An experiment in embedding and distributing programming throughout an undergraduate degree

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(thanks to Joe Hope, ANU)

Background and context (1)

Australian National University

NATURAM PRIMUM COGNOSCERE RERUM

- One of Group of Eight
- Research-intensive
- Faculties and Research Schools (Department of Physics and RSPE)
- Approx 150 physics academics
- Approx 150 PhD students

Background and context (2)

- Three year BSc
- Majors (and minors)
- Honours year as pathway to PhD
- Elite (UAI 82+)
- Elite degrees: PhB and BSc (Advanced)

Level 1	Level 2	Level 3	Level 4
100 (+150)	60-70	30-40	15-20
20	15	10	10

Degree structure

Advanced Physics 1	Quantum Mechanics	Theoretical Physics	Advanced Theoretical Physics
Advanced Physics 2	Statistical Mechanics	Nuclear Physics	Condensed Matter Physics
	Electromagnetism	Particle Physics Plasma Physics	Physics of the Earth
	Waves and Optics	Fluid Physics	Atomic Physics
		Computational Physics	Optical Physics
		Research Projects	Photonics
			Research Projects

Major and minor learning goals

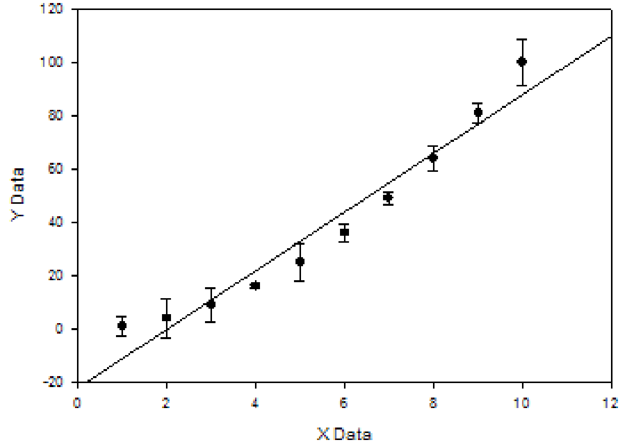
Students who complete the Physics major will be able to:

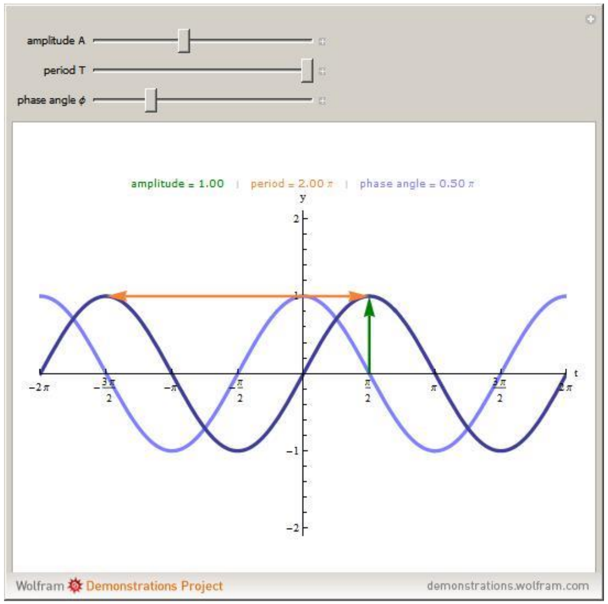
- …
- **Use mathematical, computational and experimental skills to solve conceptual and quantitative problems in physics.**
- Demonstrate skills including: equipment familiarity, data gathering, record keeping, data analysis, dealing with uncertainty, experiment design, and comparison with theory.
- …
- Be both creative and rigorous in the design and construction of scientific investigations of physical systems.
- …

Process (1): articulating desired learning

Level 1

- Plot 1D/2D/3D graphs (functions)
- Plot data with error bars
- Basic statistical analysis of data: averaging, standard errors, lines of best fit
- Solve systems of algebraic equations (analytically and numerically); root finding
- Perform integrals (analytically and numerically)
- Solve ordinary differential equations (analytically and numerically)





