3D Printing of Magnetic Multi-Material Hydrogels

IIB Project Midterm Presentation ~ Nanoscience Centre, Cambridge

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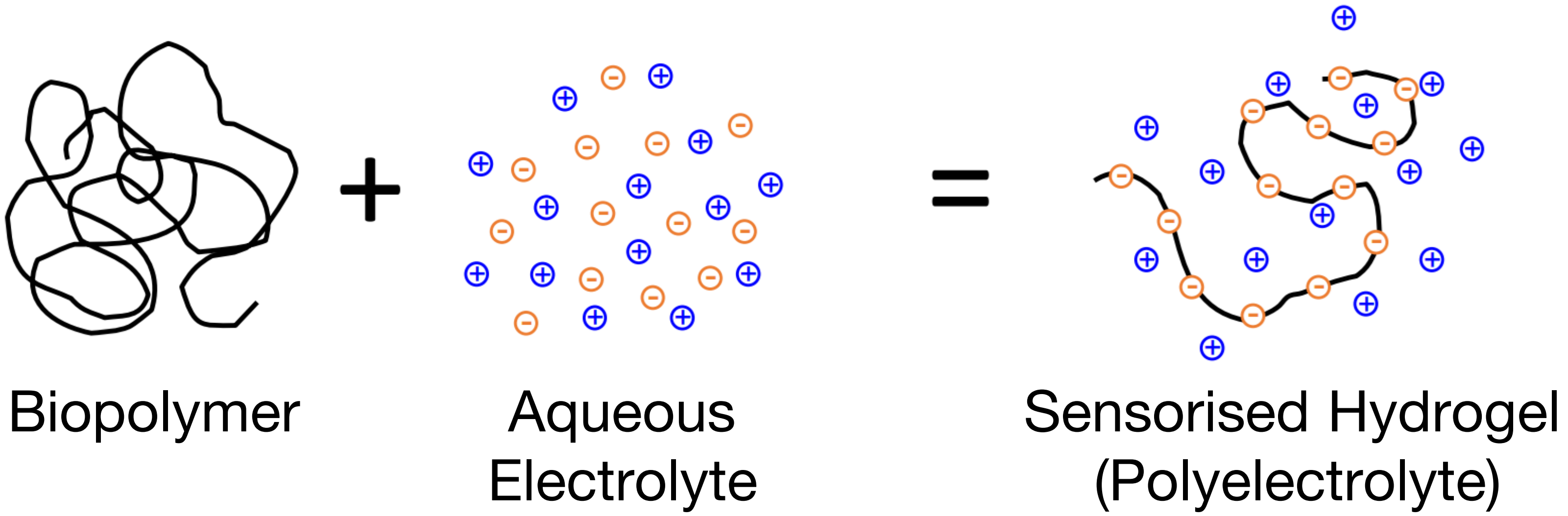
Presentation Outline

Introduction

What is the motivation for the project?
What's in the literature so far?

Responsive Hydrogels

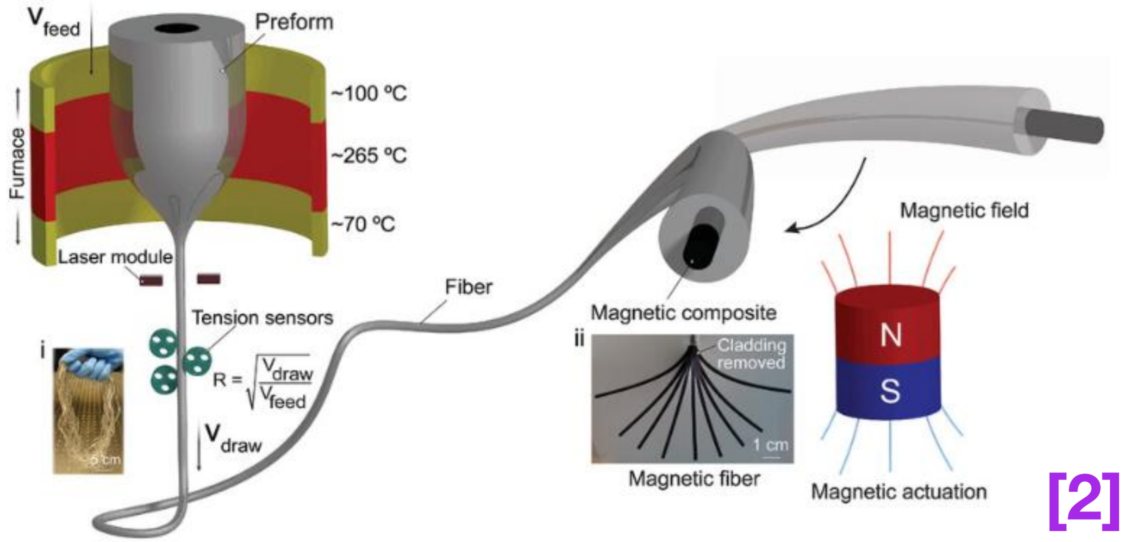
Materials that deform under external stimuli



Hydrogels are highly flexible, biocompatible, bioresorbable materials. They are used extensively as scaffold materials in tissue engineering. [1]

