UNIVERSITY OF OXFORD

Development and Implementation of an Integrated Interdisciplinary Practical Chemistry Course

Craig Campbell

University of Oxford

ViCEPHEC, Bristol, UK

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Introduction

- New Undergraduate Chemistry Teaching Laboratory was opened Sept 2018.

- Two laboratories:
  - First Year (up to 100 students)
  - Second/Third Year (up to 100 students)
- Analytical Suite
- Furnace Room
- Cold / Dark Room / Biological Suite
- Computational Suite

Introduction

- New Undergraduate Chemistry Teaching Laboratory was opened Sept 2018.

- Opportunity to develop new approach to teaching practical chemistry at Oxford.

What new practical course do we want to develop?

Why Design a New Practical Course?

- Value of performing practicals often under-appreciated.
- Opportunity to design a coherent, interwoven new course.
- Expose students to modern scientific developments.

- Better prepare students for Part II research year:
  - Confidence with practical skills, including general scientific practice
  - Ability to assess data quality, perform data analysis / interpretation
  - Problem solving and decision-making
  - Scientific communication skills

- Better align transferable skills with those sought by prospective employers.

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Mission Statement for New Practical Course

To inspire an awareness, appreciation, and enjoyment of practical science.

Focus on specific, tangible aims:

1. To develop practical and problem-solving skills
2. To promote safe laboratory working practices
3. To promote aspects of scientific thinking
4. To introduce students to scientific practices as used by the scientific community
5. To improve communication skills, including proficiency at scientific writing
6. To provide an experimental foundation for theoretical concepts and phenomena

Design Specific Objectives: Integration and Interdisciplinary Nature

- Integration of the course:
  - Develop holistic approach
  - Practicals combine both synthesis and measurement
  - Highlight where practical course aligns with theoretical course

- Interdisciplinary nature of course:
  - No segregation of course along traditional discipline lines *Inorganic, Organic, Physical, Analytical, Computational, Biological*
  - Highlight application of chemistry at interface with other sciences

Our Approach: Skills Course

- Lab course meeting in 2015 suggested new approach to the teaching of lab courses:
- Focus first part of course on introducing the key practical skills and techniques of the course.
  - Reduce cognitive load.
  - Understanding purpose of techniques.
  - Gain confidence in knowing ***how*** and ***when*** to use techniques.
- Support student learning outside of labs with virtual chemistry library resources (Learning Science).

Learning Science

What Is The Purpose of Labs? Conference, June **2015**, University of Oxford, Oxford, UK

