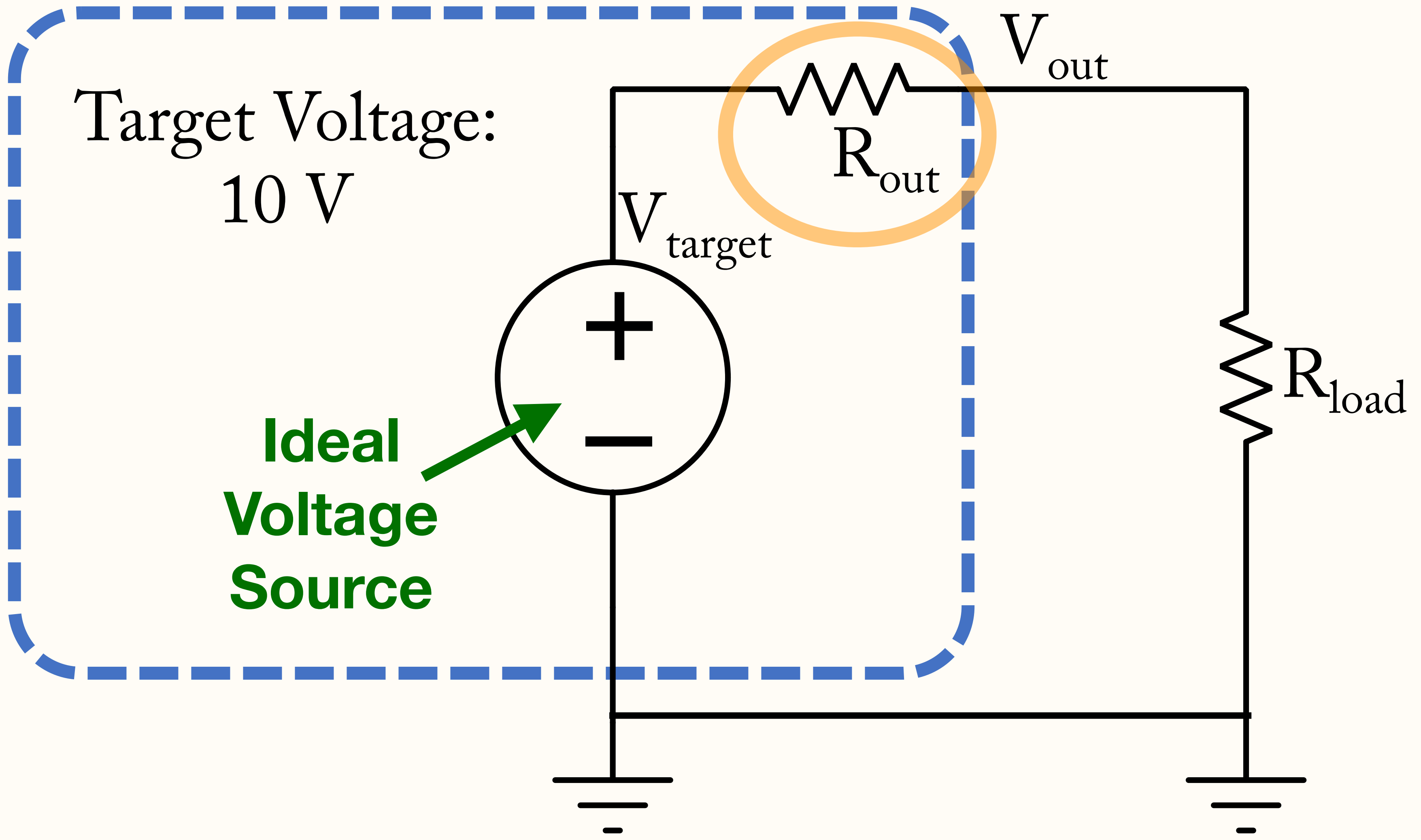


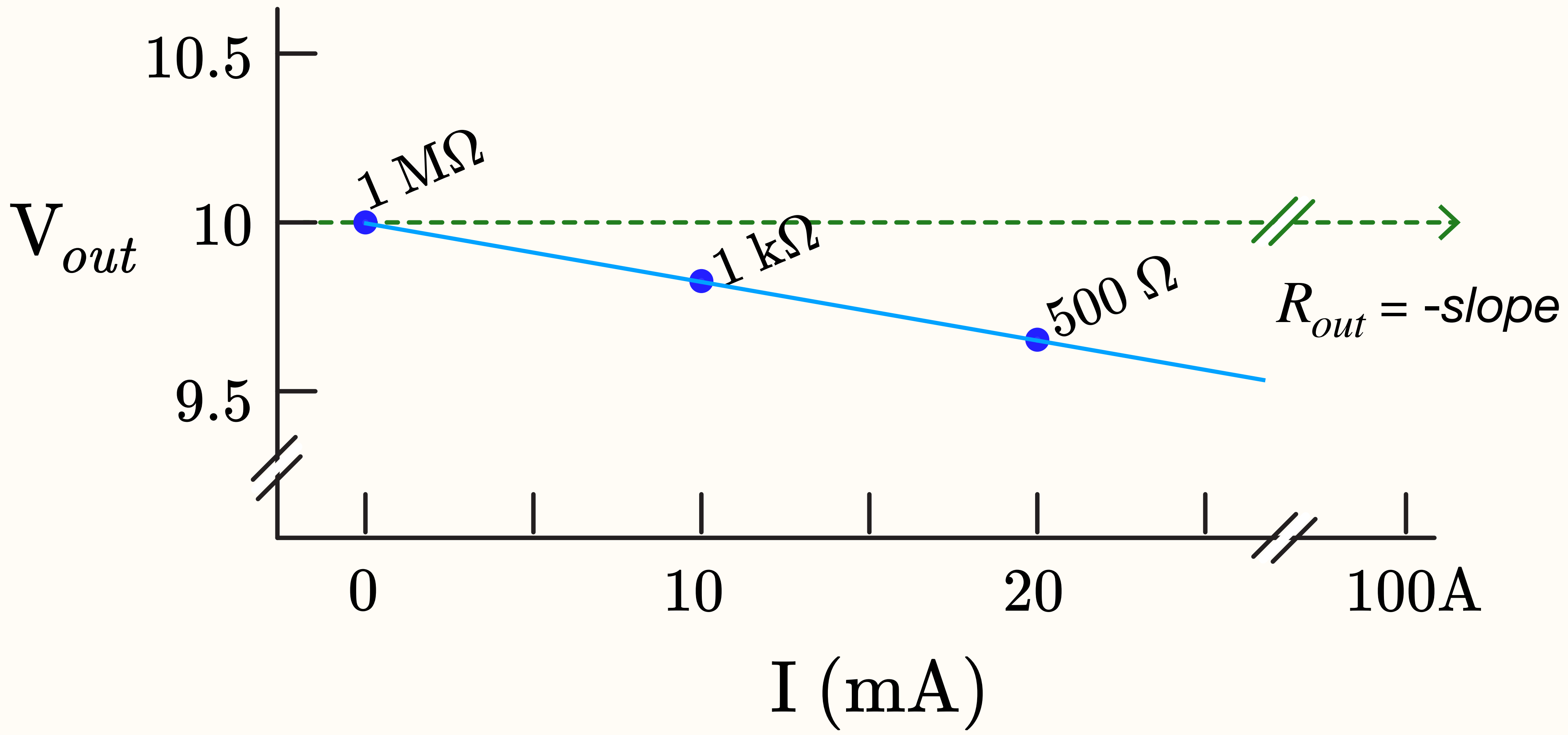


A *Real Voltage Source* departs from ideal behavior: V_{out} drops as R_{load} decreases.

Modeling Real Voltage Sources

Real voltage source



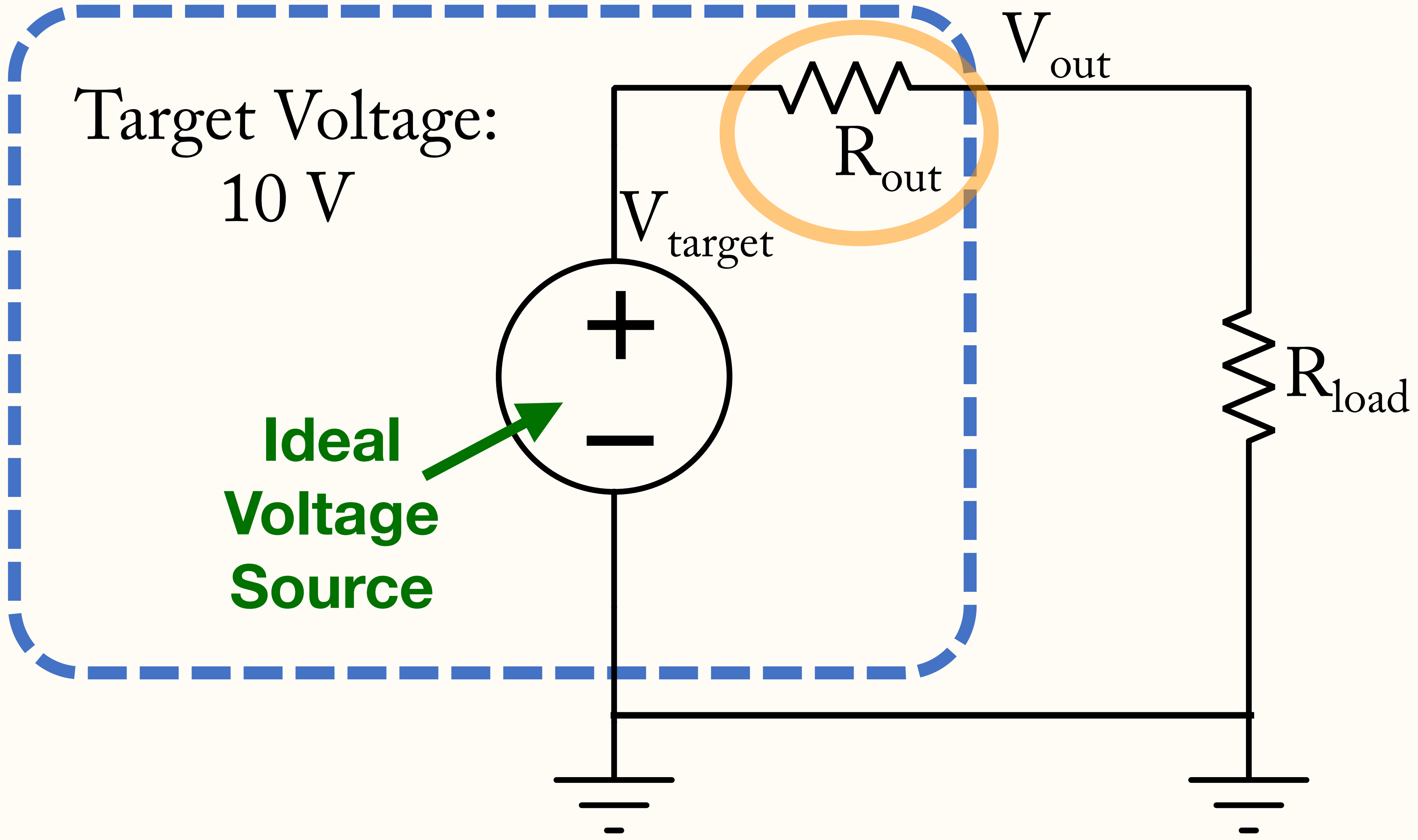


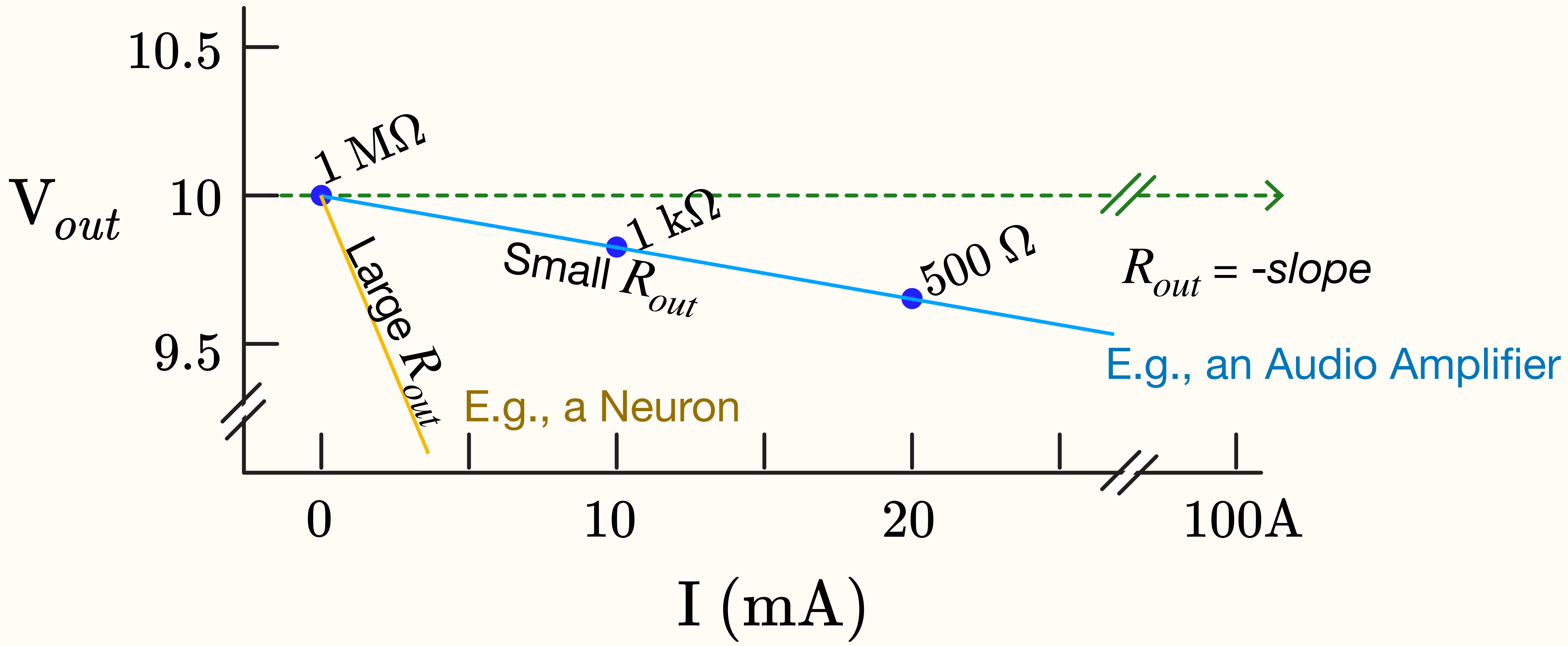
A *Real Voltage Source* departs from ideal behavior: V_{out} drops as R_{load} decreases.

- This behavior can be modeled as an ideal voltage source in series with an output resistor (R_{out})
  - (The true underlying circuit is different: there are no ideal voltage sources)

