THE ROLE OF SYSTEM DYNAMICS
IN THE PROMOTION OF
SCIENTIFIC COMPUTATION LITERACY

An exploration - comprising an Analytical Study and an Empirical Survey - of System Dynamics' potential for promoting scientific reasoning and computational thinking, and in modifying the science learner's epistemological commitments, respectively.

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Daniel Roque Mendes
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FOREWORD

The underlying context of the study was developed through observations made during the author's twenty years teaching practice as Physics and Integrated Science instructor in comprehensive schools in London and Hamburg, particularly - and since 1979 - as teacher at Internationale Schule Hamburg e.V.. From a background of varied experience with trials and applications of computer systems adopted in computer-oriented learning and instruction environments, but with particular emphasis placed upon science learning environments, specific interest in the concepts, methodology and computational environment of JAY W. FORRESTER's System Dynamics was subsequently identified. In this work, System Dynamics was acknowledged and appreciated as a means of intensifying the learning of scientific method on the one hand, while promoting the acquisition of scientific and computational knowledge on the other. In the middle 80's a systematic approach towards providing answers to key questions and issues raised in various studies and discussions relating to the implementation of Computers in pre-university education was initiated. Intensive discussions in Germany centred round the significance of computers in schools in general and learning in particular, while Anglo-American countries concentrated on the curricular bases and om the institution of different levels of "Computer Literacy" for the coming generation of computer users. In the treatise presented here, an aspect of the role/contribution of computers in pre-university science education - specifically, in the learning/instruction of scientific reasoning and scientific computation - is examined through both analytical and empirical surveys. The treatment as such is characteristically exploratory in nature and was undertaken with the intention of compiling a pilot-study with respect to an innovative, practical, lesson-oriented and instruction-driven curricular programme delivered to pre-university students at Internationale Schule Hamburg e.V.. Subsequent, hermeneutic theses developed provide material that lends itself for empirical analysis under realistic conditions.

I would like to express deep gratitude to my dissertation advisors Professor ROLF OBERLIESEN of Universität Bremen and Professor JÖRN BRUHN of Universität Hamburg for their kindness, patience, backing and invaluable guidance over several years. My wife PETRA, my children and my parents-in-law provided full and unrelenting moral support. Finally, I would like to thank the pupils and the scholastic environment of Internationale Schule Hamburg e.V. for academic and scientific inspiration.

CONTENTS

0 INTRODUCTION

This introductory chapter presents the conceptual theme and the context of our research. Specific contemporary issues concerning science education, the integration of computers in selected aspects of science learning (and instruction) and relating directly to this study, are first introduced. Essentially, the viability of a fusion between some aspects of scientific literacy and specific computer literacy objectives is explored and initiated as the basis of our concept of Scientific Computation Literacy.

The factors considered to influence the development and the assimilation of the concept of scientific computation - for the subsequent promotion of scientific computation literacy - and a potential environment for developing scientific computation in an educational context are then put into context. The roles of the concepts and methodology of System Dynamics, which are considered to provide the appropriate environment for developing and promoting scientific computation, and of DYNAMO - the programming language associated with System Dynamics - which is considered to provide the computational tool, are analysed and rationalised.

The analyses are complemented with observations and empirical studies carried out with two individual pupils and two separate groups of pre-university pupils, respectively, at Internationale Schule Hamburg e.V. who were formally exposed to elements of the System Dynamics methodology. Twenty years teaching experience in Physics and Integrated Science (up to pre-University level) at Internationale Schule Hamburg e.V. contribute to the instructional background and provide pedagogical rationale for the environment within which the empirical surveys were conducted.

0.1 New Information Technology in Science Education

A noteworthy statement - particularly to be found in scientific education literature and research publications in English (SCIENCE COUNCIL OF CANADA 1984, ROYAL SOCIETY 1985, AAAS 1989, LEDERMAN 1992, International Baccalaureat Group IV Programme Of Studies 1998) - with reference to science education during the second half of the 20th Century and leading towards science education for the beginning of the 21st century, and an aspect also constituting a prominent goal of many policies and initiatives in science curricular development, has been concerning the issue of scientific literacy. With respect to this particular aspect, however, no clear consensus exists up to date concerning either the specific content or the methods/strategies of instruction in pre-university science education.

Although it could be as a result of such a lack of consensus that pre-university/secondary school science curricula vary widely among countries, states and even individual schools, there appears to be, nonetheless, longevity, persistence and strong agreement upon one particular objective of science learning (LEDERMAN 1992).

> “The development of student conceptions of the nature of science has been a perennial objective of science instruction regardless of the currently advocated pedagogical or curricular emphasis.“ (LEDERMAN 1992, 331).

That is, upon the development of science as a way of knowing and the acquisition of an appreciation of the nature of scientific reasoning; and this aspect has always been prominently and powerfully advocated as should be constituting a primary objective of science instruction (NSSE 1960, AAAS 1989, LEDERMAN 1992).

At a more specific level - and at one that relates directly to this study - the aspect of scientific literacy which is concerned with the appreciation of the nature and aims of scientific reasoning implies acquiring a grasp of scientific method, in conjunction with some understanding of the more important scientific ideas underlying scientific modelling:

> “An appreciation of the nature, aims and general limitations of science, e.g. a grasp of the scientific approach, the deployment of rational arguments, the ability to generalise, systemise and extrapolate, and to appreciate the roles of theory and observation.” (JENKINS 1994, 4).

Consequently, this also includes an appreciation of some general limitations of scientific method. We subscribe to the perspective and the attitude that an understanding of scientific reasoning also serves the widely recognised goals of improving critical thinking[1] and contributes to general scientific literacy:

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[1] Critical thinking, problem solving, reasoning, logical thinking and higher order thinking skills are terms often used interchangeably to refer to a learner’s ability to analyse a problem situation and come to an appropriate conclusion or solution. These terms are, however, by no means considered equivalent.

> "Learning about scientific reasoning provides some insight not only into particular scientific findings but also into the general nature of science as a human activity. It is an activity that engages an increasing proportion of our population, requires an increasing fraction of our resources, and impinges on an increasing number of our other activities. The better we understand it, the better off we all will be." (GIERE 1991, 5).

During the 1970s and continuing on even well into the 1990s, it was also suggested that all students, in addition, needed to acquire a degree of computer literacy. ARTHUR LEUHRMANN coined the phrase "computer literacy" in 1972 (ANDERSON et al. 1981, 128-143) to help focus attention on computers as an emerging basic of education. The most commonly used definitions of computer literacy have, however, changed over the past twenty years (PLOMP and de WOLDE 1985, PLOMP and REINEN 1994) reflecting the growth, development and evolution of computer hardware technology as well as software engineering. Information Technology [2] embraces all the current notions of computer hardware and software technology applications in education.

In response to this trend and for the purpose of identifying and establishing any emerging or changing directions for computers in education that could suggest any new, clear conceptualisations of computer use in particular educational contexts, KAY, on two occasions separated by a period of three years (KAY 1989, 1992), has managed to extract six relatively distinct (but some degree of overlap may be traced) perspectives or stages on computer literacy; this was done from a comprehensive review of the literature on computer literacy. This led KAY (1992) to argue - and such arguments take on added significance in 1998 (GODDING 1998) - that since significant advances in computer technology keep forcing educators to re-evaluate educational goals, that educators stop focusing on how to learn to use computers and start focusing on how to apply Information technology, i.e., to focus on the functionality or applicability of computer hardware and software in relation to educational needs.

With particular respect to the learning of science, we consider this functional perspective in this study as paramount and interpret KAY´s

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[2] The current notion of Information Technology comprises two distinct components corresponding to two different levels of usage in education (GODDING1998):

- Information and Communications Technology - ICT – lower secondary school level

- Information and Learning Technology - ILT – tertiary level argument to require that computer literacy be a functional level of knowledge and skills in using Information Technology and as a communication tool to be used for the purpose of learning and understanding (our selected aspects of) science and, subsequently, for using one's scientific knowledge. Within this context of science learning, the current status in terms of resources, applications and potential of information technology in Science Education may be presented as below (GODDING 1998):

- Word-processing/Desk Top Publishing
- Spreadsheets
- Databases
- CD-ROM/ **Science Curriculum Software**
- Multimedia
- Data-logging and Remote Sensing
- Control Technology
- Internet/World Wide Web
- Digital Capture & Video-logging

It is, therefore, within this aspect that we identify - in particular, within the domain of Science Curriculum Software which we have highlighted above - a significant and potentially powerful role for JAY FORRESTER's System Dynamics in the acquisition of understanding and appreciation of scientific reasoning for the learner. We support this position by adopting the perspective that computers, having transformed the very nature of the scientific problem-solving process through scientific computation methods, can radically alter what it means for learners to understand and solve scientific problems. And, therefore, since the other primary objective of science education is to help learners become better at solving specific types of scientific problems they encounter or will encounter in future, we consider that this also requires that scientific literacy be scientific problem-solving oriented and computationally significant, i.e., selected aspects of computer literacy to be pitched at a level that is consistent with the primary objectives, overall level and content of the particular problem-solving aspect of the science education that the learner is receiving.

Consequently, we analyse in this work the process by which the concepts and methodology of System Dynamics could provide the opportunity, mechanisms and environment to give the necessary prominence to key aspects of scientific modelling and to scientific method in science learning, while also providing the learner with the opportunity to acquire a significant level of computer literacy.

These issues are partly dealt with in CHAPTER 1 and partly in CHAPTER 2 but in significantly more detail in CHAPTER 3.

The computer-oriented modelling and simulation methodology of System Dynamics, is also fundamentally responsible for some recent software and curricular developments for Physics education, the most notable and prominent of these being MODUS (1992) and STELLA (1994); the UNIVERSITÄT BREMEN Reports on Modelling and Simulation in Physics (BETHGE & SCHECKER 1992), a development of the early STELLA (STELLA II, MANDINACH 1989), is particularly noteworthy in relation to our work. Our involvement with System Dynamics, however, distinguishes itself from such developments in that it gives prominence to the intrinsic, underlying methodology of science, i.e., principally to the development and promotion of scientific reasoning.

