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On the Understanding of Computer Network Protocols

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Computer Network Protocols

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Abstract

How students' learn about network protocols is studied in a project-centred, internationally distributed, university course in computer systems taught jointly by two universities. Insights into students' understanding of basic concepts within computer networks are gained through an empirical phenomenographic research approach.

The use of phenomenography as a research approach makes it possible to learn about computer science, as it is experienced by the students. The context in which the research is carried out and issues concerning by whom the context is experienced, are investigated and form a part of the methodological basis.

Students' understanding of some protocols that are used within the project, as well as their experience of the general concept of network protocols are investigated, and different ways of experiencing the protocols are discerned. Some aspects that indicate good learning outcomes are identified, such as being capable of understanding a protocol in different ways and of making relevant choices between the ways it could be experienced according to the context in which it appears.

Based on these results a discussion on learning and teaching is developed. It is argued that a variation in the context in which the protocol is experienced promotes good learning, since different ways of experiencing a protocol are useful with different tasks to hand. A student with a good understanding of network protocols can choose in a situationally relevant way between different ways of experiencing a protocol.

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This thesis is based on two publications, written between 2001 and 2002.

Paper A: Anders Berglund. (2002). *How do students understand network protocols? A phenomenographic study*. Technical Report, 2002-006, Department of Information Technology, Uppsala University, Uppsala, Sweden.

Paper B: Tom Adawi, Anders Berglund, Shirley Booth, Åke Ingerman. (2002). *On context in phenomenographic research on understanding heat and temperature*. Revised paper presented at EARLI 2001, Fribourg, Switzerland, 2001. Submitted to Learning & Instruction.

Comments on my participation:

Paper A: I alone did the work preceding the publication as well as the writing. I discussed my work and my writing during the whole process with my supervisors.

Paper B: I have participated equally with the other authors in the work preceding the publication and in the writing. The empirical data that is referred to stems from an on-going research project by Tom Adawi. Shirley Booth brought an understanding of the theoretical foundations of phenomenography into the project.

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Introduction

1. Overview of the thesis

Learning of network protocols has been studied in a project-based, internationally distributed, university course in computer systems taught jointly by two universities. The work presented in this thesis concerns students' understanding of network protocols¹. Insights into the students' understanding of basic concepts within computer networks have been gained through phenomenographic research approach.

In this introduction I will explore the background and the goals of my research project. I will describe the framework in which my research is performed by giving an overview of the internationally distributed course – the Runestone initiative – its history and its aims, and by investigating the relationship between this project and related research projects. I will also describe some aspects of computer and data communication as well as of phenomenography, the research approach used in this project, that are relevant for the work presented here.

The technical report *Understanding computer network protocols* (Berglund, 2002) is the core part of this thesis and will be referred to as "Paper A" throughout this introduction. The report presents empirically based results on how students who participate in the Runestone course understand network protocols. Students' understanding of some protocols that are used within the project as well as their experience of the general concept of network protocols are investigated, and different ways of experiencing the protocols are discerned. Some features that indicate some aspects of a good learning outcome are identified: to be capable of understanding a protocol in different ways and of making relevant choices between the ways it could be experienced according to the context in which it appears.

The research is performed in a phenomenographic tradition. The aim of phenomenography is to analyse and describe qualitatively different ways in which a phenomenon can be experienced. It is thus an empirical research approach that puts the learner in focus, and the researcher studies the learners' ways of experiencing their study object, that is, what they are learning (Marton & Booth, 1997). Maintaining focus on the object of study is a feature of phenomenography that is important for my choice of a research approach. Phenomenography offers a possibility for me as a researcher to learn about computer science, *as it is experienced by the students*. Learning does not take place in a vacuum, but rather in a complex situation, where different aspects of the environment, together with the subject matter and the students

¹ A (computer) network protocol is a set of rules that enable communication between computers. The terms *network protocol*, *communication protocol* and *protocol* are used as synonyms in this report.

themselves, interact. The role of the context² of research, as well as issues concerning by whom the context is experienced, are further developed in Paper B, *On context in phenomenographic research on understanding heat and temperature* by Adawi, Berglund, Booth and Ingerman (2002), which is the next part of this thesis. This paper is a contribution to the methodological underpinnings of the phenomenographic research approach and supports the research that is described in Paper A.

2. The Runestone initiative

Runestone is a joint computer science education research and development project, based on a project course in computer systems and software engineering initiated and run by Uppsala University (UU), Uppsala, Sweden and Grand Valley State University (GVSU), Allendale, MI, USA. From the start in 1998 the initiative was aimed to create an advanced course in computer science taught in a non-traditional way, that could serve as a framework, a source and a resource for research into computer science education (Daniels, 1999). The course is supported by a framework of computer science educators and computer science educational researchers at GVSU and UU, and also at University of Texas at Austin, Austin, TX, USA, St. Edwards University, Austin, TX, USA, Open University, Milton Keynes, UK, University of Kent, Canterbury, UK, and Chalmers University of Technology, Göteborg, Sweden. As will be further developed in section 3.3, other aspects of the students' learning and collaboration have been investigated by other researchers within this project.

In this section I will briefly describe the project course the students are taking, present the aims of the initiative and give an overview of its history.

2.1 The student project

The students who take this project-based course are advanced students in computer science at the two universities and are in their third or fourth years of studies. The work in the projects is performed in virtual teams, normally consisting of six students, three at each university. Each group creates a software system that controls a physical device. A Brio labyrinth (see Figure 1) was used as the physical device during the first four years (1998-2001), but in the year 2002 Lego Mindstorms are used. This report is based on the setting using the Brio Labyrinth. The task that the students were to solve is discussed in more detail in Paper A. The course is taught jointly by the universities with only a minimum of face-to-face meetings between the teachers and the students. Instead, each group is assigned to one of the teachers, either at GVSU or UU.

² The word *context* has many uses in educational research. Throughout this introduction *context* can be read as "meaningful background"



Figure 1. A Brio labyrinth. The aim of the game is to move a steel ball on the board from a starting point to a final point. The knobs are used to tilt the board and in this way move the ball.

2.2 The aims of the Runestone initiative

The computer science learning objectives for the students who take the course are to learn about computer systems by developing a software system and by building virtual working teams, as indicated in Paper A. However, the complete aims of the course that the students are taking should be seen in a wider context, where the students' experience of an international collaboration is another essential goal (Daniels et al., 1998). They point out that by working in internationally distributed teams, where some of the group members live in a different country and have a different educational background, an international experience is offered that reaches students who do not participate in student exchanges. The students should also gain experience of ICT-based³ collaboration. It is also stated as one of the course goals, that the students should learn computer science concepts from their remote group members. Daniels et al. stresses that it can be assumed that the full group of students, due to the diversified skills and educational backgrounds, might be expected to produce a better software system than a local group could do.

Some objectives are formulated at the institutional level, concerning possibilities for the staff and departments involved to learn and develop. Daniels et al. state that a "secondary aim is to identify effective support structures for remote international collaboration, encompassing strategies for communication, management, and technology use". They also point out that the peer learning among the staff concerning ways of teaching, and the possibility for the initiative to serve as a platform for research on learning in computer science, are important aspects of the project.

2.3 The history of the Runestone initiative

As already said, the Runestone initiative is supported by a web of collaborating universities that contribute with teaching and research interests in the project. In this environment several papers and reports have been written on different aspects of the project. The historical development that is described in this report is mainly based on works by Daniels (1999), Last, Almström, Daniels, Erickson, Klein (2000) and by Last, Hause, Daniels and Woodroffe (2002).

The two universities have taught the distributed collaborative course since 1998, when one pilot group, consisting of eight volunteer students, carried out the project. For the students in

³ ICT is an abbreviation for Information and Communication Technology

this pilot group, technical issues such as discrepancies in programming language skills and the fact that only one hardware system, located in Sweden, was available, were more frustrating than factors that could be related to the virtual aspects of the collaboration according to Last et al. (2002).

From the following year, 1999, the course was scaled up to full classes at both universities. Table 1 show the development of the number of students. During these years the course has been jointly taught by one lecturer at each university. At both universities there have been changes of lecturers; that is, none of the lecturers teaching the course 2001 has participated in the project from its beginning. To accommodate the larger number of students, several copies of the hardware systems have been available at both sides.

Table 1. Total number of students taking the Runestone course

Year	Number of students
1998	8
1999	42
2000	93
2001	86

3. Related research

In this section I will give an overview of computer science education research. After a brief introduction to the field of research, I will discuss research projects other than the Runestone initiative. This presentation is mainly organised according to which research approach that is primarily used. In the next section I will further explore other research projects within the Runestone initiative.

3.1 Computer Science Education Research

Computer Science Education (CSEd) Research aims at improving learning and teaching within the field of Computer Science. As a research discipline it has a short history and has its roots in a range of disciplines including computer science: pedagogy, psychology, cognitive science, sociology to mention a few.

Computer science is a subject that some students find inexplicably difficult, particularly at an elementary level, as is shown in a literature survey performed by Ben-Ari (in press). It is a subject without the sort of experimental basis that physics has, or the educational tradition such as mathematics has. An essential issue for the research into computer science education is to tackle and resolve this problem.

3.2 An overview of research within Computer Science Education

A survey of the proceedings of recent years of the ACM SIGCSE (Special Interest Group on Computer Science Education) conference, the ACM ITiCSE (Innovation and Technology in Computer Science Education) and the PPIG (Psychology of Programming Interest Group), as well as the journal Computer Science Education (vol. 9 – 11) indicates that most of the projects presented were performed as case studies on specific courses, often performed,

evaluated and reported by the teacher of the course. These studies are normally driven by the needs of the computer science educators of the universities in question and address problems that have arisen in real teaching situations. Frequently the questions addressed concern the introduction of new methods, or new tools of different kinds, to teaching. Although valuable as a mean of sharing experiences between computer science educators, the results are, as also pointed out by Holmboe, McIver and George (2001) and Carbone and Kaasbøll (1998), often hard to generalise, since they are not based on pedagogically sound theories of learning or carried out with sound methodological principles.

The methodologically sound research in the field of Computer Science Education on problems related to education at university level has been dominated by cognitive psychologist approaches, with a rather abstract interest in the nature of knowledge structures, the acquisition of knowledge, and ways in which it can be made efficient. As examples can be mentioned the work performed by Baffes (1994), who has created a system that automatically identifies and recognises mistakes made by programming students. Based on the information that is collected across multiple students in a database, the program models the error and offers the student relevant feedback. Almstrum (1996) suggests that pre-university teaching in mathematical logic as well as the content of university level courses in discrete mathematics needs to be scrutinised. Her study, looking for the reasons for learning difficulties in the field and based on a large statistical material, shows that novice computer science students experience more difficulty with concepts involving mathematical logic than with other concepts in computer science. Holmboe (2000) argues that a teacher in computer science needs the means to evaluate students' mental models as well as guidelines for designing learning environments. He describes typical aspects of students' mental representations, built on an empirical study on students taking a course in system development.

Research in this tradition is often based on experiments or quasi-experiments⁴, testing hypotheses on the effects of educational devices by classical methods of psychology, comparing statistically the performance of a trial group against that of a control group before and after the former has been subjected to the device. Priebe (1997) has carried out a quasi-experiment, comparing a group of students that met in a cooperative learning environment with a group that in a classic way attended lectures. No significant differences were found between the groups. Wu (1997) has showed, in a controlled experiment on the teaching of recursion, a significant difference in the results for students that attended lectures that were based on concrete models, compared to those that were taught using abstract conceptual models. Al-Nuaim (1999) has developed and statistically validated a tool for formative evaluation of web-sites intended for education. McIver (2000) has in an experiment compared error rates for students who learned Logo or Grail as a first programming language. She compared syntax errors as well as logical errors and concluded that the design of the programming language has a substantial impact on error rates for novice programmers.

Other research projects draw their origin and motivation from pedagogical research, and have a strong focus on understanding students' learning in realistic settings. Phenomenography has been used in such research, since it allows the researchers to retain focus on the character and the structure of the subject matter, here computer science concepts and principles. It has been used to describe and analyse students' learning within the field, for example where Booth (1992) has studied what it means and what it takes to learn to program. Learning to program

⁴ A *quasi-experiment* aims at examining causality by quantitative research methods, in situations where complete control of the situation is not possible.

is characterised as a process of a growing awareness of what it means to program, in terms of both technical constituents, unthematized framework constituents and writing programs to solve problems. Teaching should, according to Booth, offer not only expert views of the subject, but also offer a rich variation in different ways of coming to an understanding of what it means to program.

In a phenomenographic study, Cope (2000) argues that the experience of learning in information systems has multiple educationally critical aspects. This is a reflection of the complexity of the desired way of experiencing an information system. It is likely that the students' learning experience becomes more effective, if active collaborative experiential learning tasks that focus on these critical aspects are designed.

In a socio-cultural research tradition (Säljö, 2000), where learning is seen as related to and dependent on the environment of the students and is built in collaboration with others – students as well as teachers – Holland and Reeves (1996) have studied students' work in a software development project. They have built an activity system (Engeström, 1987) that describes and helps understanding the context of the group work for the software developing student teams. They introduce the term *perspective* as a "view from somewhere" that is collective, historical and develops over the course. The teams took different perspectives, and as a consequence, they differed in their construal of the object of their work, the importance they gave to different sub-tasks and the way in which they carried out the work.

Few pedagogically sound research projects have been carried out that are based on the needs of computer science education, stemming from problems that have been proposed by computer scientists. The work performed by some computer scientists within a constructivist framework can be mentioned as interesting exceptions, as can the work of Cope (2000). For a constructivist, understanding and knowledge is not transferred from one individual to another. Instead, students construct their own understanding in an active process (Phillips, 1995). Ben-Ari (in press) argues that constructivism could inform teachers in computer science about models and how models should be taught, while Hajderrouit (1998) analyses how constructivist theory can be used to enhance students' learning of Java. There is a growing interest from the computer science education community for established research approaches such as constructivism.

Few of the studies performed in computer science education focus on network protocols. However, the journal *Computer Science Education*, Vol. 10, number 3, is devoted to network protocols. While most articles focus on methods of teaching or tools for teaching or for practical exercises for the students, some also analyse students' learning. Jard and Jéron (2000) present a case study on students' learning about validation of the alternating bit protocol⁵. They argue, based on their own experiences of teaching the course, that students understand the need for automated tools for protocol verification by trying to use such tools. Mester and Kruhm (2000) argue, based on their own experiences as lecturers, that animations of formal methods to a certain degree can improve students' results on exams, and that the students' ability to find imaginative solutions to particular kinds of problems increased.

The overview presented indicates that CS Education research is a small but diversified field, where researchers with different backgrounds and aims perform studies with different objectives. However, most research projects are case studies or different kind of preliminary

⁵ The *alternating bit protocol* is a simple protocol that aims at transferring data over medium that can lose data.

studies, often focusing on how students use a single resource, like other students in a collaboration, a web-tool or a purpose-made device for instruction and labs. Few, if any projects, other than the Runestone project described above, have been performed where researchers, taking their starting point from the needs of CS education have studied computer science students in a naturalistic setting, to learn how students experience different resources available for their studies, and how they use these resources in their learning.

3.3 Other research projects within the Runestone initiative

As was stated in section 2.2, the Runestone initiative was from the beginning constructed to serve as an internationally distributed course in computer systems, as well as an environment for research on students' learning in computer science. The initiative is closely related to a network of computer science educators⁶ and has generated several research projects that investigate different aspects of the students' work. Although these research projects use the same student project as their object of research and to collect empirical data, they have distinctively different research questions and theoretical backgrounds.

Hause and Woodroffe (2001) study the communication and interaction within the student teams, in order to find characteristics in the interaction patterns within teams that perform well and poorly in software engineering. Data is collected from the e-mail conversations as well as IRC⁷ sessions between the team members. The data is coded according to a set of categories developed within the research project using discourse analysis, in the sense that Coolican (1999) describes as "qualitative analysis of interactive speech, which assumes people use language to construct the world as they see it according to their interests". Preliminary findings show that communicating among the group members is important, and that the timing of the interaction is crucial.

The group development in the student teams and the role of conflicts are in focus in the work performed by Last (2002), who uses grounded theory⁸ as a research approach. In her current work, she is investigating if "group development models developed and validated with face-to-face groups require modification when applied to virtual teams"⁹ and if "certain types of conflict in a team result in a more productive team and a better product".

Pears, Daniels, Berglund and Erickson (2001) have addressed the issues of the impact of the different grading scales¹⁰ on the students' motivation to contribute to the work of the group. There it is argued, based on a statistical analyses of the students' assessment of their team-mates' work as expressed in the peer evaluation, that the different grading scales did not affect the students' level of input in the research.

⁶ The network is further described at <http://www.docs.uu.se/csergi/>

⁷ *Internet Relay Chat*, IRC, is a system for human communication over Internet. A computer running an IRC program can be used in a way similar to a text telephone and offers to the user a possibility to communicate with any other IRC user in the world.

⁸ *Grounded theory* is a qualitative approach that generates theory from observation.

⁹ Quotes from http://www.cs.stedwards.edu/~lastm/SIGCSE_2002_DC_Mary_Last.htm

¹⁰ The Swedish students had a grading scale with only two grades, *passed* or *failed*, while the American students could get grades varying between *A* and *E*, including grades with + and -, as D+ or B-

Daniels, Faulkner and Newman (2002) discuss open-ended group projects (OEGP) in computer science education in a comparative study and create a framework for describing such projects as The Runestone initiative as one example of how an OEGP can be organised. They argue, based on student evaluations, discussions with employers and their own experiences that OEGP projects, where the end-product is not well-defined, are valuable for preparing the students for their professional lives.

This overview, together with the current study, clearly indicates that there is great interest for carrying out research within the Runestone initiative, and that different research questions can be addressed from the empirical data collected in this project. The studies presented that concern the group development, characteristics of low and high performing teams, and grading of distributed projects, as well as my study, concerning the learning of computer science and the role of the environment, and together form a whole. They create a research-based overview of Runestone and students' learning and collaboration in virtual teams.

4. *Data communication and network protocols*

One important objective of the Runestone course is that the students learn about computer communication. I will in this section give a brief introduction to computer and data communication and to networks protocols, following Tanenbaum (1996) and Stalling (1997).

The communication between computers can be designed, analysed, and described in different ways. Focus can be on different aspects of the communication, whether it is the physical transmission of raw data or a semantically rich communication between two advanced application programs such as mail-programs, or at any level between these two. A strategy is needed to handle this complexity, in order to make the design of a computer network and its components a feasible task. Layered design is the completely dominating methodology used to tackle the complexity and to define tasks that can be further developed.

Communication between computers is governed by sets of rules. These rules that defines how the communication between the functional units of the communicating systems, and clarifies how it shall take place, are called *protocols*. In this thesis I refer to them as *network protocols* or *computer network protocols*.

The section starts by presenting the idea of layered models, then continues with descriptions of the layers in the TCP/IP model, which is the most important in the project the students are doing. The protocols from the TCP/IP model that are used in this project are mainly TCP, and to a lesser extent, UDP. RMI is also important in the light of the Runestone project and is presented in the following section. Then before a summary, some aspects of practical programming are discussed.

4.1 *Layered models*

As mentioned above, data and computer communication is designed in layered models. Each layer offer services to the higher levels. The services offered by a layer are implemented with the help of the services offered by lower layers. As an example can be mentioned that an application program, as a mail-program (VM-mail, Outlook Express etc) uses services or routines that from an underlying level and that for example offers the possibility to set up a

connection to another computer. This service, in its turn is implemented with the services that are offered by a lower level, such as address translations. For a user of a mail program it seems as if data from his or her mail program was transferred directly to its peer (or to a mail-server) on another computer. From a technical perspective, data is passed to lower level routines to be delivered to the corresponding application on the remote machine.

Basically, there are two layered architectures that are discussed today: The Internet architecture, which is frequently referred to as the TCP/IP¹¹ architecture and the Open Systems Interconnection architecture, OSI. The former completely dominates practical applications and will be in focus in this presentation. The OSI model is clearly defined and has well-standardised protocols. The model is mainly used as a reference in order to understand networks.

4.1.1 The TCP/IP layered design

In this section I will explore some aspects of the layered design of the TCP/IP architecture as shown in Figure 2. The link level and the physical level will be referred to as underlying networks in the presentation, since their characteristics are not important to the project described in this thesis. The terminology is consistent with that used by Tanenbaum (1996).

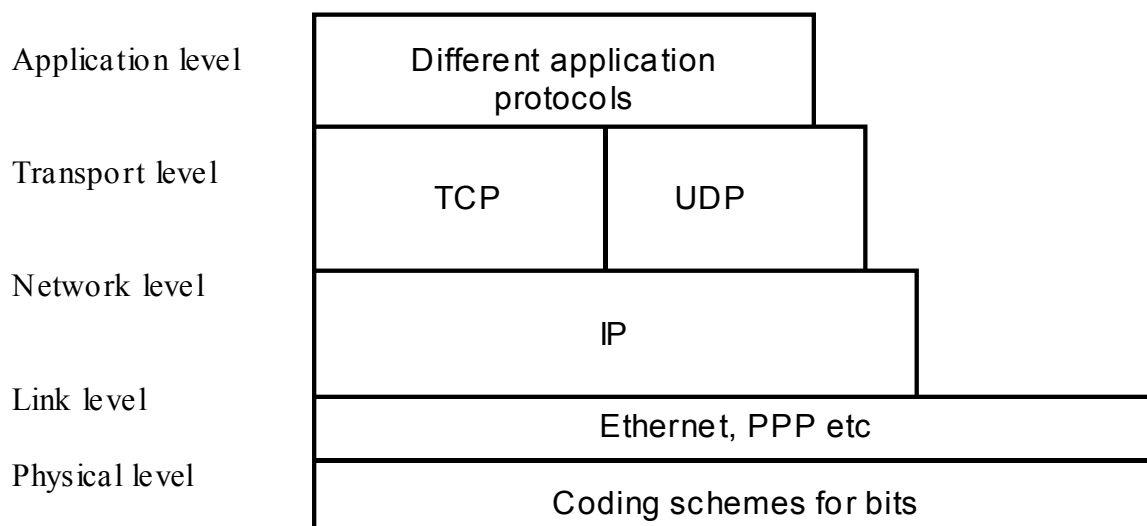


Figure 2. The TCP/IP layered model

The underlying networks

An *internet*¹² or an *internetwork* is a network that consists of a set of independent networks, that each has its own character. These networks are connected to each other through *gateways*

¹¹ TCP/IP stands for Transmission Control Protocols and IP for the Internet Protocol. Abbreviations are rarely spoken out within the field of computer communications. Acronyms are used as names of the protocols as well as the other entities discussed.

¹² I will follow the convention of writing *Internet*, with a capital *I*, when referring to the global Internet, and of writing *internet* when discussing independent internets. The Internet is a large and well-known internet.

or *routers*. The independent networks that form an internet can for example be Local Area Networks, LANs, or internets, with the recursive definition of internets. An internet is thus a logical network, that consists of a collection of physical or logical networks. This points to one of the important features of the Internet architecture: It does not prescribe any specific physical medium or any specific kind of networks to be connected. Instead it is designed for communication that goes over different kind of networks.

When describing the TCP/IP protocol architecture as a four-level model, this set of different network protocols, with their own characteristics (and their own possible layered architectures) together form the first level.

Network level

The second level is the *network* level that handles the issues of the heterogeneous structure of the underlying networks, large size of an internetwork, and its continuously changing character. It mainly offers two services to the level above itself: it handles addressing on an internet-wide level and offers tools for delivery of data to the destination. In other words, the protocol at the network level, the *Internet Protocol* (IP) accepts packages of data from a higher level, translates addresses so that they correspond to the actual physical settings and forwards the data, formatted as needed, to its destination using the services of the underlying levels.

Data are sent by the IP protocols as IP *datagrams*, packages of a limited length (less than approx. 65 000 bytes) that each contains a part of, or if data is short, the full message. The IP protocol tries to deliver the datagrams that each "travel" independently over the net of the others. Frequently datagrams need to take many steps and pass several routers to reach its destination. This issue is handled on the network level. The datagrams can however arrive to their hosts in the wrong order, corrupt or not at all. The IP protocol is a *best-effort* protocol; it tries its "best effort" to send data, but does not guarantee any qualities of the service.

Transport level

If a guarantee of delivery is needed, it must be taken care of by the layer above the IP level, the *transport layer*. The transport level offers the possibility for two computers to keep an end-to-end exchange of data. To do this, the transport layer uses the services offered by the network level. There are two dominating protocols at this level, the *Transmission Control Protocol*, TCP, and the *User Datagram Protocol*, UDP, offering different types of services to the level above.

TCP, *Transmission Control Protocol*, is reliable, connection-oriented protocol. This means that the protocol allows communication where data is delivered to any other machine on the internet without errors. Data is delivered to the user of the TCP protocol; that is, to a higher level, in the order it was sent. Issues like unreliable physical networks, different speed of the underlying networks or different sizes of data packages on different sub-networks are taken care of by TCP. A user of the TCP protocol needs to set up a connection in order to communicate with another computer, a concept that is reminiscent of a telephone call.

UDP, *User Datagram Protocol*, is an unreliable, connectionless protocol. This means that a sending computer does not get any confirmation if the data sent has reached its destination or not. Still, it is useful in applications where but where speed is important, such as video

conferencing. A user of video connection can more easily accept a loss in the quality of the image than delays of various lengths.

Application level

The two protocols described together form the transport layer. They offer services that are used by programs at the level above, at the *application* level. Here there is a large number of protocols available offering a rich variety of services that the user of a computer on an internet might want. As an example can the Hyper Text Transfer Protocol, HTTP be mentioned. It defines the rules for the communication between a Web-browser (as Netscape, Internet Explorer, Mosaic, Lynx etc) and a web-server, which stores and organises web pages. This means that anyone who wants to create his or her own web-browser (or web-server) needs to write a program that follows the rules of the HTTP. Normally the services of TCP are used to implement HTTP, since a reliable transfer of data is desirable.

Other examples of application level protocols are mentioned in Table 2.

Table 2. Some example of application protocols

Abbreviation	Full name	Purpose
SMTP	Simple Mail Transfer Protocol	Transfer of mail
NNTP	Network News Transfer Protocol	Transfer of news and support for news reading in USENET news
FTP	File Transfer Protocol	Transfer of files between computers
Telnet	Telnet	Login on other machines
NV	Network Video	Video Applications

4.1.2 Peer communication

A conclusion from the section above is an internet "looks" different for users at different levels. A user sending an electronic mail through a mail program experiences an internet in differently from a student who works on the Runestone project with a routine that implements communication between the camera and the game server (Paper A, section 2.4). While the former uses a program that implements the SMTP protocol, the latter is most probably writing a C++ or Java program that uses the services of TCP.

Figure 3 illustrates this with an example. A user of the FTP (File Transfer Protocol) protocol sees his or her program and the communication with another FTP program as the FTP protocol prescribes. Thus for him or her there is *peer communication* (marked as "a" in the picture) between two FTP programs. The user does not need to be aware of the underlying levels; they are hidden.

