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CHAPTER 12

Design and Implementation of an Inquiry-Based Mathematics Module for First-Year Students in Biomedical Sciences

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12.1. Setting the Scene

How might you design and implement an inquiry-based basic mathematics module for first-year students in biomedical sciences? What mathematical content would you choose? What decisions would you have to make? What issues would you have to address? How would you gain insight into students' learning? In this chapter, these questions are addressed relating to a first semester module in the first year of the bachelor programme Biomedical Sciences at the University of Amsterdam, which started in the study year 2018–2019.

We, the authors, formed with teaching assistants a small community of inquiry, henceforth abbreviated as CoI (Chapter 2; Jaworski, 2008; Biza et al., 2014), for designing, teaching and evaluating the module by employment of a developmental and inquiry approach. This CoI had a common purpose in exploring the teaching and learning of basic concepts and methods relevant for a mathematical perspective on processes of change in a biomedical context, in promoting an inquiry-based mathematics education (IBME) approach, in trying to understand better teaching and learning processes in such an approach and in recognising issues that arise for lecturers and students. Members of the CoI had differing roles. André Heck was the module coordinator and principal lecturer. Marthe Schut and teaching assistants had responsibility for construction of tasks that they would use in tutorials. All CoI members involved in designing and running the module shared responsibility for design of the instructional innovation, for monitoring students' learning processes, and for continuous reflection on the teaching and learning in lectures and tutorials leading to modifications during this practice and listings of points of attention for next years of teaching. In other words, they engaged in research *in* practice, also called insider research (Goodchild et al., 2013). In terms of the three-layer model of inquiry outlined in Chapter 2 (cf., Jaworski, 2019), they did inquiry in mathematics and in teaching mathematics. The innovation included inquiry-based tasks, use of the digital environment SOWISO (Heck, 2017), and use of the programming language R (R Core Team, 2019) for exploring processes of change that can be described in the form of dynamical systems. Natasa Brouwer engaged in research *on* practice collecting and analysing classroom data (outsider research).

The CoI's aim was to develop a module for first-year students in biomedical sciences that would improve the mathematical component of students' biomedical scientific literacy and make their learning of mathematics through inquiry more enjoyable. This literacy has three aspects: (1) becoming familiar with and understanding basic mathematical concepts and methods (learning mathematics), (2) engaging in the kind of mathematics that biomedical scientists apply in their work (doing mathematics), and (3) gaining insight into the increasingly more important role of mathematics in biomedical research (learning about mathematics in context). Joy of mathematics learning was considered important because motivation for learning mathematics cannot be taken for granted in this population. The CoI's approach was design research (Bakker, 2018), which means that the design of instructional materials (e.g., computer tools and learning activities) was a crucial part of the research. The main focus of this case study is to reflect and report on

- the processes within and the products of the CoI,
- issues raised during its work,
- the students' processes and achieved outcomes in the module,
- the successes and failures in meeting the goals set by the CoI, and
- lessons learned.

To this end, data was collected from audio-recorded CoI meetings, design notes, observations in lectures and tutorials, student questionnaires and interviews, and module evaluations during the study years 2018–2019 and 2020–2021.[1]

This chapter is organised as follows. In Section 12.2 we give background information about the basic mathematics module, the student population, and the envisioned role of ICT. In Section 12.3 we report on the CoI and its developmental work in 2018-2019. This includes design of inquiry-tasks, student feedback, CoI's reflections, and their ideas for improvement for the next study year. In Section 12.4 we report on the CoI's revision of the module and experiences within the study year 2020–2021. We end in Section 12.5 with recommendations for lecturers based on lessons learned.

12.2. Background Information

In this section, we present a new perspective on biomedical sciences education and the role of mathematics herein, give information about the student population, and discuss the role of ICT in the developed module.

12.2.1. Mathematics for New Biology. In the past, basic mathematics was embedded in bachelor courses in biomedical sciences for brushing up mathematical skills of students with regards to mathematical functions, basic calculations that students need in laboratory work, and models of growth. In 2017, the curriculum was reformed in line with the advice of the Biosciences Committee of the Royal Netherlands Academy of Arts and Sciences (2011) about the importance of 'New Biology' in higher education. This is a cross-disciplinary science in which omics-based techniques of analysis ('omics' like genomics, transcriptomics, proteomics, or metabolomics) and system biology enable researchers to quantify biological processes in and around cells, organs, and organisms. The importance is also reflected in the 6th edition of the textbook 'Molecular Biology of the Cell' by Alberts et al. (2015), which is used throughout the bachelor programme. The authors of this book wrote in the preface:

> We now realize that to produce convincing explanations of cell behavior will require quantitative information about cells that is coupled to sophisticated mathematical/computational approaches—some not yet invented. As a consequence, an emerging goal for cell biologists is to shift their studies more toward quantitative description and mathematical deduction.

[1] The mathematics module ran three times during the PLATINUM project in differing circumstances. We report on the development and the revision phase.

This was also one of the main messages of the BIO2010 report (National Research Council, 2003), in which the following central abilities for future biomedical researchers were listed: knowledge of fundamental mathematical concepts and methods, quantitative analysis, and mathematical modelling.

The implementation of a New Biology curriculum explains the choice for a basic mathematics module in which first-year students get acquainted with systems biology and systems medicine. In mathematical terms this means an introduction to dynamical systems in the context of biomedical processes (see Segel & Edelstein-Keshet, 2013). This includes the study of mathematical models of growth, chemical kinetics, and quantitative pharmacology with the purpose that students see where and how mathematics is applied in biomedical sciences. It helps students understand that advanced mathematics methods and techniques are needed for quantitative modelling of processes of illness and health.

The basic mathematics module was taught for the first time in the study year 2018–2019 in 9 weeks with mathematics lessons spread over two courses (Basic Statistics and Basic Mathematics for Biomedical Sciences, part 1 & 2) from November up to April, with one 2-hours lecture and one 2-hours tutorial per week. In other course weeks, statistics was taught. This spreading of mathematics lessons across a period of four months was seen as an opportunity for making strong connections with other courses taught in the same period. However, it led to an instruction sequence with gaps, which made it difficult for students to keep oversight, and complicated the examination of two different subjects. So the basic mathematics module was redesigned for the study year 2020–2021 to a module with the same work load but now taught in a single semester block (in November and December), with one 2-hours lecture and two 2-hours tutorials per week, no parallel teaching of statistics, and with examination of only the mathematical concepts and methods.