Actuation of Hydrogels

Uses magnetic fibre composites to move the hydrogel remotely



[2]

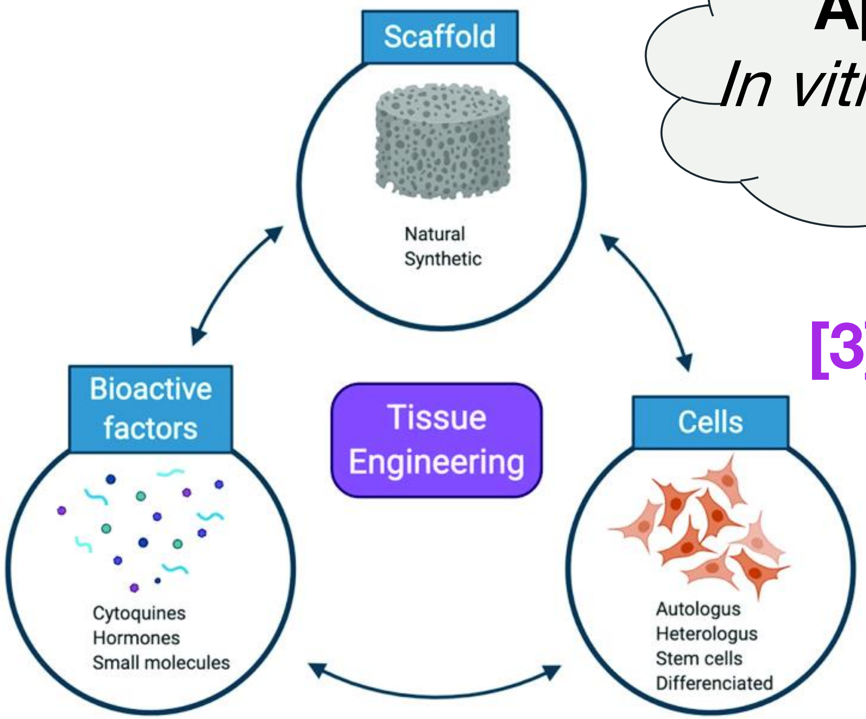
Thin magnetic fibres deform in the presence of an electromagnet.

A hydrogel in contact with the fibres is constrained to move with it.

Since the stiffness of the fibres is much higher than the stiffness of the hydrogel, the fibres are able to push the hydrogel into a shape that we can control.

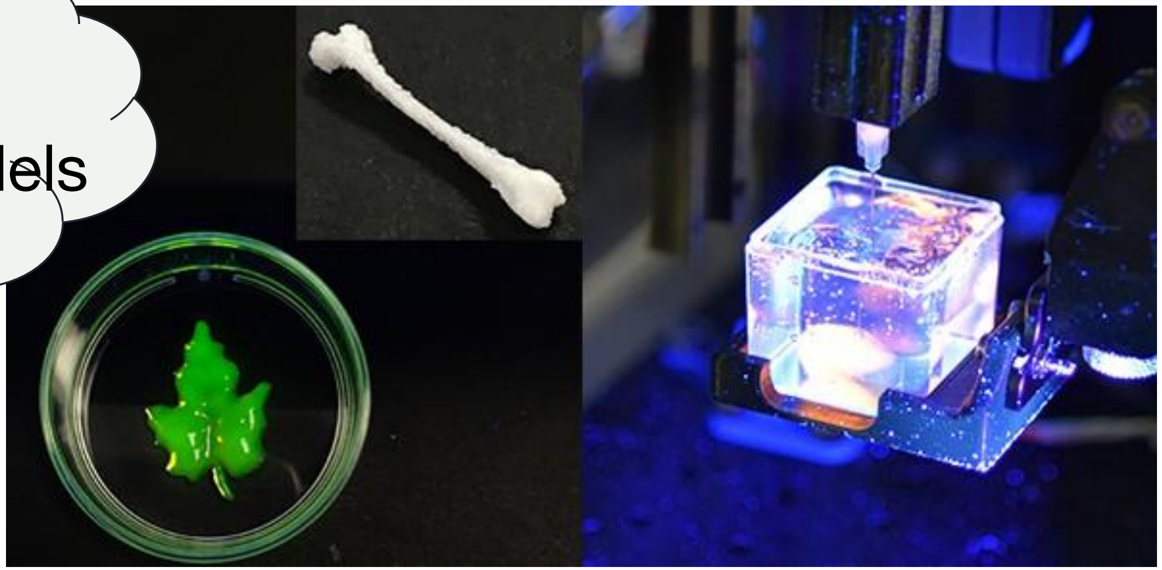
In Vitro Modelling of Organ Tissues

Implants that become part of a person's natural tissues over time



[3]

Application:
In vitro lung models



Shery's group has already built a 3D bioprinter (Printer.HM) for extruding soft materials in the Nanoscience centre. [4]

Project Goals

Optimise and synthesise the magnetic fibres
Print and integrate the hydrogel composite
Test mechanical properties of the system

