Development of Competence in Biochemical Experimental Work

Assessment of complex learning at university level

Christina Bergendahl

Akademisk avhandling

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Development of Competence in Biochemical Experimental work. 
Assessment of complex learning at university level.
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Abstract: Biochemistry is part of life science: a fast developing multidisciplinary area. The overall aims of this thesis and the work underlying it were to find ways in which to develop competence in biochemistry at university level and to assess complex learning. A particular interest was the development of experimental work as a means to promote learning.

The study focuses on changes made in two educational settings. The aim of the changes was to develop competence, amongst both students and teachers. Therefore, the research in the three first papers has in some aspects, and to different extent, the characteristics of action research. Broadly, the changes can be described as making experiments more open, with multiple formative and authentic assessment methods involving both students and teachers.

The empirical studies included questionnaires, interviews, questions asked during experimental work, written material as formulated objectives, examination questions and answers, reports, other products; and grades/judgements made by teachers and students. Collected data were analyzed in several different ways. Statistical methods included the use of mean values, paired T-tests, Spearman rank correlation coefficients and Principal Component Analysis. Interview data as well as some questionnaire data were analyzed using analytical induction techniques. Some categories were based on thematic content analysis, while others were based on Bloom’s taxonomy. Students’ attitude positions were categorized according to Perry’s framework.

The main results can be summarized as follows;

The students’ learning was improved by open ended versions of experimental work, according to both their and the researchers’ opinions. Planning, approaching problems from different perspectives and evaluating the results of their own experimental work promote the students’ capacity for higher order cognitive thinking. However, the synthesis level constitutes a threshold and particular support is needed for students with a more dualistic view of teaching, learning and experimental work.

Introducing formative and authentic assessment is a way to help students to make progress, and to develop competence. The importance was clearly demonstrated of involving both teachers and students in discussions of aims and criteria and of making them explicit. Feedback from teachers’ and students’ own reflective activities about subject content, and their learning as well as affective factors were shown to be central for complex learning.

Based on our studies, areas were identified for the critical development of competence and for promoting learning in biochemistry at university level. These areas are; multidisciplinary and complex learning, communication skills of different types, metacognitive perspectives, attitude development, and affective factors.

The students see experimental work as crucial for their learning and therefore important in terms of assessment. Therefore, experimental work can and ought to be assessed. However, similarities and discrepancies were observed between students’ and teachers’ perspectives for both the aims and assessment of experimental work. Our conclusion is that a combination of assessment methods is needed in order to be able to make a high qualitative assessment.

Keywords: experimental work, laboratory based project work, open experiments, biochemistry, life science, university level, action research, course design, aims and objectives, authentic assessment, formative assessment, competence, complex learning.

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Development of Competence in Biochemical Experimental Work

Assessment of complex learning at university level

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2004
To my family

Jessica, Tobias, Martin
and
Lasse

Låt inte småsaker
störa din sinnesro...
Livet är allför värdefullt
för att man ska offra det
på det som är
oväsentligt och
förgängligt....

Grenville Kleiser
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This thesis is based on the following papers, which will be referred to in the text by the corresponding Roman numerals:


Preface

During the years in which I have been involved with biochemistry education, as director of studies and, more recently, as a doctoral student in chemical education research at Umeå University’s chemistry department I have encountered many opinions, feelings and concerns about the teaching situation. The working situation for university teachers has changed for a number of reasons; reduced financial resources, larger classes, changes in students’ prior knowledge and a greater diversity of courses. Different categories of students are coming to the university and there is a shift of emphasis from education of a few, to mass education. All this puts higher burdens and demands on teachers, which easily leads to dissatisfaction and frustration.

I have myself been confronted with a number of practical problems concerning what to teach, how to teach and how to assess teaching. Why should I teach particular aspects of biochemistry, and why I should teach and assess them in a particular way? Action research has helped me to find answers to my own practical problems. However, I know that my need is shared by others: it is a social need more than a personal need. Since many of my university colleagues are confronted with the same problems it is an urgent task to find ways, within our culture, to improve practice and enable professional development.

My research focuses on objectives, assessment and course design as tools for boosting students’ attainment of higher order cognitive skills in the context of biochemistry and experimental work. How can a moment/course be designed to develop competence in biochemical experimental work, and how can complex learning at university level be assessed?

The aims and objectives of courses in biochemistry at the university level range from relatively general to highly specific goals. How and by whom are different aims formulated and how well are they approved, understood and explicitly formulated? The degrees to which educational aims are being fulfilled, and how they are being assessed, are interesting issues.

Good assessment of students’ knowledge, skills and abilities is fundamental to the process of learning. If we want to use assessment strategies to promote learning we need to carefully align them with aims and objectives. Often we assess in ways that are convenient to our systems rather than helpful
to students’ further development. If we want to know what students have learned and how effective the learning process has been, or if we want to support the development of the students’ learning process we have to ask ourselves: why are we assessing, what are we assessing, who is best placed to assess, when should we assess and why have we chosen a specific assessment method?
Introduction

Life science and biochemistry: challenges for research and teaching

Life science

‘Life science’ has evolved as the term for the science associated with developments in modern biology, biochemistry, biotechnology and genetic research, which are coupled to breakthroughs in genome research and molecular biotechnology. This subject area has aroused great interest partly because of its rapid progress and potential applications, and partly for the ethical questions arising from recent advances. New methods for the analysis and design of life’s building blocks will change the basis of research in research-intensive areas and developments inter alia in agriculture, the production of chemicals and new materials, sensor and computer technologies, medical diagnostics and gene therapy.

In modern molecular life science, the traditional borders between chemistry, biology, physics, medicine, mathematics and computer science are becoming increasingly blurred. Consequently, new professions, disciplines and programs have emerged.

How should this fast-evolving interdisciplinary area be conceptualized? What is its core content? The rapid development makes it difficult to keep textbook or other types of media up to date. At least for higher levels in education, educators and students will probably have to continue using several different sources and more specialized textbooks. This reality highlights the importance of developing the skill and habit of making associations and connections between different domains and topics in this wide inter-disciplinary field. It also requires a critical and reflective attitude towards conveyed information. This requirement for creativity and a metacognitive attitude in teachers and students seems to be a characteristic of ‘life science’.

The curriculum for life science at different educational levels has to be discussed and defined, and the educators have to retool, upgrade and sustain themselves as teachers and professionals.

However, as Huang (2000) points out, there is a dilemma. The fast development in the life science area has generated much excitement, which is mirrored in increased funding for this type of research from both governmental
and private sectors. This, in turn, puts great pressure on the scientist to engage in exciting research rather than spending time educating students and informing society. On the other hand, awareness of and enthusiasm for education and educational research is increasing. This can be exemplified by the clear message delivered by the president of the US Academy of Science, Bruce Alberts, in his opening address to the ASBMB meeting (American Society for Biochemistry and Molecular Biology) in San Francisco 1999: Education has to be an integral part of science. This message was even stronger at the recent ASBMB conference in Boston 2004.

**Life science and biochemistry**

Biochemistry, as a discipline, is part of life science (see above). However, biochemistry is itself a multidisciplinary knowledge area. It involves chemistry, since it deals with molecules, molecular interactions, and chemical reactions, and also biology, since it deals with living organisms. It is included in the frameworks of medicine, pharmacology and many other disciplines. On the other hand, biochemistry might simply be described as the study of the chemistry in living organisms and therefore be denoted chemical biology.

The role of biochemistry in life science is mainly associated with molecular understanding of the function of gene products and bio(macro)molecules, the structure, function and mechanism of proteins (proteomics) and the understanding of certain metabolic processes. Thus, biochemistry has a central role in advances in the life science domain.

**How should biochemistry be taught?**

Against such a background, how should biochemistry be taught? What knowledge, competences, skills and abilities should be included in a biochemistry education in the future?

The advances in computer technology and the use of databases have changed the rapidity and intensity of the flow of information dramatically, and the half-life of information has become increasingly brief. Further, biochemistry today often demands modeling and computing, and virtual laboratory exercises. In addition, developments in genetics and biotechnology have equipped us with ready-made kits for probing reactions and analysis. However, a biochemist needs to understand the chemical principles of the kits in order to evaluate and interpret results.
Due to the growing tendency towards interdisciplinary approaches in life science research Huang (2000) identifies “the development of skills and abilities to integrate” as the major challenge for the education of biochemists for tomorrow. The students have to be grounded in a wide range of areas and theories, to be able to interpret information from many different fields, and to be able to make connections and be creative.

**Professionalism and competence development in life science**

The multidisciplinarity and most other characteristics of biochemistry are shared by life science. In a far-sighted, forward-looking article (Coldstream 1997) a former director of the British Council of Industry and Higher Education stresses the challenge for universities to educate students, both undergraduates and graduates, and he identifies vocational and professional qualifications that are/will be required. In another article Huang (2000) discusses professional development in the life science domain. The competences and skills anticipated as being essential in the future are summarized in the following statements:

The process of learning is gaining in importance alongside the content. “The future working landscape is the apparently never-ending technical and organisational advance. What we are learning is obsolescent and going out of date with accelerating speed. That changes the definition of educated people. They are no longer those with a given level of achievement (knowledge, understanding, skill capability, competence, syllabus-coverage) but those who have learnt to go through life in a spirit of critical but humble questioning and learning” (Coldstream 1997).

Personal abilities predicted to grow in importance are independence and self-reliance. Other characteristics and competences that should be included and developed in education for professional development are multidisciplinary approaches, to deal with complexity in the working fields, and the ability to work in teams. Communication is increasingly important. Graduate students should be able to argue coherently within the language of their respective disciplines and to explain their ideas in lay language to those based in other disciplines, to manipulate ideas, and to express them to others confidently. Finally, there is a strong call for creativity in teaching and learning. All this has implications for curricula, learning goals and learning methods, which may need major revisions.
Demands for educational research in biochemistry teaching

Gilbert et al. (2002) identify several key areas of future research and development in chemical education. From this overview of research, they conclude:

• There have been plenty of studies of alternative conceptions: typical examples are the many reports of enquiries into students’ understanding of chemical bonding. The intention of the researchers was to produce methods to promote concept development, but in too many cases this has not been the outcome.

• Course development has been researched to a low extent. However, there are many examples of developments being produced, implemented, and even reported in journals, without any evaluation of their significance having taken place.

• There has been too little action research intended to achieve educational improvement in a particular context and to generate understanding of that and similar contexts.

• A reasonable proportion of research is intended to identify practices that are clearly effective for achieving particular educational goals. However, this research is concentrated in relatively few topic areas.

• Genuine, visionary research is sparse. Research aimed at generating new knowledge generally lacks results concerning its impact on practice, or such results are uncertain, diffuse or long-term.

• Too little research is undertaken from a particular psychological perspective with chemical education as an exemplary domain.

• Little research has been done in chemistry education at university level

Finally, Gilbert et al. (2002) point out the need to develop and research assessment in chemical education:

“The assessment of the understanding of chemistry should not simply be based on the memorization and recall of ideas as such, but rather to be set in contexts where students are likely to meet chemical ideas in the future. The specific conditions for valid and reliable assessment in chemical education do not seem to have been focused
in recent years, the literature on assessment being still largely generic, so research is needed here.” (s. 394)

The need for further educational research, in similar areas to those identified by Gilbert et al., has also been argued by Ruddock and McIntyre (1998). My conclusion is, therefore, that my research work is in a high-priority field, since it is about learning in a special setting, domain-specific and coupled to the topic, biochemistry, being learned. It can be described as action research into higher education in chemistry, with developments being undertaken and researched in order to achieve educational improvements in a particular context and to create understanding of that and similar contexts. The overall intention is to identify practices that are particularly effective for achieving particular educational goals and for assessing experimental work in biochemistry.

