

PHYS 1004

Introductory Electromagnetism and Wave Motion

Winter 2013

Course Outline

This course is designed to provide an introduction to electricity, magnetism, circuits, electromagnetic induction, and wave motion from a physics perspective for students in engineering programs. The associated laboratory and tutorial sessions meet during alternate weeks starting in the second week of term. Student evaluations will be based on labs, tutorial tests given during each tutorial session, and a final exam.

1. Calendar description

This calculus-based course introduces electricity, magnetism, oscillations, waves and optics. The laboratory is an essential and autonomous part of the course.

Precludes additional credit for PHYS 1002 and PHYS 1008.

2. Prerequisites

You must have successfully completed

MATH 1004 Calculus for Engineering or Physics or MATH 1007 Elementary Calculus 1

PLUS either be concurrently registered in ECOR 1101 Mechanics I

or else have passed PHYS 1003 Introductory Mechanics and Thermodynamics

or PHYS 1001 Foundations of Physics I

or PHYS 1007 Elementary University Physics I

(the latter with a grade of at least B-).

If you do not have both of these requirements you must check with your instructor to obtain permission of the Physics Department to take this course. If you withdraw from ECOR 1101 during the term, you will be required to also withdraw from PHYS 1004.

3. Who teaches the course, when and where

a. Lecture Timetable

CRN	Section	Times	Room	Lecturer	and contact info
10923	A	Mon 10:00 – 11:30 Wed 10:00 – 11:30	RB2200	John Armitage	Herzberg 3350 john_armitage@carleton.ca 613-520-2600 x4326 Office hours: Mon 1:00 – 2:00pm. Fri 11:00 – 12:00am
14859	B	Tues 11:30 – 1:00pm Thu 11:30 – 1:00pm	RB2200	Alain Bellerive	Herzberg 3316 alainb@physics.carleton.ca 613-520-2600 x7537 Office Hours: Tues 1:00 – 2:00pm Thurs 1:00 – 2:00pm
10927	C	Tue 6:00 - 7:30pm Thu 6:00 - 7:30pm	RB2200	Thomas Koffas	Herzberg 2410 tkoffas@connect.carleton.ca 613-520-2600 x8996 Office Hours: Fri 3:00 – 4:30pm

b. Laboratory and Tutorial Timetable

PHYS-1004 Winter 2013 Lab sections

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning 8:30am to 11:30am	L11 A	L12	L16 A	L6	L3
Noon 11:30am to 2:30pm	L2	L5 B		L4 B	
Afternoon 2:30pm to 5:30pm	L14	L7	L1	L9	L8
Evening 6:00pm to 9:00pm	L10	L13 C	L15		C

Lectures
A – John Armitage
B – Alain Bellerive
C – Thomas Koffas

Room: Herzberg 4130 (all sections)

Lab supervisors: Igor Ivanovic 3346HP

igor@physics.carleton.ca

(613) 520-2600 Ext 5796

Etienne Rollin 3368HP

erollin@physics.carleton.ca

(613) 520-2600 Ext 8922

1. Go to: **culearn.carleton.ca**
2. Enter your MyCarleton user and password
3. Click: **login**

Once you have logged in, your browser will load a page that has course links to any of the courses that you are enrolled in. Click on

Crosslist PHYS1004A PHYS1004C PHYS1004B BIT1204A
[10923:14859:10927:18328]
Electromagnetism and Wave Motion (LEC) Winter 2013

Note that after 2 hours of inactivity, cuLearn will require you to log in again (even if you are in the middle of doing an assignment, be careful, you may lose your work!)

If you are unable to access cuLearn or need help with your computing account, please contact the CCS Service Desk at 520-3700 or email ccs_service_desk@carleton.ca

Having got logged-on you can now use cuLearn to do the Pre-Class Quizzes. See the panel on the left hand side and click on the tab labelled **Quizzes**

First read the appropriate chapter sections in the textbook. Then, answer the 5 qualitative questions. Note that in general there are no second chances with the Pre-Class quiz - the exception is the first quiz PCQ0 where two tries are given so that you may familiarize yourself with the system. This means that you need to be sure of your facts before starting it. PCQ 0 is a practice quiz, it will not be counted in the final mark. Pre-Class quizzes should typically require less than 15 minutes to complete.

Due dates will be announced in class, but the normal due day will be Monday morning before 10 am.

c. Tutorials

There are 6 tutorials in the term. They start in Calendar week 3, week beginning 14th Jan, 2013. They take place in the regular Lab time slot in Herzberg 4130, usually in alternating weeks with the labs. The tutorial schedule is given later in section 6.

