Article

An Undergraduate Course to Bridge the Gap between Textbooks and Scientific Research

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This article reports on a one-semester Advanced Cell Biology course that endeavors to bridge the gap between gaining basic textbook knowledge about cell biology and learning to think and work as a researcher. The key elements of this course are 1) learning to work with primary articles in order to get acquainted with the field of choice, to learn scientific reasoning, and to identify gaps in our current knowledge that represent opportunities for further research; 2) formulating a research project with fellow students; 3) gaining thorough knowledge of relevant methodology and technologies used within the field of cell biology; 4) developing cooperation and leadership skills; and 5) presenting and defending research projects before a jury of experts. The course activities were student centered and focused on designing a genuine research program. Our 5-yr experience with this course demonstrates that 1) undergraduate students are capable of delivering high-quality research designs that meet professional standards, and 2) the authenticity of the learning environment in this course strongly engages students to become self-directed and critical thinkers. We hope to provide colleagues with an example of a course that encourages and stimulates students to develop essential research thinking skills.

INTRODUCTION

During the past decade, the importance of engaging undergraduate students in research activities gained renewed attention internationally (Boyer Commission, 1998; Simons, 2006; Hu *et al.*, 2008). Undergraduate students not only should acquire knowledge about the outcomes of past research done by others; they should also learn to initiate and do research themselves. Potential merits of undergraduate research activities are that students learn how researchers in the field work, think, and communicate and that students develop their crit-

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ical, analytical, and creative thinking skills as well as their problem-solving abilities (DebBurman, 2002; Zamorski, 2002; Durning and Jenkins, 2005; DiCarlo, 2006). There seems to be little disagreement on the importance of these potential merits. An important question, however, is how to organize undergraduate research activities within a limited 15-wk course structure. In this article, we report on an Advanced Cell Biology course that focuses on the first part of the research process: the research design. Students in this course designed a genuine research program that included four interdependent PhD proposals. This process of designing research proposals accelerates the learning of valuable academic skills and attitudes. The authenticity of the learning environment created in the course seemed to be a crucial factor for the effectiveness of the course.

Authentic Learning Environments

In the past three decades, constructivist educational philosophy has conquered ground in higher education. In short, constructivists challenge views of the learning process as the transmission of information to passive receivers. Instead, constructivists view learning as an active process of the construction of knowledge, mapping new information on

prior knowledge. This notion has led to the use of activelearning methods like problem-based learning, inquiry-based learning, collaborative learning, and experiential forms of learning (Valcke, 2000; Mayer, 2004). In contrast to instructorled courses, in which students obtain a base of scientific facts through lectures and note taking, dynamic student-centered activities are emphasized that engage students actively in constructing knowledge. According to Newmann, however, active learning does not automatically lead to a deeper understanding and to the intellectual quality we strive for: "[E]ven highly active students can produce work that is intellectually shallow and weak" (Newmann et al., 1996, p. 281). Newmann makes a case for the use of "authentic" learning tasks-tasks that simulate real-world expert practice. Authentic learning contexts of open-ended projects have been found to enhance a deep approach to learning; develop professional skills; and increase student motivation, engagement, and confidence levels (MacFarlane et al., 2006; Gulikers et al., 2008; Quitadamo et al., 2008; Gilardi and Lozza, 2009).

A deep approach to learning is characterized by an intention to understand—focusing on the concepts applicable to solving problems, relating previous knowledge to new knowledge-and it has an internal or intrinsic motivational emphasis (Biggs, 1999). Conversely, a surface approach is characterized by an intention only to complete task requirements for assessment, associating facts and concepts unreflectively. Deep approaches establish a collaborative learning environment and use acquired theory, concepts, and knowledge to solve new problems. Research-based assignments typically call for a deep approach to learning because students need to manipulate the information and ideas in ways that create new meanings. The pedagogical principle is simple. Researchers learn far more from their own research than their peers, supervisors, or students do. In doing research one learns to gather relevant and actual sources, detect new research questions, search for the best methods, communicate with peers, and present one's findings, and one gets to know the disciplinary research culture. So why not expose students to this powerful learning experience instead of telling them about it in lectures?

According to Bereiter and Scardamalia (2003), immersion is the only promising way to help students acquire these skills: "[I]f we want students to acquire the skills needed to function in knowledge-based, innovation-driven organizations, we should place them in an environment where those skills are required in order for them to be part of what is going on" (p. 56). An authentic learning environment thus generates the cognitive learning processes aimed for. A second advantage of authentic learning environments is their motivational force. Allowing students to work on a topic of their interest stimulates intrinsic motivation, which in turn enhances students' responsibility and their perseverance (Valle et al., 2003). Moreover, if students value the task at hand as worthwhile, for their future studies or their career in general, motivation will increase (Pintrich, 1999). Authentic tasks like doing research are typically tasks that have a value beyond the school setting. In addition, when students are intrinsically motivated, they experience "interest, a sense of importance, challenge, even a sense of exhilaration. Learning is a pleasure" (Biggs, 2003, p. 16).

In conclusion, engagement of students in activities that science professionals perform will 1) help students to develop scientific process skills, 2) promote their interest in and mastery of sophisticated science content, and 3) help students gain closer familiarity with scientific culture.

In this article, we describe the key elements of an Advanced Cell Biology course that exemplifies how we believe the learning environment could be designed to take into account the educational insights described above, and we discuss the validity of these elements in bridging the gap between textbooks and scientific research. In this particular course there is no practical research aspect; instead, it focuses completely on all aspects involved in the design of a research program. In our opinion, this open-ended assignment models professional behavior in the field of cell biology. It provides students with an authentic learning context within which they experience the activities (performed by professional scientists) to formulate a research project aimed at extending the knowledge beyond what is currently known. It is our aim to provide colleagues in the field with an example of a course that stimulates students to develop essential research (thinking) skills within a limited time frame.

