

Faraday cage  
electrostatic shielding cast as  
a constrained optimization  
problem, and how Feynman  
was “wrong.”

# 1st year physics with MATLAB

*Duncan Carlsmith, SERC, Oct 2020*





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# 1st-year computational curriculum

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- ❖ **What:** Physics 247-8, Introductory Physics using MATLAB, 5-cr, 2-sem, automatic honors, for ~80 first year Physics, Astronomy, and Applied Math Engineering and Physics (AMEP) students
- ❖ **How:** Tutorials with Live Scripts and integrated MATLAB analysis of laboratory data.
- ❖ **Topics:** Modeling, simulation, visualization, signal analysis, numerical techniques, symbolic algebra, intermediate and advanced mathematics, probability and statistics, and statistical analysis and interpretation of data.
- ❖ **Why:** A foundation for computation throughout the undergraduate physics curriculum.



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# Learning goals

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- ❖ Understand and apply principles of physics...
- ❖ Innovate and apply.
- ❖ Own measurements and analysis.
- ❖ Understand and apply hardware and software technologies.
- ❖ Discover and use current research and open data.
- ❖ Think computationally and scientifically (model, test...).
- ❖ Collaborate and communicate!



# 1st semester syllabus

Week	Mon	MATLAB assignment	Lab M 1:20 601, T 1:20 602, W 2:25 603, R 1:20 604 CH4136	Wed	Disc: W 1:20, 2:25 R 1:20, 2:25 Chamberlin 2104	Fri
		Tutorial	Lab			
1	no class	MATLAB onramp, MATLAB Getting Started with MATLAB, MATLAB Introduction to MATLAB, MATLAB Image processing	No lab UW Instruction begins	Measurement, Ch. 1	Ch. 1,2	Motion Along a Straight Line Ch. 2
2	Vectors Ch. 3	MATLAB Concepts in probability,	Computer vision	Motion in 2 and 3 dimensions Ch. 4	Ch. 3,4	Motion in 2 and 3 dimensions Ch. 4
3	Force and Motion I Ch. 5	MATLAB quiver plot, MATLAB More concepts in probability	Acceleration and free fall	Force and Motion II Ch. 6	Ch. 5,6	Force and Motion II Ch. 6
4	Kinetic Energy and Work Ch 7	No MATLAB	No lab	Kinetic Energy and Work Ch 7	Ch. 6,7	Exam 1, CH1-6
5	Potential Energy and Energy Conservation Ch. 8	MATLAB Curve fitting	Computation and modeling	Potential Energy and Energy Conservation Ch. 8	Ch. 8,9	Center of Mass and Linear momentum Ch. 9
6	Center of Mass and Linear Momentum Ch. 9	MATLAB StackedBallCollisions	Inertial sensors	Relativity Ch. 37	Ch. 37	Relativity Ch. 37
7	Quarks, Leptons, and the Big Bang Ch. 44	MATLAB debugging	Particle physics	Quarks, Leptons, and the Big Bang Ch. 44	Ch. 44	Rotation Ch. 10
8	Rotation Ch. 10	No MATLAB	No lab, formal lab report 1 due	Rolling, torque, and angular momentum Ch. 11	Ch. 9,10	Exam 2, CH6-9,37,44
9	Rolling, torque, and angular momentum Ch. 11	MATLAB Black Holes	Cosmic muons and radioactivity	Equilibrium Ch. 12	Ch. 11,12	Gravitation Ch. 13
10	Gravitation Ch. 13	MATLAB Ephemerides	Asteroids and bombs	Fluids Ch. 14	Ch. 13,14	Fluids Ch. 14
11	Oscillations Ch. 15	MATLAB Fit parametric curves	Simple harmonic oscillator and resonance	Oscillations Ch. 15	Ch. 15	Waves I Ch. 16
12	Waves I Ch. 16	No MATLAB	Standing waves on a string	Waves II Ch. 17	Ch. 16,17	Exam 3, CH10-15
13	Waves II Ch. 17	No MATLAB	No lab, formal lab report 2	Temperature, Heat and the first law of	Thanksgiving	Thanksgiving
14	Temperature, Heat and the first law of Thermodynamics	MATLAB LIGO Analysis	Acoustics and Doppler shift	The Kinetic Theory of Gases Ch. 19	Ch. 18,19	The Kinetic Theory of Gases Ch. 19
15	Entropy and the 2nd Law of Thermodynamics	MATLAB Exoplanets	No lab	Entropy and the 2nd Law of Thermodynamics	Ch. 20	Exam study period
						Exam 4, Ch 16-20 12/12/20, Saturday, 10:05AM - 12:05PM



## 2nd semester syllabus

Week	Mon	MATLAB lab	Lab M or T 1:20-4:15 W 2:25-5:20, CH3136 Prelab	Wed	Disc: R 1:20 2:25, 3:30	Fri
1	no class	<b>Tutorial</b>	<b>Lab</b>	Coulomb's Law, Ch. 21	Group and challenge	Coulomb's Law, Ch. 21
2	Electric Fields, Ch. 22	MATLAB Vectors and rotations	Electric Fields	Electric Fields, Ch. 22	Group and challenge	Gauss' Law, Ch. 23
3	Gauss' Law, Ch. 23	Matlab Electric fields and potentials	Magnetic field map	Electric Potential, Ch. 24	Group and challenge	Electric Potential, Ch. 24
4	Capacitance, Ch. 25	MATLAB Electrostatic induction (and the	Oscilloscopes and RC circuits	Capacitance, Ch. 25	Group and challenge	Current and Resistance, Ch. 26
5	Current and Resistance, Ch. 26	MATLAB Method of images	Electron charge to mass ratio	Circuits, Ch. 27	Group and challenge	Circuits, Ch. 27
6	Magnetic Fields, Ch. 28	MATLAB Vector Calculus	<b>No lab</b>	Magnetic Fields, Ch. 28	Group and challenge	<b>Exam 1, CH 21-26</b>
7	Magnetic Fields Due to Currents,	MATLAB Magnetic field of a coil	Magnetic induction	Magnetic Fields Due to Currents, Ch.	Group and challenge	Induction and Inductance, Ch. 30
8	Induction and Inductance, Ch. 30	MATLAB World's simplest electric train	LRC Circuit and Resonance	Electromagnetic Oscillations and	Group and challenge	Electromagnetic Oscillations and
9	<b>Spring Break</b>			<b>Spring Break</b>	<b>Spring Break</b>	<b>Spring Break</b>
10	Maxwell's Equations; Magneti	MATLAB ABCD Matrices	Mirrors and lenses	Maxwell's Equations; Magnetis	Group and challenge	Electromagnetic Waves, Ch. 33
11	Electromagnetic Waves, Ch. 33	MATLAB Diffraction	Optical Instruments	Images, Ch. 34	Group and challenge	Images, Ch. 34
12	Interference, Ch. 35	MATLAB Monte Carlo methods	<b>No Lab</b>	Interference, Ch. 35	Group and challenge	<b>Exam 2, CH27-32</b>
13	Diffraction, Ch. 36	MATLAB Bound states	Diffraction and Interference	Diffraction, Ch. 36	Group and challenge	Photons and Matter waves, Ch. 38
14	Photons and Matter waves, Ch.	MATLAB Quantum mechanics	Balmer Series	More About Matter waves, Ch. 39	Group and challenge	More About Matter waves, Ch. 39
15	All About Atoms, Ch. 40	MATLAB Electric field of an accelerated charge - 3d	Speed of light	All About Atoms, Ch. 40	Group and challenge	All About Atoms, Ch. 40



# Tutorial: Exoplanets

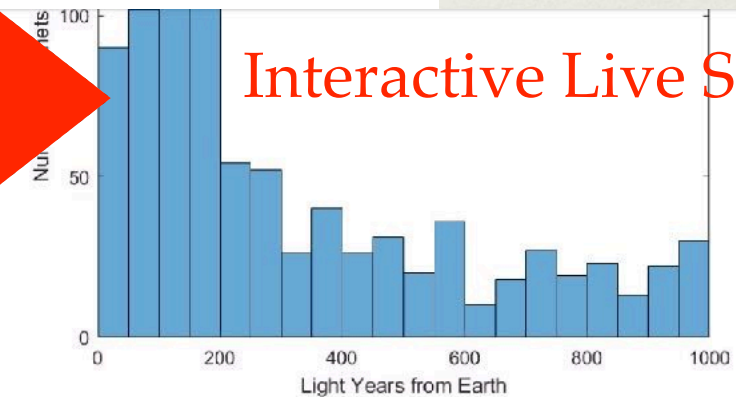
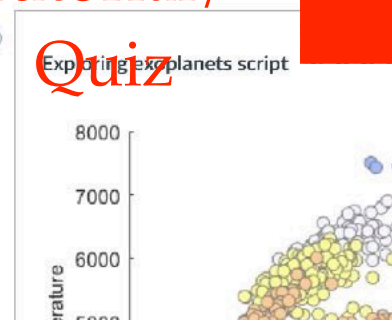
Physics 248, Week 1

The screenshot shows the Physics 248 course website. The left sidebar contains navigation links: Home, Announcements, Modules (highlighted), Grades, McGraw-Hill Connect, People, Piazza, Syllabus, Chat, Google Drive, Office 365, Discussions, Assignments, Collaborations, Pages, and Quizzes. The main content area is titled 'Welcome to Physics 248' and shows 'Week 1' with a list of items: Lecture, Electrostatics, CH21 Summary and exam guide, Lecture review: Electrostatics (Jan 27 | 2 pts), Phys248-17-ProbSolutions-Chap21.pdf, MATLAB, and MATLAB Exoplanets (Jan 27 | 60 pts). A large red arrow points from the 'MATLAB Exoplanets' link to the 'Tutorial/Quiz' section.

