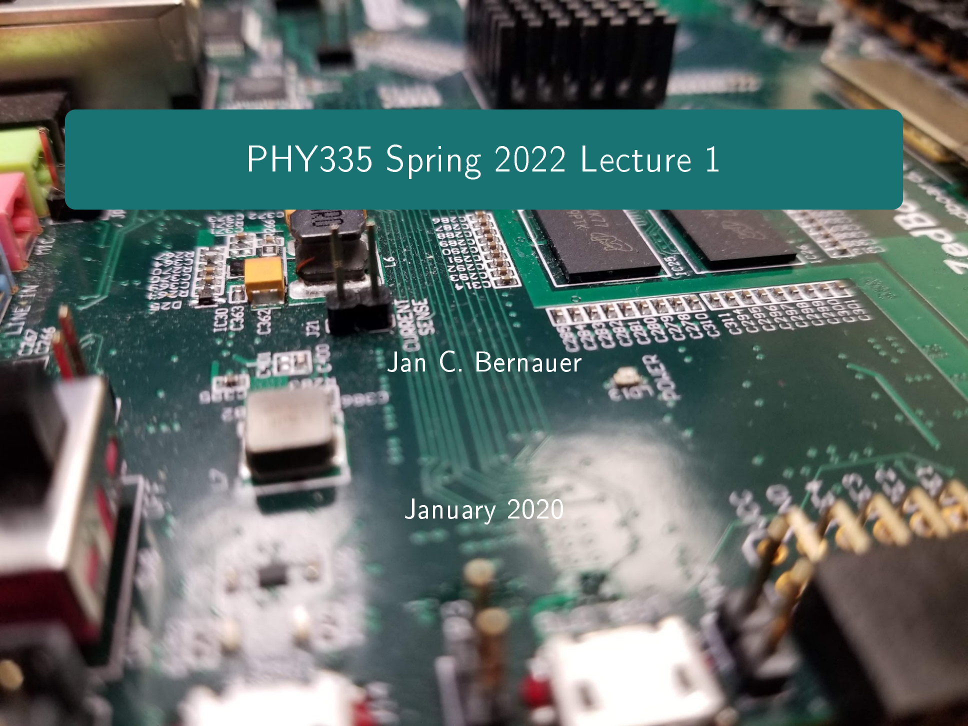


PHY335 Spring 2022 Lecture 1

Jan C. Bernauer

January 2020

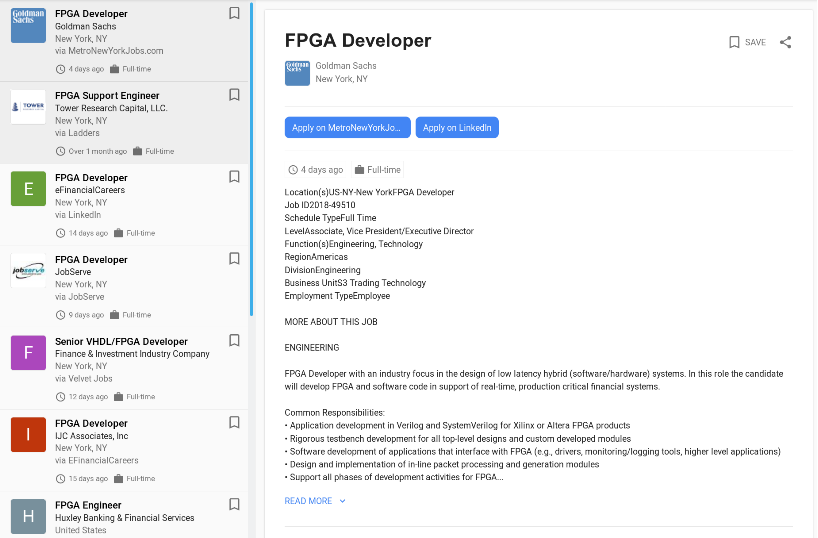
Organization

- Professor: Jan C. Bernauer
- Syllabus:
  `https://you.stonybrook.edu/phy335spring2022/`
- Classes:
  - Group 1: Tuesday+Thursday
  - Group 2: Monday+Wednesday
- TA:
  - Group 1: James
  - Group 2: Julia

How can you reach me

- Office hours: by appointment (zoom or in person). You can also come to the parallel section.
- Email: jan.bernauer@stonybrook.edu
- Phone: +1 631 632 8113

Why?


FPGA Developer
Goldman Sachs
New York, NY
via MetroNewYorkJobs.com
4 days ago Full-time
FPGA Support Engineer
Tower Research Capital, LLC.
New York, NY
via Ladders
Over 1 month ago Full-time
FPGA Developer
eFinancialCareers
New York, NY
via LinkedIn
14 days ago Full-time
FPGA Developer
JobServe
New York, NY
via JobServe
9 days ago Full-time
Senior VHDL/FPGA Developer
Finance & Investment Industry Company
New York, NY
via Velvet Jobs
12 days ago Full-time
FPGA Developer
IJC Associates, Inc
New York, NY
via EFinancialCareers
15 days ago Full-time
FPGA Engineer
Huxley Banking & Financial Services
United States
FPGA Developer
SAVE
Goldman Sachs
New York, NY
Apply on MetroNewYorkJo...
Apply on LinkedIn
4 days ago
Full-time
Location(s)US-NY-New YorkFPGA Developer
Job ID2018-49510
Schedule TypeFull Time
LevelAssociate, Vice President/Executive Director
Function(s)Engineering, Technology
RegionAmericas
DivisionEngineering
Business UnitS3 Trading Technology
Employment TypeEmployee
MORE ABOUT THIS JOB
ENGINEERING
FPGA Developer with an industry focus in the design of low latency hybrid (software/hardware) systems. In this role the candidate will develop FPGA and software code in support of real-time, production critical financial systems.
Common Responsibilities:
• Application development in Verilog and SystemVerilog for Xilinx or Altera FPGA products
• Rigorous testbench development for all top-level designs and custom developed modules
• Software development of applications that interface with FPGA (e.g., drivers, monitoring/logging tools, higher level applications)
• Design and implementation of in-line packet processing and generation modules
• Support all phases of development activities for FPGA...
READ MORE

What you will be doing

- On web page: Unit description
- Prepare theory, make a game plan to do measurements
- Work in a group of 2 to perform measurements
    - Make sure all of you contribute!
    - Make notes and record results in your lab book.
- Leave your workspace clean!
- Write a lab report
- TA's will grade lab report AND lab book

Lab report

- Intro
  - 1-2 pages
  - All relevant theory
- Data
  - Copy data from lab notebook to report
  - Circuit diagrams
  - Errors!
- Analysis
  - Did the experiment work?
  - Compare experiment with theory prediction
  - Include error discussion!
- Short summary
- You can write it by hand, I recommend LaTeXand Circuitikz
- Better write it yourself!