For the first 30 minutes of the tutorial, TA's will solve selected problems, from 20 recommended, on the board. During the next hour, students will work in groups on other problems from this set. For the last 5 tutorials (2 – 6 incl.) there will be a 30 minute test and the answers will be recorded on a Scantron sheet. The test problems will be taken from the 20 recommended problems.

The 20 recommended problems will be selected as being typical of the type of problem for those chapters covered in a two week period – see ‘Syllabus’ later. The 20 problems may be taken from two or three chapters and will be quantitative problems of varying difficulty.

What to bring: Bring your student ID card, writing instruments, and a non-programmable calculator, plus a ruler if you want. Bring along a textbook to the tutorial sessions. No other aids are allowed for the Tests. The formula sheets that make up the last two pages of this course outline will be provided to you with the first test.

Attend your own Tutorial section only. To be able to write the Test in a different section, you must obtain written permission from your lecturer. Such permission will usually be granted only for emergencies or medical reasons, or official activities such as Engineers Without Borders.

If you miss a Tutorial Test, immediately contact your lecturer and explain why. If the reason is illness, **a doctor’s note is required**. Students with valid reasons will be given written permission to write the Test in a different section later the same week if possible. If this is not possible, you must obtain permission to write a make-up test at the end of term. These will all be written on Wednesday April 10th; the time will be announced toward the end of term. Note that you need to get permission at the time you miss the test or as soon as you are back at school after an illness or accident. Retroactive permission will not be given at the end of term.

No make-up for the marking of the assignment problem – bring a doctor’s note and the total marks will be prorated.

d. Labs

Labs start in calendar week 5, week beginning 28th January. Bring your copy of the Lab Manual and a beige lab booklet with you to the first lab. For each lab you will be writing a lab report - some of these will be Short Reports, while others will be Formal Reports. Instructions on writing lab reports will be given during the lab and the format can be found in the Lab Manual. You have one week to complete the Lab report, which will be due in at the start of the next tutorial. The exceptions to this are the last two labs, for which the report will be written up and turned in before the end of the lab period. Some of the lab report is done before you attend the lab session. This is referred to as the “Prelab”. This must be written in your lab booklet. It will be checked and marked by your TA during the lab session and marks will be deducted if it is not done in advance. See page 2 of the Lab Manual.

For students repeating this course, you may request to be exempt from the lab (and have your lab mark carried forward from before) if you have completed all the lab experiments with an overall lab mark of at least 60%. You must contact your lab supervisor and obtain explicit permission to be exempt from the lab. Note that you will not be exempted from the Tutorials, which meet in alternate weeks during your lab period.

e. Final Exam

The Final Exam will be held during the exam period, April 13–27 (including Saturdays)—the date will be announced by the university by February 18th. All three lecture sections will write the Final Exam together. You may bring only writing implements, a calculator, and a ruler to the Final Exam. The formula sheets that make up the last two pages of this course outline will be provided. The Final Exam has multiple choice questions and problems requiring written solutions, from which there will be a choice. The multiple choice will include a few questions relevant to the laboratory.

f. Deferred Exams

If you miss the Final Exam for a good reason such as illness, you may apply for a Deferred Exam through the registrar's office. A Deferred Exam replaces only the Final Exam portion of your mark. Deferred Exams for Winter 2013 will be scheduled during June 10–20. In order to be eligible for a Deferred Exam you must have earned at least 7 out of the possible 32 marks on term work in the theory component of the course (i.e., the Tutorial Tests) and at least 12 out of the possible 33 lab marks.

5. Required textbook and materials

1. Textbook: Part 3: Electricity and Magnetism, and Part 4: E.M.Waves and Optics from 'Fundamentals of Physics', Halliday, Resnick and Walker, 9th Edition, J.Wiley & Sons.

Available at the Bookstore (UniCentre)

There is a custom printing specifically for Carleton University containing the chapters we will cover. Alternatively, you may use the full text

2. Lab manual: Laboratory Manual for PHYS 1004, Winter 2013 edition.

Available at Science Stores, 118 Steacie Building.

You must bring this with you to each Lab session. Students are required to purchase this year's copy of the Lab Manual. Any reference to material included in a previous version could be construed as evidence of plagiarism.

3. Lab booklets: Four (4) beige booklets, titled Carleton University Laboratory Report.

Available at the Bookstore (UniCentre). - bring one with you to each Lab session n.