12.2.2. The Student Population. The size of the student population attending the basic mathematics module is on average about 150 students. This means that it is rather difficult for lecturers to become well-informed about their students through direct contact in the short time that the module is run. For this reason, personal data of students such as mathematics background and study profile at secondary school level, mathematics anxiety, test anxiety, and motivation and engagement, were collected via questionnaires. In this subsection we report on data collected in the study year 2020–2021, but the outcomes in previous study years hardly differ.

Students' Mathematics Background and Study Profile. By students' mathematics background is meant the mathematics examination programme that students took at upper pre-university level, namely, Mathematics A or B. Mathematics A prepares for studies in social or economic sciences. Its core subjects are statistics and probability, and some calculus. Mathematics B covers the mathematics needed for exact sciences and technical studies, and mainly covers calculus. A substantial percentage (25%) of the first-year students had taken Mathematics A, which prepared them less for exact sciences. Their marks in the module exam were less good and only 50% of them passed the exam, compared to 90% of the students with Mathematics B.

Related to the mathematics background is the students' choice of study profile at upper pre-university level because it restricts the possible combinations of subjects in the examination programme. Mathematics B is obligatory in the 'Nature & Technology' (NT) profile, which is required for most studies in exact sciences and engineering. In the 'Nature & Health' (NH) profile, which prepares for studies in medicine and biology, pupils choose between Mathematics A and B. Slightly more than half of the participants of the module (55%) had an NH profile, and within this group of students 45% had chosen Mathematics A. Many students with an NH profile were less prepared for exact sciences: their marks were less good and only 69% of them passed the exam, compared to 97% of the students with an NT profile. It follows that mathematics background is the most influential factor for study success, even though the module was designed such that it would not disadvantage students with Mathematics A.

Students' Mathematics Anxiety and Test Anxiety. The level of mathematics anxiety amongst first-year students was measured via the Dutch translation of the Abbreviated Math Anxiety Scale (Hopko et al., 2003). The rescaled mean AMAS score (3.5) was low on a scale from 1 (no anxiety at all) to 10 (panic) and was a bit less than students' self-estimates (4.3). No statistically significant differences in mathematics anxiety regarding mathematics background, study profile and gender were found.

The level of test anxiety amongst first-year students was measured via the Dutch translation of the Test Anxiety Inventory (Spielberger, 1980). The mean TAI score, rescaled from 1 to 10, and the students' self-estimates were 4.6 and 5.5, respectively. A significant difference was found only in gender: female students reported a higher level of test anxiety than male students.

No correlations were found between the above emotional experiences and students' exam results. However, the lecturers noticed that students with a higher mathematics anxiety level asked more questions anonymously on the online forum of the module than other students.

Students' Motivation and Engagement. The 'Motivation and Engagement Wheel' framework (Martin, 2007) includes thoughts (motivation) and behaviours (engagement) that play a role in learning and consequently in course performance. Both are subdivided into adaptive and maladaptive forms. Adaptive thoughts consist of Self-Belief, Valuing of School, and Learning Focus, whereas adaptive behaviours consist of Planning, Task Management, and Perseverance. Maladaptive thoughts include (Test) Anxiety, Failure Avoidance, and Uncertain Control, whereas maladaptive behaviours include Self-Sabotage and Disengagement. These scales can be assessed via the 'Motivation and Engagement Scale – University/College' (MES-UC) instrument.

A significant difference was found only in gender for Planning, Anxiety, and Uncertain Control. Female students reported better planning of their work, assignments, and their study, but they were also more worried or felt more nervous (e.g., about work, assignments, exams) and were more uncertain (e.g., about how to do well or how to avoid doing poorly).

Only the group of maladaptive behaviours was significantly and negatively related to the exam mark. In the study year 2020–2021, with only online teaching during the COVID-19 pandemic, maladaptive thoughts could have been overshadowed by worries connected to the pandemic.

12.2.3. The Role of ICT Envisioned by the Module Designers. Kaput (1992) distinguished three modes of computer use in education, namely as an educational medium, as a set of tools, and as a toolmaker/mediumbuilder. The CoI that designed the basic mathematics module adopted the first two modes.

The educational medium was SOWISO (Heck, 2017), a cloud-based environment for learning, practising and assessing mathematics that allows randomised examples and exercises with automated feedback (Figure 12.1). The designers of the module created tailormade GeoGebra-based tools (Figure 12.2) and simulations (Figure 12.3) with the Easy Java/JavaScript Simulations (EjsS) toolkit[2] (Garcia et al., 2017),

[2] EjsS is an authoring tool for non-programmers to create interactive simulations in Java or Javascript, mainly for teaching or learning purposes. (see the website `www.um.es/fem/EjsWiki`)

which served as tools for promoting students' conceptual understanding of mathematics through inquiry

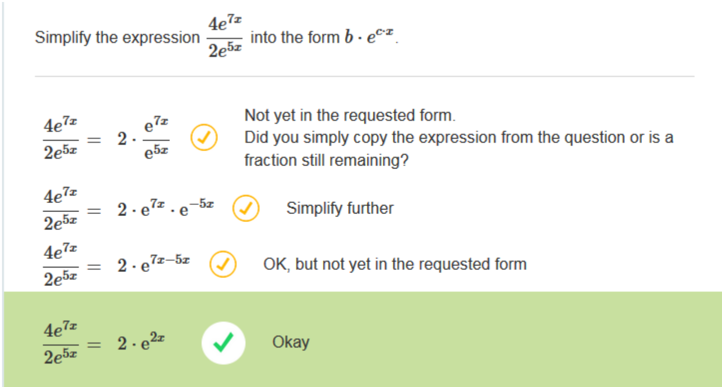


FIGURE 12.1. A simplification task in SOWISO with feedback.

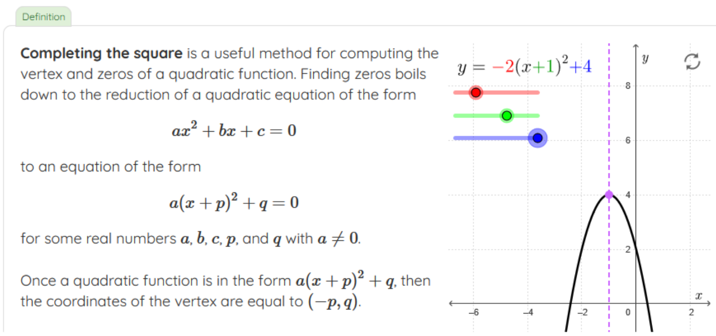


FIGURE 12.2. A GEOGEBRA tool embedded in a SOWISO theory page.

