

https://dspace.org/

# Difficulties of mechanical engineering students in developing integrated knowledge for the cross-discipline of mechatronics : a conceptual investigation.

**Bailey-McEwan, Michael**

**2010-08-06**
http://hdl.handle.net/10539/8371

Downloaded from a DSpace repository. https://dspace.org/

# DIFFICULTIES OF MECHANICAL ENGINEERING STUDENTS IN DEVELOPING INTEGRATED KNOWLEDGE FOR THE CROSS-DISCIPLINE OF MECHATRONICS: A CONCEPTUAL INVESTIGATION

Michael Bailey-McEwan

A research report submitted to the Faculty of Humanities, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Education (Tertiary Teaching)

Johannesburg, 2009

**DECLARATION**

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Education (Tertiary Teaching) in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

_____

Michael Bailey-McEwan

this _____ day of December 2009

---oOo---

**ABSTRACT**

Mechatronics is a modern interdisciplinary engineering field, embracing the traditional disciplines of mechanical and electrical / electronic engineering, as well as control and information technology, in producing automated, easy-to-use, multi-functional products and systems for domestic, commercial and industrial use. It has been the candidate's experience, corroborated by other universities' experiences, that mechanical engineering students in a first mechatronics course (in their third year of study) have considerable difficulties in grasping the common principles governing the behaviour of mechanical and electrical devices – especially in the course's laboratory project reflecting the applied nature of mechatronics. This project seeks to conceptually analyse the causes of these difficulties, and posit suitable remedies.

Drawing upon the theories of Basil Bernstein, an educational sociologist, suggests that a first- and second-year mechanical engineering curriculum comprising subjects by discipline recontextualises engineering knowledge from production (engineering practice) to education as a collection-type *educational code* that does not emphasise the commonality of the principles governing different physical systems. In turn, this suggests that the corresponding form of knowledge tending to develop in the student is a Bernsteinian *horizontal knowledge structure* – a collection of sub-disciplinary bodies of knowledge that link uneasily only at their boundaries. The conceptual development theory of Lev Vygotsky, a cognitive psychologist, suggests that such collection-type horizontal knowledge structures do not attain true conceptual level, but are 'complexes', where the links between knowledge bodies are on the basis of common, perceived factual features. Such knowledge structures are not adequate for mechatronics; the grasp of common principles demanded by this cross-discipline requires a Bernsteinian *hierarchical knowledge structure*. Here, bodies of disciplinary knowledge are subsumptively integrated under common principles, so this structure amounts to a Vygotskian system of true concepts connected by abstract, logical *relations of generality*.

For mechatronics, a suitable system of true concepts connected by relations of generality exists in the conceptual tool of *bond graphs*. These reveal the common governing principles of different physical systems by representing them as interconnected components handling various forms of energy through general *effort* and *flow variables*.

The *'Double Move in Teaching and Developmental Learning'* of the developmental psychologist Mariane Hedegaard seems a promising way of aiding students' horizontal knowledge structures to develop into the desired hierarchical knowledge structures in mechatronics. A welcome opportunity arose in 2009 to *begin* (in contrast to previous years) the third-year mechatronics

course *with* its laboratory project, and thus with one key feature of the 'Double Move': problem-solving by situationally necessitated research activities. A hoped-for increase in students' motivation was not detected, but the project was most frequently cited as the most valuable aspect of the course.

Further work, by empirical research, should be carried out to test the validity of these conceptual analyses and posited remedies.

---oOo---

To my lovely honey wife, Margaret, a pearl among pearls

To my mother, Pamela Bailey-McEwan;
my mother-in-law, Lorna Dixie;
the memory of my father, Ronald Alexander Bailey-McEwan (1916-2002),
and the memory of my father-in-law, Vincent Edward Dixie (1920-1994)

To my beloved daughter and son-in-law, Dawn and Martin,
and my beloved son and daughter-in-law, Gordon and Leighanne

Finally, to my friend and fellow-engineer Dr Paul Richard Roberts, who outstandingly *lives* the integrative principles described herein

**ACKNOWLEDGEMENTS**

This research report arises partly from work carried out in the third-year undergraduate mechatronics course in the School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg, South Africa. The author is grateful to the Head of this School, Professor E.A. Moss, and to his Head of Stream, Professor T.J. Sheer, for their support and encouragement.

The author is greatly indebted to his project supervisor, Ms L. Slonimsky, for her constant interest and helpful, exacting supervision during the years of completing this research report on a part-time basis.

**PREFACE**

Upon graduating in 1972 with a bachelor's degree in electrical engineering, the candidate underwent a graduate training programme on two gold mines of the South African mining group that had sponsored his studies. This programme emphasised that with the heavy machinery and structures prevalent on mines, one was an engineer *first* and a disciplinary (electrical, mechanical, etc.) engineer *second*. Whatever branch of engineering one was qualified in, understanding of fundamental mechanical, electrical and other (e.g. chemical) aspects of machinery, processes, systems and structures was expected.[A] In this programme and the candidate's subsequent engineering career, he was compelled to rapidly become familiar with aspects of other engineering disciplines! This awakened his interest in the underlying similarities governing the behaviour of electrical and mechanical devices, and hence in teaching students to appreciate the functioning of such devices from a unified, transdisciplinary point of view.

[A] Even the law required this: the subjects for the Government Engineer's Certificate of Competency (Mines and Works), which the candidate had to obtain to legally assume charge of machinery, were mainly mechanical, not electrical.

**CONTENTS**

**DECLARATION** ... **ii**

**ABSTRACT** ... **iii**

**ACKNOWLEDGEMENTS** ... **v**

**PREFACE** ... **vi**

**CONTENTS** ... **vii**

**LIST OF FIGURES** ... **x**

**LIST OF TABLES** ... **xi**

**GLOSSARY OF ABBREVIATIONS** ... **xii**

**GLOSSARY OF TERMS** ... **xii**

**1. INTRODUCTION** ... **1**

**1.1 General Introduction** ... **1**

**1.2 Outline of Research Report** ... **2**

**2. BACKGROUND** ... **5**

**2.1 Teaching of Mechatronics at Universities** ... **7**

2.1.1 'Mechatronics I' Course, School of MIAE, University of the Witwatersrand, Johannesburg ... 8

**2.2 Inadequate Knowledge Acquisition in Mechatronics** ... **9**

**2.3 Question Prompting Research** ... **14**

**2.4 The Wider Context: Multi- and Inter-Disciplinary Grounding Required in Graduate Engineers** ... **14**

2.4.1 The Key to Interdisciplinarity: a Design-Oriented Approach ... 15

**2.5 Deficiencies of Traditional Engineering Curricula** ... **20**

**3. CROSS-DISCIPLINARY GROUNDING OF ME STUDENTS IN EE TECHNOLOGY: PERCEIVED DEFICIENCIES AND REMEDIES ATTEMPTED** ... **23**

**3.1 Perceived Deficiencies** ... **23**

**3.2 Remedies Attempted** ... **24**

**3.3 Interdisciplinary Approaches to Mechatronics Education** ... **25**

**4. BASIL BERNSTEIN: EDUCATIONAL SOCIOLOGIST** ... **27**

**CONTENTS** (continued)

**4.1 Classification and Framing ..... 28**

**4.2 Educational Knowledge Codes: Collection and Integrated Types ..... 29**

**4.3 Codes of Production ..... 30**

**4.4 The Curriculum and the Pedagogic Device ..... 31**

**4.5 The Move from Pedagogies to Knowledge Structures ..... 32**

4.5.1 The Hierarchical Knowledge Structure (HiKS) in Vertical Discourse ..... 32

4.5.2 The Horizontal Knowledge Structure (HKS) in Vertical Discourse ..... 33

4.5.3 Essential Distinction between Hierarchical and Horizontal Structures ..... 33

**5. LEV VYGOTSKY: COGNITIVE AND DEVELOPMENTAL PSYCHOLOGIST ..... 34**

**5.1 Vygotsky's Developmental Levels of Concepts ..... 34**

5.1.1 Applicability of Vygotsky's Preconceptual Developmental Levels to Students ..... 36

**5.2 Vygotsky's Zone of Proximal Development ..... 39**

**6. CRITICAL RESEARCH QUESTIONS ..... 40**

**7. ANALYSING MECHATRONIC KNOWLEDGE: THE CODES AND KNOWLEDGE STRUCTURES OF BERNSTEIN ..... 41**

**7.1 Codes of Production and Interdisciplinary Working ..... 41**

**7.2 Bernstein's Hierarchical Knowledge Structure (HiKS) ..... 42**

**7.3 Desirable and Inferior Knowledge Structures in Mechatronics ..... 43**

7.3.1 The Horizontal Knowledge Structure (HKS) ..... 44

7.3.2 School of MIAE: Second-Year 'Collection-Type' Programme ..... 44

7.3.3 Before Mechatronics – HKS of Languages ..... 48

7.3.4 Over-Narrow Recontextualisation? Inferior Knowledge Structures in Mechatronics? ..... 48

7.3.5 Need for HKS Anterior to Mechatronics to Develop Further ..... 50

**CONTENTS** (continued)

7.3.6 First Phase – Two-Plane, Pseudoconceptual HKS..... 51

7.3.7 Deficiencies of Even a Dual-Plane HKS ..... 53

7.3.8 Second Phase – Germinating HiKS with Genuine Concepts ..... 54

**8. BOND-GRAPH REPRESENTATION OF COMMON PRINCIPLES OF MECHANICAL AND OTHER PHYSICAL SYSTEMS..... 55**

**8.1 The Bond Graph ..... 55**

**8.2 The Relational Block Diagram ..... 59**

**9. A PEDAGOGY TO ACHIEVE AN INTEGRATED KNOWLEDGE STRUCTURE IN MECHATRONICS ..... 62**

**10. CONCLUSIONS..... 71**

**REFERENCES..... 74**

**APPENDIX 1**
**'Mechatronics I' Course, School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand: Course Outline and Example of Laboratory Project..... 78**

**APPENDIX 2**
**Engineering Council of South Africa: Definitions of Terms (ECSA, 2003) ..... 105**

**APPENDIX 3**
**Inter- and Multi-Disciplinarity in "Whole Qualification Standard for Bachelor of Science in Engineering / Bachelor of Engineering" of Engineering Council of South Africa (ECSA, 2004)..... 107**

**APPENDIX 4**
**Interdisciplinary Course and Curriculum Approaches..... 110**

**APPENDIX 5**
**General Representations of Dynamic Physical Systems..... 115**

**APPENDIX 6**
**Key Aspects of Hedegaard's 'Double Move in Teaching And Developmental Learning' ..... 123**

---oOo---

**LIST OF FIGURES**


Figure 2.1 Marks for Test/Examination Question on Washing Machine Solenoid, 2007 and 2008 ..... 11

Figure 7.1 Desirable HiKS of Mechatronics in Engineering Students and Graduates ..... 43

Figure 7.2 Bernstein's (1999:163) Portrayal of a HKS in Humanities ..... 44

Figure 7.3 HKS of Languages (Sub-Disciplines) Anterior to Mechatronics ..... 48

Figure 7.4 "A Visual Presentation of a Horizontal Knowledge Structure" (Bernstein, 1996c:174) ..... 52

Figure 7.5 Preferable Pseudo-Conceptual, Two-Plane HKS Anterior to Mechatronics ..... 52

Figure 8.1 Block Diagram and Corresponding Bond Graph for Force Acting on Object of Mass *m* ..... 57

Figure 8.2 Permanent-Magnet DC Motor Driving a Load ..... 57

Figure 8.3 Bond Graph Representation of Motor and Load of Figure 8.2 . 58

Figure 8.4 Block Diagram of Motor and Load of Figure 8.2 ..... 60

Figure 8.5 Block Diagram of Motor and Load of Figure 8.2, with Speed Controller ..... 61

Figure 9.1 Depiction of Hedegaard's 'Double Move in Teaching and Developmental Learning' ..... 63

Figure A5.1 Block Diagram and Corresponding Bond Graph (de Silva, 2005:115) ..... 118

Figure A5.2 Bond Graph Representation of Force Source in a Mechanical System ..... 120

Figure A5.3 Basic Two-Port Mechanical Bond-Graph Elements (de Silva, 2005:117) ..... 121

Figure A5.4 Three-Port Junction Elements in Bond Graphs (de Silva, 2005:118) ..... 122


---oOo---

**LIST OF TABLES**


Table 2.1 MCT1 Course: Percentages of Individual Student Failures, 2004-8 ..... 9

Table 2.2 MCT1 Laboratory project: Number of Student Teams / Individuals
Failing in Assessment of (i) Functional Trials of Working Models; (ii) Whole Project ..... 10

Table 7.1 Programme for Second Year of Study for Bachelor of Science in Engineering in School of MIAE (University of the Witwatersrand, 2009) ..... 44

Table 7.2 Programme for First Year of Study for Bachelor of Science in Engineering in School of MIAE (University of the Witwatersrand, 2009) ..... 46

Table 8.1 Bond Graphs: Effort and Flow Variables for Basic System Components ..... 56

Table 9.1 Key Aspects of Hedegaard's 'Double Move' in a Mechatronics Laboratory Project ..... 65

Table A1.1 ECSA Exit-Level Outcomes Addressed by 'Mechatronics I' Course ..... 81

Table A4.1 Interdisciplinary Course and Curriculum Approaches to Mechatronics Education in Recent Literature ..... 111

Table A5.1 Linear Graphs: 'Through' and 'Across' Variables for Types of Systems [Single-Type Systems] (after de Silva, 2005:57) ..... 117

Table A5.2 Mechanical System Elements: Linear- and Bond-Graph Representations Thereof (de Silva, 2005:58;116) ..... 117

Table A5.3 Bond Graphs: Effort and Flow Variables for Basic System Components ..... 119

Table A6.1 Key Aspects of Hedegaard's 'Double Move' Depicted in Figure 9.1 ..... 123


---oOo---

## GLOSSARY OF ABBREVIATIONS

Words or phrases in italics indicate cross-references in this glossary.

| | |
|---|---|
| CLTD | Centre for Learning, Teaching and Development, University of the Witwatersrand |
| ChE | chemical engineering |
| CpE | computer engineering |
| ECSA | Engineering Council of South Africa |
| EE | electrical engineering; this includes electronic engineering |
| EE2 Course | Course ELEN2000, 'Electrical Engineering', given by *School of EIE* to second-year students of the *School of MIAE* |
| HKS | horizontal knowledge structure (Bernstein, 1996c) |
| HiKS | hierarchical knowledge structure (Bernstein, 1996c) |
| MCT1 Course | Course MECN3012, 'Mechatronics I', given by *School of MIAE* to its third-year undergraduate students |
| MCT2 Course | Course MECN4012, 'Mechatronics II', given by *School of MIAE* to its fourth-year undergraduate students |
| ME | mechanical engineering |
| MIAE | mechanical, industrial and aeronautical engineering |
| SAQA | South African Qualifications Authority |
| School of EIE | School of Electrical and Information Engineering, University of the Witwatersrand |
| School of MIAE | School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand |

## GLOSSARY OF TERMS

Words or phrases in italics indicate cross-references in this glossary.

| Term | Definition |
|---|---|
| cross-disciplinary | As for *interdisciplinary* |
| curriculum (ECSA definition) | "the definition of how a programme is to be executed, including the purpose the learning, the outcomes or learning objectives, set of compulsory and elective courses, content to support achieving the outcomes, learning activities, methods and media for teaching/training and learning, assessment plan, and a plan for evaluating the quality and effectiveness of delivery" (ECSA, 2003) |
| device | "**1** a thing made or adapted for a particular purpose, esp. a mechanical contrivance" *(Concise Oxford Dictionary,* 1990*).* "**1 f :** a piece of equipment or a mechanism designed to serve a special purpose or perform a special function" (*Merriam-Webster's Collegiate Dictionary,* 2006) |
| discipline [engineering] | "a major subdivision of engineering such as the traditional fields of Chemical, Civil, or Electrical Engineering, or a *cross disciplinary* field of comparable breadth. (see *sub-discipline*)" (ECSA, 2003) |

**GLOSSARY OF TERMS** (continued)

| Term | Definition |
|---|---|
| electronics | "**1** a branch of physics and technology concerned with the behaviour and movement of electrons in a vacuum, gas, semiconductor, etc. **2** the circuits used in this" *(Concise Oxford Dictionary,* 1990*).* |
| engineering | "1: At its most general, Engineering is the entire field of activity of professional engineers, engineering technologists and technicians. 2: Engineering as a university degree, such as the B.Sc.(Eng), and as a professional activity is concerned intellectual and conceptual work using engineering knowledge and engineering competencies to conceive, create designing and implementing, components, systems, engineering works, products and processes and to solve problems of economic or social value. The process is based on scientific knowledge, requires synthesis of knowledge, and takes into account wider issues. 3: Engineering is also used to describe a way of working to create or improve an end product that is useful, reliable and viable." (ECSA, 2003)[B] |
| engineering, electrical | "the branch of engineering concerned with the practical applications of electricity in all its forms, including those of the field of electronics" ("Electrical And Electronics Engineering", *Encyclopædia Britannica*, 2006). |
| engineering, electronic | "... that branch of electrical engineering concerned with the uses of the electromagnetic spectrum and with the application of such electronic devices as integrated circuits, transistors, and vacuum tubes" ("Electrical And Electronics Engineering", *Encyclopædia Britannica*, 2006). |
| engineering, mechanical | "the branch of engineering concerned with the design, manufacture, installation, and operation of engines and machines and with manufacturing processes. It is particularly concerned with forces and motion" ("Mechanical Engineering", *Encyclopædia Britannica*, 2006). |
| interdisciplinary | a context of use, at least somewhat integrative, of tools, techniques and methods of more than one [engineering] discipline. *Cross-disciplinary* is taken to have identical meaning |
| model, modelling [of *engineering system*] | "Models of systems are simplified, abstracted constructs used to predict their behaviour" (Karnopp, Margolis & Rosenberg, 1990:4) |
| multidisciplinary | a context of serial or parallel, but essentially not integrative, use of tools, techniques and methods of more than one [engineering] discipline |
| School | School of MIAE in Glossary of Abbreviations above |
| sub-discipline [engineering] | "a traditional subdivision of an engineering *discipline,* for example structures and hydraulics as sub-disciplines of Civil Engineering, or a combination of areas of comparable breadth." (ECSA, 2003) |

[B] Note: this is a verbatim extract from the reference, and has grammatical errors and missing words.

**GLOSSARY OF TERMS** (continued)

| Term | Definition |
|---|---|
| system [engineering system] | "**2** a set of devices (e.g. pulleys) functioning together" (*Concise Oxford Dictionary,* 1990). "**7.** ENGINEERING assembly of components: an assembly of mechanical or electronic components that function together as a unit" (*Microsoft® Encarta® Dictionary,* 2005). |
| technology | "the application of scientific knowledge to the practical aims of human life" (*Encyclopædia Britannica,* 2006). |
| the University | University of the Witwatersrand, Johannesburg, South Africa |
| transdisciplinary | a context of "integrated use of the tools, techniques and methods from various [engineering] disciplines"[C] |

---oOo---

[C] Kozmetsky, G, Generational Road Maps and Commercialization of Science and Technology, *J. Integr. Design Process Sci.,* Vol. 1, No. 1, 1997, pp. 4-8; cited in Ertas *et al.,* 2003:289. "Transdisciplinarity is the application of theories, concepts or methods with the intent of developing an overarching synthesis" (Lattuca, L.R. [2001], *Creating Interdisciplinarity: Interdisciplinary Research and Teaching among College and University Faculty,* Nashville: Vanderbilt University Press; cited in Nikitina, 2002).

# 1. INTRODUCTION

## 1.1 General Introduction

Today's hypercompetitive, but environmentally and socially stressed world is demanding goods and services that are not only cost-effective, but are reliable, multi-functional, environmentally sustainable, energy- and resource-efficient, and fast. "Indeed, today's consumer routinely expects devices that possess smartness, adaptability and other forms of sophistication" (Hargrove, 2002:344). Put another way, such goods and services should, in the words of the Standard Bank's advertising slogan, be "simpler, better, faster" – that is, easier, more advantageous, and faster *to use,* while performing functions that may be highly complex. Furthermore, they must perform these functions *efficiently* – with the minimum use of energy and other resources – and *acceptably* from environmental and social viewpoints.

The profession of engineering is involved whenever such goods or services make use of known natural laws of the universe in handling matter, energy or information to perform their desired functions. In essence, engineering is concerned with applying the knowledge base of the natural sciences to enhance the quality of life of mankind. The Engineering Council of South Africa (ECSA) defines the professional activity of engineering as, "intellectual and conceptual work using engineering knowledge and engineering competencies to conceive, create, designing and implementing, components, systems, engineering works, products and processes and to solve problems of economic or social value"[1] (ECSA, 2003).

"Simpler, better, faster" goods and services, having to satisfy the abovementioned multiple criteria, of necessity have to use areas of knowledge originating from different branches of the natural sciences. For example, the modern motor-car's components make use of the principles of (at least) mechanics, electricity and chemistry. Any of these branches of the natural sciences may yield a technology that is best suited to the purpose of a component or subsystem of the car. The principles of mechanics are suited to producing a strong and stable car body; those of electricity are suited to producing effective lighting and convenient control; and those of chemistry are suited to efficient chemical combustion as the source of motive power. Moreover, as technology advances, one technology may supplant another; for example, as the energy-storing abilities of batteries increase, electricity may supplant chemical combustion as the source of motive power for motor-cars.

The traditional disciplines, or branches, of engineering, such as mechanical, electrical and chemical engineering, naturally originated from their parent

[1] Note: this is a verbatim extract from the reference, and has grammatical errors.

branches of the natural sciences. Yet, as the example of the modern motor-car demonstrates, in any goods or services where the functions are many and complex, more than one branch of the natural sciences – and hence of the traditional engineering disciplines – is inevitably involved. As goods and services become more multi-functional, engineering practice is becoming increasingly integrated across traditional engineering disciplines. The education of engineers has to meet this challenge, aligning more closely with Hirst's view of engineering as a practical example of *fields* of knowledge, these being:

> "... held together simply by their subject matter, drawing on *all* forms of knowledge that can contribute to them."
>
> (Hirst, 1965:131; candidate's emphasis)

This project focuses upon one particular area of this challenge: the *effective, optimal* integration, within the undergraduate engineering curriculum, of subject-matter of the disciplines of mechanical and electrical engineering to produce the integrated knowledge in students necessary for the new mechanical-electrical-'automational' cross-discipline of *mechatronics,* defined in Section 2 below. Thus it explores a particular sub-area of the larger question of effective, optimal integration in the engineering curriculum, this question being presently intensively debated in the literature (e.g. Froyd and Ohland, 2005; Ertas *et al.*, 2003; Harrison, Macpherson and Williams, 2007; Heitmann, 2005; Spinks, Silburn and Birchall, 2006; Traylor, Heer and Fietz, 2003).

The project confines itself to firstly, conceptual *analysis* of the problems of curriculum integration in this sub-area, and secondly, exploring and identifying meaningful conceptual *bases* for such curriculum integration. It leaves for further work the necessary empirical research to validate this analysis and the proposed conceptual bases.

### 1.2 Outline of Research Report

Section 2 first introduces mechatronics, its philosophy, and the consequent requirement for integrated mechanical-electrical knowledge in engineers. It briefly surveys universities' mechatronics learning programmes. It then describes the undergraduate first course in mechatronics at the School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg – and the disquieting failure rates in both this course as a whole and its laboratory project over the last six years. Two indicators point to the real difficulty – inadequately integrated, interdisciplinary mechanical-electrical-electronic knowledge in students. The initial question prompting the research thus emerged: in sum, how could the electrical-electronic knowledge required for mechatronics be transmitted more effectively and integrally to mechanical engineering students? Section 2 also emphasises the necessity of integrated knowledge in the essence of engineering –

the engineering design process – to achieve the synergy so necessary therein. Finally, it reviews key observed deficiencies in traditional engineering curricula: while their courses may embrace multiple engineering sub-disciplines (subjects), the different paradigms involved in teaching these and the resulting insulation between sub-disciplines foster neither interdisciplinarity nor ability to solve engineering problems.

Section 3 enlarges more upon the difficulties of mechanical engineering students in grasping electrical and electronic technology, and reviews the remedies attempted at universities – including interdisciplinary approaches in both courses and curricula. It then poses key queries: what is meant by interdisciplinarity and its difference from mere multidisciplinarity, and *how* do various curricula foster or hinder development of interdisciplinarity in the student engineer? Theoretical concepts are needed to analyse the nature of interdisciplinarity and multidisciplinarity – in courses, curricula and knowledge produced thereby. We accordingly turn to Basil Bernstein, an educational sociologist, and Lev Vygotsky, a developmental and cognitive psychologist, for appropriate concepts.

Section 4 introduces Bernstein. His concept of *educational knowledge codes* – regulative principles behind education – brings to light two opposed regulative principles by which curricula categorise and control knowledge. In curricula with *integrated codes,* boundaries between subjects tend to lose their significance, whereas in curricula with *collection codes,* such boundaries are rigidly maintained and teachers (educators) maintain tight control over subject-matter and how it is taught. Bernstein's interest afterwards shifted to what types of knowledge were accordingly produced in learners. He defined two corresponding integrated- and collection-type *knowledge structures* in learners, calling these *hierarchical* and *horizontal* respectively. In a hierarchical knowledge structure (HiKS), bodies of knowledge are subsumptively integrated under common, generally applicable principles. By contrast, in a horizontal knowledge structure (HKS), bodies of knowledge are merely collected, and maintain their identities as specialised 'languages'. Links between such 'languages' are only at their boundaries.

Section 5 introduces Vygotsky, beginning with his three distinguishing levels of concept development in learners – syncretic grouping, 'complexes' and potential concepts. These emerged through tests done on children, but, because adults and older children do not abandon preconceptual thinking, these levels, particularly the last two, apply to students as well. Vygotsky defines genuine conceptual systems as ones of hierarchically organised, intellectual ideas connected by relations of generality. (The similarity to Bernsteinian hierarchical knowledge structures is obvious.) By contrast, in 'complexes' there is no such hierarchical organisation, and the bonds between ideas are concrete and factual, not abstract and logical. However, the pseudoconcept, the

most advanced form of 'complex' reasoning, is so difficult to distinguish from a true concept that it often passes for one. Section 5 then briefly outlines Vygotsky's Zone of Proximal Development (ZPD). This zone is Vygotsky's theory of a learner's dynamic intellectual development, *in social interaction with others,* through 'spontaneous' concepts from her/his everyday experiences interacting with the 'scientific', subject-matter concepts presented in formal classroom instruction. This ZPD is the basis of the developmental psychologist Mariane Hedegaard's pedagogy of the 'Double Move in Teaching and Developmental Learning', which seems a promising way to achieve an integrated mechatronic knowledge structure in students.

These concepts of Bernstein and Vygotsky compelled the candidate to extend the scope of his critical research questions far more widely than that of the abovementioned initial question prompting the research. The question was not merely one of effectively and integrally *transmitting* knowledge. First, to what extent did the Bernsteinian *educational knowledge codes* underlying the undergraduate curriculum, course syllabi and pedagogy integrate the engineering sub-disciplines required for mechatronics? Second, how could *full, proper* development of the integrated knowledge structures and genuine concepts in students that were desirable for mechatronics be achieved? Third, were technical concepts available that provided a sound basis for such integration – that adequately codified the common principles underlying the operation of engineering physical systems? Fourth, was there a promising alternative pedagogy that would facilitate such development in students from their current levels of development, and also motivate them more powerfully to do so? The critical research questions thus emerging are stated in Section 6.

Section 7, after a brief recapitulation of Bernstein's knowledge structures, shows how his hierarchical knowledge structure (HiKS) is complemented by Vygotsky's genuine conceptual system with relations of generality, and points out that this is the desirable mechatronic knowledge structure for mechatronics. It then points out that the collection-type first- and second-year undergraduate engineering programme fosters a *horizontal* knowledge structure (HKS) – a collection of 'languages' (separate bodies of knowledge) that is an inferior knowledge structure for mechatronics. It is, in fact, a Vygotskian 'complex', and needs to develop further. Since there can be organisation and linking within a HKS, it *can* develop further – first into a two-plane, pseudoconceptual HKS. This still has serious deficiencies, though, because the languages are still not integrated, but uneasily linked at their boundaries. *Moreover, being a pseudoconceptual system, it can often pass, under insufficiently searching assessment, for a genuine conceptual system. Therefore, it should not stop at this level of development,* but develop still further into an HiKS with genuine mechatronic concepts.

However, this requires a unifying conceptual tool, revealing and systematising the common laws governing the behaviour of physical devices and structures in different engineering disciplines. Such a tool is available in the *bond graph,* complemented by the *relational block diagram,* which more clearly brings out the natural interactions between a physical system's components, and how artificial control may be added to meet performance objectives. Both these conceptual tools are described and exemplified in Section 8; together, they encapsulate the key general principles in the desired HiKS for mechatronics.

Finally, in Section 9, Hedegaard's 'Double Move in Teaching and Developmental Learning' (Hedegaard, 1990; 2002), which is based on Vygotsky's 'zone of proximal development' [ZPD], is explored. This seems a promising way of realising this desirable integration in students' mechatronic knowledge structures. A welcome opportunity of implementing one key aspect of this 'Double Move' – situationally-necessitated research activity in the laboratory project of the third-year mechatronics course of 2009 – is described in some detail, and students' reactions thereto outlined. No hoped-for increase in motivation was detected, but the aspect of the course cited most frequently as being most valuable was this laboratory project. There is encouragement, therefore, to continue revising this mechatronics course in this vein.

## 2. BACKGROUND

The word *mechatronics* was coined by a Japanese engineer in the late 1960s (Ashley, 1997:61). Bradley, surveying a wide variety of definitions given in the literature, concludes,

> "... most of the definitions do manage to agree in some way that mechatronics is concerned with the integration of its core technologies to generate new and novel technological solutions in the form of products and systems in which functionality is integrated across those core technologies, with information technology and software engineering then providing the 'glue' which binds the whole together." (Bradley, 2004:276)

As its name suggests, mechatronics is an interdisciplinary field; it combines mechanical, electrical and electronic engineering, and information processing (for automation), in producing automatic, cost-effective domestic, commercial and industrial devices, such as washing machines, 'autofocus' cameras and industrial robots (Alciatore and Histand, 2003:2; Bolton, 2003:1,2). Central to all these devices are their automatic capabilities; they can do some or most of their task(s) without human intervention. [2]

[2] The need for automation arose as soon as technology embraced mechanisation, replacing physical (mechanical) power from humans or animals with mechanical power obtained from inanimate sources, such as wind, water or steam. Immediately there was a problem: the intelligence (information-processing capability) of a human or animal enabled that human or ani-
...

One of the best definitions of mechatronics is an early one from Craig (1994):

> "... the *synergistic* combination of mechanical engineering, electronics, control engineering, and computer science. The key element in mechatronics is the *integration* of these areas through the *design* process."
>
> (Craig, 1994, quoted in Alciatore & Histand, 1995:799; candidate's emphasis)

Craig's above definition captures the three essential concepts of mechatronics: *synergy, integration* and *design*. The word 'synergy' deserves closer attention even here. Synergy is formally defined as "the combined effect of drugs, organs, etc. that exceeds the sum of their individual effects" (*Concise Oxford Dictionary*, 1990). But here, synergy is on a further plane; it must more than just *exceed* the sum of individual effects; it must permit other possibilities altogether. Integration and design are not sufficient; synergy is more than either. Buckminster Fuller, the famous American architect-engineer, captures this in his definition:

> "Synergy is the unique behaviour of whole systems, unpredicted by behaviour of their respective sub-systems' events." (Fuller, 1961:55)

Lyshevski (2002:197) states that mechatronics "integrates mechanical, electrical and computer engineering areas". It involves mechanics because humans are mechanical creatures, interacting with their surroundings through mechanical forces and motion. It involves electrical technology because energy in the form of electricity is easily transmitted and converted into heat, light, sound, physical motion, and so on. It involves electronic and computer technology because this can process information, at speeds impossible with other technologies, to achieve the automation required. In consumer products, in manufacturing, in process, automotive or aerospace engineering, and even in buildings and structures, mechatronics is affording 'intelligent' functions and features that were not possible or cost-effective before. Therefore, today's mechanical, industrial and aeronautical (MIAE) engineers must be familiar with this integrated approach to engineering – or "run the risk of being left out of the interesting work" (John F. Elter, Vice-President, Strategic Programs, Xerox Corp., New York, USA, quoted in Ashley, 1997:63). It is no longer enough for a mechanical, industrial or aeronautical engineering graduate to be strongly grounded in her/his own branch, or sub-division, of engineering and its sub-disciplines.[3] S/he must also be sufficiently familiar with the integration, *from the design stage,* of electrical, electronic and control

---

mal to suit the power provided to the desired task; but analogous self-control from inanimate sources was not guaranteed. Self-control had to be built either into the device extracting power or into the source providing it. Wind could destroy a windmill as well as power it; or more often and inconveniently, when the wind direction changed, a windmill no longer faced squarely into the wind and power therefrom diminished or vanished.

[3] For example, fluid dynamics, mechanics of solids, thermal systems, operations management, manufacturing technology, aircraft structures, and aero- and flight dynamics.

technologies into systems, devices and structures in mechanical, industrial and aeronautical engineering.

Of course, such integrative familiarity requires effective grounding in the relevant electrical, electronic and control technologies themselves. However, what is meant by 'effective'? As is shown in Section 8 below, "Bond-Graph Representation of Common Principles of Mechanical and Other Physical Systems", effective grounding not only requires the *additional* knowledge of electrical and electronic subject-matter. Integrated knowledge of the underlying, common principles governing the behaviour of *mechanical, electrical and electronic devices alike* is required. For integrating these technologies demands knowledge of how to integrate them – not just knowledge of each separate technology on its own. In turn, knowledge of *how* to integrate requires *integrated knowledge* – inescapably meaning knowledge of the principles common to, and underlying, all of these technologies. Later, in Section 7 below, "Analysing Mechatronic Knowledge: the Codes and Knowledge Structures of Bernstein", it is submitted that a Bernsteinian *hierarchical knowledge structure* is therefore required for adequate, integrated grasp of such common principles.

### 2.1 Teaching of Mechatronics at Universities

Mechatronics was being labelled "a new design strategy" from 1990 (Berardinis, 1990:50). Indeed, in 1991, the journal *Mechatronics* was launched (Daniel & Hewitt, 1991). Still labelled "emerging" in 1995 (Alciatore & Histand, 1995:799), mechatronics is now a recognised cross-discipline; moreover, it is progressing from cross-disciplinary (where the emphasis is on integrating older disciplines) to *thematic,* where these older disciplines fade from primary view and mechatronics becomes a theme in its own right – having an almost primary disciplinarity of its own (Grimheden & Hanson, 2005:183-191).

Universities throughout the world now offer learning programmes in mechatronics, and report teaching approaches therein (e.g. Das *et al.*, 2005; Turner, 2005; Harrison & Deanes, 2005; Mina *et al.*, 2005, Grimheden & Hanson, 2005; Firth, Surgenor & Wild, 2004; Driscoll & Villanucci, 2004; Newman *et al.*, 2003; Shooter & McNeill, 2002; Hargrove, 2002; Brown & Brown, 2002; Krishnan *et al.*, 1999; Ume & Timmerman, 1995; Alciatore & Histand, 1995). Typically, mechatronics courses are offered at senior or graduate level to bi-disciplinary classes of mechanical engineering (ME) and electrical engineering (EE) students (for example, Das *et al.*, 2005; Turner, 2005; Brown & Brown, 2002; Krishnan *et al.*, 1999). Some universities, though, begin *exposure* to mechatronics, through other courses, even at first-year level (e.g. Yost, 2000; Newman *et al.*, 2003). Reflecting the applied nature of mechatronics, major parts of all courses are team-based, hands-on laboratory exercises and/or mini-projects, followed by design-build-test laboratory projects. Some

syllabi require ME students to take a prerequisite course in electrical engineering basics, to adequately prepare them for the electrical and electronic aspects of mechatronics (e.g. Krishnan *et al.*, 1999:13d4-4). Despite such courses, it is sometimes found that ME students lack sufficient prior comprehension of the principles of electricity and electronics (e.g. Turner, 2005:82; Shooter & McNeill, 2002:340-1). More advanced courses, for example on modelling and simulation of mechatronic systems, may build upon a first course (e.g. Das *et al.*, 2005:284-8).