Intro

- You have to write this BEFORE the unit starts.
- When the unit starts, let a TA or me sign it.
- Will be part of the report grade!

Books

- Use the one you like.
- I really like Art of Electronics (AoE)
- Chapters on web page are in reference to AoE, 3rd edition

Timeline

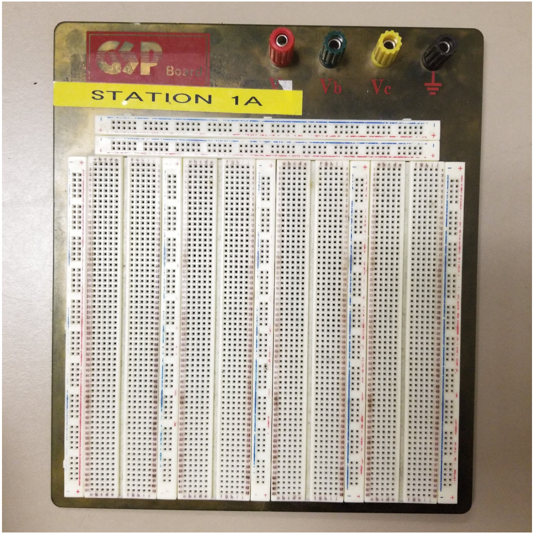
UNIT	SUBJECT	LAB DATES	REPORT DUE ON	ADDITIONAL MATERIAL
0	Introduction	01/24+25		
1	Lab instruments, signals, resis-tors	01/26+27, 01/31+02/01, 02/02+03	02/9+10	AoE Chapter 1.1 to 1.3
2	Capacitors, Inductors, RC filters	02/07+08, 02/09+10, 02/14+15	02/21+22	AoE: Chapter 1.4 to 1.5,1.7 (6)
3	Diodes and DC power	02/16+17, 02/21+22	02/18+19	AoE Chapter 1.6 \
4	Simulation and PCB design	02/23+24, 02/28+03/01	03/07+08	(no lab book required)
5	Operational amplifiers	03/02+03, 03/07+08, 03/07+08, 03/09+10, 03/21+03/22	03/30+31	AoE Chapter 4
Midterms	Midterms, units 1-5	03/23+24		
6	Transistors and Transistor cir-cuits	03/28+29, 03/30+31, 04/04+05, 04/06+07, 04/11+12	04/20+21	AoE Chapter 2,3
7	Digital electronics, TBD	04/13+04/14, 04/18+19, 04/20+21, 04/25+26, 04/27+28	05/04+05	AoE Chapter 10,(11),12.1-12.3, 13.1-13.5 (13.5-13.14)
Finals	(Units 1-7, focus on 6-7))	05/04+05	Training on 05/02+03	

- Everybody has a laptop?

Safety

- Do not put any component in a power outlet.
- The voltages the power supply provides are generally safe. But as a habit, do not touch powered electronics if you can avoid it.
- Many components will release smoke when burning out. That smoke is toxic.
- Some components can explode when too much current flows through them. Beware of eye damage!
- Wash your hands.

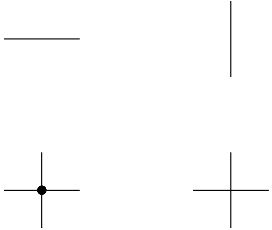
Things in the lab: Breadboard



- Base for your circuit
- DO NOT FORCE THICK WIRES INTO IT!
- Each group has one. Put a label on it and store from lab-day to lab-day

Things in the lab: Jumper wires

Schematic symbols:

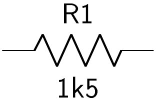


connected   not connected

- Please keep them sorted
- Exist as flexible and stiff variants

Things in the lab: Resistor

Schematic symbol:



- Color coded with rings

Resistor color codes

5 Band color code resistor

Color	1st digit	2nd digit	3rd digit	Multiplier	Tolerance
Black	0	0	0	10^0	
Brown	1	1	1	10^1	1% (F)
Red	2	2	2	10^2	2% (G)
Orange	3	3	3	10^3	
Yellow	4	4	4	10^4	
Green	5	5	5	10^5	0.5% (D)
Blue	6	6	6	10^6	0.25% (C)
Violet	7	7	7	10^7	0.10% (B)
Gray	8	8	8	10^8	0.05%
White	9	9	9	10^9	
Gold				10^{-1}	5% (J)
Silver				10^{-2}	10% (K)

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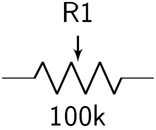
Gray	8	8	8	10^8	0.05%
White	9	9	9	10^9	
Gold				10^{-1}	5% (J)
Silver				10^{-2}	10% (K)

- 9-2-3 $\times$100 - 1% $\longrightarrow$ 92,3 kOhm (92k3)

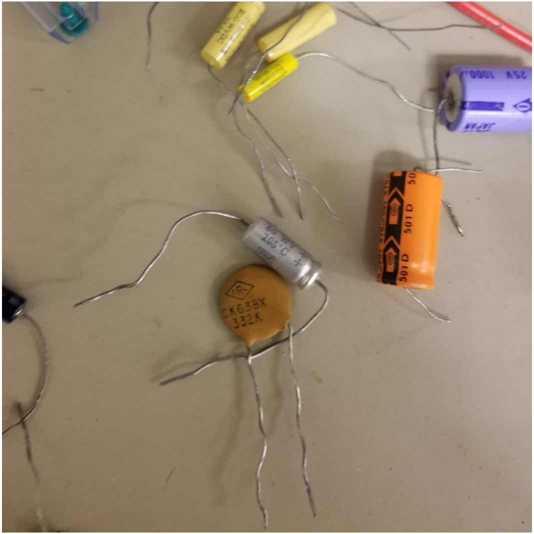
Things in the lab: Potentiometer

Schematic symbol:

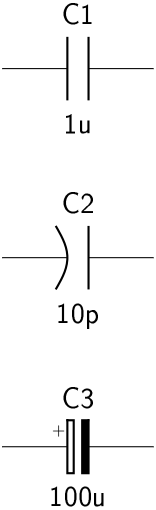


- 3 connections = 3 poles!

