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Complexity Theory and Physics Education Research

The Case of Student Retention in Physics and Related Degree Programmes

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ACTA
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UPSALIENSIS
UPPSALA
2015

ISSN 1651-6214
ISBN 978-91-554-9303-5
urn:nbn:se:uu:diva-259413

Dissertation presented at Uppsala University to be publicly examined in Häggsalen (Å10132), Ångströmlaboratoriet, Uppsala, Friday, 2 October 2015 at 09:29 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor of Physics Ismo Koponen (Helsingfors University).

Abstract

Forsman, J. 2015. Complexity Theory and Physics Education Research. The Case of Student Retention in Physics and Related Degree Programmes. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1273. 185 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-554-9303-5.

This thesis explores the use of complexity theory in Physics Education Research as a way to examine the issue of student retention (a university's ability to retain its students). University physics education is viewed through the concepts of nestedness and networked interactions. The work presented in this thesis covers two main aspects from a complexity theory perspective: (1) institutional action to enhance student retention; and, (2) the role of students' in-course interaction networks. These aspects are used to reframe student retention from a complexity theory perspective, as well as to explore what implications this new perspective affords. The first aspect is addressed by conceptualizing student retention as an emergent phenomenon caused by both agent and component interaction within a complex system. A methodology is developed to illustrate a networked visualization of such a system using contemporary estimation methods. Identified limitations are discussed. To exemplify the use of simulations of complex systems, the networked system created is used to build a simulation of an "ideal" university system as well as a Virtual world for hypothesis-testing. The second aspect is divided into two sections: Firstly, an analysis of processes relating to how students' in-course networks are created is undertaken. These networks are divided into two relevant components for student retention – the social and the academic. Analysis of these two components of the networks shows that the formation of the networks is not a result of random processes and is thus framed as a function of the core constructs of student retention research – the social and academic systems. Secondly, a case is made that students' structural positions in the social and academic networks can be related to their grade achievement in the course.

Keywords: Physics Education Research, Complexity Theory, Student Retention

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To Jenny, Adrian, and Julius.

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. My contributions in each paper are outlined below each paper.

I Forsman, J., Linder, C., Moll, R., Fraser, D., & Andersson, S. (2014). A new approach to modelling student retention through an application of complexity thinking. *Studies in Higher Education*, 39(1), 68–86.

My contribution: I put forward the idea to the Paper. I designed and distributed the data collection tool, then analysed the results. I was the first author.

II Forsman, J., Van den Bogaard, M., Linder, C., & Fraser, D. (2014). Considering Student Retention as a complex system: A possible way forward for enhancing Student Retention. *European Journal of Engineering Education*. doi: 10.1080/03043797.2014.941340.

My contribution: As first author I proposed the fundamental ideas for the Paper. I developed and implemented the MMST analysis in this article.

III Forsman, J., Mann, R. P., Linder, C., & Van den Bogaard, M. (2014). Sandbox University: Estimating influence of institutional action. *PLoS ONE,* 9(7), doi: 10.1371/journal.pone.0103261.

My contribution: As first author I put forward the main ideas of the Paper. Further, I implemented the methodology.

IV Forsman, J., Moll, R., & Linder, C. (2014). Extending the theoretical framing for PER: An illustrative application of complexity science, *Physical Review Special Topics-Physics Education Research*, 10(2), 020122.

My contribution: As first author I put forward the main ideas for the Paper. I designed and distributed the questionnaire and analysed the data set.

V Forsman, J., Linder, C., & Moll, R. (Manuscript). Exploring Indicators for Academic Success Using Complexity Thinking and Network Analysis to Investigate Students' Social and Academic Network Structures.

My contribution: I was first author, proposing the concept of the Paper. I designed and distributed the questionnaire and analysed the data set.

Supporting work

This thesis also draws on the following:

Article

Enghag, M., Forsman, J., Linder, C., MacKinnon, A., & Moons, E. (2013). Using a disciplinary discourse lens to explore how representations afford meaning making in a typical wave physics course. *International Journal of Science and Mathematics Education*, 11(3), 625-650.

Conference Proceedings

Forsman, J. & Andersson, A. (2013). Course Experience Questionnaire Map – Ett verktyg för identifiering av förändringar av undervisnings-verksamhet? In Gir Gunnlaugsson (Ed.), *I stort och smått – Med studenten i fokus*, Universitetspedagogisk utvecklingskonferens 16 oktober 2013 (pp. 67 – 79).

Fraser, D., Forsman, J., Van den Bogaard, M., Linder, C., & Moll, R. (2013). Probing Student Experience and Success in an Engineering Programme Through Development of a Questionnaire and Complexity Analysis. In: *Research in Engineering Education Symposium (REES2013)*, Kuala Lumpur, Malaysia, 4 - 6 July, (pp. 65- 71).

Andersson, S., Forsman, J., & Elmgren, M. (2012). Studenters upplevelser av första året. In: Geir Gunnlaugsson (Ed.), *Universitetspedagogisk utveckling och kvalitet - i praktiken*. Paper presented at Universitetspedagogisk utvecklingskonferens 6 oktober 2011 (pp. 9-20).

Fraser, D., Moll, R., Linder, C., & Forsman, J. (2011). Using complexity theory to develop a new model of student retention. In: *Proceedings of the Research in Engineering Education Symposium 2011*. Research in Engineering Education Symposium, 4-7 October, 2011, Madrid, Spain, (pp. 1-6).

Forsman, J., & Andersson, S. (2010). Två teoretiska modeller för studentavhopp från universitetsutbildning. In: Britt-Inger Johansson (Ed.), *Att undervisa med vetenskaplig förankring - i praktiken!*: Universitetspedagogisk utvecklingkonferens 8 oktober 2009 (pp. 81-90). Uppsala: Universitetstryckeriet.

Forsman, J., Andersson, S., Andersson Chronholm, J., & Linder, C. (2010). Disciplinära diskurser i naturvetenskap och matematik. In: Britt-Inger Britt-Inger Johansson (Ed.), *Att undervisa med vetenskaplig förankring – i praktiken!*: Universitetspedagogisk utvecklingskonferens 8 oktober 2009. (pp. 41-47), Uppsala: Universitetstryckeriet.

Conference Presentations

Forsman, J., & Andersson, S. (2014). Kartläggning av student-upplevelser som verktyg för professionell reflektion. Presented at *NU2014 Conference*, Umeå, 8-10 October.

Forsman, J., & Andersson, S. (2013). Course Experience Questionnaire Map (CEQM). Presented at *Konferens i universitetspedagogisk utveckling*, Uppsala, October 16.

Forsman, J., Van den Bogaard, M., Linder, C., Fraser, D., Verbraeck, A., & Andersson, S. (2013). Challenges in Engineering Higher Education: Understanding Student Retention as a Multilevel Complex Phenomenon. Presented at *the 21st Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*, University of the Western Cape, Bellville, South Africa, 14 - 17 January.

Andersson, S., Forsman, J. & Elmgren, M. (2012). Studenters upplevelser av första året. Presented at the *Konferens i universitetspedagogisk utveckling*, Uppsala, October 16.

Forsman, J., Moll, R., Andersson, S., & Linder, C. (2011). The Complex Nature of Physics and Engineering Students' Academic and Social Networks in Higher Education. Presented at the *National Association for Research in Science Teaching, NARST, Annual International Conference*, Orlando, Florida, 3-6 April.

Forsman, J., & Andersson, S. (2010). Studenters stödjande nätverk: Presented at the *NU2010 Dialog för lärande* Conference, Stockholm, 13-15 October. .

Forsman, J., & Andersson, S. (2010). Att arbeta med studentretention. Presented at the *NU2010 Dialog för lärande* Conference, Stockholm, 13-15 October.

Forsman, J. (2010). Using Complexity Thinking and Network Theory when Modeling Higher Education Student Trajectories in Physics and Engineering Physics. Presented at *JURE 2010, Connecting Diverse Perspectives on Learning and Instruction Conference*, Frankfurt, Germany.

Forsman, J. & Andersson, S. (2010). Kritiska aspekter för "lyckade fysikstudier". Presented at '*TUK2010 Faculty of Science and Technology's University Pedagogical Conference'*, Uppsala University, Uppsala, 18 May.

Forsman, J., Andersson, S., Andersson Chronholm, J. & Linder, C. (2009). Disciplinära diskurser i naturvetenskap och matematik. Presented at the *Universitetspedagogisk utvecklingskonferens*, Uppsala, Sweden, October 8.

Forsman, J., & Andersson, S. (2009). Studentavhopp - Varför sker det och hur kan det motverkas? Presented at the *Konferens i universitetspedagogisk utveckling*, Uppsala, 8 October.

Enghag, M., & Forsman. J. (2009). Students evaluations of themselves as disciplinary practitioners. Presented at *GIREP-EPEC 2009 International Conference*, Leicester, 17 – 21 August.

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Contents

Glossary and Abbreviations

Table 1. *Glossary and abbreviations of how terms are used in this thesis.*

Term	Explanation
Academic dismissal	A process whereby a student is required to leave their degree programme by their university, due to, for example, unfinished courses.
Academic network	A network of students' academic interaction.
Academic system	A system of academic of norms, rules, expectations.
Adaptation (evolution)	System changes due to internal and/or external influences of the system.
Agents/Components	This refers to those parts of a system that structurally make up the system (for example, students, teachers, rules, expectations, behaviours, etc.).
Betweenness centrality	A measure of how frequently one particular node is on the shortest path amongst the set of all shortest paths between all pairs of node (see Centrality).
Centrality	How "central" a particular node is defined to be in a network. There are several ways of measuring this (see, Betweenness Centrality, Closeness Centrality, Eccentricity, Eigenvalue Centrality).
Closeness centrality	Closeness centrality is an ordinal measure of how "close" every other node is, and it is calculated through the inverse of sum of shortest path between nodes.
Cluster diversity	Cluster Diversity helps characterize each node's possible maximum spread 'in the system'.
Clustering coefficient	The likelihood that a node's two adjacent nodes are also adjacent to each other.
Complex system	Systems that are composed of interacting agents (components) that self-organize and that as a whole have the possibility to show properties and dynamics that are common for complex systems
Component/Agents	This refers to those parts of a system that structurally make up the system (for example, students, teachers, rules, expectations, behaviours, etc.).

Degree (referring to a property of a node in a network).	Number of adjacent (connected) nodes to a particular node.
Eccentricity	A measure of (inverse) centrality that is defined as the longest of the shortest paths to a particular node.
Edge	A link/connection between two nodes in a network.
Eigenvalue centrality	A measure of a nodes centrality that is made up of a node being central and also connected to other central nodes.
Emergence	Patterns and behaviour of a complex system that cannot be reduced to the influence of any individual component.
Fractal similarity	A characterisation of the similarity between nested levels of a complex system that is based on the mathematical concept of fractals.
Fractals	Curves or geometrical figures where each part of the curve or figure has the same structure as the whole.
Horizontal nestedness	The diverse set of clusters of constituent parts that lie within the same vertical nested level (see nestedness and vertical nestedness).
Institutional departure	When a student leaves university and does not return to their studies.
Institutional stop-out	When a student leaves university and later returns.
MCMC	Markov Chain Monte Carlo is a class of statistical methods for sampling from a probability distribution through creating a Markov chain. Used, for example, in Bayesian statistics, computational physics, and computational linguistics.
MMST	Multilayer Minimum Spanning Tree consists of layers of Minimum Spanning Trees (MSTs).
MST	Minimum Spanning Tree is a type of network which connects all nodes with the lowest total edges possible and contains no loops (triangles, circles, etc.).
Nestedness	This concept is divided into vertical and horizontal nestedness (see vertical nestedness and horizontal nestedness).
Node	A node is one of the two basic parts of a network (the other being an edge). A node can represent a person, an agent/component, etc..
PageRank	An iterative metric that is similar to Eigenvalue centrality. All nodes in the network get an initial PageRank, and then get updated until the calculation converges.

Path	A way through a sequence of nodes that begins with the starting node, follows adjacent nodes through the network, and ends at the end node.
PER	Physics Education Research.
Scale invariance	Property or behaviour independent of the nested level in which it is observed. Logical dichotomy to scale variance.
Scale variance	Property or behaviour that depends on the nested level in which it is observed. Logical dichotomy to scale invariance.
Social network	A network constituted of people and their social interaction.
Social system (as per Durkheim's work)	A system of rules, norms and values that get created at the same time. This is done by the individuals residing in the system. The social system has an agency that is separate from the individuals.
Social system (as per Tinto/Spady's work)	A system of rules, norms, and values that only include the *social* rules, norms, and values within a university.
SPSS	Statistical Package for the Social Sciences is a Windows based data analysis program that is commonly used in the social sciences.
Student attrition	The process of students leaving their university studies.
Student attrition model	A model of the process of students leaving their university studies.
Student dropout	A process whereby students prematurely leave their university studies.
Student integration model	A model of the process of students who decide to stay or leave a university.
Student retention	University's ability to retain their students.
Student stop out	A process whereby a student who leaves a programme/ university/institution later returns to their studies.
System departure	A process whereby a student leaves the higher education system all together.
Topological diversity	A measure developed to characterize a particular node's tendency towards being scale variant, or scale invariant.
Vertical nestedness	Different levels/scales with regards to the size of the aggregated agents/components in a complex system. These levels can not only function differently in terms of the size of the nested level, but can also function differently on different time-scales (see nestedness and horizontal nestedness).
Virtual world	A constructed representation of real world practice based on the work done by Donald Schön.
Voluntary withdrawal	The process whereby a student leaves a university by choice and not by academic dismissal.

Prelude

In 2010, I was a laboratory assistant for a class of engaged and intelligent physics students. As I got to know the students in the class, I thought that most of them would get their degrees in the designed programme time. I met them again in late 2011 and by then only about half of the students were still on-track towards completing their degree on time. At the time, I was doing a literature review of the field of student retention – i.e., university's ability to retain their students – and I was surprised that the same kind of pattern of retention that I found in the literature could also be noticed with the physics students I had met. To delve more deeply into the retention patterns at the University I began looking in more detail into how many physics students actually complete their degrees within the prescribed timeframe. What I found was that less than one fifth of the students complete their physics degree on time.

I began to search for a way to better understand the process of student retention in a way that could help me formulate better solutions to this problem. During this time, I discovered three important aspects of student retention. Firstly, that there are no simple solutions; each article I read in the field seemed to suggest different strategies to enhance student retention, and even when two articles had similar research setting and/or research participants the results often felt incommensurable or even contradictory. Secondly, I discovered that there are clusters of different aspects of students' experiences that affect retention at a university; individual aspects, classroom aspects, university aspects, societal aspects, etc. Thirdly, the most influential cluster affecting student retention is composed of aspects related to student interactions within a course.

How the sheer number of different aspects affecting student retention that I had read about could fit together within a guiding theoretical framework was, at the time, hard - if not impossible - to wrap my head around. This is when I started reading *complexity thinking* (Davis & Sumara, 2006). Through this theoretical framework the seemingly different clusters of aspects could be seen as parts of systems, and each cluster would affect only a few other clusters. For me, all these clusters together would then form a system of student retention. One major advantage of using this theoretical framework was its focus on the effects of *interactions* and analysis of *systems*. Further, complexity thinking is embedded within non-linearity; the same action would not necessarily lead to the same result. I began to realize that even though the field of student retention has its roots in understanding how interactions shape students' experiences, a focus on systems and properties of non-linearity were missing from the research on student retention and the efforts that these research reports were guiding to deal with the problem.

My first hurdle was to discuss the particularities of complexity thinking with fellow researchers at a conference for young researchers. Here I met Maartje van den Bogaard, a researcher interested in student retention in engineering programmes with a significant portion of physics in the curricula. Maartje was working on a similar problem to mine, but from a different point of departure. She had already compiled and conducted a questionnaire that included critical aspects of student retention of first-year students. We decided to exchange ideas and work together on a common research project. This took place while I was busy gathering data sets on students' interaction within physics courses in Sweden.

My second hurdle arose after I had an empirical data set I was satisfied with; how to use these data set to show how important aspects previously found by student retention research could be visualized and modelled as a system? When I started my Ph.D. studies, no work had carried out using student interaction networks, and only a handful of articles mentioning student retention, in the fields of Physics Education Research (or even in related Engineering Education Research). No apparently useful methods were available within the fields of both student retention and Physics Education Research. Thus, I engulfed myself into an exploration of methods that would lead to how descriptions of student retention as a system, and analysing students' interactions within a classroom, could be made possible. In this process, I became influenced by Gee's (2005) theory building idea that he characterized as "making your own soup"- i.e., designing an innovative research theoretical framework and its methodology that *works* for the problem at hand. My "soup", if one can call it that, has drawn on a wide array of methodologies from multiple disciplines all related to the study of complex systems in order to further the understanding of student retention in physics and related engineering programmes.

The third hurdle arose after I had immersed myself in an extensive period of theoretical and methodological development; how to identify strategies to enhance student retention in this system that I had visualised and modelled? I went on to devise two ways through which this would be possible. Firstly, it is possible to use these visualisations of a system of student retention as a representative *Virtual world* (Schön, 1983), i.e., to use a representation[1] as a tool for thinking. When using this strategy, however, it is paramount that it is undertaken by people who are knowledgeable about the system that they are working in and that suggestions are then are only applicable to the local system. I found that this is mainly because much of the information becomes

[1] A simplification of reality.

“hidden” in the representative *Virtual world*. The second way of identifying possible strategies to enhance student retention is through simulation of system-changes. I developed a methodology that could be used as a way to, not only visualize educational issues from a systems point-of-view, but also to estimate the effects and certainty of changes in such systems.

Through using the lens of complexity theory I was able to characterize two different, but critical, parts of physics students’ interaction within courses; a social and an academic part. I went on to show that these are important for students’ grade achievement, which is a prerequisite for students who wish to continue their studies, i.e., critical for student retention.

As I reached the end of this thesis work, I again checked on the cohort of students I met in the beginning of my PhD studies. Although I could not have been able to even guess the outcome when I first started, I now begin to appreciate the official statistics. Of the 110 registered students in the cohort starting 2008, only twelve had completed their degree on time.

1. Introduction

1.1. Why is student retention research important?

Currently, one of the most important objectives for higher education institutions is to "produce" a sufficient number of scientists and engineers to satisfy the requirements of the society that they serve (Stephens & Richey, 2013). To-date, much of their effort has been structured around trying to improve the recruitment of students. The driving logic here being that improving programme registration will "translate" into improving student retention, i.e., improving the university's ability to retain students.

The research reported on in this thesis stems from a concern about student retention and from the growing number of well publicized major initiatives, many of which originate in the United States. These initiatives are primarily being driven by a country-wide university failure rate, which for a long time now has been exceeding 50% for students studying engineering (Committee on Science, Engineering, and Public Policy, 2007, p. 98). For example, the Carnegie Foundation announced an initiative early in 2010 to invest 14 million dollars to enhance students' "college readiness" (Carnegie Foundation for the Advancement of Teaching, 2010).

The lack of success that such initiatives typically result in – the continuing decline in graduation rates in both the European Union and the United States, particularly in science, engineering and technology oriented areas – have created a renewed challenge for higher education institutions. This challenge involves creating conditions that are *more* likely to enhance student retention and progression. Generally, a major challenge to reform- and transformation-initiatives is the lack of certainty in the outcomes of these initiatives.

Furthermore, most developed nations have experienced (and continue to experience) a huge increase in demand for well-qualified science, and engineering and technology graduates. At the same time, there has been a deteriorating interest in careers in science, and engineering and technology (for example, see European Commission, 2004; Committee on Science, Engineering, and Public Policy, 2007; Stephens & Richey, 2013). Much of the increased demand is being driven by the need to have personnel in science, and engineering and technology who are capable of contributing to formulating solutions to the many challenges that are increasingly emerging from an ever-growing globalized network of nations (Stephens & Richey, 2013).

Internationally, there is an increasing percentage of students who either do not manage to successfully complete their degree requirements in science and engineering programmes in the designed time period, or who do not graduate at all in the field (Organization for Economic Cooperation and Development, 2009; Committee on Science, Engineering, and Public Policy, 2007). Looking at graduation rates, Sweden (as an example of a strong modern economy) is ranked in the middle of the OECD member countries. The percentage of university students that complete the Swedish Master of Science Programme in Engineering (4,5 years) within five years has decreased from 30% in 1987 to 19% in 2004 (and within seven years has decreased from 60% in 1987 to 50% in 2004) (see Figure 1). At the same time the number of new entrants to these programmes of study increased by 50% (Statistics Sweden and National Agency for Higher Education, 2003; 2005; 2007; 2009; 2010).

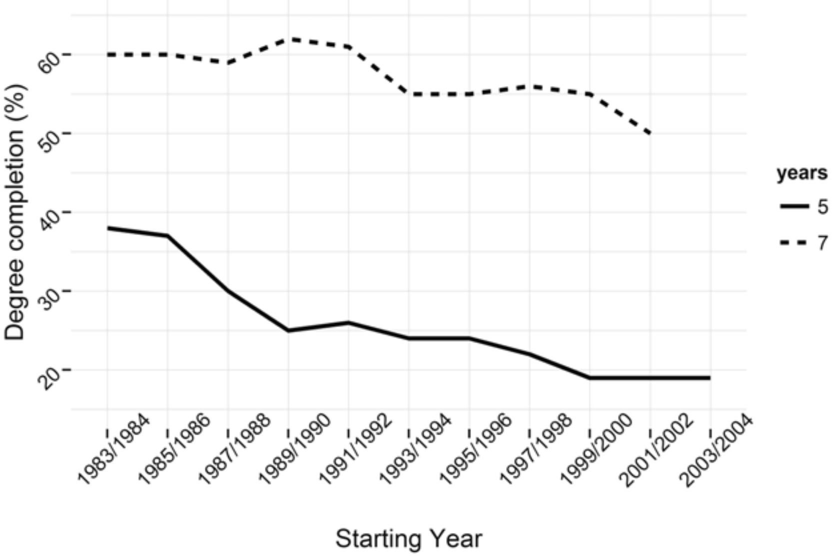

Figure 1. Percentage of Master of Science in Engineering students completing their degree within five and seven years for the starting cohorts of 1983-2004. (Statistics Sweden and National Agency for Higher Education, 2003; 2005; 2007; 2009; 2010).

Further, the number of degree programme students who do not graduate *at all* has increased from roughly 20 to 30 percent between the starting cohorts of 2001/02 and 2005/06 (Statistics Sweden; 2013).

In Sweden, the number of students in pure physics programmes is relatively small. The Master of Science in Engineering programmes, situated in a similar educational context to that of physics students, provide a sufficient number of students to be able to examine the long term trend of graduation rates. Therefore, the problem of student retention is of paramount importance in both physics and associated engineering programmes in Sweden.

1.2. Is better recruitment not the answer?

It is common practice for universities to try to "improve" their recruitment strategy in order to enhance student retention. What "improve" means here is to attract more students to a programme and in this way increase "the right" first-year students; those who are more inclined to stay and finish their studies on time. However, such recruitment initiatives have tended not to recognize that it is "very unlikely that there is another hidden pool of students that we might magically discover if we change or further improve our selection procedures" (Allie et al., 2009, p. 3).

The United Kingdom, as another European Union example, has recently set up several major initiatives and policies aimed at recruiting more students to participate in science, and engineering and technology education. Smith (2010) reports that there is no strong empirical evidence showing that these reforms have had any impact on the number of students *choosing* to study in these areas. Furthermore, the percentage of students *completing* these kinds of degrees in the United Kingdom has remained limited (European Commission, 2004).

Against the backdrop of Smith's (2010) study and the continuing withdrawal of students from their studies, I argue that there is a need to shift the focus from what the universities can do to increase the number of physics graduates by "enhancing"[2] recruitment efforts, to what universities can do while the students are enrolled in their programmes, i.e., focus on *enhancing student retention*.

1.3. What can we do?

Even though the field of student retention concerns itself with how universities can support students while they are at the university in a way that will increase the number of graduates, the implementations of the theories that the field has developed have not led to any simple road-map for how the universities can better deal with student retention. Thus, modelling efforts of student retention – with its associated achievement, learning, and progression goals – remains an extremely relevant area of research.

Most of the work on the modelling of student retention has been aimed at informing institutional action (for example, see Tinto, 2010; Braxton, 2000). The most progressive research in the area (such as Tinto, 1975; 1982; 1987; 1997; Bean, 1980; 1982) has, for some time, acknowledged that student retention needs to find a better way to take into account the "complex" nature

[2] Enhancing here being increasing the number of students as well as finding the "the right kind" of students.

of student retention. The "complex"[3] nature of these modelling efforts has become apparent to many stakeholders in the field, for example, see Spady (1971), Bean (2005), and Cabrera et al. (1993). However, this "complex" nature has not been explicitly incorporated into their modelling efforts. Consequently, the existing modelling systems are easily interpreted in linear ways; something that can be clearly seen in the action plans of many institutions. To address this issue I am, in this thesis, proposing a methodology that can inform decisions in the *complex system of student retention in physics and related engineering programmes* from an explicit complexity theory viewpoint (see Chapter 4).

To expand on the argument I made in the previous paragraph, consider the following examples. Spady (1971, p. 38) argues that the formulation of a truly comprehensive model of student retention needs a perspective that "regards the decision to leave a particular social system [i.e. studies in higher education] as the result of a complex social process". More recently Bean (2005, p. 238) argues that "students' experiences are complex, and their reasons for departure are complex"[4]. There are many other examples, see Spady (1970; 1971), Cabrera et al. (1993), Yorke and Longden (2004), Barnett (2007), the collection of articles in Braxton (2000), and Tinto (2010).

Like the notion of "complexity", social networks have been present, albeit in the background, in the development of theoretical models used to understand student retention. This is especially evident in the work of Tinto (1975; 1982; 1987; 1997) who is widely recognized as the "founding father" of student retention research. During the many years of his research, Tinto came to appreciate that advances in student retention research need to employ "network analysis and/or social mapping of student interaction... [to]...better illuminate the complexity of student involvement" (Tinto, 1997, p. 619). Also, it has been known for some time that the structures of social networks are connected to student grade achievement (for example, see Thomas, 2000; Sacerdote, 2001; Rizzuto et al., 2009), and thus student retention.

The theoretical and empirical work that I report on in this thesis reflects how complexity theory can be used in Physics Education Research to make a case for a new modelling of student retention. I do this using complexity theory while building on previous theoretical and empirical work such as the *Student Integration Model* (Tinto, 1975; 1982; 1987; 1997) and the *Student Attrition Model* (Bean, 1980; 1982).

[3] The usage of the word "complex" includes the everyday meaning "complicated". The way I am using the word "complex" in my thesis follows Chapter 4 on complexity theory.
[4] Yet another example where the word "complex" may be being used to mean '"complicated".

1.4. Research Questions

The research work that I carried out for my thesis emerges from a core issue in Physics Education Research (PER): that of determining *how to enhance student retention of students studying physics?* As pointed out earlier, this issue is critical because of the acute societal need for more physicists and engineers throughout the world.

Further, characterization of the process of student retention from a new perspective, complexity theory, and identification of actions to enhance student retention within the field of physics has the distinct possibility of better informing decisions made by teachers, policy-makers, and students. From here, a general research aim arises: *How to conceptualize and carry out analysis of student retention for university physics students using a complexity theory perspective?* I address this aim by answering the two research questions:

> Research Question 1: *In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?*

> Research Question 2: *Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?*

The answers to the above Research Questions 1 and 2 are derived from the answers to the research questions / research aims reported in **Papers I-V**. The relationship between Research Questions 1 and 2 and the research reported in **Papers I-V** is detailed in Table 2.

Table 2. *How the research questions in the thesis relate to the research questions / research aims from the Papers*

Research Questions	Research Questions / Research Aims from Papers
In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?	From **Paper I**, research aim: *Illustratively explore the potential advantages of applying complexity thinking to the problematic issue of student retention.* From **Paper II**, research questions: (a) *How can the complex system of an educational situation be represented by framing it in terms of its networked structure and nestedness?* (b) *How can the representation created in this way be used in order to inform decisions regarding enhancing student retention?* From **Paper III**, research question: *How can targets for changes in institutional practice be effectively identified using an empirically-informed Sandbox University?*
Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?	From **Paper IV**, research aims: (a) *How to situate central constructs from student persistence research within a framework of complexity science* (b) *To illustrate the viability of using methods available from complexity science to analyse the structural aspects of students' networked interactions.* From **Paper V**, research question: *What are the indicators for grade achievement as a function of social and academic network measurements?*

To obtain a sufficiently large number of participants for my research, I used data sets from Sweden and the Netherlands where, like in Sweden, engineering programmes have a significant portion of physics.

The data set collected in Sweden facilitated the theoretical and methodological work reported in **Paper I, Paper IV**, and **Paper V**.

The collaboration with the institution in the Netherlands enabled the collection of the data set that facilitated the theoretical and methodological work presented in **Paper II** and **Paper III**. It also provided me with the opportunity to use an existing questionnaire instrument that had already been validated (see **Paper II**).

What follows is a brief description of the higher educational systems in both countries. Since most of the research reported on in the literature review on student retention (Chapter 3) is done in the USA., a brief overview of the higher educational system in that country is also given.

The higher education sector in Sweden is legislated for, guided and funded by the Government. The majority of Swedish Higher Education institutions are public authorities. Sweden has approximately 50 Higher Education institutions ranging from research universities to more vocationally oriented institutions. Funding is based on the number of registered students and their performance equivalents[5] (Swedish National Agency for Higher Education, 2008). Swedish students may apply to take individual courses as well as degree programmes. Students studying a degree programme in areas such as physics and related engineering will have course choices that are linked to professional or vocational enhancement. To be admitted to a Swedish Higher Education institution, students need to fulfil general entry requirements and often also programme- or course-specific requirements. Once these requirements are met, a selection process can only be instituted if applicants cannot be guaranteed a place due to student numbers and/or space constraints (Swedish National Agency for Higher Education, 2008). Then, the selection process is, in most cases, based on final school grades or the Swedish Scholastic Aptitude Test for Higher Education.

Higher education in the Netherlands is divided into research institutions and institutions of applied sciences. Currently there are around 50 such institutions in the Netherlands, both private and public. To gain access to research institutions students need to either have completed upper secondary school studies or have passed their first year of courses at an applied science institution. Students are committed to a particular degree programme. If there are too many students applying for a particular degree programme, a weighted lottery is carried out to choose between the applicants (Netherland Organisation for International Cooperation in Higher Education, 2014). Students pay tuition fees to be allowed to study at each institution and the fees are fixed for different categories of students (Eurypedia, 2014).

Higher education institutions in the USA are legislated for and guided by both the Federal Government and by the government of the state in which they are situated. Public institutions get their funding partially from the State and partially from student tuition fees. Currently there are approximately 2900 four-year institutions and 1800 two-year institutions, both private and public. Admission to higher education in the USA is usually based on SAT[6] or ACT[7] test scores, but some institutions have much more extensive entrance requirements, such as essays and letters of recommendation. Typically, students are initially admitted to a particular university and not to a specific department or course major, with such selections usually taking place as the students progress through the system (U.S. Department of Education, 2014).

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[5] In essence, if a student passes all their courses, the institution will get full funding for that student. If a student passes, say, half a prescribed set of courses, the funding will decrease accordingly.

[6] Scholastic Aptitude Test.

[7] American College Testing.

1.5. What was undertaken to answer the Research Questions?

To be able to answer the research questions, I delved into the experimental, theoretical, and methodological aspects of complexity research and student retention research.

The literature review is presented in three parts: Physics Education Research (Chapter 2), Student Retention (Chapter 3), and Methodology: Part 1 - Introduction to Complexity (Chapter 4).

The methods I investigated and used to answer the research questions are summarized in Chapter 5: Methodology: Part 2 – The Method. The data collection and ethical aspects are described in Chapter 6: Methodology: Part 3 – The Data Collection and Associated Ethical Considerations.

To answer Research Questions 1 and 2 (see Sections 7.3.3 and 7.3.4), a conceptual understanding of the complex system in which student retention is a process needed to be gained. Hence, it was critical to examine the theory embedded within complexity research. In doing so, I identified established constructs, mainly as metaphorical tools[8], to develop a theoretical framework to enable contemplation of student retention in university physics and related engineering education from a new and novel perspective. This is presented in the thesis as part of crafting a fruitful description of the system that I needed to better understand (see Section 7.2).

[8] Tools for thinking.

2. Physics Education Research

2.1. Introduction

This thesis is situated in Physics Education Research (PER). Physics Education Research at Uppsala University is a research division in the Department of Physics and Astronomy. As such, it is discipline-based education research that focuses on physics and astronomy, and related engineering educational contexts in higher education. PER is a field of study that is particularly well established throughout the USA. There, Lillian McDermott and her research group at the University of Washington and Edward Redish and his group at the University of Maryland are widely credited with establishing the epistemic foundations that legitimized PER as a discipline-based education research endeavour whose appropriate "home" is within departments of physics, and physics and astronomy. The following statement that was adopted by the American Physical Society in May 1999 well captures the spirit of this legitimation:

> In recent years, physics education research has emerged as a topic of research within physics departments. This type of research is pursued in physics departments at several leading graduate and research institutions, it has attracted funding from major governmental agencies, it is both objective and experimental, it is developing and has developed publication and dissemination mechanisms, and Ph.D. students trained in the area are recruited to establish new programs. Physics education research can and should be subject to the same criteria for evaluation (papers published, grants, etc.) as research in other fields of physics. The outcome of this research will improve the methodology of teaching and teaching evaluation. The APS applauds and supports the acceptance in physics departments of research in physics education. Much of the work done in this field is very specific to the teaching of physics and deals with the unique needs and demands of particular physics courses and the appropriate use of technology in those courses. The successful adaptation of physics education research to improve the state of teaching in any physics department requires close contact between the physics education researchers and the more traditional researchers who are also teachers. The APS recognizes that the success and usefulness of physics education research is greatly enhanced by its presence in the physics department.

Downloaded from http://www.aps.org/policy/statements/99_2.cfm
9 June, 2015

PER is also represented in several highly regarded physics research journals, for example, European Journal of Physics, American Journal of Physics, and Physical Review Special Topics Physics Education Research.

There are currently roughly 110 PER[9] groups across the world. Around 90 of these are in the USA. Sweden has three PER groups, which are located at Uppsala University, Umeå University, and Kristianstad University. PER groups are currently conducting research that offers both diversity and depth, as illustrated in Table 3.

Table 3. *An illustrative selection of leading PER groups showing examples of their recent research interests.*

University	
University of Maryland	Students' identities, expectations and epistemologies
	Difficulties in applying mathematics in physics
	Learning as a social phenomenon
	Students' mathematical sense-making in engineering.
	Student reasoning
	Professional development of teachers
University of Colorado	Learning environments (digital and analogue)
	Physics Literacy
	Using technology in advanced physics courses
	Social and contextual foundations of student learning
	Theoretical models of students' learning
	Improving student learning through the use of computer simulations
Harvard University	Interactive engagement teaching methods
	Gender issues in introductory physics courses
	The role of classroom demonstrations in physics education
Kansas State University	Collaborative Learning
	Physics epistemology
	How students' problem solving expertise transfers between mathematics, physics, and engineering
	The role of physics representations
University of Washington	The role of conceptual physics for student learning
	Physics as a culture
	Research based curriculum and teaching practice tools and materials aimed at addressing research-identified difficulties in learning physics
Uppsala University	Theoretical development of the phenomenographic perspective on learning
	Linking complexity theory and related theories to the field of teaching and learning in physics
	Exploring the role and function of representations (semiotic resources) in disciplinary knowledge construction
	Challenges in understanding physical phenomena
	The use of variation theory in physics and astronomy learning
	The roles of personal and shared narratives for physics identity building processes in physics

[9] See http://www.compadre.org/per/programs/

2.2. Brief historical overview

The need for research in the area of physics education emerged in the 1950's when the enrolment and student retention in university physics courses was seen to be of concern, particularly in the United States. These concerns took on a new urgency with the successful launching of the Soviet Sputnik (1957), which led to extensive initiatives in the United States to reform science education. These initiatives fell under the controlling influence of many prominent physicists, cognitivists, and educationalists. The initiatives profoundly influenced change in science education at all levels of education[10]. The university level reform was initially directed towards the first year of study. PER, as a research activity in physics departments, started studying the challenges that students had with learning physics, and how resources and curriculum design could be used to overcome these challenges (McDermott, 1984). Two papers written by Trowbridge and McDermott (1980; 1981) that deal with challenges in learning about velocity and acceleration are widely recognized as representing the start of contemporary PER work.

One of the most extensively used instruments to measure physics learning in PER has been the Force Concept Inventory[11] (Hestenes et al., 1992), commonly known as the FCI, which was designed to measure students' conceptual understanding of Newton's Laws. Even though this development took place in the late 1980's, the FCI is still considered by some to be an effective educational instrument. It is used to measure conceptual understanding and to compare learning outcomes pre- and post- formal instruction.

Originally, many physics teachers considered the FCI questions to be "easy" and hence were rather surprised when it turned out that a significant number of their students, post-instruction, could not answer many parts of the inventory correctly. Eric Mazur, a physics professor from Harvard University, was one of these and, as a consequence, he went on to develop a now widely used teaching approach known as Peer Instruction (Mazur, 1997). This approach emphasized highly-interactive peer-to-peer and student-teacher activity in a way that yielded significant gains in learning outcomes (for example, see Hake, 1998). The educational process involves engaging students during class using an electronic device known as a *clicker* that records students' choices (for example, see Wieman & Perkins, 2005) to promote peer-to-peer interaction, as well as providing an opportunity for student-teacher feedback. In an historically significant article, Hake (1998)

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[10] For more background, see: http://www.compadre.org/portal/pssc/pssc.cfm

[11] Other conceptual surveys have been developed since the success of the FCI, such as: Force-Motion Concept Evaluation (Thorton & Sokoloff, 1998), Mechanics Baseline Test, (Hestenes, & Wells, 1992), Heat and Temperature Concept Evaluation (Laws, 2006), Wave Diagnostic Test (Wittman, Steinberg, & Redish, 2002), Quantum Mechanics Concept Inventory (Falk & Linder, 2005), The Quantum Mechanics Conceptual Survey (see http://www.colorado.edu/physics/EducationIssues/QMCS/), and Conceptual Survey of Electricity and Magnetism (Maloney et al., 2000).

presented evidence from 6000 students that an interactive engagement approach to teaching and learning, such as Mazur's (1997), had the possibility of dramatically improving student learning, as measured by the FCI.

The work framed by the FCI led to slow but rigorous methodological growth and theoretical development in the PER community. Much of the initial framing for investigating challenges in learning physics was couched in terms of prior knowledge and so-called student misconceptions[12] (for an overview of early work on these, see the resource letter by McDermott and Redish [1999]). Later this framing started to include modelling how students worked when solving problems, for example, "naïve" and "expert" problem solving (for example, see Larkin et al., 1980) and the role of phenomenological primitives, p-prims, (diSessa, 1993). This growing theoretical base was then used to make strong links to theoretical modelling that was taking place in related research areas such as science education, cognitive science, and psychology. In particular, the influences of preconceptions, alternative conceptions, conceptual change, epistemological considerations, and forms of constructivism on learning physics were investigated. This led to powerful foundational connections being empirically established between problem solving, conceptual understanding, epistemology, prior knowledge, and the experience of learning (for example, see discussion by Redish, 2003). Then the PER community starting drawing on theoretical work, such as Ausubel's (1968) modelling of meaningful learning, advance organizers, and scaffolding. This theoretical movement began to influence the way curriculum design and teaching practice was thought about by the PER community. An excellent example of the constitution of research, theory, and informed practice can be found in McDermott, Shaffer, and the Physics Education Group at University of Washington's (2002) tutorial design and practice.

Theoretical discussions started to develop across the PER community. For example: diSessa and Marton debated the epistemological basis of p-prims in a special edition of Cognition and Instruction – Towards an Epistemology of Physics (diSessa [1993] and also see Docktor and Mestre [2014] for an extensive summary of the development of PER from an American perspective).

Further, the following examples have been discussed in relation to physics learning: constructivism (Driver & Erickson, 1983) was linked to p-prims (for example, see Hammer, 1996); epistemology (Linder, 1992); and conceptual change was challenged and refined (for example, see Linder, 1993). New modelling of learning began to emerge in PER and in the broader science education research communities (for example, see Allie et al., 2009).