In the School of Mechanical, Industrial and Aeronautical Engineering (School of MIAE), University of the Witwatersrand, Johannesburg, South Africa, where the candidate is a senior lecturer, the mechatronics courses follow a similar pattern. The first such course, 'Mechatronics I', hereinafter termed the 'MCT1 Course', is prescribed for the third year of undergraduate study. The second and final course, 'Mechatronics II' in the fourth year of study, builds upon the first course with more advanced modelling and control topics. The candidate teaches the MCT1 Course, which is now described in some detail.

#### 2.1.1 'Mechatronics I' Course, School of MIAE, University of the Witwatersrand, Johannesburg

This course is compulsory for the bachelor's degrees in all three branches of engineering – mechanical, industrial and aeronautical[4] – that the School offers. The syllabus first introduces the third-year undergraduate student to the philosophy of mechatronics – *designing* the most synergistic, integrated combination of technologies into a product or system for optimal versatility, performance and cost-effectiveness. Second, it introduces the technologies of the essential sub-systems – the measuring, control and actuating systems – of any mechatronic device, and the main features of the components available for each of these sub-systems. Finally, and just as importantly, its laboratory project is a major, team project of designing, building and testing a working model of a full-scale mechatronic device. Such model devices have included automated hoists, automated windscreen wipers, entry control booms for cars, and coin sorters. Fuller details of the course are presented in Appendix 1.

To provide adequate electrical and electronic grounding for this course, students must complete a prerequisite, second-year course in electrical engineer-

[4] Mechatronic devices and systems are integral parts of, *inter alia,* modern aircraft and modern manufacturing techniques, so it is deemed essential that industrial and aeronautical engineering graduates have adequate grounding in mechatronics. Some other universities have a similar view; for example, mechatronics courses are taken by aerospace engineering students at Tuskegee University, Alabama, USA (Harrison & Deanes, 2005:5665).

ing – hereinafter termed the 'EE2 Course' – given by the University's School of Electrical and Information Engineering (School of EIE).

## 2.2 Inadequate Knowledge Acquisition in Mechatronics

In the candidate's eight years of teaching this MCT1 Course, its electrical and electronic content has not found ready acceptance with students. A frequently expressed student complaint, both verbally and in the course and lecturer surveys processed by the University's Centre for Learning, Teaching and Development (CLTD), is that the EE2 Course is inadequate preparation for the electrical and electronic content of the MCT1 Course. In assessing student performance in the latter course, the candidate has continually observed disturbing shortfalls in understanding of the principles governing behaviour of electrical and electronic devices.

For the MCT1 Course, Table 2.1 lists the overall student pass rates, as a percentage of class size, over the years of 2004 through 2009. The pass rates for each type of assessment – homework assignments, the mid-term test, the abovementioned laboratory project, and the final examination – are also listed.

Table 2.1 MCT1 Course, 2004-9: Percentages of Individual Student Passes

| | | **Pass Rate (Percentage of Class) in Assessments by:** | | | | |
|---|---|---|---|---|---|---|
| | **No. of Students in Class** | **Homework Assignments** (weighting in course: 15%) | **Mid-Term Test** (weighting in course: 15%) | **Laboratory Project** (weighting in course: 20%) | **Final Examination** (weighting in course: 50%) | **Overall Pass Rate (% of Class)** |
| 2004 | 59 | 97 | 53 | 66 | 71 | 84 |
| 2005 | 75 | 99 | 59 | 71 | 87 | 96 |
| 2006 | 102 | 27 | 32 | –[5] | 75 | 79 |
| 2007 | 133 | 93 | 35 | 100 | 65 | 78 |
| 2008 | 95 | 85 | 46 | 97 | 82 | 87 |
| 2009 | 96 | 81 | 79 | 95 | 67 | 83 |

There are two aspects of concern in this table. First, except for 2005, the overall percentage failure rate was above 10 per cent, and in 2006 and 2007 it exceeded 20 per cent. Such overall failure rates, in the penultimate year of undergraduate study, must be of concern – especially since the high failure rates in the *laboratory project* disappeared after 2005. In 2006 and 2007, the especially high failure rates in the mid-term test and final examination led to those years' higher overall failure rates.

[5] The laboratory project was not part of the course in 2006.

Second, the main reason for the virtual elimination after 2005 of failures in the laboratory project was the reduction of its workload. In 2007, its requirements for design and manufacture of *mechanical* components were drastically reduced. From 2008, they were eliminated; pre-manufactured mechanical components just needed to be assembled. Yet the overall course failure rate remained above 10 per cent.

There are two indicators that point to the real difficulty. The first emerges from Table 2.2, which lists the failure rates not only for the laboratory projects as a whole, but also those for the most important type of assessment in these projects – the *functional trials* that assess how well the assembled model devices actually carry out their specified tasks. Failure in this trial means that a model device is mostly or completely non-functional – that is, it fails substantially or wholly to perform its task.

Table 2.2 MCT1 Laboratory Project, 2004-9: Number of Student Teams / Individuals Failing in Assessment of (i) Functional Trials of Working Models; (ii) Whole Project[6]

| 2004 | | 2005 | | 2007 | | 2008[7] | | 2009 | |
|---|---|---|---|---|---|---|---|---|---|
| **Functional Trial Failure** | **Whole Project Failure** | **Functional Trial Failure** | **Whole Project Failure** | **Functional Trial Failure** | **Whole Project Failure** | **Functional Trial Failure** | **Whole Project Failure** | **Functional Trial Failure** | **Whole Project Failure** |
| 10 teams out of 15 (67%) | 5 teams out of 15 (33%) | 11 teams out of 20 (55%) | 6 teams out of 20 (30%) | 21 teams out of 30 (70%) | 0 teams out of 30 (0%) | 29 of 95 students (31%) | 3 of 95 students (3%) | 6 teams out of 19 (32%) | 1 team out of 19[8] (5%) |

In 2005, more than half the project teams failed the functional trials, and in 2004 and 2007, two-thirds failed these trials! In 2008, the individual failures were just below one-third of the class. In 2009, one-third of the teams failed these trials.[9] What emerges from this table, therefore, is that a substantial fraction – the majority in some cases – of students *do not succeed in getting their own designed model devices to work properly.* Furthermore, such failures are not due to the individual mechanical, electrical and electronic components not working properly,[10] but *due to the ways in which they are inter-*

[6] The year 2006 is not in this table, as the laboratory project was not part of the course in that year.
[7] In 2008, students were assessed individually, not in teams.
[8] A second team only *just* passed the whole project, attaining 51%.
[9] As mentioned earlier, from 2008 the project no longer required design and manufacture of mechanical components. The main reasons for the lower failure rates in the functional trials of 2008-9 were probably the resultantly reduced project workload, and no inadequate functioning or failure of team-designed mechanical components during these trials.
[10] Such components are sourced from reputable manufacturers, and thus operate properly unless improperly used.

*connected and controlled.* Inadequate or faulty ways of interconnecting and controlling such components point to inadequate *interdisciplinarity* in students. In sum, the integration of technologies was not successful, whether the lack of understanding was of the details of individual technologies, or of how to integrate them, or of both.

The second indicator is in students' answers to *descriptive* questions (those not requiring mathematics and calculations, but rather illustrative diagrams and clearly written descriptions) in the mid-term tests and examinations of the MCT1 Course. Many such questions assess grasp of interdisciplinarity, and many students display woefully inadequate such grasp. An example is now given of such a question, asked in both the 2007 mid-term test and the 2008 final examination.

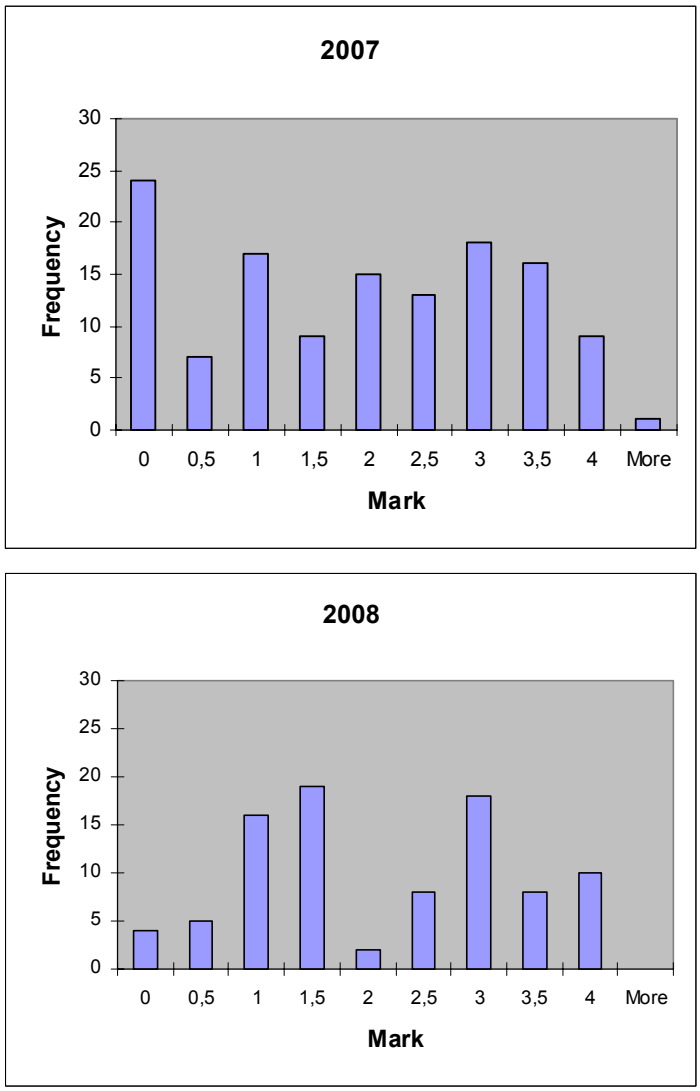



Figure 2.1 Marks for Test/Examination Question on Washing Machine Solenoid, 2007 and 2008

*In both years, this question had been one of the practice problems issued to students well before this test and examination.* Moreover, its model solution had been displayed on a notice board. The question was:

> "In an automatic washing machine, the water inlet valve is normally held closed by a spring. A solenoid, when energised, retracts and opens this valve. The solenoid operates on 220 V. A.C. After many years of service, the filter in the valve fails, allowing suspended grit to pass through it. A short while later, this grit causes the valve to get stuck in the closed position. Explain why the solenoid is then liable to burn out when it is next energised. (4 marks)"
>
> (MCT1 Examination, School of MIAE, University of the Witwatersrand, 2008)

The average marks for 2007 and 2008 were, respectively, 1,9 and 2,1 out of 4 – that is, just under and over 50 per cent! For both 2007 and 2008, Figure 2.1 shows the often-encountered bimodal distribution of concentrations in both low and high marks. The medians of the marks in both 2007 and 2008 were 2, showing that approximately half the students in either year failed this question – *after it had been issued as a practice problem and its solution published!*

What is striking about this question is its interdisciplinarity – that is, a grasp of concepts from three classes of phenomena, mechanical, electrical and thermal, is necessary to answer it properly. This is illustrated in the examiner's solution below, with its explanatory notes.

**Examiner's Solution.** When an A.C. solenoid is in the extended position, its inductance[11] is relatively low[E1] because the path length through [the gap of] air in its magnetic circuit is then at its maximum.[Ma1] Thus its impedance is lower than in the retracted position,[E2] so the initial inrush current upon being energised is high.[E3] It therefore must retract completely and quickly[Me1] so that the initial inrush current falls to its steady-state value.[E4] If an A.C. solenoid sticks in the extended position, it is likely to burn out,[E5] because the heat-dissipating ability of its coil[T1] is only adequate for the steady-state, retracted position.

Superscripted Explanatory Notes

(*Key Aspects:* E – electrical; Ma – magnetic; Me – mechanical; T – thermal)

E1: The inductance is low because, when the solenoid's iron plunger is extended, its ability to concentrate the magnetic field produced by the current flowing through the solenoid's coil of wire is least (see 'Ma1' below).

Ma1: When the solenoid's iron plunger is extended (the 'extended position'), there is an internal *air gap* between this plunger's back face and the back

[11] Inductance: the ability to store energy as a magnetic field created by flowing electric current. The inductance of a given solenoid depends only on its geometry and magnetic properties.

face of the solenoid's central cylindrical chamber in which the plunger moves. Unlike the plunger, the air in this gap has no ability to concentrate the magnetic field produced by the current flowing through the solenoid's coil.

E2: The impedance offered by the solenoid's coil to flow of alternating electric current (A.C.) is a function of both the solenoid's inductance (see 'E1' above) and, of course, the electrical resistance of the wire of the coil. The impedance increases as either of these increases, and vice versa. With the solenoid's inductance being low in the extended position, as explained in 'E1' and 'Ma1' above, the coil's impedance is thus lower.

E3: With the coil's impedance being lower in the extended position, the initial flow of electric current (the 'inrush current') upon being energised with 220 V. A.C. will be correspondingly higher.

Me1: There must be no mechanical hindrance (here, increased friction due to the grit) to the plunger retracting fully into the solenoid's central cylindrical chamber.

E4: As the plunger fully retracts into the solenoid's chamber, the air gap referred to in 'Ma1' above decreases to effectively zero. Hence the iron plunger's ability to concentrate the magnetic field produced by the current flowing through the coil increases to its maximum. The solenoid's inductance commensurately increases to a maximum, and by 'E2' above, so does the coil's electrical impedance – causing the current to fall to its lower, steady-state value at the plunger's fully retracted position.

E5: As mentioned in 'E2" above, the solenoid's coil of wire has electrical resistance, and will thus warm up due to unavoidable conversion of electrical energy into thermal energy. The rate of such conversion is proportional to the *square* of the current, though, so to double the rate of thermal energy generation, the current only needs to increase by a factor of 1,414!

T1: The materials and the geometry of the coil govern how fast it can lose thermal energy by heat transfer to its surroundings. If the rate of thermal energy generation exceeds that at which the coil can dissipate such energy to its surroundings, the coil's internal temperature will reach a value where the insulation between adjacent turns of wire breaks down – leading to short circuits and hence burn-out.

Students who answered this question inadequately – about half the class in both 2007 and 2008 – tended to confine themselves to only *one* class of phenomena, usually electrical. That is, they confined themselves to one engineering discipline, *and so failed to grasp the interdisciplinary nature of the problem.*

Why is this? Why, even though the necessary mechanical, electrical and thermal subject-matter have been taught to students prior to their first

mechatronics course, do students not integrate this knowledge into proper interdisciplinarity?

### 2.3 Question Prompting Research

As a concerned educator, the candidate began by examining the material of the EE2 prerequisite course (Jandrell & van Coller, 1998). He gradually perceived that *its material was written from a wholly electrical point of view;* there was almost no emphasis of the analogies between electrical and mechanical devices,[12] and the common, fundamental principles governing the behaviour of both. This EE2 Course thus does not awaken MIAE students to these analogies and underlying common principles, nor the need to begin integrating electrical, electronic and control technologies into their course and design work in their senior years of study. As is further illustrated in Section 7.3.2 below, it has little apparent commonality with the other second-year courses in the School. It thus gives the appearance of being a 'tack-on' course, not clearly and vitally relevant. Hence many, possibly most, of the School's students tend to 'compartmentalise' electrical engineering (EE) technology during their second-year studies, perceiving this as only marginally relevant to their main technological interests.

The concern prompting the research thus emerged: how can the detailed behavioural principles of electrical and electronic devices, their underlying common principles of behaviour with mechanical devices, and the need to integrate their technologies be transmitted more effectively to, and absorbed more integrally by, MIAE students, hence discouraging 'compartmentalisation' and the ensuing difficulties with mechatronics in their later years of study?

### 2.4 The Wider Context: Multi- and Inter-Disciplinary Grounding Required in Graduate Engineers

This 'prompting question', of course, springs from a larger one: why should graduate engineers need understanding of more than one engineering area, that of their preference? Section 2 above has already briefly justified this need for mechanical, aeronautical or industrial engineers; but the equal need for *all* engineers deserves further elaboration. Perhaps the reason is best introduced by a quote from the famous American engineer and designer of earth-moving machinery, Robert G. Le Tourneau:[13]

---

[12] For example, those between electrical transformers and mechanical gears; kinetic energy stored in a moving mass and energy stored in the magnetic field of an electrical coil through which current is flowing, etc.

[13] LeTourneau Inc., the company that he founded, still makes the world's largest earth-moving machinery.

> "…an expert in one field is no expert if one field is all he knows."
> (Le Tourneau, 1960:98)

As Ertas *et al.* (2003:291) point out, engineering problems are not naturally restricted to artificial discipline-oriented boundaries. They state, "In fact, no problem is inherently disciplinary. Disciplines are simply the manifestation of reductionism. Disciplines are necessary but not sufficient to tackle complex and large-scale design problems" (*ibid.*:290). If real engineering problems are not discipline-specific, mastery of one discipline must not be the *raison d'être* of engineering. The definition of 'engineering' adopted by the Engineering Council of South Africa (ECSA), which is the regulating body for the practice of engineering in South Africa, makes this clear.

> **"Engineering:** ... 2: Engineering as a university degree, such as the B.Sc.(Eng.), and as a professional activity is concerned intellectual and conceptual work using engineering knowledge and engineering competencies to *conceive, create designing* and implementing, components, systems, engineering works, products and processes *and to solve problems* of economic or social value. The process is based on scientific knowledge, requires synthesis of knowledge, and takes into account wider issues... "
> (ECSA, 2003;[14] candidate's emphasis)

In the U.K., the traditional model of engineering is mono-disciplinary, assuming that graduates will work as specialists (Harrison *et al.*, 2007:286). This is also the case in South Africa, as reflected in most of the branches of engineering named by ECSA (2004:1). It is well to note that the luxury of such specialist work is only viable in a large firm – Eskom in South Africa, for example – that can afford to employ enough such specialists to cover all the engineering disciplines needed in the firm's activities. Even so, this traditional mono-disciplinary model of an engineer is increasingly ill-suited to the needs of both large and small engineering companies. Large employers now expect at least readiness for multidisciplinarity; they expect graduates to join multifunctional, (that is, multi-disciplinary) teams developing complex systems (Harrison *et al.*, 2007:286). In small firms, the pressure is for interdisciplinarity; "a need for graduates who can cross disciplines, handling and integrating technologies ..." (*ibid.*). Thus, as already noted in the above quote from Le Tourneau, it is no longer – if it ever was – enough to be expert in just one engineering field or discipline.

### 2.4.1 The Key to Interdisciplinarity: a Design-Oriented Approach

Why was discipline-based education, with its disadvantages, ever adopted by engineering schools? Here, Seely (1999:289) offers a fascinating explanation: in American schools, the shift during 1945-1965 to discipline-based education arose from the need – focused by World War II – to conduct research in insuf-

[14] Note: this is a verbatim extract from the reference, and has grammatical errors.

ficiently known technologies.[15] The changes being proposed now seek to undo that emphasis, fuelled by the charge that:

> "... large numbers of engineering students leave college without the skills essential to professional engineers. Often topping the list of missing capabilities is problem-solving ability, or what engineers have called *design experience*." (Seely, 1999:285; candidate's emphasis)

Bucciarelli (2003) describes the restricted, unrealistic nature of the typical problems assigned in discipline-based engineering courses:

> "The problems are of a very special sort: Unlike design opportunities, they admit of but one solution, and usually there is but one method to get there ... One includes only information relevant to the method or the principle that the problem is intended to illustrate. There is no attention to context that has any depth, no elaboration of a scenario or situation where a practicing engineer might actually encounter a problem of this sort. Ambiguity and uncertainty are to be avoided. Required 'givens' are specified as precisely as possible without giving away the answer and, likewise, acceptable answers are expressed in cryptic, symbolic or numerical form. Evaluation of the student's work is correspondingly relatively straightforward ... The phrase 'under-determined' has no meaning here." (Bucciarelli, 2003:302)

On the other hand, the complexity and diversity that characterise real-world engineering problems are well described by the following two definitions of ECSA:

> **"Complex Engineering Activity:** has a large number of entities or influences with high level of interaction where cause and effect are not simply related. Additionally the subject requires complex model for adequate description: cannot be treated adequately by considering a part or aspect; has state, that is current behaviour is influenced by past trajectory; has a large number of operational responses; or is sensitive to disturbance or parameter variation. *Can also be applied to a problem,* system or process."[16] (ECSA, 2003; candidate's emphasis)
>
> **"Complex Engineering Problem:** is characterised by one or more of the following factors: requires in-depth knowledge that allows a fundamentals-based, first principles analytical approach; have no obvious solution and require originality and analysis; involves *wide-ranging* or conflicting *technical, engineering and other issues;* involve infrequently encountered issues; are outside problems encompassed by standards and codes of practice for professional engineering; involves wide ranges of stakeholders with widely varying needs; have significant consequences in a range of contexts." (ECSA, 2003; candidate's emphasis)

Competence in just one engineering discipline is simply not adequate for such complex engineering activities and problems. Bucciarelli (2003:296-8) points out the key deficiency of a team of discipline-oriented practitioners carrying out an engineering design: different participants work with their different, paradigmatic object-worlds, which cause each of them to view the object of

---

[15] Does this not reveal a fundamental difference of focus between research and design – disciplinarity vs interdisciplinarity?

[16] Note: this is a verbatim extract from the reference, and has grammatical errors.

design narrowly, instrumentally, and very differently from each other. "The rigid disciplinary shell of each discipline, and the precision of the disciplinary jargon tend to minimise interdisciplinary communication" (Ertas *et al.*, 2003:290). No participant has an all-encompassing, 'God's-eye view' of the design (Bucciarelli, 2003:298).

Put another way, *"an engineering design task cannot be completely broken down into sub-tasks that can be independently pursued"* (Bucciarelli, 2003:299; candidate's emphasis). The individual, object-world approaches offer no basis for optimising the contributions of all the participants, and hence the overall design, as a whole. Such approaches prevent the design being holistically viewed; unintended, unanticipated interactions between its various components or systems can thus cause failure (*ibid.*:300). This risk obviously increases with the design's complexity. Design is *inherently* multi- and interdisciplinary. Ertas *et al.* (2003:291) categorically state that present educational "disciplinary shells" are not "in-sync" with the current integration of technology. They identify the disciplinary approach's key lack of flexibility as follows: "The natural tendency for disciplines to become autonomous will always limit the effectiveness of interdisciplinary and multidisciplinary programs" (*ibid.*).

> "Educational systems, because of their massive administrative structure and reductionism can not respond in a timely manner to these demands for educating the masses in-sync with changing times. The Cartesian-Mechanistic era is approaching its maturity and is being replaced by the era of integration and combinatorics." (Ertas *et al.*, 2003:291)

The Engineering Council of South Africa (ECSA) believes that in order to contribute to economic activity and national development – that is, in order for engineers to fulfil their expected role in society – engineers' competences must attain to leading complex engineering activities and solving complex engineering problems. This is made clear in ECSA's rationale for the qualification of a bachelor's degree in engineering:

> "Skills,[17] knowledge, values and attitudes reflected in the qualification are building blocks for the development of candidate engineers towards becoming competent engineers *to ultimately lead complex engineering activities and solve complex engineering problems,* thus contributing to economic activity and national development." (ECSA, 2004:1-2; candidate's emphasis)

ECSA accordingly recognises that candidate (graduate) engineers must therefore be equipped with grounding in inter- or cross-disciplinary[18] capability. ECSA's *Whole Qualification Standard for Bachelor of Science in Engineering or Bachelor of Engineering* (ECSA, 2004) addresses this in three ways. As detailed in Appendix 3, it allows for cross-disciplinary contexts in its exit-level

[17] ECSA assigns a specific meaning to this term: see Appendix 2.
[18] See Glossary of Terms, page xii. ECSA (2003) does not define this term.

outcomes, and it stresses a systems approach in multidisciplinary work and in engineering design. Indeed, two of this standard's exit-level outcomes – those on problem-solving and engineering design – are stated as being consistent with a SAQA critical cross-field outcome requiring understanding of the world as a set of related systems (*ibid.*:11). Finally, this standard recognises emerging cross-disciplinary branches of engineering, such as 'Mechatronics' and 'Electro-Mechanical Engineering' (*ibid.*:1).

This cross-disciplinary, systems approach to engineering education is also advocated elsewhere. In the U.K., the Royal Academy of Engineering "suggests that undergraduate syllabi can better prepare graduates by promoting the importance of systems thinking and a 'whole product' holistic approach" (Harrison *et al.*, 2007:286). The CDIO (Conceive, Design, Implement, Operate) concept developed by some Swedish universities in conjunction with the Massachusetts Institute of Technology (M.I.T.) has as its overall goal that "engineers should be able to conceive, design, implement and operate complex engineering systems in a modern, team-based environment taking various societal and economic requirement[s] and a professional code of conduct into account" (Heitmann, 2005:454).

To summarise so far, candidate engineers should be equipped, *through their curriculum,* with the "skills, knowledge, values and attitudes" (ECSA, 2004:2) to permit their competences to so develop as to bring about – both in themselves and in teams – sufficient integration across disciplines in their engineering practice to ultimately lead complex engineering activities and solve complex engineering problems. Such integration hardly begins in multidisciplinary teams amounting to no more than Bucciarelli's aforementioned team of discipline-oriented participants (2003:297)!

In the USA, some authors advocate *transdisciplinary* education, this word carrying the notion of "the integrated use of the tools, techniques and methods from various disciplines" (Ertas *et al.*, 2003:289). Transdisciplinary education strives to strike a balance between holism and reductionism, and it seems that this is best achieved in the context of engineering *design.* Bucciarelli (2003:295) advocates integrating design throughout the engineering curriculum – "learning by design". Ertas et al. (2003:290-2) believe that the fundamental notions of *design* and *process* are the common threads of all disciplines; provide the patterns, insight and logic necessary to apply knowledge and skills to any problem; and introduce a greater "logical economy" in treating processes involving not only engineering activities, but business relationships. In fact, concepts and knowledge from traditionally non-engineering areas are included much more naturally in the mix (*ibid.*:292): "... engineering is becoming more about reasonable risk-taking, teamwork, change management, nontechnical decision-making, cost accounting, and marketing" (*ibid.*:291). Indeed, industries are frequently dissatisfied with the

limited non-engineering skills in their staff (*ibid.*:293). These authors suggest that transdisciplinary research and educational programs may consist of four core courses - fundamentals of design, process, systems and metrics - with supplementary courses revolving around these, and supported by a transdisciplinary team-based design project (*ibid.*:292-3*).*

In all these considerations of cross-, inter- and trans-disciplinarity, the notion of *design* is central. The Engineering Council of South Africa (ECSA) defines engineering design as follows:

> **"Engineering Design:** is the creative, iterative and often open-ended process of conceiving and developing components, systems and processes. Design requires the integration of engineering, basic and mathematical sciences. A designer works under constraints, taking into account economic, health and safety, social and environmental factors, codes of practice and applicable laws." (ECSA, 2003)

However, it is Fuller who gives a more illuminative definition of design, highlighting its roots in the discoveries of science and the essentiality of synergy:

> "...the function of design in society is to make original assumptions for the schematic employment of the appropriate behaviour characteristics of selected items of the by-science-separated constituents of the universe and to apply the new degrees of potential advantage to the evolutionary problems of the process broadly defined as 'man' ... *the principle of association of special categories of behaviour to effectuate desirable synergisms* is indicated not only in the definition of our principle, industry as human teamwork, but also as a principle in itself governing both organic and inorganic factors. *This is why we define synergy as a generalised principle. Design must imagine and discern, assume, purpose and attempt articulation, in as synergetic a manner as possible.* Design, however, cannot guarantee its results." (Fuller, 1963:276; candidate's emphasis)

Fuller then explains engineering's *implementational* role in design:

> "Engineering is the judicial authority that never assumes the initiative but decides and proves the assertions of science and design. Engineering thus establishes reliable data on the failure limits of complex associations and also measures the new synergetic behaviour characteristics discovered by design initiative. ... Engineering, then, *consolidates the net gains of science and design* in the industrial complex. *Gains are design-intuited synergies.*" (Fuller, 1963:277; candidate's emphasis)

Thus good designs utilise synergies. Fuller highlights the *raison d'être* of design: *getting synergy to do what isolated parts cannot by themselves do.* He looked at what nature does with synergy and realised that the essence of design is synergy, calling it "the integrated behaviour of nature". Fuller illustrates this well from the viewpoint of the chemist:

> "Are there, in nature, behaviours of whole systems unpredicted by the parts? This is exactly what the chemist has discovered to be true. Moreover, he had discovered that, contrary to his elementary kind of experience at school, he did not come into the chemical laboratory and find a soda fountain with spigots for hydrogen and oxygen and so forth with which you mix up the universe as you go, and then begin to make it

> work. He found the universe already in complex working order. And every time he partially separated out many of the elements from the others, he always discovered that the behaviours of the localised elements never accounted for the associated behaviour of the *a priori* complexes."
> (Fuller, 1958:96; italics in original; candidate's underlining)

A fascinating example of such synergistic design in engineering is liquid-crystal colour displays in modern laptop computers, flat-panel television sets and viewfinders for digital cameras. The orientations of molecules in liquid crystals can be changed by applying small electric fields, induced by small electric voltages. Such changes in molecule orientation in turn affect the optical properties of such crystals. The thin-film transistor (TFT) colour liquid-crystal display uses thin-film, field-effect transistors to so orientate the molecules of a matrix of liquid crystals. Light from a rear backlight enters the display, first passing through a polarising film. Polarised light then enters the three-tier (for the three primary colours, red, blue and green) liquid-crystal display matrix, which twists the three tiers of this polarised light, differently for each primary colour, to match those in the desired image. These three tiers of differently twisted light next pass through colour filters to produce three tiers of red, blue and green light respectively. The red, blue and green tiers of twisted, polarised light then pass through a second polariser that admits or blocks each colour according to its angle of twist. Finally, the admitted light reaches a multi-pixel display, which displays the desired image ("Liquid Crystal Displays", *Encyclopœdia Britannica,* 2006). Here, by synergistically utilising the electrical and optical properties of different materials, a design-intuited synergy is created, in which the behaviour of the whole system could not have been predicted from the behaviours of its parts, and is an order of magnitude more complex, and useful, than the sum of the behaviours of its parts!

## 2.5 Deficiencies of Traditional Engineering Curricula

At this point, ECSA's definition of engineering is worth repeating:

> **"Engineering:** ... 2: Engineering as a university degree, such as the B.Sc.(Eng.), and as a professional activity is concerned intellectual and conceptual work using engineering knowledge and engineering competencies to *conceive, create designing* and implementing, components, systems, engineering works, products and processes *and to solve problems* of economic or social value. The process is based on scientific knowledge, requires synthesis of knowledge, and takes into account wider issues... "
> (ECSA, 2003; candidate's emphasis)

This definition of engineering accords with Heitmann's (2005:447) observation that *problem solving* and *innovativeness* are characterising features of engineering. Yet it is in these very aspects that shortcomings in engineering education are being experienced. For example, in 2006 the Royal Academy of Engineering of the U.K. released a report on the UK industry's view of educating engineers for the twenty-first century (Spinks *et al.*, 2006). One find-

ing in that report, as summarised by Harrison *et al.* (2007:285), was that a significant minority of U.K. engineering firms found specific 'skill gaps' in problem solving; application of theory to real problems; and breadth of knowledge in their engineering graduates.

At engineering student level, Lyshevski sardonically observes,

> "There is an increase in the number of students whose good programming skills and relatively good theoretical background match with complete inability to solve the simplest engineering problems." (Lyshevski, 2002:199)

There is hardly a better summary of the deficiencies of 'traditional' engineering curricula than Jakobsen and Bucciarelli's (2007):

> "A traditional engineering curriculum comprises two or more basic sciences and a varying amount of engineering knowledge, a large part of which is in the form of paradigmatic, disciplinary knowledge. *Although the borders between engineering subjects are not very firmly established, the subjects have most often been taught separately in different courses.* As a result, it is an experience very many engineering teachers have had, that students' ability to use or build upon what they are taught in prior courses, especially the prerequisite science courses, is poor. And many studies reveal that students' understanding in fact often is insufficient to enable them to tackle problems that differ from the kinds they have already seen." (Jakobsen & Bucciarelli, 2007:297, candidate's emphasis)

These authors (*ibid.*:297) cite a recent study that reveals a key reason – concepts being used differently in individual course 'paradigms' – for students' inability to use or build upon knowledge acquired in prior courses. This study was of the teaching of thermodynamics in the Technical University of Denmark. The introductory physics course (a prerequisite science course) concentrated almost exclusively on 'closed' thermodynamic systems, where no matter enters or leaves. However, the central focus in the subsequent engineering course was naturally on 'open' thermodynamic systems, such as engines, where matter (water, steam, petrol, coal, air, and so on) of necessity is allowed to enter or leave. Thus the expanded concept of a thermodynamic system where matter enters and leaves – essential in analysing and designing so many engineering devices, like all motive engines – was virtually absent in the physics course (*ibid.*)!

Jakobsen and Bucciarelli (2007) point out that this problem has two dimensions: not only do different subjects use a concept differently, but the resulting different understandings of that concept are substantial and *paradigmatic* – that is, cast within the moulds of each discipline's paradigms. The multidisciplinary curriculum is thus also a *polyparadigmatic* one, in which each paradigm foists apparently different meanings onto concepts. Moreover, these different paradigms are not just in different engineering disciplines; they are in basic scientific disciplines too. The problem is even wider: there

are also different paradigms in theory and practice. As Jakobsen and Bucciarelli say,

> "It is here also a matter of being able to transcend borders not only between different disciplines but also between basic scientific disciplines and engineering science and, altogether, between theory and practice." (Jakobsen & Bucciarelli, 2007:298)

These authors further observe that such polyparadigmatic curricula arise in other, if not all, professional educational programmes.

Such paradigms within disciplines, both engineering and scientific, have another undesirable consequence: they tend to reinforce insulation between courses. Ertas *et al.* (2003:290) characterise a discipline as having "unified tools, techniques, and methods, and a well-developed jargon." The repositories of the core, canonical knowledge of such well-established disciplines are well-established textbooks; the faculty regards the "frozen, lifeless, unquestionable" knowledge therein as suited to being transmitted to students in a passive learning environment (Bucciarelli, 2003:303). Individual departments can claim a 'God's-eye view' of their disciplines, and so claim complete control over their corresponding courses. So students see little connection among courses; each course appears to students "as an island apart from the others" (*ibid.*:301).

> "Disciplines inevitably develop into self-contained hard shells, which tend to minimize interaction with outside entities or other disciplines. The longer a discipline evolves, the harder its shell becomes ... disciplines develop territories that are fiercely defended." (Ertas *et al.*, 2003:290)

Moreover, when assignments become more related to engineering practice, and hence are very seldom confined to just one discipline, the limitations of theoretical knowledge confined to one discipline are quickly felt:

> "Students have big problems using the very theoretical, disciplinary knowledge studied in universities, in practical situations. So, to be used in more practical assignments, theory has to be restructured and by that, it seems, built into, or encapsulated under, more practical methods." (Jakobsen & Bucciarelli, 2007:298)

Here, "practical methods" of course mean those that are more effective in "practical situations", and the reason for their greater effectiveness is that they take more account of the multi-faceted, interdisciplinary nature of such situations. Later, in Section 7.3 below, it will be seen that students' "big problems" here are symptomatic of Bernsteinian *horizontal knowledge structures* in students. With such knowledge structures, competence may not be demonstrated outside familiar contexts and circumstances (here, the environment of university teaching), because the segmental, horizontal knowledge structure is bound to the context (that of predominantly monodisciplinary university teaching and assessment)!

Returning to the specific problem that this research report considers – the difficulties and unease of MIAE (ME) students with EE technology and hence with mechatronics – the question now arises: what are the deficiencies in such candidate engineers' university curricula that contribute to deficiencies in these engineers' cross-disciplinary grounding?

## 3. CROSS-DISCIPLINARY GROUNDING OF ME STUDENTS IN EE TECHNOLOGY: PERCEIVED DEFICIENCIES AND REMEDIES ATTEMPTED

### 3.1 Perceived Deficiencies

A number of authors report the relative difficulty that mechanical engineering (ME) students have in grasping electrical and electronic technology. Shooter and McNeill (2002:340-1) note that the inevitably heavy emphasis on electronics was a concern for their ME students, but firmly believe in the necessity thereof. "To present a less electronic picture to the students was not an option we considered."

