Imperial College London

2nd Year Lab
Thermal and Electrical Waves Experiment

2022 – 2023

Charles Baynham and Richard Hobson (HoEs)

The physics

Why learn waves?

Waves → Sound

Heat

Light

Electronics

Gravitation

Quantum mechanics

Why learn waves?

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Part I

Fourier analysis

1 session

You will:

- Remind yourself how Fourier analysis is used to break down periodic signals into harmonics
- Write your own numerical integration algorithm

Part II

Thermal waves

3 sessions

You will:

- Use Fourier analysis to understand heat diffusion in a block of PTFE
- Apply your algorithm to temperature to extract the thermal diffusivity of PTFE
- Try different methods of data analysis

Part III

Electrical waves

4 sessions

You will:

- Learn how to use an oscilloscope
- Propagate pulses and waves through a lumped transmission line
- Understand reflection, dispersion and impedance

Part 1 – Fourier Analysis

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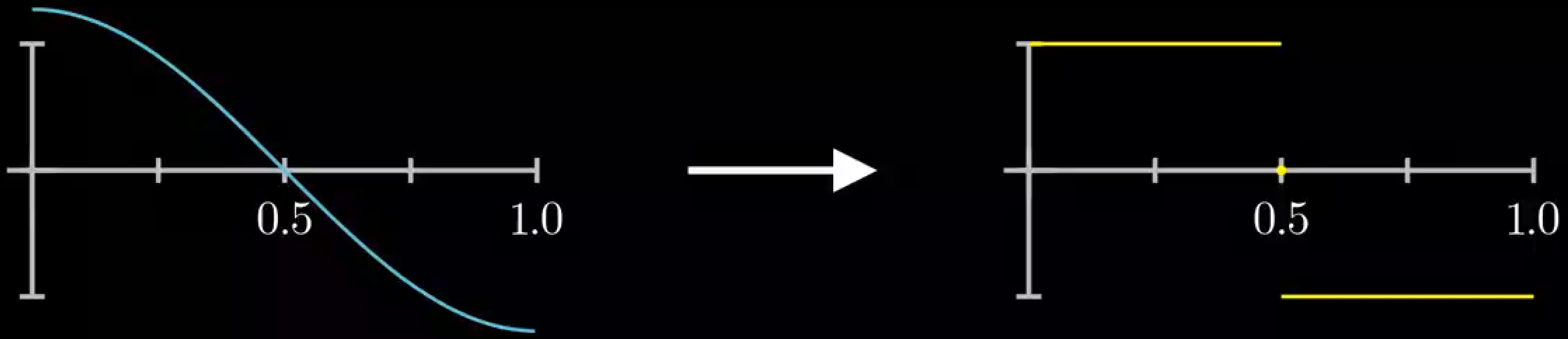


Animation from *"But what is a Fourier series?"* 3Blue1Brown YouTube series

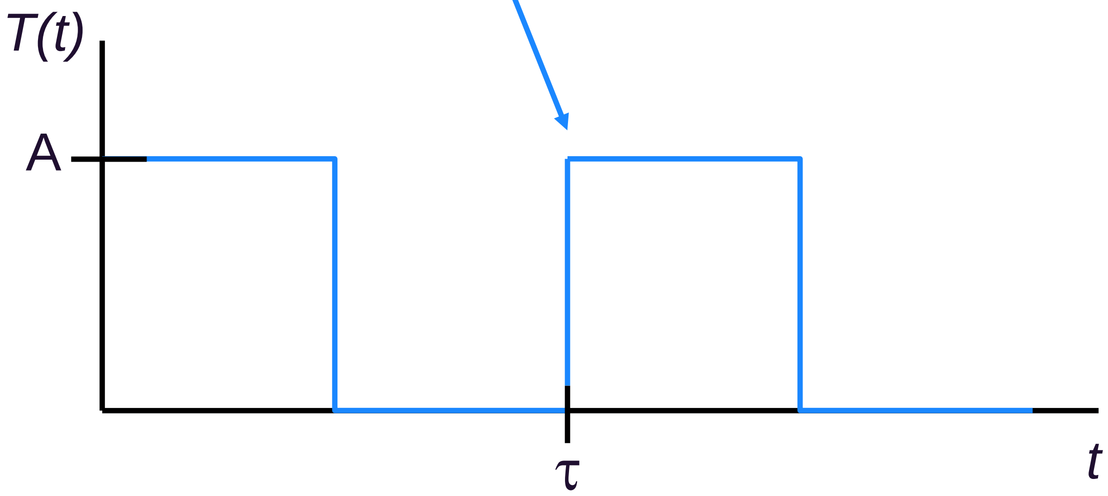
- Fourier series:

$$T(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cos\left(\frac{2\pi n}{\tau} t\right) + b_n \sin\left(\frac{2\pi n}{\tau} t\right)\right]$$

Your job today!

$$a_n = \frac{2}{\tau}\int_0^{\tau} T(t) \cos\left(\frac{2\pi n}{\tau} t\right) dt$$

$$b_n = \frac{2}{\tau}\int_0^{\tau} T(t) \sin\left(\frac{2\pi n}{\tau} t\right) dt$$



- ***What is the Fourier series of a perfect square wave?***

Practicalities

Who are we? Demonstrators and technical team

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Y2 Waves Demonstrators

Charles Baynham (HoE)

Richard Hobson (HoE)

Joseph Ovwemuvwose

Robbie Murray

Oliver Buchmuller

Sam Eardley

Ludovico Iannizzotto

Sergey Lebedev

Robert Bainbridge

Alice Josset

Anastasios Fasoulakis

Chiara Labanti

Maria Maxouti

Y2 Lab Technical Team

Graham Axtell

Ivan Hermida Estornell

Jay Hirani

How to succeed in the lab

- **Talk to your demonstrators**
  - We don't expect you to know everything. We don't know everything either! But we like to hear your questions
- **Use your time wisely**
  - This is your project. We are here to help you, but you are in charge of your time
- **Explore**
  - Experimentation is the heart of science, and understanding comes from the details
- **Add complete info in your lab books <u>as you go along</u>**
  - Someone else should be able to write your report and reproduce your results with only your lab book
- **Prepare in advance**
  - You should already know what you're going to do before you come into the lab
- **Really, talk to your demonstrators**
  - The demonstrators are here to help you and teach you. Ask us questions not just about the script but about any physics you're curious about!