PER research has increasingly incorporated broader theoretical groundings, for example, epistemological perspectives (for example, see Linder, 1992; Hammer & Elby, 2002), a learning resource perspective (for example,

[12] These have been reframed as preconceptions, naïve conceptions, or alternative conceptions.

see Hammer, 1996; Redish, 2003) disciplinary discourse perspectives (for example, see van Heuvelen, 1991; Brookes & Etkina, 2009; Airey & Linder, 2009), multimodal perspectives (for example, see Airey & Linder, 2011), measurement (for example, Buffler, Allie, & Lubben, 2001) gender theory perspectives (for example, see Danielsson, 2009), network theory (for example, Bruun, 2012; Bruun & Brewe, 2013; Koponen & Pekhonen, 2010), and complex system simulation (Koponen, 2013).

As the significance of theory building for PER work grew, so research possibilities expanded. For example, studies now include the exploration of physics learning through the following theoretical lenses: discourse theory (for example, Andersson & Linder, 2010), embodiment and distributed cognition (Gregorcic, 2015), activity theory (Gregorcic, 2014), scientific literacy (for example, Airey, 2009; Airey & Linder, 2011; DeBoer, 2000), disciplinary literacy (Linder et al., 2014), (social) semiotics (for example, Airey & Eriksson, 2014; Airey et al., 2014; Fredlund, 2013), ethnography (for example, Gregory, Crawford, & Green, 2001), representations (for example; Linder, 2013; Fredlund & Linder, 2014; Fredlund, Airey, & Linder, 2012), the use of metaphors and analogies (Haglund, 2013), self-efficacy (Lindstrøm & Sharma, 2011), attitudes towards physics and science (for example, the Colorado Learning Attitudes about Science Survey [Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006], and the Maryland Physics Expectations Survey [Redish, Saul, & Steinberg, 1998]), phenomenography (for example, Linder & Marshall, 2003), and variation theory (Ingerman et al., 2009; Linder & Fraser, 2006; Bernhard, 2007). More recently, the conceptual change model and its epistemological basis have been framed within complexity theory (see Brown & Hammer, 2013; Koponen & Huttunen, 2012). Numerous other examples can be found in recent PERC proceedings (see http://www.compadre.org/per/perc/).

Widely used examples of how PER has impacted the approaches to teaching physics, particularly at the introductory level are Peer Instruction (Mazur, 1997), Just-in-time-teaching (Novak, Patterson, Gavrin, & Christian, 1999), Physics by Inquiry (McDermott, 1996), Conceptual Physics (Hewitt, 2014), research based textbooks (for example see, Matter and Interactions and Electric and Magnetic Interactions [Chabay & Sherwood, 1999], College Physics [Etkina et al., 2013]), reasoning in physics (for example, see Viennot, 2014), design based teaching (for example, see Buty, Tiberghien, & Le Maréchal, 2004), workshop- or studio-based physics learning environments (for example, see Laws, 1991; 1997; Wilson, 1994), and Tutorials in Physics (McDermott, Shaffer, & the Physics Education Group at the University of Washington, 2002). Such shifting in perspectives on learning, teaching approach and awareness and new research-based curriculum materials have become one of the scholarly benchmarks of PER.

2.3. PER and student retention

A general overview of the research on student retention that is relevant to my thesis is presented in Chapter 3. The student retention work done in PER has been limited, but what has been done has both been insightful and interesting in that it has explored important links between physics teaching, the learning environment, and student retention. These links are briefly summarized below.

The Colorado Learning Attitudes about Science Survey (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006) showed that students' attitudes, especially in the area of personal interest in physics were connected to students' course completions.

The effect of Peer Instruction (Mazur, 1997) on student retention is a rich ongoing area of current research with new thrusts continuing to emerge. Two interesting studies reported in Lasry et al. (2008) investigated the reasons why introducing peer instruction increased student retention of the introductory physics courses from ~80% to ~95% at John Abbott College, and from ~88% to more than 95% at Harvard University.

Johannsen (2007) and Johannsen et al. (2013) studied the discourse models that physics students used to explain why they decided to leave their physics studies. Johannsen (2007) found that in his Swedish research context students used a discourse model with the following introspective component: "if students perceive that they have problems in relation to physics... they interpret those problems in terms of their own perceived abilities and social identities" (Johannsen, 2007, p. 145).

Johannsen (2012) described students' coping patterns when studying physics. His results indicated that students' successful coping strategies involve personal relevant reinterpretation of what it means to be successful with regards to the institutional expectations of the university.

Kost-Smith et al. (2010) explored how student retention between two physics courses was gender[13] biased, and found no significant differences with regard to gender for student's academic trajectories.

To explore the potential effects of students' interactions on learning and retention in a "physics learning centre", Brewe et al. (2011) used network theory to analyse how *centralities* in the network could be predicted by scheduling and attendance. They argued that these centralities could have a critical effect on student retention, and concluded that network theory accompanied by a framing of complexity thinking would be a fruitful way to conduct further empirical research. Bruun and Brewe's (2013) investigations show that the structure of physics students' interactions can be related to their grade achievement.

[13] Here, gender refers to biological sex.

2.4. Using complexity theory in PER

Physicists, biologists, computer scientists, and sociologists have used complexity theory extensively as an analytic tool for at least 15 years (for an overview, see Chapter 4). Bringing such a perspective into educational research studies has been characterized and exemplified as *complexity thinking* by Davis and Sumara (see, for example, 2006). This means that complexity thinking has only recently started to be acknowledged for its non-linear explanatory and predictive potential in educational research. It application in educational research has been limited, for example in PER, Moll led the way by using a complexity thinking framework in her doctoral thesis in 2009. Her work examined the emotions, science identities, attitudes, motivations, and decision-making of physics students in physics competitions (Moll, 2009; 2011). My thesis builds on her initiative by bringing complexity theory into the conceptual framing of student retention in Physics Education Research.

Redish (2013) has used ideas from complexity theory[14] to metaphorically start creating a non-linear theoretical framework for student learning that has begun to impact PER. This has been used to characterize levels of what Redish (2013) refers to as “the socio-cultural structure”. These “levels” range from individual neurons in the brain to the effect on how cultures affect what is happening in the classroom. It includes psychological models, small-group interactions, classroom culture, and a disciplinary culture of physics. Through his discussion on theoretical frameworks, Redish (2013) described a staircase of *emergence* and framing[15]. His work brings to the fore an understanding that what is happening in the classroom being not only affected by the individuals within the class, but also includes a wide array of influences from both inside and outside the classroom.

Very recently, not only have metaphors from complexity theory been used in PER, but complexity theory’s analytical approach has also been introduced. This includes the use of computer simulations and network theory, for example Koponen’s (2013) simulation implementation article, which views learning of scientific concepts in terms of evolution in a networked model of connected sub-concepts. Here, Koponen argues that his simulation of network patterns imply that context dependent dynamics need to be sufficiently saturated in order for learning to occur. The simulations also resulted in attractor-type states[16], which Koponen suggests correspond to generic features of real learning processes.

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[14] It is possible to interpret this kind of use of the ideas of complexity theory as complexity thinking (see Chapter 4, p. 73 in this thesis).

[15] This can be framed in terms of upwards and downwards causation in a nested complex system as described in Chapter 4, Methodology: Part 1 - Introduction to Complexity.

[16] Network structures where the evolution of patterns “get stuck” in different states.

Using network theory in PER, Bodin (2012) explored the evolution of epistemic framing of students as networks. This framing was made up of elements of students' beliefs/skills/epistemology in a wide arrange of disciplines (physics, mathematics, programming, etc.). In this article, Bodin visualized students framing by using network theory to show how students engage in problem-solving activities by shifting their framing from solving a programming task to ultimately solving a physics problem.

2.5. Relevance of this thesis for PER

As I stated in Section 1.4, the research work that I carried out for my thesis emerges from a core issue in PER: that of determining *how to enhance student retention of physics students?* As argued in the introductory chapter, addressing this issue is critical to meet the societal need for more physicists and engineers throughout the world,. Further, characterization of the process of student retention from a new perspective, and the identification of actions to enhance student retention within physics and related engineering programmes has the possibility to better inform decisions of teachers, policymakers, and students.

This thesis goes beyond the conventional foci of PER – disciplinary knowledge acquisition – to encompass university physics and related engineering degree programmes as a *system,* and it puts particular emphasis on the academic and the social side of studying physics[17]. The thesis can also be seen as part of the surge of contemporary methodological and theoretical initiatives within PER.

The theoretical side, as well as the methodology developed to answer the research questions, is applicable to other research endeavours within PER. This methodology offers the PER community a new powerful tool-set for use where physics teaching and learning should not be treated as a linear phenomenon, but rather as processes that involve numerous factors that span across multiple scales (time and space).

[17] The importance of both these sides of studying physics will become apparent in later chapters.

3. Student Retention Research

3.1. Introduction

This chapter introduces the relevant student retention constructs used in the thesis. Providing a full review[18] of the literature associated with student retention and persistence is what Reason (2009, p. 659) calls a "Herculean task". Thus, this chapter is a broad overview of relevant work in student retention and aims to give an appreciation of the diverse factors that play critical roles in shaping student retention.

In the literature on student retention, there are two categories of constructs; one classifying students who leave, and another those who stay. The first category, dealing with students who leave university, is composed of the following extensively used constructs: student attrition, student withdrawal, student departure, stop out, and dropout[19]. The second category is composed of two constructs, student retention and student persistence. I decided to follow Tinto's[20] body of work for my thesis and use the construct of student retention to characterize a *university's ability to retain their students*. Although I have chosen to use student retention as my central construct in my thesis, when referring to the work of a particular author I have used *their* construct and *their* definition of that construct.

In the first category of constructs – the one covering students who leave university studies – much of the early student retention research did not differentiate between students who left because they did not succeed academically, and students who left for other reasons. Nor did the research differentiate between students leaving universities permanently, and those doing so temporarily. Tinto (1975) argued that without such distinctions, much of the early research on student retention would be seen to provide contradictory results[21].

Tinto (1975) took the construct student dropout to mean a student leaving their studies in terms of either voluntary withdrawal or academic dismissal. In doing so, he emphasized that there are certain formal and informal aca-

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[18] Detailed reviews of student retention and persistence research have been done by: Reason (2009), Tinto (2006-2007) and Pascarella & Terenzini (1991; 2005).

[19] In this thesis, both the terms "dropout" and "drop out" have been used. The term student "drop out" is used as a verb, while "dropout" is used as a noun.

[20] Tinto was one of the founding fathers of student retention research.

[21] These seemingly contradictory results are further discussed in Section 7.2.

demic norms existing within a university culture that have an impact on students.

Bean (1980) introduced the construct student attrition, which is the process of losing students from the university.

In 1982 Tinto expanded his characterization of student dropout to include transferrals (see Figure 2). Before this expanded characterization, a student who decided to transfer to another institution could easily have been misclassified as a case of system departure or stop out (see Figure 2). For example, the reason for the transfer could be more about moving to an institution that projects a different set of values and norms – one more aligned with the students' own values and norms.

In 1987 Tinto presented a further refined range of categories for student dropout that included the essence of his 1975 and 1982 categories: voluntary withdrawal, academic dismissal, stop out, system departure, and transferrals. Student dropout was now divided into three major categories: institutional stop out, institutional departure, and system departure. Institutional stop out is when a student takes a break from their studies and then returns to the same institution. Institutional departure is when a student leaves the institution to continue their studies at another institution. System departure is when a student leaves the educational system permanently without having completed their studies. The structure of Tinto's student dropout categorization (Tinto, 1975; 1982; 1987) is summarized in Figure 2.

The second category of constructs – students who continue to pursue their degree – is composed of student retention and student persistence. Student retention is the university's ability to retain their students, while student persistence is students' aspiration to continue with their studies.

In the Swedish Higher Education context, complete withdrawal, or a changing of educational pathway is difficult to track for retention research purposes. For example, if students take leave of their studies to find employment or do something else, they are required to report their leave of absence to the institution, but this does not always happen.

Because the problem of classifying students who drop out cannot be easily solved and the risk of mis-classification of categories of student dropout is high, I focus, in this thesis, on the universities' ability to retain their students – *student retention*. I have decided to classify student retention, in line with Tinto's body of work, by its causes – either academic retention[22] (i.e., students who complete their courses and are therefore allowed to continue towards taking their degree) or social retention[23] (a social process within a university that facilitates students completing their degree).

[22] Used in **Papers I**, **II**, **III**, and **V**.
[23] Used in **Paper IV**.

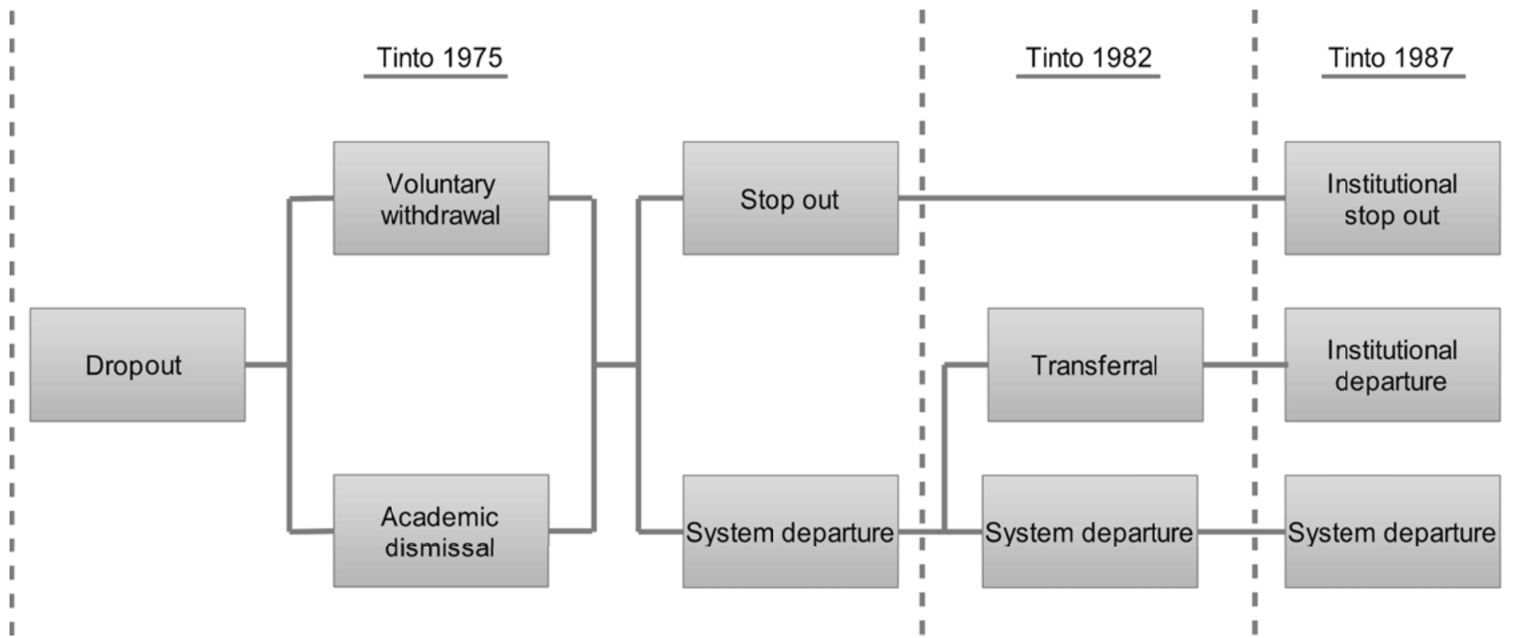

Figure 2. Conceptual schema of Tinto's categorization of student dropout.

The following sections of this chapter deal with how student retention has been modelled and concludes with a discussion of the core problem in the modelling; inconsistencies in empirical results.

3.2. Modelling student retention

Research on student retention has shown that social aspects as well as academic aspects of participation in higher education play important roles in the formation of students' academic trajectories. Here, the central theoretical modelling has been done by Tinto – the Student Integration Model (Tinto, 1975; 1982; 1987; 1997) – and by Bean – the Student Attrition Model (Bean, 1980; 1982). Although, at one level, significant differences between these models can be identified, the models share many similarities. Thus, in many ways, they can be seen to describe a multitude of factors that are complementary (Cabrera et al., 1992).

What will become apparent throughout this chapter is the large number of factors that have been found to influence student retention. In order to introduce these factors, a short general historical overview of student retention research is provided in Section 3.2.1. To be able to create such an overview of the Student Integration Model and the Student Attrition Model it is necessary to unpack the parts of each model individually, this is done in Sections 3.2.2 and 3.2.3. However, when reading these sections it is important to appreciate that it is not a question of identifying *the factor* that explains everything, but to characterize the conglomerate of factors that influence student retention.

3.2.1. General overview[24]

Yorke and Longden (2004) described how early studies of student retention within higher education were focused on university *structures*, for example, structural aspects of libraries, schedules, courses, and examination timetables. Thereafter, a shift in modelling student retention began moving towards increasingly incorporating a *social integration perspective*. This shift was largely propagated by the work of Spady (for example 1970; 1971).

According to the social integration perspective, becoming integrated within a *social system* requires learning the norms, value-systems, and beliefs through interactions within the system. The social integration perspective played a major role in the development of Spady's theoretical model; students needed to become a part of the social world of the university if departure rates were to have any chance of significantly decreasing (Spady, 1970;

[24] To add coherence to the thesis, the description in this section is largely a repeat of the overview given in **Paper I**.

1971). In Spady's model, social integration is a process that encompasses much of students' everyday life. This includes friendships, family support, the students' feeling of satisfaction, students' intellectual development, and so forth. Spady's model also includes student characteristics such as grade performance, family background, and "academic potential".

The social integration perspective gained momentum in student retention research by the potential it presented for informing students' and universities' actions aimed at working to retain more students. The theoretical model of student retention underpinning the social integration perspective grew and Tinto (1975) published an expanded version of Spady's model. Here, Tinto made a distinction between the *social system*[25] of the university and the *academic system*, and argued that students also need to become academically integrated in order to persist in their studies. He posited that some interactions that lead to social integration, for example, making friends with fellow students, do not necessarily lead towards integration into the *academic system* of the university. Tinto's (1975) *academic system* contained the academic rules, norms, and expectations that govern academic integration within the given institution's context.

During the early 1980s, many researchers in student retention research started to empirically test Tinto's work, and increasingly found that many of his constructs were indeed impacting student retention. At this time, Bean (1980), drawing on a psychological background, critiqued Tinto's model for its lack of external factors, such as economy and housing, for both the student and the university. The point of departure for Bean's (1980) model was that student attrition should be seen as being analogous to work turn-over in an employment setting. Bean's model included factors such as social experiences (for example, how students experience the social life of the university), the experience of the quality of the university (for example, students perception and experience of the "high quality" of the university), and family approval. Bean (1980) saw these factors shaping the student's attitudes and behavioural approaches within the university context.

To evaluate Bean's and Tinto's modelling, Cabrera et al. (1992) surveyed 2453 full-time US first-year students. Their findings indicate that the two student retention models have common ground and that they support each other in explanatory value. The questionnaire they designed was made up of 79 items selected from well-validated instruments previously used in student

[25] The use of the term *social system* is ambiguous in this section. This is because both Spady (1970) and later Tinto (1975) coined the terms *social systems* and *academic systems* to characterize two different aspects of integration into university life. Tinto explicitly did this through the Durkhemian concept of *social system,* which is a system of social "rules" that are built up by the individuals within the system, but is, at the same time, not connected to the individuals making up the system. In other words, a Durkhemian *social system* is more than the sum of its parts; the system is affected by, and affects, the individuals residing inside it, but is, at the same time, a free agent.

retention research (for example, see Bean, 1982; Pascarella & Terenzini, 1979).

Later, Eaton and Bean (1995), drawing on approach and avoidance behavioural theory, theorized that student's experiences shape their individual behavioural approach towards university life. Some student's experiences lead towards approach behaviour, and some towards avoidance behaviour, both affecting academic integration and thus the students' intention to leave or stay.

Tinto (1997) then undertook a case study that led him to expand his model further. He did so by introducing the notion of internal and external communities that affect student integration into the *social system* and the *academic system* of the university. He asserted that within classrooms there are internal learning communities where both the *social system* and the *academic system* coexist. Through the concept of learning communities – together with the presence of external communities (which were factors external to those of the university) – much more could now be achieved with these new constructs because they could empower teachers who wanted to improve student retention (Tinto, 1997).

Since the development of Bean's and Tinto's models very little further foundational theoretical work in the area of student retention has been reported in the literature. Braxton (2000, p. 258) argues that, due to the wide variations within the empirical trials and findings associated with Tinto's model, it should be "seriously revised". In so doing, Braxton suggests that a new foundation for such modelling needs to be developed. Furthermore, Tinto (2010) himself recently argued for the need to develop student retention models that aim to inform the institutional action of universities. In this thesis, a new foundation which is aimed towards informing institutional action is addressed in Sections 7.1, 7.2, and 7.3.

In the following two sections (3.2.2 and 3.2.3) I discuss the Student Integration Model and the Student Attrition Model by first giving a brief overview of them, and then providing a more detailed description of the models.

3.2.2. Student Integration Model

Brief overview

The Student Integration Model (Tinto, 1975; 1982; 1987; 1997) focuses on how students become integrated into academic life through socialisation and cultural assimilation. This theoretical model focuses on trying to understand what integration factors lead students to choose to stay (student persistence) or leave their studies (student departure).

In higher education, students' choices are based on their interactions within the educational environment at their university. The Student Integration Model presents student departure as a function of the students' motivation and academic ability as well as the *social system* and the *academic system* of the university. In this theoretical framework students' interaction in the university environments affect students' goal commitments and institutional commitments. The Student Integration Model posits that the stronger the commitments that the students have, the more likely they are to persist in their studies. I argue that a theoretical and empirical shortcoming of the model is the lack of structural clarity regarding how these commitments develop throughout students' academic careers.

Background influences on the Student Integration Model

Tinto's theoretical model of student integration evolved by incorporating empirical findings and new theoretical perspectives (Tinto, 1975; 1982; 1987; 1997). Part of the theoretical framework for the Student Integration Model is drawn from Durkheim's theory of suicide (Durkheim, 2004 [originally published 1961]). In Durkheim's (2004) seminal work, he made the case that suicide as a *social fact* gets "played out" by the individuals making up the system (see Section 4.8). What is pertinent here for modelling student retention is that individuals who are not fully integrated into a university have a greater tendency to leave their studies. This lack of social integration most often takes place when people find themselves holding different values to those that underpin their social environment. Tinto (1975) argued that, through the *social fact* concept developed by Durkheim, a university community is a strong social environment with its own *social system* and its own particular social values.

In 1987, Tinto added economic factors to the Student Integration Model. These economic factors related to the cost-benefit analysis of students' educational choice regarding investment in alternative educational activities – depending on how a student perceives the possible benefit of each course and educational choice, they may or may not choose to proceed with their course or programme.

Tinto (1987) also introduced van Gennep's (1960) notion of *rites of passage*, which describes how individuals claim membership within a new group. These rites of passage consist of three phases: *separation*, *transition*, and *incorporation*. All three phases describe aspects of change in a person's group membership. Separation involves the declining interaction between one's self and the members of one's former group. Transition is about how a person starts to interact in new ways with the members of the new group. Isolation, training, and sometimes ordeals ensures the breaking away from the former group and the learning of the new group's values and associated behaviours. Incorporation is about the taking on of new patterns and interactions with the new group and establishing full membership.

Thus, Tinto (1987) – by drawing on structures of suicide, economic notions, and rites of passage to community membership – brought attention to how the constraints of an institutional environment are able to negatively affect student retention. By incorporating these factors, students' conscious choices became an essential part of the modelling of student retention.

The model and empirical findings

Tinto's (Tinto, 1975, p. 95) theoretical model, which is shown structurally in Figure 3, illustrates how he proposed that students' choices get constituted. Figure 3 also illustrates the relevant connections between the students' *social system* and the *academic system* of a university and how these systems influence students' commitments and ultimately students' choices.

According to Tinto's Student Integration Model (Tinto, 1975; 1982; 1987), students come to university with critically important individual characteristics and backgrounds. These are critical because they form the basis for future interactions that affect integration into the university system. These characteristics and backgrounds are viewed as mediators for the integration of students into the university's culture and Tinto investigated their indirect effects on student persistence. He found several factors to have an impact on a students' persistence. These include: family background, which includes items such as socio-economic status; students' support from their home environment; and individual attributes, such as measured ability, attitude, impulsiveness and the ability to be flexible when having to deal with changing circumstances. A student's past educational experiences – particularly if the student got high marks before studying at the university – were shown to have a positive impact on student persistence.

Tinto's (1975; 1982; 1987) Student Integration Model hypothesizes that both goal commitment and institutional commitment play a significant role in student persistence. Goal commitment depends on how sure students are about their own goals, and how convinced they are that they will achieve these goals. This goal commitment is commonly measured in terms of educational plans, educational expectations, and career expectations. Institutional commitment is dependent on the extent to which students like or dislike the institution.

By using the Student Integration Model, Tinto (1975; 1987) suggested that if a student has strong goal and institutional commitments they would be more likely to persist in their education. In 1997, Terenzini and Pascarella reported finding that those students who chose to stay with their studies had had a higher interest in their academic programme (institutional commitment) than those who chose to leave.

Students often express study goals in a seemingly straight forward way, such as wanting to become a physicist or engineer, other student are not. This kind of uncertainty in students' study goals are not necessarily a cause for student departure (Tinto, 1987).

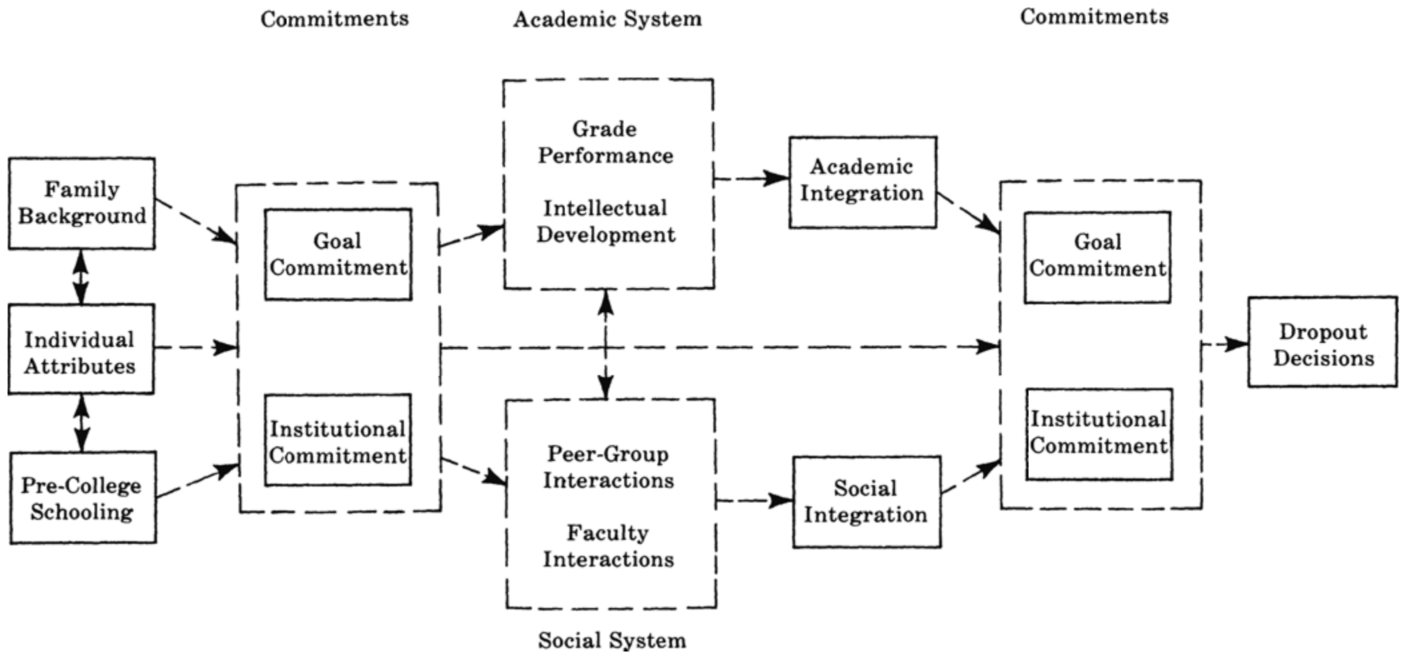

Figure 3. Tinto's (1975, p. 95) conceptual schema for dropout from university (reprinted with permission).

Students' commitments have been highly intertwined with other constructs of the Student Integration Model. If a university meets the students' expectations of career development, they tend to experience better academic and social integration (Braxton, Vesper, & Hossler, 1995). Findings by Nora (1987) show that institutional and goal commitments not only lead to higher retention amongst students, but also lead to a higher degree of academic and social integration. Academic difficulties and social isolation are often a part of students' experiences during the transition[26] from school to university. This can cause student departure.

Earlier I pointed out that Tinto (1975) introduced the idea of a *social system* and an *academic system* that can be seen to govern the students' integration within a university. I argue in Section 4.8 that it is possible to view these systems as consisting of "hidden" values that can only be learned through the students' interactions within the university systems.

Social and academic systems of the university

As pointed out earlier, within students' "complex experience" of higher education, the idea of, and its importance, a *social system* and an *academic system* evolved (for example, see Spady, 1970; 1971; Tinto, 1975; 1982; 1987; 1997).

> [The] academic and social systems appear as two nested spheres, where the academic occurs within the broader social system that pervades the campus. Such a depiction would more accurately capture the ways ... in which social and academic life are interwoven and the ways in which social communities emerge out of academic activities that take place within the more limited academic sphere of the classroom, a sphere of activities that is necessarily also social in character.
>
> (Tinto, 1997, p. 619)

Tinto (1997) argues that the *social system* and the *academic system* are interlinked in a complex way. These systems encompass every part of a student's social and academic life that takes place as they attend a university – making friendships, meeting new people and having social obligations within a social group. Tinto (1975) also argues that individuals not only need to be integrated into one of these systems, but also need to be integrated into both to have a chance to continue their studies.

For students to become integrated into the *social system* and the *academic system* there is a need for the students and institutions to find common ground between these systems' rules, norms, values, and expectations. Tinto (1975; 1982; 1987; 1997) claims that both social and academic integration occur mostly through semi-formal extracurricular activities and interaction

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[26] For a complete description, see Section 3.2.2 on Background influences on the Student Integration Model.

with faculty and administrative personnel. However, Terenzini and Pascarella (1980) argue that involvement in extracurricular activities does not have any significant impact on the students' decision to persist in their studies.

Tinto (1987) argued that students need to find some compatible academic group, social group, or some other group with whom to establish membership and establish contacts with in order to have a higher likelihood of persisting in their studies. Some students, instead of seeking social membership within the university's *social system*, seek out sub-cultures that exist within a university. Making new contacts and the ability to adjust can be facilitated for students in one of these groups, communities, or institutions (Tinto, 1987).

Both *student* ↔ *student* and *student* ↔ *faculty* interactions are important for student persistence (Terenzini & Pascarella, 1977; 1980; Pascarella & Terenzini, 1980), but *student* ↔ *faculty* interactions seem to be the most important element in the *academic system*. This is especially true when the contacts between students and faculty are outside the formal settings in a classroom (Tinto, 1987). Empirical findings suggest that not only the frequency, but also the quality of the interactions between students and faculty has an impact on student retention (Terenzini & Pascarella, 1980; Nora, 1987).

The lack of student integration can be associated with a student's isolation, meaning the lack of interactions between the student and other students, or the university faculty (Tinto, 1987). Tinto pointed out that students are need to be coerced into adapting to the social and academic setting of the university when they first start their studies, and if that fails, the student may end up leaving the institution or the education system all together. A problem with creating such coercion plan is that students could find the setting too alien to adapt to.

Berger and Braxton (1998) report that first-year retention is strongly related to an institution's ability to inform students about the institution's expectations and rules, and the fair enforcement of these rules. Also, the students' willingness to be a part of making those rules, and other decisions, affects the retention of first-year students. This means that "how everything works" needs to be very clear for both the students and the faculty.

Academic integration can be measured in terms of a student's grades and intellectual development during their years at the university (for example, see Spady, 1970; 1971; and Tinto, 1975; 1987). Intellectual development is the development of a student's own personality and self-reflection on their own intellectual integration into, and within, the *academic system*. If the intellectual culture is too alien for the students to handle – making it nearly impossible to interact with – then, this may lead to student departure (Tinto, 1975). According to Perry (1968) intellectual development is the most crucial aim of university studies and Tinto (1987) argues that intellectual development is an on-going process that requires students finding new ways of interacting within the *social system* and the *academic* system.

Tinto (1987) describes intellectual development in terms of occurring in the *academic system* and being guided by the institution's epistemology – how knowledge claims are made and what knowledge is valued. The intellectual development of a student is argued to be closely connected to the economic notions of *cost* and *benefit*. If students feel that their future intellectual development will yield greater benefit than the cost (time, money, and/or effort), it is more likely that they will persist with their studies.

Terenzini and Pascarella (1977) showed that intellectual development, as a part of the institution's *social system*, has both an indirect and direct impact on student persistence. This is due to intellectual development being longitudinal and being viewed through student ↔ student, and student ↔ faculty interaction. When students were asked to rate the positive effect that people (including faculty members, students etc.) had on their intellectual growth and their personal development, the students who persisted ranked interactions with faculty highest. Braxton, Vesper and Hossler (1995) connect goal commitments with intellectual development in their study of students' expectations when they enrolled at a university. They also relate intellectual development to strong goal commitment in combination with strong institutional commitments. Furthermore, they found that good academic and social integration occur when a university meets students' expectations of academic and intellectual development.

Students' non-interactualistic impact factors

Tinto (1975; 1982) acknowledges that students' financial situation could be an important factor for student retention. He argues that the financial situation and retention of students is closely linked to the students own view of their situation. If the students' experiences are positive, Tinto[27] theorize that students would accept a greater financial burden than when the experience of university is unsatisfactory. Also, depending on how close the student is to completing their degree, there could be a difference in how much financial burden a student may be willing to accept (Tinto, 1982).

Expanding the Student Integration Model

In 1997, Tinto expanded the Student Integration Model – that already involved integration, socialisation, quality of education, university communities, values and norms of a university, student ↔ faculty interaction, personal and institutional goals and commitments, the role of subcultures within the university, financial situations, cost-benefit analysis and much more – by introducing another aspect; classrooms as learning communities (see, Figure 4). This was to have the model encompass more factors from outside the

[27] Cabrera et al. (1993) found empirical evidence to support Tinto's claim.

university, and to call attention to what could be done by teachers within their classrooms and courses.

Tinto's (1997) study was conducted at the Coordinated Studies Program at the Seattle Central Community College where the students were form learning communities both in and of the classroom. From his study, a pattern emerged that connected learning communities, learning, and student persistence. Tinto argued that classrooms involve both the academic and social life of each student, and therefore both the *academic system* and the *social system*, which makes classrooms one of the important arenas for integration to take place. Tinto argues that for students who commute to the university, the classroom is the only place where they can be integrated into academic life. To be more precise, one could say that the academic system and the social system appear "... as two nested spheres, where the academic occurs within the broader social system that pervades the campus" (Tinto, 1997, p. 619). These systems are not separate, but are a part of each other in the university system.

As part of his expansion of the Student Integration Model, Tinto (1997) acknowledges the influence of external communities in his model (that is, factors external to those of the university that mainly effects students' goal commitments). These external communities together with the internal communities of learning made it possible to appreciate both external and internal influences on student persistence. The inclusion of these external communities is done in response to the criticism that Tinto's earlier model had had from researchers in the field of student retention research (for the earliest example, see Bean, 1980).

I now summarize how communities of learning affect student persistence under the following three topics: *building supportive peer groups*, *shared learning-bridging the academic-social divide*, and *gaining a voice in the construction of knowledge* (these are summarized from Tinto, 1997, pp. 609-613).

Building supportive peer groups. Participation in first-year communities of learning enables the formation of small peer groups. These small groups make a university seem smaller than it is, and in this way, promote learning for the students involved. If the groups are constructed within the classroom, they often transcend the classrooms themselves to form out-of-class learning communities. This positively affects their integration into the new setting of a university.

Shared Learning: Bridging the academic-social divide. One of the important parts of supportive peer groups is the shared learning. Often there is a strain between the social and academic life of students. An important part of learning communities is that the social life and academic life coexist within the shared learning community.

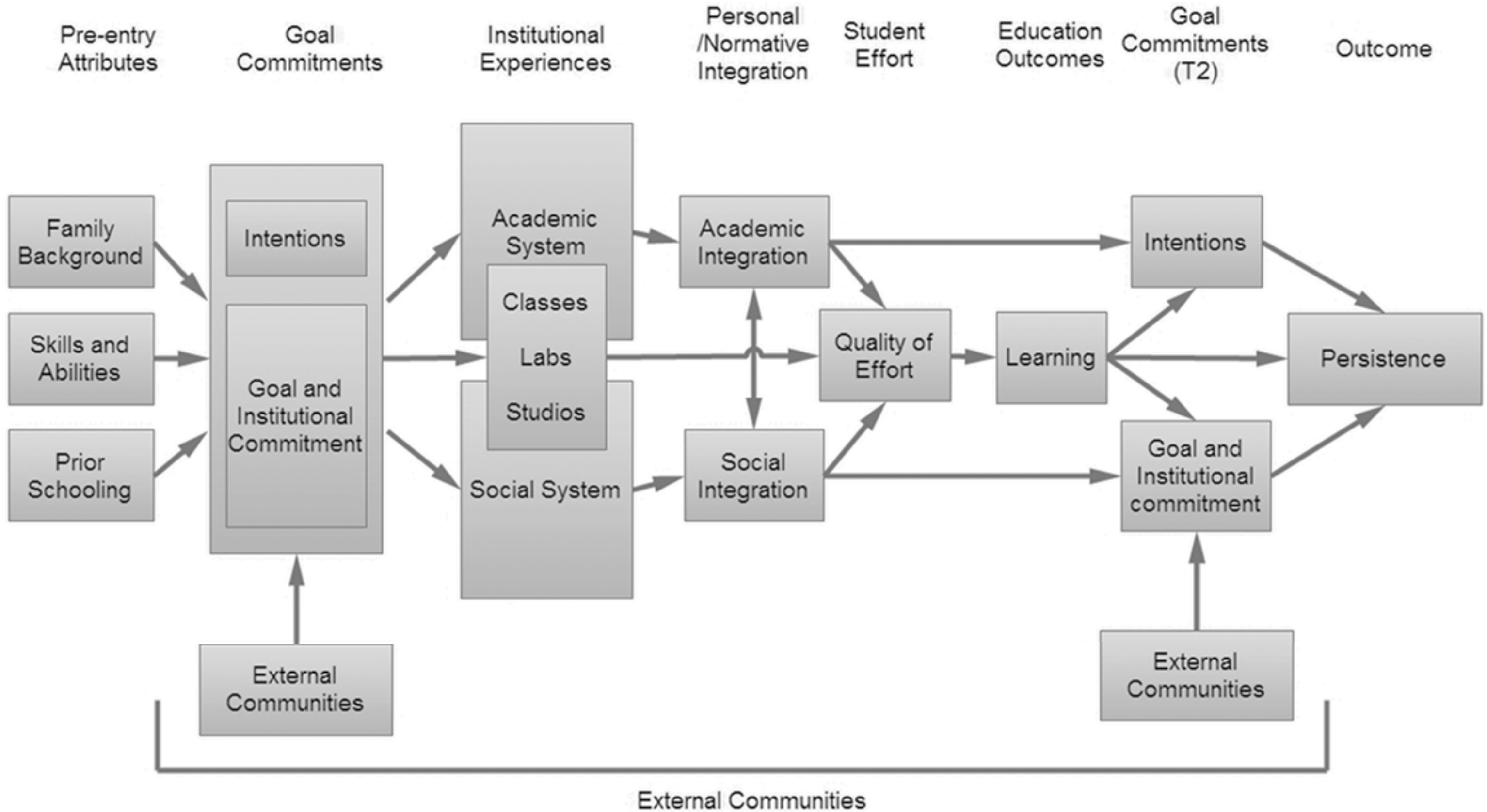

Figure 4. Expanded Student Integration Model. T2 denotes the Goal commitments students have which may change during students' time at the university (no further information is given by Tinto). (Reconstructed from Tinto, 1997, p. 615)

Gaining a voice in the construction of knowledge. Through learning communities, students may experience that they need to rethink what they know, become personally involved, and take ownership of their learning. The result of this is the generation of a sense of personal involvement and thus a richer learning experience.