Aim and research questions

The overall aim of the thesis is to explore and analyze how biochemistry students’ learning and development may be enhanced through the development of objectives, assessment methods and course design. A particular analytical focus is the development of laboratory work as a means to promote learning. The research questions posed in the four articles are:

1. Will an expository versus open-inquiry version of the same experiment have different outcomes for our students and may the instruction be better suited to some students than others? Has it bearing upon their attitudes towards teaching, learning and experimental work?
2. Can a strategic course and assessment design promote the students’ capacity for higher order cognitive thinking? What are the students’ views of their own learning process?
3. What are the students’ and teachers’ perspectives on the aims and assessment of experimental work? What are the similarities and differences?
4. To what extent do the investigations carried out constitute action research? How can action research promote professional development?

**Organization of the summary of the thesis**

The thesis summary has five parts. Part 1, the preceding introduction, is intended to introduce the reader to the fields of life science and biochemistry. Challenges both for teaching and educational research in biochemistry teaching are introduced. This first part ends by stating the aims of the research and questions addressed. Part 2 is a short summary of each of the four articles. Part 3 starts with a short summary of general biochemical knowledge about proteins and continues with a description of the biochemistry content in the courses studied. Part 4, which is concerned with the research framework and methodological approaches adopted, describes: themes related to my research and investigations/studies; research on teaching and learning in the laboratory; laboratory instruction styles; aims, instruction and assessment; and taxonomies of educational objectives. Relevant data collection and data analysis methods are presented and discussed under choice of sources and methods. In the last part, part 5, I present results, major conclusions and discussion in five areas that I found to be crucial for the development of competence in biochemical experimental work. Finally I suggest further research and give some final comments addressing the problems that have been highlighted in my studies.
Summary of the articles

I. Benefiting from an Open-Ended Experiment? A Comparison of Attitudes to, and Outcomes of, an Expository versus an Open-Inquiry Version of the Same Experiment

Laboratory work is generally considered to be an essential part of science education. Thus, the time the chemistry students spend doing experiments constitutes a substantial proportion of the total scheduled time. For over 40 years there has been a continuous mission for more open experiments. However the results have been contradictory and not always encouraging (Hodson 1996). The main learning objectives, for laboratory work in chemistry at university level, are shown to still be how to carry out standard procedures rather than how to plan an experiment to tackle a specific problem (Tiberghien et al. 1998).

The aim of the study was to investigate if different degrees of openness of instruction in the same experiment would result in different outcomes depending on the students’ attitudes towards learning.

The study was carried out with a total of 190 students in their first year of chemistry studies at university level. The students were divided into three groups. The first group was provided with expository instructions for the experiment, the second group was provided with an open-inquiry version and the last group was given a modified form of the open-inquiry version (revised open-inquiry experiment). A questionnaire was used to discover the students’ attitude positions. The outcome in the different versions of the experiment was evaluated in interviews, questions asked during the experiment, and students’ self-evaluations.

The main findings were that the revised open-inquiry version resulted in most positive outcomes regarding learning outcome, preparation time, time spent in the laboratory and students’ perception of the experiment. The students with low attitude positions needed more support to meet the challenges of an open-inquiry experiment: the support in the revised open-inquiry experiment provided a clearer explanation of the aims, and feedback from the instructor at a “checkpoint” during the experiment. In a way the research question was developed during the research due to new insights gained in the comparison between the expository and open-inquiry version. The revision was a ‘spin-off’
effect of our first attempt to compare an expository and an open-inquiry version. The second part of the study, the revised open-inquiry version, depended on these insights and can be seen as action research with an updated research question.

II. Boosting Complex Learning by Strategic Assessment and Course Design

A wide range of factors affects learning outcomes. For example, the choice of teaching methods exerts a major influence on the students’ development of knowledge and skills. The mode of assessment of the learning outcome is another important factor. Snyder (1971) describes how students can learn to see behind the formal curriculum and orient themselves to what he terms the “hidden curriculum”. Brown and Knight (1994) conclude that assessment seems to be “the heart of the student experience” and that it often defines what the students regard as important, how they spend their time and even how they see themselves as students and, eventually, graduates. Therefore, alignment of the objectives with appropriate assessment and instructions is important.

The main goals in this study were to develop, investigate and analyze teaching and assessment methods in relation to course objectives. More specifically, our research question concerned whether the choice of assessment methods can promote students’ acquisition of higher-order cognitive skills. We also believed that it was essential to find out more about the students’ views of their own learning process. Our hypothesis was that by using a strategic course design and adequate choice of assessment, the students’ capacity for higher order cognitive thinking would be enhanced.

The subject of the study was a practical 10-week biochemistry course, at master level. In the original course design assessment consisted of a written exam at the end of the course. Dissatisfaction with this method led to course development, resulting in a revised design of the course. In the new design five different formative and authentic assessment methods were introduced: a written exam, laboratory work, a seminar, a grant proposal and a poster. Multiple types of data were collected: questionnaires, observations, interviews, written exam questions/answers, objectives, students’ written reports/products and grades/judgments made by the teachers. The test population consisted of 48 students.
The importance of the psychomotor, cognitive and affective domains for internalization was supported. We identified affective and psychomotor factors in the students’ work as powerful stimuli for their learning. The students’ perception of their own learning is related to their control over their learning process. We conclude from our study that a strategic choice of assessments and instructional design aiming at analysis, synthesis and evaluation can be used as a driving force to promote more complex learning. The students were capable of achieving these objectives. However, the synthesis category constituted a threshold in the students’ cognitive development. We did not find any single teaching/assessment method to be clearly the best for enhancing higher order thinking or for achieving all desired objectives. Instead, a combination of strategically selected methods seemed to be best.

III. Aims and Assessment of Laboratory Based Project Work in a Master’s Level Biochemistry Course. Students’ and Teachers’ Perspectives

Our studies of the new course design (article II) showed that the students identified the experimental work as the main source of their increased sense of autonomy and self-confidence. The experimental period was regarded as important, as it effectively promoted learning in an active and creative way. Most of the students also stressed the point that they learned how to work, plan and think more independently during the course. Since laboratory work was considered a crucial part of the course, there was a need to develop a high quality assessment of it.

Laboratory work occupies a large proportion of the time the students spend on a chemistry course, but its importance is seldom assessed or reflected in course marks. Hodson (1996) stresses the impact of assessment and emphasizes the importance of assessing practical work. Important laboratory activity outcomes can be assessed in the cognitive, affective and psychomotor domains (Dechsri et al. 1997). Self-assessment and peer-assessment are seen as parts of a learning process. Self-assessment is exceptionally useful in helping students reach their learning goals. It is a strong formative educational tool that can be used in order to bring about behavioral changes in students with regard to their own learning processes (Orsmond and Merry 1996).

The purpose of this study was to investigate and compare students’ and teachers’ aims and assessments of the experimental work in a master level biochemistry course.
In the first part of the study students were interviewed with a particular focus on their opinion of laboratory work assessment. An extensive group-interview was performed with the teacher responsible for the course and the two laboratory instructors in order to highlight teachers’ criteria for assessing the experimental work. In the second part of the study 26 students responded to a questionnaire, asking them to articulate what they regarded as goals for laboratory work. The answers were compiled into a list, which was complemented with aims the teachers thought were missing. After the course the students assessed their own fulfillment of the aims and the teachers made corresponding assessments of each student. Finally, 13 students were interviewed regarding their opinions about who could best assess what.

The students unanimously agreed that the laboratory work should be assessed. Most of them expressed the belief that the cognitive criteria could best be assessed by the teacher, personal skills by themselves and social skills by their laboratory partners. There are considerable similarities, but also differences, in what the students believe have been assessed and what the laboratory instructors really assessed. Aims formulated by students could be categorized as belonging to the psychomotor, the affective, and the cognitive domain, respectively. Alignment between aims and assessment criteria is seen, but there is also some misalignment. One conclusion from this study is that it seems to be important that aims and assessment criteria are formulated and discussed cooperatively by teachers, laboratory instructors and students.

IV. Action Research as a Means of Professional Development: Reflections on Research and Action in University Chemistry Education

Central issues facing university chemistry educators are how to develop the best ways of designing, teaching and assessing undergraduate courses, and the forms of professional development needed by university staff to deliver them. This article begins with a discussion of the role of professional development in Swedish universities, providing necessary background for reporting the aims, methods and results of two different chemistry education projects, and aspects of action research that are relevant to them.

The purpose of the investigation described in the article was to determine the extent to which the investigations carried out in the first two projects (articles I and II) constitute action research and whether this is important for professional development. Is it possible to conceive of these two
studies in ways other than conventional research on the best ways of teaching science, and what forms of understanding did the staff involved gain?

Considering the projects as action research can be justified on the basis that action research has three main pairs of characteristics, namely that it is: cyclic and systematic, reflective and active, participatory and emancipatory. Both projects were systematic, but the second was more cyclic than the first. The research questions for both projects were generated by us as teachers, arising from problems that we had experienced with teaching. The second project involved more complex data-gathering over a longer period of time without isolating variables. The research led to a positive development for teachers, researchers, laboratory instructors and students.

Study of university chemistry education should likewise aim to gain new knowledge and enhance development of chemistry education at all levels. The projects outlined in this paper have made it possible for me to deepen my professional knowledge and competence in my own work and to promote action research as an important contribution to enhance the quality of teaching (or quality assurance) at the university. One argument in favor of action research is that it provides a sharper focus for professional development generally, and for university chemistry education in particular, for instance, by increasing student interest and recruitment in chemistry.
The biochemistry context

This biochemistry section starts by summarizing general biochemical knowledge about proteins to help readers that are not familiar with the topic understand the content of the studies performed. This is followed by two sections describing in more detail the biochemistry content of the different courses: the laboratory work investigated in article I and the experimental work investigated in articles II and III.

Proteins – function

Proteins are biological macromolecules constructed from one or more unbranched chains of amino acids. Proteins in all living organisms are synthesized from twenty different amino acids, each of which has a different side chain ("R-group") that determines its specific properties (Figure 1). The shape (structure) and other properties of each protein are dictated by the precise sequence of amino acids it contains.

![Figure 1: Structure of the amino acid Alanine in its predominant form at pH 7.](image)

A typical protein contains 200-300 amino acids. However, some proteins are much smaller, for example insulin, and some are much larger. The largest known to date is titin a protein found in skeletal and cardiac muscle, which contains 26,926 amino acids in a single chain.
Every function in the living cell depends on proteins. For example: the transport of materials in body fluids and the structure of cells heavily depends on proteins; the receptors for hormones and other signaling molecules are proteins; the motion and locomotion of cells and organisms depends on contractile proteins; biochemical reactions are catalyzed by enzymes, which are proteins; transcription factors that turn genes on and off to guide the differentiation of the cell and its later responsiveness to signals reaching it are proteins; and there are many more functions of proteins. In addition, proteins are essential nutrients for heterotrophs.

The sequence of amino acids in a protein is determined by the sequence of nucleotides in the gene (DNA) encoding it. In other words, a particular sequence of nucleotides specifies a particular sequence of amino acids via transfer RNA (t-RNA) molecules, each specific for one amino acid and for a particular triplet (codon) of nucleotides in messenger RNA (mRNA). In this way the codons in a mRNA molecule are translated into the sequence of amino acids in the protein. In eukaryotes, the processes whereby DNA is transcribed into mRNA occur in the nucleus, whereas the translation of mRNA into polypeptides occurs in the cytoplasm. In prokaryotes (which have no nucleus), both these steps of gene expression occur simultaneously.

