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From Dublin descriptors to implementation in Bachelor labs

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Abstract. A description of the implementation of a completely renewed setup for Physics Bachelor labs is given. The renewed setup made use of the latest educational research insights and is described from the general Dublin descriptors and the CALOHEE assessment and National domain specific reference frame up to the concrete learning objectives that we aim for in the Bachelor practicals. A choice between more open and closed labs is discussed. This study makes use of educational design research and therefore mostly tests design principles. In general, the design principles behind the renewed setup have worked and students have been given a need to perform each step in the research process. Despite the courses becoming more challenging, students' results have gone up. We attribute this to specific types of iterations within the closed practicals and on the alternation between closed and open labs. Overall, most students attained the experimental skills that we aimed for and by the end of the practicals in year 2 most students also obtained the most relevant CALOHEE dimension of 'Experimental design and scientific inquiry', designed to assess students after year 3. The remaining obstacles are identified and suggestions for future improvements are given.

1. Introduction

One of the aims of physics education in university is to try to educate our students to become objective researchers. In our university, students finalize their Bachelor degree with a research project of 20 EC which is carried out within the various research groups of our department. This is a first step for students to become independent researchers.

In many universities as in ours, practicals were part of those courses that needed to be taught but did not have a clear educational vision behind it. In 2017 it was stated that there was a need for better preparation of our students to perform their Bachelor research projects. There had been little change to the practicals given to the students over the last decade or so. Most practicals were structured in so-called 'cookbook' labs which may be fine to illustrate theory but are not the best way to attain research skills [1,2]. There was also a wish for better cohesion with various theory courses and a wish to align the labs with the research done in the research groups of our university.

This called for a drastic redesign of our Bachelor labs and gave us a chance to implement a clear educational vision on the need for practicals. To connect that vision to the more general Dublin descriptors [3] we compared the concrete learning goals we aim for in our labs with those descriptors. We did the same for the dimensions in the Tuning document (based upon those descriptors) that specify the expected learning outcomes for a physics Bachelor within the EU [4].

Out of the five Dublin descriptors our labs aim to contribute to two of them: 2. Applying Knowledge and Understanding, and 4. Communication. Even though communicating the results is an essential part of our labs in this paper we will focus on the research skills that we hope to develop in our students (Applying Knowledge and Understanding).



2. Educational design

In this section we will discuss our educational vision behind the redesign of our labs. First we discuss the concrete learning objectives that we set for the students and how they connect to both theory and the Dublin descriptors. Next, we will discuss the design principles behind the redesign of our Bachelor labs.

2.1. Learning objectives

We took our time (about half a year) to write down all the concrete learning objectives we aimed for with the practicals and then added all the learning objectives that we wanted to add because of the reasons mentioned in the introduction. In the end we came up with about 120 learning goals.

The learning goals were subsequently rewritten in a SMART way [5]. This made it clear that various learning objectives fell under similar categories: e.g. ‘Students are able to use a [specific] apparatus’ was grouped under ‘Using the manual students are able to setup [any] apparatus’). This resulted in about 50 groups of learning goals.

These grouped learning goals could be made more *engaging* and *rewarding* for the students by grouping them one step further and rewriting them in a SMARTER way [6]: e.g. ‘Using the manual students are able to setup any apparatus’ became part of the group ‘Students are able to independently collect trustworthy results from an experiment’. This gave us the following 6 categories of learning objectives.

Table 1. Our 6 categories of learning objectives for the labs.

Category	Learning objective
I	Based on a specific problem students are able to write a measuring plan from which it may reasonably be expected that it will deliver usable results.
II	Based on a measuring plan students are able to write an analysis plan from which it may reasonably be expected that it will deliver an answer to the research question.
III	Students are able to write a data management plan.
IV	Students are able to independently collect trustworthy results from an experiment.
V	Students are able to independently and critically analyze an experiment.
VI	Students are able to communicate their research and that of others in a structured and catchy manner, both written and verbally.

