

Beyond research based teaching: Teaching interdisciplinary research and pushing students beyond their training

D. K. Dysthe¹ and H. Austrheim²

1 Department of Physics

2 Department of Geoscience

University of Oslo

ABSTRACT: Interdisciplinarity involves using approaches and methods from different disciplines for solving the problem at hand. Based on our experience from interdisciplinary research we believe that this is most effective when researchers that are firmly rooted in their own discipline learn *sufficient* theory, methods and practice of other disciplines to communicate and work in teams doing *research* together. The course «Methods in PGP» focused on teaching *sufficient* methods to all students to solve the *research* problem to be worked on in «PGP case study». The methods should be *sufficient* for the research and the training should be *sufficient* for the students to understand the approach of the other disciplines. Thus geologists with no mathematics or IT training had to pose problems mathematically and solve them analytically and by computer simulation and mathematicians and physicists had to do field mapping and analyse minerals. The research problem was always chosen from the ongoing research at the CoE PGP and changed from year to year. Consequently, both courses had to be modified, developing new curriculum every year. «PGP case study» always had a *real* research problem where the teachers did not know the outcome or even fully the direction of the research at the start of the semester.

1 INTRODUCTION

To reach the ambitions to become one of the best research Universities in Europe, UiO through its strategic plan call upon innovation, creativity, interdisciplinarity and research based teaching. In spite of this, examples of true research based teaching and interdisciplinarity are few. There exist no formula for how innovation and creativity can be enhanced and it is questionable if at all students can be trained to become more innovative. We report here on 11 years of experience of interdisciplinary (Physics-Geology) research based teaching and attempts to train students to become more innovative. In this hindsight we will try to put our endeavour in context.

1.1 The development of an interdisciplinary research and education environment

In 1998 the Strategic university program “Fluid Rock Interactions” was initiated at the University of Oslo. A mixture of senior and young professors, PhD students and postdocs from the Geoscience and Physics departments started working together. Over the next 5 years a truly interdisciplinary culture was developing that came into full bloom with the award of the Centre of Excellence “Physics of Geological Processes” (PGP) in 2003. PGP was committed to forming a separate MSc program that enrolled the first students in August 2004. From this semester on all new MSc and PhD students at PGP had to take two 10 ECTS credit introductory courses cross-listed between the Physics and Geoscience departments: Fys-Geo 4200 “PGP Case study” and Fys-Geo 4300 “Methods in PGP”. The goal was clear from the outset: Students with basis in their own BSc discipline should learn by doing; engage in research themes central to PGP in the same manner as in all research projects at PGP: working together in interdisciplinary teams and employ all the five research methods: field observation, analytical measurements on rocks, experiments, theory and numerical simulation. The first two methods are traditional to Geology, the latter three traditional to Physics.

1.2 Interdisciplinarity

Interdisciplinarity is considered to be the key to future development of research and to societal development [1]. The recent Strategic Advisory Board report to the University of Oslo [2] commented that “*At present, interdisciplinary activities mostly take the form of collaborations among participants from different disciplines, rather than the exploration of truly integrated interdisciplinary areas. ... At*

UiO learning and education appears not to be considered as a communal space constituted by criss-crossing investigations. ... students are forced to choose a specific study programme right from the start. 'Crosslisting' of courses (...) is underdeveloped. ... UiO should become considerably more interdisciplinary. Barriers between traditional disciplines should be removed without weakening standards of disciplinary excellence." We believe that the story we will now tell about the PGP introductory courses are an exception to this observation.

Even if one does not have the goal (like UiO) to become a leading European research university one may recognize that in most industrial companies the science educated personnel are required to work in teams with personnel with a different background. So how do you teach true interdisciplinarity to students?

1.3 Innovation

The Bachelor training in Sciences at most universities is focussed on basic knowledge and skills that are well established. Hardly a question is posed without the existence of a definite answer the professor can produce at will. The authoritarian culture installed in the students leaves little room for curiosity. On the other hand, the first steps towards learning innovation in research is to

- see that the world is full of open, unanswered questions,
- believe that the questions you pose may be of general interest and importance,
- trust that you have (or can acquire) the abilities and skills necessary to find answers to your questions.