AIMS AND ELEMENTS OF THE ADVANCED CELL BIOLOGY COURSE

Context and Course Organization

Dutch science curricula integrate research-like experiences at the undergraduate level, but in many cases the level of research is limited to relatively small experiments that often have a "cookbook" character. To meet the reality of the research professional even more, we have developed an Advanced Cell Biology course in a liberal arts and science college (University College Utrecht [UCU], the international undergraduate honors college of Utrecht University) at the upper-undergraduate (300) level that focuses on writing and defending a research proposal as an open-ended, authentic assignment.

The UCU bachelor curriculum consists of minimally 24 courses with a maximum class size of 25 students each. UCU students complete 4 courses per 15-wk semester, each course having a workload of about 200 h (7.5 European Credit Transfer and Accumulation System credits) consisting of 60 contact hours (i.e., 4 contact hours per week in 2 sessions) and approximately 140 h of self study.

All students who enter the Advanced Cell Biology course (300 level) are life science majors and have completed their prerequisites of an introductory biology course (100 level) and a textbook-based cell biology course (200 level). Students have had virtually no lab experience, with the exception of a 200-h science lab module. Over the past 7 yr, class size of the Advanced Cell Biology course varied between 12 and 25 students. Depending on class size, students were divided into three to four teams of four to six students each.

Bridging the Gap between Textbooks and Scientific Research

During the development of an undergraduate biology student into a skilled cell biology PhD student, an important step has to be taken, and that is to bridge the gap between textbook knowledge and scientific research skills. From textbooks the students learn the condensed knowledge from review articles and primary research on which general consensus has been reached by the scientific community, whereas in current research articles presented in journals, consensus about the observations and interpretations has generally not yet been reached. The knowledge presented in primary research articles often still leads to discussions and debates between professionals as well as the requirement to design further research to resolve inconsistencies in the current knowledge about a specific topic. Therefore, the knowledge from the literature has to be translated into questions that have not yet been answered and for which the solution can be obtained in the laboratory using appropriate methods and techniques. In addition, modern cell biological research also requires high-level academic skills and competences such as critical thinking, collaboration between scientists, and oral and written communication.

This implies a big leap forward in students' academic development. To achieve these skills and competences, students need to move from acquiring the disciplinary theory, neatly ordered in textbooks and lectures, to reading primary articles and engaging in the actual scientific discourse. Furthermore, students need to get acquainted with the way modern science is performed and which methods and technologies are currently used. A second gap students need to bridge is that of comprehending the ideas of others toward finding a promising niche in cell biology research and formulating their creative research ideas in a convincing way using solid argumentation. A third shift concerns the degree of self-regulated learning in which students are expected to be able to work more independently and take full responsibility for their actions and decisions. These aspects are covered in the course objectives (Table 1).

Course Design

In order to help students achieve these learning objectives, a mock research environment is created in which students act as young researchers, preparing a research program to be assessed by external experts using professional international criteria. The design of a research project has been chosen as the leading assignment. Within the limited course time, it is impossible to allow students to do a complete research project. Designing a research project is a compact and clearly defined stage in research, which gives students a good opportunity to get on top of the current cell biology research, including the methods and techniques used, and to acquire skills in critical

Table 1.Course objectives

By the end of the course, students will:

- 1. Have developed a critical attitude
- Have increased their understanding of the scientific discovery process and their ability to think scientifically
- 3. Understand the state of the art in the chosen field of interest in cell biology
- Be able to identify research opportunities and formulate research questions and research hypotheses that are based on recent primary literature
- Understand techniques used in contemporary cell biology research
- Have increased their ability to collaborate with peers and integrate individual talents
- Be able to communicate advanced scientific topics effectively both orally and in written form

thinking, cooperation, and communication. As key elements of this course, which should help students to bridge the gap described above, the course design focused on 1) learning to work with primary articles in order to get acquainted with the actual discussion in the field, to learn scientific reasoning, and to identify opportunities for further research; 2) formulating a research project with fellow students that would fit into a coherent research program of four different projects; 3) getting thorough knowledge of relevant methodology and technologies used within the field of cell biology; 4) developing cooperation and leadership skills; and, finally, 5) participating in the authentic assessment of students' work-the presentation and defense of the research projects for a jury of experts. Furthermore, the course activities were completely student centered: The students were empowered to take the lead in the process of generating ideas and formulating the research projects, whereas the instructors' role was to be a facilitator and learned peer, offering discussion, constructive feedback, and critical advice but never imposing their ideas or point of view.

We will describe these key elements in relation to our aims of providing a deep learning experience in which students develop the knowledge, skills, and attitude necessary to design a professional research plan.

Course Organization

In this course, the students develop a research program consisting of three or four research projects, each project comprising 4 yr and leading to a PhD thesis. The different research projects need to be coherent within the overall topic of the research program. Because students have to work together as well as individually, a hierarchical structure has been chosen to optimize communication between students. During the first class session, the students form three or four teams of four to six students each, and they elect a program leader as well as three or four project leaders, one per project team. These people are responsible for communication between the student teams as well as with the teachers. Furthermore, these leaders are responsible for the coherence of the projects, ensuring that the projects together constitute a solid, interdependent, and coherent program.

During class hours, all students meet with the instructor(s), present papers, and discuss their progress. The students use the nonclass hours (about 140) to read the literature, develop and discuss the project and the methodologies with their project team members, visit specialists, and prepare for the written and oral presentation of the research program. During the whole course, the students organize plenary meetings outside class hours to discuss the progress they make. These meetings, in which the teachers are not involved, may reach frequencies of five times per week at the end of the course. The total workload of the teacher is approximately 200 h, consisting of class hours, reading different drafts of the progress of their projects and on the participation of the students in the course. The course is characterized by four different phases.