The 'Quiz Instructions' page for the MATLAB Exoplanets module. It states: 'Started: May 1 at 6:52pm'. The title is 'Quiz Instructions'. The section is 'MATLAB Exoplanets'. The text reads: 'Extrasolar planets (exoplanets) are the focus of a relatively recent exciting research area. It is now established that planetary systems are ubiquitous. Planets, invisible to the eye, orbit the visible stars nearest to Earth. The study of such systems will illuminate the origin of our own planetary system and the origin of life itself, and potentially even provide evidence for extraterrestrial life. In this exercise, you will use examine current exoplanet data available at the NASA Exoplanet archive (<https://exoplanetarchive.ipac.caltech.edu/index.html>). MATLAB supports a data structure called a table (<https://www.mathworks.com/help/matlab/ref/table.html>) for columnar data as you might encounter in a spreadsheet. The exercise will introduce several ways to create and manipulate such tabular data. Additionally, the use of application programming interfaces for rapid access to such data will be illustrated.'

Tutorial/  
Quiz

Interactive Live Script



Where is the nearest exoplanet?

```
idx = find(exoplanets.st_distance == min(exoplanets.st_distance))
name = char(exoplanets{idx, 'st_name'}) ;
dist = 3.26*exoplanets{idx, 'st_distance'};
fprintf('The nearest exoplanet is around %s, %4.2f light years f
```

The nearest exoplanet is around Proxima Cen, 4.21 light years f

...at types of stars have  
The exoplanet archive has  
information about the host star's spectral type for about 940 of the 3400  
entries. We can get a sense of the distribution of star types from a scatter

Computational  
techniques

- ❖ This example: Access NASA data via direct download, and using an API within MATLAB, to characterize exoplanets and their host systems.

wedded  
with science



Fuse learning about current, voltage, resistance, permanent magnetism, Biot-Savart with mechanics, Lorentz force, friction, eddy current losses, and computation, all in one cool toy


# Tutorial: World's simplest electric train

Study  
peer-reviewed  
article (Am. J.  
Physics).

Run  
interactive live  
script.

Solve  
multidimensional nonlinear  
constrained optimization  
problem.

Create symbolic speed  
objective function.



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Started: May 1 at 9:07pm


Quiz Instructions

MATLAB World's simplest electric train



The "world's simplest electric train" is an engaging simple motor that illustrates the principles of electromagnetic theory. Watch the video [Simple Electric Train](#)





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World's simplest electric train

G. Criedo, and N. Alamo

Citation: American Journal of Physics 84, 21 (2016)  
View online: <https://doi.org/10.1119/1.4933295>  
View Table of Contents: <http://ajpt.scitation.org/>  
Published by the American Association of Physics Teachers

Articles you may be interested in  
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Rotating saddle trap as Foucault's pendulum  
American Journal of Physics 84, 26 (2016); 10.1119/1.4933295  
The homopolar motor: A true relativistic engine  
American Journal of Physics 84, 26 (2016); 10.1119/1.4933295



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Download and install in your MATLAB path the analysis Live Script [WorldsSimplestElectricTrain.mlx](#) ([WorldsSimplestElectricTrain.pdf](#))





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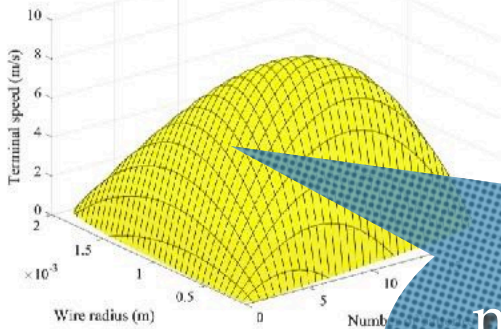
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Terminal speed dependence on wire radius and no. of batteries



Plot terminal speed versus the remaining parameters nb and rw as a function of the solution.

```
figure
fcontour(f, range, 'Levellist', [8:10])
zlim([0 10])
xlabel('Number of batteries'); ylabel('Wire radius (m)'); zlabel('Terminal speed (m/s)')
hold on; plot(sol.nb, sol.rw, 'ro', 'LineWidth', 2); hold off
legend('Velocity contours', 'Maximum')
```



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or long enough.

Important design optimization formula

$$v = \frac{V}{C} - \frac{(R \cdot g \cdot \mu_0 \cdot C^2) \cdot R \cdot t}{2 \cdot B \cdot m \cdot r \cdot s \cdot e}$$
$$v = \frac{g \cdot \mu_0 \cdot r \cdot s^2 \cdot \left( \frac{8 \cdot r \cdot h \cdot m \cdot \pi \cdot m^3}{3} + m \cdot b \cdot n \right) \cdot \left( R \cdot c \cdot n + R \cdot b \cdot n + \frac{2 \cdot r \cdot c \cdot h \cdot w \cdot (2 \cdot m + l \cdot b \cdot n)}{r \cdot w^2 \cdot s} \right)}{4 \cdot B \cdot m \cdot r \cdot s^2 \cdot \pi^2 \cdot \sigma^2}$$

where

$$\frac{r \cdot c^3}{l \cdot h \cdot b \cdot n^2 + r \cdot c^2} = 1$$

A plus 2+1=3 washers+2 spherical magnets . Panasonic AA bat. 14.5 mm OD , mass 27.9 gm

ity of vacuum

umber of turns in train length

ength between contact points so 1\_bat+2\*L\_washers+2\*R\_bat

agnetic moment of spherical magnet

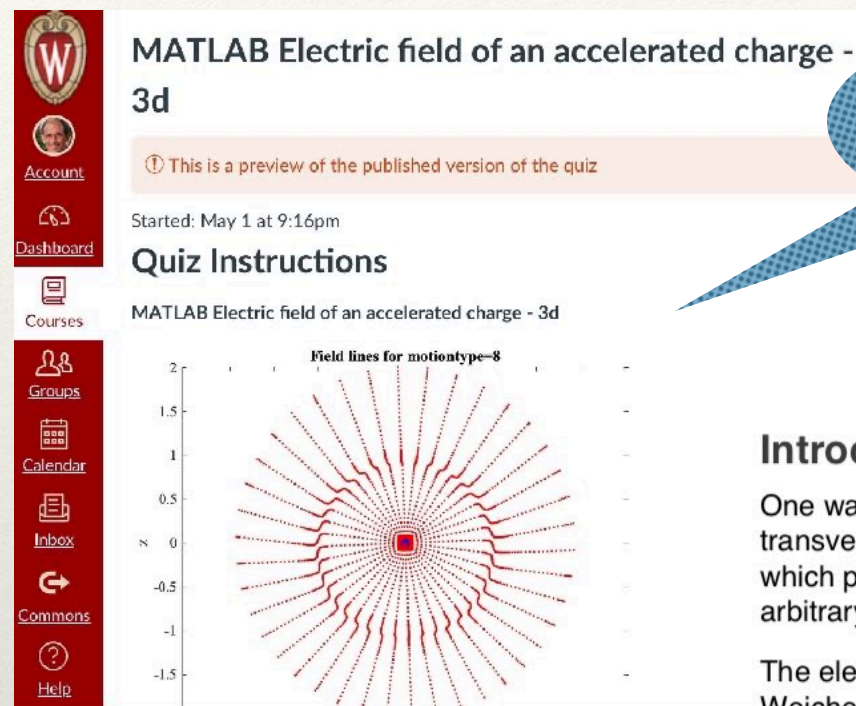
us = magnet radius

tion seems high. Perhaps this concerns the wide pitch of the coil appropriate to a smooth plating alloy on plate of wire material.