For Turner (2005:84), describing the teaching of an interdisciplinary mechatronics class at senior[19] level, this is "the major difficulty in our implementation ... unprepared mechanical engineers when it comes to electricity and electronics". He describes an underlying aversive mindset as "epidemic":

> "One of the more frustrating challenges in this course has been the lack of proficiency of the mechanical engineering students in electricity and electronics. Despite taking a physics course on electricity and a basic electronics course, there is an epidemic mindset of 'I do not understand electricity and I never will.'" (Turner, 2005:82)

Significantly, he adds,

> "The electrical engineering students do not typically face the inverse problem. Despite not having many classes in forces or dynamics, they seem comfortable learning these topics." (*ibid.*)

Das *et al.* (2005:283) refer, in their abstract, to the University of Detroit Mercy's requirement implying the same thing: in their junior[20] year, the ME students are specifically required to take a "survey" course in EE that leads in to the Mechatronics course (Krishnan *et al.*, 1999:13d4-4). This course incorporates laboratory activities on essential mechatronic components – sensors, actuators and micro-controllers (Carlson *et al.*, 2000:T4A-1). *These authors do not mention a corresponding requirement for EE students to "survey"*

---

[19] *US usage:* "of the final year of a university, high school, etc." (*Concise Oxford Dictionary,* 1990); *US education:* "a student in the last year of high school or college" (*Microsoft Encarta Dictionary,* 2005).

[20] *US usage:* "of the year before the final year at university, high school, etc." (*Concise Oxford Dictionary*, 1990); *US education:* "relating to or involving students in the third year of high school or college in the United States" (*Microsoft Encarta Dictionary,* 2005).

*ME topics*.[21] The candidate's own university has a similar prerequisite; as outlined in Section 2.1.1 above, the MIAE students take the prerequisite EE2 Course as preparation for their mechatronics courses. As outlined in Section 2.2, though, notwithstanding this prerequisite course, the candidate has continually observed disturbing shortfalls in understanding of principles in the electrical and electronic content of the third-year (MCT1) mechatronics course – in essence, the same frustrating challenge described above by Turner (2005:82-4).

### 3.2 Remedies Attempted

The obvious remedy is preparatory work – as the first part of a course, or parallel to it, or in prior courses. Hargrove (2002:349-50), describing a mechatronics design course integrated from two previous courses in his university's core ME programme, mentions that early laboratory exercises were revised to include programming micro-controllers, and interfacing to sensors and actuators. This is likewise so in the candidate's own teaching; two preliminary laboratory exercises are devoted to the same techniques in the MCT1 Course. An essential element of the University of Detroit Mercy's preparatory EE course (Carlson *et al.*, 2000:T4A-1) is introducing mechatronic components, such as sensors, actuators and micro-controllers, in laboratory exercises as well as course material.

Turner (2005:82) describes a parallel remedy: to "place the burden on the student" for "acquiring missing or forgotten knowledge", through giving homework assignments to prepare for each laboratory exercise. To assist with this, the 'virtual lectures' on the class website include ones instructing ME students in electricity (*ibid.*). These teach EE from a mechanical perspective; for example, "Voltage and current are compared to pressure and fluid flow" (*ibid.*).[22] Notably, Turner's electronic laboratory exercises are individual, *not* team-based; each student has his own equipment and is compelled to work through the exercises (*ibid.*:80). Turner specifically states that these exercises are "partially remedial", to compensate for ME students not retaining sufficient knowledge from their basic electronics course. Some ME students in fact complained of the lack of sufficient aids to learning electrical topics through self-study (*ibid.*:83).

---

[21] It should not be presumed, though, that EE students find the interdisciplinarity of mechatronics unchallenging. Das et al. (2005:295-6) report on a pre-course survey at the University of Detroit Mercy's first offering of a new course in modelling and simulation of mechatronic systems for senior ME and EE students. Although the proportions of ME and EE students in this first class are not given, this survey indicated that 50% of students had little or no understanding of mechatronic systems; 79% had little or no experience with mechatronic systems; and 93% thought they had little or no ability to model a mechatronic system!

[22] This feature has been taken further in the more integrated approach of Driscoll and Villanucci; two team-taught systems courses show the similarities between electrical, mechanical, thermal and fluid systems (2004:10441).

Nevertheless, Turner implicitly acknowledges that this is not enough; he twice notes that changes are being made elsewhere in his university's curriculum to address this "serious issue beyond this course" (*ibid.*:82). Recognition inevitably seems to dawn that *prior* work remains essential for effectively equipping ME students with the necessary background for study of mechatronics.

### 3.3 Interdisciplinary Approaches to Mechatronics Education

Recently reported interdisciplinary approaches to mechatronics education fall into two broad classes. The first is interdisciplinarity in one or more courses devoted to mechatronics, sometimes preceded by a preparatory EE course. The second is more ambitious, integrated and wide-ranging: interdisciplinarity in the *curriculum*. Appendix 4 summarises both approaches as they are reported in recent literature.

Four papers from the University of Detroit Mercy (the columns summarising these four papers are shaded in Table A4.1 of Appendix 4) give the most comprehensive account of the first approach – interdisciplinarity in courses. Key features of this university's programme are introducing mechatronics in the first-year 'Introduction to Design' course; having a prerequisite 'Introduction to Mechatronics' course at senior level; including assessment specialists on the staff team; and emphasising teamwork through an initial team-building exercise. The papers of Turner (2005) and Hargrove (2002), which have been discussed above, report similar introductions of interdisciplinarity.

It is worth noting that all of these reported approaches have, inevitably, started to introduce interdisciplinarity into the curriculum too – either by adding preparatory courses (the University of Detroit Mercy's, and Turner's (2005) approach) or by integrating previous courses (Hargrove, 2002). Three papers go further, reporting more ambitious, wide-ranging introductions of interdisciplinarity into whole curricula. Mina *et al.* (2005) report the introduction of 'learning streams' at the University of Iowa, which vertically integrate subject matter across traditional courses, and "emphasise fundamentals through their application"(*ibid.*:F1D-5). Two key features of learning streams are problem-based design (spanning traditional boundaries and topics) and staff collaboration across disciplines. 'Mechatronics Systems' is one such learning stream in that University's ME programme (*ibid.*:F1D-6).

Driscoll and Villanucci (2004) describe a *five-year* interdisciplinary, electro-mechanical engineering programme at the Wentworth Institute of Technology. They imply that four years may not be enough to produce adequate mastery of electro-mechanical interdisciplinarity when they aver that:

> "... the addition of one more academic year to a classical four year engineering programme results in a tremendous amount of additional engineering coursework being included in a dual-discipline engineering pro-

> gramme without any substantive loss in programme coverage or depth."
> (Driscoll and Villanucci, 2004:10442)

Finally, Newman *et al.* (2003) report on a foundational *tri-disciplinary* programme at the University of Denver, where all computer engineering, electrical engineering and mechanical engineering students take the same courses – most of which are co-taught by lecturers from these three disciplines – for the first two years of study. Only in the third year do students choose a discipline from these three to major in. Interdisciplinarity continues to be emphasised, though, in team-based, multidisciplinary projects in this year, where the teams must have one student from each discipline.

*However, what is meant by this desirable type of knowledge, 'interdisciplinarity'? What are its key characteristics that distinguish it from mere multidisciplinarity, and so make it more effective? And how and why do various curricula foster, or hinder, development of interdisciplinarity in the student engineer?* We need theoretical concepts to bring to light the key ways in which engineering curricula present and regulate the transmission of knowledge and its *meaning;* and the key types, strengths and limitations of the knowledge that these curricula accordingly foster. Specifically, these concepts should illuminate the key features of curricular material; organisation of that material; transmission of knowledge; and types of knowledge produced in mechatronics education.

To address this question, it would seem natural to turn to psychology, specifically educational psychology, concerned as this is with cognitive development and the optimisation of learning.[23] However, we have to go further than just psychology. We have to ask how the educational curriculum develops, and is recontextualised, from the world of production, the world of work – here, engineering practice. In considering this, it is necessary to move beyond mere educational psychology to social interaction in society – both initially, in how the curriculum is derived from engineering practice, and finally, in how fit the engineering graduate is to participate in engineering practice. For this reason – because both the origin of the problem and the application of any solution are in the world of engineering practice, the world of work – we turn to a sociologist, an educational sociologist, who links the fields of production and education. This is Basil Bernstein.

We turn to Bernstein, and the cognitive and developmental psychologist Lev Vygotsky, for the theoretical concepts needed, in sum, to "render knowledge visible". Bernstein's *educational knowledge codes* bring to light the key ways in which curricula categorise and control the knowledge to be transmitted. His *pedagogic device* illuminates the set of codes – the tacit regulative princi-

[23] "Educational Psychology", *Encyclopædia Britannica,* 2006.

ples – for selecting knowledge deemed appropriate for designated learners; transforming such knowledge into forms deemed suitable to transmit to them; and evaluating the knowledge acquired by them. Finally, Bernstein's *knowledge structures* pinpoint the key types, strengths and limitations of such acquired knowledge in the student (the knower). In these aspects of acquired knowledge – types, strengths, limitations and evaluation – Bernstein's work is valuably complemented by Vygotsky's theory of *conceptual development,* developed in tests on children, but here applied to students. Vygotsky's notions of *'complexes'* – concrete and factual associations of key features of subject-matter – and how these develop into proper *concepts,* where the associations become abstract and logical – shed much light on the internal development of students' acquired knowledge, and in particular, on how 'complexes' can functionally masquerade as concepts during evaluation. We begin with Bernstein.

## 4. BASIL BERNSTEIN: EDUCATIONAL SOCIOLOGIST

Basil Bernstein (1924-2000), a British sociologist and linguist, is mainly known for his contributions to educational sociology. Maton and Muller (2007:29) describe a key advantage of his approach as "its capacity to render knowledge visible as an object of study". In the work of this report, we draw upon Bernstein as a curriculum theorist. His expanded concepts of first, types of *curriculum*, and second, types or structures of *knowledge* acquired by learners in such curriculum types, provide the theoretical concepts we need here.

Bernstein's approach probes deeper than the curriculum as a mere syllabus of subject-matter. What are an educational system's underlying values – conveyed implicitly or explicitly to, and reproduced in, learners? What counts as knowledge? What are the essential, desirable qualities or attributes of knowledge that are prized and rewarded? Further, how effective is such *educational* knowledge in its purpose – serving society in the field of production?

For Bernstein, formal educational knowledge is not brought about just through curriculum. An educational system comprises *three* "message systems" that should be treated as a whole – curriculum, pedagogy and evaluation. Defining these:

> "Curriculum defines what counts as valid knowledge, pedagogy defines what counts as a valid transmission of knowledge, and evaluation defines what counts as a valid realisation of this knowledge on the part of the taught." (Bernstein, 1977:85)

The underlying principles that shape these three message systems – curriculum, pedagogy and evaluation – Bernstein termed the *educational knowledge code* (*ibid.*). This concept of *code* began in Bernstein's earlier work, and was

central to Bernstein's sociology (Sadovnik, 2001:690). Maton and Muller (2007) sum up just how central it was:

> "The principal concept Bernstein placed at the centre of his explanation of social and cultural reproduction, transformation and change was, at least initially, that of *code*."
>
> (Maton & Muller, 2007:16; emphasis in original)

As an educator interested in the relatively poor performance of working-class children in language subjects at school, he began with a socio-linguistic theory of 'language codes'. In this theory, *restricted* code denotes relatively condensed language used for communication between people of similar culture and acquaintance with the material being communicated; *elaborated* code denotes more voluminous, explicit language necessary for communication when no such similarities exist. Soon, however, his concept of code deepened and expanded, moving away from linguistic repertoire towards its underlying function: conveying *meaning*. Code came to denote "a general principle or set of rules for the regulation and distribution of meaning" (Maton and Muller, 2007:17), and Bernstein began examining how such codes influenced pedagogic discourse and practice (Sadovnik, 2001:689). In Bernstein's own definition of the nature and functions of a code,

> "Thus a code is a regulative principle, tacitly acquired, which selects and integrates meanings, forms of realizations, and evoking contexts ..."
>
> (Bernstein, 1990:101)

### 4.1 Classification and Framing

In order to clarify how codes performed these functions in an educational system, Bernstein developed the sub-concepts of *classification* and *framing*. In essence, *classification* refers to the organisation of knowledge into curriculum (Sadovnik, 2001:689); however, relations of power determine the contexts or categories created within that curriculum, and the inter-relations between these (Maton & Muller, 2007:17). In strong classification, the categories (of subject-matter) in a curriculum are well insulated from each other – the insulation arising from the perceived necessity of maintaining power over each category to preserve its identity and independence. *Framing* refers to how knowledge is transmitted through pedagogic practices, and especially to how rigidly the communication enabling such transmission is controlled. "Therefore, strong framing refers to a limited degree of options between teacher and students; weak framing implies more freedom" (Sadovnik, 2001:689).

The essential natures of an educational system's first two message systems, curriculum and pedagogy, can thus be expressed in terms of classification and framing:

> "From the perspective of this analysis, the basic structure of the message system, curriculum is given by variations in the strength of classification, and the basic structure of the message system pedagogy is given by

> variations in the strength of frames. It will be shown later that the structure of the message system, evaluation, is a function of the strength of classification and frames.' (Bernstein, 1977:89)

Indeed, Bernstein later sums up the nature of this third message system – evaluation – as follows. With strong classification and framing, the evaluative system emphasises attaining *states of knowledge* rather than *ways of knowing* – this being the emphasis under weak classification and framing (*ibid.*:99).

### 4.2 Educational Knowledge Codes: Collection and Integrated Types

On the formal basis of the strengths of classification and framing, Bernstein accordingly outlined two types of educational knowledge codes, *collection* and *integrated* (Bernstein, 1977:90). In essence, these denoted strongly and weakly classified curricula respectively. Relative strengths of classification and framing give rise to sub-types of each code.

In a collection code, the knowledge is strongly classified; it is organised into mutually insulated hierarchies of subjects, and distributed as such (Bernstein, 1977:103). The boundaries between such subject hierarchies are rigidly maintained. The teachers[24] (educators) within each such hierarchy have high discretion; power over the subject-matter to be taught and control over the manner of teaching it. Strong subject loyalties and identities tend to develop, and such a system perpetuates itself as pupils[25] become lecturers and transmit the same messages (*ibid.*:95).

An integrated code is fundamentally different, but it is first important to understand what Bernstein means by 'integration'. He does not mean a curriculum of different subjects focusing upon a common problem (*ibid.*:101). *He means more than that.* Integration means that two or more *apparently* different subjects are *subordinate* to some general principle(s) applicable to all. In Bernstein's words,

> "... there must be some general relational idea, a supra-content concept, which focuses upon general principles at a high level of abstraction. ... Whatever the relational concepts are, they will act selectively upon the knowledge within each subject which is to be transmitted. The particulars of each subject are likely to have reduced significance. This will focus attention upon the deep structure of each subject, rather than its surface structure. I suggest this will lead to an emphasis upon, and the exploration of, general principles and the concepts through which these principles are obtained." (Bernstein, 1977:101-2)

That is, the boundaries between such subjects tend to lose their significance and become blurred as the general relational idea(s) expose the inner natures and governing principles of each subject, and the *similarities* between these

---

[24] Bernstein uses "teacher(s)"; the application in this research report is obviously to lecturers.
[25] Bernstein uses "pupil(s)"; the application in this research report is obviously to students.

inner natures and principles. The basis of an integrated code, then, is clear general principles that are overt, elaborate and very explicit (*ibid.*:110). The various contents or subjects are subordinated to these principles. Hence, in contrast to collection codes, teachers tend to have reduced power and control over the subject-matter being taught and how to teach it; *the general governing principles themselves are more reliable and convincing guidelines here.* These general principles, being accessible to pupils too, thus tend to give *pupils* more discretion in the educational system (*ibid.*:101), and the most important quality of knowledge becomes the ways of knowing rather than the states of knowledge of individual subjects (*ibid.*:101-2).

Bernstein names some important sub-types of integrated codes: *teacher*-based, where one teacher blurs the boundaries between different subjects that s/he teaches, and *teachers*-based (more difficult to introduce), where teachers integrate either within a common subject or across different subjects (*ibid.*:93). Integrated codes can thus cross subjects (*ibid.*); indeed, their key power lies in this feature.

### 4.3 Codes of Production

In considering the autonomy of education, Bernstein was led to examine the relationships between education and production's requirements for it. Here, classification was immediately useful: he defined the relative autonomy of education "in terms of the strength of the classification between the category education and the category production" (Bernstein, 1977a:188).

Additionally, his concepts of classification and framing yielded remarkable insights into the regulative principles of different forms of production. These regulative principles he called the *codes of production.* In his terminology, the agents of production are all people who are involved at various roles therein: "unskilled, skilled, technologists, managers, administrators, etc." (*ibid.*:181-2). If these various roles are strongly classified, the relationships between them "are stable, sharply distinguished, the functions well insulated from each other, and the agents are not interchangeable"(*ibid.*). The opposite holds for weak classification. An act (or unit) of production is a *realisation* of an agent. If the primary act (primary unit of production) is tightly controlled and specified, and different between agents (thus divisive), the framing (control) is strong. The opposite is true for weak framing, where the primary unit of production is relatively co-operative (less divisive) and has more flexibility. Codes of production can vary all the way from very strong classification and framing ("isolated agents; divisive act") to weak classification and framing ("integrated agents across categories; integrated act") (*ibid.*:183-4). As will be seen in Section 7.1 below, Codes of Production and Interdisciplinary Working, these codes immediately shed light on the key factors *promoting or hindering*

interdisciplinarity (vs mono- or multi-disciplinary practice) in both engineering production (practice) and education.

### 4.4 The Curriculum and the Pedagogic Device

Collection and integrated curriculum codes were only one feature of Bernstein's analysis of pedagogic practices; his codes address all three abovementioned message systems. That is, they regulate not only the nature of curricula, but also how knowledge is transformed into pedagogically suitable forms, and then transmitted to, and evaluated in, learners. Bernstein termed this set of codes – regulating the key aspects of knowledge selection, transformation and evaluation in pedagogy – the *pedagogic device.*

Within this device, the code(s) regulating *syllabus* in the curriculum he termed *distributive rules,* determining what knowledge in society's field of production is to be transmitted, and to whom. This knowledge has next to be transformed into forms suitable for pedagogy, that is, into pedagogic discourse (Maton & Muller, 2007:19). However, such transformation inevitably involves recontextualisation: the aspects of the knowledge deemed most important for effective transmission, that is, for teaching and learning, are unlikely to be the same aspects deemed most important where the knowledge is applied – in society's field of production. The knowledge is thus recontextualised, through the second set of codes – *recontextualising rules* – and so becomes educational knowledge (*ibid.*) This recontextualised knowledge is deemed suitable for pedagogic transmission. Finally, a set of evaluative criteria are needed to assess how effectively this educational knowledge has been transmitted to, and acquired by, learners. To develop these criteria, the already-transformed pedagogic discourse has to be further transformed (*ibid.*). The underlying codes governing this second transformation are Bernstein's third set of codes in his pedagogic device: *evaluative rules,* which operate in the field of reproduction – the field of transmission, acquisition and evaluation.. These three sets of rules, operating upon knowledge in the respective fields of production, recontextualisation and reproduction, constitute the 'arena' of the pedagogic device (*ibid.*).

This pedagogic device then gave rise to a further question: what is the nature of the *knowledge itself* inside the pedagogic fields of recontextualisation and reproduction?

> "For, in setting forth these ideas and making a case for the necessity of a theory of the pedagogic device, Bernstein highlighted the absence of an analysis of pedagogic discourse itself and raised questions of the forms taken by knowledge, issues he came to realize had not been answered by his account of the device." (Maton & Muller, 2007:21)

In sum, the pedagogic device did not actually show the *nature* of pedagogic discourse and knowledge; that is, a focus on the forms of knowledge, rather

than pedagogic communication, was necessary (Maton & Muller, 2007:22). This applied also, and especially, to the forms of knowledge in the field of production – "the knowledge from which pedagogic discourse is created" (*ibid.*).

## 4.5 The Move from Pedagogies to Knowledge Structures

As Maton and Muller (2007:14) point out, knowledge itself thus became increasingly central to Bernstein's thinking in his final works. First, Bernstein probed the nature of discourses, both pedagogic and 'everyday', categorising them into *horizontal* and *vertical* types.

Bernstein (1996c:170) calls a body of "everyday, oral or common-sense knowledge" a *horizontal discourse* (HD). Such bodies are "local, segmental, context dependent, tacit, multi-layered, often contradictory across contexts but not within contexts" (*ibid.*). Within such a discourse, there is no organisation into levels of recontextualisation and their management (*ibid.*:174). Thus the context prevailing at any time can be said to "drive the discourse".

On the other hand, a body of knowledge called a *vertical discourse* (VD[26]) is not segmental, but more organised in both structure and components. Vertical discourses consist of "specialised, symbolic structures of explicit knowledge" (Bernstein, 1999:161). Such knowledge is circulated through forms of recontextualising (*ibid.*:159; 1996c:171), because the validity and applicability of such structures of knowledge are not confined to one unique context, but extend to others. The discourses used in schools are vertical; they are intended to produce non-segmental competences applicable to more than one context (*ibid.*:179).

Maton and Muller sum up the distinction well:

> "Where the knowledges of horizontal discourse are integrated at the level of *relations* between segments or contexts, the knowledges of vertical discourse are integrated at the level of *meanings* which are related hierarchically ... (1999a: 161)."
>
> (Maton & Muller, 2007:23; candidate's emphasis)

Bernstein probed vertical discourses further, recognising that their internal structures were of two markedly different types – both organised, but differently.

### 4.5.1 The Hierarchical Knowledge Structure (HiKS) in Vertical Discourse

The first is a *hierarchical knowledge structure,* abbreviated as 'HiKS'. This is "a coherent, explicit, systematically principled structure, hierarchically organised" (Bernstein, 1996c:171), "as in the natural sciences" (*ibid.*:172). Such

[26] This is the candidate's abbreviation; Bernstein (1996c) does not provide an abbreviation for this term.

a hierarchical knowledge structure "appears to be motivated by what we have called an *integrated code*"[27] (*ibid.*:173; emphasis in original), that structures the knowledge by integrative expansion:

> "The principle of the structuring of this knowledge moves the realisations towards more and more general propositions which *integrate knowledge at lower levels* and across an expanding range of *apparently different phenomena*." (Bernstein, 1996c:173; candidate's emphasis)

### 4.5.2 The Horizontal Knowledge Structure (HKS) in Vertical Discourse

The second type Bernstein perceptively calls a *horizontal knowledge structure,* or HKS.[28] Such a structure is "a series of specialised languages[29] with specialised modes of interrogation and specialised criteria for the production of texts" (*ibid.*:171), "as in the humanities and social sciences" (*ibid.*:172), but "motivated by what we have called a collection code or serial code" (*ibid.*:173). This structures the knowledge by *appending* further such languages as distinct entities, not integrating them:

> "...the constraints on the production of this knowledge (a crucial feature of this code) create a series of expanding, non-translatable, specialised languages with non-comparable principles of description based on different, often opposed, assumptions. ... Horizontal knowledge structures develop by *addition* of another specialised language."
> (Bernstein, 1996c:173, emphasis in original)

### 4.5.3 Essential Distinction between Hierarchical and Horizontal Structures

As Maton and Muller point out (2007:24), both these hierarchical and horizontal knowledge structures are products of our human minds. The key distinction between them is that HiKSs *integrate* knowledge *and* the assumptions on which that knowledge is based, whereas HKSs do not:

> "For example, Bernstein argues that in hierarchical knowledge structures acquirers do not have the problem of knowing whether they are speaking or writing physics: 'the passage from one theory to another does not signal a break in the language; it is an extension of its explanatory / descriptive powers' (1999a: 164). In horizontal knowledge structures acquirers are faced with an array of languages based on different, often opposed assumptions, making it less clear that one is indeed speaking or writing sociology." (Maton & Muller, 2007:24)

In both forms of knowledge structure, clashes do occur between different theories, but the ways in which these clashes are accommodated are fundamentally different. In HiKSs, a new theory, to be adopted, must both go beyond and successfully subsume its predecessors. However, in HKSs, the ac-

---

[27] Bernstein sometimes uses similar terminology to mean different things. Here, "integrated code" means the integrated *educational knowledge* code referred to in Section 4.2 above. It does not mean the integrated nature of the HiKS itself.

[28] This is Bernstein's (1996c) abbreviation.

[29] Note: each such language may well have a hierarchical knowledge structure, but such structures of each such language are unlikely to correspond.

ceptability of a new theory is likely to be signalled by the development of a new language, incorporated by collection into the HKS. Differences between this and previous languages are difficult to settle by empirical research, and are the subject of critique (*ibid.*).

Finally, it must be carefully noted that Bernstein's horizontal and vertical discourses, and the HiKSs and HKSs of vertical discourses, are distinct from structures of curriculum:

> "Bernstein is exploring the symbolic products of the field of production ...; the notion of recontextualization highlights that a knowledge structure is not necessarily a curriculum structure or pedagogic structure, and his theorization is not simply a recasting of pedagogic codes. Thus, in terms of Bernstein's concepts as they currently stand, one would not describe a school curriculum in terms of exhibiting a horizontal or hierarchical knowledge structure." (Maton & Muller, 2007:28)

## 5. LEV VYGOTSKY: COGNITIVE AND DEVELOPMENTAL PSYCHOLOGIST

Lev Semenovich Vygotsky (1896-1934), a Russian cognitive and developmental psychologist, is known for his contributions to the fields of child development and cognitive psychology. This report utilises two of his contributions: his theories of developmental forms of concepts in children and adults, and of the 'zone of proximal development' in learners.

His *Thought and Language* was his most popular book (Kozulin, 1990:205). Kozulin sums up the theme of Vygotsky's research therein:

> "He [Vygotsky] wanted to understand how a *concept* – an intellectual idea – is related to its *meaning* and the latter to its various *verbal embodiments*." (Kozulin, 1990:206; emphases in original)

However, as Bruner points out in introducing the first English translation of this book – first published in Russian, posthumously, in 1934 – it is, on a deeper level, a profound theory of intellectual development and education:

> "The present volume ... ties together one major phase of Vygotsky's work, and though its principal theme is the relation of thought and language, it is more deeply a presentation of a highly original and thoughtful theory of intellectual development. Vygotsky's conception of development is at the same time a theory of education." (Bruner, 1961:v)

In the work of this report, we draw upon this book's theory of how concepts develop – in children, but also in adolescent and adult students – and by analogy, use this theory to illuminate the nature of the difficulties of engineering students in understanding mechatronics.

### 5.1 Vygotsky's Developmental Levels of Concepts

It is first necessary to define the term 'learned adult' as used in this report. 'Learned adult' will be taken to mean an adult whose grasp of a concept has

developed to understanding the implications of the complex relations between this concept's *general governing principles* and *particular phenomena* to which it is being applied.

In the above quote, Kozulin indicates that by 'concept' Vygotsky meant 'intellectual idea'. Vygotsky himself notes here, importantly,

> "Real concepts are impossible without words, and thinking in concepts does not exist beyond verbal thinking. That is why the central moment in concept formation, and its generative cause, is a specific use of words as functional 'tools'". (Vygotsky, 1986:107)

The prompting point for Vygotsky's investigations here was the realisation that just because a child uses correct names for objects and processes does not mean that s/he has learned (developed) the *underlying concepts* that adults mean and understand when using those names (Kozulin, 1990:213). Thus communication by means of words (correct names) is no guarantee of fully developed concepts in the communicator. Put another way, fully developed concepts in the communicator are not guaranteed if the *purpose* (function) of the communicated words does not *require* these fully developed concepts (assigned to those words or communication by learned adults) in the communicator. Any lesser level of concept development that serves the purpose (function) of the communication will do. Such lesser levels of concept development are thus *functional equivalents* of concepts, which, as Kozulin (*ibid.*) observes, differ from real concepts in the type of generalisation involved and the way words are used to designate them. Vygotsky's own summation is,

> "We are faced, then, with the following state of affairs: A child is able to grasp a problem, and to visualise the goal it sets, at an early stage in his development; because the tasks of communication and understanding are essentially similar for the child and the adult, *the child develops functional equivalents of concepts at an extremely early age,* but the forms of thought that he uses in dealing with these tasks *differ profoundly from the adult's in their composition, structure and mode of operation.*" (Vygotsky, 1986:101-2; candidate's emphasis)

Vygotsky's three distinguishing levels of concept development, ably outlined by Kozulin (*ibid.*:213-6), and emerging through the well-known 'Vygotsky's blocks test', which studied concept formation in children,[30] are:

(1) syncretic grouping, where a child groups blocks on the basis of diffuse 'feeling' of what characteristics belong together;

(2) 'complexes', *which are capable of serving as functional equivalents of concepts* because they reflect certain features actually shared by some objects. However, *there is no hierarchical organisation of these different features;* all are functionally equal, and each of them can become the ba-

[30] The methodology of this test is described by Vygotsky (1986:103-5), and summarised by Kozulin (1990:212-3).

sis for selection. Bonds between components of a 'complex' "are concrete and factual, rather than abstract and logical" (*ibid.*) The most advanced form of 'complex' is the *pseudoconcept,* so called because phenotypically (that is, in its visible manifestations) it is often indistinguishable from a genuine concept;

(3) potential concepts, beginning with elementary, isolating abstractions. Here, the key development beyond the 'complex' is that *an abstracted trait is not easily lost among the other, non-abstracted traits* (Vygotsky, 1986:139).

These three levels are aptly termed *preconceptual* levels of development. Vygotsky himself brilliantly outlines how a potential concept finally develops into a genuine one:

> "Only the mastery of abstraction, combined with advanced complex thinking, enables the child to progress to the formation of genuine concepts. A concept emerges only when the abstracted traits are synthesised anew and the resulting abstract synthesis becomes the main instrument of thought." (Vygotsky, 1986:139)

As mentioned above, though, these three preconceptual levels emerged through the 'Vygotsky's blocks test' carried out on children. *Are they applicable to students having difficulty with 'learned adult' concepts, like mechatronic concepts?* In his foreword to the second, revised English translation of *Thought and Language*, Kozulin is quick to point out that preconceptual thinking is a part of adults' resources:

> "One of the most important discoveries in Vygotsky's study is 'pseudoconceptual' thinking; a form of child's reasoning that phenotypically coincides with reasoning in the adult and yet has a different, preconceptual nature. ... Vygotsky observed in addition that *preconceptual, and even mythological, thinking* not only is characteristic of children and the mentally ill, but *also forms the basis of the everyday, normal reasoning of adults.*" (Kozulin, 1985:xxxii-xxxiii; candidate's emphasis)

### 5.1.1 Applicability of Vygotsky's Preconceptual Developmental Levels to Students

That is, adults and older children do not abandon preconceptual thinking. Vygotsky (1986:113) observes, "Remains of complex thinking persist in the language of adults." Kozulin elaborates on when adults and older children are likely to resort to such thinking:

> "It is also important to remember that preconceptual types of representation are retained by older children and adults, who quite often revert to these more 'primitive' forms depending on their interpretation of a given task and on their chosen strategy for solution." (Kozulin, 1990:213)

For example, when adults group cups with saucers, or tables with a chair and couch, such groups are 'complexes' (*ibid.*). "Even healthy adults," says Vygot-

sky (1986:115), "when speaking of dishes or clothes, usually have in mind sets of concrete objects rather than generalised concepts."

Now adolescents are persons between childhood and adulthood, and most undergraduate students, except for a minority of 'mature students',[31] are either in or just out of this category. Vygotsky (1986:108) notes that the tasks, demands and intellectual stimulation confronting the adolescent as s/he enters the adult world are an important prompting factor in the emergence of conceptual thinking. Moreover, as Kozulin (1990:213) points out, "the level of truly conceptual problem solving is achieved only by adolescents." Nevertheless, as Vygotsky elaborates,

> "Even after the adolescent has learned to produce concepts, *he does not abandon the more elementary forms; they continue for a long time to operate, indeed to dominate,* in many areas of his thinking. As we have mentioned earlier, even adults resort to complex thinking." (Vygotsky, 1986:140; candidate's emphasis)

Now naturally, the tasks in engineering studies are not on the level of children distinguishing between Vygotskian blocks, but on far higher levels. Engineering students are required to reason about and *conceptualise* engineering problems, using mathematical concepts and principles of the basic sciences (Associated Assessment Criteria 1.(c) and 2.(b), ECSA Exit Level Outcome 2, Appendix 3). Thus, certainly in their third and final undergraduate year, such students' conceptual development should be at the level of genuine concepts. However, the characteristics of the Vygotskian 'complex' raise a warning flag: *do the assessing instruments used to evaluate whether ECSA's assessment criteria are being met unequivocally reveal whether students' concepts are genuine or not?*

For, as mentioned above, the most advanced form of 'complex' at Vygotsky's abovementioned preconceptual level (2) – the pseudoconcept – *is often indistinguishable, phenotypically, from a genuine concept.* This means, for undergraduate students, that if their level of concept development is *evaluated* as being at the level of genuine concepts, *but is actually at pseudoconceptual level, they will not have the necessary genuinely conceptual, hierarchical understanding deemed adequate for reasoning about and conceptualising engineering problems* (as required by the abovementioned ECSA Exit Level Outcome 2).

*Is this why many students pass examinations well in early undergraduate years* – when 'complex' (pseudoconceptual) reasoning may pass itself off as conceptual reasoning – *and fail in the more demanding assessments of later*

[31] "Mature student: a student aged 25 or over who has gone into higher or further education later than is usual, especially after working or raising a family" (*Microsoft Encarta Dictionary,* 2005).

*years, when only conceptual reasoning will do?* For, as Kozulin (1990:215) observes, Vygotsky's most advanced form of 'complex' reasoning – the pseudoconcept – *is the functional equivalent of a concept "par excellence",* being on the borderline between prelogical and logical thought. Thus a pseudoconcept can convincingly pass itself off as a genuine concept:

> "... functionally it looks so like true concepts that adults often do not notice the difference. This observation indicates how deceptive functional appearance can be. 'Thought-complexes' can appear as if they are concepts, thus concealing their actual substructure. The use of one and the same words and the understanding they bring about may correspond to only a superficial level of functional communication, *while the underlying intellectual substructures of the communicants may remain alien to each other* ..." (Kozulin, 1990:217; candidate's emphasis)

Indeed, if the communicants are a 'learned adult' (as defined above) lecturer and an engineering student whose development in the subject-matter being assessed is still at preconceptual level, these communicants' intellectual substructures – expressly, the causal-dynamic relations between components therein[32] – *will* be alien to each other, as Vygotsky points out, because they originate differently:

> "More detailed study of the last type of complex [the pseudoconcept] reveals that phenotypical similarity between complexes and real concepts coexists in this case with genetic dissimilarity. *Causal-dynamic relations that engender pseudoconcepts are essentially different from those giving birth to a concept proper.* What we confront here is the appearance of a concept *that conceals the inner structure of a complex."* (Vygotsky, 1986:119; candidate's emphasis)

Kozulin (1990:218) succinctly sums up the problem: *different types* of thinking may lead to one and the same cognitive product, so this does not necessarily signify *similar reasoning* (thinking). The difficulty of identifying whether the thinking of students originates from genuine concepts or pseudoconcepts is well expressed by Vygotsky:

> "The outward similarity between the pseudoconcept and the real concept, which makes it very difficult to 'unmask' this kind of complex, is a major obstacle in the genetic analysis of thought." (Vygotsky, 1986:121)

In sum, it is well to recall the essential difference between a 'complex' and a concept. As noted above, in a 'complex' there is no *hierarchical* organisation (in its causal-dynamic relations) of its different features (components). On the other hand, in a concept – specifically, concepts relating to structured subject-matter, which Vygotsky calls 'scientific concepts' – the organisation is hierarchical and logical (Kozulin, 1990:222). This theory of Vygotsky is utilised in Section 7.3 below, "Desirable and Inferior Knowledge Structures in Mechatronics", to suggest that the collection-type first- and second-year un-

---

[32] Even though the components themselves – key elements of subject-matter – may be mostly or entirely the same in both communicants' substructures.

dergraduate engineering syllabi, not emphasising general principles applying to both mechanical and electrical phenomena, do not promote hierarchical and logical connections of the relations between various classes of such phenomena. Hence the conceptual development of students is not decisively promoted beyond the 'complex' level.