The script and your OneNote lab book

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- The **script** has all the basic information you need to go through the experiment
  - **Appendix** at the end – useful info, e.g. math/physics derivations

- **Tasks throughout the script:** Key milestones, help with assessment and time keeping
  - These are not intended to be a list of questions you need to answer, but are a guide through the experiment that helps your demonstrators ensure you are on track

- **You must document your lab session work in your OneNote lab book in real time during each session**
  - This is part of your continuous assessment
  - Pen and paper approach? Not a problem! Take a photo / scan and paste into your OneNote
  - **We recommend a 'hybrid' approach**: some things easier typing, some others easier pen+paper, etc.
  - The lab PCs are set up for OneNote and python (Spyder) but you are welcome to use your own device

Resources in OneNote

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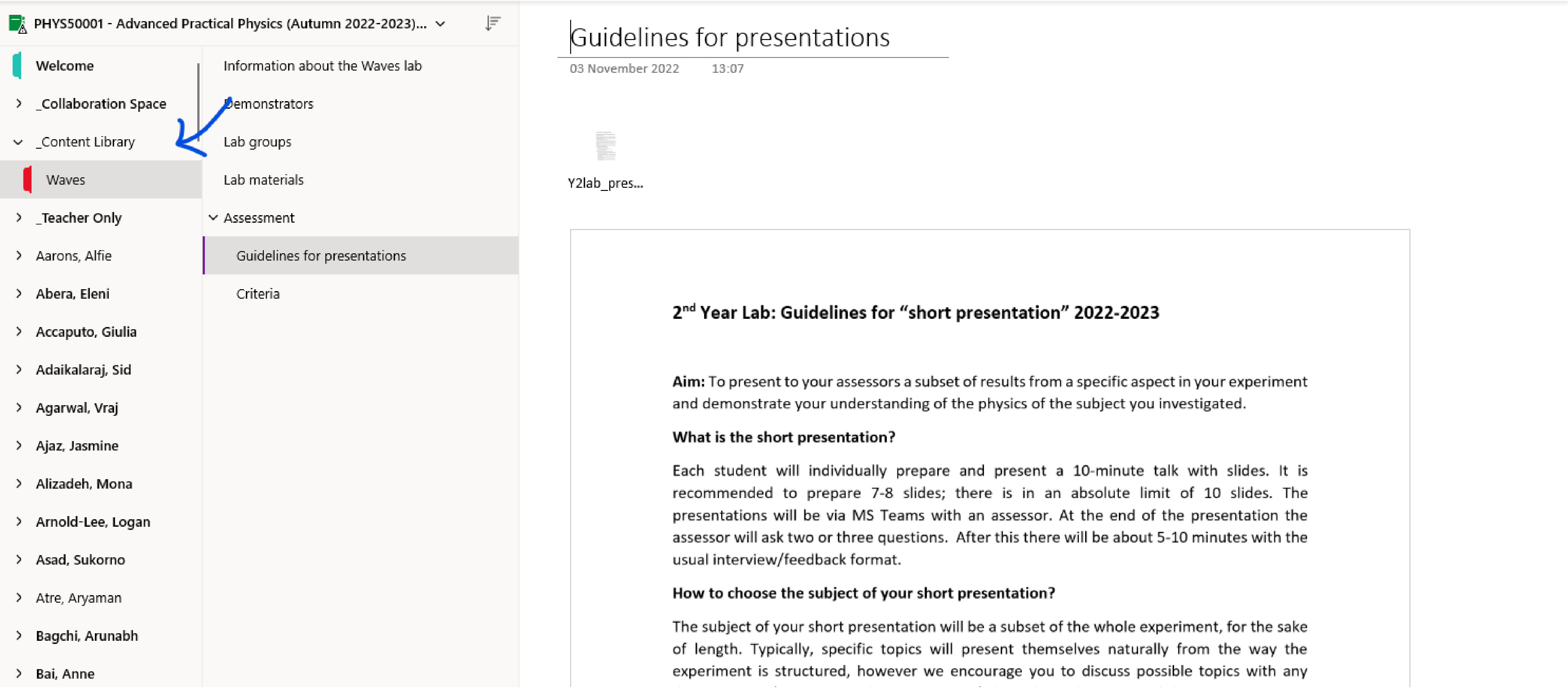

2nd Year Lab: Guidelines for "short presentation" 2022-2023

Aim: To present to your assessors a subset of results from a specific aspect in your experiment and demonstrate your understanding of the physics of the subject you investigated.

What is the short presentation?

Each student will individually prepare and present a 10-minute talk with slides. It is recommended to prepare 7-8 slides; there is in an absolute limit of 10 slides. The presentations will be via MS Teams with an assessor. At the end of the presentation the assessor will ask two or three questions. After this there will be about 5-10 minutes with the usual interview/feedback format.

How to choose the subject of your short presentation?

The subject of your short presentation will be a subset of the whole experiment, for the sake of length. Typically, specific topics will present themselves naturally from the way the experiment is structured, however we encourage you to discuss possible topics with any

Lab attendance and absences

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- Please be on time
- Please sign in the attendance sheet in the lab at the start of each session
- Any absences please email the HoEs beforehand (c.baynham@imperial.ac.uk or r.hobson@imperial.ac.uk), fill in the form on Blackboard and inform your lab partner that you will be absent

Assessment

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Report:

- For this lab, reports will be given as 10-minute presentations
- You will have 3 working days to submit your slides from the end of your last session
- Before this, you will be contacted to arrange a time

Continuous assessment:

- You will also receive a mark for your work in the lab, including your note-taking skills
- One demonstrator will be assigned to you personally

PLEASE CHECK YOUR E-MAILS

Why learn waves?

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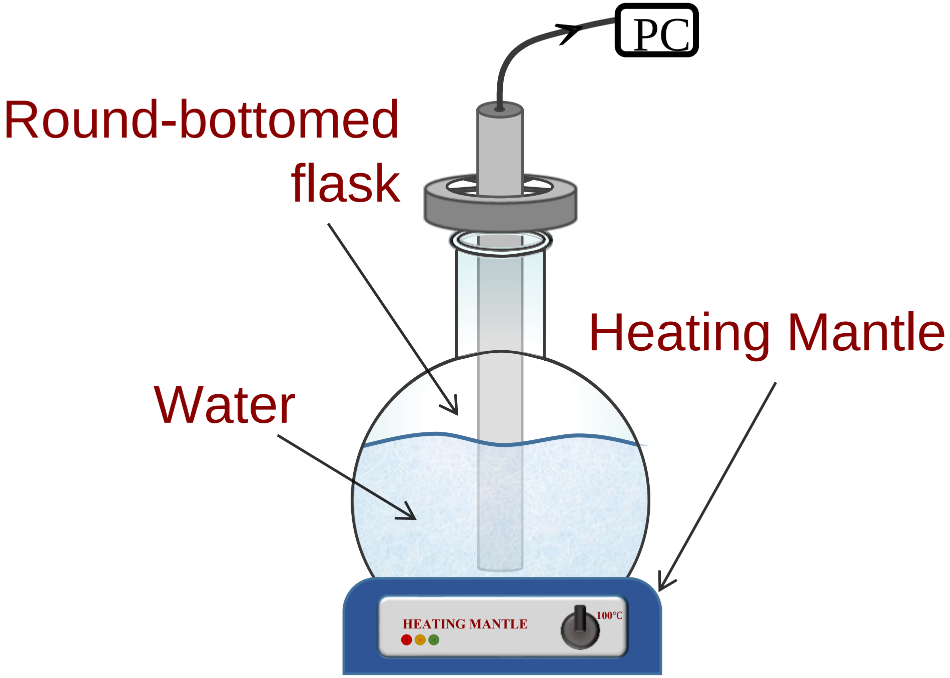
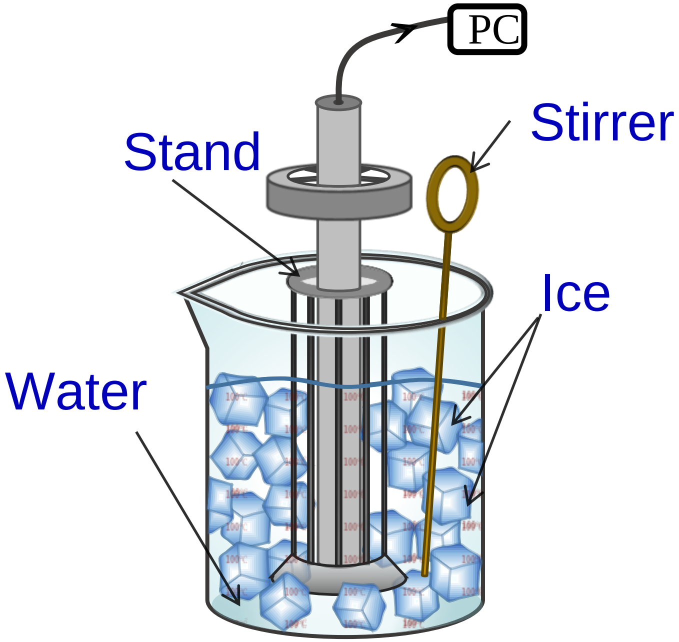
Thermal Waves – Diagrams in the script