Visualize electromagnetic radiation as transverse component of wiggles  
in electric field lines flying at light speed.

# Tutorial: Radiation from an accelerated charge



The image shows the MATLAB interface for the 'Electric field of an accelerated charge - 3d' script. On the left is a red sidebar with icons for Account, Dashboard, Courses, Groups, Calendar, Inbox, Commons, and Help. The main window displays the title 'MATLAB Electric field of an accelerated charge - 3d' and a message: 'This is a preview of the published version of the quiz'. Below this, it says 'Started: May 1 at 9:16pm' and 'Quiz Instructions'. The main plot area shows 'Field lines for motiontype=8', which are red lines radiating from a central point, representing the electric field of an accelerated charge.

Tutorial

## ElectricFieldOfAcceleratedCharge3d

Finds electric field lines of a point charge undergoing arbitrary motion in three dimensions

Author: D. Carlsmith

### Table of Contents

Introduction.....	
Exploration of functions.....	
motion, particlepath, particle, and displaymotion functions.....	
Try this: Understand particle and particle path functions.....	
Try this: Choose another motion and display it.....	
Anonymous functions and use of fzero to find retarded time.....	
Try this: Understand retarded time function calls.....	
Retarded time for uniform motion.....	
Try this: Vary the motion to increase the particle speed and e.....	
for uniform motion.....	
Electric field lines.....	

Relativistic EM  
theory lesson

Computation  
lesson

## Introduction

One way to develop an intuition about electromagnetic radiation is to visualize the transverse component of ripples in electric field lines about a charge which propagate at light speed away from the charge. This script calculates the electric field for arbitrary motion.

The electric field of a point charge  $q$  in arbitrary motion in vacuum in SI units is given by the Liénard-Wiechert formula which derives from Maxwell's equations:

$$\mathbf{E}(\mathbf{x}, t) = \left\{ \frac{q}{(1 - \mathbf{n} \cdot \mathbf{v})^3} \left\{ \frac{1 - v^2}{R^2} (\mathbf{n} - \mathbf{v}) + \frac{\mathbf{n} \times [(\mathbf{n} - \mathbf{v}) \times \dot{\mathbf{v}}]}{R} \right\} \right\}_{\text{retarded}}$$

## Anonymous functions and use of fzero to find retarded time

This script uses several anonymous functions defined using the @ symbol. See [https://www.mathworks.com/help/matlab/matlab\\_prog/anonymous-functions.html](https://www.mathworks.com/help/matlab/matlab_prog/anonymous-functions.html) for an introduction. Let's try to see how these work.

Define a function of three arguments returning a time interval  $t$  minus a retarded time  $t_r$  minus the light travel time from the particle position at the retarded time to a position  $\mathbf{x}$  at time  $t$  for a uniform motion.

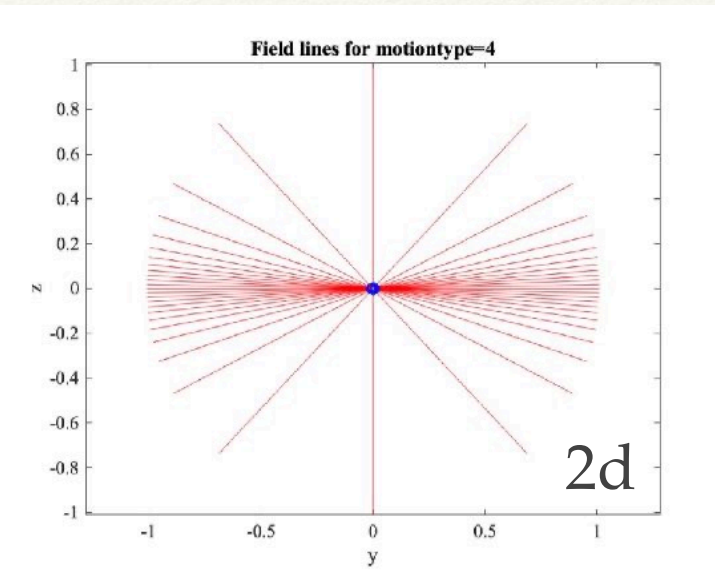
```
motiontype=2;  
particlepath=motion(motiontype);  
mytimedifferencefunction = @(t,tr,x)...  
    ( t-tr-norm(x-particle(tr,particlepath)) );
```

Live script riddled  
with "Try this"s

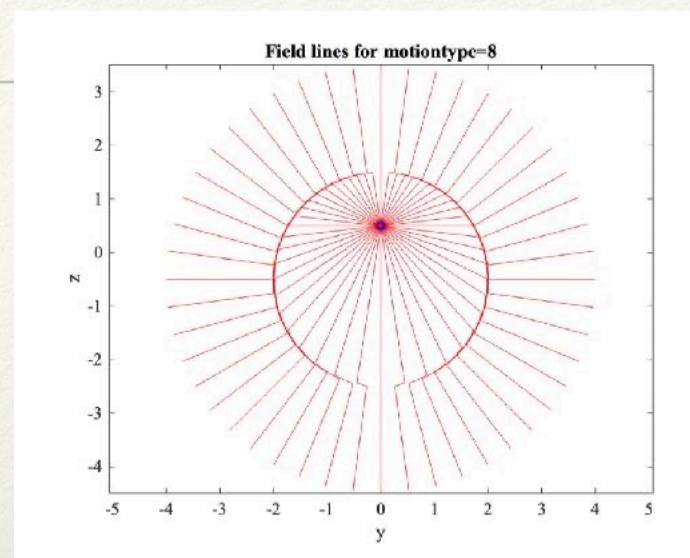
- ❖ Find retarded time for any observation point and arbitrary 3d parametrized motion.
- ❖ Solve system of ode's for field lines using LW formula given retarded time.



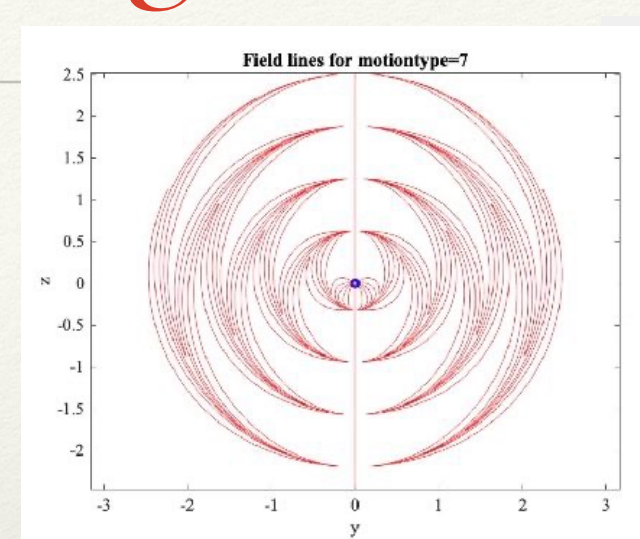
# Electric field lines of charge in motion in 3d