This total break with the Bachelor training of the students was the starting point for our teaching.

1.4 Research (based) education

Research universities in Europe and USA developed from the notion of Wilhelm von Humboldt of unity of research and teaching [3]. This unity is also connected to Bildung (dannelse, the overall education of the individual, developing integrity and intellectual independence) as opposed to Ausbildung (utdannelse, training for employment). In the spirit of Humboldt the Norwegian institutions of higher education are required to give "research based education" (forskningsbasert utdanning) [4]. There is, however a wide range of interpretations of the concept "research based education" from "education in agreement with research" to the more Humboltian "training in scientific method in cooperation with a practising researcher" [5]. The latter interpretation that is close to our practise is mostly relevant at MSc and PhD level education although it has been used on BSc level with success as well [6]. The research training we describe in this paper is clearly a basis for a career as researcher, but we argue that the skills developed, the spirit of autonomy and method of enquiry are important to our future work force and the protection of democracy.

1.5 Differences between Geology and Physics

Geology is traditionally a descriptive science based on systematic field observation and analysis of rock samples from the field when back in the laboratory. Since the observed patterns are petrified remains of several very slow processes that occurred inside the Earth's crust there is an important creative element to infer what has happened. The qualitative descriptions of sequences of events leading to the complicated present day observations are seldom well constrained. Geology has traditionally had strong links towards chemistry with the development of the field geochemistry by Goldschmidt 1926[8]. However many geological processes, such as mountain building, fracturing, earthquakes and avalanches can only be understood by applying physical principals and laws.

Physics has, since Gallilei focused on picking apart the complicated Nature and describing the simple constituents in universal laws in mathematical form that have predictive power. As the fundamental laws are now known, physics today applies the same reductionist approach to complex systems with interaction of many forces and processes.

The BSc training at the Geology department at UiO has until now not required any mathematics or computer science whereas the physics BSc at UiO has 50 ECTS credits mathematics and computation and only 10 credits physics during the first year. Thus the BSc training of the two main groups of students starting the introductory PGP courses was extremely different.

2. CONTENT AND FORM OF THE COURSES AND THE PHILOSOPHY BEHIND

Many introductory courses are constructed to give a broad overview of the field. Since this was an introduction to interdisciplinary research we quickly realized that it was better to focus on a single topic per year and the limited the number of theories and methods to those necessary to solve the problem.

2.1 The topics of the case study

The topic of the case study changed from year to year and was chosen based on the following criteria: We were looking for research avenues that were in the developing stages internationally or that we could sense would become important in the nearest future and thus where we could play a leading role. Since the project work was based on field data we were looking for topics where we could draw advantages from Norwegian nature and climate. The project should contain problems that could be addressed through geological and physical working techniques and principles. The annual change of topics and field areas, although challenging for the lecturers, were fundamental to keep the innovation up both for students and teachers not to fall into traditions and repetitions. The topics chosen span a wide range from “Fracturing and alteration of the oceanic lithosphere, exemplified by the Leka and Røragen ophiolite complexes”, “CO₂ sequestration in ultramafic rocks”, “Green concrete”, “Ice wedging of surface fractures” and “Friction melting in deep earthquakes”.

In the methods course we restricted the choice of fundamental processes involved so that learning the necessary theoretical concepts did not take too much of the students time. The key processes *fracturing* and *transport and reaction* were kept throughout the 11 years because they were fundamental for much of the research in PGP at the time and to allow development of good and effective exercises.

2.2 The organization of the teaching

The semester started with 2-6 weeks of teaching an introduction to the field area and the topic of the year was given together with exercises in methods followed by a field camp for 3-4 days at the chosen field area. We looked for accommodation where we could stay together also at night to continue discussions and learning. The case study field camp was fundamental to collecting field data (rock samples, maps, images, and measurements) to be used in the subsequent part of the course and in the Methods course. The field camp was also used to create a group feeling and as many of our students were from abroad, they were given the first taste of Norwegian nature and wildlife.