Michaelmas - Magnetic Fibres

Ansys Granta | Solidworks | Comsol | Cura

Microscopy

3D Printing

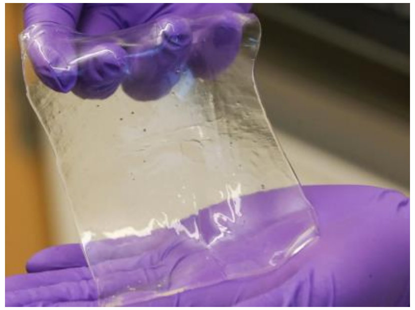
Perform structural analysis, material selection and computational modelling

Make different compositions of magnetic fibres

Aim to find the stiffest material that can deform under a magnetic load

Lent and Easter - Hydrogel Printing

Forming and Testing the Hydrogel Composite



Lent

Synthesise a biocompatible hydrogel

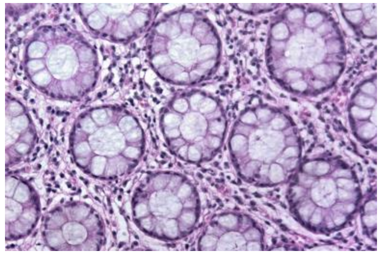
Use Printer.HM to print the hydrogel onto the best magnetic fibres