N. Hennah, M. K. Seery, *J. Chem. Educ.* **2017**, *94*, 844-848

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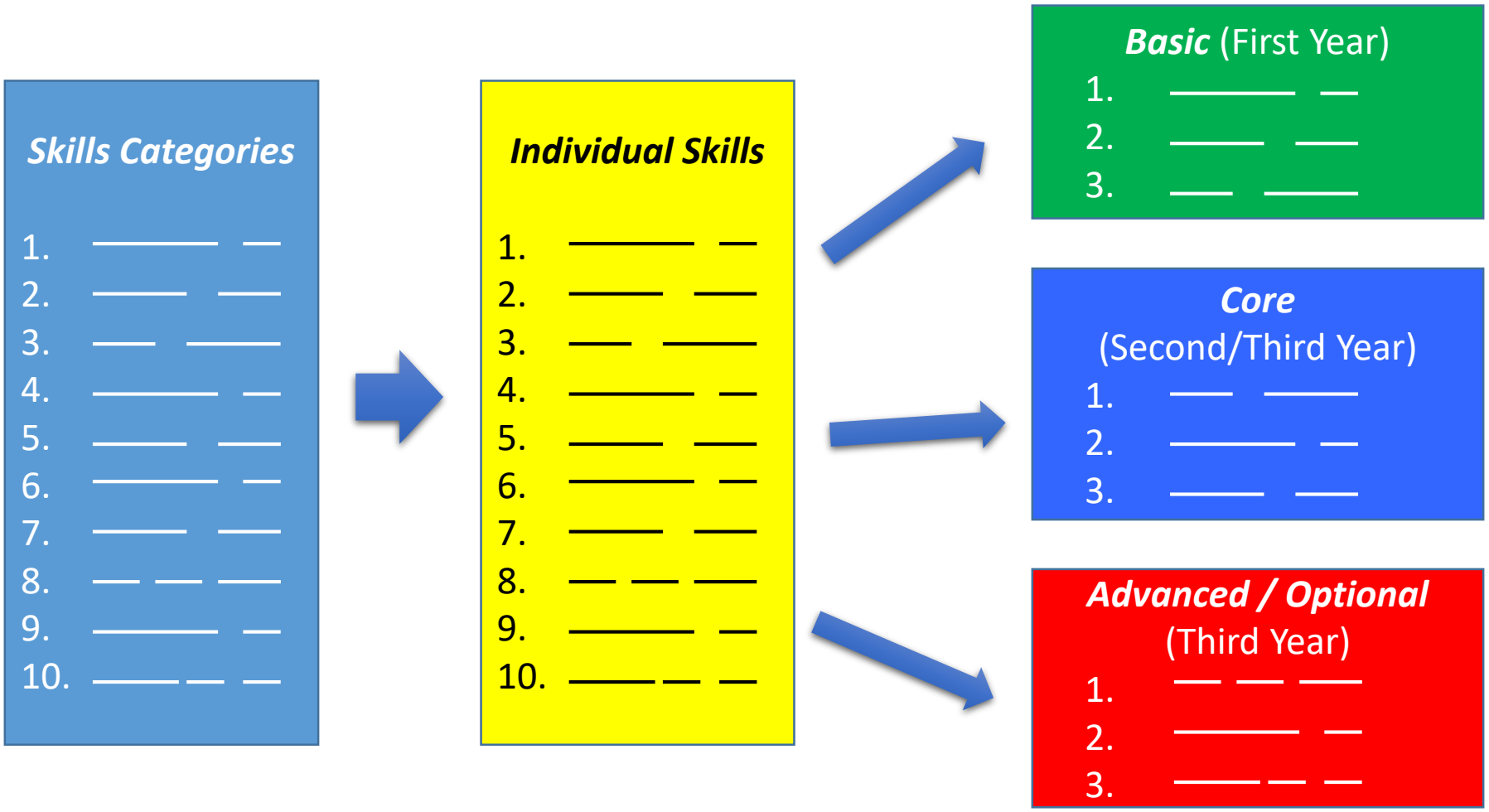
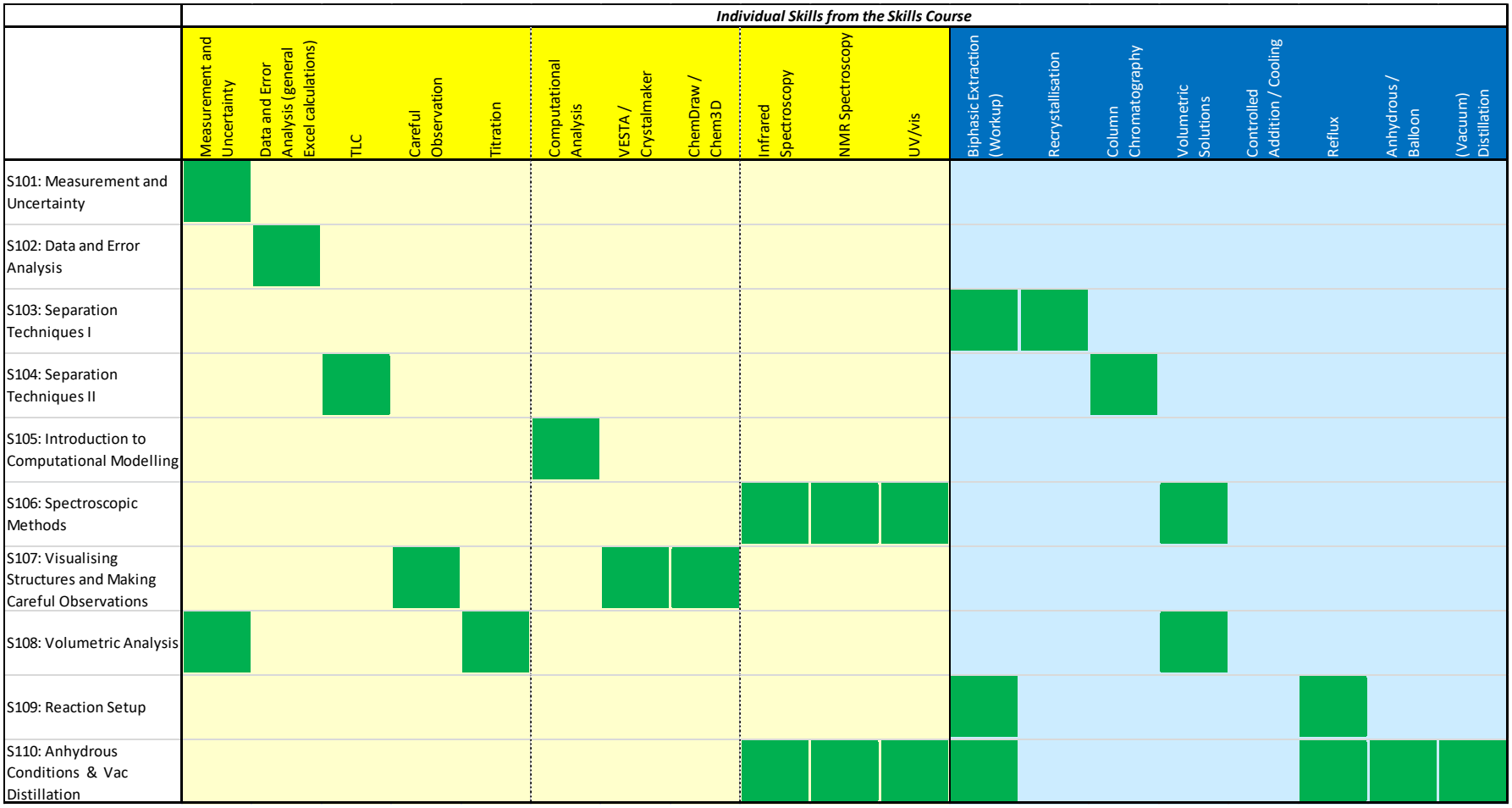
Skills Mapping



First Year Skills Practicals: Skills Mapping



Post-Skills: Choice Practical Course

- ***Choice Course*** to follow Skills Course.
  - Reinforce learning of identified fundamental skills.
  - Utilise multiple skills from the Skills Course, clearly identified in the lab manual.

- Allow introduction of more advanced theoretical course content; greater data analysis and interpretation.

- Emphasise integrated (synthesis and measurement), and cross-discipline nature of chemistry (inorganic, organic, physical, analytical, computational, biological).