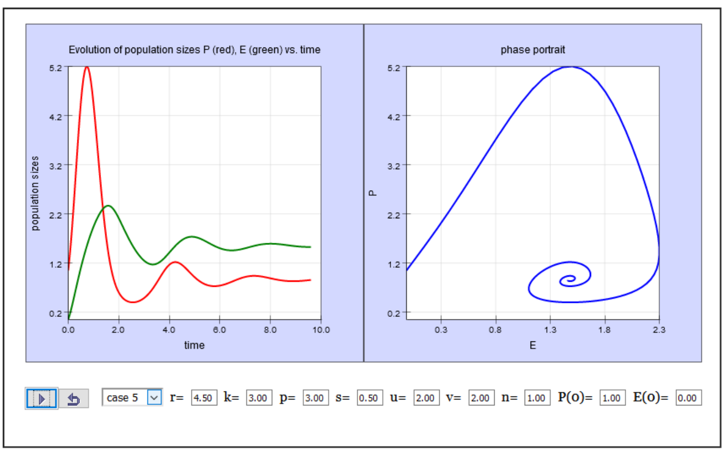


FIGURE 12.3. An EJSS-based user interface for exploring the immune response model of Mayer et al. (1995). The case of chronic coexistence of virus and antibodies is shown.

Figure 12.4 illustrates how the R programming language (R Core Team, 2019) and RStudio (RStudio Team, 2019) were used in the module as expressive tools that allow students to solve mathematical models numerically in the same way as biomedical scientists use this mathematical software.

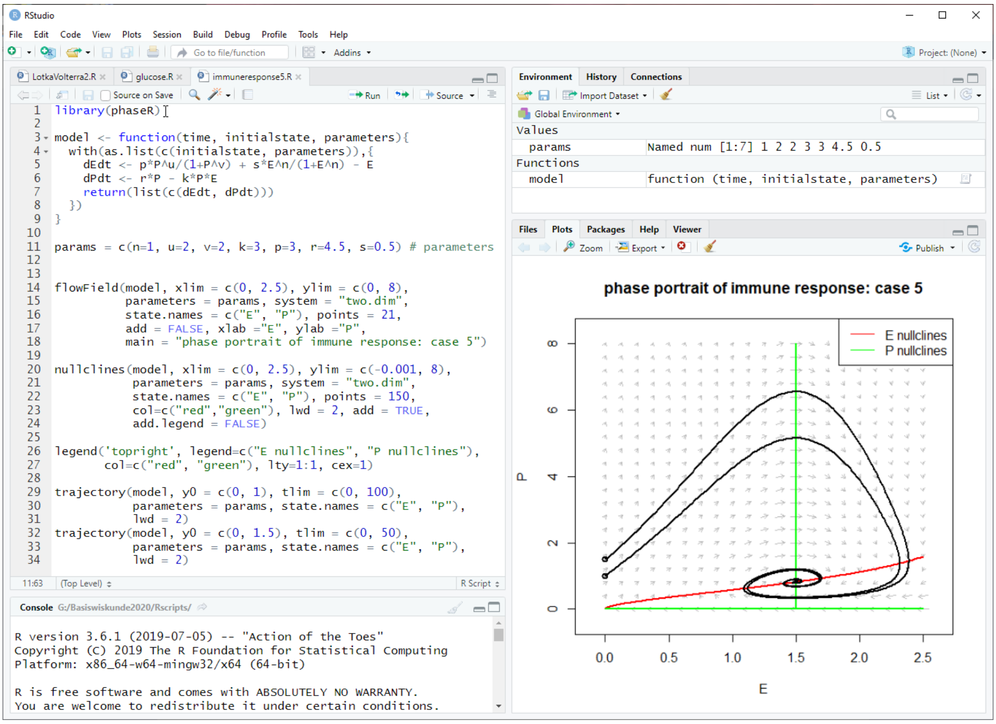


FIGURE 12.4. Worked-out solution in R and RStudio of the case of chronic coexistence in the immune response model.

The module designers created microworlds for students to familiarise with fundamental concepts of ordinary differential equations (ODEs) and with ways to compute, visualise, and analyse solutions. These microworlds were implemented in GeoGebra, EjsS, and Coach[3] (Heck, 2012). Examples are microworlds for drawing a direction field of a system of ODEs and solutions in the phase plane (Figure 12.5), and diagrams for single neuron models (Heck, 2019).

The CoI applied principles of the original Universal Design framework Story (2010), adopted in PLATINUM to support students with identified needs (see Chapter 4), in the design of ICT-tools for student inquiry. We illustrate this in Figure 12.6 with a randomised GeoGebra-based exercise for drawing a lineal element at a random point for a randomly generated differential equation. The creator of this exercise applied the principle of 'simple and intuitive use' here. His thinking in doing so was that the students' learning curve of using a slope field tool would be reduced by a tool menu that contains only the necessary tools for drawing a lineal element, selecting and deleting objects. He applied the 'tolerance for error' principle in the sense that the user can sketch a reasonable approximation of the lineal element to get it marked

[3]Coach is an activity-based, open multimedia authoring environment that is designed for STEM education and offers students a versatile set of integrated tools for inquiry of natural phenomena, mathematics, science, and technology (see the website www.cma-science.nl)

as correct. The 'size and space for approach and use' principle is supported by the full-screen button at the lower-right corner of the GeoGebra-based tool that rescales the tool to fit the whole screen. In addition, visually impaired persons are supported in SOWISO by the display of mathematical formulas via MathJax, which works with any ARIA screen reader and can be brailled or transformed to speech output, and by zooming of formulas in ways that are adjustable to one's wishes.

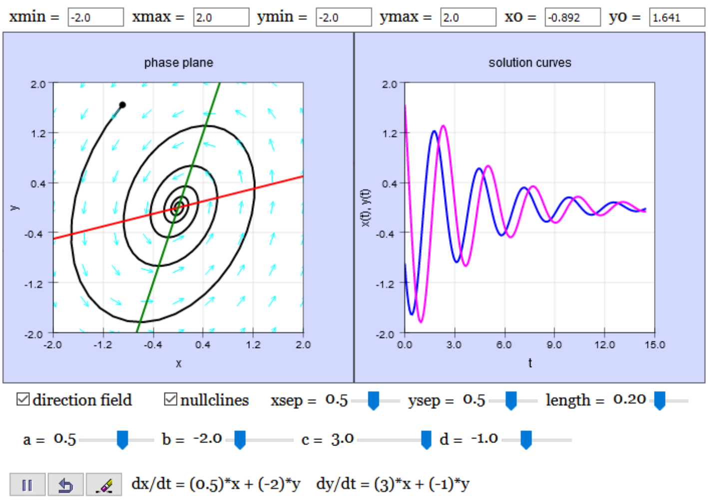


FIGURE 12.5. An EJSS-based dedicated tool to explore solutions of a linear system of two ODEs.