6. Lab and tutorial schedule.

n.b. 'Week' refers to Week number in the calendar year

Tutorials start in calendar week 3, the week of Jan 14th 2013.

Labs start in calendar week 5, the week of Jan 28th 2013.

Week 3 Tutorial 1: Background material

Week 4 Tutorial 2: Coulomb and Electric Field, Test 1: Ch21, 22.

Week 5 Lab 1: Electrostatics

Week 6 Tutorial 3 Gauss' Law and Potential , Test 2: Ch23, first part Ch24

Week 7 Lab 2: Oscilloscope I

Week 8 Mid term break 18th Feb – 22nd Feb.

Week 9 Tutorial 4 Capacitance and Resistance, Test 3: Ch25, 26.

Week 10 Lab3: Oscilloscope II.

Week 11 Tutorial 5: Circuits and Magnetism Test 4 Ch 27, 28, 29

Week 12 Lab 4: Magnetic Force Lab.

Week 13 Tutorial 6 Induction, EM Waves Test 5 Ch 30, 31.

Week 14 Lab 5: Optics Lab.

Week 15 No Tutorials or Labs

Classes end on April 10th (which follows a Friday schedule) There are no Labs or Tutorials that week, but during a normal week there would be a lecture for section A. Therefore the last lecture for section A will be Monday 8th April, whereas for Sections B and C it will be Tuesday 9th.

7. Lecture and Tutorial test schedule

1 ½ hrs lecture twice a week. Classes start Monday 7th Jan.

(n.b. 'Week' indicated is calendar week of 2013)

Lecture	Week	PCQ	Tutorial	Test	Labs
1. Background material: Math Toolbox	2.				
2. Physics toolbox	2.				
3. Ch 21: Electric Charge, Coulombs Law	3	0	1		
4. Ch 22: Electric Fields	3	0	1		
5. Ch 23: Gauss Law and Electric Flux	4	1	2	1	
6. Gauss' Law continued	4	1	2	1	
7. Ch 24: Electric Potential	5	2			1
8. <i>Review, catch-up, Apps</i>	5	2			1
9. Electric Potential (cont'd)	6	3	3	2	
10. Ch 25: Capacitance	6	3	3	2	
11. Ch 26: Current and Resistance 26-1 – 26-7	7	4			2
12. <i>Review, Catch-up, Apps</i>	7	4			2
<i>Reading Week Feb 18 – 22nd, 2013</i>		<i>8</i>			
13. Ch 27: Circuits	9	5	4	3	
14. Ch 28: Magnetic Fields	9	5	4	3	
15. Ch 29: Mag Fields due to currents, Ampere's Law	10	6			3
16. <i>Review, Catch-up, Apps</i>	10	6			3
17. Ch 30: Induction and Inductance, 30-1 to 30-11	11	7	5	4	
18. Induction continued	11	7	5	4	

	Lecture	Week	PCQ	Tutorial	Test	Labs
19.	Ch31: EM oscillations	12	8			4
20.	<i>Review, catch-up, Apps</i>	12	8			4
21.	Ch 32: Maxwells Eqns 32:1 – 32:5	13	9	6	5	
22.	Ch 33: EM Waves 33-1 – 33.5, 33.6 – 33.9	13	9	6	5	
23.	Ch 34: Images (Reflection) 34-1 – 34-7	14	10			5
24.	Ch 34: Lenses.	14	10			5
25.	<i>Course review</i>	15				

Classes end on April 10th (which follows a Friday schedule) There are no Labs or Tutorials that week, but during a normal week there would be a lecture for section A. Therefore the last lecture for section A will be Monday 8th April, whereas for Sections B and C it will be Tuesday 9th.

8. University policies

You may need special arrangements to meet your academic obligations during the term. For an accommodation request the processes are as follows:

- a. **Pregnancy obligation:** write to me with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details visit the Equity Services website: <http://www2.carleton.ca/equity/>
- b. **Religious obligation:** write to me with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details visit the Equity Services website (as above).
- c. **Academic Accommodations for Students with Disabilities:** The **Paul Menton Centre** for Students with Disabilities (PMC) provides services to students with Learning Disabilities (LD), psychiatric/mental health disabilities, Attention Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorders (ASD), chronic medical conditions, and impairments in mobility, hearing, and vision. If you have a disability requiring academic accommodations in this course, please contact PMC at 613-520-6608 or pmc@carleton.ca for a formal evaluation. If you are already registered with the PMC, contact your PMC coordinator to send me your **Letter of Accommodation** at the beginning of the term, and no later than two weeks before the first in-class scheduled test or exam requiring accommodation (*if applicable*). After requesting accommodation from PMC, meet with me to ensure accommodation arrangements are made. Please consult the PMC website for the deadline to request accommodations for the formally-scheduled exam (*if applicable*) at <http://www2.carleton.ca/pmc/new-and-current-students/dates-and-deadlines/>