0.2 Principal Research Objectives

In order to identify and assess the contribution that System Dynamics could make to the promotion of scientific reasoning and to the exploration of the learner's own intuitive scientific knowledge, we examine principally the extent to which the learning of System Dynamics is compatible with the objectives of science learning and the significance of scientific computation within such learning. This form of exploration would be in conformation with our acknowledgement that Information Technology be incorporated within the context of the particular science education that the learner is receiving, and such exploration, therefore, comprises an analyses of the potential and the effects of computation in our particular, overriding aspects of scientific reasoning at the pre-university level - viz., those primarily concerning scientific modelling and the scientific method at a fundamental level – and from an epistemological perspective.

The second aspect of this research is concerned with the development of a contrived view of scientific computation and, consequently, with acquiring information about the manner with which the learner can relate to such knowledge of scientific method and of scientific modelling and model-testing within the context of her/his current science learning. We attempt to obtain this standpoint by assessing the learner's own impressions and judgement of the degree to which s/he believes that System Dynamics has enabled her/him to gain insight into key aspects of scientific method and of scientific modelling; another of these aspects also concerns the societal context of System Dynamics implementation

The methodology employed will serve to establish the extent to which aspects of scientific reasoning and the insights gained by the learner justify the implementation of System Dynamics within a science learning program.

0.3 Methodology

Two separate surveys, therefore, characterise the methodology adopted to provide the critique to the theses - a Qualitative Analysis, which constitutes the primary feature of the research and forms the bulk of CHAPTER 1, CHAPTER 2 and CHAPTER 3, and an Empirically-based Pilot/Experimental Study, which forms the second feature of our study and to be found in CHAPTER 4.

We propose that, potentially, the learning/instruction of the processes of scientific model-construction and scientific model-testing - as characterised in scientific - reasoning can be modified and extended with the scientific computation (in this particular context computer-based and simulation) tools and environment characterised by System Dynamics. The use of modelling and data interrogation requires the employment of a specific-purpose tool (language), that comprises a particular mode of computer programming, in conjunction with computer simulation. Implementation of one such computation tool, however, involves skills that are distinctly different from mastering the rudiments of a programming language. Thus de-emphasising instruction and training in traditional computer programming in favour of problem solving through computation, scientific computation is regarded as a systematic, exploratory, imaginative, scientific problem-solving activity. Scientific problem-solving as a systematic activity implies an initial exploration of the problem situation, followed by the definition of the problem and explication of the scientific algorithm, and winding up with the exploration of various solutions until the simplest (and most elegant) alternative has been obtained - but always keeping sight of the overall scientific goal. The computer is perceived in a context where the exploration ideas relevant to science and computation are manifested. And scientific computation literacy implies that computational features, and the process of exploring the scientific context of problem and solution, and not the products, are scientific-educationally paramount.

As a first strategy within the methodology, therefore, we establish the theoretical rationale, the context and an educational basis for scientific computation by focusing on our notion of scientific computation and the derivation and validation of the concept of educationally-oriented scientific computation, and we relate these aspects to those principal features of scientific literacy and computer literacy of interest. A principal aspect of this strategy is to treat the validation of the concept of scientific computation in terms of its relationship to pre-university science learning and instruction - but with particular reference to scientific modelling and scientific method - and concentrates on the exploitation of a relevant scientific computation environment which fits into a conventional science learning environment.

Another significant aspect of this strategy is to establish the societal context of scientific computation through the notion of a value-base and one which is in line with a science-technology-society approach to curricular development. The validity and potential of the mechanisms of the System Dynamics methodology within such a science learning environment is examined. In so doing, we make the attempt to establish System Dynamics with DYNAMO as a particular cross-disciplinary environment and scientific computation tool that achieves significance because it extends into areas of pre-university Biology, Chemistry and Physics. This, essentially, comprises the qualitative aspect of the research and constitutes the first survey.

Through the main empirical study - which was preceded by a preliminary pilot study involving a group of twelve, pre-university students - we attempt to assess the role of System Dynamics as an agency for promoting an appreciation/acknowledgement of scientific reasoning amongst a separate group of ten pre-university students through our concept of scientific computation literacy. This forms the second major component of the methodology.

The instrument used for this study was a questionnaire (see **APPENDIX A**) comprising three parts and administered prior to and post a series of lessons on the elements of System Dynamics to a group of ten students at the Internationale Schule Hamburg e.V.. The students - a significant number of who felt that were not confident about their proficiency in spoken English - indicated that they would be more comfortable at providing brief, written responses rather than having the information elicited through a formal interview. The nature of the questionnaire was also intended to facilitate the acquisition of quantitative data and the responses are, consequently, are subjected to quantitatively-supported descriptive-statistical treatment.

The findings are interpreted in the light of the epistemological - objectivistic to constructivistic - commitments that the ten students in their pre-university stage are presumed to have and, in particular, that may have been established through their participation in the scientific component of the Theory Of Knowledge course (see APPENDIX B) that was conducted as part of their program of pre-university studies. The scientific component of the Theory Of Knowledge course is essentially designed and constructed to instil in the student an appreciation of the elements and aspects of scientific reasoning as part of her/his program of studies within the entire, obligatory Theory Of Knowledge (International Baccalaureat) course. In this respect a group comprising about ten to twelve students is considered optimal - and achievable at Internationale Schule Hamburg e.V. - for a Theory Of Knowledge course, particularly for promoting discussion and for allowing for exchange of ideas and, therefore, the group size is considered appropriate for the second component of the survey.

0.4 Guide to Contents

In the beginning stages of the study, the concept and domain of Scientific Computation is defined and an educational (instructional/learning) context for Scientific Computation Literacy is explored and treated. This characterises the content of CHAPTER 1. By making reference to key arguments arising from particular developmental models of learning and through the adoption of science educational perspectives, the function of System Dynamics as a vehicle for implementing and transporting the concept of scientific computation is considered and rationalised, and its role in the learning of the scientific method is appreciated and/or acknowledged.

Manifestation of scientific method is shown to crystallise by considering different examples taken from appropriately-selected aspects of pre-university level Biology, Chemistry and Physics learning in conjunction with the cross-disciplinary nature and epistemological position assumed by the System Dynamics modelling methodology in the formulation of scientific hypothesis. With particular respect to the intrinsic scientific and the computational features of scientific computation within the context of the System Dynamics Methodology, however, deeper analyses necessitates the delineation of the domain of scientific computation into two separate components, viz., the scientific component and the computation component. The analyses of these two individual components are treated separately in CHAPTER 2 and CHAPTER 3, respectively.

CHAPTER 2 is primarily concerned with rationalising the scientific aspect of scientific computation with respect to learning and instruction of scientific method and scientific modelling adopting the alternative perspective and principles of Cybernetic systems. The social context of science and the role of System Dynamics through the concept of the value-base is treated.

CHAPTER 3 examines the computational aspect of scientific computation with respect to the learning of scientific problem solving with the computer. From the perspective that DYNAMO programming offers a particularly learner-friendly (cf. PASCAL, LOGO) scientific problem-solving tool and a debugging environment, an attempt is made to relate scientific exploration through algorithmic formulation, computational processes and computer-based activities to the evaluation of scientific hypotheses.

The empirical pilot study is contained in CHAPTER 4. The study constitutes analyses and discussions of the outcomes of two student projects and an appreciation-oriented series of sessions on System Dynamics administered to two separate groups of students at the Internationale Schule Hamburg e.V. involved in scientific studies at the pre-university level.

The deliberations which reflect the students' own perceptions and opinions - and which are highly interpretative and, in addition, partly substantiated by statistical inferences that were based upon answers to a questionnaire - are intended to provide an indication and an assessment of the potential of System Dynamics for meeting the specified scientific literacy and computer literacy objectives associated with our notion of Scientific Computation Literacy.

CHAPTER 5 synthesises the principal findings of CHAPTER 1, CHAPTER 2, CHAPTER 3 and CHAPTER 4, and reviews the contribution of this research to the concept of Scientific Computation Literacy.

The principal contribution has been to demonstrate the role of System Dynamics in the learning and instruction of scientific reasoning, particularly in the meeting of the predominant scientific literacy objectives - the learning/appreciation of scientific method and of scientific modelling. A further contribution has been to assess any relevant changes in the role of computer literacy. The chapter also concludes by reviewing some of the questions raised by this thesis and by outlining further research that could be (profitably) carried out.

1 RATIONALISING the CONTEXT of Educational Scientific Computation and the Role of System Dynamics

1.1 Contextually-Relevant Issues in the Education of the Scientific Method

For the science specialist or the aspiring scientist, on the one hand, scientific reasoning is the kind of reasoning that practising (in particular, natural) scientists use in the process of making scientific discoveries. For some (CAPRA 1982, LANGLEY et al. 1987, GIERE 1991) for example, it is adequate to regard any approach towards the acquisition of science knowledge as scientific if it satisfies two primary conditions, viz., all such scientific knowledge must be based on systematic observation, and this must be expressed in terms of self-consistent, but limited and approximate deductive models [3] .

> "These requirements - the empirical basis and the process of model-making - represent to me the two essential elements of the scientific method. Other aspects, such as quantification or the use of mathematics, are often desirable but are not crucial"; (CAPRA 1982, 415-416).

In this statement we identify the underlying approach that characterises much of the learning/instruction in the traditional pure science disciplines – particularly in Physics.

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[3] Although deductive arguments may be immune to doubts about whether their conclusions are true given that their premises are true, they are not immune to doubt about whether their conclusions are true; the conclusion of a deductive argument is only as secure as the premises from which it is drawn (GOWER 1997). This particular standpoint is, generally, not elaborated in scientific educational issues in practice.