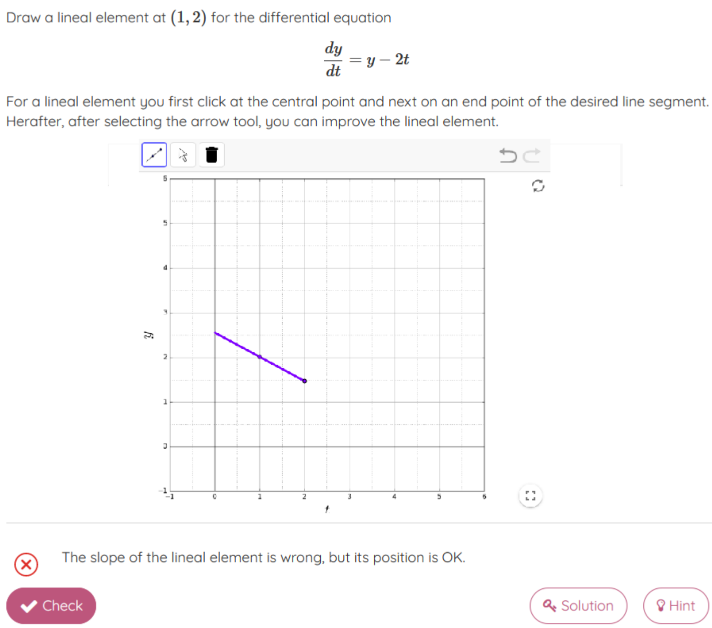


FIGURE 12.6. A screen shot of a randomised GeoGebra-based exercise in SOWISO with automated feedback.

12.3. Work of the CoI on the First Version of the Module

This section is a retrospective analysis of the design of the module taught in the study year 2018–2019 and experiences with the instructional materials in practice. The CoI consisted of the authors and one teaching assistant, who was a master student in physics employed for both instructional design and teaching in the tutorials. The analysis is based on voice recordings and notes of eight CoI meetings, classroom observations, and module evaluations by students. The ideas about IBME and what was learned from existing inquiry-based approaches to teaching and learning differential equations will be exemplified by inquiry tasks developed by this team. Feedback of students and reflections of the CoI on the module are discussed.

12.3.1. Finding the Structure and Contents of the Module. In the first meeting, two weeks before the start of the module, the CoI agreed that the module in the New Biology curriculum would be structured toward quantitative mathematical modelling. This means that students would explore mathematical models with digital tools. It was planned that they would carry out mathematical explorations with real enzymatic data (Moss et al., 1996), pharmacokinetic data (Mas et al., 1999; Heck, 2007) and with a published preditor-prey model of immune response (Mayer et al., 1995). These explorations were meant to convey to students that there is often more than one mathematical model for a phenomenon possible. They were included in the module to sensitise students for the quality of a model and to convince them that understanding of a model is not the main goal, but understanding of the modelled phenomenon and the mathematics needed for that purpose.

The CoI's view on modelling instruction was that students learn most efficiently when it is done in a progressive way: students first get acquainted with simple models, such as exponential growth, and improve them by changing or adding details before they construct their own models. The duration of this module did not allow for students to make their own models. The module would give students an orientation on system biology and systems medicine with the hope and expectation that they would start to appreciate mathematics as a powerful means to explore processes of change in biomedical contexts.

The CoI planned the structure and contents of the module in a backward direction. Looking at the desired end point of the module, the CoI discussed what would be the mathematical concepts needed in the hypothesised learning trajectory. Many discussions were about pedagogical questions like how to promote conceptual learning through an inquiry approach and how to deal with alternative conceptions. The structure and contents of the module crystallised, based on classroom experiences, and ended with five parts:

(1) basic mathematical functions and numerical differentiation;
(2) basic growth models;
(3) chemical kinetics and quantitative pharmacokinetics;
(4) basic concepts and methods of dynamical systems;
(5) applications in a biomedical context.

The mathematical focus was on main concepts of the theory of dynamical systems like direction field, stability of an equilibrium, asymptotics of solutions of (systems of) ordinary differential equations, and more importantly the concept of solving a differential equation algebraically, numerically and graphically. The lecturers explored how to use R for studying dynamical systems in a uniform and consistent way so that students would not get lost in the pool of different specialised R packages for studying differential equations. Concretely, this means that they inspected textbooks, similar courses, and examples of R use on Internet, and discussed own R scripts written in the process of finding a unified approach of R use. The principal lecturer wrote a reference chapter, based on the textbook of Soetaert et al. (2012), before the start of the module. It summarises the basics of R, regression analysis in R, and investigation of differential equations with R. It served as a guideline for the CoI to prepare R-based tasks and instructions, and it helped students look up short explanations of R use.

12.3.2. Implementing IBME. The CoI adopted the following conceptualisation of IBME formulated by Dorier and Maaß (2014):

> IBME refers to a student-centered paradigm of teaching mathematics and science, in which students are invited to work in ways similar to how mathematicians and scientists work.

The CoI members designed tasks to promote student inquiry by paying attention to

- underpinning mathematical methods;
- representing mathematical concepts;
- providing evidence and argumentation;
- exploring/evaluating multiple methods for solving a single problem;
- motivating learning by real biomedical examples.

They enriched lectures with inquiry-based tasks in which students were invited to express own ideas. An example is the task of inventing methods for computing a numerical derivative of a quantity from data only (Figure 12.7). Sometimes small-group work with worksheets in lectures preceded plenary discussions. An example is the worksheet task shown in Figure 12.8.

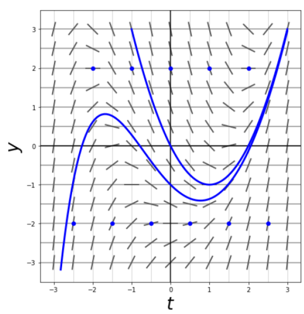
Given are the following values of a function $y(t)$ in the neighbourhood of $t = 1$:

t	0.7	0.8	1.0	1.1	1.2
$y(t)$	0.741	0.819	1.000	1.105	1.221

What is the best approximation of $y'(1)$?
(exact answer = 1 because the function $y(t) = e^{t-1}$ has been used.)

Try several methods and compare the results with each other.

FIGURE 12.7. An inquiry task used in a lecture.