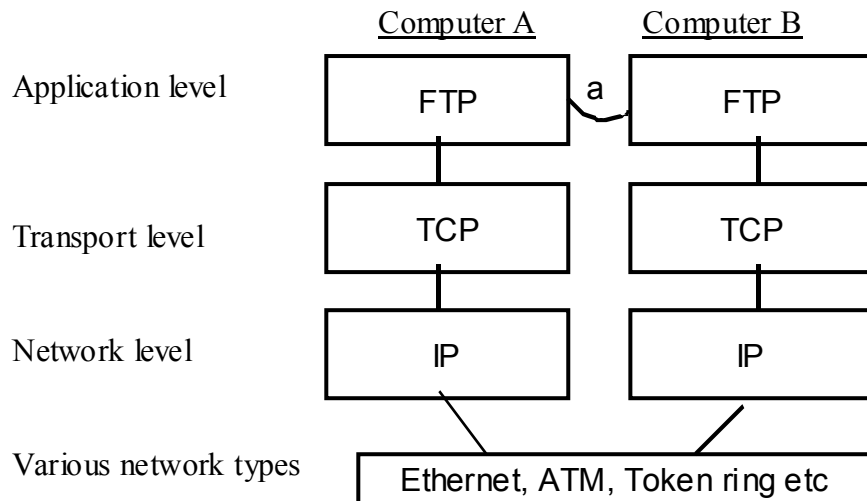


Figure 3 An example of peer communication in a layered model

4.1.3 Dependencies between protocols in the TCP/IP architecture

As has been mentioned, the TCP/IP protocol hierarchy is created to allow communication over networks with different characteristics, and to make it possible to create application programs for large numbers of purposes. The internet architecture is diversified and constantly evolving, new protocols are created, and existing protocols are updated with new versions. A way to visualise in which level different protocols are and on which other protocols they depend, is through a protocol graph, Figure 4.

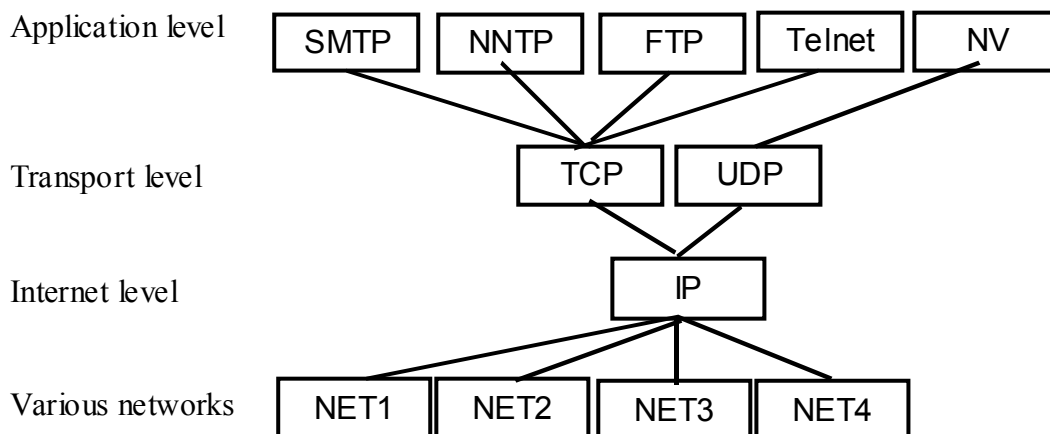


Figure 4. Internet protocol graph

The network level, with the Internet Protocol as its only protocol, is in the centre, and serves to make a communication over different networks, marked NET1, NET2 etc in the picture. On the level above the network level, there are two protocols, TCP and UDP that both use the services of IP. At the application level, there are a large number of protocols, whereof only a few, with their abbreviations explained in Table 2 are shown in the picture. Most of these protocols are implemented over the support provided by TCP, since TCP offers a reliable

communication. NV (Network Video) uses UDP, since for video applications speed is a crucial factor, while it is easy to accept losses in data.

4.2 *Remote Method Invocation*

RMI, *Remote Method Invocation*, provides programmers with a facility to access code or objects on a remote machine. It is implemented on top of TCP/IP. As is mentioned in Paper A, it is closely related to the object-orientation¹³ in the programming language Java. An object-oriented program can be viewed as a set of interacting objects. The execution of an object-oriented program takes place in the objects and in the interaction between the objects. Java RMI offers the possibility to execute Java programs where the different objects are distributed on different machines¹⁴ over an internet. To a programmer this means that RMI offers the possibility to use routines (called methods within the terminology used) that exist on remote machines as if they were available on the local computer.

When transferring unformatted text between computers, all characters are, at least in simple cases (a Western 26-character alphabet, no uncommon control characters etc), treated in the same way. There is no semantically complex information in the characters that influences how the transfer should be made, with the exception of well-defined situations as indications of the end of transfer. When communicating between objects the situation is different: Parts of the data that is transferred is information about other parts of the data. A call to a method on an object contains information about addresses, permissions, data to be transferred etc. This extra complexity offers the possibility to write programs that are distributed over a set of computers in a reasonably easy way, but demands that the programmer handles security issues etc in a correct way.

4.3 *Data communication in practice*

As was mentioned earlier, a protocol is a set of rules that defines communication between two entities. The term is used for a protocol as an abstract entity, with formally defined rules, as well as for a programming package that implements the protocol. In this section, I will briefly describe, in a rather concrete way, some of the routines that are used by the students when they write code for the project, with the aim of explaining with what tools the students practically work during their project.

There are several possible protocols that can be used within parts of or the whole project. Three standard protocols have frequently been used during the Runestone project: TCP, UDP, and RMI. Some students have designed and implemented their own purpose-written application level protocols, based on TCP. Many possible protocols have never been used by

¹³ *Object-orientation* is based on the idea that a program consists of a set of communicating entities. The execution of the program takes place within these entities, and in the interaction between them. Java and C++ are programming languages that support this style of design and programming. There is a vast literature on object-oriented programming and object-oriented programming languages. Budd (1999) discusses the ideas behind object-orientation and Java.

¹⁴ By *machine* I refer to a *virtual machine* that can, in short, be described as a simulated computer that runs on another computer. In other words, a virtual machine is a program, that, when executed, behaves as a computer with well-defined properties. Virtual machines are one of the underlying techniques for platform-independent programs. Java that can be run on different kinds of computers and in different environments has a virtual machine. Java's virtual machine is (at least in theory) the only program that has to be rewritten to run Java in a new environment.

the students; for example CORBA (Common Object Request Broker Architecture) has never been used during the years of the Runestone project, as far as I know. In this presentation (mainly following Harold, 2000) I will discuss practical issues of the TCP protocol, which is the most commonly used protocol by the students in the Runestone project.

TCP sockets, or the *TCP socket programming interface* are used by a programmer who wants to access the services of TCP, most frequently in order to transfer data. This is a common task within the Runestone project. Sockets offer to the programmer practical routines, or mechanisms, to transfer data from one computer to another. A socket can be seen as an endpoint of a communication connection between two computers. This endpoint is easily accessible to a programmer through routines that are accessible from a library or integrated in the programming language. While the concept of sockets, stemming from UNIX, is now generally accepted, details of the implementations vary to a certain degree with different programming languages and operating systems. Java, however, offers an abstracted, standardised interface for sockets that is not dependent on the operating system.

The following basic operations¹⁵ can be performed by a TCP socket:

- Connect to a remote machine
- Send data
- Listen/Wait for incoming data
- Receive data
- Close a connection
- Bind the connection to a port
- Accept connections from the remote machine on the bound port.

While the first five are rather intuitive (the reader can compare them to a telephone call), the last two aim at making it possible to have several connections to one computer. These two are only needed in the phase when the connection is established. The details of their use are outside the scope of this presentation.

The following steps indicate one of many possible ways in which a programmer can use TCP sockets. Details are omitted below:

1. A new socket is created
2. The new socket tries to connect to a remote machine
3. The connection is established and its details are agreed upon
4. Now, data is transferred
5. The connection is closed by any (or both) of the computers.

Each of these steps (except number 4) normally corresponds to one or a few lines of code, frequently using the routines of the TCP sockets.

The connection offered (number 4) is full duplex; that is, both computers can send and receive data simultaneously. Data does not have any predefined meaning. What data means depends on decisions taken by the programmer. He or she can, for example, decide to communicate through commands with an HTTP server (a Web server), transfer a file where the data does

¹⁵ Implementations of TCP sockets offer a considerably larger set of routines. Normally they represent variations of the routines presented here.

not have any meaning for the transfer itself (but that most probably has an interpretation for the users), or by a purpose-written protocol. This means that the code handling data transfer can vary enormously in size and complexity from a few lines to long complex code units.

My intention is that this section should give insights in what the students do, when they are coding in the Runestone project. The specification that they get does not demand that a specific solution is taken or that a specific protocol is used. On the contrary, the students are encouraged to take their own design decisions and to find their own solutions to different questions.

5. *Phenomenography*

While the previous section has focused on the object of the students' studies, computer networks, in this section I will describe the research approach that I have chosen. As stated in the first section of this introduction, the aim of my research is to understand how university students understand, or experience, computer networks, in order to propose ways of improving learning in distributed projects in computer systems. To address this issue, I have decided to use a phenomenographic research approach, a decision that I will justify later.

The section starts with a discussion about the object of research and the aims of a phenomenographic research project, highlighting aspects that are important to the project that I describe in Paper A. In the next sub-section, I will discuss what learning means in the light of the current research project. Then I will explore, referring to my current study, some aspects of how a phenomenographic research project can be performed. As a summary, I will return to the issue of phenomenography as a research approach in my research about students' understanding of network protocols when they take an international distributed course in computer systems.

5.1 *The object of research*

Marton (1994) describes phenomenography as an empirical research approach in the following way:

Phenomenography is the empirical study of the limited number of qualitatively different ways in which we experience, conceptualise, understand, perceive, apprehend etc, various phenomena in and aspects of the world around us. These differing experiences, understandings etc are characterised in terms of categories of description [...] form [...] hierarchies in relation to given criteria. Such an ordered set of categories of description is called the outcome space of the phenomenon [...]
(p. 4424)

Since then, phenomenography has also taken a theoretical turn in relation to learning, but for my purposes Marton's description of empirical studies of ways of understanding or experiencing is appropriate.

In section 3 of Paper A, a phenomenographic research project is described in the following way:

A phenomenographic research project [...] aims at analysing and describing the variation in ways in which central concepts of the subject matter are understood or experienced by the learners. In my study, university students' experience of computer networks is in focus, and

phenomenography offers the possibility for me, as a researcher, to investigate the students' own experience of network protocols.

One of the keystones of phenomenography is that phenomenographic researchers can arrive at a limited number of qualitatively distinct categories of description which succinctly and adequately cover the countless ways in which a phenomenon can be experienced, or understood. The results are articulated in a set of qualitatively distinct categories of description that express the variation in how a phenomenon is experienced by the learners, called the outcome space. The outcome space that I arrive at thus gives me, as a computer scientist and phenomenographer, the possibility to relate the students' understanding of computer network to the goals of the education, as it is expressed in the course descriptions and as I, as computer scientist, understand the protocols. The strong focus on the object of the students' learning is an important feature of phenomenography as a research approach in the research that I present in this thesis, maintaining as it does the subject matter that is of prime interest to me as a teacher.

Phenomenographic research is not performed in controlled experiments or as quasi-experiments, but in "close proximity (both spatial and conceptual) to the learning situation [the students] find themselves" (Booth, 2001). She continues by arguing that it is not a quantitative methodology:

The results are descriptive and lie at a collective level, in the sense that individuals are seen as contributing fragments of data that together constitute a whole and collective experience [...]. (p. 172)

The outline above indicates the roles that are given to the phenomenon (here: network protocols) and the experiencers (students taking an internationally distributed course in computer systems) in a phenomenographic research project. The object of the research is the relationship between these two entities; that is, the students' experience of network protocols. Neither the experiencer nor the phenomenon in focus can alone serve as study objects. This perspective, a second order perspective, is illustrated in Figure 5, where arrow (a) indicate the relationship between the learner and the object of their learning. At the risk of oversimplifying, the researcher investigates this relationship, and is in the same way a learner who learns about the students' experience of a particular phenomenon, as is indicated by arrow (b).

5.2 A phenomenographic research project

In this section I will discuss some important aspects of the different phases of a phenomenographic research project. However, right from the start I want to stress that such a project is not linear in its character. Rather, the nature of a phenomenographic research project, where the aim for the researcher is to analyse and describe the experience of a learner, encourages an iterative way of working. Still the phases presented here give an overview of the work that I performed in the study that is presented in this thesis.

5.2.1 Formulating the research question

The aim of a research project is basically formulated at the outset of a study. Here, as we argue in Paper B, the researcher is the main actor and is influenced by the context in which he or she lives and works. This also influences the research questions he or she can, and finds useful, to address.

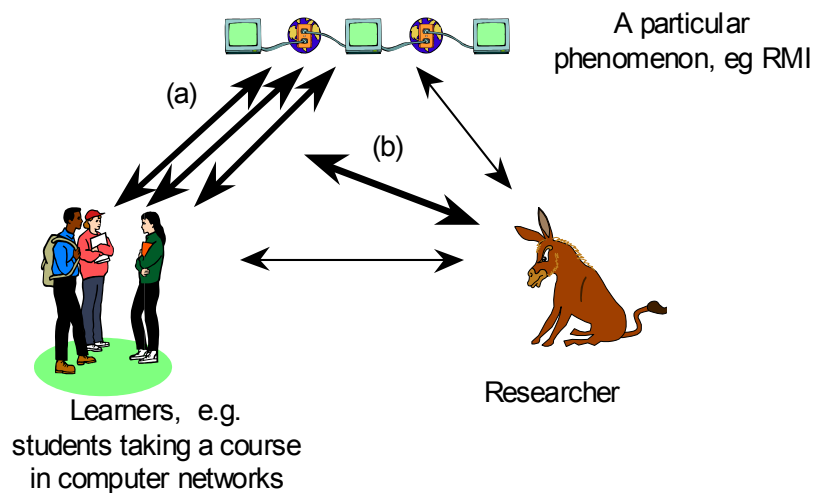


Figure 5. A description of the second order perspective, used in phenomenography.

5.2.2 Data collection

As Booth (2001) points out, "phenomenographic research into learning is empirical in that the source of data are the learners themselves" (p. 172). The aim of the data collection is to collect expressions of the varying ways in which a particular phenomenon is experienced within a group. The predominant way to collect data in phenomenographic research projects in general, as well as in the project presented here, is through interviews. In order to maximise the richness of data collected, the interviewer enters into a dialogue with the interviewee. The interview is normally based on a script of relevant questions, but has an open form, where the interviewer encourages the interviewee to talk freely and interesting statements from the interviewee are followed up.

Phenomenographic research projects do not aim at certifying causal relationships, or at finding quantitative measurements of learning. Instead, a picture of the understanding and the learning about a phenomenon across a group is created. This goal offers to the interviewer a possibility to improvise, without losing sight of the phenomenon under investigation, during the interview, and to let the interviewees talk.

A possible way to increase the richness of data is described in Paper B. We suggest that the interviewer can deliberately vary the setting of the phenomenon that is discussed, with the aim that the interviewee should experience different contexts for the phenomenon under investigation, and express his or her experience of the phenomenon in a variety of ways. In the research presented in this thesis, this has been practised. As an example can be mentioned the two excerpts from the first interview with Albert presented in section 6.1.1 of paper A, both discussing RMI, but the interviewer introduces the discussion theme in two different contexts.

5.2.3 Analysis

The aim of the analysis is to create an outcome space consisting of a limited number of categories of description that together express the ways in which a particular phenomenon is experienced by a collective. The researcher normally forms a pool of meaning that contains

all individual expressions that has been collected. Here the researcher can analyse the individual expressions outside the context from which they originally stem in order to create categories of description that reflect experience of the particular phenomenon at a collective level. The researcher recontextualises the individual statements in the categories that he or she creates and that now reflect the different ways in which a phenomenon is experienced. This is a dynamic process where the researcher "engages in with this pool of data and seeks critical differences that can act as catalysts for an understanding of the whole" (Booth, 2001, p 172). The statements are thus analysed in the context of each individual interview and in the context of the collective. It is also analysed in the context as it is experienced by the researcher himself or herself, a context that is formed by his or her understanding of the original data, the growing results, as well as his or her experience as a phenomenographer and as specialist within the subject area. (Paper B).

This point is clearly illuminated by Paper A. It would not have been possible to interpret the students' statements of computer network protocols without an understanding of the area, since the analysis is based on the researcher's interpretations of the students' experience of *network protocols*.

The creation of the categories is an iterative process, where the researcher starts with a tentative understanding, and then, through reconsiderations and refinement, reaches a description that he or she finds relevant to address the research question and honest to the data. In a sense, the process can be seen as a discussion between the researcher, the collective of the interviewees, the pool of meaning and the developing categories of description. This way of working cannot be taken as algorithmic - phenomenography is not prescriptive and consequently does not demand that certain steps are taken. Instead it is a research approach that puts forward certain principles, while "the actual methods used vary according to the specific question being addressed" (Booth, 2001, p 172).

5.2.4 Results and deployment of results

A phenomenographic research project leads to, as has been discussed above, a set of categories that together describe the experience within a group of a particular phenomenon. The results are stripped of their original context, and can be viewed as the outcome of the research project. Because of the selection of students in the study, to cover variation in important criteria such as educational achievement and motivation, a generalisation of the categories of description can be made to groups of similar students.

However, with the goal I have formulated for my research project (section 1 in Paper A), the focus is on the application in the teaching and learning situations of the universities. A way to apply the results is to bring them back to their original context. As we point out in Paper B, the results can be applied at the individual level, at collective level or at the level of the researcher.

At the *individual level*, the researcher can turn the outcome space back on the interview, to let the results illuminate the original interview. This is practised in Paper A, where a good understanding of a network protocol is described as a capacity to shift in relevant ways between different ways of experiencing the protocol.

At the *collective level*, studies can be used as a foundation for conclusions about the variation in how a certain phenomenon is experienced in a larger group of students. An understanding

of the variation in the ways a network protocol is experienced, is certainly a good tool for teachers both when planning teaching and in the classroom. The results in Paper A indicate that teaching ought to be planned and performed in a way that encourages the students to understand the protocols in different ways.

Finally, at the *level of the researcher*, the results become a part of the researcher's understanding of his field, and thus inform future research. To a certain degree this line of reasoning is visible in Paper A, where the results from section 4, that concern variation in students' understanding of individual protocols, have informed me as a researcher in my analysis of the general concept of network protocols, that is presented in section 5. Furthermore, the results presented in this thesis will be an important building-stone in my future work concerning understanding of network protocols in the context of the course that the students take.

5.3 My choice of phenomenography in relation to my research objective

The aim with this project, as is stated in Paper A, is "to explore university students' learning of advanced computer science concepts in an internationally distributed project course" with an overall objective to improve learning and teaching of computer networks at the universities.

There are several reasons why this research is performed with a phenomenographic approach. The strong focus on the object of the students' learning is important to me, since it gives me, as a computer scientist, the possibility to learn about the students' understanding of computer science. The results of a phenomenographic research project, as mine, also reflect and express the students' experience in a relatively direct way. Results are not described in abstract ways as for example cognitive models or statistical correlation. I find that this closeness to the students' world and to the subject area offers rich possibilities to give results that can be used to obtain my initial goal, which is to improve education.

6. Conclusions and future work

In this thesis I have investigated the understanding of computer network protocols among students who participate in an internationally distributed university course in computer systems. The research has been performed with an empirical phenomenographic approach. This approach offers to me, as a researcher, the possibility to explore network protocols, as they are understood by the students. Critically different ways of understanding network protocols have been identified. It is argued that students' understanding of a protocol is related to the context in which the protocol is experienced.

Recommendations for teaching of computer systems in distributed projects are made, based on the results. Universities should teach computer networks in a way that encourages students to understand network protocols in these critically different ways, and that stimulates them to shift between these ways depending on the task at hand.

In my ongoing work which will be reported in my doctoral thesis I will explore the role of the context further and in what ways the context of an international group project, as it

experienced by the participants, interact with their learning. In the continuation of this project I will take a broader perspective, and I will also study the international group work, as it is experienced by the participants. The context of the project that the students undertook, analysed as an activity system, will be related to the learning of computer networks. The upcoming work, which also has an overall goal of improving teaching and learning in computer systems at universities, aims at identifying issues in group projects that promotes learning.

7. References

- Al-Nuaim, H. A. (1999). *Development and Validation of a Multimedia User Interface Usability Evaluation Tool in the Context of Educational Web Sites*. PhD thesis, George Washington University, Washington, DC, USA.
- Almstrum, V. (1996). Investigating student difficulties with mathematical logic. In N. Dean and M. Hinchey, (eds.), *Teaching and Learning Formal Methods*. London, UK: Academic Press.
- Ashworth, P. D. & Lucas, U. (2000). Achieving empathy and engagement: a practical approach to the design, conduct and reporting of phenomenographic research. *Studies in Higher Education*, 25, 295-308
- Baffes, P. (1994). *Automated student modelling and bug library construction using theory refinement*. PhD thesis, University of Texas at Austin, Austin, TX, USA.
- Ben-Ari, M. (in press). Constructivism in Computer Science Education, Accepted for publication in *Journal of Computers in Mathematics and Science Teaching*.
- Booth, S. (1992). *Learning to program: A phenomenographic perspective*. Gothenburg, Sweden: Acta Universitatis Gothoburgensis.
- Booth, S. (2001). Learning Computer Science and Engineering in Context. *Computer Science Education*, 11(3). 169-188.
- Budd, T. (1999). *Understanding Object-Oriented Programming Using Java*. Reading, MA, USA: Addison-Wesley.
- Carbone, A. & Kaasbøll, J. (1998). A survey of methods used to evaluate computer science education teaching. In *ACM SIGCSE/SIGCUE Conference of Innovations and Technology in Computer Science Education (ITiCSE'98)*.
- Coolican, H. (1999). *Research Methods and Statistics in Psychology. Second Edition*. London, UK: Hodder & Stoughton.
- Comer, D. (1997). *Computer Networks and Internets*. Upper Saddle River, NJ, USA: Prentice-Hall.
- Cope, C. (2000). *Educationally critical aspects of the experience of learning about the concept of an information system*. PhD thesis. La Trobe University, Bundoora, Victoria, Australia.
- Daniels, M., et al. (1998). RUNESTONE, an International Student Collaboration Project. In *Proc of Frontiers in Education (FIE'98)*.
- Daniels, M. (1999). *Runestone, an International Student Collaboration Project. NyIng report No 11*. Linköping, Sweden: Linköping University. Also available at <http://www.docs.uu.se/~matsd/NyIng.html>
- Daniels, M. , Faulkner, X., Newman, I. (2002). Open Ended Group Projects, Motivating Students and Preparing them for the 'Real World'. In *Proc. Conference on Software Engineering Education and Training*, Covington, KT, USA
- Derrick, J. & Fincher, S. (2000). Teaching Communication Protocols. *Computer Science Education*, 10(3). 195 - 202.
- Engeström, Y. (1987). *Learning by expanding. An activity-theoretical approach to developmental research*. Helsinki, Finland: Orienta-konsultit.

- Hajderrouit, S. (1998). A constructivist framework for integrating the Java paradigm into undergraduate curriculum. *SIGCSE Bulletin*, 30(3), 105 – 107.
- Harold, E. R. (2000). *Java Network Programming. Second Edition*. Sebastopol, CA, USA: O'Reilley
- Hause, M. & Woodroffe, M. (2001). *Team Performance Factors in Distributed Collaborative Software Development*. In *Proc. Psychology of Programmers Interest Group (PPIG)*, Bournemouth, UK..
- Holland, D. & J. R. Reeves (1996). Activity theory and the view from somewhere: team perspectives on the intellectual work of programming. In . A. Nardi (Ed.) *Context and consciousness: activity theory and human-computer interaction*, 257-281. Cambridge, MA, USA: MIT Press.
- Holmboe, C. (2000). A framework for knowledge: Analysing high school students' understanding of data modelling. In *Proc. Psychology of Programmers Interest Group (PPIG)*.
- Holmboe, C., McIver, L., George, C. (2001). Research Agenda for computer science education. In *Proc. Psychology of Programmers Interest Group (PPIG)*.
- Jard, C. & Jéron, T. (2000). An educational Case Study in Protocol Verification and Distributed Observation. *Computer Science Education*, 10(3), 203-224.
- Last, M. (2002). *Virtual Teams in Computing Education*. Available on-line at
http://www.cs.stedwards.edu/~lastm/SIGCSE_2002_DC_Mary_Mast.htm
- Last, M., Almstrum, V., Daniels, M., Erickson, C., Klein, B. (2000). An International Student/Faculty Collaboration: The Runestone Project. In *Proc. ACM SIGCSE/SIGCUE Conference of Innovations and Technology in Computer Science Education (ITiCSE'00)*.
- Last, M., Hause, M., Daniels, M., Woodroffe, M. (2002). Learning from Students: Continuous Improvement in International Collaboration. Accepted for publication in *Proc. ACM SIGCSE/SIGCUE Conference of Innovations and Technology in Computer Science Education (ITiCSE'02)*
- Lipnack, J., & Stamps, J. (1997). *Virtual Teams: Reaching Across Space, Time, and Organizations with Technology*. New York, NY, USA: John Wiley and Sons.
- Marton, F. (1994). In *The International Encyclopedia of Education*. Second edition, Volume 8. Eds. T. Husén & T. N. Postlethwaite: Pergamon. Also available at:
<http://www.ped.gu.se/biorn/phgraph/civil/main/2approach.html>
- Marton, F. & Booth, S. (1997). *Learning and Awareness*. Mahwah, NJ, USA: Lawrence Erlbaum Associates.
- McIver, L. (2000). The Effect of Programming Language Error Rates of Novice Programmers. In *Proc. Psychology of Programmers Interest Group (PPIG)*.
- Mester, A. & Krumm, H. (2000). Animation of Protocols and Distributed Algorithms. *Computer Science Education*, 10(3), 243 –266.
- Pears, A., Daniels, M., Berglund, A., Erickson, C. (2001). *Student Evaluation in an International Collaborative Project Course*. Presented at the Wise workshop of the SAINT conference, San Diego, CA, USA.
- Phillips, D. (1995). The good, the bad, and the ugly: The many faces of constructivism. *Educational Researcher*, 24(7), 5 – 12.
- Priebe, R. (1997). *The effects of cooperative learning on content comprehension and logical reasoning*. PhD thesis, University of Texas at Austin, Austin, TX, USA.
- Stalling, W. (1997). *Data and Computer Communications*. Upper Saddle River, NJ, USA: Prentice-Hall.
- Säljö, R. (2000). *Lärande i praktiken: Ett sociokulturellt perspektiv*. Stockholm, Sweden: Prisma. (in Swedish)

- Tanenbaum, A. S. (1996). *Computer Networks. Third edition*. Upper Saddle River, NJ, USA: Prentice-Hall.
- Tuckman, B. (1965). Developmental Sequence in Small Groups. *Psychological Bulletin*, 63, 384-399.
- Wu, C.-C. (1993). *Conceptual models and individual cognitive learning styles in teaching recursion to novices*.
PhD thesis, University of Texas at Austin, Austin, TX, USA.