Phase 1, weeks 1–4: Get to know the topic. A general topic is provided at the beginning of the course on which approximately eight research and eight review articles are distributed by the teachers. The research papers will be studied and presented by the students in duos, with a specific emphasis on

the scientific questions and the methodology described. The students also present and discuss the review articles, which are aimed to broaden their knowledge in the specific field. In both cases, all students are encouraged to question critically all aspects of the papers. Students receive a handout with suggestions on how to analyze an article, such as: What is the main question the authors want to solve? Did they use appropriate techniques? Were control experiments included? Is the main question answered in the conclusion? In addition, students receive a handout that focuses on critically listening to the presentations by fellow students. Usually the teachers are specialists in the field of study and are aware of the new developments in this field. At the end of this phase, the students are able to select a focus within the overall topic of the research proposal.

Phase 2, weeks 5–7: Identify a meaningful gap in the current *knowledge*. In this phase the students focus on the research field covering their interest by searching for (additional) recent primary literature and review articles with the aim to get a detailed understanding of the state of the art and to identify possible gaps in the current knowledge. The findings are presented in class in an informal way, leaving ample time for discussion on the topics of their research program and research projects. These presentations may be short Power-Point presentations or chalkboard talks. On average the students read at least 15 articles each in more or less detail. At the end of the phase, the students are able to formulate their research focus more precisely, suggest titles for the projects, and have a vague idea about the experimental approach. During class hours, the teachers act as critical scientists, asking critical questions about the proposals and suggestions made by the students.

Phase 3, weeks 8–12: Propose detailed experiments using appropriate research methods and techniques. In this phase the students elaborate in detail on their research project by studying recent literature, visiting scientists in the laboratories of University Utrecht, or contacting scientists abroad by email. Findings, ideas, and proposals are discussed in class and in meetings outside class hours. The teachers may facilitate the visits of the students to specific research laboratories and the contact with specialists in the fields of interest.

Phase 4, weeks **13–15**: *Finish the proposal and prepare for the jury defense.* In this phase the students finish writing their proposals and prepare the defense for the jury. The jury defense is very formal; the students prepare a PowerPoint presentation of 2 h, in which usually eight students participate to present the proposals of the various project teams. Usually the project teams choose the students with the best presentation skills. Following the presentation by the students, the defense takes another 1.5 h in which all students are involved. The jury members are asked to include students who did not present in the discussion. The teachers merely observe this event and are not involved in the presentation and defense.

Examples of the research proposals are accessible at www.uu.nl/university/college/EN/studying/advancedcellbiology.

Five Key Course Elements

1. Primary research papers: getting to know and critically evaluate the actual research. During the first 4 wk of the

course, the students need to become familiar with the state of the art of the specific field of the program. To get the process started, the teachers choose a selection of recent primary research and review articles covering the field of study. The students will study these papers with special emphasis on the questions and the technical and methodological approach addressed in the primary papers and present and discuss them in class. Primary literature serves as the most important means of communication within the scientific community. The highly technical and jargon-filled language that is used often represents an initial learning barrier for students. Primary literature addresses the frontiers of scientific inquiry and can be used to instruct students on the scientific method and the nature of scientific reasoning: A scientific article poses a research question, demonstrates the events that led to the answer, and poses new questions. In addition, it has been shown that the ability to comprehend and use primary literature improves critical-thinking skills as well as the understanding of scientific discussions and the research behind textbook knowledge (DebBurman, 2002). To be able to think beyond borders of current knowledge, the students have to develop a critical attitude toward published articles. They have to learn to question the methodology used in papers, to question the conclusions of the authors, and to question the approach of the authors. By doing so, the students will become familiar with finding their own solution to the problems posed by the authors of the articles. This attitude is required to identify gaps in knowledge, to recognize research opportunities, and to be able to propose their own research question, the methodology to be used, and the approach to be followed. In short, the use of primary research articles in this course is meant to 1) increase the knowledge of the students with respect to the state of the art of research findings in a specific field; 2) increase their ability to read and understand primary research articles; 3) increase the knowledge of the students with respect to state-of-the-art methodology and technology; 4) help them to become biologically literate and get acquainted with ways of thinking, communicating scientific ideas, and persuading peers using appropriate arguments; and 5) encourage students to develop a critical attitude.

2. Formulation of the research question: from comprehending the ideas of others toward finding the niche. During the first session of the course, the topic of the research proposal is provided to the students. Examples of the topics were regulation of cell cycle progression at checkpoints (e.g., the spindle checkpoint), protein quality control, interplay between mitochondria and cell cycle progression, and chromosome separation during mitosis. Generally, the topic is broad, allowing the students to choose their own specific field of interest, which ensures the interest of the students in the topic and results in a sense of commitment to the topic.

The formulation of the research questions is an important but difficult task for the students. Undergraduate students often accept the knowledge in textbooks and in written papers without questioning its validity. To be able to formulate a research question, the students have to learn to read critically. The difficulty and complexity of this stage could be overwhelming for students and can cause initial insecurity, which in turn can decrease their motivation (Valle *et al.*, 2003). In this stage, it is important that the teachers try to maintain or repair the students' trust in their own competencies to succeed, but without falling back into the role of instructor and taking over the lead. Trust, support, and constructive feedback or guidelines help. This is practiced also in reading, presenting, and discussing the primary research articles in class. Students will learn that critique of written publications is possible and even that those articles contain mistakes and flaws as well. As soon as this stage has been reached, our experience is that the students are also able to formulate new research questions. Within 4 wk, the students have formulated the main topic of their program and the research questions of the projects.

3. Finding proper research methods: getting acquainted with state-of-the-art technology and methodology. After formulating their research questions, students start to write the proposal, and in this period, they gain specific knowledge on their topic and methodology by searching recent articles on the topic. In this phase, students write a paper on the state of the art of the background of their project. An important aspect of a research proposal concerns the application of the appropriate methods and equipment. Undergraduate students are usually quite unaware of the new developments in specific areas. Therefore, in the study of the research articles described above, specific attention is given to the Materials and Methods sections of these papers. In addition, the students are encouraged to visit the nearby laboratories of Utrecht University and to increase their knowledge of specific methodology by contacting specialists in the field. Experience in the past has shown that scientists are usually extremely helpful to the students. In addition, students enjoy contact with faculty and experience the visit to a lab and/or the discussion with a specialist as enrichment during the process of the formulation of a research proposal.