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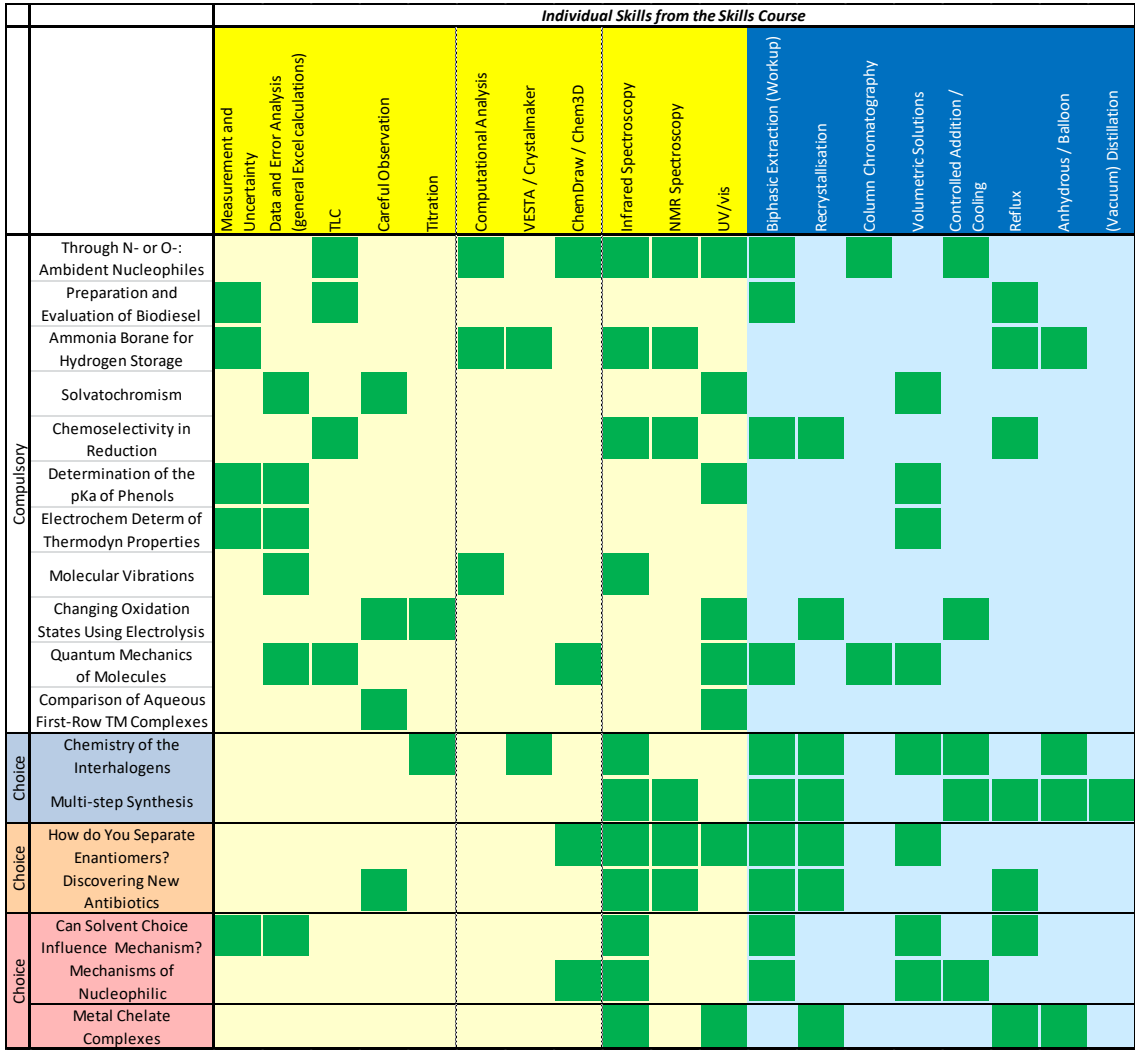