Paper A:

How do students understand network protocols? A phenomenographic study

Anders Berglund. (2002). *How do students understand network protocols? A phenomenographic study*. Technical Report, 2002-006, Department of Information Technology, Uppsala University, Uppsala, Sweden.

How do students understand network protocols? A phenomenographic study

Anders Berglund

Abstract. University students' understanding of network protocols is in focus in this report. With an overall aim to improve learning and teaching in computer systems at a university level, an empirically based study has been performed. In the study, the different ways in which students understand three specific network protocols – TCP, UDP and RMI – as well as the general concept of a network protocol have been investigated with a phenomenographic research approach.

Qualitatively different ways of understanding or experiencing network protocols are discerned. The identified critical differences between the understandings are "how" or "as what" the protocols are understood, "as a part of which framework" the protocols exist, and "in what way" the protocols are described. Although experienced as different, the three protocols are understood as being parts of similarly frameworks.

Recommendations for teaching of computer systems in distributed projects are made, based on the results. Universities should teach computer networks in a way that encourages students to understand network protocols in these critically different ways, and that stimulates them to shift between these ways depending on the task at hand.

1. Introduction to this study

The work presented in this report is a phenomenographic study of students' understanding of network protocols. In this section I will briefly describe the purpose of the study and give an outline of the content of the report

1.1 Purpose of this study

The purpose of this study is to explore university students' understanding of advanced computer science concepts in an internationally distributed project-centred course. In the

present report, I will focus on the understanding of network protocols¹, and I will analyse and describe the variations in the ways that the protocols are understood.

The overall objective of my research is to learn about students' learning in computer science, in order to offer possibilities and tools for students, teachers and the universities to improve learning and teaching. While the central issue in this report is variation in *what* the students learn, in my future work, I will study the variation in *how* they learn, and the interaction between these two aspects.

1.2 Structure of this report

The work presented in this report is a phenomenographic study of students' understanding of network protocols. The content and the structure of the report are as follows.

The project-centred course the students are taking as well as its context within the universities, the Runestone initiative is described in section 2. There are technical and pedagogical descriptions of the project the students perform and a brief overview of the computer science concepts that will be in focus of the investigation.

The objectives for using a phenomenographic research approach together with a short overview of some key aspects of phenomenography in this study is presented in section 3 that also points out some methodological issues.

Section 4 presents, based on the data collected, an analysis of different ways of experiencing the three standard network protocols TCP, UDP and RMI in the group of students.

Results on students' understanding of the general concept of a network protocol are presented in section 5. The analysis is based on the results presented in section 4 as well as the empirical data.

In section 6 case studies of individual students' learning are studied in the light of the results presented in earlier sections. These empirically based case studies form the basis for a discussion about students' learning and implications for teaching.

Finally, the report is summarised in section 7.

2. The Runestone initiative, its content and objectives

The research presented in this report is performed within an international networked project, the Runestone initiative. The Runestone initiative, and the research performed within its framework, is centred around an internationally distributed project-centred course in computer systems. This section will focus on the project-based course.

¹ A (computer) *network protocol* is a set of rules that enable communication between computers. See section 2.5 for a further discussion about this concept. The terms *network protocol*, *communication protocol* and *protocol* are used as synonyms in this report.

2.1 The aims of the student project within Runestone

The learning that is investigated in this research takes place in a course about distributed computer systems and real-time programming in the Runestone initiative (Daniels, 1999). The students, who are majoring in computer science, take the Runestone course during their third or fourth year at Uppsala University, Uppsala, Sweden and Grand Valley State University, Allendale, MI, USA.

During the course, the students work in internationally distributed teams to jointly develop a software system that is intended to solve a technically advanced computer science task. In the spring term, 2001, when the data was collected for the research that is presented here, the task was to write a program that gives an end-user the possibility to "play" with a Brio labyrinth (see Figure 1).

The labyrinth is a Swedish toy, the aim being to manoeuvre a steel ball from a starting point to a final point on the board, by tilting it so that the ball moves without falling into any of the holes. The original labyrinth has, as is shown in the left picture of Figure 1, knobs that are used to control the angle of the board. The labyrinth that was used was modified to have motors to control the board and a camera to give feedback to the controlling software system, as in the right picture of Figure 1. There were 14 groups of five or six students, each group comprising by students from both universities, collaborating mainly by e-mail and Internet Relay Chat, IRC².



Figure 1 A Brio labyrinth, and a modified version with a camera and motors added

On the Web-page related to the course³ the students' project was described in the following way:

This project involves designing and implementing a distributed, real-time system to navigate a steel ball through a board by tilting the surface of the board via positioning motors. The board and ball are a modified version of the well-known Brio Labyrinth game. A monochrome digital video camera focused on the board is available to aid in navigation. The user interface is presented through a web browser. Users who play the game specify a path for the ball to follow, then get feedback on the result of their run.

² Internet Rely Chat, IRC, is a system for human communication over Internet. A computer running an IRC program can be used in a way similar to a text telephone and offers to the user a possibility to communicate with any other IRC user in the world.

³ <http://www.csis.gvsu.edu/class/brio/BrioProject/ProjectDesc/BrioProjectOverview.html>

This project has elements of real-time control (the Brio game), low-level distributed systems (multiple CPUs to gather data, drive motors), and high-level distributed systems (web interface, network programming), in addition to some demanding requirements on the language used to implement portions of the project (dynamic code loading, security).

As should be clear from the description above, it is a rather large and complex project that the students were given to solve. Several smaller sub-problems had to be solved in order to create the software system that was needed. The results of these smaller tasks were to be integrated to form a working software system. The time for the full task was limited to approximately 8 weeks to fit the universities' requirements on exam periods etc. This period is too short for the students to create a well-functioning software system. Different groups managed to finish different sub-tasks, a result that was expected by both teachers and students.

During the spring term of 2001, the students were given code that had been produced in the previous spring term and were asked to improve it by making three major changes of their own choice. Year 2001 there was one group who managed to complete the task and that produced a working software system that in large corresponded to the specifications, while the other groups presented results that still were not judged to be complete by the teachers.

2.2 The learning objectives from the universities' perspective, the official "what"

Looking at the official documentation at the two universities, descriptions of the course content can be found.

At Grand Valley State University (GVSU) the course is the senior project course for majors. The following course objectives are described:

1. Experience software maintenance and development phases.
2. Integrate experience and knowledge from other courses and apply them to a project.
3. Experience working in a distributed team.

At Uppsala University the Runestone project course is part of a large course that spans over three-quarters of the academic year. The project corresponds to one third of this course, and comes at the end of the full course. It is preceded by coursework on computer networks, real-time systems and distributed systems.

The aim of the full course is described thus:

The course provides basic knowledge of the design of distributed systems and their underlying communication subsystems with special focus on real time and embedded applications and control systems.

When the project starts, the students have encountered the teaching about the theoretical aspects of the course content, and have done several smaller practical labs. The course content is described in the following way:

[...]. Methods for achieving user transparency, eg synchronization, interprocess communication, distributed control and consistency primitives. Time handling, fault tolerance, language support and scheduling for real time control. Case studies.

Neither of the two course descriptions specify the content of the project in any detail. In fact, in the Swedish course description it is not mentioned explicitly, but looking at other official

documentation it becomes clear that a project is required, though it is not specified what kind of project is expected.

The educational framework into which the project should fit is set by these descriptions. It should be a senior project for majors, where a software system should be developed that should, according to the GVSU specification, require the application of experience from earlier courses. Uppsala University is more explicit on the content of the project: Computer networks, distributed systems and real time control.

2.3 The collaboration from the universities' perspective, the official "how"

The course objectives, as they are presented by the two universities, do not specify the technical content of the course in detail, and are still more open when discussing how the international project should take place.

The web-site for the course, that was used jointly by the two universities, gives more detailed information about how the course was planned for the spring of 2001, and applies to both universities. It states some major aspects⁴:

There are two major aspects of this project.

- Developing the software.
- Building a virtual work team.

Software development involves splitting up the work and allocating it to members of the group, and making sure that your group understands what is happening in the project. Consequently one of the major features of this project is for each group to have a regular contact with one of the teaching staff to report on the progress they are making and to ask questions that might develop.

A total of 96 students participated in the course. All groups except one (that only had Swedish participants) consisted of two to three students from each university, making up to a total of five to six students in each group. Two teachers, one from each university, taught the course in collaboration. There was also technical support with issues like operating systems and practical questions concerning the functioning of the Brio-board. At GVSU this service was offered by the technical staff of the department, while it in Sweden was given as a task to the group that was formed only of Swedish participants.

All interaction with the teachers, whether local or not, as well as the interaction with group members at the other university had to be made using forms of ICT⁵, such as chat and e-mail. An initial physical meeting was arranged in Sweden, in the US a few meetings were arranged, mainly to teach Java. Each group of students was assigned a teacher, either in Sweden or in the US. It was decided to keep regular weekly meetings with the teachers, where the groups should report the progress they had made, and discuss problems and other issues that had risen during the week.

A general overview of the planning, as it was expected to be done by the students is described at Figure 2, taken from the web-page of the course.

⁴ <http://www.csis.gvsu.edu/class/brio/BrioProject/>

⁵ *ICT* is an abbreviation for Information and Communication Technology

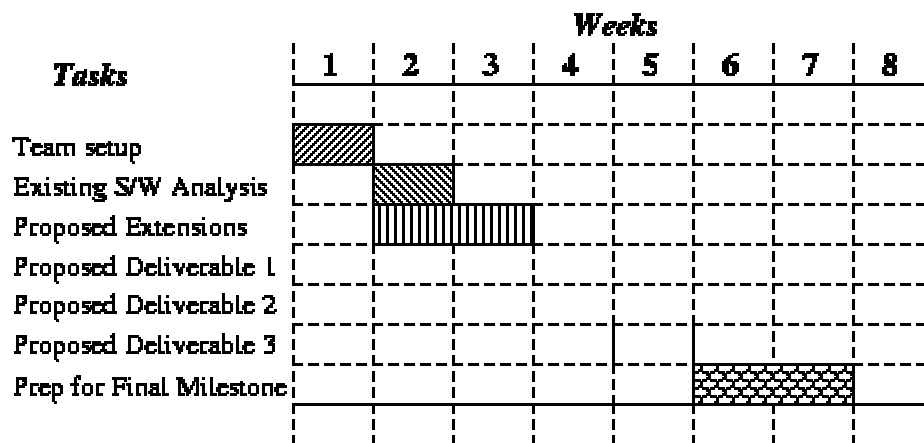


Figure 2 A time plan for the students' work in the project

The gradings were based both on the process the students went through, mainly evaluated through the weekly meetings and the outcome of the work. There were both individual and group-based components in the grading. The grading systems and the related issues are further discussed in Pears, Daniels, Berglund and Erickson (2001).

2.4 A technical description of the student project

On the web-site of the student project⁶, a technical description of the setting and the requirements for the results produced by the students is available. As was pointed out earlier in this section, the task that is given to the students is to produce a software system that makes it possible for an end-user to control the labyrinth using any web-browser on Internet.

In Figure 3 the main components of the project are found. The system as a whole consists of some inter-connected sub-systems that might run on the same computer or on separate computers. The hardware, operating systems, standard communication solutions etc are supplied by the two universities, while the task of the students is to write the required software.

The end-user should have the possibility to draw a path that he or she wants the ball to follow. He or she should then be able to follow the movements on the screen that the ball makes on the physical board. The client⁷, written in Java, offers this visual interface to the end-user.

⁶ <http://www.csis.gvsu.edu/class/brio/BrioProject/>

⁷ The concepts of a *clients* and *servers* are fundamental within the field of computer communication. A client, as an active participant, is a computer that initialises a dialogue by sending a request for data or for another service. The request is sent to a passive server that answers requests to provide services and normally sends data or offers a service as a reply to the request. The two concepts are normally referred to as a pair.

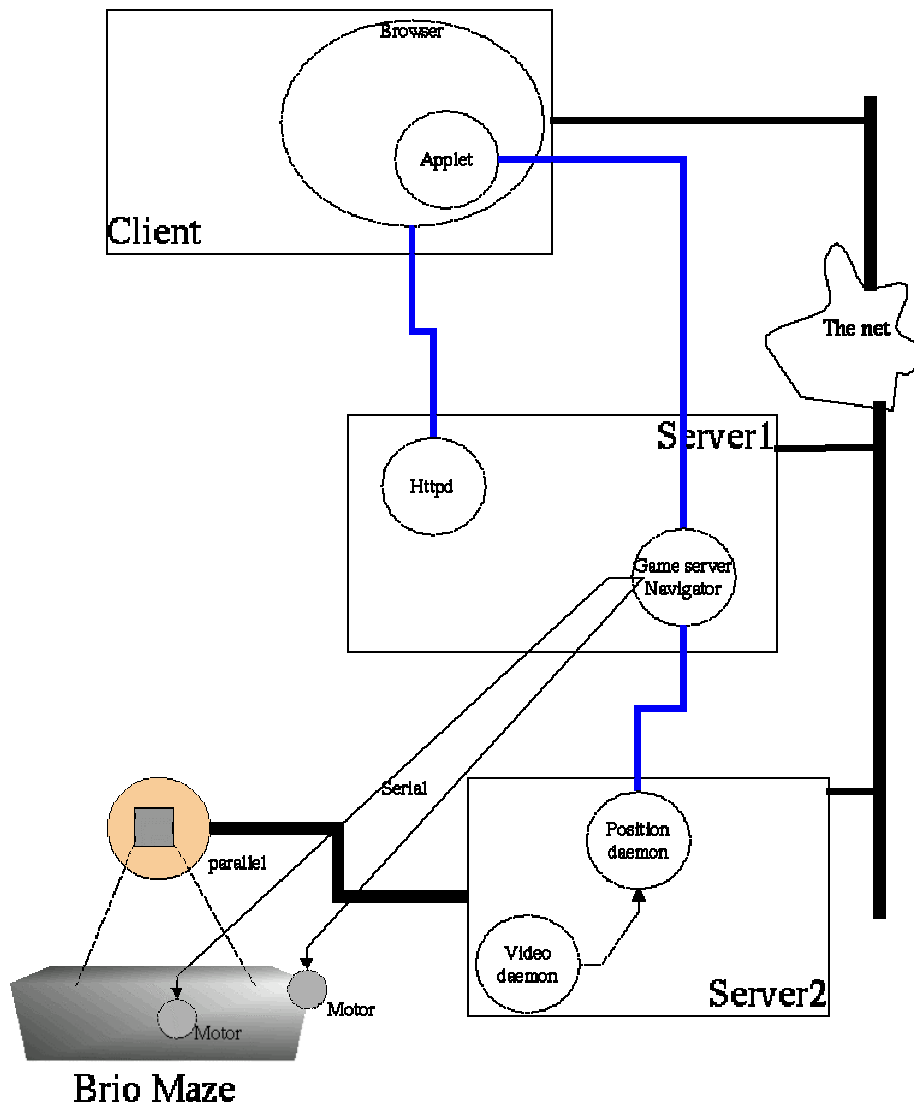


Figure 3 The architecture of the Brio system

The movements of the board are controlled by step-motors⁸ that have a serial connection⁹ to the game server (marked as server 1 in Figure 3), which can be seen as the centre of the system.

The system needs to keep track of the movements of the ball in order to be able to control the motors in a relevant way. This requires feedback, which is fed into the system through a camera that constantly supervises the board, as seen in Figure 1. The camera is connected to the video server (server 2 in Figure 3) through a parallel connection.

⁸ A *stepmotor* is a type of electric motor, which is fed with electric pulses. For each pulse, the motor turns a certain angle. This feature makes stepmotors useful in computer-controlled devices.

⁹ Data that is transmitted in *serial* mode, in contrast to parallel mode, is transmitted one bit (or unit) at the time. All bits use the same (physical) connection. Data that is transferred in *parallel* mode is sent in parallel simultaneously on several lines, one bit (or unit) on each line.

The purpose of the video server is to interpret the images from the camera and transfer the information the camera offers into information about the ball: its position, speed and direction of movement etc.

The game server acts as the coordinator of the system, getting information from the camera through the video server and information on user's demands from the applet¹⁰. From this information the game server should calculate how the motors should move, and send the required information to the motors for these movements to take place. This server should also provide the information about the movements of the ball and the status of the system to the applet.

The hardware is available at each university, and except for the cameras, where different brands with different characteristics are used, it is basically the same at both places. The Brio boards and the physical equipment are getting old, and the variations between the different boards are considerable. These variations between the boards add a difficulty to the task: The programme system ought to be written in a way that makes it work correctly on most of the boards.

As should be clear from this description, there are several places within the system where communication between two computers or virtual machines¹¹ or a hardware controller and a computer takes place. The focus of this study is the students' experiences and understanding of the network protocols that can be used in this project, and as will be shown in this report, there are a number of possible ways of understanding them.

2.5 The network protocols taught

As noted previously different aspects of computer and data communication are basic components of the Runestone course curriculum. Many different network protocols have evolved over the years with different properties and for different applications. However, a consensus has emerged on a few of all possible protocols that could be used being relevant for education and their roles in education (Derrick & Fincher, 2000). This section briefly describes three standard communication protocols that are frequently taught, and that can be used by the students in their project work to different degrees. For deeper understanding of the different protocols, as well as the context to which they belong, refer to standard literature in the field, such as Stalling (1997) and Tanenbaum (1996).

To communicate between computers a set of rules is needed, specifying what should be sent and how it should be interpreted. Stallings (1997) defines network protocol in the following way:

Set of rules that govern the operation of functional units to achieve communication (p. 780)

¹⁰ *Applets* are Java programs that are intended to be run in a web browser, such as Netscape, or by a dedicated appletviewer. Applets are frequently used to implement graphical interfaces.

¹¹ A *virtual machine* can be described as a simulated computer that runs on another computer. In other words, a virtual machine is a program, that, when executed, behaves as a computer with well-defined properties. Virtual machines are one of the underlying techniques for platform-independent programs. Java that can be run on different kinds of computers and in different environments has a virtual machine. Java's virtual machine is (at least in theory) the only program that has to be rewritten to run Java in a new environment.

The protocols contain information about message formats, formats for control information, responses to messages, timing requirements as well as information about how errors or other unexpected events should be handled.

Network protocols are standardised. Software that offers the programmer the routines that are needed to handle the communication has been developed for the important protocols. As an example can be mentioned that TCP software (Transmission Control Protocol) offers, among other routines, procedure that listen for incoming messages, that sets up connections, sends messages and closes down connections.

This report mainly concerns the students' understanding of some standard communication protocols: TCP, UDP and RMI¹². To different degrees it is possible to use these protocols in their project and they are normally described as important protocols for computer communication.

TCP, UDP and RMI are all *end-to-end protocols*. This means that they offer services that a program developer or programmer can use when developing application programs for end-users. A programmer who is a user of these end-to-end protocols does not normally need to think about the underlying layers. For example, he or she can completely disregard the physical appearance, as voltages used or frequencies used by the communicating computers to transmit a message. In other words, one could say that a protocol "is" a set of rules, but the concept of network protocols also captures some elements of data semantics.

TCP, *Transmission Control Protocol*, is undoubtedly the most widely used of the three protocols, since it forms the basis for data transfer over Internet and other networks based on the same technology¹³. TCP offers connection-based services.¹⁴ This means that a programmer who uses TCP needs to make his or her program establish a connection in order to communicate with another computer, similar to when we need to dial a number and wait for an answer to be able to communicate over the telephone. It is a reliable protocol, in the sense that the sending program gets a confirmation or acknowledgement from the receiver that the information has arrived.

UDP, *User Datagram Protocol*, is a connectionless protocol. This means that a sending computer does not get any confirmation if the data sent has reached its destination or not. This makes it unreliable, or unsafe. Still, it is useful in applications where some losses can be accepted, but where speed is important, such as video conferencing.

¹² TCP, UDP and RMI are abbreviations. Within the field of computer science the abbreviations are usually used instead of the full names.

¹³ There is a common convention of writing *Internet*, with a capital *I*, when referring to the global Internet, and of writing *internet* when discussing independent internets. An independent *internet* or *internetwork* is a network that in its turn consists of a set of networks that are connected in a way so that they interconnect to form a whole network. The parts that make up an internet can be Local Area Networks (for example within a building) or other internets.

¹⁴ The word *connection* can have different meanings. As I use the word in this report, a connection has to be created or "set up" between two of the many computers on a network. Setting up a connection resembles in many ways making a telephone call.

RMI, *Remote Method Invocation*, is closely related to the object-orientation¹⁵ in Java, since its purpose is to allow Java objects, distributed over a network, to communicate. To a programmer, RMI provides access to routines (called methods with the terminology used) on remote machines as if they were available on the local computer.

Data that is transferred using UDP or TCP does not have any kind of meaning assigned to it. These protocols are restricted to the transmission of data, and leave issues concerning its interpretation to be implemented by the application programs; that is, to the programs that use TCP or UDP. RMI, on the other hand, is intended for transfer and manipulation of objects, entities that have intended meanings or interpretations. This higher level of abstraction clearly makes RMI a more complex protocol. Consequently security policies and related issues become more demanding for the programmers.

3. *The study*

I have chosen to use primarily a phenomenographic approach to address my questions about students' learning. The results of a phenomenographic research project are, as is argued by Marton and Booth (1997), insights into qualitatively different ways in which a phenomenon is understood.

A phenomenographic research project thus aims at analysing and describing the variation in ways in which central concepts of the subject matter are understood or experienced by the learners. In my study, university students' experience of computer networks is in focus, and phenomenography offers the possibility for me, as a researcher, to investigate the students' own experience of network protocols.

One of the keystones of phenomenography is that phenomenographic researchers can arrive at a limited number of qualitatively distinct categories of description which succinctly and adequately cover the countless ways in which a phenomenon can be experienced, or understood. The results are articulated in a set of qualitatively distinct categories of description that express the variation in how a phenomenon is experienced by the learners, called the outcome space. The outcome space that I arrive at thus gives me, as a computer scientist and phenomenographer, the possibility to relate the students' understanding of computer network to the goals of the education, as it is expressed in the course descriptions and as I, as computer scientist, understand the protocols. The strong focus on the object of the students' learning is an important feature of phenomenography as a research approach in the research that I present in this thesis, maintaining as it does the subject matter that is of prime interest to me as a teacher.

In the next sub-section, I will discuss aspects of the students and the interviews, while the larger part of the section will focus on the aspects of the use of phenomenography in this research project. Finally, I will discuss some methodological decisions that I have taken.

¹⁵ *Object-orientation* is based on the idea that a program consists of a set of communicating entities. The execution of the program takes place within these entities, and in the interaction between them. Java and C++ are programming languages that support this style of design and programming. There is a vast literature on object-oriented programming and object-oriented programming languages. Budd (1999) discusses the ideas behind object-orientation and Java.

3.1 *The interviews*

Ten students have been selected as candidates for interviews in the US and nine in Sweden on two occasions during the spring of 2001. The students were selected to obtain a variation in backgrounds, earlier study results, gender, age, motivation to take this course as indicated in a background questionnaire etc. The students participated on a voluntary basis in the study. They did not get any credit for participating, but got two movie tickets each as a sign of recognition. With a few exceptions, the students attended both interviews. Those who did not attend all had different reasons for this, including illness, exchange studies abroad, and shortage of time.

The interviews were carried out by the author of this report, in Swedish with the students in Uppsala and with a Swedish exchange student at Grand Valley State University and in English at Grand Valley State University and with an exchange student from a European country studying in Uppsala. The first interview was made a few weeks after the course had started, while the second was carried out after the end of the course. The interviews have been transcribed by native Swedish and English speakers respectively. Excerpts of interviews in Swedish are translated into English by the author of this report.

The results presented in this report are based on the first interviews in both countries as well as the second interview in Sweden. Nine of the interviews from the US have been used and five from the first set of interviews in Sweden. From the second set of interviews in Sweden four interviews are used. Some of the interviews from Sweden have been impossible to use, due to poor quality of the recording, while other interviews have been judged as less interesting for the research project. The second set of interviews in the US is currently being transcribed and will, together with all relevant Swedish interviews, be available for future research.

Excerpts from interviews are presented in this report to illustrate different aspects of the categories created and to make the results open to inspection. When referred to in the text, the students are assigned names by me that are not related to their real names. All students who are currently studying in Sweden have been given names that start with an "S", while names that start with an "A" indicate that the student is currently studying in the US. Alec is thus an American student, while Samuel and Sven are Swedish students. In the excerpts of the interviews the statements of the students are preceded by their name and the number 1 or 2, indicating if the statement is from the first or the second interview. Staffan2 is thus intended to indicate a statement made by Staffan during the second interview.

Since there are considerably fewer females than males taking the course, I have chosen not to indicate if any particular quote is from an interview with a male or a female. Four of the students interviewed were female. Instead I refer to all students by "he". The purpose of this is to respect the anonymity of the students. The females could, since they are few, easily be recognised by schoolmates or teachers. The research design and the way of presenting the data that I have chosen make it impossible to address gender issues in the current report. Since the data collected contains statements from individual students, it could be possible to address gender issues in my later research in this project.

3.2 The use of phenomenography as a research approach in this study

The process of a phenomenographic research project is not algorithmic, and does not in any way follow a specific pre-defined path. The result does not describe causal relationship, but instead focuses on more complex understandings and relations.

Phenomenography as such offers a framework of theoretical and practical tools, but leaves to the researcher to design his or her research. In the coming sub-sections I want to draw attention to some specific aspects that have become important during this phenomenographic research project. Marton and Booth (1997) give deeper insights into phenomenography in general and discuss aspects that are not touched on below.

3.2.1 Collecting data

As stated by Adawi, Berglund, Booth and Ingerman (2002) a goal of the data collection is to maximise the variation in the pool of meaning. In the current study this means that I, as a researcher, am eager to collect material that can support a creation of a rich and expressive picture of the different understandings of network protocols. Two obvious ways of getting a large variation is by selecting students in a way that you can hope that they will express different understandings, and by interviewing the students in a way that encourages richness in their answers.

When making a selection of students, as a researcher I have tried to construct a sample, where students with different interests, backgrounds, earlier results, attitudes to their studies etc are represented. Data for this selection were taken from different sources. Important information came from a questionnaire before the start of the course, where the students were asked about their expectation. Previous study results in computer science, as well as study results from other subject areas that were available in the records of the two universities, were also used.

As a researcher, you start an interview with a set of open questions, based on your ideas of what you want to learn from the interviewee. To the interview you bring your understanding of the topic for the interview, in this case computer networks, as well as your understanding as a phenomenographer. During the interview, which normally is semi-structured, the researcher interacts with the interviewee in order to explore his or her understandings of the phenomenon in focus. The researcher can ask follow-up questions, nod or in other ways encourage the interviewee to reveal his or her experience of the phenomenon that is in focus during the dialogue.