Modeling Real Voltage Sources

Real voltage source





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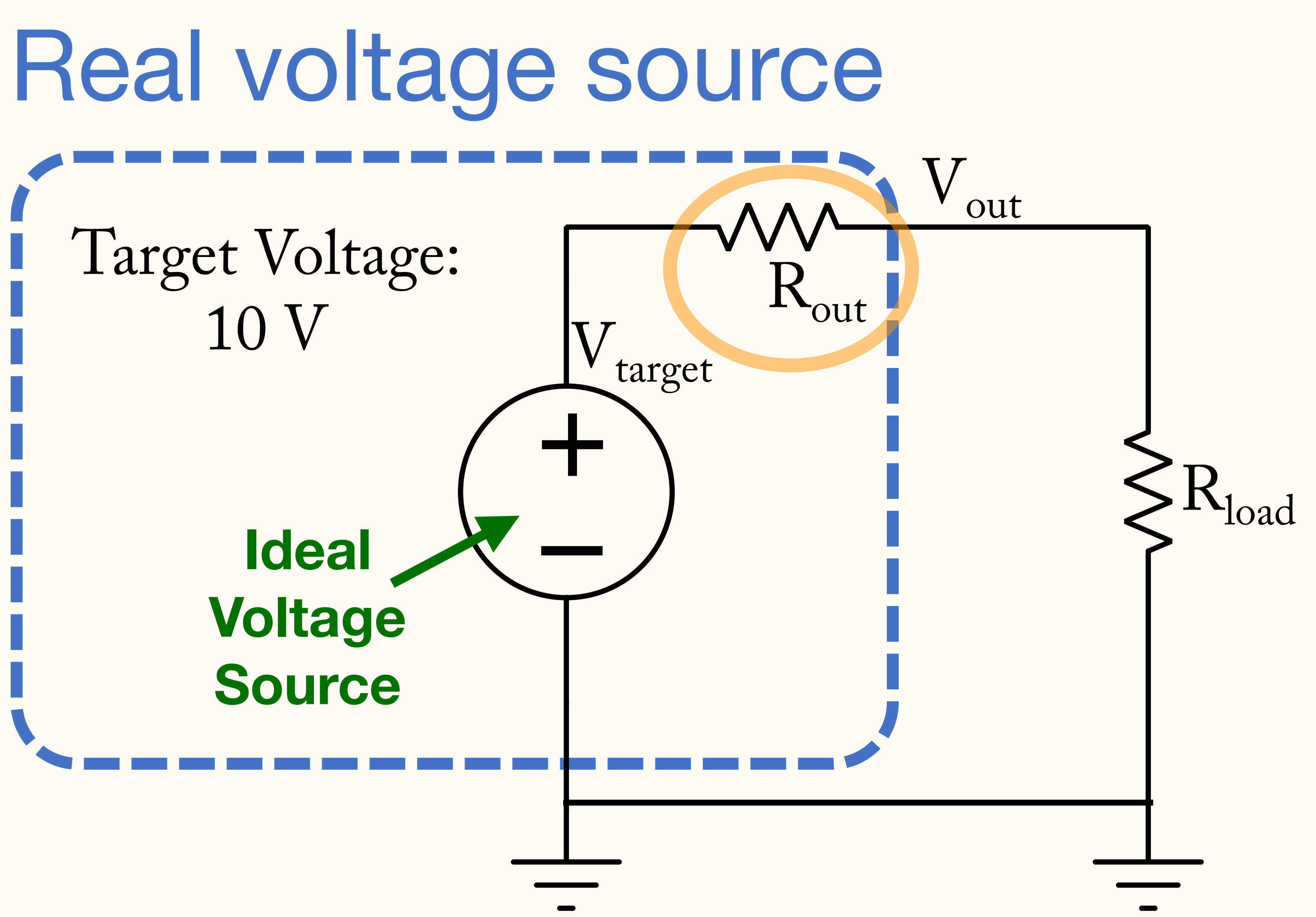
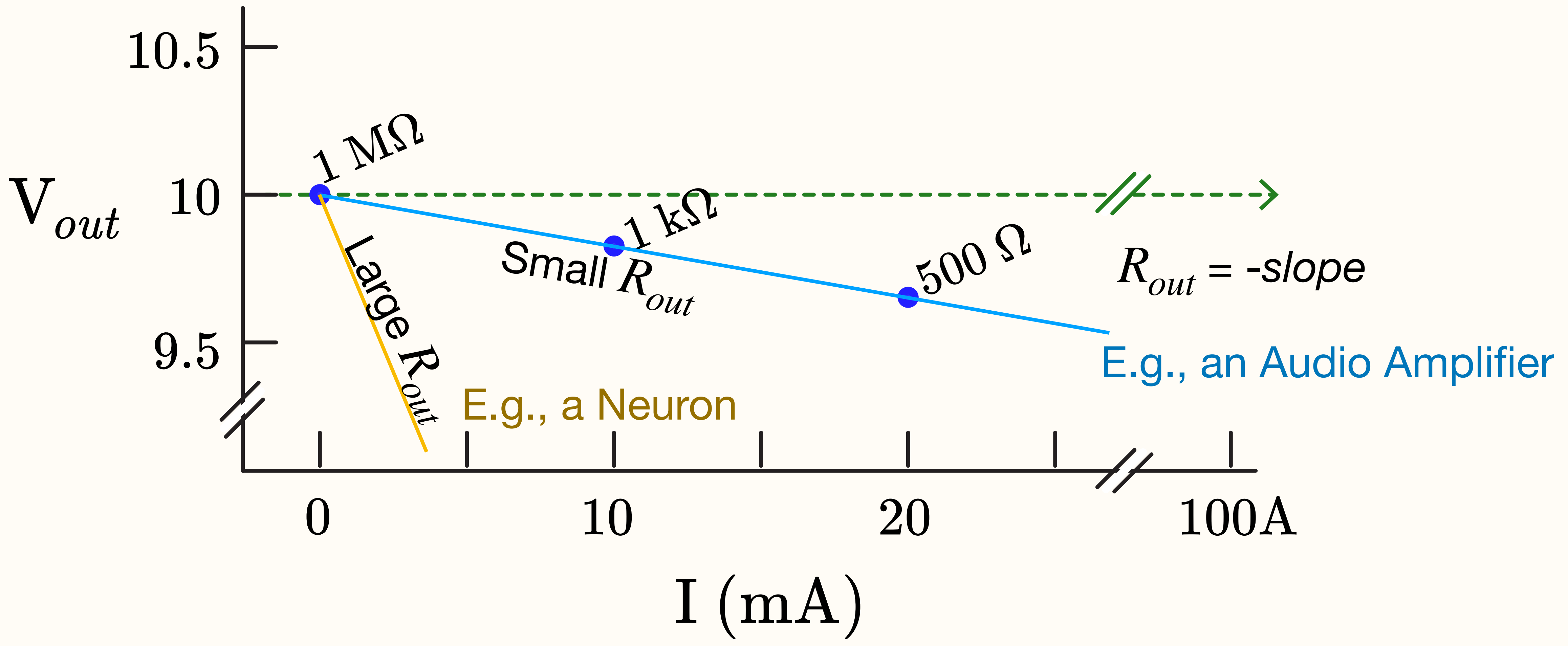
Modeling Real Voltage Sources





Output impedance (R_{out}) quantifies how close to ideal a voltage source is:

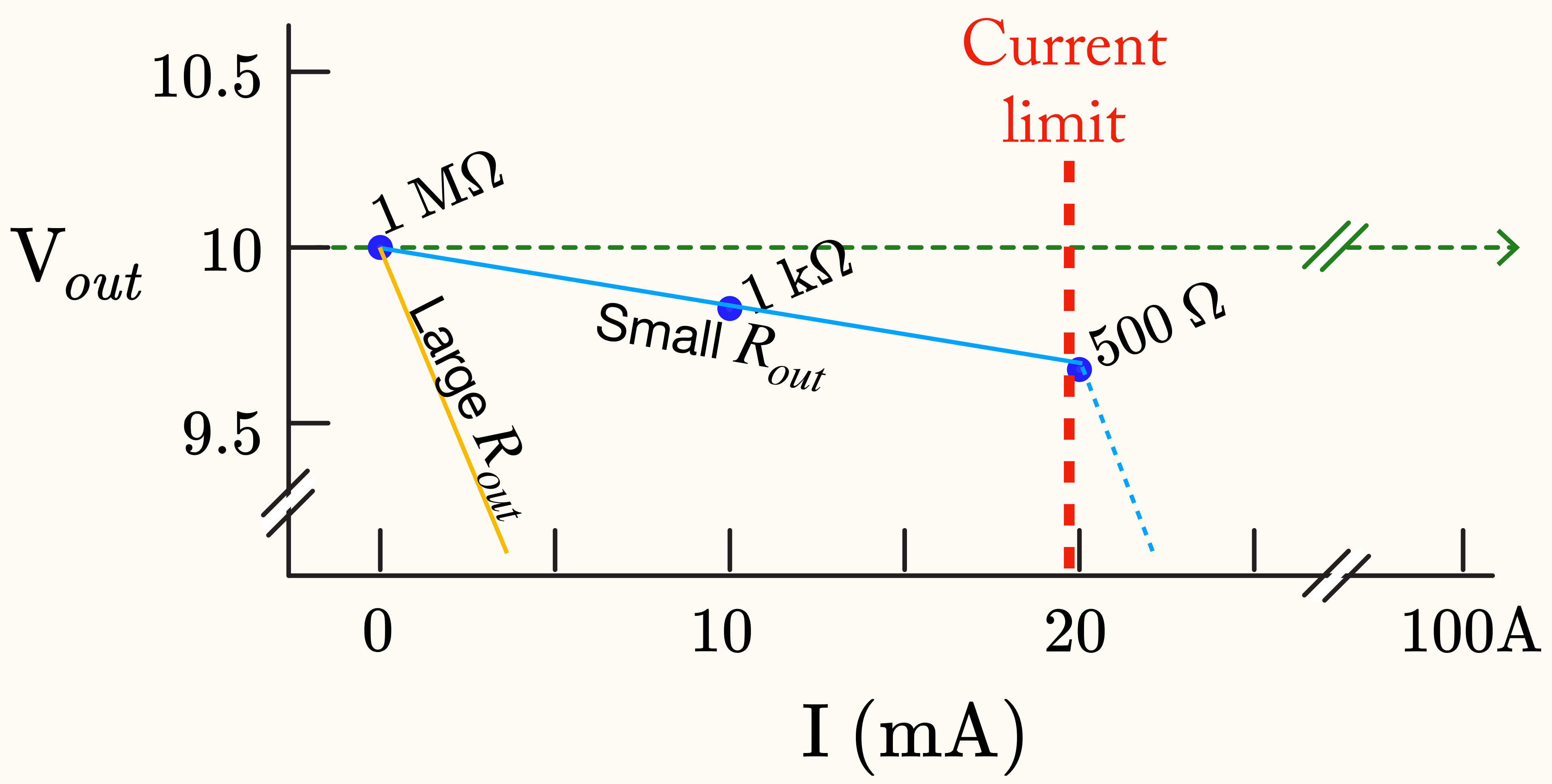
Low R_{out}

- Approximates an ideal voltage source
- Can output high current
- Minimal voltage drop-off, even at high current
- "**Powerful**" output signal

High R_{out}

- Non-ideal voltage source
- Only outputs minimal current
- Significant voltage drop-off with current
- "*weak*" output signal

Modeling Real Voltage Sources

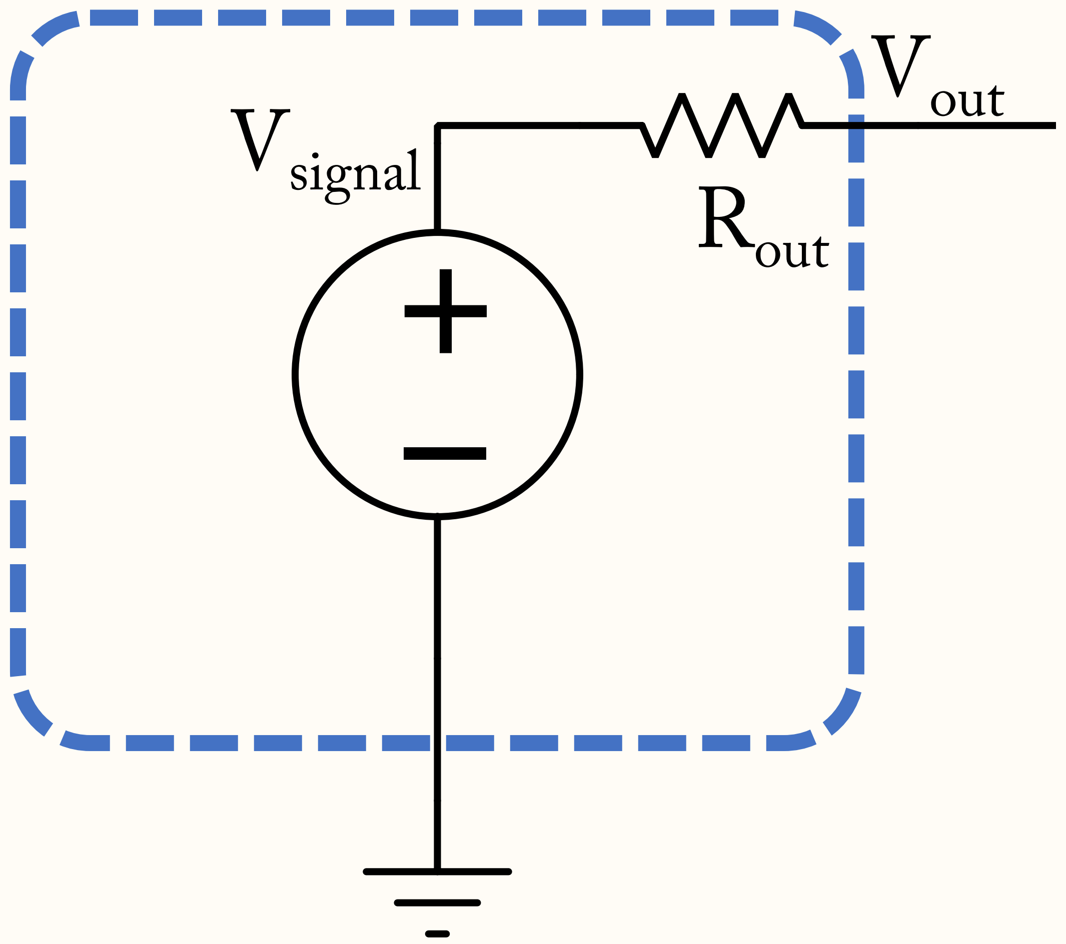


Some voltage sources have a rated current limit:

- Beyond this limit: voltage output might drop dramatically
- Example: Analog Output of DAQ some boards
- Could also be considered "*weak*" output sources

Input & Output Impedance

Signal Source

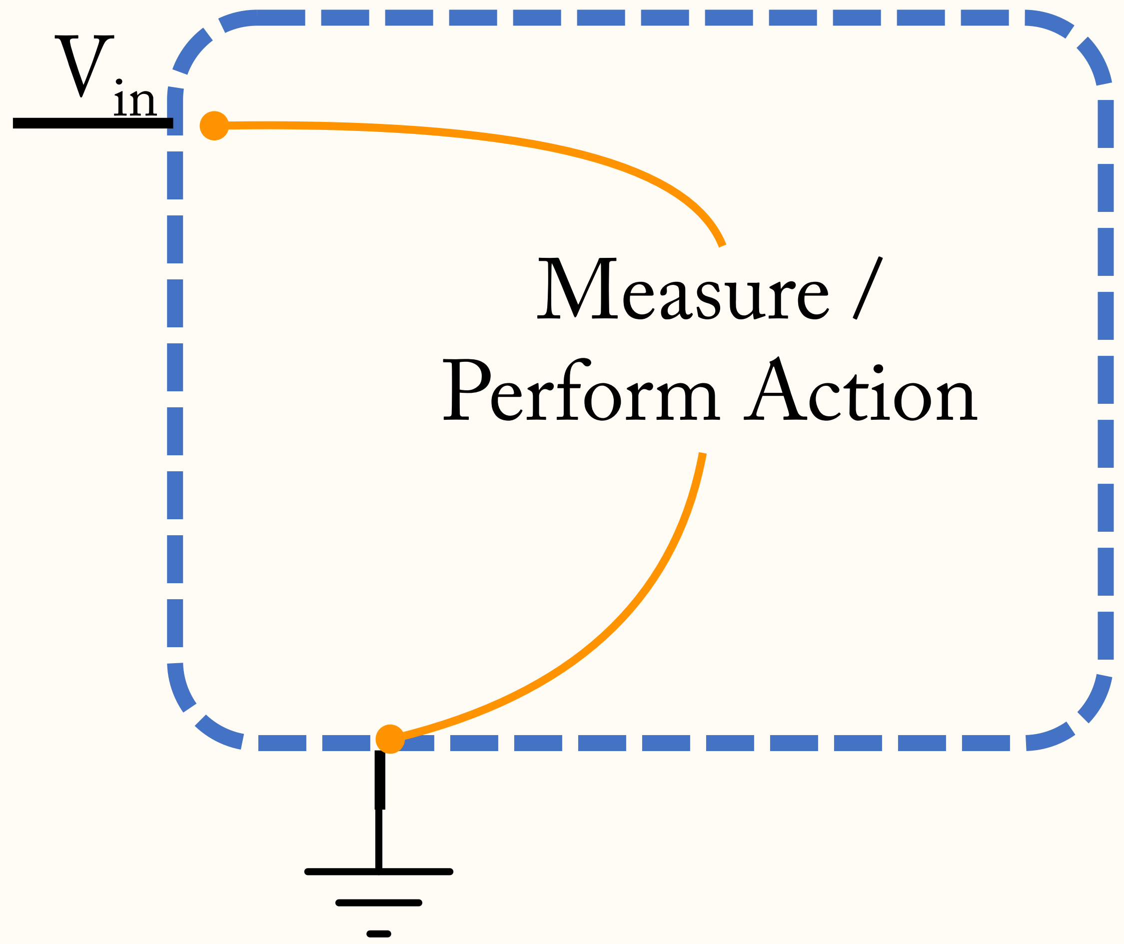


Output Impedance:

Output voltage drops as you draw more current.