You can visit the Equity Services website to obtain more detailed information (see above)

d. Copying, plagiarism, and other forms of cheating

You should read and be familiar with the university's policies on academic integrity, given in Section E.14 of the Academic Regulations of the University:

<http://www4.carleton.ca/calendars//ugrad/current/regulations/acadregsuniv14.html>

In this course, these rules are relevant mainly for lab reports (do not copy someone else's) and tutorial tests and the final exam (do not attempt to use unauthorized materials or collaborate with other students). A report will be sent to the Dean of your Faculty, for possible further disciplinary action.

Reference material for exam and tutorial tests - PHYS1004 Winter 2013

$$\begin{aligned}
 N_A &= 6.022 \times 10^{23} \text{ mol}^{-1} \\
 G &= 6.674 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \\
 g &= 9.81 \text{ m s}^{-2} \\
 m_e &= 9.109 \times 10^{-31} \text{ kg} \\
 m_p &= 1.673 \times 10^{-27} \text{ kg} \\
 e &= 1.602 \times 10^{-19} \text{ C} \\
 k &= 1/(4\pi\epsilon_0) = 8.988 \times 10^9 \text{ N m}^2\text{C}^{-2} \\
 c &= 2.998 \times 10^8 \text{ m/s} \\
 \text{Permittivity, free space,} \\
 \epsilon_0 &= 8.854 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2} \\
 \text{Permeability, free space,} \\
 \mu_0 &= 4\pi \times 10^{-7} \text{ T m A}^{-1} = (\text{H/m}) \\
 1 \text{ J} &= 1 \text{ N m} \quad 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \\
 1 \text{ C} &= 1 \text{ A s} \quad 1 \text{ V} = 1 \text{ J/C} \\
 1 \Omega &= 1 \text{ V/A} \quad 1 \text{ F} = 1 \text{ C/V} \\
 1 \text{ Wb} &= 1 \text{ T m}^2 \quad 1 \text{ H} = 1 \text{ T m}^2 / \text{A} \\
 1 \text{ Hz} &= 1 \text{ s}^{-1} \quad 1 \text{ T} = 1 \text{ N/(A m)} [10^4 \text{ Gauss}] \\
 (1+x)^n &= 1 + nx + n(n-1)x^2/2! + \\
 &\quad n(n-1)(n-2)x^3/3! + \dots \text{if } |x| < 1 \\
 \sin(\alpha \pm \beta) &= \sin \alpha \cos \beta \pm \cos \alpha \sin \beta \\
 \cos(\alpha \pm \beta) &= \cos \alpha \cos \beta \mp \sin \alpha \sin \beta \\
 \text{Uniform linear acceleration: } v_f^2 &= v_i^2 + 2a\Delta s \\
 s_f &= s_i + v_i\Delta t + \frac{1}{2}a(\Delta t)^2 \quad v_f = v_i + a\Delta t \\
 \text{Uniform circular acceleration: } |\vec{a}| &= \frac{v^2}{r} \\
 \text{Spring-block: } F &= -k\Delta s \quad U_{sp} = \frac{1}{2}k(\Delta s)^2 \\
 W > 0 &\Rightarrow \text{energy transferred to an object by force} \\
 K &= \frac{1}{2}mv^2, \quad \Delta K = K_f - K_i \quad U_g = mgh \\
 \text{Ignoring dissipative energy losses:} \\
 \Delta E_{\text{sys}} &= \Delta K + \Delta U = W_{\text{ext}} \text{ or } E_f = E_i + W_{\text{ext}} \\
 \text{Conservation } E_{\text{mech}} &\text{ in an isolated system } (W_{\text{ext}} = 0): \\
 \Delta E_{\text{mech}} &= \Delta K + \Delta U = 0 \\
 \text{Work-KE theorem: } \Delta K &= W_{\text{net}} \quad [\text{J}] \\
 \text{Work } W_{\text{force}} &= \int_i^f \vec{F} \cdot d\vec{s} \quad [\text{J}] \\
 \text{Power } P &= dW/dt = \vec{F} \cdot \vec{v} \quad [\text{W}] \\
 \Delta U &= U_f - U_i = -W_{\text{force}} \quad [\text{J}] \\
 \text{If external agent does work against force:} \\
 \Delta U &= W_{\text{ext}} \\
 \text{A force is conservative if the work to move a mass or} \\
 \text{charge between two points is path independent.} \\
 \text{Coulomb's Law:} \\
 F_{1\text{on}2} &= F_{2\text{on}1} = \frac{k|q_1||q_2|}{r^2} \quad [\text{N}]
 \end{aligned}$$