Each group treated the field data during the field camp and afterwards and handed in a field report 2 weeks after the camp. The rest of the semester each group had weekly (or more frequent) meetings with the teacher and other research staff to discuss the scientific questions and how to proceed with analysing rock samples from the field and how to do modelling, experiments and finding relevant literature. In parallel there were more methods exercises that were often relevant to the case study. All the methods teaching was performed in the following manner: 2-4 hours introduction, 1-2 weeks individual and group work on practical exercise and group report writing. Reports from each group were commented and a revised report was handed in and commented.

The students were organized in groups of 3-5 persons. Each group should have at least one member from each discipline geoscience or physics/mathematics. This was critical for the learning outcome of the students because the exercises were so demanding that the students had to teach and help each other to solve them. Because there were methods from both geology and physics all students would both help and be helped at various times during the semester. A few years there were not enough students from one discipline or the other. Then we had to modify some exercises and lower the standards. In the methods course the groups were changed deliberately to ensure that students interacted with many different students and to aid the evaluation of each student's contribution to the reports. In the case study the students decided during the field camp which topic they would focus on and thereby groups were formed that lasted the whole semester.

Both the case study and the methods course required several teachers/researchers to be involved since they involved both geology and physics and application of research methods from several specialities (theoretical physics, numerical simulation, experimental physics, field geology, geochemistry and optical and electron microscopy). No teacher was allowed to simply lecture about their own favourite

research. Through thorough discussions about content and form the teachers decided on an exercise (for the methods course) that would be practically realizable in a week. For the case study the students, the responsible teacher and other researchers all took part in discussing what the interesting questions were and which analysis, simulation or experiment would be pertinent to perform. Then the student group and the expert researcher would enter an intensive period (1-4 weeks) of teaching necessary theory and methodological issues and performing the analysis, simulation or experiment and finally treating the data and writing about it in the final report. Each group would go through several such rounds of discussing the observations in field and in samples brought from the field and employing new methods in their investigation of the central processes of study.

We have found that by focussing on practical exercises with very directed introduction the students were able to perform tasks and master methods they never imagined. This is one aspect of pushing the students beyond their training. Physics students that had hardly been out in nature would map patterns and structures observed in the field and analyse rock textures. Geology students that had never programmed or studied mathematics since high school programmed numerical simulations and developed image analysis programs in Matlab. For example: The introduction to Matlab was done in a classroom with PCs where 2 and 2 students entered exactly the commands the teacher entered on a PC displayed by a projector. After 1 hour of general commands the teacher would spend 2 hours to introduce concepts like: how an electronic image is formed, how it is represented by a matrix of numbers, how operations like changing contrast and brightness can easily be represented mathematically, the mathematics of converting colour images to grey scale and black and white, concepts of image segmentation of image correlation etc. Then the instruction in front of PCs continued with applying all the concepts to a few example images. Then the students had to perform an experiment, collect images and develop Matlab programs to apply similar sequences of analysis to the series of images from the experiment.

2.3 The response of the students to research based teaching

Students were often frustrated to start with by the teamwork as opposed to working and being assessed individually. All students did quite quickly realise that collaboration was the only way to complete the tasks given. Another source of frustration at the onset of the semester was the lack of clear answers that they had got used to in their bachelor training. The professor answering “I do not know, but we can try to find out together” pushes the students beyond their training and into a real innovative mindset necessary for real research.

2.4 Research achievements – scientific and applied

The results obtained through our two interdisciplinary courses have paved the way for new larger research project funded by Norwegian Research Council, Horizon2020 and oil industry providing funding for PhD and master students. Following the more planned results the curiosity based research also led to important unexpected discoveries. For example: The mineral pyroaurite, which is known as an environmental mineral that can adsorb heavy metals from contaminated water, was discovered in one of the studied area. A master thesis carried out in order to test if naturally formed pyroaurite had the same environmental effects as the experimentally produced pyroaurite used in water purification today. In the studied sample pyroaurite was coexisting with the mineral dypingite that unexpectedly turned out to be a much stronger adsorbent than pyroaurite. This new adsorbent may represent a potential industrial product for water rinsing and as such a subject that may be patented.

2.5. A future multi-interdisciplinary approach totally devoted to research and innovation

In retrospect we can see that nature is so rich on interesting interdisciplinary problems that we could also have pick a field area and develop the project from the observation we made. This however would have made the preparation and introduction to the course difficult. It is evident that the involvement of additional sciences (modern chemistry and biology) would have been beneficial to solving some of the problems we were addressing and probably created new interesting interdisciplinary research fields.