Tinto (1997) argues that it is through the formation of these learning communities that learning and student persistence become interlinked in a way that facilitates an expanded model of student integration. Tinto saw this model as taking into account both his, and other's in the field earlier findings. Critically, to see student persistence as portrayed in Figure 4 implies that "... choices of curriculum structure and pedagogy invariably shape both learning and persistence on campus..." (Tinto, 1997, p. 620).

3.2.3. Student Attrition Model

This section is divided into two parts; a brief overview of the Student Attrition Model, and a more extensive and detailed review.

Brief overview

In 1980 Bean published his explanatory model of student retention – the Student Attrition Model. In this model, student beliefs play a major role in that they are theorized to be formed by student experiences (for example, courses, social experiences, institutional quality).

In 1995 and 2000 Eaton and Bean extended the model with further refinements (Eaton & Bean, 1995; Bean & Eaton, 2000). They did this by including a schema of how psychological processes affect academic and social integration. In other words, the new modelling included acknowledging that students' beliefs shape their attitudes, which, in turn, shape their behavioural intentions and approaches. Thus, Eaton and Bean's model can be seen to emphasize the importance of *individual* behavioural approaches in the modelling of student retention.

The model and empirical findings

Through a path analysis of a causal model of student attrition, where student departure was taken to be analogous to turn-over in work organizations, Bean (1980) highlighted aspects of the departure puzzle that were different from those of Tinto (1975). Through the addition of turn-over theory Bean (1980) was able to explicitly include background variables and translate variables (such as pay) to their analogies in the education system. He used this theoretical development to survey 1171 first-year university students and mapped out how each of his variables impacted (both directly and indirectly) students' dropout behaviour.

Bean (1980) began with a large number of variables and by using a stringent statistical analysis (path analysis) found a set of variables that accounted for the most variance in dropout. For females the variables were: institutional commitment (also an important part of Tinto's Student Integration Model), performance, campus organizations, practical value, opportunity to transfer, development, routinisation, goal commitment, satisfaction, communication (rules), centralization, distributive justice, and staff/faculty relationships. For males the variables that had the most impact on student dropout were: institutional commitment, satisfaction, development, routinisation, communication (rules), and housing.

Building on his 1980 study, Bean (1982) found ten variables that accounted for the most variance in dropout. All these variables are also interrelated, but to summarize, the following variables vis-à-vis the total mean effect of each variable, emerged as most significant: grades, opportunity to transfer, practical value, certainty of choice, loyalty, family approval, courses, student goals, student's desired major, and students' occupational certainty (after completing their major) (Bean, 1982).

Extension of Student Attrition Model

While accepting Bean's (1980) model of student attrition Eaton and Bean (Eaton & Bean, 1995; Bean & Eaton, 2000) extended the Student Attrition Model by drawing on psychological theory that deals with coping with stressful situations. According to this theory, the choice of behaviour to cope with a stressful situation is dependent on previous experience of coping. There are two different paths that could be taken: to approach, or avoid, the stressful situation.

Eaton and Bean's (1995) Approach and Avoidance Model (see Figure 5) consisted of four core constructs: academic approach, academic avoidance, social approach, and social avoidance. The academic approach construct is composed of the positive acts that students employ to enhance academic success: choosing courses, preparing for tests, developing relationships with faculty, and doing course work. The academic avoidance construct is composed of the behaviours that students use to avoid, neglect, or be passive in academic situations. The social approach is composed of the positive acts students employ to enhance social success: making friends and engaging in social activities. The social avoidance construct is composed of the acts that students use to withdraw, avoid or otherwise not be a part of socialisations. These four core constructs consist of several variables, which were measured through a questionnaire in Eaton and Bean's (1995) study. The questionnaire was based on Bean's (1980; 1982) work and responses from 262 students were used.

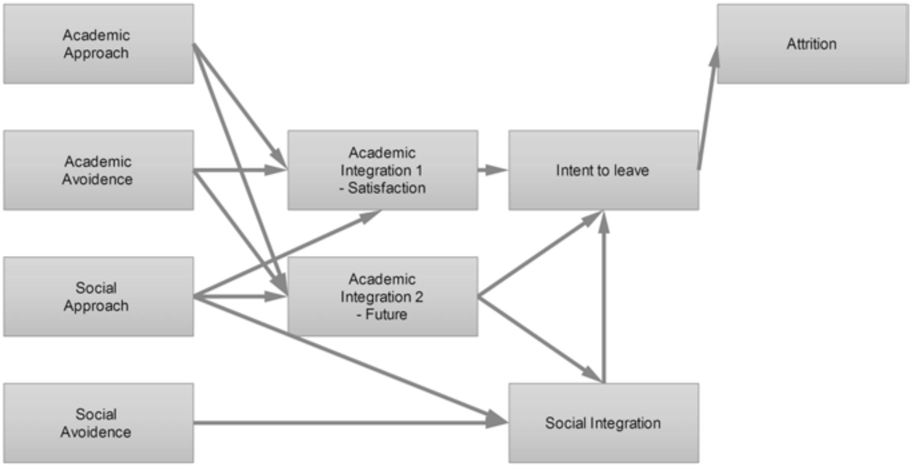

Figure 5. Eaton and Bean's Approach and Avoidance Model (1995, p. 621; my re-drawn version).

The Approach and Avoidance Model takes into account the effect of background characteristics on persistence: student prior educational attainment (that covered high school grade-point average and number of university preparatory courses taken), and family educational attainment and support (that covered student family educational attainment and how supportive the family had been in the students' studies).

The variable *intent to leave* had the most predictive power for student attrition followed by *family educational attainment* and *support*[28]. The group of variables that strongly affect the intent to leave were: current academic integration, future academic integration, and social integration. These are taken to indicate that if students do not perceive themselves as being successfully integrated into the university environment, both socially and academically, then they will tend to leave their studies (attrition).

3.2.4. Integration of student retention models

It was argued by Cabrera et al. (1992, p. 143) that further development of an integrated model of the two dominant student retention models would provide better explanatory value in, what they referred to as "explaining reasons to leave college". To evaluate, compare, and contrast both the Student Integration Model and the Student Attrition Model, (how much variance each accounted for) Cabrera et al. (1992) surveyed 2453 full-time first-year students[29] at a university in the USA. The questionnaire used was designed to

[28] These variables are not directly visible in Figure 5 because Eaton and Bean had them as subsections of the larger ”boxed” constructs.
[29] These students turned out to be all younger than 24 years old, which has been one of the critiques of the study.

measure the variables from both models that Cabrera et al. thought to be the most important.

The variables with high explanatory value for student retention were: frequency of contacts with faculty and academic staff, interactions with faculty and academic staff, faculty and academic staff concern for student development, academic and intellectual development, peer relations, values, certainty of institutional choice, and goal importance.

Cabrera et al. (1992) found that both models had explanatory value regarding student retention, and therefore argued that there is a need to further develop models that encompass both the Student Integration Model and the Student Attrition Model. As mentioned earlier, due to the wide variations within empirical trials and findings associated with Tinto's model, researchers have argued that it should be "seriously revised" (Braxton, 2000, p. 258; Braxton & Hirschy, 2004) – even suggesting that a new foundation for such a model should be developed. While some researchers see the Student Integration Model and the Student Attrition Model as separate and distinct, in agreement in Cabrera et al., I would argue that it is important to acknowledge that both models "regard persistence [and/or retention] as the result of a complex set of interactions over time" (Cabrera et al., 1992, p. 145). Thus, if student retention research is to move forward, it has become absolutely imperative to find new ways to model student retention as an integrated whole[30].

3.3. Inconsistencies of factors affecting student retention

Contemporary research in the field of student retention has remained grounded in Tinto's Student Integration Model or Bean's Student Attrition Model, and their extensions. Empirical research on the constructs of these models and their relation to student retention has shown inconsistencies in outcomes (see, for example Reason, 2009). The inconsistencies found have been argued to be the result of the measurements of, for example, the somewhat hard-to-define constructs of the two models (for example, see Beekhoven et al., 2002). However, I argue that the inconsistencies of the observed effects on student retention are only in part due to those hard-to-define constructs. In support of my argument consider the case of the effect of students' age[31] on student retention. This variable has been found to both negatively and positively affect student

[30] See Chapters 5 and 7.

[31] More cases can be found in Reason's (2009) review, which contains, for example, the effects of biological sex, institution size, and participation in extra-curriculum activities. Other findings suggest that financial aid (Dowd & Coury, 2006) also has an unstable effect on student retention.

retention for different groups of students (Reason, 2009). As such, it provides an excellent example of a variable that is not problematic in terms of having a clear definition (Reason, 2009). It is arguably more likely that it is the treatment of the effects of factors as direct causal effects[32] that lies at the root of the problem. This adds additional evidence to the argument that a new way of conceptualizing student retention is needed. This led to my investigating using complexity theory which offers a new way of modelling and conceptualizing the process of student retention as *a process in a complex system* that does not treat all factors as having direct causal effects.

3.4. Student retention and complexity theory

In order to discuss the relationship between the core concepts of student retention and complexity theory, the next chapter is dedicated to the foundational constructs of complexity theory. The discussion on how the core concepts of student retention can be discussed in terms of complexity can be found in Section 4.8.

[32] Effects that are generalized to be applicable for all contexts, and for all students.

4. Methodology: Part 1 - Introduction to Complexity Theory

4.1. Introduction

Chapters 4, 5, and 6 present the three parts of the methodology I used in this thesis. This chapter (Part 1) gives the theoretical basis of the methodology that I developed, Chapter 5 (Part 2) goes on to present the methods that are important when applying complexity theory in Physics Education Research for the case of student retention, and Chapter 6 (Part 3) describes the data collection with its associated ethical aspects.

Entire books have been devoted to the ontological, epistemological, methodological, and empirical aspects of complexity theory. What I present in Part 1 (this chapter) is my summary of the aspects of complexity theory that are relevant for my thesis.

The main aim of this chapter is to introduce the theoretical and conceptual basis I used to provide the answers to the research questions as posed in the introductory chapter and repeated below:

1. *In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?* and,
2. *Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?*

This Chapter starts with giving a rationale of why complexity theory is chosen, it goes on to describe complexity theory, and gives examples of the properties and dynamics of complex systems. I then proceed to explore the setting for how complexity theory can be used as a framing to examine student retention and present two approaches by which this becomes possible.

4.2. Why the focus on complexity theory?

To further the understanding of student retention there is a need to develop a theoretical framework that incorporates previous work in student retention research and also embeds new phenomena and methodologies to identify fruitful interventions that have been lacking in previous efforts to model student retention.

In the introduction to this thesis, I argued that the idea of a complexity component has been ubiquitous in the field of student retention (see Section 1.3) and that the notion of complexity has mostly been used to say that student retention is "too complicated to understand"[33]. This is because researchers have identified a multitude of critical factors that may play a role in students' decisions to continue with their studies. Also, these factors are not independent of one another, which make it a very "messy" system to deal with. The theoretical framework that is put forward in this chapter thus incorporates these multiple interacting factors within the modelling of complex systems.

Further, theoretical and methodological problems arise as the two models of student retention (the Student Integration Model [see Section 3.2.2] and the Student Attrition Model [see Section 3.2.3]) can be argued to focus on two levels of the system being studied – jumping between the individual and the system level. This is addressed through the complexity theory notion of nestedness and fractals/scale-invariance/scale-variance discussed later in this chapter (see Section 4.5).

Empirical inconsistencies found in factors affecting student retention between different student cohorts can be seen as problematic (see Section 3.3), but only if they are thought of as linear cause-effect relationships between two aspects. If they are seen as potentially non-linear[34], through an application of complexity theory, then the inconsistencies could - instead of being problematic – be seen as truly reflective of the intrinsic nature of the critical factors found.

4.3. What is complexity theory?[35]

Complexity theory[36] aims to describe and understand complex systems and their capacity to show order, pattern, and structure. Especially important is how these orders, patterns and structures seemingly emerge spontaneously in the absence of centralized control from interactions between the complex systems' components. Complexity theory has taken root and emerged in a

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[33] This is supposition on my part, as "complexity" seems to have been mostly used as an argument for when the explanatory power of the modelling efforts fall short (the earliest example can be seen in Spady, 1970).

[34] Having a non-linear relationship between cause and effect.

[35] To add coherence to the thesis, the description in this section is largely a repeat of the overview given in **Paper I**.

[36] Although most of the literature dealing with the notion of complexity uses "complexity theory", it is also known as "complexity science".

wide range of disciplines, generating a theory that essentially transcends disciplines (see Waldrop, 1992, for a detailed outline of the historical development of complexity theory. Also, see Mitchell [2009] for an overview of applications of complexity theory in a wide array of disciplines). Complexity theory is not characterized by a particular research method, but by a methodological perspective (i.e., a way of thinking) that employs a range of methods to study complex phenomena (Davis & Sumara, 2006).

In terms of complexity theory, complex phenomena are distinct from complicated phenomena, which are mechanical, predictable and can be fully understood by examining their component parts. To obtain a reasonable portrayal of a complex phenomenon, an understanding of the properties of the components alone is not sufficient. Thus, what is central in describing or understanding a complex system is identifying the components, their interactions, and the higher order behaviours and properties that emerge from the complex system. Examples of these are system behaviours, properties and structures or the "structuring structures"[37] of the complex system (Davis & Sumara, 2006; Mitchell, 2009; Morrison, 2005). In this way, a case can be made to characterize complexity theory as being distinctly different from a traditional view in terms of the way power of prediction is conceptualized. In other words, the evolution of a complex system is, in a classical sense, largely unpredictable and uncontrollable.

One can conceptualize the essential aspects of the structure, dynamics, and predictability of complex systems through: metaphors (for example, see Gilstrap, 2005), computer simulations (for example, see Brown & Eisenhardt, 1997) and systems of modelling (for example, see Mowat & Davis, 2010). The essential aspect of complex systems, and what has given rise to complexity theory's widespread use across many disciplines is that all complex systems share similar structures and dynamics. The behaviour of complex systems such as society, organisms, or the internet can only be conceptually discussed as somewhere in-between complete order and complete disorder. Any attempt to measure or distinguish one system as "more complex" than another often breaks down (Mitchell, 2009). If a system is to be identified as being a complex system what needs to be investigated is the presence of structures and dynamics that are common amongst complex systems, not the complexity itself (Davis & Sumara, 2006).

Mitchell (2009) describes four threads of research on complex systems. These are: *Dynamics* – how systems change over time; *Information* – how systems can be represented and what the symbols and communications are within the system; *Computation* – how systems process information and act on the result; and, *Evolution* – how systems adapt to constant change. Mitchell (2009) acknowledged that each of these threads can produce entire disci-

[37] "Structuring structures" refers to things such as rules of the structure or structures whose interaction affects the structure of the system.

plines of research, but *all* are essential for research dealing with complex systems.

Broadly speaking, the goals and uses of complexity theory can be divided into two strands that offer cross-disciplinary insight into complex systems.

The first strand suggests that a theoretical framework based on complexity theory and its methodology can be used to combine, or explain previously incommensurable ideas. For example, Morrison (2005) discusses this from an educational context, and Wolfram (2002) who aimed to encompass Mathematics, Physics, Biology, Social Sciences, Computer science, Philosophy, Art, and Technology in what he called a "New Kind of Science".

The second strand, which is more common in the research on complex systems, is the development of methodologies framed by complexity theory. For example, exploring how similar the information processing within an ant colony is to that of humans in a city. Or, how similar the information flow within a network of neurons in a brain is to the flow of information in an economic network. In short, to describe this second strand, it is argued that all complex systems are similar in both their structure and dynamics, thus, as argued by Davis and Sumara (2006), it should be possible to use the same metaphors and methodologies to explore *all* such systems.

4.4. When is a system taken to be a complex system?

There is not *one* agreed upon definition of complexity[38]. However, as a starting point an examination of phenomena that are taken to be complex by researchers that draw on complexity theory is discussed in this section[39]. The section is divided into two sub-sections. The first sub-section uses three examples – ant colonies, the brain, and the immune system of the human body – in order to discuss the role of interactions in complex systems. The second sub-section also uses three examples – the controlling structure of the E. Coli bacteria's DNA, a food web, and a social network – in order to discuss the role of interaction networks in complex systems.

4.4.1. The role of interactions in complex systems

Ant colonies are regarded as complex systems. Each colony can consist of hundreds of thousands of individual insects. Each individual acts according to very simple rules, for example, seek out food and respond in simple ways to chemical signals. Many ants acting together can, however, show complex behaviour such as generating structures to transverse otherwise impossible terrain to gather food (see Figure 6 that shows ants forming an ant-bridge).

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[38] See definition(s) of complexity in Section 4.6.

[39] This section draws on the excellent introduction to complexity by Mitchell (2009).

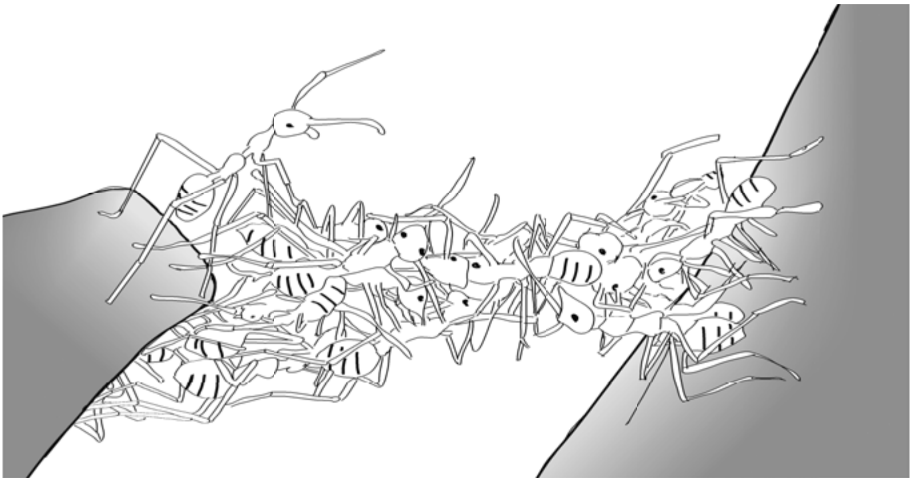

Figure 6. Ants forming a bridge

The seemingly obvious explanation of this behaviour is that ant colonies are made up of leader ants, which control the worker ants. The structures built by ants do not, however, require such external control. The activity is characterized as originating from simple interactions between the ants and the basic rules each ant responds to. The exact workings of the structure and function of these kinds of interactions in complex systems are still subject to extensive research (for example, see Granovskiy, 2012).

The brain is also considered to be a complex system where relatively simple components with limited spatial reach and types of communication give rise to rich and complicated global behaviour. The brain is made up of relatively simple components called neurons and it is believed that the actions and activation patterns of networks of groups of neurons is what is central to the function of the brain (Mitchell, 2009).

As illustrated in Figure 7, each neuron only has a limited reach to other neurons and thus, the main volume of information communicated is between neighbouring neurons. This is similar to the previous discussion on similarity between different complex systems, where the actions of ants in an ant colony respond to signals from neighbouring ants and respond to those signals in a relatively simple way. How these signals are then amplified or dissipated in the whole network of components can be argued to be the basis for the large scale behaviour of the complex system (Morrison, 2009; Davis & Sumara, 2006).

Exactly how the activity of individual clusters of neurons relates to the large-scale behaviour of the brain is currently only partially understood and is still under debate.

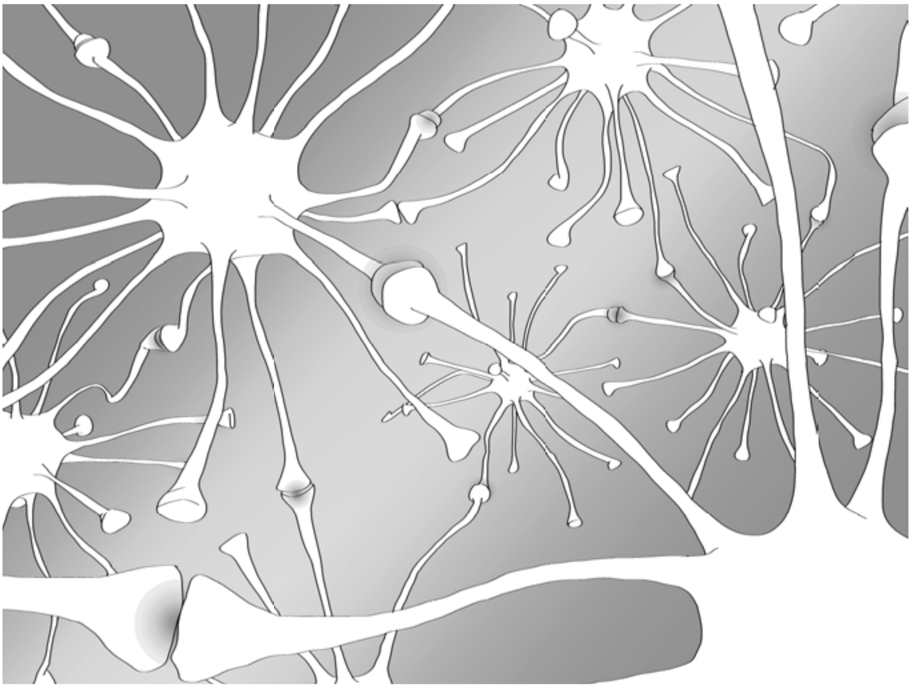

Figure 7. Illustration of neurons. This illustration is accurately reconstructed from an illustration of brain neurons given by http://dx.doi.org/10.15729/nanocellnews .2014.08.26.002.

I now use the immune system to further exemplify the role of interactions in complex systems. I have chosen to do so because I see the immune system as providing a neat example of where relatively simple components exhibit a large-scale complex behaviour. I also see this example as being able to form a bridge between this section and the section on the role of interaction networks in complex systems (both the interaction between agents [cells] and the networks of interactions – the cascading effects of the immune system as a network – are important in the immune system). The behaviour I wish to exemplify here comes from how the constituent components signal, control, and adapt to each other, and external systems. The immune system is similar across species; there are multiple cell types that are distributed throughout the body, where each cell responds individually without any central command (Mitchell, 2009).

Cells in the immune system can recognize molecules, which correspond to invading cells (for example, bacteria) and send off a large number of other types of molecules (antibodies) to combat an "intruder". When such an event occurs, the cell that was first activated (i.e., "recognized" the "intruder") then divides at a much higher rate, and the daughters of this cell will "remember" the particular pathogen that was encountered, thereby giving the body immunity.

Other types of cells that are active in the immune system have an interesting (and also very particular) response when first encountering intruders. These cells divide and the daughters that survive through a Darwinian process are those that are better in detecting and hunting down particular pathogens. When the cell that first encounters the pathogen releases its antibodies it activates a diverse set of “other types” of cells. One of these types is responsible for destroying the invaders that have been tagged by antibodies. Others help with long term immunities of the body.

The outcomes of these diverse set of cells can be viewed as a network of signals where the detection of “intruders” sets off a cascade of other cell actions. In this way, as a large scale system behaviour, the immune system becomes better and better at detecting and hunting down certain kinds of pathogens.

4.4.2. The role of interaction networks in complex systems

In addition to understanding how individual components of a complex system behave, it is also critical to understand how the networked interactions (or signalling systems) between the components take place. How the behaviour of a system responds to information that is then distributed, amplified, dissipated, and clustered within the system is dependent on both the individual components of the system and also the pattern that is distributing that information.

To exemplify how networks are being used in research on complex systems and how to understand simple networked systems, I draw on the following three examples: the controlling structure of the Escherichia Coli (E. Coli) bacteria’s DNA, a food web, and a social network.

Figure 8 shows the estimated structure of the regulatory network of the E. Coli bacteria’s DNA, which regulates the cells response to changes in environment. An example of the functions of these regulatory networks is when a yeast cell encounters a sugar molecule. It will activate the genes that create the enzymes necessary to make use of the molecule. In this example, the links in the interaction network are of only *one type*; the links indicate which of the DNA segments have a possibility to become expressed (activated) at the same time. Later examples will involve multiple types of links.

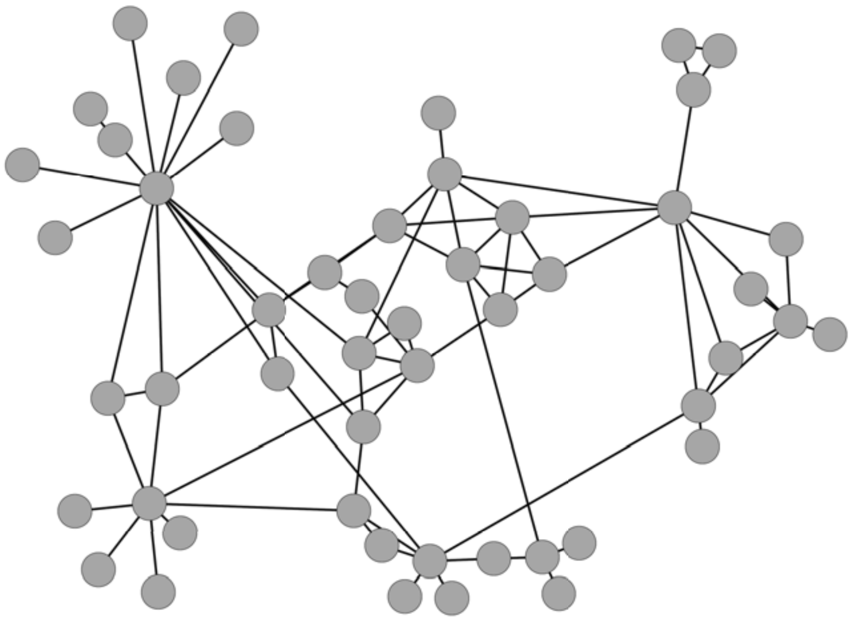

Figure 8. Illustration of the estimated regulatory network created by using the partial correlation estimations as implemented in GeneNet (Schäfer et al., 2006) for the E. Coli bacteria. The nodes are the different gene expressions in the bacteria's DNA that can be activated, while the links correspond to which other sets of gene expressions tend to be activated at the same time. This visualization was created using package iGraph (Csardi & Nepusz, 2006) for the statistical environment **R** (r Core Team, 2013) using the data obtained from Schmidt-Heck et al.'s (2004) study.

In Figure 8 one can observe a fairly simple regulatory network, which corresponds to gene expressions. This network is a constitution of fairly simple components where environmental changes, much like those of the immune system, can cause cascading effects throughout the system. These kinds of systems are not stable, but change over time as the bacteria evolves. Even small environmental changes can lead to drastic changes of gene expression due to the potential of cascading effects of the network, for instance, for the E. Coli bacteria.

Moving upwards in terms of scale, the next example that I use to discuss the role of interaction networks in complex systems is the food web[40] found in Otago Harbour in New Zealand (Mouritsen et al., 2011). At first glance, the animals, parasites and bacteria that are parts of this particular food web could not be considered to be "fairly simple" components. However, the food web shares similarities with much smaller systems in that: it is based on interactions between components; it evolves over time as each component adapts; there is a possibility for cascading effects; and, it changes as the environment changes.

[40] A network of "who eats whom" in nature.

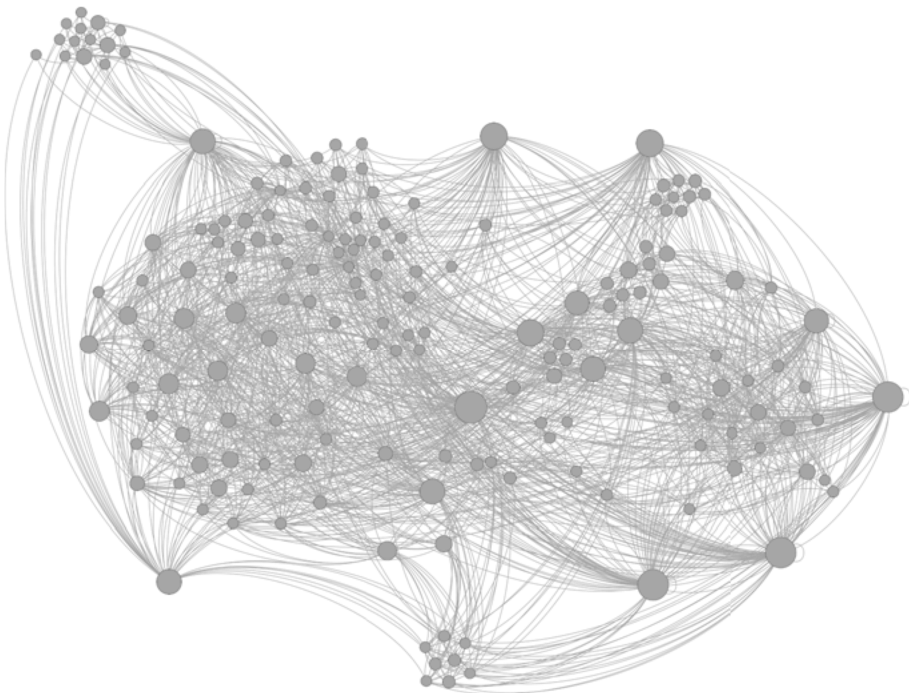

Figure 9. Illustration of the food web from Otago Harbour, New Zealand (Mouritsen et al., 2011). This food web contains 142 species/assemblages and 1924 links. Each link corresponds to either a predator/prey relationship, or a parasite/host relationship. The raw data set is available from: http://esapubs.org/ archive/ecol/E092/173/

Such food webs do not only adapt to external changes, but also to internal changes. External changes that could cause the food web to adapt, could, for example, be a flood that could potentially affect the food for the herbivores. This, in turn, could cause the habitat to be unable to sustain the same amount of prey for the predators – dynamics that could potentially change the system as a whole. Internal changes, for example, could be that a predator begins to hunt different prey, which shifts the balance slightly from the earlier prey, causing changes that could affect the whole system[41].

This particular food web, illustrated in Figure 9, is also unique because it does not only represent one type of node, nor one type of link between the nodes. The links represent predator ↔ prey, or host ↔ parasite relationships. The nodes represent the different animals that were present in Mouritsen et al.'s (2011) study.

The third and last example that I want to discuss in terms of the role of interaction networks in complex systems is a social network that has links that are registered as face-to-face contacts (see Figure 10). It is easy to argue that the components constituting this network are not simple – the network has

[41] For example, see predator/prey simulations at: http://www.phschool.com/atschool/phbio/active_art/predator_prey_simulation/index.html

properties similar to those of other complex systems. This interaction network portrays a complex system that is based on component interaction; it evolves over time as each component adapts, there is a possibility of cascading effects, and the system changes as the environment changes.

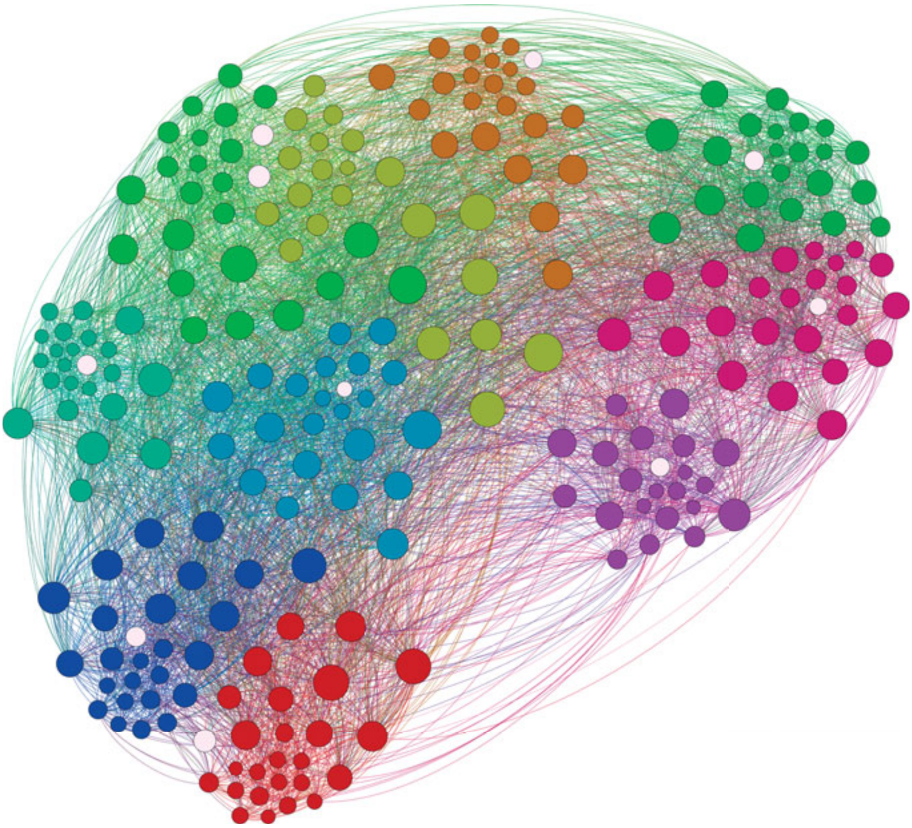

Figure 10. Illustration of a social network that has links that are registered as face-to-face contact: a contact network (Stehlé et al., 2011) containing classes of pupils (coloured clusters) and teachers (white nodes) and their interactions during one day of primary school (raw data set available from SocioPatterns Collaboration at http://www.sociopatterns.org).

Problems arise, however, in what constitutes a link between nodes. In this example (Figure 10) there is no explicit detail of what the information exchange between these contacts entails. The properties of the interaction network are dependent on what constitutes a link, and how the links are characterized[42]. This then, in turn, affects the characterization of *what* is cascading and *what* drives the evolution of the system.

[42] See Section 7.4 for a discussion of how the relevant interactions within a university course affect academic success and student retention.

This final example has added significance for my thesis work because it is the kind and size of system that educational research could be expected to be able to generate – a complex system of students' course-level interactions. The example in Figure 10 is the kind of complex system in which it would be possible to study the interactions of students and teachers as a function of, for example, educational outcomes.

4.5. Properties and dynamics of complex systems

I now turn to explaining the basic concepts of complexity theory, which are relevant for the research I did for my thesis: *evolution*; *emergence*; *feedback*; *connectedness*; *nestedness*; and, *scale (in)variance*.

Researchers in disciplines that regularly use complexity theory agree that a complex system is "more than the sum of its parts" (see, for example Cohen et al., 2011; Sawyer, 2005). This means that the foci of the research are on systems that are composed of interacting agents[43] (also referred to as components) that self-organize, and that as a whole have the possibility of showing properties and dynamics that are taken to be typical for complex systems. Educational systems are complex systems as they share properties and dynamics common to complex systems. The commonalities relevant for this thesis are presented below:

Evolution, also often referred to as *adaptation*, is a central construct in complexity research. Each system continuously self-organizes in order to better adapt to the internal and external influences that affect the system (Davis & Sumara, 2006). The adaptation of complex systems is taken to be a process whereby the system *learns* (for example, see Davis & Sumara, 2006); complex systems are learning systems (Capra, 2002).

Emergence can be said to be the result of self-organization (for example, see Cohen et al., 2011) where the components self-organize[44] through their interactions. This gives rise to patterns and behaviour of the system that cannot be reduced to the influence of a particular component. This connects to the notion that complex systems lack a particular "leader" that controls and regulates the properties and behaviour of the system. From a complexity stand point, reducing a phenomenon to its simplest form means exploring the rules by which the components interact and what networked patterns emerge from these rules of interaction within the system.

Feedback between interacting components within a complex system is critical. Negative feedback acts as a regulator (Davis & Sumara, 2006) and

[43] How many agents are necessary for such a system is, in itself, debatable. Currently the only answer seems to be: *enough for the system to show properties and dynamics that are identifiable as complex (*for example, see Davis and Sumara's [2006] discussion *on simple, complicated,* and *complex systems*).
[44] An example of this is given in Section 4.4.1 – Ants "building" an ant-bridge.

forces the system towards an equilibrium state. Negative feedback is a dampening mechanism that acts negatively on a system's response to internal and external signals. Positive feedback is troublesome for systems that are moving towards an equilibrium state because the feedback changes (amplifies, grows, and develops) the information processing within the system. The classical example of positive feedback is the "butterfly effect", where small changes within the system cause large and unpredictable outcomes. However, different structural aspects of complex systems can cause time-delays in the feedback from the system in terms of the time between the cause and the effect of that cause (for example, see Sterman, 1994).

Connectedness characterizes how all agents/components of a complex system are connected (have a relation) to all other agents/components within the system in some way[45] (for example, Davis & Sumara, 2006; Cohen et al., 2011).

The structure and dynamics of *nestedness* of complex systems can be characterized in two dimensions: *vertical* (visualized and further discussed in Figure 21, Section 7.2.1); and, *horizontal* (further discussed in Section 7.2.1). It is important to point out that agents/components of the complex system are more interrelated within a nested level than between nested levels (Davis & Sumara, 2006).

Vertical nestedness is described by Davis and Sumara (2006) in terms of referring to different levels/scales with regards to the spatial size of the aggregated components. For example, vertical nestedness within an educational context could be where students are nested within social and academic groups. These groups are nested within a course, then nested within departments, then in schools, universities, and these in turn are nested in the society around them. These different nested levels function differently with regards to change over time (temporal change). An example of this is that an individual tends to make changes within a shorter time span, than, for example, society as a whole.

Horizontal nestedness is when each vertical nested level in a complex system is viewed from a "side view". Each vertical nested level is composed of diverse clusters of constituent parts, i.e., are horizontally nested. An example from a relevant educational setting is that students' social and academic groups, which are present on one vertical nested level (the classroom level), are diverse and do not reside in only one classroom, and not necessarily within one department, or one university, or one country. Put another way, horizontal nestedness is a description that characterizes the diverse set of clusters of constituent parts within the same vertical nested level (also see discussion by Lemke, 2010).

The notion of nestedness leads to questions about the relationship between different nested levels of a system. Properties and behaviours within a

[45] For an example of how complex systems' components are connected, see Section 4.4.2.

complex system can be *scale-free* (Davis & Sumara, 2006), in that they show similar, if not identical, recurrences across both the vertical and horizontal nestedness of a system. Further, similarities across nested levels of a complex system that are not fully identical are characterized as having a *fractal* similarity (Davis & Sumara, 2006); they are not identical but similar. Here, fractal similarity draws on the concept of fractals from the discipline of mathematics. Fractals can be curves or geometrical figures where similar patterns recur at all scales. An example of this is the Koch snowflake. Creating a Koch snowflake starts with an equilateral triangle, then: (1) dividing each side of the triangle in three segments of equal length; (2) drawing an equilateral triangle that has the middle segment from step 1 as a base; and, (3) removing the line segment that made up the base of the triangle in step 2. These three steps can be iterated and, by design, Koch's snowflake is therefore similar across different spatial levels, and thus is fractal. Fractal similarity is metaphorically used to describe similarities of properties and dynamics between nested levels. A relevant aspect of student retention that potentially shows fractal similarity across levels, is students' *feeling of belonging*. Such a *feeling of belonging* runs across what students feel when they belong in a programme, belong in a particular course, belong at a particular university, or in a city where the university is situated.

I argue that in order to understand the relationships that occur between properties and behaviours within complex systems between different nested levels, the introduction of *scale variance* (for example, see Morrison, 2008) and its logical dichotomy *scale invariance* can be used by further exploring how behaviour and properties of complex systems can be seen to range from being scale invariant (i.e., scale-free) to being scale variant[46]. The first extreme (scale invariant) suggests that a property or behaviour is identical across all nested levels while the last extreme (scale variant) suggests that a particular behaviour or property is only present and valid in one (or a few) nested levels (horizontal or vertical).

Davis and Sumara (2006) argue that *level jumping* between different nested levels is needed in order to understand critical issues in education. These critical issues can be affected by components whose influence originates from a number of nested levels in a complex system. Using the idea of level jumping, Davis and Sumara suggested that one should explore a given complex system in order to establish which nested levels are relevant for the educational situation being studied. Further, Davis and Simmt (2006) and Davis (2008) argued that using complexity theory[47] successfully in educational research means being aware of several aspects that are happening at the same time. These different aspects can be addressed by level jumping

[46] I developed these two constructs for **Paper II**. More discussion is given in Section 7.2.

