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Tracking and supporting student learning in practical laboratory exercises spread over several days

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Introduction

In natural sciences, practical exercises including laboratory work are a central part of student education (Hofstein & Lunetta, 2004; Reid & Shah, 2007). Different aspects such as the level of education, (current) educational goals and the specific discipline have to be considered when designing meaningful laboratory exercises (Hofstein & Lunetta, 2004; Hofstein & Mamlok-Naaman, 2007). Even the relevance of laboratory exercises may vary in different disciplines, they are a suitable approach to combine various positive aspects: (1) students get the chance to connect theoretical knowledge with practical applications, and subsequently, to better internalize theoretical knowledge, (2) students have the indispensable possibility to gain hands-on experience in important methods they may need to address scientific questions later in their career, and (3) it is a good way to diversify teaching beyond lecturing and other theoretical teaching approaches which per se appears to be beneficial for (diverse) learners (Tanner & Allen, 2004). In particular, practical laboratory exercises have the advantage that they are based on a cognitive constructivism learning approach, which means hands-on experience in this context, following the theory of Jean Piaget (Dolin, 2015) which may be the only truly suitable way to convey practical skills in important methodologies to students in a scientific context. Laboratory exercises in biology courses typically foresee group work which spurs social interaction between students (Hofstein & Lunetta, 2004). Thus, this teaching format may additionally benefit from peer learning-based social constructivism following the theory of Lev Vygotsky (see Dolin (2015)) by elements of (1) more or less self-dependent coordination between different groups in the laboratory, and (2) coordination of work within individual groups and delivery of possible group assignments.

Although practical exercises are valuable tools in university teaching in natural sciences, planning and running such teaching units can be challenging. Especially when working with biological systems, the time course of experimental work can be quite lengthy which means that individual work steps of experimental approaches have to be spread over several days. Therefore, it is not enough that a teacher of such exercises gets information on the initial knowledge and preparation level of the students. It is necessary to assure a minimum of preparation on each individual day to maintain a meaningful exercise in the given time schedule, and that students are prepared when handling expensive and/or dangerous equipment and material in laboratories. Furthermore, the students' development in context of the course aims, their awareness of the current status of their work and their understanding of the dynamically developing content has to be observed and supported over several days. Only when students can keep track of the progress, i.e. the development of their experiments and connection between the individual course days, they have a chance to obtain a complete understanding of the work conducted during the exercise, and subsequently achieve the aims of an exercise or a course. Obviously, this appears to be more challenging in exercises that are spread over several days with possible gaps of few days in between than in short exercises conducted within one day. Considering these aspects, it may not be appropriate to (only) rely on tools such as online quizzes or instruction videos for preparing students outside the classroom. Therefore, reliable and efficient tools supporting a teacher in addressing these challenges in class to maintain a good and supportive learning environment for students participating in such laboratory exercises are very valuable.

Methodology

The challenging teaching scenario

In the study year 2016/2017, I took over the laboratory exercise "Tracking Gene Expression" from a colleague which is part of the course "Plant Genomics". This course is embedded in the BSc programmes "Biology" and

"Biology-Biotechnology" at the University of Copenhagen, Department of Plant and Environmental Sciences. Eleven students in their 2nd or 3rd year of BSc studies participated; for the laboratory exercise, the students were divided into four groups (three groups of three students, one group of two students).

Based on my experience in teaching this exercise the year before, I decided in agreement with the course responsible to completely change the programme of the exercise this time. This decision was based on student feedback from the year before and due to technical reasons (availability of material and equipment). Due to these changes, it was the first time that the exercise was taught in the particular laboratory and with this specific programme. In addition, I was largely lacking experience which level of background knowledge can be expected from the students attending this course. The new exercise comprised three individual experimental approaches with specific work step sequences. These approaches are used to analyse the same biological material that allows the correlation of results derived from the different approaches. The experimental work of the exercise is spread over three days with a gap of six days between the first two and the last course day in which students should do some calculations. As usually done, the students received written instructions including detailed laboratory protocols several days in advance and were asked to at least briefly go through them as preparation before the first day of the exercise.
Basic aims of the exercise are that students are able to:

- perform and understand the methods used in the exercise
- connect the individual work steps, i.e. keeping track of experimental work over several days
- understand the results including a basic interpretation
- understand the theoretical background of the methods (covered by accompanying lecture by another teacher)

Ideally, students should further be able to:

- judge the value of the obtained results
- correlate the obtained results derived from the three approaches with each other and subsequently make an advanced interpretation of the results
- transfer knowledge to decide which methods to use to address scientific problems in a specific way

A jointly developed flowchart as a tool in practical exercises spread over several days

Discussing the challenges of conducting this exercise (see above) with experienced colleagues, specifically the challenges

1. how to determine the initial levels and to assure a minimum level of preparation of the students in the beginning of the exercise and
2. how to keep track of their progress and to support them in an appropriate and dynamic way throughout the exercise to
3. achieve the course aims in terms of managing the practical work (in time) and understanding the basic underlying principles in the context of the whole exercise were identified to be the most critical. One suggestion was to implement a flowchart of the whole exercise which is jointly developed in dialogue with the students on a whiteboard in class. Following this, I developed a layout of a respective flowchart (Fig. 4.1) and an initial implementation plan (Table 4.1) for this exercise.

Student feedback

Considering the fact that this exercise was conducted the first time with this programme, it was the intention to get a very open basic feedback (by email or anonymously via Socrative; https://www.socrative.com/) on the exercise, for example what they experienced as (very) positive or what needs to be improved. Therefore, to avoid any bias, no initial request to evaluate the joint development and subsequent use of the flowchart was intended. Given the flowchart leads to the intended result to support the students in their learning and understanding, it should be named as a positive experience. In a second step, specific feedback addressing the flowchart may be requested.

Evaluation based on own experience

In addition to student feedback, the effect of implementing a jointly developed flowchart as a central element of the exercise was evaluated based on experiences from previous teaching of similar exercises, namely “Basic Methods in Plant Molecular Biology”. Important aspects of this evaluation comprise:

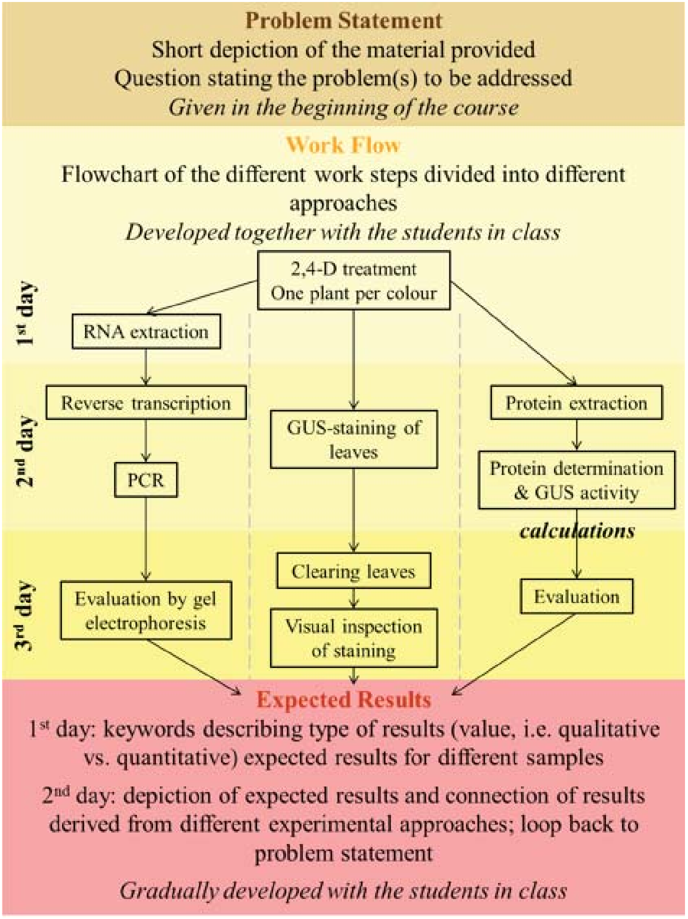

Fig. 4.1: *Outline of the flowchart as a central part of a practical exercise spread over several days.* The flowchart consists of three sections and includes the individual work steps of the exercise which are spread over several days. The first section is given in the beginning of the exercise and presents the problem statement, i.e. description of source material and the scientific problem to be addressed (brown). The second section describes the distribution of individual tasks over the course of the exercise, exemplified by the work steps of the laboratory exercise "Tracking Gene Expression" in the course "Plant Genomics" (yellow). In this example, the work is spread over three course days and split into three approaches leading to results of different value which are addressed in the third section that shows the expected results (red). The second and third sections are jointly developed in collaboration with the students during the exercise.

1. Estimation of student understanding of the content based on the final discussion of obtained results and case studies

Table 4.1: Implementation plan for a flowchart as a central element in laboratory exercises spread over several days.

Day of exercise	Flowchart section	Action(s)	Intended effect
1, Beginning	Problem Statement	Questions and discussion on source material and scientific problem in plenum. If no answers are given, buzz groups are initiated followed by plenum discussion.	Familiarize students with the basics of the exercise →avoids to early on lose students due to lack of initial understanding. Teacher can estimate the level of understanding and preparation of the students.
	Work Flow	Teacher guides through the different approaches, thereby develops individual work step sequences step by step in dialogue with the students. Includes questions targeting student understanding, i.e. question-answer sequences, buzz groups and discussions in plenum.	Familiarize unprepared students with the content and recapitulate content for prepared students and put the different work steps into context. Outlook on the upcoming workload. Teacher can estimate how far the students understand the concept of the whole exercise and which parts may need special attention.
	Expected Results	Questions on expectations regarding (1) concrete results of the individual approaches, and (2) value of these results. Can be supported by buzz groups and plenum discussion. Adding short keywords to the flowchart based on answers.	Short outlook on the results before starting the practical work.
2, Beginning	Problem Statement	Question on the starting point of the exercise and scientific problem.	Recapitulation of the exercise framework to set the scene and focus of the students. Teacher can check the understanding of the concept.
	Work Flow	Questions on the different approaches and the current progress, i.e. what has been done so far, what will be done on that day.	Recapitulation of previous work. Awareness/preparation of the work steps to be performed on the current day. Connection of the work steps conducted on different days.
Shortly before first results are obtained	Expected Results	Refining the expected results by illustrations depicting the specific results that will be obtain, e.g. colour staining.	Visualization of the results to support understanding and interpretation of the results. Preparation of students for the results from analyses they perform(ed) the first time → connect results with practical procedures. Looping back to scientific problem, i.e. why to expect certain results and what they would mean → connect results with scientific problem.
3, Beginning	Problem Statement	Question whether there are indications to answer the problem based on primary results obtained in the end of day 2.	Setting the scene again; initial connection of preliminary results and the scientific problem. Teacher can check the understanding of the concept.
	Work Flow	See day 2; extended by specifically addressing unclear or problematic steps/aspects retrospectively.	See day 2; extended by overall connection of previous work with the last work steps and upcoming results.
End	Expected Results	Guided cross-check of expected vs. obtained results. Discussion of the results and their value.	Validation of results. Clarification of unexpected results. Interpretation of results, connecting the information obtained by individual approaches.
	All sections	Final plenum discussion and recapitulation.	Connect scientific problem, methods and outcomes with the aims of the exercise to facilitate a holistic understanding. Highlight the need and value of the different approaches, i.e. which to choose to obtain what kind of information to solve a certain scientific problem. Clarify problematic issues connected to the exercise [→ also input for developing the exercise in future].
1 to 3	All sections	Spontaneous discussions between teacher and students or between students based on the flowchart. Individual students "consulting" the flowchart.	Reference point for orientation for students during the progress of the exercise and for exchange/discussions.