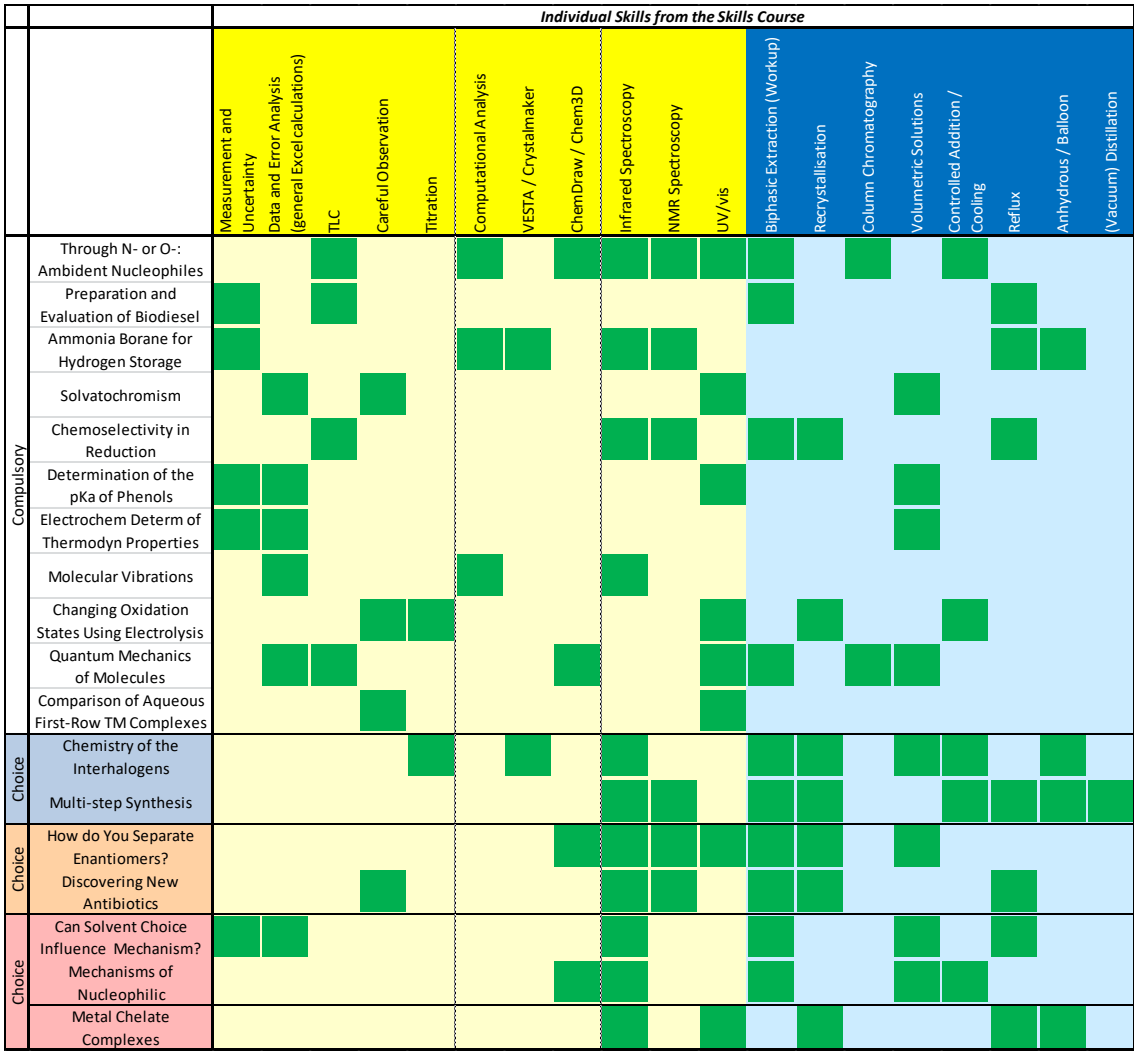
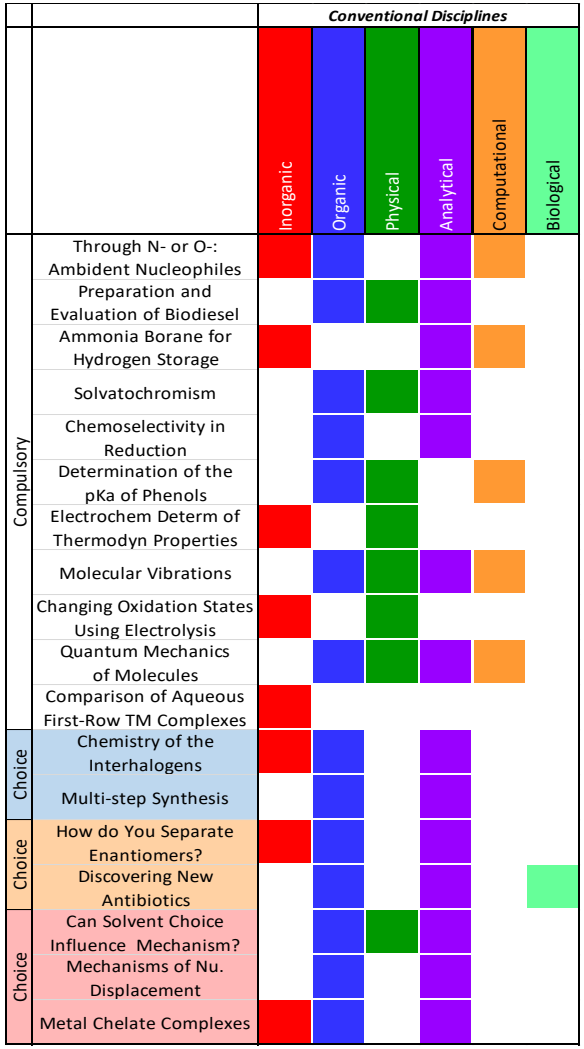
First Year Choice Practicals: Mapping