However, one gene sometimes gives rise to more than one protein. The mRNA can be cut or rearranged in a controlled way, rendering several different mRNAs which, in turn, results in different proteins. Further, when the mRNA has been decoded into a polypeptide chain (a polymer of amino acids) the protein is seldom ready for use until some trimming or modification has occurred. Therefore, the number of different types of proteins exceeds the number of genes in an organism. For example, about 30 000 genes have been identified in the human genome, whereas the number of different proteins in human cells has been predicted to be in the range of 100 000-200 000.

Advances in genome research have brought about a revolution in life science in many ways. The whole genomes of several eukaryotes, over 1000 viruses and over 100 microbes (these numbers are continuously rising), have been sequenced and all three domains of life – bacteria, archaea, and eucaryota - are represented, as well as many viruses and organelles. At the time of writing, the 30th of July 2004, 174 completed microbial, 19 Archaeal, 1344 viral and 20 eukaryotic genomes have been compiled in the NCBI (National Centre for Biotechnology Information) database.
For the protein chemist, as for other life science specialists, this accelerating development, in combination with the fact that the number of proteins exceeds the number of genes (see above), opens up an enormous field for protein research (proteomics).

**Protein - structure and stability**

The function of a protein (except when it is serving as food) is absolutely dependent on its three-dimensional structure (shape), and the shape of a protein is determined by its sequence of amino acids (the primary structure). Its ability to fold in the proper three-dimensional structure is largely intrinsic. However, certain factors complicate the folding of proteins. For example; enzymes that add sugars to certain amino acids may be essential for proper folding, and specific proteins, called molecular chaperones, may enable a newly-synthesized protein to acquire its final shape faster and more reliably than it otherwise would.

When proteins lose their shape, becoming “denatured”, they lose their function. A denatured enzyme ceases to function, and a denatured antibody can no longer bind its antigen.

A number of conditions and agents can, however, disrupt this structure (denaturing the protein). For example, conditions altering the electrostatic interactions between charged amino acids (e.g. changes in salt concentration and changes in pH), changes in temperature (which may reduce the strength of hydrogen bonds), the presence of reducing agents (which may break S-S bonds between cysteins) and hydrophobic agents (which affect the structure of water-soluble globular proteins*). None of these agents breaks peptide bonds between the amino acids, so the primary structure of a protein remains intact when it is denatured.

* The side chains (R groups) of amino acids such as phenylalanine and leucine are nonpolar and hence interact poorly with polar molecules like water. For this reason, most of the nonpolar residues in globular proteins are oriented toward the interior of the molecule whereas polar groups such as aspartic acid and lysine are generally located on the surface, exposed to the solvent. When nonpolar residues are exposed at the surface of two different molecules, it is energetically more favourable for their two "oily" nonpolar surfaces to approach each other closely, displacing the polar water molecules between them.
Protein – Enzymes

The catalysis of biochemical reactions is done by enzymes, and virtually all enzymes are proteins (a few ribonucleoprotein enzymes have been discovered and, for some of these, the catalytic activity is in the RNA part rather than the protein part).

Enzymes bind temporarily to one or more of the reactants of the reaction they catalyze, and in doing so they lower the amount of activation energy needed and thus speed up the reaction (figure 2).

In order to do its work, an enzyme must interact with at least one of the reactants. In most cases, the forces that hold the enzyme and its substrate are noncovalent, such as hydrogen bonds, ionic interactions and hydrophobic interactions. Most of these interactions are weak, so successful binding of an enzyme and its substrate requires the two molecules to approach each other closely over a fairly broad surface. This requirement for complementarity in the configuration of the substrate and enzyme explains the remarkable specificity of most enzymes. Thus, a common analogy for this complementarity is that a substrate molecule binds its enzyme like a key in a lock.

Figure 2. Effect of an enzyme on activation energy.
However this model does not take in account an important property of proteins, their conformational flexibility. In addition to this static picture there is a model, the induced-fit model that takes into account the fact that the proteins have some three-dimensional flexibility. The binding of the substrate induces a conformational change in the enzyme that results in a complementary fit once the substrate is bound (figure 3). The binding site has a different three-dimensional shape before the substrate is bound. Generally, a given enzyme is able to catalyze only a single chemical reaction or, at most, a few reactions involving substrates sharing the same general structure.

The activity of enzymes is strongly affected by changes in pH and temperature. Each enzyme works best at a certain pH and temperature, its activity decreasing at values above and below that point. This is not surprising considering the importance of the shape in enzyme function and of noncovalent forces, e.g., ionic interactions and hydrogen bonds, in determining that shape.

**Comparison of an inorganic and a biological catalyst**

The experiment studied in article I was ‘Comparison of the catalytic effect of MnO\textsubscript{2} and Catalase’. This used to be one of four experiments in the ‘Chemistry of life’ section of the introductory chemistry course at Umeå University. The experiment was very similar to one described by Kimbrough et
al. (1997) except that the students examined the catalytic activity of MnO₂ as well as catalase. The task was to investigate how hydrogen peroxide-conversion activity is affected by different physical and chemical conditions and to compare the efficiency and sensitivity of the enzyme catalase and the inorganic catalyst, MnO₂. After completing their laboratory work the students were expected to have gained insight into the relation between the structure and function of enzymes. They should have been able to explain and describe in detail the primary, secondary, tertiary and quaternary structure of proteins; understand the general properties of proteins; understand what an enzyme is and how enzymes work; understand the principal difference between the biological catalyst and the non-biological catalyst MnO₂, and describe the characteristics of an active site, substrate binding and factors that effect enzyme activity.

The laboratory work was performed in two different ways; in an open-inquiry version and an expository version.

In the expository version of the experiment the students performed the experiment in accordance with detailed instructions. The amount of potato (the source of catalase) and MnO₂ to be used were given, and the technique for preparing the cell extract was described in detail. The substrate to use and exactly how to measure the reaction velocity, to determine the temperature and pH optima, and to evaluate the results, were also described in detail.

In the open-inquiry version the task was to formulate a question that could be tested experimentally, to plan and carry out an experiment designed to answer the question, and to evaluate the experiment. In doing this, the students had to seek information by themselves. In other words, the students were expected to use their knowledge to formulate a hypothesis, propose how to test it, plan and perform the experiment, and finally to evaluate and discuss their results.

In the open version of the experiment the students investigated the effects of a wide range of factors, typically the effects of pH, temperature, inhibitors, substrate concentration, and catalyst concentration etc. on the rate of the reaction. Several experimental procedures were used, most of which included some kind of oxygen volume measurement, but some students used a spectrophotometric determination and others used a ‘time to float’ measure for filter papers impregnated with catalyst.

Problems and questions often emerged after a while when the students carried out the open-inquiry version of the experiment. Examples of questions
raised included the following. If I use different pH buffers how do I know that it is not the buffer substances (citrate, phosphate etc.) that affect the activity and not just the different pH? What should I warm up and when: the substrate H₂O₂ in advance, the catalyst in advance and/or the mixture. Some realized that the potato extract most of them used as a source for catalase buffered their solutions. Some students came up with problems such as, ‘What is the distribution of enzyme in different parts of a plant’? ‘Are there differences between species’? ‘How do I know exactly how much catalase I have in this tube, compared to the concentration of MnO₂? They realized that it was very difficult to change just one parameter at a time.

As a result of our studies described in Paper I the comparison with MnO₂ was excluded. The reason for this decision was that it was difficult to compare MnO₂ to catalase in many respects and it led to superficial and incorrect discussion. It was very difficult for the students to determine the exact molar amount of catalase in a piece of potato (even if the mass of the piece was carefully determined). Therefore a true comparison of the efficiency of the two different catalysts was impossible. In addition, the reaction mechanism involving MnO₂ is complex (too advanced to cover satisfactorily in this course) and products other than oxygen are formed. Furthermore, MnO₂ is not a true catalyst since some is consumed during the reaction. The experimental work undertaken now is “Study of a biological catalyst: the enzyme Catalase”.

**Development of protein purification strategies and characterisation of a protein**

The task of the laboratory project work in the course investigated in articles II and III is to develop a purification procedure for a protein, to characterize its physiochemical properties and, if possible, its function as carefully as possible. The course is an advanced level biochemistry course, taken by the students in the middle or later parts of their respective programs. It can be characterized as a Master’s level course. The planning of the experiments and strategies, and the choices of methods and analysis are decided by pairs of students working together. One to three laboratory instructors (graduate students) support the 10-20 students on the course. Most of the project work is performed in close association with the research laboratories, and research instruments are used for many of the analyses. The results of the project work are presented in a poster. The students also present the project in a
written grant proposal, in which they summarize the literature on their protein, their own results and conclusions, then propose and justify a “future investigation” (hypothesis and experiments).

The experimental work starts after an introductory, theoretical section of the course, lasting about three weeks, in which different methods for protein purification, characterization and investigation strategies are covered and discussed. At the start of the laboratory project work the only information the students are given is an N-terminal sequence (5-10 amino acids) of an “unknown” protein and a raw material (a source, starting material) containing the protein (a cell extract or tissue). The students work in pairs on their experimental project, and each pair of students is given a different protein. The proteins vary from course to course since they are chosen from the proteins that the research groups at the department are currently studying.

The first task for the students is to identify their protein. A common strategy here is to start with a computerized database search. The next step is usually to make a literature search and/or to make predictions of some properties of the protein using computer programs available on the web, and to do some initial tests e.g. a stability test. The students also have to develop a detection method for their protein at an early stage in order to identify it. Since the raw material (tissues or cells) in most cases contains hundreds or thousands of other proteins and other biomolecules it is necessary to find a method to identify, and quantify, their target protein. The students therefore, at an early stage, have to develop a detection method for their protein. Since the first laboratory-based task is to work out a purification method for the protein, and all protein separation methods exploit specific properties of the protein of interest (e.g. mass, charge, solubility, stability, affinity or hydrophobicity) it is also helpful to have knowledge of some property of the protein to be purified. The next stages are therefore usually to collect enough information and do some initial experiments. Based on the knowledge that can be collected in this way purification steps can be proposed, tested and optimized.

Amongst the methods used are electrophoresis, spectrophotometry, and chromatography. The methods used depend on properties and available amounts of the target protein and impurities. Often several (usually 2-6) purification steps are needed for sufficient purification. Examples of separation (purification) methods used are solubilization, selective precipitation, ion exchange chromatography, hydrophobic interaction chromatography, immobilized metal affinity chromatography, affinity chromatography, size exclusion chromatography, ultrafiltration, and dialysis. The recovery and the
increase in purity of the target protein during the purification procedure is continuously followed by a range of analytical methods including spectroscopic measurements, enzyme activity measurements, immunological methods and SDS-polyacrylamide electrophoresis (SDS-PAGE). The purification sequence is developed on a small scale. Usually this sequence has to be scaled up in order to get enough material (purified target protein) for the subsequent characterization of the target protein.

The next task is to characterize the physiochemical, structural, and functional (chemical and biological) nature of the protein. The information that can be gathered during this part of the project work and within the time limit of the course depends on several factors. Some factors influencing the results are the purity of the protein (the degree of success in the purification part of the project), its stability, and the amount of purified protein, time and equipment available. Usually the students are able to determine the native molecular mass, subunit molecular mass and oligomeric organization of the protein, its pI and spectroscopic properties (e.g. specific molar absorbance at 280 nm, and absorbance and fluorescence spectra). The identity of the protein can be verified through mass spectrometry (MS), N-terminal sequencing, amino acid analysis, and activity measurements or affinity determinations. The content of secondary structural elements can be estimated through CD-measurements. There are also various other types of analyses that are more relevant to specific groups of proteins, for example analysis of their kinetics, stability, folding properties, ligand binding and so on.