2. Quality of final reports submitted by the students
3. The teacher's role and perspective on the exercise compared to similar exercises without using this tool

Optimizing the flowchart and its use

After evaluation of the exercise with a focus on the impact of using the flowchart as a central element of it, a plan to improve the flowchart and its use for the future will be developed.

Results

The jointly developed flowchart facilitates active communication and orientation

Despite lacking experience in whiteboard teaching, the concept of jointly developing a flowchart together with the students turned out to be very valuable for me to getting into dialogue with the students. As indicated in the implementation plan for the flowchart (Table 4.1), the exercise started with a discussion on the basic scientific question and source material. It was a natural process to allow students to discuss in buzz groups when questions seemed a bit difficult to answer due to different reasons which were (1) lack of preparation, (2) limited initial understanding of the topic, and (3) possibly initial reservations to speak in plenum. This initial phase was quickly overcome, and when jointly developing the work step sequences it became a relatively vital and interactive process between the teacher and the students compared to previous experiences. Thus, the jointly developed flowchart (Fig. 4.2) was a good initiation of the exercise by facilitating the interaction between the teacher and the students. As assumed, the first outlook on the "Expected Results" was somewhat limited as the students lacked the connection to the work steps which they did not perform yet. Nevertheless, when completing this section on the second day, it was obvious that priming this part on the first day was very beneficial for the students' understanding, although its implementation was not ideal - due to unexpected time issues; one student group that had some spare time was asked to make a suggestion on the flowchart which later was briefly discussed with all participants. Ideally, all participants individually or in their groups had to think about the illustration of the expected results before adding anything to the flowchart. Therefore, although the students still seemed to very well perceive and understand that part, its implementation needs some optimization.

Already during the exercise feedback from some students indicated that they are happy with this approach, having the flowchart step-by-step developed together on a whiteboard that stays in the laboratory. Thus, it served as a common basis of communication of the content of the exercise between the teacher and the students, but also between individual students. In addition, it was observed that students actively used the flowchart for their orientation. It also improved my confidence as a teacher running this exercise the first time, as I had the flowchart as a common basis to refer to which resulted in a better overview of the status and progress of the students, and

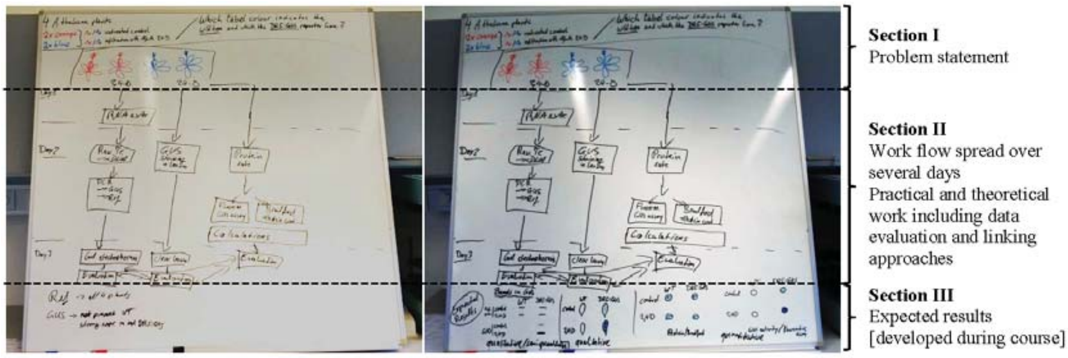

Fig. 4.2: *Flowchart jointly developed with the students in class*. The picture shows the flowchart after day 1 (left panel), and the finalized flowchart after day 2 (right panel) with the three sections corresponding to the scheme depicted in Fig.1.

which created a feeling of control, but also flexibility in running the exercise. Thus, the flowchart on the whiteboard facilitated a good “scientific” exchange between all participants in the exercise (including the teacher) as well as understanding of the content and the discussion partner.