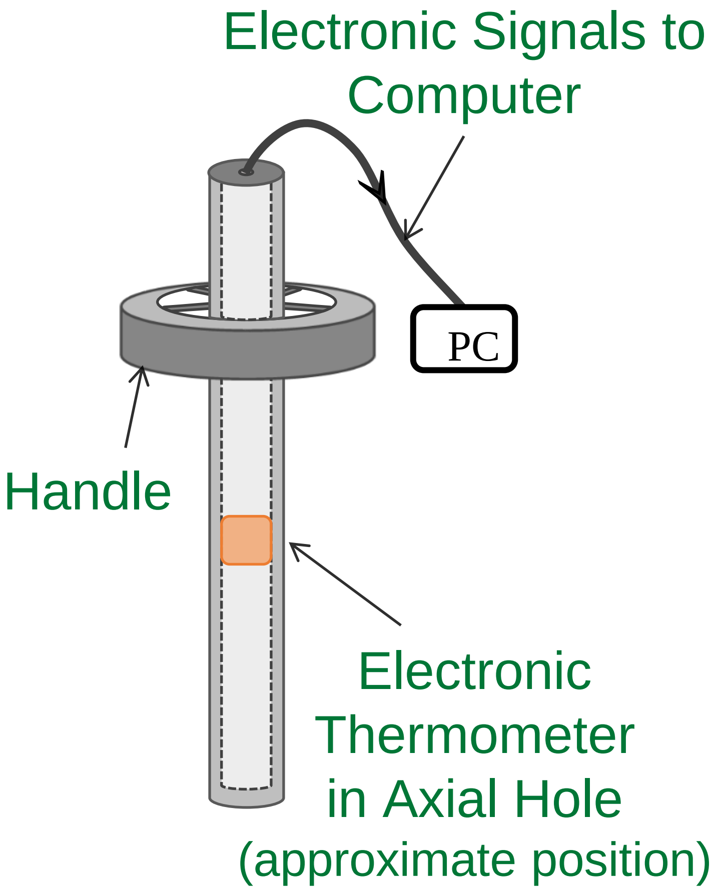
HOT BATH (100˚C)



COLD BATH (0˚C)



PTFE CYLINDER



How was the data taken?

Part 2 – Thermal waves

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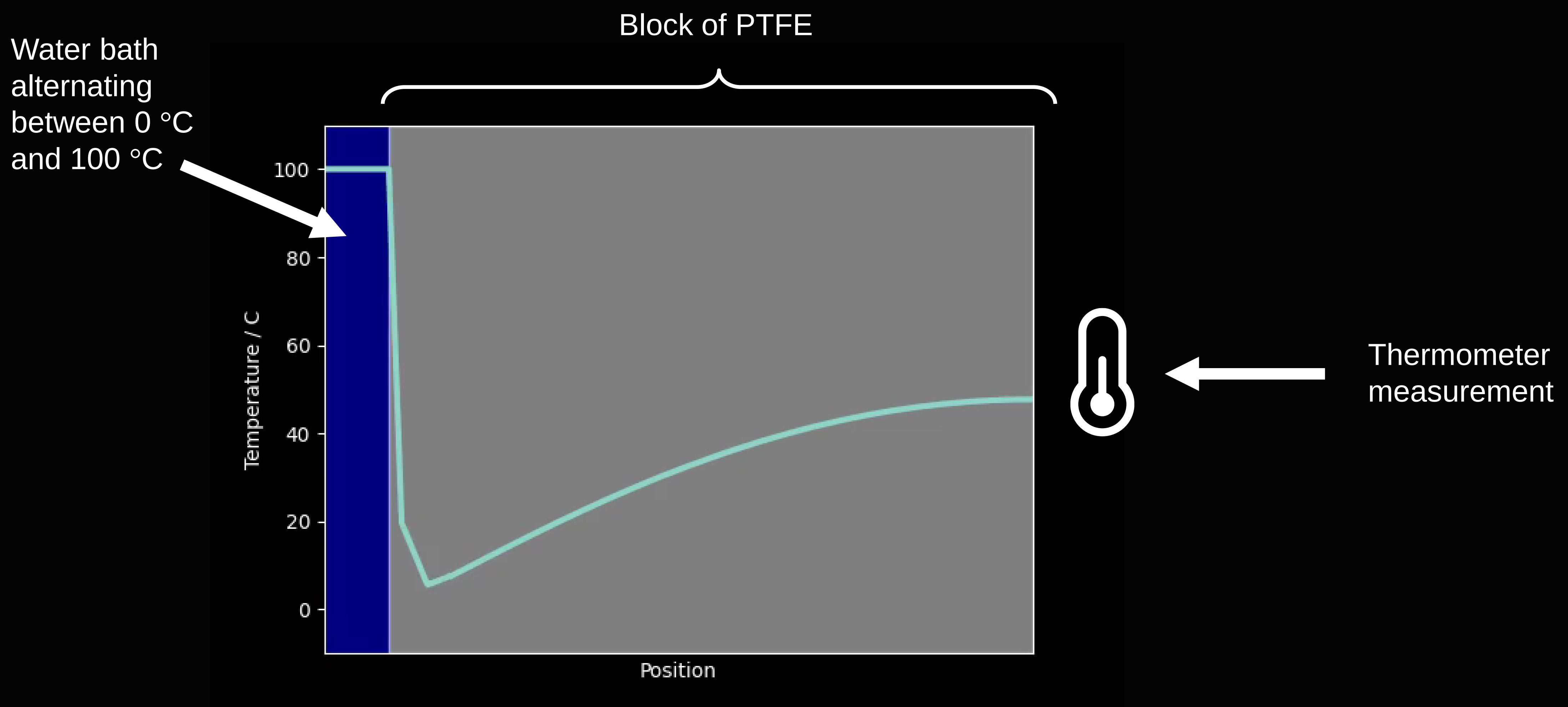