3 EVALUATION

In both courses we announced that 75% of the grade was based on reports handed in and 25% based on a final exam. Because all reports were written by a group, the assessment of the contribution of each student was the most difficult. The role of the final exam was to assess if the students were able

to explain the content of the reports that were handed in. In the methods course the students would have to answer questions about one of the reports randomly drawn. The random choice of report could often be hard on a student that got a report on a method from another field (for example for a geology student who would have to explain how to use the theory of fractals to make a mathematical model of hierarchical fracturing). If the student had great difficulties with one topic they would get some questions about other topics to assess if the student was generally weak or not. In the case study course the oral exam was started by the student giving a presentation about some part of the case study and then he/she was examined about the report. The examination would often take the form of a scientific discussion between good students and the examiner.

Almost all reports that were handed in in both courses were of high standard and the starting point for all would therefore be a C or a B. We would sometimes get a spread in grades from A to E within a single group. This could be argued to represent more than 25% weight of the final exam. This deviation from the stated weight is problematic. On the other hand, also the students knew that there were large differences between them and it would be unfair to give both the student who had done everything and the student who did nothing the same C. Oral exams are difficult and require very good preparations by the examiner. We have seen several times that we could have been more systematic in our examination and following assessment. We found that using the same sensor for both courses every year has helped us in maintaining a stable grade level and keep the assessment relatively fair. Some students however have felt unfairly treated during the exam and by our grading of the exam.

4 CONCLUSIONS

The two 10 ECTS courses developed to train new students to take part in the interdisciplinary Centre of Excellence “Physics of Geological Processes” gave in depth introduction to interdisciplinary research in accord with goals of Norwegian higher education and the strategy of the University of Oslo. We judge the training to have been very effective at pushing the students far beyond their basic training and into an innovative mind-set.

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APPENDIX

List of case study topics and field area

2004	??
2005	??
2006	??
2007	Impact fragmentation of rocks. Garnos meteorite crater
2008	Alteration and fracturing during serpentinization of ultramafic rocks. Leka and Feragen
2009	Alteration and fracturing during serpentinization of ultramafic rocks. Feragen.
2010	CO2 sequestration in ophiolites. Solund.
2011	Deep earthquakes: fracturing, friction and pseudotachylites. Holsnøy. New friction melting experiment developed by student.
2012	Reaction driven fracturing, mineral CO2 sequestration. Feragen
2013	Reaction driven fracturing, weathering & pulverization, green concrete. Feragen
2014	Ice wedging, carbonation reaction sequences. Feragen. New ice wedging experiment developed by students.

List of methods exercises

- Fracture (all 4 were used every year from 2008 on)
 - Experiment on flour on an extending substrate: Image analysis, strain analysis and quantification of segmented images in Matlab. No prewritten code.
 - Discrete element simulations of a material with different degrees of randomness on an extending substrate: Running simulations, quantification of resulting images. Prewritten simulation code, analysis developed by students in Matlab.
 - Algorithmic model of fracturing of material on extending substrate: Fractal analysis, theory of elasticity with fracture criterion, theoretical analysis, simulation of algorithmic model with varying parameters in Matlab. No prewritten code.
 - Field mapping of fractures. Different methods for presenting sets of fracture and relations between them. Image analysis of fracture sets.
- Diffusion / convective transport and reaction/ crystal growth (A subset of 3-4 were used depending on the case study)
 - Analytical solutions to diffusion equation with different boundary conditions, analytical calculations on and Matlab simulation of random walk.
 - Experiment designed from desired outcome (CO2 diffusion causing carbonate crystallization, heat diffusion and fracturing...) Preparing all equipment, performing experiment with time lapse photography and image analysis and diffusion analysis in Matlab.
 - Finite element or finite difference simulation of the same diffusion (and sometimes reaction) process as in the experiment.
 - Scanning electron microscopy (SEM) and electron microprobe (EMP) analysis of element concentration profiles into mineral grains. Develop analysis of data in Matlab to quantify how long the grain surface was exposed to given element.
 - Random walk coupled to surface growth with varying growth rules in Matlab. No prewritten code
 - Use of geochemical code PhreeqC to calculate possible mineral and fluid histories consistent with observations on field samples using SEM and EMP.
 - Finite element simulation of Stokes flow.