Also identified with the context of scientific method – particularly in academic disciplines and promoted in a historical context in aspects of traditional science learning and epistemology (see International Baccalaureat, Theory Of Knowledge; **APPENDIX B**) - and, consequently, particularly prominent in physical science education programs, are the treatment and role of aspects such as the process of deductive and inductive reasoning and the analytical, mechanistic and reductionistic approach of Classical Physics.

However we also consider that the potential of synthetic and systemic/holistic thinking - as powerfully advanced by SCHAEFER (1984) and occasionally manifested in much Biology learning/instruction - and the inductive reasoning [4] process, should also be allocated due consideration, status and treatment as a fundamental aspect within the sphere of scientific method.

Regarded from an entirely different perspective, however, and one which legitimately and inevitably has educational ramifications, distinguishing and characterising science strictly by a scientific method has been argued to be doubtful on the grounds that the methods scientists employ are as varied as the disciplines scientists study (CHALMERS 1982, WOLPERT 1992, GOWER 1997). FEYERABEND (1993) [5] also makes a strong case for the claim that none of the methodologies of science that have so far been proposed are successful, and argues that the methodologies of science have failed to provide rules adequate for guiding the activities of scientists (CHALMERS 1982). While we are prepared to appreciate these positions, we consider their significance to be of secondary importance in the learning/instruction of scientific method as strictly presented in our particular context.

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[4] In certain aspects of science learning in particular, although inductive reasoning may not be truth-preserving - since it does not guarantee a true conclusion when true premises are provided - its potential is in that, although one is risking a false conclusion, if the conclusion is true then it can have significant educational value in that one may be led into thinking that the risk is worth taking (GOWER 1997).

[5] PAUL FEYERABEND (1993) argues against method insofar as he has shown that it is not advisable for the choices and decisions of scientists to be constrained by the rules laid down by or implicit in the method of science. According to the most extreme view that has been read into FEYERABEND's writings (FEYERABEND 1993), science has no special features that render it intrinsically superior to other branches of knowledge.

For the non-specialist in a science subject, viz., for the science pupil, on the other hand, learning to understand and appreciate scientific reasoning is a matter of acknowledging and assimilating - and of acquiring some knowledge of some of the evaluation procedures of - those scientific findings appropriate to their particular level of science; (GIERE 1991).

We contend that the purpose of instruction in scientific reasoning, at the pre-university level and extending into the tertiary level, has been specifically to help the science learner to acquire cognitive skills in understanding of the scientific process and the necessary reasoning skills, and in evaluating scientific material - as found in textbooks and (appropriately selected) professional printed sources; (DAEDALUS 1983, GIERE 1991, BASTIAN 1993). We adopt the position that:

> "Assimilating scientific information requires some conception of what science is all about and some special skills in evaluating the information one receives"; (GIERE 1991, 2).

Therefore, at this particular stage towards the establishment of the educational standpoint and the contextual basis of our treatise, we contend that a method-oriented and structurally-characterised account of scientific inquiry is crucial, even necessary and that this can be of significant value to a learner seeking to understand the nature of science and, to a significant extent, even to evaluate/appreciate the outcomes of particular scientific inquiries. And with relation to this work, in particular, we acknowledge that its most attractive and, from a learner’s viewpoint, its most significant feature lies in the fact that it provides a formalised account of some of the commonly adopted impressions concerning the character of science, its explanatory and predictive power and its objective and its semantic clarity and reliability compared with the other forms of knowledge that the learner may have acquired through her/his involvement in other disciplines and through other learning schemes.

Understanding of such scientific process, we contend, will lead to the acquisition of knowledge of the processes in the formulation of relevant models; evaluating scientific hypotheses refers to the process in which deciding whether or not given data provides evidence for regarding a particular model as a tolerably good representation of some real world object or process (GIERE 1991). This is the concept of rationality that we regard as important to the learning and, consequently, to the instruction of scientific reasoning.

A key aspect to be derived particularly from a cognitive science-oriented study of the scientific process based on information extracted from research and findings in cognitive psychology, artificial intelligence, the philosophy of science and the history of science – and an aspect we contend has a significant bearing on the perspective we adopt - also tends to underline HERBERT SIMON'S hypothesis that the mechanisms of scientific discovery, based on domain-specific framework, are not significantly different from the processes observed in simple human problem-solving situations (HOLLAND et al. 1986, LANGLEY et al. 1987). LANGLEY et al. advance the (originally SIMON'S) hypothesis (LANGLEY et al. 1987) that problem-finding and problem-formulating are simply variations of the problem-solving process - and that problem-discovery is a significant aspect of problem solving[6].

Also, and with reference to these claims and findings, cognitive-science research on human problem solving indicates that humans, in solving many kinds of problems, use both special and general methods. Methods applied to a particular domain, when available, may be far more powerful than general methods that make no use of the knowledge and structure of the domain (SIMON 1977).

With particular reference to process of scientific discovery and, therefore towards the standpoint we have elected to adopt with respect to the role played by scientific reasoning in this process, LANGLEY et al. claim that

> "..... if there is no single 'scientific method', there are at least a number of scientific methods that are broadly applicable over many domains of science. ..... that relatively general methods do play (and have historically played) a significant role in scientific discovery, that such methods are numerous, that they can be identified, and that their effects can be studied." (LANGLEY et al. 1987, 46),

As such, LANGLEY et al.'s claim does become significant when it comes towards the establishment of a context that has educational potential and value for scientific reasoning, since it may seem reasonable to presume that some scientists have more effective methodological principles and problem-solving methods than others at their disposal, or the heuristics

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[6] This hypothesis is based on major claims of having developed computer programs that make scientific discoveries over a wide range of topics using SIMON's problem-solving approach (LANGLEY et al. 1987). By contrasting the method by which the computer program BACON (LANGLEY et al. 1987) discovers KEPLER's third law with KEPLER's own methods, LANGLEY et al. (1987) have shown how similar heuristics can generate scientific laws associated with names of COULOMB, OHM and SNELL.

possessed by one scientist may provide that scientist with a comparative advantage only in some relatively limited domain of science.

Nevertheless, we do not elect to take issue here with SIMON's problem-solving claim that science is distinguished by scientific method, or with whether one particular methodology will capture the process of science is correct or not. The issue, however, that is seen to be required to be resolved here, is to the extent to which the computer’s ability to simulate problem-solving, as in the BACON (LANGLEY et al. 1987) program, or its employment in scientific problem-solving - if and when correctly interpreted and appreciated - can be of significance or relevance and can be meaningfully implemented - in science education.

At this level of resolution, and at the level within which most of our analysis and discussion will be conducted, however, one is primarily interested in the learning (and instruction) of scientific methodology adopted and the application of a computational process as an essential component of this methodology. We elect to adopt as a significant standpoint, therefore, that H. SIMON’s hypothesis contains an important idea particularly conducive to our aspect of science education - and one that addresses the research question - namely, that at least part of scientific reasoning can assume problem-solving of a structured kind, that it can provide a cognitive structure for interpreting the problem, and that it is one whose essence - under particularly appropriate circumstances and conditions - can be captured within a context of computation. It may be construed - from an instructional perspective - that through a specified computer program, the computer provides both a learning environment and instructional-oriented procedure for expressing a problem-solving methodology using symbolic representation that is used in the methodology itself.

With respect to such a concept of rationality, therefore, we primarily argue in this paper that the scientific problem-solving structural features – partly dealt in this chapter (1.2) and partly in 2.7 - and the computational methods – which are treated in 3.5 - underlying FORRESTER's System Dynamics can also be regarded to provide such mechanisms and an adequate account of the manner in which some important elements and features of scientific reasoning, and of scientific method in particular, can be elaborated, instructed, understood, interpreted and/or appreciated.

However, while LANGLEY et al.’s computer programmes were developed to enable the eventuality of independent discovery of new scientific laws through the computer programming mechanisms, we consider System Dynamics to provide scientists/science learners - through its conceptualisation scheme, i.e., those structuring principles and systematic thinking procedures required by the methodology, and its computational features, i.e., through simulation-oriented programming - with the means of obtaining (further) insight into scientific problem-solving.

1.1.1 Specific Scientific and Computational Issues related to Education in Science with Computation

The notion of what computation is has developed a considerable degree of vagueness and flexibility, and the activity of computation carries as many different interpretations as there are reasons for using computers. Formally, computation serves the purpose of improving itself not only with regard to the difficulties of the processes of Numerical Analysis [7], but also with regard to the problems of the formation of models of physical processes.

Three standard and formal meanings, however, that one may consider to be particularly appropriate and applicable in capturing the essence that is at the core of learning and instruction of scientific problem solving with computation, can be extracted and summarised (from DAVIS & HERSH 1986), viz.,

- the Computer Scientist's Meaning:

  An abstract conceptualisation of the very simple operations known as computation is provided by the TURING machine [8], (see also PENROSE 1990). The order in which a computer carries out the

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[7] DAVIS & HERSH regard Numerical Analysis is an algorithmic approach to a problem, as the science and art of obtaining numerical answers to certain mathematical problems and to comprise the strategy of computation as well as the evaluation of what has been accomplished; (DAVIS & HERSH 1981, 161).

[8] In ALAN M. TURING's view, a calculation is a finite sequence of simple steps taken in a certain order. All computation can be broken down and then built up from such steps; the term "compute" is to summon the operation of the TURING machine.

computation is governed by the specific program that is written by a programmer. Standardisation of this process constitutes the coding of a programming language. This meaning, however, carries secondary significance in the development of our treatise.

- the Arithmetic meaning,

  In the Arithmetic meaning, to compute is to carry out the four standard arithmetic operations: addition (principally), subtraction, multiplication and division [9], over and over again, and on varying amounts of data, viz., the computer is understood, primarily, in terms of its computing capabilities.