Success of the exercise

A central part of estimating the success of the exercise was the final discussion of the results as well as discussion of case studies, i.e. published research using the methods that were performed in the exercise. Overall, the students were very well aware of the work they performed and the meaning and value of the results. They were able to recapitulate the individual methods, what they are useful for, and how they may complement each other. Furthermore, they could explain how the different results are connected, and how they may be combined to answer scientific questions on another (higher) level. When discussing the case studies, the students were able to transfer their knowledge on the learned methods to the presented research. While the basic understanding of their own work was much better than experienced in similar courses, it was the first time that I can say that the students were able to transfer their knowledge. In previous courses, this turned out to be a very critical aspect which is probably connected to the observed lack of basic understanding. The high level of understanding was in a similar way reflected also in the final reports which were in average on a better level than experienced before. Importantly, no group failed to describe the

Table 4.2: Compiled feedback referring to the used flowchart/whiteboard provided by students after class.

Responses by email	Student 1	Overview on whiteboard, nice structure of exercise
	Student 2	I really liked the flow chart and that you went through it so thoroughly. It gives a very good overview combined with the protocol.
	Student 3	Great with introduction to the experiment with board overview, but don't expect the students to have read for the next many lab days, usually we only read the stuff we are supposed to do for the day.
Anonymous responses*	Student 4	The flow-chart and the run-through created a nice overview of the exercise (very pedagogical)
	Student 5	White board layout, nice structure
	Student 6	Great with board overview before exercise
	Student 7 [*commented*]	The exercise was well described in the lab by Dominik, so there was no confusion. He was also very good at asking questions, so you had to think about some aspect you might not have thought about. *Teacher's comment: As these points were performed with the use of the flowchart/ whiteboard, this feedback can be regarded as a positive evaluation of this tool.*
	Student 8	I like the way you used the whiteboard to tell about the different results in the exercise. That made a good brush-up and was along a good learning point.

Students were asked to provide feedback on positive aspects and on points with potential for improvement of the whole practical exercise in general. All feedback related to the flowchart are included in the table.
*via Socrative; https://www.socrative.com/

work performed, to present the results and to provide valid interpretation. This means that all basic aims of the exercise have been achieved which was not all the time the case in previous courses. Instead, the final discussion and the reports highlighted very specific challenges in important steps of the process from the scientific problem to the results, namely certain calculations. A plan will be developed to address these specific challenges in future courses.

Students' perception of the flowchart

In addition to the in-class experience during the course of the exercise, the flowchart was often highlighted as a very positive aspect in the feedback provided by the students after completing the exercise. They were initially simply asked for feedback on aspects they perceived as positive and those that could be improved. Eight out of eleven students provided feedback of which seven named particularly the flowchart/whiteboard as the most (or one of the two most) positive aspects of the exercise, while one student referred indirectly to it (Table 4.2). This positive evaluation after class confirmed the very positive impression during the course of the exercise. Unfortunately, a second request for feedback specifically tailored to the improvement of the flowchart/whiteboard could only be sent in the very end of the course when the students were preparing and conducting their exams which resulted in no further input from the students. This specific aspect is planned to be taken up in future.

Discussion

The jointly developed flowchart supports student learning

The implementation of the jointly developed flowchart supported the students very much in achieving the primary aims of the exercise. While the joint development in itself facilitated the preparation of the students and their active contribution to creating the illustration of the framework, the final flowchart served as a common reference point throughout the course of the exercise. Based on the fact that the flowchart was jointly developed also the students could claim ownership, i.e. they could relate to it more easily as if it was just presented by the teacher. Furthermore, in contrast to previously used work step sequences for individual experimental approaches which were presented isolated from each other and as series of bullet points (see Appendix A), this flowchart allowed to interconnecting the different approaches which were followed in parallel. Also the illustration itself may have a beneficial effect, as individuals may grasp the concept more easily from this than only from text. In addition, the integrated repetitive elements in the implementation plan, i.e. that individual points are discussed and recapitulated (from slightly changing perspectives) several times, are most likely very beneficial to increase the understanding of the students and to internalize the obtained knowledge.