- Multiple skills utilised in Choice Practicals.
- Generally involve both Synthesis (blue) and Measurement (yellow).
- Generally multi-disciplinary.
- Introduce other skills that will be utilised by students in subsequent years.

First Year Choice Practicals: Mapping





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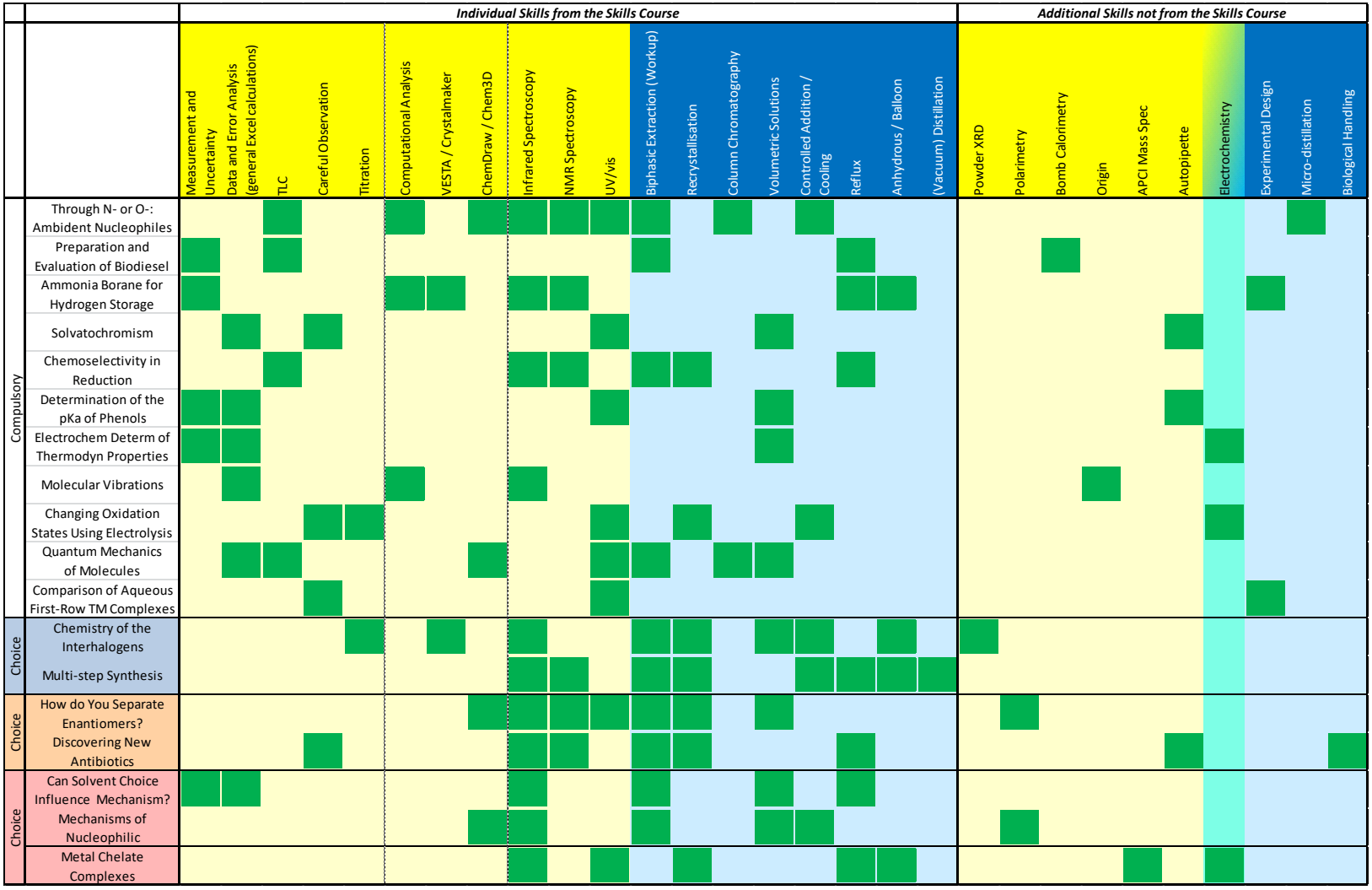

Pedagogical Approach

Overall Structure

- Students work in pairs
- Students need to work both together and individually
- Number of practicals requiring larger group data analysis
- In-lab questions to probe understanding of techniques / chemistry

Skills Course

- Expository style
- Instruction manual and Prelab quizzes focus on key aspects of techniques

Choice Course

- Primarily expository style, with elements of experimental design, decision-making
- Some practicals have no set ‘answer’ – genuine investigation
- Focus on understanding chemistry and critical thinking

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Implementation: First Year Students

Pre-lab Assessment

- Questions in VLE Canvas (Auto-marked)

In-lab Assessment

- Pre-set questions on practical techniques, theory & reasoning behind processes
- Assessment of active participation in practical and practical competence
- Adherence to safety, organisation of workspace

Sign-off Assessment

- Check of clean, tidy workspace on finishing
- Assessment of suitable data quality

Post-lab Assessment

- Report outlining practical objectives, results, analysis and discussion

Qualitative Assessment of Year 1

Grading

- Pass / fail system for First Year Course.
- All students demonstrated required ability to perform tasks throughout the year, and progress to Second Year Practical Course.
- Generally students very able to discuss purpose and implementation of practicals.
- Overall quality of written reports significantly better than in previous course.

Initial Student Feedback

New course strategy (Skills Course then Choice Course) generally well received:

- 83% students believed Skills Course prepared them for the subsequent practicals (37 respondents)

- Students appear confident (>70% confident or very confident) across most techniques and skills (29 / 36 skills and techniques)

  - Exceptions:

    NMR spectroscopy (64%)
    Team-working (57%)
    Waste management (55%)
    Electrochemical techniques (55%)
    VESTA (54%)
    Gaussian calculation (54%)
    Column chromatography (45%)

- Inconsistent interactions with demonstrators

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Course Refinement: Next Iteration

- Introduce Pre-Skills Course in Week 1:
  - Revise A-Level (or equivalent) prescribed practical techniques
  - Introduce basics of spreadsheets
  - Introduce basics of spectroscopic techniques
- Provide greater demonstrator training on techniques.
- Adjust lengths of tasks to provide students more time in-lab for digestion of techniques.
- Reduce time spent on analysis / reports outside of lab time.

Acknowledgements

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Dr Matthew Harris

Senior Technicians:
Charlotte Farrell
Louise Hutchison

Technical Staff:
Mukarram Ali
Tom Birkett
Jennie Botham
Harry Lingard-Bright
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Administrator:
Ben Challen

What Is The Purpose Of Labs?