You see above the direction field that corresponds with the ODE

$$\frac{dy}{dt} = t^2 - y - 2$$

and two solution curves.

Sketch solution curves through the blue grid points.
What can be said about the behaviour of solutions?

FIGURE 12.8. A worksheet in which students sketch solution curves and conjecture about asymptotic behaviour of curves.

Regarding tutorials, CoI members rephrased exercises taken from previous courses like Basic Mathematics for Psychobiology to make them more inquiry-based (cf., Dorée, 2017), included visual explorations of mathematics via ICT tools and JavaScript-based simulations, and introduced mathematical programming in a biomedical context.

All elements of IBME mentioned above and linking of mathematical content to real biomedical inquiry come together in the final teaching unit about enzymatic kinetics. In this unit, students explore the Michaelis-Menten model and its effectiveness in explaining real data taken from a research paper (Moss et al., 1996).[4] It is an example of guided and structured student inquiry, meaning that students follow directions and hints in a structured teaching-learning path based on professional practice of parameter estimation, but conclusions are predominantly based on the investigation carried out by an individual student or pair of students. In Table 12.1, the subtasks are typified according to the 5E learning cycle model of Bybee et al. (2006).

Subtask	*Activity*	*E-emphasis*
1	Giving meaning to kinetic variables	Engage
2	Defining and understanding the Michaelis-Menten model as ODE	Engage
3	Estimating the initial concentration of the substrate	Explore
4	Transforming data to a linear model	Engage
5	Computing reaction rates and drawing the Lineweaver-Burk plot	Explore
6	Estimating parameters via the Lineweaver-Burk plot	Engage
7	Doing a numerical sensitivity analysis of kinetic parameters	Explore
8	Using the Eadie-Hofstee plot and the Hanes-Woolf plot	Elaborate
9	Doing nonlinear regression with the Michaelis–Menten formula	Engage
10	Doing nonlinear regression using the differential equation	Elaborate

TABLE 12.1. Subtasks in the enzymatic kinetics teaching unit.

This teaching unit goes beyond what students learn in traditional courses with respect to critical thinking, in particular about the use of evidence and the relationship between evidence and explanation.[5] The use of evidence is addressed in the regression subtasks 6-10 in which students determine the quality of various regression methods (linear and nonlinear) by graphical comparison of computer results with the data. This shows that data analysis involves decision making and exploration to come to scientifically underpinned answers and conclusions. The relationship between evidence and explanation is addressed when students are confronted with an unexpected result that needs an explanation for making progress. For example, students do not get a straight line in the Lineweaver-Burk plot (subtask 5-6) with a simple numerical differentiation method, need an explanation for this (subtask 7), and must explore other differentiation methods or other linearisations (subtask 8).

12.3.3. Learning From Research Literature. The outer layer of the three-layer model is developmental research inquiry and this commonly involves studying research literature on the subject of interest. The most recent literature review about teaching and learning of differential equations was published by Lozada et al. (2021).

[4]The first tasks were inspired by inquiry activities created by Coolidge (2008).

[5]Most textbooks that discuss enzymatic kinetics mention only the Lineweaver-Burk equation as a linearisation of the problem of estimating parameters in the kinetic model. They do not discuss the side effects of this linearisation on the statistical analysis and its results, other possible linearisations, and the use of values found in a linearised setting as initial values for a nonlinear regression method. In the PLATINUM teaching unit we pay attention to all of this in student tasks.

CoI members benefited from the MAA Research Sampler (Rasmussen & Whitehead, 2003) and the review by Rasmussen & Wawro (2017) about students' conceptual understanding of differential equations, equilibrium solutions, bifurcation, and graphical approaches. In these reviews, it is pointed out that the concepts of direction field and solution of a differential equation have many facets that affect student understanding. Cited research papers gave CoI members food for thought about student misconceptions and helped them create teaching units for introducing new mathematical concepts about dynamical systems (e.g., worksheets like in Figure 12.8).

Inspecting research literature about teaching and learning differential equation, the CoI came across and got interested in the publications about the Inquiry Oriented Differential Equations (IODE) course (Rasmussen & Kwon, 2007; Rasmussen et al., 2018). In this course, based on Realistic Mathematics Education, emphasis is on student reinvention of mathematical concepts, teacher inquiry into student thinking, and student inscriptions and their role in the development of the mathematics. CoI members discussed this approach in early meetings and they found this conceptualisation of IBME attractive and shared the idea that students should be routinely invited to explain and justify their mathematical thinking, their solution strategies, and actions in open-ended activities. This is reflected in the basic mathematics module through the added short questions like "Why?" and tasks like "Explain your reasoning" or "Compare with the previous result" to prompt students to think more deeply about the mathematics that they applied, to provide arguments for the choices that they had made in applying mathematical methods, and to explore the effectiveness of several techniques by experimentation and comparison.

Yet, after ample discussion, the CoI came unanimously to the conclusion that they would not adopt the IODE approach because of the guided reinvention and emergent modelling principles. These principles are at odds with the usual way of teaching in biomedical courses where main concepts are discussed in class by lecturers, but not reinvented by students. Also, differing mathematics background of students would complicate the reinvention process.[6] The size of the student population was too large[7] and the student-teacher contact time was too short for this approach.

12.3.4. Feedback From Students. The CoI collected student feedback via a questionnaire with Likert scale statements, rating questions, and open text fields for remarks. The feedback addressed the students' appraisal of the module (instructional design, instructional materials, learning activities and their inquiry nature), the use of the SOWISO environment, the use of R and RSTUDIO, and the points for improvement of the module. Main results are listed as mean values in Table 12.2 for the study years 2018–2019 and 2020–2021.

The Likert scores confirm that students in 2018-2019 had a neutral or positive opinion about the instructional design of the module and the use of SOWISO. However, they found the level of the mathematics module too high, and programming in R difficult and hardly contributing to better understanding of mathematics. The following comment supports this conclusion:

[6]For an IODE class at a school of engineering, consisting of 25 academically strong students, Habre (2020) reported that reinventing knowledge was demanding and in some cases required the intervention of the instructor to control and lead the discussion. Our annual group of about 150 first-year students in biomedical sciences is far more heterogeneous and probably less strong in mathematics.

[7]As far as we learned from research literature, RME approaches have been implemented and researched only in classrooms with 15 to 30 students (many authors of papers on such approaches do not mention or are vague about the number of students involved in their research studies). The feasibility and effectiveness for large student populations is thus unclear.

I found that the R tasks made the content just more complicated. I liked the pen-and-paper tasks most, but the exercises in SOWISO were also fine. In case R tasks must be embedded in this course, I think more attention must be paid to them.