Things in the lab: Capacitors

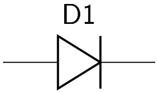


Schematic symbols:

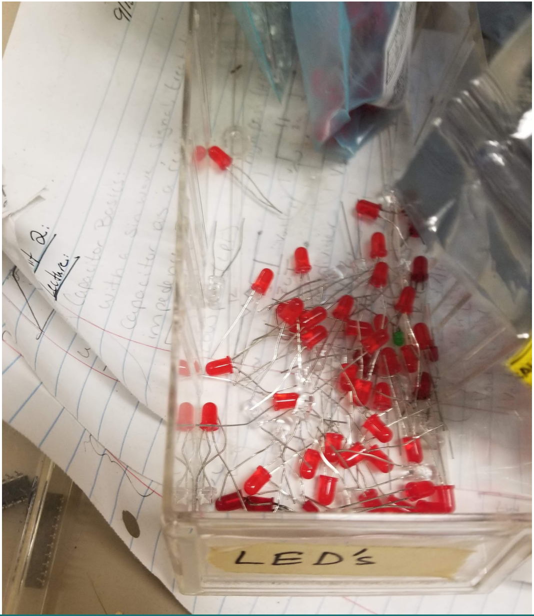


Things in the lab: Diodes

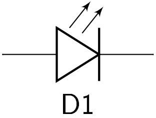
Schematic symbol:



Things in the lab: Light Emitting Diodes

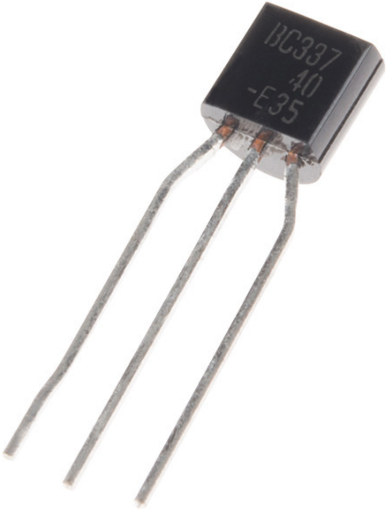


Schematic symbol:



- Long leg: Anode, +
- Short leg: Cathode, -
- NEVER WITHOUT A CURRENT LIMITING RESISTOR

Things in the lab: Transistors



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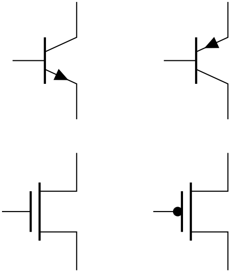
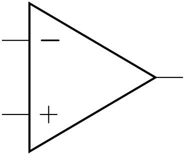


For us most often OPAMPs:



Things in the lab: DMM

- Digital Multi-Meter
- Measures Voltages, Currents, Resistance

Things in the lab: DMM

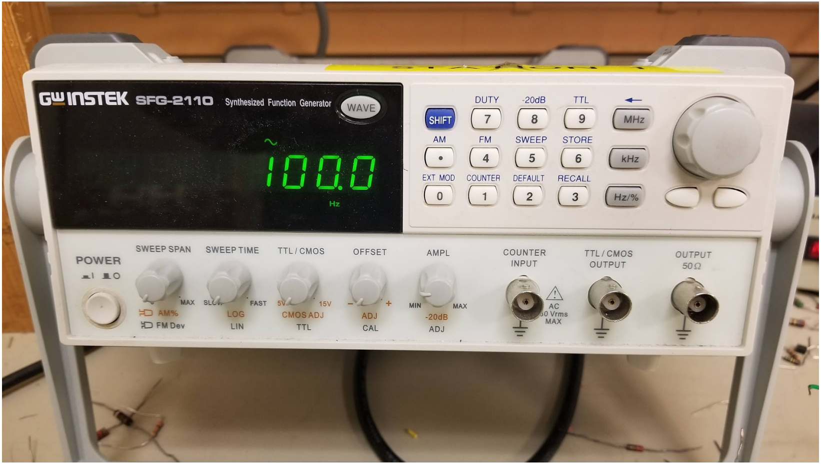
- Digital Multi-Meter
- Measures Voltages, Currents, Resistance

Things in the lab: Not a DMM

Things in the lab: Power supply

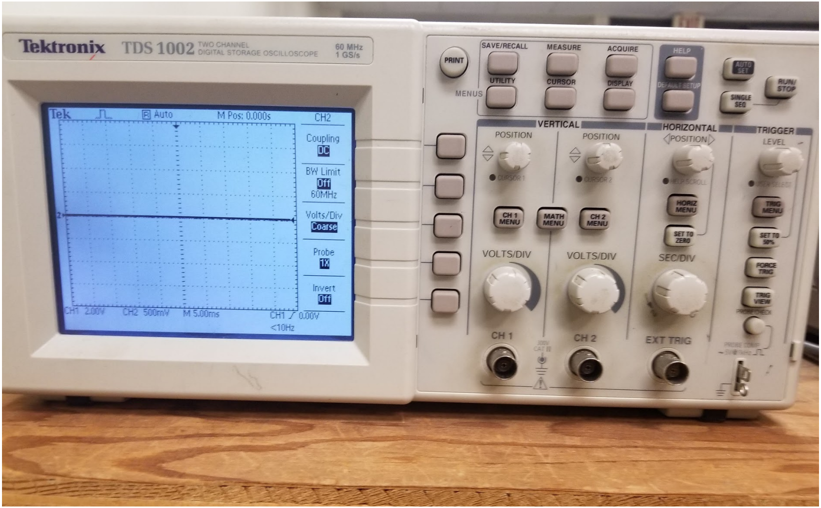
- Generates constant voltages (and 60 Hz sine waves)

Things in the lab: Signal generator / Function generator



- Generates time-varying voltage signals

Things in the lab: Oscilloscope



- Displays voltages as function of time
- Or correlation between two voltages

Things in the lab: Oscilloscope

Intro to error analysis

- In physics, the error of a measurement is an estimate of the uncertainty.

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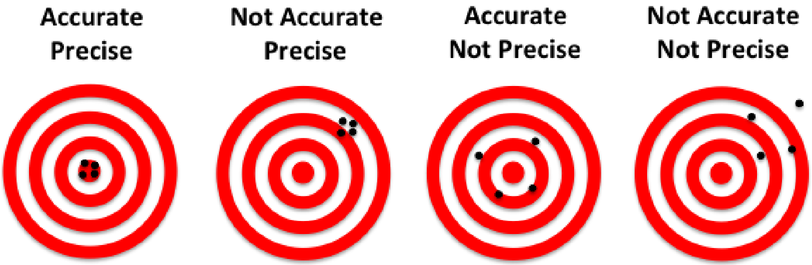
- Any real measurement has limited precision, and limited accuracy.



Precision / accuracy example

Measure a mass with a scale

Precision ($\sim$statistical error):

- Repeated measurement: How well do the values agree?
- But also: How many gradations/digits

Precision / accuracy example

Measure a mass with a scale

Precision (∼statistical error):

- Repeated measurement: How well do the values agree?
- But also: How many gradations/digits

Accuracy (∼systematic error):

- How close is 1kg on the scale to real 1kg?

Average of repeated measurements will have better precision, but unchanged accuracy.

Uncertainty bands/ranges

- The measurement process will give a measured value around the true value, according to a probability distribution.
- That makes a measured value an instance of a random variable.
- We can find a range which contains a specified probability.
- Turn it around: Make a statement about the true value being inside a range around the measured value.

