Physical sciences/Nanoscience and technology [URI /639/925]
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Title: Broadening Students' Minds

Standfirst: Philip S. Lukeman and Stefan Howorka provide a training programme to improve the interdisciplinary breadth and depth of a nanoscience research group.

The interdisciplinary nature of nanotechnology makes high demands of academic and industrial research groups, and requires expertise that cuts across – and sits between – chemistry, physics, materials science, engineering, and biology[1]. Maintaining a large, scientifically broad group can to some extent address this challenge, as can collaboration with external specialists. But both of these approaches require significant time and financial resources, and they do not translate naturally into an interdisciplinary mentality within the minds of group members.

Many group leaders working in nanotechnology have noted that their students have difficulties developing an ability to think about research in an interdisciplinary manner. This can hinder both the productivity and morale of a group. It can also hinder an individual student's writing skills and ultimately their development as an independent scientist. Although universities have begun to recognize this demand and some offer interdisciplinary training courses aimed at nanotechnology (typically at the master's degree level) graduates from these programmes are few, and their training seldom matches the specific interdisciplinary mix required for a particular research group. Interdisciplinary graduate training programmes for PhD students at the department/institute level have been proposed and implemented[2,3]. However, these are typically broad, not group-science focused, and do not benefit from peer-learning. The study of successful approaches to genuinely interdisciplinary graduate programmes is also still in its infancy[4,5].

We describe a training programme, initially developed in the Howorka group, that can help improve students' interdisciplinary skills. The programme can be tailored to any specific group, is easy to implement, and takes advantage of the established pedagogical concepts of peer-led learning[6]. The programme is developed from the widely-used idea of a 'literature/journal club', but is set in the context of a group's interdisciplinary research. The training has three phases.

**1. Foundation – defining the interdisciplinary syllabus of the research group**. The first and most important phase introduces disciplinary subtopics to students who lack the relevant background. In essence, students run multiple lectures for each other to cover the research area of the group. The lecture topics, selected by the principal investigator (PI), resemble sessions of classical undergraduate courses based on basic and advanced textbook material. For example, the research of one of our groups (Howorka) is focused on DNA origami nanopores that span lipid bilayers, and the syllabus used is shown in Table 1. Example curricula for soft matter, systems chemistry, and plasmonic studies are suggested in Table 2.

Learning is enhanced by questions set by the presenting student to be answered by their peers. A subset of questions is to be answered during the lecture, while the remainder are a homework assignment. A feedback loop is set up where the presenting student grades these answers.

As the PI assesses the students' questions and answers, the Socratic method – that is, prompting questions that make students clarify their assumptions, provide evidence for their assertions and ask questions about questions – can be used to refine further question/answer sessions. The PI can also advise students on effective presentation habits: classic examples[7] include avoiding information overload in slides, not making unnecessary assumptions about the technical background of peers, and how to effectively structure lectures so that Socratic questions flow from links between topics.

The lecture series can be run multiple times with different yet coherent topics until the desired learning outcome is achieved.

In the Howorka group, the act of developing these lectures forms a core knowledge that all lab members must possess by a certain stage in their time in the lab. Reports from the group show that students enjoyed giving and receiving lectures. The students also reported intellectual 'ownership', familiarity and increasing confidence in approaching new material.

**2. Implementation 1 – applying the background knowledge to interdisciplinary publications**. In the second phase, contemporary research papers are presented and discussed in a 'literature club' format. Students present research data from a field outside their original undergraduate training, and prepare questions about the publications to be answered at the end by their peers. The presentation, therefore, tests and applies the successful training outcomes from the Foundation phase. In the second phase, students are also expected to describe the interdisciplinary links that are needed to understand each paper. For example, a student originally trained in chemistry will present a paper from the field of biophysics, and will highlight how biophysical experiments link to chemistry and biochemistry.

**3. Implementation 2 – enhancing group knowledge of research projects.** In the third and final phase, a student presents their own research project, with explicit instructions to utilize the depth and breadth that the previous two phases have instilled. In their project presentation, research links between disciplines are highlighted, while still being accessible to a non-specialist for the respective area. For multi-member projects, students can also jointly present their work. If applicable, the students are also expected to make links to other research projects or explain a specific research methodology not yet outlined in earlier stages.

Experience with the training programme in the Howorka group has yielded a number of positive observations. There is increased cohesiveness in the group not only by learning from peers but also by better comprehending the scientific basis of the projects of group members which leads to more productive intra-group discussions. Individual students are able to write better first drafts of paper introductions, as they have a grasp of the wider context of their work. Students see their research from a broader interdisciplinary perspective and can more critically evaluate their experimental plans, which leads to improved research productivity.

We also expect the programme to lead to a number of additional positive outcomes. For example, the students should be able to generate original proposals more easily, and gain more from conference attendance, as they contextualize their science more deeply. The students should also be better prepared to meet the demands of employers in a wide range of jobs, as they have experience applying expertise to new fields.

This training programme develops directly applicable skills that should be of value to a student in their progression through graduate school and beyond. Furthermore, the approach requires the use of multiple sources and investigational techniques, peer collaboration, synthesis of knowledge, and the development of metacognitive skills; the programme is therefore an Authentic Task as described by Coppola[8,9].–By adopting this training programme (or one similar to it), we believe that all members of an interdisciplinary research group can benefit.

Philip S. Lukeman is in the Department of Chemistry, St. John's University, Queens, New York 11439, USA.
e-mail: phil.lukeman@gmail.com

Stefan Howorka is in the Department of Chemistry, Institute of Structural Molecular Biology, University College London, London WC1H 0AJ, UK.
e-mail: s.howorka@ucl.ac.uk

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**Table 1: Interdisciplinary lecture series:  DNA-origami pores**

DNA structure (primary, secondary, tertiary structure; A, B, Z-DNA; canonical and non-canonical base pairs, RNA vs DNA, Holiday and other multi-way junctions)

DNA biochemistry (enzymatic synthesis, mechanism, replication fork, helicase)

DNA chemistry (solid-phase synthesis, chemical modification at bases, nucleosides and phosphates for labelling and membrane anchoring)

Design tools for DNA nanotechnology (software choice and the principles underpinning the models used by the software, predictions of structural stability)

Computational biology (approaches to simulate DNA, molecular dynamics).

Protein membrane pores (as template, general features, different types, selected ion channels, transporters, single channel current recordings)

The units can be presented as either single or double lectures.

**Table 2 Example curricula for other interdisciplinary topics.**

**Soft Matter: Colloidal self-assembly**

Statistical Physics (integral equations, perturbation theory),

Wetting, capillary forces: a physical approach (contact angles, transitions, spreading)

Intermolecular forces(molecular recognition, electrostatics, H-bonding, dispersion forces, solvation)

Colloidal chemistry (DVLO to curvature, anisotropy/patches and surface functionalization)

Characterization techniques (microscopy, light scattering)

**Systems chemistry: Designing far-from-equilibrium systems**

Reaction dynamics (Equilibria, autocatalysis, self-replication)

Energy flows in biology (coupled enzymatic systems, Energy coins "ATP/FAD/NAD", photo/electrochemical gradients)

Outside the 'flask' paradigm (Flow reactors, reaction-diffusion systems, compartmentalization)

Useful modelling concepts (Self-assembly, network theory, tile theory, oscillator theory)

**Plasmonic studies: tuning nanoparticles for sensing applications**

Plasmons (Simple models of surfaces; drude/lorentz model),

Characterization (Bulk vs single molecule spectroscopy, in-situ x-ray/TEM/EELS)

Nanoparticle synthesis (gas phase, liquid phase-sol gel/micellar synthesis, ligand effects)