A final grouping of these categories gave us the learning objective for all lab activity of the students in preparation for and including their 20 EC Bachelor research project: ‘Students are able to perform an 80 hour research project independently, from first conception to presenting and reporting.’ To check the validity of our categories of learning objectives we compared them to objectives mentioned in literature and in reports related to the Dublin descriptors. Etkina [7] describes 7 measurable scientific abilities which similar to our groups of concrete learning objectives can also be interpreted as groups of more concrete abilities:

Table 2. Etkina’s 7 categories of measurable scientific abilities.

Category	Scientific ability
A	Ability to represent physical processes in multiple ways.
B	Ability to devise and test a qualitative explanation or quantitative relationship.
C	Ability to modify a qualitative explanation or quantitative relationship.
D	Ability to design an experimental investigation.
E	Ability to collect and analyze data.
F	Ability to evaluate experimental predictions and outcomes, conceptual claims, problem solutions, and models.
G	Ability to communicate.

Etkina's categories can be easily compared to the categories we came up with. Most are combinations of several of our categories of learning objectives. Only our data management plan category (III) does not seem to have a comparable measurable scientific ability in Etkina's list. A comparison is given in the following table.

Table 3. Comparison of our 6 categories of learning objectives to Etkina's 7 categories of measurable scientific abilities.

Scientific ability (Etkina)	A	B	C	D	E	F	G
Learning objective (Logman & Kautz)							
I	X	X		X			
II	X	X	X	X		X	
III							
IV		X			X	X	
V		X	X		X	X	
VI	X						X

A similar comparison can be made with the five Dublin descriptors [3] and the nine dimensions of the CALOHEE Assessment Reference Framework for Physics [4] based on those descriptors. The Dutch universities have created a list of competencies in the Dutch Domain Specific Reference Framework for Physics [8]. Because these are based on the CALOHEE dimensions they are very comparable.

Both the descriptors and the reference frameworks address a complete Bachelor in physics. The Dublin descriptor that covers research skills is descriptor 2: 'Applying Knowledge and Understanding'. The CALOHEE framework subdivides this descriptor into two dimensions: 'Experimental design and scientific inquiry' and 'Problem solving'. The Dutch framework names their subdivisions competencies renames the first one to 'Experimental skills' and adds four competencies to the CALOHEE dimensions: 'Modelling skills', 'Mathematical skills', 'Computer skills', and 'Familiarity with basic and applied research'.

Our categories of learning objectives as well as the CALOHEE dimensions are groups of more concrete subcategories. The subdivisions for the CALOHEE dimension of 'Experimental design and scientific inquiry' can be classified under our categories of learning objectives as follows: Learning objective I covers the subdivisions 'Experimental design and methodology', 'Instrumentation', and 'Safety'. Learning objectives II & V cover 'Data analysis', and learning objective IV covers 'Experiment documentation'. For the CALOHEE dimension of 'Problem solving' we can classify the subdivisions similarly. Learning objective I covers the subdivision 'Problem framing' and 'Creative and innovative thinking', learning objective IV covers 'Solution procedure and execution', and learning objective V covers 'Analytical thinking', and 'Validation of results'.

The Dutch Domain Specific Reference Framework also contains more elaborate descriptions of its required competencies in the shape of learning objectives. These can be used to make the comparison complete. For example, the framework states the final learning objective for the most related competency 'Experimental skills' as follows:

On completion of the B.Sc. the students should

1. have become familiar with most important experimental methods.
2. **be able to perform experiments independently, as well as to describe, analyze, and critically evaluate experimental data.**
3. be able to scientifically report the findings.

These learning objectives (especially the second one) are very comparable to our main learning objective.

2.2. Design principles

Not only did we want to clarify our educational vision by setting clear and cohesive learning objectives, we also wanted to clarify our educational vision by showing both the students and the university the need for performing experiments during the Bachelor. To show the students that need, we adopted the problem posing approach [9,10] as our main didactical approach:

1. *Every step in the learning process should be useful in solving a problem and thus give the students a reason to perform that step.*

To develop specific measuring and analytical skills Holmes has developed Structured Quantitative Inquiry (SQI) Labs [11]. Like us, she also encountered a tradition of so-called cookbook labs and found that in such labs students generally do not reflect upon their work. In her SQI-labs the students are still given a method but the way in which the students perform it is up to them. At the end of her labs she added an extra iteration in which students need to improve the accuracy of their results in a follow-up investigation. This gives the students a reason to critically analyze their method [11].