Statement	μ_{2018}	μ_{2020}
The goals of the mathematics module were clear to me.	2.7	3.7
The structure of the course was clear to me.	3.2	4.0
I found the contents of the mathematics module interesting.	2.7	3.5
Through the extra attention paid to applications I saw the usefulness of the mathematics module.	2.9	3.9
I learned a lot in the mathematics module.	3.3	4.0
I had enough preknowledge for the mathematics module.	3.1	3.8
I still have not well understood all parts of the math module.	3.8	2.8
The level of the mathematics module was too high for me.	3.7	2.6
In general I found that the mathematical exercises were clear.	3.2	4.1
In general I rated the level of the mathematical exercises as good.	2.5	4.1
The working of SOWISO was clear and I could work well with it.	3.5	4.5
The feedback in the SOWISO excercises was good.	3.5	3.8
I learned much from the short tasks in the lectures (e.g., inventing a numerical differentiation method and practising with direction fields).	3.6	4.0
I appreciated that the use of R was addressed in the lecture.	3.7	4.2
The working of the RStudio was clear to me; I could work well with it.	2.5	3.4
The R tasks helped me better understand the mathematics.	2.1	2.6
I disliked the spreading of the mathematics module over a long period and I prefer a module taught in consecutive weeks.	4.1	–
I liked that the module was in a short period of 7 weeks. I prefer this compared to a module spread over a long period.	–	4.3
I prefer separate courses in mathematics and statistics.	4.3	3.8
In some mathematical problems you had to explore things by yourself. This type of 'inquiry-based learning' had appeal for me.	2.7	–
I prefer tasks in which I am instructed about the expected outcomes and what to do.	–	4.1

Table 12.2. Main results of the questionnaire in the study years 2018–2019 and 2020–2021 consisting of 5-point Likert scale (1=*strongly disagree*, 5=*strongly agree*) statements.

Other points of criticism of students after the first run of the module were about the work load, the course pace, the combination of statistics and mathematics in a single course, and the spreading of mathematics over a long period of time.

Students were asked to mark the lectures, the tutorials, and the mathematics module as a whole on a scale from 1 (*very poor*) to 10 (*excellent*). The median values of these marks were all equal to 7 (meaning *generous pass*). One of objectives of the module was that students would enjoy learning mathematics in the biomedical context. The following comment of a student illustrates that lecturers play a crucial role herein:

The lecturers really did their best to let students pick up that the course was not all about the exam, but that the subjects taught were really interesting. This motivated me to do my best to better understand the course materials.

12.3.5. Reflections of the CoI. As a CoI, we were happy with the pass rate of 70% and details of students' experiences which showed us where students were positive about the module and where they were less satisfied. We agreed with students that improvements were needed concerning the use of R and RSTUDIO, the relationship between the statistics and mathematics parts of the courses, and the large amount of contents within the mathematics module.

As module designers and lecturers, we considered the R tasks as opportunities for students to explore mathematical concepts by inquiry. But many students were in fact still coming to grips with the use of R and RSTUDIO as tools to carry out tasks rather than for learning mathematics. An instrumental approach to digital tool use in mathematics education helped us understand students' difficulties.[8] We concluded that many students were not far enough in the process of instrumental genesis, i.e., in developing suitable utilisation schemes and techniques in order to transform tools as artefacts into instruments suitable for a task or activity.

We illustrate the complexity of instrumental genesis of using R and RSTUDIO with the 'simple' task of plotting the graph of a function. Many abilities, of both technical and conceptual character, can be distinguished: having developed essential graph sense (delMas et al., 2005; Heck, 2012, Subsection 4.2.5), being familiar with structural components of graphs (cf., Kosslyn, 1989), being able to interpret the result of graphing and see how improvements can be made, realising that one variable is plotted against another in a two-variable graph,[9] having basic knowledge about the user interface of RSTUDIO (writing and running R scripts, the concept of workspace, etc.), being able to enter a syntactically correct plot command,[10] knowing how to define a mathematical function in one variable in R and understanding how it can be applied simultaneously on a sequence of values, knowing how to create a sequence of values, and knowing options in the plot command and how to specify them.

So, one must take many things into account for the instrumentation scheme of plotting the graph of a mathematical function in a command-driven software environment like RSTUDIO. Students cannot be expected to figure this out all by themselves and lecturers must carefully introduce students to the basics of programming in R for doing mathematics. This is called instrumental orchestration in the instrumental approach. Referring to the taxonomy of instrumental orchestrations (Drijvers et al., 2013), we applied whole-class technical demonstrations, discuss-the-screen, and explain-the-screen orchestrations in lectures and tutorials. In addition, we used individual technical support, individual discuss-the-screen, and guide-and-explain in tutorials.

The applied instrumental orchestrations without doubt had helped students familiarise with the technology and learn to do mathematics with it, but they had not been optimal because of the process of double instrumental genesis in which we as lecturers were involved. This means that we were on the one hand developing schemes for use of R in doing mathematics and on the other were developing schemes for use in teaching our students how to use R for learning and doing mathematics. We also had not realised that the instrumental genesis of students during the statistic part of the

[8]An instrumental approach in mathematics education focuses on the interactions between students, teachers, and artefacts. This approach analyses mediations attached to the use of a given artefact and instruments developed by the subjects from this artefact along instrumental geneses (see Trouche, 2020a,b).

[9]In case of a plot of the function $y = f(x)$, a collection of points of the form $\big(x, f(x)\big)$ must be computed for various choices of x.

[10]In order to plot $y = f(x)$ one must create two sequences of values x and y, and provide them in the right order in the plotting command plot$(x, y, \dots)$. This ordering is opposite to the usual ordering in scientific language: in science for example, one calls a graph of a quantity y with respect to another quantity x a y-x diagram, whereas in mathematics it is called an x-y diagram.

course had a different orientation than the one needed for the tool use in the mathematics module. In statistics tutorials, students had copied and adjusted R commands and scripts to carry out a computational task, while in mathematics tutorials they were expected to write R scripts for doing mathematics. As a result, many students stumbled over technicalities in R and RStudio, lost oversight over what they were trying to achieve, and forgot to think about the mathematics addressed in the computer tasks. This affected the performance of students in IBME tasks the most. As a CoI, we conceived a plan for revision of the learning trajectory for the use of R and RStudio toward a better promotion of the students' instrumental genesis.

The revision would be combined with a reduction of the contents of the mathematics module to essential concepts and methods, and better tuning of the learning trajectory to the mathematical abilities, programming skills, and scientific content knowledge of the students.