The outline for the semi-structured interviews can be found in appendices of this report. It is worth pointing out, that the outlines only served as a framework and as a guideline for what issues that should be discussed. There were many improvisations during the interviews, in order to follow up statements by the students and in other ways try to increase the variation in the ways of speaking about the phenomenon as much as possible. As can be seen from the scripts, several issues were discussed that are not further elaborated in this report. These topics are open for future analysis.

The openness to the experiences of the interviewee, which is an important feature of a phenomenographic research project, creates possibilities for the researcher to draw new conclusions about the interviewees' ways of experiencing a phenomenon, but does not in any way imply that the researcher can get a full picture of the understandings of an individual. Instead as a researcher you only get limited insights into the interviewee's experience of the

phenomenon. To draw this conclusion still further: The interviews are learning occasions not only for the researcher, but also for the student. This is a dynamic process, where the interview influences the interviewee's as well as the interviewer's experience of the phenomenon.

3.2.2 *Analysing data*

The goal of the analysis, as well as the phenomenographic research project as a whole, is to reveal the experiences of the phenomena (here network protocols) in focus of the study at hand. The non-algorithmic structure of a phenomenographic research puts the interaction between the researcher and the data in the centre of such a process. Statements made by the students are decontextualised, that is, taken out of the context¹⁶ or meaningful background in which they were originally uttered, to be recontextualised, that is, put into another context. The categories of description that are created in this way are the researcher's recontextualisation of the data. This recontextualisation is made in an iterative process, where the researcher starts with a tentative understanding, and then through reconsiderations and refinement reaches a description that he or she finds relevant to address the research question and honest to the data. In a sense, the process can be seen as a discussion between the researcher, the pool of meaning and the developing categories of description. In other words, when I, as a researcher, create categories of description my goal is to describe the different ways of experiencing network protocols that I have met in the group of students.

The results, as categories of description of certain phenomena, are to be interpreted at the collective level. A tool for the researcher, when studying the collective level, is to look for logical consistency for the categories created. As pointed out by Marton and Booth, such a logical consistency often takes a hierarchical form: An advanced way of experiencing something can be "more complex, more inclusive (or more specific)" (p. 107) than another, less advanced way of experiencing the same thing. The framework in which the network protocols are experienced will be described and studied as structures in this report. It is worth noting that the categories and the hierarchy are interpretations made by the researcher, and are expressions of the researcher's view on data, combined with his/her understanding of the subject matter and of phenomenography as a research approach. That is, the analysis is an aspect of the researcher's experience of the students' experiences. A further discussion on issues concerning the perspective of the researcher can be found in Adawi, Berglund, Booth and Ingerman (2002).

I also want to draw the attention to an aspect concerning the translation and interpretation of the interviews. In the excerpt below Sven has misunderstood, or does not remember, the correct meaning of the abbreviation RMI.

Sven2: Remote, and then there is Indication, but what is the other, in the middle then. I am not so
Interviewer: Method
Sven2: Remote Method Indication
Interviewer: And what's that?

¹⁶ The word *context* has many uses in educational research. For a discussion of its use in phenomenography, and especially aspects on who is experiencing the context, see Adawi, Berglund, Booth and Ingerman (2002). Throughout this section of this report the word context can be read as "meaningful background"

This can have several explanations, and as a researcher one should be careful not to draw any firm conclusions. Apart from indicating unfamiliarity with the concept, it can be a matter of the language: Since his mother tongue is Swedish, it is not obvious that the word "invocation" is a part of his normal English vocabulary. A possible Swedish translation is "anrop", a word that does not resemble it. The other two words offer less difficulty: The Swedish equivalence of "method" is "metod"; here there are clearly similarities. The word "remote" is frequently used within the field of computer science and is most probably part of the English vocabulary of an advanced undergraduate student in computer science.

Another language related issue, that has appeared as a small problem is the distinction between a generic *internet*, as a set interconnected network and the global *Internet* (see footnote on page 35 for a discussion about the difference between the two words). Neither in Swedish nor in English is it possible to hear a difference between the two in the statements made by the students. The context in which the word is used only occasionally offers help for an interpretation. As a consequence, the distinction between *Internet* and *internet* has to a certain degree to be guessed. I have preferred to use the word *internet* in cases when I have hesitated about the interpretation, since *Internet* is one specific *internet*. This means that the word *internet* covers both generic internets and the global Internet.

3.3 *Some methodological decisions*

In this section I will discuss some of the methodological decisions I have taken during this project and their implications for the results I present, based on the insights I have gained during the work, my considerations of the research questions, and discussions with colleagues within computer science.

In the analysis I decided not to discuss those few excerpts from interviews where students gave the plain answer "I do not know" as an answer. They are excluded, since they do not express a specific way of experiencing the protocols.

Differences between expressions *within* the categories have also not been explored. Differences within categories could relate to how well students articulate their understandings or how sure they are of the relevance of what they say, as the following example (that will be further analysed in section 4.1.3) illustrates. One could speculate about possible differences in the understandings expressed by Albert and Allan in the following interview extracts:

- Interviewer: Um, what is TCP?
Albert1: TCP, um, it's um, part of the internet protocol. It's used with part of the internet protocol typically. Um, it's one of the methods of communications, I don't know a whole lot about it, as far as the whole, um, design construction behind it.
- Interviewer: Um, you've talked about TCP. What is TCP?
Allan1: Basic concepts.. it's a protocol language, I guess you can call it, that you just put your data in and it's sent across the network using the different protocols you want to use, like IP or.. I can't think of any other protocols off the top my head. But it is more or less a packet that you put your data in and you send across and it has some features such as, keeps things in order when you, um, when you get to the, um, when it gets to the server you want to go to.

In section 4.1.3 I develop my arguments for interpreting these excerpts as expressing an understanding of TCP that I describe as "a connection over a network".

The categories of description that are created describe *qualitatively* different ways of experiencing a phenomenon, and are the smallest unit of the analysis. I use the term *category of description* as it is presented in Marton and Booth (1997). When discussing the phenomenographic research they state that:

[...] the individual categories should each stand in clear relation to the phenomenon of the investigation so that each category tells us *something distinct* about a particular way of experiencing the phenomenon. (p. 125, my italics)

This use corresponds well to the definition of the word *quality* that is found in Webster (1979) "that which belongs to something and makes or helps to make it what it is; characteristic element; [...]". It would be possible to argue that one of the students above expresses this quality "better" than the other, with regard to some criteria. However, in this phenomenographic research project I have decided not to study this kind of difference; it is the quality of the *categories* that is in focus, and not the quality of the ways in which individuals express themselves.

Nor have I made any quantitative analysis of the answers the students gave. A phenomenographic research project is designed to be understood across a collection of people, a population of interest, and the results do not describe individuals. A statistical analysis would demand that individuals or individual expressions be counted. As already described, the selection of students and the interviews aim at obtaining rich data for a phenomenographic study, and a different approach would need to be taken to get a good sample for a statistical study.

4. Students' understanding of individual network protocols

The students were asked during the interviews to describe what they meant by TCP, UDP and RMI. When opening the subject of discussion, the three protocols were treated as three different topics by the interviewer. Later in the conversation about specific protocols comparisons were frequently made, often on the initiative of the students.

The opening question was normally "What is TCP?" followed by similar questions for the other protocols. There was no particular order in which the protocols were introduced by the interviewer. On the contrary, often the decisions about the order of the protocols were taken as a consequence of the flow of the conversation, for example by the interviewer referring to earlier statements made by the student.

This section focuses on the students' understanding of TCP, UDP and RMI. Aspects that will be discussed are students' understandings of the meaning or use of the protocols, their technical characters, and the framework to which they belong.

4.1 Students' understanding of TCP

Three qualitatively different ways of experiencing TCP have been identified within the group of students. Table 1 gives an overview of the categories of description. Differences between the categories are found in the framework of which the protocol is experienced as a part, as what the protocol is experienced and in what way it is described.

Table 1. Categories of description for TCP.

As what is TCP understood?	
1.	TCP is understood as safe communication between two specific computers and is described in a concrete way
2.	TCP is understood as a connection over an internet and is described in an abstract way
3.	TCP is understood as a standard communication tool in a framework that includes and goes beyond computer networks, and is described at a meta-level

A fundamental difference between the three ways of experiencing TCP is the framework of which the network protocol forms a part. Similar experiences of frameworks have been identified for the students' understanding of UDP and RMI, as well as for their understanding of the general concept of a network protocol. In the coming sections I will explore the understandings of TCP, that I have identified.

4.1.1 An overview of different ways of experiencing TCP

The first category describes an understanding where TCP is related to an experienced framework that consists of two specific computers, where data is transferred between these two computers. The network only exists as a background to this transfer. In the second category the framework is broader: TCP is experienced as integrated with and a part of an internet. Finally, in the third category, the framework has its limits outside an internet and the world of computers, and also takes human decisions into account. Here TCP is the result of decisions taken by a committee.

TCP is, in all the three categories, experienced as an inseparable part of the framework to which it belongs. The protocol is integrated with specific computers, the network, or the world outside the network. A protocol needs its surroundings for its existence, and could thus not exist without the world of which it is a part. Neither would its surroundings be the same without the protocol.

The experiences of what TCP "is" or "means" differs between the three categories. The "meaning" of the protocol is closely related to the experienced framework of which the protocol is a part. When TCP is related to two specific computers, it is understood as a safe¹⁷ way of communicating, that is, a user can know that no data is lost during the transfer. In the second category TCP is understood as a connection over the network. A connection has to be created or "set up". Once the connection is there, it offers safe communication. In category three TCP is experienced as a part of a framework that reaches outside the world of computers. TCP is a standard tool for communication; as a standard it is decided by a committee. The fact that it is a standard is what makes it useful.

When talking about TCP, as well as the other network protocols, the students frequently referred to the technical characterisation, or technical properties, of the protocol, telling the interviewer "how the protocol works". No variation in the understanding of this technical characterisation for TCP has been found in data. TCP is experienced as a protocol with

¹⁷ In the analysis presented in this report, I use the word *safe* as synonymous to the word *reliable*.

acknowledgement in the three categories. Rather, the technical characterisation is thus what gives a specific protocol its character that makes it possible to recognise TCP as TCP or UDP as UDP etc.

An analysis of the different aspects of the categories of description for TCP is summarised in Table 2. The first column indicates what TCP is experienced as. The second column focuses on the world or framework in which TCP is experienced. The next column shows the technical characteristic that is understood for TCP. Finally, the last column indicates in what way TCP is described.

Table 2. Aspects of the different categories of description of TCP

	As what is TCP experienced?	As a part of which framework is TCP experienced?	What is the technical character of TCP?	How is TCP described?
1.	Safe communication	A framework of two specific computers	TCP is a protocol with acknowledgement	In concrete terms
2.	A connection	A framework of an internet		In an abstract way
3.	A standard for communication	A framework of a world outside the network		On a meta-level

A relation between the experienced frameworks expressed in the three categories can be identified: The framework is wider in category 2 (an internet) compared to 1 (two computers), and still wider in category 3 (a world outside the network). Thus, there is a hierarchical structure that relates to the framework in which TCP is experienced as a part. A similar structure can be found when looking at how TCP is described: The level of abstraction increases from category 1 over category 2 to category 3. In the higher categories, the TCP is experienced as a part of a wider framework and in a more abstract way. In a way, the categories can be seen as inclusive: 1 is included in 2, and 2 in 3.

It is often the case that the students shift between two (in rare cases three) ways of experiencing TCP, as will be discussed later in section 6.1. However, many of the students do not shift between different ways of experiencing the phenomena.

In the following sections I will show some data and present the arguments that made me draw these conclusions. Since the material from the interviews is rich, only a small selection of excerpts can be presented in this report¹⁸.

4.1.2 TCP as a safe communication between two computers

This category of description describes an understanding of TCP where the protocol is experienced in a framework of two specific computers that communicate. The protocol is explained in concrete terms and is experienced as safe communication.

Andy's statements during the first interview clearly show the focus on two computers:

¹⁸ The author can on request supply the complete interviews subject to guarantee that the integrity of the interviewees will not be abused by any form of unauthorised publication

Interviewer: What is TCP?

Andy2: That is ... you communicate with .. between client and server with TCP packets.

Here, Andy describes TCP as communication between a server and a client. The explanation given refers to two specific computers: a client and a server. The concept of client-server implies that the issue of communication is integrated with the computers, since a server and a client could not be imagined without communication between the two in the field of computer science. The communication is the basis for the existence of a server and a client.

In the continuation of the dialogue, the issue of safe communication is raised by Andy:

Interviewer: What is a TCP packet?

Andy2: That's a type of packet, that one sends, that contains also ... so that one can get... one must. It is a safe communication so that one knows ... three-way, so that one always knows it arrived or not, in contrast to UDP.

Andy here points out that TCP is a safe communication and says that TCP informs whether data, in the form of a TCP packages, has arrived or not. Also, by mentioning "Three-way" he indicates that there is an acknowledgement sent by the receiving computer.¹⁹

Staffan also talks about his understanding of TCP as a safe communication between two specific computers during the second interview:

Interviewer: What is TCP IP then?

Staffan2: It is sort of ... a safe connection we send a stream of data back and forth and it's checked that there is no errors and suchlike [...] we've read about this

Staffan answers the question concerning TCP by saying that there is a stream of data "back and forth" in order to check that there will be no errors. The expression "back and forth" indicates that there are two well-defined end-points, between which data is sent. He also expresses the view that it is a safe protocol by saying that TCP checks that the stream of data "is no errors". He uses the expression "safe connection" to explain that TCP offers safe communication. By the expression "safe connection", I understand that he points out that the communication is safe. As was mentioned in section 2.5, my use of the word "connection" is somewhat different in this report. The words "back and forth", as well as his discussion of errors, clearly indicate to me that he uses the word in a way that differs from the usage I have chosen in this report.

Sebastian explains safely during his second interview his understanding of TCP and particular the use of acknowledgements to make sure that information arrives. In the following excerpt he starts by telling in what parts of the project his group has used TCP:

Sebastian2: No, down from the server and down to the hardware, the bits where we use TCP/IP.

Interviewer: What is that?

Sebastian2: It is...it is a communication protocol which uses...ack?

Interviewer: Acknowledgement?

¹⁹ *Three-way* indicates in fact that there is an acknowledgement sent to confirm the arrival of the first acknowledgement. This technique is used when setting up a TCP connection between two computers to make it possible for the computers to agree on different parameters for the communication.

Sebastian2: Yes, an acknowledgement, That is, that I know that the information I send has arrived correctly, and what comes back has also arrived. There is a bunch of other stuff that I have to look out for.

He says that an acknowledgement is sent by the TCP²⁰ protocol, and that there is a control performed by the protocol if the confirmation arrives or not. By the words "I know that the information I send has arrived correctly", he indicates the reason for the acknowledgement: To get a safe communication between the two specific, communicating computers that he is focusing on.

Since the interview with Sebastian is made in Swedish and later was translated into English, a word about the hesitation in the third statement of the excerpt of the interview might be required. When explaining what a communication protocol is Sebastian first has difficulties finding a Swedish word (*bekräftelse*), so he turns into English and starts saying "ack...", for acknowledgement in a hesitant voice. As an interviewer, I then present the Swedish word to him, which he uses in the next statement. It is worth noting that Sebastian studied computer networks and TCP as an exchange student in another language before taking this course. His hesitation can therefore be interpreted as a question of language and terminology and probably not as related to the concept as such.

As we have seen in this section, this category of description describes an understanding of the TCP, where the protocol is used for transferring data between two specific computers. TCP uses acknowledgements to verify that the information arrives safely at the destination. Clearly, all descriptions relate to concrete entities, like specific computers, packages of data or confirmations.

4.1.3 *TCP as a connection over a network*

This category expresses an understanding where TCP is related to and integrated with an internet as a whole. TCP offers a possibility to create connections over a network. The understanding of the protocol is expressed in abstract terms.

When Albert was asked what TCP is during the first interview, he talks about TCP as a part of an internet:

Interviewer: Um, what is TCP?
Albert1: TCP, um, it's um, part of the internet protocol. It's used with part of the internet protocol typically. Um, it's one of the methods of communications, I don't know a whole lot about it, as far as the whole, um, design construction behind it.

Albert talks about TCP as an internet protocol and mentions that it is a part of an internet.

Axel also expresses a way of experiencing TCP as a part of the Internet, that is as a part of an internet, as can be seen the following excerpt of the first interview:

Interviewer: [...] Um, I want you to talk about TCP.
Axel1: TCP/IP?
Interviewer: Ya.

²⁰ IP, Internet Protocol, is an underlying protocol, providing the basic services used to implement TCP. TCP, together with the underlying internet protocols are often referred to as *TCP/IP* or the TCP/IP stack

Axel1: TCP/IP is how almost everything on the Internet communicates. IP addresses and everything, and that's um, one of the fundamentals behind RMI also. One could give it the address where the object is [...] the IP address [...]

Beginning by saying that it "is how almost everything on the Internet communicates", he indicates that he regards the protocol as very important and as a part of Internet as a whole. The importance of the protocol is emphasised by his reference to IP-addresses²¹ and to RMI.

Another student, Allan, also stresses that TCP is a part of an internet:

Interviewer: Um, you've talked about TCP. What is TCP?

Allan1: Basic concepts.. it's a protocol language, I guess you can call it, that you just put your data in and it's sent across the network using the different protocols you want to use, like IP or.. I can't think of any other protocols off my head. But it is more or less a packet that you put your data in and you send across and it has some features such as, keeps things in order when you, um, when you get to the, um, when it gets to the server you want to go to.

He says that TCP is a protocol language²² that is used for sending data across a network. In this way, he clearly indicates his view that TCP is an integrated part of the network. He then explains its main feature, as he sees it: The order of data is kept when sent to the application program through the TCP socket²³, although data physically might have arrived to the server in any order. This makes the protocol safe.

In the same interview with Axel that was mentioned above, he talks about TCP as a connection:

Interviewer: But what are the specifics about the TCP protocol, some characteristics of it?

Axel1: Ah, some characteristics of it. Well, I don't know a lot of the underlying characteristics of it [...] numbers with dots [...]

Interviewer: You can't tell me, you can't say anything about the differences between UDP and ...

Axel1: I don't really.. UDP and TCP are different in that TCP is a connection protocol and UDP is connectionless. Um, I've never quite completely understood exactly how one's connected and what is not. So, that is the most I can really say.

Axel tells the interviewer that he does not know any technical details, and continues by pointing out the important difference between TCP and UDP: TCP is a connection-based protocol, in contrast to UDP.

The entities Axel mentions are described in an abstract way: He refers to other protocols in a comprehensive line of reasoning, instead of talking about packages or flows of data.

²¹ An *IP address* is a unique 32-bit number that is assigned to computers on an internet. This address is used for all communication with the host. IP addresses are written as four decimal numbers with dots between. As an example 130.238.8.89 is address of the computer used by the author of this report.

²² The term *protocol language* refers to a formal language, not to a natural ("spoken" "human") language, within the field of computer science. A formal language is used to express statements about calculations in a general sense as for example giving instructions to a computer.

²³ A *TCP socket* is an endpoint of a connection between two computers originally created in a Unix environment. It is used by a programmer as a mechanism for transferring data.

In this section, a way of experiencing TCP has been described where the protocol is seen as a connection over an internet, and at the same time, as an integrated part of the network. The protocol is build on a technology with acknowledgements, and is experienced as a connection.

4.1.4 TCP as a standard communication tool

This category of description expresses an understanding where TCP is seen as a part of an experienced framework that goes outside networks to humans decisions about the protocol.

In the following part of the first interview, Adam expresses such an understanding:

Interviewer: So, what is TCP then?
Adam1: Well that I have studied in some networking classes um, Transfer Control Protocol, something along those lines. Um, that is just a protocol for computers to communicate with each other. That's a standard that was created by a committee somewhere, sometime, and it's just a, it's a protocol, meaning that it's, it specifies um, the layout and the size and what's in the header and footer of packets being sent across networks and things like that. So it's, it's a standard communication tool

He argues that TCP is a standard that is created by a committee. The form of the packages sent is the result of conscious decisions, taken by the committee.

Later, when the choice of TCP instead of RMI as the principal protocol for their project is discussed, he continues:

Interviewer: Yes, but can you tell why you have chosen TCP?
Adam1: Right, it's for one thing it doesn't require this registry running in the background. It's sort of a universal standard so that, you know, our applet can be run on any computer anywhere and still communicate with the game server running on Linux or whatever. Um, so I guess just being a standard and being more flexible than RMI.

TCP has two advantages over RMI, according to Adam. One is technical: TCP is simpler since it does not require a complicated background program to be run. The other advantage is that TCP as a well-defined standard increases the flexibility.

Adam compares the use of RMI and TCP on several occasions during the whole interview. From his remarks above and comments in general, it is clear that he takes for granted that TCP offers safe communication. It is never spoken out aloud, rather it can be seen as a condition for the rest of the conclusions.

Adam reasons about TCP without making direct references to the technical structure or the entities in the communication process. Rather he talks about standards, flexibility, and tells the interviewer that size and design of packages are decided, without mentioning what the packages look like. In this way, he talks about properties of the protocol in an indirect way, from a position outside the two protocols, telling the interviewer how decisions about the protocols are taken and what the consequences of the decisions are. This can be seen as reasoning at a meta-level²⁴ about the protocol.

²⁴ I use the term *meta* in words like meta-level to indicate a reasoning that goes "beyond, higher, transcending" (Webster, 1979). A meta-level reasoning about a protocol goes beyond discussions of the properties of the

In this category of description, TCP is seen as related not only to computers, but to human decisions as well. The discussion is mainly focused on how decisions are taken and the consequences of the design, and is thus held at a meta-level.

4.2 *Students' understanding of UDP*

Three qualitatively different ways of experiencing UDP have been identified. The categories of description that have been created for UDP, and that are presented in Table 3, share its structure and main properties with the findings for TCP. The categories of description as they are presented in Table 1 for TCP are thus basically the same as for UDP. The important difference that has been identified is that UDP is recognised as an unsafe or connectionless protocol without an acknowledgement.

Table 3. Categories of description for UDP

As what is UDP understood?	
1.	UDP is understood as an unsafe communication between two specific computers and is described in a concrete way
2.	UDP is understood as connection-less communication over an internet and is described in an abstract way
3.	UDP is understood as a standard communication tool in a framework that includes and goes beyond the network, and is described at a meta-level

During the interviews, a large number of students spontaneously compared the two protocols and pointed out differences between them.

Since the similarities between the two protocols are strong, I will only briefly sketch the experience of UDP that has been discerned within the group, without presenting the full analysis that I have made, nor the data.

Table 4 gives a more detailed picture of the experience of UDP. The first column indicate as what the UDP is experienced, in analogy with the corresponding table for TCP, Table 2. In category 1, UDP is experienced as an unsafe protocol. For communication that uses unsafe protocols, the sender does not get any confirmation from the receiver if information has arrived. With this protocol the sender does not know if data is lost and if it therefore needs to resend data.

The understanding that is expressed in category 2 is of UDP as a protocol that does not set up a connection. A connection demands that the sending computer gets a confirmation that data arrives to the receiving computer. Without the possibility to obtain a confirmation, data can be sent without ever be received. In the concept of a connection lies an interaction that is not fulfilled in protocols that does not have an acknowledgement

As is indicated in the third column, UDP is experienced as a protocol without acknowledgement within the three categories. This is the technical aspect that characterises

protocol, and takes the protocol as a whole as an object of discussion, that is open to variation in other dimensions.

UDP, and makes UDP recognisable as UDP. Comparing with TCP, it is notable that TCP is recognised as a protocol with acknowledgement. This way of characterising the two protocols, as having or not having an acknowledgement, is thus aspect that takes different values for the two protocols.

Table 4. Aspects of the different categories of description of UDP

	As what is UDP experienced?	As a part of which framework is UDP experienced?	What is the technical character of UDP?	How is UDP described?
1.	Unsafe communication	A framework of two specific computers	UDP is a protocol without acknowledgement	In concrete terms
2.	Connectionless communication	A framework of an internet		In an abstract way
3.	A standard for communication	A framework of a world outside computer networks		On a meta-level

4.3 Students' understanding of RMI

Different ways of experiencing RMI have been discerned in the group of students. In many important ways the identified understandings resemble the structure that was described for TCP and UDP. However, the picture of the students' experience of RMI is somewhat more complex than the pictures given in the previous sections. A possible reason for the complexity found in the data is the purpose, design and function of RMI. RMI gives a programmer a possibility to create a program which, in its turn, can start other programs on other computers or machines²⁵. That is, RMI offers not only a possibility to transfer data between different computers (as do UDP and TCP), but also to transfer and execute code on other computers. This means that RMI from the programmer's perspective offers more possibilities than the other two protocols, but becomes at the same time more complex and thus more complicated for him or her to handle.

4.3.1 An overview of different ways of experiencing RMI

Three different categories of description that together express the students' experience of RMI have been identified in the data. A critical difference between the categories of description has been found in the frameworks in which the students experience the protocol: The protocol is experienced as a part of an environment that consists of two computers, as a part of an internet, or as belonging to a world that goes beyond computers. This difference is closely related to how, or as what, the protocol is experienced.

To describe the increased complexity, I have created three subcategories of the first category that relates to two specific computers. The subcategories differ in the roles the two computers play in the communication: Undefined roles in the first subcategory, different but not clearly specified roles in the second, and finally, differentiated and well defined roles in the third. Other aspects that have been found, and that differ between the subcategories, are in the understanding of the function or the purpose of the RMI, whether it is used for data transfer or

²⁵ By *computer* I refer to a physical computer, a computer that actually can be touched. The term *machine* refers to a *virtual machine*. For a further discussion on *virtual machines*, see section 2.4.

something more than data transfer, or if its purpose is to use resources on different machines. The categories that have been discerned are summarised in Table 5.

Table 5. Categories of description for RMI

	What is RMI understood as?
1a	RMI is understood as data transfer between two specific computers and is described in a concrete way
1b	RMI is understood as something more than data transfer on two specific computers and is described in a concrete way
1c	RMI is understood as being for using resources on specific computers and is described in a concrete way
2.	RMI is understood as being for sharing resources over an internet and is described in a abstract way
3.	RMI is understood as a standard tool in a framework that includes and goes beyond a computer network, and is described at a meta-level

The categories identified correspond in large to the descriptions made of the students' understandings of TCP (see section 4.1). In the project the students could use both TCP and RMI, and the two protocols could to a certain degree be substituted for each others. The fact that the protocols are experienced as being an integrated part of a similar environment can thus be seen as a confirmation of the soundness of the result. There are no internal contradictions in these results.

As mentioned briefly above, three subcategories have been identified within the first category of description. The framework in which the protocol is experienced is the same: Two communicating computers. Also, the protocol is described in a concrete way in the three sub-categories. The roles of the two computers, and the interpretation of what RMI "is" differs between them.

In the first sub-category, 1a, no differentiation or clear roles between the two computers are articulated. Here, RMI is experienced as data transfer. Within the field of computer science, the point of using RMI is to have a possibility to call methods²⁶ on other computers or virtual machines. The understanding expressed in this category is thus in a technical perspective too simple or even incorrect. For file transfer, there are simpler protocols.