Content-related problems are often also related to the complexity of the task and to the fact that the students have to seek information from many different sources and combine them. Also, the professional limitations of different experts and collaboration with other disciplines can be problematic and put high demands on the students. An example: A specialist (not a biochemist) was helping the student to do mass spectroscopy. After running the students sample he was suggesting that the two peaks (representing two different masses) in the spectrum and two bands seen on the student’s SDS-gel might be due to heterogenous glycosylation of the protein. The students accepted this explanation since it was a suggestion from an expert. Later he realized that this was a mistake. However, to be able to evaluate the expert suggestion the student had to be critical and compare the proposal of the expert to his own knowledge of the protein and the source of the protein. In this case the protein was expressed in E. coli and therefore could not have been glycosylated. There must, in this case, be another explanation. Only if the
student remembers these facts there can be a meaningful discussion with the mass spectroscopy specialist on alternative conclusions.

Another possible problem is that the student has to realize that theoretical approximations are not empirical results. For example, students are sometimes surprised that their protein does not bind to an ion-exchange column after they have calculated its pI from the predicted amino acid sequence, and concluded that it “should” bind at the selected pH. Some students do not realize (or remember) that when the pI is calculated from its amino acid content it is a theoretical prediction. However, in the native protein some charged amino acids are exposed on the surface while others are hidden inside the protein or involved in salt-bridges. Furthermore, some amino acids could be cleaved off or the protein may have been post-translationally modified. All of these possibilities will affect the pI of the protein, and this can only be determined experimentally. The student has to realize that theoretical approximations are not empirical results.
Research framework and methodological approach

Research on teaching and learning in the science laboratory

There is a widespread assumption that laboratory work is an essential feature of a university chemistry course. But Benett and O’Neale (1998) raise the question “What is laboratory work for? In other words what are the objectives and what are the outcomes?” My concern is how we handle these questions in our education. Does laboratory work have a weak spot concerning its aims, outcome and assessment? Science education studies have relatively seldom analyzed the assessment of laboratory work, but have rather concerned its aims and objectives. Moreover, most of the studies published so far have been conducted at primary and secondary school level for example (Hofstein et al. 1976; Lubben and Ramsden 1998; Lawrence et al. 2001) and less at university level for example (Benett and O’Neale 1998; Johnstone and Al-Shuaili 2001). I have not found any earlier study in which the students were involved in the process of formulating aims and assessment criteria of experimental work at Master’s level.

Hegarty-Hazel (1990) defined laboratory work as “a form of practical work taking place in a purposely assigned environment where students engage in planned learning experiences……interact with materials to observe and understand phenomena” (page 4). This seems to indicate a focus on observing, verifying theories, a given procedure and a predetermined outcome. In our laboratory work however, the aim is wider; we put the emphasis on thinking skills, information seeking, problem solving, and multi-disciplinarity. We focus on the process and the planning, on communicative skills and teamwork. The experiments and projects are open-ended, and the process and/or outcome are not determined in advance. To avoid misunderstandings and misinterpretations I have therefore chosen to use “experimental work” when talking about the laboratory activities in our investigations.

There is a multitude of research papers and reviews on learning, teaching and assessment in the school laboratory situation in science education. One reason for this interest is the general opinion that laboratory work has a distinctive role and unique potential. However, there has been difficulty in obtaining convincing data on the effectiveness of learning in the laboratory,
because of the complexity of factors related to laboratory work *per se* and to the use of assessment procedures that have often been inadequate (Lazarowitz and Tamir 1993). According to Lazarowitz’s and Tamir’s research review, science laboratories should above all provide the following: concrete experiences and ways to help students confront their misconceptions, opportunities for data manipulation through the use of microcomputers, opportunities for developing skills in logical thinking and organization, and opportunities for building values, especially as they relate to the nature of science.

There have also been numerous attempts to describe, map and clarify aims of laboratory work (Kerr 1963; Lynch and Ndyetabura 1983; Kempa and Ward 1988; Laws 1996; Benett and O'Neale 1998). These studies have mainly concerned the situation in secondary schools, but to a large extent they also apply to higher education. The major aims of laboratory work may thus be summarized as the development of: manipulative skills, observational skills, and the ability to plan experiments and interpret experimental data (Buckley and Kempa 1971). In addition others list affective aims: interest in the subject, enjoyment of the subject, and a feeling of reality of phenomena talked about in theory (Johnstone and Al-Shuaili 2001). Experimental work at university level may however have more complex and demanding aims that need to be defined and explored.

Since the 1960s there has been an ongoing quest for more ‘open’ experiments, with numerous contradictions and not always encouraging results (Hodson 1996). In a recent extensive report on laboratory work in Europe Tiberghien et al. (1998) conclude that the objectives of most laboratory activities in chemistry at the university level concern how to carry out standard procedures rather than planning an investigation to address a specific question or problem.

What happens in laboratory work is a complex matter. Beside the attitudes of the students and the instructors, the learning environment, the pre-knowledge and the style of instruction are key interactive aspects that complicate the performance and interpretation of education-related research. Further, beyond the discussion regarding, for example, the effectiveness of different laboratory instruction styles, the terminology adopted, e.g. ‘open experiments’, is inconsistent and sometimes even confusing.

The type of experimental biochemistry work at university level that I focus on has both similarities to and differences from open-inquiry laboratory
work in schools. Thus, they are similar to open-inquiries, i.e. laboratory work without detailed written instructions. However, the experimental work discussed in articles II and III differs from laboratory work at lower educational levels because of its length and complexity. The first study (article I) analyzes the outcomes of different kinds of experimental instruction, the second (article II) presents results from the strategic use of different assessment methods and analysis of the different outcomes, and the third (article III) is more specifically concerned with the assessment of experimental work. Benefiting from an open-ended experiment, article I, compares the openness of laboratory work and the effect it has on students with different attitudes. The results from this first study, which was carried out as a one-day experiment during an introductory undergraduate chemistry course, prompted us to examine a whole course design. Articles II and III focused on a 10-week advanced biochemistry course that has a large experimental part. The latter can be better described as a laboratory-based project work at Master’s level. The results presented in article II showed that the students strongly believed that experimental work was important for their learning. Therefore, our aim in the studies described in article III was to find a way to design a high quality assessment regime for experimental work. The purpose of article IV was to determine the extent to which the investigations carried out constitute action research and to find out if and how action research can promote professional development.

**Laboratory instruction styles**

Domin (1999), in his analysis of different styles of laboratory instruction suggests a taxonomy which distinguishes between four different laboratory instruction styles: expository, inquiry (or open-inquiry), discovery and problem-based. Each instruction style is characterized by three descriptors: outcome (predetermined or undetermined), approach (deductive or inductive) and procedure (given or student generated), see table 1.
Table 1. Descriptors of laboratory instruction styles.

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<th></th>
<th>Outcome</th>
<th>Approach</th>
<th>Procedure</th>
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<tbody>
<tr>
<td>Expository</td>
<td>Predetermined</td>
<td>Deductive</td>
<td>Given</td>
</tr>
<tr>
<td>Inquiry</td>
<td>Undetermined</td>
<td>Inductive</td>
<td>Student generated</td>
</tr>
<tr>
<td>Discovery</td>
<td>Predetermined</td>
<td>Inductive</td>
<td>Given</td>
</tr>
<tr>
<td>Problem-based</td>
<td>Predetermined</td>
<td>Deductive</td>
<td>Student generated</td>
</tr>
</tbody>
</table>

Domin 1999, p.543

Expository instruction is the most common instruction style. Here the teacher defines the topic, the outcome, and directs the students’ action. Expository approaches have been criticized for placing little emphasis on thinking skills and planning. Also, they are judged to be ineffective for concept building.

In open-inquiry laboratory instruction the students formulate the problem within broad given areas, and the outcome is undetermined. The learners generate their own procedures, and the inquiry-based activities are inductive. It effectively gives student ownership of the laboratory activity, but this requires the students to relate the investigation to previous work, to state the purpose of the investigation, predict the results, identify the procedure and perform the investigation. This type of laboratory work is designed to help the student to develop their thinking process and to engage in an authentic investigation-process. This requires higher-order thinking processes (Raths et al. 1986) as components of the inquiry. The open-ended inquiry approach, however, can be criticized for placing too much emphasis on the path of scientific process (at the cost of content), and for being time consuming.

In the discovery laboratory the teacher guides the learner towards discovering a desired outcome. The discovery approach is inductive. This type of approach has been criticized partly for having the same weaknesses as the expository laboratory and for being even more time-consuming.

In problem-based instruction, the teacher provides a problem and the necessary reference material, and guides the student towards a successful solution. The problems have a clear goal, but there are several viable paths toward a solution. This type of approach is time-consuming and poses high demands on both teachers and learners. On the other hand it fosters the development of higher-order cognitive skills, in particular through the implementation and evaluation of student-generated procedures. The problem-based laboratory is deductive in approach. Therefore, the learners must have
had some exposure to relevant concepts, principles and experimental techniques before performing the experiment.

In the laboratory work described and analysed in article I the instruction was presented in two versions. In the first the entire experiment was described in detail, the outcome was predetermined, the approach deductive and the procedure given. According to Domin’s taxonomy this version of the instruction was expository. In the second version the task was to formulate a question that could be tested experimentally. The students had to plan and carry out an experiment designed to answer the question, and evaluate the experiment. This is a typical example of an open-inquiry experiment.

The practical laboratory project work described in papers II and III is more problematic to classify in accordance with Domin’s taxonomy. The teacher gave the problem, there was a clear goal (to purify and characterize a protein), but there were several viable paths toward a solution. Further, the learners had been exposed to the principles and relevant experimental techniques before performing the project. In this sense the project work had the characteristics of a problem-based activity. On the other hand, the students generated their own procedures, related the investigation to previous work, stated the purpose of each investigation within the project, predicted the results, identified the procedure and planned and performed the investigation. They also interpreted the results, compared them to literature data and theory, evaluated them, and proposed the next step in the iterative process. The outcome was undetermined; neither the student nor the teacher knew the outcome of the investigation i.e. they did not know how to purify the protein and/or the properties of the protein in advance. Therefore, the practical laboratory project work described in papers II and III can be classified as partly open-inquiry.

Aims, instruction and assessment

Aims and objectives of education range from relatively general to very specific. Krathwohl and Payne (1971) distinguished between global, educational and instructional objectives. Global objectives provide a vision for the future. Educational objectives occupy the middle range on the continuum, as they are more specific than global objectives, but more general than the objectives guiding the day-to-day instruction. I have used Sutton’s (1985)
definition of aims as general statements of what the teacher intends to achieve, while objectives are specific statements of what the students should be able to accomplish as a result of being taught in the laboratory. The aims of higher education in Sweden are stipulated in the Swedish Higher Education Act (Chapter 1, §9). Aims are also articulated in the study programme, for example chemistry, and objectives are expressed in the course syllabus and also, maybe, in material prepared for specific moments or experiments. Aims in the Higher Education Act are centrally decided, while the others are locally decided by the faculty and teachers involved.

Assessment may be defined as the collection of information, both qualitative and quantitative, obtained through various tests, observations and other techniques that are used to determine the performance of individuals, groups or programs (Doran et. al 1993). Measurement is a related term, but not as wide-ranging as assessment. Measurement has generally been defined as the process of teachers’ testing. Evaluation is the process of making carefully determined value judgments and decisions related to the issues and concerns a given assessment has focused on. In European and Australian literature and research, the term assessment is used to assign what we do to students in the learning situation. This is also how we have used the concept in the appended articles. Evaluation concerns the quality and effectiveness of our practice. In U.S. assessment and evaluation are used without this clear distinction.

In practice, formative and summative assessments are often intertwined. Summative assessment, if handled appropriately, provides meaningful and useful feedback and thereby aids development. In addition, both summative and formative assessment involve judgments, and judgments are based on values which may, or may not, be explicit to the assessors themselves or to the assessed (Brown et. al 1997). Education has a specific problem in that everyone is familiar with the process of schooling, and therefore has a view about the appropriateness of ways of assessment. There is a need to avoid listening to anecdotal stories and to find out more about these processes through research.