[47] Here, Davis (2008) called the field/approach *complexity science*. I decided to use the term complexity theory in this case in order to produce a more coherent description.

between, in the example used by both authors, curriculum, cultural perspectives of mathematics, and individual understanding of mathematics. Such examples represent different “levels” of aspects that can affect the studied system. David and Simmt (2006) and Davis (2008) argued that all are critical for understanding the nature of what is happening in a learning situation.

By conceptually bringing together level jumping (Davis & Sumara, 2006) and the notion of scale variance (Morrison, 2008), I argue that in order to understand the studied system, in addition to examining multiple levels of the complex system (level jumping), it is also necessary to investigate the extent to which components across nested levels of a system are scale variant (or scale invariant)[48].

4.6. Characterization(s) of the term complexity – when can a system be taken to be a complex system?

My discussion of relevant complexity constructs and how the term complexity is used in the literature comes at this late stage in this chapter because the disciplines investigating complexity have not yet agreed on a single definition of its meaning. This is primarily because researchers in these disciplines have different *objects of study* and therefore have developed different measurements to reflect when a system can be taken to be a complex system. Lloyd (2001) collated a list of measurements of complexity gathered from a diverse set of disciplines and concluded that the reason for why the sheer number of ways of measuring complexity is overwhelming may be because:

> ...the problem of measuring complexity is the problem of describing electromagnetism before Maxwell's equations. In the case of electromagnetism, quantities such as electric and magnetic forces that arose in different experimental contexts were originally regarded as fundamentally different. Eventually it became clear that electricity and magnetism were in fact closely related aspects of the same fundamental quantity, the electromagnetic field. Similarly, contemporary researchers in architecture, biology, computer science, dynamical systems, engineering, finance, game theory, etc., have defined different measures of complexity for each field. (Lloyd, 2001, p.7)

Lloyd’s list contains over 40 different definitions, which he divided into three broad categories:

- *How hard is it to describe the system?*
  This category is often measured in terms of how much information is needed to describe the system.

[48] See Section 7.2 and **Paper II**.

- *How hard is it to create the system?*
  This category is often measured in terms of time, energy, or monetary capital.
- *What is the degree of organization of the system?*
  This in turn is divided into two sub-categories:
  - *Effective complexity*
    The difficulty in describing the structure of the system.
  - *Mutual Information*
    The amount of information shared between parts of the system.

For the educational context of my thesis, the characterization of complexity that is used draws on the properties and dynamics common to complex systems as discussed in Section 4.5. Educational systems can be taken to be complex systems in that they share similarities with other complex systems (see Sections 4.4 and 4.5) – they are made up of a number of agents/components (students, teachers, study behaviour, social factors, financial factors, etc.) that interact (exemplified in Section 4.4.1). This interaction creates interaction networks that have different functions throughout the system as exemplified and discussed in Section 4.4.2. If the system is complex, then something *new* emerges from the networked interactions between the components of the system that cannot be traced back to the properties of the components making up the system. Educational systems that are complex systems adapt to both internal and external influences and evolve over time through, for example, policy, curriculum reforms, and economy.

From my perspective, it is fruitful to think about complex systems as systems that *cannot be represented in a "compact" form*. By this I mean, for example, systems such as a simple illustration or a mathematical expression that "fails" to present the complexity of the system. I argue that educational systems cannot be presented in a "compact" form. My argument is based on the fact that, as stated earlier, educational systems are composed of a large number of agents/components and aspects on multiple nested levels, which have multiple internal and external influences. I have tried to present the studied educational system in a "compact" form in Figure 26, Section 7.3.2. However, this picture represents, at best, a *contour description* (meaning a model of the complex system) and not the complex system itself. In doing this, I am taking into account some of the inherent properties of a complex system, such as the networked structure and the interconnectedness of such systems, which have been missing in the modelling of student retention up until now.

It is important to think about complexity, not only as a system's property or behaviour, but also as a function of what kind of understanding one hopes to gain from describing the system as a complex system. This can be exemplified by contrasting the following two questions: "How do we get students to pass a course in mechanics?" and "How do we get students to become physicists?". It is clear that these two questions differ in scope and the number of possible influences that can affect the outcomes. Also, there is a major difference in the time-scale on which these two questions operate, making the second question much broader than the first. Therefore, answering the second question using a complexity theory perspective is necessary if an understanding of the system is to be gained.

I now give a more comprehensive overview of complexity theory as used in educational sciences.

4.7. Complexity theory in educational research[49]

Following the links made in the previous section between educational systems and complex systems, a more comprehensive overview of this relationship is given in this section.

An educational system is a system consisting of everything that involves academic teaching and learning across all levels – laws, policies, funding, administrative offices, teachers, facilities, staff, computers, books, teaching resources, and students, to name a few. All components of educational systems are interdependent in some way and thus all educational systems can be taken to be complex systems as they are made up of multiple interacting agents/components on different nested levels (see Section 4.5). They are made up of a number of *agents/components* (students, teachers, study behaviour, social factors, financial factors, etc.) that interact (as exemplified in Section 4.4.1). These interactions creates interaction networks that have different functions throughout the system and create the opportunity for *emergence* to occur as exemplified and discussed in Section 4.4.2.

Complexity theory can be used by researchers that are interested in investigating problem situations in education that can be identified as complex systems. Davis and Sumara (2006) introduce the term *complexity thinking,* which is derived from complexity theory, to describe and understand complex systems and their capacity to show order, patterns, and structure in educational activities. The use of complexity thinking as "a way of thinking and acting" (Davis & Sumara, 2006, p. 25) in education essentially provided the basis for a new grounding for educational research that explicitly draws attention to the significance of seeing a complex system to be a learning system. As such, the movement towards the use of complexity thinking in education has been propagated by the need to have a theory to provide tools to "grasp the complex processes of learning" (Jörg et al., 2007, p. 1).

From a complexity thinking perspective, the process of education stops being viewed in linear terms. Instead, education is viewed in terms of a process of continuous adaptation (Davis & Sumara, 2006) where students and

[49] For coherency of the thesis, this section resembles the discussion in **Paper II**.

all aspects present in the system affect not only the recursive adaptation of students, but also the complex system of education itself.

In complex systems, coming to understand relationships between cause and effect depends on the nature of the system in question. A straightforward approach is to find a part of the system educators wish to change, change it, and then see what happens in the system. However, design and implementation of strategies for understanding the relationship between cause and effect in complex systems is problematic. This is a consequence of the multiple temporal and spatial scales that systems and sub-systems operate on (Sterman, 1994) (*Nestedness* see Section 4.5). In particular, the time delay between implementation of action and feedback from the system is probably the most important constraint in the study of complex systems (Rahmandad et al., 2009; Sterman, 1994). While this applies to educational systems in general, it is particularly pertinent to student retention where the effect of implementing institutional action to enhance student retention typically has a time line of months, or even years. This holds true even when assuming neither distortion nor error in the feedback from the system (Rahmandad et al., 2009); after the time required for effects to be observed, it is possible – and likely – that many agents/components of the system, such as policy, students, and lecturers will have changed.

Another cause for concern that arises from investigations into the relationships between cause and effect in complex systems is that the current state of the information can be "fuzzy" or incomplete (Sterman, 1994). For example, in educational systems it is hard, if not impossible, to know the current state of all learners, be it disciplinary knowledge, health, social networks, or any other dimension. Some of the problems of getting to understand the current state of any system are innate properties of the system, or of the agents/components (for example, students' feelings and thoughts). Further, the decision to only examine a particular part of the system means that we do not get information about the other parts of the system not focused on.

Delayed feedback, and "fuzzy" or incomplete information about the system greatly impacts on the opportunity for learning something about complex systems in the real world. The limited and "fuzzy" information also creates an ambiguity in the relationship between cause and effect. This is because the effect of, for example implementation of educational methods, can either be a cause of the implementation, or the changes in exogenous or endogenous variables of the system (Sterman, 1994).

Stephens and Richey (2013) argue that to overcome the constraints of doing educational research in complex systems, research must be aimed at: (1) obtaining a better understanding of education as a complex system, and (2) exploring empirical methods for analysing complex systems. In addition, Rahmandad et al. (2009), Sterman (1994), and Davis and Sumara (2006) have pointed out that to learn about complex systems and their dynamics it is critical to initiate, or simulate, actions in such systems and collect the feedback from these systems.

At the time of writing this thesis, educational researchers are increasingly using a complexity thinking perspective to frame investigations of educational systems. For an example of this consider the use of complexity thinking in mathematics education reported on by Davis and Simmt (2006). Using complexity thinking as a framework for interpretation they model and discuss learning-for-teaching as several nested levels of a complex system of mathematics learning: subjective understanding, classroom collectively, curriculum structure, and mathematical objects. They describe how each level of complex organization exhibits similar structures and dynamics but operate within different time-scales and in different units of analysis. They argue that subjective understanding can have a faster rate of change than the mathematical objects (for example multiplication, subtraction, etc.) in society. Davis and Simmt (2006) present a case for treating the nested levels in their study as scale free, because at each level of analysis, or scale, similar properties existed. Other high profile educational researchers have used nestedness to describe knowledge as a complex system (for example, from mathematics see Mowat and Davis, 2010).

The first comprehensive use of complexity thinking as a framework in Physics Education Research was done by Moll (2009) for her doctoral thesis work. This seminal work examined the emotions, science identities, attitudes, motivations, and decision-making of physics students in physics competitions.

The initial inspiration for my thesis work came from Davis and Sumara's (2006) extrapolation of complexity theory for educational research, which they characterized as complexity thinking. This is why I used the term complexity thinking for the work reported on in **Paper I**. As my research developed I began drawing more inspiration from the mathematical side of complexity theory. Thus, I started using the term complexity theory and complexity science in my later papers as it was needed for my theoretical and methodological development.

4.8. Complexity theory and social systems

In this thesis and in **Paper IV** I draw on Sawyer's (2005) seminal work on the concept of *social systems* and its relation to individuals. This section gives a brief summary of the framing used by Sawyer – that Durkheim's (2004) concept of a *social system* (and its *emergence*) can be better understood through the application of complexity theory. To do this I use the foundational concepts of student retention research that Tinto and Spady used, namely that of the social system and academic system and integration into both of these systems (see Section 3.2.2). Both of these researchers started their theoretical development for modelling student retention by drawing on Durkheim's (2004) concept of social systems.

Both Durkheim (2004) and Sawyer (2005) discuss aspects of the structuralism paradigm in terms of how elements of society can be understood in relation to a larger societal structure (social system). Both discuss how these social systems are created, what relations the social systems can have with elements of society, and the interactions between the individuals making up society.

In terms of complexity theory, Sawyer's (2005) central argument combines *social emergence* and *downward causation* from the social system to the individual using the concept of emergence. Here, *social emergence* is how a *social system* originates from the interactions of individuals, and *downward causation* reflects how, in its creation, the *social system* becomes external to the individuals making up the social system and gets "played out" by the individuals of the system.

Sawyer (2005) drew mainly on two concepts from Durkheim (2004), *sui generis* and *social facts*. Sawyer argues that *sui generis* is a process that can be taken to be similar to the contemporary use of *emergence*. *Social facts*[50] (such as agency, intention, discourse patterns, collaborations, sub-cultures, norms, beliefs, and expectations) are argued by Durkheim to be *sui generis* properties of the social system. The *sui generis* property of a system depends on the size of the group, the number of individuals who have relationships, and the frequency that these individuals have relationships. Put another way, using concepts from complexity theory, a complex system shows emergence if the system has a sufficient number of agents/components and a sufficient number of interconnections between these agents/components.

By bringing together Sawyers (2005) work and the notion of social and academic systems (Spady, 1970; 1971, Tinto, 1975; 1982; 1987; 1997), I believe I make a convincing case for seeing the social and academic systems of the university as being dependent on students' interactions, and that the social and academic interactions within a course are dependent on the social and academic system of the university. I use this argument to form the theoretical foundation of **Paper IV**, **Paper V**, and for the analysis and discussion of social and academic interactions given in Sections 7.4.1 and 7.4.2.

[50] To enhance readability, *social facts* are called *rules of interaction* in **Paper IV** and in Sections 7.4.1 and 7.4.2.

4.9. Two possibilities for gaining insight into “what works” in complex systems

I propose that there are two ways to simulate the possible effects resulting from actions taken in educational (complex) systems. The first is to use computer simulation methods from systems research (see Sections 5.4 and 5.6, and **Paper III**). This requires a model that consists of the relevant critical aspects and their relations to each other in order to estimate by mathematical simulation how changes affect the system (or any target). The second approach is to use what Schön (1983) calls a *Virtual world* – a “world” that helps professionals within the system contemplate actions to create hypothetical outcomes (see Section 7.3.3, and **Paper II**).

4.9.1. Computer simulations

Computer simulations of a real world system are composed of the system and mathematical update rules of the system-parts (Cohen et al., 2011). The system is a representation of the components and the interrelationships that can be simulated or estimated. The components are the constituent parts that are sought to be changed or estimated. The update rules are the mathematical formulations through which the system-parts are updated.

Cohen et al. (2011) argues that computer simulations offer several distinct advantages in educational research – they enable researchers to discover what happens when variables are manipulated; it is less time consuming than exploring changes in a real world system; and, the cost of real-world testing is significantly higher (and it is sometimes impossible/impractical) than in a simulated system. The advantages of computer simulations are that they allow control of feedback and relax constraints that are present in the real world.

Computer simulations o educational research are not commonly used as their use evokes the following kinds of concerns:

- the underlying model or system that is to be simulated is not representative of the real world;
- simulations only take into account the initial parameters and do not commonly introduce new influences during the runtime; and,
- the model used is often too simplistic, and does not account for “complex human behaviours”.

However, Cohen et al. (2011) argue that these concerns do not necessarily speak against the use of simulations in educational research, but rather raise awareness of the need for refinement and development in the area.

4.9.2. Virtual world[51]

The second option to simulate what possible effects can result from an action in educational complex systems is to develop what I decided to call a representative model for a *Virtual world* (Schön, 1983). This model opens up the possibility of drawing on the professional expertise of active agents within the system, not in terms of creating hypothetical changes by using a computational method, but through the experiences that active agents in the system have acquired. Sterman (1994) proposed the use of Schön's *Virtual world* to address the problems associated with working with complex systems in real time. Using a *Virtual world* makes it possible for practitioners to "manage some of the constraints to hypothesis-testing experimentation that are inherent in the world" (Schön, 1983, p. 157). As an example of the use of a *Virtual world*, Schön (1983) describes an architect working with a drawn world (which could also be referred to as a representative model for a *Virtual world*):

> Some variables which are interlocking in the build world can be separated from one another in the world of the drawing … a building shape can be considered while deferring the question of the material from which the shape is to be made.… As an architect's practice enables him to move back and forth between drawing and building, he learns how his drawings will "build" and develops a capacity for accurate rehearsal. He learns, for example, how drawings fail to capture qualities of materials, surfaces, and technologies. …Drawing functions as a context for experiment precisely because it enables the designer to eliminate features of the real-world situations… but when he comes to interpret the results of his experiments, he must remember the factors that have been eliminated.
>
> (Schön, 1983, pp. 158-159).

Sterman (1994) characterized this as a recursive and adaptive process where the *Virtual world* provides immediate feedback on actions in the system in a way that is highly constrained or impossible in the real system. Thus, the use of a *Virtual world* also provides a platform for experimentation. Sterman argues that knowledge of the critical elements of the complex system, and the relationship between them, are essential to know – what might be manipulated in the complex system and what the possible outcomes might be.

In **Paper II**, I propose the development of a visualization of a system that can be used as a representative model for such a *Virtual world* in order to enable a new dimension of exploration of student retention. My position is that this development will provide new insights into possible remedial actions and what their impacts might be. The visualization developed in **Paper**

[51] I have defined the construct *Virtual world* as Schön (1983) did. I have not used this constructs as commonly used – i.e., to mean virtual worlds such as Second life and Minecraft.

II shows the structure of the interrelations between the components of such a system (see Section 7.3.2, Figure 26) and how, through this methodology it may become realistically possible for particular sets of knowledgeable agents to simulate particular sets of actions. An important part of the conclusion that I present in **Paper II** is that through the use of the *Virtual world* many of the concerns about the use and the interpretation of the results of using computer simulations of complex systems can be dealt with. However, at the same time I see the possibility for a new concern to arise: my exploratory use of a representative model for a *Virtual world* still does not fully address all the "unease" lying behind what practitioners see as cause and effect in the system (misinterpreting causal links, or extinguish negative group processes, implementation failure. For further in-depth discussions, see Sterman, 1994).

4.9.3. Discussion

The use of computer simulations and a *Virtual world* for gaining insights into "what works" in complex systems both have their drawbacks and thus can only serve as part of the solution. I argue that neither can be done without referencing a real-world environment, either by drawing on experience of active agents in the system, or drawing on previous peer-reviewed research. This "failure" to reference a real-world environment can be exemplified as creating a model from gathered data sets that show that student-grade has a direct one-to-one relationship with their course attendance. I further argue that for this to be established as a reliable and valid claim of causality between their course attendance and grades, there is a need to bring this hypothesis back into the real world and through changes in, for example, a course, to test if an increase of students' course attendance *does* increase students grade achievement or not.

Both computer simulations and *Virtual world* can serve towards creating more effective functional action strategies. Adopting such an approach can be seen as being similar to how aircraft in their primary design phase get designed and simulated *before* building and testing in a wind-tunnel, and how chemists first simulate how certain compounds interact *before* trying them out in a "real life" laboratory.

5. Methodology: Part 2 – The Methods Components

5.1. Introduction

The methodology that I developed for my thesis research consists of the theory and methods that I found necessary to provide good answers to my two research questions:

1. *In order to explore viable options for real world practice to enhance student retention, how can informative modelling of action within the complex system be established?*
2. *Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?*

Below, Table 4 gives a summary of the role that **Papers' I-V** research questions and aims play in constituting the answering of these two research questions that I give in this thesis. From Table 4, it is seen that my *Research Question 1* is answered using the results obtained for the publication of **Papers I**, **II**, and **III**, and my *Research Question 2* is answered using the results obtained for the publication of **Papers IV** and **V**. This constitution, summarized in Table 4, gives the structural links between all the methodological components presented in this chapter. With these structural links in mind the aim of this chapter is to:

- introduce the components of network theory that I feel are important for generating a conceptual understanding of what underpins these methods;
- introduce the methods I considered in order to make the needed estimations of network structures, and then describe the method that I chose to use – Multilayer Minimum Spanning Tree Analysis;
- introduce the method I used to explore nestedness (see Section 4.5) of complex systems;
- introduce an overview of the available methods for estimation of outcomes of changes in networked systems; and,
- introduce the method I used to show how networked structures of students' interactions are related to grade achievement.

Table 4. *How the research questions for **Papers I-V** are related to my thesis research questions and the associated structural outline of my methodological components in relation to these research questions and their research contexts.*

Research Questions	Research Questions and Aims Used to Publish Papers I-V	Methodology: Theory	Methodology: Methods	Data collection context	Paper(s) I draw on:
In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?	From **Paper I**, Research Aim: *Illustratively explore the potential advantages of applying complexity thinking to the problematic issue of student retention.* From **Paper II**: Research Question: (1) *How can the complex system of an educational situation be represented by framing it in terms of its networked structure and nestedness?* Research Question (2) *How can the representation created in this way be used in order to inform decisions regarding enhancing student retention?* From **Paper III**, Research Question: *How can targets for changes in institutional practice be effectively identified using an empirically-informed Sandbox University?*	Student retention research (pp. 39-57) Complexity theory (pp. 68-71) Network theory (pp. 82-92)	MMST analysis (pp. 98-105) Topological diversity (p. 90) Cluster diversity (pp. 90-91) Gibbs sampling (pp. 105-111) *Virtual world* and computer simulations (pp. 77-78)	*Sweden* Described in Section 6.2, and **Paper I.** (N = 51) *The Netherlands* Described in Section 6.2.2, **Paper II**, and **Paper III** (N = 573)	**Paper I** Method: p. 73. Results: pp. 75-81. **Paper II** - Method: pp. 4-5, and 15-17. Results: pp. 6-10 **Paper III** - Method: pp. 2-4, Results: pp. 4-7.
Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?	From **Paper IV**, Research Aims: (1) *how to situate central constructs from student persistence research within a framework of complexity science*, and (2) *illustrate the viability of using methods available from complexity* From **Paper V**, Research Question: *What are the indicators for grade achievement as a function of social and academic network measurements?*	Student retention research (pp. 39-57) Complexity theory (pp. 68-71) Network theory (pp. 82-92)	Degree distribution analysis (pp. 85-87) Network measurements: (pp. 87-88)	*Sweden* Described in Section 6.2.3, **Paper IV**, and **Paper V**. ($N_1 = 68$, $N_2 = 66$)	**Paper IV** - Method: pp. 4-6, Results: pp. 6-9. **Paper V** - Method: pp. 5-6, Results: p. 6.

Note: Except for the page numbers in the last column, which refer to pages in the relevant papers, page numbers refer to this thesis.

5.2. The methods I considered

The methods I present in this section are drawn from across those research disciplines that extensively deal with issues of complexity using complexity theory and network theory.

In order to answer my Research Question 1, I needed ways to create a model of, and simulate action in, a complex system. The methods discussed in this section thus explore:

- possible ways to estimate network structure (to create a model of a complex system from a data set – see Section 5.4, **Paper I**, and **Paper II**);
- how the concept of nestedness can be analysed and visualized (how to investigate key structures and dynamics of complex systems that may influence the outcome of suggested actions – see Section 5.5, **Paper I**, and **Paper II**); and,
- how outcomes of changes in the estimated complex system can be simulated – see Section 5.6 and **Paper III**.

My quest to make quality estimates of network structure without having concrete information about how critical factors of student retention are interconnected led me into an exploration of methods that have been used to estimate the controlling structures of DNA in biological informatics (Section 5.4). I ended up drawing on this research because my explorations revealed that the field of biological informatics is at the forefront of methodological development in generating estimations of network structure.

In order to answer my Research Question 2, I needed to find optimal ways to: analyse the structure of students' interaction networks; and, analyse students' structural positions in these networks. The exploration of the structure of students' interaction networks involved looking at the degree distribution of the network (Section 7.4.2 and **Paper IV**). I chose this method because I found that it provided an exceptionally fruitful way to explore how a network gets formed over time. To investigate how student in-class interaction network could meaningfully be linked to student outcomes, I used social network measurements (Section 5.3.2) together with ordinal regression (Section 5.7). For both parts, also see **Paper V**.

My discussion of these explorations starts with my discussion on network theory.

5.3. Network Theory[52]

5.3.1. Introduction[53]

The key to successful research involving complex systems lies in the tools developed in network theory. This is because the systems in question are made up of many different interacting components that are essentially made up of networks of interactions.

The fundamental conceptualizations in network theory are the structural relations between components in a network (Knocke & Yang, 2008). Here, the essential components of a network are the nodes (vertices) and the links (connections, edges) between the nodes. The meanings of these terms are illustrated in the next section.

5.3.2. Network concepts and measurements

Introduction

The discussion in this chapter soon becomes mathematically complicated. An integral part of understanding this is a conceptual appreciation of the meanings of the constructs of nodes and edges. Thus, I start by providing a simple well-illustrated introduction to nodes and edges, and use that to introduce the relevant mathematics.

The *nodes* represent the *components* that make up a network, and the *edges* represent the *relationships* – connections – between the nodes (see Figure 11).

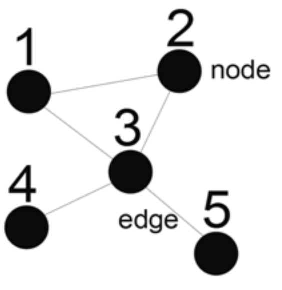

Figure 11. A simple (un-weighted and undirected) network illustrating what is meant by nodes and edges.

There are two common attributes of networks: weight, and direction. These attributes are illustrated in Figure 12.

[52] To add coherence to the thesis, this section resembles the argument in **Paper IV**.
[53] The mathematical descriptions in Section 5.3 are derived from Newman (2003).

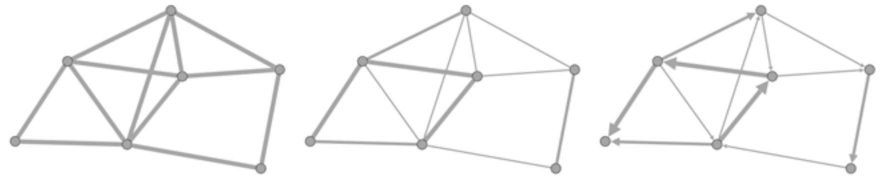

Figure 12. From left to right, illustrations of: an unweighted network; a weighted network; and, a weighted and directed network.

Figure 12 (left image) shows an unweighted network with no directionality; all edges have the same importance and the edges have no direction (inward or outward). Figure 12 (centre image) shows a weighted network that shows the relative importance of the edges; the wider edges are stronger than the thinner edges. Figure 12 (right image) shows a weighted network where the links have directionality. This image does not only show the relative importance of the edges, it also shows the directions of the links.

A network such as the one given in Figure 11 is typically described mathematically using what is known as an *adjacency matrix*. Such a matrix, A has elements A_{ij} such that,

$$A_{ij} = \begin{cases} w, & \text{if there is an edge between nodes } i \text{ and } j \\ 0, & \text{otherwise} \end{cases}$$

where w is 1 if the network is un-weighted. When given another value it indicates the strength of the connection when the network is weighted. The elements $i = j$ are zero when the network does not have any self-edges (i.e., a node connected to itself), but they can take any value if the network allows for weighted self-edges.

Figure 11 can be used to generate an illustrative example of an adjacency matrix, viz:

$$A = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

To provide an example of how such an adjacency matrix is created from Figure 11, examine row 1 (the top row) of $A_{1x5} = (0,1,1,0,0)$. The first element is 0, this represents a node that has no edges to itself (self-edges); the second element has a value of 1, this represents the edge between node 1 and node 2; the third element has a value of 1, this represents the edge between node 1 and node 3; the fourth and fifth elements have the value 0, this represents there being no edges between node 1 and the nodes 4 and 5. Complementary properties to also notice in the adjacency matrix are: firstly, because the network contain no self-edges, all the elements in the diagonal (left-top to right-bottom) of the matrix *A* are zero; and, secondly, because the example matrix represents an un-directed network, it is symmetrical.

Degree

When two nodes are directly connected by an edge, these two nodes are said to be adjacent. Then, a node's *total degree* is the number of adjacent nodes it has. The total degree (k_i) of node *i* in the example network given in Figure 11 is made up of the sum of each row. The total degree then gets calculated using the adjacency matrix A_{ij} representation through the application of Equation 1.

$$k_i = \sum_{j=1}^{n} A_{ij} \qquad \text{(Equation 1)}$$

For a directed network, there is the possibility of differentiating between inbound edges and outbound edges, where the *sum of each row* is the *in-degree* and the *sum of each column* is the *out-degree*. This can be calculated through the adjacency matrix A_{ij} by using Equations 2 and 3.

$$k_i^{in} = \sum_{j=1}^{n} A_{ij} \qquad \text{(Equation 2)}$$

$$k_j^{out} = \sum_{i=1}^{n} A_{ij} \qquad \text{(Equation 3)}$$

Degree distribution

The degree distribution (the distribution of k_{in}) is a fundamental network property, and the study of different distributions becomes essential for the exploration of possible processes that drive the construction of the network (Newman, 2003). The degree distribution (Equation 4) can be thought of as the *probability for a randomly chosen node to have (in or out) degree k*, i.e., as a kind of probability density function.

$$p_k = \frac{\text{number of nodes with degree } k}{\text{total number of nodes}}, \; k = 0,\, 1,\, 2,\, \ldots\, ,\infty \qquad \text{(Equation 4)}$$

The degree distribution of a network is often indicative of the processes that formed it. The commonly found power-law distribution in networks is considered to be most likely dependent on *preferential attachment*. This conceptually translates into nodes with a higher degree attracting more nodes to create edges to that node (Newman, 2003). At the same time there are other distributions that suggest other driving processes. Two examples of these processes are: (1) the removal/joining of nodes that have been modelled by a Weibull model (a continuous probability distribution – see McPherson et al., 1992); and, (2) the Price's creation model (Newman, 2003) can be seen to exhibit power-law characteristics through the beta and gamma functions. However, while the degree distribution may be suggestive of a certain network evolution, it is not sufficient to pinpoint the exact process through which it was created.

When it comes to estimating the fit of a degree distribution of a particular network to known degree distributions, it is possible to do this using what is known as the AIC_c criterion (Hurvich & Tsai, 1988). This is given by Equation 5,

$$AIC_c = 2k - 2\ln(L) + \frac{2k(k+1)}{n-k-1} \qquad \text{(Equation 5)}$$

where k is the number of parameters in the theoretical distribution; n is the sample size (number of observed nodes); and, L is the maximized value of the estimated likelihood function – i.e., the probability of observing the observed degrees in the network as a random sample from the theoretical distribution being tested.

The AIC_c is a sample size corrected version of the Akaike Information Criterion (AIC [Akaike, 1970]). I used this estimation approach for the study reported on in **Paper IV** because it was possible to make the case that the networks in the study were somewhat small, which was why I chose to use the AIC_c as it takes the sample size into account. In **Paper IV**, the degree distribution of students' in-course interaction networks were studied. In doing so, eleven common distributions (Power-law, Normal, Log-normal, Exponent, Poisson, Cauchy, Gamma, Logistic, Binomial, Geometric, and Weibull) were evaluated using the AIC_c criterion. The Gamma distribution and the Weibull distribution were found to be optimal. This allowed me to evaluate the parameters for these two distributions using the generalized gamma function (Stacy & Mihram, 1965) given in Equation 6.

$$\mathrm{f}(\mathrm{x};\mathrm{a},\mathrm{v},\mathrm{p}) = \frac{|p|\, x^{pv-1} e^{-\left(\frac{x}{a}\right)^{p}}}{a^{pv}\Gamma(\mathrm{v})} \qquad \text{(Equation 6)}$$

These three distributions (Gamma, Weibull, and generalized Gamma) can be examined together with the degree distributions of the networks to show

how similar these three distributions can be to the empirical distribution of the networks.

Both the Gamma and the Weibull distributions are covered by the generalized gamma function's special cases [Gamma distribution: f(x; a, v, 1), Weibull distribution: f(x; a, 1, p)], which allows the evaluation of the parameter *a* to be significantly different[54] across these types of networks. In **Paper IV**, the estimations of attribute "*a"* were undertaken using non-parametric bootstrap methods based on maximum likelihood estimations. This was implemented by the package *fitdistrplus* (Delignette-Muller et al., 2013) in the statistical environment **R** (r Core Team, 2013).

Clustering coefficient

Clustering coefficient (or transitivity) is the likelihood that a node's two adjacent nodes are also adjacent to each other. This is calculated as per Equation 7,

$$C_c = \frac{3(\text{number of triangles in the network})}{(\text{number of connected triplets of nodes in the network})} \qquad \text{(Equation 7)}$$

where $0 \le C_c \le 1$, and where 0 corresponds to no edges in the network, and 1 indicates that all nodes are adjacent to each other.

Centralities

In the study of networks one is often interested in the influence that a node can have on the network as a whole. Therefore, it is important to find central nodes of a network, meaning those nodes that could have a large effect in a network. A large number of metrics and methods for finding these central nodes have been established, each of which give slightly different results. Each of the metrics has slightly different interpretations and heuristics. The basic construct that many of the measurements are based on is the idea of a *path*.

Path

A "path way" through a sequence of nodes that begins with the starting node, follows adjacent nodes through the network, and ends at the end node is denoted as a *path* between nodes in network theory. In the illustrative network given in Figure 11, the longest path is 2 (for example, between nodes 5 and 1 there are two edges that a path goes through). When every node in the network is reachable (i.e., there exists a path between every node) the network is said to be connected. If there are many paths between

[54] In other words, this is interpreted as implying that the rules around which the network is built are unlikely to be due to chance alone.

two given nodes, the distance, and the number of edges in the different paths can be used to find the shortest path (geodisc path) between nodes (Freeman, 1978) – paths that minimise either the number of edges to traverse or the sum of edge weights.

Betweenness Centrality

Betweenness centrality is a measure of how frequently one particular node is on the shortest path amongst the set of all shortest paths between all pairs of nodes. Nodes that are more frequently a part of the shortest path between nodes are often interpreted as having a high degree of "control of communication" (Freeman, 1978, p. 224) in the network. This is defined and calculated as follows:

$$g(i) = \sum_{j \neq i} \frac{\sigma_{ij}(i)}{\sigma_{ij}} \qquad \text{(Equation 8)}$$

where σ_{ij} is the number of shortest paths between nodes *i* and *j,* and $\sigma_{ij}(i)$ is the number of those paths that pass through *i*.

Closeness Centrality

Closeness centrality is an ordinal measure of how "close" every other node is, and it is calculated through the inverse of the sum of shortest paths between nodes. Information can be spread more effectively from nodes with high closeness centrality to the whole network (Freeman, 1978). This is defined and calculated by Equation 9,

$$Closeness(i) = \frac{1}{\sum_{j \neq i} d_{ij}} \qquad \text{(Equation 9)}$$

where d_{ij} is the shortest path between nodes *i* and *j*.

Eccentricity

Eccentricity is a measure that is defined as the longest path to a particular node. Thus, a node with the *lowest* eccentricity of a network is the *most central node*, while a node with *highest* eccentricity is the *most "separated"*, or "on the edge" of a network.

Eigenvalue (Kats) Centrality

The eigenvalue centrality measures a node being central *while also being connected to other central nodes*. Thus, this metric is designed to find nodes with what could be called “important” links. It is defined and calculated by Equation 10,

$$e(i) = \frac{1}{\lambda} \sum_{k} A_{ik} e_k \qquad \text{(Equation 10)}$$

where λ is a non-zero constant. This can be re-written in matrix terms as Equation 11,

$$\lambda e = eA \qquad \text{(Equation 11)}$$

where the eigenvalue centrality e is the eigenvector of the adjacency matrix (A) with the eigenvalue of λ. Here I need to point out that e in both equation 10 and 11 is the same eigenvalue centrality. I do this because it is important to note that the centrality of node i is the ith element of e, which has the condition that all elements of e must be positive for a unique solution to exist.

PageRank

PageRank was developed by Google (the name refers to the main inventor: Larry Page) as a way to rank the importance of search engine results. The approach applied by PageRank takes into account the incredibly complicated and massive structure of the Internet. The rationale behind this ranking is similar to that of eigenvalue centrality. However, to solve the vector for the eigenvalue centrality for the entire Internet would be impractical (if not impossible). As a feasible alternative, the PageRank algorithm iterates through a given network updating the centrality as it proceeds using Equation 12,

$$R(i) = k \sum_{v \in C_i} \frac{R(v)}{L_v} \qquad \text{(Equation 12)}$$

where C_i is the set of nodes that node i is linked to; L_v is the number of other nodes that are linked to i; and k is a constant. The PageRank algorithm is an iterative metric, which means that all nodes in the network get an initial PageRank, and are then continuously updated until the calculation converges. Interestingly, if a new node appears in the network the local updating for that node’s PageRank also gets updated fairly quickly depending on the connections it has to other nodes.

Diversity

I use the measurement of node diversity in this thesis in two ways. The first is with respect to the adjacent nodes, and the second is with respect to the different clusters of nodes that a node is adjacent to. The first is measured through *topological diversity* and the second through *cluster diversity*.

For the work I present in this thesis, I decided to re-name these two constructs to "distance them" from their original use as measurements of diversity in social networks[55]. Thus, the measurements I made drawing on these constructs are *not* about how *socially diverse* the students in the study are, but rather about how diverse the links in a network system are. Particularly, in **Paper II**, I used these constructs tentatively to indicate how a node is diverse in its connections to other nodes and in its connections to other clusters of nodes.

Topological Diversity[56]

Computationally, topological diversity describes how much information is required to describe a particular node in relation to how many edges connect that element to other nodes and the distribution of those edge weights. Analytically, as shown in Equation 13, the topological diversity (D_{top}) is related to the Shannon Entropy ($H(\mathrm{X}) = -\sum_i P(x_i)\log_2 P(x_i)$ [Shannon, 1948]) of node *a*, and is normalized by the number of *a*'s links (*k*).

$$D_{top} = \frac{-\sum_1^k \mathrm{P}_{ak} \log_2(\mathrm{P}_{ak})}{\log(k)} \qquad \text{(Equation 13)}$$

Equation 13 calculates the topological diversity, where P_{ak} is the edge weight that links nodes *a* and *k* proportionally to the total edge weight of all the edges originating from node *a*. As an example, if a node has two links with equal edge weights to two other nodes, this node will have a lower topological diversity than if it would have had with two different edge weights. A node is said to have a high topological diversity when it is connected differently (with different edge weights) with many other nodes.

Cluster Diversity[57]

Cluster Diversity helps characterize each node's possible maximum spread *in the system*. In the equation that is used to calculate cluster diversity (Equation 14 – D_{clu}), P_{ac} is the edge weight between a given node *a* and cluster *c*:

[55] As a proxy for their *social diversity*, Eagle et al. (2010) developed two measurements to analyse how diverse people are when making phone calls. Here, the authors focussed on how diverse people are in their contacts, both in respect to who they call, and also how diverse their phone contacts are with respect to the receiver's area code.

[56] To add coherence to the thesis, this section is based on **Paper II**'s definition of topological diversity.

[57] To add coherence to the thesis, this section is based on the definition of cluster diversity given in **Paper II**.

$$D_{clu}(a) = \frac{-\sum_{1}^{k} \mathrm{P}_{ac} \log_2(\mathrm{P}_{ac})}{\log_2(k_c)} \quad \text{(Equation 14)}$$

In Equation 14, the sum of the Shannon entropy (Shannon, 1948) for the distribution over all elements and all clusters – $\mathrm{P}_{ac}\log_2(\mathrm{P}_{ac})$ – is divided by the logarithm of the number of clusters identified (k_c). I point this out because in **Paper IV** the infomap algorithm for community detection (Rosvall & Bergström, 2008) was used to calculate k_c.

5.3.3. Network theory and social network theory in educational research

The use of network theory (the mathematical foundations used to calculate and define pairwise relationships between objects) and social network theory (applied network theory for the study of social structures consisting of social actors) in educational research over the last decade has started to intensify and expand. This has probably mainly been due to the availability of extensive online courses, course web sites, and social networking. In particular, students' use of online social networks, such as Facebook, has helped drive such educational research (for example, see Eodice & Gaffin, 2008; Grabmeier, 2009).

In educational research, network theory has also started to be used to examine traditional learning situations. Such studies have used network theory to, for example: characterize students' interactions in small group discussions (for instance, see Bruun, 2011); the relation of students' formal and informal networks to academic achievement (for instance, see Cho et al., 2007); and, students' sense of community (for instance, see Dawson, 2008).

Work inspired by complexity theory using social network theory has proposed that social network theory can provide insight into critical epistemological implications for curriculum design (Gilstrap, 2011). However, despite this growth in usage, a comprehensive framework of tools that handle the educational complexity of networks still needs to be developed (Gilstrap, 2011). Gilstrap (2011) suggests using Davis and Sumara's (2006) complexity thinking framework, which, as discussed in Section 4.7, was derived from applications of complexity theory in other disciplines.

5.3.4. Network theory in student retention research

Social networks are present in the foundational work done by Tinto and Spady, albeit in the background, in the development of their theoretical models of student retention. This is particularly apparent in the work of Tinto (1975; 1987; 1997) and the work he drew on for his early modelling of student retention (for example, see Durkheim, 2004; Spady, 1970; 1971). In much of this work, the importance of social networks is discussed in propositional-reductionist ways. What underpins this, is a search for ways to capture structures and dynamics of social networks within metaphors, and about the structuring of these into measurable variables.

In the introductory chapter of my thesis, I point out that it has been widely recognized that research into student retention needs to employ "network analysis and/or social mapping of student interaction... [to]...better illuminate the complexity of student involvement" (Tinto, 1997, p. 619). In other words, it has essentially been appreciated for some time that the structures of social networks significantly affect different aspects of student experiences of higher education. Examples of this include student satisfaction, academic performance, institutional commitment, and study intentions. Such aspects, in turn, are found to be strongly related to student retention (for example, see Rizzuto et al., 2009; Sacerdote, 2001; Thomas, 2000). However, the use of network theory in the area of student retention research is still in its infancy and much more growth is needed if a better understanding of the many important features of student interactions is to be obtained.