Modeled as a resistor on the output line (output impedance)

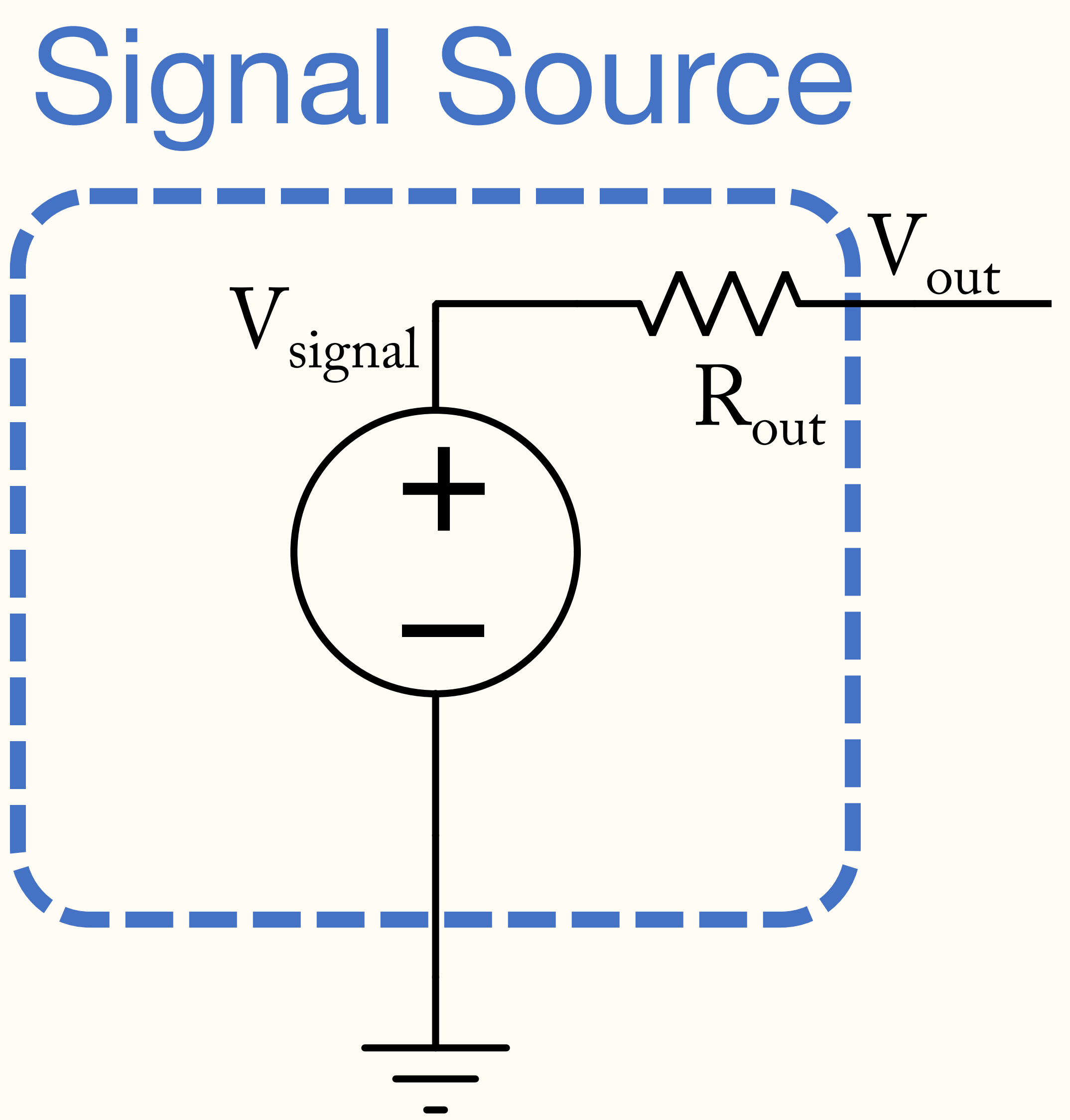
Readout Device

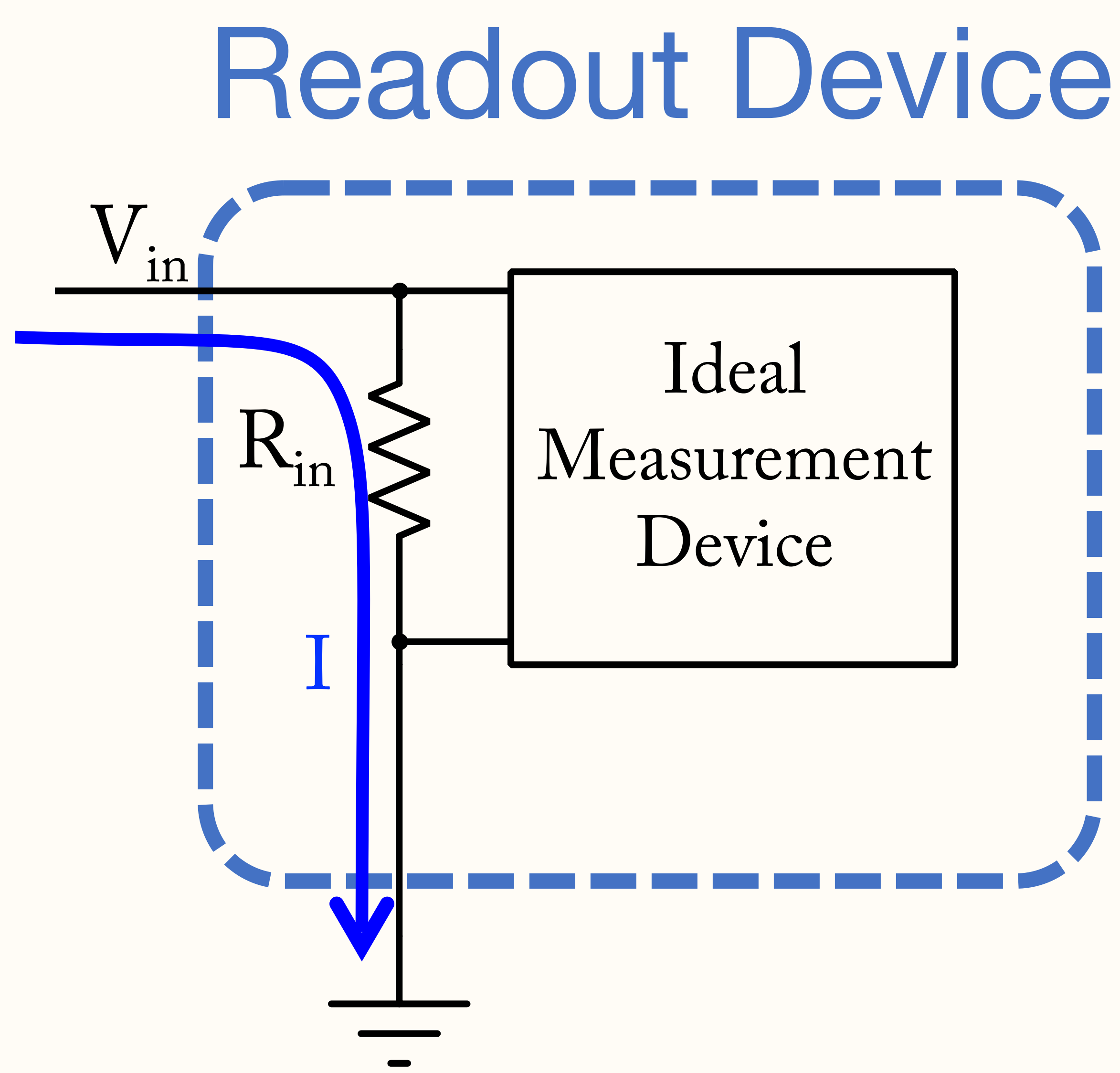


Input Impedance:

What about real input lines?

Input & Output Impedance





Output Impedance:

Output voltage drops as you draw more current.

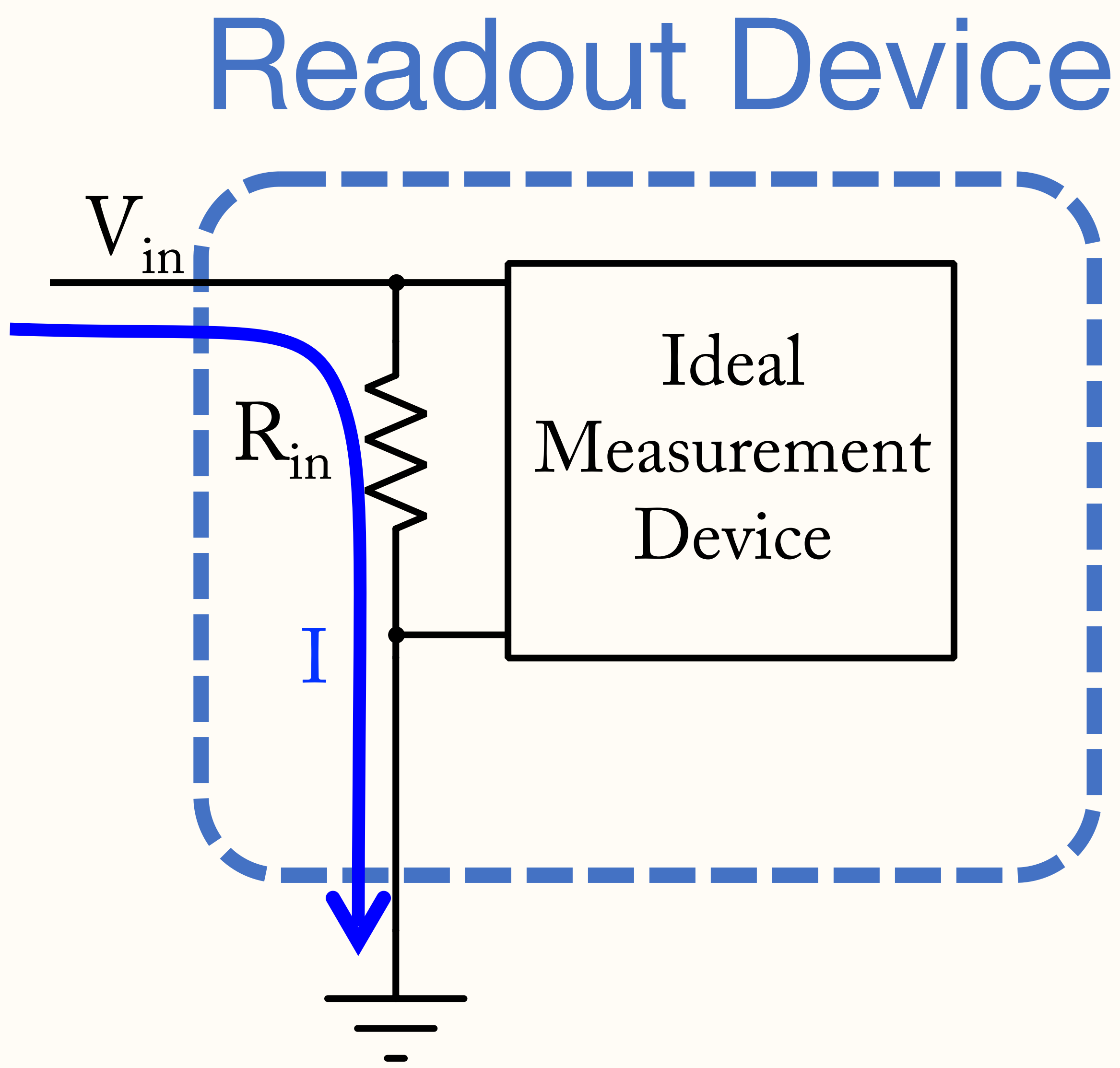
Modeled as a resistor on the output line (output impedance)

Input Impedance:

Input lines draw *some* current while measuring V_{in}.

Modeled as having a resistor between the input pin and ground (input impedance)

Input & Output Impedance



Input impedance (R_{in}) quantifies how close to ideal a readout device is:

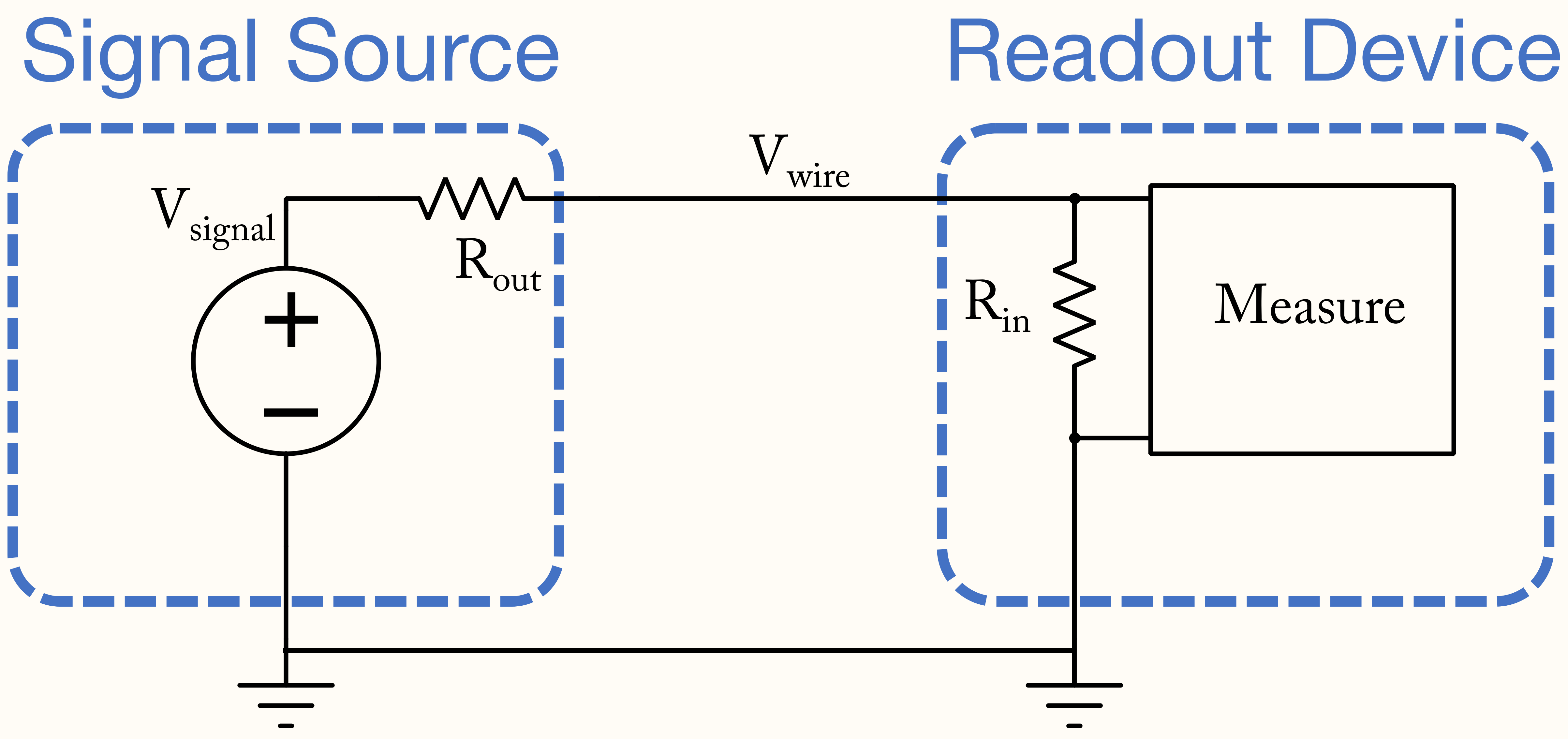
High R_{in}

- Approximates an ideal readout device
- Draws very little current from input pin
- "*Non-invasive*" input device

Low R_{in}

- Non-ideal readout device
- Draws significant current from input pin
- "***Power-hungry***" input device

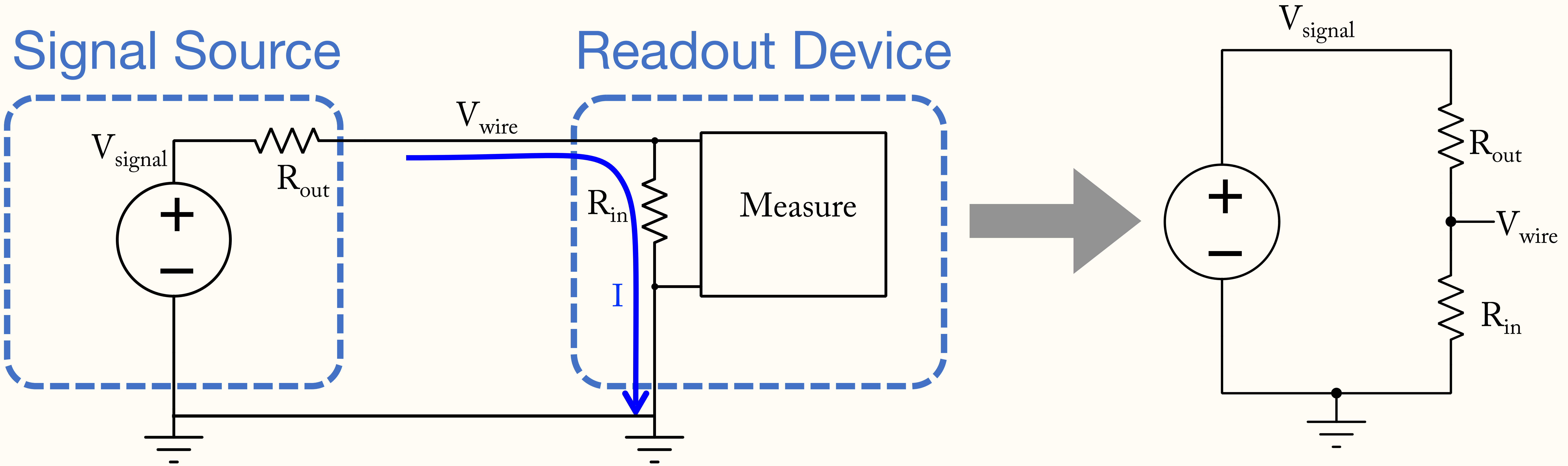
Input & Output Impedance



How does V_{wire} compare to V_{signal}?

Can you spot the voltage divider?