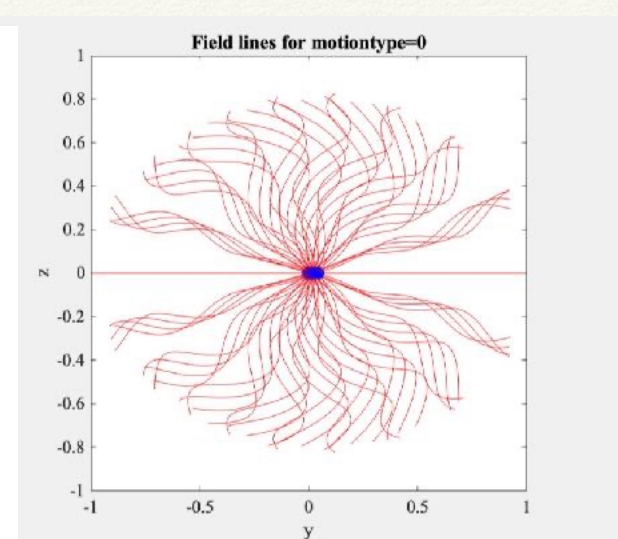
Relativistic uniform motion



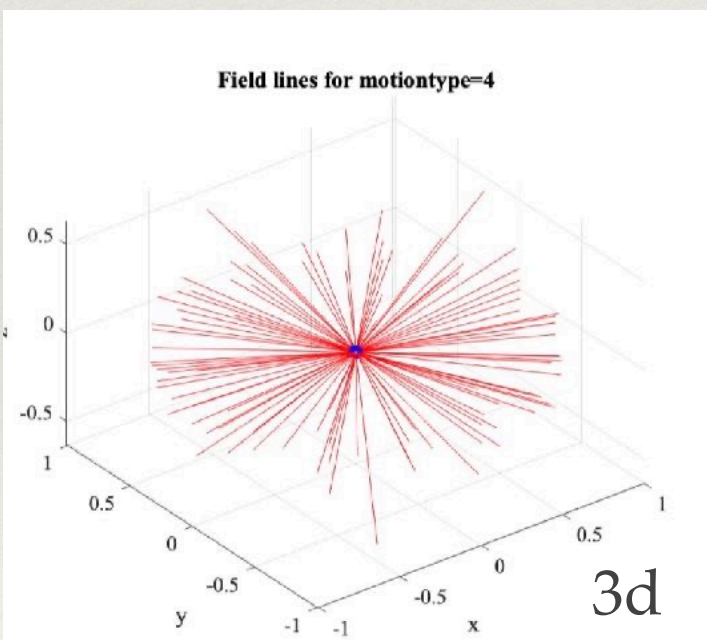
Relativistic impulse



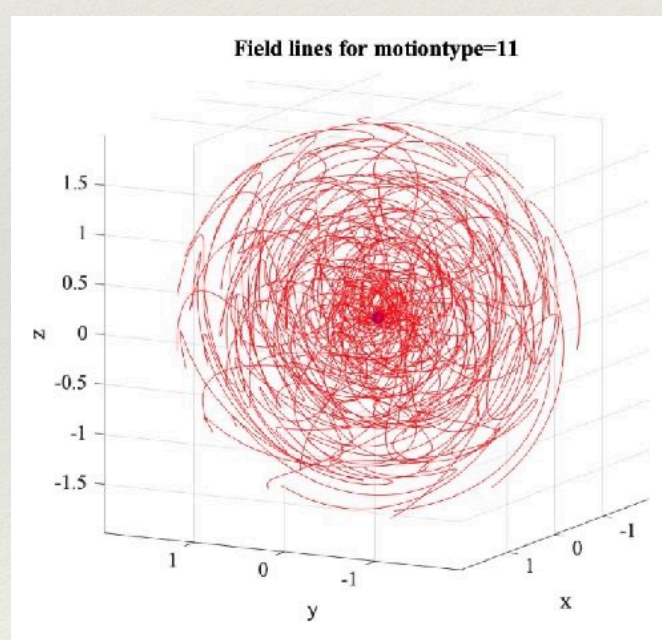
Relativistic oscillator



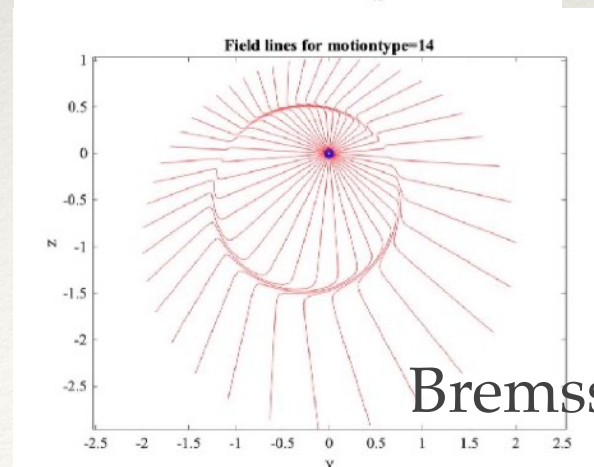
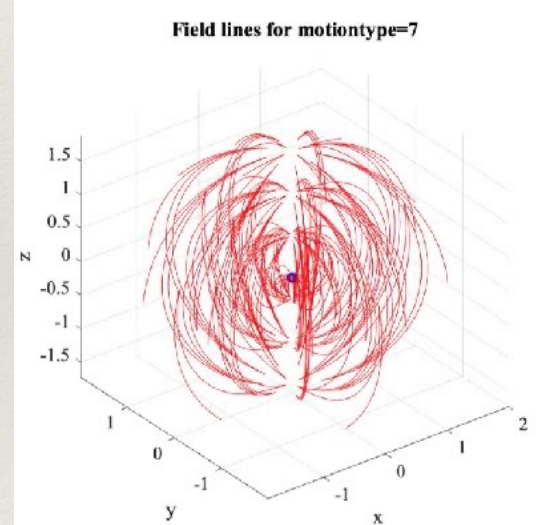
Movies



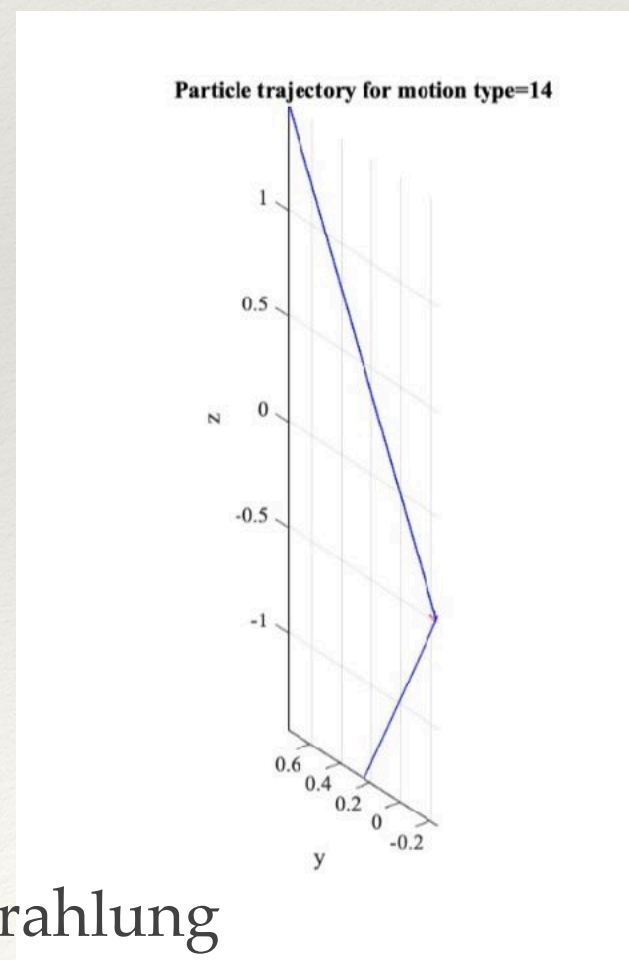
Relativistic uniform motion



Circular motion 3d



Bremsstrahlung



❖ Sweet!



# Prelab and Lab : Inertial sensors

Prelab and lab hyperlinked quizzes.  
All submissions are electronic and electronically assessed.

## Inertial sensors lab

⚠ This is a preview of the published version of the quiz

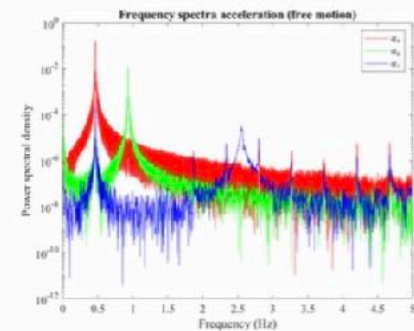
Started: Oct 18 at 8:38pm

## Quiz Instructions

### Inertial sensors lab

Mobile phone inertial acceleration sensor on inertial forces. This lab is an opportunity to use mobile phone sensor data to explore motion. In the pre-lab, the motion of a cellphone suspended by its charging cable is studied. In this lab, the data analysis is extended and a number of additional projects are suggested.

Your group must pick at least one of the suggested experiments, collect data with a sensor data collections app, analyze your data with MATLAB, and submit here a pdf of your



Wow! Look how sharp those peaks are. One sees the swing in  $a_x$  then the up-down at twice the frequency in the  $a_y$ . The bar rocking frequency seen in  $a_z$  seems to be around 2.5 Hz.

```
% figure('Name','Frequency spectra gyro(free motion)');  
% semilogy(wfreq_win,wox_win,'red');  
% hold on  
% semilogy(wfreq_win,woy_win,'green');  
% semilogy(wfreq_win,woz_win,'blue');  
% title('Frequency spectra gyro(free motion)');  
% h = legend('Sw_x$','Sw_y$','Sw_z$');  
% set(h,'interpreter','latex');  
% xlabel('Frequency (Hz)');  
% ylabel('Power spectral density');  
% h = legend('Sw_x$','Sw_y$','Sw_z$');
```

Plot the angular velocity frequency spectra.