### 5.2 Vygotsky's Zone of Proximal Development

Kozulin (1990:221) records that the next step in Vygotsky's program was to compare concepts actually learned by a child in school through formal, logical, decontextualised, structured classroom instruction – these being the abovementioned *'scientific' concepts* – with "those spontaneously acquired through everyday activity", termed *spontaneous concepts.* The latter emerge from a child's reflections on immediate, everyday experiences; they are thus experientially rich, but 'complexes', being unsystematic and highly contextual (*ibid.*:222).

Of course, as noted above, concepts, including 'scientific' ones, are not just transmitted to the child; they must develop in the course of the child's own intellectual development. *How do these scientific concepts develop, and how can they best be assisted to develop?* Vygotsky realised that the potential of developing must exist in every learner, to different degrees, but how was this potential firstly to be gauged, and secondly to be best exploited? Hence he developed his theory of the *zone of proximal development,* springing from his theory that "we become ourselves through others". This means that, in the course of childhood and lifelong development, we acquire our higher mental functions – "the higher forms of behaviour" characterising the personality – through social interaction with others. Vygotsky hence argued that a child's intellectual abilities (potential) could be much more sensitively gauged through her/his progress achieved in cooperation with an adult (Kozulin, 1985:xxxiv-xxxv).

Vygotsky himself defines the zone of proximal development (ZPD) thus: "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined by problem solving under adult guidance or in collaboration with more capable peers" (Vygotsky, 1978:86). Kozulin points out that this zone, termed *zo-ped,* is dynamic, being the meeting place, in the child's prevailing state of intellectual development, between spontaneous and 'scientific' concepts:

> "In this connection, Vygotsky used the term *zo-ped,* the 'zone of proximal development', the place at which a child's empirically rich but disorganised spontaneous concepts 'meet' the systematicity and logic of adult reasoning. As a result of such a 'meeting', the weaknesses of spontaneous reasoning are compensated by the strengths of scientific logic. The depth of *zo-ped* varies, reflecting children's relative abilities to appropriate adult structures. The final product of this child-adult cooperation is a so-

> lution, which, being internalised, becomes an integral part of the child's own reasoning." (Kozulin, 1985:xxxiv-xxxv; emphases in original)

This research report utilises this theory in Section 9 below, 'A Pedagogy to Achieve an Integrated Knowledge Structure in Mechatronics'. The pedagogy there, based on Hedegaard's 'Double Move in Teaching and Developmental Learning', is based on Vygotsky's 'zone of proximal development', and utilises social interaction in project teams to bring the desired integrated knowledge structures about.

## 6. CRITICAL RESEARCH QUESTIONS

We are now in a position to formulate the critical research questions of this project. As key concepts, Bernstein's codes of education, codes of production and knowledge structures – the latter in conjunction with Vygotsky's 'complexes' and 'genuine concepts' – are used.

1. How do Bernstein's codes of education *conceptually* explain and illuminate the strengths and weaknesses of the way mechatronics is taught, with reference to the graduate engineer's suitability for serving society's required codes of *production?*
2. How do Bernstein's knowledge structures *conceptually* point the way to producing mechatronic knowledge that preserves the detail(ed knowledge) of each discipline, but integrates all such knowledges across disciplinary boundaries?
3. How can mechatronic conceptual development in students be prevented from stopping at Vygotskian 'complex' level – even at the highest such level, pseudoconceptual – and fostered to full logical, hierarchical, conceptual level?
4. Is there a basis to integrate mechanical and electrical disciplinary knowledge? More generally, what technical concepts are available that codify and set out common principles of operation of all types of physical systems – thermal, mechanical, electrical, fluidic – and so provide bases for integration, and full conceptual development, across disciplinary boundaries?
5. Finally, how can the desirable integrated knowledge structure best be produced, that is, best be *developed,* in students? What conceptual ways are available to do so – preferably those that motivate the student, that is, build upon her/his motives for pursuing engineering? Moreover, what ways are there to *develop* such learning, such knowledge structures, in students, *from their initial, current levels of development*?

# 7. ANALYSING MECHATRONIC KNOWLEDGE: THE CODES AND KNOWLEDGE STRUCTURES OF BERNSTEIN

With regard to the first two critical research questions, three theoretical concepts of Bernstein are most elucidative. First, his codes of production, introduced in Section 4.3 above, illuminate the essential natures of *acts* of production, and hence provide additional conceptual justification for interdisciplinary working. Second, his codes of education, introduced in Section 4.2 above, and his hierarchical and horizontal knowledge structures, introduced in Section 4.5 above, illuminate hindrances in traditional engineering curricula to effectively teaching EE technology and hence mechatronics to ME engineering students.

## 7.1 Codes of Production and Interdisciplinary Working

As outlined in Section 4.3 above, Bernstein's (1977a:183-4) codes of production can vary all the way from very strong classification and framing ("isolated agents; divisive act") to weak classification and framing ("integrated agents across categories; integrated act"). Bernstein points out a key consequence of the strength of the framing, that is, the strength of control over production – this consequence being the resulting *relationship* of each act (sub-product) to the final product:

> "The degree of fragmentation or divisiveness refers to the relationship between the act and the final product. *The more fragmented or divisive the act(s), the less like the final product is its realisation. The more integrated the act, the more like the final product is its realisation,* that is, its consequence." (Bernstein, 1977a:182; candidate's emphasis)

The second sentence in this quote remarkably illuminates Bucciarelli's view in Section 2.4.1 above that, in a team of discipline-oriented practitioners carrying out an engineering design, *different practitioners work with their different, paradigmatic object-worlds,* which cause each of them to view the object of design narrowly, instrumentally, and very differently from each other. Consequently:

> "No participant has, at any stage in the process, a comprehensive, all-encompassing understanding of the design. No participant has a 'God's-eye view' of the design." (Bucciarelli, 2003:298)

The individual, object-world approaches offer no basis for optimising the contributions of all the participants, and hence the overall design, as a whole. There is thus no guarantee that each participant's contribution (in Bernstein's terms, each act of production) will have all the desired features of the final product (in Bernstein's words, will be "like the final product in its realisation"). At best, such a team of discipline-oriented practitioners operates according to Bernstein's second code, +C +F, of production – related agents *within* a category (each category being one or more levels of technical practitioners), but divisive acts of production (1977a:183). On the other hand, an

interdisciplinary team of practitioners, where each member has at least basic familiarity with *each* discipline (team classification is thus relatively weak), and the acts of production are integrated, that is, jointly performed by at least most of the team (team framing is thus relatively weak) would approach Bernstein's fifth code, –C –F, of production – integrated agents across categories (all levels of technical practitioners), and integrated acts of production (*ibid.*:184). Bernstein's key conceptual contribution here is to highlight the inherent divisive or integrative properties of the way production is controlled – its framing.

It is worth noting that these codes of production can also apply to tasks that students perform in their education – the obvious example being the team-based laboratory exercises and projects undertaken by students in their mechatronics courses.

### 7.2 Bernstein's Hierarchical Knowledge Structure (HiKS)

As outlined in Section 4.5.1 above, Bernstein's *hierarchical knowledge structure,* abbreviated as 'HiKS', is "a coherent, explicit, systematically principled structure, hierarchically organised" (Bernstein, 1996c:171). It structures the knowledge by integrative expansion:

> "The principle of the structuring of this knowledge moves the realisations towards more and more general propositions which *integrate knowledge at lower levels* and across an expanding range of *apparently different phenomena.*" (Bernstein, 1996c:173; candidate's emphasis)

In such a structure, Bernstein's "more and more general propositions" are remarkably similar to, and enhanced by, Vygotsky's (1986) notion of 'scientific concepts', which, following Hedegaard (2002:40),[33] can be understood today as *subject-matter concepts*. Vygotsky's 'scientific concepts' are organised into structures that are hierarchical, logical, formal and decontextualised (Kozulin, 1990:222). Moreover, Vygotsky throws light on one important aspect of such structures that Bernstein does not mention. The necessary relations *between* 'scientific concepts' – that is, between Bernstein's "more and more general propositions" – must be *relations of generality:*

> "In the acquisition of scientific concepts, the system must be built simultaneously with their development. The concept of system organisation thus becomes a crucial one ... Concepts do not lie in the child's mind like peas in a bag, without any bonds between them. If that were the case, no intellectual operation requiring coordination of thoughts would be possible, nor would any general conception of the world. Not even separate

[33] "... it seems a little odd and old-fashioned when Vygotsky distinguishes between scientific and everyday concepts. However, if we change terminology and substitute 'scientific' with 'subject matter', Vygotsky's distinction does not seem so odd today. It is easy to infer from Vygotsky's examples (1982, 1985-7) that scientific thinking in his terminology covers the methods of thinking one finds in the different subject-matters in school." (Hedegaard, 2002:40)

> concepts as such could exist; their very nature presupposes a system ... If every concept is a generalisation, then the relation between concepts is a *relation of generality."* (Vygotsky, 1986:197, emphasis in original)

On the other hand, the upward/downward vertical relations by which, in Bernstein's quote immediately above, his "more and more general propositions" integrate knowledge across "an expanding range of apparently different phenomena" we will term *integrative relations of applicability* – or, *subsumptive integration*.

## 7.3 Desirable and Inferior Knowledge Structures in Mechatronics

The key relations within a desirable hierarchical knowledge structure (HiKS), then, are its *relations of generality* between general propositions or concepts, and its *integrative relations of applicability* between these propositions / concepts and apparently different phenomena. This, of course, is the desirable mechatronic knowledge structure in student and graduate engineers: a range of knowledge spanning sub-ranges of knowledge of *apparently* different electrical and mechanical phenomena, and integrating these through general propositions realised as applying equally validly to all such sub-ranges. This mechatronic knowledge structure can be visualised as in Figure 7.1.

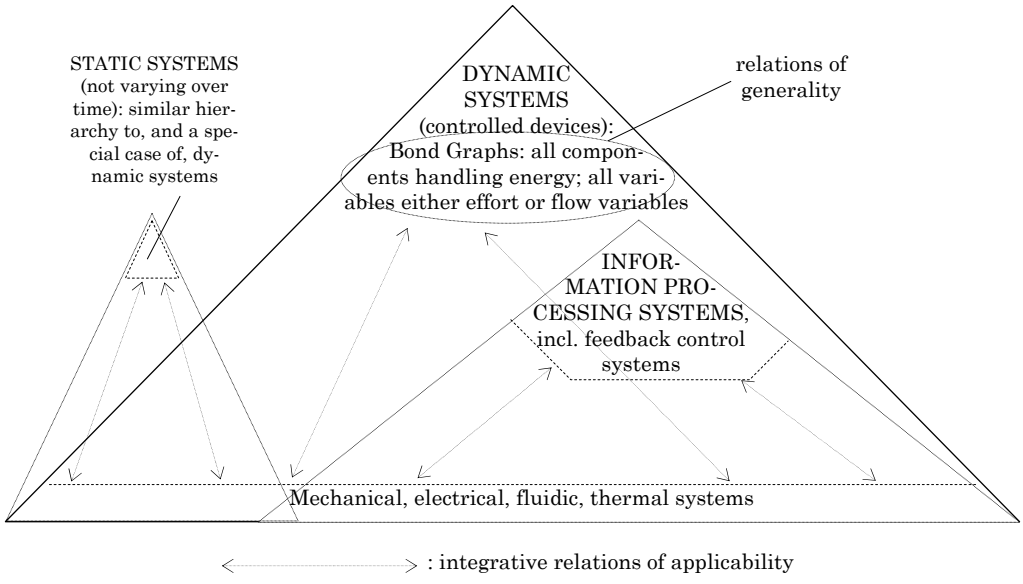



Figure 7.1 Desirable HiKS of Mechatronics in Engineering Students and Graduates

As Bernstein notes (1996c:172; 1999:171), there can be more than one hierarchy in an HiKS. Figure 7.1 reflects one possible division of mechatronics into three related hierarchies: those of dynamic systems, static systems and information-processing and control systems. All these systems are defined and briefly explained in Appendix 5.

### 7.3.1 The Horizontal Knowledge Structure (HKS)

As outlined in Section 4.5.2 above, Bernstein posits another type of knowledge structure in a vertical discourse: a *horizontal knowledge structure,* or HKS. This structures the knowledge by *appending* further such languages as distinct entities, not integrating them, as Bernstein explains in the quote repeated from Page 33:

> "...the constraints on the production of this knowledge (a crucial feature of this code) create a series of expanding, non-translatable, specialised languages with non-comparable principles of description based on different, often opposed, assumptions. ... Horizontal knowledge structures develop by *addition* of another specialised language."
>
> (Bernstein, 1996c:173, emphasis in original)

Figure 7.2 is Bernstein's (1999:163) visual portrayal of such a HKS in the humanities and social sciences: a serial collection of such specialised languages $L^1$, $L^2$, ..... $L^n$.

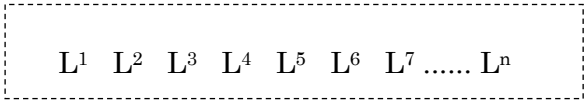



Figure 7.2 Bernstein's (1999:163) Portrayal of a HKS in Humanities

### 7.3.2 School of MIAE: Second-Year 'Collection-Type' Programme

Does such a HKS exist only, though, for the humanities and social sciences? The common programme for second-year students in all three branches of mechanical, industrial and aeronautical engineering in the School of MIAE is listed in Table 7.1. Does this programme not have the essential nature of a Bernsteinian *collection-type* educational knowledge code, as outlined in Section 4.2 above, where knowledge is strongly classified into mutually insulated subjects?

Table 7.1 Programme for Second Year of Study for Bachelor of Science in Engineering in School of MIAE (University of the Witwatersrand, 2009)
{ ►: engineering sub-discipline }

| **Course Code** | **Course Name and Summarised Syllabus** | **Credit Points** |
|---|---|---|
| ►ELEN2000 | Electrical Engineering *(basic circuit theory; semiconductor devices; analogue and digital electronics; power circuits; electric motors)* | 18 |
| MATH2011 | Mathematics II (*advanced algebra and calculus*) | 27 |
| ►MECN2000 | Fluid Mechanics I *(fluid statics, viscous flow, fluid dynamics, fluid momentum)* | 12 |

| Course Code | Course Name and Summarised Syllabus | Credit Points |
|---|---|---|
| ►MECN2001 | Applied Mechanics A<br>*(Statics – equilibrium in 2 and 3 dimensions; friction; forces and bending moment in beams. Mechanics of solids – stress and strain; theories of failure; statically indeterminate, thermal and assembly problems; torsion; bending stresses; combined loading)* | 18 |
| MECN2002 | Mechanical Engineering Design and Materials *(analysis, synthesis of machine components and assemblies; dynamic load systems; power transmission; joining and fastening; general introduction to engineering materials; effects of processing materials; degradation, application and selection of materials)* | 27 |
| ►MECN2003 | Computing Skills & Software Development *(computer hardware; software for engineering analysis; programming principles; object-oriented programming; programming project)* | 12 |
| MECN2004 | Society and the Engineer | 15 |
| MECN2005 | Mechanical Engineering Laboratory I *(planning, conduct, reporting of experiments; experimental errors; introduction to measuring systems and instruments; series of practical lab. experiments in several sub-disciplines*) | 9 |
| ►MECN2006 | Thermodynamics I *(energy and the First Law; properties' of pure substances; energy analysis of simple engineering systems; the Second Law; entropy and its implications)* | 12 |
| ►MECN2007 | Applied Mechanics B *(kinematics of particles, plane kinematics of rigid bodies; kinetics of particles and systems of particles; Newton's Second Law – motion, work, impulse and momentum; plane kinetics of rigid bodies)* | 12 |
| A student shall also complete the following special requirements to the satisfaction of the Senate:<br>Vacation Work I (Mechanical)<br>Practical Training | | |

For, except for the naturally closely related courses of MECN2001 and MECN2007 – Applied Mechanics A and Applied Mechanics B – the syllabuses of Table 7.1 indicate little or no *apparent* commonality between the engineering sub-disciplines (indicated by ► in this table). Not surprisingly, the clearest example of this is between the syllabus of ELEN2000, Electrical Engineering, and all other syllabuses. Moreover, the courses covering engineering sub-disciplines are presented and examined separately by separate lecturers, who have high discretion in the subject-matter being taught and in the manner of teaching it – another key feature of Bernstein's collection-type educational knowledge code.

This is not to claim that the real common principles and applicability of these engineering sub-disciplines are nowhere introduced, applied and integrated.

For example, in Course MECN2002, Mechanical Engineering Design and Materials (one of the two courses with the most credit points), key aspects of Applied Mechanics A (statics and materials) and Applied Mechanics B (kinematics and kinetics) are inevitably brought together and applied in design exercises and projects. Nevertheless, most of the second-year curriculum is devoted to presentations of engineering sub-disciplines that appear (to students) to be insulated from each other. To the student, this curriculum thus appears as the *collection type* of Bernstein (1977b:80). The contents stand in a well insulated, closed relation to each other; "... the contents are clearly bounded and separated from each other ..." and "... the student has to collect a group of especially favoured contents in order to satisfy some external criteria; perhaps, but not always, a public examination" (*ibid.*). There is relatively little subsumptive, Bernsteinian integration in this curriculum; its engineering sub-disciplines are not presented as subordinate to key unifying ideas that reduce their isolation from each other (*ibid.*).

Even the common programme, listed in Table 7.2, for first-year students in all three branches in the School is collection-type: little or no subsumptive integration is apparent between either the courses or the topics within a course. It can be argued that such integration is inappropriate at first-year level, which is mainly devoted to grounding in key natural sciences. Yet, in passing, is the first year of study too early to at least remark on any common principles *applying to these natural sciences?* For example, could key common principles[34] applying to the main topics in Course PHYS1014, Physics 1E in Table 7.2 not be remarked on or noted?

Table 7.2 Programme for First Year of Study for Bachelor of Science in Engineering in School of MIAE (University of the Witwatersrand, 2009)
{ ►: engineering sub-discipline }

| **Course Code** | **Course Name and Summarised Syllabus** | **Credit Points** |
|---|---|---|
| CHEM1033 | Chemistry I (Auxiliary) *(exposing students not proceeding to second qualifying course in chemistry to principles and practical considerations underlying chemical phenomena in engineering, industrial and mining processes)* | 15 |
| MATH1014 | Mathematics I | 30 |

[34] For example, those underlying physical work performed by electric, magnetic or mechanical systems, or systems involving the surface tension of liquids. A brief introduction thereto is in Sections 2.2.4 and 2.2.5, Chapter 2 of Moran & Shapiro, 2004.

| Course Code | Course Name and Summarised Syllabus | Credit Points |
|---|---|---|
| ►MECN1001 | Introduction to Mechanical Engineering and Design *(design methodology; product life cycle; material selection; manufacturing methods; engineering modelling; elementary probability and statistics; tolerances; introduction to engineering economics; technical communication; aspects of applied engineering; the complementary role of theory and practice)* | 21 |
| ►MECN1003 | Engineering Drawing<br>*(Engineering drawing standards; freehand sketching; orthographic, oblique, isometric and auxiliary projections; fundamental spatial relations and intersections; sectioning; developments; assembly drawings; dimensions and tolerances; perspective drawing; revolutions; application of descriptive geometry; graphical analytical techniques; introduction to computer aided drawing (CAD).*<br>*Selected topics from: introduction to the preliminary design process, concept generation, design development and concept assessment)* | 27 |
| PHYS1014 | Physics 1E *(main topics)*<br>*(geometrical optics; thermal physics; hydrostatics; waves; physical optics; surface tension; electricity; magnetism; modern physics)* | 30 |
| PHYS1015 | Mechanics<br>*Statics: force vectors and vector operations; moment of a force; arbitrary coplanar force systems acting on a rigid body; equivalent force systems, reduction and a resultant. Equilibrium of a rigid body in two dimensions, equations of equilibrium in their alternative forms, scalar and vector formulation. Centre of mass and centroid for the volume, the area and the line. Mass moment of inertia of a rigid body about an axis, moment of inertia for an area.*<br>*Dynamics: kinematics of a particle; rectilinear and plane curvilinear motion (rectangular and normal/tangential coordinates). Kinetics of a particle; rectilinear and plane curvilinear motion (rectangular and normal/tangential coordinates). Work-energy and impulse-momentum relationships* | 30 |

Given these collection-type programmes, particularly that of the second year in Table 7.1, what corresponding knowledge structure will they foster in the student – which will obtain when s/he commences mechatronics in the third year of study? It is submitted that the type of knowledge structure fostered will tend to mirror this collection-type curriculum; the student will tend to perceive the various engineering sub-disciplines as "non-translatable, specialised languages with non-comparable principles of description based on differ-

ent, often opposed, assumptions" (Bernstein, 1996c:173). As such, this knowledge structure, anterior to the introduction of mechatronics, is likely to be a horizontal knowledge structure (HKS), as now further described.

### 7.3.3 Before Mechatronics – HKS of Languages

Of course, each such language (engineering sub-discipline) certainly has hierarchy within itself. Figure 7.2 can be enhanced accordingly to represent the HKS anterior to the introduction of mechatronics as in Figure 7.3. In this figure, each language (engineering sub-discipline) is a hierarchical knowledge structure *in itself,* but these languages are *collected* into a *horizontal* knowledge structure.

Note that the languages in this HKS have *strong grammars* (Bernstein, 1996c:174; 1999:164). These languages, being engineering sub-disciplines, "have an explicit conceptual syntax capable of 'relatively' precise empirical descriptions and/or of generating formal modelling of empirical relations" (Bernstein, 1999:164). Of course, these languages use the HKS of mathematics as a tool of precise description and modelling, and Bernstein regards mathematics as a HKS possessing the strongest grammar (*ibid.*).

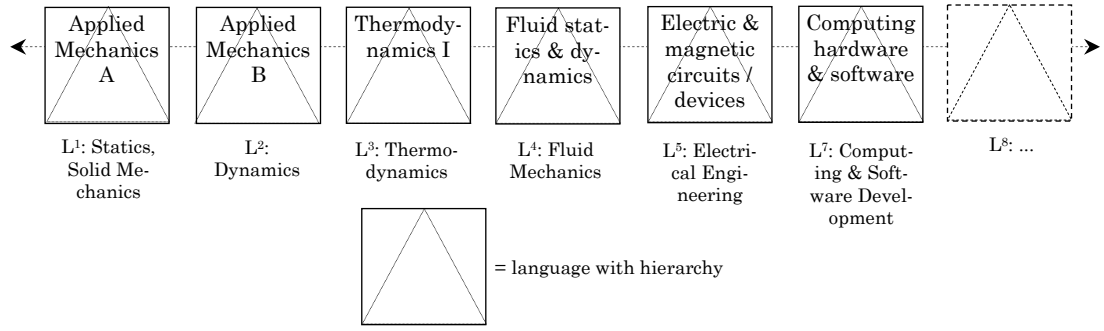



Figure 7.3 HKS of Languages (Sub-Disciplines) Anterior to Mechatronics

### 7.3.4 Over-Narrow Recontextualisation? Inferior Knowledge Structures in Mechatronics?

All the languages (sub-disciplines) of Figure 7.3 are themselves vertical discourses with hierarchical knowledge structures. Yet it is well to note that these are *pedagogic* discourses, not the real discourses in the field of engineering practice. These real discourses have been recontextualised and differentiated to produce the pedagogic discourses. Moreover, the principles of such recontextualisation are arbitrary, as Bernstein explains:

> "The social units of a vertical discourse are constructed, evaluated, distributed to different groups and individuals, structured in time and space by *principles of recontextualisation.* We have context specificity through *segmentation* in a horizontal discourse and context specificity through *recontextualising* in a vertical discourse."
>
> (Bernstein, 1996c:172; emphasis in original)

Furthermore, the recontextualised, transformed, *pedagogic* discourse(s) are mediated, and thus imaginary in the sense of being "abstracted from its social base, position and power relations"[35]:

> "As pedagogic discourse appropriates various discourses, unmediated discourses are transformed into mediated, virtual or imaginary discourses. From this point of view, pedagogic discourse selectively creates *imaginary subjects*." (Bernstein, 1996b:47; emphasis in original)

The candidate believes that if the "imaginary subjects" (vertical sub-discourses of subject-matter) of ME and EE are over-narrowly recontextualised – both prior to and during the teaching of mechatronics – and thus too far abstracted from their 'real' position in engineering in the field (Bernstein's "original site of effectiveness", 1996b:47), *the knowledge structures produced in student and graduate engineers will tend to be the inferior, ineffective HKSs. The very restrictions and omissions in the recontextualised, transformed vertical sub-discourses ("imaginary subjects") – and the ideologically imposed classifications (in the Bernsteinian sense) between these – may unintentionally but inherently withhold the information to form the integrative links, the relations of generality, for the desirable HiKS, thus compelling a semi-segmented HKS at best.*

It must be recalled that in a horizontal discourse, there are no organised levels of recontextualisation and their management (Bernstein, 1996c:174). Now because both an HD and an HKS are serially, segmentally structured, Bernstein's observation below on the limitations of a horizontal discourse seems to apply to an HKS as well:

> "In the case of horizontal discourses the competencies or literacies acquired are *segmental.* These competencies / literacies are contextually specific *and* context dependent embedded in ongoing practices and directed towards specific goals. Their activation requires the local context, practices and relationships. Where such contexts, practices and relationships are absent, or cannot be unproblematically read, the competence / literacy may not be demonstrated."
>
> (Bernstein, 1996c:179; emphasis in original)

This therefore highlights another key shortcoming of the inferior HKS in mechatronics: *competence may not be demonstrated outside familiar contexts and circumstances,*[36] because the segmental knowledge structure is bound to the context.

On the other hand, the strength of a vertical discourse is as follows:

---

[35] This is Bernstein's definition of 'imaginary' (1996b:53, Note 1).

[36] The obvious example is that a student with such an HKS may not demonstrate competence outside tests, examinations and other assessments in the "imaginary subjects" of *pedagogic* discourse in mechatronics, because that student's HKS has difficulty in extending to the *production-type* discourse of mechatronic practice, which frequently involves unfamiliar situations – the "complex engineering problems" of ECSA (Appendix 2).

> "School contexts created by vertical discourse are directed to the production of classified competences or performances of a *non-segmental type*. These procedures are not consumed by their context and are linked not to context but to other procedures organised temporally. The initial context takes its significance from the future and not from the present. It is not that these contexts are unembedded, but that they are differently embedded from the segmental contexts of horizontal discourses."
> (Bernstein, 1996c:179; emphasis in original)

The key observations here are that (i) the procedures are not consumed by their context, that is, they have a relevance beyond the immediately prevailing context, and (ii) the initial context takes its significance from the future, which is taken to mean that this initial context – created by recontextualisation, as the discourse is vertical – *is designed to apply widely, across many specific contexts that may be anticipated in the future.* This would fit in with the abilities inherent in a vertical discourse with an HiKS – the preferred knowledge structure in mechatronics.

### 7.3.5 Need for HKS Anterior to Mechatronics to Develop Further

The HKS anterior to mechatronics of Figure 7.3, then, is not desirable *for* mechatronics. It is in fact a Vygotskian 'complex', because there is as yet "no hierarchical organisation of the relations between different attributes of the selected blocks" (Kozulin, 1990:214). The student knows that all the blocks (sub-disciplines) have to be there to enable the necessary interdisciplinary or multidisciplinary approach in solving mechatronic problems. But s/he has no organisational grasp of these languages' common features and principles. Moreover, these languages, in their original forms in Figure 7.3 learned *before* beginning mechatronics, may indeed be non-translatable to differing extents. The apparent common features are the obvious ones at the boundaries of the languages – and this is why the languages are deemed necessary for mechatronics. Yet some or most common features apparent on the surfaces or boundaries of languages, do not suggest mutual translatability. It is intuitively easy to translate between obviously related languages, like solid mechanics and fluid mechanics.[37] However, it is not intuitively easy to translate between fluid dynamics (or mechanical kinetics) and the dynamics of electric or magnetic systems. Nor should all languages necessarily be mutually translatable, such as solid mechanics on the one hand, and computing and software development on the other. For, as seen in Figure 7.1, there is more than one hierarchy in a HiKS, suggesting difficulties in mutual translation that may not be worthwhile or desirable to overcome.

As already mentioned, Figure 7.3, the likely knowledge structure anterior to mechatronics, is a Vygotskian 'complex'. *How does it gradually change into*

[37] These have significant common features like compressibility of material (solid or fluid), momentum obeying Newton's Second Law, and so on.

*the desirable HiKS, with general concepts and relations of generality, of Figure 7.1?* For knowledge structures do change in character, otherwise there would be no developmental learning. What, then, are the significant phases in this change, from a Vygotskian 'complex' to Vygotskian pseudoconcepts, to Vygotskian potential concepts, and finally to a fully-fledged HiKS?

The first phase, it is submitted (and this should start, and probably does in most students, well before the mechatronics course – for example, in the MECN2002 design course of Table 7.1[38]), is the development of a HKS into two planes of horizontality, not just horizontal linking of languages on one plane.

### 7.3.6 First Phase – Two-Plane, Pseudoconceptual HKS

There can be organisation and linking within a HKS. Bernstein says, "... as in the case of sociology, there may well be two interacting horizontal discursive planes. One could be called a general approach plane (GAP) and the other a problem plane" (1996c:173). Bernstein first describes the GAP:

> "In the case of horizontal knowledge structures the GAP plays an analogical role to general theory in hierarchical knowledge structures. The GAP is a space where *meta languages* are produced which attempt to provide a basic orientation, a language of description and the rules of its use, which legitimise how phenomena should be understood and interpreted.[39] GAP theories are really theories about what counts as proper description of the specific phenomena of a particular horizontal knowledge structure (HKS)." (Bernstein, 1996c:173; emphasis in original)

Thus, in an HKS with a GAP, the theories (the meta-languages) in the GAP must relate to each specialised language in that HKS – i.e. establish links with these specialised languages. However, as long as the HKS remains an HKS, it would seem that any such links are at these languages' *boundaries;* the languages as distinct entities are preserved (that is, classified in the Bernsteinian sense – Bernstein, 1996a:20), not integrated; and any power relationships between them (Bernstein, 1996a:19-20) are thus also maintained.

Bernstein's second horizontal discursive plane in an HKS, the "problem plane", "is produced by empirical study of particular problems or areas" (*ibid.*:173). After referring to this as the specific problem plane, or SPP, Bernstein immediately draws attention to the segmental structuring of both planes:

> "Both GAP and SPP are segmentally structured, by different languages in the case of GAP, *and* by different problems and by different languages in the case of SPP. Thus specialised language from GAP may cut across

[38] Or, even better, in the first-year Course MECN1001, "Introduction to Mechanical Engineering and Design" (University of the Witwatersrand, 2009).
[39] As is clear from Bernstein's endnote here, he is thinking of approaches in sociology, but the analogy with different fields in engineering is there.

> a series of problems or the same problem may be described by different languages in the GAP. It is not uncommon for the SPP to develop a local, context-specific language." (Bernstein, 1996c:174; emphasis in original)

In view of Bernstein's above assertion that "the GAP plays an analogical role to general theory in hierarchical knowledge structures", an HKS with a GAP and an SPP does have verticality; the two planes are on different levels, as Bernstein illustrates in his visual presentation of a horizontal knowledge structure, reproduced in Figure 7.4.

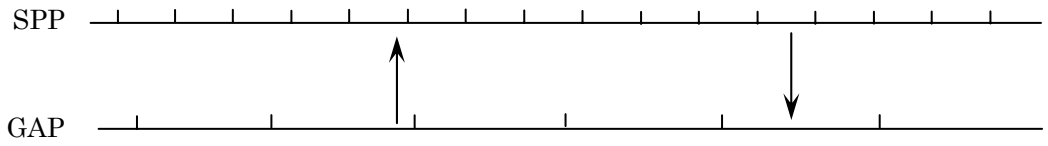



Figure 7.4 "A Visual Presentation of a Horizontal Knowledge Structure" (Bernstein, 1996c:174)[40]

Such a structure of mechatronic knowledge could be as in Figure 7.5. Here, the meta-languages produced are the first attempts to link the apparently non-translatable languages of, say, mechanical kinetics and electrical dynamics. An example of the beginnings of such a meta-language is found in the Notes for Course ELEN2000, 'Electrical Engineering' of Table 7.1:

> "Similarly the total energy stored in a capacitor with voltage $v_C$ is given by $w = \frac{1}{2} \cdot C \cdot v_C^2$ in Joules (J) *which is analogous to potential energy.*
> .....
> "Similarly the total energy stored in an inductor carrying a current $i_L$ is given by $w = \frac{1}{2} \cdot L \cdot i_L^2$ in Joules (J) *which is analogous to kinetic energy.*"
> (Jandrell & van Coller, 1998:14,15; candidate's emphasis)

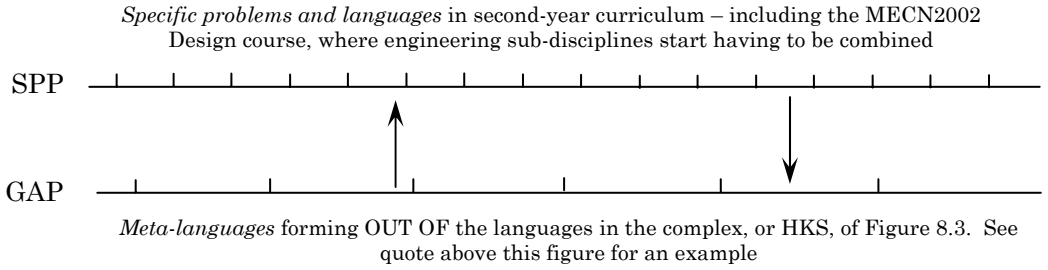



Figure 7.5 Preferable Pseudo-Conceptual, Two-Plane HKS Anterior to Mechatronics

We can see the Vygotskian *pseudoconcept* forming in this example. First, there is the recognition that there are analogies [similarities] in the forms of energy being handled in mechanical kinetics and electrical dynamics – two of the languages in the original HKS of Figure 7.3. This recognition in turn

[40] The arrows in this visual presentation presumably denote the interactions between the GAP and the SPP.

suggests a general principle, the beginning of a meta-language, describing apparently different phenomena – the key feature of a concept.

> "The pseudoconcept serves as a connecting link between thinking in complexes and thinking in concepts. It is dual in nature: a complex already carrying the germinating seed of a concept." (Vygotsky, 1986:123)

The metamorphosis of the original HKS of Figure 7.3 into the *two* horizontal GAP and SPP planes of Figure 7.5 represents this Vygotskian "germinating seed of a concept". This is because the GAP plays an analogical role to general theory in hierarchical knowledge structures (Bernstein, 1996c:173). *This means it is starting to function like a concept:* as Kozulin puts it,

> "A pseudoconcept, while retaining its 'complex' substructure, functions very much like a concept, and thus marks the borderline between prelogical and logical thought." (Kozulin, 1990:215)

So, in this pseudoconceptual structure – this dual-plane HKS – the GAP, though segmentally structured, produces meta-languages that are the beginnings of concepts.

Unfortunately, this is where the development of many, possibly most, students' knowledge structures seems to stop during their undergraduate years. The example of the descriptive question on a solenoid in Section 2.2 above, from the MCT1 Course examination in 2007 and 2008, illustrates this.

### 7.3.7 Deficiencies of Even a Dual-Plane HKS

*It is submitted that this type of HKS, with a GAP and an SPP, represents the far less desirable, inferior, deficient but prevalent mechatronic knowledge structure in student and graduate engineers.* It is deficient because the separate languages of the two disciplines – ME and EE – are not integrated by the *students* in *their* knowledge structures. They remain separate and segmented – specialised languages in an HKS. Thus the *students'* knowledge structures, instead of being the desired HiKSs, are effectively HKSs with a GAP and an SPP. The meta-languages of the GAPs in these students' HKSs relate the separate languages of ME and EE *only at their boundaries,* as if they were:

> "... non-translatable, specialised languages with non-comparable principles of description based on different, often opposed, assumptions." (Bernstein, 1996c:173)

Thus the separate languages (sub-disciplines) of ME and EE are *preserved,* and *uneasily linked at their boundaries,* rather than integrated. Moreover, the SPPs of the students' HKSs, segmentally structured in both these languages and specific problems encountered, are thus ineffectively equipped (in comparison to the desirable HiKSs) to solve mechatronic problems. Furthermore, such a two-plane HKS, being a pseudoconcept, *can often pass functionally for the desirable HiKS.* Repeating the quote from Kozulin of Page 38,

> "Another important feature of the pseudoconcept is that functionally it looks so like true concepts that adults often do not notice the difference.