2. *An SQI-lab design will be implemented when the focus of the labs is on measurement and analytical skills so students will see the need for using or developing these skills.*

To address the more general research skills Etkina has developed an Investigative Science Learning Environment (ISLE) [12]. Within such an environment students start with observing phenomena and gradually build their own experiment to test their interpretation of their results. The experiments students perform in such an environment are much more open in nature: students are allowed to choose their own topic of interest within certain boundaries and develop their own measuring and analysis method.

3. *An ISLE-lab design will be implemented when the focus of the labs is on general research skills so students will see the need for using or developing these skills.*

We do not want the students to be hindered by lack of apparatus, measuring, analytical and programming skills in the more open ISLE labs. Therefore we decided to use the more closed SQI experiments to teach our students the measuring and analytical skills needed to be able to perform an open ISLE experiment within the same topic afterwards.

4. *The open ISLE experiments will be preceded by a more closed SQI experiment in which students' apparatus skills, application of relevant physics knowledge, and analytical skills will be developed. That way these basic skills will not obscure the assessment of students' research skills during the open ISLE experiment. Such a strategy is implemented for every topic that we want to cover.*

In earlier implementations of our labs we had found some other issues as well: students did not prepare well for their lab sessions, students did not keep their lab journal properly, and students did not see the need to write a report on their findings. We tried to address these issues and make students see the need for these steps by trying out the following design principles:

5. *A need for preparation can be present in closed SQI practicals by giving the students limited time to perform their experiments.*

6. *A need to keep a proper lab journal can be present in closed SQI practicals by its iterative nature in which they build on their earlier lab notes to improve their results.*

Taking the above into account, our research question became: "To which extent do our redesigned practicals contribute to the students attaining our main learning objectives and in which way do our design principles contribute to those results?"

3. Educational design

Implementation of our redesign started 2 years ago in the first year of the Bachelor. Last year it was implemented in the second year of the Bachelor. Based on an evaluation the first year was readjusted.

3.1. Implementation in year 1

At our university we have 6 lab courses of 1 ECTS each and a connected 1 ECTS Presentation & Communication course in the first year of the Bachelor. As described in design principle 4 we start with a more closed SQI course to teach the students the necessary measuring and analytic skills to perform a

subsequent open ISLE experiment in which we develop and assess students' general research skills (design principles 2, 3, and 4). This is repeated three times to cover all 6 courses and to connect to the 3 research themes of the university. Connecting the labs to the research themes is what makes our practicals locally relevant and different from other universities if they were to implement a similar strategy.

The university has Biophysics & Soft matter, Quantum Mechanics, and Optics as research themes. Courses 1 & 2 concern experiments in the area of Soft matter. Courses 3 & 4 concern experiments related to Oscillations & Waves and prepare students for research in Quantum Mechanics. Courses 5 & 6 concern Optics. Courses 3 to 6 connect to the Classical Mechanics and Optics courses given in the first year of the Bachelor. In the first year there is no course on Soft Matter or Biophysics.

In the first year of implementation we focused on replacing the cookbook practicals by less closed practicals. They were less closed in a sense that the research question and method were posed to the students but everything else was up to the students. The concerned practicals (courses 1, 3, and 5) were not completely of the SQI-type yet because they lacked any built-in iteration other than students remeasuring the data on their own accord. The even courses (2, 4, and 6) were made completely open only limited by the connected research topics mentioned above. Thereby these practicals could focus on developing research skills in a similar way as ISLE labs.

In the second year of implementation the iterative nature of SQI-practicals was implemented. In course 1 this was done by making the 4 sessions within the course 2 times 2 sessions. This means that session 3 builds on skills that were developed during session 1 and session 4 builds on skills that were developed during session 2. This should strengthen the need for students to keep a proper lab journal (design principle 6).