- the Scientist's meaning,

  To the scientist, the computer is simply a device[10] that processes discrete information by performing sequences of logical operations on that information and on its own program. Through its property of being able to handle vast amounts of arithmetic and to perform symbolic manipulations, the computer can also be considered to become a tool for eliciting knowledge and gaining insight in key phases of the scientific process.

While the first two meanings - the computer-science and the arithmetic meanings - provide a notion of the technical and/or machine-oriented dimensions of a computational activity, we may resort to the scientific interpretation and the scientist’s perspective of computation to initiate the scientific context with respect to learning and instruction. In the educational context, one may regard the computer as a quiescent tool or resource which enlists that the thread of scientific activity is independent of

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[9] In the category of higher arithmetic one would also include the operation of extracting roots and the employment of elementary transcendental function, culminating in the concept of Numerical Analysis or elementary Scientific Computation.

[10] An assemblage of logical gates not operating as a Turing machine but functioning reliably in minimal time. A physicist working at the production level is not concerned with the use – even to Physics – to which an assemblage of gates is to be put. (DAVIS & HERSH 1986, 142).

the computer, even though the computer may be used extensively from time to time.

Within this context, conceptually, a mathematical model of a scientific process is proposed or initiated; its validity and/or its utility is (also conceptually) questioned; the model is programmed into the computer; the model is run to see if it predicts how the world really behaves; if it appears to fulfil all the criteria, its validity is accepted; if it does not do so, the model is modified and the entire procedure is repeated.

We note in addition, and regarded from a learning/instruction standpoint, since figures/numbers can be considered to be processed into information by computers, Scientific Computation can be regarded as a means of transforming (scientific) data - that is fundamentally in an abstracted form of information - into another form of knowledge that is more amenable as a basis for scientific treatment and/or action.

Further computation may form the basis for the transformation of one scientific procedure into another [11].

Computation to the scientific researcher thus becomes a tool for eliciting knowledge and can quite legitimately, therefore, be considered to be another of the means towards obtaining scientific knowledge [12] and, consequently, can be regarded to be serving a dual purpose.

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[11] Observed from our particular science education perspective, an interpretation of Scientific Computation was optimally captured by WEIZENBAUM who wrote:

> "Computers make possible an entirely new relationship between theories and models. .... Theories are texts. Texts are written in a language. Computer languages are languages too, and texts may be written in them. We may include all languages, specifically also natural language, that computers may be able to interpret. .... The point is that computers do interpret texts given to them, i.e., texts determine computers' behaviour." (WEIZENBAUM 1976, 144 -145).

WEIZENBAUM went on to add:

> "Theories written in the form of computer programs are ordinary theories from one point of view. ..... But the computer program has the advantage not only that it may be understood by anyone suitably trained in its language, just as a mathematical formulation can be readily understood by a physicist, but that it may also be run on a computer. ..... A theory written in the form of a computer program is thus both a theory and, when placed on a computer and run, a model to which the theory applies." (WEIZENBAUM 1976, 144 - 145).

[12] Others that have been mentioned being deduction, induction, experimentation and experience, analogy and metaphor, intuition, and even guesswork and revelation. (DAVIS & HERSH 1986, 151).

Through the computer-oriented and scientifically-formalised concepts of "Scientific Computation" [13], i.e.,

> ".... the reason for getting numerical answers to scientific problems ..... (154); ..... a means of getting insight [14] into algorithmic procedures and to gain confidence that the computer delivers ..... (155); as a tool for eliciting knowledge to be used as the occasion necessitates ..... (158)" (DAVIS & HERSH 1986),

the computer has imposed a remarkably different perspective to the traditional view of what it meant to approach and solve a scientific problem and this, consequently, we consider to have provided a third alternative to the theoretical-experimental emphasis in science (particularly Physics) education - the Computational procedure. Such an aspect we do not necessarily regard to be simply an extension of either the theoretical procedure or the experimental procedure, but as a procedure that can provide a new, powerful way of doing scientific

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[13] and of "Computability", i.e.,

> "..... an algorithmic procedure for answering mathematical questions of a general nature ..... (66); ..... an idea which cuts across all areas of mathematics (86) ..... has some fundamental relations to practical computing ..... (92) (PENROSE 1990).

[14] According to R.W. HAMMINGS, computation is not done in isolation but for real-world reasons; his theory of Scientific Computation carries the motto, "the purpose of computing is insight, not numbers", and conveys the meanings:

- "that computation should be intimately bound up with both the source of the problem and the use that is going to be made of the answer - it is not a step to be taken in isolation, and that are ascribed to difficulties that are intrinsic to the process of scientific calculation on a digital computer .....
- and to the existence of competing algorithms for any particular task;" (HAMMINGS 1973, 3-5).

research and, therefore, we regard to be offering another facet in the quest to learning about scientific method.

From a purely scientific perspective, however, computation can be regarded as serving the purpose of improving itself not only with regard to the difficulties of the processes of Numerical Analysis , but also with regard to the difficulties of the formation of models of physical or social processes.

From an interdisciplinary Physics-and-Mathematics (/Physics-with-Mathematics) education angle, the roles played by mathematical theory, computational physics and experiment are, therefore, seen to be complementary. Each process can contribute in part to the understanding and learning of physical processes. IAN SLOAN captures this in the following statement:

> "Though Scientific Computation is an art, ... a proper approach to Scientific Computation can be taught. One aspect is ..... the importance of well-structured and well-documented code. ..... it is even worthwhile sacrificing efficiency in the interests of creating a simpler and more understandable code. But even a well-structured program can give the wrong answer, so that a proper attitude to checking is required. ..... In fact, I approach checking as a creative activity, calling for much imagination in the devising of checks. .....";
> (DAVIS & HERSH 1986, 162).

Problem-solving ability - an important high-level skill that finds place in most physical science instruction because it represents a higher level activity than the learning of facts – is used to indicate a certain level of comprehension of the scientific concepts and the principles in addition to the facts that have been learnt. Learning problem-solving implies developing the ability to solve a problem given a set of conditions not previously encountered. As such, problem-solving objectives - principal among which being those that require the learner to synthesise, generalise or evaluate - are difficult to teach because all such behaviours are considered to reside within the learner.

From the vantage point of both the scientific process and the learning/instruction of cross-disciplinary science, Scientific Computation enlists the appreciation of the notion of computation as an essential part and process of learning about scientific problem-solving and, therefore, also becomes another of the avenues to the acquisition of scientific knowledge – and thereby also serving duality of purpose. When adopting a strictly educational perspective, therefore, this form of computational process can also be seen to have the potential to provide an effective, but non-traditional learning context and to provide the cognitive tools for modelling specific scientific concepts, in particular, those that can be graphically displayed and manipulated by a computer. In this context, we identify in the System Dynamics simulation runs one such vehicle for providing the computational environment and the mediating computer simulation tools for learning about key aspects of scientific method that also suggests strong conformity with the view of learning that was offered by the VYGOTSKY-LEONT'EV-LURIA School (VYGOTSKY 1978).

This view of learning is (re)gaining credibility and application in research on instructional technology (c.f. NEWMANN et al. 1989) and particularly in education (c.f. MOLL 1990) and we, therefore, make reference here to the significance of this perspective. The theory essentially proposes that learning results from interaction that accompanies assisted performance as the learner is helped to accomplish a meaningful task. Task-oriented, assisted interactions are mediated by „social/cultural“ signs or cognitive tools. Learning or understanding occurs when the learner successfully internalises or appropriates the tool-mediated actions (VYGOTSKY 1978). We consider this proposition later and in greater detail, particularly with respect to our notion of learning through debugging, in 3.5

Consequently, if we can communicate to one such computational machine the behaviour of the model, the machine can simulate the physical model. In the simulation mode. One is, in this case, essentially comparing two structurally-different but intrinsically-identical mathematical models, and this dramatically alters the conventional situation - namely in secondary Physics education - by enhancing the status of the mathematical representation and of mathematical experimentation. Computer simulation can be considered, therefore, to be fundamentally a computational technique in which abstract models - of what is considered the crucial aspects of the physical situation - are set up and run on the computer. Through a computer simulation, the scientist can explore consequences of certain mathematical formulations; s/he is thus extending the range of applicability of mathematical models.

In terms of Scientific Computation, this means that if one is able to communicate to the computer enough information about how the scientific/physical model - conjectured to obey some mathematical laws or equations - will behave, then the model can be simulated by the computer so as to provide a specification - the solutions to the mathematical equations - of the model. In many cases, the differential equation, whose solution is to be computed, is proposed as the model for (some dynamic) aspects of the physical situation.

Such a finite mathematically-oriented procedure, or sequence of specified actions within a mathematical context, leads us to the notion of an algorithm - whose structure can also be considered to assume the form of a computer program - and is regarded one of the most important notions in modern mathematics;

> "..... since much of mathematics is concerned with finding effective procedures for doing all sorts of different things ..... and there exists deep mathematical questions, having to do with the fundamental nature of mathematics itself .....", (WEIZENBAUM 1976, 46-47).

As a consequence, this particular aspect of computation can be seen to enhance the status of mathematical representation and of mathematical formulation in the scientific process. An approach that is algorithmic is summoned when the problem at hand requires a numerical answer which is of importance for subsequent work either inside or outside of the purely mathematical content (DAVIS & HERSH 1986) [15]. Essentially, therefore, one is comparing and contrasting two distinct entities - each of which has its own object properties - a mathematical model (given, for example, by one or more difference equations) and the physical model.

The ultimate test of the utility and/or validity of the model comes from its predictive or explanatory value to the physical problem originally posed. Scientific Computation also enables the scientist, and consequently, provides the science student with the means, to gain insight into the algorithmic procedures, and to gain confidence in the answers that the computer delivers.