Measure flexibility of the system with an electromagnet

Easter

Print a model lung tissue seeded with epithelial cell culture

Demonstrate *in vitro* actuation of the tissue with an electromagnet



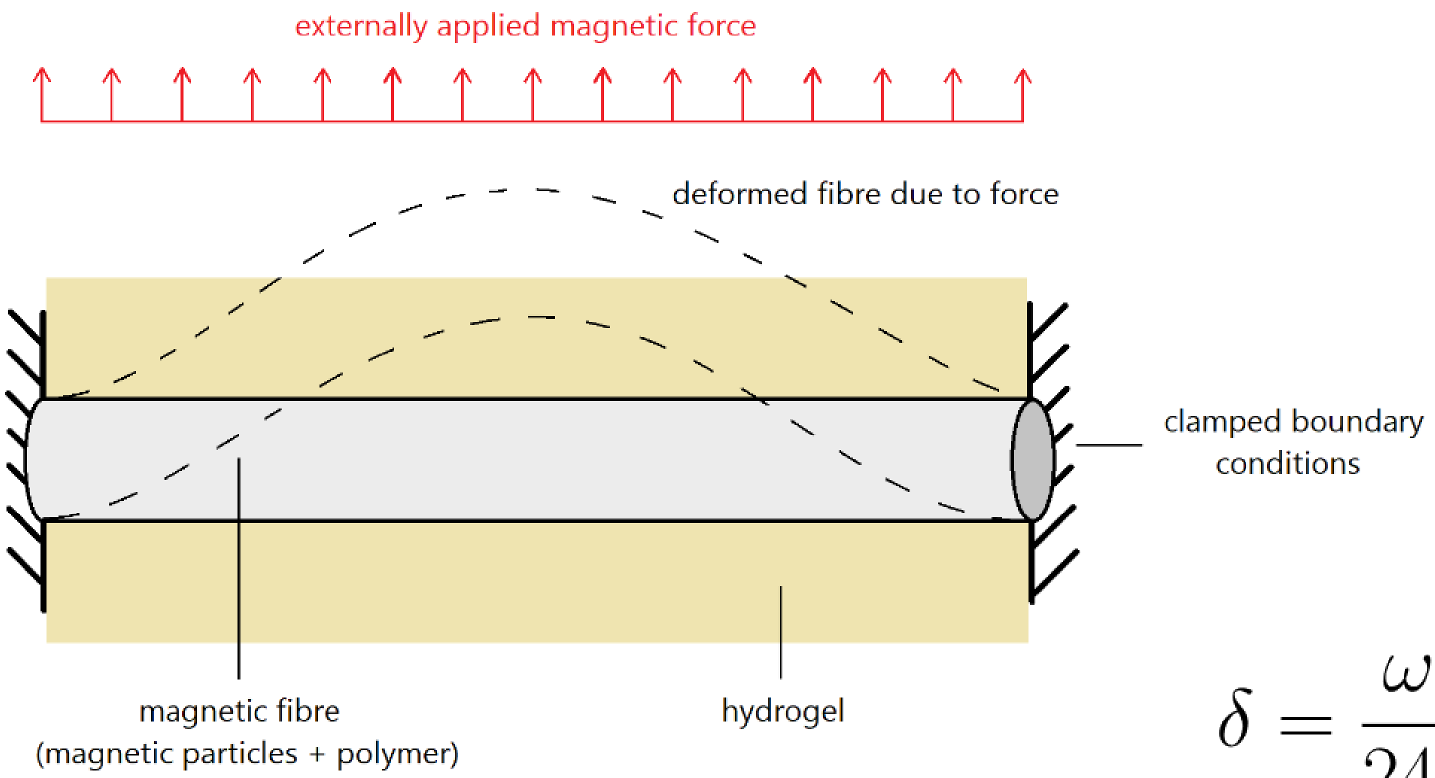
Theory

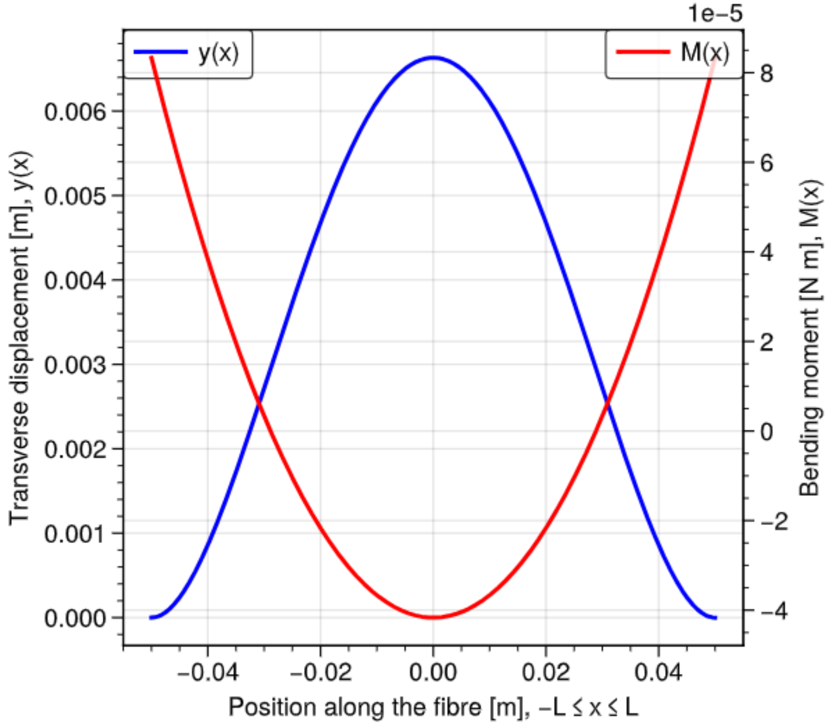
Simulate the Fibres
Select the Best Materials

Structural Modelling and Analysis

Setting Up the Model of a Fibre

[5]



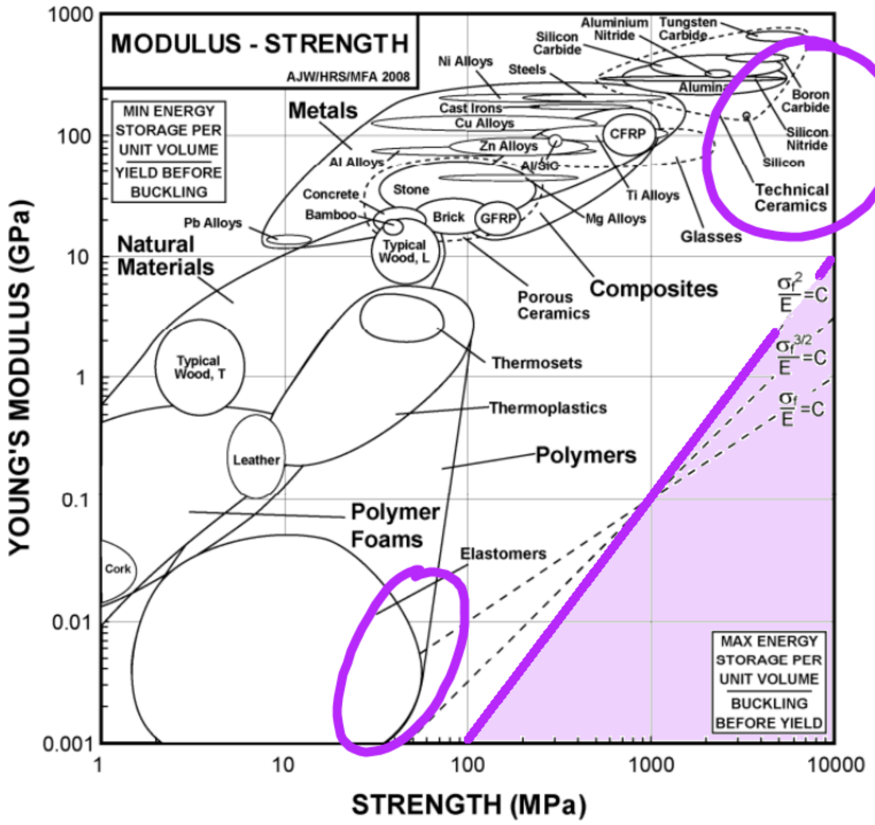


$$\delta = \frac{\omega L^4}{24EI}$$

$$\sigma_{\max} = \frac{4\omega L^2}{3\pi r^3}$$

Material Selection

Trade-Offs Between Stiffness and Magnetisation



[6]

This is a **stiffness-limited design** material selection problem.