Process (1): articulating desired learning

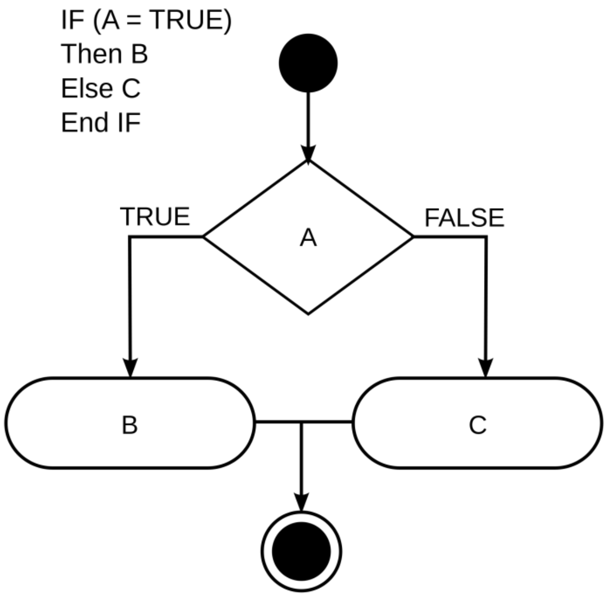
Level 2

- Calculate quantities using linear algebra
- Iteration
- Visualise high dimensional data
- Write simple algorithms
- Input/output of datasets

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad \mathrm{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

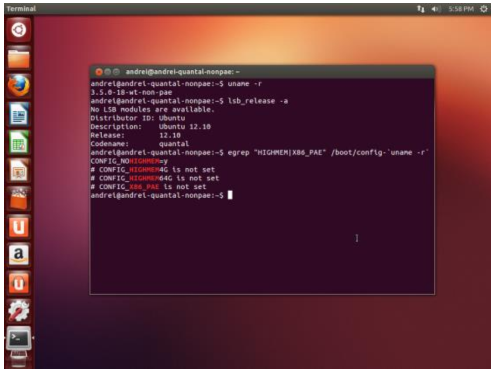
$$[\sigma_1, \sigma_3] = -2\, i\, \sigma_2$$

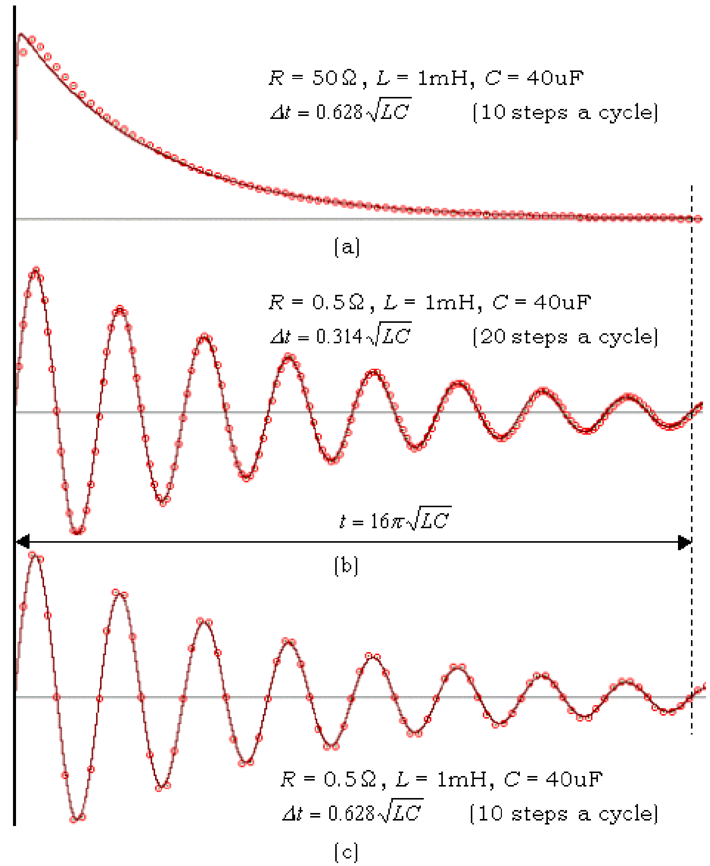


Process (1): articulating desired learning

Level 3

- Solve partial differential equations
- Confidence with new packages, unix
- Produce (computational) models from physical problems