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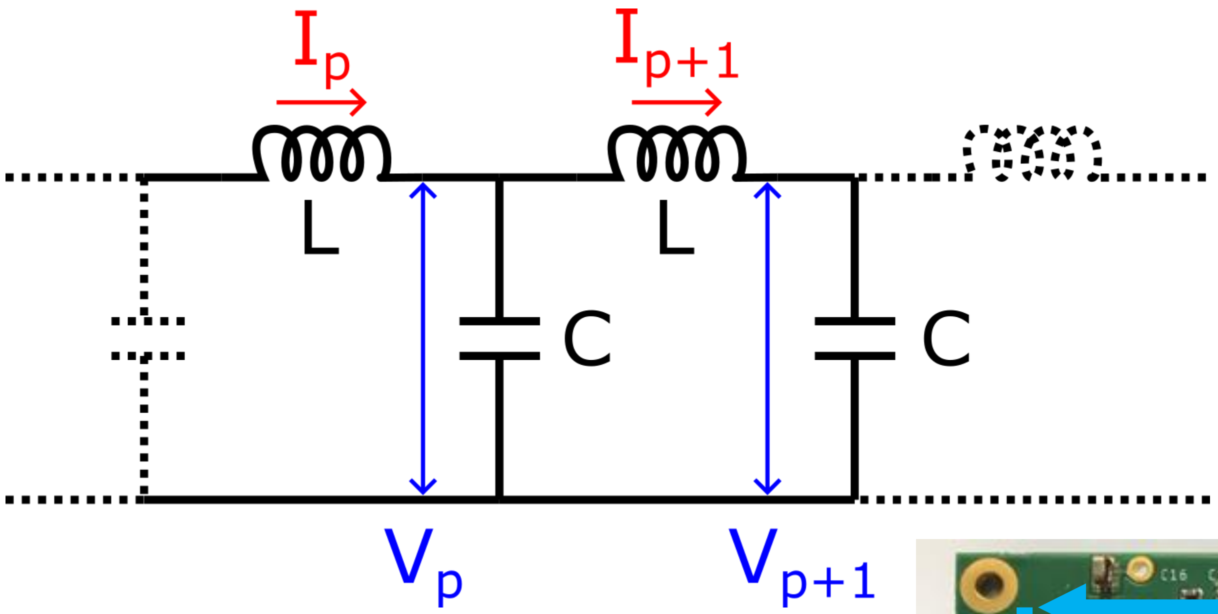
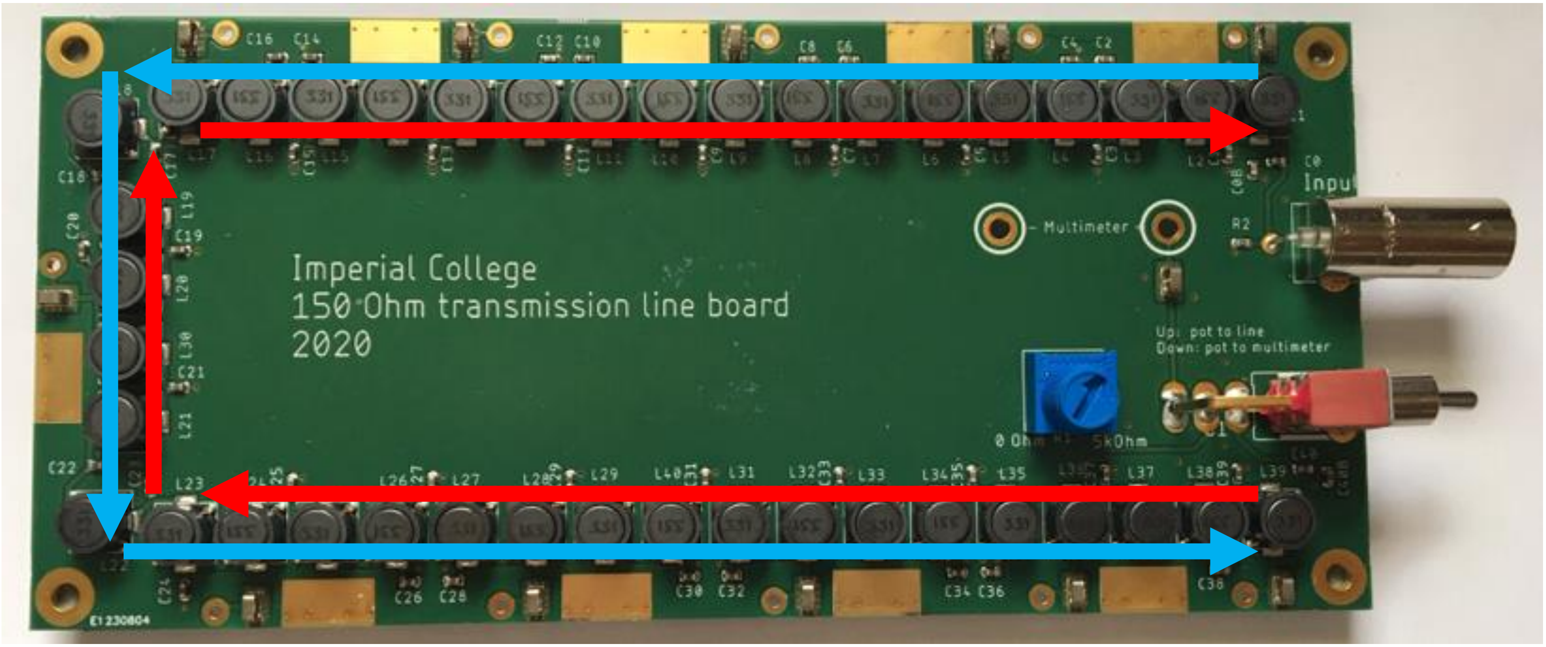


A "lumped transmission line"



Recap / intro slides

Session 1:

Fourier analysis and numerical integration

Session 1: Fourier analysis and numerical integration

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- **Numerical integration:** Aim is to understand how it works and develop a ‘simple’ numerical method that you can apply to your data in Thermal Waves

$$T(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[a_n \cos\left(\frac{2\pi n}{\tau} t\right) + b_n \sin\left(\frac{2\pi n}{\tau} t\right) \right]$$

$$a_n = \frac{2}{\tau} \int_0^{\tau} T(t) \cos\left(\frac{2\pi n}{\tau} t\right) dt$$

$$b_n = \frac{2}{\tau} \int_0^{\tau} T(t) \sin\left(\frac{2\pi n}{\tau} t\right) dt$$

- Built in integration -> **Black box** -> not useful! -> **We want you to develop your own** ~~code~~ **analysis tool**
- What ‘language’ to use? **Anything** as long as you can show us your procedure and test that it works (**Excel**, Python, Google Sheets…)

- **Test functions: Semi-circle or sine wave ->** Download from Blackboard

Session 1: Fourier analysis and numerical integration

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- Expected goals for this session: Entire Part 1 (Tasks 1.1 – 1.3)

- **If you can't finish during the session, you'll need to catch up before the next session (*)!**

(*) The expectation is that you spend roughly the same numbers of hours outside the lab

We'd much rather you spend time preparing for next session rather than catching up!