5.4. Potential methods for the estimation of network structures

In order to answer Research Question 1, I needed to find a suitable method to estimate the structure of a complex system.

Disciplines such as biology and sociology have, for a long time, viewed networks as an integral part of their core conceptual foundations. However, this is not the situation in the educational domain, here it is still very much in early stages of growth and development. Thus, it is challenging on several fronts to use network representations for educational research. This means that I had to draw on methods developed by other disciplines to find effective and appropriate tools to estimate how networks in educational systems could meaningfully be estimated.

I now describe my exploration of the methods that I could potentially have used to meaningfully estimate network structure from an educational data set in order to make it possible for me to create a model of a complex system. Since my intention is to focus on illustrating only the fundamental differences between the methods, the descriptions that I give only deal with their respective starting points. On the other hand, I provide a much more in-depth description of the method that I decided to use (see Section 5.4.7).

5.4.1. Correlation networks

The creation of correlation networks typically uses Pearson correlations. This is the most common method used in bioinformatics (Langfelder & Horvath, 2008).

The Pearson correlation (r) is calculated using:

$$r_{ab} = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2}\sqrt{\sum_{i=1}^{n}(b_i - \bar{b})^2}} \qquad \text{(Equation 15)}$$

where $\bar{a}$ and $\bar{b}$ are the means of variables a and b respectively, and i is the index.

The Pearson correlation forms a correlation matrix that shows how all variables correlate. A cut-off of significant correlations is identified in order to create a weighted adjacency matrix (by finding an adequate p-value or by another selection criterion). The resulting adjacency matrix is analysed as a network.

5.4.2. Partial correlation networks

The partial correlation network approach is commonly used in the study of regulatory gene networks (see, for example, Peng et al., 2009). This approach goes one step further than traditional correlation network analysis. Correlations that seem strong can be affected by confounding variables, and thus cannot be taken to represent a *causal* link. A classic example of a correlation that at face value would reflect an erroneous causality is that of fire trucks and fires. Fire trucks and fires are frequently observed at the same time and place. It would be incorrect to assume that the strong correlation between the fire truck and the fire points to the cause of the fire. Thus, since the cause of the fire is not captured by this correlation – a classical correlation – an alternative correlation is needed. This is called a partial correlation, which is used to find unique relationships between two factors while eliminating the influence of a third confounding factor – i.e., towards finding the essential causal link between two factors.

Instead of using the correlation matrix and finding a cut-off of significant values, the partial correlation network approach takes its starting point as the partial correlation matrix. This is calculated using Equation 16,

$$PC(\mathrm{a},\mathrm{b}\,|\,\mathrm{c}) = \frac{r_{ab} - r_{ac}r_{bc}}{\sqrt{(1-r_{ac}^2)(1-r_{bc}^2)}} \qquad \text{(Equation 16)}$$

where r_{ab} is the Pearson correlation between variable *a* and *b*, and r_{ac} and r_{bc} are the correlations to the potentially confounding variable, c.

As with correlation network analysis, a suitable cut-off gets sought in order to find a networked representation of the studied system through various statistical techniques (Peng et al., 2009).

5.4.3. Multidimensional scaling

In **Paper I**, I show that using Multidimensional Scaling (MDS) (Schiffman et al., 1981), or more precisely the similarity matrix that MDS produces, is a very viable starting point for estimating the networked structure of a system. **Paper I** discusses using MDS as a possible method for estimating network structure in a physics education context.

To implement MDS the data set is re-calculated as a distance matrix (as per Equation 17), where variables that have similar values have a small distance.

$$D(a,b) = \sqrt{(a-b)^T (\mathbf{a}-\mathbf{b})} \qquad \text{(Equation 17)}$$

where *a* and *b* are the vectors of variables **a** and **b**. *T* is the transverse matrix operator.

Using the distance matrix of the original data set (called D), the method goes through the following steps in order to create a *similarity matrix*:

1) Create a two-dimensional matrix with arbitrary points.
2) Using step 1, calculate a distance matrix (as per Equation 17, call this $\hat{D}$).
3) Evaluate the Euclidian distances between D and $\hat{D}$.
4) Adjust the positions of the arbitrary created matrix ($\hat{D}$) so that the Euclidian distances between all points in $\hat{D}$ are more similar to that of the original data set (D).
5) Repeat steps 3 to 4 to maximize the fit between D and $\hat{D}$.

After the MDS method has produced a matrix solution, the similarity matrix ($\hat{D}$) can be used as a starting point for estimating the networked structure of an analysed system in a similar fashion to that of the correlation matrix; a cut-off is introduced for the distance values in order to create a weighted adjacency matrix. The cut-off can be chosen in regards to a specific criterion, such as finding the lowest cut-off where all nodes are *connected* in a network (as I did in **Paper I)**. The resulting adjacency matrix is then analysed as a network.

5.4.4. Multilayer Minimum Spanning Tree analysis[58]

Multilayer Minimum Spanning Tree (MMST) analysis follows the spirit of estimating networked structure from a correlation matrix (see the correlation network analysis introduced in Section 5.4.1), but there are important differences. In contrast to a correlation network, where everything tends to get connected to everything else, doing a MMST analysis results in the identification of *edges.* Importantly, this identification is not dependent on the choice of a cut-off based upon the strength of correlations; they are determined through the *reproducibility* of the edges. Thus, MMST aims to identify the strongest edges – the edges that are valid in most subsets of the data set – and weak edges.

Why is this significant? Consider an example where a correlation is only valid and present in a few subsets of a data set. A correlation analysis could easily "miss" this when analysing a full data set. Therefore, MMST estimation favours edges that are both *always,* and *sporadically,* present in the system.

The MMST analysis is a well-established and respected method for doing quality network estimation (Grönlund et al., 2009). It is also relatively straightforward to implement. The original implementation of the algorithm bootstraps (Davidson, 1997) the data set before a Minimum Spanning Tree (MST) gets created for each subset of the system. These MSTs corresponds to the strongest significant Pearson correlations (as per Equation 15), and the MMST is created by the union of all MSTs created (see Figure 13).

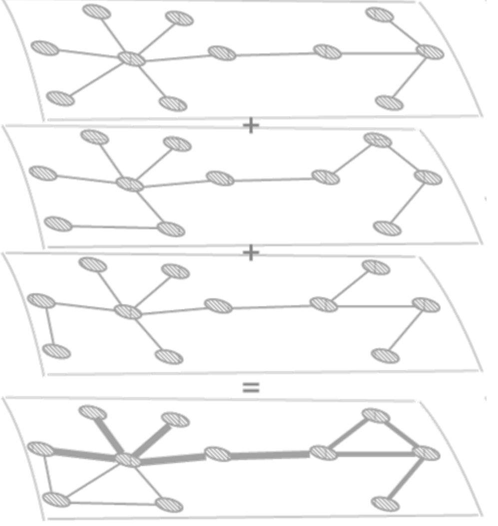

Figure 13. Visualization of the heuristic of the MMST analysis from Grönlund et al. (2009, p. 317.)

[58] To add coherence to the thesis, the description in this section is largely a repeat of the method sections given in **Paper II** and **Paper III.**

In Section 5.4.7, I discuss my implementation and development of MMST analysis for use in educational research. I did this by using the statistical environment **R** (r Core Team, 2013). Both the original and my implementation of the MMST analysis generate a weighted adjacency matrix that can be used for network analysis.

5.4.5. Bayesian networks

The Bayesian approach represents an alternative starting point for doing network estimations in that it does not rely on a correlation matrix in order to estimate a network structure. This approach uses the Bayesian concept, which aims at portraying the dependence structures of interaction components. Constructing such a Bayesian network is mathematically formulated using calculations of probabilities and conditional interdependencies between the interacting components to construct a network. As I did not use this approach in my work, I provide a limited introduction here, but do so by drawing on the expansive introduction to Bayesian networks given by Friedman et al. (2000). Figure 14 illustrates the core components of a Bayesian network that I needed for this introduction. It provides a visualization of the first step towards building a Bayesian network from a data set, in my case, a network and how this network is interpreted.

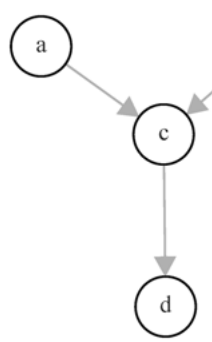

Figure 14. A visualization of a Bayesian network. This network implies the following conditional interdependencies: I(c | a, b) and I(d | c). The network also illustrate how node *a* is independent of node *b*. The joint probability distribution of this network is: P(a, b, c, d) = P(a)P(b)P(c | a ,b)P(d | c).

Figure 14 shows how a Bayesian network can be represented as a joint probability distribution. However, there are multiple ways of constructing networks to portray a joint probability distribution. As such, there are multiple *equivalence classes* of networks from which *a single one needs to be chosen* when estimating the networked structure of a data set. The criterion for this choice is based on what is known as “a Bayesian score”, which reflects how well the network “fits” the data set (see Cooper & Herskovits, 1992, for a more complete description).

5.4.6. Comparison of potential methods

In order to make a comparison between the potential methods for estimation of network structures that I identified, I simulated a sample data set. My first step in creating such a correlated data set was to create a random network (Erdos & Renyi, 1959) that was used as a basis for simulating a sample data set.

To test the methods with “reasonable depth”, I created a sample network size that ranged from 40 to 150, with incremental steps of 10. I chose this size because it would generate data sets that could be considered comparable to educational data sets. Working towards this goal, I also made each variable (node) have 200 to 1200 simulated measurements with incremental steps of 100 (this quasi-corresponds to sample size). To accommodate for different strengths of edges between different nodes, three types of edge weights were randomly assigned: Strong (where the signal to noise ratio was 100 to 1), medium (where the signal to noise ratio was 50 to 1), and weak (where signal to noise ratio was 10 to 1).

In the simulations that I ran, the values of nodes were assigned randomly between 1 and 5. From the created network, the simulated measurements were drawn from a random distribution with a fixed standard deviation of 0.2, and a weighted mean of the adjacent nodes (mean of the adjacent node values with respect to the edge weights). This was much like a single iteration of Gibbs sampling (see Section 5.6.2).

To illustratively compare the possible methods, I used the measurement of *Accuracy*, which is calculated as follows:

$$\text{Accuracy} = \frac{\sum \text{True positive} + \sum \text{True negative}}{\sum \text{All outcomes and predicted outcomes}}$$

Having given an overview of the estimation methods that I explored, I present my findings in Table 5. This table shows the mean accuracy and standard deviation of all different network sizes and across all simulated measurements. Table 5 shows that the standard deviation in all simulated measurements is very small and the mean accuracy across all sizes and all number of samples is therefore similar, and are presented as a final result for my simulated data sets.

Table 5. *Comparison of the Accuracy of network estimation methods.*

Estimation Method	Mean Accuracy	Standard deviation
MMST	83% (70% / 59%)	2% (1% / 1%)
Bayesian	80% (69% / 58%)	3% (2% / 1%)
Correlation	80% (69% / 58%)	1% (1% / 1%)
Multidimensional Scaling	78% (68% / 58%)	1% (1% / 2%)
Partial Correlations	27% (36% / 44%)	2% (12%/ 5%)

Note: The three accuracy measurements for each method correspond to the calculated accuracy when ídentifying different strengths of links in comparison to the original created network. [strong (strong + medium) / all types)]

The different methods that I considered all produce similar accuracy ratings and thus I was able to consider them all suitable for the task of identifying relevant network structures in correlated data sets (this confirms the work of Allen et al., 2012). Thus, I concluded that the choice of method is less dependent on the accuracy of the method and more dependent on the difficulty of conceptualization and implementation with respect to how the methodology works in the studied system.

5.4.7. The method I chose for network estimation – Multilayer Minimum Spanning Tree analysis

I chose to use the Multilayer Minimum Spanning Tree (MMST) analysis for network estimation as it turned out to be both very robust and relatively simple for me to implement. Thus, I also was able to better accommodate its analytical assumptions.

For me to effectively implement the MMST analysis method for my research purposes I needed to make some changes to the original MMST approach (Grönlund et al., 2009). I made these changes to both accommodate the data set that was to be analysed and the time constraints that arose from the needed run-time for the analysis.

General workflow of the MMST analysis

Each step of my MMST analysis is summarized in Table 6. This table (next page) also shows the difference between the original MMST analysis as implemented by Grönlund et al. (2009) and my implementation.

Table 6. *Comparison between the original and my implementation of the MMST analysis.*

Original MMST analysis	My implementation of the MMST analysis
1. Draw a subset of the data set **Jack-knife bootstrap**	1. Draw a subset of the data set **Classic bootstrap** (Section 5.4.7)
2. Calculate a correlation matrix **Pearson correlation**	2. Calculate a correlation matrix **Spearman correlation**
3. Transform to a distance matrix	3. Transform to a distance matrix
4. Find a MST for the distance matrix **Kruskal's algorithm** **Keep only positive links**	4. Find a MST for the distance matrix **Prims Algorithm** **Keep both positive and negative links** **Randomize top two strongest correlations**
5. Add the MST to the MMST	5. Add the MST to the MMST
	6. Calculate relative difference between edges in two MMSTs constituting of the same number of MSTs a. If relative difference is >5%, then start from 1. b. If relative difference is <5%, then the MMST creation is finished.
Significance test after all MSTs have been added to the MMST	**Significance test** for each link in Step 4, as well as checking **reproducibility** in Step 6 to ensure that the method is creating similar MMSTs from the data set.

Each step and details of the implemented changes are discussed in Sections 5.4.7. Step 1 is discussed on p. 99, Step 2 is discussed on p. 100, and Step 4 is discussed on p. 101 (Step 3 and Step 5 are not further discussed because they are identical to the original MMST analysis).

Changes made to step 1 in the MMST analysis: Bootstrapping

The implemented MMST analysis uses a re-sampling technique known as "bootstrapping" that followed Davidson (1997) in order to find both common and unusual links across the total sample studied (in each re-sample and MST creation, new links have a chance to be found).

For my implementation I chose a re-sampling technique than was different to the original MMST method used by Grönlund et al. (2009). In their method they did a jack-knife re-sampling using equally sized random samples in order to estimate the networked structure. In place of this, I used a more classical bootstrap technique in that the *random sized* random samples were used to facilitate the calculation of Spearman correlations (see p. 100), and used these results to estimate the networked structure. This choice was guided by the uncertainty[59] about what sample-size for the jack-knife bootstrapping would be suitable.

Changes made to step 2 in the MMST analysis: correlations

To accommodate the data set analysed in **Papers II** and **III**, my implementation of the MMST analysis used the Spearman correlation (ρ) (Spearman, 1910):

$$\rho = 1 - \frac{6\sum_i d_i^2}{n(n^2-1)} \qquad \text{(Equation 18)}$$

where $d_i = x_i - y_i$ is the difference between the *ranks*[60] of x_i and y_i.

I chose to use the Spearman correlation instead of the Pearson correlation since they differ in their underlying assumptions about what constitutes suitable data sets to analyse. The assumptions of the Pearson correlation are:

1. the variables are continuous;
2. the relationship between the variables is linear;
3. no significant outliers exist; and,
4. the variables are (approximately) normally distributed.

In contrast, the assumptions of the Spearman correlation are:

1. the variables are measured by ordinal, interval, or ratio scales (for example, Likert scales are permitted); and,
2. the variables are monotonically related (for example, bell shaped relationships are not permitted).

By using the Spearman correlation in the implementation of the MMST algorithm I was able to meet the underlying assumptions of the correlations: The data set used for the analysis in **Papers II** and **III** are more suited to analysis using the Spearman correlation because they are neither normally distributed, nor continuous.

[59] This “no-choice” resulted, quite interestingly, in discussion of nestedness and scale-invariance that is discussed in Section 7.3.2 and **Paper II**.

[60] Both x and y are ranked (1, 2, 3 ...) and their respective ranks are compared. In the case of two identical numerical values competing for the same rank, they are both ranked as the average rank of their positions. Example: two variables with identical values are ranked 3 and 4, their rank is then recalculated to be 3.5 = (3 + 4) / 2.

Changes made to step 4 in the MMST analysis: creating MSTs

Creating the MSTs starts with using the Spearman correlation in my implementation of the MMST algorithm. The Spearman correlation matrix is then transformed to a distance matrix (as per Equation 19)

$$d_{ab} = \sqrt{2(1 - |\rho_{ab}|)} \qquad \text{(Equation 19)}$$

where the distance d_{ab} is the distance between variables *a* and *b*. This distance has a small value when the Spearman correlation (ρ_{ab}) is large.

In this step of the MMST analysis, the distance matrix gets used to find a MST that links the strongest Spearman correlations together in a tree-type network. The original MMST analysis (Grönlund et al., 2009) used Kruskal's algorithm (Joseph & Kruskal, 1956) to find this MST. However, I used an algorithm that is better optimized in terms of time of computation to find MSTs – Prim's algorithm (Prim, 1957). This algorithm is available in the package iGraph (Csardi & Nepusz, 2006). The optimized Prim's algorithm ran 300 times faster than my un-optimized version of Kruskal's algorithm. Both Kruskal's and Prim's algorithms were implemented and tested. I found no differences in the resulting MMSTs produced. These two approaches to finding an appropriate MST are summarized in Table 7.

Table 7. *Comparison of Prim's and Kruskal's algorithm to find a MST.*

Prim's Algorithm	Kruskal's Algorithm
1. All nodes are marked as "not visited". 2. Any node *v* is chosen as starting node and is marked as "visited" (defined as being in cluster *C*). 3. The smallest weighted edge, which connects one node (*v*) inside the cluster *C* with another node (*u*) outside of *C*, is chosen and is added to the MST. 4. The process is repeated until a spanning tree is formed.	1. Each node is in its own cluster. 2. Take the link *e* with the smallest edge-weight: a. if *e* connects two nodes in different clusters, then *e* is added to the tree and the two clusters are merged, b. if *e* connects two nodes, which are already in the same cluster, ignore it. 3. Continue until *n-1* edges have been selected.

My approach brought the following to the original MMST analysis in Step 4 in Table 6.

Firstly, it recognized that edges can be both positive and negative. This becomes useful when wanting to find out if it was the strongest positive or negative relationship between elements that was estimated. To do this, I kept track of the positive and negative correlations in each subset of the data set, and correspondingly assigned negative or positive edge weights to the edges in the MSTs constituting the MMST.

Secondly, the original MMST analysis applies degree – degree correlation analysis (Sneppen & Maslov, 2002) to ensure that each link is significant in the creation of an MMST. However, such an analysis is normally applied to much larger networks than the network created for **Papers II** and **III**. To ensure link-significance in my implemented MMST analysis, I only kept links in each MST that corresponded to correlations with significances $p \leq 0.01$. This means that the probability for the null-hypothesis is <1%. Also, significantly, in **Papers II** and **III**, the number of MSTs making up the MMST was increased until the difference between two MMSTs that were created by the same number of MSTs was below the 5% error for each edge. Thus, my selection of *true* links was proportional to how frequently they were found when comparing two different runs of the same data set (see Sections 5.4.7 and 7.3.2 for more details).

Thirdly, my implementation of the MMST analysis randomizes the top two strongest correlations in each sub-set of the data set by alternating between them while creating the links. This takes into account the possibility that the data set might be "noisier" than the data set used in Grönlund et al. (2009). My implementation also overcomes ordering bias, and, together with the forced significance in each MST, allows for detection of *weaker* links in the networked system. In this way, a link in the created MMST would be *weak* because it would reflect rare signalling events rather than merely links based on chance.

5.5. Method to explore nestedness of complex systems

In order to fully answer Research Question 1, ways to describe how the concept of nestedness can be analysed and visualized were needed. This is important as nestedness is a key property of complex systems (see Section 4.5), and in my case would influence the outcome of suggested institutional actions.

Exploratory Factor Analysis (EFA) is proposed in **Paper I** (and is discussed in Section 7.3.1) as a way to estimate the nested structure of complex systems. Consideration was given to EFA because it is a commonly used method in educational research, and if this method was shown to suffice, then it would be a good approach to use to analyse nestedness of complex systems. EFA is commonly used to study patterns and order within data sets by comparing angles between points in a multidimensional space. The starting point for this analysis is a correlation matrix that is made up of the intercorrelations between the variables in a given study. In other words, EFA is a method to identify variables that have "commonalities" (Kim & Mueller 1978). It does this by using the intercorrelations between the items to establish the levels of "commonalities". Variables that are highly intercorrelated get classified into the same factor.

From a complexity theory point of view, those parts of a complex system that reside in the same nested level (see Section 4.5) are more interrelated than the parts in different nested levels. Therefore, parts of a system which reside in the same nested level should share commonalities/be interrelated in a way that could potentially be identified by the EFA.

Mathematically, $x_{ij} = \lambda_{i1}\xi_{j1} + \lambda_{i2}\xi_{j2} + \ldots + \lambda_{ip}\xi_{jp} + \partial_{ij}$, EFA expresses the intercorrelations in a set of questions (*i*), for every respondents answer (*j*), into *p* number of factors (ξ). The method assumes that respondent *j*'s answer to question *i* (answer denoted as x_{ij}) can be modelled. Here λ are factor loadings, and the size of the term ∂_{ij} is interpreted as how much information cannot be accounted for in *p* identified factors.

I used the software package for statistical analysis, SPSS[61], in **Paper I** to perform the EFA analysis. The estimation of factor loadings (λ) was done through the method of principal axis factoring; the factor loadings (λ) were iteratively estimated through minimizations of the un-weighted sum of squares between respondents answers and the fitted x_{ij}. As the aim of this methodology is to find clusters of variables which can be interpreted as nested levels (see Section 7.3.1), I chose this method because it mainly considers shared variance between variables and seeks the least number of factors that account for that shared variance.

The size of the data set used illustratively in **Paper I** (described in Section 6.2) could be argued to be, perhaps, too small for the intended illustrative purpose. The case I make for disagreeing with this argument comes from the perspective that a useful way to view EFA is to see it in terms of what Hofstede et al. (1990, p. 299) has called "ecological factor analysis". This is an analysis where the stability of the analysis does "…not depend on the number of aggregate cases but on the number of independent individuals who contributed to each case". The questions included in the questionnaire (see **Paper I**, Appendix A for details) were taken from several peer-reviewed articles and thus, were tested and tried in other contexts.

The starting point of the EFA in **Paper I** was a normalized matrix consisting of the questionnaire data set, the students' Higher Education Credits achieved within and outside their programme, retention (re-enrolment in the second year), age, and gender.

In **Paper I**, I used the following three methods as proposed by Dziuban and Shirkey (1974) to achieve an appropriate correlation matrix of items to be used for the EFA: anti-image correlation measure (MSA) of sampling adequacy; Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy; and, Bartlett's test of sphericity.

The KMO measure tests if the partial correlations among the variables are sufficiently large. The measurement is used in two ways: (1) by using measurement of each variables' KMO_j, (the anti-image correlation matrix [MSA]) variables that are below 0.5 are removed (Kaiser 1970); and, (2) the overall KMO measure (the KMO measure of sampling adequacy) is used to ensure

[61] SPSS is a statistical environment that is mostly used in the social sciences.

that the correlation matrix is suitable for EFA (measurements of around 0.7 or above is recommended – see Kaiser & Rice, 1974). The measure is calculated through Equation 20,

$$KMO_j = \frac{\sum_{i \neq J} r_{ij}^2}{\sum_{i \neq J} r_{ij}^2 + \sum_{i \neq J} u_{ij}^2} \qquad \text{(Equation 20)}$$

where the KMO_j is the KMO measure of variable *j*; r_{ij} is the observed correlation between variable *i* and *j;* and, u_{ij} is the partial correlation between variable *i* and *j*.

Bartlett's test of sphericity checks to what extent the correlation matrix is similar to an identity matrix – it checks if the elements that are not in the diagonal of the correlation matrix are not close to 0. It is given in Equation 21,

$$\chi^2 = -\left(n - 1 - \frac{2p+5}{6} \right) \times \ln |R| \qquad \text{(Equation 21)}$$

where, under the null hypothesis, the test follows a χ^2 distribution, where *p* is the number of variables; *n* is the number of samples, and |R| is the determinant of the correlation matrix. If the correlation is equal to an identity matrix, |R| = 1.

To decide on the number of factors in the EFA, I used a scree test (Figure 15). "The scree test involves examining the graph of the eigenvalues … and looking for the natural bend or break point in the data where the curve flattens out. The number of data points above the 'break' ... is usually the number of factors to retain" (Costello, 2005, p. 3). To generate the scree plot, every item is treated as a vector that has an eigenvalue (length) of 1.0, before the optimizations of the sum of the vector projections on factors are carried out.

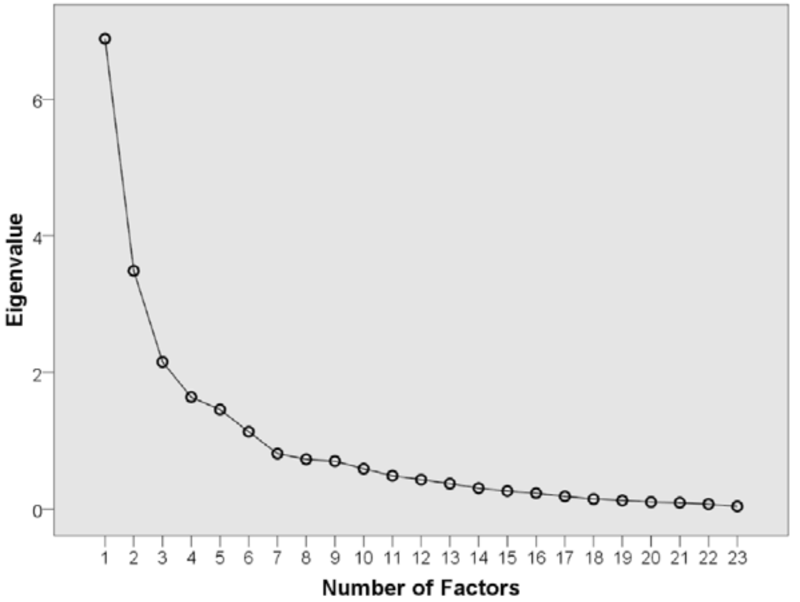

Figure 15. Scree plot of the eigenvalues for each factor from **Paper I**.

The eigenvalue in Figure 15 means that, for example, an eigenvalue of seven (One Factor) provides us with the information that all significant loadings in One Factor can be grouped to give seven times as much information as a single variable.

5.6. Potential methods for estimation of change in networked systems

In order to answer Research Question 1, I also needed a method to estimate the effect of changes in a complex system.

To estimate effects of a proposed change in a networked system requires knowledge about what inferences can be drawn from unobserved values through an interpretation of the observed values. There are several ways to do this, but in this overview section I deal only with the two common techniques that I considered – Belief Propagation Algorithm(s), and a Markov Chain Monte Carlo (MCMC) sampling technique called Gibbs Sampling. The reasoning behind my choice of the Gibbs sampling as the appropriate method is discussed in Section 5.6.2.

5.6.1. Belief propagation algorithm(s)

The Belief Propagation Algorithm (BP) was first introduced by Pearl (1988), and since then has spawned many different techniques to infer values in a network, or network-like structure. A good example of the use of the BP algorithm can be found in Murphy et al. (1999). The BP algorithm is exact (converges to an exact point and not to an estimate) on *tree* (networks with no loops), and *if* the algorithm converges in a *loopy network*, then it does so near a fixed point (Yuille, 2002). These aspects make the algorithm potentially problematic for the kind of networked structure studied for **Papers II** and **III.** This is because the network in these papers contains many loops.

For completeness, I will now provide a brief explanation of the Belief Propagation Algorithm. The BP algorithm introduces the concepts of nodes sending "messages" to adjacent nodes. These messages from the adjacent nodes decide which value the node gets given. Two useful examples that can be used to understand how this algorithm works are: Firstly, you think it is not going to rain. I then tell you that it is cloudy. That information changes your mind to believe that it is probably going to rain, so you take an umbrella when you go out. The second example is a loopy example: I tell both you and your friend Bob that it is cloudy. You notice that Bob takes an umbrella when he goes out. This information leads you to believe that it is *definitely* going to rain, and so you also take an umbrella. This belief can be so strong, that on your way out, you believe that it is probably *already* raining, even through the information you have received thus far is only about it being cloudy. The loopy example shows how extreme beliefs can result from interaction between agents/components.

Algorithms that are closely related to BP (which have not been used to the same extent as the BP algorithm – see Murphy et al., 1999), or MCMC samplings are, for example, the CCCP Algorithms (Yuille, 2002) and the Expectation Propagation (Minka, 2001). An extensive overview of alternative methods to the MCMC methods can be found in Wainwright and Jordan's (2008) work. These closely related algorithms are more advanced versions of the BP algorithm in that they do tend to converge (Yuille, 2002). These alternative methods are, however, more cumbersome to explain and implement than the method that I used for **Paper III** – Gibbs sampling.

5.6.2. Gibbs sampling[62]

Gibbs sampling is a Monte-Carlo methodology that iteratively estimates the value of each unfixed node in a network. This aspect of the estimation is based on the conditional probability distribution of the node's value with respect to the current estimated values of adjacent nodes. Gibbs sampling is a special case of the Metropolis-Hastings algorithm (Hastings, 1970). Over several iterations the values generated for each unfixed node (i.e., nodes with a variable value) converge to the joint posterior probability distribution for

[62] To add coherence to the thesis, the description in this section is largely a repeat of the method section given in **Paper III**.

those node's values. This is conditional on the constant values of the fixed nodes. In this way, Gibbs sampling can be used to determine the most likely change for one node based on forced changes for another.

The Gibbs sampler is designed as a Markov process, i.e., the next value only depends on the current value of each node. The dependencies can be thought of as a stochastic process without memory, where the memory of the previous node's values is "forgotten" with each step forward. An example of such a process is radioactive decay. If I were to estimate how many nuclei were to decay in a sample in the next second, I would only need to know how many nuclei are present *now*. The information of *when* each of the nuclei decayed would not be needed. Analogically, the Gibbs sampler creates a Markov chain, where a sample drawn at time t is not dependent on the sample drawn at time t-1.

This Markov chain generated can be denoted as a recursive matrix operation, which specifies the probability of being in a state i, after being in state j. The Transition matrix, T, is defined through Equation 22,

$$T_{ij} = \Pr(\text{ state}(t+1) = i \mid \text{state}(t) = j) \qquad \text{(Equation 22)}$$

where, in Gibbs sampling, the state is the value of all nodes and t is the iteration process. If there is a probability π of being in state j at a time t, the probability of being in a state i at the time $t+1$ calculated through Equation 23,

$$\pi(t+1) = \sum_j T_{ij} \pi(t) \qquad \text{(Equation 23)}$$

which is given in the matrix form by Equation 24.

$$\pi(t+1) = T\pi(t) \qquad \text{(Equation 24)}$$

The matrix form implies that the Gibbs sampler is designed, through it being a Markov process, to converge around a particular stable distribution π, which is no longer dependent on t. In this case, the joint probability distribution of the values of the nodes is conditional on the fixed information (i.e., the structure of the estimated network, and on the fixed value nodes).

Two techniques that are commonly used when implementing a Gibbs sampler are *thinning* and *burn-in*. *Thinning* is used to reduce autocorrelation, which is about making sure that each following sample is not dependent on the previous sample (if it was dependent on the previous sample, this would mean that the samples are not drawn independently from the posterior distribution).

To implement *thinning* in the Gibbs sampler, only one of multiple draws of the sampler is recorded, while the other draws are not used to estimate the distribution. In the case of the work I presented in **Paper III**, only one of every 100 draws was recorded to estimate the distribution.

Burn-in is used as a way to ensure that only *permitted* values are drawn. This means that if the initial guess is not a part of the estimated distribution it takes a while for the Gibbs sampler to converge and to begin to draw from the desired distribution. Implementing a *burn-in* in the Gibbs sampler means rejecting the first drawn samples to use in estimating the distribution. In **Paper III**, I rejected the first 1 000 samples.

The BP algorithm and Gibbs sampling make use of the same idea – both use "beliefs" of adjacent nodes to update the belief of the node. The difference for Gibbs sampling is that it generates a single value drawn from the joint probability distribution of all nodes, whereas the BP algorithm is designed to keep track of the whole distribution of each node.

My implementation of the Gibbs sampler followed Equations 25 and 26 and, over the iterations, the values of each node were re-estimated based upon re-estimations of values of adjacent nodes. My Gibbs sampler for **Paper III** drew its samples from a normal distribution where the mean of this distribution is the weighted mean of the adjacent nodes.

The weighted mean is calculated using Equation 25,

$$\mu_i^* = \frac{\sum_j w_{ij} n_j}{\sum_j w_{ij}} \qquad \text{(Equation 25)}$$

where the estimated mean is μ_i^*; w_{ij} is equal to the edge weight between adjacent aspect i and j; and, n_j is the value of aspect j.

The standard deviation used for the Gibbs sampling was estimated by the unbiased estimator for the weighted sample variance by using Equation 25,

$$\sigma_i^2 = \frac{\sum_j w_{ij}}{\left(\sum_j w_{ij}\right)^2 - \left(\sum_j w_{ij}^2\right)} \sum_j w_{ij} \left(n_j - \mu_i^*\right)^2 \qquad \text{(Equation 26)}$$

where w_{ij} is then the edge weight between aspect i and j; n_j is the value of aspect j; and, μ_i^* is the estimation of the weighted mean (as per Equation 25). Thus, the standard deviation is low when the adjacent nodes are of similar value, and high when adjacent nodes have values far from each other.

I chose to use the Gibbs sampler as it is very straightforward to implement in a networked system. In what follows, I give two examples of implementation of Gibbs sampling, a one-dimensional implementation, and a two-dimensional implementation.

Example 1 (one-dimension): Let $f(x) = 4\sin(x) + x$, where $-8\pi < x < 8\pi$. An introduction of a noise-rate of 80% is made that removes 80% of the data points in the range ($-8\pi < x < 8\pi$) uniformly at random. I considered this a one-dimensional network, where position *f*(*x+2*) has a relationship to *f*(*x+3*) and *f*(*x+1*), illustrated in Figure 16.

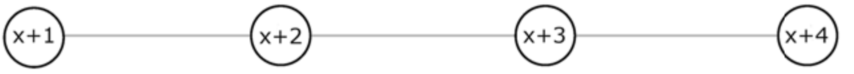

Figure 16. Example of a one-dimensional network.

Estimation of the values of the removed data points was done through a simple Gibbs sampler. The Gibbs sampler for a particular data point drew from a normal distribution with an un-weighted mean of the two adjacent positions, and a standard deviation as per Equation 26. The "further away" the neighbouring positions are in numerical value, the larger the standard deviations are in the Gibbs sampler I used. The Gibbs sampler ran until it converged around a stable distribution.

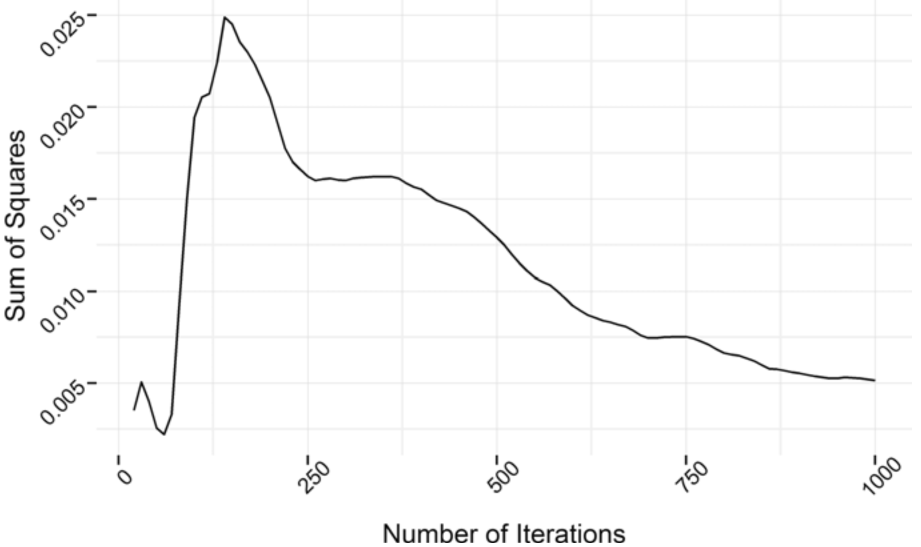

Figure 17. Plot of the sum of squares[63] between the original function and the estimated data points for 1 000 iterations of Gibbs sampler estimation of missing values.

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[63] Sum of Squares $= 1 - \dfrac{\Sigma(y-\overline{y})^2}{\Sigma(y_r - \overline{y}_r)^2}$ where *y* is the original function, $\overline{y}$ is the mean of the original function, y_r is the estimated values, and $\overline{y}_r$ is the mean of the estimated values. The Sum of Squares converges toward zero when the estimation (y_r) iteratively gets closer to the values for the function (*y*).

Example 2 (two-dimensions): This second example shows the implementation of the Gibbs sampler in a two-dimensional lattice network structure. I give this example to illustrate how the sampler works in a network with loops. A suitable visual example is that of a picture, a pixelated image. Each pixel has a relationship to the adjacent pixel. This can be seen as a network where pixel *a* is adjacent to pixel *b, c, d,* and *e* (see Figure 18), and therefore, pixel *a* is related to pixels, *b, c, d,* and *e*.

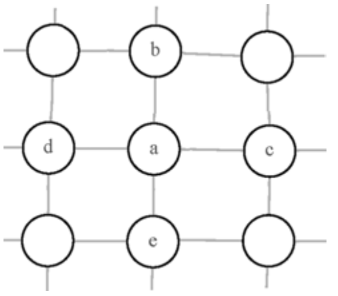

Figure 18. Example of a two-dimensional lattice network of a picture.

Figure 19. An example of a two-dimensional lattice network estimation through Gibbs sampling: (a) original picture; (b) picture that was introduced to an 80% noise-rate (the removed pixels are visualized as black); (c) 1 iteration; (d) 2 iterations; (e) 4 iterations; and, (f) 6 iterations of Gibbs sampling.

The photograph in Figure 19b has undergone the same procedure as in the example for the one-dimensional network in Example 1. This process begins after the first photograph (Figure 19a) has been corrupted by introducing a noise-ratio of 80%[64] (Figure 19b). The Gibbs sampling drew its samples from a normal distribution using an un-weighted mean of the four adjacent positions, and a standard deviation as per Equation 26. Figures 19c – 19f show the results of the iterations of the Gibbs sampling.

Figures 19b – 19f show how the Gibbs sampler gradually estimates the removed pixels (the black pixels) by using the information available in the adjacent pixels. The fuzziness of the photograph that can be seen in Figure 19f, when compared to the original picture (19a), is due to removing information that the Gibbs sampler cannot precisely estimate.

In **Paper III**, I used the same method that is exemplified in the one- and two-dimensional examples, but the networked structure was more complicated.

5.7. Method to show how networked structures of students' interactions are related to grade achievement

In order to answer the second part of Research Question 2, a method to relate students' interaction patterns with their grades was needed. In **Paper V**, students' position in their social and the academic interaction networks was related to their grade performance by using ordinal regression. I chose not to rely on Pearson or Spearman correlations to look at the tendency of getting a particular grade. I made this choice because my aim was to explore whether grade achievement was more related to the students' academic interaction network, or to the students' social interaction network, or a combination of the two. This aim could not be met if I only analysed Spearman or Pearson correlations.

5.7.1. Ordinal regression[65]

For **Paper V**, a network analysis of students' structural positions in the social interaction network and the academic network measurements were related through ordinal regression (Johnson & Albert, 2004) to students' course grade achievement. An ordinal regression was done to examine how social and academic network measurements can act as indicators for academic success. This was undertaken by using the implemented functions in the package called MASS (Venables & Ripley, 2002) for the statistical environment **R** (r Core Team, 2013). Six measurements (in-degree, eccentricity, between-

[64] The noise rate in this picture could be greatly increased and still it would be possible to reproduce a clean image again. This is because the removal of data was uniformly random and the information retained in the picture is much larger when compared to a one-dimensional network – the potential adjacent information for each data point is doubled.

[65] To add coherence to the thesis, the description in this section is largely a repeat of the method section given in **Paper V**.

ness centrality, PageRank, clustering coefficient, and eigenvector centrality – see Section 5.3.2 for details) where used for my ordinal regression in **Paper V**. All permutations using one to six measurements was done in order to test which measurement combinations would be best suited to predict grade achievement.