During the writing process, the students have many opportunities to present their thoughts and ideas in class to be discussed and questioned. During this period, the students learn to be critical toward each other, realizing that a critical attitude increases the quality of the proposal as well as the coherence of the research program as a whole. Specific attention is given to the introduction because the introduction should both be concise and provide sufficient background to fully understand the relevance of the research question.

4. Cooperation between students and groups: learning to work as a professional science team. Research in the science field is not an individual venture; scientists work in groups on research programs. In the Advanced Cell Biology course, the class simulates a research team, in which members need to find a balance in cooperation and competition, just like real research teams. In this way, the authenticity of the task is enhanced, and students get the opportunity to improve their teamwork and leadership skills. From experience elsewhere it became clear that teamwork is one of the most effective elements of the authentic learning environment (Gilardi and Lozza, 2009). In addition, by working together on an overall research program, the students may experience a sense of community building.

Although students work in teams, individual tasks are required to achieve a group effort, like those of the program leader and the project leaders who were mentioned previously. Additional general tasks are critical readers, whose task it is to follow in detail the written products of another team and to provide feedback indicating flaws in reasoning, inconsistencies, and aspects that require further clarification; editors, who are responsible for the written proposal; and, finally, students who will prepare the oral presentations for the jury. It should be stressed here that in addition to the specific responsibilities of the students mentioned above, all students are responsible for the whole program and they can be questioned by the jury on all aspects of the program.

5. The presentation for the jury: learning how to convince a *jury.* The aim of the course is to design a research proposal according to the standards of national science foundations. According to Biggs (2003), courses are effective as long as the course elements are in alignment: When deep learning is aimed for, teaching and assessment methods should all be focused to provoke deep learning. In this course, an external jury is invited to assess the students' work, using the same criteria that are used to assess professional research proposals, which adds to the authenticity of the work students perform and supports their motivation to invest the best of their capacities in this assignment. The jury obtains the final program, including all proposals, 5 d before the presentation. The jury consists of four members, two from UCU and two from Utrecht University or another university. Usually the jury contains two cell biology specialists, one biologist, and one nonbiology scientist. The broad composition of the jury requires that the proposal should be clearly formulated for both specialists in the field and for nonspecialists. In addition, due to this broad composition, students can expect questions ranging from why they chose the specific topic and approach, to the design of specific experiments, to details of the techniques they are proposing to use.

The students present the different proposals, including a general introduction, to the jury during an uninterrupted 2-h period. They explain the research proposal, the coherence of the projects, and the individual projects. They are allowed to choose the best presenters of their team. After presentations, the jury questions the students. All students participate in this event since they are all responsible for the whole program.

Following the presentation and the discussion, the jury evaluates the program as a whole and the separate group projects. In addition, they evaluate the quality of the presentations and the defense by each project team and then provide their overall qualification, which may include a ranking of the projects. The jury evaluates the program as if it were a regular research proposal submitted to the national research fund.

Assessment of Students

In this course, the students are assessed individually and as a team, as outlined in Table 2. The individual assessment focuses on the quality of their active participation in this course and the quality of the academic skills they were able to show throughout the course. Furthermore, the teams are assessed with respect to the quality of the cooperation within teams (including problem-solving capacities) and the cooperation between teams. The final product determines an important part of their final grade (40%) and consists of the following items: the novelty, originality, feasibility, and readability of the research proposal they managed to formulate. Finally, the quality of their final presentation and their performance during the jury defense is included.

Table 2. Assessment of the students in the cou	ırse
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Activities and products	Credit points
Individual	35
Active participation (e.g., in class discussions, presentations)	20
Excelled as an individual (e.g., in discussions/ideas/ leadership, as critical reader, or in any other program-supporting activity)	15
Group work	25
Cooperation in each project team (within team)	15
Cooperation between project teams (within program)	10
Final product	40
Readability/novelty/originality/feasibility of the research proposal	
Meets criteria of a national funding agency	
Presentation and defense	
Ranking by jury	
Total	100

RESULTS OF COURSE EVALUATIONS

This course has been evaluated in several ways. Students evaluated this course through the UCU standard course evaluation form as well as with an additional evaluation form that focuses on the students' learning gains. Results of both student evaluations of the six times the course has been given in the format described here are discussed below. Alumni were also asked to give their opinion of the course in hindsight, especially of how the course influenced their career. Furthermore, the members of the jury were asked to assess the quality of the students' work and also the quality of this specific course.

Evaluation by the Students

Students evaluate the course with a standard online evaluation form with 16 items, which students score on a 5-point Likert scale, and 3 open-ended questions. The mean scores of the 11 relevant items of the standard course evaluations from 2003 to 2008 are compared with the mean scores of the other 300-level science courses in the same period (see

Table 4.	Student evaluations of the opportunities the co	urse offered
or skills	levelopment (mean scores on a Likert 5-point s	scale)

Skills	Mean scores 2003–2007 (<i>n</i> = 81)
Orally presenting (scientific) information Writing about a scientific topic Discussing scientific topic in class Cooperation (like dividing tasks to achieve a common goal) The capacity to solve problems	$\begin{array}{c} 4.76 \pm 0.43 \\ 4.65 \pm 0.56 \\ 4.53 \pm 0.65 \\ 4.64 \pm 0.56 \\ 4.53 \pm 0.57 \end{array}$

Table 3). Only the nine relevant items for this course format are presented; items about lecturing skills are left out. The results of the student ratings show that students evaluated the course positively.

All items score highly except the item about the "assessment methods" (item 3 in Table 3). According to the students' comments, this was because, especially in the beginning of the course, students did not know exactly what was expected from them and what criteria the jury would use. In this respect, the design of the course (student-driven learning community) is very different from the usual courses they followed. The main positive difference in the students' ratings of Advanced Cell Biology, compared with other 300-level science courses, is the learning gain students experienced (item 2), with a mean score of 4.7 and 3.9 for the other 300-level science courses. The mean student rating of the overall quality of this course (item 11) is 4.5, which is significantly higher than the 3.9 mean score of the other 300-level courses.