1.1.2 Scientific Computation in Science Education

As a scientific tool for modelling and simulating scientific problem situations, the computer can be perceived to have provided a unique dimension to mechanisms and, therefore, to the nature of scientific problem-solving. In implementing the computational technique which is known colloquially, but particularly in mathematical jargon/literature, as computer modelling and computer simulation, the following four-step process is typical and didactically significant (summarised from DAVIS & HERSH 1986, 79):

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[15] Algorithmic thinking, modular thinking, systems thinking, state thinking and meta-thinking are the intellectual components of Computer Science; (DAVIS & HERSH 1986, 126).

1. an abstract/mathematical model taking into consideration the crucial aspects of a process or physical system is proposed and set up;

2. the model is then run on a computer to question its validity and/or utility - thereby taking the form of mathematical experimentation;

3. the experimenter/learner observes and interprets the results to predict how the system really behaves;

4. the experimenter/learner then changes the parameters and again observes what happens.

In the above process, we perceive the notions of mathematical model and experiment in relation to the computer to provide the essential link between the process of computation as adopted by experts (in Numerical Analysis, DAVIS & HERSH 1986) and an educationally-oriented interpretation for the significance of Scientific Computation, as well as to provide the necessary factors that constitute the underlying computational environment.

In order to provide for the didactical significance and justification for computation in scientific processes, described again in the mathematics literature as

> “a scientific tool for eliciting knowledge to be used as the occasion necessitates“ (DAVIS & HERSH 1986, 158),

we first elect to make reference to, and therefore retrieve and adopt in this paper, DAVIS and HERSH’s interpretation of HAMMING’s (1973) motto (“the purpose of computing is insight, not numbers“ - DAVIS & HERSH 1986, 158) which, in essence, regards and comprises the process of Scientific Computation (summarised from DAVIS & HERSH 1986, 154-155):

1. to be intrinsically bound up with the source of the problem and the use that is going to be made of the answer,

2. to be intrinsic to the process of (scientifically-oriented) calculation as carried out on a computer, and

3. is to gain insight into algorithmic procedures and to gain confidence in the answers that the computer delivers.

Consequently, whereas 1 and 2 bear direct relevance to the scientific and societal context of our notion and perception of educationally-relevant

Scientific Computation, 3 provides the relevance and function of the role of the computer within these contexts. As such, the rationale for the concept of Scientific Computation with respect to the specified Scientific Literacy and Computer Literacy objectives can be considered to be given a degree of significance and status.

1.2 Role of Computers in Current Science Educational Practice and Research

Science education has, in the last thirty years, tended to be characterised by developments in three particular approaches to science learning/instruction (AITKENHEAD & RYAN 1992, LEDERMAN 1992, VOOGT 1994). These may be outlined as:

- an enquiry based approach;
- an approach emphasising the science-technology-society relationship;
- an approach stressing the importance of the learner's conceptual change when learning science.

All three approaches above require educationally-oriented environments which assume a markedly more active role of the learner, and approaches which are in sharp contrast to more traditional ones. From both a functional angle and from an implementation perspective, Simulations, CD-ROM/ Science Curriculum Software, Multimedia, Data-logging and Remote Sensing (Virtual Science Lab/Dry-Labs) and Databases are claiming significant potential roles in the anticipated effects and developments in science education driven by the steady integration of new Information Technology (GODDING 1998).

Of particular significance here are also two long-standing, broad perspectives underlying use of computer systems in science education provided by SCAIFE & WELLINGTON (1993) and COLLIS (1994):

1. Functionality relative to <u>rationales for use</u> - as governed by the different rationales behind the use of software. A categorisation within this perspective - adopting a system's view of computers in education - presents
    - social,
    - vocational,
    - pedagogical,
    - catalytic,

- industrial) and
- cost-effectiveness

considerations behind the effectiveness and the utility of computer systems. Initially, only the pedagogical and catalytic considerations are seen to bear direct relevance in the setting for the promotion of scientific computation literacy.

2. Functionality relative to types of use - through which computers are integrated in the science learning process - and characterised between authentic (desirable and purposeful) learning and inauthentic (unnecessary and irrelevant) learning.

In a seminal paper dating back to 1977, KEMNIS et al. (1977) identified four paradigms by which students learn through the use of computer systems:

- the instructional paradigm - which characterises much of the early use of computers in education, falling under the umbrella of CAL (Computer-Assisted Learning) and now largely superseded although still considered to have untapped potential - in explicit attempts to instigate and control learning.

- the revelatory paradigm - this has led to the development of computer-based simulations (and the resulting Virtual Science Lab/Dry Labs) in Science learning.

- the conjectural paradigm - reverses the psychologically inappropriate and educationally unsatisfactory controlling role of the computer in the instructional mode, and puts the learner in control of the computer.

- the emancipatory paradigm - signifies the integral role of the computer as a natural tool for thinking and creating - not necessarily only to be employed as a labour-saving device - but bearing in mind the authenticity (desired learning) and the context of the particular activity; this enlists the preliminary development of the embodied concepts.

The first two paradigms - the instructional paradigm and the revelatory paradigm - are generally found to be significant and, therefore, assume relevance only when considered in a historical and in a traditional context.

The conjectural paradigm, however, suggests the use of modelling and data interrogation employing a specific-purpose tool that comprises a form of programming, but whose utilisation and implementation involves skills that are distinctly different from mastering the rudiments of a programming language.

We show in 3.5 and in 4.5 that, through DYNAMO, the computational mechanisms underlying System Dynamics correspond to this paradigm's significance in providing the authentic and purposeful computational environment and conditions for students to get involved in the basic aspects of computer-oriented modelling.

The focus of control, moreover, is indicated by the role changing from the computer to the learner and onus being placed on the latter as the type of computer system shifts along the paradigms. And, therefore, at a functional level in which pedagogical and catalytic considerations are considered in the operationalisation of software, we see that the System Dynamics methodology allows us to readily operate and function within the conjectural-to-emancipatory paradigms in the implementation of those computer-based resources relevant to our particular aspect of science learning and the learning of scientific computation.

Modelling systems and microworlds – characterised by a System Dynamics and DYNAMO computer-modelling and simulation system, and a description compatible with the System Dynamics environment - are considered specific types of computer simulations (SCAIFE & WELLINGTON 1993) and, from an information technology-oriented perspective, scientific models can be classified as quantitative, semi-quantitative and qualitative (COX 1994).

Currently,

- Programming Languages,
- Authoring Tools,
- General Purpose Software, and
- Educational Modelling Packages

are used to provide scientific modelling opportunities in education (SCAIFE & WELLINGTON 1993, VOOGT 1994).

System Dynamics and DYNAMO are also available as one such package. However, while there are notable exceptions (MODUS 1991, STELLA

1994), the dominant paradigm for educational software and modelling packages for pre-university scientific disciplines, particularly Physics, is the delivery of content and for enrichment - which we refer to here as first-order effects from computers.

Such science “Black Box“ software packages are generally characterised by the following features (SCAIFE & WELLINGTON 1993):

- they give no indication of their internal structure;
- instructional content focuses on the recall of facts and algorithms;
- they are instruction-centred and serve primarily as enrichment or for occasional correction of misconceptions;
- tool-oriented applications are confined to data-base, spreadsheet and graphic capabilities;
- they are limited (i.e., they have high-threshold and low-ceiling), and focus on the product.

In contrast, the learning-wise more desirable “Glass-Box“ features would enlist the following attributes:

- their internal workings should be transparent;
- they provide a learning environment for motivating higher-order thinking, problem solving and deeper understanding;
- they are learner-centred, content-free environments - the computer serves as a major way that the student learns to think and to accomplish learning and understanding;
- they have tool-oriented applications and serve as problem-solving tools,
- they are open-ended (i.e., they have low-threshold and high ceiling) tools focusing on the process rather than on the product.

In particular, we consider the presence of these particular learner-oriented educational features in a software package as providing an environment and scientific content that we consider to be more compatible what scientific problem-solving with the computer means and necessitates, and which may provide the learner with the notions and utilities to acquire appreciation and/or understanding of such a problem-solving process.

1.3 The Social Context of Science

Content related to the nature of science, e.g., science's epistemology and its social context, has been an issue that has been acquiring increased significance and forms an integral part in scientific education primarily because of interest of teaching and portraying science through a science-technology-society approach (AITKENHEAD & RYAN 1992) and/or in the context of the history and philosophy of science (International Baccalaureat 1998).

Among a number (eight) of the interpretations of scientific literacy cited by JENKINS (1994), three [16] that are prominent in school science but that are

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[16] The other five are:

- an appreciation of the nature , aims and limitations of technology, and how these differ from those of science.

also of particular significance in the context of scientific computation literacy. They are:

- an appreciation of the nature, aims and general limitations of science, e.g. a grasp of the scientific approach, the deployment of rational arguments, the ability to generalise, systematise and extrapolate, and to approach the roles of theory and observation;

- an appreciation of the interrelationships between science, technology and society, including the role of scientists and technicians as experts in society and the structure of the relevant decision-making processes;

- a general grounding in the language and some of the key constructs of science.

As such, and within the context of providing and effecting a more transparent application of educational software , the overriding manifesto and themes of this work are generally, therefore, also concerned with the investigation into specific second-order effects enlisting a more purposeful

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- a knowledge of the way in which sciences and technology actually work, including the funding of research, the conventions of scientific practices and the relationships between research and development.

- a basic ability to interpret numerical data, especially data relating to probability and statistics.

- an ability to assimilate and use technical information and the products of technology, including ‘user competence’ in relation to technologically-advanced products.

- some understanding of where, and from whom, to seek information and advice about matters relating to science and technology.

and more comfortable - in a computer-based learning context, and more meaningful - in a science-learning context introduction of a computer culture into a particular, fundamental aspect of science education but where the emphasis is still placed on scientific modelling and on scientific method.