- Labs are not an effective vehicle for learning (Hawkes):
  - Student benefit *vs* cost from labs significantly lower than benefit/cost of lectures and tutorials
  - Students do not get significant enjoyment from this investment

- Student-centred objectives (Kirschner and Meester):
  - To perform practical work
  - To formulate and test hypotheses
  - To design simple experiments to test hypotheses
  - To use knowledge and skills in unfamiliar situations
  - To interpret experimental data
  - To investigate and solve problems

S. J. Hawkes, *J. Chem. Ed.* **2004**, *81*, 1257

P. A. Kirschner and M. A. M. Meester, *Higher Education* **1988**, *17*, 81

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Additional Attributes

- Enable exploration of concepts / activities ***not encountered*** through lectures and tutorials, e.g.
  - time management
  - decision-making
  - organisation
  - communication (written and verbal)
  - ICT

- Provide insight into lab-based roles in academia and industry.
- Demonstrate the interdisciplinary, connected, nature of chemistry.

N. Reid and I. Shaw, *Chem. Educ. Res. Pract.* **2007**, *8*, 172
T. M. Clark, R. Ricciardo, T. Weaver, *J. Chem. Educ.* **2016**, *93*, 156

Key Skills Categories

1. General scientific skills
2. Safety in the laboratory
3. General laboratory technique
4. Handling of liquids
5. Handling of gases
6. Preparative/synthetic methods
7. Purification and separation techniques
8. Thermodynamic and kinetics measurements
9. General analytical techniques
10. Spectroscopic, spectrometric, and optical techniques
11. Data analysis
12. ICT skills

First Year Skills Course

1. Measurement and Measurement Uncertainties
2. Data and Error Analysis
3. Separation Techniques
    i. Biphasic Extraction and Recrystallisation
    ii. TLC and Column Chromatography
4. Volumetric Analysis
5. Visualising Structures and Careful Observations
6. Spectroscopic Methods
    i. Infrared
    ii. NMR
    iii. UV/vis
7. Reaction Setup
8. Introduction to Anhydrous Conditions in Synthesis and Purification by Vacuum Distillation
9. Introduction to Computational Chemistry

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Illustrative Elements of Complete Skills List

7. Purification & separation techniques:

Technique	Classification	Year Group Introduced
Vacuum filtration	Basic	First
Solvent extraction	Basic	First
Distillation	Basic	First
Recrystallisation	Basic	First
Thin layer chromatography	Basic / Core	First
Column chromatography	Basic / Core	First
Gas chromatography	Core	Second/Third
Sublimation	Core	Second/Third
Gel electrophoresis	Core	Second/Third
HPLC + Chiral HPLC	Advanced / Optional	Second/Third

Example Choice Practical: Chemistry of the Interhalogens (12 hours)

- ***Skills / Techniques:***

- *Measurement and Uncertainty*
- *Volumetric Analysis*
- *Crystal Imaging Software (VESTA)*
- *IR Spectroscopy*
- *NMR Spectroscopy*

- *Powder XRD**

- *Reaction Setup*
- *Controlled Addition of Reagents*
- *Biphasic Extraction*
- *Recrystallisation*

First Year Skills Course

1. Measurement and Measurement Uncertainties
2. Data and Error Analysis
3. Separation Techniques
    i. Biphasic Extraction and Recrystallisation
    ii. TLC and Column Chromatography
4. Volumetric Analysis
5. Visualising Structures and Careful Observations
6. Spectroscopic Methods
    i. Infrared
    ii. NMR
    iii. UV/vis
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UNIVERSITY OF OXFORD

- To coincide with the development of a dedicated Teaching Laboratory facility, we set out to overhaul the undergraduate Practical Course, constructing a new course with a different emphasis on both its delivery structure and substance. One novel aspect of our approach was development of key practical and analytical skills through a dedicated “Skills” Course, followed then by a set of “Choice” practicals. These Choice practicals revisit the key skills, but require higher level thinking and exploration of concepts related to the practicals.
- Additionally, we set out to develop an integrated course that demonstrates the interdisciplinary nature of the chemical sciences, including use of computational analysis and application in biochemistry/drug discovery.
- This talk will cover the process by which the course was redesigned, with a particular focus on the First Year course. This will cover the planning, development and implementation of the new course, which has recently been completed by the first cohort. Discussion of the challenges, successes, lessons learned, and aspirations for the next iteration of the course will be discussed.

Data on LearnSci Resource Usage

Strong correlation with skills and techniques students struggled to use:

Most viewed Learning Science resources:

- TLC Technique (140 Users)
- Error Analysis (100 Users)
- Column Chromatography Technique (93 Users)
- Use of a Separating Funnel (62 Users)

Key Skills Categories

1. General scientific skills
2. Safety in the laboratory
3. General laboratory technique
4. Handling of liquids
5. Handling of gases
6. Preparative/synthetic methods
7. Purification and separation techniques
8. Thermodynamic and kinetics measurements
9. General analytical techniques
10. Spectroscopic, spectrometric, and optical techniques
11. Data analysis
12. ICT skills

First Year Skills Course

1. Measurement and Measurement Uncertainties
2. Data and Error Analysis
3. Separation Techniques I and II
4. Introduction to Computational Chemistry
5. Spectroscopic Methods
6. Visualising Structures and Careful Observations
7. Volumetric Analysis
8. Reaction Setup
9. Introduction to Anhydrous Conditions in Synthesis and Purification by Vacuum Distillation

Key Skills

1. General scientific skills

Make careful and accurate observations (B)
Keep accurate scientific notes (B/C)
Make a proper record of observations (B)
Draw appropriate graphs neatly and efficiently (B)
Prepare a report describing the reasoning for your conclusion (B/C)
Exhibit best practice with regard to ethical scientific behaviour (B)
Develop the ability to design experiments (B/C)
Be able to work well alone or as part of a team (B/C)