Performance Index: maximise $$\frac{\sigma_y^2}{\omega E}$$

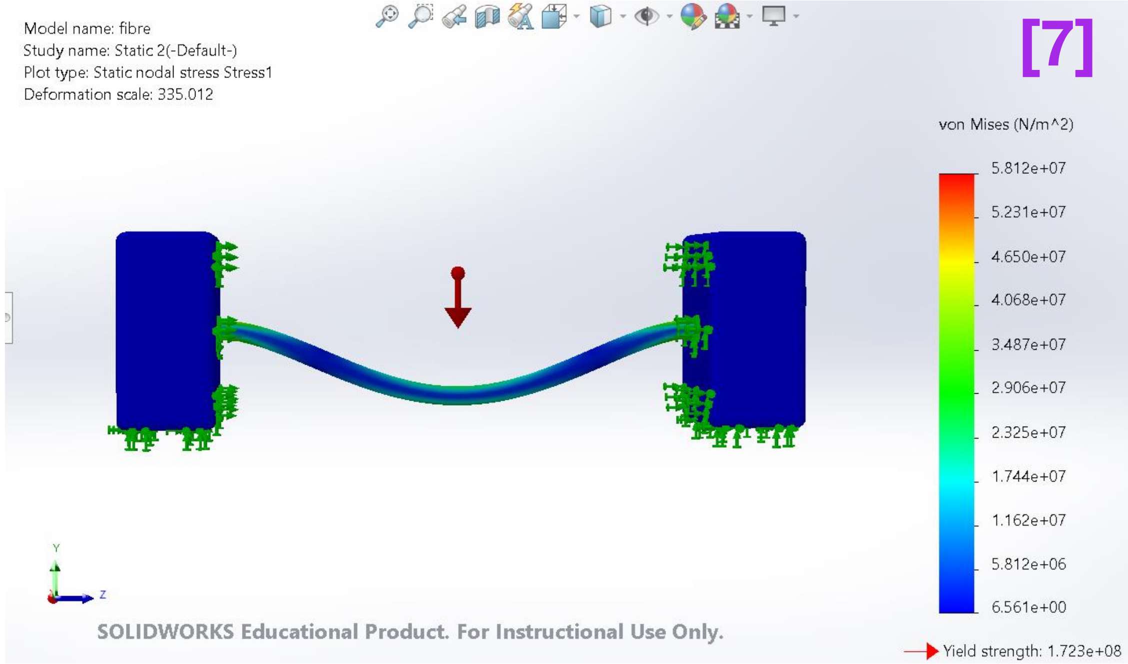
σ_y [Pa]: fibre yield stress

E [Pa]: fibre Young's modulus

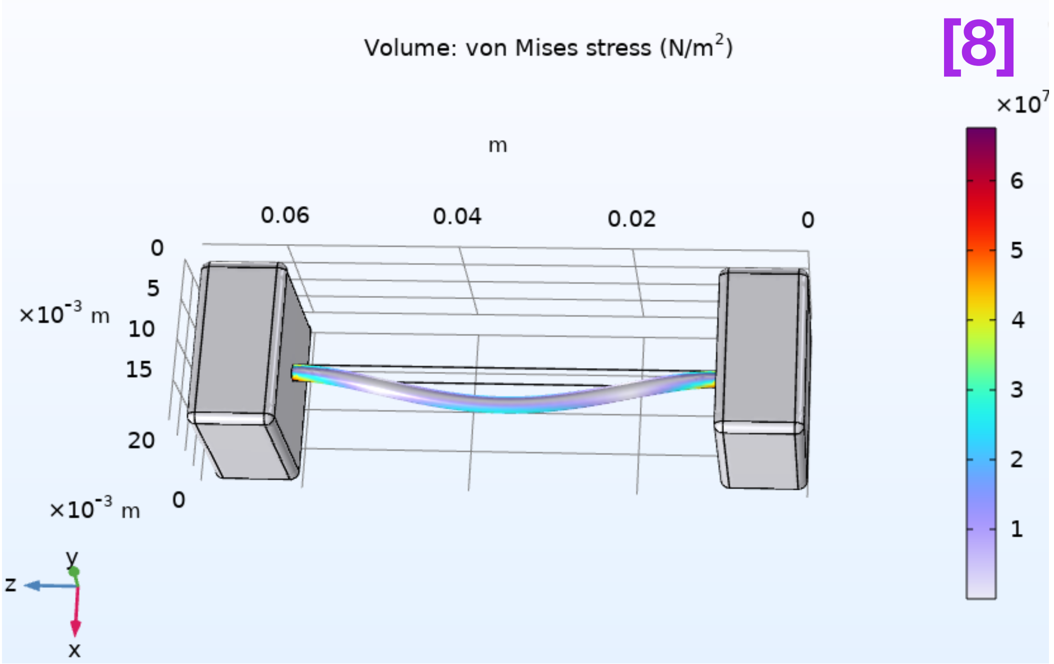
ω [N m^{-1}]: magnetic force per unit length

Computational Modelling

Useful for Checking Order-of-Magnitudes of Properties



SOLIDWORKS: simple setup



COMSOL Multiphysics: simulation

Procedures

Make Magnetic Polymer Solution
Program Spinner
Extrude Fibres
Observe Under Microscope
Assess Quality and Deformation