Process (2): he who shouts loudest …

Wolfram Mathematica

MATLAB

NATIONAL INSTRUMENTS LabVIEW

```
#include <stdio.h>

main()

{
   printf("hello, world\n");
}
```

Process (3): implementation

Level 1

- Labs
- Homework

Level 2

- Labs
- Homework, course extensions
- Linux

Level 3

- Mini-projects

Introductory Exercise: The Helical Spring

Learning Objectives

The purpose of this activity is to introduce you to the laboratory, get you started keeping a logbook and introduce the *Mathematica* software which you will be using in several experiments this semester. The topic of this experiment is the helical spring. You may have done experiments on springs at school, so you may find some of this experiment familiar. However the main purpose here is to learn about *Mathematica* and practice keeping a logbook, making careful measurements and calculating uncertainties.

Skills

- Learn how to plan and carry out a simple experiment
- Learn to use *Mathematica* to perform simple calculations
- Learn how to graph experimental data and derive information from your graphs using *Mathematica*
- Learn how to calculate uncertainties

Experimental Aim

Find the spring constant for the spring provided.

Next, you will learn how to plot your data. First you have to enter your measured data which you can do like this:

`x:=`$\{x_1, x_2, x_3, \ldots\}$
`y:=`$\{y_1, y_2, y_3, \ldots\}$
`dy:=`$\{dy_1, dy_2, dy_3, \ldots\}$

to refer to individual elements of your data, for example you need the second x-value, `x[[2]]` will give you the corresponding number. If your data is equally spaced, you may not have to enter every point:

`x:=Table[{j,{ j,1,10}}]`
gives you a vector x with 10 entries ranging from 1 to 10 in steps of 1.
`x:=Table[{j,{ j,10,20}}]`
gives you a vector x with 11 entries ranging from 10 to 20 in steps of 1.
`x:=Table[{j,{ j,0,20,4}}]`
gives you a vector x with 6 entries ranging from 0 to 20 in steps of 4.

Once you have finished all the calculations, you have to put your data into an appropriate shape for plotting it:

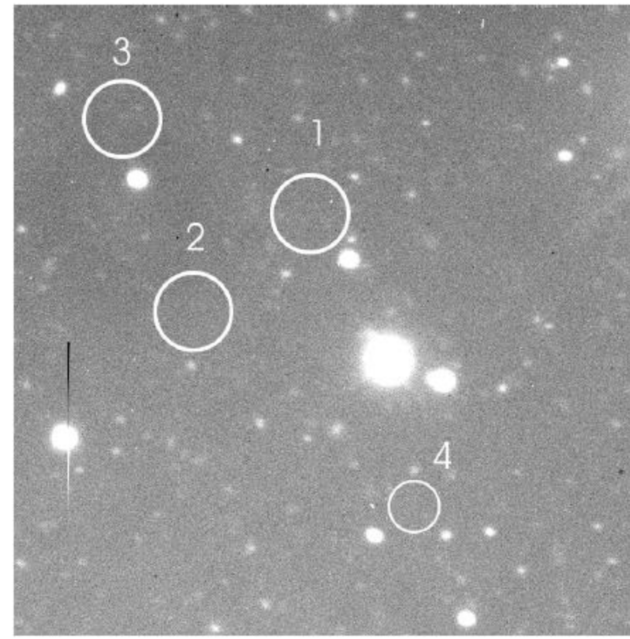
```
Needs["ErrorBarPlots`"]
plotdata:=Table[{{x[[j]], y[[j]]}, ErrorBar[
dy[[j]]]}, {j,1,Length[x]}]
```

You need to "treat" the uncertainties of your data with the function `ErrorBar` to make them ready for plotting. The command `Needs-["ErrorBarPlots`"]` loads the mathematica package that is needed to do plots with error bars. Please note the single quotation mark after

Lab 1: Find the Star

Learning Objective

This is a computational lab. Astronomical images will be plotted and analyzed using *Mathematica*. The aim is to acquire basic data handling skills and learn about uncertainties and noise.