Key Skills

2. Safety in the laboratory

Awareness of emergency procedures (B)
Proper storage of chemicals (B)
Proper disposal of chemicals (including organic solvents) (B)
Identification of known toxic substances and other hazards (B)
Proper disposal of sharps and broken glass (B)
Safe use of vacuum lines and gas cylinders (B/C)
Choice of suitable heating and cooling methods (B)
Choice of suitable concentrations (B)
Safe handling of cryogenic liquids and solids (C)
Safe handling of syringes (B)

Key Skills

3. General laboratory technique

Correct use and care of balances (B)

Proper use of volumetric glassware, reading a meniscus (B)

Use of appropriate thermometers for a given measurement (B)

Key Skills

4. Handling of liquids

Appropriate methods of carrying, pouring and shaking liquids, including ultrasound/sonication (B/C)

Choice of appropriate glassware, including required precision where relevant (B)

Use of pipettes (B)

Use of burettes (B)

Preparation of molar, volume percent, and mass/volume solutions (B)

Proper dilution of solutions (B)

Methods for solution filtration (B)

Key Skills

5. Handling of gases

Safe use of gas cylinders and pressure regulators (C)

Pressure measurements (B)

Use and maintenance of vacuum pumps (C)

Use of vacuum lines (C)

Key Skills

6. Preparative/synthetic methods

Use of hotplates and other heating methods (B)
Use of reflux apparatus (B)
Inert atmosphere methods (C)
High-pressure methods (A)
Multi-step syntheses (B/C)
Microscale techniques (C)
Schlenk line techniques (C/A)
Glove box techniques (A)
Solid state techniques, including ceramics, chimie douce, and microwave methods (C/A)
Synthetic electrochemistry (B/C/A)
Nanoparticle and thin film synthesis (A)

Key Skills

7. Purification and separation techniques

Distillation (B)
Recrystallisation (B)
Solvent Extraction (B)
Evaporation and sublimation (C)
Vacuum filtration (B)
Column chromatography (B/C)
Thin layer chromatography (B/C)
Gel electrophoresis (A)

Key Skills

8. Thermodynamic and kinetics measurements

Bomb calorimetry (C)
Solution calorimetry (C)
Thermal analysis (C)
Enzyme assays and kinetics measurements (B/C)
Photometric kinetics measurements and flash photolysis (C/A)
Stopped flow kinetics measurements (C/A)
Cyclic voltammetry (C)

Key Skills

9. General analytical techniques

Use of melting point apparatus (B)
Use of analytical balances (B)
Volumetric analysis (B)
Titrations (acid-base, complexometric, redox, and precipitation) (B)
Qualitative techniques for inorganic analysis (B)
Gravimetric analysis (B)
Gas chromatography/mass spectrometry (C)
High pressure liquid chromatography (C)
Powder X-ray diffraction (fingerprinting B, otherwise C, or with intensity analysis A)
Single crystal X-ray diffraction (A)
Use of magnetic balance (B/C)
Use of pH paper and pH meters, including calibration (C)
Conductivity measurements (C)
Solid state electrical conductivity (A)
Electrochemical techniques, including preparation of electrodes (C/A)

Key Skills

10. Spectroscopic, spectrometric, and optical techniques

Spectrophotometers, use and maintenance (C)
Atomic spectroscopy (C)
Microwave spectroscopy (C)
Infrared Spectroscopy (B/C)
Raman Spectroscopy (C)
UV-visible spectroscopy (B/C/A)
Fluorimetry (C/A)
Polarimetry (B/C)
Mass Spectrometry (C)
NMR spectroscopy (including multinuclear and solid state) (C/A)
ESR spectroscopy (A)
Use and care of optics (C)
Optical microscopy (C)
Atomic force microscopy (A)

Key Skills

11. Data analysis

Distinguish between accuracy and precision (B)
Calculate and report measurement uncertainties (B)
Use significant figures properly (B)
Use units properly (B)
Use correct chemical formulae and correctly balanced equations (B)
Apply appropriate statistical analysis (B/C)
Graph plotting and curve fitting (B)
Be able to identify point groups (C)
Be able to use crystal structure parameters (C)
Analysis of ^{1}H and ^{13}C NMR data (C)
Anslysis of IR and UV/vis spectra (B/C)
Analysis of powder X-ray diffraction data, including search/match and Rietveld methods (C/A)

Key Skills

12. IT skills

Use of word processing and spreadsheet packages (e.g. MS Word, Excel) (B)
Use of popular software packages (e.g. ChemDraw, Crystalmaker, Origin, LabVIEW) (C)
Chemometrics (C)
Computational Chemistry and chemical simulations (C/A)
Basic programming skills (C)
Information Technology and Library Resources (C)
Internet resources (B)
Literature searches (B)
Use of electronic lab notebooks (C)

Use of LearnSci Resources

Resource	No. of Uses	No. of Different Users
Thin Layer Chromatography (TLC) Rf Measurement Simulation	285	140
Thin Layer Chromatography (TLC) Video	230	122
Error Analysis: Combining Errors Guide	229	100
Thin Layer Chromatography (TLC) Setup Simulation	179	93
Column Chromatography Video	152	93
Separating Funnel Technique Simulation	134	62
pH Indicators Guide	128	84
Error Analysis: Standard Deviation Guide	120	71
Column Chromatography Simulation	114	86
Separating Funnel Video	110	58
Error Analysis: Percentage Error Guide	97	63
Calorimeter for Measuring Enthalpy Change of Neutralization Video	93	65
Rotary Evaporator Video	79	53