Case studie beskrivelse og læringsmål	Metodekurs beskrivelse og læringsmål
Felt og laboratoriebasert studium der det gis en innledende innføring i den geologien og fysikken i prosesser som er relevante for case-studiet. Felt-studie med 3d-kartlgging og prøveinnsamling. Tolkning av bergarter og prosesser. Teoretisk introduksjon til relevante prosesser. Avbildning av prosessene på laboratorie- og numeriske modeller. Eksperimentelt og numerisk studium av prosessene. Analyse av resultater og integrasjon. Studentene lærer gangen i forskningsbaserte prosjekter i et tverrfaglig miljø. De får fordypning i et konkret problemområde som er sentral i aktiviteten ved PGP-senteret. De lærer å anvende metoder fra FYS-GEO4300 - Metoder i geologiske prosessers fysikk på et konkret problem. Studentene jobber i tverrfaglige grupper, slik at de lærer tverrfaglig kommunikasjon og samarbeid. Studentarbeidet bør bli av en kvalitet på det nivå som kreves av en vitenskapelig publikasjon, og hvis arbeidet er av god nok kvalitet vil resultatene bli forsøkt publisert. UiO's holdning til, og regelverk om fusk er gjennomgått som en obligatorisk del av undervisningen. I den forbindelse har studenten fått informasjon om god siteringspraksis, etisk og kritisk bruk av kilder og en gjennomgang av sentrale litteraturdatabaser.	Emnet er sentrert rundt to temaer; diffusjon og sprekkdannelse. Det gis en innføring i betydningen av disse prosessene i naturen (i f.eks. kontaktmetamorfose og jordskjelv). Hovedvekten legges på å gi en innføring i forskjellige metoder for å forstå disse prosessene teoretisk og i naturen. Dette innebærer bl.a. feltobservasjon, prøveinnsamling, lysmikroskopi, elektronmikroskopi, tolkning av mikrostrukturer, seismikk, matematisk modellering av prosessene, simulering med løsning av differensiallikninger og med diskret elementmetoder, eksperimentdesign, infrarød avbildning og billedbehandling. Emnet skal bringe studentene i kontakt med forskningsfronten innen felt-, eksperimentelle- og numeriske metoder brukt i geologiske prosessers fysikk. Emnet gir også studentene trening i å skrive fullstendige rapporter fra mindre forskningsprosjekter.

Table 1: Course descriptions and learning goals from Student Web.

Feedback from 4 male physics MSc students 2, 8 and 10 years after taking the courses

A (2005): Viktigste punkt jeg har fått ut fra kurset:

- Jeg må si at det viktigste jeg lærte fra kurset var hvor mye ukjent fysikk ikke er funnet ut av. Etter en bachelorgrad har man lært utrolig mye og man kan nesten få følelsen av at det meste er gjort og forstått - det er ikke sant! Det var inspirerende.
- Det er faktisk mulig for meg å gjøre noe interessant. Hvilket også er inspirerende.
- Dersom man setter tall på det man studerer så åpner muligheten seg for at flere metoder kan anvendes til å forstå systemet / prosessene. Dette er artig fordi det motiverer at man gidder å lære seg flere eksperimentelle metoder, teori, og numerikk.
- Kurset viste meg at man kunne gå ut i naturen og faktisk studere fenomen som man kan kontrollere i laben. Det har utviklet hvordan jeg ser på naturen rundt meg. Jeg føler at flere av kursene, særlig dette, åpnet for at jeg kunne gå ut i naturen å kikke for å kunne la meg inspirere til å ta med meg fenomenene inn på fysikklaboratoriet.
- Dermed har kurset fjernet endel 'kunstige' skiller om hva som er ditt og hva som er datt. Cross disciplinary blir på en måte meningsløst, siden jo alt blir naturfag (eller fysikk kan du kanskje si).
- For min egen del har kurset vært viktig både fordi det har åpnet opp for flere inspirasjonskilder. I tillegg har det gitt meg trua på at jeg kan gjøre noe sjøl.