> This observation indicates how deceptive functional appearance can be. 'Thought-complexes' can appear as if they are concepts, thus concealing their actual substructure. The use of one and the same words and the understanding they bring about may correspond to only a superficial level of functional communication, while the underlying intellectual substructures of the communicants may remain alien to each other." (Kozulin, 1990:217)

Vygotsky elaborates:

> "What we confront here is the appearance of a concept that conceals the inner structure of a complex ... Although the results are identical, the process by which they are reached is not at all the same as in conceptual thinking." (Vygotsky, 1986:119)
>
> "The outward similarity between the pseudoconcept and the real concept, which makes it very difficult to 'unmask' this kind of complex, is a major obstacle in the genetic analysis of thought." (*ibid.*:121)

Thus *this inferior dual-plane HKS with its GAP and SPP may not be recognised as such except by searching assessment and evaluation.*

### 7.3.8 Second Phase – Germinating HiKS with Genuine Concepts

How can this pseudoconceptual HKS change further, or be transformed, into the desirable HiKS, with its concepts and relations of generality, of Figure 7.1? For this pseudoconceptual HKS could develop further, as Bernstein suggests, by the introduction of a new language (1999:163), but it should not, because this amounts to just adding this new language whilst retaining the horizontal structure – even if this new language subsumes several of the older, previous languages. Rather, as noted above, this pseudoconceptual HKS has taken on the *potential* of abstraction by metamorphosing into two horizontal discursive planes – one of which, the GAP, plays an analogical role to general theory in hierarchical knowledge structures; its "theories" are,

> "... really theories about what counts as proper description of the specific phenomena of a particular horizontal knowledge structure (HKS)." (Bernstein, 1996c:173)

Therefore, in order to become a structure of genuine concepts, this pseudoconceptual HKS should rather develop into the desirable HiKS of Figure 7.1. Its GAP should metamorphose further from meta-languages – the germinating seeds of concepts – into genuine concepts, able to be linked by relations of generality, and having vertical, integrative relations of applicability. These concepts should form by the singling out of certain common attributes (Vygotsky, 1986:145), and *uniting or separating objects on that basis* (*ibid.*:135-6). But what are the 'objects' here?

The 'objects' are engineering physical systems, or devices, that handle matter and energy and process information to perform desired tasks. Solid mechanical, hydraulic, pneumatic, electric, or thermal systems (these being defined in Appendix 5) may perform very different tasks, handle very different quantities and qualities of matter, energy and information, and appear to be very

unlike, *but their common attributes lie in the ways – analogous ways – that the systems, or their subsystems or components, handle matter, energy and information.* Thus we are driven to seek a suitable, general way of representing the common principles by which all such systems handle matter, energy, and the information packaged in these. We find an eminently suitable representational technique in *bond graphs.*

## 8. BOND-GRAPH REPRESENTATION OF COMMON PRINCIPLES OF MECHANICAL AND OTHER PHYSICAL SYSTEMS

It has been well observed that:

> "Reality has, in principle, a complexity which cannot be taken in all at once, so that all influencing factors can never be accounted for. Hence a choice of these factors has to be made." (Wolf, 1986)

What are the influencing factors in reality that have to be chosen to most clearly reveal the commonality of the ways in which different physical systems operate? In the late 1950s, Professor H. Paynter started developing the *bond graph* representation of behaviour of dynamic systems (Karnopp *et al.*, 1990:viii). In bond graphs, the key influencing factors in reality are *effort* and *flow variables.* Examples are pressure difference (an effort variable) and fluid flow (a flow variable) for fluidic systems, or voltage difference and current for electrical systems. Effort and flow variables are thus different for different systems, but all accomplish the same thing – transfer of energy between components of a system. Thus bond-graphs can represent seemingly very different systems *and clearly bring out their common operating principles.* As Karnopp et al. summarise:

> "It is a remarkable fact that models based on apparently diverse branches of engineering science all can be expressed using the notation of *bond graphs* based on energy and information flow. This allows one to study the *structure* of a system model. The nature of the parts of the model and the manner in which the parts interact can be made evident in a graphical format. In this way, analogies between various types of systems are made evident, and experience in one field can be extended to other fields." (Karnopp, Margolis & Rosenberg, 1990:5; emphasis in original; candidate's underlining)

It is worth noting that another, somewhat related graphical technique for representing system behaviour is the *linear graph.* This symbolises energy flow between system components as being accomplished by 'through variables' and 'across variables' (de Silva, 2005:57-68). However, as elaborated upon in Appendix 5, bond graphs are both more intuitive and more informative.

### 8.1 The Bond Graph

In bond-graph representation of systems, all interconnections between components are symbolised as energy flows. Thus *the common function of all*

*components as handling energy* (which, for mechanical and fluidic components, involves handling matter too) *is emphasised from the start.* All inputs to components or the system, as well as outputs from components or the system, are in the forms of either *effort variables* or *flow variables*. For any component, the product of the appropriate effort variable and its associated flow variable gives the energy flow into or out of that component. Table 8.1 lists effort and flow variables for basic mechanical, electrical, fluidic and thermal (heat-transferring) system components.

Table 8.1 Bond Graphs: Effort and Flow Variables[41] for Basic System Components

| **Type of Component** | **Effort Variable** | **Flow Variable** | **Basic Components** | |
|---|---|---|---|---|
| | | | ***Energy-storing*** | ***Energy-dissipating*** |
| Mechanical (translational) | Force (force difference) | Velocity (translational) | Object possessing inertia due to its mass<br>Spring (stiffness element) | Frictional damper |
| Mechanical (rotational) | Torque (torque difference) | Velocity (rotational) | Object possessing *moment of inertia* due to its mass and configuration<br>Rotary spring (stiffness element) | Rotary frictional damper |
| Electrical / Electronic | Voltage (Potential Difference) | Current | Inductor<br>Capacitor | Resistor |
| Fluidic (Hydraulic / Pneumatic) | Pressure Difference | Fluid Flow-Rate | Fluid storage element (fluid capacitor)<br>Element with *fluid* inertia due to *fluid's* mass (fluid inertor) | Element offering resistance to fluid flow (fluid resistor) |
| Thermal (Heat- Transferring) | Temperature Difference | Heat Transfer Rate | Thermal energy storage element (thermal capacitor) | Element offering resistance to heat transfer (thermal resistor) |

As an example, a basic object of mass $m$ is shown in the block diagram of Figure 8.1. The input thereto is an *effort variable,* force; the resulting output is a *flow variable,* velocity. Figure 8.1 also shows the corresponding bond graph. The bond's half-arrow indicates the direction of energy flow when both the ef-

[41] More correctly, effort and flow *difference* variables.

fort variable (here, force *f*) and the flow variable (here, velocity *v*) are positive according to a chosen sign convention. The effort and flow variables are marked, respectively, above and below the bond. The short vertical stroke at one end of the bond indicates causality (i.e. the input that causes the output) as explained in Appendix 5.

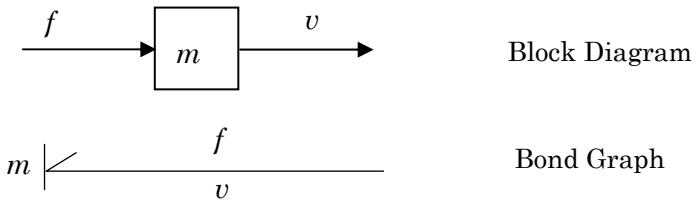



Figure 8.1 Block Diagram and Corresponding Bond Graph for Force Acting on Object of Mass *m*

Appendix 5 explains the key features and elements of bond graphs. Basic single-port components as in Table 8.1, with one input and one output, are represented as in Figure 8.1. As outlined in Appendix 5, bond graphs also permit *two-port* components, such as mechanical transformers[42] and gyrators in mechanical systems; electrical transformers in electrical systems; and *converters* between different energy forms, such as pumps converting mechanical energy to fluidic energy, or motors converting electrical energy to mechanical energy. Of necessity, bond graphs must allow junctions for common effort or flow variables, as also explained in Appendix 5.

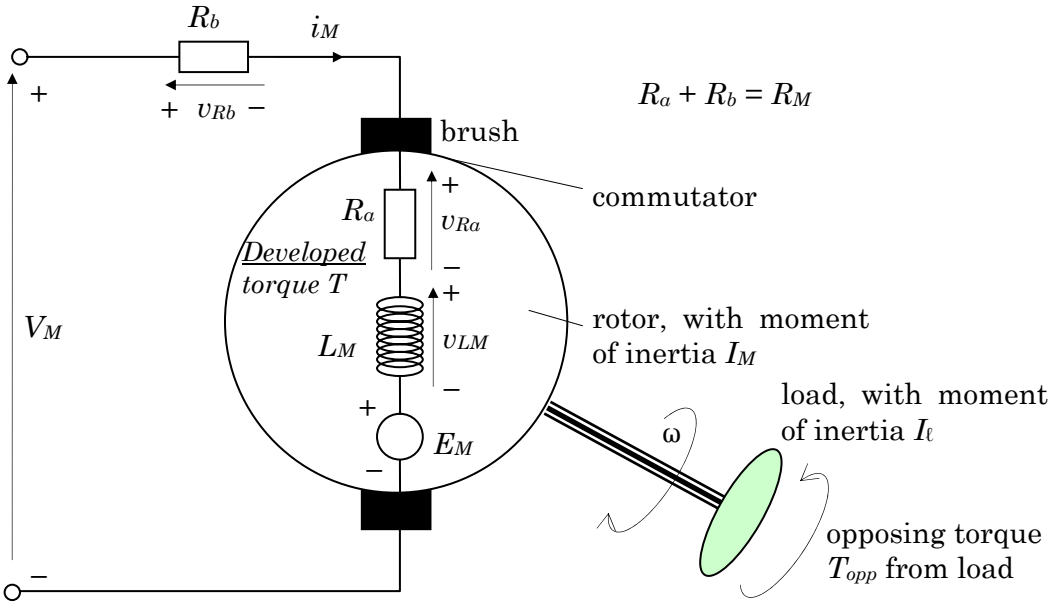



Figure 8.2 Permanent-Magnet DC Motor Driving a Load

[42] Both translational types such as levers, and rotary types such as gears.

As an example of the utility of bond-graph representation in an electro-mechanical system, a permanent-magnet DC motor driving a load of moment of inertia $I_L$ is shown in Figure 8.2. The motor's rotor itself has a moment of inertia of $I_M$. $R_b$ is the resistance of the brushes and their wiring; and $R_a$, that of the coils in the rotor itself. The sum of $R_b$ and $R_a$ is the total motor resistance $R_M$. $L_M$ is the inductance of the rotor. $E_M$ is the back e.m.f. (electromotive force) developed by the rotor when it is rotating, and corresponds to the conversion of electrical into mechanical energy.

The bond-graph representation of this electro-mechanical system is in Figure 8.3. This graph comprises:

(i) two common-current junctions, emphasising that the *same* current $i_M$ flows through all electrical components in the motor;

(ii) one energy transformer (converter), which is the motor's rotor, converting electrical to mechanical energy;

(iii) one common-speed (rotational speed) junction, emphasising that the motor's rotor and the driven load have the *same* speed.

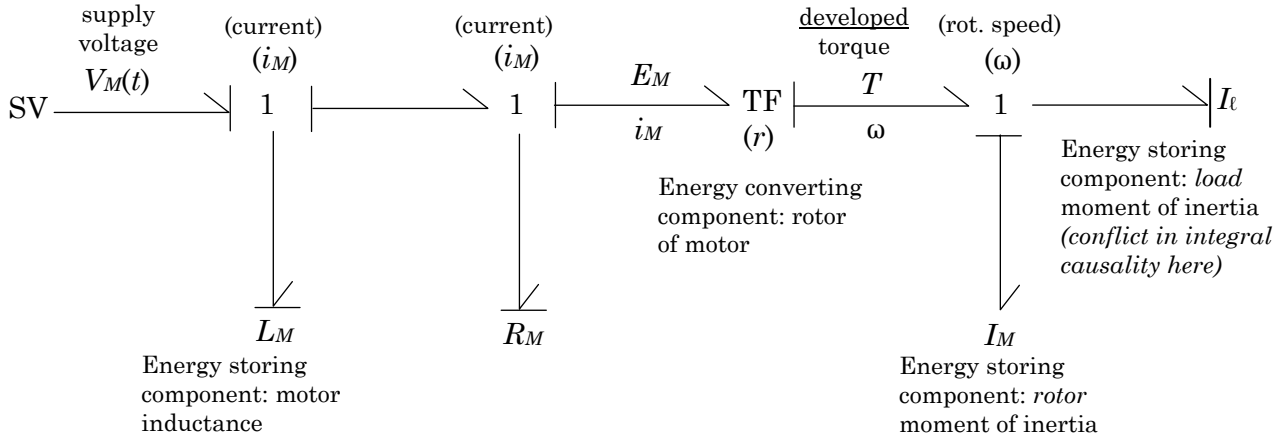



Figure 8.3 Bond Graph Representation of Motor and Load of Figure 8.2

There are three energy-storing components in the motor and load of Figure 8.2: the motor with inductance $L_M$, the motor rotor with moment of inertia $I_M$, and the load with moment of inertia $I_\ell$. However, *the energy-storing functions of these three components are not all independent,* as this bond graph reveals by one *conflict of integral causality*. As explained in Appendix 5, all energy-storing components are assumed to have integral causalities, which, for these three components, are:

$$i_M = \frac{1}{L_M}\int v_{LM}\cdot \mathrm{d}t \qquad \omega_M = \frac{1}{I_M}\int T_M \cdot \mathrm{d}t \qquad \omega_\ell = \frac{1}{I_\ell}\int T_\ell \cdot \mathrm{d}t \quad (8\text{-}1)$$

The rotational speed of the motor is obviously the same as that of the load; that is, $\omega_M = \omega_\ell$. The bond graph displays the same fact in its common-speed junction (ω). Now, the bond connected to $I_\ell$ has its stroke at its near end (to

$I_\ell$), meaning that torque $T$ is its output. This conflicts with integral causality, which specifies that rotational speed ω should be the output. Hence, as explained in Appendix 5, this system has only two independent ways to store energy: in the motor inductance $L_M$ as energy in a magnetic field, and in the motor's rotor and load as rotational kinetic energy. (The motor's rotor and the load are directly coupled, and so cannot store energy independently.) Thus the integral causalities for Figure 8.2 are correctly written as:

$$i_M = \frac{1}{L_M}\int v_{LM}\cdot \mathrm{d}t \qquad\qquad \omega_{M,\ell} = \frac{1}{I_M + I_\ell}\int T_{M,\ell}\cdot \mathrm{d}t \tag{8-2}$$

In sum, the advantages of bond-graph representation of systems are:

- the energy flows between components, and the associated effort and flow variables, stand out, emphasising the common functions of components in handling energy (and matter);
- the revealing of conflicts in integral causality is advantageous in modelling complex systems with many energy-storing components.

Bond graphs can be further enhanced, using *active bonds,* to represent the effects of adding automatic control to systems to produce required behaviour (Karnopp *et al.*, 1990:23,27). It is important to be able to predict system behaviour, in order to address questions such as:

(1) is the system naturally stable – that is, does it control itself adequately, or will it go out of control?[43]

(2) if the system requires additional, artificial control to meet its performance objectives, then *with* this added, artificial control, does it both meet these performance objectives and remain stable?

## 8.2 The Relational Block Diagram

In addressing such questions here, it will be clearer to use another representation of systems, the relational block diagram, rather than bond graphs with active bonds. The utility of such block diagrams, and the way in which they complement bond graphs, is well illustrated in the system of Figure 8,2, a permanent-magnet DC motor driving a load. Figure 8.4 is the block diagram of that system.

First, this block diagram reflects the information yielded by the bond graph of Figure 8.3. The two integral causalities of (5-2) above are indicated by the dashed enclosures in Figure 8.4. All effort and flow variables of the bond graph are likewise in Figure 8.4. The effect of the system's energy-converting

[43] Assuming that the input(s) to the system are bounded, i.e. have lower and upper limits that the system can tolerate.

component, the motor's rotor, depicted as TF (*r*) in the bond graph of Figure 8.3, is shown in the two blocks labelled [TF] in Figure 8.4. The first such block reflects the relation between motor current $i_M$ and developed torque $T$; the second, the relation between rotational speed ω and back e.m.f. $E_M$.

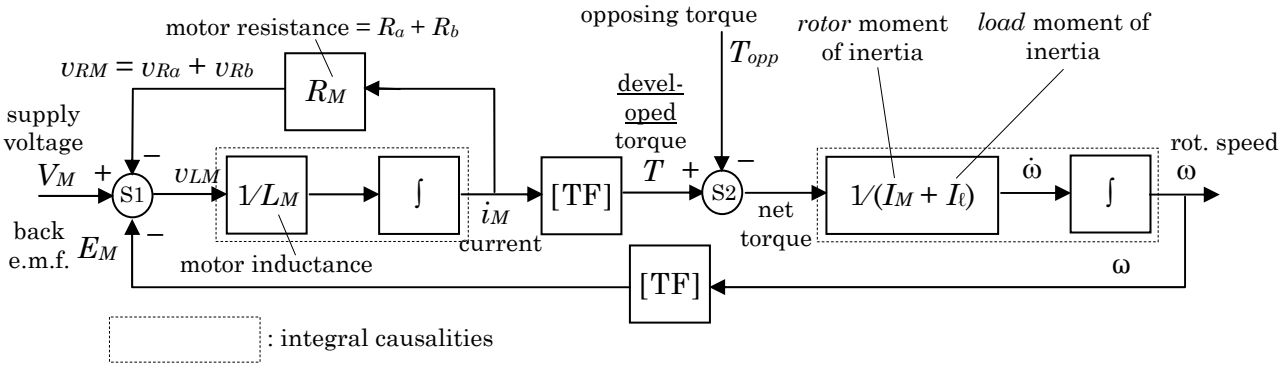



Figure 8.4 Block Diagram of Motor and Load of Figure 8.2

The real utility of the block diagram, though, lies in its illustration of the nature of the interactions between the system's components, and the consequent interdependencies of the effort and flow variables. Figure 8.2 illustrates, on the basis of Kirchhoff's laws for electric circuits, that the back e.m.f. $E_M$ and the voltages $v_{Ra}$, $v_{Rb}$ and $v_{LM}$ across the motor's resistances and inductance all oppose the voltage $V_M$ applied to the motor. This is reflected in the two loops of *negative feedback* in Figure 8.4. There, the applied voltage $V_M$ enters the summing junction S1 positively, but the voltage $v_{RM}$ developed by the motor resistance $R_M$, and the back e.m.f. $E_M$, enter this junction negatively (that is, feed back negatively into it). What leaves summing junction S1 is thus the net difference between $V_M$, $v_{RM}$ and $E_M$, this difference being the voltage $v_{LM}$ across the motor inductance $L_M$. This voltage, in turn, is the input to the first integral causality relation in Figure 8.4, the output of which is the motor current $i_M$. This current is the origin of the first negative feedback loop – through the resistance $R_M$, producing the voltage $v_{RM}$[44] feeding negatively into summing junction S1.

The first [TF] block in Figure 8.4 then converts this motor current to the developed torque $T$, which feeds positively into the second summing junction S2. The opposing torque $T_{opp}$ from the load feeds negatively into this junction. What leaves it is thus the *net torque* (the difference between $T$ and $T_{opp}$). This net torque is the input to the second causality relation, the output of which is the rotational speed ω. This speed is the origin of the second negative feedback loop – through the second [TF] block in Figure 8.4, producing the back e.m.f. $E_M$ also feeding negatively into summing junction S1.

[44] Through Ohm's Law, $v_{RM} = i_M R_M$.

These two negative feedback loops constitute *natural feedback,* inherent in the system. Such loops give systems their natural stability – for example, the characteristic of settling down to steady operating conditions when the input is steady. Figure 8.4 illustrates the natural stability of the system of Figure 8.2 as follows. At steady operating conditions, both motor current and rotational speed are steady. For motor current $i_M$ to be steady, the output from summing junction S1 (this output being the net voltage $v_{LM}$ across motor inductance $L_M$) must be zero, so the applied, input voltage $V_M$ is equalled by the sum of $v_{RM}$ (due to the resistance $R_M$) and the back e.m.f. $E_M$ (due to the rotational speed ω). Likewise, for rotational speed ω to be steady, the output from summing junction S2 (this output being the net torque) must be zero, so the developed torque $T$ is equalled by the opposing torque $T_{opp}$ from the load.

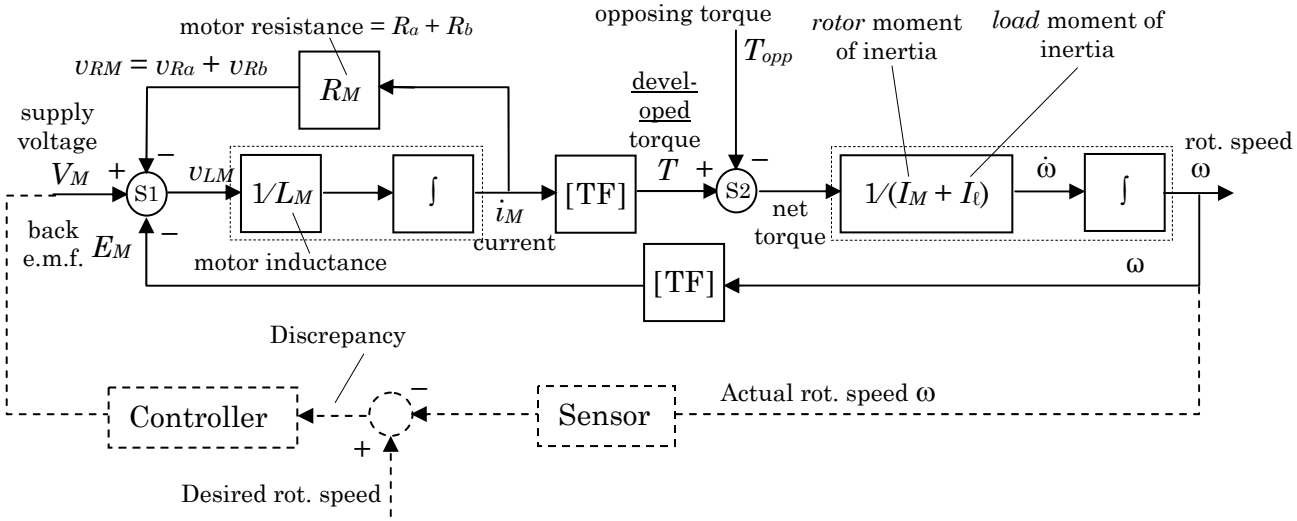



Figure 8.5 Block Diagram of Motor and Load of Figure 8.2, with Speed Controller

If a system such as that of Figure 8.2 requires additional, artificial control to meet its performance objectives, extra components and artificial feedback loops will generally be necessary. For example, if speed control of the system of Figure 8.2 is desired, the additional feedback loop and controller required are shown in dashed outline in Figure 8.5. Here, the actual rotational speed is sensed (measured) and then compared with the *desired* rotational speed; the discrepancy between these is passed to the controller, which calculates how to adjust the voltage $V_M$ and does this to maintain the desired, constant speed.

In sum, the bond graph aids in the correct modelling of a system, representing all components, be they mechanical, electrical, hydraulic, pneumatic, or heat-transferring, as handling energy. Once such a system is correctly modelled, the block diagram can then be drawn to represent the interactions between components, including natural feedback. Artificial control to meet performance objectives can be added into the block diagram. The bond graph and the block diagram together encapsulate the key general principles in an

integrated, hierarchical knowledge structure applicable to mechatronic systems.

It must be noted that the candidate has not yet incorporated bond graphs into the MCT1 Course that he teaches. Relational block diagrams have only been incorporated at an elementary qualitative level. Both these conceptual tools are highly abstract. Therefore, if they are fully, integrally incorporated into the course as envisaged, it is realistic to expect significant pedagogical problems, as the prerequisite courses completed by students (the EE2 Course, for example) will not have prepared them for such abstraction. Neither will the predominantly collection-type programmes of the first and second years of undergraduate study, referred to in Section 7.3.2 above, have done so. How best to address such problems is left for further work. However, a start has been made at considering this in the next section; a key feature of the 'Double Move' pedagogy described therein is effective in fusing of students' 'everyday' *and previously acquired* concepts with the subject-matter concepts presented in a course.

## 9. A PEDAGOGY TO ACHIEVE AN INTEGRATED KNOWLEDGE STRUCTURE IN MECHATRONICS

With the bond graph, then, as the conceptual tool revealing the common principles by which mechanical, electrical and other systems handle matter, energy and information, the question remains of how to realise Bernstein's desirable hierarchical knowledge structure (HiKS) in engineering students.

For a suitable pedagogy, we turn to Hedegaard's *'double move in teaching'* (Hedegaard, 2002:42-3), which is based upon Vygotsky's zone of proximal development (ZPD). This 'double move' pedagogy also integrates a vital consideration – that of motives and motivation in the student (*ibid.*, 2002:21;55-68). Hedegaard's two basic assumptions spring from both:

> "The 'double move in teaching and developmental learning' is built on two basic assumptions about children's functioning:
>
> - that the child appropriates cultural knowledge, skills and motives through social interactions with other participants of a cultural practice, usually more skilled adults and older children;
> - that the child's own intentional activity is one of the conditions for his or her development of concepts, skill and motives."
>
> (Hedegaard, 2002:17)

Its aim is *developmental* learning (*ibid.*, 17), by teaching within the ZPD (*ibid.*, 81), integrating the children's everyday concepts with subject-matter concepts (*ibid.*, 79). Possibly the best way in which Hedegaard herself encapsulates her 'double move' conceptualisation of teaching-and developmental learning is,

> "... Vygotsky's concept of the zone of proximal development transformed into a conceptualisation of teaching and learning as a double move between situated activity and subject-matter concepts."
>
> (Hedegaard, 2002:43)

The graphical depiction in Figure 9.1 attempts to illustrate the essential aspects of this double move. The vertical axis represents development in learning, rising from everyday concepts – associations or connections between concrete examples of complex reality – to subject-matter concepts, namely hierarchical, interdependent relations between such examples and the subject's general laws describing and predicting these. (*For mechatronics, it must be noted here that 'everyday' concepts include concepts acquired during prerequisite courses.*) The horizontal axis represents time; this axis meets the vertical, developmental axis at point O, marking the beginning of a course in the subject-matter. Time to the left of O, where the teacher's planning is done, is *before* the course; time to the right of O, where developmental learning is envisaged, is *during* the course.

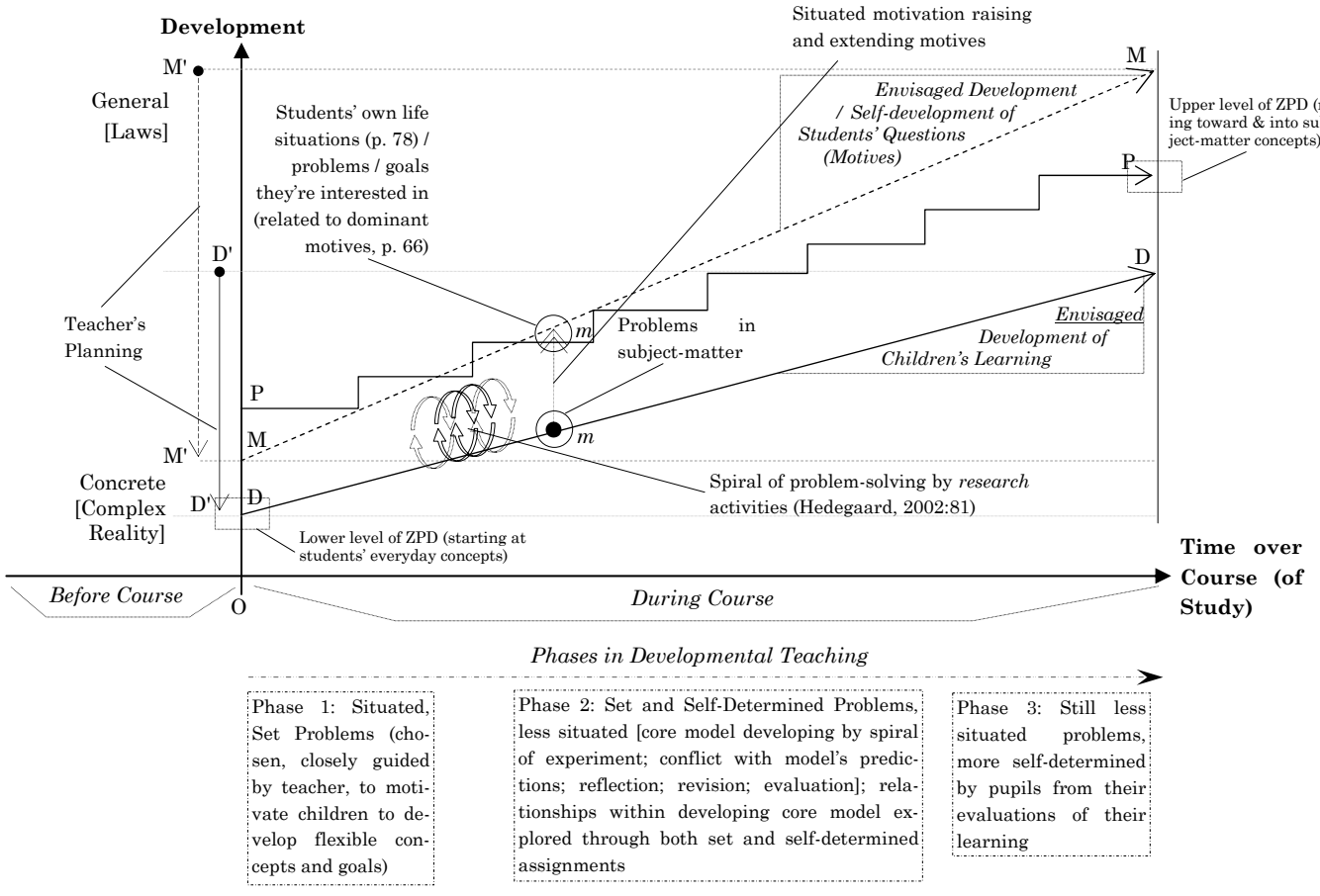



Figure 9.1: Depiction of Hedegaard's 'Double Move in Teaching and Developmental Learning'

Figure 9.1 shows, first, envisaged development in students' learning – within their continually rising ZPD. The slanting, upward-arrowed trend line D-D denotes the students' envisaged development *during* the course. This devel-

opment always marks the lower level of the continually rising ZPD, and must start from the actual development at the beginning of the course – this actual development being at the level of everyday (*including, as mentioned earlier, previously acquired*) concepts. Development within the ZPD occurs as students begin acquiring the subject-matter concepts and develop *core models* of the conceptual relations within the subject-matter (Hedegaard, 2002:86). The stepped trend line P-P marks the continually rising upper level of the students' ZPD – rising toward and into subject-matter concepts. *Before* the course, the teacher's planning to achieve the students' envisaged development D-D is shown by the downward arrow D'-D', between the same levels of development. Downward arrow D'-D' and slanting upward trend line D-D thus illustrate the two moves in the 'double move in teaching and developmental learning'.

Second, Figure 9.1 shows envisaged development in the students' *motives,* denoted by the slanting, upward-arrowed trend line M–M. The teacher's corresponding planning before the course is shown by the downward-arrowed line M'-M', between the same levels of development as M–M. Following Hedegaard's definitions (2002:55), *motives* here denotes the goals that characterise a student's actions over the entire course; *motivation* denotes the dynamism and actual goals that characterise a student's relationship to his surroundings in any concrete activity or situation within the course.

> "Motivation characterises the dynamism evinced in a person's actions in concrete, everyday situations. But motivation also has a second meaning: it can characterise the dynamism that gives direction to a person's life, and which influences the goals he sets himself. In order to differentiate between the two I will use the word *motivation* to refer to that dynamism and the actual goals that characterise a person's relationship to his surroundings in concrete activities or situations; the word *motives* will be used to describe the goals that come to characterise a person's actions in different activities over a longer period of time, motives can be seen as the central dynamic factors in a person's development of his or her personality." (Hedegaard, 2002:55; her italics)

In Figure 9.1, the envisaged, situated *motivation* at any stage of the course is represented by the vertical riser *m–m* with the double-headed arrow. The strength of this motivation depends on the difference between the (envisaged) developmental learning of the student and the (envisaged) development of her/his motives. The double-headed arrow symbolises this situated motivation *raising* the student's motives for higher levels of development. (As Hedegaard (2002:78) notes, such situated motivation at any stage of the course is created by the conflict between the predictions of the student's core model and the phenomena introduced in the teaching.)

The phases in the developmental teaching are depicted below the horizontal axis in Figure 9.1. Over the course, these phases progress from situated problems, chosen and closely guided by the lecturer, to less situated problems,

more self-determined by the students. These problems are solved in a spiral of research-type activities: development occurs as students, individually and in their groups, continually *re-formulate their core models* in spirals of experiment; conflict between experimental results and those predicted by the core models; reflection; revision and evaluation. The correspondence between Figure 9.1 and the key aspects, in Hedegaard's own words, of the 'double move' are outlined in Appendix 6.

Table 9.1 outlines how these same key aspects in Hedegaard's 'Double Move' might apply to teaching of mechatronics through a laboratory project. Furthermore, in the 2009 Mechatronics I laboratory project, it was attempted to implement one key aspect. The practice of previous years had been, in each week of the semester-long Mechatronics I course, to present the theoretical material in three morning lectures, and to run the laboratory project in one two-hour afternoon session. In 2009, this was departed from: the project was run 'full-time' during the first quarter. That is, it was given *all* morning lecture periods and afternoon sessions of the first quarter, ending at the end of that quarter. The theoretical material was then presented 'full-time' in the second quarter; that is, lectures on the theoretical material were likewise given during *all* that quarter's morning lecture periods and afternoon sessions. The main reason for so re-organising the course was to terminate the project at the end of the first quarter, to prevent students using this project as an excuse for 'cutting' lectures of other third-year courses near the end of the second quarter, with examinations imminent. However, a welcome opportunity was thereby provided to *begin* the course with one key aspect of Hedegaard's 'Double Move': a 'spiral of problem-solving' by research activities, demanded by the very nature of this project – researching how to make a given mechanical device work automatically and meet given performance specifications. The third column of Table 9.1 outlines the activities in the 2009 laboratory project that correspond to key aspects of the 'double move'.