The second subcategory, 1b, describes an understanding of RMI goes beyond the pure idea of transfer, but its features are not clearly articulated. RMI is experienced as something more than transfer, and the two computers involved are assigned different but still unclear roles.

The roles of the two computers or machines are well-defined in the third sub-category, 1c, where RMI is understood as being a tool for using resources that are located at another computer or on another virtual machine. In the second category of description an understanding is expressed where RMI is integrated with an internet as a whole. The purpose

²⁶ *Methods* are functions or procedures that exist within Java objects. Executing a Java program corresponds to calling or executing methods.

of the protocol, what it "is", is understood as a tool for sharing and using resources over a network.

There is a close correspondence between category 1c and category 2: An understanding of RMI is expressed, where RMI is for using resources in both of them. The critical difference lies in how RMI is experienced: In the second category RMI is understood as an abstract method of sharing resources and as an integrated part of an internet, referring not only to the two concrete computers or machines that communicate, as in category 1c.

Finally, a third category of description has been identified, in which the protocol is experienced as a standard in a framework that extends beyond the network, and that is discussed on a meta-level.

It is worth noting that the experience of the internal technical characterisation is different between RMI on one hand, and TCP and UDP on the other. Although the protocols are recognised by the students as a part of, and integrated with, the same environment, differences in their internal structure are experienced. While TCP and UDP were described in similar ways, the descriptions of RMI differ from this in important ways. In computer science this makes sense: While UDP and TCP are mainly used for data transfer, RMI is used for transferring and executing both code and data, and is thus considerably more complex.

In categories 1a and 1b, where RMI is described as a tool for data transfer or as a communication tool that goes beyond data transfer, the internal technical structure is not clearly articulated by the students. In the second category, the technical structure of RMI is described as an interaction between objects on virtual machines, which is clearly an abstract view of the protocol. For the third category there is not enough empirical material to draw a full picture of the different aspects that are implied for RMI; although it is possible to identify a way of experiencing RMI in a framework that goes outside computer networks, and thereby to create the category of description, there is not enough data to completely inspect the technical characteristic. The aspects of the understandings of RMI are summarised in Table 6.

Table 6. Aspects of the different categories that describes RMI

	As what is RMI experienced?	In which framework is RMI experienced?		What is the internal technical characterisation?	How is RMI described?
1a	RMI is related to data transfer	Two specific computers	Two computers with undefined roles	Not clearly articulated	In concrete terms
1b	RMI is something more than transfer		Two computers with different roles	Not clearly articulated	
1c	RMI is for using resources		Two computers with well-defined roles	Methods on another computer that is called	
2.	RMI is for sharing resources on an internet	An internet		Interacting objects virtual machines	In an abstract way
3.	RMI is a standard tool	A world outside computer network		Not articulated	On a meta-level

The three sub-categories of category 1 show a clear hierarchical structure. The understanding expressed in category 1a is not very useful for solving computer science problems, and can be seen as an uninteresting special case of the use of RMI or even as incorrect. 1b indicates a somewhat more relevant understanding, since it is closer to the understanding within the field of computer science, but is still not rich enough to be useful to solve technical problems using the features of the protocol. In 1c an understanding is expressed that helps solving practical programming, since RMI is understood as a tool for sharing of resources, and in this sense 1c expresses a better understanding than 1b, which in its turn is better than 1a.

The hierarchical structure that is formed of categories 1, 2 and 3 is somewhat more complex. There is a hierarchical structure in the framework as a part of which the protocols are experienced, although this does not imply that an understanding that is expressed in a higher category, with a broader framework, by necessity includes understandings expressed in lower categories. The structure can be understood in another way as well: An understanding expressed in a higher category is needed to evaluate and judge decisions that are taken based on an understanding that is expressed in a lower category.

4.3.2 RMI in a framework of two computers

In this first category of description we meet an understanding where two communicating computers form the experienced framework of which RMI is an integrated part. But there are differences in how the roles of the two computers are experienced, and these form the basis for the distinction between sub-categories. The experience of what RMI "is" also differs between the sub-categories.

The subcategories are:

- 1a Two computers with unidentified roles. RMI is for data transfer
- 1b Two computers with different, but unspecified roles. RMI is for more than data transfer
- 1c Two computers or machines with different, well defined and specified roles. RMI is for using resources

The communication that takes place and the entities involved are described in concrete terms in all three sub-categories.

File transfer between two computers with undefined roles

In this sub-category RMI is experienced as a method for file transfer in a framework that consists of two computers, where their roles or the functions are not articulated.

An illustration can be found in the second interview with Sven.

- Interviewer: [...] what is RMI?
[...]
- Sven2: That is, it is a ... one moves files between, yes....for instance if I were to use RMI that was sort of ... I have the game server and a file that had marbleinfo and so the information on [...] speed so then I want to move over to mine...and then I should use RMI, hard to explain, but ...
- Interviewer: But there are lots of ways to move information what is the thing that is typical for RMI?
- Sven2: Now I am stuck....

Sven talks about RMI as a tool for transferring files. He refers in a very concrete way to the project he is working on and gives an example referring to a specific file that had to be transferred. The term "Game server" refers to the program module that controls the whole software system in the project, while "marble info" refers to some specific information about the ball, possibly its speed and position. Sven states that he should use RMI to move a file, containing "marble info" to "mine", most probably referring to the module that he was working on. There are two specific computers in his argument: The computers the file is moved between. Other computers, or a network, are not mentioned.

Anthony also describes transfer of data between computers in his first interview:

Interviewer: You talked about Java RMI. What is RMI?

Anthony1: I don't even know. I know it's a type of protocol used between, um, talking between two machines.

The discussion continues and UDP and TCP are discussed. The interviewer returns to the subject of RMI:

Interviewer: Could you relate RMI to this?

Anthony1: Um, no. I'd probably say that RMI is just another version of TCP.

Anthony, as Sven, talks about RMI in a framework of two communicating computers, and does not assign them any different roles. Instead, he refers to TCP, see section 4.1.

The understanding expressed in this sub-category is an extreme simplification of the normal use of RMI. It is not a proper way to characterise RMI from a computer science perspective, since it does not capture the specifics of RMI, the features that distinguish RMI from most other protocols, such as TCP or UDP, and makes it possible to recognise RMI as RMI.

Something more than file transfer between two computers with different roles

This sub-category differs from the previous one, since the two computers are described as having different, but yet not clearly defined roles.

Samuel focuses on the communication between two computers, the server and the computer his program is executing on in the following excerpt:

Interviewer: Can you explain to me what Java RMI is?

Samuell: Yes, exactly, but also wants to have some some ... one wants ... what does one say ... one will order or order ... one wants to make a request so to speak, they, that is pretty good, that is sort of, I don't really know ... I now now sit here and speculate here ... I ... I... I don't know so much Java either and I am totally new to this Javathingumy all the time really, but I never worked with Java so that, um, I believe that it is like like some type also, um, ah, protocol to communicate with with servers and such.

He talks about requests and communication with a server. Since he mentions a server, one can deduce that he considers the other of the two communicating computers as a client²⁷, and in

²⁷ As mentioned earlier, the active part in the communication between two computers is often called a client while the server is a passive part.

this way assigns them different roles. He does not mention file or data transfer, nor does he have a well-articulated advanced understanding of the protocol. His expressions "order" and "to make a request" as well as his discussion of a server (and implicitly about a client) are relevant for the normal use of RMI as a tool for computer communication. At the same time, the explanation he offers of what RMI "is": "... type of [...] protocol to communicate with servers and such" is unspecific and does not indicate an understanding of how RMI is intended to be used.

During the second interview, when the interviewer returns to the subject of RMI, Samuel expresses a similar understanding:

Interviewer: [...] What is RMI?
Samuel2: Remote Method Invocation
Interviewer: Yaa
Samuel2: It's something one uses if one wants to find some sort of address which doesn't exist in its own own frame for it for this code which one makes. It it ... it is a concept that understand, but here its used in Java., eh...and Java I don't know anything about actually.
Interviewer: You have not used that?
Samuel2: No [...]

He expresses an understanding of RMI, where the protocol is used to find an address, which is not within the frames of the code currently being executed, in order to access external code or other objects via this address.

This sub-category describes an understanding of RMI as a protocol between two computers, where the two computers have different, but undefined roles. The interaction between the computers is understood as going beyond a pure file transfer. In a computer science perspective, this understanding still does not capture the particular properties of RMI.

Using resources on two computers with well-defined roles

In this sub-category RMI is experienced in a framework of two computers, as a tool for executing programs on another machine and in that way to use the resources of another computer.

Staffan gives a description in concrete terms on his view of RMI. During the first interview he says:

Interviewer: RMI?
Staffan1: Oh, that's Java's version of client server, it has a stub and a skeleton which one uses. You send you from your client ... you can fetch and allow to execute things from the server via. It feels as if they are local on your ... on your client, but you execute from the server actually.

RMI is used on two computers, a client and a server. The client can execute a program on the server, according to the explanation offered by Staffan. This program is used as if it were residing on the client. In the beginning of his explanation, he talks about a stub and a skeleton²⁸. This, together with the fact that he talks about the role of client indicates that he

²⁸ A *stub* that resides on the client offers the same interface as the server object to a program on the client. It takes the call and passes it to its corresponding server object. The *skeleton* that resides on the server side takes the call of the stub, and forwards it to the server object, waits for an answer, and sends this answer back to the stub. Stubs and skeleton together form a layer in the architecture of RMI.

experiences RMI as integrated with the two computers that are used in the communication process.

He expresses a similar understanding during the second interview:

- Interviewer: [...] What is RMI?
Staffan2: It's a sort of Java client server model..you can execute. It has something to do with stubs and skeletons. You execute ... I'm not sure how it works ... we had nothing of that kind in our project as it is right now, but ...
Interviewer: What is stub? What is skeleton?
Staffan2: Ah, it it generates something ... you have the production on the server anyway and I think that is the skeleton and then this is generated in a way that I don't understand how it works but anyway you can execute those methods, those functions, which ... which are on this or that computer over there even though it seems like they are on your own computer. It something like that.

After stating that he is not sure how it works, he says that it can be used for executing methods or functions on another computer as if it were on your own.

In the following excerpt of the discussion the interviewer starts by referring to an earlier statement made by Stig, where he says that the group was reading about RMI in order to learn more about the protocol:

- Interviewer: [...] We start by RMI, which you had read about. What is that?
Stig1: It is ... it is Remote Method Indication means that that is with Java in order to...sort of as server client they will be able to communicate with each other. One should be able to use a client, should be able to use code that is on another computer or machine by setting up a connection just ... sort of ... like ...a shell so that one should be able to. It looks like as though one can use, that one like has all the information there, but... communication fetches somewhere else.
Interviewer: You said as client server: What does client server mean in that case?
Stig1: Oh, it is that hard to explain ...such things.... you know what it is, but um...it's like a a client mostly program wants to get information from a server.... then they have to communicate with each other in some way and then one can decide...like sort of connect to each other in some wayit is a special port or something...and that is, yes, that is used ...so we have one of these to the server in ours...in this project.
Interviewer: And RMI is kind of special case, or?
Stig1: Yes, I think so. Used when it has to do with Java ... a Java client

Stig clearly states that the purpose of RMI is to offer one machine the possibility to use code on another machine. He also indicates that this has applications, namely when a program wants information from a server. It is clear that he sees RMI as a way of using resources that are available on a computer other than the one you are currently executing your program on. In his explanation he talks about "communicate with each other" and "setting up a connection" on a "special port", clearly focusing on the two communicating machines. Stig's words "on another computer or machine" I understand to refer to a physical computer, but then he broadens his view to include a virtual machine in his explanation. However, he still only refers to *two* computers or machines, not to any network as a whole.

In this sub-category, RMI is understood as a tool for using resources on a different computer. RMI is understood and described in a concrete way in the experienced framework of two communicating computers.

4.3.3 *RMI for sharing resources on an internet*

In the previous section, a category of description where RMI is experienced as a part of a framework that consists of two computers has been described. The communication that took place between the two computers is understood in three different ways, as transfer, as something more than transfer, and as using resources on another computer.

In this section, the framework that forms the basis for the category of description is different from that of two computers of the previous category: RMI is seen as a part of an internet as a whole, and is experienced as a way of using or sharing resources on the network.

In the excerpt below, taken from the first interview with Abraham, this perspective is clearly visible.

Interviewer: [...] Um, what is RMI? Java/RMI?
Abraham1: Ah, Remote Method Invocation.
Interviewer: Ya, OK
Abraham1: Very nice. It allows two Java virtual machines to talk to each other. They, an object on one machine could instantiate an object that lives on another machine and use that one's methods. That's how RMI is useful.

Abraham talks about RMI as a tool that offers the possibility for two Java virtual machines to communicate. He then talks about objects that "live" on another machine and possibilities to use the methods of this object. Although he talks about two machines, he does not give any reference to two specific machines. Instead, he focuses on the object, and experiences the machines as a place where the object "lives". In this rather abstract perspective the focus is clearly not on the physical computers, and not even on the virtual machines. Instead, they create the space where the objects live. Thus, the framework is an internet, a broader framework than the one presented in category 1.

Axel, during his first interview, expresses a similar understanding, but is more explicit on the usage of RMI:

Interviewer: We have talked about RMI?. OK what is RMI?
Axel1: RMI is Remote Method Invocation which is basically, you have a Java object on one machine somewhere, it doesn't matter where, and then you have a Java object on another machine somewhere, it doesn't matter where. And then you can, either one can call the other, or they can each call each other um. It's, basically, you have to register the object in the RMI registry and then essentially it works just like the other object on the same machine. It is a little bit slower than maybe a socket would be, but it's fairly stable if you can get the security issue right.

Axel explicitly says the objects that call each other may be on any machines. It is not important to him where they are. Having one object call another, or having two objects call each other, implies that they use each other's methods, meaning using or sharing resources. Axel shows an understanding of RMI where the protocol is seen as a way to use resources in a framework of the internet.

Sebastian opens the discussion about RMI by a general description, and then continues his reasoning by going deeper into his explanation during the first interview:

Interviewer: [...] What is RMI?
Sebastian1: Yes, that combination of letters stands for Remote Method Invocation, which means that one can call a command from one virtual Java machine on another.

Interviewer: Can you please say a bit more on that?

Sebastian1: Yes ... No ... but that is roughly the picture I have of it actually, I don't know exactly what happens then what ... where the command went.... where it gets executed somewhere, which processor it is that will work on it, which of the two virtual machines it is that...

Interviewer: ... that executes.
[...]

Interviewer: Hmmmm, what, what could one use RMI for both in the project and in general. What is the point of the concept?

Sebastian1: No, no, but it feels like I can win something by that ... that ... if I for example if I have a server and a client, so if I should execute a command that is on the server if I can execute it here without having the thing itself so that it executes here so the server gains from that. [...]

Sebastian starts by giving a "school book" explanation to RMI. However, immediately after giving this explanation, he talks about an aspect of the concept that he does not grasp: He does not understand on which machine the code is executed. The question he raises is, seen in a technical perspective, relevant and can be taken as an indication that the first explanation, although it has a "school book style" had a meaning for him and was not only a quote that he had memorised from a book. He later gives an argument for using RMI ("it feels like I can win [...] if I can execute it here"), that is consistent with his explanation.

An understanding of RMI, where RMI is experienced with an internet as a framework has been met in this category of description. The protocol is used for sharing resources over the network and is described in abstract terms.

4.3.4 *RMI in a framework that goes beyond a network*

In section 4.1.4, evidence was presented that TCP could be experienced in a framework that went beyond a computer network, and that also considered human decisions. TCP was discussed as a standard communication tool, and the students expressed an understanding of TCP at a meta-level. A similar way of experiencing RMI can also be identified.

In the excerpt below, Adam discusses the choice of TCP, instead of RMI, for all communication throughout the code of the project:

Adam1: Between, like the game server and the video and motor, you mean? [...]

Interviewer: And you will just accept that they are TCP. So what you do is that you go for overall a TCP solution. OK Ya.

Adam1: Right. And it's my impression that it doesn't matter what one part communicates in, because if it is communicating with RMI to the client, but with TCP to the motor, I mean it's just different ways of formatting the information, in a sense, so..

Interviewer: Ya, ya.

Adam1: If it isn't TCP, you know, it doesn't really affect..

He argues that RMI and TCP can be seen as different ways of formatting the information, where different protocols can be used to solve different sub-problems. He mentions communication with the motor and the technical communication between the server and the client. The choice between the protocols, seen in this perspective, is not important, continues his argument. He talks about the two protocols as two different ways of formatting data and as two different instances of the same phenomenon. The comparison that he makes requires him to reason about the protocols from an outside position, where properties of individual protocols are abstracted; that is, he talks about RMI at a meta-level.

Alec also uses a meta-level reasoning to express his understanding of RMI:

- Alec1: [...] But it's very lengthy and verbose, as far as a lot of work, and this RMI is quick and concise, but it seems to take away some of the flexibility.
- Interviewer: Uhum.
- Alec1: There are probably ways to do things that I'm not talking to..., that I'm unable to do now, that I'm not aware of but, um, as of now it seems to take away some of the flexibility. I've also discovered that there's, like you were discussing, the security, which has to do with a..
- Interviewer: Uhum
- Alec1: [...] a policy file that, um, that I have little or no knowledge of, just discovering it, but that I've begun some research on it and, um, as far as how that works. [...]

This is a meta-level discussion of RMI. Alec says that there might be solutions he does not know at the moment of the interview. His judgement, that the solutions he has found are inflexible, and that there ought to be other solutions, demands that he takes a position outside RMI, where he can abstract and talk about what properties he expects the protocol to have to be a good standard tool. Also, this argument requires that he is consciously aware of the fact there are decisions taken on the design of RMI.

In this category, RMI is understood as a standard tool and is experienced as a part of a framework that goes beyond a computer network and that is described a meta-level.

5. Students' understanding of the general concept of a network protocol

In the previous section an analysis of how students understand TCP, UDP and RMI as individual network protocols has been made. A question that naturally arises in the context of this section is what common properties of network protocols are experienced, and what could be said about students' ways of experiencing the general concept of a "network protocol"? In this section I will explore this issue further.

5.1 Different ways of experiencing network protocols

An analysis of the students' understanding of the concept of network protocols as a whole could be made in several ways. An obvious alternative option would be to ask the question to the effect: "What is a network protocol?" during the interview. However, such a question was not asked, and the issue of the general concept of a network protocol was not raised explicitly during the interviews.

Another possibility would be to re-analyse the interview extracts concerning the individual network protocols in the light of the analysis made for the individual protocols and the categories of description that were created. This re-analysis could form the basis for a possible creation of categories for the concept of network protocols. Yet another possible attempt is to go directly to the interviews to look for statements about protocols in general during the interviews about the specific protocols. In this section, I combine the two latter approaches. Thus the original analysis form a background to the interview extracts that in different ways address the general concept of a network protocol. The statements are, in other words, recontextualised at a collective level, as is proposed in Adawi, Berglund, Booth and Ingerman (2002).

An important aspect of the categories of description that were created for TCP, UDP and RMI is the framework of which the protocols are experienced as parts. As was pointed out in earlier sections, the protocols are experienced as integrated with their environment. They would not exist without the environments to which they belong, and the environment in which they can be found would not be the same without them. In other words, there exists no computer communication without some kind of communication or network protocol.

The frameworks that have been identified for the individual protocols are

1. two communicating computers
2. an internet
3. a world beyond computer networks

The framework can be seen as one aspect of the ways that protocols are experienced, and since the analysis has given similar results on the framework for all three of them, it can be assumed that this aspect is also relevant for the experience of frameworks or backgrounds for the idea of a network protocol. I use this as a starting point, and I will explore this question further by considering these categories of description alongside some interview extracts on the general concept of a network protocol.

The findings for the general concept of a network protocol are summarised below and in Table 7. The next sections present the evidence leading to these results.

Table 7. Ways of experiencing the general concept of a network protocol

	What is the general concept of a network protocol experienced as?	Which framework is the concept of network protocols experienced as integrated with?
1	A protocol is a way of talking/communicating between two machines	One (or more) specific computers
2	A protocol is a method of communication on an internet	An internet
3	A protocol is a set of rules that are used on an internet	An internet
4	A protocol is a standard	A world that goes beyond computer networks

Four categories of description have been identified. The critical difference between the four is the qualitative ways in which the general concept of a network protocol is experienced. Two of the protocols are experienced in the framework of an internet. As I will argue in the coming sections, the qualitative differences between the categories are important, and as a consequence, separate categories do more justice to the data.

The first category of description expresses an understanding where a network protocol is experienced as a way of talking or communicating between two computers. The critical difference between categories 2 and 3 is how, or as what, network protocols are experienced. Category 2 describes an understanding where a protocol is a method of communication over

an internet, while 3 expresses and understanding where a protocol is experienced as a set of rules. The general concept of a network protocol is experienced as a standard, and as such related to human decisions in category 4.

As was the case for the individual protocols, a hierarchical structure can be identified. In the higher levels of the hierarchy the protocol is experienced in a wider framework. It can also be argued that the understanding of what a network protocol "is" shows a hierarchical structure, where the level of abstraction increases from category 1 to 4. In category 1, a concrete understanding is described, with communication between two specific machines. In 2, the protocols are understood as methods of communication, which represent a more abstract understanding. With the experience of network protocol that is described in 3, the protocol is understood as a set of rules. A set of rules, is, by its pure definition, an abstract entity. And finally, in category 4, the understanding of a protocol can be described as a standard. This understanding demands, as was mentioned earlier a possibility to reason about the properties of the rules, and from where they stem, not only to see the rules themselves.

5.1.1 Network protocol as a way of communicating between two computers

In this category of description an understanding is expressed where network protocols are experienced as methods of communication, or methods of talking, between two computers.

Anthony articulates such an understanding during his first interview:

Interviewer: You talked about Java RMI. What is RMI?

Anthony1: I don't even know. I know it's a type of protocol used between, um, talking between two machines.

He says that he only knows that RMI is a protocol that is used for communicating between two computers. The interviewer continues by about TCP:

Interviewer: Uhum. What is TCP?

Anthony1: TCP is another type of protocol .. used between two machines. There is TCP and there's UDP that's one of the things that I actually do remember from ah, networking class. And I believe TCP sends packets to one machine and then there is some sort of response saying that they got the packets or not.

He talks about TCP as another type of protocol, which is also used between two machines. He spontaneously mentions UDP, as another protocol. By referring to the three protocols in this way, it is clear that Anthony experience that properties are shared between protocols: The three protocols mentioned are for communication or talking, and are experienced in a framework of two computers or machines.

5.1.2 Network protocol as a method of communication over an internet

The general concept of a network protocol is experienced as a method of communication over internet in category of description 2.

During the first interview with Albert, he expresses an understanding of TCP as a method of communication over an internet in a statement that has in part been discussed in section 4.1.3:

Interviewer: Um, what is TCP?
Albert1: TCP, um, it's um, part of the internet protocol. It's used with part of the internet protocol typically. Um, it's one of the methods of communications, I don't know a whole lot about it, as far as the whole, um, design construction behind it. Um, I'm learning it pretty deep, in depth in my.. I'm going to learn it pretty in depth in my network class, but um, I can't think of what TCP stands for right now.. Transfer Call Pad .. I can't remember off hand. But it, it is used as one of um, the other, as one of the connections as also, as is UDP, a TCP/IP protocol.

In this dialogue about TCP Albert mentions UDP as a protocol with similar characteristics, without being sure of the exact differences between the two. TCP is, according to him, a part of the Internet protocol, and is one of the methods of communication. In other words TCP is a method of communication that is related to an internet, and not only two communicating computers.

When prompted on the differences between the two protocols, Albert stresses the similarities in his answer:

Interviewer: O.K What is difference?
Albert1: I don't know (laughter).
Interviewer: That's fine, that's fine.
RedU1: I know, I know that it's part of it and it's separate. But it's just a different type of protocol that you use to communicate. I know that, but..

Later during the interview, Albert mentions RMI when answering a question about sockets:

Interviewer: There is another word you mentioned there, and that's socket. What is a socket?
Albert1: A socket is pretty much like a, a port that is opened up on the server, or that is requested by the client and, it's assigned a number. And it's just sitting there and listening and um, it's just an open port and that port is um, designed to use a specific type of protocol, you know whether it be TCP, um, or the RMI. And it's opened up to listen on that and once it receives that connection you know, it connects on that port. So it's like an outlet socket, you know, you connect it in, you communicate and then when it's down it gets turned off and then that port is either closed or it stays open if it's required by the server.

On reading Albert's statements, it is clear that he experiences UDP, TCP and RMI as being protocols that share important properties and that are basically experienced in a similar way, and a part of the same framework. In the interview with Albert there are similar statements indicating a relationship between the protocols. There are differences between the three, but they are all closely related, as he experiences them. From this I deduce that my interpretation of his understanding of what the general concept of a network protocol is, is relevant also when related to UDP and RMI. Protocols are methods of communication.

Axel experience TCP and RMI as methods of communication in a framework of an internet as well:

Interviewer: OK That's fine, that's fine. Um, I want you to talk about TCP.
Axel1: TCP/IP?
Interviewer: Ya.
Axel1: TCP/IP is how almost everything on the Internet communicates. IP addresses and everything, and that's um, one of the fundamentals behind RMI also. One could give it the address where the object is [...] the IP address [...]

As was shown in a previous section (section 4.1.3) he understands UDP as a protocol that is similar to TCP. The three of them are clearly experienced as integrated parts of Internet. He

talks about the protocols as "how almost everything [...] communicates". I interpret this, together with his statement that TCP is a fundamental protocol, as an expression of an understanding of network protocols as a methods of communication over an internet.

In this section, a category of description has been identified, where the general concept of a network protocol is experienced as a method of communication in a framework of an internet.

5.1.3 *Network protocol as a set of rules*

The experience of the general concept of a network protocol is related to an internet in category 3 and is understood as a set of rules.

Allan says that it is a protocol language used for sending data across a network, in an excerpt that was discussed in section 4.1.3

Interviewer: Um, you've talked about TCP. What is TCP?

Allan1: Basic concepts... it's a protocol language, I guess you can call it, that you just put your data in and it's sent across the network using the different protocols you want to use, like IP or.. I can't think of any other protocols off my head. But it is more or less a packet that you put your data in and you send across and it has some features such as, keeps things in order when you, um, when you get to the, um, when it gets to the server you want to go to. [...]

His statements that TCP is "a protocol language", that you "put your data in", and that different protocols might be used for the actual transfer, mean to me that he experiences protocols as a set of rules, since a protocol language in computer science is a formal language or a set of rules. He does not regard his answer as only valid for TCP, since he talks about different protocols, without wanting to mention or without being capable of mentioning others by name. By mentioning IP, Internet Protocol, Allan relates to an internet.

Adrian tells the interviewer during the first interview that his group plans to remove RMI:

Interviewer: Um, what is RMI? What is Java/RMI? The thing that you're removing?

Adrian1: I don't know, and that's why we're removing it.