In course 3 (oscillations and waves) the iteration was implemented by having the students perform 2 comparable experiments from different subdomains (e.g. electromagnetic and acoustic waves) within each session and using the same apparatus. In course 5 (optics) this was done by demanding an iterative approach in improving the accuracy of earlier results. In this manner all three SQI-practicals could now be focused on apparatus skills, application of relevant physics knowledge, and analytical skills.

Summarizing, in year 1 we used 3 types of iteration: building on earlier apparatus and measurement skills, transferring knowledge from one domain to another, and improving the accuracy of earlier results. Furthermore, we made sure that if students do not prepare their session they will not be able to finish the analysis of their results within the given time. During the first session they were informed that in the fourth (and final) session they were to hand in their lab journal for grading immediately after the session (design principle 5).

By giving the students feedback on their preparation at the beginning of the first three sessions they were given a need for training the first two learning objectives (writing a measuring and analysis plan: learning objectives I & II). We think that practicals in themselves call for the other learning objectives except for writing a data management plan (learning objective III). We left that learning objective up to the final research project in the third year of the Bachelor.

The learning objectives that are to be developed while performing the experiments (learning objectives IV & V) were implemented by structuring the manual and giving the students instructions on keeping a lab journal and writing a report following that same structure. Halfway through each session students are given feedback on their lab journals and the structure within which to develop their research skills. To give the students some time to develop their skills, for course 1 we only graded the lab journals for the final two sessions. For all the other courses the complete lab journals were graded.

We think that the open practicals show the students a natural need for developing all the research skills except for writing a data management plan (learning objectives I, II, IV, V & VI). To assess the research skills we used both the ISLE-practicals and the SQI-practicals.

Course 1 has been adapted the most and has been adapted in both years of implementation, courses 3 & 5 were adapted only last year. Courses 2, 4, and 6 were all made as open as possible in the first year.

3.2. Implementation in year 2

Implementation has now reached year 2 of the Bachelor. In the second year of the Bachelor we have created 3 new and connected courses of 3 ECTS, 5 ECTS, and 2 ECTS with an inquiry component of respectively 1 ECTS, 2 ECTS & 2 ECTS. Course 1 covers Fourier transforms, course 2 covers the 2D Fourier transform, Feedback & Noise. Course 3 is an open practical in which the minimum requirement is that students make use of some form of feedback and noise analysis.

Similarly to year 1, courses 1 & 2 consist of closed SQI practicals on apparatus skills, analytical skills, and the application of relevant physics knowledge. The only iterative component is that the results from previous practicals are used in subsequent practicals. These first two courses are followed by an open ISLE practical in course 3 to develop and assess students' research skills.

4. Method

Because we have redesigned the course we will use the method of design research [13] to evaluate it. This means that beside evaluating the learning outcomes we will also evaluate to which extent the design principles worked.

At our university an interfaculty institute takes care of evaluating every course taught at the university by means of anonymous questionnaires put to students at the end of each course. A summary of the evaluation is given to each lecturer after all the results have been analyzed. Such a summary contains the following variables: overall appreciation of the course, comparative study load, swiftness of reply, information accessibility, appeal to further study, quality of study materials, accessibility of learning management system, availability of practice materials, clearness of what to expect in the assessment, representativeness of the assessment, clearness of connection between practicals and lectures, available time for homework, quality of given feedback, and an opportunity for students to put in their own remarks on the course.

For a qualitative discussion of the design principles we will also use observations by the lecturer and the teaching assistants, most of whom had experience with earlier versions of the same or related courses.

To assess the learning outcomes quantitatively we captured the percentage of students that took part in each course and that finished it successfully. For year 1 we can compare these results for the year before and the two years during our redesign.

Because course 1 in the first year of the Bachelor has been adapted the most we will illustrate all results with the results from that course and extend the results to other courses when this is illustrative. Year 2 has been implemented only for one year now and consists of completely new courses so we can only discuss the results qualitatively. However, we will compare quantitatively the results of the final practical of year 2 to the CALOHEE dimension of 'Experimental design and scientific inquiry'. This dimension is based on the Dublin descriptor of 'Applying Knowledge and Understanding' and designed to assess year 3 students.

The number of students varies per course, but as an indication for course 1 in year 1 we had the following number of students that filled in the evaluation forms: 2016-2017: 133 out of 154; 2017-2018: 148/195; 2018-2019: 99/163. In year 2 we had 58 responses from 60 students.