Table 9.1: Key Aspects of Hedegaard's 'Double Move' in a Mechatronics Laboratory Project

| **Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning'** | **Application to Learning Mechatronics through a Mechatronics Laboratory Project** | **Corresponding Activities in 2009 Mechatronics Laboratory Project** |
|---|---|---|
| "The teacher's planning must advance from the general laws to the surrounding reality in all its complexity. In order to explain these laws the teacher must choose con- | The students' learning must develop from preconceived actions (initial lab. exercises) to symbolisation, by working devices, of the knowledge they obtain through their research | Three initial lab. exercises were given<br><br>These 'working devices' were the given mechanical devices that had to be |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| crete examples that demonstrate the general concepts and laws in the most transparent form. Whereas the teacher's planning must advance from the general to the concrete, the children's learning must develop from preconceived actions to symbolisation of the knowledge they obtain through their research, finally resulting in a linguistic formulation of relations."<br>(Hedegaard, 1990:274-5) | [project and concurrent coursework], finally resulting in a linguistic formulation of relations [the project report]. There should also be links to the theory in the Mechatronics course. | automated to given performance specifications<br><br>A written project report was required<br>A few lectures in the first quarter were devoted to theory deemed essential prior to the project |
| "In the double move approach, the process of instruction runs as a double move between the teacher's model of subject-matter concepts of a problem area and the students' everyday cognition and knowledge." (Hedegaard, 2002:78) | Note: for "students' everyday cognition and knowledge" read "students' everyday *and previously acquired* cognition and knowledge". | |
| Within a spiral of problem-solving, the students begin by working with situated problems chosen by the teacher; they gradually acquire the concepts and develop a *core model* which is continually being revised & refined; this equips them to approach different tasks; through this diverse problem-solving, students become able to evaluate their learning (Hedegaard, 2002:78) | Here, students begin by working with situated problems in the form of initial *laboratory exercises* [on micro-controllers, sensors and actuators linked to a device being controlled] as situated problems; the continually revised & refined *core model* that they develop is that of the physical laws and information processing governing the behaviour of the complete controlled device. This device should be that of the project (or sub-devices thereof), but for | The initial lab. exercises (with flexible options) were: (i) controlling lamps just using electrical hardware; (ii) the same exercise, but using a programmable controller and software, to illustrate the greater ease of making changes to software rather than hardware to accommodate changing performance specifications<br><br>These exercises were carried out on a sub-device of the project (its electrical control board) |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| | breadth of experience, other mechatronic devices can also be included. | Breadth of experience was given through a third exercise – equipping the board with electrical safety hardware (circuit breakers and earth rails) |
| "The teacher guides the learning activity both from the perspective of both the general concepts and methods of a subject-matter area and from the perspective of engaging students in 'situated' problems that are meaningful in relation to their developmental stage and life situations." (Hedegaard, 2002:78)<br>"... the students are given tasks that motivate them for research activity so that a relation between the pupils' own problems and the problems in a subject area is created. The learning motive thereby can become connected to subject-matter concepts ..." (Hedegaard, 2002:21) | This is difficult. Unlike children, students' big questions about life do not readily relate to this kind of subject-matter – so what are appropriate students' problems or goals? For some students, these are their natural curiosity or interest in the subject-matter (a stimulating motive, Hedegaard, 2002:63-4); for some others, a dominant motive of improving people's quality of life; for possibly most others, just the hurdle of passing (a step towards a dominant meaning-giving motive {such as wealth or fame?},[45] Hedegaard, 2002:63). In this case the content of teaching (the subject-matter) is secondary (Hedegaard, 2002:65). | Unfortunately, no increased motivation (compared to previous years) could be detected. A mere 55 out of 96 students completed the multiple-choice faculty survey of student opinions of the complete course (project plus lecture material). Of these 55, 22 selected 'neutral' on the statement "I was motivated to read or do extra work"; 14 agreed therewith, and only 9 strongly agreed therewith. The 41 students who did not complete the survey were most likely not strongly motivated! |
| "Five factors can be conceptualised as crucial in the double move approach for how teaching can lead to developmental learning. These are:<br>(a) "formulation of problems that involve the | These are the initial laboratory exercises, having | Most students did attempt the flexible options, but |

[45] Note here, Hedegaard (2002:63-4) saying that *"change in the motivation* hierarchy *is the primary indicator of* development *in the child from one stage to the next"* (candidate's emphasis).

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| central conceptual relations and methods, as well as motivate the children attending the class, ..." (Hedegaard, 2002:82) | flexible options after the compulsory basics to increase motivation. | the motivation was most likely that of acquiring knowledge useful for the coming project |
| (b) "content analyses and formulation of germ cell/core models, ..." (*ibid.*, 82)<br>{ a core model being a person's own abstractions of a subject-matter area (*ibid.*, 86) } | The continually revised and refined *core model* is that of the physical laws and information processing governing the behaviour of the complete controlled device or its sub-devices; other devices may also be included. | One opportunity given to students here was to temporarily dismantle their given mechanical devices into functioning sub-devices and experiment with each such sub-device to learn its characteristics (e.g. where most friction arises, and why) |
| (c) "analogy to research methods, ..." (*ibid.*, 82);<br>"Thus there is a double move in instruction: The teacher must guide instruction on the basis of general laws, whereas the children must occupy themselves with these general laws in the clearest possible form through the *investigation* of their manifestations. That is why *practical research activities* with objects, films and museum visits are such an important part of instruction, especially during the early periods." (Hedegaard, 1990:275; candidate's italics)<br>"The solution is ... to use a teaching approach that motivates the pupils to plan and participate in research activities with | This is essential – to evoke both the stimulating motive, *and* (self-) development.<br>Students should be required to keep a log-book to record and analyse their experiences, and document their progress toward their own goals. | A summary of these experiences was requested in the project reports<br>Such investigations were self-prompted through the experiences of working with the given devices<br>Here, the 'practical research activities' were the project itself |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| the objective of creating a link between the pupils' own questions and the problems that are central to the subject being taught." (Hedegaard, 2002:81) | | |
| (d) "phases in teaching, which are based upon progressive and qualitative changes in the children's appropriation of knowledge and skills;" (*ibid.*, 82)<br><br>This is developmental teaching, whose phases are dialectically linked to phases in learning; the three phases in developmental teaching are (*ibid.*, 89):<br><br>(1) helping children to develop flexible concepts and formulate goals about the thematic relationships in a course of subject-matter – here, pupils are just set assignments (*ibid.*, 90); | This will be the {flexible} initial lab. exercises, where the flexibility will be in options after the compulsory basics. | |
| (2) formulation and expansion of these thematic relationships in the form of a germ-cell model for the problem area being investigated – where the relationships within the germ-cell model are explored through various assignments – here, pupils are both set assignments and re- | As above, the continually revised & refined *core models* are those of the physical laws & information processing governing the behaviour of the complete controlled device.<br><br>The assignment set will now be the <u>basic</u> project, with the students being required to formulate *their* | Extra features – such as smoother accelerations and decelerations under automatic control – were |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| quired to formulate problems (*ibid.*, 90); | *own* additional enhancements thereto. | encouraged and rewarded |
| (3) enable children to learn how to critically evaluate what has been learned concerning their own skills; the conceptual relationships being investigated; and the content of the teaching being used to shape the germ-cell model – here, pupils must set tasks that allow evaluation, *and* they are set assignments that allow them to evaluate both the capability of the germ-cell model, and further knowledge and skills they would like to acquire (*ibid.*, 90). | The assignment here that will be set is the <u>project report</u>. Here, they will be required to evaluate (i) their skills, the investigated conceptual relationships & content of teaching given – and (ii) the capabilities of their core models. Then they must describe & justify the further knowledge & skills they would like to acquire. | The project report did require a description of the principles of operation of the controlling hardware and software incorporated into the given mechanical device. It also asked for a description of the main learning experiences |
| (e) social interaction, communication, co-operation between children." (*ibid.*, 82)<br><br>"This type of teaching and learning in school favours co-operation between teacher and learner and between learners in problem formulation and problem solving within a subject domain." (*ibid.*, 2002:78)<br><br>"... children's development takes place through their relation to the class and to the groups in the class." Group solving processes were used to develop the children's intellectual proc- | The project is a <u>team project</u>. A team leader should be nominated. This is an example of <u>production, not just education</u> (Bernstein), so working on different tasks in a group promotes interdisciplinarity, so long as the tasks are not divisive and the agents are not isolated. Agents should be integrated across categories, and the acts should be integrated too. | Each 5-person team chose a team leader<br><br>One undesirable trait noticed was that some teams 'compartmentalised' the work; one member would work with the electrical hardware, one would program the software, one would write the project report, and so on |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Application to Learning Mechatronics through a Mechatronics Laboratory Project | Corresponding Activities in 2009 Mechatronics Laboratory Project |
|---|---|---|
| esses. Children would work on different tasks in a group with a shared motive for the entire activity (Hedegaard, 1990:279) | | |

It was hoped that this alternate way of conducting the project in a more concentrated fashion in 2009 would have increased the situated motivation of students in the MCT1 course. Unfortunately, as noted in Table 9.1, no increased motivation (compared to previous years) could be detected. However, 25 of the 55 students completing the faculty survey of student opinions of the complete course named the project as being the most valuable part of the course. Some comments from those 25 students were:

> "The practical portion of the course is enjoyable and gives us a better physical appreciation for the subject. This is missing from many of the other courses."
>
> "Practical project:- got to see the problems and fix them rather than only receiving theoretical information."
>
> "The practical part of the course was interesting and exposed students to the real world of problem solving."
>
> "The project done in the first semester really helped in reinforcing the theoretical knowledge studied in the lecture notes. It was good to see how electronics and mechanics can be merged into one system."
>
> "The project was most valuable as we were able to learn certain principles not instilled in second year, by practical means."
>
> "The projects given at the beginning of the year were more valuable as they related industry situations with what we do in class."

Of note is that these comments reflect students' rightly directed desire for knowledge more directly applicable to engineering practice, the world of work – put another way, for Bernsteinian codes of education that correspond more closely to codes of production. No other aspect of the course was so frequently named as being the most valuable. There is encouragement, therefore, to organise the MCT1 course similarly in future years – with the laboratory project 'full-time' during the first quarter of the course – and to revise other aspects of the course to increase students' motivation and the hierarchical, conceptual quality of the knowledge they acquire.

## 10. CONCLUSIONS

This project has attempted to conceptually analyse, on the basis of Bernstein's and Vygotsky's theories, the difficulties encountered in producing in-

tegrated knowledge of mechatronic principles, especially those of electricity and electronics, in mechanical engineering students at the candidate's own university. The claims that emerge from this conceptual analysis are:

(1) the curriculum of the Mechatronics I course at the University's School of MIAE – in common with similar curricula at other universities – has, in its recontextualisation, organisation and transmission of knowledge, more a Bernsteinian *collection* type of educational knowledge code than an *integrated* type;

(2) such curricula hence do not foster an adequate, sufficiently subsumptively integrated, Bernsteinian *hierarchical knowledge structure* of genuine mechatronic concepts in the knower – the mechanical engineering student. Rather, the knowledge structure likely to ensue is a Bernsteinian *horizontal* one of specialised 'languages' – bodies of knowledge of engineering sub-disciplines – uneasily linked only at their boundaries. This amounts to a Vygotskian preconceptual 'complex' at best, inadequate for the purposes of mechatronics and for the interdisciplinary demands of engineering practice;

(3) moreover, the methods of assessing students' mechatronic knowledge must take into account the possibility of such inferior, horizontal-type knowledge structures – existing as Vygotskian preconceptual 'complexes' – successfully masquerading as genuine conceptual knowledge and going undetected, so allowing students with materially inadequate knowledge to proceed to the final year of study, or even graduate.

The conceptual tool of bond graphs, complemented by relational block diagrams, offers an alternative principle of recontextualisation that should foster development of students' typical horizontal knowledge structures – produced by the *collection* codes of their earlier undergraduate studies – into the required hierarchical ones. Bond graphs subsume the governing principles of different types of physical engineering systems into relations of generality, so they are on the level of a Vygotskian genuinely conceptual system. However, they demand a corresponding level of conceptual, abstracting ability in students. Consequent pedagogical problems are likely to arise, especially because of the contrast with the collection-type codes of students' earlier undergraduate studies.

Hedegaard's 'Double Move', aimed at developmental learning within learners' dynamic zones of proximal development, seems a promising pedagogy to foster Bernstein's desirable hierarchical knowledge structures in engineering students. The key principle is integrating students' everyday experiences of the real world, plus their previously acquired knowledge, with formalised subject-matter concepts. The obvious, suitable vehicle for this is the laboratory project in the mechatronics course. Here, it is envisaged that experien-

tially rich spontaneous concepts, *arising from working experiences in this laboratory project* and illuminated by previously acquired knowledge, will move upwards, meet and fuse into downwardly developing subject-matter concepts. It is also envisaged that students' motivation will thereby be increased.

As mentioned in the Introduction, this project confines itself to conceptual analysis of the problem, and exploring conceptual bases for remedies. Further work, in the form of empirical, field research, should thus be carried out to test the validity of this conceptual analysis and the proposed remedies. As Bernstein observes,

> "Conceptual elegance is attractive, but only when it has the living quality which comes from empirical exploration." (Bernstein, 1977:4)

---oOo---

## REFERENCES


Alciatore, D.G. and Histand, M.B. (1995) Mechatronics at Colorado State University, *Mechatronics,* Vol. 5, No. 7, pp. 799-810.

Alciatore, D.G. and Histand, M.B. (2003) *Introduction to Mechatronics and Measurement Systems,* 2nd Edition, McGraw-Hill, 2003.

Ashley, S. (1997) Getting a Hold on Mechatronics, *Mechanical Engineering,* American Society of Mechanical Engineers (ASME), New York, USA, May 1997, pp. 60-63.

Berardinis, L.A. (1990) Mechatronics: a New Design Strategy, *Machine Design,* Vol. 62, No. 8, pp. 50-58.

Bernstein, B. (1977) *Class, Codes and Control, Volume 3: Towards a Theory of Educational Transmissions,* 2nd Ed., Routledge and Kegan Paul, London, 1977.

Bernstein, B. (1977a) Aspects of the Relations between Education and Production, Chapter 8 in *Class, Codes and Control, Volume 3: Towards a Theory of Educational Transmissions,* 2nd Ed., Routledge and Kegan Paul, London, 1977.

Bernstein, B. (1977b) On the Curriculum, Chapter 4 in *Class, Codes and Control, Volume 3: Towards a Theory of Educational Transmissions,* 2nd Ed., Routledge and Kegan Paul, London, 1977.

Bernstein, B. (1977c) On Classification and Framing of Educational Knowledge, Chapter 5 in *Class, Codes and Control, Volume 3: Towards a Theory of Educational Transmissions,* 2nd Ed., Routledge and Kegan Paul, London, 1977.

Bernstein, B. (1977d) Aspects of the Relations between Education and Production, Chapter 8 in *Class, Codes and Control, Volume 3: Towards a Theory of Educational Transmissions,* 2nd Ed., Routledge and Kegan Paul, London, 1977.

Bernstein, B. (1990) *Class, Codes and Control, Volume 4: The Structuring of Pedagogic Discourse,* London, Routledge, 1990.

Bernstein, B. (1996a) Chapter 1 – Pedagogic Codes and their Modalities of Practice, in *Pedagogy, Symbolic Control and Identity: Theory, Research, Critique,* Taylor & Francis Ltd, London, 1996.

Bernstein, B. (1996b) Chapter 2 – The Pedagogic Device, in *Pedagogy, Symbolic Control and Identity: Theory, Research, Critique,* Taylor & Francis Ltd, London, 1996.

Bernstein, B. (1996c) Chapter 3 – Discourses, Knowledge Structures and Fields: Some Arbitrary Considerations, in *Pedagogy, Symbolic Control and Identity: Theory, Research, Critique,* Taylor & Francis Ltd, London, 1996.

Bernstein, B. (1999) Vertical and Horizontal Discourse: an Essay, *British Journal of Sociology of Education,* Vol. 20, No. 2, pp, 157-173.

Bolton, W. (2003) *Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering,* 3rd Edition, Pearson Education Ltd, U.K., 2003.

Bradley, D. (2004) What is Mechatronics and Why Teach It? *International Journal of Electrical Engineering Education,* Vol. 41, No. 4, Oct. 2004, pp. 275-291.

Brown, N.J. and Brown, O.T. (2002) Mechatronics: "a Graduate Perspective", *Mechatronics,* Vol. 12, 2002, pp. 159-167.

Bruner, J.S. (1961) *Introduction* to Vygotsky, L.S., *Thought and Language* (Hanfmann, E. & Vakar, G, ed. & transl.), MIT Press, 1962 (original work published as *Myshlenie i Rech,* Moscow and Leningrad: Sotzekgiz, 1934), pp. v-x.

Bucciarelli, L.L. (2003) Designing and Learning: a Disjunction in Contexts, *Design Studies,* Vol. 24, 2003, pp. 295-311.

Carlson, E., Yost, S.A., Krishnan, M. and Das, S. (2000) Outcomes-based Assessment for Comprehensive Curriculum Development in Mechatronics, *Proceedings, 30th Annual Frontiers in Education Conference,* IEEE, 2000, Vol. 1, pp. T4A-1 – T4A-5.

*Concise Oxford Dictionary* (1990) Eighth Edition, Oxford University Press, 1990.

Craig, K. (1994) Mechatronic System Design at Rensselaer, in *Proceedings of the Workshop on Mechatronics Education,* sponsored by the Synthesis Coalition of the National Science Foundation, Stanford, CA, USA, July 1994, pp. 24-7.

Daniel, R.W. and Hewitt, J.R. (1991) Editorial, *Mechatronics,* Vol. 1, No. 1, 1991, pp. i-ii.

Das, S., Krishnan, M., Yost, S.A. and Zimmerman-Oster, K. (2005) Advanced Mechatronics: Development of a Course on Modelling & Simulation of Mechatronic Systems, *2005 ASEE Annual Conference and Exposition: Conference Proceedings,* ASEE, 2005, pp. 283-298.

de Silva, C.W. (2005) *Mechatronics: an Integrated Approach.* CRC Press LLC, Florida, USA.

Driscoll, F. and Villanucci, R. (2004) A Nontraditional Approach: Implementing and Overseeing a Multidisciplinary Electromechanical Engineering Program, *2004 ASEE Annual Conference and Exposition: Conference Proceedings,* ASEE, 2004, pp. 10437 – 10445.

Encyclopædia Britannica (2006) *Encyclopædia Britannica Ultimate Reference Suite DVD,* 2006.

Engineering Council of Southern Africa [ECSA] (2003) *Definitions of Terms to Support the ECSA Standards and Procedures System,* Document G-04, Draft 6, 8 Jan. 2003. {ECSA Standards and Procedures Initiative, Development Website Home Page, http://www.ee.wits.ac.za/~ecsa, accessed on 2007-10-19.}

Engineering Council of Southern Africa [ECSA] (2004) *Whole Qualification Standard for Bachelor of Science in Engineering (BSc(Eng))/Bachelor of Engineering (BEng): NQF Level 7,* Document PE-61, Revision 2, 26 July 2004.

Ertas, A., Maxwell, T., Rainey, V.P. and Tanik, M.M. (2003) Transformation of Higher Education: the Transdisciplinary Approach in Engineering, *IEEE Transactions on Education,* Vol. 46, No. 2, May 2003, pp. 289-295.

Firth, K., Surgenor, B. and Wild, P. (2004) A Task Based Approach to Mechatronic Systems Education, *Proceedings of ESDA04: 7th Biennial Conference on Engineering Systems Design and Analysis,* 19-22 July 2004, Manchester, U.K.; Paper No. ESDA2004-58475, 10 p.

Froyd, J.E. and Ohland, M.W. (2005) Integrated Engineering Curricula, *Journal of Engineering Education,* Vol. 94, No. 1, pp. 147-164.

Fuller, R. Buckminster (1958) Later Development of My Work, Chapter 4 in *The Buckminster Fuller Reader,* Meller, J. (ed.), Penguin Books, 1972, pp. 69-97 (originally published in *R I B A Journal,* October 1958).

Fuller, R. Buckminster (1961) Influences on My Work, Chapter 3 in *The Buckminster Fuller Reader,* Meller, J. (ed.), Penguin Books, 1972, pp. 44-68 (originally published in *Architectural Design,* July 1961).

Fuller, R. Buckminster (1963) Design for Survival – Plus, Chapter 11 in *The Buckminster Fuller Reader,* Meller, J. (ed.), Penguin Books, 1972, pp. 270-284 (originally published in *Ideas and Integrities,* 1963).

Grimheden, M. and Hanson, M. (2005) Mechatronics – the Evolution of an Academic Discipline in Engineering Education, *Mechatronics,* Vol. 15, 2005, pp. 179-192.

Hargrove, J.B. (2002) Curriculum, Equipment and Student Project Outcomes for Mechatronics Education in the Core Mechanical Engineering Program at Kettering University, *Mechatronics,* Vol. 12, No. 2, pp. 343-356.

Harrison, G.P., Macpherson, D.E. and Williams, D.A. (2007) Promoting Interdisciplinarity in Engineering Teaching, *European Journal of Engineering Education,* Vol. 32, No. 3, June 2007, pp. 285-293.

Harrison, O. and Deanes, V.K. (2005) Enhancing Engineering Problem Solving Skills in a Mechatronics Course, *2005 ASEE Annual Conference and Exposition: Conference Proceedings,* ASEE, 2005, pp. 5663-5670.

Hedegaard, M. (1990) The Zone of Proximal Development as Basis for Instruction, in: *Course Reader (EDUC4017): Educational Theory, Research and Enquiry I: Teaching and Learning, Unit 1 and 2* (Macdonald, C., compil.), School of Education, University of the Witwatersrand, Johannesburg, South Africa, 2005, pp. 267-289. {Originally published in 1990 in Moll, L.C. (ed.), *Vygotsky and Education,* Cambridge Book Company.}

Hedegaard, M. (2002) *Learning and Child Development,* Aarhus University Press, 2002.

Heitmann, G. (2005) Challenges of Engineering Education and Curriculum Development in the Context of the Bologna Process, *European Journal of Engineering Education,* Vol. 30, No. 4, December 2005, pp. 447-458.

Hirst, P. (1965) Liberal Education and the Nature of Knowledge, in: *Philosophical Analysis and Education,* Archimbault, R. (ed.), London: Routledge and Kegan Paul, pp. 113-138.

Jakobsen, A. and Bucciarelli, L.L. (2007) Transdisciplinary Variation in Engineering Curricula: Problems and Means for Solutions, *European Journal of Engineering Education,* Vol. 32, No. 3, June 2007, pp. 295-301.

Jandrell, I.R. and van Coller, J.M. (1998) *ELEN207 (Electrical Engineering) Course Notes,* School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, South Africa.

Karnopp, D.C., Margolis, D.L. and Rosenberg, R.C. (1990) *System Dynamics: a Unified Approach,* 2nd Edition, John Wiley & Sons, Inc., USA.

Kozulin, A. (1985) Vygotsky in Context [foreword to Vygotsky, L.S., *Thought and Language* (Kozulin, A., rev. & ed.)], Cambridge, MA: MIT Press, 1986).

Kozulin, A. (1990) Language and Thought, in: *Course Reader (EDUC4017): Educational Theory, Research and Enquiry I: Teaching and Learning, Unit 1 and 2* (Macdonald, C, compil.), School of Education, University of the Witwatersrand, Johannesburg, South Africa, 2005, pp. 205-248. {Originally published in 1990 (same title) in *Vygotsky's Psychology: a Biography of Ideas,* Massachusetts: Harvard University Press.}

Krishnan, M., Das, S. and Yost, S.A. (1999) Team-Oriented, Project-Based Instruction in a New Mechatronics Course, *Proceedings, 29th ASEE/IEEE Annual Frontiers in Education Conference,* IEEE, 1999, Vol. 2, pp. 13d4-1 – 13d4-6.

Kutnick, P. (2001) Expanding the Predominant Interpretation of ZPD in Schooling Contexts: Learning and Mutuality, in: *Learning in Classrooms: a Cultural-Historical Approach* (Hedegaard, M., ed.), Aarhus University Press, 2001, pp. 77-94.

Le Tourneau, R.G. (1960) *Mover of Men and Mountains,* Prentice-Hall, Inc., 1960.

Lyshevski, S.E. (2002) Mechatronic Curriculum – Retrospect and Prospect, *Mechatronics,* Vol. 12, pp. 195-205.

Maton, K. & Muller, J. (2007) A Sociology for the Transmission of Knowledges, in Christie, F. & Martin, J. (eds), *Language, Knowledge and Pedagogy,* London, Continuum, pp. 14-33.

*Merriam Webster's Collegiate Dictionary,* 2006, in: *Encyclopœdia Britannica Ultimate Reference Suite DVD,* 2006.

*Microsoft Encarta Dictionary,* in: Microsoft® Encarta® Premium Suite 2005, © 1993-2004, Microsoft Corporation.

Mina, M., Somani, A., Tyagi, A., Rover, D., Feldmann, M. and Shelley, M. (2005) Learning Streams: a Case Study in Curriculum Integration, *Proceedings, 35th ASEE/IEEE Frontiers in Education Conference,* IEEE, 2005, pp. F1D-5 – F1D-9.

Moran, M.J. and Shapiro, H.N. (2004) *Fundamentals of Engineering Thermodynamics,* 5th Edition, John Wiley & Sons, New York.

Newman, K.E., Rosa, A.J., DeLyser, R.R., Thompson, S.S. and Whitman, R.K. (2003) The Interdisciplinary Undergraduate Curriculum at the University of Denver, *Proceedings, 33rd ASEE/IEEE Annual Frontiers in Education Conference,* IEEE, 2003, Vol. 3, pp. S4A-6 – S4A-10.

Nikitina, S. (2002) Three Strategies for Interdisciplinary Teaching: Contextualising, Conceptualising, and Problem-Solving, *Interdisciplinary Studies Project, Project Zero,* Harvard Graduate School of Education, MA, USA, 35 p.

Sadovnik, A.R. (2001) Basil Bernstein (1924-2000), *Prospects: the Quarterly Review of Comparative Education* (Paris, UNESCO: International Bureau of Education), Vol. 31, No. 4, December 2001, pp. 687-703.

Seely, B.E. (1999) The Other Re-Engineering of Engineering Education, *Journal of Engineering Education,* Vol. 88, No. 3, pp. 285-294.

Shooter, S. and McNeill, M. (2002) Interdisciplinary Collaborative Learning in Mechatronics at Bucknell University, *Journal of Engineering Education,* Vol. 91, No. 3, July 2002, pp. 339-344.

Spinks, N., Silburn, N. and Birchall, D. (2006) *Educating Engineers for the 21st Century: the Industry View,* 2006, Royal Academy of Engineering, London, UK. Available on-line at http://www.raeng.org.uk/news/releases/henley/default.htm (accessed 2009-02-16).

Traylor, R.L., Heer, D. and Fietz, T.S. (2003) Using an Integrated Platform for Learning to Reinvent Engineering Education, *IEEE Transactions on Education,* Vol. 46, No. 4, Nov. 2003, pp. 409-419.

Turner, M. (2005) Lessons in Teaching an Interdisciplinary Mechatronics Class, *2005 ASME International Mechanical Engineering Congress and Exposition: Mechanical Engineering Education; Mechanical Engineering Technology Department Heads,* ASME, 2005, Paper No. IMECE2005-80074, pp. 79-84.

Ume, C. and Timmerman, M. (1995) Mechatronics Instruction in the Mechanical Engineering Curriculum at Georgia Tech, *Mechatronics,* Vol. 5, No. 7, pp. 723-741.

University of the Witwatersrand, Johannesburg (2009). *Degrees and Diplomas in Engineering and the Built Environment: Rules and Syllabuses,* University of the Witwatersrand, Johannesburg, South Africa.

Vygotsky, L.S. (1978) *Mind and Society: the Development of Higher Psychological Processes,* Cambridge, Massachusetts: Harvard University Press.

Vygotsky, L.S. (1986) *Thought and Language* (Kozulin, A., rev. & ed.), Cambridge, MA: MIT Press, 1986 (original work published as *Myshlenie i Rech,* Moscow and Leningrad: Sotzekgiz, 1934).

Wolf, G. (1986) Technical Development Procedures, *Sulzer Technical Review,* Vol. 68, No. 3, 1986, pp. 4-6.

Yost, S.A., Krishnan, M. and Das, S. (1999) Mechatronics: a Comprehensive, Interdisciplinary Curriculum Development Initiative, *Proceedings, 29th ASEE/IEEE Annual Frontiers in Education Conference,* IEEE, 1999, Vol. 2, p. 13a1-1.

Yost, S.A. (2000) Introducing Mechatronics in a First-Year Intro to Engineering Design Course, *Proceedings, ASEE Annual Conference: Engineering Education Beyond the Millennium,* ASEE, 2000, pp. 3823-3826.

---oOo---

# APPENDIX 1
# 'Mechatronics I' Course, School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand: Course Outline and Example of Laboratory Project

## A1.1 Course Description

The course comprises both theoretical material, assessed individually, and a team-based laboratory project. In sum, the content of the course is:

> "Introduction to mechatronics: synergistic use of mechanical, electrical, electronic, control and information technologies to optimally perform tasks. Dynamic characteristics of mechanical and electrical drives and actuators. Measurement theory and analysis. Signal conditioning and measurement systems. Elementary automatic control. Computers and micro-controllers in mechatronics. Laboratory project."
>
> (University of the Witwatersrand, Johannesburg, 2009:220)

Until 2008, this laboratory project involved designing and building a working model of a mechanical-electrical device, automating it through a micro-controller, and then testing it. Key mechanical and electrical components, as well as the micro-controller, were supplied. Student project teams had to specify and source the balance of electrical or electronic components, as well as design the balance of mechanical components for manufacture in the School's Engineering Workshop.

In 2006, the number of students in the course increased to 102 from the 2005 number of 75. Class sizes in 2007 and 2008 were 133 and 95 respectively. Unfortunately, the School's Engineering Workshop did not have sufficient capacity to manufacture mechanical project components for the correspondingly higher numbers of student project teams. Consequently, the requirements for design and manufacture of mechanical components were drastically reduced in 2006 and 2007, and in 2008 the School decided to eliminate them altogether. From 2008 on, the scope of the laboratory project was thus reduced to automating a pre-assembled mechanical-electrical device, through a micro-controller and associated electrical components, and then testing it.

The course outline and information form, given to students at the start of the course, is presented on the next two pages. It lists the:

- course outcomes from the viewpoints of instructional objectives and ability development;
- assessment composition, criteria and due performance requirements;
- detailed course content;
- features of the planned teaching and learning process; and
- applicable ECSA 'knowledge areas' (ECSA, 2004), and their weightings in the course.

**University of the Witwatersrand, Johannesburg**
SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING

COURSE OUTLINE AND INFORMATION FORM

| | |
|---|---|
| Course name | MECN3012 – Mechatronics I |
| Coordinator and other staff | Dr M. Bailey-McEwan (SWE105), Mr K. Midor (C8, RP-Composites Facility) |
| Course SAQA credits | 15 |
| Pre- and co-requisites | Pre-requisites: MECN2007, ELEN2000, MECN2003 |

Course Goals
The main goals of this course are to:

- introduce the systems concept as the framework for the integrated approach of mechatronics;
- promote familiarity with measurement systems for common physical quantities; with common mechanical, pneumatic, hydraulic and electrical actuators; and with a modern programmable logic controller (PLC);
- in the laboratory exercises, obtain a grounding in applying a PLC to controlling simple mechatronic devices;
- in the laboratory project, develop basic ability to design and synergistically integrate mechanical, electrical and electronic components, controlled by a PLC, into a working, cost-effective mechatronic device.

| Course Outcomes | Assessment |
|---|---|
| **Instructional Objectives.** At the end of the course you should be able to:<br>1. analyse simple devices and actuation systems with pneumatic, hydraulic, mechanical and electrical components, and assess their suitability for specific applications;<br>2. specify and assess steady-state measurement systems for common physical quantities; specify sensor characteristics for dynamically varying such quantities;<br>3. apply a programmable logic controller (PLC) to processing and conditioning signals to and from simple actuation and measurement systems;<br>4. realistically model the above devices and actuation and measurement systems in designing a simple mechatronic device, and appreciate issues involved with practically applying theory therein.<br>**Ability Development.** The aim is to develop individual (and in the laboratory exercises, some *team*) ability to select, design and synergistically integrate mechanical, electrical and electronic components into a working mechatronic device. Particularly important abilities are to select components and systems best matching the task to be performed; and, in designing the mechatronic device, to model real mechanical, electrical and electronic components, making realistic assumptions in doing so and recognising the limitations of such models. | Composition of the final course mark (100%):<br>Examination in June: 50%<br>Assignments (two): 15%<br>Class test (MONDAY 6 APRIL): 15%<br>Laboratory Exercises (two) and Project: 20%<br>Each laboratory exercise will involve student teams in assembling a circuit of electrical and electronic components, and programming a PLC to make that circuit perform specified tasks. A brief describing the laboratory project will be issued separately.<br>Assessment criteria<br>For the examination, the test and the assignments, the assessments will be based on an understanding and knowledge of the engineering, computing and IT content covered in the lectures and laboratory sessions, as demonstrated in written answers to examination, test and assignment questions. The two assignments will also be assessed on the effectiveness of communication in the written answers (20% of the marks). For the laboratory exercises, the assessments will be based on three main criteria: the functionality of the circuit built; the neatness and economy of its assembly and interconnections; and the flowcharting and robustness of any PLC program written. A minimum final mark of 50% must be obtained for the course.<br>Due Performance requirements<br>All laboratory exercises and assignments must be completed and submitted on time; late submissions will not be accepted. **Failure to submit all assignments, to participate in all laboratory exercises, or to write the class test will result in the withdrawal of permission to write the examination** unless an acceptable medical certificate or other appropriate documentary evidence is provided.<br><br>ECSA Outcomes Assessed at Exit Level: 5, 8, 9 |

| Detailed Contents | Knowledge Areas And Weight |
|---|---|
| The systems concept in product design and analysis. Overview of measurement, control and actuation systems. The mechatronics approach in realising these systems in a working product.<br>Pneumatic and hydraulic actuation systems: regulating valves, cylinders, motors. Mechanical actuation systems, including elementary kinematic chains in robotics. Electrical actuation systems: relays, solid-state switches, solenoids, the permanent-magnet DC motor. Design of simple actuation systems.<br>The general measurement system: purpose, structure, elements. Static characteristics of measurement system elements. Propagation of errors and accuracy of measurement systems in steady state. Dynamic characteristics of measurement system elements.<br>Amplification, filtering, sampling. Analogue-to-digital (A/D), digital-to-analogue (D/A) conversion. Pulse width modulation.<br>Sensors and transducers: performance terminology. Systems measuring displacement, position, proximity, velocity, force, fluid pressure and flow, liquid level, temperature and light.<br>Micro-controller structure and applications. Programmable logic controllers (PLCs): basic structure, input/output processing, programming, mnemonics, internal components, data handling, analogue input/output. | Engineering Sciences 55%<br>Design and Synthesis 20%<br>Computing and IT 15%<br>Complementary Studies 10% |

**Teaching and Learning Process**

*Lectures* – lecture material will generally be presented using overhead projection of transparencies plus expositions on the blackboard. Students are expected and encouraged to attend all lectures. Experience shows that students who do not attend lectures regularly are likely to fail. Discussions during lectures are encouraged!

*Notes* – printed notes will be issued to cover the main topics in the course. You are strongly advised to take supplementary notes during lectures. Supplementary reading sources are listed below.

*Assignments* – the two assignments will be issued for individual submission, by the dates and times specified. Solutions will thereafter be published on the 3rd Year Notice Board.

*Laboratory Exercises* – you will be required to work in teams of four or five to carry out the two exercises in the laboratory during the first quarter. The procedures and schedules for these exercises are issued separately. Attendance at all exercises is compulsory.

*Laboratory Project* – a brief describing this project will be issued separately. It will be done during the first quarter, and will involve assembling a circuit of electrical and electronic components, and programming a PLC to make a mechanical/electrical device *automatically* perform a specified task. A small amount of building and physical adjustment of some parts of the controlled device may be involved.

*Prescribed Textbook* – Bolton, W., *Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering,* 4th Edition, Pearson Education Ltd, U.K., 2008.

*Recommended References:*

1) Bentley, J.P., *Principles of Measurement Systems,* 4th Edition, Pearson Education, 2005.
2) Alciatore, D.G., and Histand, M.B., *Introduction to Mechatronics and Measurement Systems,* 3rd Edition, McGraw-Hill, 2007.

***Time requirements:***

Contact time: 39 lectures (29 h) + laboratory sessions (39 h)
Minimum self-study time (including assignments, etc): 79 h Total: 147 hours

**Times and Venues**

| Day | Topic | Time | Venue |
|---|---|---|---|
| Tuesday | Laboratory Exercises / Project (*1st Quarter*)<br>Tutorials (*2nd Quarter*) | 14:15 – 17:00 | SWE107K (PC Pool) / Mechatronics Laboratory (*1st Quarter*)<br>Venue t.b.a. (*2nd Quarter*) |
| Wednesday | Lecture | 10:15 – 11:00 | P 114 |
| Thursday | Laboratory Exercises / Project (*1st Quarter*)<br>Lectures (*2nd Quarter*) | 08:00 – 09:45 | SWE107K (PC Pool) / Mechatronics Laboratory (*1st Quarter*)<br>OS 3 (*2nd Quarter*) |

## A1.2 ECSA Exit-Level Outcomes Addressed in Course

At the bottom of its first page, the course outline states that it addresses three ECSA exit-level outcomes. Table A1.1 below indicates the manner in which it addresses each.