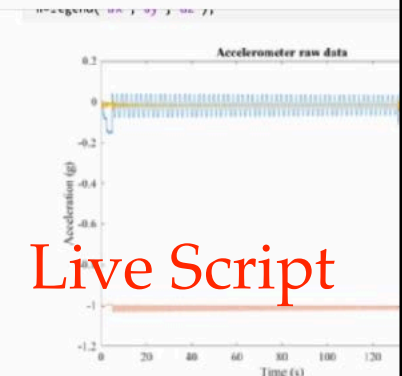
```
figure('Name','Frequency spectra gyro(free motion)');  
semilogy(wfreq_win(wfreq_wincs),wox_win(wfreq_wincs),'red');  
hold on  
semilogy(wfreq_win(wfreq_wincs),woy_win(wfreq_wincs),'green');  
semilogy(wfreq_win(wfreq_wincs),woz_win(wfreq_wincs),'blue');  
title('Frequency spectra gyro(free motion)');  
h = legend('Sw_x$','Sw_y$','Sw_z$');  
set(h,'interpreter','latex');  
xlabel('Frequency (Hz)');  
ylabel('Power spectral density');  
h = legend('Sw_x$','Sw_y$','Sw_z$');
```



AT&T Wi-Fi 8:41 PM 96%

## Quiz Preview

Done



Live Script

Very nice! The phone goes up and down ( $a_y$ ) twice every period of gravity all day swinging or not.  $a_x$  should vanish, but it oscillates a bit on the knife-edge.

Let's have a look at the gyro.

figure

AT&T Wi-Fi 8:41 PM 96%

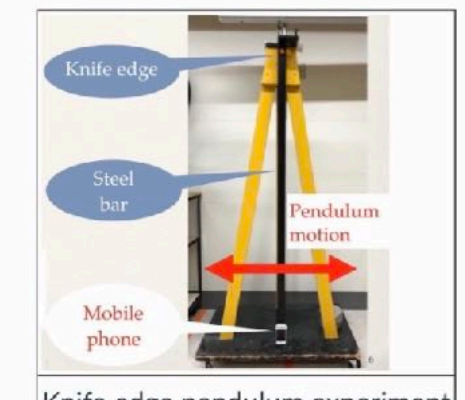
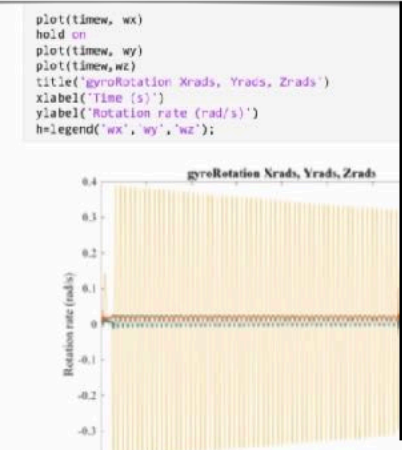
## Quiz Preview

Done

Upload a pdf of a Live Script executed with figures inline. You may collaborate on your code but the Live Script must be your own and should be individually well-commented.

At the top, provide the names of your collaborators and for each their contribution to the

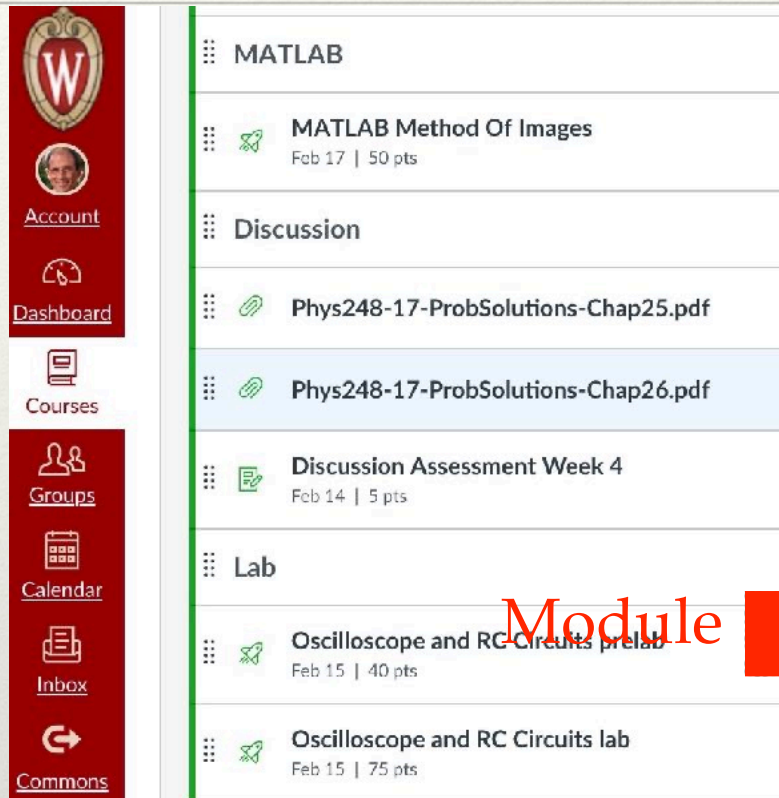
MATLAB FFT of mobile phone inertial sensor data





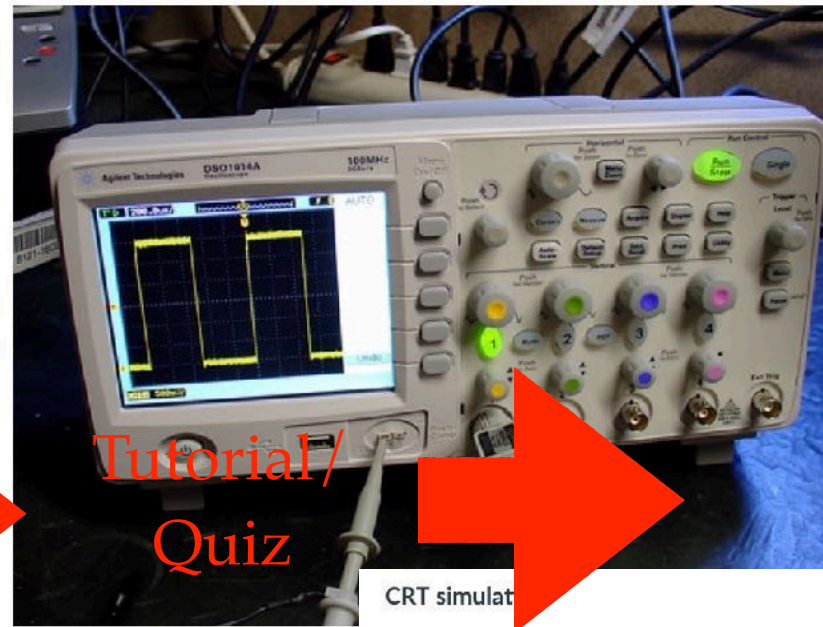
# Pre-lab: Oscilloscope

Physics 248, Week 4ish



Module

Oscilloscope and RC Circuits prelab

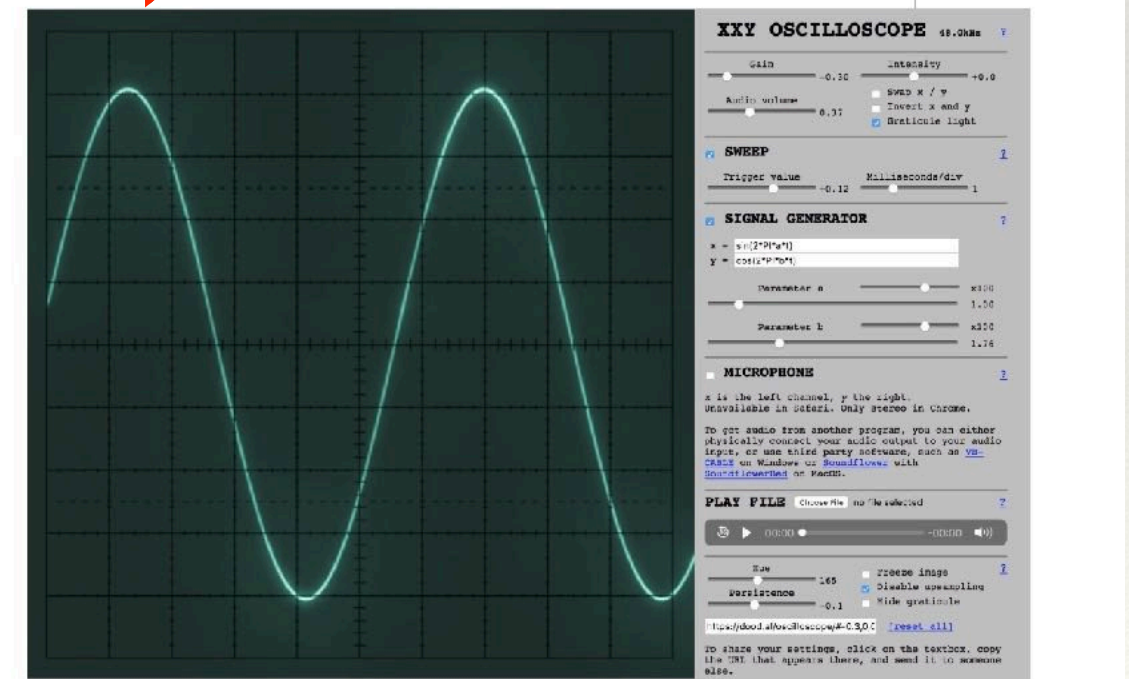


Tutorial/  
Quiz

Figure 1: Image of the front panel of the oscilloscope.