5. Results

5.1. Year 1

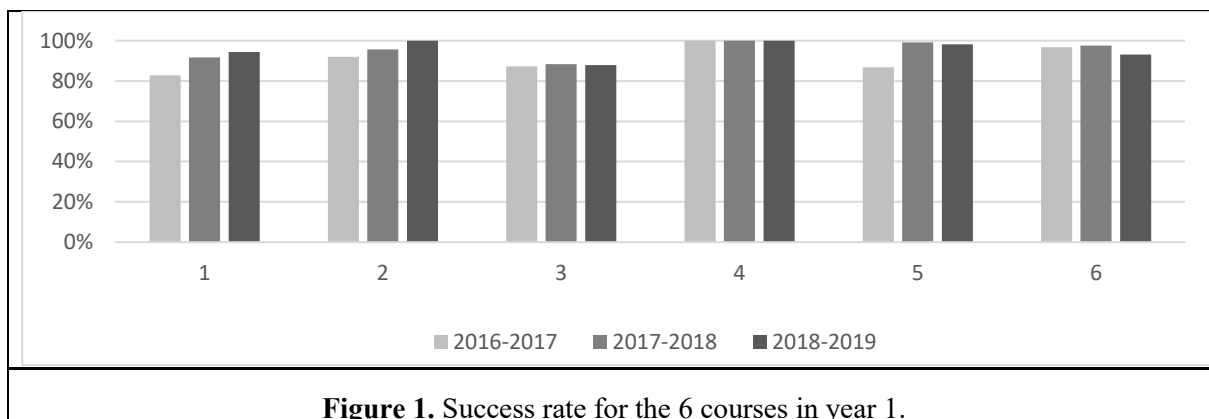
Implementation started 2 years ago in year 1. We begin by describing the results for course 1 because it is the course that has been adapted the most and we will extend those results to the other courses wherever this is meaningful.

The overall appreciation of the course remained the same before and after the redesign (6.7 out of 10). The only variables in the questionnaire that showed discernible changes were the quality of study material and the representativeness of the assessment. Both went up a little. Students remarked that they find the new course challenging ("*It is nicely challenging*"), however their assessment of the comparative study load remained the same. They also noted their developing apparatus and computer

skills (“*You learn how to use the measuring equipment and Python*”), the connection with theoretical courses (“*Practicals and lectures are a good combination*”), the need for preparation (“*Very clear to see that preparation is necessary*”) and appreciated the independence that they got (“*Lots of independence!*”).

The teaching-assistants confirm (from memory) the idea that the course has become more challenging. They also expressed the wish that they had had the course like this, mostly because the new course addresses the analytical skill of error propagation which they had to develop by themselves during their Master study. The lecturers confirm the better results on error analysis, and the better use of Python for analysis and data representation. They also mention that the course seems to run more by itself. The qualitative results described above hold for courses 2 to 6 as well.

In spite of the course being more challenging the number of students that passed the course over the number of students that took part in course 1, 2, and 5 has grown after each adaptation (see Figure 1). Courses 3 and 4 maintained the same success rate. Only course 6 got some lower (but still quite satisfactory) results (93%). The reason behind the lower results for this course is not yet understood. Where course 1 used to show the lowest results, after the redesign it is now course 3 that shows the lowest results. In future adaptations courses 3 and 6 will need the most attention.



We did find that limiting the available time to finish the sessions of the SQI labs showed the students a need to prepare their experiments. After the first session of course 1 students realized that preparing is useful to finish the sessions within the given time (design principle 5). The number of students that had prepared the sessions well went up from about 50% to almost all (99%)(learning objectives I & II).

For the SQI labs (courses 1, 3, and 5) we can say that the iterative nature improved the results for courses 1 and 5 (design principle 6). In course 1 the subsequent sessions build on the apparatus and research skills learned in the earlier sessions. In course 5 the subsequent session asks the students to improve the accuracy of the results. For course 3 the iteration had no impact on the results. In course 3 the iteration was within one session and intended to transfer the research skills from the electromagnetic to the mechanics domain or vice versa.