Input & Output Impedance



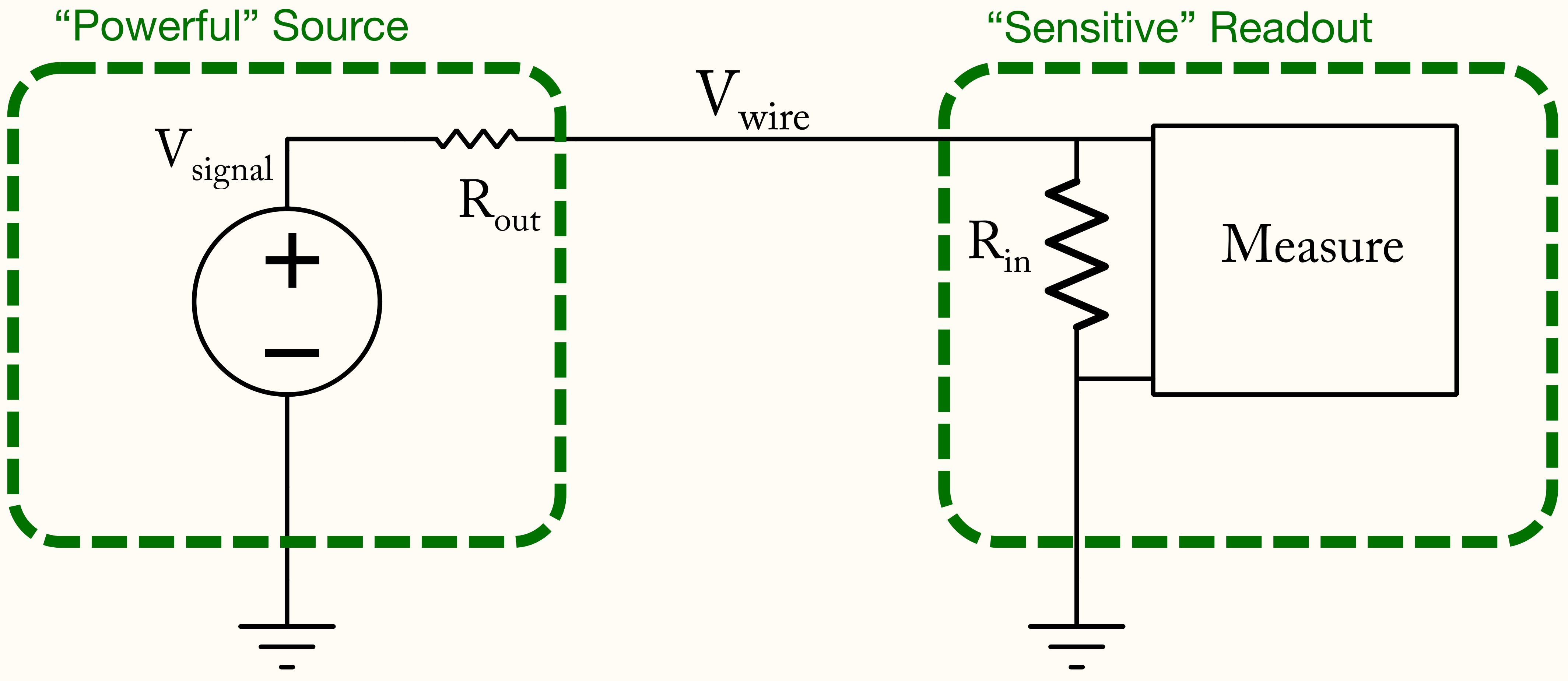
Input & Output Impedance (Resistance)

- V_{wire} will be smaller than V_{signal} unless $R_{out} << R_{in}$

$$V_{wire} = V_{signal} \frac{R_{in}}{R_{in} + R_{out}}$$

Input & Output Impedance

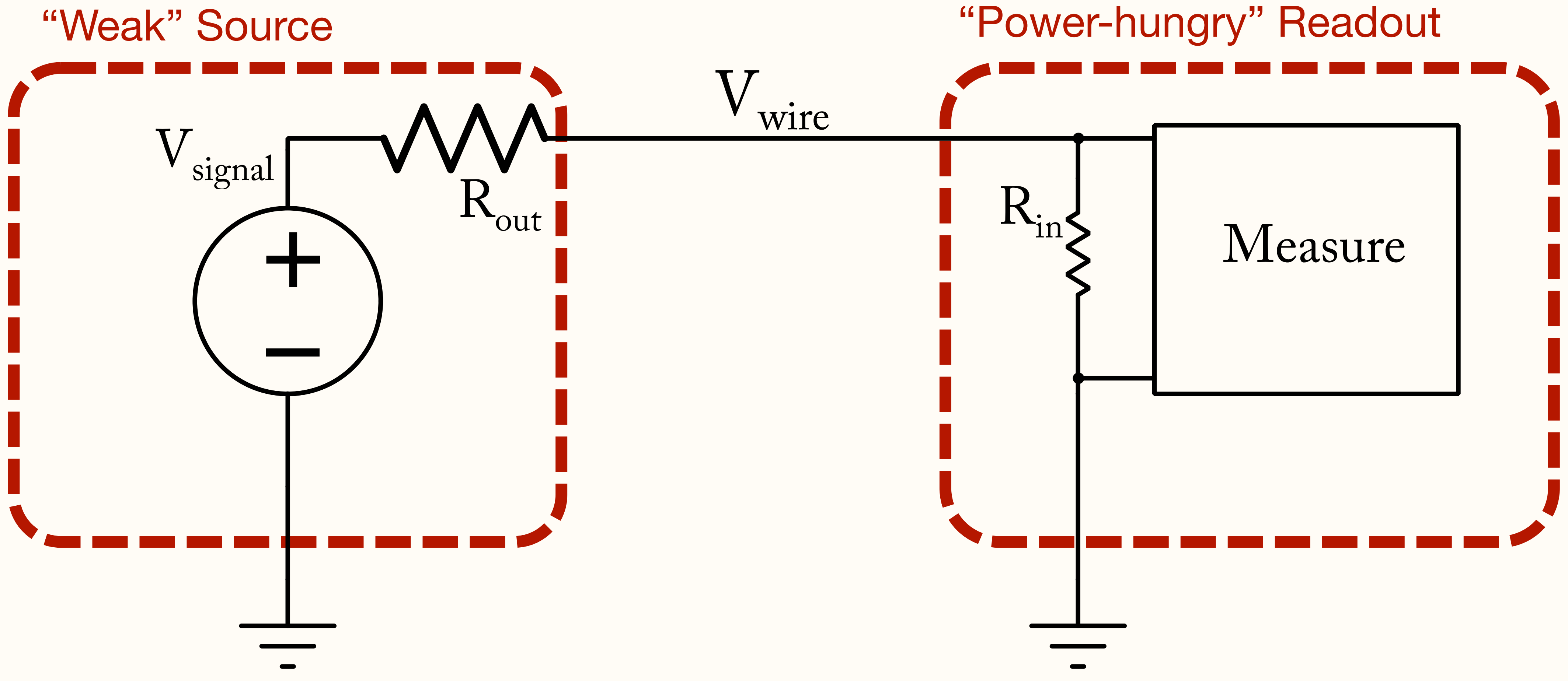
Good: $R_{in} \gg R_{out}$



$V_{wire} = V_{signal}$

- Many lab instruments are designed to "play nicely" with one another:
  - Have low R_{out} and high R_{in}

Problematic: $R_{out} \geq R_{in}$



$V_{wire} < V_{signal}$ (due to voltage divider)

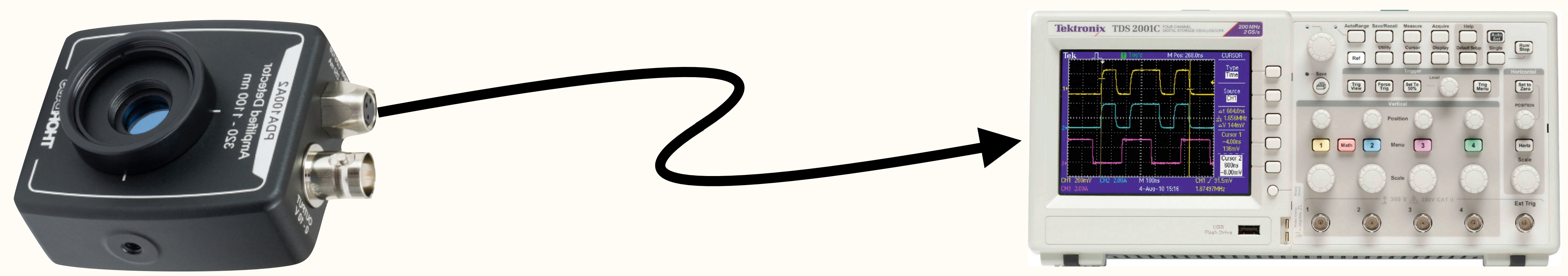
- Watch out for large R_{out} (e.g., sharp electrodes)
- Watch out for low R_{in} (power-hungry devices)

Input & Output Impedance

Good: $R_{in} \gg R_{out}$

No Attenuation

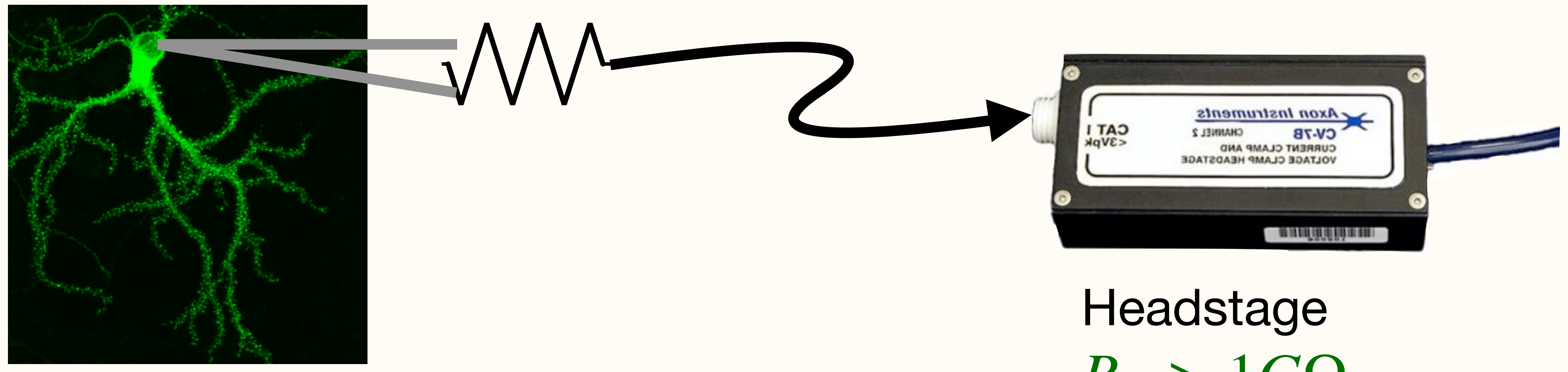
“Standard” Source **“Standard” Readout**



Amplified Photodiode
$R_{out} = 50\Omega$

Oscilloscope
$R_{in} = 1M\Omega$

“Very Weak” Source **“Ideal” Readout**



$R_{electrode} \approx 10\mathrm{M}\Omega$

Headstage
$R_{in} > 1G\Omega$

Problematic: $R_{out} \geq R_{in}$

Attenuated Signal

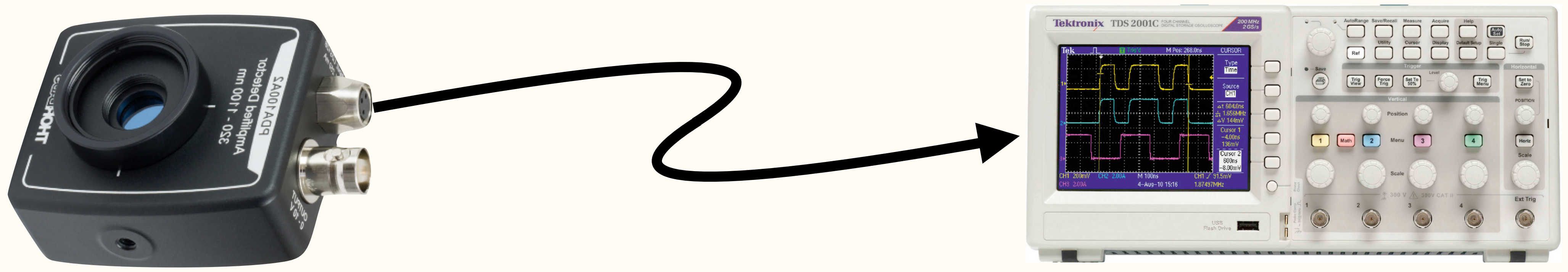
Input & Output Impedance

Good: $R_{in} \gg R_{out}$

No Attenuation

“Standard” Source

“Standard” Readout

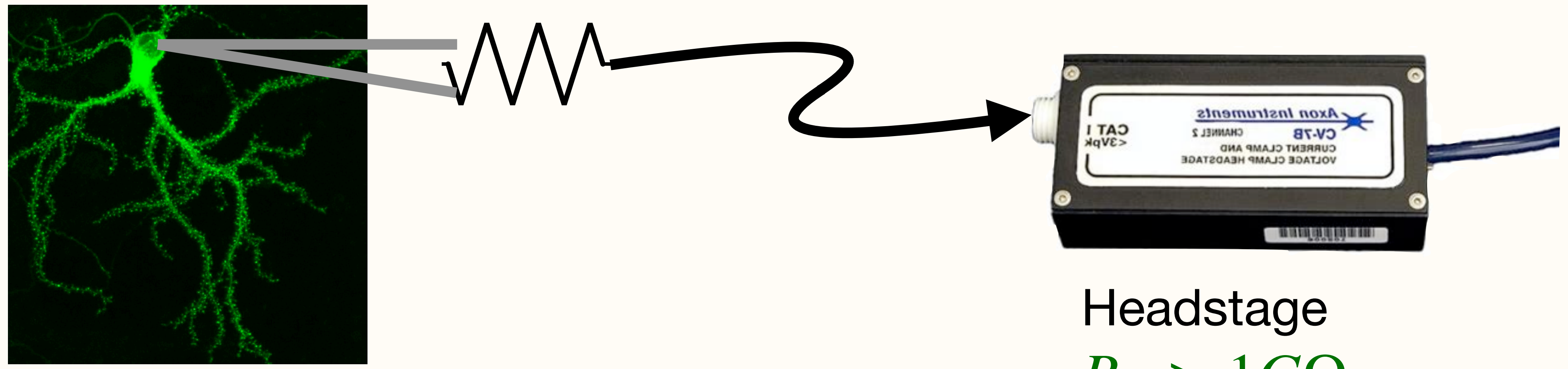


Amplified Photodiode
$R_{out} = 50\Omega$

Oscilloscope
$R_{in} = 1M\Omega$

“Very Weak” Source

“Very Sensitive” Readout



$R_{electrode} \approx 10\text{M}\Omega$

Headstage
$R_{in} > 1G\Omega$

Problematic: $R_{out} \geq R_{in}$

Attenuated Signal

“Very Weak” Source

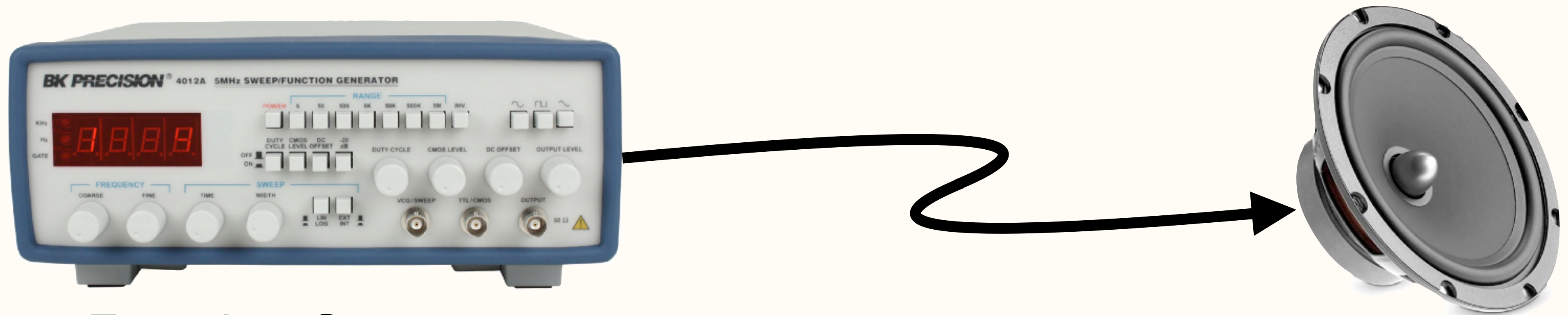
“Standard” Readout

$R_{electrode} \approx 10\text{M}\Omega$

Oscilloscope
$R_{in} = 1M\Omega$

“Standard” Source

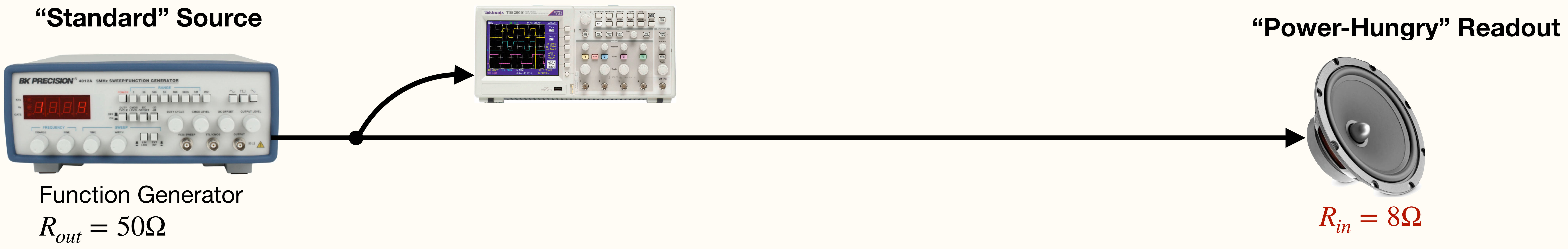
“Power-Hungry” Readout



Function Generator
$R_{out} = 50\Omega$

$R_{in} = 8\Omega$

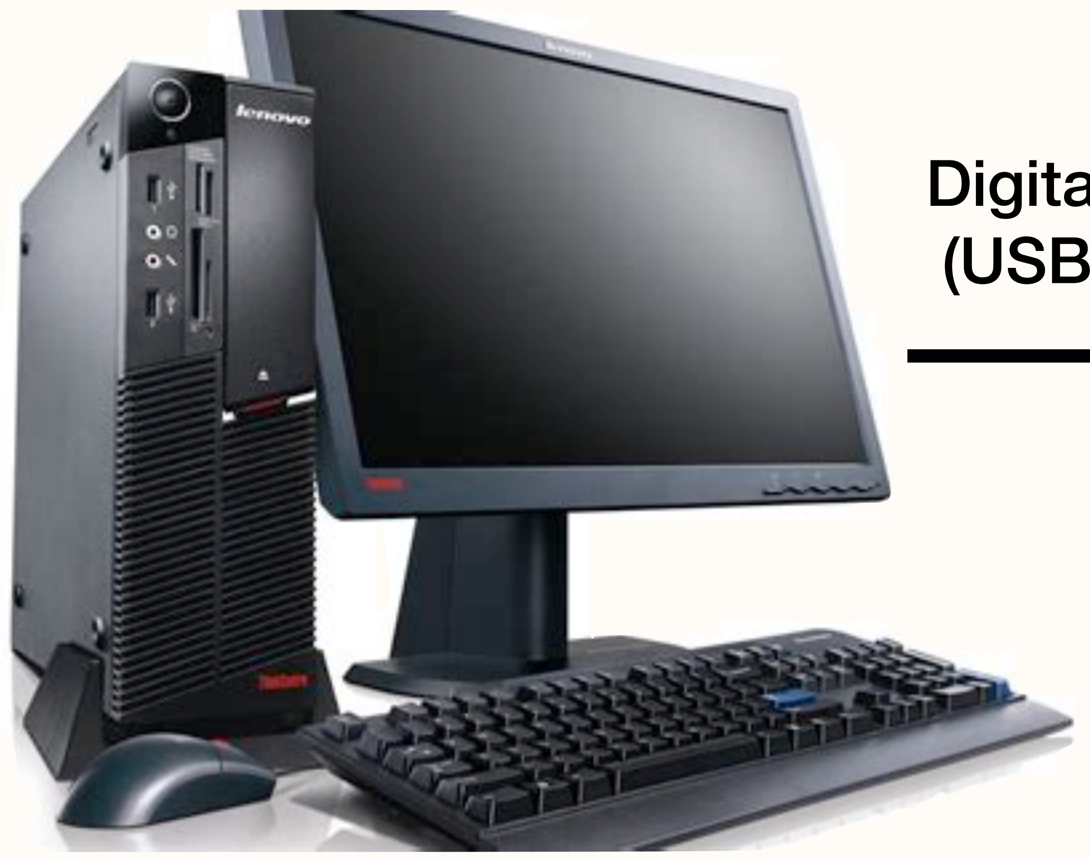
Impedance Demo



Putting It All Together

1. Audio Stimulus Delivery

- Generate auditory waveform on PC
- deliver to speaker



Digital signal
(USB cable)