Based on the fact that achieving the primary aims of the exercise which especially includes a basic understanding of methods and results was not a problem in contrast to previous courses, this approach revealed the specific problems students are commonly struggling with. In cases when students are struggling with the basic primary aims of such exercises, these specifically problematic aspects may be covered and not addressed in an appropriate way. During this exercise, in particular two aspects turned out to be challenging for the students: (1) certain pipetting schemes that include the preparation of so called master mixes, and (2) more complex calculations of enzyme activities (despite repeated, relatively detailed instructions). Both points are very specific, but apparently were not limiting the understanding of the overall concepts. In contrast, the overall understanding of the students seemed to be on a higher level than in previous courses. According to the SOLO-taxonomy of understanding (Mørcke & Rump, 2015), they achieved a relational qualitative level which typically was not at all the case in previous courses. This can most likely be related to the structure of the exercise which is centred on the flowchart/whiteboard implementation. Even though some teachers may have reservations to use whiteboards and other "analogue" tools (in our increasingly technological world combined with a possible lack of experience in their use), the positive result of using the whiteboard in this exercise underlines that simple tools can be very useful to improve teaching and support learning. Furthermore, the feedback provided by the students clearly demonstrated their appreciation as it apparently supported their understanding and learning. This seems more important than the use of modern high-tech tools which is in agreement with studies on preferred teaching techniques of natural science and medical students (Novelli & Fernandes, 2007; Waheeda & Murthy, 2015).

The flowchart as the common ground for changing teacher roles

The flowchart also provided a good basis for the teacher to facilitate a supportive interaction with the students. It helped to keep track of the progress of the students, bringing situations very easily back to normal, e.g. when it seemed that time runs short, as no big explanations are needed when referring to an already known scheme. The flowchart was also a good tool for the teacher to shift between different roles (Beck, 2002), e.g. when developing or recapitulating sections of the flowchart at different time-points, either for the purpose of getting back/keeping on track or just to change the scene to diversify the teaching-learning environment. During the exercise itself, i.e. when the students perform their practical work, the teacher's role varies between a coach (high order of teaching approach, close proximity to the students) for specific tasks and a supervisor (chaos/distance) for the "students' project" covered by the exercise. When developing the flowchart or referring to it during daily recapitulation and discussions as a common basis, the teacher has the chance to switch to the role of a participant (chaos/proximity) or functions as a moderator which moves the teacher away from the students and increases the order in the teaching approach (Beck, 2002). I experienced this diversified teacher role as a suitable way to adjust the teaching-learning environment in relation to different needs and it seemed also to be beneficial for the resulting understanding of the students.

Outlook

The implementation of a jointly developed flowchart as a central reference point and guide through practical exercises which are spread over several days turned out to be an excellent tool to facilitate student learning as well as to support teaching – at least in this specific case. It is aimed to incorporate this approach also in other similarly structured exercises where appropriate. For this specific exercise, following actions will be undertaken in future courses to optimize the use and value of the already developed flowchart:

1. Requesting specific feedback on the perception and function of the flowchart (including suggestions to improve it) from students
2. Implementing schemes tailored to the specific aspects that turned out to be challenging for the students, i.e. students have to fill out schemes for the critical pipetting steps and calculations which will be collected and discussed in plenum (possibly referring to the flowchart)
3. To facilitate that every participant has to deal with the illustration of the "Expected Results" section of the flowchart, a questionnaire (see Appendix B) will be distributed which the students have to fill out; the results serve as a basis for a joint discussion when developing this section on the whiteboard

Acknowledgement

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A

Excerpt of the work flow of a similar course (Basic Methods in Plant Molecular Biology) with in parts comparable content and challenges as in the exercise addressed here.