For the ISLE labs (courses 2, 4, and 6) course 2 showed improvement, course 4 could not be improved upon and did not show any decline in results, but course 6 did show a slight decline. However, in the first year of implementation there was no decline for course 6 so this decline likely has a cause outside of its open ISLE nature.

The SQI-labs worked well in preparing the students for the open ISLE practicals because during the ISLE experiments only few questions were asked about the analysis of results and almost none on necessary knowledge or on how to use the apparatus (design principle 2). During the ISLE practicals the questions of the students focused almost completely on the research itself (design principles 3 and 4).

Assessment of each learning objective becomes more strict per course because the level of the course goes up as students progress. The results per learning objective vary somewhat around the passing rate

of each course. The learning objectives that limited the results for passing the course the most were describing a measuring and analysis plan (learning objectives I and II). The other learning objectives (IV, V, and VI) showed better results than the given averages in Figure 1 and thus have reached a satisfactory level for each course. These results also show that most students saw the need for taking every step in doing research and explicitly note each step in their lab journal during each course (design principle 1).

5.2. Year 2

Implementation has now reached year 2. Since there were no directly related courses in the past we keep the results confined to mostly qualitative results.

Again students and teaching-assistants find the course challenging especially the combination with learning how to use Python. Students liked the combination of theory and practicals (“*Good combination practicals/theory*”) and noted the connection with theory (“*Nice topic which you have to deal with every day (especially noise)*”). Independence in open practicals was again appreciated.

However, students did not see the need for preparation even though there was a limited time available to finish the experiments of each session (design principle 5). Perhaps this was caused by the just-in-time readiness of the practicals. The lecturer and teaching-assistants confirmed that there were too many practicals per session. The teaching-assistants also found that the students were less proactive during the closed practicals (the first two courses). It appeared that the students did not see the need for every step in the practicals (design principle 1).

The lecturer also noted that the students saw less need for keeping a proper lab journal during the closed practicals (design principle 6). Apparently it is not enough to convince students to keep a lab journal by iterating the results from previous computer practicals in subsequent computer practicals. This could be caused by it being a computer practical and previous results can be retrieved by using the programming code only without making use of a lab journal. There is no iteration within the sessions themselves.

The SQI-labs in year 2 did not work as well in preparing the students for the open ISLE practicals because during the open ISLE experiments several groups of students still asked a lot of questions about necessary knowledge or on how to use the apparatus or analyze their results which they should have obtained during the SQI-labs (design principles 2, 3, and 4).

Course 1 had a 98% success rate, course 2 scored 94%, and course 3 scored 90%. Again, the results per learning objective vary somewhat around these numbers. For the first two (closed) practicals the biggest obstacle was again describing a measuring and analysis plan (learning objectives I and II: 19% of our students had a low score (≤ 6 out of 10) for this objective) and interpreting the results (learning objective V: 16% low score).

And even though these were still an issue in the final (open) course the main difficulty there was both getting trustworthy results and analyzing those results critically (learning objectives IV (30% low score) and V (23% low score)). Clearly, these skills are harder during open practicals.

Again, these results show that most students saw the need for taking every step in doing research and explicitly note each step in their lab journal during each course (design principle 1). However, compared to year 1 the students apparently saw less need for a critical analysis of their results during computer practicals.

If we compare the score of 90% for the final course to the CALOHEE dimension of ‘Experimental design and scientific inquiry’ we assess that 87% of our students have the knowledge for this dimension, 90% have the skills for this dimension and 93% have the autonomy and responsibility for this dimension.

6. Conclusion

We have shown that the learning objectives we have developed for our students can be connected to the Dublin descriptors (and the related dimensions of the derived CALOHEE Assessment and Dutch Domain-Specific reference frameworks). The learning objectives also indicate which of these descriptors and dimensions they cover. Expanding on that, we have also shown that our program helped most of our students to attain the related CALOHEE dimension at the end of year 2 even though this

dimension is designed to assess year 3 students. However, we do note that the final course in year 2 was a 2 EC open project which is still small compared to their final 20 EC Bachelor project in year 3.