Alignment refers to the degree of correspondence among the objectives, instruction, and assessment (Anderson and Krathwohl 2001). They argue that the degree of alignment is determined by comparing objectives with assessment, objectives with instruction, and instruction with assessment. Assessments need to be well matched to subject aims and objectives and expected outcomes of learning.
**Taxonomies of educational objectives**

*Different taxonomies and frameworks*

A range of different evaluation tools and frames of reference have been proposed in order to compare learning outcomes and to communicate results of educational evaluations.

One of the earliest and most widely used systems is the Bloom taxonomy. In this scheme, three major learning domains are defined: the cognitive, the affective, and the psychomotor. Only the cognitive domain was developed initially by Bloom et al. (1956). The affective domain was developed later by Krathwohl et al. (1964) and they express frustration and, to some extent, failure in their attempts to classify the affective objectives, which they recognize as an important task. Simpson (1966) and Harrow (1972) provided frameworks for the psychomotor domain. The psychomotor domain includes muscular and motor skills, coordination, and manipulation of material and objects.

Another conceptual framework for educational objectives, by Hauenstein (1998), sought to bring consistency to taxonomy building in all three domains: the cognitive, the affective and the psychomotor. He also added a new domain – the behavioural domain. The work of Haladyna (1997) is more focused on the assessment of higher order thinking, the upper level of most frameworks, and the typology for higher-level test items. Zoller (1993) proposed another mode of classifying learning outcomes. He defined lower order cognitive skills (LOCS) as learning outcomes involving knowing and understanding, while the higher order cognitive skills (HOCS) were more complex, including problem-solving, decision-making (decision-selection, personal communication), system critical thinking, and participation in relevant interactions between science, technology, the environment and society. Biggs and Collis (1982) developed a taxonomy, SOLO (structure of the observed learning outcome) to classify students’ answers. This is a hierarchy with five levels (prestructural, unistructural, multistructural, relational and extended abstract) that are used to classify the structural complexity of students’ responses.

Understanding students more effectively is essential in order to create learning environments that encourage and challenge students to develop more
complex thinking. A wide range of individual difference dimensions of thinking processes have been studied with respect to diversity in learners, including intellectual capacity, motivation, emotional issues, values, social skills, critical thinking skills, learning style or typology, and developmental processes (especially, cognitive-developmental stage models). All these differences have some usefulness when exploring learning issues, the difference in cognitive performance being among the most critical. Several models depict these intellectual differences, one widely used framework with direct relevance to characteristics of students-as-learners is the Perry scheme (Perry 1970) of intellectual and ethical development. This framework describes students’ approaches to knowledge and learning.

**Bloom's taxonomy**

Most traditional educational objectives fall into the cognitive domain. Such objectives range from simple recall of facts to highly original and creative ways of combining and synthesizing new ideas and material. The “Bloom taxonomy” (Bloom et al. 1956) includes an ordering of the cognitive domain within different levels. Its authors asserted that the classification is hierarchical, starting with knowledge as the “lowest” cognitive level. The second group of objectives, intellectual abilities and skills, are: comprehension, application, analysis, synthesis and evaluation. Knowledge is defined as involving the recall of specifics and universals, the recall of methods and procedures, or the recall of a pattern, structure or setting. The knowledge objectives emphasize most strongly the psychological processes of remembering. The second group of objectives refer to organized modes of operation and generalized techniques for dealing with materials and problems. The abilities and skills objectives emphasize the mental process of organizing and reorganizing material to achieve a particular purpose. The comprehension level represents the lowest level of understanding, at which the person knows what is being communicated and can make use of the material or idea being communicated without essentially relating it to other material or considering its fullest implications. The application level is described as the use of abstractions in particular and concrete situations. The abstractions may be in the form of general ideas, rules of procedures, technical principles and theories, which must be remembered and applied. The analysis level encompasses the breakdown of communications into their constituent elements or parts, and making explicit the relations between expressed ideas. The synthesis level is about putting parts and
elements together to form a whole. This involves the process of arranging and combining pieces, parts, elements, in such a way as to make a pattern or structure that was not clearly there before. Evaluation is about judgements of the value of material and methods for given purposes, including both qualitative and quantitative judgements about the extent to which material and methods satisfy certain criteria. The criteria may be determined by the students or given to them.

In 2001, a revision of Bloom’s taxonomy of educational objectives was presented by Anderson and Krathwohl (2001). The original handbook focused on assessment while the revised version was also strongly concerned with planning curricula, instruction and assessment, and the alignment of these three activities. Compared to the original taxonomy three main changes can be discerned. First, the categories comprehension and syntheses were renamed as understanding and creation, respectively. Second, the taxonomic order of synthesis/create and evaluation/evaluate was interchanged, and third, the original taxonomy had one dimension while the revised framework is two-dimensional, recognizing both the cognitive process dimension and the knowledge dimension. The cognitive process dimension spans six categories of increasing cognitive complexity: remembering, understanding, applying, analyzing, evaluation, and creation. The knowledge dimension starts with more concrete and ends with more abstract knowledge: factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge.

The affective domain includes objects described as receiving, responding, valuing, organization, and characterization by a value complex. Bloom’s “affective domain” is very similar to the processes covered by the concept of internalization. Bloom et al.’s classification of the affective domain can be seen as a continuum progressing from a level at which the individual is merely aware of a phenomenon, being able to perceive it. At the next level individuals are willing to attend to the phenomenon, and at a further level still they respond positively to it. Eventually they may feel strongly enough to go out of their way to respond. At some point in the process they conceptualize their behaviour and feelings and organize these conceptualizations into a structure. This structure grows in complexity, as it becomes integrated into their life outlook.
Perry’s scheme

The Perry scheme (Perry 1970) describes students’ attitudes to learning and has been used to analyse and understand students’ intellectual and ethical development. It is a framework for both listening to and understanding student perspectives on knowledge and learning. The model describes a pattern of increasing cognitive complexity that has proven to be useful for analysing teaching/learning in attempts to measure the general education outcomes of university courses. Perry particularly documented the qualitative change in the attitudes of students during their years at university, shifting from dualism to contextual relativism. He described a series of nine stages, representing specific ways of understanding the world.

In this thesis, modified versions of Bloom’s taxonomy and Perry’s scheme will be used when describing and analysing educational objectives and outcomes.

Choice of sources and methods

I have found a combination of quantitative and qualitative methods to be most appropriate for addressing my research questions. Each individual research problem has influenced my relative emphasis on different ways to tackle it. To answer the research questions in the articles different methods for data collection and data analysis were used, see table 2. None of the methods alone fully addresses my research questions. The advantages of the quantitative approaches are that they allow the reactions of more students to be measured, facilitating comparison and statistical aggregation of the data. This gives a broader, more generalizable set of findings. By contrast, qualitative methods, like the interviews, produce detailed information about a smaller number of students and cases. This increases the depth of understanding of the cases and situations studied, but reduces generalizability.
Table 2. Summary of data collection methods and data analysis methods.

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<tr>
<th>Data collection Method</th>
<th>Article I</th>
<th>Article II</th>
<th>Article III</th>
<th>Data analysis method</th>
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<td>Questionnaires</td>
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<td>Mean value/paired T-test</td>
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<td>Categorization based on Bloom’s taxonomy.</td>
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<td>Analytical induction/thematic content analysis.</td>
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<td>Mathematical methods.</td>
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<td>Interviews</td>
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<td>Analytical induction/thematic content analysis.</td>
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<td>Mathematical methods.</td>
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<td>Check sheets for asked questions</td>
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<td>Written material</td>
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<td>Categorization based on Bloom’s taxonomy.</td>
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<td>Analytical induction/thematic content analysis.</td>
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<td>Grades and judgments made by teachers</td>
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<td>Spearman rank correlation coefficients. Principal component analysis.</td>
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Collected data were analyzed in different ways. Mathematical values and methods employed included: mean values, paired T-tests, Spearman rank correlation coefficients and Principal Component Analysis. Interview data as well as some questionnaire data were analyzed using the technique of analytical induction based on Abell and Smith (1994). Some categories were based on Perry’s framework.
thematic content analysis, other categorizations were based on Bloom’s taxonomy and the students’ attitude positions were categorized according to Perry’s framework.

Concerning the attitude questionnaire one source of error may be that the students’ attitudes were measured by calculating mean values from their answers to one questionnaire with 19 statements on one or two occasions. Both the statements in this questionnaire and the analysis have been refined for later investigations.

One of the goals of the first project (article I) was to find out what students were actually learning during the experiment. Triangulation of three different methods was used for this purpose: questions asked during the experiment, interviews and students’ self-evaluation after the experiment. Asking the instructors to classify the students’ questions gave valuable information about students’ thinking while they performed laboratory work, reflecting the learning process. In the self-evaluation we obtained quantitative information telling the same story as the interviews and the questions asked during the laboratory work. When comparing the students’ self-evaluation on the Bloomian scales after performing the experiment chi-square tests were used. Significant differences, with \( p \)-values < 0.05 were found. These are not presented in the article but were presented to the referees before the article was accepted. One problem with educational research, working with humans, is that it is impossible to carry out different investigations with the same students, because as soon as they do something key educational variables change. Our way to compare the different versions of the experiment was to let different groups of students carry out the different experiments, but comparing the results may be of doubtful validity since there were different students in each group. However, we tried to make the groups as equal as possible and described some variables.

The main focus for article II was to investigate whether a strategic course and assessment design promotes the students’ capacity for higher order cognitive thinking. The students responded to a questionnaire after three weeks, containing open-ended questions regarding their experience of the written exams. At the end of the course in-depth, semi-structured interviews were carried out with the students to find out their opinion about what they had learned during the course to find out more about the students’ own views. To analyze some of the data presented in article II a simplified variant of Bloom’s taxonomy was used for analysis and categorization. Two or three persons in the
teaching staff classified the questions, objectives and products. To identify possible correlations between the grades for the different assessment methods Spearman rank correlation coefficients were calculated then, to interpret and evaluate the results more fully, principal component analysis (PCA) was applied.

The Hawthorne Effect (Roethlisberger and Dickson 1939) refers to the fact that any intervention tends to have positive effects merely because of the attention of the research team, leading to enhanced performance because of the motivational effect of the attention received. This could have influenced our investigation, but on the other hand the Hawthorne effect is exactly what we were aiming to achieve in the new course design. The real control is what we want to create in the students’ learning environment, and we want them to be co-investigators of their own learning process.

In the investigations reported in article III the interviews were recorded and analyzed using the “Qualitative Media Analyzer”, QMA (Skou 2001), enabling coding marks to be directly associated with passages in the sound file. All interviews were listened through several times and passages judged to contain information about students’ views about assessment and criteria were identified and categorized. In the second part of study the first questionnaire, with the open question about the students’ ideas of the aims of experimental work, was distributed to get their spontaneous answers and to collect their ideas in their own words. The resulting list of aims, which was later used for choosing important/unimportant aims and for students’ self-assessments and teachers’ judgements, was based on students’ and teachers’ own ideas and expectations. We categorized each of the goals and criteria as belonging to the psychomotor, affective, or cognitive domains. However, when categorizing I found a weakness: it was very hard to categorize some of the aims since different persons interpret different words differently. The categorization is based on my interpretation. That was one of the main findings – that it is important to discuss and clarify the meaning of formulated words and sentences. Listening to the teachers’ motivation and judgements for different grades gave information about what they explicitly argued that they graded. It could be argued that the only thing I really know is what they said they graded, which may not be what they really graded. Much research has been related to the distinction between what teachers say they do and what they really do: which are not necessarily the same. Since the teachers in this case are not
educated teachers I know that they did not feel any demands to answer “the right way”. Furthermore, another common problem is that you only know what a person expresses orally or in writing, it is more difficult to know their inner feelings, and what is really going on inside their heads.