Expected value

Expectation value of a function of a random variable:

$$E[f(X)] = \int_{-\infty}^{\infty} p(X)f(X)$$

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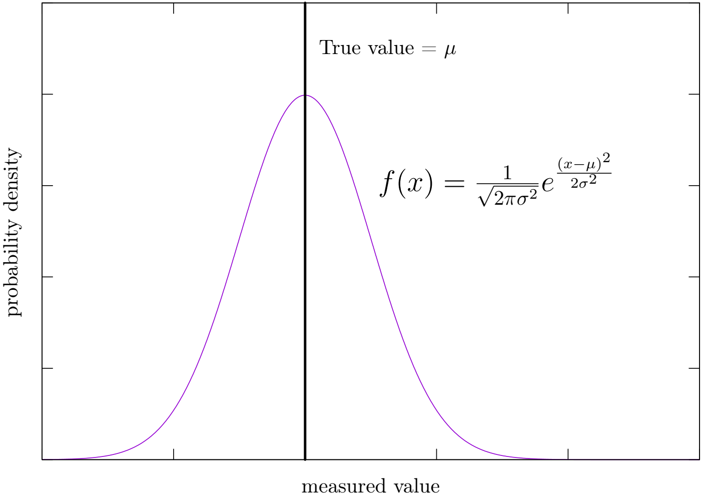
Commonly used definition

- Many error distributions are Gaussians (= normal distribution)



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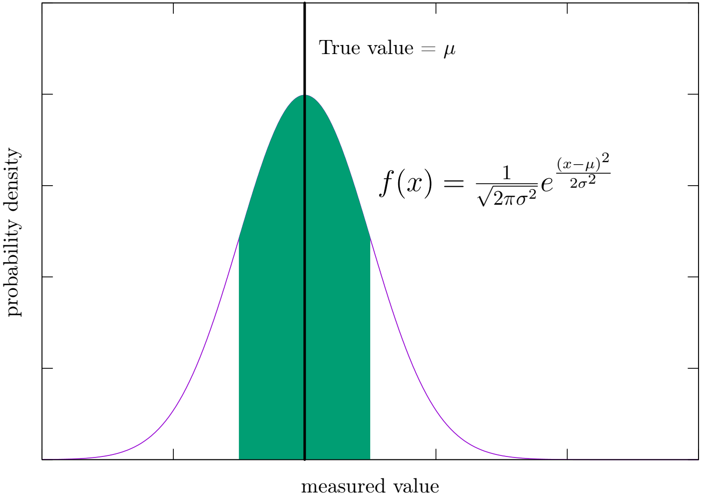

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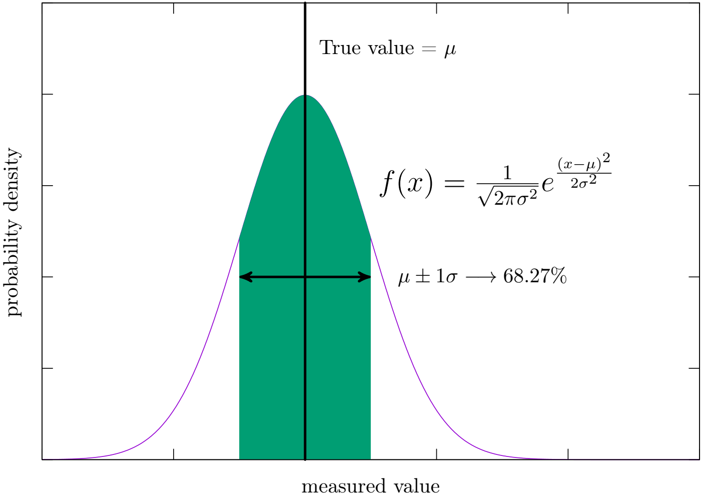

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Taylor around the expected values for X_i:

$$
\begin{aligned}
Z &= f(X_1, X_2, X_3, \ldots) \\
&\approx f(\mu_1, \mu_2, \mu_3, \ldots) + \left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2) + \ldots
\end{aligned}
$$

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\end{aligned}
$$

Expected value:

$$
E(Z) = E\left(f(\mu_1, \mu_2, \mu_3, \ldots)\right) + \left.\frac{\partial f}{\partial X_1}\right|_{\mu} E(X_1 - \mu_1) + \ldots
$$

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$$E(Z) = f(\mu_1, \mu_2, \mu_3, \dots)$$

How do errors propagate? II

$$Z \approx f(\mu_1, \mu_2, \mu_3, \ldots) + \left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2) + \ldots$$

Variance:

$$Z \approx f(\mu_1, \mu_2, \mu_3, \ldots) + \left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2) + \ldots$$

Variance:

$$\begin{aligned} Var(Z) &= E\left((Z - E(Z))^2\right) \\ &= E\left(\left(\left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2) + \ldots\right)^2\right) \end{aligned}$$

How do errors propagate? II

$$Z \approx f(\mu_1, \mu_2, \mu_3, \ldots) + \left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2) + \ldots$$

Variance:

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Multiply out:

$$Var(Z) = E\left(\left(\left.\frac{\partial f}{\partial X_1}\right|_{\mu} (X_1 - \mu_1)\right)^2\right) + E\left(\left(\left.\frac{\partial f}{\partial X_2}\right|_{\mu} (X_2 - \mu_2)\right)^2\right) + \ldots$$

How do errors propagate? III

$$Var(Z) = E\left(\left(\left.\frac{\partial f}{\partial X_1}\right|_{\mu}(X_1-\mu_1)\right)^2\right) + E\left(\left(\left.\frac{\partial f}{\partial X_2}\right|_{\mu}(X_2-\mu_2)\right)^2\right) + \dots$$

How do errors propagate? III

$$Var(Z) = E\left(\left(\left.\frac{\partial f}{\partial X_1}\right|_{\mu}(X_1 - \mu_1)\right)^2\right) + E\left(\left(\left.\frac{\partial f}{\partial X_2}\right|_{\mu}(X_2 - \mu_2)\right)^2\right) + \dots$$

$$Var(Z) = \left.\frac{\partial f}{\partial X_1}\right|_{\mu}^2 E\left((X_1 - \mu_1)^2\right) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu}^2 E\left((X_2 - \mu_2)^2\right) \dots + \text{mix. T.}$$

How do errors propagate? III

$$Var(Z) = E\left(\left(\left.\frac{\partial f}{\partial X_1}\right|_{\mu}(X_1-\mu_1)\right)^2\right) + E\left(\left(\left.\frac{\partial f}{\partial X_2}\right|_{\mu}(X_2-\mu_2)\right)^2\right) + \ldots$$

$$Var(Z) = \left.\frac{\partial f}{\partial X_1}\right|_{\mu}^2 E\left((X_1-\mu_1)^2\right) + \left.\frac{\partial f}{\partial X_2}\right|_{\mu}^2 E\left((X_2-\mu_2)^2\right) \ldots + \text{mix. T.}$$

$$Var(Z) = \sigma_Z^2 = \left.\frac{\partial f}{\partial X_1}\right|_{\mu}^2 \sigma_{X_1}^2 + \left.\frac{\partial f}{\partial X_2}\right|_{\mu}^2 \sigma_{X_2}^2 + \ldots + \text{mix.T.}$$