The newly designed courses appear to be more challenging to the students than before. It has a built-in cohesion with other courses and a built-in connection to the local research departments which make the practical courses locally relevant. In spite of putting these extras into the design of the course the redesign still gives the same and sometimes even better results.

Closed SQI-practicals as described by Holmes seem a proper way to teach students apparatus skills, analytical skills and connect to their knowledge of physics (design principle 2). However, during the practicals in year 2 this did not work as well as in year 1. This may be because the students did not see the need for keeping a proper lab journal which in its turn may have been caused by the computer programming nature of those practicals. The programming code alone seems to be enough for the students to replicate their results.

The open ISLE practicals as described by Etkina can be used to assess all research skills (design principle 3). They can show which skills are the biggest obstacles for students in becoming an independent and objective researcher. During year 1 these skills were preparing their measurements and analysis (learning objectives I and II). For year 2 these were getting trustworthy results and analyzing those critically (learning objectives IV and V). This change in biggest obstacles from year 1 to year 2 may have been caused by the fact that the SQI-labs in year 2 did not work as well as in year 1 (design principle 4) or by the fact that these skills are more difficult to show explicitly in a lab journal for computer practicals. Either way, improvements in the closed practicals of courses 1 and 2 in year 2 are necessary. It was shown during course 1 that giving the students limited time to finish their labs showed the students the need to prepare their sessions even for SQI-labs (design principle 5). Even though the time for the practical sessions was limited as well, in year 2 it did not give the students a need to prepare their sessions. This may have been caused by the impromptu nature of these courses. In the future we need to have all material ready well in advance so students will have ample time to prepare.

The iterative nature of SQI practicals seems to show the need for keeping a proper lab journal (design principle 6). Two types of iteration seem to improve the overall results for those courses as well. Improving the accuracy of one's results (year 1, course 5) as suggested by Holmes works nicely. We want to add another possible type of iteration in which subsequent practicals builds upon earlier attained research skills (year 1, course 1). An iteration in which students need to transfer their knowledge from one domain to another did not influence the final results for a course (year 1, course 3). An iteration in which students only need to build upon earlier results from a computer programming lab from an earlier session seem to hinder the final results (year 2, courses 1 and 2). However, this may also have been caused by students assuming that their programming code alone is enough to replicate their results.

Overall, most students (>90%) attained the learning objectives that we intended them to learn. In the end, the majority of students were able to write a proper measuring and analysis plan (learning objectives I and II) but out of all the learning objectives these were the two that most students struggled with in year 1. Independence in open practicals is appreciated by the students and the need for getting trustworthy results and a critical analysis thereof seems to be inherent to such practicals (design principle 1). However, students do have trouble in showing trustworthy results that are critically analyzed (learning objectives IV and V). Especially in year 2 when computer programming is involved.

7. Discussion

All results are based on a limited number of students and they performed all experiments in varying duos. This of course limits the validity of our conclusions. Furthermore, a first implementation of a new design always brings along various issues. However, the general idea behind the redesign seems feasible. For year 1 minor adaptations seem to be necessary. Even though the results for course 3 are above 90% that course deserves the most attention as its results are currently the lowest. Of course the choice of experiments influences the results but perhaps the iterative nature of course 3 can be adapted.

For year 2 more drastic adaptations seem to be necessary. This is of course not strange as year 2 is only in its first year of redesign. The impromptu nature will improve next year by itself because a basic set

of practicals is now available. This will give the students ample time to prepare their sessions. We will need to show the need for keeping a lab journal in computer practicals better. Perhaps this may be done by changing the type of iteration to improving the accuracy of results or building upon previously learned research skills instead of previously attained computer results. More attention also needs to be given to how students can explicitly show that they obtained trustworthy results and interpreted those critically. A next iteration hopefully will show similar improvements as have been observed for the year 1 courses.

We had to be concise in presenting our results. More results can be obtained from the author. The results themselves could have been better aligned with the learning objectives. To be able to do so we are now in the process of developing grading rubrics aligned with the learning objectives. That will be a good step towards a more objective measuring of research skills. With all the above in mind we are looking forward to the results for the Bachelor theses the coming year.

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