My checking of the different permutations of different network measurements led to a large number of models (2509) that I needed to test. Due to this, I used the *BHY procedure* (see, Benjamini & Yekutieli, 2001) in order to choose the *best fit* models according to their significance level. The procedure starts by sorting the *significance value* of the models in decreasing order in a list ($P_{(k)}$), and finding the indices (k) that satisfy the chosen lowest significance using Equation 27,

$$P_{(k)} \leq \alpha \frac{k}{m \cdot c(m)} \qquad \text{(Equation 27)}$$

where m is the total number of tests, and $c(m) = 1$ when the tests are independent, or positively correlated. The BHY procedure finds the largest k where the corrected α (significance level) "passes" the BHY procedure in the list of significances ($P_{(k)}$), i.e., the resulting list ($P_{(k)}$) includes only significances below the corrected significance level.

The significance level of $p < 0.01$ was chosen. This lowered the acceptable significance as per the BHY procedure to $p < 0.01/2509$. The tested variables had positive correlations in the data set, which altered the BHY procedure to cover such relationships between the tested models (i.e., $c(m) = 1$). This was undertaken, when testing multiple different models because the *false discovery rate* is significantly higher if the standard cut-off allowed is $p<0.01$ for each tested model.

6. Methodology: Part 3 – The Data Collection and Associated Ethical Considerations

6.1. Introduction

This section covers the third part of the methodology; describing the data collection and ethics. The section on data collection describes why and how the data sets were collected, and the section on ethical considerations covers ethical aspects associated with each paper covers the basic principles of ethical research.

6.2. Data collection

6.2.1. **Paper I**

The data set used for the example modelling in **Paper I** was collected from two sources: student records and a questionnaire.

Student records were used to obtain students' demographic information, such as age and gender, student retention, and information regarding students' academic achievement, which were the Higher Education Credits obtained inside and outside of the programme.

A questionnaire (**Paper I** - Appendix I) was developed that drew on previous student retention research. This was further developed through discussion with colleagues and students. The questionnaire[66] was based on aspects, derived from both the Student Integration Model and the Student Attrition Model which provide high explanatory value for student retention (Cabrera et al., 1993). Since the data set was to be used only for illustrative purposes, the questionnaire was not subjected to any specific reliability and validity analysis.

In 2009, the questionnaire was handed out to students who were attending a typical first-year university physics course at a highly regarded traditional Swedish university at the end of their first year (second semester) of university study. To maximize the questionnaire completion-rate, a venue that facilitated a discussion of aims and the associated ethical considerations was

[66] Explained in detail in **Paper I**.

chosen. Most students present at the venue agreed to participate in the questionnaire (n = 51). Thirty-two of the participating students were registered for a four and a half year Master of Science Programme in Engineering Physics, twelve were registered for a three year Bachelor of Science Programme in Physics, and the remaining seven were registered in a four and a half year Master of Science Programme in Materials Engineering.

Using this questionnaire, **Paper I** explores and exemplifies how complexity thinking could be used in research aimed at modelling a complex system of student retention in university physics and related engineering programmes. This modelling gave explicit consideration to how attitudes, beliefs, self-reported experiences, Higher Education Credits Achieved, physiological gender, age, and retention are interlinked and how they could be envisioned as a self-organized networked and nested complex system by the use of multidimensional scaling and network theory.

Complex systems are networked constellations of components, which for **Paper I** are the students' viewpoints of their experience of higher education physics in their first year. Each item is considered to emerge from and be nested within multiple complex systems. Given the decentralized, networked nature of complex systems, illustration of the structure and dynamics of a complex system, in which student retention is a process, is argued to be possible in **Paper I**. This is done using exploratory factor analysis, multidimensional scaling and network theory. These methods are used to partially answer Research Question 1 in Section 7.3.1.

6.2.2. **Papers II** and **III**

The data set for **Papers II** and **III** was collected in the fall of 2010 at a highly regarded university in the European Union, which offers three-year bachelor degrees for a wide variety of engineering and science programmes. The studied cohort consisted of first-year engineering students using an online questionnaire that was made available to all the students in this cohort. The response rate for the questionnaire was 25% (573 of 2292). The questionnaire was constructed from the literature on student retention (Van den Bogaard, 2012; 2015). It was mainly based on the Student Integration Model and Student Attrition Model, however it also included questions that were selected based on interviews with a selection of first year students at the same university. These additional questions were included because the respondents in the interviews raised new aspects which could be of importance for student retention (Van den Bogaard, 2015). The final questionnaire contained 79 questions. These questions included all possible aspects which could potentially affect student retention, such as regarding students' backgrounds (such as parental level of education), social and academic integration (such as union membership), academic confidence (such as self-reported confidence of skill in maths and science), motives (such as job prospects), and commitment (such as staying at that university). Furthermore, the questionnaire also contained questions regarding student study behaviour (such as a deep approach to learning) and on the students' perceptions of the educational climate (which was operationalized in four topics: perceptions of teachers, assessment, facilities, and curriculum organisation).

To pair the questionnaire with student achievement, scheduling, etc., it was combined with data sets from the central student administration and from the curriculum and programme structures at the university. The items in the questionnaire and rationale behind the development of the questionnaire are given in **Paper II -** Appendix 2 and **Paper III -** Appendix S1 and S2.

The analysis of this data set is used to complete the answering of Research Question 1 in Sections 7.3.2 and 7.3.3.

6.2.3. **Papers IV** and **V**

Data collection for **Papers IV** and **V** was aimed at exploring the structures of a social and an academic network in a university physics setting. In order to do so, a network questionnaire following the methodology of Morrison (2002), which is a widely accepted methodology used in social network analysis (Marsden, 2011), was developed and tested. At the end of the Spring term 2010, a final version was given to students in two courses in an engineering programme at a Swedish university (a four and a half- year degree programme made up of core courses in physics, mathematics, and computer science, and a research project requiring at least six months of full-time work). The two courses were: a Mechanics II course (Course One); and, a computing science course (Course Two). Typically, these courses have a lecture format with separate problem-solving and student laboratory sessions. The teaching approaches include being both traditional (chalk-and-talk) and highly interactive. Thus, the design of the learning environment specifically provides several venues to accommodate a range of both instructor and student-initiated group activities.

The network questionnaire asked the students to list the names of the people in their courses with whom they interacted. The students were then asked to characterize the nature of their interactions with each of these people on a scale from only social (1) to only academic (5) with *both* social and academic being (3).

Figure 20 shows the cover page used for the network questionnaire.

In this survey, if you choose to participate, we ask you to write the names of other students within your course with whom you have been interacting. Further, you are asked to classify your interactions as either social or academic on a five degree scale. A marking to the far left would mean that you mainly have a social relationship. A marking to the far right would indicate that your relationship to that person is mainly academic – you are mainly studying in groups, discuss the courses and/or content of courses.

Name:	Social				Academic
X	O	O	O	O	O

Indicate that you have a relationship to student X, which is mostly social (we sometimes study together and do coursework, but on the broader scale of things we do social things together).

Name:	Social				Academic
X	O	O	O	O	O

Indicate that your relationship with X is evenly balanced between doing social or academic activities together.

Name:	Social				Academic
X	O	O	O	O	O

Indicate that your relationship with student X is mostly academic, and you have – at some point – done something social together.

Figure 20. Cover page of the network questionnaire (From **Paper IV**, p.5, reprinted with permission)

In order to investigate students' interpretations of what constitutes social interaction and academic interaction, focus group discussions (Robson, 2002) with four groups (12 randomly selected students) were conducted. The results from the focus group discussions provided a data set that I could use to contrast with Tinto's (1997) discussions on student integration and socialisation. The focus group discussions produced eight examples of social interaction and nine examples of academic interaction. These examples were member checked (Robson, 2002); validating that the categories I had created covered what the students had discussed.

Examples of social interaction involved doing the following with other students:

- pausing while studying;
- going to student pubs;
- participation in "exam parties";
- going out for lunch or dinner;
- doing sports or working out;

- playing board games;
- engaging in student organizations; and,
- participating in student activities.

Examples of academic interaction involved doing the following with other students:

- studying;
- discussing problems;
- discussing solutions to problems;
- doing laboratory work;
- doing hand-in exercises;
- study visits;
- going to lectures;
- studying for exams; and,
- going to labour-market events.

The focus group descriptions were very similar to the descriptions given by Spady (1970; 1971) and Tinto (1975; 1987; 1997) of social and academic interactions. This made it possible for me – presented in Section 7.4 and in **Papers IV** and **V** – to examine the core foundation of student retention – the importance of social and academic interactions and their relationship to the social and academic systems.

The Mechanics II course (Course One) questionnaire was answered by 68 students, which resulted in a network of 122 students (54 more students in the course were mentioned in the questionnaire responses of others). The computing science course (Course Two) questionnaire was answered by 66 students, which resulted in a network of 107 students (41 more students in the course were mentioned in the responses of others). Only the students who answered the network questionnaire were used[67] in analysis of degree distribution, path length, and clustering coefficient. All students mentioned were used in the visualizations of the networks.

The analysis of this data set is used to answer Research Question 2 in Section 7.4.

[67] The data on degree, path length, and clustering coefficient could be estimated for students who did not participate in the questionnaire, but, following ethical guidelines, I chose to remove those students from the analysis.

6.3. Ethical considerations

6.3.1. **Papers I**, **IV**, and **V**

The ethical guidelines, provided by the Swedish Research Council (SRC) (Vetenskapsrådet, 2002) and the European Commission (EC) (European Commission, 2010) were followed both in the planning, data collection, and data analysis of the studies reported on in **Papers I**, **IV**, and **V**. I made sure that the ethical aspects of the study were discussed with the participants.

Both the SRC (Vetenskapsrådet, 2002) and the EC (European Commission, 2010) emphasize the importance of informed consent and the voluntary nature of participation in studies. In every instance of data collection, the participants were informed verbally and in writing about the intended use of the data they provided (Appendix I).

All participants were provided with my personal contact information while being informed that their participation was voluntary and that they could withdraw their participation at any time before the results of the analysis was published. Participants were informed that if they did not want to take part in the questionnaire they could leave or they could wait for a while and hand in a blank questionnaire.

The SRC (Vetenskapsrådet, 2002) and the EC (European Commission, 2010) state that all data sets containing personal information need to be constructed in such a way that they cannot cause harm to the participant in any way. No sensitive personal data was collected in the study. However, information that could be used for the identification of individuals within the data set was removed from the analysis, and is therefore not present in any of the results.

Also, to protect personal information, electronic data files that could be used to identify individuals within a data set are stored on a separate hard drive. This hard drive is not connected to the Internet. All questionnaires are kept under lock and key, and stored in such a way that personnel outside the research division cannot access the data set.

I have on several occasions had informal follow-up discussions with some of the participants about the analysis or the results of the analysis from these papers. I have also kept contact information available for participants who expressed an interest in how and when the published material would be available. Copies of the papers were sent to these participants.

6.3.2. **Papers II** and **III**

The university where the data set for **Papers II** and **III** was collected required no specific ethics submission, nor had an ethics board in place, nor had any formal procedures to be followed in human subjects' research. Even though this was the case, a non-formal committee of university researchers and administrators was gathered before data collection to approve the design of the study. This committee consisted of the Director of Student and Teacher Services and two research professors. Moreover, the data collection followed the ethical guidelines as described by Cohen et al. (2011). This means that informed consent by students was obtained by disclosing full information of the goals of the study, which researchers and administrators were involved, and how they could be contacted. The information that they provided on the questionnaire used for these papers would be linked with data sets from the central student database. However, it was made explicitly clear that both sets of data would only be stored and used after any information that personal traceable information had been removed. Participation was voluntary and could not affect their grades. The participants agreed to the terms of research by entering their unique student ID that made it possible to link the questionnaire answers to the university's student database. Students who did not agree to these terms of research, or who did not complete the questionnaire in full, were removed from the data set, and none of their information was saved. Any information that could be used to identify individual students was removed before any analysis on the data set was undertaken. All items included in the questionnaire were strongly grounded in previously published peer-reviewed research (See **Papers II** and **III**).

7. My Journey to Answer my Research Questions

7.1. Introduction

In Chapter 1, I introduced the aim of my thesis: *How to conceptualize and carry out analysis of student retention for university physics students using a complexity theory perspective?* My journey to achieve this aim involved traversing through several stages of methodological and theoretical development in order to answer my two research questions:

> Research Question 1: *In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?*
>
> Research Question 2: *Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?*

In this chapter I present how I constituted the parts of my journey to answer these two research questions, and to present the answers themselves. Hence, I have divided the format of the chapter into three parts. The first deals with my formulation of a "system description" of the university physics educational system (essential parts of this system being made up of student retention elements). This is done to "set the scene" for the research question answers that I go on to provide: describing the theoretical foundations that underpin my constitution of the university physics educational system. The next two parts of the chapter summarize my results for each research question.

7.2. System description of the educational system of university physics

This section gives a system description in which student retention is a process. This is done in Sections 7.2.1 and 7.2.2 using the complexity theory concepts of nestedness and networks. Earlier, in Chapter 4, I described how such characterization is needed to inform readers how I envision the system. In so doing, I am using my theoretical foundation to present a realistic understanding of the properties and dynamics of the system. The characterization of the educational system that I present has two foci: firstly, *what* can one gain understanding of, and secondly, *how* to facilitate that understanding. In Sections 7.2.1 and 7.2.2, I draw extensively on the student retention discussion in Chapter 3 and the complexity theory discussion in Chapter 4.

7.2.1. Nestedness

As a complex system, university physics education is comprised of several interacting agents/components over a number of nested levels – Figure 21 illustrates this. It shows what I mean by the *vertical nestedness* (see Section 4.5) of the educational system and how I see students being nested in the *social* and the *academic system* of the university (which are in turn are nested within different courses). These courses are themselves nested within different university departments, and, finally, the university is nested within society. All these levels of nestedness affect each other and this occurs mainly between neighbouring levels.

From the relatively simplistic model presented in Figure 21, important influences such as curriculum, financial and social support, sense of belonging, and the desire to continue and complete a programme, operate on different nested levels (see Chapter 3). At the same time, the nested systems that I present operate over multiple temporal scales (for example, the process of student retention usually takes less time than the development of new policies).

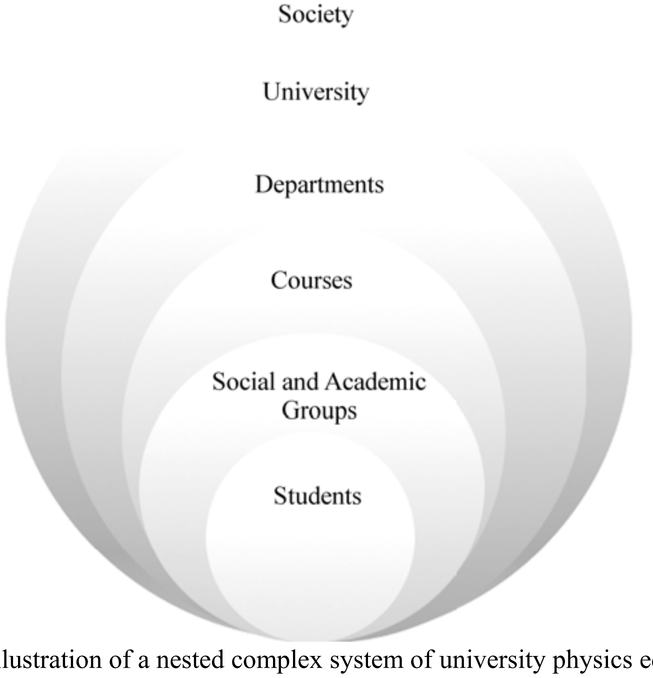

Figure 21. Illustration of a nested complex system of university physics education.

The notion of nestedness can also be viewed from a *side view* (i.e., *horizontal nestedness*, see Section 4.5). Each nested level is made up of a range of diverse clusters of constituent parts – students are diverse, the academic and social groups are diverse in its constituent parts, and not all social and academic groups reside in only one course, or only one department, or even within one university. An example of *horizontal nestedness* is that a student can be nested within several different groups of students, and not only belong to a particular social (or academic) group – work, friends, family, etc. All these groups are within the same vertical nested level, but can function very differently for students. The notion of horizontal nestedness stresses the importance that, for educational systems, parts at the same vertical nested levels is not only influenced by different neighbouring vertical nested levels, but also by the different horizontal nested levels.

The *vertical* and *horizontal* nestedness of complex systems calls for a critical view of *levels of analysis*. Such an analysis will depend on which level of this nested system, for example, the student level, or the classroom level, that gets to be studied. Then, different rationales and explanations for the phenomenon being studied might be found. Such an appreciation is echoed in research on turn-over in work organizations. For example, in such a study Hausknecht et al. (2011) argues that it is not valid to assume a one-to-one relationship between effects on the individual level and effects on the collective level.

7.2.2. Conceptually combining networks and nestedness

Complexity theory explicitly acknowledges the connectedness and interactions between the multitudes of aspects that are recognized as being influential in a given situation. As previously discussed (see Section 4.4.2), the agents/components of a complex system can be seen in terms of having networked interactions. These are, in such a case, a mix of emergent (for example: feeling of belonging, students' experiences) and non-emergent (for example, teachers and students) agents/components.

Conceptually bringing together the concepts of *networked interactions* and *nestedness* is what makes it possible see the educational system as a multilevel (nested) network (see Figure 22). The main influence of the different nested levels occurs within each level, but there are also both "upward" and "downward" influences. Upward influences are characterized as emergent phenomena[68], such as the "feeling of belonging", which is only a valid construct when individuals have something to which they feel they belong.

[68] See Section 4.5.

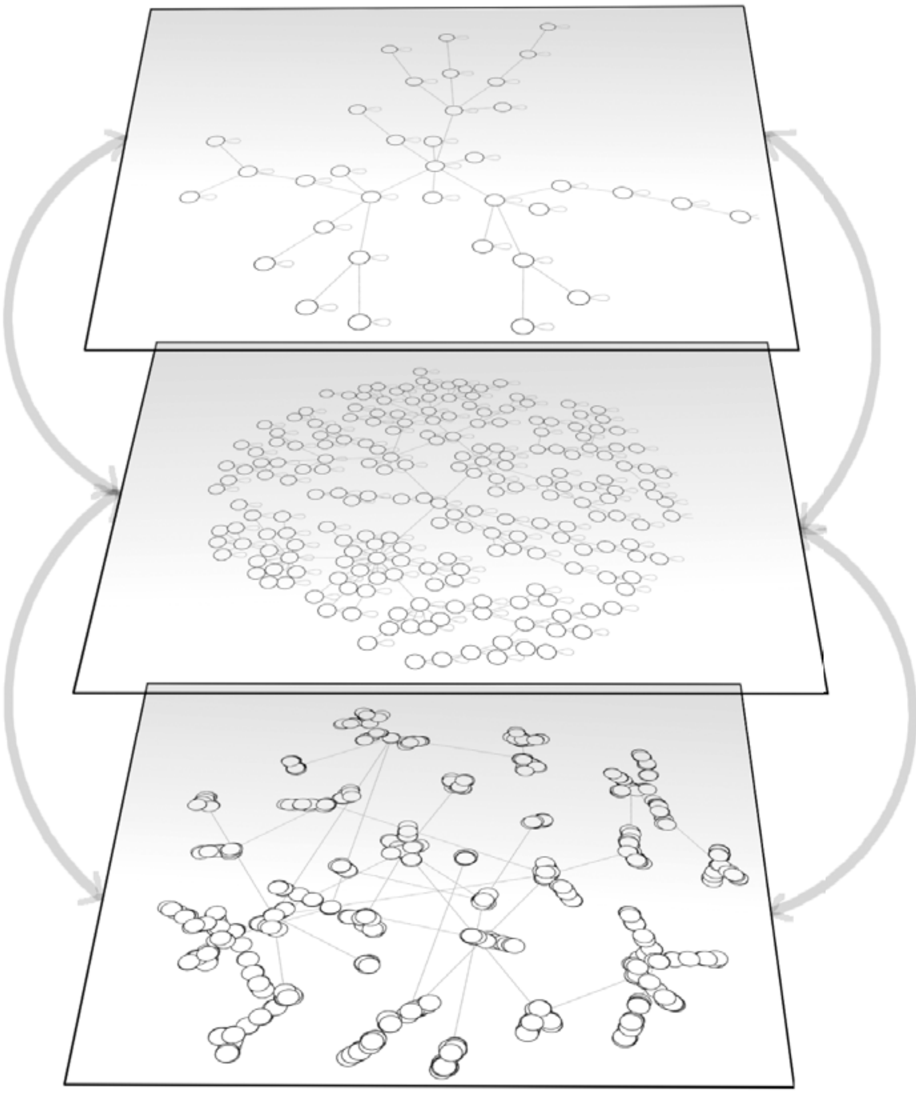

Figure 22: Illustration of a multilevel (nested) network.

This can be exemplified in cases where students feel that they "belong" to, say, university physics as an academic discipline[69] (i.e., identify themselves as a university physics student). Downward influences often act as constraining mechanisms on the rules through which the lower level agents interact, such as the "feeling of belonging" affecting the initial decision with whom to interact, and how to do so (*rules of interaction* [Sawyer, 2005]).

[69] The "feeling of belonging" is often what student retention research use when measuring student integration to the university systems, both social and academic (see Section 3.2.2).

This downward influence can be exemplified as the effects of how choices and what types of interaction occur when a student who feels that they belong to the academic discipline of physics gets to meet another physics student: the influence being dependent on both students feeling that they belong to university physics as a discipline. These two properties (upward and downward influence) of a complex system are both dealt with in Section 7.4.1.

As described in Section 4.7, complexity theory (and thus, complexity thinking) can be applied in educational research in order to explicitly acknowledge that learning systems are complex systems. Such complex systems must be adaptive and self-organizing systems, whose global behaviour is an unpredictable[70] and emergent property from the interactions of components/agents (for example, Davis & Sumara, 2006). This implies that gaining insight into a complex system is affected by the nature of the system studied.

Section 4.5 characterizes the concepts of *scale variance* and *scale invariance* as a way to describe how properties and behaviours in a complex system can either be stable across nested levels, or only be valid in one, or a few, nested levels. For example, in Figure 22, scale *invariance* occurs when a component that is present on different levels of the system is connected to other components *in a similar way*, while scale *variance* occurs when a component is present on different levels of the system, yet is connected *differently* across each of the nested levels. The two constructs can be used to characterize stability of properties in complex systems. And while the concept of *stability of elements across different levels of a complex system* is, at the time of writing this thesis, novel in educational research, it is not novel in research dealing with human-environment complex systems (Davis & Sumara, 2006; Manson, 2008). Such stable or unstable patterns are, as argued for in Section 4.6, critically important to investigate, which I did when answering Research Question 1 (see Section 7.3).

In summary, my characterization of the educational system of university physics education using the concepts of nestedness and networks, questions the assumption of a one-to-one relationship between previously identified critical elements and their function at different nested levels. This characterization needs to be explicitly problematized in any modelling of student retention[71].

How can the relationship between these nested levels of the system under study be investigated? The following two sections address this question from the institutional policy viewpoint (i.e., how can we learn what works?) and also from the potential role that student interaction networks can play.

[70] Here, unpredictable is used in a classical sense, mainly meaning the impossibility for *exact* prediction of *everything*.

[71] See for example, **Papers II** and **III**.

7.3. Results for Research Question 1

To answer Research Question 1, I built on the research questions and aims that I answered for **Papers I**, **II**, and **III** (see Table 4, p. 81), and the provision of my answer unfolded through three stages.

Stage 1: When proposing the use of a new theoretical framework, a case needs to be made that this new framework would potentially be fruitful. Thus, **Paper I** illustrate the ability for complexity thinking to incorporate previous constructs of student retention research.

Stage 2: **Paper II** improves the methodology proposed in **Paper I** and discusses: (a) limitations of institutional action to enhance student retention; and, (b) how a *Virtual world*[72] can be used to gain insights into what outcomes certain actions to enhance student retention in the system might be in a complex system.

Stage 3: **Paper III** develops a methodology through computer simulations in order to estimate what outcomes proposed action to enhance student retention might be in a complex system.

Each of these stages and how they get to constitute my answer are now discussed in detail.

7.3.1. **Paper I** – Complexity thinking as a fruitful way to study student retention[73]

In **Paper I**, I address the first critical issue to answer Research Question 1 as well as provide a foundation for a new way forward in modelling student retention. That is, the theoretical foundation that is considered, must not only incorporate previous findings and constructs, but also provide tools to furthering the understanding of student retention. In doing so, I set out to illustrate that complexity thinking has the possibility of incorporating these earlier constructs by using the theoretical tools available from complexity thinking to build a complex model of student retention. In short, **Paper I** shows how a complexity theory[74] perspective can provide new insights into institutional action to enhance student retention. It does so in terms of advocating paying attention to items that have the potential to influence *the complex system as a whole*, as well as student retention. This means that constructing institutional action that aims to enhance aspects affecting student retention

[72] See Section 4.9.2 for a description of a *Virtual world*.
[73] Empirical data used is described in Chapter 6 and **Paper I**.
[74] A note about the use of the term complexity theory and complexity thinking in this section – both terms are used. Complexity thinking is used to frame student retention in **Paper I** because of its reliance on the work done by Davis and Sumara (2006). **Paper II** uses the term complexity theory because it uses methods developed in Bioinformatics in order to establish a network structure. **Paper II** also discusses what this new modelling affords as it combines the network with an interpretation of the nestedness of the system.

should not be seen as direct linear influences, but mainly as *influencing* what takes place indirectly *through other aspects*.

Paper I – illustrative analysis

To illustrate a network of a complex system that has student retention as an integral process, I analysed the questionnaire results using multidimensional scaling to calculate the distances between points of data in multidimensional space (see Section 5.4.2). The relative closeness between items is seen as the "likeness" or "similarities" (Schiffman et al., 1981) of those items. By creating this multidimensional space it is possible to calculate transformed "multidimensional proximity" (relative closeness) between items, which is what I did. Analysis of the created network was done by using StatNet (Handcock et al., 2003), which is a freely available package for **R** (r Core Team, 2013), the software environment for statistical computing and graphics that I used for analysing networks. Using this package, identification of "important" nodes can be done by analysing each node's centrality (see Section 5.3.2).

According to complexity thinking, components of a complex system interact locally (Davis & Sumara, 2006). Therefore, it is possible to argue that components (in my case, items on the questionnaire) that have a high relative closeness to other components in the multidimensional scaling analysis can be regarded as being connected[75] and thus be within each other's "zone of influence". In the multidimensional scaling analysis of the questionnaire data set, the answers and their similarities were regarded as a representation of the complex system's emergent structure. This afforded me the possibility to create a basis for visualization and measurements of component interaction through the use of network theory.

To illustrate how nestedness of a complex system in which student retention is a process can be analysed, I used Exploratory Factor Analysis (EFA). As mentioned earlier in Section 5.5, I chose this approach because EFA is commonly used to study patterns and order within multidimensional data in a multidimensional space. In my kind of study, a useful way to view EFA is to see it as essentially what Hofstede et al. (1990, p. 299, emphasis added) call "ecological factor analysis" – an analysis where the stability of the analysis does "…not depend on the number of aggregate cases *but on the number of independent individuals who contributed to each case*".

The variables used in the analysis were the students' answers from the questionnaire responses. EFA considers these items to have "commonalities" (Kim & Mueller, 1978) that get constituted using the covariance between the items in order to classify them into factors. This implies that those components (items on the questionnaire) that have commonalities have higher covariance, and thus greater "commonality" than components that are far apart.

[75] "Connected" is used as a broad term that encompasses the interaction, communication, and dependence between the different components of the system.

From a complexity thinking perspective, these “commonalities” are interpreted as *a self-organized pattern of different nested systems*. Hence, I would argue that the factors provided by the EFA can be considered as *separate nested levels of a complex system* of student retention in higher education (enrolled in physics and associated engineering programmes).

EFA also has the potential to show that some of the components will be present, and have a high enough projection (loading value), in one or more factors. In my study I saw these components as playing a role within, in complexity thinking terms, multiple nested levels, and that the levels’ shared interactions.

Paper I - illustrating the “networked nature” of a complex system in which student retention is a process

Using the respondents’ questionnaire answers, it is possible from the above described analysis method to provide an illustration of the complex networked system (Figure 23). In order to estimate the networked structure for **Paper I**, I used the multidimensional scaling approach. In doing so, I iteratively lowered the cut-off (i.e., higher values) of the calculated similarities until all nodes were connected (as guided by the property of *connectedness*, see Section 4.5). This process is illustrated in Figure 23a-e. I call this visualization an illustration – the networked model had many of its less important components removed in order to make it possible to get to “see” the more important components and connections. At the same time I argue that my illustrative model has the possibility to contain complex interrelationships (due to its networked nature) and structures for differentiation in information feed-back and feed-forwards (as shown by the closeness centrality and betweenness centrality analysis – see Figure 24). My illustrative model can thereby be seen to contain “structural affordances” for all the components that emerge to impact on student retention – even though every part of the network has the possibility to have an impact on retention, the main impact of all items in the analysis is theorized to be through the indirect influences of other constructs.

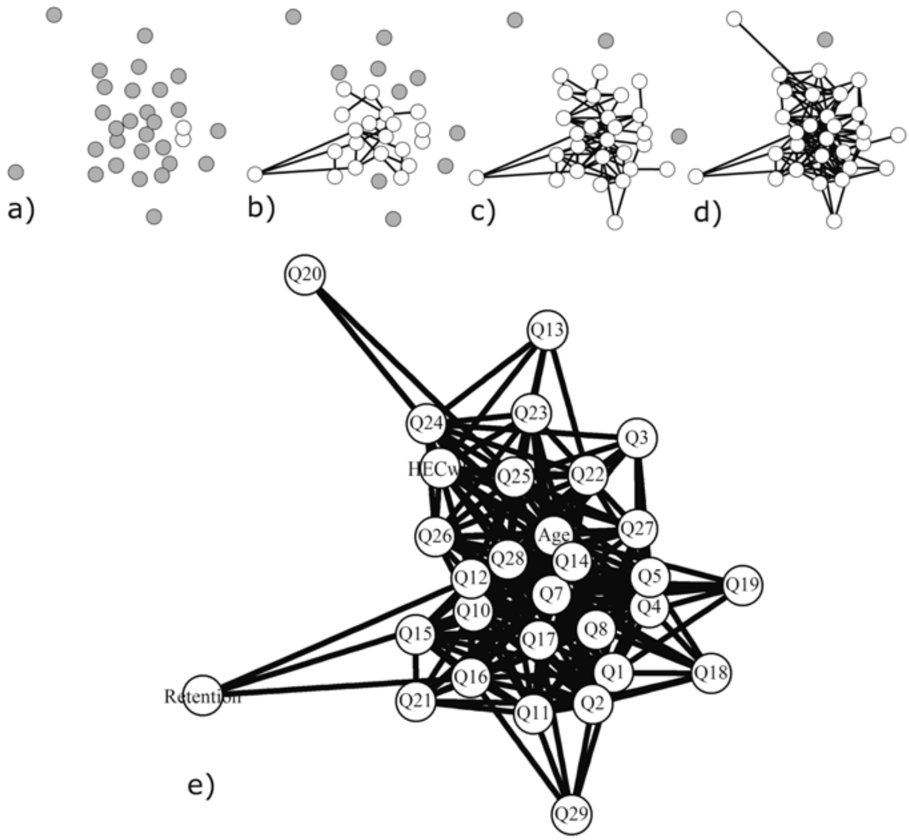

Figure 23. Top, from left to right: Iteratively changing the similarity value to find a cut-off when all nodes are connected [(a) 0.05,(b) 0.1,(c) 0.15, and (d) 0.2], where grey nodes are those which are not *connected* in the network. Bottom: (e) Illustrative example of a contour of a complex system of student retention (cut-off of 0.25).

Furthermore, **Paper I** illustrate how the identification of the critical components of this network model is possible through network measurements of closeness centrality and betweenness centrality (see Figure 24). Nodes with high closeness centrality and high betweenness centrality both distribute information effectively to a large proportion of the system. These nodes are in a position of "control" of other nodes' influences on the system. Figure 24 shows nodes that are "close" to other nodes and nodes which have a high frequency of being "between" other nodes. Consideration of this figure (24) reveals that there are seven items with relative high betweenness centrality and closeness centrality. These are (the Q-numbers in the square brackets refer to the items in the questionnaire that was used for the **Paper I** study):

- [Q12] institutional quality;
- [Q7] satisfaction with one's course curriculum;
- [Q25] faculty support;
- [Age] of the students;
- [Q14] students' satisfaction of being at the university;
- [Q10] the feeling of belonging at the university; and,
- [Q28] students' view physics as connected to everyday life.

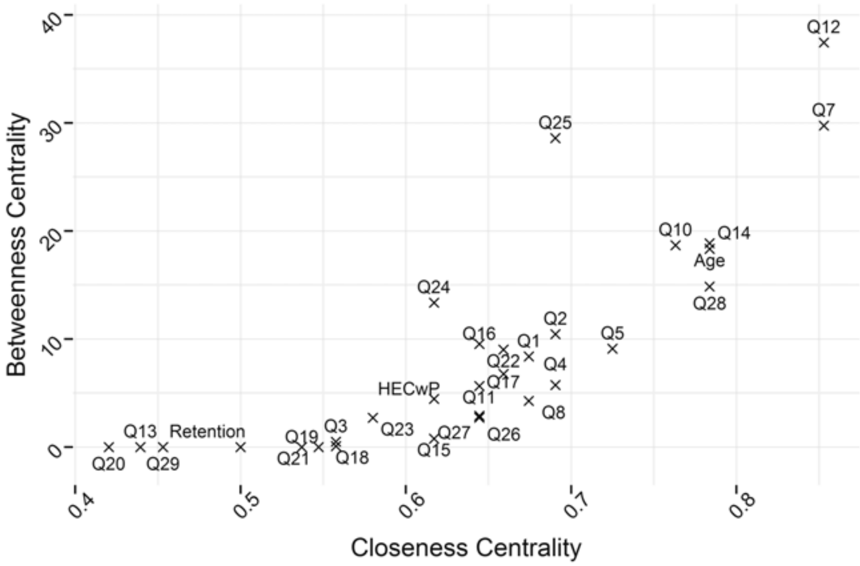

Figure 24. Closeness centrality and betweenness centrality scatter plot of the network created by the multidimensional scaling analysis proximities of items. All numbered markers correspond to the same question number. Marker "Retention" corresponds to the measurement of student retention. Marker named "HECwP" corresponds to students' Higher Education Credits achieved "Within their Programme". Marker "Age" corresponds to the age of the students. Note: Q27 and Q26 are on top of each other.

One item, [Q25], *faculty staff has provided me with the support I needed to succeed in my studies*, stands out because even though the closeness centrality is relatively low, it has high betweenness centrality. I interpret this as meaning that the component may present a possible *gateway for influence*[76] within the overall complex system of student retention.

It is important to note that my analysis uses constructs from both from the Student Integration Model and the Student Attrition Model in a new way. It

[76] A *gateway of influence* could be seen as a component in a networked structure that could potentially cause a cascading effect of influence in the whole system. On the other hand, it could also greatly dampen (or even completely block out) any other influence in the system.

suggests that these components of student retention are not independently incommensurable components, but every construct previously established by these models is a part of a whole. The analysis opens a possibility for new ways of evaluating the different constructs of modelling for their importance to the system as a whole.

If complexity thinking was not applied in the analysis of the data set, the analysis could easily end up only paying attention to the factors which are close (i.e., directly linked) to the variable retention; [Q10], “I feel I belong at this university”, [Q12], “My close friends rate this university as a high quality institution”, [Q16], “I am confident I made the right decision in choosing to attend at this university”. This could cause [Q16] to be identified as a very important aspect of student retention, while in the networked analysis it is only in the middle of the closeness centrality items, and has very low ”control” of the information flow in the system (betweenness centrality). Furthermore, other critical aspects of student retention would be ”hidden” in the analysis such as: [Q7] “I am satisfied with my course curriculum”; [Q14] Students’ satisfaction of being at the university; [Q25] faculty support; [Q28] “first year physics courses have been inspiring”; and, the [Age] of the students. In **Paper I**, I conclude that using complexity thinking and the available theoretical tools can show new ways to move forward with research into student retention.

Paper I - illustrating the nestedness of a complex system in which student retention is a process

As student retention has significance on many societal levels and is important at course, programme, and university levels, it is critical that the theoretical framework of complexity thinking is applicable and provides tools to find answers to research questions at different levels of a university.

Analysis of the different items from **Paper I’s** questionnaire was used to create a model of a nested system. This was to illustrate how different parts of a complex system of student retention could be considered levelled or nested within each other. To create such an illustrative model[77], I analysed the multidimensional structure of the data set from **Paper I** using EFA to explore the possible nested structure of a complex system.

The criteria I set (see Section 5.5 and **Paper I**) resulted in me getting four factors to emerge from the EFA. For illustrative purposes, I characterized them as follows: Degree Programme Components (Factor 1), Social Components (Factor 2), Institutional (quality/reputation) Components (Factor 3), and Support Components (Factor 4). My interpretation of the factors from the EFA was guided by network theory and complexity thinking. Thus, each

[77] It could be argued that the data analyzed in **Paper I** may not contain a sufficiently large sample size for a stringent EFA, thus the characterization of the different identified systems is an illustrative example.

factor got to be characterized as a networked component, meaning "a group of nodes that are mutually interconnected." (Proulx et al., 2005, p. 345).

According to complexity thinking, nested systems have fuzzy borders, meaning that these can share components. Thus, I analysed adjacency using the number of items they share – see Table 8, viz: Factor 1 shares two items with Factor 2; Factor 2 shares five items with Factor 3 and one item with Factor 4; and, Factor 3 shares one item with Factor 4.

Table 8. *Factor loadings from the EFA. Light grey shading denotes the items that have a loading above 0.32 in more than one factor.*

Item	Factor 1	Factor 2	Factor 3	Factor 4
H.E. credits programme (HECwP)			0.542	
Retention			0.934	
Q1. Best university programme	0.788			
Q2. Family approval		0.472		
Q3. Satisfied with finances				0.836
Q4. Finances - focus on studies				0.833
Q5. Finances - teacher demands				0.796
Q7. Satisfied with curriculum	0.328	0.458		
Q8. Close friends encouragement		0.580		
Q10. I belong at my university		0.637	0.447	
Q11. Future employment	0.464	0.390		
Q12. My close friends rate this institution as high quality			0.313	
Q14. Satisfied with experience of higher education		0.687	0.411	
Q15. Easy to make new friends		0.842		
Q16. Right choice - university		0.683	0.399	
Q17. Right choice - programme	0.758			
Q19. It is important to get a degree from this programme	0.708			
Q21. Initiation weeks		0.855		
Q22. First year courses fit together				0.459
Q23. Previous knowledge		0.385		
Q24. Clear educational trajectory		0.447	0.396	
Q25. Faculty support		0.345	0.322	0.461
Q29. I intend to re-enroll	0.835			

Complex systems are networked constellations of components, which means that the result can be interpreted as each factor (i.e., networked component) providing the “contour markers” for a nested level. Here, what I did was to visualize and analyse the adjacency of the nested levels (Figure 25, left side) and then rank them by their relative sizes (Figure 25, right side).

A “networked” schema of the links between the different systems (Figure 25, right side) was created. The number of components with a significant loading in the factor is used for a schematic “size characterization” to model the systems as a nested complex system in Figure 25 (left side).

Support Components

The *Support Components* that I obtained from my EFA were mainly composed of financial attitudes and satisfaction, university reputation, and family support. The financial aspect is central to the Support Components in this model. Three items in the questionnaire asked students about their financial situation and the most important influence on the complex nested system of student retention was found to be students’ feeling that their financial situation gives them the freedom to focus on their studies. As mentioned earlier, financial impact has empirically been found to be significant in earlier attempts to model student retention (for example, see Cabrera et al., 1993; Paulsen & John, 1997).

Although the item corresponding to the students’ families had a loading (0.314) below the cut-off (0.32) and thus did not meet the loading criterion for EFA, I still consider it to be an influence in Support Components. Earlier research such as Bean (1982), Spady (1970; 1971) and Bean and Metzner (1985) have proposed that family approval is a part of the reason why students continue their university studies.