The mixed terms: Covariance

Let's look close at the mixed terms:

$$\text{mix. T.} = E\left(2\,\frac{\partial f}{\partial X_1}\bigg|_{\mu}(X_1-\mu_1)\,\frac{\partial f}{\partial X_2}\bigg|_{\mu}(X_2-\mu_2)+\ldots\right)=$$

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$$\text{mix.T.} = 2\,\frac{\partial f}{\partial X_1}\bigg|_{\mu}\,\frac{\partial f}{\partial X_2}\bigg|_{\mu}\,E\left((X_1-\mu_1)(X_2-\mu_2)\right)+\ldots$$

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$$\text{mix.T.} = 2\,\frac{\partial f}{\partial X_1}\bigg|_{\mu}\,\frac{\partial f}{\partial X_2}\bigg|_{\mu}\,E\left((X_1-\mu_1)(X_2-\mu_2)\right)+\dots$$

Covariance, a measure how two random variables correlate:

$$cov(X_1, X_2) = E\left((X_1-\mu_1)(X_2-\mu_2)\right)$$

Independent random variables $\longrightarrow cov(X_1, X_2) = 0$

Error propagation for independent variables

$$Var(Z) = \sigma_Z^2 = \left.\frac{\partial f}{\partial X_1}\right|_{\mu}^{2} \sigma_{X_1}^2 + \left.\frac{\partial f}{\partial X_2}\right|_{\mu}^{2} \sigma_{X_2}^2 + \dots$$

$$\sigma_z = \sqrt{\left(\frac{\partial f}{\partial X_1}\sigma_{X_1}\right)^2 + \left(\frac{\partial f}{\partial X_2}\sigma_{X_2}\right)^2 + \dots}$$

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$$\sigma_z = \sqrt{\left(\frac{\partial f}{\partial X_1}\sigma_{X_1}\right)^2 + \left(\frac{\partial f}{\partial X_2}\sigma_{X_2}\right)^2 + \dots}$$

Examples:

- $Z = X + Y \longrightarrow \sigma_Z^2 = \sigma_X^2 + \sigma_Y^2$

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- $Z = X \times Y \longrightarrow \sigma_Z^2 = (\mu_Y \sigma_X)^2 + (\mu_X \sigma_Y)^2$

Electricity: Voltage and Current

To understand a circuit, we need to understand the behavior of two physical quantities:

- Voltage: Formula symbols U,V, rarely E. Voltage is the electrical potential difference between two points. Moving one coulomb (1C) electrical charge to a potential which is 1 Volt (1V) higher requires 1 Joule energy.

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N.B.: Technical current direction = positive current flows from higher potential to lower potential (electrons the other way)

Voltage and Current II

We say:

- We have x Volts voltage drop across this component
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- Through component A flows x amps.
- Into that pin flow x amps.
- Out of that other pin flows y amps.

Energy and Power

- We know: $U = \frac{E}{Q}$

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- And: $Q = I \cdot t$
- So $E = UIt$, or $P = E/t = UI$

Kirchhoff's laws

- The sum of all currents into a point is zero.
  Or: The sum of all currents into a point is equal to the sum of all currents out of a point. (KCL)
- The sum of voltage drops in a loop is zero.
  Or: Things hooked up in parallel have the same voltage. (KVL)

Resistors: Coupling U and I

Materials have a specific resistance, or resistivity ρ.
We can calculate the Resistance of a homogeneous piece as

$$R = l/A \times \rho$$

(N.B.: In general, R and ρ can be functions of time, temperature etc.)

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We can also define a conductivity $\sigma = 1/\rho$ and a conductance $G = 1/R$
Units: $[R] = 1\Omega = 1\text{Ohm}$, $[\rho] = 1\Omega m$, $[G] = 1S = 1\text{Siemens}$

Ohm's law

The ideal resistor is "ohmic", that is, R is constant, and voltage and current are following Ohm's law:

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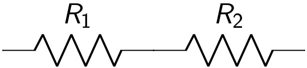
This means

$$P = RI^2 = U^2/R$$

This is the power which is converted to heat inside the resistor.

Resistors in series and parallel



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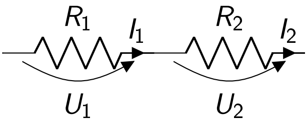

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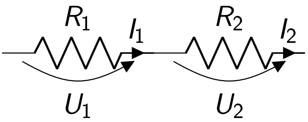

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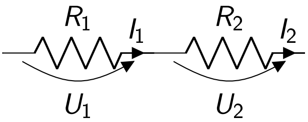

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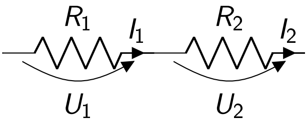

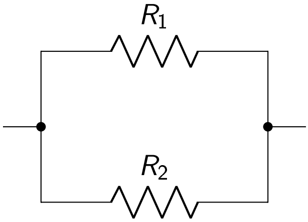

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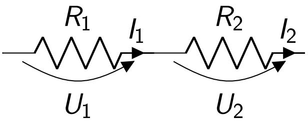

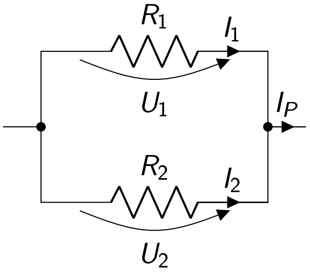

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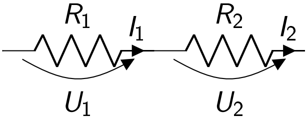

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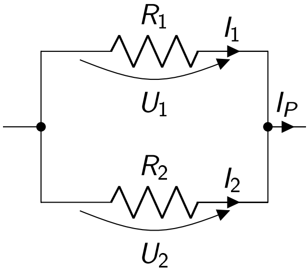

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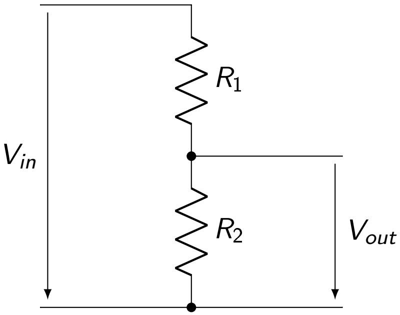
Equivalent resistance is $R_{eq} = U/I_P = \frac{1}{1/R_1 + 1/R_2}$

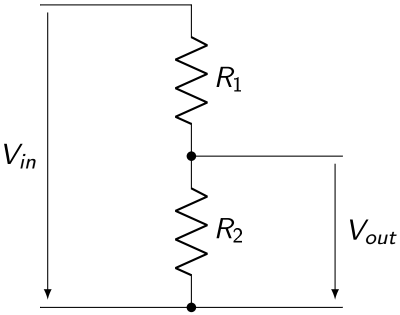
Or: $G_p = G_1 + G_2$

Voltage divider



What is V_{out} as function of V_{in}?