In addition to the standard online evaluation, students also reflected on their learning gains in another course-specific evaluation form, which focused on the development of specific skills. Table 4 shows the results of the student evaluations of the opportunities this specific course offered to develop their skills. Student ratings were high on all skills (writing, presenting, discussing, cooperating, and problem solving), ranging from 4.5 to 4.8 on a 5-point scale.

In their comments, given both in the open-ended questions of the UCU standard form and in the additional evaluation form, students reflected on their learning gains and their

Table 3. Mean student evaluation scores on Advanced Cell Biology in comparison with the means on all advanced science courses over theyears 2003–2008

		Mean Adv. Cell. Bio. $(N = 78)$	Mean Science Department 300 courses ($N = 717$)
		1 = strongly disagree; 5 = strongly agree	
1.	My interest in the subject matter has increased as a consequence of this course.	4.3	3.9
2.	I learned a great deal in this course.	4.7	3.9
3.	Assessment methods are appropriate.	3.4	3.6
4.	The feedback on my performance is helpful.	3.8	3.5
5.	The course was well organized.	4.1	3.5
6.	The instructor stimulates thinking and my desire to learn.	4.3	3.8
7.	Active student involvement was encouraged.	4.6	4.1
8.	The instructor is an expert in his/her field.	4.5	4.3
9.	How many hours did you spend on this course <i>on average per week</i> (including classes)? (1: < 6 h; 2: 6–10 h; 3: 11–14 h; 4: 15–18 h; 5: > 18 h)	12.3 h	9 h
10.	The degree of difficulty in this course was $(1 = too easy; 5 = too difficult)$.	3.7	3.4
11.	How would you evaluate the overall quality of this course? $(1 = fail; 5 = very good)$	4.5	3.9

Table 5. Selection of typical student comments on their learning gains

Students were asked to elaborate in two or three sentences on what they really learned in the course. For the purpose of this table, the responses are categorized according to the course objectives as described in Table 1.

- In this course, I really learned how to think critically, and see flaws in our own work or that of other groups.
- I also learned not to trust information in published papers and there is no such a thing as "accepted truth," because results from a research should be defined with the cell types, methods used, etc.
- Getting a grasp on critical, scientific thinking that is essential for a future in research/clinical problem-solving strategies.
- 2. Increase student understanding of the scientific discovery process and how to think scientifically
 - This course was helpful to learn the academic process of writing such a project much more than learning the biological details.
 - Overall, I think I have contributed to an interesting research proposal and could experience first-hand what is involved in such a process.
 - It covers a different concept: it is valuable in gaining experience regarding the planning and coming-up with research. Valuable skills
 - that are not really taught in other courses.
- 3. Understand the state of the art in the chosen field of interest in cell biology
 - By reading papers, you still increase factual knowledge, e.g., cell types, techniques, etc.
 - Overall my knowledge and interest in cell biology has greatly increased.
 - I also learned that "knowledge" is vital for further research.
 - The originality and the fact that we were able to apply what we learned in the previous courses.
- 4. Develop the ability to identify research opportunities and formulate research questions and hypotheses that are based on recent primary literature
- To define an idea and then research the current knowledge from current publications. I found this a really good aspect of this course in developing this crucial skill.
- I really learned to be creative in hypothesis formulation.
- Find the gaps in this picture and formulate a hypothesis.
- 5. Understand techniques used in contemporary cell biology research
 - I learned a lot about methods for all sorts of fields in molecular and cell biology.
 - I really learned application of techniques in your own research.
 - By reading so many papers you become more acquainted with methods and experiments in the field of cell biology.
- 6. Increase the ability to collaborate with peers and integrate individual talents
- I learned how to properly collaborate with other group members in such a way that we learn from and use each others strengths and complement each others weaknesses.
- Better understanding of group/cooperation dynamics.
- Cooperation, group work, accepting comments/critique.
- 7. Increase the ability to communicate science effectively both orally and in written form (communication skills)
 - The importance of arguing, supporting your decisions with arguments.
 - Experiencing how research proposals actually are written, the whole process. My writing skills have definitely improved from this.
 - How to best present scientific information to both my own group and the entire class (and the jury).

experiences of the course. Table 5 shows a selection of typical student comments on these issues. According to the students, they gained a deeper understanding of cell biology and of the research techniques. Moreover, they felt they could synthesize and apply the knowledge learned in previous courses. However, as one of the students stated, "I learned so much more than I could ever have gotten from a textbook." Reading and critically evaluating primary articles seemed to be one of the most important learning experiences for the students. Students also frequently mention the improvement of their teamwork skills. Although they have worked in teams quite often in their previous years, the intensive cooperation in this project during the whole semester considerably improved their skills to make use of each other's strengths. Furthermore, students mention their problem-solving skills, research-design skills, communication skills, and an increase in their self-regulation competence. Overall, the learning objectives, stated in Table 1, were amply met, according to the students.

A selection of typical students' statements from the evaluation forms is presented in Table 6. In general, students were enthusiastic about designing their own research program. Students took up the challenge, worked very hard, were very motivated, and managed to cooperate efficiently during the project. Although students experienced stress at times, they rather enjoyed the process and had a feeling of accomplishment at the end of the course. One of the students summarized his or her experiences as follows:

The course really challenges the students to think critically and creatively about research to be set up and research that has already been done. I think this course is a really great intermediate between school classes and the 'real' world of research. It required so much more than just reading a book and making an exam, it was really helpful in developing reading, writing and presenting skills, but it also helped me to be able to better (and quicker) analyze papers, interpret figures etc. and at the end, after the jury presentation and everything, there is a feeling of pride, that you actually really accomplished something.

Below, we discuss the students' comments, organized around the five key elements of the course, as described earlier.