The oscilloscope, known as a cathode ray tube (CRT) oscilloscope, is used to observe and measure the time-dependent voltage of a circuit. The purpose of the prelab is to introduce the student to the oscilloscope and its use in measuring the time-dependent voltage of a circuit.

Authentic simulation of  
analog scope



CRT simulation

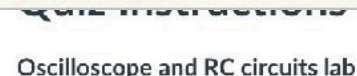
[https://dood.al/oscilloscope/#-0.3,0,0,0,1,1,0.24,2,1,sin\(2\\*PI\\*a\\*t\),cos\(2\\*PI\\*b\\*t\),2,1,2,1.76,165,-0.15,1,0](https://dood.al/oscilloscope/#-0.3,0,0,0,1,1,0.24,2,1,sin(2*PI*a*t),cos(2*PI*b*t),2,1,2,1.76,165,-0.15,1,0)

For an authentic feeling simulation of a CRT oscilloscope screen, open in a new

- ❖ Introduction to oscilloscopes.
- ❖ Play beforehand and learn about historical technology.



# Physics 248, Week 4ish



# Lab



Study digital scope specs and manuals

# ❖ Introduction to oscilloscope and RC circuits



It is always important to understand the specifications of your equipment. Visit the manufacturer's site <http://www.testequipmentdepot.com/tektronix/oscilloscope/tds2001c.htm> and download the data sheet for this representative oscilloscope. The direct link is [http://www.testequipmentdepot.com/tektronix/pdf/tds2000c\\_data.pdf](http://www.testequipmentdepot.com/tektronix/pdf/tds2000c_data.pdf). The scope you will use in this lab is similar to this one. Find in the data sheet the input impedance of the scope. It will likely be specified as an equivalent resistance in parallel with a capacitance. The capacitance will short out frequencies higher than about  $1/RC$ .

# Extract and fit scope data on RC circuit response on laptop with MATLAB. Own it!

### Question 1

TDS2001c specification: maximum input voltage

What is the maximum input voltage of the TDS 2001c according to the data sheet?

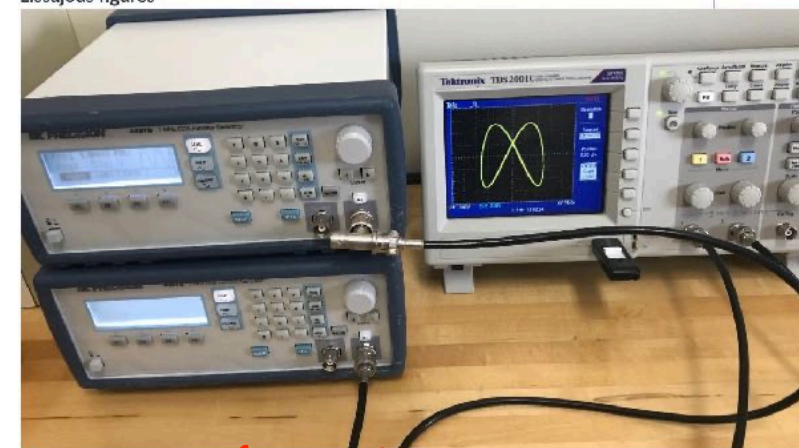


# Study function generator specs and manuals

A function generator (also called a signal generator) is designed to supply periodic standard voltage signals into standard electrical loads of 50 Ohms or greater. Typically a sine-wave, square-wave, and triangular wave or ramp wave are selectable from the front panel along with their amplitude and frequency.

Download the data sheet for a low cost function generator <http://www.testequipmentdepot.com/instek/pdf/stg1003.pdf> and notice the

### Lissajous figures



### Question 11

UW-Libraries  
<https://ezproxy.library.wisc.edu/login?url=%27...>

10 pts

### RC circuit and capacitors in series and parallel

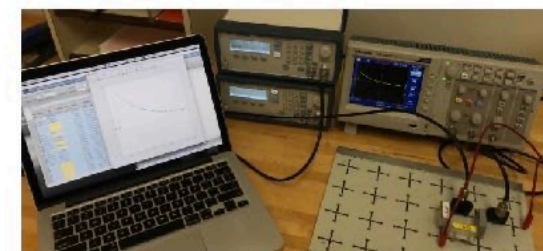


Figure 1: Setup for observing a series RC circuit

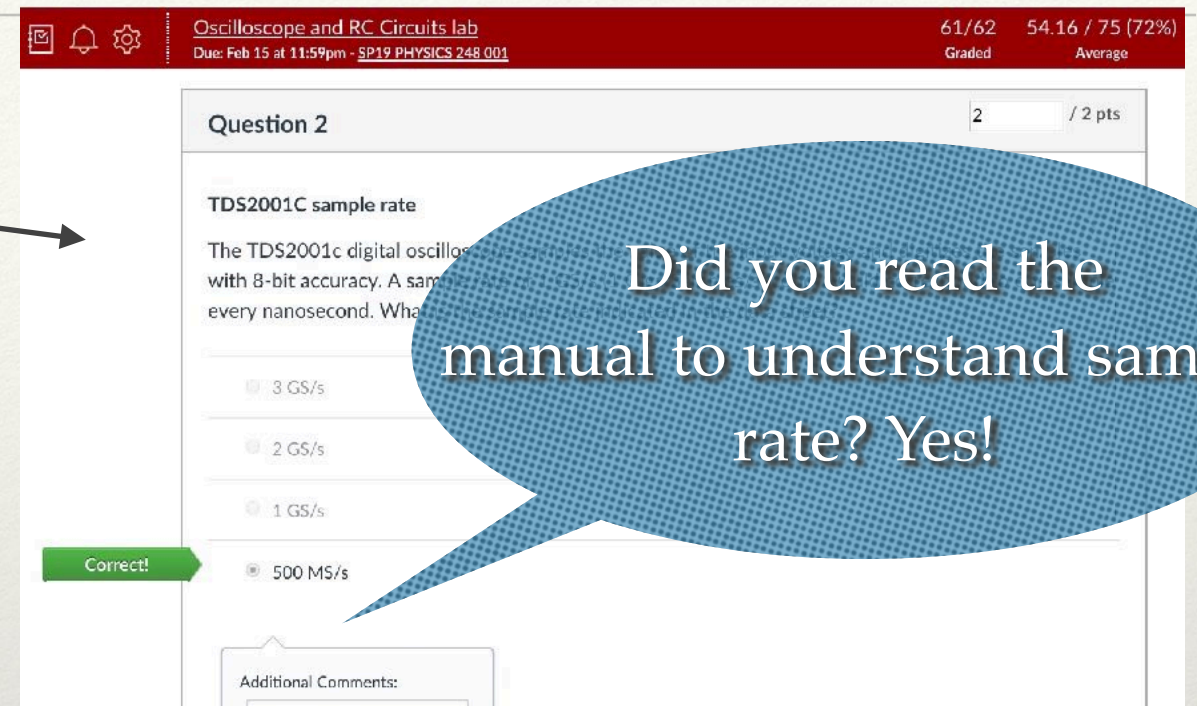
If a resistor and capacitor are connected in series and the pair driven by a function generator square wave with voltage oscillating between zero and a value  $A$  and with period  $T$  (or compared to the characteristic time  $\tau = RC$ ), the voltage  $V$  between the resistor and capacitor will not follow the square wave precisely. Instead, starting at the rising edge of the square wave, the voltage  $V$  will approach  $A$  exponentially with time constant  $\tau$ , and, starting at the falling edge, the voltage  $V$  will approach zero with the same time constant.