Shell Theorems: A shell of uniform charge: 1) attracts or repels an external charge as if all of the shell's charge were at its centre; and 2) exerts no net electrostatic force on a charge in its interior.

$$\vec{E} = \vec{F}/q_0 \quad [\text{N C}^{-1} \text{ or V/m}]$$

Electric Dipole

2 charges $+q, -q$ separated by s ; dipole moment $|\vec{p}| = qs$ directed from $-q$ to $+q$

$$\vec{\tau} = \vec{p} \times \vec{E} \quad U = -\vec{p} \cdot \vec{E}$$

Electric Fields:

$$\text{point charge: } |\vec{E}| = \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \text{ and } \vec{E} = |\vec{E}|\hat{r}$$

non-conducting ∞ sheet: $|\vec{E}| = \sigma/(2\epsilon_0)$

conducting ∞ sheet: $|\vec{E}| = \sigma/(\epsilon_0)$

Gauss's Law:

$$\Phi_e = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{in}}}{\epsilon_0}$$

Electric potential, $V = U/q_0$ [V] where U is the electrostatic potential energy

$$\Delta V = V_f - V_i = -\int_i^f \vec{E} \cdot d\vec{s}$$

$$\vec{E} \text{ from V: } E_s = -\frac{\partial V}{\partial s}$$

$$V \text{ of point charge: } V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$$

$$\text{System of 2 charges: } U_{12} = V_1q_2 = \frac{1}{4\pi\epsilon_0} \frac{q_1q_2}{r}$$

for several charges: $U = U_{12} + U_{13} + U_{23} + \dots$

$$\text{Capacitance: } C = Q/\Delta V_C \quad [\text{F}]$$

$$\text{parallel-plate capacitor: } C = \frac{\epsilon_0 A}{d}$$

$$\text{in series: } 1/C_{\text{eq}} = \sum_i 1/C_i$$

$$\text{in parallel: } C_{\text{eq}} = \sum_i C_i$$

$$U_C = \frac{1}{2}C(\Delta V_C)^2$$

$$u_E = \frac{1}{2}\epsilon_0 E^2$$

with dielectrics: $\epsilon_0 \rightarrow \epsilon = \kappa\epsilon_0$,

dielectric constant: $\kappa = \epsilon/\epsilon_0$

$$\text{Current: } I = dQ/dt \quad [\text{A}]$$

Current density: \vec{J} : $|\vec{J}| = I/A$ in direction of \vec{E} .

v_d is drift speed: n_e is conduction e^-/m^3

$$J = n_e e v_d$$

$$\text{Resistance: } R = \Delta V_R/I \quad [\Omega]$$

Ohms law $\Rightarrow R$ independent of ΔV_R

$R = \rho L/A$ units of resistivity ρ are $[\Omega\text{m}]$.