Voltage signal
(low power)

Voltage signal
(high power)

$R_{in} = 8\Omega$

PC/Software
- Generate audio waveform

DAQ Board
- Digital to analog (D to A) conversion
- Low power/low current output

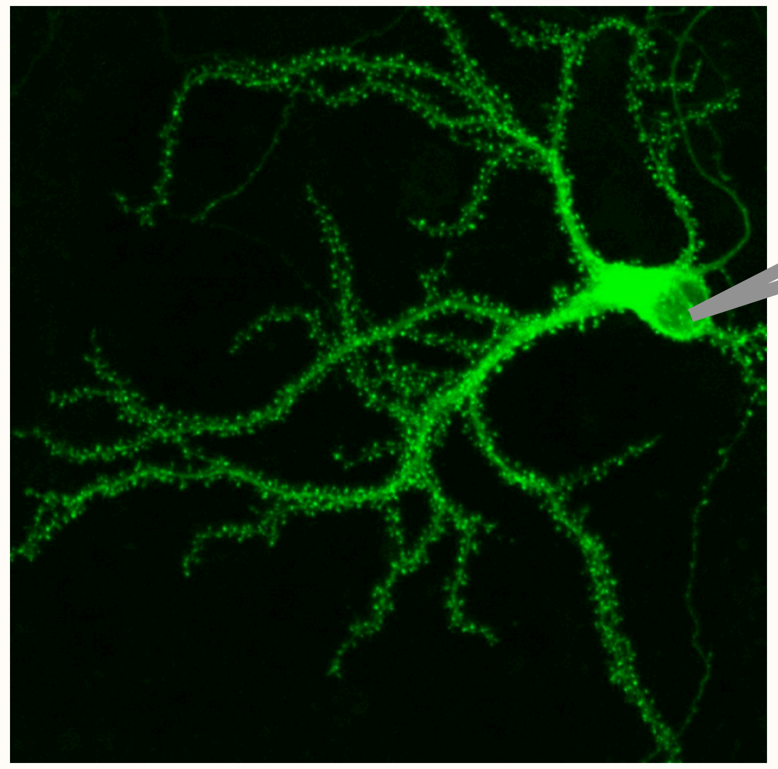
Audio Amplifier
- Convert low-current signal to high-current signal

Speaker
- Low input impedance,
- Requires high-current (high-power) input to generate sound

Putting It All Together

2. Intracellular Current-Clamp Recording

- Measure voltage across cell membrane, save to disk



Membrane Voltage

Voltage signal
low amplitude
very high R_{out}
("weak" source)

Electrode

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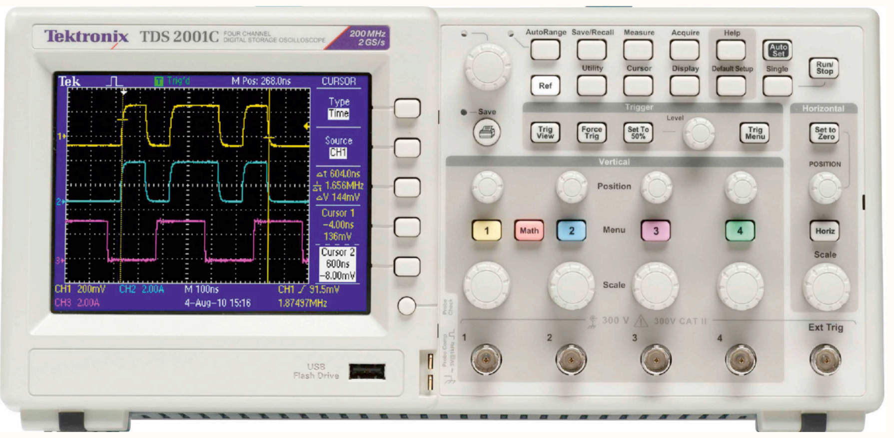
Ephys Headstage & Amplifier

- Read in "weak" high impedance signal
- Generate low impedance output
- Amplify signal amplitude
- High- and Low-pass filters

Voltage signal
high amplitude
low R_{out}



Oscilloscope

DAQ Board

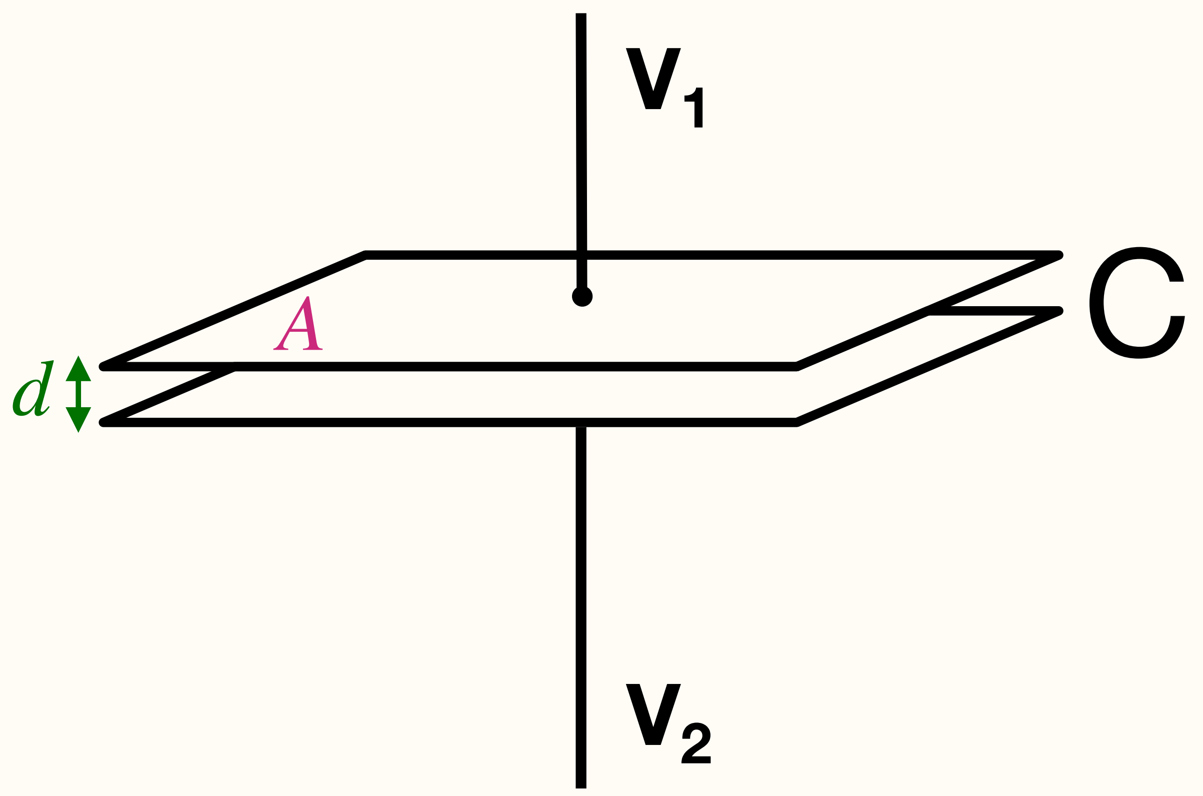
- Analog to digital conversion

Digital signal

PC/Software

- Display/analyze/save membrane voltage

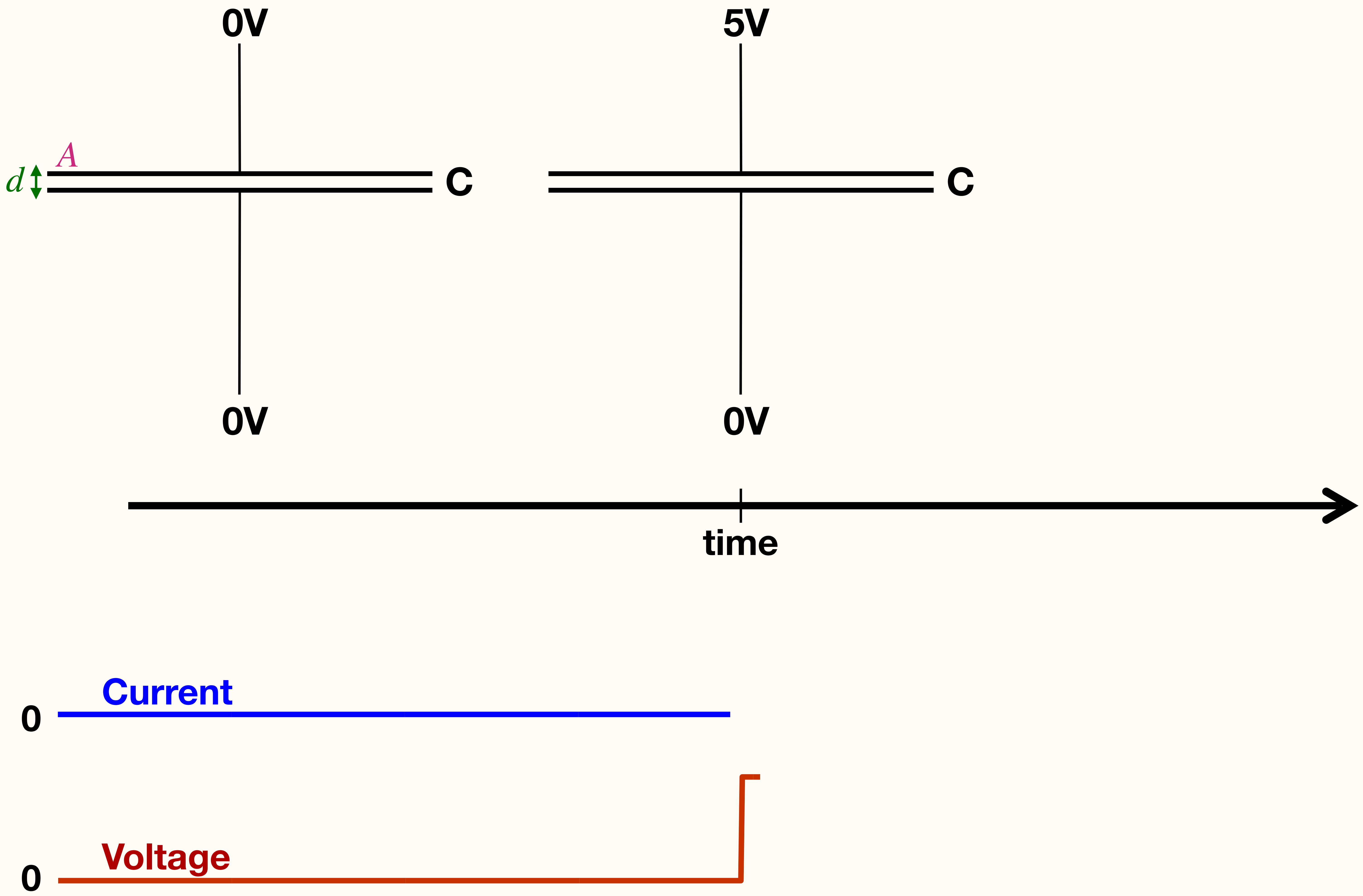
Capacitance



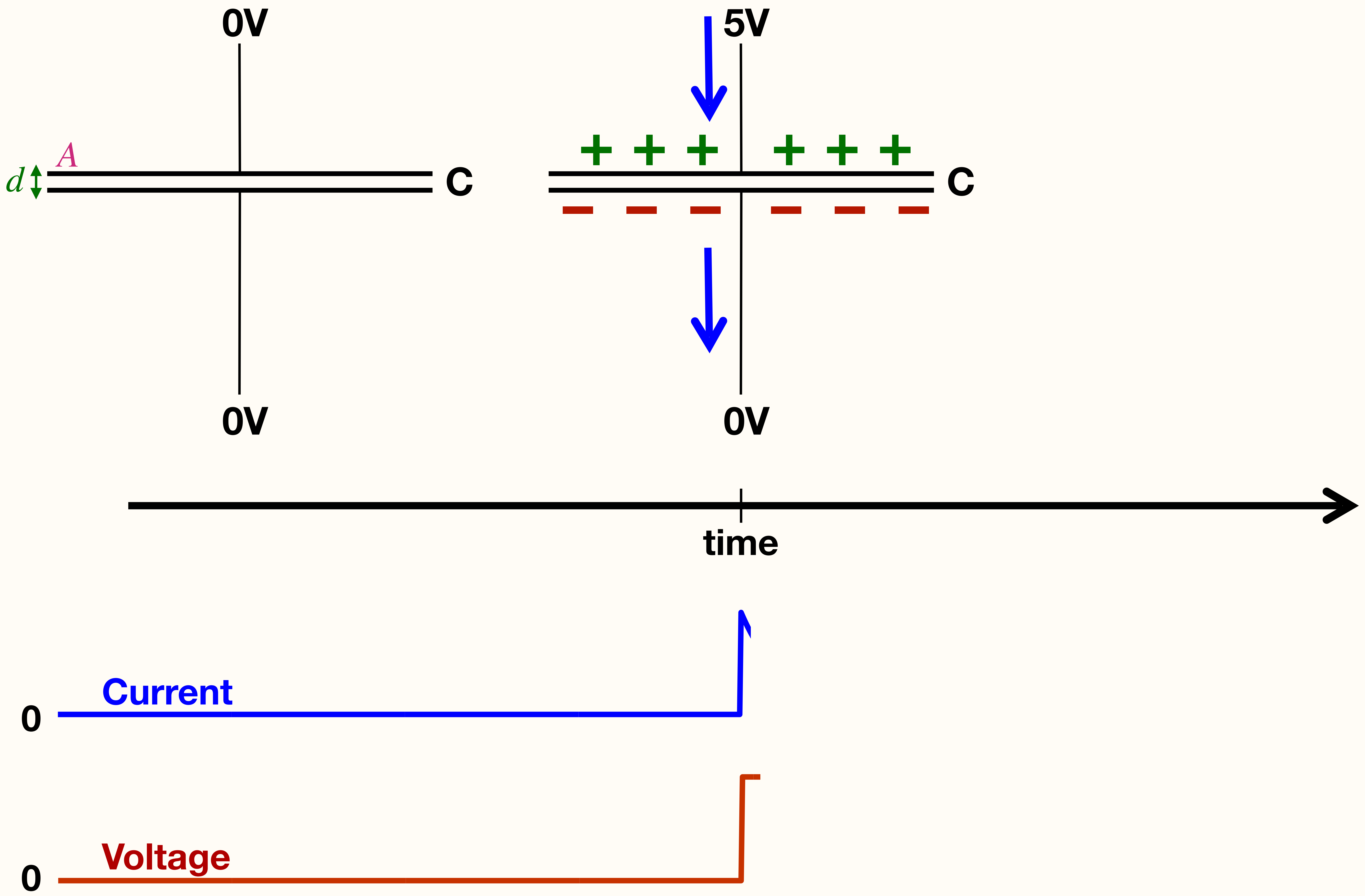
Capacitor: Two conductive surfaces (e.g., metal plates) separated by a small gap

- Allows current to pass through in a *frequency-dependent manner*
- How??