To investigate if these formulated aims could be used as criteria for the student’s self-assessment and the laboratory instructors’ assessments, the students were asked to grade their goal accomplishments. The laboratory instructors made corresponding evaluations of the students’ goal accomplishments. Most research on self-assessment has been concerned with comparisons of teacher, self and peer marks. However, validity cannot be estimated solely by comparing students’ and teachers’ marks. Peer assessment and self-assessment can be included as part of a triangulated approach to assessment, whereby student learning is evaluated (Breitmeyer et al. 1993; Denzin and Lincoln 1994). The question then is whether the purpose is to achieve agreement among the various assessors or whether it is to achieve completeness by seeking several perspectives on the performance being assessed (Breitmeyer et al. 1993; Sim and Sharp 1998), i.e. not to achieve agreement among the different participators, but to seek completeness by including multiple perspectives.

Bloom’s taxonomy was developed by a group of college and university examiners. They believed that a common framework for categorizing educational objectives could promote the exchange of test items, test procedures, and ideas about testing. It has provided a basis for test design and curriculum development throughout the world. It has also been used to enable aims at university level to be communicated, and widely used by teachers to construct and analyze written exam questions. Since we wanted to use the same taxonomy for classifying aims/objectives, exam questions and outcomes we found Bloom’s taxonomy useful for classifying skills and capabilities when attempting to match attainments in assessment tasks against those we wanted students to learn during a course.

We decided to use Bloom’s taxonomy and the three domains since we found it was widely used in continuing professional development courses for university teachers. The teachers at the chemistry department were familiar with this taxonomy since we had used it in earlier course evaluation projects. For many of my seminars and presentations I found Bloom’s taxonomy helpful for communicating teaching and learning goals, to both students and teachers. It is seen as quite complex but it is often used in natural sciences. We used a simplified variant of the framework in which the six main categories were
applied, without subcategories. Sometimes in the articles we refer to the first three first categories as “lower Bloom” and the following three as “higher Bloom” categories.

**Validity**

In quantitative research validity and reliability are important terms. Validity depends on careful instrument construction to ensure that the instrument measures what it is supposed to measure. In qualitative studies a more commonly discussed parameter is credibility (Patton 2001).

Action research requires different criteria for reliability and validity compared to more conventional research approaches (Andersson and Herr 1999). Examples of such criteria are outcome validity, process validity, democratic validity, dialogic validity and catalytic validity. We argue that the research carried out is reliable and valid since we fulfil the criteria in the following way: the research found solutions to the problems we were facing as teachers (outcome validity), the activities generated were educative and informative (process validity), and were undertaken in collaboration with the partners involved (democratic validity). Moreover the research was discussed with peers in different settings (dialogic validity) and the degree to which the research transformed the realities of those involved was substantial (catalytic validity).

My role as teacher, director of studies and researcher, varied in the different studies. In the first study (article I) it was felt to be important for us as researchers and authors not to have been involved in the teaching of the participating student groups. Nevertheless, we generated the research questions arising from problems we had experienced with teaching. For the research carried out for article II the second author was the teacher responsible for the course (the biochemist), and gave some of the lectures. Thus, she had insight into the biochemistry taught and her biochemical knowledge in this special field was also essential for doing some of the analyses, judging and grading. As the first author, I was a researcher from the student’s perspective and not really involved in the teaching, but carrying out interviews and handling questionnaires. At the beginning of the course I explained my research interest: to make our education and teaching better for our chemistry students. The
students were asked if they were willing to participate and I promised that their responses/answers would be handled confidentially; the identity of individual respondents would not be mentioned and the presentation of the results would be done in such a way that no individual person could be identified. I recognize that our positions, mine as director of studies at the biochemistry department and the second author as the teacher responsible for the course, and our engagement in the study are sources of potential bias in the collection and analysis of the data. We have used multiple sources and methods, collecting information from various perspectives i.e. triangulation as a way to reduce the risks with being both researchers and teachers. In a way we evaluated both the new course design and ourselves. Furthermore, both the students and the laboratory instructors might have been more willing to talk about their opinions and concerns than they would in more standard positions because they were active participants in parts of the investigations.
Major conclusions and discussion

The overall aim of the work underlying the thesis was to investigate and analyze how to develop laboratory work to promote learning. To summarize, the main findings are that the students achieve complex learning through planning, approaching the problem from different perspectives and evaluating the results of their own experimental work. Introducing formative and authentic assessment is a good way to help the students progress and develop competence. It seems to be important to involve both teachers and students in discussions of aims and criteria and to make them explicit. Feedback from teachers’ and students’ reflective activities about learning as well as affective factors is important to promote learning.

Results from article I show that the students’ learning was improved by the open versions of the experiments, according to both their own and the researchers’ opinions. Particular support was needed for the students with a more dualistic view of teaching, learning and experimental work. A strategic course and assessment design of laboratory based experimental work (article II) was shown to promote the students’ capacity for higher order cognitive thinking. However, the synthesis level constitutes a threshold. Further, the students recognized the experimental work as crucial for their learning and therefore important to assess. Experimental work can and ought to be assessed but valid qualitative assessment requires a combination of methods to be deployed (article III). Areas of both similarities and discrepancies between students’ and teachers’ perspectives on the aims and assessment of experimental work were identified. In article IV, the studies carried out and described in article I and II were analyzed. It is argued that the studies carried out have several characteristics of action research, to varying extents, and that action research can promote professional development. In the remainder of this final part of the thesis I will expound my conclusions.

Development of competence

The aim of the changes made to the courses was to develop competence in biochemistry at university level, amongst both students and teachers. Broadly, the changes can be described as making the experiments more open,
with multiple formative and authentic assessment methods involving both students and teachers. Based on our studies we have identified five areas critical for development of competence in biochemical experimental work at university level.

- complex learning
- communication
- metacognitive perspectives
- attitudes
- affective factors

Of course there are many areas in a complex network, I will present and discuss the five most striking areas identified in my research. To facilitate the discussion (and understanding) of the issues involved I decided to pick some of the results from the articles and discuss them in one area even though many results could be discussed and related to many areas. However I will start with pointing at some perspectives that are seen as important abilities and skills in the literature and some examples of how competence is defined.

Objectives of higher education and the abilities and skills expected of graduate students have been the subject of extensive research and development efforts. For example, Nightingale et al. (1995) on the basis of collaborative research and consultation of university teachers, distinguish a number of crucial abilities which should form the basis of assessment: critical thinking and judgment, problem solving and planning, performing procedures and demonstrating techniques, managing and developing oneself, accessing and managing information, demonstrating knowledge and understanding, designing/creating/performing and communication.

Within the field of life science and chemistry, there is a stress among researchers not only on subject knowledge and skills in designing and conducting courses. Also, social and personal abilities such as cooperation and teamwork, communication skills, increased self-confidence and confidence are emphasized by several scholars (Coldstream 1997; Garratt 1997; Benett and O'Neale 1998). Affective factors, such as interest, feelings, emotions are found to be important in the learning process: “We are entering a new era where we will be asked to acknowledge that affect, imagination, intuition and attitude as outcomes of science instruction are as at least as important as their cognitive
“Competence” is often used in educational documents and research, and it is defined in a number of ways. Earlier, the concept mainly meant qualification in a narrow sense. Today, it rather denotes the ability to manage different demands in a specific situation and activity (SOU 1991; Ellström 1996). Competence cannot be seen merely as knowledge and skills, but imply a deeper and more complex understanding (Andersson 2000). Andersson discusses the competences required in modern working life, arguing that people used to large degrees of structure and direction will have problems. Persons used to working independently and sometimes under great pressure will manage best. He also suggests that universities have to strive to provide academic education, with requirements to train the students in higher order cognitive skills.

Challenging complex learning

Different perspectives may be included in complex learning. Here it will be discussed as a higher order cognitive process, encompassing skills like analysis, synthesis and evaluation. This is complex both since the cognitive, affective and psychomotor domains are involved, and because the content is approached from several different perspectives.

The results from article I indicate that the revised open-inquiry version was the most beneficial for all students. Interviews analyzed according to the Bloomian scale showed that the students had carried out more complex learning with this version. In the old design, described in article II, grading was based on the written exam at the end of the course. This represented a traditional course with summative assessment. Analysis of the questions showed that 25 % of the
questions were of higher Bloom categories. When talking about higher Bloom categories I mean analysis, synthesis and evaluation (see p. 32). In the new course design five formative and authentic assessment methods were introduced (home exam, seminar, laboratory work, a grant proposal and a poster) and the proportions of objectives aimed at promoting higher Bloom categories were raised to 50-70 %. Analysis of the outcome shows that it was harder for the students to attain the higher level of analysis, synthesis and evaluation at an early stage in the course i.e. in the home exam. However, after the course, the students argued that the assessments provided a beneficial push at an early stage in the course.

Difficulties in advancing to the synthesis level are one of our main findings, as noted in articles I, II and III. Difficulties in advancing to the synthesis category were observed for all assessment methods in article II, but they were most clearly displayed by the students in their attempts to write grant proposals. The students were often able to make some of the connections and perform a few synthesis processes, but failed to exploit the majority of the possibilities. This inductive process seems to be a very complex cognitive process requiring experience, imagination and creativity. Many students also testified that they experienced difficulties in writing the grant proposal since they were not used to this kind of writing. Nevertheless, many also reported that once they had started writing it became more fun, they felt more motivated, and it was perceived as an important, useful exercise for the future. Interpretation of our data suggests that synthesizing seems to be harder than evaluation, and that it constitutes a threshold in the student’s cognitive development. This observation is in accordance with a recently published revision of Bloom’s taxonomy (Anderson and Krathwohl 2001) in which the authors changed the name of the category “synthesize” to “create” and interchanged the order of synthesize/create and evaluation/evaluate. Synthesis probably includes a rather complex, creative process.

One of the conclusions from article II is that cognitive factors as well as affective and psychomotor factors appear to be important components for internalization and have to be considered in a course design where higher order cognitive skills are desired. Aims that the students’ formulated regarding the laboratory work (article III) could be categorized in the three domains. The conclusion when comparing formulated aims and assessment criteria is that several of the cognitive and in part complex goals that were specified as the most important by the students, did not constitute assessment criteria for the
laboratory work. The laboratory instructors did not assess how well these aims were fulfilled, and the students did not believe that they were being assessed. I will argue that failing to align some of the most important goals of the course with the assessment is not effective for the learning process, this is seen in results based on the investigations carried out in article I, II and III.

The formative assessment introduced to the course (article II) was designed to widen the opportunities to approach a problem in different ways and offer different ways to encourage higher order thinking. The intention was to introduce a strategic choice of assessment and to assess a range of abilities and skills. By strategic choices of assessment I mean methods of assessment to improve the effectiveness of learning and attain the learning goals. By strategic choice of methods I also mean aligning them to ensure a progression of higher order thinking, introducing methods in a logical sequence to give coherence and to place them in time and content in a manner that was helpful to the students’ further development. The formative assessment was utilized to stimulate complex learning. By using a differentiated assessment sequence students with different skills and talents were also given a greater opportunity, compared to traditional assessment, to show their attained abilities and skills. We chose the grant proposal as an assessment method to train and assess the students’ higher levels of cognitive skills. Fellows (1994) notes that students’ writing provides a means to access their structure of disciplinary thought and ways of thinking and knowing, like opening a window into their thinking processes. Writing demands interaction with prior knowledge because it requires the writer to retrieve, synthesize and organize information in order to communicate with others. Assessing the lower-order cognitive skills in the continuous written exams fulfilled the objectives set for the first part of the course, and these skills were deepened by tackling the work associated with the take-home examination questions, and further challenged during the students’ laboratory-based project work. Laboratory-based project work is a skill-developing activity. The poster-making and grant proposal-writing exercises were designed to promote high cognitive skills. These were performed toward the end of the course, and dealt with the same theoretical framework and experimental material.