Skills

- Analyze and visualize data with *Mathematica*
- Learn about improving the signal to noise ratio through averaging over multiple measurement.

Experimental Aims

Find out for a real astronomical photograph if there is a star (or a galaxy) in a certain spot.

Try to zoom in on one of those regions (do you still remember from your first lab - the helical spring - how to specify an index? You give a span of indices by `30;;40`). `Dimensions` will help you to find out how many pixels there are in the image.

Level 1 revised: excel in the lab

- **Dark energy lab**
  - Manipulating and plotting data in excel
  - Basic modelling

Part 4 – In Excel, plot the size of the universe as a function of time (with error bars).
Does it look as you expect?

Part 5 – Test the "Null Hypothesis" that the expansion rate is constant.
If you can disprove the null hypothesis, you will have good evidence that the expansion rate really is changing.

To do this, plot a model in which the size of the universe varies uniformly with time (i.e. Size versus time is a straight line).

Plot the model and the data in one graph and see whether the model is an acceptable fit.

Print out this plot and attach it to your logbook. Write down your conclusions and reasoning.

Level 1 revised: python in the lab

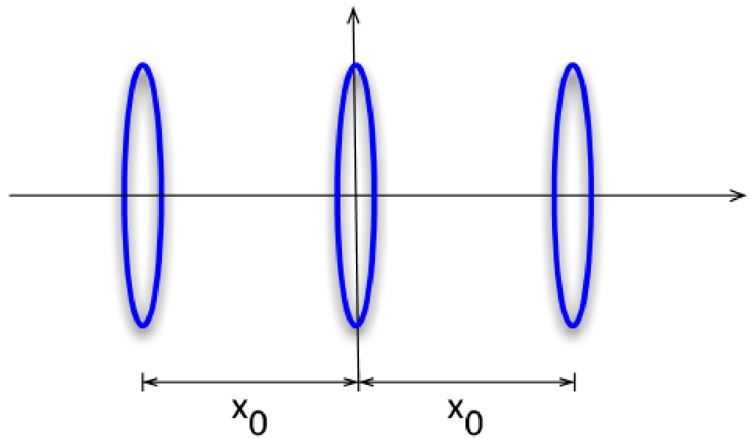
- **Quantum cryptography (real data)**
  - Importing data
  - Plotting
  - Modifying templates
- **Higgs boson (fake data)**
  - Importing data
  - Plotting
  - Handling arrays
  - Analysing data

Level 1: coursework

- **Electrostics**
  - Editing a template
- **Local magnetic fields**
  - More importing, plotting and analysing
  - Editing a template

2. The potential due to 3 rings:

In addition to the original ring at the origin, two more rings are added to the setup at positions $-x_0$ and $+x_0$ along the x-axis, as shown in the figure.



The left and right rings have the same radius R as the first ring but are positively charged with +Q. You can write the potential due to each individual ring as a function of the radius R, the location x_0, the ring charge, and the arbitrary point x. This is an example of how we define a function and use it:

```
f[x_, y_] := x^2 - y^2
```

```
f[1, -3]
```

Now, using your result for the single ring, define the functions Vleft, Vright and Vcentre for the potential for each of the 3 rings. Note that Vcentre is exactly the result you had before, it just needs to be written as a function (use the copy and paste here). You need a bit more thought for the other two rings, but not that much...

```
Vleft[] :=
```

Level 2: Chaos lab

1. The equation

The non – linear pendulum equation is :

$$g\,M\sin(\theta(t)) + L\,\gamma\theta'(t) + L\,M\,\theta''(t) \;=\; f\sin(\Omega t)$$

where g is acceleration due to gravity, L is the length of the pendulum, M is the Mass, γ is the damping, f is the magnitude of the driving force and Ω is the frequency of the driving force.