Connect in series a resistance of order 1 kOhm and a capacitance of order 1 microfarad so  $\tau \simeq 1 \text{ ms}$ , and drive the pair with the function generator with a square wave of period of order 10 ms and amplitude of 5 V. A breadboard setup is

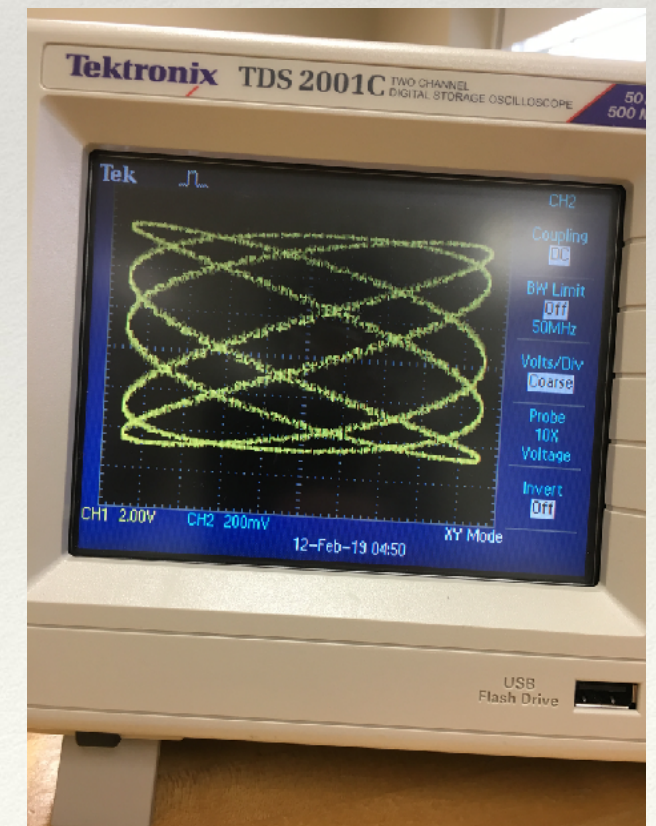
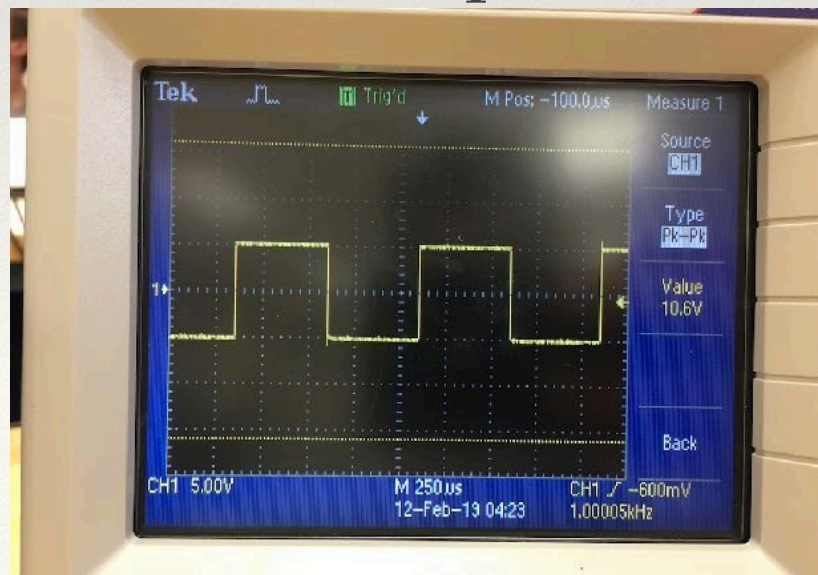


# Lab assessment

- ❖ Autograded baseline questions
- ❖ Phone photos
- ❖ Text
- ❖ Plots
- ❖ Tables
- ❖ Live scripts



Example student photo submissions





# Journal style lab reports

❖ Journal style lab reports, in addition to submitted plots and live scripts

### Compound and Cellphone Camera Microscopes

**Abstract**— This report discusses microscope image processing for both a compound microscope and a digital microscope consisting of a spherical lens attached to a cellphone camera. The results obtained from the experiments examine magnification and the relationship between the positions and distances of objects, images, focal points, and near points while discussing limitations of both the cell phone and compound microscopes.

#### I. INTRODUCTION

There are many ways in which our acquisition of knowledge is limited; the most problematic of these limitations is our inability to see things at the microscopic level. Therefore, microscopes are crucial instruments because they allow us to view objects that are too small to be seen by the naked eye. For this reason, microscopes have become pivotal tools for researching and analyzing the minuscule in areas including medicine, biology, chemistry, and physics.

The procedure discussed in this report describes the configuration used to produce a compound microscope with two converging lenses and includes the equations and calculations that describe the necessary positions of the lenses and the object in order to produce a virtual, inverted, magnified image. Following this discussion is an assessment of the value and efficacy of a cellphone camera microscope as opposed to a standard optical microscope. Finally, this report qualitatively and quantitatively evaluates the effectiveness of the digital microscope and the methods used to construct the compound microscope.

#### II. METHODS

##### A. Constructing a Compound Microscope

In order to construct a compound microscope, two strong, converging lenses were aligned in series in front of an object, each having a focal length measured to be about 4.3 cm. The setup is modeled by Figure 1.

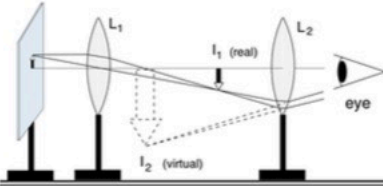


Fig. 1. compound microscope configuration [1]

The lenses were positioned such that the object was located just outside the focal length of the objective lens, which created a real, inverted image. The image produced by the first lens was positioned just inside the focal length of the second lens, the eyepiece. That image then served as the object of the eyepiece, which, as a magnifier, produced an enlarged, virtual, inverted image of the original object. The lenses were adjusted so that the image produced was clearest, and then measurements of the lens positions, object distance, and distance between the lenses were taken.

The equations required to calculate the focal lengths, first image position, the position of the object of the second lens, and the final image position relative to the second lens were, respectively:

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$
$$s_i = \frac{s_o f_1}{s_o - f_1}$$
$$s'_o = L - s_i$$
$$s'_i = \frac{s'_o f_2}{s'_o - f_2}$$

Where  $L$  denotes the distance between the lenses,  $s_o$  indicates the distance from the objective lens to the object,  $f_1$  and  $f_2$  represent the focal lengths of the objective and eyepiece lenses, and  $s_o'$  and  $s'_i$  indicate the distance of the real image to the eyepiece and the virtual image distance relative to the eyepiece, respectively.

##### B. Constructing a Digital Microscope

In order to create a digital microscope, a spherical lens with a radius of about 0.5 mm was affixed to the camera lens of the cell phone. Adding an external lens reduced the near point distance of the phone, which had been 5.85 cm, to within 1 mm, so that the image presented to the camera was at an infinite distance.

Slides of stained biological samples including frog red blood cells were imaged to test the effectiveness of the digital microscope. As the focal length of the sphere was of the order of a millimeter or so, the results of this experiment are qualitative rather than quantitative, assessing image quality, color, and aberration.

### III. RESULTS

#### A. Compound Microscope

Included below are tables including our measurements and calculations of the positions and distances of the lenses, objects, and images in the compound microscope setup.

$f_1$	$f_2$	$L$
4.3	4.3	10.63
$\pm 1.0$ cm	$\pm 1.0$ cm	$\pm 1.00$ cm

TABLE I  
FOCAL LENGTHS AND DISTANCE BETWEEN LENSES

$s_o$	$s_i$	$s'_o$	$s'_i$
12.56	6.54	4.09	-83.75
$\pm 0.05$ cm	$\pm 1.71$ cm	$\pm 1.98$ cm	$\pm 885.76$ cm

TABLE II  
MEASURED AND CALCULATED OBJECT AND IMAGE DISTANCES

An error of 1 cm was assigned to the values of  $L$ ,  $f_1$ , and  $f_2$  because both the precision of the ruler and the error in estimating the position of best focus contribute to the error in those measurements. One can notice that the error values on the calculated image and object distances grow due to error propagation, ultimately leading to an error of 886 cm on the final calculated distance of the virtual image, whose value is much larger than expected.

#### B. Digital microscope

Included below is the cell phone microscope image of frog red blood cells with the cellphone at the near point distance of about 1 mm.

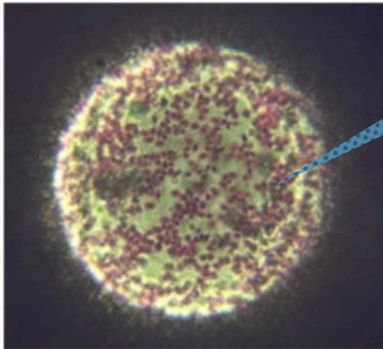


Fig. 2. digital microscope image of frog red blood cells

Although spherical aberration is prominent at the less-distinguished edges of the image, the enlarged image allows

one to see the individual blood cells as well as distinguish the nuclei inside them. It was discovered that the clearest image was produced with a more yellow light source placed about a meter below the slide, and since more light at a closer distance to the slide tended to wash out the cells in the image, the light source was obstructed by a sheet of printer paper.