Voltage divider



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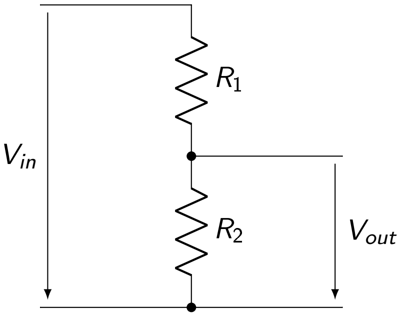

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Ohms law: $V_{out} = R_2 I = V_{in} \frac{R_2}{R_1+R_2}$

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

DMM and internal resistance: Voltage measurement

An ideal voltmeter

- Infinite resistance
- Therefore no current through voltmeter
- Will not influence a circuit under test

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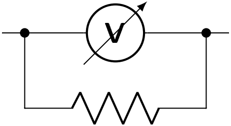

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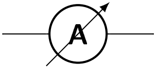

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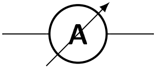

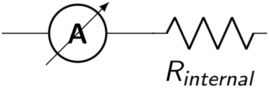

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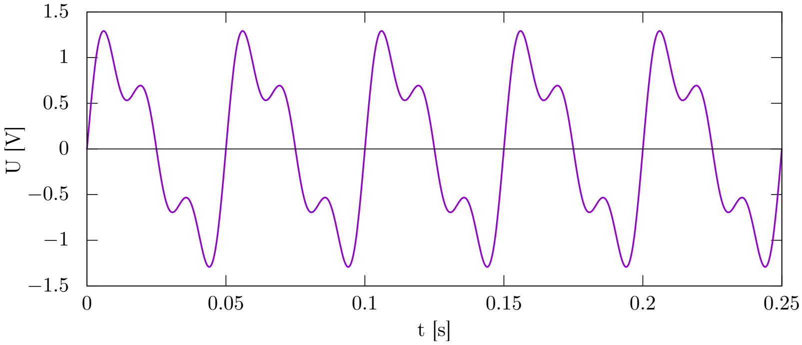
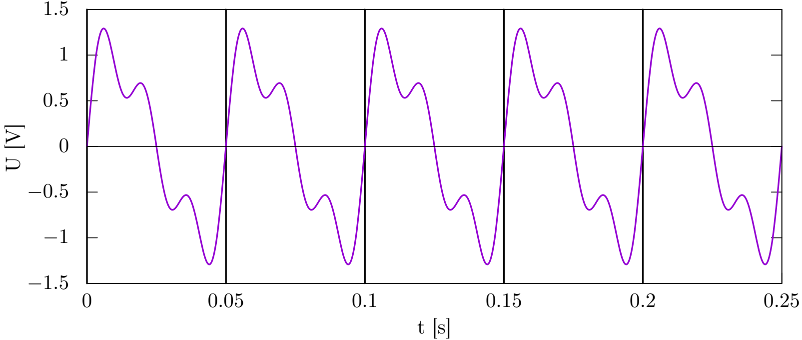
Periodic signals



- A signal is periodic if it repeats itself after a fixed time T, the period

Periodic signals



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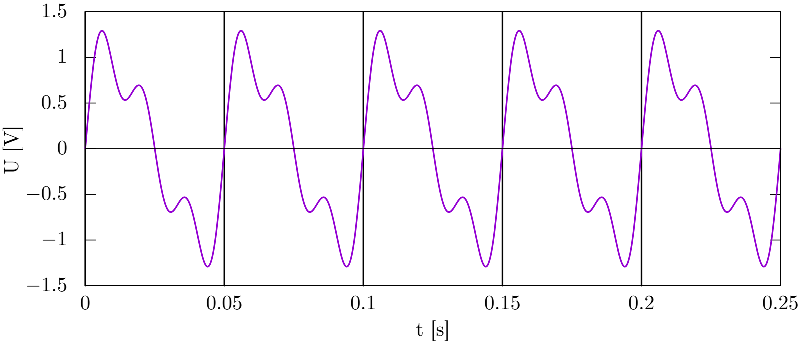

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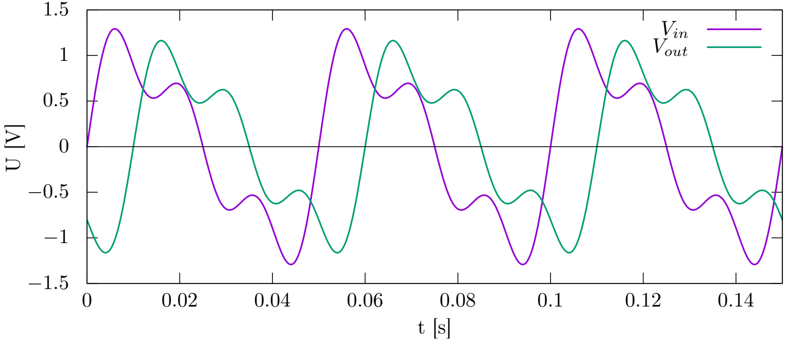
- Here, $T = 0.05s$.
- The signal has a frequency $f = 1/T = 20Hz$ (Hertz)

Phase



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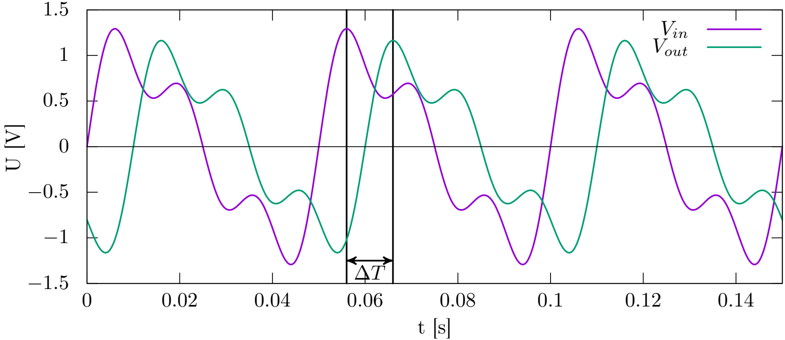
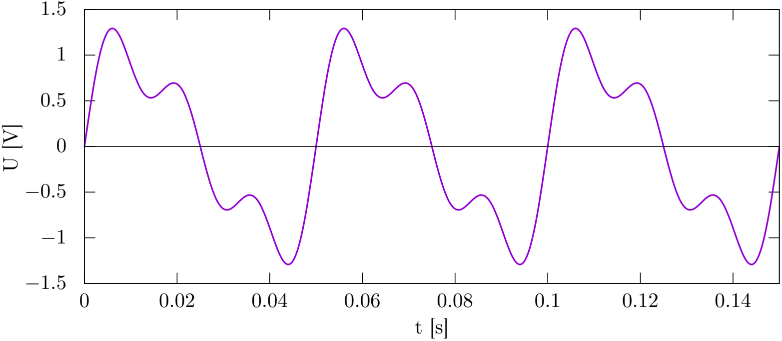