In this program you will look at *a* few different regimes of this equation and get *a* handle on how complex *a* "simple" pendulum can be.

2. Linear motion on resonance.

In this first example, we look at the simple (linear) pendulum. The motion is plotted in 4 ways!

```
equations =
  {M L θ''[t] + γ L θ'[t] + M g θ[t] == f Cos[Ω t], θ[0] == ipos, θ'[0] == ivel};
(* This is how we define the equation in Mathemetica.  The double
 "=" sign is used to make an equation.  A single equals sign just
 assigns a value. Each equation is separated by a comma.  The
 initial velocity and position are ivel and ipos respectively*)
```

Ex 1. Non-linear motion......

Using the above as template, compare the linear and non - linear pendula.

Level 2: Chaos lab

Ex 2. Transistion to Chaos

Change the drive frequency to 2/3, the drive amplitude to 1.2 and the damping rate to 6/100. Slowly reduce the damping rate to 5/100 and record what happens. Use the tools developed above to analyse the behaviour.

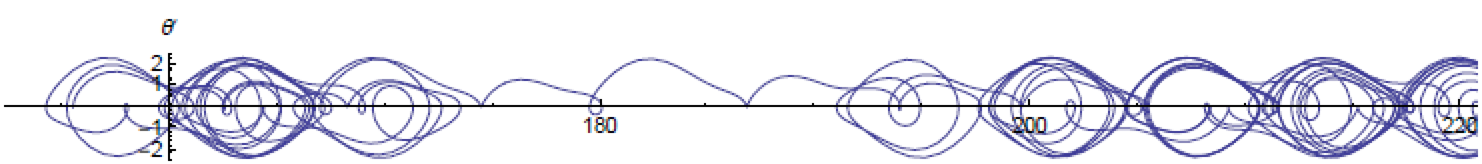
```
parameters =
  {M → 0.1, L → 10 , g → 10, f → 1.2, γ → 0.051, Ω → 2 / 3, ipos → 0, ivel → 0};
T = 2 π / Ω /. parameters;
equations = { M L θ''[t] + γ L θ'[t] + M g Sin[θ[t]] == f Sin[Ω t],
   θ[0] == ipos, θ'[0] == ivel} /. parameters
```

$$\left\{1.\ \mathrm{Sin}[\theta[t]] + 0.51\,\theta'[t] + 1.\ \theta''[t] == 1.2\ \mathrm{Sin}\left[\frac{2\,t}{3}\right],\ \theta[0] == 0,\ \theta'[0] == 0\right\}$$

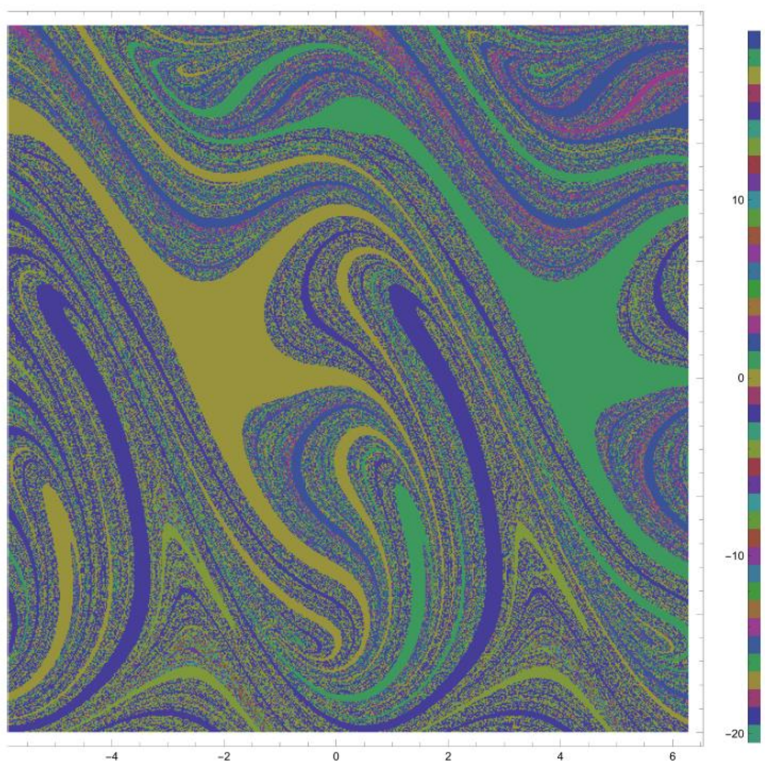
```
solution = NDSolve[equations /. parameters, θ, {t, 0, 20 000 T}, MaxSteps → 10^8 ]
```