B (2007): Jeg husker dessverre best at evalueringen i begge fagene opplevdes som den mest urettferdige evalueringen jeg har erfart på UiO (det ene verre enn det andre). Det la en demper på det meste av videre studielyst på PGP på det tidspunktet.

C (2013): Hva jeg trodde jeg skulle lære i FYS-GEO kursene:

- Samarbeid på tvers av fagretninger
- Hvordan geologer jobber i felt
- Knytte geologi og fysikk sammen, forklare geologiske prosesser med fysikk.

Hva jeg lærte i FYS-GEO kursene:

- Samarbeid på tvers av fagretning og med internasjonale studenter. Dette er en erfaring jeg har satt pris på, og som jeg ikke har fått i noen andre kurs på Blindern.
- Jeg lærte litt om hvordan geologer jobber i felt. Jeg lærte å knytte dette til eksperimenter, ved for eksempel sprekkdannelse. Der vi observerte sprekkdannelse i felten og forsøkte å forklare prosessen bak ved eksperimenter.
- Jeg lærte mer om rapportskriving, mye på grunn av dyktige stipendiater som tok kurset og veiledningen vi fikk av disse da vi skrev rapport.

Læringsmetode i FYS-GEO kursene:

- Jeg likte at pensum var åpent og at mye av læringen lå i at vi skulle utforske ting vi syntes var interessant.
- Dette gjorde at man gjerne gikk litt lenger enn man hadde gjort om pensum bare var definert av en bok.
- Det var spennende at det vi gjorde var tett knyttet opp mot forskning og at mye av det enda ikke var forklart. (Grønn sement osv)

Den største påvirkningen jeg fikk av de to kursene var nok samarbeid med andre fagretninger, rapportskriving og arbeidsmetoder, fra det og observere noe til det å kunne forklare prosessen som ligger bak.

D (2013): The main goal of the course was to exploit the different skills within the group, geologists and physicists at the MSc and PhD level working together to produce scientific data about some case study. The work was guided from the professors, that had the main ideas, and that had suggestions on how to analyze samples and collect data. The rest of the work was mainly up to the groups, dividing the different work tasks and objectives among themselves.

Another main goal of the courses were to learn methods for analyzing samples and collecting data. Computer labs and experiments were conducted in plenum, where the students were free to have fun and test things for themselves afterward.

The groups had very different people with different backgrounds, so it was fairly easy to divide tasks, of course the ones that were best on something usually ended up doing that part, but during the labs and so, these people were very useful to help and show the other guys.

We were able to reproduce results, create our own, and back up the results, showing that the group could work together as a team. Also the groups made several hand-ins that met the requirements of the courses. So I would say that everybody learnt good cooperative skills, some programming, and some good routines for conduction of experiments.

The concepts and the theory were not that difficult, but some parts of the analysis were demanding, and of course fun to overcome. I think that I expected to learn more about, and perhaps to hear more about experience with results from different methods of sample analysis. How well can we trust the results, and what sources of error can be met?

We got a very good introduction to image analysis, something I did not expect. This was a very fun part of the project work, and we could easily see the benefit/importance from it.

The courses are part of my MSc degree (20/120p). In my master thesis I am doing molecular dynamics simulations of nanostructured tight rocks, and the behaviour of fluids within such pores. The knowledge of some geology has been important for my understanding of the systems that I am looking at. To get hands-on experience with working in a team is important, leader skills can be tested and developed. Also a quite good understanding, but as I am working on it now I realize that it could have been even better, of diffusion processes were gained. The concept of diffusion is ok enough, but the fact that looking at it on different timescales will produce very different results and knowing what they mean, should have been explained better.

I was not so happy to hear, when I had finished my oral exam, that the results I was in charge of, and that I was told to present, were not found to be important enough to back up the final paper because

one sample was obviously contaminated (but still a result). So I was told that I should have focused more on the other parts.

This should have been caught up when we did our final presentations of the project work, and we got our feedback to what we should do on the oral exam.

But all in all, the courses were very fun to work with, and I enjoyed the field trip and the social part of working together as a team!