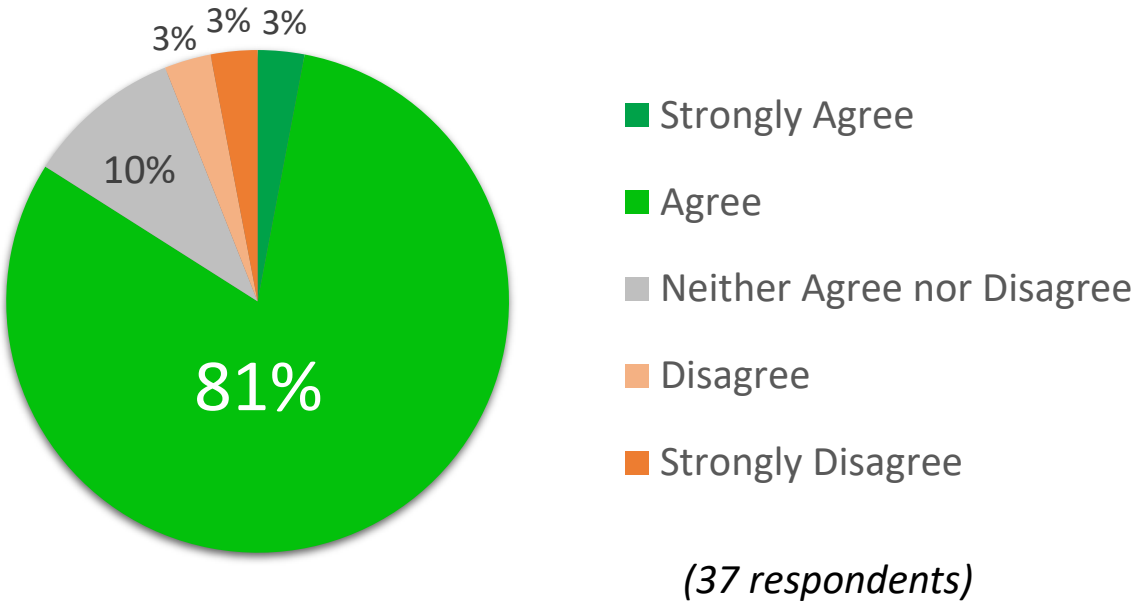
Student Confidence Surveys

Surveyed students (26 respondents) upon completion of Skills Course on their confidence with various skills:

	Measurement and Uncertainty	Data and Error Analysis (general Excel calculations)	TLC	Careful Observation	Titration	Computational Analysis	VESTA / Crystalmaker	ChemDraw / Chem3D	Infrared Spectroscopy	NMR Spectroscopy	UV/vis	Biphasic Extraction (Workup)	Recrystallisation	Column Chromatography	Volumetric Solutions	Controlled Addition / Cooling	Reflux	Anhydrous / Balloon	(Vacuum) Distillation
Very confident (requires minimal guidance)	8	4	27	8	35	15	8		27			27		28	35		23	23	
Confident (assured but may need a small amount of guidance)	46	36	38	50	46	23	50		46			38		20	46		50	23	
Could complete with some guidance	38	48	12	27	19	46	27		23			12		24	19		19	42	
Not confident (would need considerable guidance)	4	8	27	12	4	23	12		4			27		32	4		12	15	
Unable to complete task without supervision	4	4	0	4	0	0	4		0			0		0	0		0	4	
No answer	0	0	0	0	0	0	0		0			0		4	0		0	0	
Score	3.5	3.28	3.77	3.49	4.24	3.51	3.49		3.96			3.77		3.56	4.24		3.96	3.67	
No of respondents	26	25	26	26	26	26	26		26			26		25	26		26	26	

End-of-Year Survey of Students

***Question*:**
The Laboratory Skills Course prepared me for the Choice Practicals



(37 respondents)

End-of-Year Survey of Students

"All non-specialised techniques(…) were covered in the skills course, so I could just go and do them during the choice course without much trouble."

"The key techniques were laid out clearly and explained(…) in the 'skills' lab manual so that they could be referred back to when doing the 'choice' practicals.
Certain skills such as running a column were forgotten by the time we had to do them in the choice practicals."

It largely depended on the senior and junior demonstrators running the experiment. Often it was explained well and concisely with useful experimental tips and thought provoking questions about what we were actually doing."

"The use of the various pieces of apparatus in early practicals meant I knew what to do mostly in later ones without supervision."

Student Confidence Surveys

- 84% of students responded that Skills Course prepared them for completing the Choice Practical Course (37 respondents)

- Minimal number of respondents felt could not complete all tasks without direct supervision (<5%)

- Low confidence for ICT skills:
  - Data analysis in Excel
  - Visualising structures in ChemDraw and VESTA
  - Gaussian computation

- Variable confidence with:
  - Column chromatography
  - TLC
  - Biphasic workup purification

Student Feedback

- Students disliked repetitive nature of serial dilution and UV/vis analysis on extensive number of samples
- Students engaged less when did not understand purpose of what they were doing
- Time to complete full written reports far too long

Pedagogical Approach: Cognitive Apprenticeship

- Provide opportunities for students to engage in thinking processes:
  - ***Model***
  - ***Coach***
  - ***Scaffold***
  - ***Fade***

- Teachers enable students to
  - ***Articulate:*** verbalise knowledge and thinking
  - ***Reflect***
  - ***Explore:*** pose and solve their own problems