All assessments in the Master’s level course (article II) had similar and high loading values (in the first dimension) when evaluated with principle component analysis (PCA). The similarities in loading indicate that they are all important for the distribution of the grades, i.e. all of them are good assessment
methods for measuring learning outcome. In the second dimension interesting differences are seen. The assessment outcomes of the seminar and poster were positively correlated, while they are far apart and negatively correlated, from the grant proposal assessment. Thus, it seems that the seminar/poster and the grant proposal are the most differentiating in dimension two. A similar conclusion was drawn from the Spearman rank correlation analysis. The course deals with both the theory underlying various biochemical methods and the practical application of these methods for solving the tasks in the project work. Since these aspects of biochemical knowledge are common themes in the course, as well as in all assessments, we of course expect some correlation between the assessments, as we observed. However, it is exciting to try to find out why the marks for the seminar and poster are grouped together, while they are far apart from the grant proposal assessments. Possible explanations may be that the seminar was oral, the poster presentation was both written and oral but the grant proposal was only presented in written form. Grading criteria included both criteria related to knowledge of biochemistry (the content), and the way it was presented. Since both the biochemistry content and the ability to give, for example, an oral presentation are assessed, the results allow the relationship between biochemistry knowledge and skills assessments to be probed.

**Emphasizing communication**

When analyzing my data I realized how important communication, i.e. the process of exchanging knowledge, ideas and thoughts, was for learning. Some examples presented and discussed below illustrate the value of this interchange between individuals.

Communication skills are a central issue in all forms of education. In the context of university education in biochemistry they include informal and formal research discussions, seminars, talks, poster presentations, writing reports, papers and applications, web-site production and sometimes video or computerized productions. The receiver of the information can be either persons within the home discipline, other disciplines or the public in general. The importance of communication of content is often mirrored in course content. In article I, the results are presented and discussed in a written laboratory report, while in article II, other examples used are the seminar,
poster presentation and grant proposal. But the more informal discussions with peers and colleagues, which might be the most important type of communicative activity in the laboratory, are seldom emphasized in educational settings in science.

One of the two important changes made to improve the revised open-inquiry version of the experiment compared to the open-required version (article I) was that it was pointed out to the students that planning and evaluating the experiment were also important aims, apart from learning chemistry. One extra page that described and communicated this aim to the students was introduced into the laboratory instruction. During the open-inquiry experiment, the questions that the students asked about practical details and the theoretical context included a higher frequency of reflective questions than those asked during the expository version. This gave valuable information about students’ thinking while they performed laboratory work, indicating that they knew what they were doing and had knowledge of the theory connected with the experiment. The other important change was to introduce a scheduled discussion, a checkpoint between the instructors and the students, halfway through the experiments. The students described what they had done so far and had the chance to discuss their results and their plans for further laboratory work. This was introduced since we discovered that many useful points emerged during the interviews while the students described what they had been doing and their results. Without the feedback many of them seemed to get stuck, but with some feedback and helpful questions from an experienced teacher (the interviewer) they made progress. Results from article III show that the two students with lower grades accepted that they had to think for themselves, but were of the opinion that they needed some guidance and opportunities to test their thoughts on someone else.

Difficulties in advancing to the synthesis category were observed for all assessment methods included in the new course design (article II). Evidence of this can be seen in the responses of the written exams as well as in the lack of discussion during the seminars. The same problem was seen in making the poster. However, the discussions with the evaluator and visitors during the poster session often stimulated advancement to synthesis level. This interaction appeared to help the students in their learning process, or to display their learning more effectively.
The new course design (article II) was intended to make the aims more explicit, communicate them to the students and align the assessment strategies with the aims of the course. This was felt to be very important and difficult but instructive for the teachers giving the course. One vision for the new course design was to train the students to communicate their knowledge and skills in different ways. This was felt to be important for their future working life, and thus an authentic assessment. What we really could judge and assess, for example through the grant proposal, was what the students showed in their written presentation. If they were able to communicate their higher order cognitive thinking, it was seen in the written grant proposal or the seminar. The advantages with evaluating/assessing/investigating the experimental work and what the students really do in the laboratory was that it provided a way to assess what was going on inside their heads, what they did (and how they did it) and not just how good they were at expressing things orally or in writing.

The results in article III indicate that there was considerable accordance, but also some differences, between what the students believed was judged and what the laboratory instructors actually assessed during the experimental work. Alignment between aims and assessment was seen, but some misalignments were also found. There was obviously a range of unspoken expectations, implicit criteria and hidden assumptions that were never communicated. One example is the fact that both students and laboratory instructors mentioned the importance of time spent in the laboratory, but they emphasized different aspects. Another example is that students, in contrast to the laboratory instructors, did not consider discussion of questions relating to their task with peers and teachers as important. Further examples are provided by the questions asked by the students during the experimental work. Some interview results indicate that students were afraid of asking stupid questions. Fruitful discussions between students and instructors could go amiss if the students thought that it was tactically advisable to ask fewer questions, since that would give them a better grade. The risk is that assessments in such cases could impair the conditions for good learning. There is a need to clarify the meaning of terms and phrases, through discussion. Therefore a desirable improvement of the course would be that teachers and students determine and discuss goals and criteria cooperatively. There is a risk of learning becoming ineffective if goals and criteria are not firmly established and explicitly expressed by all of the participants. By letting the students contribute, we believe learning is stimulated and hence progressed instead of being restricted. This is in
accordance with e.g. Strachan and Wilcox (1996), who suggest that a development of assessment criteria together with the students is a prerequisite for successful assessment.

Rust et al. (2003) argue that if QAA (Quality Assurance Agency) experts are unable to make standards explicit after months of learned debate, we should, perhaps, begin to question the single-minded focus on explicit articulation of standards. It is difficult to relinquish the notion that academic standards can be documented and codified in such a way that they may be available for the passive consumption of all stakeholders in higher education. However, our research experience has been that, without active involvement through discussion and debate, the development of a common view on standards and levels is problematic. Emphasis on explicit articulation of assessment criteria and standards is not sufficient to develop a shared understanding of ‘useful knowledge’ amongst teachers and students.

**Introducing metacognitive perspectives**

According to Pintrich, (2002) metacognitive knowledge involves knowledge about cognition in general as well as awareness of and knowledge about one’s own cognition. Pintrich claims that regardless of the theoretical perspective, researchers agree that over time students become more aware of their own thinking, as well as more knowledgeable about cognition in general. The meaning of this general term development varies, but it incorporates the development of metacognitive knowledge, metacognitive awareness, self-reflection and self-regulation. Another, similar, definition is provided by Hacker et al. (1998): “definition of metacognition ought to include knowledge of one’s knowledge, processes and cognitive and effective states: and the ability to consciously and deliberately monitor and regulate one’s knowledge, processes and cognitive and affective states”. Among researchers there is a consensus that metacognition is important for learning. Students tend to learn better when aware of a metacognitive perspective (Bransford et al. 1999). In my examples and discussion about metacognition, reflection is considered a metacognitive activity since it is included in the definitions above.

When the students were asked what they learned from the different assessment methods at the end of the 10-weeks Master’s level course (article II)
many of them referred to the feedback after each assessment and its importance for their learning process. These occasions apparently made them reflect on their own learning and increased their control over their learning process. Some students referred to some kind of metacognition when asked if they had changed in any way during the course, indicating that they were more aware of their own learning process. My studies show that the inclusion of instructional activities, which provide both learning and assessment opportunities, has the advantage of increasing students’ metacognition.

A comparison of the student’s self-assessment of their goal fulfillment and the laboratory instructor’s assessment of the student’s goal fulfillment revealed that they coincided in 50% of the cases (article III). The clearest pattern that emerged is that some students underestimate, while others overestimate, their performance. The students that underestimate themselves most are students with high grades, i.e. high-achieving students, and those that overestimate themselves most are students with low grades, that is low-achieving students. These results are in accordance with other investigations concerning higher education, which indicate that high-achievers tend to underestimate and low-achievers tend to overestimate their performance (Falchikov and Boud 1989; Orsmond et al. 1997). One interpretation is that what a particular student weights into a formulated goal can vary. A high-achieving student can underestimate himself/herself due to high internal demands in this respect. The set of problems associated with individual students and laboratory instructors having different internal demands could be solved using more unambiguous and discussed formulations. Another idea is that the general goals/criteria can be easier to interpret if they are formulated specifically for each course, in this case relating to the purification and characterization of proteins. The criteria should also be expressed at some different levels.

The students unanimously agreed that the laboratory work should be assessed (article III) since it is something they invest a considerable amount of time doing, they find it beneficial to receive feedback in order to progress, and it provides an indication that laboratory work is important. Since the students envisage problems on who best can assess what, we suggest that both summative and a formative assessments should be included in future courses. Based on our results a conceivable model includes that the teachers mainly assess the cognitive criteria. This summative assessment for grading is then partly separated from formative assessment for feedback and development. The idea would then be to complement the summative assessment with a formative
assessment at the end of the course. For the formative self- and peer-assessment the same jointly formulated and discussed criteria could be used, as those the teacher used, maybe focused more on the affective domain. This model would serve as an opportunity for the students to develop their metacognition for their future professional life. This triangulation can also serve to uncover the presence of multiple perspectives about the performance being assessed. It should not be taken for granted that different raters should all agree on the quality of a performance (Sim and Sharp 1998).

Could the laboratory experience and the assessment/discussion offer students the opportunity to call upon higher-order thought processes and to further develop and refine both these skills and the ability to practice self-motivated learning? Hopefully the suggested assessment model can encourage careful work in the laboratory, improve laboratory skills and promote good laboratory practices if the students are highly involved in their work. The suggested assessment format, with both summative and formative modes of assessment and a discussion, provides students opportunities to see the relationship between the grade they receive and their knowledge. Marks given by students can be as accurate and reliable as those given by lecturers, as long as marking criteria are clearly explained (Orpen 1982). Peer evaluation also has the interesting implication of signaling a different relationship between lecturers and students. It presumes and contributes to a collaborative role rather than an adversarial one (Andresen et al. 1992).

By involving students in all aspects of assessment, like defining assessment aims and criteria, students are made aware of the benefits of successfully meeting the challenge of the experimental work and see the assessment as one component of this challenge. Having the students practice self-assessment based on these criteria should help make them aware that it is in the process that the actual learning takes place. This will then promote a situation that is effective for learning. The ability of students in higher education to use self-assessment skills for monitoring and planning progress is often assumed. Enhancing their ability to assess their own and others’ work against given marking criteria is useful. Self-assessment and peer-assessment is something students ought to learn. To assess your own and others work is a way to problematize what you do, to see your own and others’ strong and weak attributes. It is useful to train this perspective since working life demands that the individuals will have more responsibility for their own competence development. As part of the peer assessment process, students are encouraged to develop an appreciation of marking criteria. One of the purposes of self-
assessment is to develop ways in which students can become more critical and perceptive about their learning (Boud 1989).

Promoting attitude development

Research on the development of attitudes of university students originates from William Perry’s work (Perry 1970). Perry’s work has been modified (Fitch 1984; Finster 1991), and applied in science education (Mackenzie et al. 2003). Finster has adopted the Perry scheme in the context of chemical education and given examples of how attitude position could affect how, for example, the role of the teacher, assessment and experiments is viewed.