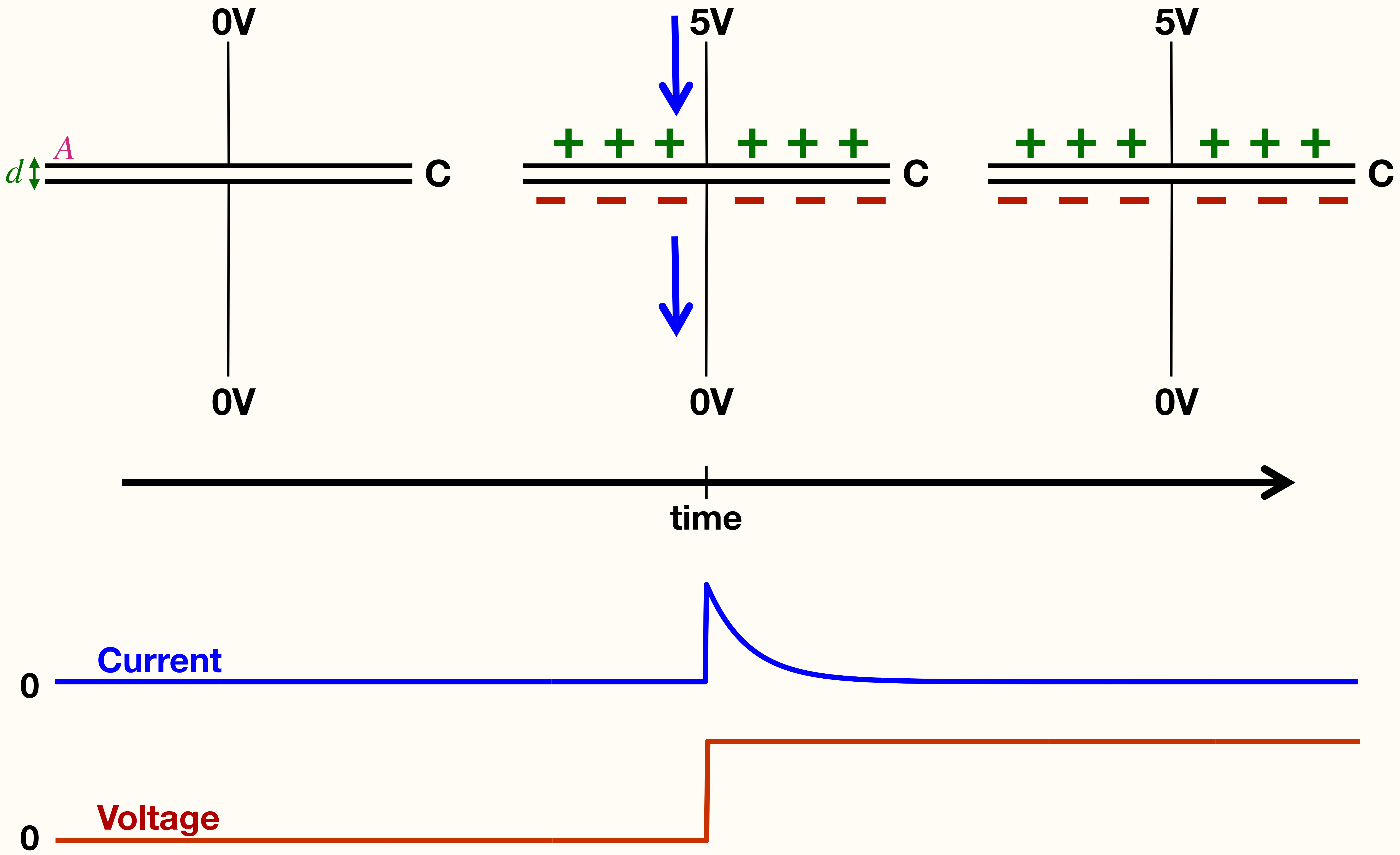
Capacitance



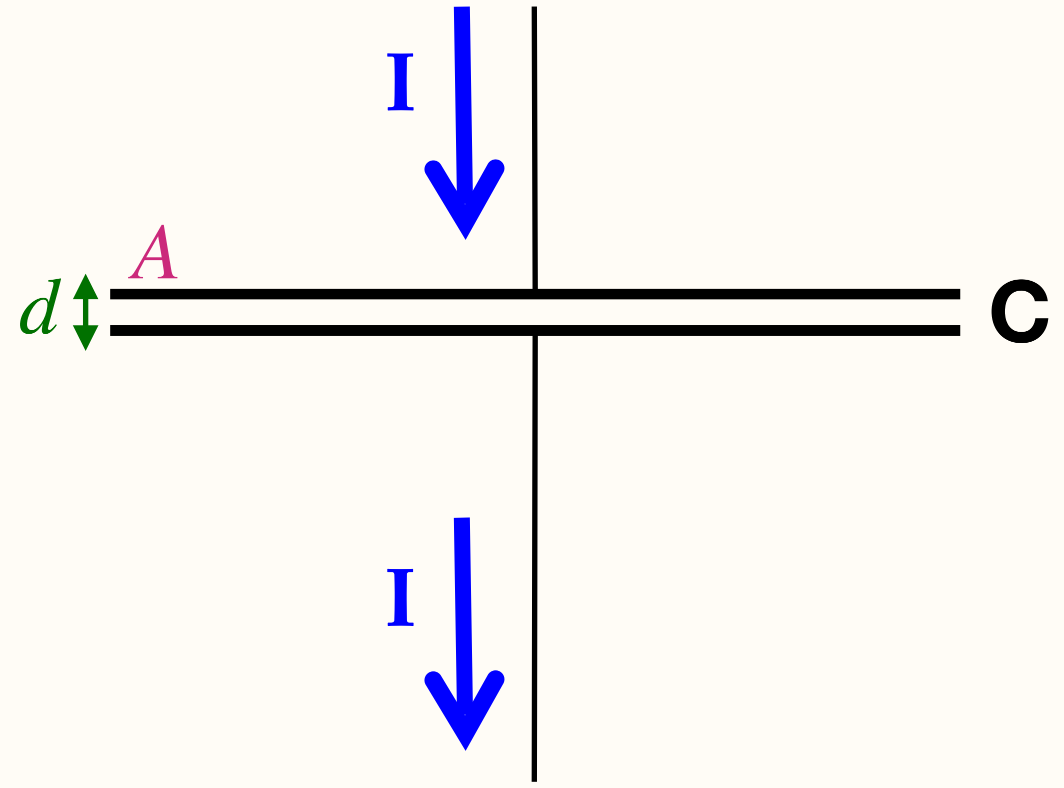
Capacitance

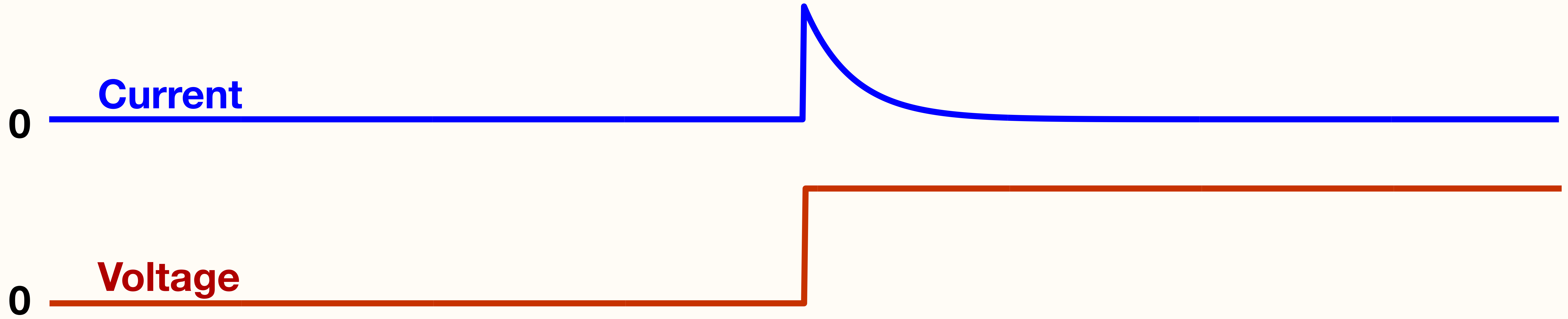


Capacitance



Capacitance

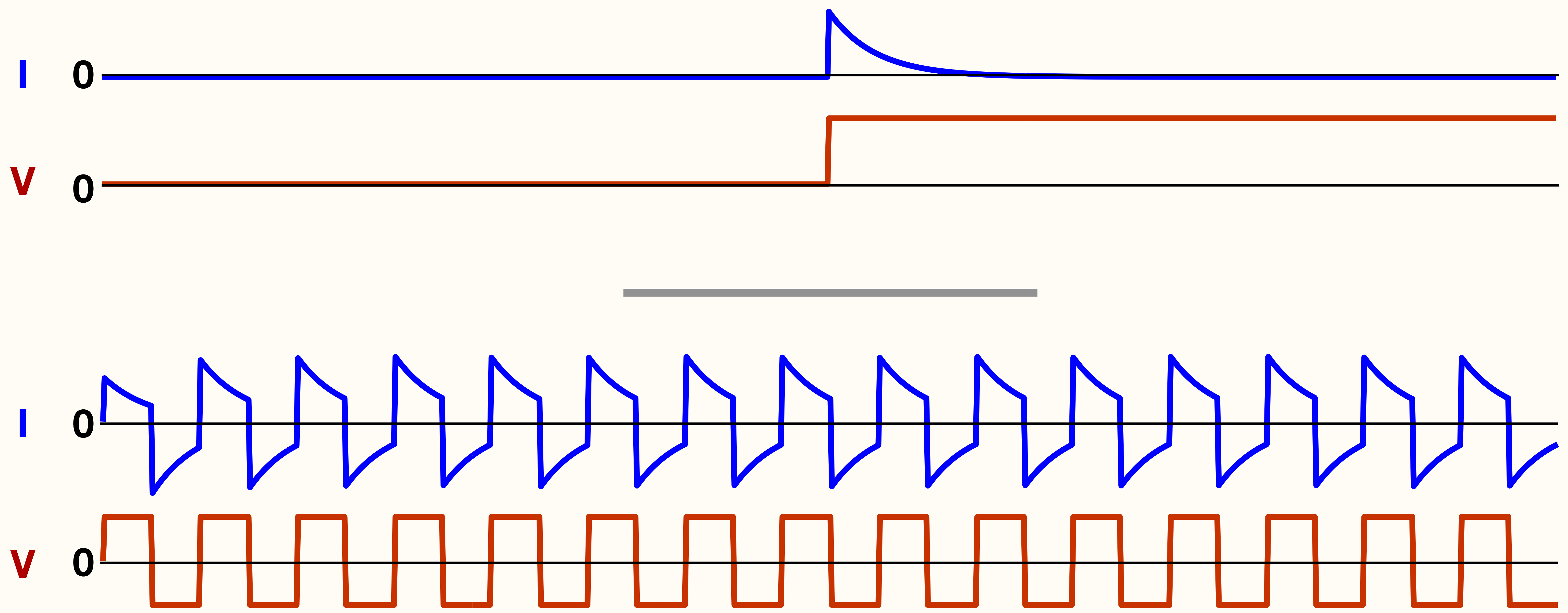




Capacitance:

- Current through a capacitor is proportional to the *rate of change* in voltage: $I = C\frac{dV}{dt}$
- Capacitance is proportional to (surface area)/distance: $C \propto \frac{A}{d}$

Capacitance



Capacitor behaves differently at high & low frequencies:

- Low Freq -> high resistance
- High Freq -> low resistance

$$I = C\frac{dV}{dt}$$

Simulation
https://tinyurl.com/yab7mpho

Impedance

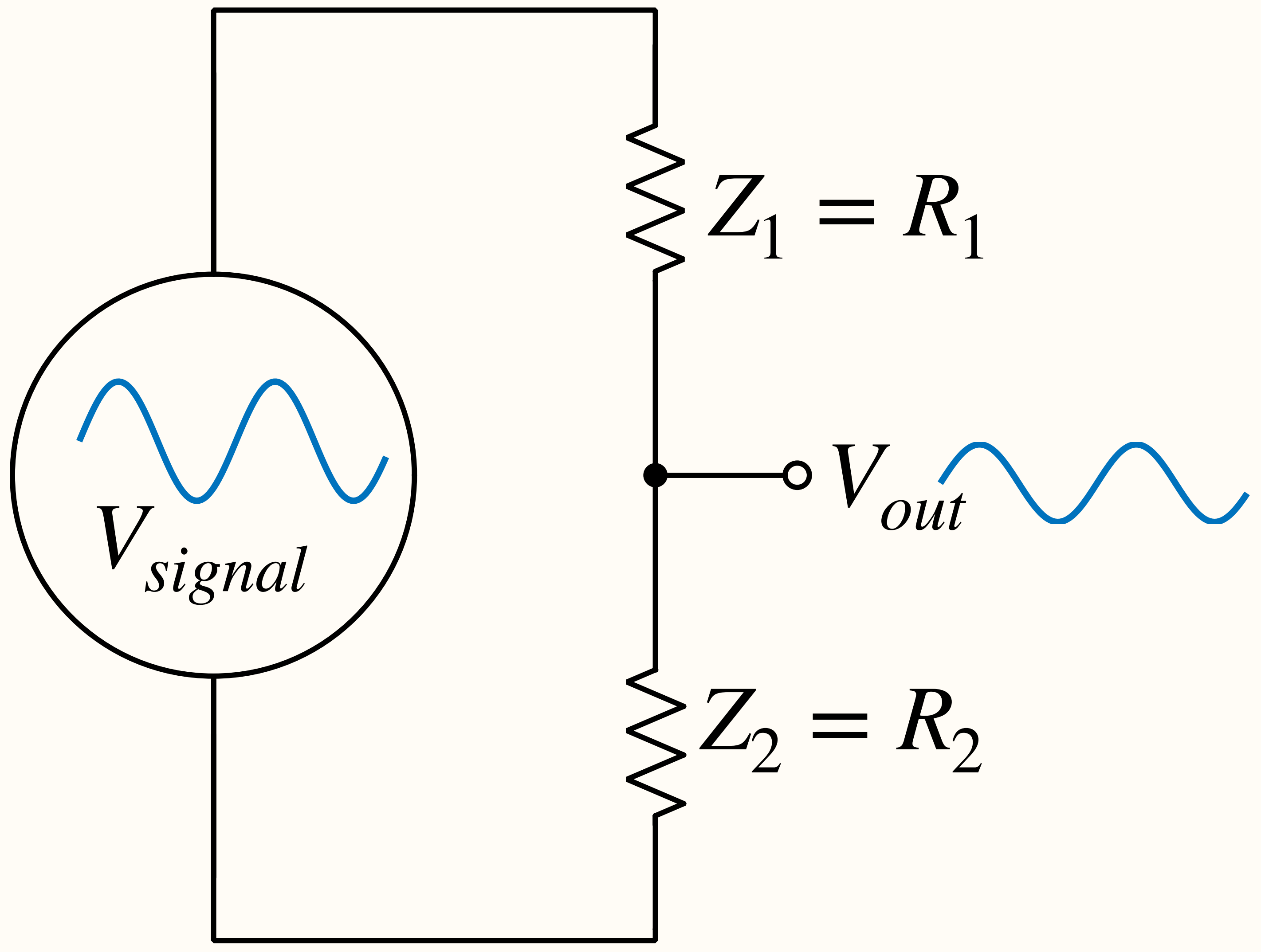
Impedance (Z) captures the frequency-dependent nature of resistance for capacitors (and other circuit components).