Through its orientation in the nestedness of a complex system of student retention, Support Components has the largest time scale for change. In this model, Support Components is closest to, and has the greatest influence from other components of society[78]. Furthermore, there is a weak link between Support Components and Social Components, as they share the item *faculty[79] support* (see Table 8 and Figure 25, right side).

[78] Since there were no such components in the data set, this conclusion is theoretically based.
[79] Faculty here refers to all staff at a university.

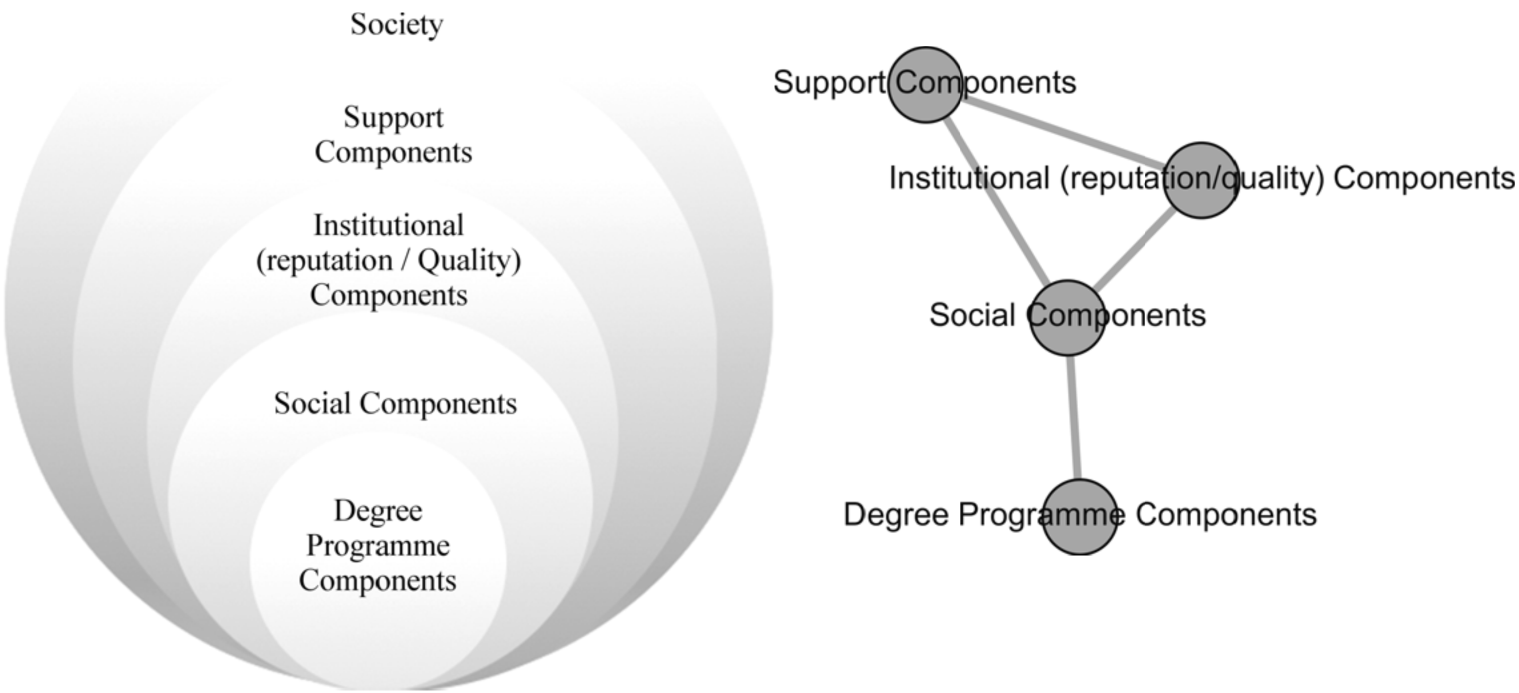

Figure 25. Two schemata of complex systems of student retention in higher education. Left side: A way of visualizing the nestedness of the complex systems. Right side: A way of visualizing the complex systems' networked adjacency.

Social Components

The *Social Components* that I obtained from my EFA are made up of parts of the everyday life of individuals that make up the university experience for a student, for example, students, teachers and the social spheres that they inhabit. Making new friends (Spady, 1970; 1971; Tinto, 1975; 1987; 1997; Bean & Metzner, 1985), the "initiation" period at the start of university, friends' encouragement to continue with one's studies (Bean, 1980; Stratton et al., 2008) and a general sense of "satisfaction" (Kuh & Hu, 2001) are all important Social Components. The item *belonging* is also a part of this nested level which could indicate that social connections with both fellow students and teachers are important to fostering a "feeling of belonging" at the university (also see Tinto, 1975; 1987; 1997).

The classroom experience of learning has also been found to be important by other researchers (for example, see Lasry et al., 2008). Having university courses that "felt like" a continuation of one's pre-university schooling plays an important positive role in student retention. This outcome resonates well with Tinto's (1975; 1987; 1997) conclusion that "prior schooling" experience is strongly connected to student retention.

Social Components has its strongest connection to Institutional (reputation/quality) Components. Social Components are also weakly connected to Support Components by sharing one item in the results of the EFA: students' feeling that they are satisfied with their course curriculum, and students' feeling that their degree will be important for them for future employment.

Institutional (reputation/quality) Components

Successfully completing the courses that are a part of a programme is typically part of the formal requirements to continue to the next year of study in a programme. The students' course completion and thus achieving whatever credit that is needed to pass a course, is a part of *Institutional (reputation/quality) Components*. By successfully completing the courses, students decrease the risk for what Tinto (1975) calls "academic dismissal".

At this point I need to contextualize this to Sweden where no direct academic dismissal is allowed. Here, programmes have courses that have prerequisites, which if not successfully completed become obstacles to programme progression. Then, the consequences of such a lack of stipulated academic progress leads to a loss of financial support from the Swedish government. This may be why my modelling shows that if students successfully complete their programme courses, the tendency is for them to continue to progress in their programme.

A well-recognised component that has emerged from other student retention research is the "feeling of belonging" at the university (for example, see Tinto, 1975; 1987; 1997; Bean, 2005). In my analysis, belonging is also part of Institutional (reputation/quality) Components. Aspects of belonging at the university, such as being satisfied with the experience of higher education, and students' feeling that they made the correct choice in choosing a particular university, are also a part of Institutional (reputation/quality) Components. The students' feeling of belonging is also strongly connected to Social Components.

From my analysis, I also found that the students' friends' sense of the university's reputation emerged as important, which confirms the results reported by Sung and Yang (2008).

In my modelling outlined in **Paper I**, faculty support is also a part of Institutional (reputation/quality) Components. Such faculty support and faculty interactions are aspects that have been connected to student retention for a long time (for example, see Astin, 1977; Hovdhaugen & Aamodt, 2009; Spady, 1970; 1971).

Institutional (reputation/quality) Components has its strongest connections to Social Components through sharing the following five items from the results of the EFA: students' feeling of belonging at the university; students being satisfied with the experience of higher education; students' feeling that they have made the right choice of university study; students' having a clear educational trajectory; and, students' feeling that the faculty is supportive.

Degree Programme Components

This level contains items that link the students' attitudes about their degree programme and their experiences of higher education. Degree Programme Components is made up of six items relating to programme choice, and degree importance: students' views about their own programme; their choice to study in the particular programme; their satisfaction with their course curriculum (comparable to Cabrera et al., 1993); the importance of a degree (comparable to Bean, 1980; Tinto, 1975; 1987; 1997) from a particular programme, that the degree will secure future employment (comparable to Bean, 1980; 2005); and, students' own plans of re-enrolling in the programme (comparable to Bean, 1980; and to Braxton, 2000). As illustrated in Figure 25 (right side), Degree Programme Components, is nested within Social Components, Institutional (reputation/quality) Components, and Support Components, which implies[80] that Degree Programme Components has the shortest time scale for change.

[80] In complexity thinking, it is argued that "smaller" complex systems have a faster rate of change (See Section 4.5 on *nestedness*).

7.3.2. **Paper II** - establishing a model of the system[81]

Rationale for the method development presented in Papers II and III

Paper I illustrated how a complex system, in which student retention is a process, can be analysed through the lens of complexity thinking. I make a case in **Paper I** for appreciating the usefulness of using a complexity thinking perspective and also identify two areas that need to be developed in future research: the sample size and the methodology.

The theoretical and empirical foundation that I presented in **Paper I** and in Section 7.2 implies that answering Research Question 1 must logically be linked to the limitations[82] of gaining insights about this multilevel nested system. Rahmandad et al. (2009), Sterman (1994), and Davis and Sumara (2006) all argue that to learn about complex systems and their dynamics it is critical to initiate, or simulate, action in such a system and to then collect the feedback from this system. However, to do this in real-time in the educational system would have serious limitations, as previously discussed in Section 4.7. The most critical of these would be the time required for changes to have effects. Thus, I wanted to create a model of the complex system in which it was possible to simulate action.

My first attempt to create such a model of a complex system is found in **Paper I**. Here, I explored if the statistical techniques that are common in Physics Education Research, Multidimensional Scaling and Exploratory Factor Analysis, could suffice. However, at that point in time, creating such a representation that covers both nestedness and, at the same time, also captures the networked structure of a complex system proved to be impossible using only one method. This is because the Multidimensional Scaling method proposed in **Paper I** could only estimate an un-weighted network with no way to differentiate between important and unimportant links. Further, my EFA method proposed in **Paper I** could only identify different nested levels. Combining the two methods could not be done because editing and changing these two methodologies in the statistical environment (SPSS) I was using at the time is not possible[83]. However, in **Paper I**, I was able to show and argue for a complex system approach and its usefulness to frame thinking about student retention. I was also able to show how the interrelationships between nested levels, as well as aspects that are critical to student retention, get brought to the fore in the interpretation of the methods used.

In summary, this sub-section has provided the rationale for the method development presented in **Papers II** – strengthening the sample size and

[81] Empirical data described in Chapter 6, and **Papers II** and **III**.
[82] Limitations of gaining insights about Complex Systems is discussed in Section 4.7.
[83] This was the main reason for me changing my statistical platform to **R**. In this environment, the methods are available in **R** code for editing, while also being able to draw on several methods, or implement them yourself, in order to fully explore and tweak the possible methods for a given problem.

developing suitable methodology to analyse both the nestedness and, at the same time, capturing the networked structure of a complex system in which student retention is a process. This is done in the next sub-section.

Paper II – creating a representative model

In order to create a representative model in which to implement institutional action aimed at enhancing student retention, **Paper II** presents a new and novel way of approaching this goal – the Multilayer Minimum Spanning Tree (MMST) analysis (see Section 5.4.4 and 5.4.7). In Section 5.4.6, the commonly used statistical techniques were compared and contrasted with the methods for **Papers I** and **II.** And, significantly, I found my MMST approach to have greater accuracy for detecting true[84] links between nodes.

Thus, in **Paper II** I use MMST analysis to establish a networked model of the system that I identified and described in **Papers II** and **III** (Figure 26 shows the estimated network structure that I describe in both papers). The underlying model of Figure 26 serves as my first step towards gaining the insights needed to simulate action in the system.

[84] An estimated link that was present in the original simulated network, see Section 5.4.6.

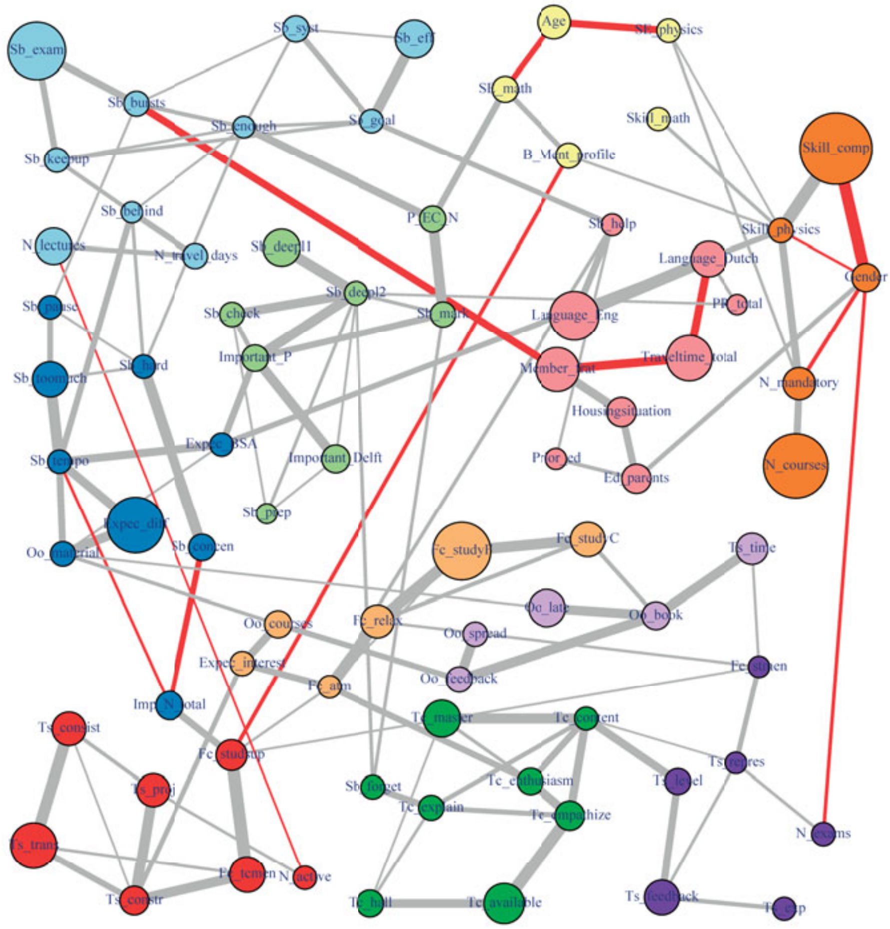

Figure 26. Figure of the identified networked structure of aspects which has previously found to influence student retention. The widths of the links represent how stable the links are, with thicker lines indicating more stability in the structure. Grey links are positive edge weights and red links are negative edge weights. The size of the elements represents the inverse Topological Diversity, where large elements have low Topological Diversity and small elements have high Topological Diversity. The visualization removed the 15% lowest edge weights. The colors represent clusters (infomap algorithm [Rosvall & Bergström, 2008]). The aspects (node labels) are described together with the relevance of including each particular aspect in **Paper II**, Appendix 2.

To explore and discuss the possibilities and limitations of institutional action to enhance student retention I used the edge weights (the widths of the links, see Section 5.3.2) of the created model (summarized in Figure 26) to characterize scale (in)variance, which is done in **Paper II**. The role that scale (in)variance played in my exploration and subsequent discussion of the possibilities and limitations of institutional action aimed at enhancing student retention needs to be discussed because I see such structures being able to reliably function in a way that is similarly to how the complex system could function. I do this in the next sub-section.

Paper II – development and characterization of scale (in)variance

Paper II presents a way to interpret the weights of the links in relation to nestedness through a concept I call *scale invariant structures*. As I pointed out at the end of the last sub-section, the relevance of *scale invariant structures* comes from the fact that these structures would function similarly in most nested levels. This makes them ideal targets for institutional action. The logical dichotomy, *scale variant structures*, would result in a system dynamic that functions differently across different scales. This means that targeting this kind of dynamic would, to some extent, always have varying resulting effects.

Such scale invariant structures can be characterized as relationships between aspects of a system that are stable across different level of analysis. Earlier I pointed out (see Section 7.2) that my separating of the levels of a nested complex system was based on the difference in scales on the different levels – for example, a student, a course-network, and a department. In the MMST analysis, different random sized sub-sets of the data set are used to create a correlation matrix. This correlation matrix is then re-formulated into a distance matrix where, using the fewest number of links and the lowest edge weights (distances) possible, minimum spanning trees get generated to link all elements. In this process, over several iterations of the algorithm, different edges are identified. The frequency that each possible edge gets included in the spanning tree determines the *strength* of connection between two elements. If the same link is detected in all MSTs that make up a MMST, then the link is *not* dependent on (1) the groups of students, nor (2) the size of the sub-sets used. This, however, does *not* imply that a *particular aspect* is scale invariant, only that certain specific links are stable.

In order to characterize an *aspect's* tendency towards scale invariance, **Paper II** uses a mathematical model drawn from social diversity. This model is split into two distinct concepts: Topological Diversity[85], and Cluster Diversity[86].

Topological Diversity illustrates the range of scale variance for the elements of the system ranging from 0 to 1 (to characterize being from most scale invariant to most scale variant). My literature search in this area indicates that this is the first time that the diversity in the different levels of a complex system has been reported being examined in this way – see Figure 27, which shows that, for my analysis, there is a broad range of elements with medium Topological Diversity and only a few elements in the low and high ends of the distribution of Topological Diversity.

[85] See background and calculation of this concept in Section 5.3.2 on p. 90.
[86] See background and calculation of this concept in Section 5.3.2 on p. 90.

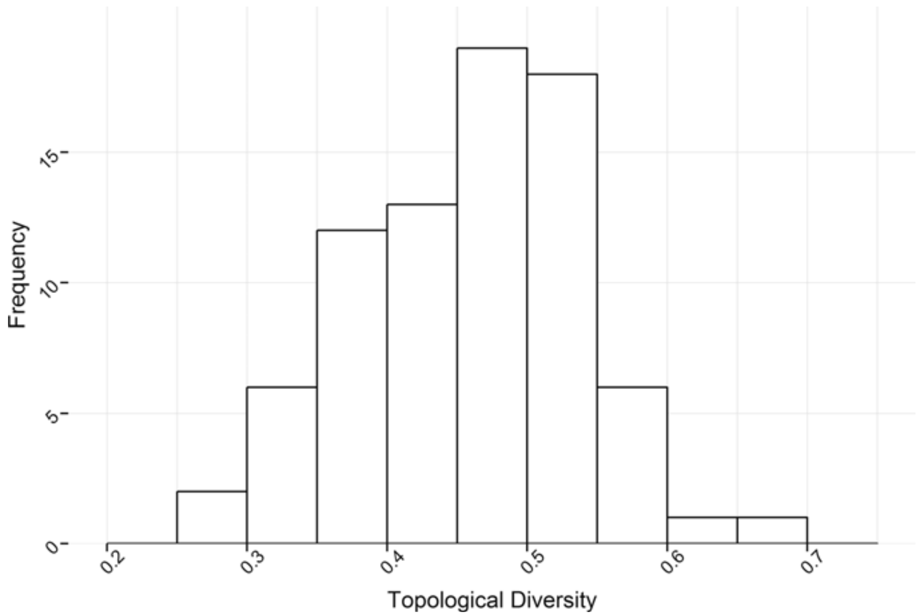

Figure 27. Distribution of the Topological Diversity calculated for **Paper II**.

From this characterization of scale invariant aspects an important ramification for the implementation of student retention action may be identified: deciding to use an "arbitrary" set of aspects of student retention for action has a high chance of being both partially scale invariant and partially scale variant. In other words, while some effects might be reproducible and function as expected, a significant portion of the effects will most likely become very sporadic and, in some cases, end up being *completely random*. This would explain many of the contradictory results reported in student retention research[87]: the reported application of these "arbitrary" aspects can often be seen, to some extent, to be scale variant, and because of this, the effects were unable to generate the needed stability in the given system.

The introduction of the concept of scale invariance therefore adds a new dimension to the discussion of "what works" in student retention. The successful, although contradictory, implementations of methods to enhance student retention should not be put against each other in terms of "right and wrong", but should be seen to imply that the chosen targeted aspects are most likely inherently scale variant. In other words, the seemingly contradictory results can then be due to the nature of the studied systems and/or the targeted aspects.

Paper II also introduces the concept of *Cluster Diversity*, which is characterized as an indication of the "potential reach" of an aspect to have influence in more than one cluster of aspects. For example, aspects can function

[87] See overview on inconsistencies in student retention modelling in Section 3.3 on p. 56.

as links between, for instance, students' study behaviours and students' experiences of teachers' expertise. Theoretically, aspects that are scale invariant and also have the potential to have system wide influence should be the ideal targets for institutional action that aims to enhance student retention. However, the results of my analysis for **Paper II** identified *no such aspects*. This implies that designing institutional action to enhance student retention has trade-offs between possibilities for system-wide influence and scale invariance. And these need to be recognized and taken into account in any action planning and implementation.

Paper II presents a more sophisticated methodology than **Paper I.** This is why the claim made in **Paper I,** that to enhance student retention is to direct action towards identifying the most influential aspect to change, gets refined in **Paper II** as follows: enhancing student retention effectively means to direct institutional action towards identifying the most influential *scale invariant* aspects in each cluster of components in the system (in my Figure 26 example, the clusters are indicated by colours). In other words, from a complexity system perspective, institutional actions targeting only scale invariant aspects to enhance student retention would then mean that it is very likely that a targeting of multiple elements of the system is needed. However, many of these aspects can easily be beyond the reach of change unless the needed system-wide perturbations are acceptable and doable. Due to this, it is possible to argue that action plans of universities to enhance student retention easily get postponed, or abandoned, or modified in unproductive ways. Furthermore, any action aimed at only a handful (or sometimes only one) of elements of the system of student retention is also very unlikely to end up having a significant impact on student retention.

In summary, I repeat my conclusion that these insights surely provide a significant proportion of the explanation for why so many efforts at enhancing student retention have had such limited success. And, that there is a need for a much wider-ranging set of actions in the light of the links found between the elements of the system.

7.3.3. **Papers II** and **III** – Initiating change in the system[88]

In the previous section I used my results to argue that targeting a wider-ranging set of scale invariant aspects is needed for *any* student retention action plan to have reasonable possibility for success. As argued in Section 7.3.2, the first step towards identifying an effective set of wider-ranging actions is to simulate action using my refined model that is given in **Paper II**.

As I discussed in Section 4.7 and 4.9, there are generally two ways that I see it being possible to simulate the kind of change needed in the complex

[88] Empirical data used described in Chapter 6 and **Paper III**.

system of student retention: (1) using a Schönian *Virtual world* exercise; and, (2) using generalized computer simulations that are built on student retention research. The Schönian *Virtual world* exercise is discussed briefly in **Paper II**, and computer simulations in **Paper III**.

Paper II - Virtual world

Paper II makes the case that the visualization given in Figure 26 in my thesis can be fruitfully used as a representative model for a *Virtual world.* In so doing, in **Paper II,** I also show that the representative model in Figure 26 facilitates new possibilities for potential institutional action that is aimed at enhancing student retention: the visualization can provide a basis for discussion of proposed general and localized possible targets of institutional action that engage practitioners.

A university will have a range of practitioners, such as policy makers and implementers, who will have had valuable extensive experience working with issues related to student retention. It is possible for these practitioners to bring their knowledge to engage with the kind of representative model that I created for **Paper II** as a *Virtual world*. I envisage that they would do this by "interrogating" different parts of the system and their relationships (also see Sterman, 1994). In this way I anticipate that they would also be learning about the complex system nature of student retention. Obviously these practitioners would need to bring some knowledge about how the representation was made and its advantages and implications to such a *Virtual world.*

The *Virtual world* that I am proposing is made possible because the visualization I created shows that critical aspects of student retention are all interlinked and that it offers the possibility to meaningfully explore what the outcome of a particular action might be. This means that it makes it possible to change selected aspects of student retention and see what the resultant changes then afford student retention – what (and how) interlinked aspects are likely to be affected. At the same time, it becomes possible to notice what the effects may be, such as, hypothetically reducing or increasing edge weights between aspects and how this may affect the uncertainty level associated with a given student retention aspect.

While such a representative model can help with contemplation about what impact institutional actions might have, Sterman (1994) stresses that the use of *Virtual world* still present unsolvable complications when it is used to explore the implementation of certain actions. This is due to what is known as "game playing" (this term characterizes the kind of situation that arises when agents/components within the system start to follow private agendas or local incentives).

Before moving on to a discussion on using computer simulations to estimate outcomes of proposed student retention action, I need to point out that in Chapter 9 on future work, I argue that empirical exploration of how networked visualizations can be used as a *Virtual world* is needed (see, for example Figure 26). For this, **Paper II** provides the framing needed.

Paper III - computer simulation[89]

The theoretical claim that I made in **Papers I** and **II** and summarised earlier is that the effective enhancement of student retention calls for directing institutional action towards the *scale invariant* aspects identified as being the most influential in each cluster of components in the system so that they get to be explicitly addressed. My **Paper III** builds on this by investigating the likely effects of such changes when examined through empirically-based computer simulations of a computer-generated "ideal" educational system.

For **Paper III** I developed a method to simulate change using the networked representation[90] that I created as a skeleton for **Paper II**.

There are generally two ways of constructing a skeleton for system simulation of processes within higher education physics and related engineering – one theoretical and the other empirical. The program proposed by Sabelli et al. (2013) represents an attempt to construct a skeleton from a theoretical standpoint. A problem with this kind of approach is that any simulation of such a system will result in the outcomes of the skeleton being limited by the theory itself. This is because the conclusions drawn are only as reliable as the assumptions made in the underlying theory.

In the spirit of the framing of my thesis, I argue that choosing an appropriate simulation must take into account the nonlinear feedback and interaction effects that are present in higher educational systems (also, see Davis & Sumara, 2006; Sabelli et al., 2013). This is critical since without such a framing for a simulation, realistic and meaningful "what if" questions simply cannot get posed. To pose such questions, it is essential to allow for multiple parts of the system to adapt to the suggested implementation. For a simulation such as the one I discuss in **Paper III**, the students' course completion has to get chosen as the target to enhance. This is because it is an integral part of student retention[91].

Because of the nature of the system, not all aspects can be changed. The critical aspects of student retention, as measured by the instrument detailed in Section 6.2.2, were divided into three categories (see Table 9): the constant (consistent) category; the first-order variable category; and, the second-order variable category. Those aspects that cannot be changed in a reasonable time-period, such as parents' education, constitute the constant category. The first-order variable category is constituted by aspects that are possible to

[89] To add coherence to the thesis, the description given in this section is largely a repeat of the introduction given in **Paper III**.
[90] **Paper II** and Section 7.3.2 (p. 136).
[91] See Chapter 3 on Student Retention, on pp. 42 - 56.

change (within reason), while the second-order category consists of aspects that can only be changed by changing adjacent aspects.

Table 9. *Three categories of critical aspects of student retention.*

Constant Category	First Order Category	Second Order Category
Students' age	Teacher expectations	Re-enrolment expectations
Stem profile combination*	University facilities	Students' experiences of university facilities
Students' parents' education	Scheduling	Degree importance
Students' biological gender	Course materials	Language skills
Students' housing situation	Teacher behaviours	Fraternity membership
Students' impairments	Travel time to campus	Course materials
Students' exposure to university PR	Assessment and feedback	Study behaviour
Students' prior education		Students' self-evaluated skills
Previous achievement in mathematics		
Previous achievement in physics		

* see details in **Paper III**, Appendix S1.

In order to estimate influence and uncertainty of a change for a given aspect in the target, Gibbs sampling[92] was undertaken in the networked system. This Monte-Carlo methodology estimates the conditional probability for values of unknown elements in the network based on chosen values of other nodes. It therefore can be used to determine the likely change in one node based on forced changes in another.

Each update of Gibbs sampling involves the estimation of all interrelated aspects in a random order. My Gibbs sampling process ran for 60000 iterations with a burn-in period of 1000 and with a thinning of 100 (for more on this see Section 5.6.2). The estimations that I obtained represent the quantitative improvement of the target aspect when a source aspect is improved from 20% below to 20% above the average of the measured aspect.

The resulting estimations were compared with the estimated standard deviation of each aspect. These can be interpreted in terms of the following – targets that show greater potential for bringing positive change tend to have a larger span of possible resulting effects.

[92] See Section 5.6.2 (p. 105) for the use of the Gibbs sampler.

Table 10. *Results from the Gibbs Sampling from **Paper III**.*

First Order Aspects	Estimated Change (%)	Estimated Standard Deviation (%)
Teacher expectations - Expec_difficulties	11	30
Course materials - Cm_material	9	32
Teacher behaviours - Tb_empathize	8	30
Teacher behaviours - Tb_content	8	30
Course materials - Cm_feedback	8	30
Course materials - Cm_late	7	30
Teacher behaviours - Tb_enthusiasm	6	29
Teacher behaviours - Tb_explain	6	30
Assessment & feedback - Af_level	6	30
Assessment & feedback - Af_constr	6	30
Teacher behaviours - Tb_available	5	30
Teacher expectations - Expec_interest	5	28
Scheduling - N_lectures*	5	80

Note: Only aspects where effect sizes have a >5% mean positive estimated effect is reported.
*Highly unstable.

Table 10 shows estimations of the most influential aspects. Of note here is the high variance of the effect estimation of the number of lectures [labelled N_lectures]. N_lectures is the number of scheduled hours of lecture during the first year. In Figure 26 it is possible to see that this aspect is negatively related to the number of days that students need to travel to campus and to the number of scheduled hours for active teaching formats, such as project works and practicals. This would suggest that increasing the number of scheduled hours for lectures would require students who commute to spend more time travelling thereby reducing the number of hours scheduled for learning sessions. This suggests that it is possible to see how an estimated effect may result in a positive or negative influence on the credits obtained, however, not in a consistent way (resulting effects).

An interesting question then arose for me: How did my Gibbs sampling estimations relate to other research? The largest estimated effect comes from improving teachers' ability to deal with students' expectations [Expect difficult], which relates to students' experience of teachers' feedback on how students are doing in their courses. Teacher feedback (especially feedback that deals with students' expectations) has long been recognised as an important factor for student learning outcomes within the field of educational research. From the network estimations, the most likely effects associated with improving teachers' abilities to deal with students' expectations is that they would positively affect students' study behaviour (particularly dealing with the experienced pace of study in a course).

In Figure 26, it is shown that the strongest connections to students' credit-achievement are their study behaviours. These results are consistent with the results obtained in other student retention research, such as those dealing with the positive influence from course materials and scheduling

[Cm_material, Cm_feedback, Cm_late, and N_lectures] (Bean, 1980; 1981; Yorke & Longden, 2004). Also, from the viewpoint of integration of students into the academic system, I see teachers' behaviour in handling students' difficulties and interests [Expec_difficult] as a way to contribute to students becoming integrated into the rules, norms, and regulations of the university (Tinto, 1975; 1982; 1987). I also see student ↔ faculty interactions, such as teachers being available outside of the classroom [Tb_available], having a large positive (see, for example Nora, 1987; Pascarella & Terenzini, 1980). I see all of these examples as being part of what I have called social and academic integration, which occurs mostly through semi-formal extracurricular activities and interaction with faculty and administrative personnel (also, see Tinto, 1975; 1982; 1987; 1997). As described earlier in Section 3.2.2, empirical findings suggest that not only the frequency, but also the quality of the interactions between students and faculty has an impact on student retention. This can be observed in the estimated effect of teachers' enthusiasm (see category [Tb_enthusiasm] in Table 10) as well as being available outside of the classroom, see category [Tb_available] in Table 10.

First-year retention has also been found to be strongly related to an institution's ability to inform students about its expectations and rules, and the fair enforcement of these rules. Especially important is that assignments and grades need to have clear goals and transparent assessments (Berger & Braxton, 1998). This can also be found because the experienced level (see category [Af_level] in Table 10) and experienced usefulness (see category [Af_constr] in Table 10) of the feedback is estimated to have a positive influence.

The approach that I put forward in **Paper III** enables the effective identification of successful and stable initiatives within higher education physics and related engineering that affect students' credits achieved and thus student retention – something that has been lacking in the literature up until now. I would also argue that the congruency that my work has with previous research in student retention suggests that the methodology has validity for the context studied.

The results in **Paper III** can be compared to the claim I put forward in **Papers I** and **II** – *to enhance student retention effectively means to direct institutional actions towards identifying the most influential <u>scale invariant</u> aspects in each cluster that need to be addressed*. It may be noted that the identified influential aspects in **Paper III** do not have a one-to-one relationship between the invariant aspects as identified in **Paper II**. However, the aspects identified in **Paper III** all fall in the middle of the scale between scale invariant and scale variant as per **Paper II**'s identification. I interpret this to mean that these aspects have both a scale invariant component and a scale variant component. This can be seen in Table 10 through the moderately high standard deviation for achieving an outcome when improving these.

Further, the aspect related to scheduling (category [N_lectures] in Table 10) is found, through the analysis in **Paper II,** to be at the high end of the scale – that is, basically scale variant. This scale variance is shown by the aspect being estimated to have a high standard deviation in its likely effects (meaning that changing scheduling may have very different outcomes for different students). It is through all of the above cases that I am able to confidently argue that **Paper I**, **II**, and **III**'s results are comparable with each other.

7.3.4. A succinct answer to Research Question 1

In summary, in order to answer Research Question 1, I crafted and tested (theoretically and empirically) two methodologies, computer simulations and Schön's *Virtual world*. Both of these take into account the *nature* of the system that needs to be improved in order to establish how the modelling of outcomes of actions within a complex system can be used to inform student retention action. All of the discussion in Section 7.3 presents the new theoretical and methodological foundation that I created for the modelling of the core issues of student retention in higher education physics and related engineering education. In other words, I have provided two new methodological approaches to answer my Research Question 1: *In order to explore viable options for real world practice to enhance student retention, how can an informative modelling of action within the complex system be established?*

Based upon the discussion in Section 7.3, I go further and argue that my work also presents a generalizable and adaptable methodology for identifying complex interactions for educational systems. By this I mean that I have presented a new way for doing educational research in general, and Physics Education Research in particular, into how manipulations of system parts may affect educationally significant outcomes.

7.4. Results for Research Question 2

Answering Research Question 2, builds on the research questions answered in **Papers IV** and **V** – see Table 4 (p. 79) for the links between the research questions in **Papers I** through **V** and the research questions answered for this thesis.

The answer to the first part (Sections 7.4.1 and 7.4.2) of Research Question 2 builds on **Paper IV** where I situated the core constructs of student retention in complexity theory and related this to an empirical study of student interaction patterns within two courses. The answer to the second part of Research Question 2 (Section 7.4.3) is then built on **Paper V** where I show how a division between the social and the academic networked interaction of students can be used to predict students' grade achievement in a course.

Answering Research Question 2 represents a case study that covers a small cross-section of the studied system, whereas Research Question 1 was answered on a system level. As such, Research Question 2 represents a study that is closer to the university physics-teacher and related engineering classroom setting.

7.4.1. **Paper IV** - situating core concepts of student retention research in complexity theory

This section starts by relating the core concepts of student retention to network theory (see Section 5.3) through the concept of social systems (see Section 4.8). I do this because the discussion that follows essentially forms an integral part of the story needed provide an in-depth answer to the first part of Research Question 2. I begin by discussing the relationship between the foundational constructs of student integration from student retention research and the concepts of adaptation from complexity theory, as indicated in Section 3.4 in this thesis.

As pointed out in Chapter 3, throughout the history of student retention research the idea that student retention needs to be situated within a complex system perspective has been tacitly acknowledged. Like complexity, social networks have been present, but also in the background, in the development of theoretical models used to understand student retention. This is especially apparent in the work of Tinto (1975; 1987; 1997) who recognized that student retention research needs to employ "network analysis and/or social mapping of student interaction... [to]...better illuminate the complexity of student involvement" [1997, p. 619]. Recently, research has indicated that the number of possible social links to other students is of significance when predicting academic fit (Rizzuto et al., 2009) (i.e., students' congruency with the academic system). Further exploration of peer effects in random housing allocation for college has shown that the person with whom you share a room with during college years tends to have an effect on GPA scores (Sacerdote, 2001). However, these effects diminish over time (Sacerdote, 2001). When examining effects on previously identified critical constructs from student retention research, the structure of the social networks can even have significant negative effects on retention and related constructs (Thomas, 2000). At the same time, it has also been recognized that students' social networks can be a source of both support and stress for students (Maundeni, 2001). These effects are clearly not linear, however, hitherto, complexity theory together with social network analysis has not been employed to examine the structure of students' social networks and academic networks as resulting from *two* sets of *social systems* –the social system and the academic system.

My in-depth examination of the foundational work of Spady and Tinto from a complexity theory perspective led me to conclude that it is the conceptualization of the nature of adaptation that distinctly differentiates Spady, Tinto, and complexity theory. While Spady (1970, p. 41) accepts that the outcome of the adaptation from his model – "normative congruence" – is a multifaceted concept, I found that he depicts the student essentially as an active agent within a static environment. For example, he argues that students' interactions within the university "provide the student with the opportunity of assimilating successfully into both the academic and social systems of the college" (Spady, 1970, p. 77). The notion of a static environment is also what Tinto describes when he claims that in the process of student interactions a student will "… continually modify his [sic] goal and institutional commitments in ways which lead to persistence and/or to varying forms of dropout" (Tinto, 1997, p. 94). From the point of view of complexity theory, adaptation is a co-dependent construct between both the individuals and the systems in which the individuals are situated. Hence, it is not only the students' adaptation to the institutional environment that is critical, but also the institutional environment's adaptation to the students[93].

Since the institutional environment is made up of the social system and the academic system of the university it is proposed here that these systems can be analytically viewed as complex systems. By giving consideration to Spady's and Tinto's characterization of the social system and the academic system that I discussed in Section 3.2.2, and comparing these with a complexity theory perspective, the social system and academic system can then be characterized as consisting of what Sawyer, in his reading of Durkheim, called *social facts* (see Section 4.8). Examples of these could be agency, intention, discourse patterns, collaborations, sub-cultures, norms, beliefs, and expectations (for readability these social facts are taken to be equivalent to *rules of interaction*).

These rules of interaction, divided into the realms of social life and academic life within an institution, form and are formed by social interactions and academic interactions between students, staff, and faculty, thus creating two systems of rules: the social and the academic. Furthermore, due to these interaction types being ubiquitous, the two types of interactions can be seen to be continuously creating two entangled and ever-present systems. From a complexity theory perspective, the *emergence* of a *social* and an *academic system* is dependent on interactions within the system, while at the same time

[93] The institutional adaptation must be admitted to be a slowly responding system and may well have been even slower moving in the time of Spady than it is today. So perhaps the static environment assessment may not have been that unrealistic at that time. The fact that universities are now more interested in the topic of student welfare does support the idea that there is at least a willingness to become active. Certainly institutions' adaptation is limited because of the debate and potential costs involved. Whether institutions become more active agents remains to be seen.

the interactions within the system are dependent on the two component systems. Thus, there are recursive adaptations between student interaction and system structure. In other words, the networked interactions, the social system, and the academic system are all co-adapting. Therefore, differences in the structure and dynamics of the social system and the academic system should influence structures and dynamics of the networked interactions of individuals who are participating. This leads to the formation of a social network and an academic network (that are nested within a larger combined network), and the co-formation of the social and academic systems.

In summary, this section argues that the structures of students' interaction networks are tied to the core concepts of student retention research – the social system and the academic system. This leads to an investigation that only covers *one level of analysis* – students' course interactions – that, theoretically, has minimal influence from other neighbouring nested levels (see Section 4.5).

7.4.2. **Paper IV** - the empirical study of students' networked interaction[94,95]; random or not?

I argued in Section 7.4.1 that there is a theoretical relationship between individual's interaction and the social system that is created as the individuals interact. To explore if this is the case, **Paper IV** illustrates how an empirical exploration into how the processes of network creation are structured. This is done to explore if the processes are similar to random processes, or tend to be structured – i e., is there an empirical relationship between students' interactions and the social systems that are created as the students interact? In other words, is it possible to compare two structured processes of network creation to find differences in the *rules* that construct the network? If so, then it is of paramount importance to do this in relation to exploring the fundamental nature, i.e., social and academic integration, of student retention. Then, physics students' course interaction network is not only of importance when it comes their physics learning (Brewe et al., 2012) but also for their retention. However, if these networks are created randomly and each student has a random position in the network, then a network analysis of students' course interactions in relation to learning, or retention, is limited to being descriptive and does not offer any practical, didactic, or pedagogical implications.

In order to find out if these networks are random in nature, average path length (see Section 5.3.2) was calculated to globally measure how far away students tended to be from one another in each network (Table 11).

[94] To add coherence to the thesis, the description in this section is based on the results section of **Paper IV**.
[95] The Empirical data used is described in Chapter 6 and **Papers IV** and **V**.