Fibre Composition

Solvent + Polymer + Magnetic Powder → Magnetic Solution

+

+

+

→

DMF
(N,N-dimethylformamide)
85% weight

Acetone
(propanone)
15% weight

$\underbrace{\qquad\qquad}_{\text{Solvent}}$

Solvent

Polystyrene
sets viscosity
30% weight

Polymer

Iron oxide
(iron(II, III) oxide)
sets magnetism

Magnets

Magnetic solution

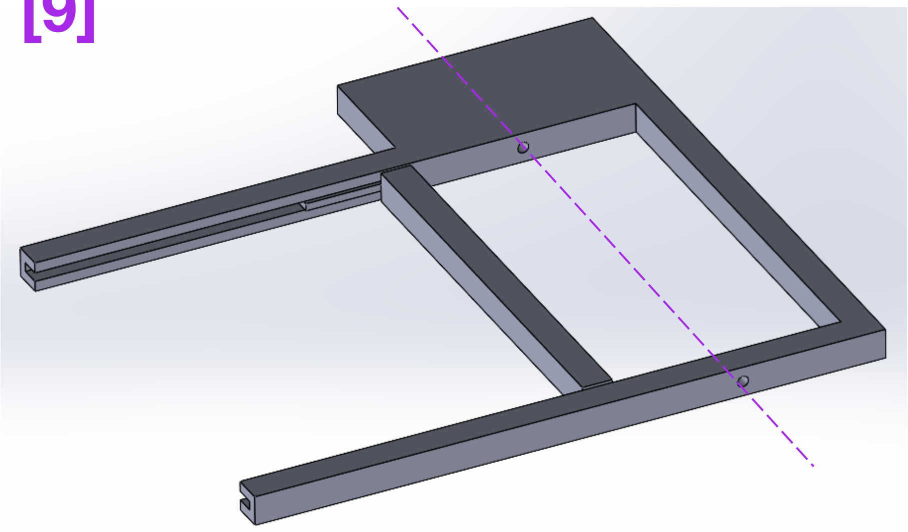
Spin-ready

We may also use PEO (high M_w PEG) or polyurethane as the polymer.

Spinning the Fibres

3D Print a Moveable Frame, Spin with Robot Arm and Pump

[9]



A robotic arm is programmed to hold a syringe containing the magnetic solution

A calibrated pump extrudes the solution through the syringe at a steady rate while the robot arm moves along the frame

An Arduino microcontroller rotates the frame, winding the fibre around the frame

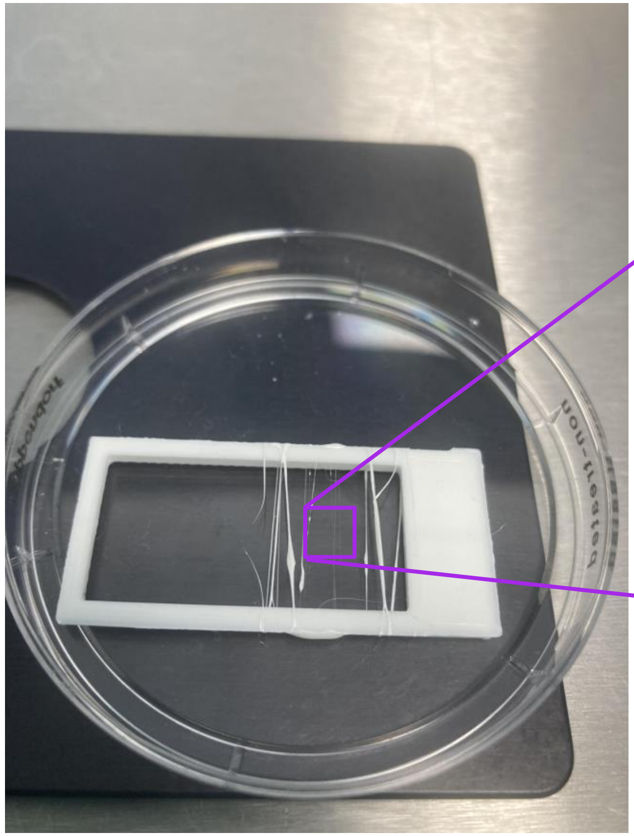
The fibres can then be examined under a light microscope
The deflection under a magnet can be measured with varying iron content