Conductivity $\sigma = 1/\rho$ $[\Omega^{-1}\text{m}^{-1}]$

$$J = \sigma E \quad J = n_e e v_d$$

$$R \text{ in parallel: } \frac{1}{R_{\text{eq}}} = \sum_i \frac{1}{R_i}$$

R in series: $R_{eq} = \sum_i R_i$
 Power, $P = iV$ (general case).
 If Ohm's law holds: $P = i^2 R = V^2/R$
 emf: $\mathcal{E} = \frac{dW}{dQ}$ [V]
 Kirchhoff's Rules:
 Loop: $\sum_i \Delta V_i = 0$
 Junction $\sum_i I_i = 0$
 RC circuit:
 Discharging: $Q(t) = Q_0 e^{-t/\tau}$ $\tau = RC$ [s]
 Charging: $Q(t) = Q_{max}(1 - e^{-t/\tau})$ $Q_{max} = C\mathcal{E}$
 Magnetic fields: Force from \vec{B}
 moving charge: $\vec{F}_{on\ q} = q\vec{v} \times \vec{B}$
 wire current: $\vec{F}_{wire} = I\vec{\ell} \times \vec{B}$
 2 parallel wires: $F_{||\ wires} = \frac{\mu_0 \ell I_1 I_2}{2\pi d}$
 (|| attract, anti|| repel)
 Ampere's Law: $\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{through} + \mu_0 \epsilon_0 \frac{d\Phi_e}{dt}$
 long straight wire: $\vec{B} = \frac{\mu_0 I}{2\pi d}$ (tangent to circle, rhr)
 $B_{solenoid} = \mu_0 n I$ where $n = N/\ell$
 Biot-Savart Law, current element $I d\vec{s}$:
 $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{s} \times \hat{r}}{r^2}$
 Magnetic dipoles:
 loop's magnetic dipole moment: $\vec{\mu} = NIA$ (rhr I)
 mag field on axis: $\vec{B}_{loop} = \frac{\mu_0}{4\pi} \frac{2\vec{\mu}}{z^3}$
 Torque on current loop: $\vec{\tau} = \vec{\mu} \times \vec{B}$
 Potential energy of magnetic dipole: $U = -\vec{\mu} \cdot \vec{B}$

Magnetic Flux through loop:
 $\Phi_m = N \int_{loop} \vec{B} \cdot d\vec{A}$ [Wb]
 Faraday's Law: $\mathcal{E} = -\frac{d\Phi_m}{dt}$, or $|\mathcal{E}| = \left| \frac{d\Phi_m}{dt} \right|$
 with direction of induced current such that
 induced \vec{B} will oppose the change in Φ_m .
 Induced electric field: $\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$
 Inductance: L [H] = [Wb/A]
 solenoid: $L = \frac{\Phi_m}{I} = \frac{\mu_0 N^2 A}{\ell}$
 $\mathcal{E}_{coil} = L \left| \frac{dI}{dt} \right|$ direction from Lenz's Law
 $\Delta V_L = -L \frac{dI}{dt}$
 $U_{inductor} = \frac{1}{2} LI^2$ $u_B = \frac{1}{2\mu_0} B^2$
 LR circuit: $I = I_0 e^{-t/\tau}$ $\tau = \frac{L}{R}$

oscillatory motion: $x(t) = A \cos(\omega t + \phi_0)$
 angular frequency ω [rad/s]
 frequency $f = \omega/2\pi$ (Hz)

period $T = 1/f$ [s]
 Spring-block system: $U = \frac{1}{2} kx^2$
 x displacement, k spring constant $\omega = \sqrt{\frac{k}{m}}$
 LC Circuit: $\omega = \sqrt{\frac{1}{LC}}$
 $Q(t) = Q_0 \cos(\omega t + \phi_0)$

AC circuits:
 capacitive reactance: $X_C = 1/(\omega C)$ [Ω]
 inductive reactance: $X_L = \omega L$ [Ω]

$$I_{rms} = I_{max}/\sqrt{2} \quad V_{rms} = V_{max}/\sqrt{2}$$

$$\mathcal{E}_{rms} = \mathcal{E}_{max}/\sqrt{2} \quad P_{ave} = I_{rms}^2 R$$

Travelling waves:
 $v = \lambda f$ $k = 2\pi/\lambda$ $\omega = vk$
 $D(x, t) = A \sin(kx - \omega t + \phi_0)$

Electromagnetic waves:
 $E = E_{max} \sin(kx - \omega t)$, $B = B_{max} \sin(kx - \omega t)$
 $c = 1/\sqrt{\epsilon_0 \mu_0}$ $E = cB$ $\vec{E} \perp \vec{B}$
 Poynting vector: $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$ [W/m²]
 $I = S_{ave} = E_{rms}^2 / (c\mu_0)$
 index of refraction: $n = c/v$

Surface area of sphere: $4\pi R^2$
 Volume of sphere: $\frac{4}{3}\pi R^3$

Error Propagation Equations
 $\sigma_z = \left[\left(\frac{\partial z}{\partial x} \sigma_x \right)^2 + \left(\frac{\partial z}{\partial y} \sigma_y \right)^2 + \dots \right]^{\frac{1}{2}}$
 for $z = ax + by - cu + \dots$
 $\sigma_z = \left[(a\sigma_x)^2 + (b\sigma_y)^2 + (c\sigma_u)^2 + \dots \right]^{\frac{1}{2}}$
 for $z = Ax^n y^m u^{-p}$
 $\sigma_z = z \left[(n\sigma_x/x)^2 + (m\sigma_y/y)^2 + (p\sigma_u/u)^2 + \dots \right]^{\frac{1}{2}}$