1. Learning to work with primary articles, in order to get acquainted with the field of choice, to learn scientific reasoning, and to identify opportunities for further research. In the process of searching for a suitable research topic, students usually need to change the angle a few times, which requires additional reading of primary articles. Some students experienced this as frustrating; others said it taught them the fuzzy process of research. Most students, however, realized that the

^{1.} Develop a critical attitude

Table 6. A selection of student statements from the standard course evaluation, organized by learning objective

1. Developing a critical attitude

- Students can also realize that the field of cell biology is not so clear cut, many things are still unknown and have yet to be discovered. Therefore such a course gives excellent mental stimulation, and enables one to think critically.
- Especially great that we learned to really critically discuss and review our own proposal and background papers. It will help us later! 2. Learning the scientific discovery process and how to think scientifically
 - The fact that students were given an opportunity to formulate their own research proposal, and get a flavor of the difficulty and effort involved in putting together a scientific research proposal.
 - I liked the fact that, basically for the first time in my academic career in Science, I had the chance to finally explore more, shift from the theory studying to a more practical approach, and I really feel more of an "insider" than "observer/learner" in this amazing field of science.
- It showed us what research really is (fuzzy process).
- 3. Understanding the state of the art in the chosen field of interest in cell biology
 - You really produce something new that is on the frontier of science, a unique piece of work based on questions that still need to be answered. This in contrast to most papers, which are about collecting existing information and putting that together.
- 4. Identifying research opportunities that are based on recent primary literature
 - Reading papers was one of the most useful and important lessons I got in this class.
 - We kept on reading, changing the angle required more reading, which was frustrating a bit.
 - Once read a paper was rarely useless, as it contributed to knowledge about methods but could also become important later as the project evolved.
- It helped us to evaluate the gaps and novel findings that some researchers presented.
- 5. Learning techniques used in contemporary cell biology research
 - I had little experience in lab work, sometimes get stuck with easily solvable questions.
 - It forces you to look into less conventional techniques, which broadens your scope in regard to methodology.
- 6. Group cooperation and commitment
 - Everybody had their role and I think we could rely on each other for it to work.
 - Group atmosphere was good. All the nights we spent working on the project with the entire class are a good evidence of this.
 - Everyone was very helpful and enthusiastic to help other group members.
 - It was the commitment of all of us who made such coherence possible.
- 7. Communication and presentation: about the jury presentation
 - I enjoyed the jury presentation and the discussion. It really was a closure of a big project we all worked hard on and gave us the opportunity to show that we did and defend it well.
 - Everybody was really motivated to make it perfect.
- 8. Motivation, hard work, engagement, and the "joy-of-it"
 - I liked the idea of writing a research proposal; it made me feel very scientific.Doing something "real," not just learning theory.

 - Course was challenging and extremely motivating...it incited my aspiration to continue the graduate studies in the research field.
 - Although stress is high in this course, I don't think it should be changed because of how much you learn and the sense of accomplishment you get at the end.
 - ... it so often did not really feel a burden to work till late as it was also a lot of fun and you learned so much.
 - Although it has been rather stressful. . .making such a project from scratch gives a very good feeling of accomplishment.

reading contributed to their knowledge about methods and experiments in the field of cell biology, that it was necessary to identify an interesting and challenging gap to focus their research on, and that it was helpful to evaluate and qualify novel findings that researchers presented. After a while, it became easier to understand the papers and to review them critically. Students found they were stimulated to think critically and not to take the scientific information for granted, even though respected researchers presented it.

2. The formulation of a research project with fellow students that would fit in a coherent research program of four different projects. Without exception, students liked the task of writing their own research proposal; it was challenging and motivating according to the students. They liked the idea of being involved in an attempt to advance the frontiers of scientific knowledge in a particular field and to create a unique piece of work based on questions that still need to be answered. This contrasts with most papers that students write, in which they usually collect and put together existing information. Some of the students experienced problems at the beginning of the course, from not knowing precisely what was expected of them, and some of them experienced stress

at the end, because of the strict deadline and the pressure of an external jury judging their work. However, in their comments at the end of the course, students appeared to be happy with the learning gain and proud of the quality of their work.

The task of proposing a research project was new for students, and so was the responsibility of the roles that went with it. Students were expected to change their role from "course takers" to "near colleagues," and the teachers accordingly changed their role from instructors to informed peers and facilitators. Typical facilitator tasks range from asking critical questions, providing constructive feedback, raising issues students should think about, providing tips on how to approach experts, helping to establish contact with specific researchers, and so on. On average, students adapted well, enjoyed the challenge, and took the responsibility we expected them to take, although some students would have preferred more instructional help and guidance in the beginning.

3. Getting thorough knowledge of relevant methodology and *technologies.* Designing the methods section of the research plans was quite difficult for students. The reading of primary articles helped them get acquainted with the methodological possibilities, but as methodology sections in science articles

are quite condensed, students found them difficult to understand in the beginning. Because most of the students had little experience in the research lab, they had various practical questions for which they needed to consult experts.

4. Cooperation and leadership. According to the students, group work in this course was very constructive. Students in some groups complained about unequal input by the different group members, but in most groups, students were very committed and cooperated in a good atmosphere. The division of roles for each group member facilitated the teamwork; everybody had his or her own role, and students could rely on each other.

5. The presentation and the defense of the research projects for a jury of experts. The presentation of their work for an external jury was very motivating, according to the students. Students were eager to deliver their best work and worked very hard to present their cases to the jury and defend the choices they made. The final presentation gave students a feeling of accomplishment and pride.

Problems Students Face

During the course, the students usually face several problems. Especially in the beginning, they experience problems with respect to the formulation of the research questions and the methodology to be applied. In this stage, they may feel completely lost in the wealth of information they collect. Furthermore, a group size of four to six students might experience a temporary withdrawal of one member. Usually students do urge each other to be committed and share a fair part of the activities. For some students freedom is confronted by postponing some decisions, which later on leads to stress in order to keep the deadline. Students then realize the importance of time management skills. Some students find it difficult to adapt to the change in the role of the teacher from instructor to one of facilitator, learned peer, and advisor. Therefore, we emphasized the different role of the teachers in the beginning of the course.