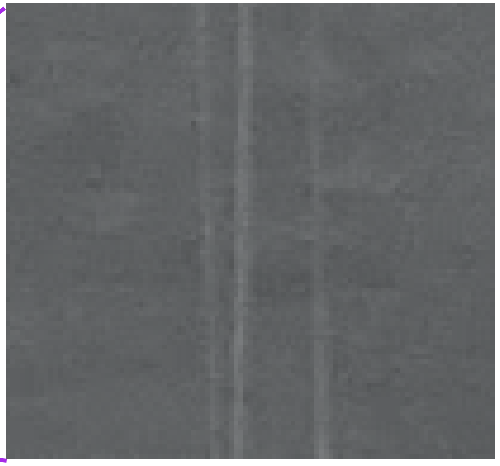
Results

Suitability of Fibre Solution
Spinnability
Achievable Length Scales

Qualitative Spinnability

Some Compositions Work Better Than Others





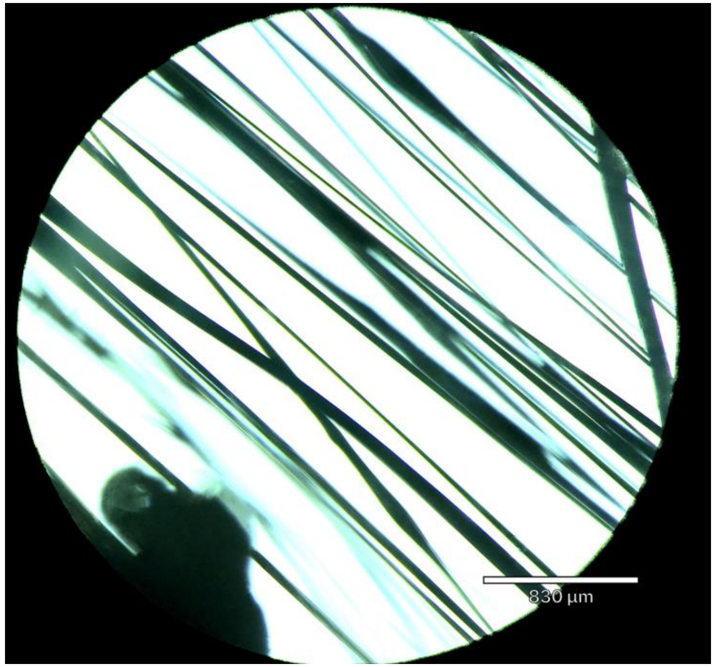
Our PEO-based solutions did not produce spinnable solutions.

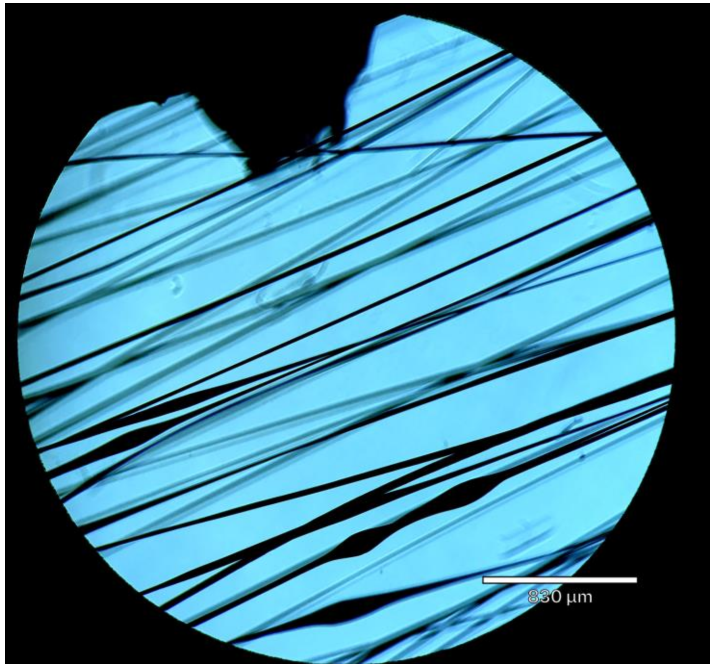
Using polystyrene gave spinnable fibres in all iron proportions with varying viscosity.

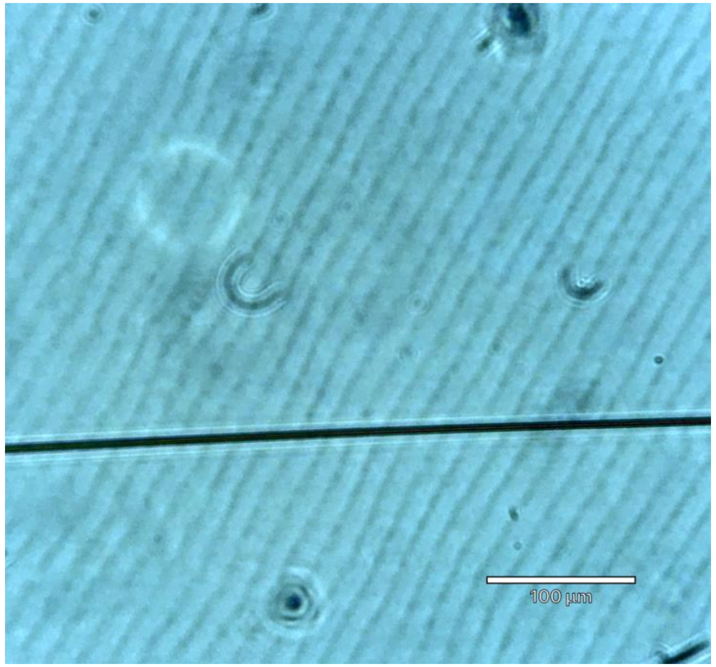
Distance between fibres ~ 1 mm
Thickness of fibres ~ 10+ µm