- Resistor: $Z_{Res.} = R$, is constant across all frequencies.
- Capacitor: $Z_{Cap.} = \frac{1}{fC}$ (for frequency f)
  - $Z_{Cap.}$ is large at low frequencies and drops as f increases

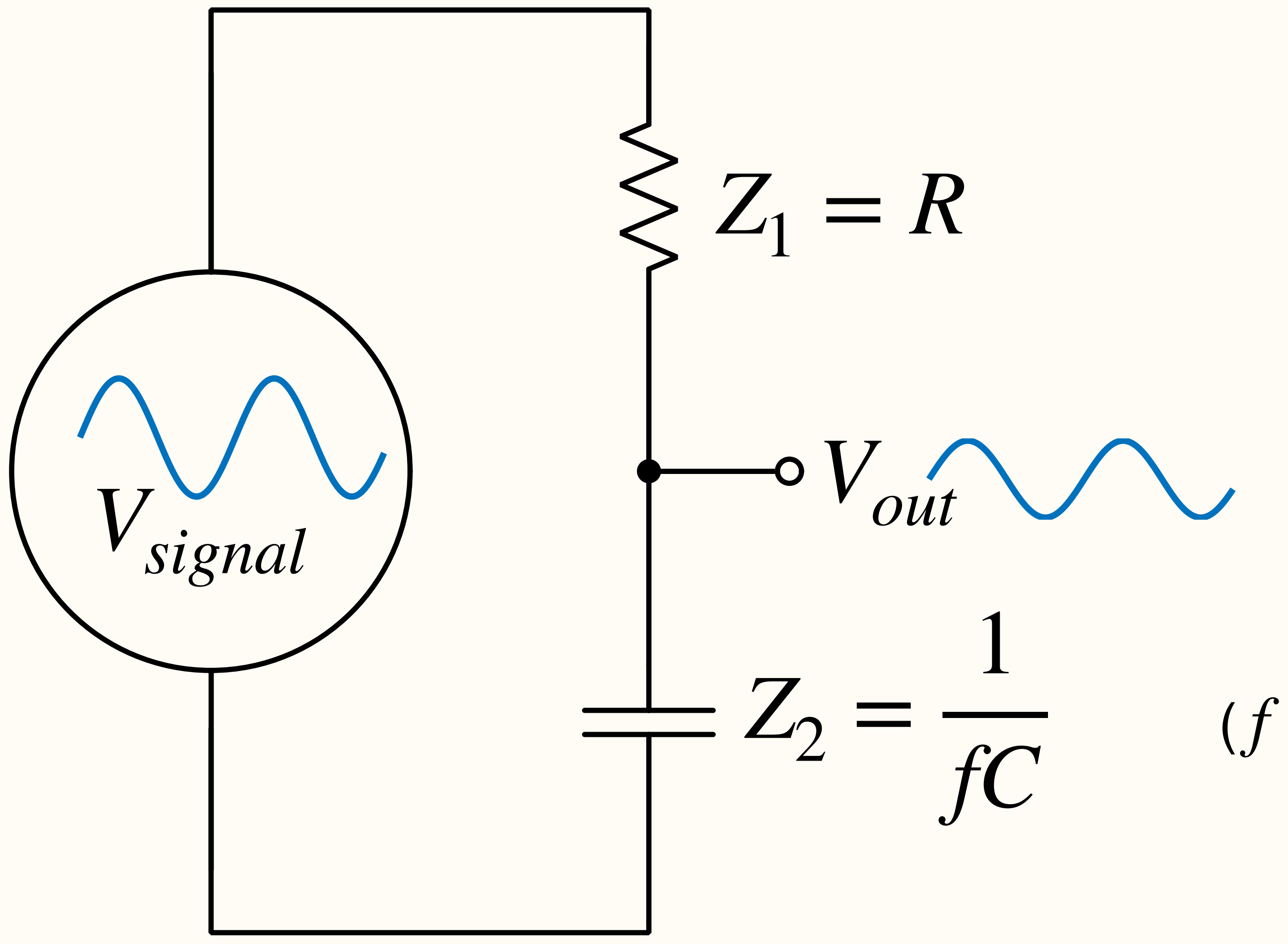
NOTE: *Impedance ($\mathbf{Z}$) is actually a complex number that includes phase information.*
For our purposes, we'll consider only the magnitude of this value $Z = \|\mathbf{Z}\|$

RC Circuits

Voltage Divider



RC Filter



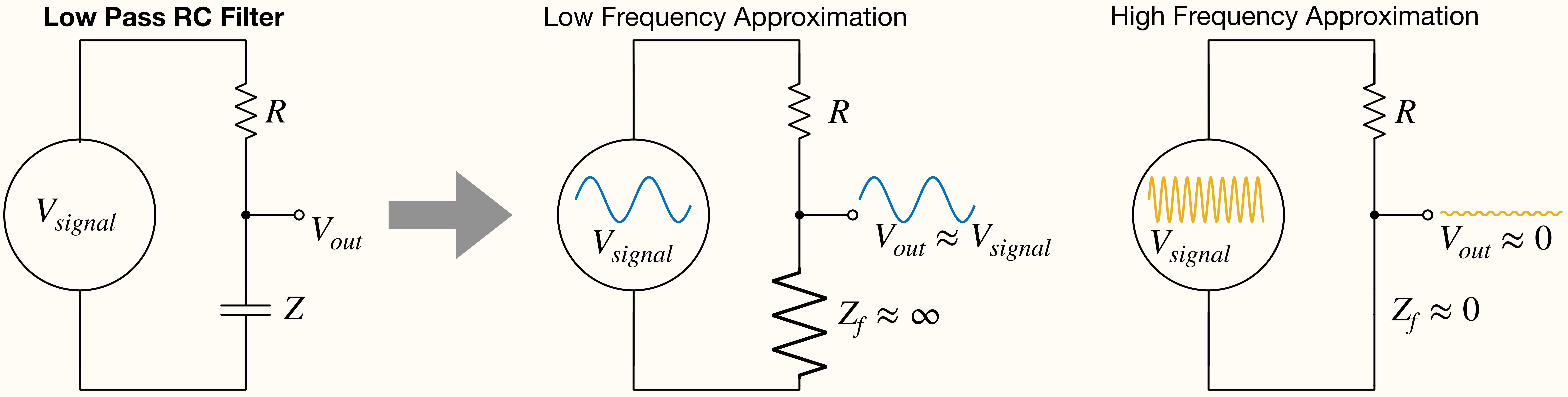
(f : frequency)

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{signal}$$

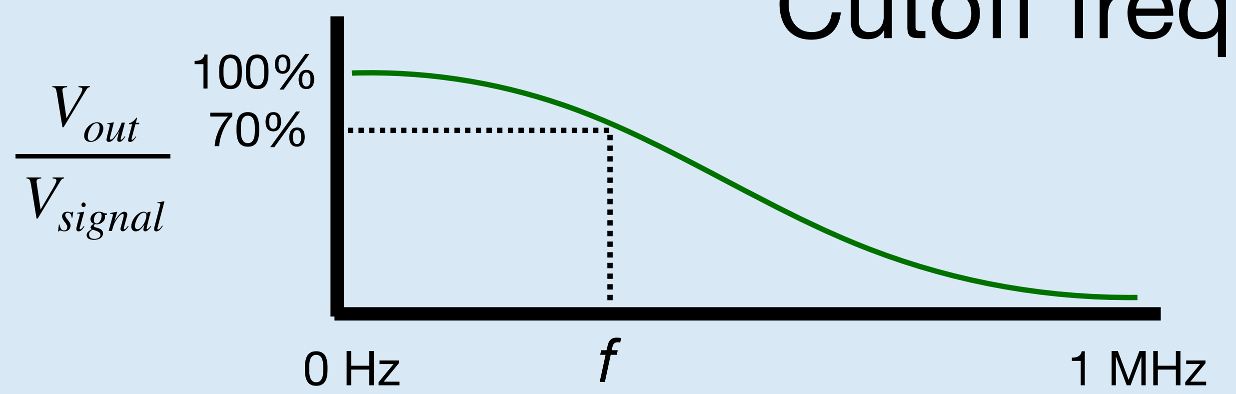
$$V_{out} \approx \frac{Z_2}{Z_1 + Z_2} V_{signal}$$

Attenuation is frequency-dependent

Low Pass RC Filter



$$V_{out} \approx \frac{Z}{R+Z} V_{signal}$$

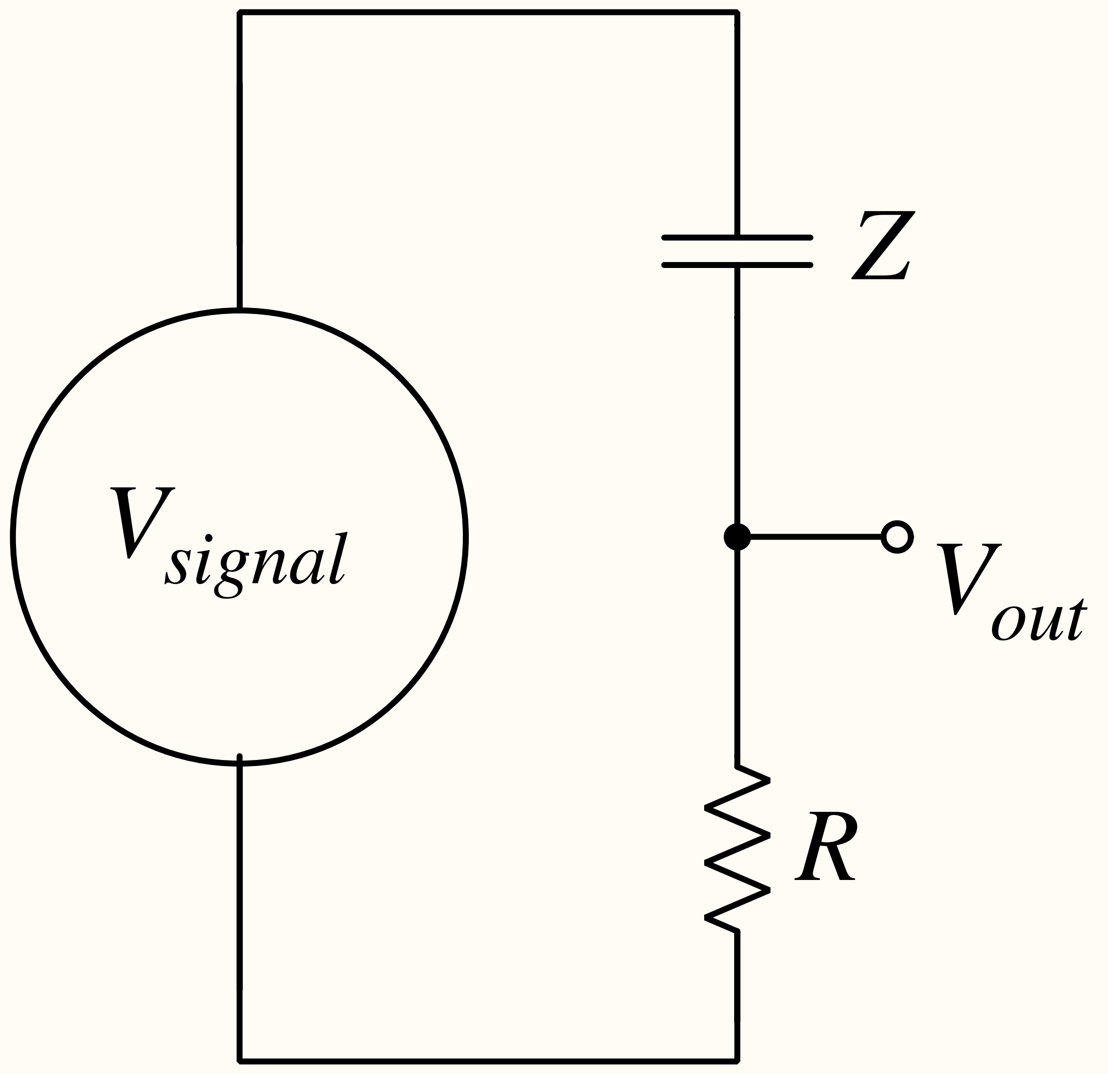


Cutoff frequency, $f = 1/(2\pi RC)$

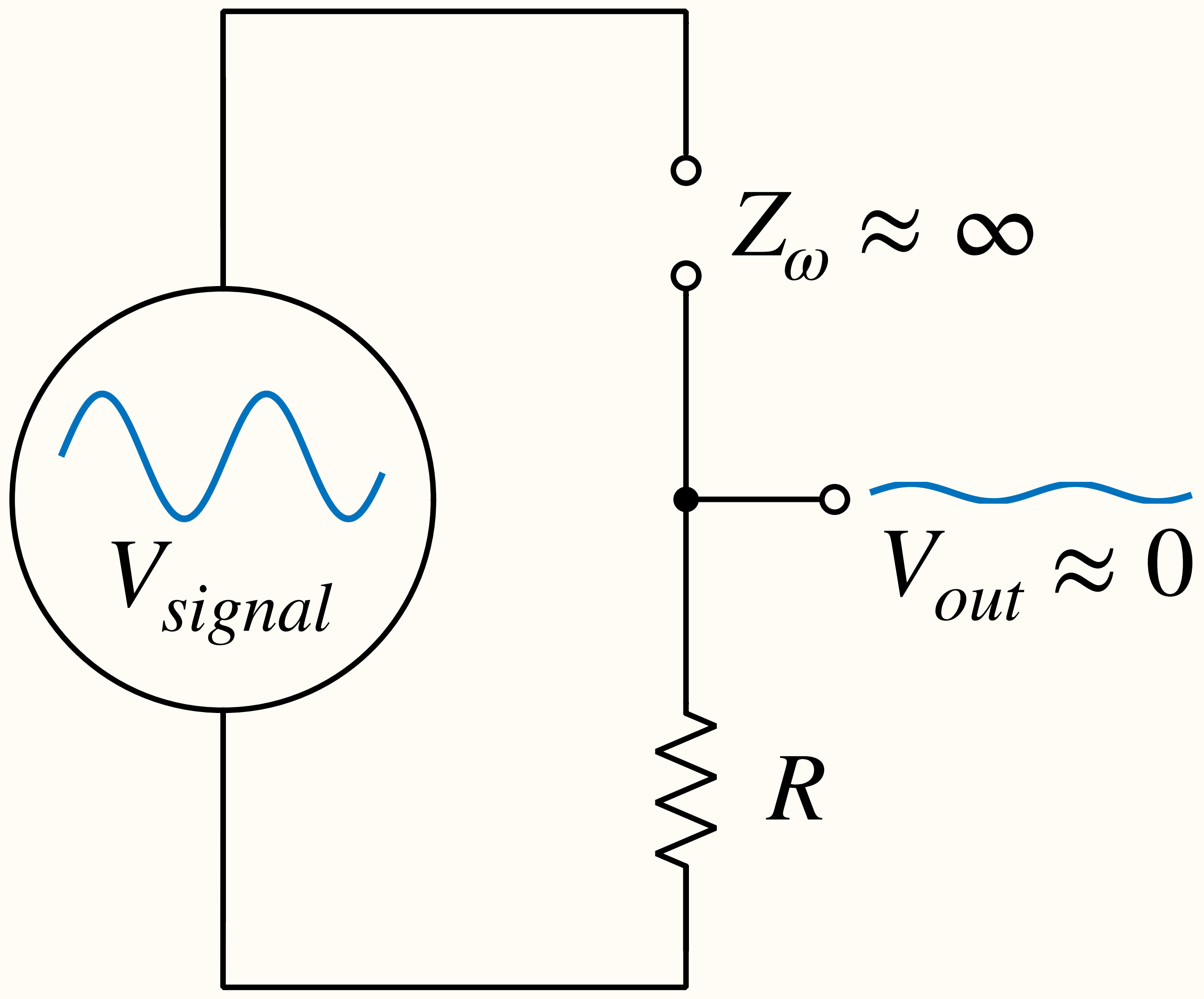
f: frequency in Hz
R: resistance in Ω
C: capacitance in F