{{θ → InterpolatingFunction[{{0., 188 496.}}, <>]}}

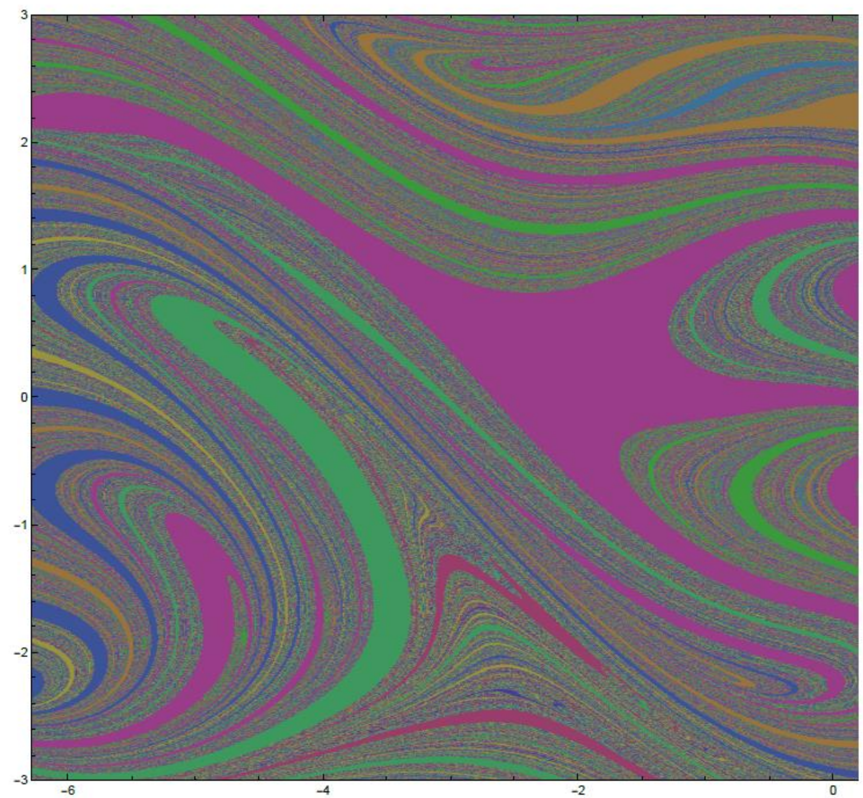
```
ParametricPlot[{θ[t], θ'[t]} /. solution,
 {t, 19 900 T, 20 000 T}, AxesLabel → {θ, θ'}]
```



```
basins = ParallelTable[
   parameters = {M → 1 / 10, L → 10, g → 10, γ → 10 / 1000, f → 1, Ω → 1};
   evolution =
    NDSolve[{equations /. parameters}, θ, {t, 0, 300 π}, MaxSteps → ∞];
   Round[θ[t] / (2 π) /. evolution /. t → 300 π][[1]],
   {ivel, -4, 4, 0.003}, {ipos, -4 π, 4 π, 0.003}];
(* This tablates the trajectories as a function of the initial conditions
 and figures out what phase the settle about. The number of point
 specified here takes a reaaaaaly long time to run with lots of cores.*)
```




```
(* here's an even bigger one that took dayas to make *)
```