Interviewer: OK

Adrian1: 'Cause we don't know enough about it. I, it's.. I've read briefly whole paragraphs about it. It's basically enabling it to get around security features that TCP/IP wouldn't allow. Um, or standard HTTP protocols. Um, like RMI, I guess allows complete access to certain files. Whereas if you go to HTTP, it's going to be a little bit slower, and you, there you have to worry more about the security issues, what you want to have access to.

The group plans to remove RMI to get around certain security features, and profit from, as they understand it, the less severe rules of TCP. To get around security features is to avoid certain rules, since the security features mainly consist of rules that govern certain operations that guarantee security. From this argument and his discussion about allowing access, I interpret that he experiences the protocols as sets of rules, that is, rules that are somewhat different for different protocols.

In other words, he expresses an understanding of network protocols as a set of rules experienced in a framework of an internet.

5.1.4 Network protocol as a standard

Adam explains during the first interview what a network protocol is, in a statement that has earlier been discussed in section 4.1.4:

Interviewer: So what is TCP then?

Adam1: Well that I have studied in some networking classes um, Transfer Control Protocol, something along those lines. Um, that is just a protocol for computers to communicate with each other. That's a standard that was created by a committee somewhere, sometime, and it's just a, it's a protocol, meaning that it's, it specifies um, the layout and the size and what's in the header and footer of packets being sent across networks and things like that. So it's, it's a standard communication tool

He starts by saying that the purpose of a protocol is to get computers to communicate. He then points out that TCP is a standard for a protocol, which was created by a committee. A protocol, in its turn, specifies the format on data sent across the network. TCP is, with this understanding, one of many protocols. A standard is, according to Adam, a set of rules that are created by a committee, that is, a result of human decisions.

In this category of description, we have met an understanding where a network protocol is experienced as a standard in a framework that goes beyond a computer network.

6. A discussion on learning and teaching

As has been stressed throughout the report, the objective of this phenomenographic research project as a whole is to gain insights in the students' learning of computer communication when taught in an internationally distributed project-oriented course. This report focuses on variations in the students' experience of network protocols, while my future work will study variations in learning in the context of the course and the interplay between their experience of learning and the context they experience.

Different ways of experiencing the concept of network protocols in general as well as the three specific network protocols TCP, UDP and RMI have been identified and presented. A network protocol is, of course, understood in a context by an individual. This means that an individual experiences the protocol against the background of and interacting with a specific environment. In the analysis (see section 3.2.2) this background is stripped away; in other words, the statements made by individuals are decontextualised. The decontextualisation is an analytical tool for the researcher to draw conclusions about the distinctly different ways a phenomenon, as for example RMI, is experienced within the group. The individual statement is then, as has been described earlier, recontextualised through a dynamic process into a context at a collective level that is created by the researcher: the outcome space of the categories of description. The coming sections will explore and develop the results presented in earlier sections and related them to learning and teaching.

6.1 Shifts between different ways of experiencing network protocols

In order to address the issues of learning and of what constitutes a "good understanding" of computer networks, I consider the results in the context that they originally stem from, that is

from the interviews. I will show that there are shifts between different ways of experiencing a specific phenomenon, and from this I will draw conclusions about learning.

Categories of description can only be created by the researcher for a group, at a collective level. Individuals experience particular phenomenon differently at different moments, which is to say that shifts can occur spontaneously and rapidly. With a distinction that was articulated by Pong (1999), shifts in focus can occur as inter-contextual shifts, when the context shifts, that is when a new subject is discussed, but also as intra-contextual shifts within the same context, either spontaneously by the student or as a part of a conversation.

Many intra-contextual shifts have been identified in the data that forms the basis for this paper. The students in this study are advanced students in computer science in their third or fourth year, and as such they have had the opportunity to meet different views from their teachers, books etc on computer science. This might be a reason why they take different stands on various computer science issues throughout their studies.

6.1.1 Case studies on shifts between different ways of experiencing network protocols

An example of such an intra-contextual conceptual shift from experiencing TCP as communication between two computers, expressed in concrete terms, to experiencing TCP as related to an internet, expressed in abstract terms, can be found in the following part of the first interview with Anthony:

Interviewer: Uhum. What is TCP?

Anthony1: TCP is another type of protocol .. used between two machines. There is TCP and there's UDP that's one of the things that I actually do remember from ah, networking class. And I believe TCP sends packets to one machine and then there is some sort of response saying that they got the packets or not [...]

Here, in the first part of the discussion of TCP, Anthony tells the interviewer that he understands that TCP is used between two machines, for the concrete purpose of sending packages. TCP has, according to him, a kind of response that indicates whether a package has arrived or not, that is, TCP has an acknowledgement.

The dialogue continues:

Interviewer: So what's the implications of this?

Anthony1: Um, it, it all depends on how you're coding it. It depends on how secure the network you're on. And if you actually trust just sending it out and just assuming that it gets there.

When the discussion continues Anthony gets a question about the implications. He argues that the implications depend on how "you are coding it", that is what your program actually does, and your understanding of the quality of the network.

His focus changes thus from experiencing packages sent between two machines to experiencing TCP as a part of a network that he discusses in abstract terms and assigns properties, like trust. In this case, the shift was triggered by the interviewer asking a question that encouraged the student to reflect further on the subject. .

Another example of an intra-contextual shift that a student spontaneously made during the interview can be found in the continuation of the extract of Sebastian from section 4.1.2. He says:

Sebastian2: Yes, an acknowledgement, That is, that I know that the information I send has arrived correctly, and what comes back has also arrived. There is a bunch of other stuff that I have to look out for. That the communication really works as it should, yes, between two software-created gadgets, that are sockets and ports.

By the end he mentions sockets and ports as "software-created gadgets". Here he shifts his focus and talks about abstract items, and thus expresses another way of experiencing the protocol.

Similarly several shifts between different ways of experiencing RMI have been identified. An example of an inter-contextual shift can be found when comparing the following two excerpts of the first interview with Albert. In the first excerpt, the discussion is about the changes the group has decided to make to their project (see section 2). The interviewer introduces the question of the changes, but the concrete change that gives the direction to the continuation of this part of the interview, comes from the student.

Interviewer: Ya, exactly.

Albert1: Um, the client and server separation, um, is going to involve a little bit more. In fact it will probably involve quite a bit more. The reason for that is because it looks like they're really, really close on the way it was structured using RMI and the, the layout of the classes and the way that the classes used each other, but it was really kind of odd when we started looking into it and the way that they structured it and the way that they're trying to send information back to the client. Um, the way that they currently send, like the path that was run, back to the client so you can see the path that was run, um, was that the navigation class sent it directly to the client. And the way it receives the client object as it's passed from the server, the client calls the method and it passes itself to the server and then the server passes it to the navigation. And then the navigation class uses that object, the client object, to call a function to send the path that was run back directly to the, excuse me, client.

Interviewer: Back to the client?

Albert1: Yeh. Back to the client, which, um, the way that we've been reading about RMI, is not the way that it should be done. [...]

In this context, the client-server separation, which is one of the changes that the group has decided to make, Albert discusses in detail the interaction between the server and the client. He mentions data that is sent, and discusses which methods that are called and on which objects they can be found. He clearly expresses an understanding where RMI is used as a tool for using resources and is seen in relation to two specific machines: the client and the server.

Later during the interview, the interviewer asks him about RMI:

Interviewer: You have mentioned some here. What is RMI, could you explain that to me please?

Albert1: Um [...] But it stands for remote method invocation and what it is, is you have an interface that is, um, that a class, um, uses this interface and the client also uses this interface. And the way that that happens is that, um, the server implements the methods to be used remotely. So there is only a few methods that are being used remotely, and it registers in the RMI registry the name of the object. And so when the client wants to use those methods, what it does is it does a look-up on that server. You pass up the server and you pass up the object that you want to look up. And what it returns is that it returns that object, and then, in this client,

you use that object as you would a local object. You could call functions on it, stuff like that, um..

Interviewer: You use it as if, as if it was a local object although it is an object on the server.

Albert1: Correct.

Interviewer: OK

Albert1: So you can call methods that are actually located on the server and it does things like that. And that's the basic concept of it. It gets pretty involved if you do call back, um, which I haven't been able to find too much on..

This time he explains the function of RMI, without referring to any specific machines or computers. He does not mention explicitly that objects can be on any machine. However, his use of the words "remote" and the general attitude in his explanations clearly indicate that he experiences RMI in a framework of an internet.

Another case of shifts can be found in the first interview with Alec:

Interviewer: You are going to Java RMI, what is RMI?

Alec1: It's um, a remote method communication. Um, Java sets up interfaces between two, let's see, um, classes, objects, and in the interface are methods that are available to the other class. And nothing else within the class. [...]

Here, he expresses an understanding where RMI is related to an internet (category 2), especially by mentioning "remote method communication". He articulates his understanding in an abstract way using words like "class" and "objects" and talks about the methods in the interface. He continues:

[...] RMI starts a connection on the port. It's not really a port, it's a registry number, and between, on that registry number they can communicate but only in the interface between the two. Um, I found, right off the bat, that you can't just compile these classes regularly. There is a RMI compiler. The RMI compiler creates two classes, a stub-class and a skeleton-class and these are needed for the communication between the interfaces. These are set up, um, separately to the communication. Um, I found that particularly interesting because it takes a lot of the work out. The hard coding I know and C++ I've seen the coding, I've never actually coded it. [...]

The discussion here moves towards coding, how to make a particular connection, between two specific machines or computers to work, and expresses a way of experiencing RMI, that is described in category 1c. He chooses words that have concrete denotations.

The continuation is interesting:

[...] But it's very lengthy and verbose, as far as a lot of work, and this RMI is quick and concise, but it seems to take away some of the flexibility.

Interviewer: Uhum.

Alec1: There are probably ways to do things that I'm not talking to.., that I'm unable to do now, that I'm not aware of but, um, as of now it seems to take away some of the flexibility. I've also discovered that there's, like you were discussing, the security, which has to do with a..

Interviewer: Uhum

Alec1: .. a policy file that, um, that I have little or no knowledge of, just discovering it, but that I've begun some research on it and, um, as far as how that works. [...]

This excerpt can be understood as a meta-level discussion about RMI. He says that there might be solutions he does not know at the moment of the interview. His argument is that the solutions he has found are inflexible. To make this judgement, that the solutions are inflexible, and that there, as a consequence, ought to be other solutions, demands that he takes

a position "outside" RMI, where he can talk about what properties he expects the protocol to have. This is an indication of a shift to experiencing RMI as related to a world that goes beyond computer networks (category 3).

Alec has made spontaneous inter-contextual shifts from 2 to 1c and further to 3.

6.1.2 *Implications of shifts in ways of experiencing a protocol*

In the discussion about shifts between different ways of experiencing network protocols three qualitatively different types of shifts have been identified: spontaneous intra-contextual shifts, triggered intra-contextual shifts, and inter-contextual shifts. These results harmonise well with the results about inter-contextual and intra-contextual conceptual shifts that are articulated by Pong (1999).

The cases of shifts that have been studied are summarised in Table 8.

Table 8. Cases of shifts between different ways of experiencing network protocols

Name of student	Type of shift(s)	Categories of descriptions for the shifts
Anthony	triggered intra-contextual	1 → 2
Sebastian	spontaneous intra-contextual	1 → 2
Albert	inter-contextual	1, 2
Alec	spontaneous intra-contextual	2 → 1 → 3

For the intra-contextual shifts, the table shows the order in which the students expressed a certain way of experiencing the protocol, since the shift happened during a single episode of the interview. In the case of inter-contextual shifts, the order is not relevant, since the different ways of experiencing the protocol were expressed during different parts of the conversation.

Although there are many cases of shifts within the data, this does not imply that all students shift between all understandings. For each individual, it is possible to identify the most advanced understanding he shows during the interviews. With some rare exceptions all shifts found in the data are between categories 1 and 2.

Also, there are students who, although provoked by the interviewer, just express one way of experiencing the protocols. As examples of students who do not shift during the parts of the interviews that are analysed for this report can be mentioned Sven, who expresses an understanding that can be identified as category 1 (see section 4.3.2), and Adam (see section 4.1.4 and 4.3.4) who expresses a stand that is described in category 3.

6.2 *Conclusions about learning*

It has been said earlier in this report, but it is worth repeating: The way(s) a certain student experiences a specific phenomenon, such as RMI, can change. Nor does a student have a given limit for the capacity to reach an advanced understanding. Rather, the student interacts with the phenomenon. His understanding of the phenomenon is then shaped by the

phenomenon in the context in which the phenomenon is experienced, in the environment where the learning takes place, and the student him- or herself with his or her interests and previous understandings. Thus, it is worth studying what constitutes a good understanding, and how the universities can act to promote good understanding among their students.

Marton and Booth (1997) argue that relevant or meaningful learning is a change in the learner's capability of experiencing something in a new or different way. This definition of learning does not only indicate that some learning is meaningful, but also points out that there are less relevant forms of learning. Pure rote-learning without a related different or deeper understanding, or the learning of a new program construct that is not related to or does not offer any new possibilities to develop thinking or programming, are, according to this argument, not examples of meaningful learning.

They also discuss good learning and argue that the ways in which learning is experienced "differ in richness (different aspects of learning that are discerned and held in focus simultaneously) and situational appropriateness (which particular aspects held in focus under the prevailing conditions)." (Marton & Booth, 1997, p. 55). I will take this as a starting point for a discussion about situational appropriateness and richness of the students' experience of network protocols.

6.2.1 Situational appropriateness of ways of experiencing network protocols

A conclusion that can be drawn from the argument of Marton and Booth, mentioned above, is that the task at hand indicates which way(s) of experiencing a protocol are the most fruitful.

Relevance for programming

A way of experiencing a protocol in a framework of two computers and described in a concrete way is closely related to programming. The descriptions made by the students resemble the terminology that is used in different programming situations that relates to communicating computers or machines. It can be assumed that this perspective is fruitful for solving concrete programming issues.

A quote from Sebastian can illustrate this. On a question from the interviewer about UDP, he compares UDP and TCP:

Interviewer: UDP?

Sebastian1: UDP.... but that is another form of communication. TCP/IP is set up ... like TCP, in contrast to UDP, TCP sets up communication between two points, and they talk to each other and make sure that they don't drop anything sort of.

As was explained in section 2.2, TCP and UDP offer procedures, or operations, to a programmer who writes application programs. The procedures for TCP offer services like setting up a connection or sending data. The statements by Sebastian above can directly be related to programming issues for using TCP in an application program. Similarities between his statements and some basic operations on TCP sockets are shown in Table 9.

Table 9. Similarities between Sebastian's statements and basic TCP operations

Sebastian's statements	Basic TCP operation
set up	Connect to a remote machine
talk to each other	Send data
talk to each other	Receive data
implicit, a connection that is set up, also has to be closed	Close a connection

In the continuation, Sebastian returns to UDP. His way of talking is still close to the issues of programming:

Sebastian1: UDP is [...] that the client asks what does this mean. Or what is this, or any question, whatever, and, so the server answers. And the server doesn't care in the end if the answer gets there or not. It is only a question and an answer, and then it is up to the client. If it feels that I didn't get any answer, it gets to ask again.

Here he talks about what a client that uses UDP has to do: If no data has arrived, the client has to repeat the question. This line of reasoning is close to the steps taken by a program that uses UDP.

Relevance to program design

A framework where the protocol is experienced as an integrated part of a network is useful for discussing the properties of protocols or which protocol to use in a particular situation. Issues like in what situations and in what way a protocol is useful come into focus here. It can thus be assumed that this way of experiencing a protocol is fruitful for design purposes.

An excerpt of the first interview with Abraham (see section 4.3.3) can serve as an example:

Interviewer: [...] Um, what is RMI? Java/RMI?
 Abraham1: Ah, Remote Method Invocation.
 Interviewer: Ya, OK
 Abraham1: Very nice. It allows two Java virtual machines to talk to each other. They, an object on one machine could instantiate an object that lives on another machine and use that's one methods. That's how RMI is useful.

Abraham explicitly discusses the advantages of RMI when asked what it is. He clearly has an understanding of what the purpose of RMI (use objects on another machine as a resource). This understanding is useful for deciding when to use RMI, and when to choose another protocol.

Relevance to policy issues

The meta-level discussions that concern what possible protocols there could be, and what properties they could have, characterise an understanding that is described in the third category. This understanding is useful for policy discussions.

This position is clear in the quote below (see section 4.3.3), where Alec argues that he is not aware of all features of RMI:

[...] But it's very lengthy and verbose, as far as a lot of work, and this RMI is quick and concise, but it seems to take away some of the flexibility.

Interviewer: Uhum.

Alec1: There are probably ways to do things that I'm not talking to..., that I'm unable to do now, that I'm not aware of but, um, as of now it seems to take away some of the flexibility. [...]

Alec argues that RMI, as he understand it, is quick and concise, but it is not as flexible as he thinks it ought to be. His conclusion is that he does not know the features of the protocol well enough. Reasoning thus, he discusses what properties a protocol should have. This line of argument is relevant when considering policy questions, as how to design network protocols.

6.2.2 Richness in ways of experiencing network protocols

In the previous section I have argued that different ways of experiencing network protocols are useful for different tasks at hand. I have pointed to the need for a fruitful variation, by showing examples of the relevant ways of experiencing the specific network protocols. Different ways of experiencing a network protocol are shown to be useful for solving different kind of practical problems. The examples given above are intended to illustrate the relevance of being capable of experiencing a phenomenon in different ways. I do not argue that the examples show the only or not even the principal situation when a particular way of experiencing a phenomenon is useful.

Another argument for different ways of understanding network protocols being useful is presented in section 4.1, where it is argued that an understanding expressed in a higher category of description offers the broader perspective needed to inspect and evaluate an understanding expressed in a lower category of description. An example can serve to illustrate and concretise the reasoning. To evaluate the solution to a problem solved in a concrete way concerning two interacting computers, as for example the coding of a program using TCP, it is necessary to shift to an understanding where the program is experienced in the framework of a network, and is discussed in an abstract way. By "stepping outside" the original reasoning to look at the problem as an issue of design instead of as an issue of coding, questions about the relevance of the solution can be discussed.

For solving complex or new problems it is thus necessary to shift between different ways of experiencing a protocol, since problem-solving involves different sub-tasks. To shift perspective, whether a shift is intra- or inter-contextual, triggered in a discussion or spontaneous, is not alone sufficient for problem-solving. Shifts have to be made in a relevant way, and the student needs to be capable of evaluating when and why a specific way of understanding a protocol is fruitful.

6.3 Implications for teaching

In section 7.1.1, we have seen that there are students who shift in situationally relevant ways between different ways of experiencing network protocols. It is also argued in the previous sections that an objective for a teacher is to promote variation in the ways network protocols are experienced. In this section I combine these two conclusions and discuss implications for teaching and for future research concerning teaching of network protocols.

Marton and Pang (2001), Pong (2001) and Lo (2001) among others have studied the relation between teaching and students' understandings. They argue, based on empirical research, that a meaningful variation in the presentation of a phenomenon in a teaching situation improves learning. Thus, a first implication of their conclusion is that a teacher of computer networks

should create a variation in how he or she presents the concepts he or she wants the students to understand. However, in situations where the students work in projects, this kind of advice, although good, is hard to implement directly.

Still, since a systematic variation in the students' experience of a phenomenon is desirable, it is worth further developing the issue of variation. A point of departure is Adawi, Berglund, Booth and Ingerman (2002), where we argue that variation in the context in which a phenomenon is experienced during a research situation supports that the phenomenon is experienced in new or different ways.

In our work we make a distinction between two different meaning of context in phenomenographic research projects. The *prepared context* is "defined by or observed by, or indeed experienced by, the researcher; that is, what the researcher considers to be relevant for the interviewee to make sense at the situation at hand", while the *experienced context* is "experienced by the participant; that is, what the participant experiences as being relevant for making sense of the situation at hand". The two terms do not denote two different contexts, but express two different ways of seeing and analysing a context and serve in this way as an analytic tool.

A similar distinction can be made in a teaching situation: A teacher presents a phenomenon in a context, which he or she prepares for the discussion with the students. We do not know how an individual student experiences either the phenomenon or the context. In a phenomenographic research project we can discern different ways of experiencing the phenomenon within a group, but we can only get glimpses of the ways the context is experienced. Still, the phenomenon is not experienced in a vacuum by a student. The phenomenon is experienced in the context the student experiences. We can only speculate on what constitutes this experienced context. The student's study objectives, his previous understanding of the phenomenon, discussions with other students, and the physical learning situation are some factors that to different degrees, together with the prepared context as offered by the teacher, form the experienced context for a student.

Thus our work in Adawi, Berglund, Booth and Ingerman (2002) offers another approach to the issue of variation in how a phenomenon is understood. A teacher can, and ought to, create a teaching situation in a way that promotes variation in how the context of the phenomenon taught is experienced. For a project course, like Runestone, where no lectures are held, this approach is promising.

In my future work concerning the Runestone initiative, I will study the relation between the learning and the context of the learning in order to identify factors that promote variation and thereby good learning. My belief is that the project work in Runestone, through the interaction between the participants of the project group jointly aiming at attaining a shared goal, will support that phenomena being experienced in different contexts and thus in different ways. I will then use the results presented in this report, as well as the full pool of meaning that has been collected. Focus will be on how variation is created and how contextual factors affects variation. However, it remains to be seen if the belief holds, and in that case, in what way variation is encouraged.

7. *Conclusions and summary*

In this report, I have presented university students' understanding of network protocols. The students, who are advanced students in computer science, have taken part in an internationally distributed project course that is jointly taught by two universities. The aim of the student project is to produce a software system to control the movements of a computer-controlled mechanical toy.

Qualitatively different ways of understanding or experiencing network protocols are discerned in this study, which has been carried out with a phenomenographic research approach. Based on these results a discussion about learning and teaching is given. It is argued that a variation in the context in which the protocol is experienced promotes good learning, since different ways of experiencing a protocol are useful with different tasks at hand. A student with a good understanding of network protocols can choose in a situationally relevant way between different ways of experiencing a protocol.

The ways in which students understand three specific network protocols – TCP, UDP and RMI – as well as the general concept of a network protocol have been studied. Although the protocols are experienced as different by the students, the three protocols are understood as being parts of similarly experienced frameworks. The three qualitatively distinct frameworks consist, respectively, of two communicating computers, a computer network, or a world beyond computer networks.

When TCP is seen in a framework of two computers, it is understood as a safe way of communication, while RMI seen in the same framework is understood: as a tool for data transfer, as something more than data transfer, or as a tool for using resources. This way of understanding is discussed by a student in a concrete language, and is found to be useful for solving programming problems.

In a framework related to an internet, TCP is experienced as a connection, while RMI is a tool for using resources. Discussions related to this way of experiencing protocols use abstract concepts and can be shown to be fruitful for taking design decisions.

When the two protocols are seen in a framework that includes, and extends outside, computer networks they are experienced as standards. Human decisions are taken into account in meta-level discussions about the networks. The understanding that is expressed in this category of description is relevant for policy discussions.

Different ways of experiencing the general concept of a network protocol are also discerned, related to the three frameworks described above. A network protocol can be understood as a way of communicating between two computers, a method of communication, or set of rules or a standard in a world that extends beyond computer networks.

Based on the results presented in the report ways to improve teaching of computer networks are discussed. It is proposed that, universities should teach computer networks in a manner that encourages students to understand network protocols in different ways, and that stimulates them to shift between these ways depending on the task at hand.

8. References

- Adawi, T., Berglund, A., Booth, S. & Ingerman, Å. (2002). *On context in phenomenographic research on understanding heat and temperature*. Revised paper presented at EARLI 2001, Fribourg, Switzerland, 2001. Submitted to Learning & Instruction.
- Booth, S. (1992). *Learning to program: A phenomenographic perspective*. Gothenburg, Sweden: Acta Universitatis Gothoburgensis.
- Budd, T. (1999). *Understanding Object-Oriented Programming Using Java*. Reading, MA, USA: Addison-Wesley.
- Daniels, M. (1999). *Runestone, an International Student Collaboration Project. NyIng report No 11*. Linköping, Sweden: Linköping University 1999. Also available at <http://www.docs.uu.se/~matsd/NyIng.html>
- Derrick, J. & Fincher, S. (2000). Teaching Communication Protocols. *Computer Science Education*, 10(3). 195 – 202.
- Lo, M.L.(2001). *Variation in Practice*. Presented at EARLI 2001, Fribourg, Switzerland.
- Marton, F. & Booth, S. (1997). *Learning and Awareness*. Mahwah, NJ, USA: Lawrence Erlbaum.
- Pang, M.F., Marton, F. (2001). *Bringing Learning about*. Presented at EARLI 2001, Fribourg, Switzerland.
- Pears, A., Daniels, M., Berglund, A. & Erickson, C. (2001). *Student Evaluation in an International Collaborative Project Course*. Presented at the Wise workshop of the SAINT conference, San Diego, CA, USA.
- Pong, W.Y. (1999). *The dynamics of awareness*. Presented at the 8th EARLI conference, Göteborg, Sweden.
- Pong, W.Y. (2001). Making Conscious Use of Variation. Presented at EARLI 2001, Fribourg, Switzerland, 2001.
- Stalling, W. (1997). *Data and Computer Communications*. Upper Saddle River, NJ, USA: Prentice-Hall.
- Tanenbaum, A. S. (1996). *Computer Networks. Third edition*. Upper Saddle River, NJ, USA: Prentice-Hall.
- Webster. (1979). *Webster's new twentieth century dictionary of the English language*. Unabridged. Second edition. NY, NY, USA: Simon&Schuster.

9. Appendices

The questions that are written within parenthesis are follow-up questions that I had prepared to use if needed.

9.1 Outline for interview 1

Test recorder

Introduction

(Feel free to say anything, not being capable of giving an answer is OK, do not wait for questions - just say what you have in mind, nothing will reach anyone outside the research team).

About yourself and your group

For the recorder, what is your name?

In which group are you

Who are the other members in your group?

Who is group leader? How did he/she become the leader?

What would you say is the function of the group leader?

Do you agree on this? (the others in the group?)

How have you divided the job between yourselves?

(How did this happen? How do you think the others regard this?)

Do you have a clear task? What is your task, as you see things?

About the project

Which code have you selected?

Tell me about this code?

(Why did you choose this particular code?)

(Which strengths and weaknesses does it have?)

How did you make the choice?

(Personal opinions? Criteria based on the code? Group leader?)

How do you want to develop this code?

(Why do you want to develop these particular issues?)

How did you take this decision?

What expectations do you have on your solution?

(Have you talked about possible problems? Or brilliant solutions?)

About knowledge of the subject area and computer networks

Would you say that you in the group, together, know enough computer science to solve the problem?

(If not, what is missing?)

(If anything is missing, how do you plan to go about to learn this?)

(Do you think you have enough practical experience in the group?)

Who knows what? How does this influence your collaboration?

(What re your strengths and weaknesses?)

Where can you contribute yourself?

Are you good at computer networks? (In theory? Hands-on?)

I am going to ask you to tell me about some concepts. Talk freely, I am not looking of anything in particular.

What is RMI?