Table A1.1 ECSA Exit-Level Outcomes Addressed by 'Mechatronics I' Course

| **ECSA Exit Level Outcome** (ECSA, 2004) | **Applicable Assessment in Course** |
|---|---|
| **"Exit level outcome 5: Engineering methods, skills and tools, including Information Technology**<br>***"Learning outcome:*** Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.<br>***"Associated Assessment Criteria:***<br>The candidate:<br>1. Uses a method, skill or tool effectively by:<br>a) Selecting and assessing the applicability and limitations of the method, skill or tool;<br>b) Properly applying the method, skill or tool;<br>c) Critically testing and assessing the end-results produced by the method, skill or tool.<br>2. Creates computer applications as required by the discipline.<br>***"Range Statement:*** A range of methods, skills and tools appropriate to the disciplinary designation of the program including:<br>1. Discipline-specific tools, processes or procedures;<br>2. Computer packages for computation, modelling, simulation, and information handling;<br>3. Computers and networks and information infrastructures for accessing, processing, managing, and storing information to enhance personal productivity and teamwork;<br>4. Basic techniques from economics, business management, and health, safety and environmental protection." | 1. Effective use of mathematical modelling methods and skills in building *integrated* models of mechanical-electrical systems, capable of realistically predicting behaviour of such physical systems<br><br>2. In the laboratory project, automating a device by incorporating a micro-controller, and programming this |
| **"Exit level outcome 8: Individual, team and multidisciplinary working**<br>***"Learning outcome:*** Demonstrate competence to work effectively as an individual, in teams and in multidisciplinary environments.<br>***"Associated Assessment Criteria:*** The candidate demonstrates effective individual work by performing the following:<br>1. Identifies and focuses on objectives;<br>2. Works strategically;<br>3. Executes tasks effectively; | *Effective individual work:* this is addressed in every course, not just mechatronics |

| **ECSA Exit Level Outcome** (ECSA, 2004) | **Applicable Assessment in Course** |
|---|---|
| 4. Delivers completed work on time.<br>The candidate demonstrates effective team work by the following:<br>1. Makes individual contribution to team activity;<br>2. Performs critical functions;<br>3. Enhances work of fellow team members;<br>4. Benefits from support of team members;<br>5. Communicates effectively with team members;<br>6. Delivers completed work on time.<br>The candidate demonstrates multidisciplinary work by the following:<br>1. Acquires a working knowledge of co-workers' discipline;<br>2. Uses a systems approach;<br>3. Communicates across disciplinary boundaries.<br>***"Range Statement:*** Tasks require co-operation across at least one disciplinary boundary. Disciplines may be other engineering disciplines or be outside engineering." | *Effective team work:* An assessment sheet was drawn up in 2006 (see Section A1.3.6 below), but such assessments have not been done yet<br><br>*Multidisciplinary work:* 2. and 3. are assessed in the laboratory project, through its combination of mechanical, electrical and electronic components, and the required programming of its micro-controller |
| **"Exit level outcome 9: Independent learning ability**<br>***"Learning outcome:*** Demonstrate competence to engage in independent learning through well developed learning skills.<br>***"Associated Assessment Criteria:***<br>The candidate shows evidence of being an effective independent learner by the following:<br>1. Reflects on own learning and determines learning requirements and strategies;<br>2. Sources and evaluates information;<br>3. Accesses, comprehends and applies knowledge acquired outside formal instruction;<br>4. Critically challenges assumptions and embraces new thinking.<br>***"Range Statement:*** Operate independently in complex, ill-defined contexts requiring personal responsibility and initiative, accurately self-evaluate and take responsibility for learning requirements; be aware of social and ethical implications of applying knowledge in particular contexts." | *Reflection on Own Learning:* the laboratory project report requires a summary of the team's learning experience(s), and recommendations for future such projects<br>*Knowledge Acquired Outside Formal Instruction:* in ascertaining and comprehending the detailed behavioural characteristics of the laboratory project's components, and learning the programming language of its micro-controller |

## A1.3 Example of Laboratory Project

The 2005 laboratory project is presented here. As has been noted in Section A1.1 above, this was the last laboratory project requiring student teams to specify and source some electrical or electronic components, and design some mechanical components for manufacture in the School's Engineering Work-

shop. Students in each branch of engineering in the School – mechanical, industrial and aeronautical – were given a unique project relevant to their branch. The projects were:

- Mechanical – entry control boom for cars;
- Industrial – coin sorting machine;
- Aeronautical – lift and drag force measuring 'rig' for a model aircraft in a wind tunnel.

Students were required to work in teams of four or three. The full handout for the mechanical project is given in Section A1.3.1 overleaf. This handout details the project brief; the specific design tasks; the resources and equipment provided; the financial provision for additional resources and equipment that teams might require; the scheduled tutorial and laboratory sessions; the health and safety rules for working in the laboratory; the competencies expected of project teams; the allocation of marks and deadlines; and the requirements for the final project report. Sections A1.3.2 and A1.3.3 following contain the corresponding briefs and specific design tasks for the industrial and aeronautical projects respectively.

Initial exercises, which counted towards the project mark, were given to familiarise students with the micro-controller, its programming software and its capabilities. Apart from these preliminary exercises, the assessed 'milestones' in the project were (as indicated in Item 10 of Section A1.3.1):

(1) submission of manufacturing drawings for the mechanical components to be manufactured;

(2) the quality of the completed mechanical, electrical and electronic construction of the model device;

(3) the performance of this device when tested in an operating trial;

(4) the written report by each team on the project, documenting the operating requirements, constraints and optional features added; the design process and full design specification; and the team's learning experiences and recommendations for future such projects.

For the mechanical project, Sections A1.3.4 and A1.3.5 following contain the assessment sheets for the second and third milestones – the construction of the model device, and its performance in the operating trial. The assessment sheets for the industrial and aeronautical projects were similar. Section A1.3.6 contains an assessment sheet, prepared in 2006, for the quality of teamwork displayed during the project; such assessments were not done, though, due to lack of time for the necessary interviews with teams.

A1.3.1 Handout, 'Mechatronics I' Laboratory Project, 2005 (Mechanical)

| **PROJECT: (MECHANICAL** ENG. STUDENTS**)** | **ENTRY CONTROL BOOM FOR CARS** | **Starting Date: Tues. 22 February 2005** |
|---|---|---|
| | | **Ending Date: Tues. 10 May 2005** |

## 1 OBJECTIVES

The objectives of this project are to:

(i) develop your ability to design and synergistically integrate mechanical, electrical and electronic components, connected by a control architecture, into a working, cost-effective product; and

(ii) enhance your appreciation of the issues involved in practically applying theory in mechatronics.

## 2 PROJECT BRIEF

Students must work in teams of four or three. The project is to design, build and test a scale model of a boom controlling the entry of cars to a parking area. This boom must:

(a) wait, in the horizontal (lowered) position, for a scale model of a car to approach it;

(b) once a scale model of a car is at the boom and a button is manually pressed, take between 3 and 4 seconds to rise smoothly to the raised (nearly vertical) position;

(c) remain up until that car, and only that car, has passed underneath. The boom must remain up so long as any part of that car remains underneath it;

(d) take 2 seconds[1] to fall, rapidly but smoothly. Moreover, the tip of the boom must come to rest in its horizontal position with a speed of no more than 20 mm/s;

(e) then wait in the lowered position for the next car, whereupon it must repeat steps (b) through (d).

Table 1 Required Performance Quantities

| *Quantity* | *Value* |
|---|---|
| Width of roadway | 0,9 m max. |
| Length of boom (from tip to centre of rotation) | 1 m |
| Time of rise | 4 sec. max. |
| Raised position | 85°-90° to horizontal |
| Time of fall | 2 sec. |
| Tip speed at end of fall | 20 mm/s max. |

## 3 SPECIFIC DESIGN TASKS

The following components of this boom must be designed or selected:

- the 1-metre arm, to suit the motor selected from 5.2 below;
- the sensor(s) detecting the presence of a car underneath the boom;

[1] To prevent another car passing underneath ("tailgating") before it has closed.

- the entire mechanism lifting and lowering the boom, coupled to the selected motor;
- the measuring, display and control system, partly or wholly implemented using the GPC450 micro-controller.

Once designed, all mechanical components must be manufactured in the Mechanical Engineering Workshop. *The Laboratory and Workshop Procedures for the Third Year Laboratory Course, contained in "Information for Third Year Students" (issued at the start of the academic year), apply here.*

## 4 CHALLENGES IN PROJECT

To begin with, these are 2. (a) through (e) above.

## 5 RESOURCES AND EQUIPMENT PROVIDED

### 5.1 Resources and Equipment Shared between Teams

None.

### 5.2 Resources and Equipment Provided per Team

Table 2 Mechanical, Electrical, Electronic Resources per Team

| *Amount* | *Description* | *Reference* |
|---|---|---|
| | *M E C H A N I C A L* | |
| | | |
| | *E L E C T R I C A L A N D E L E C T R O N I C* | |
| 1 | 12V DC Motor, with rated speed of either 330 or 60 RPM | |
| 1 | GPC450 Micro-Programmable Logic Controller,[2] mounted on plastic board, with 25-pin I/O connector; 9-pin programming connector; and 12-volt power connector | GPC450 manual and soft-ware |

N.B. *Teams must acknowledge receipt of the equipment in this table by signature. Any breakages or loss thereof must be repaired or replaced by the team, in its own time and at its own expense. Marks may be deducted for loss or breakage as well.*

## 6 ADDITIONAL RESOURCES AND EQUIPMENT REQUIRED

An amount of up to R150 will be available to each team for purchasing extra components and materials. Additional expenditure is for the team's account, but should be recorded in the final report. Refunds will be authorised by Dr Bailey-McEwan, after 10 May, upon proof of purchase. Teams are requested to submit all such receipts at the same time.

[2] Designed by Mr J P Stiekema, School of Electrical and Information Engineering.

## 7 TUTORIAL / LABORATORY SESSIONS

These are on Tuesday afternoons, during 14:15-16:00, initially in SWE118 and then in the PC Pool and / or Mechanical Engineering Laboratory. Dr Bailey-McEwan and three postgraduate tutors will conduct these sessions.

The first three sessions, on 22 February and 1 and 8 March, will introduce:

[1] the project;

[2] the GPC450 micro-controller; its design and protective features; and its "C" programming language and environment. Good practices in constructing electrical and electronic circuits will also be emphasised. Two preliminary assignments will be carried out in the sessions on 1 and 8 March.

The remaining sessions will be devoted to the project. For milestones and deadlines, please see Section 9 below.

## 8 HEALTH AND SAFETY IN MECHANICAL ENGINEERING LABORATORY

*All rules in "Information for Third Year Students" apply to this project.* In particular, students must remember and understand:

(i) the Laboratory and Workshop Regulations, displayed at the entrance to the Laboratory;

(ii) the "Procedure for Working After Hours in the Mechanical Engineering Laboratory / Workshop", also displayed there.

IF IN DOUBT, ASK.

### 8.1 Chief Technician's Rules for Working in the Mechanical Engineering Laboratory

A. Students will not be allowed into the Laboratory for scheduled sessions unless the responsible staff member (here, Dr Bailey-McEwan) is there to supervise them.

B. No tools, equipment or workpieces are to be left unattended on the work tables, benches or on the floor in the open laboratory areas. *All such items found will be confiscated and not returned.* Students are to make use of the seven (7) lockable cupboards, underneath the main workbench, to securely store their tools, equipment and workpieces. Mr Möller will issue keys on payment of a refundable deposit of R10.

C. Work areas must be left in a clean and tidy state. Students will not be allowed to work in any area not so left until it is restored to such a state.

## 9 COMPETENCIES

Each three- or four-person team is expected to demonstrate competency in:

- managing the design process, recognising restrictions on resources, and meeting deadlines;
- accessing, assessing and utilising relevant information and data;
- converting a broad task statement into a well-defined Product Requirement Specification (PRS);
- applying good design practice to all elements of the design;

- assembling all components into a mechanically and electrically neat and robust working model;
- testing and optimising this working model to maximise its effectiveness and efficiency;
- communicating effectively and clearly in writing and through drawings and sketches.

## 10 ALLOCATION OF MARKS AND DEADLINES

| *Item* | *Mark* | *Deadline (Tues.)* |
|---|---|---|
| P R E L I M I N A R Y  A S S I G N M E N T S | | |
| Lighting LEDs by switches | 10% | 1 March |
| Speed control of motor / Switching of solenoid | 15% | 8 March |
| M I L E S T O N E S  I N  P R O J E C T | | |
| Submission of manufacturing drawings for mechanical components | 15% | 15 March |
| Manufacture by Workshop of mechanical components | | 12 April |
| Mechanical, electrical, electronic construction complete | 15% | 26 April |
| Operating trials (randomly selected teams) | 25% | 4 May |
| Operating trials (the remaining teams) | | 10 May |
| P R O J E C T  R E P O R T | 20% | 10 May |
| **T O T A L** | **100%** | |

## 11 PROJECT REPORT

This should be brief, with between 10 and 20 pages of typed text (excluding tables, figures and appendices). It is to be typed in 1½ spacing and be in the following format:

- Executive Summary
- Declaration (that the report is the team's own work)
- Contents
- Statement of Task
- Product Requirement Specification – clearly specifying all the requirements and constraints that the boom must meet, as well as its non-quantifiable desired (optional) features
- Design Development - explaining all assumptions and decisions made, and analyses done. Samples of detailed calculations should be in one or more appendices
- Design Specification – describing the detailed design of the boom. It is to include:
  - ⇒ a short, overall description of the boom;
  - ⇒ a drawing of its general arrangement;
  - ⇒ detailed engineering drawings, according to SABS 0111, of all mechanical components, and of sub-assemblies of these components as appropriate;
  - ⇒ detailed descriptions and clearly labelled diagrams of all circuitry;

⇒ a full listing of the control program used in the GPC450 micro-controller, together with a flowchart and a description of how this program is intended to work;

⇒ a table of itemised costs of all mechanical, electrical and electronic components used (excluding the equipment in 5.1 and 5.2 above)

- a summary of the team's learning experience(s), and recommendations for future such projects
- Bibliography
- References
- Appendices – including samples of detailed calculations

---oOo---

A1.3.2 Handout (First Page), 'Mechatronics I' Laboratory Project, 2005 (Industrial)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING
MECN361 - Mechatronics I **(2005)** *Page P (I)-1*

| **PROJECT: (INDUSTRIAL** ENG. STUDENTS**)** | **COIN SORTING MACHINE** | **Starting Date: Tues. 22 February 2005** |
|---|---|---|
| | | **Ending Date: Tues. 10 May 2005** |

## 1 OBJECTIVES

The objectives of this project are to:

(i) develop your ability to design and synergistically integrate mechanical, electrical and electronic components, connected by a control architecture, into a working, cost-effective product; and

(ii) enhance your appreciation of the issues involved in practically applying theory in mechatronics.

## 2 PROJECT BRIEF

Students must work in teams of four or three. The project is to design, build and test a working machine to:

(a) sort a batch of 20 (twenty) coins – consisting of any combination of South African 5c, 10c, 20c, 50c, R1, R2 and R5[1] coins – into their denominations;

(b) place the coins so sorted into separate bins by denomination;

(c) do both (a) and (b) within 2 (two) minutes.

## 3 SPECIFIC DESIGN TASKS

The following components of this machine must be designed or selected:

- all necessary mechanisms to sort and place the coins, per 2. (a) and (b) above;
- electric motor(s) and / or solenoid(s) – or other devices – to actuate these mechanisms
- sensors to measure the properties of the coins
- the measuring, display and control system, partly or wholly implemented using the GPC450 micro-controller

Once designed, all mechanical components must be manufactured in the Mechanical Engineering Workshop. *The Laboratory and Workshop Procedures for the Third Year Laboratory Course, contained in "Information for Third Year Students" (issued at the start of the academic year), apply here.*

## 4 CHALLENGES IN PROJECT

For example, two of these are:

- error-free distinguishing between coins of nearly the same dimensions;
- completing the task within the time given in 2. (c) above.

……

[1] The OLD R5 coin, not the new, inlaid one.

A1.3.3 Handout (First Two Pages), 'Mechatronics I' Laboratory Project, 2005 (Aeronautical)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING
MECN361 - Mechatronics I **(2005)** *Page P (A)-1*

| **PROJECT: (AERONAUTICAL** ENG. STUDENTS**)** | **LIFT AND DRAG FORCE MEASURING "RIG" FOR A MODEL AIRCRAFT IN A WIND TUNNEL** | **Starting Date: Tues. 22 February 2005** |
|---|---|---|
| | | **Ending Date: Tues. 10 May 2005** |

## 1 OBJECTIVES

The objectives of this project are to:

(i) develop your ability to design and synergistically integrate mechanical, electrical and electronic components, connected by a control architecture, into a working, cost-effective product; and

(ii) enhance your appreciation of the issues involved in practically applying theory in mechatronics.

## 2 PROJECT BRIEF

An existing wind tunnel in the Laboratory is available for this project. Details are in Table 1 below. The model aircraft can be any suitable 1/72 scale, plastic model available from hobby shops.

Students must work in teams of four or three. The project is to design, build and test a working "rig" *(i.e. a system or apparatus)* to:

(a) tilt this aircraft to any desired pitch between -10° and +30°;

(b) measure and display the lift and drag forces at this pitch.

Table 1 Specifications of Available Wind Tunnel

| *Quantity* | *Value* |
|---|---|
| Cross-sectional dimensions of test section of wind tunnel | ~308 mm × ~308 mm |
| Minimum wind speed | ~10 m/s |
| Maximum wind speed | ~50 m/s |

## 3 SPECIFIC DESIGN TASKS

The following components of this "rig" must be designed or selected:

- all necessary mechanisms to support and tilt the aircraft, and to measure lift and drag forces;
- electric motor(s) to actuate these mechanisms;
- sensors to measure the aircraft's pitch and the lift and drag forces;
- the measuring, display and control system, partly or wholly implemented using the GPC450 micro-controller.

Once designed, all mechanical components must be manufactured in the Mechanical Engineering Workshop. *The Laboratory and Workshop Procedures for the Third Year Laboratory Course, contained in "Information for Third Year Students" (issued at the start of the academic year), apply here.*

## 4 CHALLENGES IN PROJECT

For example, two of these are:

- designing the mechanism to separately measure the lift and drag forces, ensuring that the effect of pitch moment is eliminated;
- ensuring that this mechanism has the minimum influence (interference) on the air-flow pattern around the aircraft.

## 5 RESOURCES AND EQUIPMENT PROVIDED

### 5.1 Resources and Equipment Shared between Teams

This is the abovementioned wind tunnel.

### 5.2 Resources and Equipment Provided per Team

Table 2 Mechanical, Electrical, Electronic Resources per Team

| *Amount* | *Description* | *Reference* |
|---|---|---|
| | *M E C H A N I C A L* | |
| | | |
| | *E L E C T R I C A L A N D E L E C T R O N I C* | |
| 1<br>1 | 12V DC Motor, with rated speed of either 330 or 60 RPM<br>GPC450 Micro-Programmable Logic Controller,[1] mounted on plastic board, with 25-pin I/O connector; 9-pin programming connector; and 12-volt power connector | GPC450 manual and soft-ware |

N.B. *Teams must acknowledge receipt of the equipment in this table by signature. Any breakages or loss thereof must be repaired or replaced by the team, in its own time and at its own expense. Marks may be deducted for loss or breakage as well.*

## 6 ADDITIONAL RESOURCES AND EQUIPMENT REQUIRED

An amount of up to R150 will be available to each team for purchasing extra components and materials. Additional expenditure is for the team's account, but should be recorded in the final report. Refunds will be authorised by Dr Bailey-McEwan, after 10 May, upon proof of purchase. Teams are requested to submit all such receipts at the same time.

## 7 TUTORIAL / LABORATORY SESSIONS

These are on Tuesday afternoons, during 14:15-16:00, initially in SWE118 and then in the PC Pool and / or Mechanical Engineering Laboratory. Dr Bailey-McEwan and three postgraduate tutors will conduct these sessions.

……

[1] Designed by Mr J P Stiekema, School of Electrical and Information Engineering.

### A1.3.4 Assessment Sheet (Construction): 'Mechatronics I' Laboratory Project, 2005 (Mechanical)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING
MECN361 - Mechatronics I **(2005)** *Page P-C-1*

**PROJECT: ENTRY CONTROL BOOM FOR CARS**
**MECHANICAL, ELECTRICAL & ELECTRONIC CONSTRUCTION**

**Mark Allocation** **Date:** _____ **Group No.** _____

| **ASPECT** | **Poor** / not done **[0]** | **Fair** (part-ly done) **[2]** | **Satis-factory** **[5]** | **Good** **[7]** | **Excel-lent** **[9]** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Mechanical** | | | | | | |
| Housing of boom mechanism se-curely, stably mounted on mounting plate | 0 | 4 | 10 | 14 | 18 | |
| Boom length[1] | 0 | | 20 | | | |
| Boom stiffness | 0 | 2 | 5 | 7 | 9 | |
| Post to hold boom in horizontal posi-tion? | 0 | 2 | 5 | 7 | 9 | |
| Motor mounted and coupled[2] to shaft | 0 | 4 | 10 | 14 | | |
| Device to hold boom in vertical position? | 0 | 4 | 10 | 14[3] | | |
| Position monitoring disc or equivalent device(s) mounted | 0 | 4 | 10 | 14 | | |
| Position monitoring sensor aligned with disc or equiv. de-vice | 0 | 4 | 10 | 14[4] | | |
| Sensor(s) to detect car underneath boom mounted | 0 | 4 | 10 | 14 | | |
| Extra features (specify in "Re-marks") | | | 15 | 21 | 27 | |
| **SUB-TOTAL** | **(Full marks,** excl. extra features: **126)** | | | | | |

[1] Must be between 0,9 m and 1 m from pivot point to tip.
[2] By flexible, spring-type coupling or equivalent.
[3] Award this mark for secure & neat mounting.
[4] Award this mark for good alignment, robustness of mounting, etc.

| **ASPECT** | **Poor** / not done **[0]** | **Fair** (part-ly done) **[2]** | **Satis-factory** **[5]** | **Good** **[7]** | **Excel-lent** **[9]** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Electrical & Electronic: Boom** | | | | | | |
| Position monitoring sensor(s) wired on housing & mount-ing plate | 0 | | 10 | 14[5] | | |
| Motor wired on housing & mount-ing plate | 0 | | 10 | 14 | | |
| Sensor(s) to detect car wired on hous-ing & mounting plate | 0 | | 10 | 14 | | |
| **Electrical & Electronic: GPC & Breadboard** | | | | | | |
| Motor connections to screw terminals correct[6] | 0 | | 10 | 14[7] | | |
| Motor protection diode connected correctly[8] | 0 | | 10 | | | |
| Coil of DPDT relay (for H-bridge) con-nected correctly[9] | 0 | | 10 | | | |
| *Position monitor:* LED connected cor-rectly[10] | 0 | | 10 | | | N/A if micro-switches or other devices used |
| *Position monitor:* phototransistor / micro-switches con-nected correctly[11] | 0 | | 10 | | | 20 if ALL micro-switches / other device(s) con-nected correctly |
| GPC450: pin 24 connected to ground (negative rail) on breadboard | 0 | | 10 | | | |

[5] Award this mark for neat wiring on hoist mounting plate.
[6] Must be connected, through a pair of screw connectors, between (i) +12V rail; (ii) OP3 (pin 18) on GPC450.
[7] Award this mark for neat wiring from breadboard to screw connectors.
[8] Side with white stripe must be connected to +12V rail.
[9] Between GPC's +12V rail and an output (OP) port.
[10] If LED: between +12V or +5V and ground, with current-limiting resistor to limit volt drop across LED to 1,7V at a current of 20 mA.
[11] Between an input (IP) port of the GPC and ground.

| **ASPECT** | **Poor** / not done **[0]** | **Fair** (part-ly done) **[2]** | **Satis-factory** **[5]** | **Good** **[7]** | **Excel-lent** **[9]** | **REMARKS** |
|---|---|---|---|---|---|---|
| GPC450: pin 22 (suppression pin) connected to EITHER pin 25 OR positive (+12V) rail on breadboard | 0 | | 10 | | | |
| Breadboard: gen-eral neatness of wiring | | | 15 | 21 | 27 | |
| Extra features (specify in Remarks column) | | | 10 | 14 | 18 | |
| **SUB-TOTAL** | **(Full marks,** excl. extra features: **143)** | | | | | |
| **T O T A L O F M A R K S : (Full marks,** excl. extra features: **269)** | | | | | | |

---oOo---

### A1.3.5 Assessment Sheet (Operating Trial): 'Mechatronics I' Laboratory Project, 2005 (Mechanical)

**PROJECT: ENTRY CONTROL BOOM FOR CARS**
**OPERATING TRIALS**

**Mark Allocation** **Date:** _____ **Group No.** _____

| **ASPECT** | **Poor /** not done | **Fair** (part-ly done) | **Satis-factory** | **Good** | **Excel-lent** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Trial 1a: Boom Horizontal** | | | | | | |
| Boom position (mm): | | Start _____ (0°) | | | | Finish _____ (85-90°) |
| | | Inaccuracy: _____ | | | | Inaccuracy: _____ |
| Boom: accuracy of positioning[1] | 0 | 2 | 5 | 7 | 9 | |
| Time of rise (sec.): _____ (4 sec. max.)<br>Inaccuracy: _____ [abs(4 – time of trip)] | | | | | | |
| Time taken for rise[2] | 0 | 4 | 10 | 14 | 18 | |
| Degree of smooth-ness of rise | 0 | 4 | 10 | 14 | 18 | (visual) |
| **SUB-TOTAL** | **(Full marks: 54)** | | | | | |
| **Trial 1b: Boom Vertical** | | | | | | |
| Boom position (mm): | | Start _____ (85-90°) | | | | Finish _____ (0°) |
| | | Inaccuracy: _____ | | | | Inaccuracy: _____ |
| Boom: accuracy of positioning | 0 | 4 | 10 | 14 | 18 | |
| Time of fall (sec.): _____ (2 sec. )<br>Inaccuracy: _____ [abs(2 – time of trip)] | | | | | | |
| Time taken for fall[3] | 0 | 4 | 10 | 14 | 18 | |
| Degree of smooth-ness of fall | 0 | 4 | 10 | 14 | 18 | (visual) |
| **SUB-TOTAL** | **(Full marks: 54)** | | | | | |

[1] Limits on av. inaccuracy: excellent, ±1°; good, ±2°; satisfactory, ±5°; fair, ±10°; poor, greater still.
[2] Limits on inaccuracy: excellent, ±0,5 sec.; good, ±1 sec.; satisfactory, ±1,5 sec.; fair, ±2 sec.; poor, greater still.
[3] Limits on inaccuracy: excellent, ±0,25 sec.; good, ±0,5 sec.; satisfactory, ±1 sec.; fair, ±1,5 sec.; poor, greater still.

| **ASPECT** | **Poor /** not done | **Fair** (part-ly done) | **Satis-factory** | **Good** | **Excel-lent** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Trial 2a: Boom Horizontal** | | | | | | |
| Boom position (mm): | | Start _____ (0°) | | | | Finish _____ (85-90°) |
| | | Inaccuracy: _____ | | | | Inaccuracy: _____ |
| Boom: accuracy of positioning | 0 | 4 | 10 | 14 | 18 | |
| Time of rise (sec.): _____ (4 sec. max.)<br>Inaccuracy: _____ [abs(4 – time of trip)] | | | | | | |
| Time taken for rise | 0 | 4 | 10 | 14 | 18 | |
| Degree of smooth-ness of rise | 0 | 4 | 10 | 14 | 18 | (visual) |
| **SUB-TOTAL** | **(Full marks: 54)** | | | | | |
| **Trial 2b: Boom Vertical** | | | | | | |
| Boom position (mm): | | Start _____ (85-90°) | | | | Finish _____ (0°) |
| | | Inaccuracy: _____ | | | | Inaccuracy: _____ |
| Boom: accuracy of positioning | 0 | 4 | 10 | 14 | 18 | |
| Time of fall (sec.): _____ (2 sec. )<br>Inaccuracy: _____ [abs(2 – time of trip)] | | | | | | |
| Time taken for fall | 0 | 4 | 10 | 14 | 18 | |
| Degree of smooth-ness of fall | 0 | 4 | 10 | 14 | 18 | (visual) |
| **SUB-TOTAL** | **(Full marks: 54)** | | | | | |

**TOTAL FOR 4 TRIALS: _____** **(Full marks: 216)**

---oOo---

### A1.3.6 Assessment Sheet (Teamwork), Proposed in 2006: 'Mechatronics I' Laboratory Project

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG
SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING
MECN317, 318 or 371 **(2006)** *Page TW-Ass-1*

## MECHATRONICS PROJECT: ASSESSMENT OF TEAMWORK

**Date:** _____ **Mech./Indust./Aero.:** _____ **Team No.** _____

| **ASPECT** | **Poor** / not done **[0]** | **Fair** (part-ly done) **[2]** | **Satis-factory** **[5]** | **Good** **[7]** | **Excel-lent** **[9]** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Gantt Chart** | | | | | | |
| Divisions of work (Mech., Elect., Financial, Admin. / Secretarial, etc.[1]) | 0 | 4 | 10 | 14 | 18 | |
| Itemisation (breakdown) of Mech. work[2] | | 4 | 10 | 14 | 18 | |
| Itemisation of Elect. work[3] | 0 | 4 | 10 | 14 | 18 | |
| Itemisation of Financial work[4] | 0 | 4 | 10 | 14 | 18 | |
| Itemisation of Admin./Secr. work[5] | | | | | | |
| Overall co-ordination of planned work[6] | 0 | 4 | 10 | 14 | 18 | |
| Tracking of actual work / updating of chart[7] | 0 | 6 | 15 | 21 | 27 | |
| Structure & layout of chart | | | | | | |
| Additional features | | | | | | |
| | | | | | | |

[1] E.g. Instrumentation.
[2] Aspects of Mech. work considered and their planned co-ordination: e.g. (i) manufacturing drawings & steps in drafting & finalising them; (ii) specification, sourcing & ordering of mechanical components not manufactured.
[3] Aspects of Elect. work considered & their planned co-ordination; see analogous examples in Footnote 2.
[4] Budgeting, tracking real and planned expenditure, etc.
[5] E.g. scheduling team meetings; compiling regular 'action minutes', updating Gantt chart.
[6] Individual tasks having logical predecessors and successors, & showing inter-dependencies; time constraints and critical tasks highlighted; etc.
[7] Regular updating showing differences between planned & revised deadlines & milestones, etc.

| **ASPECT** | **Poor** / not done **[0]** | **Fair** (part-ly done) **[2]** | **Satis-factory** **[5]** | **Good** **[7]** | **Excel-lent** **[9]** | **REMARKS** |
|---|---|---|---|---|---|---|
| **Teamwork in & Co-Ordination of Project (Interview with Team)** | | | | | | |
| 'Action' minutes of team meetings[8] | | 8 | 20 | 28 | 36 | |
| *Other Documentation:* e.g. functional analyses, manufacturing drawings, design calculations, budgets, quotes | | 8 | 20 | 28 | 36 | |
| Leader's acquaintance with project status, & planned & actual progress | 0 | 6 | 15 | 21 | 27 | |
| Leader's delegation, co-ordination of work | 0 | 6 | 15 | 21 | 27 | |
| Status of project progress w.r.t. Gantt chart: plans to compensate for slippage, etc. | 0 | 8 | 20 | 28 | 36 | |
| Additional features | | | | | | |
| | | | | | | |
| **T O T A L O F M A R K S :** | | | | | | |

---oOo---

[8] Recording of progress & milestones achieved; tasks (with deadlines) to be done by designated individuals, etc.

# APPENDIX 2
## Engineering Council of South Africa: Definitions of Terms (ECSA, 2003)

*(Note: these definitions are verbatim extracts from the reference, and have grammatical errors and missing words.)*

**Broadly-defined Engineering Problem:** are parts of or systems within complex engineering systems; can be solved by application of well-proven analysis techniques; involve a variety of factors which may impose conflicting constraints; belong to families of problems which are solved in well-accepted ways; may be partially outside those encompassed by standards or codes of practice; involves several groups of stakeholders with differing and occasionally conflicting; have consequences which are locally important, but may extend more widely.

**Capability:** the capacity of a person to complete a specified assessable action in a defined range of complexity, context and purpose. Capability results from learning and is specified in terms of knowledge, skill, abilities and values.

**Competence:** A professionally or occupationally competent person has the attributes necessary to perform the activities within the profession or occupation to the standards expected in employment or practice.

**Complex Engineering Activity:** has a large number of entities or influences with high level of interaction where cause and effect are not simply related. Additionally the subject requires complex model for adequate description: cannot be treated adequately by considering a part or aspect; has state, that is current behaviour is influenced by past trajectory; has a large number of operational responses; or is sensitive to disturbance or parameter variation. Can also be applied to a problem, system or process.

**Complex Engineering Problem:** is characterised by one or more of the following factors: requires in-depth knowledge that allows a fundamentals-based, first principles analytical approach; have no obvious solution and require originality and analysis; involves wide-ranging or conflicting technical, engineering and other issues; involve infrequently encountered issues; are outside problems encompassed by standards and codes of practice for professional engineering; involves wide ranges of stakeholders with widely varying needs; have significant consequences in a range of contexts.

**Concept:** an abstract or general idea, a mental model, a mental creation, idea of a class of objects.

**Conceptual:** involving abstract or generalised ideas, expressed in a general form or notation.

**Content***: *traditionally,* topic list or "shopping list" syllabus describing the subject matter of a course or training module; a general specification for the profile of knowledge in an accredited programme.

**Convergent problem:** one having a definite solution.

**Curriculum:** the definition of how a programme is to be executed, including the purpose the learning, the outcomes or learning objectives, set of compulsory and elective courses, content to support achieving the outcomes, learning activities, methods and media for teaching/training and learning, assessment plan, and a plan for evaluating the quality and effectiveness of delivery.

**Discipline:** a major subdivision of engineering such as the traditional fields of Chemical, Civil, or Electrical Engineering, or a cross disciplinary field of comparable breadth.

**Divergent problem:** one having no definite solution due to complexity or lack of definition, requiring judgement to determine when proposed solution is adequate.

**Engineering:** 1: At its most general, Engineering is the entire field of activity of professional engineers, engineering technologists and technicians. 2: Engineering as a university degree, such as the B.Sc(Eng), and as a professional activity is concerned intellectual and conceptual work using engineering knowledge and engineering competencies to conceive, create designing and implementing, components, systems, engineering works, products and processes and to solve problems of economic or social value. The process is based on scientific knowledge, requires synthesis of knowledge, and takes into account wider issues. 3: Engineering is also used to describe a way of working to create or improve an end product that is useful, reliable and viable.

**Knowledge:** comprises theory and information which may be formal, factual, descriptive or empirical; (intellectual) acquaintance with a range of facts or information; theoretical or practical understanding of an art, science, language, ....; information obtained by study (OED); *in Blooms Taxonomy:* a level of intellectual activity characterised by actions including arrange, define, label, list, memorize, name, rank and recognize.

**Problem solving:** is the ability to get answers to questions through a conscious, organised process. In Engineering the answers are usually but not necessarily quantitative.

**Programme:** a structured, integrated teaching and learning arrangement, usually coupled with examination leading to a qualification.

**Well-defined Engineering Problem:** can be resolved using limited theoretical knowledge but normally require extensive practical knowledge; are discrete components of engineering systems; can be solved in standardized ways; involve several issues, but with few of these exerting conflicting constraints; are frequently encountered and thus familiar to most practitioners in the practice area; are encompassed by standards or documented codes of practice; involve a limited range of stakeholders with differing needs; have consequences which are locally important but not far reaching.

---oOo---

## APPENDIX 3
## Inter- and Multi-Disciplinarity in "Whole Qualification Standard for Bachelor of Science in Engineering / Bachelor of Engineering" of Engineering Council of South Africa (ECSA, 2004)

In this Standard, ECSA first allows for cross-disciplinary contexts in its exit-level outcomes.