Level 2: Racing robots with LabView

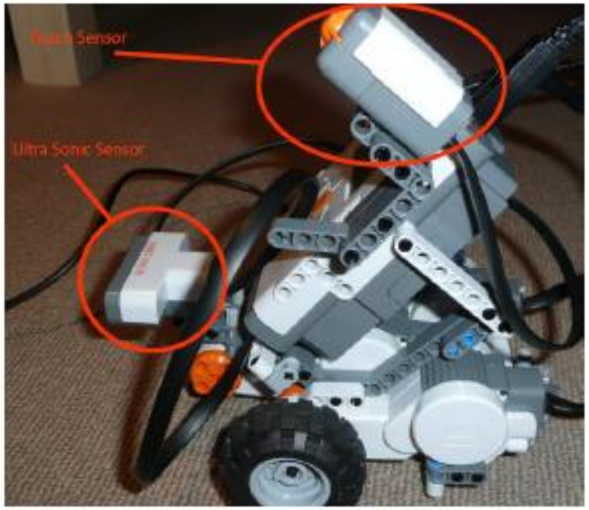
Aim

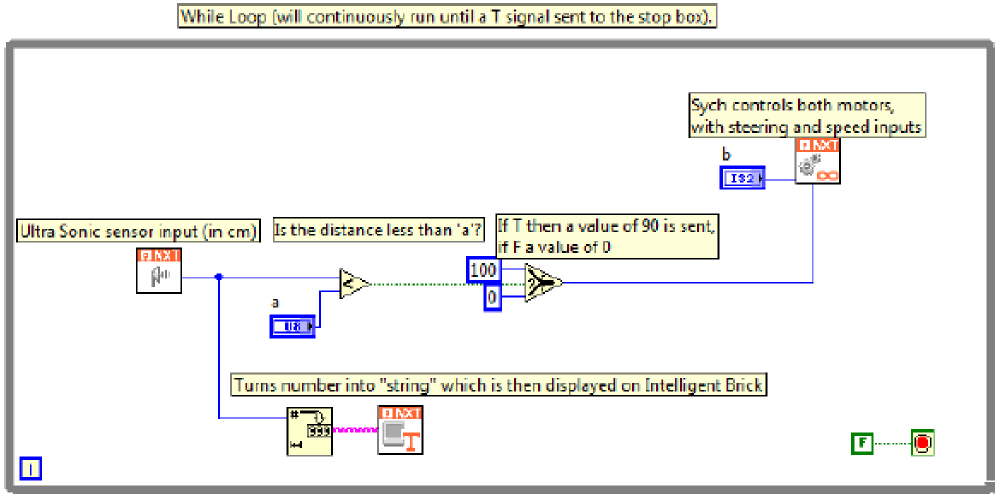
To create a robot that will follow the track provided as fast and as accurately as possible.

Learning Outcomes

Learn about and apply feedback control;

Develop basic LabVIEW programming skills;





Level 2: Coursework

- Quantum Mechanics
  - Plotting electron probability density distributions (infinite cuboid well)
  - Animating time-dependent states (ISW, HO)
  - Wave packets and Fourier transforms
- Electromagnetism
  - Calculating grads and curls
  - Plotting surfaces and field lines, e.g.

Q1. Plot the electric field lines and equipotentials for two point charges q_1 and q_2 when

(a) $q_1 = q_2 = +q$

(b) $q_1 = 4q_2$

(c) $q_1 = -q$

Q2. Now plot the field lines for three point charges with one of the point charges located on the y-axis ($y \neq 0$), midway between the other two charges on the x-axis. Assume that all are positively charged.