What is UDP?

What is TCP?

What is Client/Server?

What is sockets?

Some of these you will use in your project. Tell me which ones?
(Where?)
(Why?)

Communication between humans

How would you say that the communication works
with the others in Sweden?
with the rest of the groups in the US?
with other groups?
with teachers and support?

About this way to work

How would you say it works?
Do you have any worries about problems that might arise?
(Technical?)
(Course related? (Milestones, assessment rules)
(Different ways of working? Language etc?
(What is your role in all this?)

Sum up

What would you say you would learn on this?
(In Computer Science?)

9.2 *Outline for interview 2*

Introduction

(as last time: say what you want, not being capable of answering is fine, do not wait for questions - just talk, noting will be forwarded to the teachers)

About you

For the tape, what's your name?
To which group do you belong?

About the project

Which code did you choose?
How have you developed the code?
How do you feel about the result?
What do you think the others think?
Does it meet your expectations?
Which problems and good experiences have you had with the collaboration?
(Different cultures/languages? course rules, like Milestones or meeting rules? different grading systems?
different teachers?)
Which problems and good experiences have you had with the communication issues?
Which problems and good experiences have you had with the technical/CS issues?

Your part of the project

Which were your tasks, as you see it?
How would you judge your result?
Did your own work meet your expectations?
How have you distributed the work between yourselves?
(How did this happen?
What do you think the others would say?
How well does this go with your planning?
What became as you had planned?
What became different?
Why?)

Communication between humans

(You said earlier
Can we go deeper into ...)

How would you say that the communication has been
with the others in the group in the US?
with the others in the group in Sweden?
other groups?
teachers and support team?
How does this fit your expectations? Problems? Good points?

About learning

About what you have learned?
What would you say you have learned from all this (in CS?)
(in computer networks)
(about communication between humans)
(about projects)

About knowledge of the subject area and computer networks

I will ask you about some concepts, related to computer networks.
Please talk freely - there is not anything special I am looking for.
(have you used this concept? How?)
What is RMI?
(How has it worked out for you?
Have you had problems?
Have you used the registry? What is it ?
Have you had security problems? What is security manager?
Tell me more
How come these kind of problems appear?
How did you work to solve them?)
What is UDP?
(Why did you use this protocol?
Have you had any problems?
Why did they appear?
How did you work to solve them?)
What is TCP?
(Why did you use this protocol?
Have you had any problems?
Why did they appear?
How did you work to solve them?)
What is client/server programming?
What characterise a client? a server?
What is sockets?
What is ports? (Is the concept the same thing as serial parallel
ports?)
(What is the relation between these?
Have you used them?)

Round up

What would you say are the advantages and disadvantages to work in
this way?
(What has felt "good"? What has felt "wrong"?)
What would you say as a conclusion that this has meant for you?
CS knowledge?
Technical?
On a human level?

Paper B:

On context in phenomenographic research on understanding heat and temperature.

Tom Adawi, Anders Berglund, Shirley Booth, Åke Ingerman. (2002). *On context in phenomenographic research on understanding heat and temperature*. Revised paper presented at EARLI 2001, Fribourg, Switzerland, 2001. Submitted to Learning & Instruction.

On Context in Phenomenographic Research on Understanding Heat and Temperature

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Abstract. Starting from an empirical study of lay adults' understanding of heat and temperature, we distinguish between different meanings of "context" in phenomenographic research. To confuse the variation in ways of experiencing the context(s) of the study with the variation in ways of experiencing the phenomenon of study is to risk losing fundamental insights. We discuss context as experienced and as interwoven with the experience of the phenomenon, and analyse its significance in two dimensions: (1) the stage of the research project: formulating the question, collecting data, analysing data and deploying results; and (2) "who is experiencing" the context: the individual, the collective, or the researcher. The arguments are illustrated from the empirical study.

1. Introduction

While discussing the analysis of data from a phenomenographic study of lay adults' understanding of the concepts of heat and temperature (Adawi, in preparation) and discussing the issues that arose, we found ourselves repeatedly returning to the meaning of the "context" for the participants and for ourselves as researchers. And a realisation that we were referring to the notion of "context" in a number of subtly different ways. This led to an attempt to systematise the issues and our responses to them, with reference to both the study in progress and the relevant literature. It is this process of systematisation and the results that we report here, with the aim of developing a way of conducting ourselves in relation to context in our work in researching learning and understanding.

The issue of context appears in a number of guises in educational research. Our arguments are grounded in the phenomenographic approach to studying experience, which means that we are problematising the meaning of and influence of context in aspects of phenomenography – methodology, method, theory development – and phases of phenomenographic research – formulating a research question, collecting data, analysing data, and describing, communicating, generalising and deploying results. Note that we are not explicitly dealing with "context" of learning as such here, important as this might be (van Oers, 1998; Linder,

1993; Linder & Marshall, 2001; Pong, 1999), but with "context" as an issue of phenomenographic research methodology.

First we need to establish what we mean above by the "phenomenographic approach to studying experience". Phenomenography is based on "an interest in describing the phenomena in the world as others see them, and in revealing and describing the variation therein" (Marton & Booth, 1997, p. 111). This implies the researcher taking a second-order perspective on the research phenomenon, devising appropriate methods of data collection and analysis to enable a description of the ways in which the phenomenon is experienced to emerge as a set of descriptive categories, related both logically to one another and empirically to the research question. The situation against which the phenomenon is experienced by others is, in this simple view, relegated to a background; in fact, the analysis deliberately strips away contextual features of the data in order to focus clearly and exclusively on the phenomenon, as experienced. Indeed, to confuse the variation in ways of experiencing the context of a study with the variation in ways of experiencing the phenomenon of study is to risk losing fundamental insights. Focus is not on the way in which the researcher experiences the phenomenon, but on the ways the research participants do; in contrast, it is the researcher who experiences a variation in how the phenomenon is experienced, and seeks meaning and structure in this variation.

But of course, whether it is a research participant or a researcher who experiences a phenomenon, there is always situation with social, spatial and temporal dimensions which lends it meaning. Just as when we experience, we always experience *something*, we always experience that something *as* something; that experience *as* something would be quite different if we placed ourselves in some other grouping of people, or location, or epoch. As pointed out by Marton and Booth (1997),

We cannot separate our understanding of the *situation* and our understanding of the *phenomena* that lend sense to the situation. Not only is the situation understood in terms of the phenomena involved, but we are aware of the phenomena from the point of view of the particular situation. And, further, not only is our experience of the situation moulded by the phenomena as we experience them, but our experience of the phenomena is modified, transformed and developed through the situations we experience them in (p. 83).

If we replace "situation" with the synonymous "context", we are encouraged to start to study the context which gives meaning to the phenomenon.

Let us return to the notion of context in a more general sense and ask, what does it mean in a general sense? There are dictionary definitions: It is defined in Chambers English Dictionary (1990) as follows: "*n.* the parts of a discourse or treatise which precede and follow a special passage and may fix its true meaning: associated surroundings, setting". And in Merriam Webster (online) we find more detail: "1: the parts of a discourse that surround a word or passage and can throw light on its meaning; 2: the interrelated conditions in which something exists or occurs", and that its etymology is Middle English, "weaving together of words, from Latin *contextus* connection of words, coherence, from *contexere* to weave together, from *com* + *texere* to weave".

The dictionary definitions confirm the everyday understanding of "context", and the etymological description brings to light the sense of inter-relatedness. It can mean either the text into which a particular passage is woven and which casts light on the passage, or the socio-spatial setting or situation in which an event occurs, and which is intimately related to

the event. In either case, an *outsider*, whether a reader or an onlooker, can gain meaning of a focal passage or event, through consideration of the context, whether language or experienced. We immediately note the contrast with the phenomenographic project of describing phenomena (and by implication the context of the phenomena) as experienced by the *insiders* or research participants.

Ekeblad and Bond (1994) have made a similar distinction between the ways in which two different research forms treat the notion of context. On the one hand, in "an *experientialist* perspective ... the research question is designed to seek an understanding of what it is that is experienced" whereas, on the other hand "an explanatory or *externalist* approach to research assumes that we are looking at the impact of context *on* an individual" (p. 148; our italics). The first, experientialist, perspective is in line with what we take as our starting point, but nevertheless criticism from this point of view can be found from what we might call the phenomenological fraction of the phenomenography tradition (Ashworth & Lucas, 1998; Ashworth & Lucas, 2000; Friberg, 2000). The "externalist" perspective leads researchers to observe events and to analyse them from within their theoretical and methodological frameworks, rather than seeking to see them through the experiences of the actors in the events.

We will take up other perspectives on context and other forms of research in the discussion following our systematisation of what "context" signifies for the phenomenographic study on understanding heat and temperature, which we generalise to phenomenographic studies in a wider sphere.

2. Analysis of Context – whose context?

The phenomenographic study of lay adults' understanding of heat and temperature by Adawi, from which we draw examples throughout this paper¹ is, as many phenomenographic studies, mainly based on phenomenographic interviews. Such interviews are generally described as semi-structured and open, the most important feature for this paper being that the interview offers a number of openings from which the interviewer and the interviewee are able to explore the phenomenon of interest. Two groups of adults participated in the study, some with only elementary schooling in physics and some who were taking an introductory overview course in physics for the general public given by Adawi, typically without prior experience of physics at the university level. The interview design offered the participants the opportunity to discuss and explain heat and temperature in some everyday situations, such as in cooking, with the aim of exploring their conceptualisation of heat and temperature. As well as the transcribed interview material, the textual pool of meaning was constituted of a number of written commentaries on the nature of heat and temperature, collected from the whole group attending the course.

Since the analysis takes its starting point in the pool of meaning thus constituted from the data, the quality of the data is crucial for what might emerge from the analysis. However, determining the quality of the data is not unproblematic, and a discussion of shared and unshared cultures, use of language, as well as the distribution of power has ensued. The

¹ Note that this paper does not report the study as such, or its analysis and its results. In the paper we assume the study as a typical phenomenographic study, and take it as our starting point for a methodological consideration of context in phenomenographic studies in general.

interviews are in no way an objective probe into the interviewee's experiences of the phenomenon of interest, in which dialogue is seen as being comprised of containers of the interviewee's thoughts that are passed over to the researcher for inspection; on the contrary, we see the interviews as a complex interplay between the interviewer and the interviewee, which can range in nature from an interrogation to a negotiation. From our point of view, it is important to distinguish between the two actors in this situation: the *researcher* (and/or the interviewer) who has taken the initiative to the interview, set the topic and in various ways prepared the situation in the ambition that it should be centred on some specific topic, question or phenomenon, and the *interviewee*, whose motives only can be seen through what she or he does or says. There is an imbalance of power in the nature of data collection which the researcher cannot totally redress in spite of attempts to soften it. In such a situation of imbalance, in which context can be (and is) used in many ways, we have found it worthwhile to make a distinction between two different meanings of context:

The *prepared context*, as defined by or observed by, or indeed experienced by, the researcher; that is, what the researcher considers to be relevant for the interviewee to make sense of the situation at hand. (For example, in Adawi's interviews, two knives of different materials and a cooling cup of coffee were important parts of the prepared context.)

The *experienced context*, as experienced by the participant; that is, what the participant experiences as being relevant for making sense of the situation at hand, this being interwoven with the experience of the phenomenon under consideration.

We found that our understanding of the pool of meaning was enhanced by switching between consideration of these two ways of seeing context – now regarding the experienced context, now the prepared context – and weighing the two against one another. This resembles the approach to researching learning and sense-making known as intentional analysis (Halldén, 1988; Booth, Wistedt et al., 1999) where a consideration of the range of potential contextualisations that an actor is calling upon while making sense of some task or phenomenon is an explicit phase of the research process. Similarly, the phenomenological reduction involves a process of imaginative variation over ways in which a phenomenon is being seen or conceptualised (Uljens, 1993).

In making explicit the distinction between the prepared and the experienced context, we introduce another tool for analysing the variation which constitutes the pool of meaning. It also leads to a consideration of the researcher's need to be aware of what might be taken for granted in the forms of discourse that the researcher, who prepares the context, and the interviewee, who experiences it in some idiosyncratic way, in answer to a criticism levelled at phenomenographic interviews as data (Säljö, 1997, p. 177), which characterises the phenomenographer as tending to treat interview data as being directly linked to experience.

And thus the critical questions were formulated: *When we speak of context in phenomenographic research, whose context are we speaking of? Who is experiencing the context? How can we describe and account for context in a phenomenographic study where the prepared context is apparent but the experienced context is lost in the analysis? How can the researcher work towards an awareness of the context during the stages of the phenomenographic study?*

Within the research project on understanding heat and temperature, in our attempt to systematise our thoughts on context we have discussed it in three distinct levels, referring to whose experience of context we are dealing with.

- 1) context at the level of the researcher, of relevance throughout the phenomenographic study;
- 2) context at the collective level, which is the level of greatest interest to the phenomenographic project; and
- 3) context at the individual level, with its importance at the time of data collection and in deploying the results.

2.1 The researcher's context

It can be claimed that when engaged in a phenomenographic study on learning the researcher stands in the same relation to the object of research as the learner stands to the object of learning. The object of research is embedded in a context, and this context can be said to be what lends meaning to the object. We call this context the experienced context of the researcher. Thus, in the example we are taking throughout this paper, the researcher is informed by such contextual factors as the theoretical and empirical research approaches, physics knowledge, physics educational research, and problems associated with learning and teaching physics. Different aspects come into focus at different phases, constituting a temporal dimension of changing character. The researcher's context is, unless explicitly taken up, visible neither in the original data nor in the results.

A central element in the phenomenographic researcher's context is the researcher's own awareness of the role s/he is playing in the study and the preparations that were made for the context of the data collection – here the prepared context of the interview. The researcher in our case played, perhaps, two roles, being for half the interviewees their teacher on a conceptual physics course for lay people at the university, while for others he was a neighbour, a friend of a friend, a colleague of a colleague, or suchlike, as half the interviewees were non-physicist adults with no direct social or family contacts. He introduced himself to all participants as a doctoral student of physics education with an interest in how adults understand the concepts, the phenomena and the principles of physics. Clearly, physics entered the prepared context; or, to put it in another way, the relation between researcher and participant was characterised by an element of physics.

In preparing the context of the interview he drew on his broad knowledge of anecdotes and everyday effects to do with heat and temperature (for example, why it is so difficult to open the door to the freezer right after it has been closed²), in order to open paths of discussion in as natural way as possible, deliberately trying to avoid the demand for a strict natural science discourse from the outset. Nonetheless, in analysing the interview data the researcher can not ignore the power of the situation to bring caution into the interviewee's responses.

Our point here is that the researcher is not devoid of curiosity and insight when doing her or his research, and neither could nor should be so. Some phenomenologists (Ashworth & Lucas, 1998) would demand that the researcher bracket pre-knowledge and pre-suppositions, in order not to frame the results of the research in his or her own terms, but to let the research subject speak and thus reach the essential. It has, on the other hand, been argued forcefully that a

² Try it!

phenomenographer engaged in understanding the variation in ways in which students experience, whether heat or recursion or the mole, needs a thorough and multi-faceted understanding of the concepts in question, at all phases of the research (Lybeck, 1981). The researcher moves to and fro, between seeing the phenomenon against his or her own "professional" knowledge context and seeing it as expressed by others, at all phases of the study. What the researcher does need to apply is a process of reflexivity (Hammersley & Atkinson, 1983), becoming aware of the influence of his or her conceptual understanding over the whole research undertaking, aware of what is being bracketed and what is essential to the research undertaking.

The issue of bracketing in phenomenographic research has recently been raised by Ashworth & Lucas (2000), drawing on the phenomenological tradition. They argue that "... it is the student's experienced world that phenomenographic research bases itself on, and therefore steps must be taken – at the beginning and throughout the research – to bracket anything that would lead us from the student's experience." (p 297) while recognizing that a complete bracketing of the researcher's previous knowledge is not possible: "The attempt to bracket will only be partially successful. Some ways of viewing the world are likely to be more difficult to set aside than others." (p. 299). However, where they argue for entering the life-world of the individual we doubt the possibility of this, and we argue for no more than a selective bracketing to avoid steering data and analysis on preconceived paths. By selective bracketing we mean that the researcher retains an awareness of those aspects of his or her knowledge, which are necessary for understanding above all physics-related utterances of the pool of meaning, in order to let the data speak for itself.

2.2 The collective context

The second level of context we will consider comes into play when data is being studied as a whole, and fragments of data are brought into varying juxtapositions in the analysis process. The analysis that the researcher engages in involves a hermeneutic consideration of elements of the textual pool of meaning, seeing them now as isolated fragments, now in relation to the whole from which they are taken (interviews or written commentaries), now in relation to elements from other, similar wholes, and now in relation to the totality of data or to dimensions of that totality. During this process the researcher is taking different views on the content of the pool, focusing respectively on the extract as such and what it might mean set in different contexts, on the fragment as an element of an interview and what the context of the interview design says about it, on the fragment as one of a set of fragments which indicate different sense making and imply different contextualisations.

When analysing the interviews, the researcher finds that light is shed on some utterance made by one interviewee by reading it against the background of the context deduced or assumed by the researcher from reading an interview extract by another interviewee. Switching between these two perspectives allows the researcher to let an aspect of a phenomenon as experienced by one participant interplay with an expression of an experienced context that originates from another participant. This leads us to introduce the notion of *the experienced context of the collective*.

An example of how the researcher uses the concept of the experienced context of the collective to further the understanding of individual utterances is when A1 says that body heat is not "useful", and compares it with other forms of energy:

- I: What can't you use it [body heat] for?
 A1: It [body heat] is not like, for example, solar energy or electrical energy, or something like that. It's body heat that is left over when one has eaten.
 I: Yes, one can't use it for anything?
 A1: Not anything in particular, not anything productive exactly. But it depends on if you mean heat in general, then I don't know. Then it's different.

These statements can be understood against the background of the following excerpt from the interview with A2, a mathematician who talks about the relation between the concepts of heat and work, and gives an example:

- A2: Mm, that heat...what can I say, one can use some of it...to do work.
 I: In what context?
 A2: Well, the fact that boiling water can lift the lid on a saucepan...how it [the air] expands and can do work.

These two statements put together bring up a new meaning in terms of the nature of heat: A2 introduces the concept of work, which she relates to the usefulness of heat (i.e. some of the heat can be converted into useful work), in a similar manner to A1. A1's statements can be understood in the context of work as specific examples of when heat and other forms of energy (e.g. electrical energy) can be converted into useful work, but he only expresses a partial whole for these specific examples to relate to.

If the interviews had been studied one by one, this relationship would not have come to light. Thus, the collective context is more than the sum of the individual experienced contexts and has served as a tool to analyse the pool of meaning. Referring again to intentional analysis, we can say that whereas the intentional analysts draw on their own experiences to find variation of potential contextualisations, here the researcher is drawing on the *empirical* collective contextualisation for analysis.

Inherent in the different kinds of context that we bring about and experience in our phenomenographic research are cultural qualities, e.g. uses of language and rules of communication, which are usually taken-for-granted, and are thereby rendered invisible. Marton and Booth (1997) point out that without variation, with only one aspect available to experience, one can not begin to see that aspect. Glimpses of the cultural aspects of the context are occasionally visible to the researcher in the data because of the variation in cultural experience that the individuals of the collective bring to the pool of meaning

As an example of this, A3 offers the following answer to the question "What do you think heat is?":

- A3: It is something pleasant, I can say. But if one is thinking of it scientifically, then it is the motion of atoms.

A3 implies that she is adapting to a particular cultural context, since she is being interviewed by a researcher, whom she knows to be physicist, a scientist. A4, picturing heat as related to the movement of electrons, says:

- A4: When I'm trying to think of it logically, that's the way I would think. In everyday situations I wouldn't think this way, but now I do.

The interviewee is expressing a certain cultural aspect of the context for the interviews, different from everyday experience. He is influenced by this cultural aspect since his experience is situated in an environment which the interviewer, the dominating part, has chosen. This is an example of a collective context in the sense that A3 elaborates on A4's statement on what an everyday way of thinking of heat could be: something "pleasant". But more important, the two quotes, through their explicit articulation of the cultural aspect, give a background against which all the other quotes can be seen: the interviewees are engaged in establishing themselves in what they feel to be a – somewhat foreign – scientific culture, and reacting to its demands.

Here we have introduced the idea of a collective context, which is present, though normally neglected, in the pool of meaning, and the way in which it facilitates the researcher in (1) making better sense of individual utterances, and (2) bringing to light otherwise neglected aspects of the cultural assumptions present in the study. Now let us consider what the individual's contextualisation means for the research and the researcher.

2.3 The individual's context

When an individual experiences something or talks about a phenomenon, for example during a phenomenographic interview, some aspects of the phenomenon come into focus, while others remain in the background. The phenomenon is thus experienced against and interwoven with an experienced context, what we can refer to as the *experienced context of the individual*

Examples of different experienced contexts of individuals can be seen in the following extracts, which originate from the interviewees responses to the question "What do you think heat is?" A1 (already quoted in section 2.2) replies:

- A1: Heat is energy. That, I think, is what I think of.
- I: Yes?
- A1: And it's about... I see it as some kind of waste product, something that is left in some way. Something that is not especially useful.
- I: That's interesting...
- A1: At least not body heat. But body heat in general is energy in some form, I suppose.
- I: What can't you use it for?
- A1: It [body heat] is not like, for example, solar energy or electrical energy, or something like that. It's body heat that is left over when one has eaten.
- I: Yes, one can't use it for anything?
- A1: Not anything in particular, not anything productive exactly. But it depends on if you mean heat in general, then I don't know. Then it is different.

The initial theme is heat, which brings with it a context of energy and the usefulness of different forms of energy, with which the notion of heat is intertwined.

A4, meeting this question for the first time in the interview, answered, in contrast:

- A4: In all matter, there are electrons, and they can be affected. It is like electricity: heat is created, and then it feels hot.
- I: So heat has to do with electrons?
- A4: I'd think so. But, the sun, what does it heat?
- I: Yes, is that electrons too?
- A4: It's light really, light rays... that affect what? I don't know.

- I: How does the heat come to the earth from the sun? There are no wires from the sun, right?
- A4: No, it seems like no heat is coming from the sun to the earth. Well, it is the rays of the sun.... They are probably not so hot in reality, but they probably influence something in our atmosphere, I could imagine, and then it becomes hot. That it is the light that is heating. It has to be something with electrons which exist in the air and in matter, in all materials.

We can only speculate about the individual's context in this extract, but we can, as researchers, create a context in which to interpret the quote. It includes the notion of electrons, which are seen as the microscopic origin of heat, through some sort of mechanism (which we will return to in 3.4). As context we can reveal that A4 is an electrician by profession, and that he is well aware that his discussion partner is a physicist. The existence of such a mechanism and its effects are the focus of attention – what we might refer to as the theme of awareness, following Gurwitsch (Gurwitsch 1964; Marton & Booth, 1997) – while its nature is taken for granted and a part of the context – or the thematic field. Also, the two situations mentioned, electricity and the sun, in which the phenomenon of heat seems relevant, are part of the experienced context and not the focus of attention.

The interview extracts above show that A1 and A4 not only have different views of heat, but also experience them as intertwined with different experienced contexts. We see glimpses of this experienced context through different utterances during the interview, but we never get the whole picture, since the context, as such, is not in focus during the interview.

No interview is perfect, and we would now like the interviewer to have continued: "What are electrons, do you think?" and then eventually related the ensuing discussion back to the notion of heat. This points to an aspect of the interviewer's craft that has not been elaborated on in the phenomenographic literature. Our consideration of the context of the individual – comprising the interviewer's knowledge about the personal and educational background of the interviewee, the prepared context, and the interview discussion that has gone before – give the interviewer a potential tool to distinguish the theme from the thematic field at specific and critical points in an interview, in order to encourage an elaboration on the thematic field which can later give grounds for understanding the interviewee's experience of the context as well as the phenomenon.

3. Analysis of context in the context of a phenomenographic study

In the previous section we tried to analyse three levels of the phenomenographic research project – that of the researcher, that of the phenomenographic collective, and that of the individual research participant – and discuss the implications of considering context at these three levels. We will now analyse context in another dimension of empirical phenomenographic research – that of the phases of the study.

We argue that the outcome of a phenomenographic research project could be strengthened by the researcher being aware of the implications of context and its various aspects during the stages of the research project. While these stages are not, of course, clear cut, but rather parts of an iterative process, we will separate them analytically and discuss context in relation to them using the terminology introduced above.

3.1 Formulation of research question

The aim of a research endeavour is formulated at the outset of a study, the main actor at this stage being the researcher, who himself³ is influenced by the context he lives in and works in. The goal is formulated in the socio-cultural environment the researcher is a part of and against a background of what issues and results are perceived as being relevant there. In the example we are taking, this includes the researcher's and his colleagues' understanding of physics, an involvement with the pedagogy of physics and a desire to foster understanding of physics phenomena as they impinge on the everyday life of the public. Similarly, the research strategy is influenced by the educational research culture that prevails at his university, and phenomenography is seen to be immediately appropriate for a study with understanding and experience of an area of science in focus. The research question, then, emerges from the researcher's background and immediate context, and is formulated within a field of research related by subject interest and by methodological approach.

In phenomenography, it is the phenomenon (or set of phenomena, here heat and temperature) of interest that is in focus. This phenomenon is known to the researcher in some way (here as a physicist), and the goal and the strategy are aimed at revealing how it is known or understood to others (here lay adults), in other words to inform the research question. In formulating the research question, therefore, the researcher has to be open to ways of knowing the phenomenon other than his own, and has to be open to the research participants experiencing the context in unexpected ways – what we called selective bracketing. The researcher should thereby be avoiding two potential traps: excluding the participants' experienced context(s) from the context of the research question, and taking a common cultural ground for granted.

3.2 Data collection and context

What are the relevant aspects of context in data collection, if one is to maximise the variation in the pool of meaning? Starting with the researcher, the researcher acts in his or her experienced context where a particular interview is seen against the background of earlier interviews and the anticipation of the interviews to be done. That context can be seen as if the interviewee of a particular interview, through the mediation of the researcher, participates in an on-going discussion around a certain phenomenon both with the researcher and all the other interviewees, the latter being intellectually present while physically absent.

The researcher has a certain aim: he wants a particular phenomenon to become the focus of mutual attention in such a way that the participant can reveal the ways in which he or she experiences it, seen from varying angles, against different backgrounds. To achieve this, he *prepares* contexts for the participants to engage with, to experience, and to speak in. In the case of eliciting written texts, this might involve devising a scenario for the participant to relate to. In holding interviews, it includes, in addition, choosing the environment where the interviews are held, choosing the theme of the interview, working out what questions to ask, planning specific follow-up questions that might be needed, and remaining open and flexible, patient and persistent throughout.

³ Since our researcher into how adults experience heat and temperature is a man, we will use the male prepositions to refer to him. Of course, a female researcher would be in exactly the same situation, and would need to analyse her influencing context.