Microscopy

Fibres Should be as Uniform as Possible







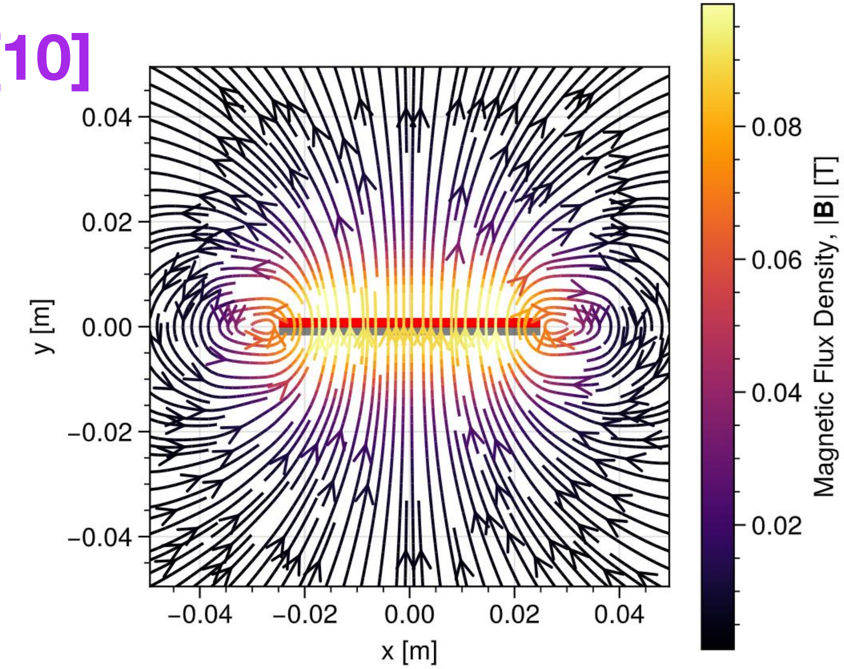
Polymer-only fibres
$d \sim 50$ µm

Magnetic fibres, 30 wt% iron oxide
$d \sim 10$ µm

Magnetic Responsiveness

Fibres Should Deflect in a Magnetic Field

[10]



Analytic magnetic flux density around a cuboidal bar magnet

The response to a magnet was difficult to control. It was either too weak to observe or too strong, and the fibres would fall into the magnet, breaking due to their fragility.

These simple tests were performed with a permanent magnet. Going forward, an electromagnet will be used, whose field can be controlled by current input.

Work To Do

Finish Building Extrusion Apparatus
Test More Fibre Compositions
Finalise Material Choices

End of Term Target

The Fibre Composition will be Selected

3D print frames that are easier to move

Control pump syringe using Python program

Set up electromagnet for formal deflection tests

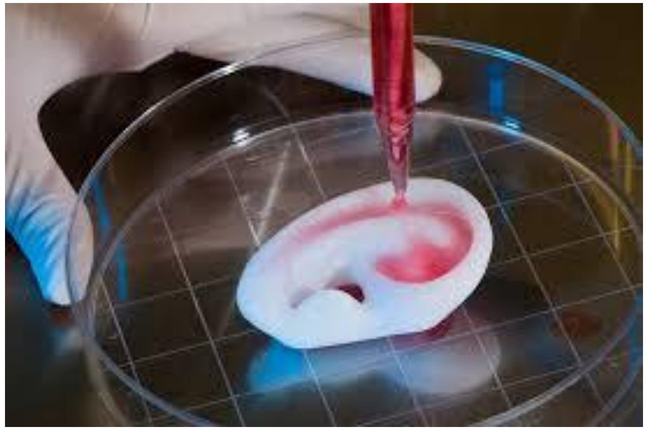
Select materials for optimal fibre composition

Now

~4 lab hours (1-2 days)

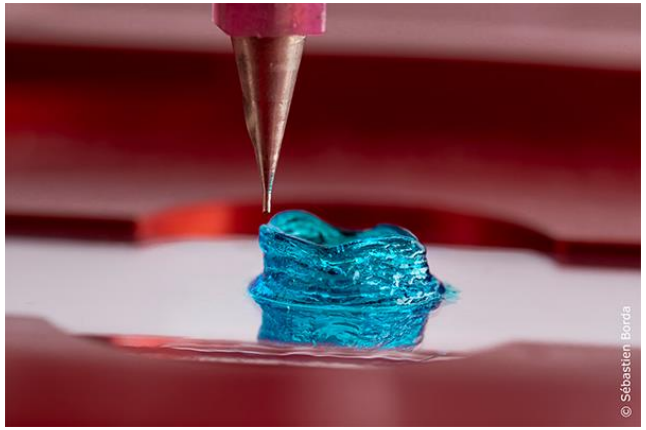
~4 lab hours (1-2 days)

~8 lab hours (2-4 days)



Thank You

Q & A



Sources cited in this presentation

[1] Y. Hong, Z. Lin, Y. Yang, T. Jiang, J. Shang, and Z. Luo, “Biocompatible conductive hydrogels: Applications in the field of biomedicine,” Int. J. Mol. Sci., vol. 23, p. 4578, Apr. 2022

[2] H. Banerjee, A. Leber, S. Laperrousaz, R. La Polla, C. Dong, S. Mansour, X. Wan, and F. Sorin, “Soft multimaterial magnetic fibers and textiles,” Adv. Mater., vol. 35, p. e2212202, Aug. 2023

[3] L. R. Doblado, C. Martinez-Ramos, and M. M. Pradas, “Biomaterials for neural tissue engineering,” Front. Nanotechnol., vol. 3, Apr. 2021.

[4] I. M. Lei, Y. Sheng, C. L. Lei, C. Leow, and Y. Y. S. Huang, “A hackable, multi-functional, and modular extrusion 3D printer for soft materials,” Sci. Rep., vol. 12, p. 12294, July 2022.

Own Content: photographs of experimental results not referenced

[5], [10]: Created in Python. [6]: CUED Materials Databook, CUED. [7], [9]: SOLIDWORKS models. [8]: COMSOL model.