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Recap / intro slides

Sessions 2-4:

Thermal Waves experiment

Session 2: Thermal Waves (1 of 3)

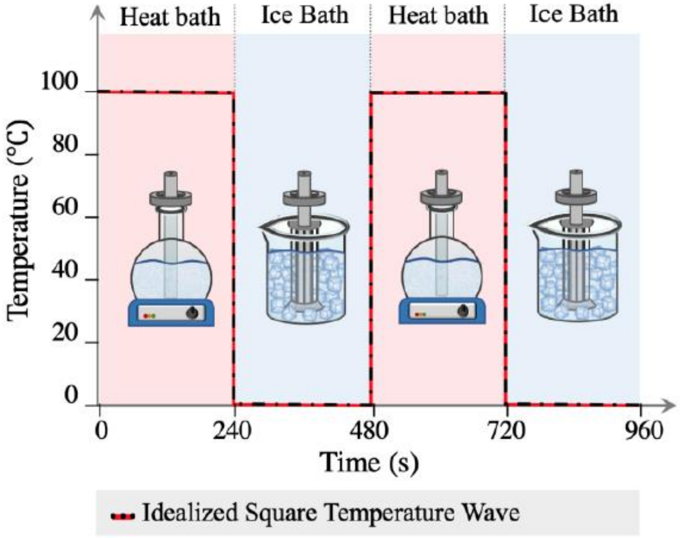
Recap of Session 1:

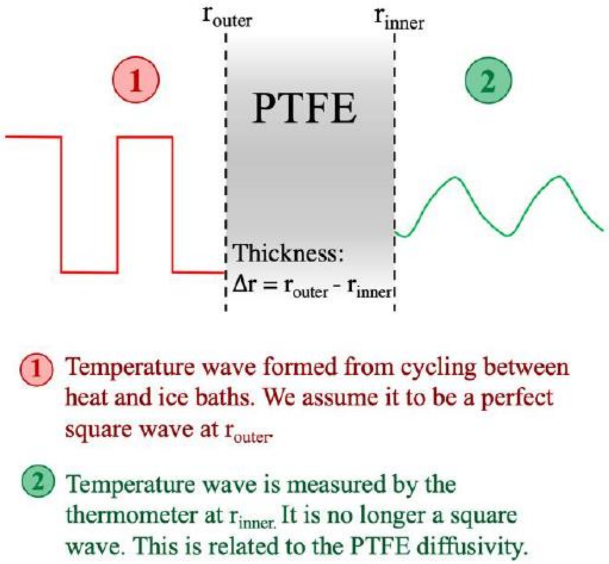
- *You have analysed a square wave into its* ***Fourier components***
- *You have a method to perform* ***your own numerical integration of a dataset***
- ***You have talked to your demonstrators (or vice versa!)***

Thermal Waves experiment

- Your overall goal with this experiment is to **obtain a measurement of the thermal diffusivity *D*** of a material
- The material? PTFE -> *Teflon* (also a TM brand)

- How? Launch a 'thermal wave' through a PTFE cylinder



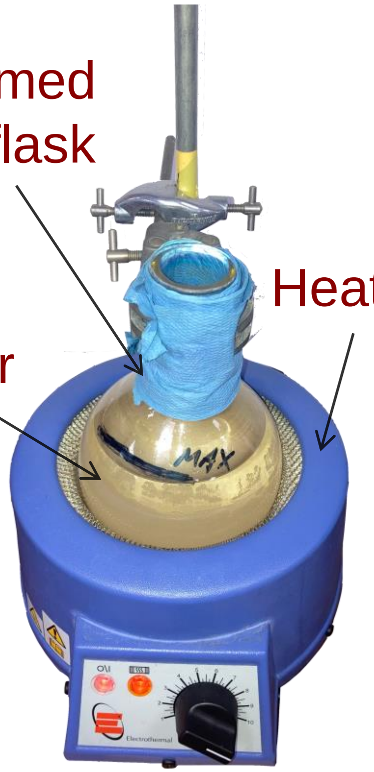


Analysis of experimental data + model of heat transfer -> *D* (with uncertainties)

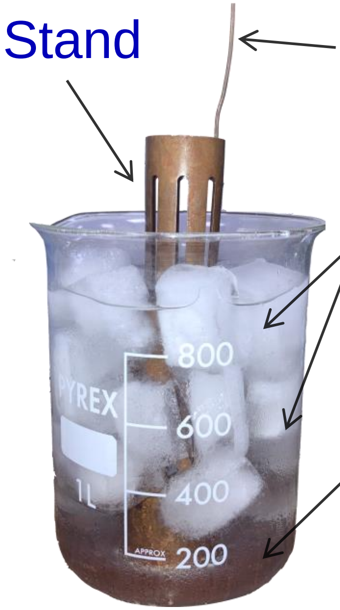
Thermal Waves – Equipment used in the Lab

THERE IS AN EXPERIMENTAL APPARATUS ON DISPLAY APPARATUS IN 2nd YEAR LAB

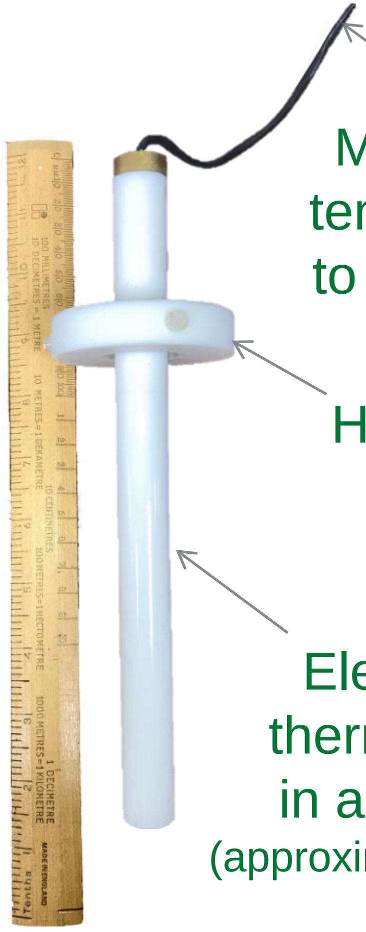
HOT BATH (100˚C)



COLD BATH (0˚C)