Also because science education ought to, by its very nature, continuously and rapidly progress both in depth and in breadth – the latter, because scientific processes are being inevitably shaped by evolving social factors - content related to the appreciation and learning of nature of science can never be considered to be stable but in a state of transition. Furthermore, scientific activity continues to engage an increasing proportion of the world’s population, and requires the exploitation of an increasing fraction of the Earth's resources.

We consider, in our particular educational context, that since scientists have the obligation to examine the social implications of their work, not in order to decide how or if it should be used, but in order to make clear the reliability of the interpretations of the observations, the social context and social content of scientific activity thus directly influence the aims and objectives of science learning/instruction. We contend that, as well as strengthening the theoretical basis of scientific knowledge, BLOOM's prognosis is still relevant, namely that science curricula must encompass knowledge that has

> "..... survival value, seeking to provide students with intellectual abilities and social values relevant to scientific world of the future. .....“ (BLOOM et al. 1971, 564),

that any developments in science education must take into consideration related sociological issues, and that science must be studied in a social context; this continues to be an imperative in the development of science curricula (ROBERTS 1982, FLEMING 1989).

The teaching of science content must correspond to a purpose or intent. While the content specifies what is to be taught, the intent deals with the issues of why the content is to be learned. This is addressed through the curriculum emphasis which has been explained as follows:

> "A curriculum emphasis in science education is a coherent set of messages to the student about science - rather than within science. Such messages constitute objectives which go beyond learning the facts, principles, laws and theories of the subject matter itself - objectives which provide answers to the student question: "Why am I learning this ?" (ROBERTS 1982, 245).

In relation to this perspective of the influence of culture and society upon the learner's scientific development, a socially and culturally-oriented psychological view that we consider to bear appropriate significance and relevance, particularly within the context of Scientific Literacy underlined by this thesis - and one that we understand and consider also to bear compatibility with VYGOTSKY's unique perspective upon the function and meaning of computer tools - is FEUERSTEIN's Theory of Mediated Learning (1980).

FEUERSTEIN - like VYGOTSKY (1978) and BRUNER (1986) - also regards learning as occurring in a social context through social interaction. For VYGOTSKY, society provides a tool-kit of concepts and ideas and theories that permit one to get to higher ground mentality; He believed that modernisation of the peasant through collectivisation and mechanisation could be described in the same way as one described the growth of the child from pre-scientific to scientific thinking, and says:

> "Human nature presupposes a specific social nature and a process by which children grow into the intellectual life around them;" (VYGOTSKY 1978, 88).

FEUERSTEIN, on the other hand, asserts that it is not the culture that is depriving, but that the individual, or her/his group, that is deprived of her/his own culture. Culture is not defined as a static inventory of behaviours, but as the process by which knowledge, values and beliefs are transmitted from one generation to another. The key features of this theory are summarised as (FEUERSTEIN et. al., 1980, 1991):

- Understanding purpose;
- Taking control of one's own learning;
- Learning to become individuals functioning within society.

Consequently, in investigating the significance and relations of developments, and the probable social and cultural impact on changing educational requirements, we make reference to three major changes and trends that characterise the last ten years - but that are observed from an European or Western perspective - that are currently significant:

- Fluctuations in economic growth - leading to periods of economic depression, the reappearance of protectionism and structural unemployment.
- The dominance of the economic/industrial superpowers, their polarisation and increasingly blatant imperviousness.

- Awareness of the need to preserve the biosphere.

In order to promote a realistic, non-mythical understanding of the nature, process as well as the social aspects of science, we consider, therefore, that the learning of science is required to become amenable to social control and cultural influences, and the approach to scientific inquiry (through scientific method) must emphasise the socially contingent nature of knowledge production and validation, and on the pluralistic nature of the sciences.

A scientific inquiry program has inevitably also to be constantly re-examined for its appropriateness and relevance for preparing individuals for a life-style in a society that is characterised by fearsome uncertainties and dissonances that can no longer be ignored, as well as by changes brought about by the social consequences of technological development - itself based on scientific discovery. In the words of MERCHANT (1980):

> “In investigating the roots of our current environmental dilemma and its connections to science, technology and the economy, we must re-examine the formation of a world view and a science .... The contributions of such founding fathers of modern science as BACON, HARVEY, DESCARTES, HOBBES, and NEWTON must be re-evaluated.“ (MERCHANT 1980, xvii).

More specifically, education [17] is also required to become anticipative and to react without amends in order to inculcate in everyone a comprehensive awareness of contemporary global trends and the tendencies they represent for the future, together with the necessity to be vigilantly aware of the possible consequences of existing trends - if only to ensure that they do not continue in their present form.

We contend that studies based on or oriented towards System Dynamics have ramifications that can enable achievement of the transformation of a problematic situation by inquiry as occurring in the experienced world - and to extend the learner's engagement with aspects of knowing that the

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[17] On the educational needs of society undergoing change, ALEXANDER KING prescribed:

"One of the greatest contemporary needs is for a widespread and deep understanding of the world situation, without which even the wisest governments will be powerless to introduce corrective policies which may entail painful and unpopular measures. The creation of such an understanding is an urgent requirement of our education systems, as yet frequently ignored." (KING 1985, 234).

learners themselves find problematic - through its environmental and technological features and, particularly, through its applications.

Reflections within this context retrieve and suggest a perspective first adopted by DEWEY on how technology supports learning and a perspective with which technology can enable communication and enable learners to engage in inquiry. DEWEY located the place of technology in a central place in inquiry; he viewed inquiry as a productive craft, and technology as the tools of the craft (DEWEY 1938a). HICKMAN (1990) summarised the manner in which DEWEY considers technology could function to enhance inquiry:

- technology should provide stable, long-term access to problematic situation that may occur infrequently or be short-lived;

- technology should focus attention on specific attributes while nonetheless retaining the broader context of the situation;

- technology should augment ways of behaviour so that their meaning is more readily available to others;

- technology should enable the experiential and experimental dimensions of learning.

We contend that System Dynamics' technological – hardware, software and environmental - facilities conform to DEWEY's technology-based and inquiry-oriented approach and can be extensively functional in providing the type of inquiry-based environment conceptualised by him. With respect to this, we examine in more detail in CHAPTER 2 (2.6 and 2.7) and CHAPTER 3 (3.4 and 3.5), those procedures by which the elements of the System Dynamics methodology provide the structuring mechanism and set of interdisciplinary Scientific Computation tools/technical support that are/is required to extend the learning of scientific method and the prevailing environment into different scientific domains. We adopt this standpoint as a fundamental, underlying postulate in this paper and, at this juncture, we also make particular reference to the LIMITS TO GROWTH Report (MEADOWS et al., 1973) and its sequel, the BEYOND THE LIMITS Report (MEADOWS et al., 1992) as a potentially powerful means for providing the social/cultural environments and knowledge resources to validate our postulate. Because of its affiliations with System Dynamics, such social/cultural knowledge or mode of interaction which - exists at the tacit level - provides a socially-based, interdisciplinary and authentic-learning inquiry opportunity that can be addressed directly, thus becoming explicit in the course of the interaction. As tacit knowledge, however, this social/cultural knowledge can influence information processing with or without students being aware of it (WINNIE and BUTLER 1995).

The BEYOND THE LIMITS Report (MEADOWS et al., 1992) is supplemented extensively by (primary and secondary) literary resources and computer simulation software for both research and teaching purposes, and with the basic ideas inherent in FORRESTER's original WORLD 3 (MEADOWS et al., 1973) model featuring prominently. The technical documentation for the WORLD 3/91 model, the set of WORLD 3/91 computer equations and the corresponding simulation software (DYNAMO/STELLA compilers) comprise the set of tools/technology and interactive environments required to experiment with (and revise) WORLD 3/91. We regard this use of external support from tools that scaffold tasks to have positive implications in the accomplishment of Scientific Computation Literacy.

1.4 Objectivism and Constructivism / Constructionism in General and Computer-Oriented Science Learning and Instruction

This particular subsection provides some background detail for and relates to - and is further developed in the empirical survey conducted - CHAPTER 4 and is primarily concerned with viewing, through the notions of constructivism/constructionism and objectivism, aspects of the learner's own perceptions and personal convictions of the content and context of her/his science learning of science so far. The manner in which these impressions and perceptions may be influenced as a result of interaction with elements of Scientific Computation through the unconventional culture of a System Dynamics environment is studied and analysed.

With particular reference to the students involved in the Empirical studies in CHAPTER 4 – and the stage they have reached with respect to their learning - it may be stipulated that in the course of their scientific learning experiences and the resulting acquisition of their scientific knowledge, these students have developed individualistic ideas about knowing and learning in science, which in turn are likely to interact with further schooling experiences. That is, by the time the students have completed the pre-university stage, we contend that their views of science are often set, and they can be considered to have developed definite attitudes towards the scientific knowledge that they have acquired and to patterns of learning that have led to the acquisition of this knowledge. Constructivism and objectivism are considered to be prime, contrasting aspects of learning behaviour that have contributed to, and influenced, the adoption of such attitudes and patterns.

Mainstream western science education is based on an objectivistic epistemology (LAKOFF & JOHNSON 1980, LAKOFF 1987) - an individual born into this world is born into a world in which there already exists much knowledge.

> "In the analysis of knowledge, the objectivist gives priority to the characteristics of items or bodies of knowledge that individuals are confronted with, independently of the attitudes, beliefs or other subjective areas of those individuals; (CHALMERS 1982, 115).

Thus objectivism holds that there is an objective reality consisting of objects - and these can be accurately described by scientific concepts - that have fixed properties and relations among each other. Consequently, such objects are used to make statements (about nature) which are, consequently, considered to contain definite truth values – secular knowledge of a scientific nature - with respect to scientific knowledge.

Within the sphere of scientific education, objectivism implies that scientific knowledge is treated as something outside rather than in the minds or thoughts of individuals. Manipulation of the scientific concepts - which receive meaning by correspondence to reality - constitutes scientific thinking. Acquisition of scientific education corresponds to the acknowledgement of a body of knowledge that one is confronted with and which represents the current stage of development.