Table 11. *Measurements of clustering coefficient and path length of students' interaction networks.*

Course networks	Simulation of random network–mean clustering coefficient	Clustering coefficient	Z-value	Average path length
C1 S + A	0.027 ± 0.004*	0.393	91.5	3.8
C1 S	0.027 ± 0.005*	0.364	67.4	3.6
C1 A	0.026 ± 0.005*	0.247	44.2	4.5
C2 S + A	0.050 ± 0.004*	0.519	117.25	5.4
C2 S	0.041 ± 0.004*	0.424	95.75	4.3
C2 A	0.034 ± 0.005*	0.374	68	2.8

Note: C1 is Course One, C2 is Course Two, S+A denotes the combined network, S denotes the social network, A denotes the academic network, and the asterisk denotes standard error of 1000 random simulated networks of the same size and the same number of links.

Also, calculations of the clustering coefficient (Newman, 2010) were carried out to compare how tightly grouped the networks were (see Table 11). The measurement is for the whole network, which results in a unique numerical value for the network (as per Equation 7 in Section 5.3.2). The clustering coefficient of the analysed networks was compared to the mean and standard error of the clustering coefficient in 1000 random network simulations with the same number of nodes and links.

For all of the networks of both courses the measured clustering coefficient was a factor of 4–15 times larger than the corresponding simulated random network. This result shows that the structure of the network is far from random and implies that students' interactions follow sets of rules (Newman, 2010). The z-value[96] was calculated to investigate if the measured networks were likely to be similar to the random simulated networks. As the z-value is above 60, the likelihood that the clustering coefficients of the measured networks are similar to those of the simulated random networks is extremely small.

In order to compare if the social and academic network processes differ, an estimation of the degree distribution (distribution of nodes in-degree[97]) was carried out for each of the networks, following the method outlined in Section 5.3.2. Two classes of distributions were found to be likely candidates for describing the distributions of the networks found in each course: the Gamma distribution; and, the Weibull distribution. However, these distributions cannot easily be compared as they are two different families of distributions.

Figures 28 and 29 shows the degree distribution of Course Two from **Paper IV**, as well as the fitted, albeit in a limited way, distributions of the two

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[96] $z = \frac{M - \mu}{SE}$, where M is the mean of the simulated networks, μ is the measured clustering coefficient, and SE is the standard error of the clustering coefficient of the simulated networks.

[97] Number of "in-coming" edges.

classes of distributions, as well as the fitted variant of the generalized gamma function (Equation 6[98]).

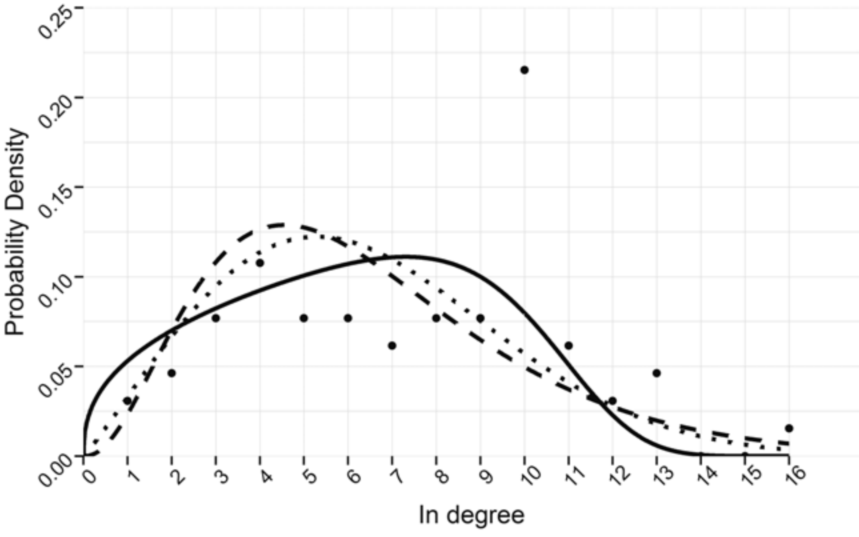

Figure 28. Shows the degree distribution of the social network of Course Two from **Paper IV**. The dots represent the degree distribution, the solid line is the generalized Gamma function, the dashed line is the Gamma function, while the dotted line is the Weibull function. Note: The in-degree is the number of "in-coming" links to each node.

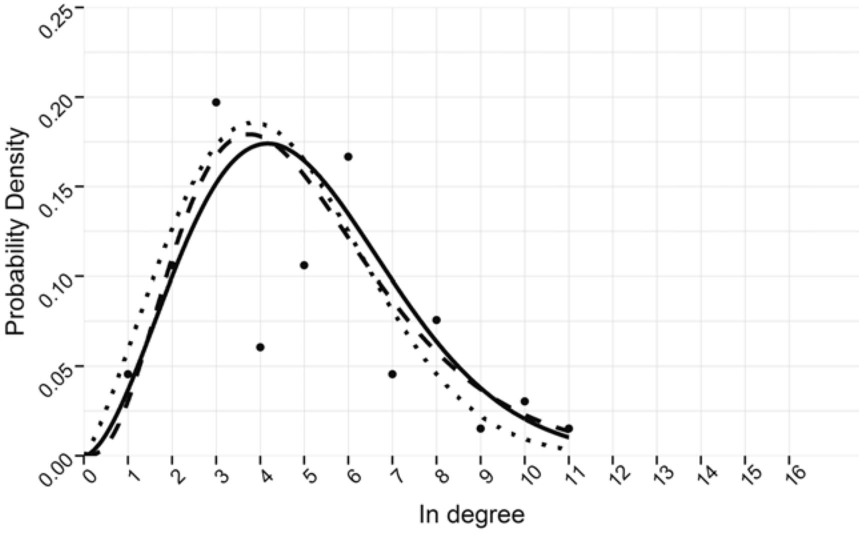

Figure 29. Shows the degree distribution of the academic network of Course Two from **Paper IV**. The dots represent the degree distribution, the solid line is the generalized gamma function, the dashed line is the Gamma function, while the dotted line is the Weibull function. Note: The in-degree is the number of "in-coming" links to each node.

[98] Found in Section 5.3.2 on p. 85 in this thesis.

$$f\left(x;a,v,p\right)=\frac{|p|\,x^{pv-1}e^{-\left(\frac{x}{a}\right)^{p}}}{a^{pv}\Gamma\left(v\right)}$$ (Equation 6, from Section 5.3.2)

To be able to compare these distributions, Equation 6[99] was useful as it offered a way of comparing the two distributions. The estimation of the *a*[100] parameter, using the method outlined in Chapter 5 (see p. 85) gave an estimation of the 95% confidence intervals for the *a* parameter. These confidence intervals are used to identify the differences between the networks (Table 12).

Table 12. *Estimation of the parameter a in the generalized gamma function with 95% confidence intervals.*

Networks	a	2.5%	97.5%
Course One, Combined Network	1.57	1.18	1.99
Course One, Social Network	1.38	1.04	1.73
Course One, Academic Network	1.26	0.92	1.61
Course Two, Combined Network	8.44	7.64	9.25
Course Two, Social Network	7.29	6.39	8.17
Course Two, Academic Network	5.59	5.00	6.32

The estimated parameter (*a*) for the generalized gamma distribution between Courses One and Two showed that the two courses' interaction networks are significantly different. The social network of Course Two fell outside the 95% confidence interval in comparison to the academic network of the same course – the implication being that the rules of interaction differ between the social and the academic interaction networks. Furthermore, both classes of distribution – as estimated from the degree distribution – are found in other systems that are identified as being complex (Cheng et al., 2008; Newman, 2003, p.494). In other words, they also follow a set of interaction rules. From here it becomes possible to empirically describe such course interactions as complex systems.

My illustrative analysis (detailed in **Paper IV**) found that, not only is the interaction pattern of student in university physics classes *not* random, but there are *two* systems of rules that affect interaction in *two* different interaction networks. This finding suggests that researchers, educators, and policy

[99] When estimating the parameters in Equation 6, the starting value needs to be provided to the optimization algorithm (Broyden–Fletcher–Goldfarb–Shanno [BFGS] algorithm). Choosing the starting value can pose a problem, as the starting values can be close to a local minimum, have such values that are not permitted in the equation, or start at a value that forces the algorithm not to converge. To work around this problem, I chose multiple starting points and tried them all out to investigate what starting values were stable.

[100] The *v*, and *p* parameters are constant when Equation 6 is used to cover the Weibull and the Gamma function. Therefore, the free parameter *a* can be estimated and compared.

makers not only need to address critical aspects of the academic environment, but the same kind of research rigor is needed to be used to address the *social* environment of university physics education.

7.4.3. **Paper V** - The influence of structural positions on students' grade achievement[101]

Paper IV illustratively established that students' networked interaction, divided into social and academic networks, do not follow random rules. **Paper IV** also found that the social and the academic networks can differ significantly. Thus, students' structural position in both networks needs to be explored if they are recognized as being important for both student retention and grade achievement. To do so, analysis of the structural aspects of the network in relation to academic achievement is undertaken here (and in **Paper V)**. Again, I have chosen grade achievement as a proxy for "academic retention" in this section, as it is a prerequisite for student retention.

The study presented in **Paper V** draws on six measurements from network theory, all of which are described in Section 5.3.2: eccentricity, betweenness centrality, PageRank, clustering coefficient, eigenvector centrality, and in-degree. In-degree, betweenness centrality and clustering coefficient have been shown to relate to social and academic integration (Thomas, 2000).

The use of eigenvector centrality in exploring grade achievement has been limited (Brewe et al., 2012; Forsman, 2011). Further, the exploration of the measurement of PageRank is also rare (Brewe et al., 2012; Bruun & Brewe, 2013). The measurement of eccentricity in relation to grade achievement has yet to be explored. **Paper V** is the first work where an explicit theoretical and empirical exploration of the connection between grade achievement and a differentiated social and academic network is reported on in the field.

In **Paper V**, the BHY procedure[102] was undertaken and 145 of 2509 models were found to be below the 0.01 significance level (as per Equation 27). Those 145 models were analysed by using the sample size corrected AIC_c criterion (as per Equation 5) to maximize the fit of the model, and at the same time minimize the number of terms in the model. This was done following the method described in the section on Ordinal Regression (see Section 5.7.1).

The following model was found to pass the procedure used:

$$GA \propto EC.s - BC.s + ID.a + EV.a$$

[101] Empirical data used described in Chapter 6 and **Paper V**.
[102] For a description of this procedure, see Section 5.7.

where GA is students' grade achievement, EC.s is the social eccentricity, BC.s is the social betweenness centrality, ID.a is the academic in-degree, and EV.a is the academic eigenvector centrality. Table 13 shows the parameters of the final model.

Table 13. *Final model of the ordinal regression analysis*

		Estimation	Std. Error	p-value
Threshold	Pass	-1.0	.21	p<.001
	Pass with honours	.70	.20	p<.001
	Pass with highest honours	1.5	.23	p<.001
Coefficients	EC.s	.54	.17	p<.005
	BC.s	-.60	.21	p<.005
	ID.a	.34	.16	p<.05
	EV.a	.57	.18	p<.005

The results from **Paper V** echo those from **Paper IV**, but now in more specific terms. Educators need to take into account these two types of network interactions, and devise plans for how students with strong social networks can also be supported academically, and how interactions in each system can meaningfully be fostered. This would support, encourage, and guide teachers wanting to use teaching approaches that are designed to improve the quantity and the quality of student interactions within a course.

In summary, what I have described in this section, together with the results from **Papers V**, presents my answer to the second part of Research Question 2: students' grade achievement is a function of student interaction networks that are dependent on the social system and the academic system of the university. Thus, the portrayal of social and academic systems, which I provided in Section 7.3.1, needs be recognized as being at the core of student retention if institutional action is to have the possibility of being successful. The analysis of the **Paper V** data set suggests that students that are structurally integrated in the academic system (having high in-degree and eigenvector centrality in the academic network) have a tendency towards higher grades and completing larger proportions of their courses. Further, for academic achievement to be possible, the students need to be socially integrated into the social networked interactions, but not at the centre of the social network (as per the negative influence on grade achievement of the betweenness centrality in the social network).

7.4.4. A succinct answer to Research Question 2

My Research Question 2 has two parts – *Taking university physics education to be a complex system, what roles of student interaction patterns emerge vis-à-vis (1) the core concepts of student retention, and (2) students' grade achievement?* – therefore the answer is summarized in two parts:

1. By conceptualizing the process of student retention as described in Section 7.4.1 and in **Paper IV**, which involved using a complexity theory perspective, it became possible for me to introduce a meaningful theoretical distinction between a *social system* and an *academic system*. This distinction made it possible to formulate a hypothesis that both of these two systems will affect the structure of students' interactions within a course. The hypothesis is tested as described in Section 7.4.2 and in **Paper IV**. In so doing, I illustratively showed that there is a possibility for these systems to have structural effects on students' networked interactions.

2. The grades that students achieve play an important role in student retention. By answering the first part of the research question it became possible for me to use measurements from both students' *social networks* as well as their *academic networks* to explore the relationship between the students' measured positions in their networked interaction and their grade achievement. The exploration of this relationship is undertaken in Section 7.4.3 and **Paper V**. The conclusion that I reached is that the measured position in the *social network* as well as the *academic network* are important for predicting students' grade achievement. This finding is congruent with the theoretical argument put forward by Spady and Tinto's line of research – that students need to be integrated into both the academic as well as the social system of the university if they are going to have a good possibility of succeeding in higher education.

The answers to my Research Question 2 suggest that: (a) as students' interaction networks are not a result of a random process, the exploration of the functions related to students' interaction can result in significant and worthwhile changes to the educational setting within a classroom; and, (b) researchers cannot only take into account a *combined* network when exploring the relationship between students' interaction and any other educational significant outcome.

7.5. In conclusion

The results discussed in this chapter lead me to suggest that the foundations of modelling student retention should be revisited from the perspective I am proposing in this thesis. Here, I have gone further than just providing a theoretical framework – I have also created a methodology that can powerfully and effectively guide such a revisit. In further support of this conclusion, the next chapter summarizes the contributions to the field of Physics Education Research that my thesis makes.

8. Contributions to the Field

8.1. Introduction

This thesis began with the following aim: *How to conceptualize and carry out analysis of student retention for university physics students using a complexity theory perspective?* In pursuing this aim I have made the following contributions to the field of Physics Education Research in my thesis. These contribution also support the conclusion I drew in Section 7.5 after presenting the answers to my two Research Questions (Sections 7.3 and 7.4).

8.2. Contributions

Novel theoretical framework:
The work presented in this thesis creates a theoretical framework that, not only informs the case of student retention (see **Paper I**), but introduces PER (see **Paper IV**) to new ideas and ways of thinking about learning and systems (see Chapters 4 and 5).

Method overview:
When I started the work presented in this thesis, no methods were readily available in the literature to mathematically explore complex phenomena in PER. My overview of methods thus serves as a starting point for new researchers in the field (see Chapter 5).

Methodological development:
Papers II and **III** illustrate a methodological advancement in PER that can be used to estimate a network structure and estimate effects of changes in a variety of areas. The methodology is tailored towards educational data sets and their anticipated sample-sizes (see Section 5.4).

Theoretical development – scale (in)variance:
Most of the aspects analysed in **Paper II** were found to have a scale variant and a scale invariant component. This implies that most study objects in PER work, would – theoretically – have a complex component. Furthermore, the introduction of scale (in)variance as a construct to understand how compo-

nent influence can be partially random, presents a new way to think about research, learning and research outcome applications in PER.

Theoretical development – the social and academic systems:
By drawing on the core foundations of student retention research, my work presented in this thesis illustrates how these two systems can be seen to influence students' networked interaction within a course (see **Paper IV**).

Social and academic systems and their ties to grade achievement:
Results presented in my thesis suggest that for academic achievement to be maximized, the students need to be structurally integrated into the social network without being at its centre. At the same time, students need to be structurally integrated into the academic network to have the greatest possibility to achieve higher grades and complete a higher proportion of their courses (see **Paper V**).

9. Future Work

This thesis took, as its point of departure, the adoption of complexity theory as a theoretical framework and used this to underpin the development of associated methods to explore student retention issues – my thesis has illustrated the usage of both theory and methods in PER using student retention as a particularly important case for physics education. I now use this background to outline how I see my thesis work being continued.

The concept of *scale (in)variance* that I presented offers the possibility of making extensive investigations into how the construct relates to other concepts in future educational research. This is particularly important for future PER and Engineering Education Research.

My description of university physics education from a complex theory perspective showed that crafting actions to change aspects of this system is not straightforward. Thus, developing tools, such as *Virtual world* (Schön, 1983) for practitioners acting as agents for change becomes highly important for future PER work.

Despite the work I have reported on in this thesis, the method of estimating a networked structure still needs to be further developed. This should encompass the possibility to assign directionality to the links. This would improve the correspondence between the real world and the modelled system. Further, it would also cut down the simulation time needed significantly.

The work I presented in this thesis on estimating the processes of student networks should be combined with *models of knowledge sharing* (Costa, 2006; Batista & Costa, 2010) and an *empirical estimation of knowledge structures in physics* (Koponen & Huttunen, 2012; Koponen & Pekhonen, 2010). This would further open up a more real-world based simulation of the learning that takes place in physics courses and the physics student laboratory. For example, such work would make it possible for new hypothesis testing and "what if"-simulations of group dynamics, teaching sequences, and knowledge systems.

Finally, as the use of network theory in education is growing, investigating organizational factors associated with physics learning and teaching is becoming increasingly important. The methodology developed in my thesis has the potential of significantly informing such research.

10. Swedish Summary

10.1. Introduktion

Det arbete som presenteras i avhandlingen har sitt ursprung i globala frågeställningar om studentretention; Hur kan universitet stävja studentavhopp och förbättra förutsättningarna för studenter att fullfölja sina studier? Bakgrunden till frågeställningen är att 50% av studenterna som började sin utbildning 2003/2004 inte avslutade sin utbildning inom naturvetenskaps-, ingenjörs-, teknik- och matematik-utbildningar (Committee on Science, Engineering, and Public Policy, 2007, p. 98).

Både nationellt och internationellt ökar andelen studenter som inte tar sin examen i tid, eller inte genomför utbildningen alls (se exempelvis Organization for Economic Cooperation and Development, 2009; Committee on Science, Engineering, and Public Policy, 2007). Sverige är i mitten av rankningen inom OECD länderna när det gäller studentavhopp. För civilingenjörsprogram (4,5 år) har andelen studenter som tar sina examina i tid sjunkit från 30 % till 19 % (1987 – 2004) (Statistics Sweden and National Agency for Higher Education, 2003; 2005; 2007; 2009; 2010). Studenter som inte alls tar sina examina har ökat från ungefär 20 % till 30 % mellan 2001/02 och 2005/2006 (Statistics Sweden; 2013). Dessutom har intresset för att läsa dessa program sjunkit (se, exempelvis European Commission, 2004; Committee on Science, Engineering, and Public Policy, 2007). De flesta länder är i stort behov av personer med en examen inom de naturvetenskapliga och tekniska ämnena vilket ger ökad betydelse för lyckade åtgärder för att öka antalet studenter som tar sin examen.

Ett antal lösningar har föreslagits och de har lett till ett antal åtgärdsprogram, som exempelvis Carnegie Foundation i USA som 2010 investerade 14 miljoner USD för att förstärka studenters ”universitets-beredskap” (Carnegie Foundation for the Advancement of Teaching, 2010). Andra lösningar föreslagits för att vända den nedåtgående trenden, som exempelvis att förbättra rekrytering, urval, och studentretention.

Lösningen på detta problem, förutom att förbättra förutsättningarna för studenter innan de börjar på en universitetsutbildning, kan vara att universiteten också måste ta in fler studenter, och dessutom *de rätta* studenterna, för att vända den nedåtgående trenden. Tyvärr är det väldigt osannolikt att sådana rekryteringsinitiativ ”ska hitta ännu en gömd kohort av studenter som vi kan, genom magi, hitta när vi förbättrar våra rekryteringsbestämmelser ytterligare” (*[egen översättning]* Allie et al., 2009, p. 3). Ett exempel på detta är Storbritannien där ett större initiativ med syfte att förbättra och utöka rekryteringen inom naturvetenskaplig-, ingenjörs- och teknologi-utbildningar nyligen genomförts. Smith (2010) har dock visat att det inte finns några empiriska bevis för att dessa reformer har påverkat hur många som söker sig till dessa utbildningar. Dessutom har andelen studenter som avslutar sin utbildning inom Storbritannien varit fortsatt begränsad (European Commission, 2004). Jag hävdar att då rekryteringsinitiativ inte har den effekt som önskas måste fokus ändras på att förbättra studentretentionen.

Studentretentionsforskning har dock visat att det inte finns någon enkel lösning på problematiken. Många olika aspekter av studenters upplevelser av universitetsutbilning verkar ha en påverkan på studentretention, och det råder för närvarande ingen konsensus över vilken aspekt som är viktigast. De statistiska och teoretiska modelleringar som gjorts kan sägas ha som mål att identifiera åtgärder för att förbättra studentretention (Braxton, 2000; Tinto, 2010), men effekterna av initiativ för att förbättra studentretention har till stor del varit små. Flertalet forskare inom studentretentionsfältet har påpekat att för att förbättra modellering måste andra sätt att se på problemet utforskas. Speciellt viktigt är det att utforska ett sätt att ackommodera ”komplexiteten” hos studentretention (Bean, 1980; 1982; Tinto, 1975; 1982; 1987; 1997).

”Komplexiteten” i studentretentionsforskningen är erkänd inom fältet (Barnett, 2007; Braxton, 2000; Cabrera et al., 1993; Spady, 1970; 1971; Tinto, 2010; Yorke & Longden, 2004), men hittills har inget arbete presenteras där komplexiteten explicit inkorporeras i den teoribildning och modellering för att hitta bättre förklaringsmodeller. Detta har lett till att tidigare modeller kan (och i vissa fall har) tolka(t)s alldels för linjärt; öka interaktionen mellan studenter för att förbättra studentretentionen!

Förutom begreppet komplexitet har användningen av nätverksteori inom studentretentionsfältet mestadels använts som teoretisk bakgrund för att argumentera kring processer för studentretention. Speciellt tydligt är det i det arbete som presenterades av Tinto (1975; 1982; 1987; 1997) där Tinto påpekat att nätverksanalys av studenters interaktioner är av ytters vikt för att undersöka komplexiteten hos studenters deltagande i undervisningen (Tinto, 1997).

Denna avhandling tar sin teoretiska utgångpunkt i komplexitetsteori och presenterar ett ramverk tillsammans med empirisk modellering kring studentretention inom fysikutbildninga för att inkorporera ”komplexitet” inom retentionsforskningen. Nedan presenteras en kort sammanfattning av svaren på forskningsfrågorna som ligger som grund för detta avhandlingsarbete.

10.2. Forskningsfrågor

Det större syftet som behandlas i avhandlingen är: *Hur konceptualiseras och analyseras studentretention av fysikstudenter ur ett komplexitetsperspektiv?*

För att det ska vara möjligt, har två forskningsfrågor har besvarats:

> Forskningsfråga 1: *Hur kan en metodologi utvecklas och testas för att undersöka vilka effekter åtgärder för att förbättra studentretention kan få i ett komplext system?*

> Forskningsfråga 2: *Vilken roll spelar studenters interaktionsmönster med avseende på: (1) fundamentala delar av studentretentions-forskning? och (2) fysikstudenters betyg på kurser?*

10.3. Hur kan universitetsutbildning i fysik beskrivas ur ett komplexitetsperspektiv?

För att undersöka universitetsutbildning som ett komplext system behöver utbildningssystemet kunna beskrivas genom egenskaper som det delar med andra erkända komplexa system. Dessa egenskaper, som delas mellan utbildningssystem och andra komplexa system, är följande:

- Många olika agenter (exempelvis studenter, lärare, etc.) och komponenter (exempelvis sociala och finansiella faktorer) som interagerar.
- Dessa agenter och komponenter är uppdelade i olika, åtskilda, nivåer.
- Det finns interaktioner mellan agenter och komponenter mellan dessa åtskiljda nivåer.
- Det finns visa regler som bestämmer hur dessa interaktioner går till (både inom och mellan nivåer).

Med utgångspunk i systembeskrivningen är studentretention ett emergent fenomen som bygger på agenter och komponenters interaktion. Detta leder till att fenomenet studentretention kan vara, i sig själv, olinjärt och svårt att förutsäga.

10.4. Forskningsfråga 1

Hur kan en metodologi utvecklas och testas för att undersöka vilka effekter åtgärder för att förbättra studentretention kan få i ett komplext system?

Denna forskningsfråga besvarades i tre steg: 1) Är det föreslagna teoretiska ramverket andvändbart för att modellera och förstå studentretention (**artikel I**)?, 2) Hur kan en modell över utbildningssystemet tas fram som stämmer överens med det vi vet om komplexa system (**artikel II**)? och 3) Hur kan den framtagna modellen användas för att undersöka vilka effekter åtgärder för att förbättra studentretention kan få (**artikel II** och **III**)?

I det första steget, som beskrivs utförligt i **artikel I**, undersöks hur väl komplexitetsteori kan användas för att beskriva ett system där studentretention är en process. Aspekter som tidigare identifierats som kritiska för studentretention beskrevs som sammanlänkade i ett system. Dessutom argumenterades hur identifiering av kritiska aspekter inom systemet kunde göras. Ytterligare presenterades hur dessa aspekter kunde delas upp för att skapa ett flernivåsystem som var uppdelade i programkomponenter (exempelvis studenters upplevelser och attityder till programmet), institutionskomponenter (exempelvis akademisk prestation och att studenter känner tillhörighet till / känna sig hemma på universitetet), sociala komponenter (exempelvis att känna att andra studenter är stödjande, att lärarna är stödjande, och att det är lätt att träffa nya vänner) och stödjande komponenter (exempelvis ekonomiskt säkerhet och nöjdhet, och en stöttande familj). Alla dessa olika nivåer är relevanta för studentretention för universitet, inte endast en av dem, vilket poängteras i **artikel I**.

Det andra steget för att besvara forskningsfrågan var att skapa en modell av utbildningssystemet. Det teoretiska argumentet i **artikel II** baserades på beskrivningen av utbildningssystemet i **artikel I** och introducerade en ny metod för att skapa en modell av systemet; Multilayer Minimum Spanning Tree Analysis[103].

Beskrivningen av systemet (**artikel II)** leder till en karakterisering av möjligheter och begränsningar av åtgärder för att förbättra studentretention vilket inkluderar en teoretisk diskussion om vad som är möjligt att veta utifrån den modell som skapades. I **artikel II** (avsnitt 7.3.2) diskuteras relationen mellan komponenter, aspekter och agenter i de olika nästlade nivåerna i systemet genom en skala mellan två extremer; *skalvarians* och *skalinvarians.* Dessa två extremer kan sägas vara egenskaper hos komponenter (aspekter och agenter) som innebär att dessa delvis är stabila eller delvis slumpmässiga. Komponenter som är *skalinvarianta* fungerar väldigt lika oavsett vilken skala som undersöks (det som gäller för en grupp studenter

[103] Denna analysmetod är jämförd med andra vanliga metoder i avsnitt 5.4.

kan gälla för alla grupper av studenter). Den andra extremen i skalan, *skal-variant,* tolkades som att komponenter kan te sig ytterst olika beroende på vilken nivå i systemet som undersöks (det som gäller för individnivå, en grupp av studenter, eller ett helt universitet är skiljt från varandra). Detta implicerar att vissa komponenter kan, i sig, tendera mot att vara stabila eller att vara slumpmässiga.

Att karakterisera studentretention som ett emergent fenomen i universitetsfysik (som system) begränsar de möjliga åtgärder som kan sättas in för att förbättra studentretention. Av de aspekter och komponenter som undersöktes i **artikel II** var de flesta mellan dessa två extremer (skalvariant och skalinvariant), vilket innebär att de var delvis stabila, men också delvis slumpmässiga. Detta leder till att de flesta åtgärder som syftar till att förbättra studentretention har delvis stabila, men också delvis slumpmässiga effekter. Dessutom visar **artikel II** (avsnitt 7.3.2) att åtgärder som syftar till att förbättra studentretention alltid är en kompromiss mellan att ha stabila effekter eller att ha en chans att ha effekter i en större del av systemet.

Det tredje steget för att besvara forskningsfrågan utnyttjade den visuella nätverkskartan som utvecklades i **artikel II**. Nätverkskartan visar hur kritiska aspekter, som tidigare har identifierats att vara viktiga för studentretention, påverkar varandra i ett system. Denna representation gör det möjligt att analysera vilka effekter olika åtgärder kan ha i systemet. **Artikel II** (avsnitt 7.3.3) argumenterar hur detta är möjligt för personer som har yrkeserfarenhet från att verka inom systemet genom med hjälp av en *Virtuell Värld*, där nätverksrepresentationen används för att postulera vilka effekter en åtgärd kan resultera i. Detta kan användas för att identifiera åtgärder som kan ha större chans att lyckas för att förbättra studentretention.

De teoretiska argumenten kring användningen av nätverkskartan som en *Virtuell Värld* som framfördes i **artikel II**, följs av **artikel III** där jag undersökte vilka möjliga effekter olika åtgärder kan få baserat på simuleringar av den empiriska modell som var framtagen i **artikel II**. Simuleringarna identifierade följande åtgärder som de som hade störst chans att resultera i en positiv effekt:

- Lärarens hantering av studenters förväntningar
- Hanteringen kring kursmaterial
- Lärarens uppträdande mot studenter
- Återkoppling och utvärdering
- Schemaläggning

Dessa aspekter med relativt höga effekter (**artikel III**, avsnitt 7.3.3) kan inte sägas vara nyckeln, då standardavvikelsen för dessa åtgärder var hög, speciellt den för schemaläggning. Detta implicerar att även om vi identifierar vad som bör göras för att förbättra studentretention, kan systemet, i sig, påverka effekterna av åtgärderna till något som inte kan förutsägas.

I **artikel I** och **artikel II** diskuteras det att åtgärder som ska förbättra studentretention bör vara riktade mot förbättra skalinvarianta aspekter inom systemet. De identifierade aspekterna i **artikel III** som kan i förlägningen förbättra studentretentionen har inte en linjär ”en-till-en” relation med de skalinvarianta aspekterna som identifierades i **artikel II**. Aspekterna som är identifierade i **artikel III** faller i mitten av skalan mellan skalinvariant och skalvariant. Detta betyder att dessa aspekter har både en skalinvariant och en skalvariant komponent, vilket är tydligt i Tabell 10 i avsnitt 7.3.3, där dessa effekter av förändringar estimerades med en hög standardavvikelse. Aspekten som behandlar delar av schemaläggning är i den övre delen av skalan i **artikel II** (mot skalvariant) vilket i Tabell 10 återspeglas med hög standardavvikelse. Detta innebär att, i detta exempel, förändringar i schemaläggningar kan ha en mycket stor positiv eller negativ effekt.

10.5. Forskningsfråga 2

> *Vilken roll spelar studenters interaktionsmönster med avseende på: 1) fundamentala delar av studentretentionsforskning? och 2) fysikstudenters betyg på kurser?*

Den andra forskningsfrågan utforskar studenters interaktionsnätverk och dess egenskaper och roll i lärandet. För att besvara den första delen av forskningsfrågan delades studenters interaktionsnätverk utefter *social* och *akademisk* interaktion. Tidigare forskning har endast undersökt ospecificerade interaktionsnätverk utan att ta hänsyn vad interaktionen innehåller. **Artikel IV** utforskar relationen mellan de fundamentala delarna av studentretentionsforskningen – social och akademisk integration (m.a.o., studenters anpassning till det sociala och akademiska systemet på universitetet). – och studenters interaktionsnätverk. Det sociala och akademiska systemet är välkända begrepp inom studentretentions-forskningen, men i **artikel IV** tolkades dessa två system (det sociala och det akademiska) som att vara uppbyggda av *regler för interaktion* (**artikel IV**, avsnitt 4.8 och 7.4.1) vilka påverkar, och är påverkade av, studenters interaktioner. Denna beskrivning implicerar att det sociala och akademiska systemet har en inverkan på nätverkens struktur och dynamik.

För att visa styrkan att dela upp interaktionsnätverket i två interaktionstyper utfördes en empirisk undersökning i **artikel IV** (avsnitt 7.4.2) som syftade till att undersöka hur dessa två nätverk skapades (m.a.o., undersökte om det sociala och det akademiska systemet kan sägas ha någon påverkan på nätverkens struktur och dynamik). Undersökningen resulterade i att:

- Processerna som skapar det sociala nätverket, samt det akademiska nätverket är inte slumpmässiga.
- Det sociala nätverket, samt det akademiska nätverket, är byggt på regler för interaktion.
- Processerna som styr utvecklingen av det sociala nätverket är skiljt från processerna som styr utvecklingen av det akademiska nätverket.

Dessa resultat implicerar att det finns två sociala system (det sociala och det akademiska) som påverkar och är påverkade av studenters interaktion. Det innebär att studenters integrationsprocess kan undersökas med hjälp av studenters interaktionsnätverk inom kurser, vilket är är av stor vikt för studentretentionsforskning.

Svaret på den andra delen av forskningsfrågan bygger på resultaten från **artikel IV** (avsnitt 7.4.2) där det visades att processerna som styr utvecklingen av dessa två nätverk inte är slumpmässiga utan kan vara ”styrda” av det sociala och det akademiska systemet. Därför är det möjligt att studera hur strukturella faktorer hos nätverket, och studenternas position, är relaterat till studenters akademiska resultat, vilket finns i **artikel V** och avsnitt 7.4.3. Dessutom, då processerna som styr utvecklingen av det sociala och akademiska processerna är skilda, är det möjligt att använda båda typerna av nätverk.

Nätverksstrukturer och studenters position i dessa undersöktes i **artikel V** (avsnitt 7.4.3) i förhållande till studenters betyg på kursen. **Artikel V** visade hur studenters position i interaktionsnätverken (både det sociala och det akademiska) kan användas för att förutsäga studenters betyg på kursen. Den bästa modellen för att förutsäga studenters betyg var följande:

$$GA \propto EC.s - BC.s + ID.a + EV.a$$

där GA är studenters betyg, EC.s är social *eccentricity* (icke central position), BC.s är social *betweenness centrality* (central position och styr mycket av informationsflödet i nätverket), ID.a är akademisk *in-degree* (hur många andra studenter som sade sig göra något akademiskt med en specifik student) och EV.a är akademisk *eigenvector centrality* (central position som är länkade till andra centrala positioner). **Artikel V** visar att den bästa modellen använder en kombination av båda nätverken för att förutsäga studenters betyg.

Resultaten från **artikel IV** och **V** implicerar att tidigare forskning som använder ett odifferentierat nätverk, utan att ta hänsyn till vad nätverket representerar, har betydande nackdelar. Ytterligare implicerar resultaten att studenters betyg på kurser inte endast relaterar till hur de studerar i olika grupper, men också hur de socialiserar inom kursen. Med andra ord, akademisk prestation är en funktion av både sociala och akademiska processer.

För att maximera chansen för studenter att prestera akademiskt bör studenten vara integrerad i den sociala gemenskapen, men inte i centrum av den (som visas av den negativa *betweenness centrality*). Dessutom måste studenten vara integrerad i den akademiska gemenskapen (som visas av den positiva *in-degree* och *eigenvector centrality*) för att ha chans till högre akademisk prestation.

10.6. Avslutande diskussion

Svaren på forskningsfrågorna gör det möjligt att beskriva möjligheter och svårigheter med att förbättra studentretention. De simuleringar som genomfördes i avhandlingsarbetet kan ge information om vad som kan vara effektivt att förbättra för att höja studentretentionen. Dessutom är studenters interaktioner en mycket viktig del i arbetet för att förbättra studenters förutsättningar för att fortsätta mot sina examina. Ytterligare har studenters interaktionsnätverk relaterats till grundläggande begrepp inom studentretentionsforskning och visat sig vara av stor betydelse för studenters betyg på kurser; vilket är en förutsättning för studenter att fortsätta mot sina examina. Avhandlingsarbetet har också beskrivit ett mycket svårförändrat system där en åtgärd inte nödvändigtvis har den effekt som önskas - även om åtgärderna riktas mot delar av utbildningssystemet som är kritiska för studentretention.

Avhandlingen har visat hur komplexitetsteori kan användas inom fysikdidaktiskt forskning genom att undersöka studentretention för fysik och ingenjörsstudenter som en process inom ett komplext system. Denna avhandling är ett första steg, och ger en bas för fortsatta studier, för att undersöka fenomen inom fysikdidaktik ur ett komplexitetsperspektiv.

Acknowledgements

I would like to start out by thanking Jenny for all her patience and support that has proved to be of utmost importance in my life, as well as during my PhD studies, and my two sons, Adrian Theodore Forsman Eriksson, and Julius Lo Forsman Eriksson, who have given me so much joy since making their appearance in 2010 and 2014.

In Uppsala, I want to thank to my supervisor Cedric Linder for guiding me throughout my PhD studies. Early in my studies, we spent numerous hours exploring different theoretical frameworks that would guide my work on student retention in physics. He has helped me through discussions drawing on his extensive background in theoretical and conceptual methodologies, and through his willingness to not shy away from new ideas and new approaches to research just because they were novel. He always considered how useful particular approaches were and never gave in to popular opinion. Throughout my PhD studies, he has always set aside time for discussing, reading, and giving feedback on my work, for which I am forever grateful. Further, I especially want to thank Anne Linder, for all her editorial comments, careful read-throughs, ideas, and insightful questions, which have been critical for my research during the whole of my time at Uppsala University. Then, for all his guidance in the field of applied mathematics, I want to thank Richard Mann; he listened to my ideas and helped me find, and discussed at length, different ways to mathematically model and estimate inferences of changes in complex systems. Also, I would like to thank John Airey for his patience when spending hours discussing research ideas, projects, and theoretical constructs. For his seemingly endless flow of research ideas, his ability to "get things done", and his sense of research planning and execution during my PhD studies, I would like to thank Staffan Andersson. I want to express my gratitude to visiting professor Rachel Moll for introducing me to complexity thinking, which has been a critical piece of the puzzle in answering my research questions and reformulating a theoretical foundation of student retention. I would like to thank all other members, past and present, of the Uppsala Physics Education division for their support and for their willingness to engage in research discussions; Jannika Andersson-Chronholm, Johan Larsson, Jesper Haglund, Tobias Fredlund, Johanna Larsson, Anders Johansson, Urban Eriksson, Anna Danielsson, Filip Heijkenskjöld, and Bor Gregorčič.

In the Netherlands, I want to thank Maartje Van den Bogaard for all the time we spent discussing, all the time spent interpreting the analysis, all her input on my research, and for her choosing to do parts of our research together. It would not have been possible to present this thesis, as it is now, without you.

I want to thank Maria Hamrin for her support when I visited Umeå University early in my Ph.D. studies. Also, I want to thank Margareta Enghag, for all her help and for introducing me to PER.

I would like to devote the last paragraph in the main body of this thesis to thank the late Duncan Fraser, with whom I had many discussions on the details of the use of complexity theory in student retention research. We discussed, at length, the possibilities of this framework and its implications in a real world practice, I spent much time grappling with the parts of the framework with his help. These discussions grew from Duncan's extensive experience of real world practice of university engineering education and focused around an action perspective; what does this new framework afford that the previous frameworks lack and how can it be used in practice to enhance student retention? Instead of only having a *theoretical* discussions he always managed to focus the discussion on actual issues in the real world practice of policy makers, teachers, and students. I will always remember these discussions and all his help in my research.

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Appendix 1 - Ethical consent for questionnaire participation (Paper I, IV, V)

Denna enkätundersökning syftar till att kartlägga studenters upplevelser av programstudier och att undersöka modeller för studentavhopp från universitetsstudier genom att undersöka viktiga faktorer som uppkommit genom tidigare forskning. Denna enkätundersökning är helt frivillig och du väljer själv efter du har fyllt i denna enkät om du vill lämna in ditt svar eller inte. När du lämnar in denna enkät, samtycker du att den information du lämnat kan användas i forskningssyfte, men endast av de som är en del av forskningsgruppen. Uppgifter som kan knytas till dig (ditt namn) kommer endast att behandlas av de som är involverade i forskningsgruppen och kommer inte att spridas till andra parter. All information kommer att avkodas för att skydda dina uppgifter. Du kan välja att medverka anonymt, men det är då viktigt att du anger det program du studerar.

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