Experimental Plan:

Approach 1: Identification of wild-type and transgenic plants

Tue: DNA isolation from *Arabidopsis* (wild type and transgenic), gel electrophoresis
Wed: PCR with primers for ITS (ribosomal DNA) und *uidA* (β-glucuronidase), induction by auxin, gel electrophoresis
Thu: GUS staining
Fri: Destaining, evaluation

Approach 2: Cloning of a reporter gene into a standard cloning vector

Sun: Growth of *E. coli* strains with the *pEG640* and *pBluescript* plasmids (supervisor)
Mon: Plasmid isolation, restriction digest, gel electrophoresis, Gel elution
Tue: Gel electrophoresis, ligation, pre-culture DH5α
Wed: Main culture DH5α, preparation competent cells, heat shock transformation
Thu: Visual inspection of the transformation, colony PCR screen
Fri: Gel electrophoresis

Approach 3: Transient transformation of tobacco plants

Sun: *Agrobacterium* pre-culture (supervisor)
Mon: Start main *Agrobacterium* culture
Tue: Infiltration of tobacco leaves
Thu: GUS staining
Fri: Destain, evaluation

B

Questionnaire draft on "Expected Results" intended to be implemented as preparation for developing the respective section in the whiteboard flowchart in dialogue with the students.

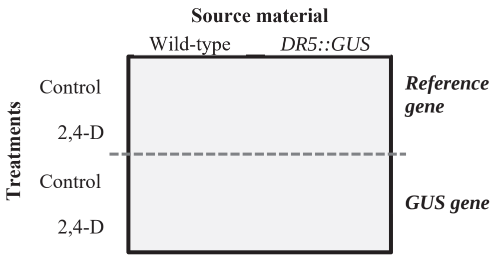
Expected results of the experimental approaches in the laboratory exercise "Tracking Gene Expression"

Dear students,

When performing experiments, it is important to think about results before obtaining them, i.e. which results are expected. This serves as a basis for the discussion and interpretation of the obtained results. As a preparation for later joint discussions of the expected results derived from our work in this exercise, please fill out the schemes below for the three approaches and hand it back to the teacher. Thank you!

Approach 1: Semi-quantitative RT-PCR

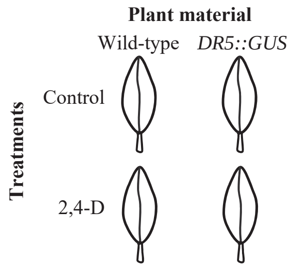
The result of this approach will be DNA bands visualized on an agarose gel. Please indicate the bands you expect to see in the scheme below:



What is the value of this result: ☐ qualitative ☐ quantitative

Approach 2: Histochemical *in situ* GUS staining

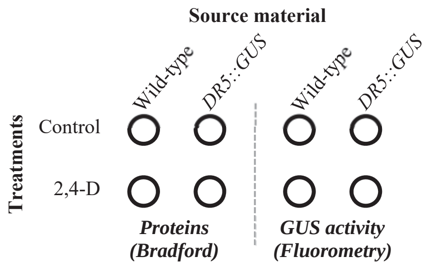
The result of this approach will be blue staining of GUS activity, i.e. the presence GUS is visualized based on its enzymatic activity in the leaf tissue. Please indicate the expected staining in the schematic leaves below:



What is the value of this result: ☐ qualitative ☐ quantitative

Approach 3: Determination of GUS activity in protein extracts

The result of this approach will be obtained by fluorometric determination of GUS activity in protein extracts, i.e. the presence GUS is visualized based on its enzymatic activity which causes a fluorescence signal. An intermediate result will be the content of protein in the extracts, visualized by a blue staining (Bradford). Please indicate the expected staining/signals (Bradford and fluorometry) in the scheme below:



What is the value of the Bradford result: ☐ qualitative ☐ quantitative

What is the value of the fluorometry result: ☐ qualitative ☐ quantitative