- Two signals of the same shape and frequency will have a phase between them.
- Here, $\Delta T = 0.01s$. The phase is $360^\circ \frac{0.01}{0.05} = 72^\circ$

Amplitudes



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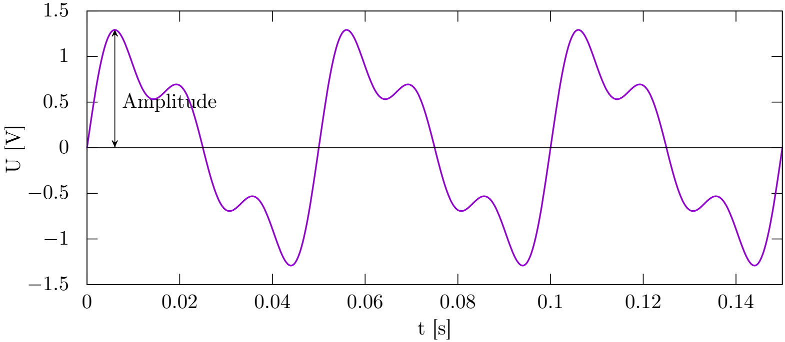

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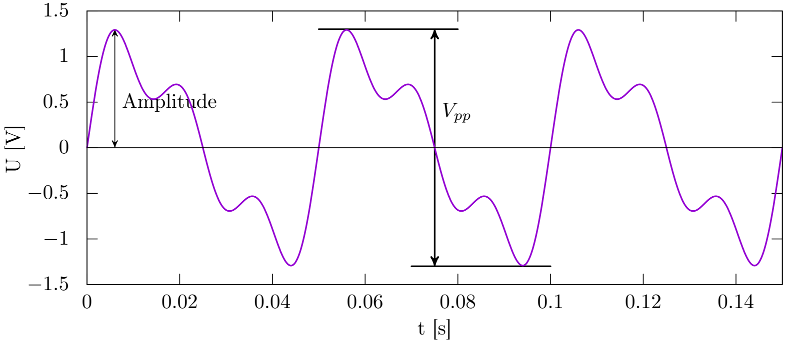

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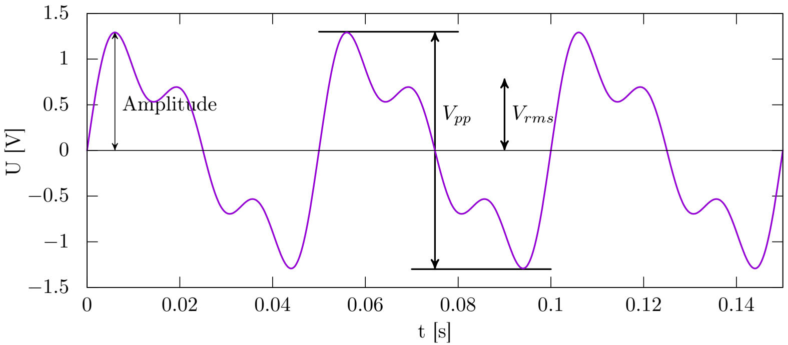

- Amplitude: $A = \max(|U(t)|)$
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- root-mean-square voltage $V_{rms} = \sqrt{\frac{1}{T}\int_0^T U^2(t)dt}$

Sine waves

General sine wave:

$$U(t) = A \cdot \sin(2\pi f t + \phi)$$

- Frequency f
- Phase ϕ (and the phase difference between two sines is $\phi_2 - \phi_1$)
- Amplitude A, $V_{pp} = 2A$
- $V_{rms} = \sqrt{1/T \int_0^T A^2 \sin^2(2\pi t/T + \phi) dt} = \sqrt{\frac{1}{2}} A$

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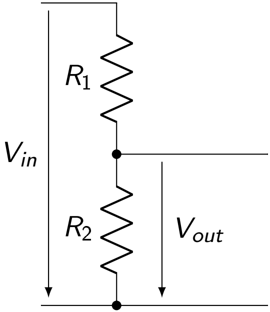
- Sometimes used as absolute measurements:
    - 0 dBm = 1 mW (in a specified load, 50Ω or 600Ω)
    - 0 dBV = 1 V(rms)

Loaded voltage divider



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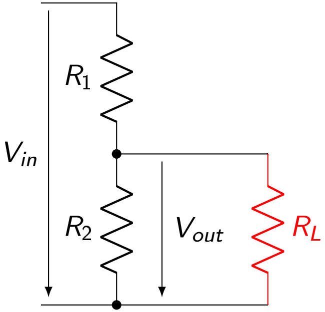

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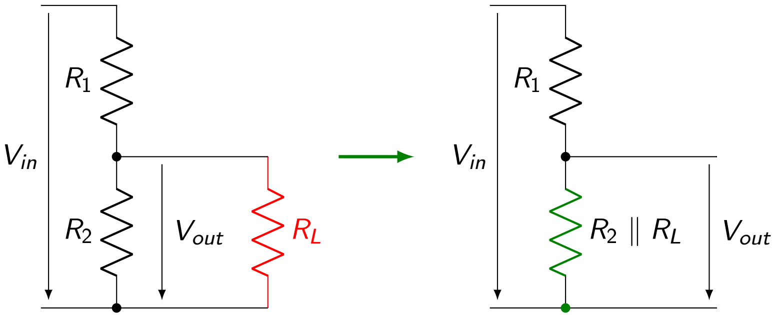

- Calculate

$$R_2 \parallel R_L = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{R_L R_2}{R_L + R_2}$$

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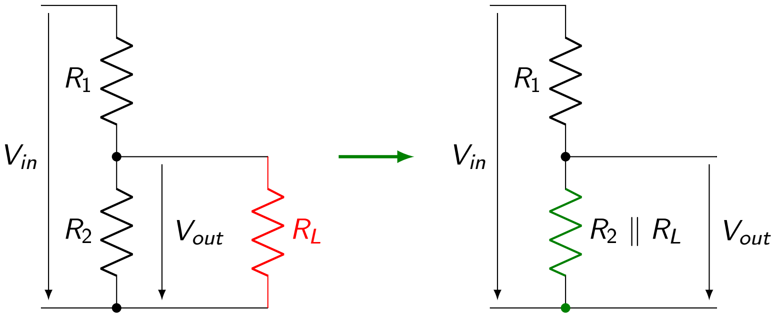

- Calculate

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- Put into formula for divider:

$$\frac{V_{out}}{V_{in}} = \frac{\frac{R_L R_2}{R_L + R_2}}{R_1 + \frac{R_L R_2}{R_L + R_2}}$$

Loaded voltage divider II

$$\frac{V_{out}}{V_{in}} = \frac{\frac{R_L R_2}{R_L + R_2}}{R_1 + \frac{R_L R_2}{R_L + R_2}}$$

$$= \frac{R_2}{R_1 + R_2} \frac{R_L}{R_L + \frac{R_1 R_2}{R_1 + R_2}}$$

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- If $R_L \gg R_1 \parallel R_2$, Voltage divider will look like a voltage source with V_{out} given by unloaded divider

Thévenin theorem

Any two-terminal network of resistors and voltage resources is equivalent to single resistor R_{Th} in series with a single voltage source V_{Th}.