PTFE CYLINDER



Thermal Waves – Diagrams in the script

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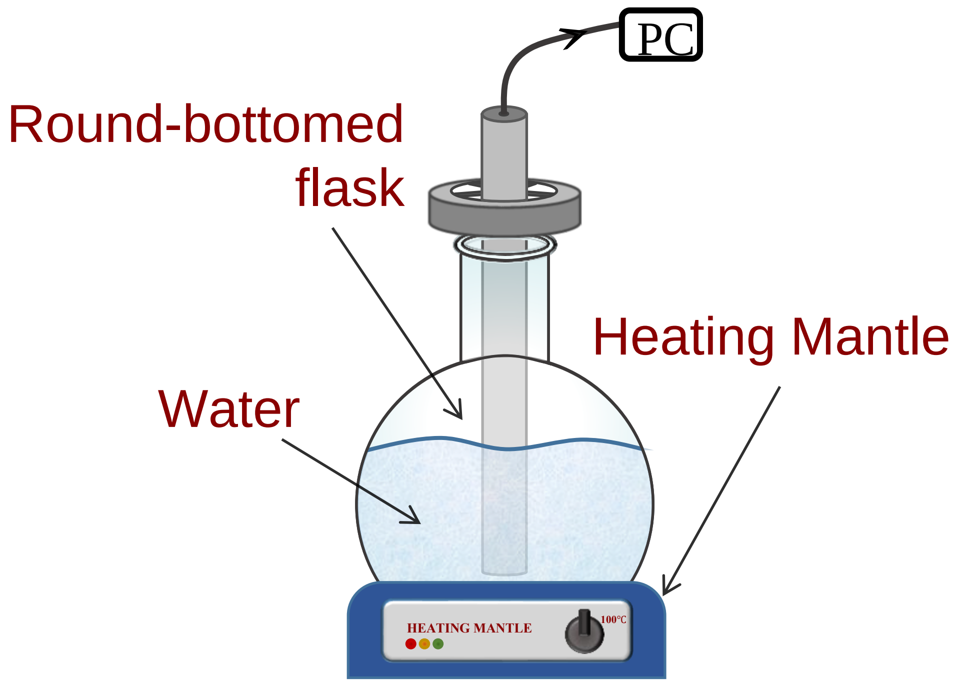

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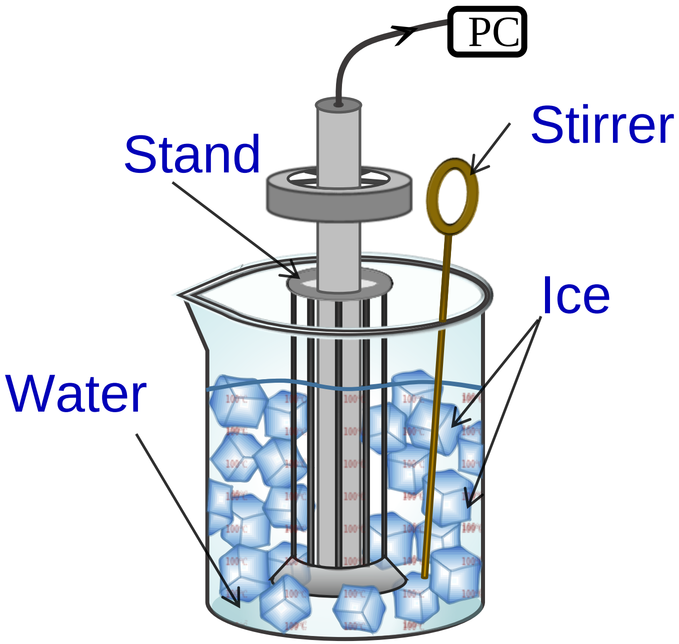

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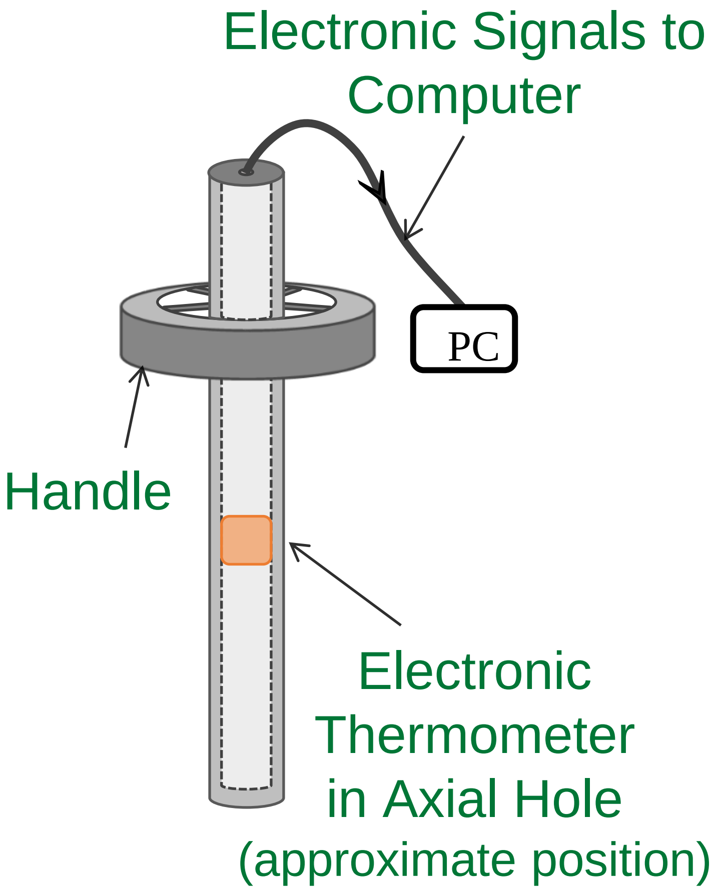

Thermal Waves – Experimental method

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RUN SLIDE IN FULL SCREEN TO PLAY MOVIE

This short clip shows the cycling of the cylinder between the hot and cold baths.

- Note that when in the cold bath, the ice-water mixture is constantly stirred to avoid the build up of a warmer layer of water in the vicinity of the PTFE cylinder.

- No stirring is needed in the hot bath due to the rising bubbles from the boiling water.

- The program used for data acquisition produces two beeps:
  1) the first one when there's 4s left in the bath
  2) the second one when it is time to change the cylinder from one bath to another