12.4. Work of the CoI on the Redesign of the Module

The redesign of the basic mathematics module taught in the study year 2020–2021 concerned the tutorials in particular. Two 2nd-year students and one 3rd-year student in biomedical sciences had taken the module in previous years and were employed not only as teaching assistants (TAs) for the tutorials but also as module developers in the two months before the start of the module. They made the R instruction more student friendly and accessible. The main idea behind the student partnership for module design was that the TAs could still see the teaching materials through students' eyes. This was considered helpful for restructuring and changing the wording of the tasks in such ways that students could better deal with the mathematical concepts and methods taught. The partnership also offered new opportunities for getting feedback from students on the module. The CoI expected that students would give more feedback in interviews to TAs, who took the module earlier, than to lecturers. In this sense the student partnership gave an extra dimension to the inner layers of the three-layer model of inquiry.

In the rest of this section we report on the redesign of the module, online teaching, feedback of students on the module, and reflections of the CoI.

12.4.1. Redesign of the Module. Weekly tutorials were split into two sessions, one with a focus on learning mathematics concepts and another focusing on learning to use R and RStudio for mathematical computations, simulations, and data analysis. The idea behind this splitting of contents and nature of tutorials was that it would make it easier for the teaching assistants in the R-based tutorials to organise interventions that assist the process of instrumental genesis, i.e., turning a computational environment into a mathematical instrument.

The TAs focused on improving the support of students for learning to program in R and helping them carry out basic mathematical tasks such as working with mathematical functions, carrying out data analysis, and solving (systems of) ODEs numerically and graphing the solutions. They used the reference chapter from 2018 about working with R to create teaching units for use at the beginning of each R-based tutorial. Students learned in this part the basics of R relevant for the mathematical topic of the lesson through practising with R in a trajectory of many small tasks. In the second part of the R-based tutorial students carried out an IBME task that needed the R abilities that they had just acquired. A worked-out solution of each IBME task was made only available to students at the end of the tutorial to compare their own solution with the lecturers' solution.

12.4.2. Online Teaching. Because the module had been realised in the format of ICT-supported instruction in SOWISO, it was rather easy to manage teaching activities in the context of a lockdown due to the COVID-19 pandemic. Lectures became ZOOM meetings and breakout rooms were used to organise small group activities (e.g., the IBME task on numerical differentiation shown in Figure 12.7), the blackboard was replaced by a pen tablet for the lecturer, and polls were added to ZOOM meetings for engaging students during the lectures. Students stayed muted during the lecture except when asked for a direct reaction, but they could ask questions at any moment via chat. We structured the student-lecturer interaction in this way in the hope that students would still experience membership of a class with a low threshold for interrupting the lecturer by asking a question. To this end, a teaching assistant continuously monitored the chat, immediately answered simple questions, and interrupted the lecturer for answering questions that seemed interesting for the whole class.

Tutorials became MS TEAMS sessions. Main reasons for using MS TEAMS instead of ZOOM were that students could use this platform also outside the scheduled contact time, have private meetings with peers whom they liked to work with, and could share application screens or digital images with each other (e.g., SOWISO screens) and pass control of applications to others (e.g., giving a TA control over the RSTUDIO environment). Especially, the screen sharing was effectively used in the interaction amongst students in a meeting and between student and TAs. Screens of SOWISO exercises with worked-out, but not fully understood solutions, as well as RSTUDIO screens with scripts that did not work, or perhaps not in the intended way, were shared and discussed.

All tutorials were organised as follows. First, all students and TAs convened in a TEAMS meeting started inside the main module channel. In this meeting, the tasks of the particular tutorial session were introduced. This could be a digitally handwritten solution of an important mathematical exercise or a demonstration of how to work with R or RSTUDIO. Next, the students moved to the channel for the working group they were assigned to and started there a private meeting with a small group of peers. The TAs remained in the main meeting. When a student or group of students needed help, they came back to the main meeting to discuss their problem with a TA, left a message for help in the chat if no TA was available at the moment, or directly invited a TA to join their private meeting. Two or three times during the tutorial, the TAs passed by in the private meetings of students to ask how things were going.

12.4.3. Feedback From Students. We refer to Table 12.2 for results of student feedback in the study year 2020–2021. All results point to a more positive appraisal of the module regarding design, quality of the instructional materials, and implementation of the module compared to earlier study years. This is also reflected in the marks given (on a scale from 1 [*very poor*] to 10 [*excellent*]) by students for the module as a whole, the lectures, and tutorials: median values increased to 8, 8, and 7.5, respectively.

The teaching assistants held online semi-structured small-group interviews to explore how students had experienced the module. Subjects were the structure and content of the module, the guidance during the tutorials, the R tasks, the links between theory and practice, and the IBME tasks. The interviewers worked in teams of two with one of them taking notes during the interview. Together they wrote a summary for discussion with the rest of the CoI in an online meeting.

Interviewees told that the transfer from school mathematics to the mathematics module was fine because it started with subjects with which they were familiar. But once the subject of differential equations started, it became more difficult to keep up with contents and pace in the lectures, especially for students with Mathematics A background. The support of teaching assistants during the tutorials was good: screen sharing to explain R code or a mathematical concept helped students move on with tasks that were at first not well understood.

The students mentioned that the mathematical level in the tutorials gradually raised and was very high when differential equations, chemical kinetics, and quantitative pharmacokinetics were studied. Pure mathematics exercises were easier than the assignments on biomedical applications. Yet the students liked that there were both types of assignments and said that "easier does not imply nicer" and that "application tasks require more insight, but add more to understanding than the pure mathematics exercises."

The discussions about the R tasks revealed that the students considered the learning curve from copying and adjusting R scripts, which was the approach in the statistics part of the course, to writing R scripts themselves in the mathematics module as steep. It helped that the R assignments were mostly done in small groups so that students could help each other. Mathematical exercises were mostly done individually.

The students mentioned that the links between theory and practice were good in general. The lectures connected well to each other, but occasionally less well to the tutorials in the same week. Some of the students wondered whether they could learn enough for the exam from the examples in course notes, the lectures, and the tutorials. This indicated an assessment-driven study behaviour directed to minimisation of time investment for passing the exam.