Level 2: coursework extension activities

Figure 1: Schematic of the MAGPIE reactor[3]

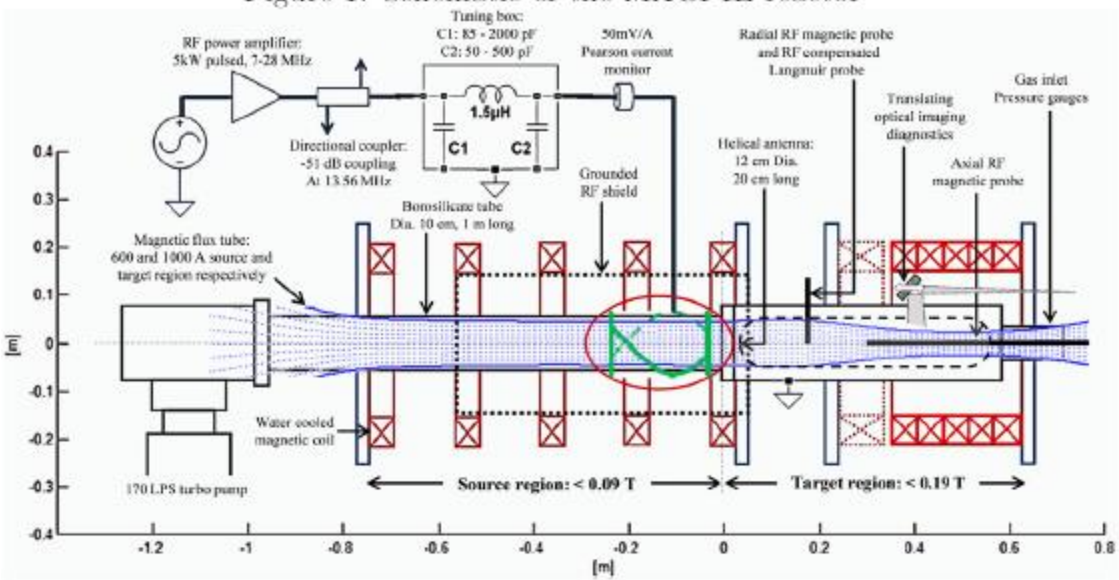
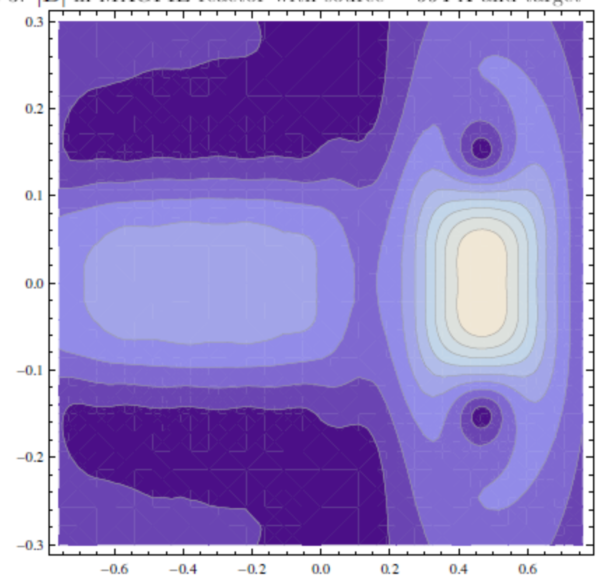


Figure 3: |**B**| in MAGPIE reactor with source = 994 A and target = 9



$$\mathbf{A}(x,z)_\phi = \frac{\mu_0}{4\pi}\frac{\pi a^2 I x}{\left(a^2+x^2+z^2\right)^{\frac{3}{2}}}\left(1+\frac{15a^2x^2}{8\left(a^2+x^2+z^2\right)^2}\right)(\hat{\mathbf{x}}+\hat{\mathbf{z}})$$

$$\mathbf{B}(x,z) = \left(-\frac{\partial A_\phi}{\partial z},\frac{\partial A_\phi}{\partial x}\right)$$

Level 3: coursework

- Theoretical physics computation project
  - Double pendulum or Duffing oscillator
  - Describe the system

    a) How many physical parameters are there? How many initial conditions?
    b) How many *important* combinations of parameters are there?
        (Hint: the important ones are dimensionless)
    c) Are there any stationary states of the system?
    d) If so, are they stable?
    e) How can you show that a system exhibits chaos?
    f) Under exactly what conditions does your system exhibit chaos?

  - Design ways to check numerical results
  - Identify key influencing parameters