#### IV. CONCLUSIONS

The procedure described in this report allowed for the construction of cost-effective compound and digital microscopes whose image processing ability is comparable to that of a typical optical lab microscope. The digital cellphone microscope produced a clear, magnified image but also produced spherical aberration at the edges of the image. Although it's a cheap alternative to a lab microscope, it required specific conditions of light source distance and intensity to be met, which hinder its ability to produce a clear image. The compound microscope was not met. As for the compound microscope, it produced a clear, magnified, virtual, inverted image. However, the setup described in this report required specific conditions of light source distance and intensity to be met, which hinder its ability to produce a clear image. The compound microscope was not met. As for the compound microscope, it produced a clear, magnified, virtual, inverted image. However, the setup described in this report required specific conditions of light source distance and intensity to be met, which hinder its ability to produce a clear image.

#### CONTRIBUTIONS

worked in collaboration with to gather the results discussed in this report. collected data and observations for the digital microscope. constructed the compound microscope and assisted in the calculations and analysis of the compound microscope system.

#### REFERENCES

[1] Carlsmith, Duncan. (2019). *Physics 248 Optical Instruments Lab*.

Red blood cells observed with cellphone microscope



# Lab assessment in Speedgrader

## ❖ Example interactive lab procedure snippet

Try imaging a small object using a magnifying lens with a few cm focal length. Then affix a glass sphere of radius  $R \sim 1$  mm directly to the surface of your cell phone camera. Affix a small object to a silicon holder that will stick directly to your phone. You may also use adhesive tape with a hole with slightly larger diameter than the sphere. Use your microscope to image a small object within a distance of order  $R$  between the object and the lens. See [http://www.physicsinsights.org/simple\\_optics\\_spherical\\_lenses-1.html](http://www.physicsinsights.org/simple_optics_spherical_lenses-1.html)

Volvox and frog red blood cells which, unlike human red blood cells, have a nucleus. To image these cells within a distance of order  $R$  between the object and the lens, you may need an air gap of order  $R$  between the object and the lens.

Provide the near point distance of your phone, the radius of the sphere, and discuss your observations here. Provide an image below of the object without the spherical lens at the cell phone camera near point, and an image using the lens, combined in one file below.

Your Answer:

Near point distance of a phone camera is approximately  $4.3 \pm 0.5$  cm

Diameter of the sphere is approximately  $0.75 \pm 0.25$  mm

Additional Comments:

Uploaded photo

Required text submission organizes work flow and documents progress

Question 7 4 / 5 pts

Upload a single file showing cell phone microscope images with and without the addition of a spherical lens.

↓ [thumbnail Image-10.png.jpeg](#)

Additional Comments:

Submitted: Apr 5 at 10:53pm

Assessment  
Grade out of 50

41

Assignment Comments

Add a Comment

Submit

[Download Submission Comments](#)

Sometimes a picture is worth a thousand words / tables / plots.



# Outcomes: Data analysis, computation, & presentation skills

## ❖ Balmer series optical spectrometer lab

### Question 4

#### Observation of the spectrum of hydrogen

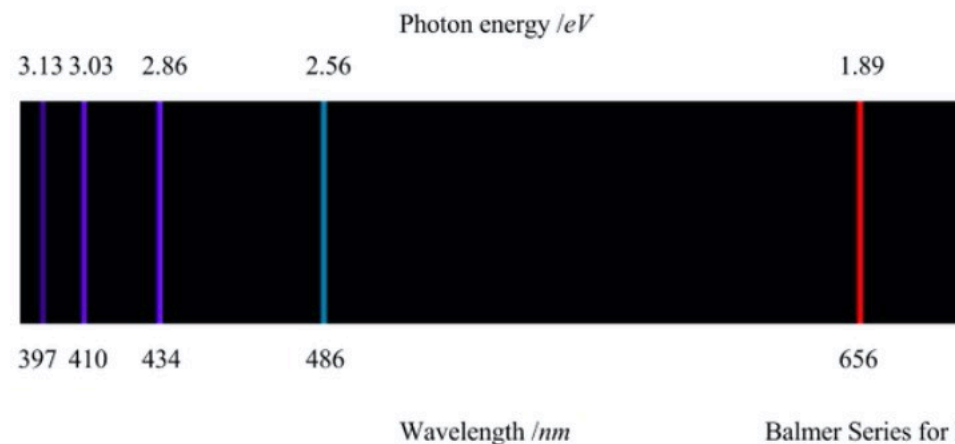


Figure 1: Spectrum of hydrogen



#### Hydrogen Emission Spectrum

Here we investigate the Balmer series of hydrogen atomic emission spectra, which is produced when electrons fall from an  $n \geq 3$  to the  $n=2$  shell. For the data we obtained,  $3 \rightarrow 2$  corresponds to the red emission line,  $4 \rightarrow 2$  corresponds to the cyan line, and  $5 \rightarrow 2$  corresponds to the violet emission line.

The Balmer formula is  $\frac{1}{\lambda} = R \left( \frac{1}{2^2} - \frac{1}{n^2} \right)$  where  $n > 2$  is the appropriate original energy level,  $R$  is the Rydberg constant, and  $\lambda$  is the wavelength of the emitted photons.

```
Ractual = 10973731.6; %units of m^-1  
  
n = [3, 4, 5]; %unitless  
lambda = [655.9, 484.8, 433.2]*10^-9;  
lambdaErr = [2.3, 1.9, 2.6]*10^-9;  
inverseLambda = 1./lambda;  
inverseLambdaErr = (lambdaErr/lambda);  
  
figure  
errorbar(n, inverseLambda, inverseLambdaErr,  
xlabel('n'); ylabel('1/\lambda (m^-1)');  
  
%inverseLambdaExpected = Ractual*(1/2^2 - 1/n^2);  
  
modelfun = @(R,x)R*(1/4 - 1./x.^2);  
model = fitnlm(n, inverseLambda, modelfun);
```

```
model =  
Nonlinear regression model:  
y ~ R1*(1/4 - 1/x^2)  
  
Estimated Coefficients:  
Estimate SE tStat  
R1 1.0993e+07 5988.1 1835.7  
  
Number of observations: 3, Error degrees of freedom: 1  
Root Mean Squared Error: 1.88e+03  
R-Squared: 1, Adjusted R-Squared: 1  
F-statistic vs. zero model: 3.37e+06, p-value: 0.000000e+00  
  
Rfitted = model.Coefficients.Estimate;  
Rfitted = 1.0993e+07  
  
RfittedError = model.Coefficients.SE;  
RfittedError = 5.9881e+03
```

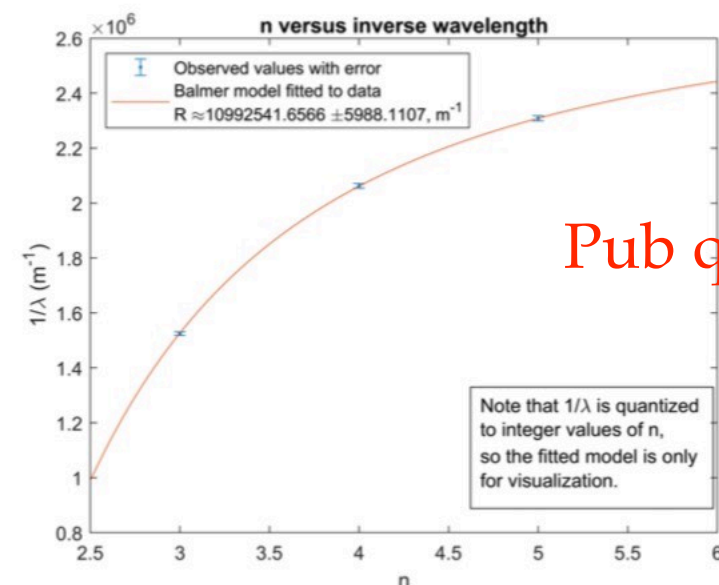
Here we can see that our fitted value for the Ry

Required pdf of executed Live Script

Commented by student in LaTeX

Student code

```
hold on  
nTest = linspace(2.5, 6, 100);  
plot(nTest, modelfun(Rfitted, nTest))  
  
legend('Observed values with error', strcat('Balmer model fitted to data \nnewline', ...  
'R \approx ', num2str(Rfitted), ' \pm ', num2str(RfittedError), ' , m^-1'), 'Location', 'right')  
  
textboxDim = [.6 .15 .3 .2];  
str = 'Note that 1/\lambda is quantized to integer values of n,\nnewline so the fitted model is only for visualization.';  
annotation('textbox', textboxDim, 'String', str)
```



Pub quality plot

This graph shows our nonlinear model fit to the data.

Nonlinear fit with standard errors=> Rydberg constant



---

Thanks for listening

---