In attitude research, attitudes are described as having three components: affective, cognitive and behavioral (Eagly 1993). When the term attitude is used in science education often the affective component is stressed, e.g. finding laboratory work interesting or boring. These kinds of factors with most stress on the affective component are discussed under the subheading considering affective factors. The attitude development discussed in this area (promoting attitude development) includes affective, cognitive and behavioral components.

The attitude questionnaire used in articles I and II reflected the students' attitudes to teaching, learning and experimental work in chemistry. For article I the purpose of this questionnaire was to find contrasting groups of students, to identify students with dualistic views (e.g. all knowledge is known, right and wrong answers exist for everything) and students with more contextual, relativistic views (e.g. all knowledge must be viewed in context, students seeing themselves as active makers of meaning). For article II the students responded to the same questionnaire twice, at the introduction and ten weeks later after the course. This was done to investigate if there had been any changes in students’ perception of learning during this course. A qualitative change during the course from a more dualistic view towards a more contextual relativism was observed. In answers to statements concerning experimental work the change was statistically significant. It was also interesting and gratifying to find that the students on the course in article II, who had been at the university for at least two more years, “scored higher” than the students on the course in article I. They had a more contextual relativistic view. This is in accordance with the
trend of development over time during university studies (Hofer and Pintrich 2002).

When the students were asked if they preferred the expository or the open-inquiry version (article I) it could be seen that students with high attitude positions readily accepted the challenge presented by an open experiment, while students with low attitude positions did not accept the challenge as easily. The challenge was a bit too demanding in the open experiment, but the minor adjustments made in the revised experiment were sufficient to enable them to accept the challenge. It has been described by Finster (1991) that progression along the attitude scheme occurs when students are challenged to function one step above their level. The students with high attitude positions that carried out the open versions readily accepted the idea and found it really fun to plan their own experiments. When analyzing self-evaluation after the experiments no major differences were seen in the categories of knowledge and comprehension. On the other hand, concerning application, analysis/synthesis, and evaluation facets the students stated that the learning outcome was higher for the open experiment and even higher in the revised open experiment. It is interesting to note that the students with low attitude positions seemed to gain most from the revision.

**Considering affective factors**

In recent years the affective dimensions of learning has been stressed. For example in 2000, there was a call for papers about the affective dimensions of learning science in the International Journal of Science Education. The guest editor, Mike Watts, stated that the call for papers was prompted by the premise that learning in science is not solely or simply a cognitive affair (Watts 2000).

Article I shows that the students were more willing to put effort into the open versions of the experiment, as illustrated by the greater amount of time spent preparing for the experiment and in the laboratory. It is also seen in the students’ self-evaluations on the Bloomian scales. After performing the experiment no obvious differences were observed between the three groups of students that carried out the different versions of the experiment with regard to knowledge and comprehension. However, with respect to application,
analysis/synthesis and evaluation the students claimed that they learnt more in
the open-inquiry (especially the revised version) compared to the expository
version. This indicates that the students felt that they gained more from the
open experiment.

Responses from the interviews with the Master’s level students (article
II) after the course, show that the students identified their experimental work as
the main source of their increased sense of autonomy and self-confidence.
Experimental work involves cognitive, affective and psychomotor factors and
they all appeared from the interviews to be important components for
internalization. It could be argued that the students in the Master’s level course
(article II) were obliged to be active since they were assessed several times with
methods that required higher order cognitive thinking. Our hypothesis was that
by using a strategic, formative and authentic course/assessment design, their
capacity for higher order cognitive thinking would be enhanced, but it could
also produce the opposite effect. Too high demands and formative assessment
might push them too hard and reduce their capacity and learning outcome.
During the interviews nearly all of the students initially testified to gaining in
self-confidence. They usually mentioned features in the affective domain, and
after a while gradually progressed to issues related more to the cognitive
domain. Secondly, they said they had learned to purify proteins and analyze
their properties by different biochemical methods. Despite our guidance and
control, the students felt they had become more independent during this course.
The experimental period was regarded as important, effectively promoting
learning in an active and creative way. Most of them also emphasized the belief
that during the course they learned how to work, plan and think more
independently.

The majority of the students in the Master’s level course found it very
stimulating and the “external evaluators” generally rated the students highly in
the creation and defense of their posters (article II). The students clearly
enjoyed showing their results to others and the effectiveness of this assessment
was confirmed in the interviews. This creative activity stimulates the affective
domain in the process of internalization. Tasks like this, requiring the use of a
combination of cognitive and affective skills, are in our experience very
effective for deepening students’ understanding of theory, and provide excellent
opportunities to develop higher order cognitive skills.

When assessing the experimental work in article III both students and
instructors assessed the students as more capable within the affective domain
than at cognitive skills. However, the students expressed the view that there were difficulties concerning assessment of the laboratory work. Most of them claimed that the laboratory instructors spent too little time in the laboratory to be able to make a fair assessment of each student’s achievement. From the interviews it also became evident that the students had a fear of asking questions since they believed they would be negatively judged if they asked too many questions or the “wrong” things. Often, they sought out the laboratory instructor only when they had a problem, and half of the students expressed concerns that asking too many questions may be judged negatively. Some of them considered how a fair picture could be obtained, and questioned what was actually assessed. The problem is, according to the students, that they themselves and their laboratory partners are really the ones that best can judge the fulfillment of some of the criteria, but at the same time they expressed concerns about difficulties associated with both peer- and self-assessment, citing problems with honesty and objectivity. Another problem mentioned is that opinions differ amongst individuals about what is important.

Our studies suggest that an important condition for higher-order thinking is that the students have to gain competence and the courage to believe in their own abilities to use new knowledge/competencies/skills. To gain these qualities, the students need confirmation of their knowledge and skills through feedback.

**Further research**

In my opinion the future employers’ perspectives of competence would be of interest for further studies. The results from paper III stimulated us to start investigating the skills and competences that are sought by experienced senior researchers, developers and employers in the life-science field at universities, institutes and biotechnology or pharmaceutical companies (Professionals). We want to compare these professionals’ views to the views and expectations of the students and graduate students reported in paper III. This type of knowledge might provide valuable information for curriculum modification and course development in future biochemistry courses at the university level. We are currently in the process of collecting and analyzing the responses from questionnaires and interviews. A very preliminary analysis of the interviews
indicates that the professionals stress the importance of developing skills related to practical work and to developing problem-solving capabilities (the scientific method). They emphasize the importance of capabilities such as: higher order cognitive skills; planning skills; and different types of communication skills. In particular, they stress the importance of starting to train these types of skills at an early stage of professional education. They also identify a broad and multidisciplinary knowledge base as important competences. However, the most striking aspect is the strong emphasis they put on a variety of affective skills and properties, such as: a questioning attitude; critical thinking; creativity; imagination; and cooperative skills. They also identify the process of learning as a competence that is gaining in importance to keep pace with the fast developments in the life science domain and the growing intensity of the flow of information.

Evaluating the relevance of the assessment raises further very interesting research questions in this field of study. What approach would maximize the strength of experimental work assessments, what could best develop competence? Would it be better for developing competence to assess the laboratory work in some other way? Other possible approaches could be to only assess the end results, i.e. the purity of the protein, how the students have succeeded in the chemical analysis of the protein, or in a conscious and controlled way to evaluate and assess laboratory notebooks kept by the students. In another study, I have gathered and analyzed the laboratory notebooks of each student. With the notebooks as starting points, interviews were made with the laboratory group in order to find clues about how the students reason and make decisions on how to proceed with the experiment. How do the students think, and what hinders/facilitates or boosts complex learning? Since we have found the synthesis level a threshold in the development of higher cognitive learning skills it would be interesting to undertake some more studies to understand and identify these thresholds in the cognitive process and develop methods to enhance these types of skills. Looking back at page 33 on how synthesis is defined by Bloom et al. it is not surprising that this is a threshold since it not is a limited skill but a rather complex coupling i.e. a central part of what today is included in competence (page 43). We are at present analyzing, by text analysis, the nature of this difficulty in the grant proposals written by the students. There is definitely a need for more research to understand if and how different assessment approaches can develop competence and in which areas.
Additional research is also needed to find out if laboratory experience and the assessment discussion suggested between the teacher, the student and his/her laboratory partner can stimulate students to higher-order thinking. Is it possible to direct the students towards more complex learning and higher order cognitive skills, using the suggested model (see page 50)? Can accelerated learning be envisioned in some way? How do the students perceive such peer- and self-assessment done from explicitly and jointly formulated aims and criteria? Is it possible to evolve competence, improve skills and abilities by practicing self-motivated learning?

**Final comments**

Initially I expressed a feeling that finding a way, within our culture, to improve practice and enable professional development is an urgent task. How can both students’ and teachers’ learning be enhanced in an action research discourse?

An advocate of action research can find support in the following two memorable quotations by George Bodner: “Our evaluation should look behind the facade of answers to the question ‘do the students like it’ towards deeper questions such as ’What do students learn that they were not learning before?’” (Bodner et al. 1999). “We can teach and teach well without having the students learn?” (Bodner 1992).

As a teacher you think you know what happens in your teaching, but frequently things unfold differently from your expectations. Making changes in course design in one way or another, changing aims, instructions or teaching/assessment methods is not an easy task and it is even more difficult to measure what really changed. What could help me and my university colleagues to rethink and change our professional practice and professionally develop? I find action research one way to solve problems and to become more reflective. We have to struggle with ideas, we need more ideas otherwise we will make the same mistakes as before. One way to promote development of competence and assess complex learning could be via embedded action research and critical self-reflection. An action research process is systematic without being burdensome for the teacher, and provides valuable practical knowledge.
From my investigations I found it important to include all involved in
the teaching/learning process for the professional development of students, laboratory instructors (doctoral students), lecturers (chemistry researchers) and chemical education researchers. The relationship between teachers and students then becomes more collaborative than usual, more attuned to collective capacity building. From the teacher’s perspective an important facility could be the opportunity to go to colleagues for help. The collaborative approach to improvement can also benefit others involved: students would clearly benefit from reflected and researched practice development and colleagues would have the opportunity to learn from each other’s experiences. Finally, the department would benefit since the action research carried out has positive implications for quality assurance.

For practice development, neither individual action nor professional practice knowledge alone is sufficient, since collective competence development is required: developing new ideas, new relationships, constructive dialogs and the creation of open spaces for discussion. If we are serious about competence development and assessing complex learning for all involved it must be reflected in a change in attitude of the whole department, it is no use thinking that it is an issue that can be left to one or two enthusiasts.

In these very last lines, trying to sum up many years of joy and struggle, I would like to present a model (figure 4) of a way to combine the development of teachers’ teaching and learners’ learning (cooperative learning) through action research. This appears to be the best way to boost both of these processes. Until recently the model for teaching was based on the hidden assumption that knowledge can be transferred from the mind of the teacher to the mind of the learner. As a metaphor we can consider enzymes and substrates. The learning environment and the design of experimental work are analogous to the enzyme that speeds up the reaction. The reaction makes the substrate, the student, as a product, a more competent student.
Figure 4. A model to sum up my final comments on ways how to develop competence in biochemical experimental work.

The lock and key model suggests that the active site in the enzyme and the substrate are exactly complementary. This static view of the enzyme and substrate as the learning environment/design of experimental work, and the substrate, respectively, is not an ideal model; representing as it does a limited view of enzyme/substrate interactions and perhaps symbolizing the epistemological approach when education was seen as transferring knowledge directly from the teacher to the learner. My attempt to sum up my findings from my research in the model is better described by an induced fit model, suggesting that the active site and substrate are only fully complementary after the substrate is bound, through adjustments in the shape of the substrate and the enzyme’s active site. Analogously, by adjusting the learning environment and design of experimental work through results from action research there will be a better match, and the result will be a more competent student.
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