High Pass RC Filter

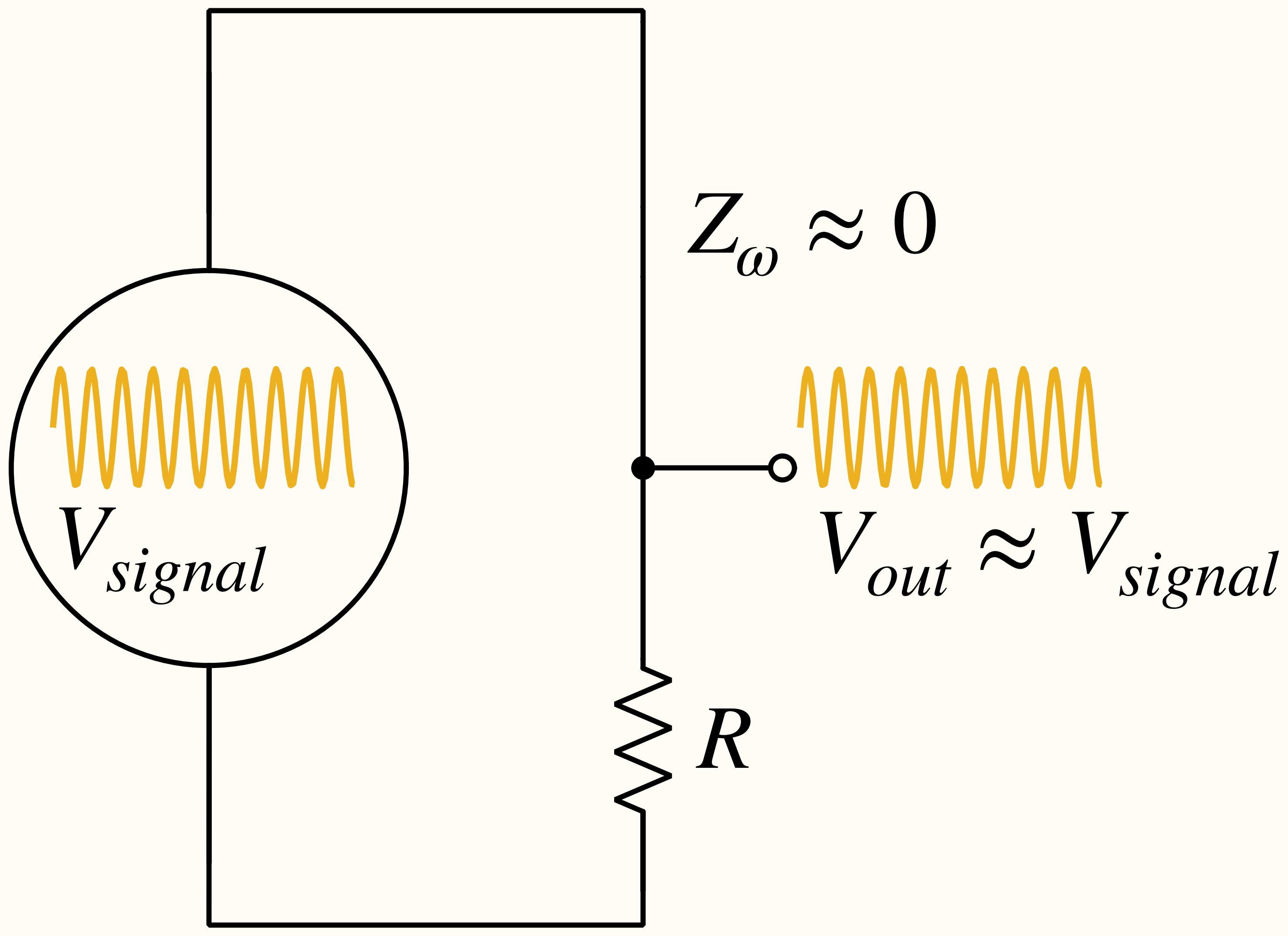
High Pass RC Filter



Low Frequency Approximation

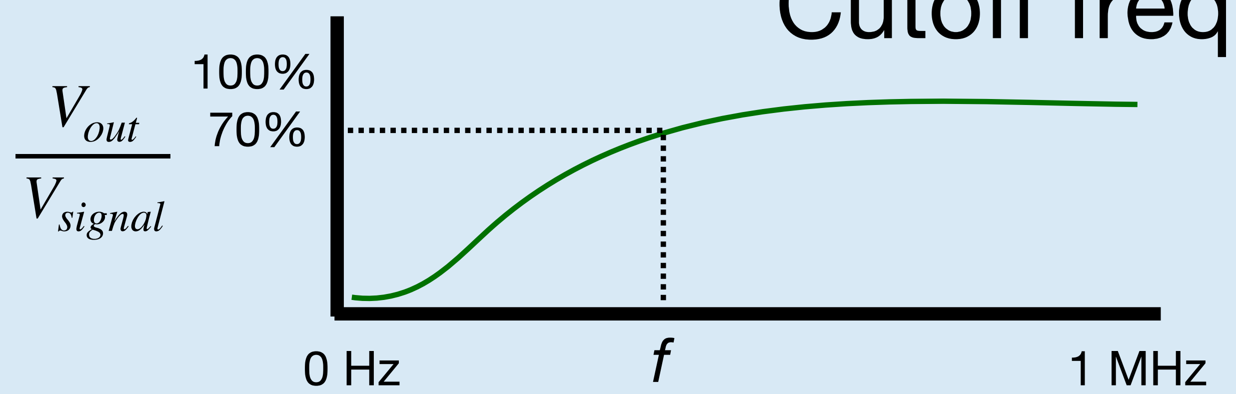


High Frequency Approximation



$$V_{out} \approx \frac{R}{R+Z} V_{Signal}$$

Cutoff frequency, $f = 1/(2\pi RC)$

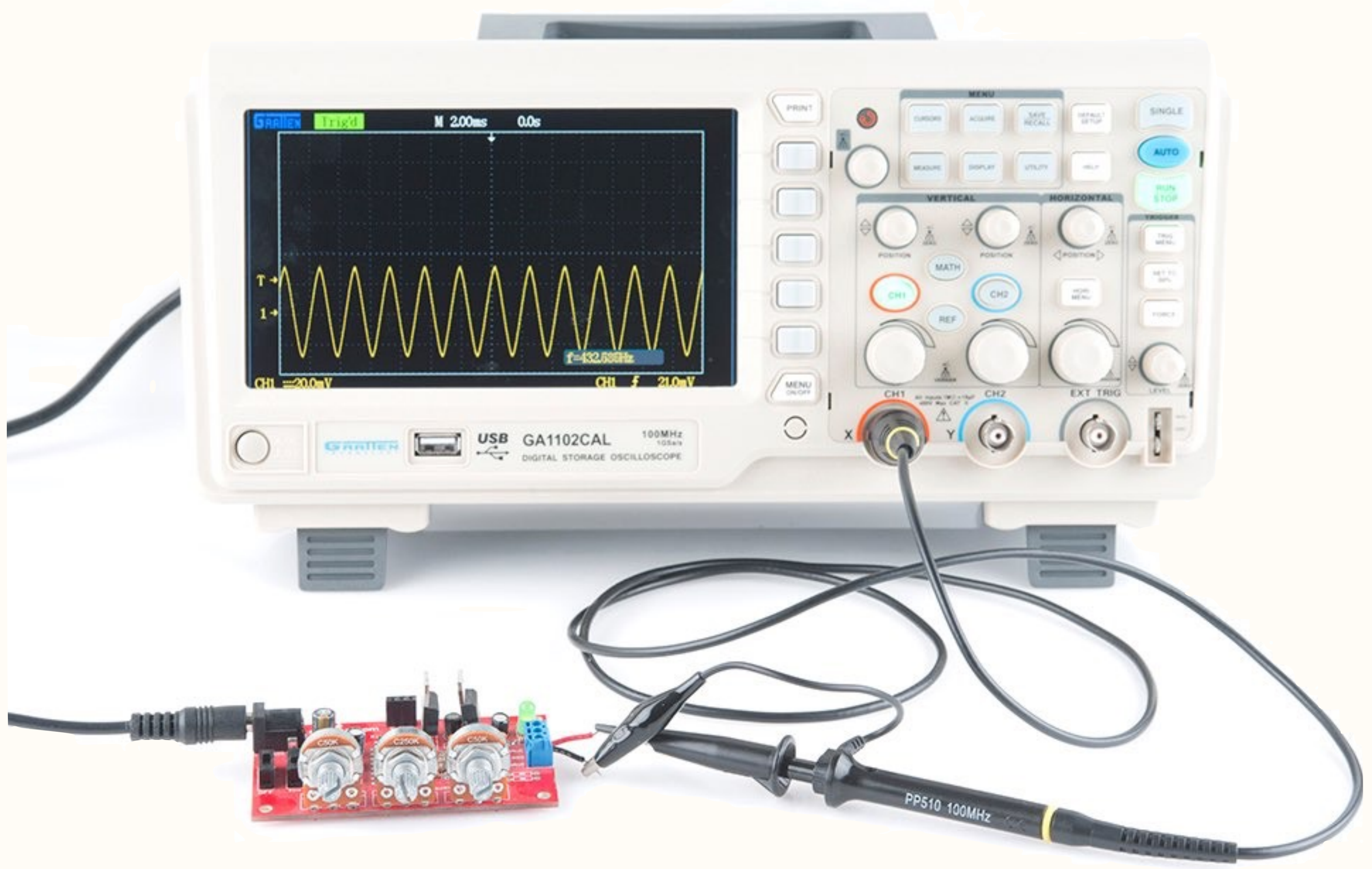


f: frequency in Hz
R: resistance in Ω
C: capacitance in F

Recap

- **Ohm's Law**: $V = IR \quad or \quad I = V/R$
- **Voltage divider**
- **Output & Input Impedance** (Voltage divider)
    - Hard to measure weak (high output impedance) signals like neurons
    - Hard to drive power-hungry (low input impedance) devices like speakers
    - Next week: Amplifiers can help
- **Capacitance**
- **RC Filters** (Frequency-dependent dividers)
    - Can be built to filter out unwanted signals
    - Next week: Can show up unexpectedly — parasitic capacitance; capacitive coupling

Measurement Instruments



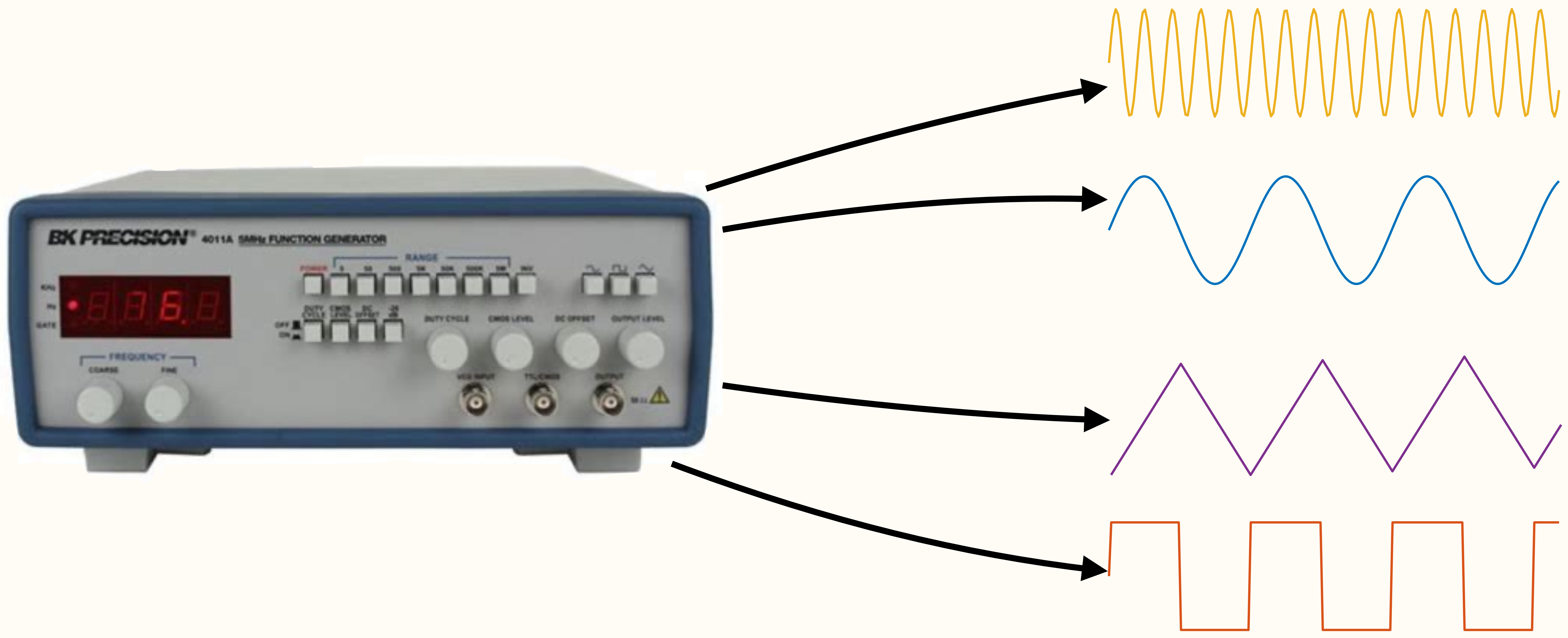
Multimeter / DMM (Digital Multimeter)

- Measure: Voltage, Current,
  Resistance, Capacitance
- Slow sampling rate; not for fast changes
- Portable, inexpensive

Oscilloscope

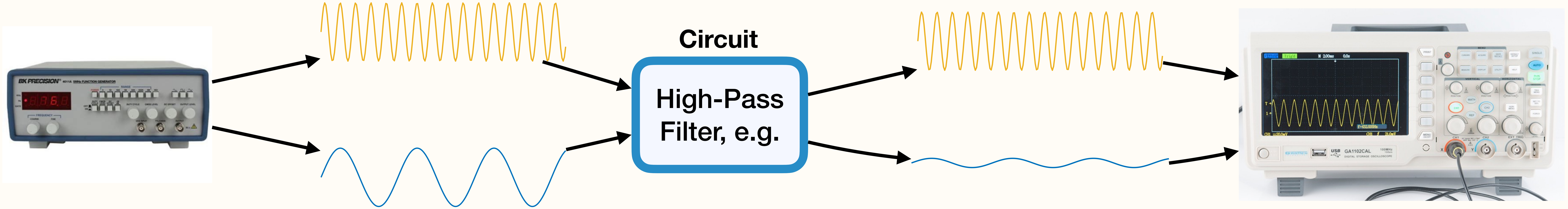
- Measure & plot: Voltage vs Time
- Triggers
- Measure frequency, pulse width, etc
- Moderate learning curve
- Worth learning to use — versatile tool:
  - https://learn.sparkfun.com/tutorials/how-to-use-an-oscilloscope/introduction

Function Generator



- Generate dynamic voltage waveforms
- Typically periodic waves, but fancier options available
- Can control frequency, amplitude, duty cycle
- Useful for characterizing or debugging electronic circuits

Function Generator



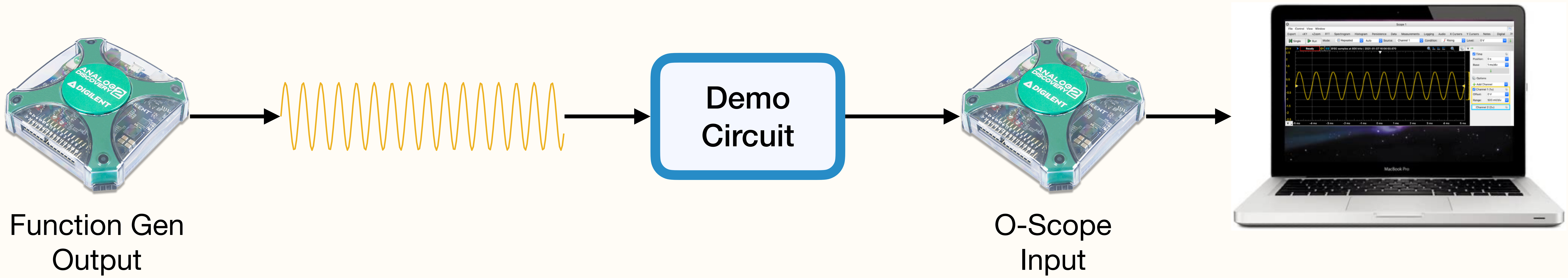
Characterizing or debugging electronic circuits

- Provide a known, controlled input (Function Generator)
- Observe/measure the circuit's output (Oscilloscope)

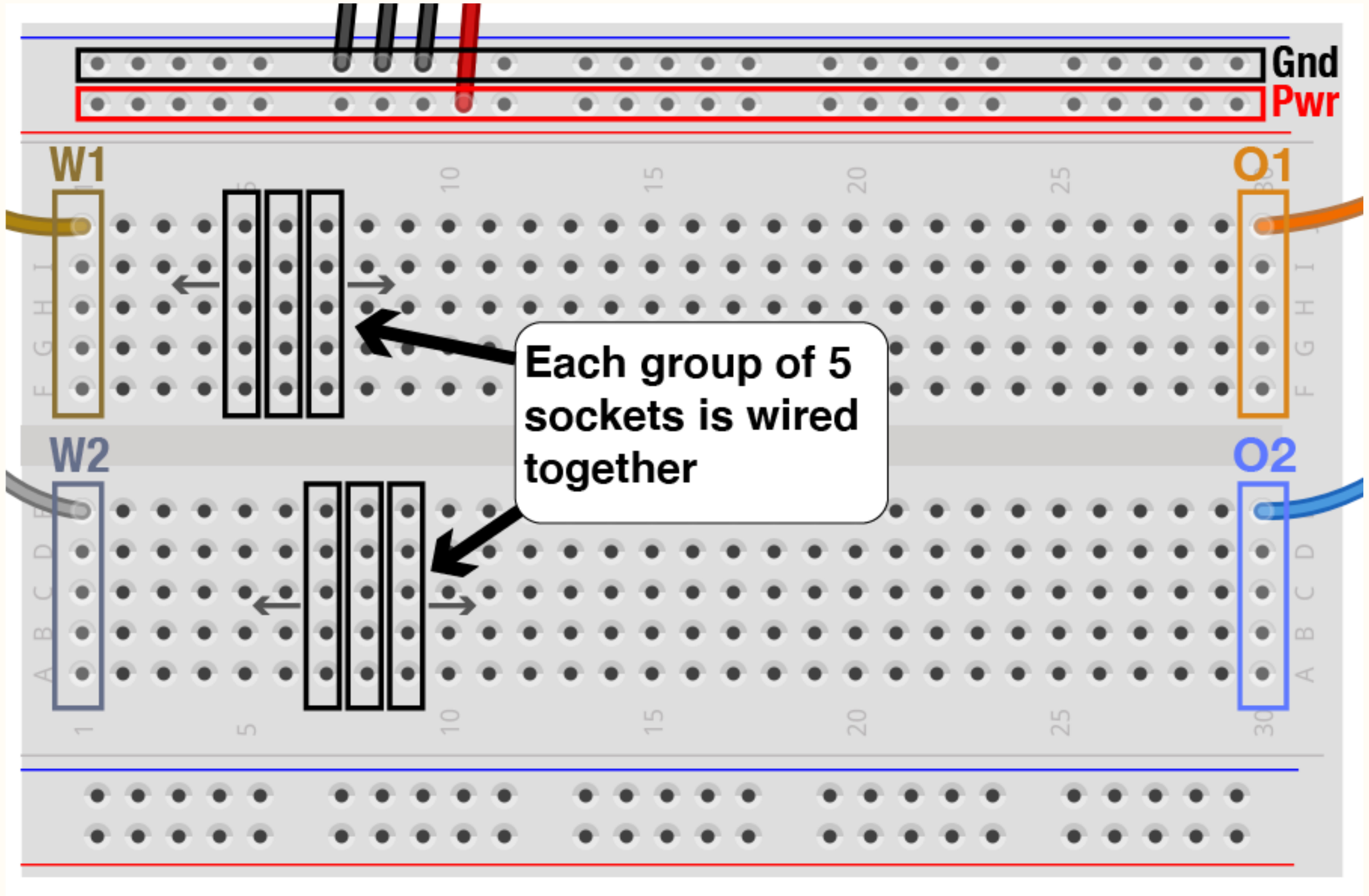
Analog Discovery 2

Assignments

Typical Assignment:



Using a breadboard



- Make connections between wires and components without solder
- All wires, components plugged into the same group will be wired together

Assignment 1

Class website: https://hms-ric.github.io/rig-nanocourse/

- Lecture slides, assignments, answer keys, reference material

Assignment 1

- Work through it at your own pace. (Work in pairs/groups if you like.)
  - Complete as much as you can in the next 60 minutes.
  - No need to complete the assignment (but you can continue at home if you like)
  - Not graded
- Email us your answers to the questions (as far as you got) by *next Wednesday*.
- Help is available:
  - Raise your hand / ask a classmate
  - Email the instructors with any questions
    - (ofer@hms.harvard.edu, pavel_gorelik@hms.harvard.edu, seyednavid_mousavi@g.harvard.edu)
  - Answer key is on the website. Feel free to check your answers when done or if stuck.