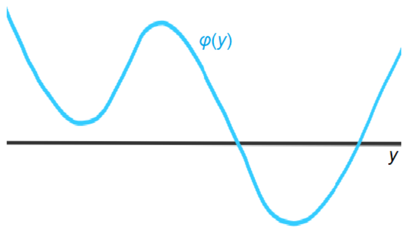
IBME tasks led to mixed reactions of students. Some students found this style of working difficult because the inquiry tasks were open, with a variety of methods that could be applied, and with no single correct result, but with an outcome that is subject to own evaluation. Without a worked-out solution they found it difficult to reflect on their own results or attempts made. Some of these students simply gave up on the inquiry tasks or did not spend much energy on them because they did not expect that more effort in these tasks would lead to higher exam results. Students who liked the IBME tasks mentioned that working on these tasks led on the one hand to new insights in applications of mathematics in biomedical sciences, and on the other hand promoted understanding because they had to think about every line of R code and look at what happened or should have happened. All students suggested that TAs would present worked-out solutions in class so that they could compare them with their own (intermediate) results instead of having to wait until next week when worked-out solutions would be made visible in the SOWISO environment.

12.4.4. Reflection of the CoI After the Revision of the Module. The CoI was pleased that the restructuring of the module and the redesign of the R tutorials had a positive effect on the students' appraisal of the module. On the one hand, it interpreted the student feedback about availability of worked-out solutions and the other comments of students as an indication that many students were still focused on getting correct answers instead of concentrating on the mathematical concepts and inquiry into mathematics in a biomedical context. On the other hand, it noticed that progress in this direction had been made. Yet, the CoI still identified room for improvement in several dimensions.[11]

[11]The CoI consisted of several persons, each with own experiences and personal reflections, and with own ideas about teaching and learning. But there were actually no strong disagreements or difference of views within the CoI and always could CoI members come to a common understanding on the evaluation of module. This is why we write sentences starting with "the CoI ..." instead of presenting individual reflections or letting one member of the CoI speak for all of them.

The CoI still struggled with the amount of content in the module of seven lesson weeks. It sympathised with the students' suggestion to introduce new mathematical concepts in smaller steps, especially out of consideration for students with Mathematics A background. This challenged the CoI to think deep about which important and instructive subjects could still be dropped from the course without lowering the ambition level too much. Also the number of contexts of applications of mathematics was reviewed by the CoI. For example, the question was raised whether chemical kinetics is necessary in an introduction to Systems Biology, but we decided to keep it (at least another year). However, the need to free space for more effective promotion of conceptual learning became evident from the following example. In the exam, students were asked to draw a phase line based on a given graph and do the same for a specific differential equation. The conceptual task was:

For the differential equation $\dfrac{dy}{dt} = \varphi(y)$ with the below graph of the function φ



(i) How many equilibria are there for this ODE based on the above graph?
(ii) Draw the phase line for the ODE based on the above graph.

The procedural task was the same, but for a concrete function $\varphi(y) = y^2 - 2y$. The success rate for the conceptual task was significantly lower than for the procedural task.

The CoI intended to elaborate on making the learning curve for working with R less steep. Three types of improvements were considered:

- paying more attention in the mathematics module to programming;
- increasing the students' computer skills during the statistic part of the course before the mathematics module starts;
- explaining the differences between the use of R in statistics and mathematics.

The CoI experienced that inquiry-based teaching and learning, especially in the R-based assignments, would benefit from discussion of IBME tasks during the tutorials, in which students are encouraged to reflect more and deeper on their work. Inquiry into students thoughts and ideas is possible only through effective interaction between students and the lecturer. The lecturer can only effectively interact with students when (s)he is able to keep an overview of what all groups of students think and do, and can choose individual, group, or whole classroom discussions according to what seems best at the moment. It is a big challenge to do this with a group of 150 students, even with the help of technology.

The lecturers had difficulty in motivating all students for doing inquiry. For example, about 30% of the students dropped out as soon as the lecturer announced in the lecture the IBME task of inventing and evaluating numerical differentiation methods shown in Figure 12.7. These students actually undermined the didactical contract by avoiding to deal with the IBME task and others may have used the task not in a way actually intended by the lecturer. This phenomenon was also encountered in the German case study described in Chapter 14. The German authors concluded that it is indicative of a fundamental principle in teaching-learning contexts, namely that no teaching can force learning. The CoI wondered whether this is related to lack of motivation for learning only, and not to the difficulty of assessment in an IBME course too. After running the revised mathematics module, the CoI found it promising that many students expressed that they had enjoyed the module and had learned much about the role of mathematics in biomedical sciences.

12.5. Concluding Remarks

In this section we share experiences for lecturers in higher education based on the lessons learned by the CoI at the University of Amsterdam. Firstly we recommend lecturers to join a community of inquiry or to start one, because it helps develop deeper thinking about higher education and sharpen the vision on instructional design of mathematics and science, and because it makes inquiry in teaching and learning easier and more doable. Collaborative inquiry helps lecturers develop an inquiry stance in practice and fosters critical alignment to the teaching-learning-practice. It offers opportunities to discuss and question established ways of teaching, to seek for new ways of classroom activities and mathematical learning of students, and to develop student tasks according to a new vision on teaching and learning. More brains and hands make work easier and help achieve more. Especially involvement of teaching assistants in a community of inquiry is strongly suggested because they have a complementary perspective on instruction. For example, they are more able to view the instruction materials as students and can help in inquiry into student learning. The following quote of a TA in this case study illustrates what was learned from interviewing students:

> All in all, I think we have collected information with which we can do something. Broadly speaking, the course was very structured and the degree of difficulty for students was okay. Some small details have come up several times, so we could do something about that. An example of this is that many students found the hints for R assignments unclear or that they led them astray. Some students suggested to include short pieces of code as a hint rather than a thought or question that should help a student further. This kind of suggestions we could discuss in the next meeting

Within a community of inquiry more informative evaluation instruments can be deployed that go beyond dealing with day to day issues arising in practice. We recommend lecturers to collect data via research-based or own questionnaires because they allow deeper analysis of student results and their course experiences than institutional evaluations can do.

Working in a community of inquiry, especially when it is organised around a particular course, also helps maintain ambitions and keep going on because one does not want to break promises made to colleagues in the mutual engagement. It seems best to get a group of lecturers together and first think of small changes in the instruction and try them out. Changing and/or extending existing tasks to tasks that promote student thinking and engagement, or making existing tasks more suitable for use by students with identified needs are good starting points for discussion.

Working together at international level helps avoid a narrow view on instruction and educational settings. One quickly realises through discussions that different views on instructional design are possible and equally valuable, and that lecturers in other countries have similar difficulties and challenges in teaching and learning. Our experience was at least that setting up a community of inquiry in the framework of the PLATINUM project enriched our work at all levels of the three-layer model of inquiry, increased our joy in instructional design and teaching our students inquiry-based activities, and increased the quality of our work.

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