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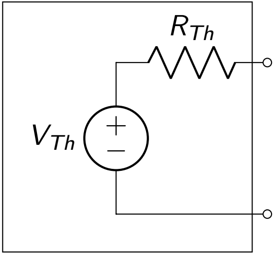
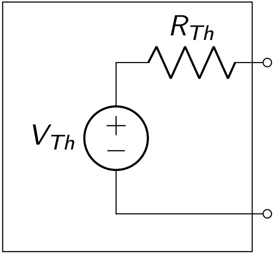
How can me measure/calculate them?

Let's assume we have a black box with two connections. We know that there are only batteries and resistors inside. So we can assume there is only one ideal voltage source and one series resistor inside:



Thévenin theorem II



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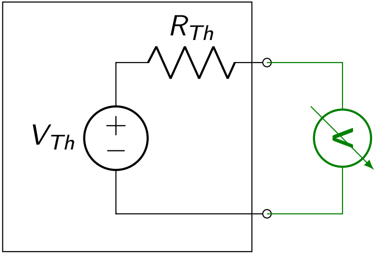

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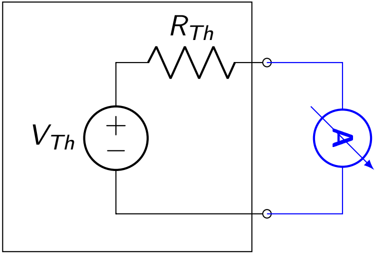
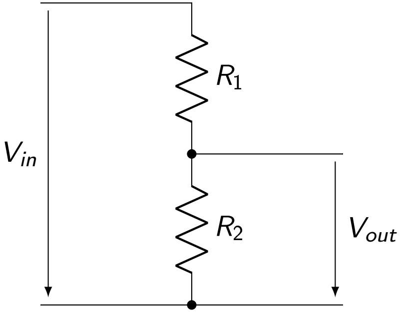


- We can get the voltage by measuring the unloaded voltage. No current flows, so there is no drop over R_{Th}, so $V_{\text{measured}} = V_{Th} = V(\text{open circuit})$
- We can measure the current when we short the two poles. Then, $V_{Th} = V_{R_{th}}$ and I_{measured} is $I_{R_{Th}}$, so $R_{Th} = \frac{V(\text{open circuit})}{I(\text{short circuit})}$

Let's try: Thévenin theorem and the voltage divider I



- We already know the open circuit voltage:

$$V_{Th} = V_{out} = V_{in} \frac{R_2}{R_1 + R_2}$$

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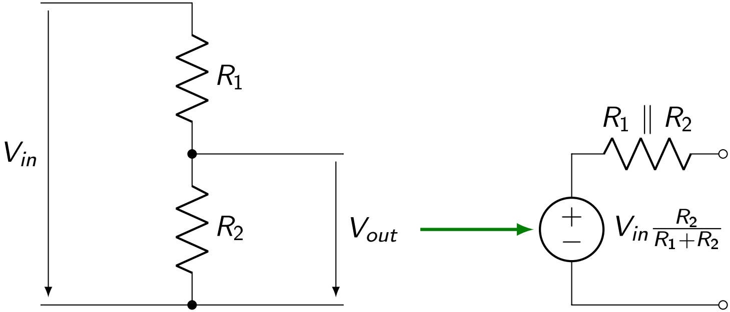

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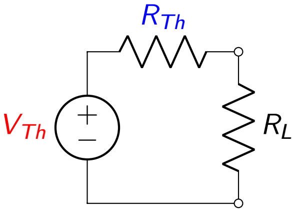
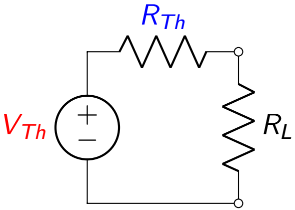
- Short circuit current: R_2 is shorted out, so we have $I = \frac{V_{in}}{R_1}$.

$$R_{Th} = \frac{R_1 R_2}{R_1 + R_2} = R_1 \parallel R_2$$

Let's try: Thévenin theorem and the voltage divider II



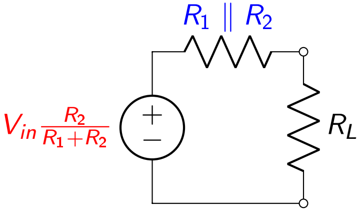
Let's try: Thévenin theorem and the voltage divider II



- This is a voltage divider:

$$V_L = V_{Th}\frac{R_L}{R_{Th} + R_L}$$

Let's try: Thévenin theorem and the voltage divider II



- This is a voltage divider:

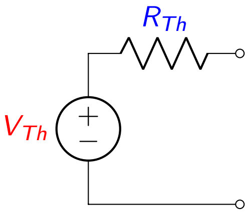
$$V_L = V_{Th}\frac{R_L}{R_{Th}+R_L}$$

-

$$V_L = V_{in}\frac{R_2}{R_1+R_2}\frac{R_L}{R_L+R_1 \parallel R_2}$$

Norton's theorem

We can also transform a voltage source with a series resistance to a current source with a parallel resistance:



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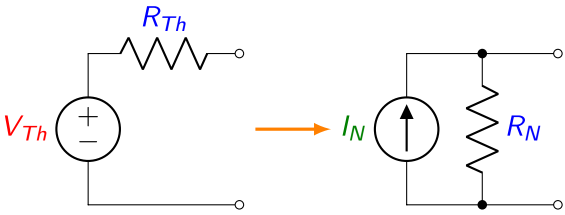

$$I_N = I(\text{short circuit}), \quad R_N = R_{Th} = \frac{U(\text{open circuit})}{I(\text{short circuit})}$$

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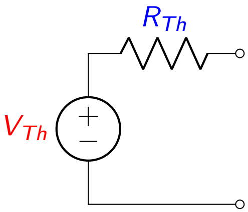

$$I_N = I(\text{short circuit}), \quad R_N = R_{Th} = \frac{U(\text{open circuit})}{I(\text{short circuit})}$$

Every two-pole network of resistors, voltage and current sources can be converted to a network of either

- Voltage source + series resistor
- Current source + parallel resistor

Alternative way to find R_{Th}

- Replace all voltage sources with shorts

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- Replace all voltage sources with shorts
- Replace all current sources with open connections
- The network is now purely made from resistors. Use the formulas for parallel and serial resistors to find R_{Th}