In Adawi's interview study, a good deal of time was spent on creating a *variation* in the prepared contexts, an effort being made to design situations with potential for opening up a variation in ways of experiencing the phenomena in everyday contexts. For example, the interviewees were handed two knives, a butter knife made of wood and a dinner knife of metal. They were asked to hold them, and then asked to explain why the metal knife felt colder, what their temperatures actually were (i.e. room temperature), to explain the discrepancy between sensation and temperature (if the knives were considered to be at the same temperature), and if they could relate this phenomenon to other everyday situations. Thus the interviewee was drawn into a discussion of the concepts of thermal equilibrium, temperature and conduction.

Another prepared context involved a cooling cup of coffee. In this case, the interviewees were asked: "If you were to cover your hot cup of coffee with a container, which container would be most effective in keeping the coffee hot – a metal one or a wooden one?" The question was followed by a discussion of the particular choice and its relation to some everyday situations. Again, an interesting discussion of the otherwise abstract concepts of heat, conductors and insulators ensued.

However, as noted in section 2.3, a prepared context (and possibly the phenomenon it was prepared to reveal) can be experienced in strikingly different ways by different interviewees – and perhaps in a way that was not originally intended by the researcher. For example, in order to break the ice after introductions and to orient the interview towards thermal phenomena, each interview started by the interviewer quoting the famous mathematician Marcel Grossman:

When I sat on a chair that someone had just vacated, and felt the heat he had left there, I used to be struck by something close to horror. No longer. I have learned in physics that heat is impersonal, through and through. (Balibar, 1993, our translation)

The interviewer then asked: "What *is it* that you feel when you sit on a chair that somebody just left?". The idea was to get the subjects to start talking about the concepts of heat and temperature: what heat and temperature are; how they are related to each other and to the sensation of hotness and coldness; how heat is transferred from one place to another and possible factors that influence the rate of heat transfer.

A5 answered the question by saying that what you feel is the heat in the chair (that has been transferred to the chair from the person sitting on it earlier) and then went on to offer a microscopic explanation of the nature of heat as well as a mechanism for heat transfer:

A5: It's a kind of motion, atoms moving when things get hot. When the person sits down on the chair, he has a kind of motion in his butt and he kind of vibrates and transfers that to the chair.

This is a response, physiological in nature, that has some elements in common with the answer a physicist might have given, and the context to the question was experienced, for whatever reason, as one of classical physics. A6, on the other hand (as well as some other interviewees), answered the same question in a completely different way:

A6: I don't really know what I feel. Perhaps I don't really like it when it's somebody that I don't know well. But if it's my wife or somebody close it's not like that.

In the researcher's context, focusing on physics phenomena, this is an unexpected answer, more psychological in nature than either physical or physiological. This example illustrates that located in the same social, spatial, and temporal surroundings, the contexts experienced by the two interviewees were radically different – physiological and psychological – and thereby, we speculate for the moment and return to in the next section, the ways of experiencing the phenomenon. This example led us to debate the role of the experienced context in the phase of collecting data of a phenomenographic interview.

We argue that by being careful to maintain an awareness of the experienced context in all its complexity in a phenomenographic study the researcher can exploit the prepared context during data collection to strengthen the content of the pool of meaning. One way of supporting a relevant variation in the experienced context of the interviewee – allowing the researcher to see the phenomenon against, and interwoven with, an even wider range of different backgrounds, and use this to see different aspects of the phenomenon – is to use a corresponding variation of the prepared context in the interview.

3.3 Data analysis and results with context in mind

Let us continue with the example we introduced in the previous section. When the two data extracts were considered in the pool of meaning, stripped of context at the collective level, that from A5, above, could be seen within a physics framework, but A6 was strange, trivial even some might think as "feel" can be ambiguous. In order to understand it more the researcher returned to the complete transcript and read the continuation:

A6 I notice it most of all if I get on a bus, and take somebody's seat

Now the interpretation becomes clearer, someone has "left" their warmth there and A6 is getting it. Focus, then, is on the psychological feeling of the interviewee, his discomfort, which at first seemed irrelevant to the study, but turned out to be related to a way of conceptualising the phenomenon of heat: it is seen as "something" that is contained in and given off by hot objects, some kind of body substance in this case, and therefore something

A2 ...unpleasant that enters the body even if I perhaps don't want it

This is related to one of the two qualitatively distinct ways of conceptualising the ontological nature of heat, *heat as a substance*⁴, found in Adawi's empirical study.

If we return to A5's response, with focus on the physiological feeling and an explanation from physics, the contrast with A6's response now becomes clearer. Heat is not being seen as some kind of substance but rather as (a form of energy) associated with the vibrational motion of

⁴ Such a way of conceptualising heat is common among physics novices and well documented in the research literature (see Reiner et al., 2000). Historically, it resembles the *caloric theory of heat*, where heat is seen as some kind of fluid (caloric) that flows from hotter objects (rich in caloric) to colder objects (with less caloric). Today, the idea that heat (or coldness) is a substance is still very much a part of our everyday language; we often hear phrases such as "close the window and keep the heat (cold) in (out)".

the constituents of the object. This is related to other of the two qualitatively distinct ways of conceptualising heat, *heat as a energy*⁵ from Adawi's empirical study.

Now we confirm what we referred to as speculation in the previous section – these two data extracts serve as catalytic fragments of two distinctly different ways of experiencing the phenomenon of heat (as a substance or as energy), and they emerged in the analysis from two distinctly different ways of experiencing (psychologically or physiologically) the prepared context. At a micro-level of analysis, returning to the prepared/experienced context at the individual level has illuminated the ways in which the phenomenon is experienced at a collective level, and clarified the results at the macro-level – the categories of description.

To cast light on the phenomenon of interest, being interwoven with the individual's experience of context, a collective level of experienced context and ways of experiencing the phenomenon is created by the researcher – a process of decontextualisation and recontextualisation, where decontextualised pieces of individual interviews are recontextualised with other pieces of interviews and the whole set of interviews.

Let us consider the role of *decontextualisation*, which is an essential aspect of the analysis stage of a study, in order to see the phenomenon clearly in the second-order perspective. The very interviews are decontextualised from the situation in which they were made. And then, as the pool of meaning is formed, individual pieces of data are removed from the prepared context and lose contact with the experienced context. The results we are aiming to reveal – the categories of description – are themselves to be decontextualised even at the collective level.

If we turn to the role of *recontextualisation*, we see this as no less than creative and analytical *contextualisation*! The researcher has the freedom to take individual extracts of data and put them into juxtaposition with other pieces of data, or with prepared contexts, or with whole interviews, or even with related research results – all in an effort better to understand the data at hand in a hermeneutic manner, as described in section 2.2. It aims at the ultimate recontextualisation of the entire pool of meaning into the set of logically and empirically related categories of description. It is an instrument to be used carefully and with due respect for the contexts in question as experienced.

As a result of this iterative, non-algorithmic analysis, the researcher finally arrives at a set of logically related categories of description, intended to describe the limited number of qualitatively different ways of experiencing of the phenomenon at a collective level. It is, however, important to note that the categories of description are "our interpretations of others' interpretations" (Johansson *et al.*, 1985, p. 249). The researcher is therefore, when analysing the data, in a learning situation, and it is then clear that the researcher's context is of fundamental importance in creating structure and meaning in the categories of description.

When formulating the categories of description the phenomenographic researcher deliberately strips away contextual features to be able to identify the essential variation in how the phenomenon is experienced. As we said in the introduction, to confuse the variation in ways

⁵ Speaking as a physicist, objects do not contain heat. The total energy that an object contains as a result of the kinetic and potential energies of its individual atoms and molecules is called *internal energy* (or sometimes thermal energy). Heat (or work), on the other hand, is a way of changing the internal energy of an object. However, this important distinction between the energy *in* a system (i.e. internal energy) and the transfer of energy *between* systems (i.e. heat or work) was not voiced in the empirical study.

of experiencing the context(s) of the study with the variation in ways of experiencing the phenomenon of study is to risk losing fundamental insights⁶. For example, if we look briefly at the two categories of description already revealed – heat as a substance and heat as energy – we can see that they are stripped of the prepared contexts: no mention of seats or knives or coffee cups; they are stripped of individual experienced contexts: no physiological or psychological feelings are seen there; and the individuals' own words are lost (though individual fragments of data are used to illustrate the categories in a full description). The collective context, or spectrum of experienced contexts – even if we have partly revealed them in the analysis – are hidden in the set of descriptions. The researcher's context is once again paramount.

In the final results we can say that the ways of experiencing the phenomenon have been abstracted or *distilled* from the different contexts in which the phenomenon is embedded. And in so doing the phenomenon has been revealed in a more nuanced sense, as a complex of related aspects, subsets of which go to make up the variation of ways in which it is experienced at the collective level. This analytical distillation process is one of decontextualisation and recontextualisation (or creative contextualisation), where the essence of the phenomenon is abstracted, decontextualised and recontextualised into the logical system of categories of description and in relation to the research question as well as this particular phenomenographic research approach.

3.4 Deploying the results in context

In an important sense the three stages already considered go to make up the phenomenographic project. What happens after the arrival at and description of the outcome space depends on the formulation of the research question, and can shift from phenomenography's second-order perspective to a first-order perspective. But the results that are then used are, in themselves, stripped of all context, unless the researcher makes a conscious effort to relocate the results in their original contexts. This can be carried out at any of our three levels – individual, collective or researcher level – as we will expand on here.

At the *individual level*, the researcher can turn the outcome space back on the transcripts of the interviews, or other collected data, and use it to illuminate the individual. This has been done in phenomenographic work such as in Beaty et al. (1997), where a well established outcome space for the ways in which adults experience the nature of learning was used to describe the development of learning in individual adult students over a number of years of distance study.

In the current study, Adawi could make use of the outcome space in a similar way, to study the physics conceptual world of one or more of his participants. For example, it is known that A4, quoted earlier, is an electrician by trade, and voices an association of heat with electrons in the extract we have given in section 2.3. This might be taken to mean that electrons underpin his entire physics world, and that any physics related context is seen in terms of

⁶ One way of confusing the two would, for example, be to create an outcome space for the phenomenon of interest in different prepared or experienced contexts. However, this does not mean that we should completely neglect the role of the context(s), even if it is not of main interest. On the contrary, as phenomenographic researchers we can gain a lot by returning to the context(s) and see how different categories of description are related to different contexts. This has been done in phenomenographic work such as that by Johansson et al. (1985), investigating university students' conceptions of force and motion in some everyday contexts.

electrons. But if his whole interview is inspected, for example the part where he is discussing why the dinner knife made of metal feels cold, we find there:

- I: Has something been transferred from your hand to the knife?
A4: Electrons.
I: Electrons?
A4: It's just a word that I'm using right now, because that's the only thing that I can imagine that it is.
I: So you picture heat as some kind of particles that are being transferred?
A4: Yes, when I'm trying to think of it logically, that's probably the way I would think of it. [...] I mean...something is travelling in the knife, since it's being heated outwards.

Now we see that a more reasonable interpretation is that he is seeking a way of expressing heat as a substance, and it is electrons that come to mind to constitute this substance. An interesting analysis of this case could be made, relating the electrician's experience to his understanding of thermal physics, by analysing what he says about the remaining prepared contexts.

To relate the outcome space to the *collective level* is the most usual turn of phenomenographic research. Studies are most often undertaken in order to gauge the variation in ways of understanding or experiencing that are likely to be found in a large group of people such as a cohort of students (e.g., Booth, 1992; Booth & Ingerman, in press) or school pupils (e.g. Neuman, 1987; Ahlberg, 1992). We have been selective here in discussing phenomenographic research principles, but suffice it to say that the collection of participants has been selected to represent the variation in the population of interest.

In Adawi's study, the interviewees were half students of a evening course on conceptual physics for the general public and half were similar adults not taking the course, while written material was taken from all the course members. Thus the results can be seen as relevant for lay adults as a whole, with a special subset of course takers. Thus, at the collective level, Adawi can describe the variation in ways in which heat, temperature and phenomena related to these concepts are experienced by lay adults, and possibly differentiate between the ways in which the course-takers have come to understand thermal phenomena from the ways in which lay adults do as a whole.

Relating the research outcome to the *level of the researcher* is on the one hand a scientific enterprise – the results enrich the researcher's understanding of his research field, they underpin future research projects and inform the formulation of future research questions. In the particular case of this study there is another, more interesting relation, and that is the relation of researcher's pedagogical research to the researcher's pedagogical practice, and to teaching in general. For this study was expressly designed to bring greater understanding of teaching through revealing the structure and meaning of central phenomena in physics as students experience them – teaching with learning in focus.

4. Summary

We summarise the main points we have made in Figure 1, relating the level of description (researcher, collective, individual) to the phase of the research undertaking (formulating the research question, collecting data, analysing data, and deploying the results) with respect to the significance of *context*. Note that Figure 1 is not intended to be seen as a linear description

of the research process, but an indication of the complex interplay between these aspect of phenomenographic research.

We start with the top left-hand box, reading downwards. The description of Adawi's physics cultural and research background that was given in section 2.1 can be generalised as the researcher's culture and the cultural, the empirical and the research history of the question itself. It is these that underpin the design of the study – how the question can be formulated, who comprises the collective from which data will be collected, how the data is to be collected, and so on. It is the researcher's task at this stage of the design of the study to devise a context for the study which will put the participants at their ease and enable a fruitful discussion to ensue, and to design contexts in which the phenomenon/a of interest can be approached in different ways to maximise the variation that can emerge during the data collection.

From here we can follow the arrow (1) to the individual level at the stage of data collection. The researcher and the individual participant engage in some activity (here interviews) in which the researcher has prepared the context(s) (here questions related to everyday experiences of heat and temperature) to which the individual responds according to her/his experience of those contexts. As the individual participants one by one contribute their data to the study (2), what is seen from the researcher's perspective as the pool of meaning increases at the collective level and the researcher becomes more insightful into the ways in which the participants experience the interview situation (3), and hence the prepared contexts. This gives the researcher successively greater opportunity to further engage with individual participants, using later interviews to explore earlier interviews and unfinished issues that arose there (4): we spoke of the collective being intellectually present though physically absent in the individual interview. Thus the pool of meaning which the researcher is to analyse is formed.

In the phase of analysing data (5), the individual participant is separated from their contribution as it goes to the collective level (6); their interview becomes recontextualised from the particular context in which it took place into the context of the totality of data, the researcher's pool of meaning. As the researcher works with this (7) – bringing individual pieces of data, interpreted in the light of their prepared context and what emerges of their experienced context, into juxtaposition, as exemplified in section 2.3 – the data becomes successively recontextualised into the emergent set of categories of description and the context is relegated to the background. Of course, there is much more to the analysis process than we speak of here, where we focus only on the issue of context and stripping away context.

The results of the phenomenographic analysis – the categories of description that form the outcome space – can be further analysed, or deployed, in various ways. In keeping with our researcher-collective-individual levels we identify three sorts of deployment, in which the results are related to the levels. Relating them to the researcher (8) puts them into the development of the empirical and research culture, where they inevitably find a place. Relating them to the collective (9) gives them the form of an overview, or – as was originally intended in this case – a qualitative evaluation of an educational measure. Relating them to the individual can be part of case studies, as for example Beaty et al. (1997).

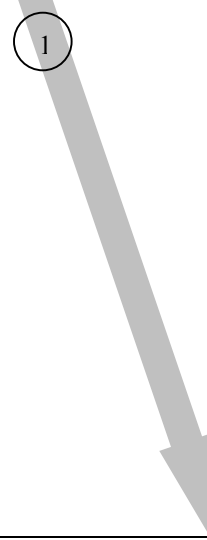
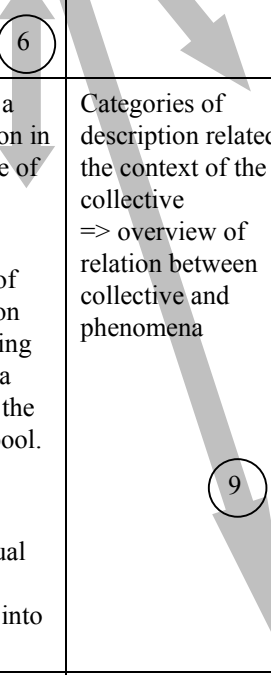
	<i>Formulating question</i>	<i>Collecting data</i>	<i>Analysing</i>	<i>Deploying results</i>
<i>Researcher</i>	Background of researcher's culture The question's empirical, research and cultural history Devising prepared contexts to introduce variation around the question and phenomenon/a involved	Researcher using insights into participants' experienced contexts to build more reflexive data Researcher extending insights into participants' experienced contexts	Emergent categories of description with context stripped away Brings phenomenon into focus, relegating context to the background	Categories of description related to the context of the research question => pedagogical considerations Theoretical development
<i>Collective</i>		Collective intellectually present in the process though physically absent Variation in ways of speaking of phenomenon/a in different prepared/experienced contexts Pool of meaning grows, embracing expressions of phenomenon/a as experienced in prepared contexts	Moving towards a recontextualisation in an outcome space of categories of description Totality of pool of meaning, variation around the meaning of the phenomena intertwined with the structure of the pool. Data decontextualised from the individual level, recontextualised into the totality	Categories of description related to the context of the collective => overview of relation between collective and phenomena 
<i>Individual participant</i>		The prepared contexts are experienced and fragments of expressions of this experience form the data collection		Categories of description related to individual's contexts => case studies

Figure 1. A summary of the stages of research and the levels of interest when considering context in phenomenographic research.

5. Discussion

With the analysis we have presented here we are able to address certain critics of the phenomenographic approach. Säljö (1997), for example, today standing outside the phenomenographic community, argues for the primacy of language over experience. Language is undeniably important in phenomenographic research: the data is most often in the form of interviews, it is transcribed interview texts that the researcher works with during analysis, and it is extracts from the text that lend meaning to the categories that are communicated as results. Säljö prefers to see these texts as examples of the ways in which interview subjects are handling the discourse surrounding the phenomenon, rather than reflecting in any way their ways of experiencing the phenomenon. Säljö's criticism can be concisely put through the following quote:

Phenomenographers in the interview situation ..., no more than any others, have access to anything except utterances from individuals made in specific situations and with varying motives. [...] The phenomenographer's choice is to consider these utterances as indicative of ways of experiencing. (p. 177)

We agree with Säljö's criticism that the assumption that what someone says is equal to what someone in fact experiences is naive. Such criticism, however, seems to confuse the individual and the collective levels, which leads to an understanding that a phenomenographic analysis is an analysis of individual *pieces* of data, where it is in fact an analysis of a *set* of pieces of data at the collective level. It is the whole of the data material, generally interviews, that goes to make up the pool of meaning with which the researcher engages to analyse structure and meaning, inextricably intertwined as they are, from the perspectives of those interviewed – not as a set of individuals but as a deliberately varied and holistic sample of the population of interest. We have characterised this pool of meaning as a relation between the researcher and the set of de- and re-contextualised data: decontextualised in that pieces are taken out of their original whole and creatively re-contextualised within the totality of data and its emergent research meaning. It is in the analysis of the pool of meaning that the context is "stripped away", made to disappear, from the phenomenon.

The naïve assumption amounts to seeing the prepared context in an interview as having a one-to-one correspondence to the experienced context, or to return to the distinction made by Ekeblad and Bond, that an experiential project can be achieved by an externalist method. But Säljö goes further than this, and argues that the phenomenographic research object rather should be a variation between different modes of discourse, to reveal the different ways in which people talk about phenomena, since differences in the discourse between the interviewer and the interviewee threaten to make data meaningless if interpreted in terms of ways of experiences. However, the arguments we produce in this paper give us the grounds to treat "differences in discourse" in terms of differences in experienced contexts to which the researcher takes a principled reflexive turn. The discourse is part of the context that is stripped away from the individual level and hidden at the collective level during the analysis, as the process of decontextualisation and recontextualisation (or creative contextualisation) strives towards a parsimonious yet sufficient set of categories of description. The form of discourse used by the interviewees is not transparent in itself – it does not comprise receptacles of meaning that can be shunted round until like is matched with like to comprise a category of likes. We prefer to see it as bearing meaning and contextually dependent, both spontaneous

and singular; and it is the phenomenographic researcher, with his or her aim to be experiential and see the world as others see it, to devise a research context that can support this contextual dependence for the meaning it bears, and can take the singular expressions and see them in contrast and in contact with other singular expressions, all in the move towards understanding.

Ashworth & Lucas (2000) take a practical perspective on how a phenomenographic study is to be made. Doing so, they briefly touch upon the issue of context, aiming to retain individual contexts in collective results:

Generalizations across individuals are of value, but it is important that the individual's unique experience is not lost. ... As such, it [the individual profile made on each interviewee in the study used as an example] provides a necessary counter-weight to any tendency to attribute meaning out of context. (p. 304)

Even though we experience the danger they point out here (the assigning of presupposed meaning to data) as real and not to be taken lightly but we prefer to characterise the phenomenographic project, as we have said many times in this paper, as taking its starting point not from the individuals, but from the collective, instead using the context of the collective in creating a "life-world of the collective" in which the research outcome, the categories of description, is based.

In a similar way, Friberg et al. (2000) seem to be taking the individual as their starting point. Discussing the issue of context in phenomenographic studies of nursing, they state of the phenomenographic object of research:

Understanding or experience as conceptions is the focus of interest. This assumption includes a contextual awareness, in which context seems to be the area where conceptions are generated or identified. The area of interest is not context itself, but the individual's understanding of a certain aspect of reality. During phenomenographical (sic) analysis, conceptions are separated from individuals. Understanding is analyzed as conceptions, "frozen thoughts". The decontextualized conceptions are constant in different situations and constitute a collective consciousness. (p. 37)

Again, we find ourselves approaching the issue from the other direction⁷, arguing for making decontextualization in the collective rather than in the individual experience, and the stripping of context transform from an obstacle for understanding of the individual to a tool for describing the collective. In contrast to these two works, the work of Pong (1999) on the influence of context on students' understanding of the economic concepts of price and trade is more in line with ours. He showed how changes in the ways participants experienced the concepts run parallel with changes in focus, and, relating, the phenomenographic results back to individuals, he showed that many of them changed both across different problem contexts (inter-contextual shifts) and within a specific problem context (intra-contextual shifts). In general these so-called conceptual shifts clearly make it impossible to relate an individual exclusively to a particular way of experiencing a phenomenon, or vice versa.

Phenomenography is in a state of ongoing development. The adherents and adepts share a mutual engagement in issues of learning and understanding, knowing and experiencing, and they strive after a second-order perspective where the participants' ways of seeing the world come to the fore in data collection, analysis and reporting. There is a growing repertoire of

⁷ And we are bemused by the idea of phenomenography dealing in "frozen thoughts".

concepts and techniques that too often remain unreported and methodologically unproblematised. This paper has been an attempt to question our own practice and methodological underpinnings as phenomenographers and relate our discussion to other such attempts, and we end with a hope that they continue to be explored, in other contexts.

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References

- Adawi, T.W. (*In preparation*) What's Hot and What's Not: Lay Adults' Conceptions of Heat and Temperature.
- Ahlberg, A. (1992). *Att möta matematiska problem. En belysning av barns lärande* [Meeting mathematical problems. An illumination of children's learning] Göteborg: Acta Universitatis Gothoburgensis.
- Ashworth, P. D. & Lucas, U. (1998). What is the 'world' of phenomenography? *Scandinavian Journal of Educational Research*, 42, 417-433.
- Ashworth, P. D. & Lucas, U. (2000). Achieving empathy and engagement: a practical approach to the design, conduct and reporting of phenomenographic research. *Studies in higher Education*, 25, 295-308
- Chambers English Dictionary (1990). London: W & R Chambers Ltd
- Balibar, F. (1993). *Einstein. Fysiker och tänkaren* (Einstein. Physicist and thinker, translated from the French *Einstein, la joie de la pensée*. Gallimard.)
- Booth, S. (1992). *Learning to program. A phenomenographic perspective*. Göteborg: Acta Universitatis Gothoburgensis
- Booth, S. & Ingerman, Å (in press) Making sense of Physics in the first year of study. *Learning and Instruction*
- Booth, S., Wistedt, I., Halldén, O, Martinsson, M. & Marton, F. (1999) Paths of learning – the joint constitution of insights. In L. Burton (Ed.) *Learning mathematics. From hierarchies to networks*. London: Falmer Press
- Beaty, E., Dall'Alba, G. & Marton F. (1997) The Personal Experience of Learning in Higher Education: Changing views and enduring perspectives. In Sutherland, P. (Ed) *Adult Learning: a reader*. London, Kogan Page.
- Ekeblad, E. & Bond, C. (1994). The nature of a conception: questions of context. In: Ballantyne, R. and Bruce, C. (Eds.) *Phenomenography: Philosophy and practice*. Centre for Applied Environmental and Social Education Research, Faculty of Education, Queensland University of Technology.
- Friberg, F. et al (2000). Context and Methodological Decontextualization in Nursing Research with Examples from Phenomenography. *Scand. J. Caring Sci.* 14, 37-43.
- Gurwitsch, A. (1964). *The field of consciousness*. Pittsburgh: Duquesne University Press.
- Halldén, O (1988). The evolution of species: Pupils' perspectives and schools' perspectives. *International Journal of Science Education*, 5, 10, pp 541-552
- Hammersley, M. & Atkinson, P. (1983). *Ethnography: Principles in practice*. London: Tavistock Publications
- Johansson, B., Marton, F. and Svensson, L. (1985). An approach to describing learning as change between qualitatively different conceptions. In West, L. and Pines, L. (Eds.) *Cognitive structure and conceptual change*.
- Linder, C. (1993). A Challenge to Conceptual Change. *Science Education* 77, 293-300.
- Linder, C. & Marshall, D. (2001) *Reflection and phenomenography: Towards theoretical and educational development possibilities*. Paper presented at the 9th EARLI conference, Fribourg, August 2001.
- Lybeck, L. (1981). *Arkimedes i klassen. En ämnespedagogisk berättelse* [Archimedes in the classroom] Göteborg: Acta Universitatis Gothoburgensis
- Marton, F. & Booth, S. (1997). *Learning and Awareness*. Mahwah NJ: Lawrence Erlbaum Ass.

- Merriam-Webster's Collegiate Dictionary, Encyclopedia Britannica Online (<http://www.eb.co.uk:180/>)
- Neuman, D. (1987). *The origin of arithmetic skills: a phenomenographic approach*. Göteborg: Acta Universitatis Gothoburgensis
- van Oers, B. (1998). From context to contextualizing. *Learning and Instruction* 8, 473-488.
- Pong, W.Y. (1999). *The dynamics of awareness*. Paper presented at the 8th EARLI conference, Göteborg, August 1999.
- Reiner, M., Slotta, J.D., Chi, M.T.H. and Resnick, L.B. (2000). Naive physics reasoning: a commitment to substance-based conceptions. *Cognition and Instruction*, 18(1), pp. 1-34.
- Säljö, R. (1997). Talk as data and practice – a critical look at phenomenographic enquiry and the appeal to experience. *Higher education research and development*, 16, p 173-190.
- Uljen, M. (1993). The essence and existence of phenomenography. *Nordisk Pedagogik*, 13, 134-147.

On the Understanding of Computer Network Protocols

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