> **"13. Exit Level Outcomes**
>
> Exit level outcomes defined below are stated generically and may be assessed in various engineering disciplinary or cross-disciplinary contexts in a provider-based or simulate practice environment. Words shown italicized have specific meaning defined in ECSA Document G-04 [1].[1]
>
> ***General Range Statement:*** The competencies defined in the ten exit level outcomes may be demonstrated in a university-based, simulated workplace context. Competencies stated generically may be assessed in various engineering disciplinary or cross-disciplinary contexts."
>
> (ECSA, 2004; candidate's emphasis)

Then, ECSA's Exit Level Outcome 8 for graduate engineers requires a *systems* approach to demonstrate multidisciplinary work:

> **"Exit level outcome 8: Individual, team and multidisciplinary working**
>
> ***Learning outcome:*** Demonstrate competence to work effectively as an individual, in teams and in multidisciplinary environments.
>
> ***Associated Assessment Criteria:***
>
> **… …**
>
> The candidate demonstrates multidisciplinary work by the following:
>
> 1. Acquires a working knowledge of co-workers' discipline;
> 2. Uses a systems approach;
> 3. Communicates across disciplinary boundaries.
>
> ***Range Statement:*** Tasks require co-operation across at least one disciplinary boundary. Disciplines may be other engineering disciplines or be outside engineering."
>
> (*ibid.*; candidate's emphasis)

Assessment criterion 2. here signifies that the systems approach characterises multidisciplinary engineering work. This approach conceptualises engineering structures, arrangements or machinery as systems;[2] is not limited to individual [engineering] disciplines, and crosses at least one [engineering] disciplinary boundary. ECSA Exit-Level Outcome 2 stresses this systems approach in the context of *cross-disciplinary* work and recognition of boundaries and limitations of engineering disciplines:

---

[1] "Definition of Terms to Support the ECSA Standards and Procedures System" (ECSA, 2003).

[2] Note: ECSA does not define 'system' or 'systems'. The *Concise Oxford Dictionary's* first two meanings of 'system' are relevant: "**1** a complex whole; a set of connected things or parts; an organised body of material or immaterial things. **2** a set of devices (e.g. pulleys) functioning together."

> **"Exit level outcome 2: Application of scientific and engineering knowledge**
>
> ***Learning outcome:*** Demonstrate competence to apply knowledge of mathematics, basic science and engineering sciences from first principles to solve engineering problems.
>
> ***Associated Assessment Criteria:***
>
> The candidate:
>
> 1. Brings mathematical, numerical analysis and statistical knowledge and methods to bear on engineering problems by using an appropriate mix of:
>
> a) Formal analysis and modelling of engineering components, systems or processes;
>
> … …
>
> c) Reasoning about and conceptualising engineering components, systems or processes using mathematical concepts;
>
> … …
>
> 2. Uses physical laws and knowledge of the physical world as a foundation for the engineering sciences and the solution of engineering problems by an appropriate mix of:
>
> a) Formal analysis and modelling of engineering components, systems or processes using principles and knowledge of the basic sciences;
> b) Reasoning about and conceptualising engineering problems, components, systems or processes using principles of the basic sciences.
>
> 3. Uses the techniques, principles and laws of engineering science at a fundamental level and in at least one specialist area to:
>
> … …
>
> c) Work across engineering disciplinary boundaries through cross disciplinary literacy and shared fundamental knowledge.
>
> ***Range Statement:*** … … Understanding of emerging issues in specialist area(s). Application of knowledge requires recognition of boundaries and limitations of disciplines."
>
> (*ibid.*; candidate's emphasis)

Moreover, ECSA includes systems in the *knowledge area* of engineering design and synthesis:

> **"Appendix A: Definition of Knowledge Areas**
>
> … …
>
> **Engineering Design and Synthesis:** is the creative, iterative and often open-ended process of conceiving and developing components, systems and processes. Design requires the integration of engineering, basic and mathematical sciences, working under constraints, taking into account economic, health and safety, social and environmental factors, codes of practice and applicable laws."
>
> (*ibid.*; candidate's emphasis)

Hence systems are included in ECSA Exit-Level Outcome 3 on engineering design:

> **"Exit level outcome 3: Engineering Design**
>
> ***Learning outcome:*** Demonstrate competence to perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.
>
> … …

> ***Range Statement:*** A major design problem should be used to provide evidence. The problem would be typical of that which the graduate would participate in a typical employment situation shortly after graduation. The selection of components, systems, engineering works, products or processes to be designed is dependent on the discipline." (*ibid.*; candidate's emphasis)

Finally, ECSA declares that its Exit-Level Outcomes (ELO) 1 and 3 demonstrate an understanding of the world as a set of related systems according to a SAQA Critical Cross-Field Outcome:

**"Appendix C: Consistency of Exit Level Outcomes with Critical Crossfield Outcomes**

| **SAQA Critical Cross-Field Outcomes** | **Equivalent Exit-Level Outcome** |
|---|---|
| "… …<br>Demonstrating an understanding of the world as a set of related systems by recognizing that problem contexts do not exist in isolation" … | "ELO 1, 3" |

"

(*ibid.*)

---oOo---

## APPENDIX 4
## Interdisciplinary Course and Curriculum Approaches

Recently reported interdisciplinary approaches to mechatronics education fall into two broad classes. The first is interdisciplinarity in one or more courses devoted to mechatronics, sometimes preceded by a preparatory EE course. The second is more ambitious, integrated and wide-ranging: interdisciplinarity in the *curriculum*. Table A4.1 overleaf summarises both approaches as they are reported in recent literature.

Table A4.1 Interdisciplinary Course and Curriculum Approaches to Mechatronics Education in Recent Literature
(shaded columns refer to papers describing programme of University of Detroit Mercy)

| | **Das *et al.* (2005)** | **Turner (2005)** | **Harrison & Deanes (2005)** | **Mina *et al.* (2005)** | **Driscoll & Villanucci (2004)** | **Newman et al. (2003)** | **Hargrove (2002)** | **Yost (2000)** | **Krishnan et al. (1999)** | **Yost, Krishnan, Das (1999)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Interdisciplinary approach in *course* | √ | √; students expected to acquire missing knowledge by self-study | √ | N/A | | | √ | √ | √ | √ |
| Interdisciplinary approach in *curriculum* | | | | √ (Mechatronics Systems); 'learning streams' vertically integrate across traditional courses & disciplines) | √ 5-year, dual-discipline eng. programme (Electromechanical Engineering[1]) | √; foundational *tri-disciplinary* programme; all CpE, EE & ME students take same courses in 1st 2 years | | √ (mechatronics introduced in first year 'Introduction to Design' course) | | |

[1] This includes a significant mechatronic component, with four EE courses covering embedded computer systems, signals and systems, and feedback and controls – as well as courses in electromechanical design and systems.

| | **Das *et al.* (2005)** | **Turner (2005)** | **Harrison & Deanes (2005)** | **Mina *et al.* (2005)** | **Driscoll & Villanucci (2004)** | **Newman et al. (2003)** | **Hargrove (2002)** | **Yost (2000)** | **Krishnan et al. (1999)** | **Yost, Krishnan, Das (1999)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Interdisciplinary students (ME & EE) | √ (senior; elective) | √ (senior; equal numbers) | √ (and aerospace eng. students) | | | | | √; and ChE, Civil & Environmental Eng. students & lecturers | | √ |
| Interdisciplinary lecturers (ME, EE & other) | √ | | √ | √ | √; interdisciplinary overseeing committee;[2] team teaching approach | √; most courses co-taught | | | √ | √ |
| Assessment specialists on staff team | √ | | | | | | | | √ (see Carlson et al., 2000) | |
| Integrated course (from other courses) | | | | √; vertical integration via learning streams | √[3] | √ | √; 'Instrumentation' course updated, integrated into 'Introduction to Design' course | | | |

[2] Also including lecturers from the Physics, Applied Mathematics & Science, and Humanities & Social Science departments.

[3] "... the addition of one more academic year to a classical four year engineering programme results in a tremendous amount of additional engineering coursework being included in a dual-discipline engineering programme without any substantive loss in programme coverage or depth."

| | **Das *et al.* (2005)** | **Turner (2005)** | **Harrison & Deanes (2005)** | **Mina *et al.* (2005)** | **Driscoll & Villanucci (2004)** | **Newman et al. (2003)** | **Hargrove (2002)** | **Yost (2000)** | **Krishnan et al. (1999)** | **Yost, Krishnan, Das (1999)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Prerequisite introductory course | √ ('Intro. to Mechatronics' at senior level) | Paper implies that this is intended | | | | | | | | |
| Laboratory (hands-on) exercises | | √ | √ (take-home) | √ | | √ | √ | √ | √ | √ |
| Project work (-based) | √ | √ (mechanical tasks, elec. power, control) | √ | | | √; interdisciplinary in 1st 2 years; multidisciplinary[4] in 3rd year | √ | √ | √ | √ |
| Team-based / -oriented | √ | √ (but indiv. performance mandated) | √[5] | √ ('learning teams') | | | √ | √ | √; incl. initial team-building exercise | |
| DESIRED OUTCOMES | | | | | | | | | | |
| Communication | √ | | √ | | | √ | | √ | √ | √ |
| Project management | √ | | | | | | | √ | | √ |
| Problem-solving | | | √; major emphasis | √; problem-based design | | √; including open-ended problems | | | | |

[4] "Ideally, each student engineering team should have one EE, ME and CpE".
[5] Mostly limited to 3 students, with one EE student and at least two disciplines in each team.

| | **Das *et al.* (2005)** | **Turner (2005)** | **Harrison & Deanes (2005)** | **Mina *et al.* (2005)** | **Driscoll & Villanucci (2004)** | **Newman et al. (2003)** | **Hargrove (2002)** | **Yost (2000)** | **Krishnan et al. (1999)** | **Yost, Krish-nan, Das (1999)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Team work | √ | | √[6] | | | √; inter- and multi-disciplinary | | (√) | | √ |
| Lifelong learning & required adapt-ing skills | √ | | | | | √ | | | | √ |

---oOo---

[6] Including assembling an appropriate multi-disciplinary team.

## APPENDIX 5
## General Representations of Dynamic Physical Systems

Preamble

Modelling a real, physical system means to construct a simplified representation thereof, neglecting all influencing factors that are not important *for the purpose of the model.* As Karnopp *et al.* put it,

> "Models of systems are simplified, abstracted constructs used to predict their behaviour." (Karnopp, Margolis & Rosenberg, 1990:4)

There are two broad categories of models: continuous-parameter and lumped-parameter models. Only lumped-parameter models are considered here. In such models, different types of elements represent different properties: for example, lumped masses represent just mass, and lumped springs represent just elasticity. However, it should be recognised that many real systems have distributed parameters – for example, a uniform metal bar has both mass and elasticity {stiffness} everywhere, and cannot be accurately modelled as two interconnected components, one having all the elasticity {stiffness} and the other having all the mass (Karnopp *et al.*, 1990:368).

> "Everything should be made as simple as possible, but not simpler." (Albert Einstein, 1879-1955; quoted in Karnopp *et al.*, 1990:368)

A physical object termed a *component* or *element* is thought of and treated as a unit, not as composed of parts (simpler objects) (Karnopp *et al.*, 1990:7). On the other hand, a physical object termed a *device* is deemed to be composed of interconnected, interacting, closely adjacent parts.[83] A set of interconnected, interacting components, devices, or both is termed a *system.* Obviously, therefore, a device is itself a system – it is composed of interacting parts, which may be components or sub-devices. It is one class of *subsystem* – a *lumped* subsystem – if it is a part of a larger system. Another class of subsystem is a *distributed* subsystem, where the distances between at least some parts are large compared to the dimensions of these parts themselves.

Subsystems are of various types. If energy flow within depends on (is accomplished by):

- physical contact between solid objects (or body forces acting thereon), the subsystem is *mechanical;*
- flow of liquid, vapour or gas (or body forces acting thereon), the subsystem is *hydraulic* or *pneumatic;*
- transfer of heat, the subsystem is *thermal;*

[83] That is, the distances between all parts are small compared to the dimensions of the parts themselves.

- flow of electrons through electrically conducting matter, the subsystem is *electrical.*

A *dynamic system* is one whose:

- behaviour (state and output(s)) varies non-negligibly over time; and
- present behaviour depends not only on present input(s) to the system, but on its present *state,* which is determined by the past {e.g. previous input(s) or previous state}.

In a dynamic system, at least one component is capable of storing significant[84] matter, energy or both; a component possessing such storage capability is said to have *state,* and the time-varying quantities indicating its state are termed *state variables.* The state of a dynamic system comprises the states of all of its such components.

In contrast, a *static system* has no component capable of significantly storing matter or energy; the system thus has no state and its behaviour [output(s)] depends only on its present input(s).

Finally, an *information-processing and control system* is a special class of subsystem that controls a main system to achieve desired objectives. It does so by receiving negligibly small flows of power (termed *signals*) conveying information on the behaviour of the main system being controlled; processing this information; and then transmitting commands to the main system, also via signals (negligibly small flows of power).

Linear Graphs Symbolising Energy Flow in Lumped-Parameter Models of Dynamic Systems

The *linear graph* is a graphical (pictorial) tool to symbolise energy flow between the interconnected components of a *lumped-parameter* model of a dynamic system, as well as energy flow into or out of such a model. In a linear graph, interconnected line segments, called *branches,* represent the lumped components (elements) in such a model. The term 'linear graph' arises from the use of these line segments, and does not imply that the model itself is linear[85] (de Silva, 2005:57).

Each branch in the linear-graph represents a single component or element in the lumped-parameter dynamic model. Each type of subsystem mentioned above is characterised by one *'through' variable* and one *'across' variable* associated with every element within it. The product of every 'through' variable and its corresponding 'across' variable has the units of power,[86] that is, en-

[84] That is, large enough to significantly affect the behaviour that is important, or of interest.
[85] Here, 'linear' means that output is directly proportional to input.
[86] Except for thermal systems, as noted in footnote 87.

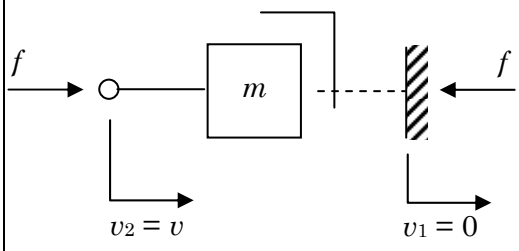
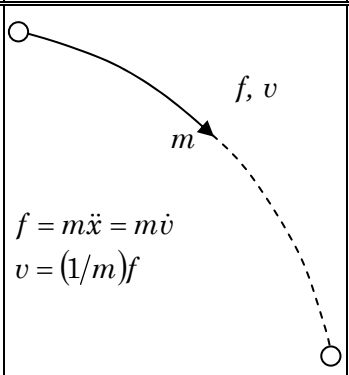
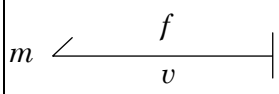
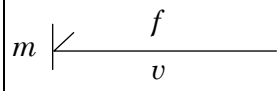
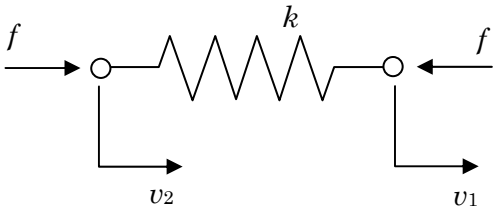
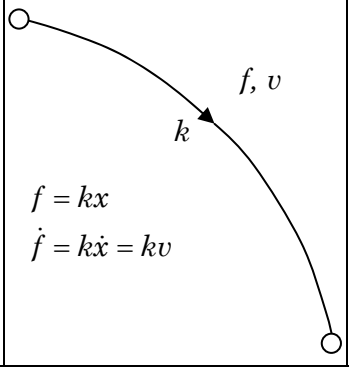
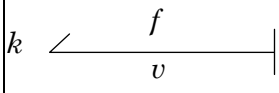
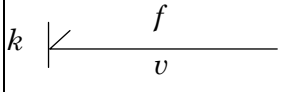
ergy flow over time (de Silva, *ibid.*) Table A5.1 lists the 'through' and 'across' variables for the different types of subsystems (single-type systems).

Table A5.1 'Through' and 'Across' Variables for Types of Systems [Single-Type Systems] (after de Silva, 2005:57)

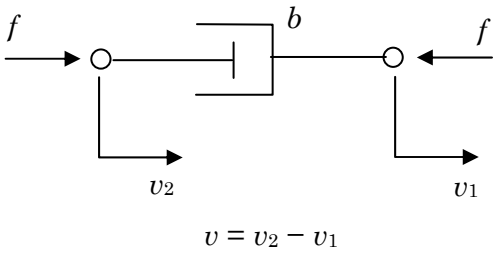
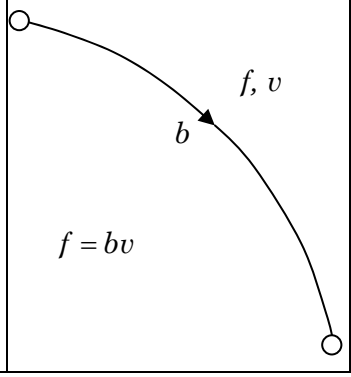
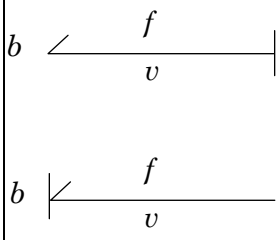
| System Type | 'Through' Variable | 'Across' Variable |
|---|---|---|
| Mechanical | Force | Velocity (*Relative to a Datum*) |
| Hydraulic / Pneumatic | Fluid Flow Rate | Fluid Pressure *Difference* |
| Thermal[87] | Heat Transfer Rate | Temperature *Difference* |
| Electrical | Current | Voltage (Potential *Difference)* |

Table A5.2 shows, for mechanical systems, the lumped components (two, energy-storing and one, energy-dissipating) and their representations by linear graphs.

Table A5.2 Mechanical System Elements: Linear- and Bond-Graph Representations Thereof (de Silva, 2005:58;116)

| Element of Mechanical System | Linear Graph Representation | Bond Graph Representation |
|---|---|---|
| Energy-Storing Element<br>Inertia: Mass $m$<br><br> | <br> | (derivative causality)<br><br><br><br><br>(integral causality) |
| Energy-Storing Element<br>Spring: Stiffness $k$<br><br> | <br> | (derivative causality)<br><br><br><br><br>(integral causality) |

[87] For thermal systems, the product of the 'through' and 'across' variables in Table A5.1 – heat transfer rate and temperature difference – does *not* have units of power. Heat transfer rate itself has units of power. Strictly, the 'through' variable must be *entropy* flow for the product of the 'through' and 'across' variables to be the heat transfer rate – this having units of power. See footnote 89.

| Element of Mechanical System | Linear Graph Representation | Bond Graph Representation |
|---|---|---|
| Energy-Dissipating Element<br>Dashpot: Damping Constant $b$<br><br><br>$v = v_2 - v_1$ | <br> | <br> |

Note that for the energy-storing inertia element, the linear graph's line segment is half-continuous and half-dashed. This is because the 'through' variable, force, does not physically travel through the element, but rather 'felt' at the two ends *of the linear graph* (de Silva, 2005:58).

This observation highlights, in the candidate's opinion, a disadvantage of linear graphs: 'through' and 'across' variables are only partly intuitive for *mechanical* systems, where force is not intuitively perceived to be a 'through' variable, and velocity is not intuitively perceived as an 'across' variable. As will now be seen, bond graphs are both more intuitive (the concepts of *effort* and *flow* being more so) and more informative.

Bond Graphs Symbolising Energy Flow and Causality in a Dynamic System

The *bond graph* is a graphical (pictorial) tool to symbolise energy flow between the interconnected components of a *lumped-parameter* model of a dynamic system, as well as energy flow into or out of the system. Branches between components, called *bonds,* perform this symbolisation, indicating both the direction of energy flow and the *causality* thereof – i.e. which quantity is the input to a component that causes its output. For example, the block diagram and the bond graph of a dynamic component $A$ with a force $f$ as input and a resulting velocity $v$ as output are shown in Figure A5.1.

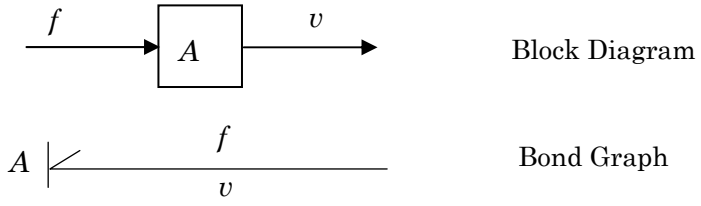



Figure A5.1 Block Diagram and Corresponding Bond Graph (de Silva, 2005:115)

The bond's half-arrow indicates the direction of energy flow when both the *effort variable* (here, force *f*) and the *flow variable* (here, velocity *v*) are positive according to a chosen sign convention. The effort and flow variables are

marked, respectively, above and below the bond – or, if the bond is vertical, on its left and right respectively. The short stroke at one end of the bond indicates causality. If this stroke is next to *A,* the input thereto is the effort variable and the output is the flow variable. If this stroke is away from *A,* then the input is the flow variable and the output is the effort variable. So in Figure A5.1, the input to *A* is the effort variable –here, force *f* – and the output is the flow variable – here, velocity *v* (de Silva, 2005:115).

State variables in bond graphs are *effort variables* and *flow variables*. Table A5.3 lists these for mechanical, electrical, fluidic and thermal (heat-transferring) components of systems.

Table A5.3 Bond Graphs: Effort and Flow Variables[88] for Basic System Components

| **Type of Component** | **Effort Variable** | **Flow Variable** | **Basic Components** | |
|---|---|---|---|---|
| | | | ***Energy-storing*** | ***Energy-dissipating*** |
| Mechanical (translational) | Force (force difference) | Velocity (translational) | Object possessing inertia due to its mass<br>Spring (stiffness element) | Frictional damper |
| Mechanical (rotational) | Torque (torque difference) | Velocity (rotational) | Object possessing *moment of inertia* due to its mass and configuration<br>Rotary spring (stiffness element) | Rotary frictional damper |
| Electrical / Electronic | Voltage (Potential Difference) | Current | Inductor<br>Capacitor | Resistor |
| Fluidic (Hydraulic / Pneumatic) | Pressure Difference | Fluid Flow-Rate | Fluid storage element (fluid capacitor)<br>Element with *fluid* inertia due to *fluid's* mass (fluid inertor) | Element offering resistance to fluid flow (fluid resistor) |
| Thermal (Heat Transfer)[89] | Temperature Difference | Heat Transfer Rate | Thermal energy storage element (thermal capacitor) | Element offering resistance to heat transfer (thermal resistor) |

[88] More correctly, effort *difference* and flow variables.

[89] As for footnote 87, the product of the effort and flow variables in Table A5.3 for thermal systems does not have units of power. Heat transfer rate itself has units of power. Karnopp *et al.* (1990:61) show that for true bond graphs representing thermal systems, the effort and flow ...

Causality

The energy-storing components in Table A5.1 are dynamic, and so their outputs depend not only on the prevailing inputs, but on their states. This is best reflected if their input-output (constitutive) relations are written in the form of *integral causality* (de Silva, 2005:117), where the outputs are the natural state variables. In a mechanical system, for example, the two basic energy-storing components are an object with mass of, say, $m$, and a spring with stiffness of, say, $k$. For both, the effort and flow variables are force $f$ and velocity $v$ respectively. Their constitutive relations with integral causality (*ibid.*) are:

Mass: $\Delta v = \frac{1}{m}\int f \cdot \mathrm{d}t$ Spring: $\Delta f = k\int v \cdot \mathrm{d}t$

In both of these, the constant of integration is the initial state of the component (initial velocity $v_0$ and initial force $f_0$ respectively). For energy-dissipative components, the relation between effort and flow variables is algebraic, so the causality is arbitrary (*ibid.*).

Inputs to the System

Inputs crossing a system's boundary to the system are represented by *source elements,* where either the effort or flow variable is specified as externally-originating with a given value. The value of the other variable depends on the system (de Silva, 2005:116). For example, in a mechanical system, a *force source* (SF) is represented as in Figure A5.2. The time-varying, externally-originating force is indicated as $f(t)$. The value of the velocity variable $v$ depends on the properties of the system to which the force source is the input.

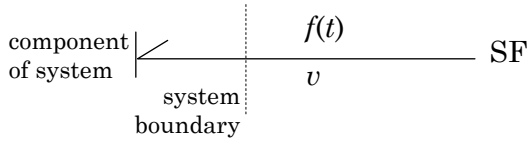



Figure A5.2 Bond Graph Representation of Force Source in a Mechanical System

Two-Port (Transformer-Type) Components

The component *A* in Figure A5.1 is a *single-port* component, that is, it has one input and one output. *Two-port* (transformer-type) components also exist, having two inputs and two outputs. The diagrams and bond-graph representations of two basic mechanical such components, the lever-type transformer and rotational gyrator, are shown in Figure A5.3 (de Silva, (2005:117). Both

---

variables must be temperature difference and *entropy* flow. However, *pseudo*-bond graphs for thermal systems, which do have temperature difference and heat transfer rate as effort and flow variables, lend themselves more easily to modelling complex systems where thermodynamic interactions play major roles (*ibid.*:447-488).

of these are simple machines, where the combination of input force and velocity represents energy inflow, and the *same* energy flow[90] leaves the output in the form of more desirable combinations of force and velocity. For the lever-type transformer, the obvious application is obtaining greater force, at the expense of lesser velocity, at the output.

It is not difficult to see that other simple mechanical machines – a block-and tackle pulley system, or a screw jack, for example – amount to such mechanical transformers. In electrical systems, the obvious analogy is the electrical transformer that converts electrical energy inflow at one combination of alternating voltage and current to the same outflow at another, more desirable combination. Furthermore, devices that convert one form of energy to another are, in essence, also transformers.[91] Examples are electric generators or motors transforming (converting) between electrical and mechanical energy; pumps, compressors or turbines transforming (converting) between mechanical and fluid energy, and so on.

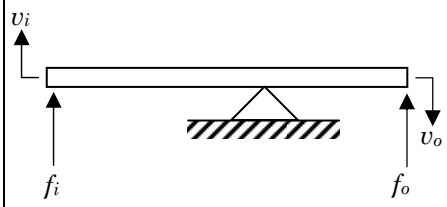
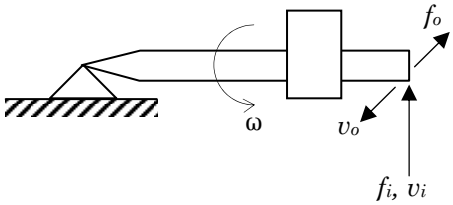
| Element | Conventional Representation | Bond Graph | Constitutive Relation |
|---|---|---|---|
| Transformer |  | $f_i$ / $v_i$ — TF ($r$) — $f_o$ / $v_o$<br>$f_i$ / $v_i$ — TF ($r$) — $f_o$ / $v_o$ | $v_o = rv_i$<br>$f_i = rf_o$<br>$f_o = \frac{1}{r} f_i$<br>$v_i = \frac{1}{r} v_o$ |
| Gyrator |  | $f_i$ / $v_i$ — GY ($M$) — $f_o$ / $v_o$<br>$f_i$ / $v_i$ — GY ($M$) — $f_o$ / $v_o$ | $v_o = Mf_i$<br>$v_i = MF_o$<br>$f_o = \frac{1}{M} v_i$<br>$f_i = \frac{1}{M} v_o$ |

Figure A5.3 Basic Two-Port Mechanical Bond-Graph Elements (de Silva, 2005:117)

Multiport Junction Elements

Next, in order to link more than two components, bond graphs necessarily have *multiport junction elements* (de Silva, 2005:118-9). For mechanical systems, the two types of such junctions are *common-force* and *common-velocity* junctions; representations and examples of three-port such junctions are

[90] Neglecting imperfections that dissipate energy in any real device. Non-negligible such dissipations can be accounted for by adding *energy-dissipative elements* to the bond graph.
[91] A more appropriate term might be energy *converters*.

shown in Figure A5.4 (de Silva, 2005:118). For a common-force junction, the sum of all velocities at the junction must equal zero; the same is true of all forces in a common-velocity junction.

Assigning causalities in a 3-port common-force junction simply consists of selecting any two of the three velocities as inputs; the third velocity is then necessarily the output (de Silva, 2005:119). The same is done with the three forces in a 3-port common-velocity junction (*ibid.*).

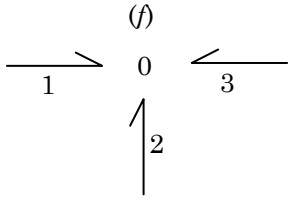
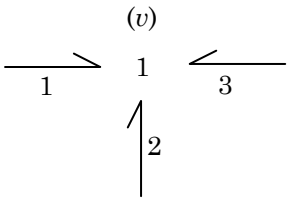
| **Element** | **Significance** | **Bond Graph Representation** | **Constitutive Relation** |
|---|---|---|---|
| Common-force junction | Compatibility (sum of velocities in a loop = 0) |   | $f_1 = f_2 = f_3 = f$ $v_1 + v_2 + v_3 = 0$ |
| Common-velocity junction | Continuity (sum of forces in a node = 0) |   | $v_1 = v_2 = v_3 = v$ $f_1 + f_2 + f_3 = 0$ |

Figure A5.4 Three-Port Junction Elements in Bond Graphs (de Silva, 2005:118)

Causality Conflicts and System Order (de Silva, 2005:117)

In modelling a system with multiple energy-storing components, the bonds of all such components are drawn with integral causality. If it is not possible to assign causalities to *all* bonds in the graph without violating this assumed integral causality, a conflict in causality exists. Such a conflict indicates that the behaviours of all energy-storing components are not independent of one another, and hence that the 'system order' (the number of *independent* energy-storing components) is less than the total number of such components.

---oOo---

# APPENDIX 6
## Key Aspects of Hedegaard's 'Double Move in Teaching And Developmental Learning'

The correspondence between Figure 9.1 in the text and the key aspects, in Hedegaard's own words, of the 'double move' are outlined in Table A6.1.

Table A6.1: Key Aspects of Hedegaard's 'Double Move' Depicted in Figure 9.1

| **Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning'** | **Figure 9.1's Depiction of these Aspects** |
|---|---|
| "The teacher's planning must advance from the general laws to the surrounding reality in all its complexity. In order to explain these laws the teacher must choose concrete examples that demonstrate the general concepts and laws in the most transparent form. Whereas the teacher's planning must advance from the general to the concrete, the children's learning must develop from preconceived actions to symbolisation of the knowledge they obtain through their research, finally resulting in a linguistic formulation of relations." (Hedegaard, 1990:274-5)<br><br>"In the double move approach, the process of instruction runs as a double move between the teacher's model of subject-matter concepts of a problem area and the students' everyday cognition and knowledge." (Hedegaard, 2002:78) | *Before Course:* downward arrow D'–D' signifies the teacher's planning from general to concrete. *During Course:* upward trend line D–D signifies the students' upward development from concrete (or everyday concepts) to general (or subject-matter concepts) |
| The conflict between the explanations offered by the student's core model and the phenomena introduced in the teaching creates situated motivation (Hedegaard, 2002:78), alternatively named situation-specific motivation (*ibid.*, 68). This leads to the development of motives (*ibid.*); development occurs through changes in the dominant motive (*ibid.*). | Upward trend line M-M denotes this upward development of motives, owing to the situated motivation *m-m* |
| Developmental teaching aims at development within the Zone of Proximal Development (ZPD) (Hedegaard, 2002:81). The social aspect of the ZPD is fundamental. "Working within the zone of proximal development requires the teacher to combine children's knowledge and proficiencies from daily lives with the subject-oriented teaching going on in the classroom environment. The situation also requires that the teacher work with an entire class at the same time." (*ibid.*, 80)<br><br>Kutnick (2001) points out that development within the ZPD occurs not only because of asymmetrical relationships – "adult guidance or collaboration with more capable peers" (Vygotsky, 1978), but also because of symmetrical relationships – mutual interaction between peers. Vygotsky in fact used this expanded concept of the ZPD, where mutual as well as hierarchical relationships support development (Kutnick, 2001). | Stepped line P-P represents the upper level of the ZPD, rising toward and into subject-matter concepts. Line M-M, the line of envisaged development, represents the lower level of the ZPD |

| **Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning'** | **Figure 9.1's Depiction of these Aspects** |
|---|---|
| "The teacher guides the learning activity both from the perspective of both the general concepts and methods of a subject-matter area and from the perspective of engaging students in 'situated' problems that are meaningful in relation to their developmental stage and life situations." (Hedegaard, 2002:78)<br>Within a spiral of problem-solving, the students begin by working with situated problems chosen by the teacher; they gradually acquire the concepts and develop a *core model* which is continually being revised & refined; this equips them to approach different tasks; through this diverse problem-solving, students become able to evaluate their learning (Hedegaard, 2002:78) | Downward arrow D'-D' signifies the teacher's planning that underpins such guidance. The spiral of problem-solving, ascending and descending between concrete and general, is shown on trend line D–D |
| "... the students are given tasks that motivate them for research activity so that a relation between the pupils' own problems and the problems in a subject area is created. The learning motive thereby can become connected to subject-matter concepts ..." (Hedegaard, 2002:21)<br>"Five factors can be conceptualised as crucial in the double move approach for how teaching can lead to developmental learning. These are:<br>(b) "formulation of problems that involve the central conceptual relations and methods, as well as motivate the children attending the class, ..." (Hedegaard, 2002:82) | (Formulation of problems) All three *phases in developmental teaching,* from situated to less situated, self-determined problems.<br>(Motivation) Riser *m-m* shows how these problems motivate the students; the envisaged motivation connects the subject-matter problems with the students' goals springing from their dominant motives (Hedegaard, 2002:66) |
| (c) "content analyses and formulation of germ cell/core models, ..." (*ibid.*, 82)<br>{ a core model being a person's own abstractions of a subject-matter area (*ibid.*, 86) } | Phase 2 of *Phases in Developmental Teaching* |
| (d) "analogy to research methods, ..." (*ibid.*, 82);<br>"Thus there is a double move in instruction: The teacher must guide instruction on the basis of general laws, whereas the children must occupy themselves with these general laws in the clearest possible form through the *investigation* of their manifestations. That is why *practical research activities* with objects, films and museum visits are such an important part of instruction, especially during the early periods." (Hedegaard, 1990:275; candidate's italics)<br>"The solution is ... to use a teaching approach that motivates | The "spiral of problem-solving" (*ibid.*:78) along line D–D, "Planned Development of Students' Learning", illustrates this. As seen, this spiral is back and forth between general and concrete, which is |

| Key Aspects of Hedegaard's 'Double Move in Teaching and Developmental Learning' | Figure 9.1's Depiction of these Aspects |
|---|---|
| the pupils to plan and participate in research activities with the objective of creating a link between the pupils' own questions and the problems that are central to the subject being taught." (Hedegaard, 2002:81) | characteristic of research activity |
| (e) "phases in teaching, which are based upon progressive and qualitative changes in the children's appropriation of knowledge and skills;" (*ibid.*, 82)<br>This is developmental teaching, whose phases are dialectically linked to phases in learning; the three phases in developmental teaching are (*ibid.*, 89):<br>(1) helping children to develop flexible concepts and formulate goals about the thematic relationships in a course of subject-matter – here, pupils are just set assignments (*ibid.*, 90); | Phases in developmental teaching along time axis<br>Phase 1: "Situated Problems" |
| (2) formulation and expansion of these thematic relationships in the form of a germ-cell model for the problem area being investigated – where the relationships within the germ-cell model[92] are explored through various assignments – here, pupils are both set assignments and required to formulate problems (*ibid.*, 90); | "Spiral of problem-solving" by research activities;<br>Phase 2 of Phases in Developmental Teaching |
| (3) enable children to learn how to critically evaluate what has been learned concerning their own skills; the conceptual relationships being investigated; and the content of the teaching being used to shape the germ-cell model – here, pupils must set tasks that allow evaluation, *and* they are set assignments that allow them to evaluate both the capability of the germ-cell model, and further knowledge and skills they would like to acquire (*ibid.*, 90). | Phase 3 in *Phases in Developmental Teaching:* "Still less situated problems, more self-determined by pupils from their evaluations of their learning" |
| (f) social interaction, communication, co-operation between children." (*ibid.*, 82)<br>"This type of teaching and learning in school favours co-operation between teacher and learner and between learners in problem formulation and problem solving within a subject domain." (*ibid.*, 2002:78)<br>"... children's development takes place through their relation to the class and to the groups in the class." Group solving processes were used to develop the children's intellectual processes. Children would work on different tasks in a group with a shared motive for the entire activity (Hedegaard, 1990:279) | Not shown |

[92] Strictly, the term *core model* should be used here. Hedegaard (2002:86) uses the term 'germ-cell model' for the ideal abstraction of the key relations in the content of a subject area. She points out (*ibid.*) that it is difficult to ensure that any chosen model is the ideal one; hence she prefers to call teachers' and students' models *core models*.