Thermal Waves – Data Acquisition Software

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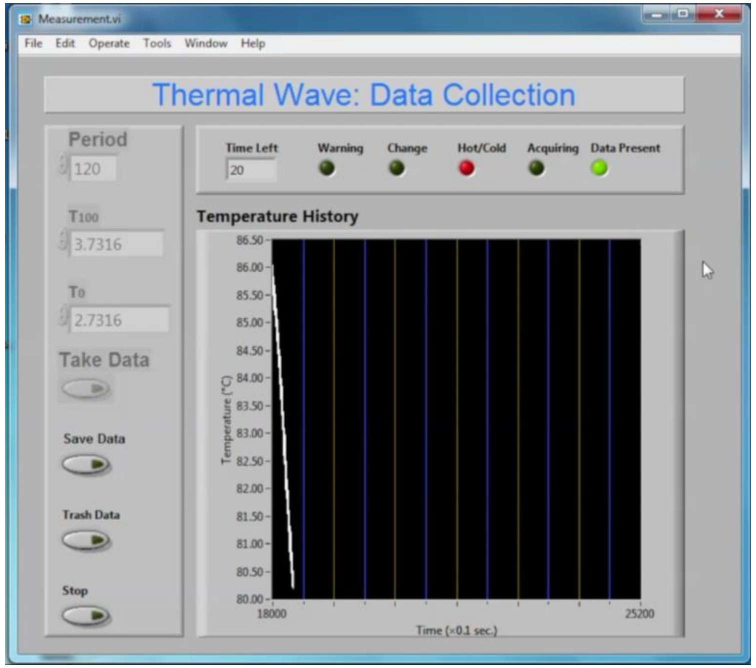
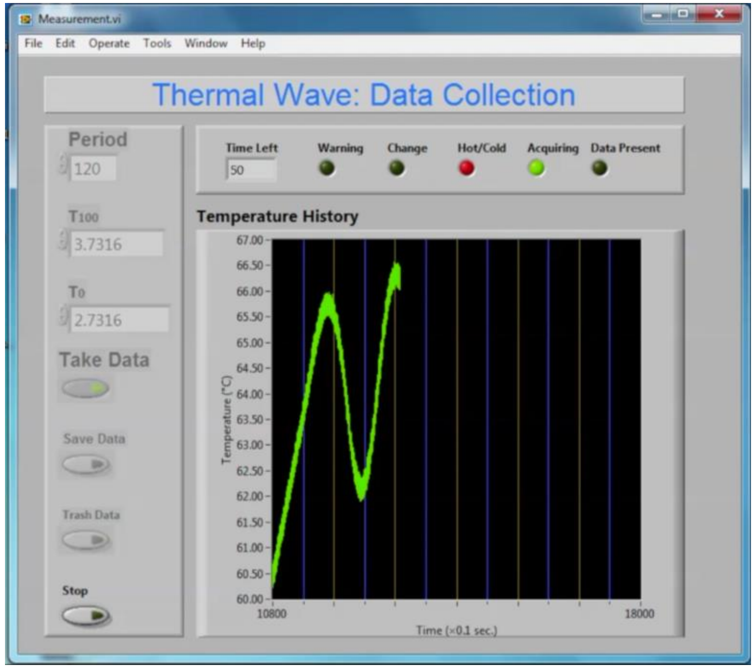
RUN SLIDE IN FULL SCREEN TO PLAY MOVIES

These short clips show how the data acquisition software looks like.

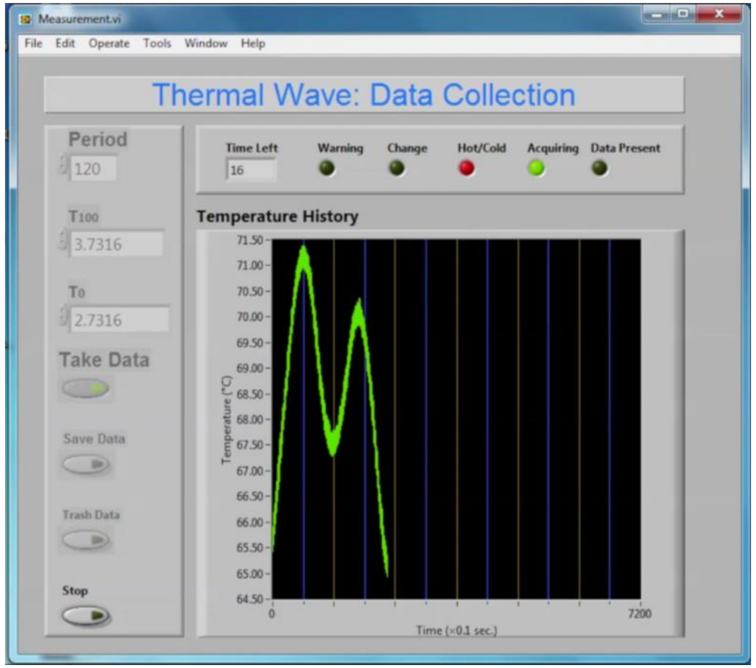
(recorded for a square wave period of 2 min. and 20x speed)



Strong temperature transient



Strong temperature transient



Slightly more stable

Session 2: Thermal Waves (1 of 3)

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- **Expected goals for Session 2:**
  - Learn basics of theory behind heat equation
  - Understand the experimental setup and its assumptions
  - **Focus on 4 min data -> First 'back of the envelope' estimate for thermal diffusivity D**
  - Plot your datasets adequately, understand the main physical phenomena from the data

- **Tasks:** Up to **Task 2.4 …**ideally

- Remember: **Lab book (log book)** -> ~~answer sheet~~ -> info/data/results **IN CONTEXT**

Session 3: Thermal Waves (2 of 3)

Recap of Session 2:

- *You know the basics of the experiment and theory / model to measure D.*
- *You have plotted your datasets and observed the main 'trends' and how they are linked to your model.*
- *You have done a first **'back of the envelope' analysis** of thermal data to get D, and your value is consistent with the expected value found in the literature.*
- *You now know **how the lab interaction works and how to manage your time in the lab***

Session 3: Thermal Waves (2 of 3)

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- **Expected goals for Session 3:**
  - Apply ‘back of the envelope analysis’ to other datasets besides 4 min data
  - Do **Fourier analysis of 4 min data**, obtain D and compare with first estimates
    - *Numerical integration needed here!*
  - Apply Fourier analysis to other datasets

- **Tasks:** Up to **Task 2.7**
  - *MAKE SURE YOU EXPLAIN **CLEARLY** YOUR BACK OF THE ENVELOPE ESTIMATES*
  - ***GETTING FOURIER RIGHT IS A PRIORITY***

- Remember:
  - Let’s see more physics discussions, don’t just answer the tasks!

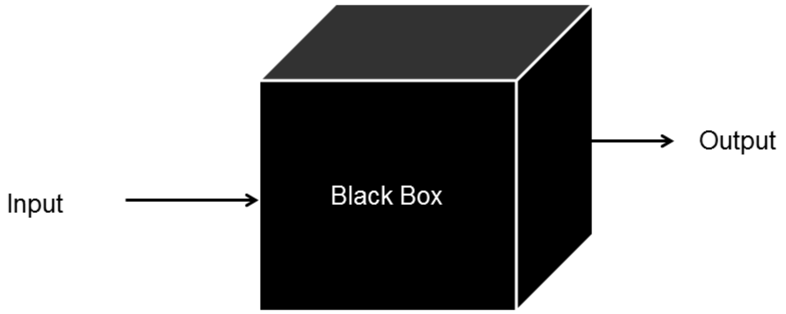
Session 4: Thermal Waves (3 of 3)

Recap of Session 3:

- *You now have several (probably different) values of D from analysing datasets with varying heating/cooling periods from:*
  - *Rough 'back of the envelope' analysis*
  - *Fourier analysis (* ***not only the fundamental frequency*** *)*
- *By plotting your results of D, you are getting an idea of the main trends and the uncertainties associated*

Session 4: Thermal Waves (3 of 3)

- **Expected goals for Session 4:**
  - Continue your **<u>Fourier analysis of datasets with different periods</u>** and obtain *D* from:
    - Transmission factor
    - Phase lag
    - Different harmonics
  - Use **<u>your measured Transmission factors and Phase lags</u>** and get *D* using Bessel calculators (Excel or Python)
  - **<u>Get a ‘final value of D’</u>** and its uncertainty