In the second part of the course, students start to understand the problems and the ways to formulate hypotheses that can be tested experimentally and begin to like the freedom and responsibility they get. In this stage, they start to experience a sense of excitement of the research as they have the strong feeling of proposing their own research. After the final jury presentation, students usually are excited about the learning path they went through.

Evaluation by Alumni

The course aims at stimulating students to bridge the gap between textbook learning and doing research, and the teachers hope to raise students' interest in pursuing a research career. To get some insight into the impact of this course on their career development, we asked about 30 alumni to respond on a questionnaire. The results of this evaluation are presented in Tables 7 and 8. Nearly all respondents thought the course influenced the choices they made after graduation. According to alumni, the course certainly succeeded in bringing research into their perspective, by giving them a taste of it and showing that they had the potential to be researchers.

Evaluation by the Jury

In addition to the student evaluations of the course, the jury members were asked to evaluate the course on five different aspects, as summarized in Table 9. As shown, novelty, readability, and the quality of the defense scored highly. The jury reported to be impressed with the way students defended their proposals and how they responded to the critical questions of the jury. Here, students showed that their knowledge of the subject was extensive and solid. The feasibility scored lower, and this is probably due to the inexperience of the students with the practical side of scientific research.

DISCUSSION

The main aims of the course described in this article were to bridge the gap between textbooks and scientific research and to increase students' understanding of the scientific discovery process by modeling professional behavior in the field of cell biology.

By providing students with an authentic learning context, in which they experience the activities performed by professional scientists that are required to formulate a research project, they were stimulated to shift from mainly consuming accepted knowledge from textbooks toward critically approaching the construction of new knowledge. To achieve the required level of understanding to accomplish this task, students needed to increase their knowledge of recent developments in cell biology and of advanced techniques in the field of cell biology. Furthermore, students had to develop their ability to identify research opportunities, formulate questions and hypotheses that are based on recent primary literature, develop a critical attitude, develop their ability to collaborate with peers and integrate individual talents, and increase their ability to communicate science effectively both orally and in written form.

According to the students' evaluation over the past 6 yr, as well as the experience of the teachers and the members of the juries who evaluated the research proposals, these objectives were achieved within the student-directed and inquiry-based course design.

An interesting question relates to whether assignments that promote active learning or inquiry-based learning are always successful. From research on the effectiveness of inquirybased learning (Mayer, 2004; Kirschner et al., 2006; Angeli and Valanides, 2009), it is concluded that just immersing students in an inquiry-based learning environment is not sufficient. In this respect, Mayer (2004) concludes, from research on the effectiveness of discovery methods, that it is not the amount of student activity that matters but the cognitive quality that the activity generates, that is, "the degree to which they promote appropriate cognitive processing" (p. 17). First, an appropriate knowledge base is needed in order to create the driving questions that generate deep learning (Newmann et al., 1996; Kirschner et al., 2006). Second, the assumption that students implicitly acquire skills like critical thinking, needed to complete the task successfully, seems to be too optimistic (Tsui, 1999; Abrami et al., 2008); critical-thinking skills should be stimulated explicitly. In other words, active student involvement does not imply a passive role of the teacher. Kirschner et al. (2006) argue that acquiring expert

Table 7. Alumni questionnaire: a selection of typical answers on the open questions

What were the most important learning gains of this course for you?

- The process of not merely coming up with a potential research topic, but to actually work out a plan to carry it out while having to take into consideration the interests of other groups as well as costs, feasibility, facilities/technical equipment. In other words, a valuable 'rehearsal' in light of a future research career. I found it very interesting to see how one continuously has to question oneself while working on and designing a research plan. Every decision one makes needs to be grounded.
- I believe what stuck with me most is that it isn't necessarily easy to find a "niche" in the field (something that I had never considered before the course and turned out to be useful during my master and now PhD... so it was extremely helpful to be "confronted/taught" with this in undergraduate so that I was prepared when the day came I had to do this in my master program!!!!
- Writing a research proposal forces you to see the whole picture within a scientific field, but also to focus on a specific research problem. It helps you to think critically but also creatively.

Did this course have additional value for your career thus far? Please elaborate.

- This course has definitely helped me in my career so far. Most PhD students at a recent retreat I participated in had not yet written a single research proposal, whereas I have written several and even received funding from a private foundation to cover some of my research costs. This would have been a lot more difficult without the experience I gained at the Advanced Cell Biology course.
- Yes, as part of the selection procedure for the University of Oxford, I gave a presentation on the research proposal that resulted from this course, which helped me secure a spot on the program (MSc in Neuroscience). Furthermore, I have been able to evaluate scientific articles much more critically, which was of help both in my course work and scientific projects.
- I think the discussions we had in class have been helpful, concretely during some of the interviews for PhD I had this month, because I had to think and argue on the spot, and with the experience from the course I felt more confident.
- Did the course increase your interest to do research?
 - Yes, it showed me how challenging and fun research could be.
 - Yes, it showed that research can be both fundamental and interesting and that thinking about these problems is engaging. Actual cell biology research is unfortunately much more labor-intensive and offers much less possibility for reasoning, theorizing and thinking.
 No, although it did give me a good impression of what a career in research would be like.
- What made this course different from a regular 300-level science course?
 - The course pushed us to a higher level. Since the teachers made us clear that this course was "our" project, everybody felt a great responsibility to obtain a high-quality end-result. Not only did this course teach us many things on a personal level, it also trained us in regard to team work.
 - ... it really broadens your view, knowledge, idea of what research is all about!!! It's a tough course, but definitely the best one I've attended during my undergraduate at UCU!!!
- Mostly the fact that the course was completely run by students, and that we were the ones lecturing, deciding on a plan of action, etc. *Did this course in any way influence your selection for your graduate study?*
 - Yes. I used it as "proof" that I was well prepared to enter a master (research) study.
 - No, but it made me doubt it. The Advanced Cell Biology course is an excellent way to get students excited about doing research and I must say it came a little too late for me.
 - Yes, it was challenging and so much fun that I decided to continue in cell biology and research.
 - This course confirmed my wish to go into scientific research, which I did after finishing my medical degree.
 - Yes, I started a research master's program after UCU and will start a PhD in order to continue with research.
 - Yes, this course increased my interest in research. I had not intended on going into research while attending UCU so this course offered me a glimpse of what it might be like.
 - I have always doubted between medicine and scientific research and the joy of this course drove me to my research master at Oxford.