Instruction/teaching, from an objectivistic position, is conceptualised as the means by which knowledge is transferred from a proficient expert to a novice or less knowledgeable individual (ROTH & ROYCHOUDHURY 1993). The learner is cast into the role of a relatively passive recipient of knowledge.

Objectivism is, consequently, seen to be opposed to an individualistic point of view according to which knowledge is understood in terms of beliefs held by individuals and is residing in their minds (CHALMERS 1982), and objectivism has, therefore, been subjected to severe criticism from areas of educational research (VON GLASERSFELD 1984, BRUNER 1986).

Impressions obtained through observation and personal teaching experiences indicate that individualism in science learning situations subscribes to the position that students as individuals generally have three fundamental ways of acquiring scientific knowledge, i.e., observing, thinking and tracing the outcomes to the foundations of knowledge. Individualism in science learning can be regarded to be opposed to objectivism and, therefore, constitutes a preliminary condition to constructivism, which has been proposed as an epistemology that is more conducive to computer-based learning environments (SOLOMON 1986, PAPERT 1993).

Central to constructivism - a view that gets support from common usage and which is an epistemology that better fits findings in philosophy of science (CHALMERS 1982, GOODMAN 1984), in sociology of knowledge (von GLASERSFELD 1984), and in social and cognitive psychology (BRUNER 1986) - lies the conviction that:

> "knowledge does not reflect an objective ontological reality, but exclusively an ordering and organisation of a world constituted by our experience"; (von GLASERSFELD 1984, 24).

Consequently, according to constructivism, scientific knowledge is invented or constructed by the individual, rather than being abstract scientific truth delivered through the instruction process; and the corresponding meaning that is individually constructed is done so by negotiation and interaction with other members of the same culture, and not simply transferred from the teacher to a less knowledgeable learner. A constructivist learning environment will, therefore, emphasise the interaction of the learner with her/his physical and social environments (ROTH & ROYCHOUDHURY 1993).

Constructionism - i.e., SEYMOUR PAPERT's "personal reconstruction of constructivism" (PAPERT 1993, 142-143) and a concept developed to undervalue abstract reasoning in science instruction - and to take into account the potential of computers in changing the epistemological structure of learning - also looks at the concept of mental and physical construction, reflection and intuition in learning, and again also denies objectivism’s obvious truth.

Perceived in the scientific sense, constructionism seeks for a scientific thinking and learning methodology and environment that will allow one to stay close to concrete situations (PAPERT 1993). It attempts to offer learners a more modern image of the nature of scientific activity..

When considered in the strictly computational sense, we can understand why PAPERT also always believed that the computer's assets have to be moulded to the learner's needs and a new kind of computational mathematics that coincides with a natural, exploratory learning and debugging process using computational entities has to evolve (SOLOMON 1986). We contend that this belief can just as appropriately be extended to computer-oriented science learning.

2 The SCIENTIFIC COMPONENT of SCIENTIFIC COMPUTATION LITERACY

2.1 The Significance of Models in Science Education

The aspects of traditional Physics education (and some aspects of Physical Science learning/instruction) that dominate and influence curricular issues as well as the instructional methodology - and those that are currently effected in practice and, consequently, those that also determine a significant portion of pre-university Physics learning experiences - were based on analysing the logic of scientific reasoning, i.e., on those characteristics of scientific method that contained elements of deductive reasoning as well as inductive reasoning. Deductive reasoning is typically manifested in the fact-finding, observation and experimentation processes that characterise Physics education. Inductive processes (as well as comprising deductive elements) include hypotheses generation, experimentation and implications. Ultimately, the experimental component is often followed by curve fitting and the application and supplementation of fundamental, relevant mathematical relationships.

The philosopher and mathematician WHITEHEAD expressed the mathematically-oriented nature of scientific method in the following rule:

> "Search for measurable elements among your phenomena, and then search for relations between these measures of physical quantities." (WHITEHEAD 1925, 66).

This statement would serve to provide an indication of the power of logical thinking and at the same time of exploiting this power, and this would also allow an interpretation of scientific method that is educationally more conducive in relation to mathematically-oriented Physics.

Such an approach to the process of preliminary scientific instruction and learning of Physics - and of related laboratory activities - has evolved as a consequence of curriculum adherence to the notion that the underlying instructional philosophy, scientific content and scientific problem-solving process themselves are guided by a dominant principle underlying scientific method. That is, upon the reliance of scientific endeavour on the method of hypothesis or the hypothetico-deductive method, generally simplified and manifested in Physics education as the theoretical and the experimental respectively.

The hypothetico-deductive method is today still seen to dominate and characterise a large part of the pre-university curriculum and an attitude towards its use has become so ingrained in our scientific culture and scientific education that it has often been solely linked with scientific method. Elements of modern Physics - which extend into the realms of atomic and sub-atomic phenomena and where many of the basic concepts of reality had to be radically revised by turning to ideas about probability, or by recognising the role played by the historical and social context within which any scientist must work - however, have shown that alternative approaches are also scientifically sound and have a valid place in the scientific enterprise. GOWER (1997) states that scientific method should also shed some light on current thinking and on the character and characteristics of scientific beliefs expressed in scientific statements:

> “A naturalistic approach to a subject which involves some social co-operation rather than solitary ratiocination, calling on the insights of social scientists, is more appropriate.” (GOWER 1997, 7)

In a further development one may consider – as we have elected to do in this treatise - incorporating elements of systems thinking and the adoption of a holistic approach with comparable validity due to their effectiveness in problem-solving in some aspects of biology and the social sciences.

Conventionally, scientific method based on deductive inference and aspects of inductive thinking, and as characterised particularly in science education and normal scientific activity, is formally set out as a circular scientific problem-solving process starting from and ending in observation in the following four well-known steps:

- Observation of a physical system;
- Formulation of a hypothesis/model;
- Deduction of consequences from the hypothesis/model, and
- Test of the hypothesis/model again by experiment/simulation.

Through the concepts and method of simulation, which introduces a degree of confirmation in scientific method through predictive and explanatory devices in science, a key aspect for inductive reasoning - which is concerned with whether a hypothesis is confirmed by given evidence – can be regarded to be introduced to complement scientific reasoning.

The concept "model", nevertheless, is (and has always been) observed to be fundamental to scientific problem-solving, since it is present at all stages from problem-definition to solution. Naturally, therefore, a large and significant part of the scientific enterprise - some would indeed believe that all of scientific work - is considered to implicate the formalisation and the construction of models.

Contemporary science curriculum guidelines have always and readily acknowledged the significance of this particular aspect of scientific problem-solving, and have adopted this standpoint specifying the building, testing and revising of a theoretical model [18] as a behavioural objective Scientific problem-solving in general is considered to be the most difficult type of objective [19] to teach because all the behaviours pertaining to problem-solving reside in the learner and must be initiated by the learner her/himself.

Essentially problem-solving, particularly in much science/mathematics education, implies a novel situation for the student wishing to attain a goal or objective, but does not know how s/he should proceed. Possession of

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[18] Perceiving the need for a finer breakdown to include the other science branches as well as applied research - and one which we consider appropriately articulated for education - ACKOFF (1971) outlined a more appropriate/practical cyclic process:

(i) formulating the problem,
(ii) constructing the model,
(iii) testing the model,
(iv) deriving the solution from the model,
(v) testing and controlling the solution, and
(vi) implementing the solution.

[19] Key aspects are summarised (adapted from BLOOM et al. 1971, MOE 1988, International Baccalaureat. 1992, 1998):

- Recognition of the need for a theoretical model.
- Formulation of a theoretical model.
- Deduction of new hypotheses from a theoretical model.
- Specification of relationships satisfied by a model.
- Deduction of new hypotheses from a theoretical model.
- Interpretation and evaluation of tests of a model.
- Formulation of a revised, refined or extended model.

the requisite knowledge and sub-skills may be at hand, but the manner in which s/he should sequence her reasoning or by which s/he develops heuristics which will enable her/him to proceed from the initial state to the goal state is, generally, a clearly missing element.

The significance of model-building (and of models) was acknowledged and succinctly captured by ROSENBLUETH and WIENER over fifty years ago in the following didactically-oriented (we consider) statement:

> "No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Such abstraction consists of replacing those parts of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of the scientific procedure." (ROSENBLUETH & WIENER 1945, 316).

Until the advent of computer-based modelling through efforts like DYNAMO (ROBERTS 1983), STELLA (MANDINACH 1989), MODUS (WEDEKIND 1991) - a profound appreciation and/or acknowledgement of this aspect of the scientific enterprise notably and persistently seemed to elude manifestation or materialisation in pre-University Physics learning. This may be attributed to the recognition by syllabus designers and educational scientists involved in setting out Physics instruction and/or learning programmes - and also accounting for the constraints placed by content size - that the essence of scientific reasoning is an integral part of the inquiry process and, therefore, most practically and realistically realised through emphasis on

- discovery of scientific problems,
- formulation of such problems, and
- obtaining solutions to the problems.

Incorporating elements of social science and systems thinking would first serve to recognise that the models classical mechanics provide are strictly logical; they are deductive models and articulations of theory.

Classical science can also be seen to embrace inductively obtained models, summarising an organised body of experimental data. Models of both these kinds are systematic thus making them conducive and adaptable for instructional treatment and for demonstration. We also regard that a secondary function of model-building and model-testing in instruction is to enable the learner to identify structure in scientific enterprise, deductively as well as inductively, and not merely to organise and/or formulate scientific detail. Otherwise, the process of model-making remains and consists of forming logical and consistent networks of concepts to interconnect observed data. In classical science the data are quantities, obtained through measurement, and the conceptual models become statements are, whenever possible, expressed in mathematical language.