~~*Internal behavior of the code is unknown*~~

Not true! You can look into the code if you want

- **Tasks:** Continue **Task 2.7**, plus final **Task 2.8**

Recap / intro slides

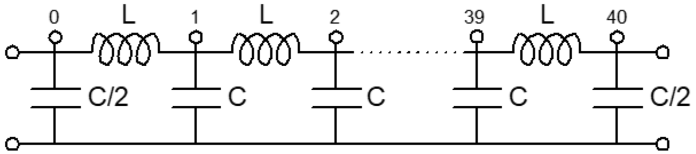
Sessions 5 - 8:

Electrical Waves experiment

Electrical Waves experiment

- Your overall goal with this experiment is to **understand the propagation of waves in a transmission line.**
- ***Transmission line?*** A medium to transport radio frequencies (RF) -> basically **a cable**
- ***How?*** Send waves with different frequencies through a cable and measure their behaviour

Real RF cable (RG-59U)



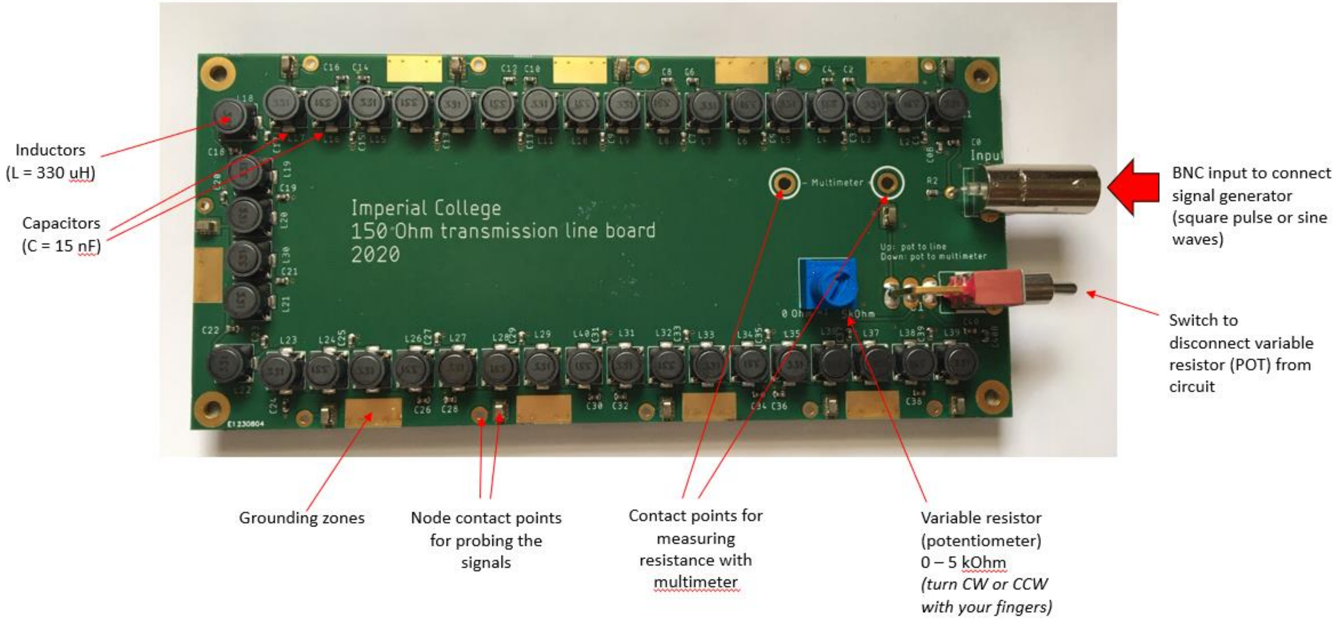
Model of RF cable (Lumped transmission line)

Measured wave behaviour + Model of cable -> Frequency response -> dispersion

e.g. you will be (amongst other results) plotting your measured dispersion relation

Electrical Waves experiment

Lumped transmission line circuit



(*) Although all circuits are identical, the L & C components have values with uncertainties
-> thus expect slightly different behaviour between your kits

Rohde&Schwarz oscilloscope with built-in signal generator

Session 5: Electrical Waves (1 of 4)

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- **Expected goals for Session 5:**
  - Go through basics of 1-D wave equation
  - Understand some relations of the transmission line (V_{phase}, Z_0, wave reflection)
  - Set up the experiment – understand main components, test that everything works
  - Measure the **behaviour of a square pulse through the line** (*sounds familiar…?*)

- **Tasks: Task 3.1 – 3.3**

- Remember: **information in your lab book needs to be written IN CONTEXT**

Session 6: Electrical Waves (2 of 4)

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- **Expected goals for Session 6:**
  - Measure the characteristic impedance of the transmission line Z_0 (uncertainties)
  - Measure the speed of propagation of a square pulse (uncertainties)
  - Characterise the pulse distortion

- *Square pulse, distortion, dispersion and reflection?* Play video between 1:06 – 1:52
  https://youtu.be/KbmOcT5sX7I?t=66

- **Tasks: Task 3.4 – 3.6**

Session 6: Electrical Waves (2 of 4)

Recap of previous session:

- *You know how to operate the oscilloscope and you have set up your experiment*
- *You have sent a 'single' square pulse through your lumped transmission line and have observed the effects of pulse reflection and distortion*

Session 7: Electrical Waves (3 of 4)

- Remember that one of the main experimental results is **the dispersion relation of the transmission line $\omega(k)$**

- **Expected goals for Session 7:**
  - Sine waves **<u>with variable frequency</u>** (AC) instead of square pulse (single ‘low’ frequency, DC)
    - Measure the wavenumber k
    - Measure phase differences at the beginning & end of the line
    - Measure voltage amplitudes at the beginning & end of the line

- **Tasks: Task 3.7 (data measurements – long!) – 3.8 (data plotting and analysis)**

Session 7: Electrical Waves (3 of 4)

Recap of previous session:

- *You have finished investigating the square pulse through the transmission line*
- *You have measurements of Z_0, V_{phase} (with uncertainties) and have compared them with expected theoretical values (also with uncertainties!)*
- *You have observed the distortion of the perfect square pulse and can explain it in terms of its Fourier components*

Session 8: Electrical Waves (4 of 4)

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- **Expected goals for Session 8:**
  - Finish measurements with sine waves -> **Wrap up the whole experiment**
  - Obtain plots of:
    - Dispersion relation of the transmission line (ω vs k)
    - V_{phase} and V_{group} vs frequency
    - Amplitude ratio vs frequency -> *check that you have enough 'resolution'!*
    - Measured vs theoretical cut-off frequency (with uncertainties)

- **Tasks:** Continue **Task 3.8:** Data plotting and analysis

  Task 3.9: Differences and similarities between the Thermal and Electrical Waves experiments.

Session 8: Electrical Waves (4 of 4)
Last session of the whole experiment!

Recap of previous session:

- *You have started to look at the behaviour of sine waves with varying frequency in your transmission line circuit*