knowledge and skills to do research takes years and that it may be a mistake to assume that students will learn these skills just by doing it. Instruction should not be limited to the processes; content-focused guidance like providing constructive feedback is needed (Tsui, 1999). Despite these insights, this course, in which the teachers' role was facilitating, appeared to be effective in developing critical-thinking skills. In our opinion, a number of factors were crucial in achieving a successful outcome in this course:

Table 8. Alumni ratings of the course and the skills they learned on a 5-point scale (N = 23)

Items	М	SD
The course had additional value for my master research program	4.3	0.6
The course improved my critical-thinking skills	4.8	0.4
The course has been helpful for my ability to design my master research plan	3.6	0.6
The course improved my research skills required for my master research	4.1	0.8

- The authenticity of the task in which students were expected and empowered to act as professionals: formulating a research project and defending it for a jury. The students knew that the jury members were going to be instructed to treat the project proposals, the coherence of the program, and the students during their defense as if they were professional scientists. This motivates the students and encourages them to give their best.
- The jury defense. The importance of presenting and defending their project at the end of this course was emphasized repeatedly. When draft versions, specific ideas, or experimental setups were discussed in class, the teachers frequently asked, "What would you say if the jury would question this aspect or would question the suggested approach?" This makes the students aware of the fact that their arguments for specific choices should be solid and well based on the current state of the art. Moreover, this focus on external jury assessment made it easier for the teachers to stick to their role as supervisors and prevented them from sliding back to a more directive instructor's role.
- The ownership students got for the task as well as the process. Students need to be empowered for this task by

Table 9.	Jury evaluation of the quality of the student proposals and
their defe	nse(N = 10)

Jury ratings of the quality of the proposal on a 5-point scale	М	SD
Novelty	4.2	0.8
Feasibility	3.2	0.9
Readability	4.3	0.7
NWO standard ^a	3.4	0.7
Defense	4.6	0.5

Jury comments:

The 10 jury members added their comments to their evaluation. A few typical jury comments are:

- I was overall very impressed with the level of expertise the students had built-up in a matter of mere weeks. The topic of the research proposals is part of my research field, and I know first hand how difficult it can be to fully grasp the issues that captivate the field. The students actively pursued advice from world-leaders in the field (I, in fact, received various positive comments about this from foreign colleagues that were contacted by the students). Although, not surprisingly, feasibility would be an issue when submitting such proposals to a grant agency, the overall quality was good and the defense was impressive.
- The report was of high scientific quality and very well readable (perfect English). It is difficult to judge if the final report meets the criteria for an NWO grant application, since the students cannot include preliminary experimental data of their own, which is essential for a proper grant application. However, the questions raised and experiments proposed are certainly up to the level of a grant application. During the defense each student showed the ambition to defend not only his/her own input, but the program as a whole. It appeared that all participating students had reached the required high quality level of this course.
- It appears to me that a viable NWO proposal could have been extracted from virtually all proposals, but that some, perhaps the majority, "as is" lacked enough focus to present them as a proposal as such.
- These students performed at an impressive level. The way they responded to jury questions and the way in which they defended their proposal was excellent, often using very good arguments! It is always difficult to qualify the level of understanding of students based on their presentations only, since they have ample time to prepare for the presentation of their proposal. However, one can qualify their level of understanding in a better way by focusing on how they respond to questions and how they behave in a scientific discussion, since they are not able to prepare for all possible questions they might have to answer. In this respect, their engagement, enthusiasm and level of understanding were impressive. The type of involvement they showed during their defense can only be reached after having read and thought a lot about a topic. That's what they apparently did!

^a NWO, the Netherlands Organization for Scientific Research, funds thousands of top researchers at universities and institutes and steers the course of Dutch science by means of subsidies and research programs.

making the course completely student driven. Students were given full responsibility for the quality and content of the final research proposal. Teachers did not enforce their ideas or opinions and refrained from immediately suggesting possible solutions. The students were encouraged throughout the course to contact professionals in the field, visit labs, and talk to scientists who use techniques that the students wanted to incorporate in their research proposal. In general, most students enjoyed the freedom and responsibility they experienced in this course and certainly in the end reported on having achieved a high level of satisfaction, confidence, and sense of accomplishment.

- The formulation of four projects within an overarching theme. This aspect of the course requires regular meeting of project leaders and the program leader to ensure a minimum of overlap between projects and a maximum of fruitful interaction between project proposals. Throughout the course, it was emphasized that the jury should not be allowed to suggest that skipping one of the projects from the program would not affect the quality of the overall program.
- Giving each student responsibility for the quality of the overall program. This leads to an interaction of students within and between the project teams to ensure high quality and interdependent projects in a coherent program. It stimulates the feeling of responsibility toward other teams, leading to fruitful suggestions for other teams. In this way, the teamwork became a natural, necessary, and fruitful aspect of the learning process.

In summary, we aimed to create a learning environment that would stimulate students to jump from lessons takers to knowledge producers. Immersing students in formulating a research project encouraged them to become self-directed and engaged learners. The fact that they were fully responsible for their choices with respect to the content of study, the precise question they wanted to answer, and the appropriate techniques to be used to get an answer appeared to foster engagement and commitment among most of the students involved, as was indicated by questionnaire data. The authenticity of the task, the responsibility students were stimulated to take, the teamwork and the sense of ownership that evolved, and especially the presentation and defense of their project to a jury of professional scientists forced students to bridge the gap and to think and behave as professional researchers.

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