From a system's perspective, however, a scientific concept or phenomena is fully understood, when it is identified as part of a larger frame in terms of structure, functional relations, cause-effect relations or combinations of these frames, and not strictly in terms of deductive/inductive logic. In educational practice, with much of the current Physics instruction and learning compartmentalising concepts and phenomena, different models are used to clarify different phenomena, and a standardised piece of mathematical argument is implemented to demonstrate how these models can explain the observations (see International Baccalaureat Physics 1998). A version of scientific method is put forth, but the underlying methodology of science is generally neglected or assumed to be implied in the presentation of subject matter. While pupils in early secondary education are still provided with instruction in standardised and well-established models of science, students in tertiary education learn that the methodology of science is still being questioned and is still changing. Students in both levels are given training in experimental methods, and results are produced in a way that suggests that science is predominantly deductive. Nevertheless, no significant developments or departures from the status quo is to be interpreted from the recently reorganised Physics programme and syllabus for International Baccalaureat (International Baccalaureat Physics 1998), which characterises one of the most recent developments at updating the status of Physics at the pre-university level in Europe and the United States of America, but may well typify other comparable efforts.

As a principal argument in this work, therefore, we consider the three components scientific modelling, scientific method and scientific problem-solving to form albeit distinct modes but, in the course of implementation in an educational context, inseparable characteristics of the scientific reasoning process and, therefore, should comprise the essential aspects in the promotion of the learning or appreciation of the process of scientific reasoning.

The essence of such an attitude is captured, characterised and typified by the following statement - which provides some guiding principles in curriculum design, but which also allows a significant amount of room for interpretation - and issued by the Conference Of The American Association For The Advancement Of Science:

> "Science teaching should stress the spirit of discovery characteristic of science itself. Discovery is possible at all levels. The simplest step for the pupil is to discover phenomena and to observe relationships new to her/him; at higher level, s/he can discover relationships by experimentation; at a still higher level s/he should learn to discover by abstract reasoning." (taken from ONTARIO - Ministry Of Education - Curriculum Guideline SSOA, 1988, 5-6).

The second argument we put forward to promote the scientific reasoning process through scientific method and scientific modelling, is to exploit in an educational context the second primary function of a model - namely that of enhancing verification. In order to delineate the characteristics of model construction through analysis and to establish links between understanding and prediction, the aspect of "modelling purpose" has, indeed, also to be considered. The search for functional relations or cause-effect relationships enables the construction of better models to aid in the prediction of the occurrence, or even of the cause of the occurrence, of future events through the control of relevant parameters.

Reverting to our educational - primarily and strictly science instructional perspective, we interpret and adopt - from DAVIS & HERSH 1986 - induction to be related to the awareness of observation and of existing theories, deduction to be related to the construction of a model and of physical conclusions drawn from it by means of mathematical derivation, and verification is related to acquiring deeper understanding of the phenomena through experimentation.

Altogether, such iterative understanding and verification - problem-solving-oriented - procedures employed in Physics instruction, and combining the aspect of experiment with theoretical notions in scientific modelling, can be educationally valuable since they would provide a more comprehensive description of scientific problem-solving, as well as supplying the agents for acquiring the proper scientific attitudes; this would serve to make the appreciation of scientific method, from the learner's perspective, substantially more feasible and accessible.

We attempt to establish that with the integration of System Dynamics, which stresses systems thinking and the underlying principles of Cybernetics, the three components - scientific modelling, scientific method and scientific problem-solving - can be made realisable in the context of learning about the scientific reasoning process.

2.2 Learning-Oriented Attitudes Towards Modelling from Issues in Computer-Based Modelling Philosophy

In computer-based modelling as practised by experts, the modelling activities and procedures are based on expertise developed through a combination of intuition, abstraction, logic, association and skill. The specific procedure governing such modelling activities itself involves generating ways of bringing specialised knowledge to bear upon every possible point in the process of solving the problem, and through finding solutions through such techniques as planning, progressive refinement and the exploitation of the knowledge of the structure of the problem domain (SPRIET & VANSTEENKISTE 1982).

To this effect, SPRIET & VANSTEENKISTE formally identify three major information sources, whose roots are to be found in scientific method, particular to computer-oriented modelling -

- Goals and Purposes,
- A Priori Knowledge and
- Experimental Data

that guide and provide the model construction criteria that is adopted by experts (SPRIET & VANSTEENKISTE 1982).

The attitude and response of the model builder towards these information sources will, subsequently, result in variations in modelling and problem-solving methodologies. Within the context of learning/instruction about scientific problem-solving through modelling, the underlying cognitive processes, deduction and induction (and abduction), can now be formally assigned the following curriculum-oriented definitions - particularly adapted and modified for computer-based modelling but possessing a significant degree of compatibility with the understanding of scientific method adopted - taken from SPRIET & VANSTEENKISTE 1982):

- **Deduction** is the reasoning - through analysis - from known principles to deduce the unknown. Whereas deductive knowledge of the laws governing the system can be obtained from a study of the scientific discipline itself, the knowledge about the structure of the specific system can only come from an insight into the system being modelled. In the case of structure, therefore, deductive model-makers rely significantly upon a priori information, i.e., they proceed from the general to the specific.

- By contrast, **Induction** is a much more uncertain process. Inductive model-makers begin by observation at the lowest level of a process and attempt - through synthesis - to induce higher-level knowledge that is compatible with the observed behaviour, i.e., they proceed from the specific to the general. The inductive model-maker is required to formulate the a priori model using assumptions, hypotheses-formulation, parameter/ variable-selection and experiment. Such form of analyses and syntheses characterise two of the most essential components of the scientific method.

- To take into account the prominence we give to the socially-scientific context of science learning and, consequently, the environment for learning about scientific problem-solving, we resort to the concept of **Pragmatism** which also serves to highlight the link between problem-solving and modelling. With particular reference to the process of induction, HOLLAND et al. state:

  "Induction is highly context dependant, being guided by prior knowledge activated in particular situations that confront the system as it seeks to achieve its goals. The study of induction, then, is the study of how knowledge is modified through its use"; (HOLLAND et al. 1986, 5).

  Pragmatism in model-making means taking a teleological point of view and tending to focus on purpose and goals. This suggests that modelling has a normative implication, i.e., inference in scientific theories must be understood in the problem-solving context. Pragmatism is used to organise knowledge in memory so as to facilitate subsequent inferences (HOLLAND et al. 1986), i.e., in the educational sense, to enable a system to organise its experience so that it has some basis for action in unfamiliar situations and to transfer information and procedures from one domain to another.

The development of the aspects Deduction, Induction and Pragmatism in the context of analysis and synthesis is regarded as constituting the development of the scientific modelling attitude that the learner could use to relate to and the instructor could employ to identify and establish the compatibility with elements of scientific method.

An additional new aspect, that is introduced in that it serves to elaborate model-development and may be regarded to provide guidance, insight and understanding in model-construction, considers four criteria that have been prominent in the history of science and that underlie the quality of a model (THAGARD 1978):

- **Concilience** - the ability of a model to explain and unify many different classes of phenomena. Concilience can be understood pragmatically as extending techniques for problem solutions to a wide variety of problems.

- **Originality** - the uniqueness of the ideas emerging from the model.

- **Simplicity** - a model should be a useful simplification of the substantive problem area.

- **Analogy** - from a pragmatic point of view, scientific theorists working in a problematic new domain often look to already understood areas as a source of transportable concepts and problem-solving techniques.

Thus we regard that any attempt to integrate a scientific modelling scheme into a instruction/learning strategy to elicit more information about, and to provide a context that the learner can relate to in acquiring an appreciation or understanding of the processes of scientific modelling, ought to exploit/accommodate a treatment that would lead to an integration of key aspects of the above-mentioned criteria. We attempt to show in the treatment in the subsequent sections that the System Dynamics methodology offers the possibility of taking into account such aspects and provides a conducive environment within which such an integration is feasible.

2.3 Scientific Computation and Computer-Oriented Scientific Modelling

H. SIMON, P. LANGLEY and their colleagues in advancing the hypothesis that certain scientific creativity can be carried out by a computer program and that a process of discovery can be described and modelled (LANGLEY et al. 1987), claim that rationality for a scientist consists in using those means available - those heuristics - for narrowing down the search for problem solutions to manageable proportions, and it is this concept of rationality that relevant to the creative process and to problem-solving in general. To them, processes of discovery and confirmation are closely interwoven. Using two examples from the history of Physics - Planck's discovery of the Law of Blackbody Radiation and Newton's Law of Universal Gravitation - LANGLEY et al. claim that if discoveries can be explained in terms of understandable cognitive processes, they should give some basis for approaching modelling through simulation of other scientific discoveries (LANGLEY et al. 1987).

SIMON & LANGLEY's central hypothesis is that particular mechanisms of scientific inquiry are not peculiar to that activity but can be analysed as special cases of the general mechanisms of problem-solving (LANGLEY et al. 1987). They do recognise science as a social process and also, since its goals when beginning to tackle a problem are usually not clearly defined, that it differs from ordinary problem-solving: finding problems and formulating them in a precise form is an integral part of science.

However, serious arguments have been posited against SIMON & LANGLEY's approach to problem-solving and the interpretations and implications (WOLPERT 1992). In adopting a curricular perspective to the level at which we are addressing scientific problem-solving issues, we see that such discussion of problems and problem-solving can be regarded to provide a rational way of introducing computers into problem-solving and appreciating their role in scientific analysis. Strong parallels can, therefore, be found to exist between SIMON & LANGLEY's computer oriented approach and FORRESTER's educationally-conducive and appealing approach, methods of representations and their respective world views of problems and problem-solving [20].

2.4 Curricular (Scientific Educational) Rationality for System Dynamics

MARTIN STARR [21], had once expressed a desire

> " ..... to affect the educational system at all grade levels - from kindergarten through post-doctoral studies - with management science techniques so that management science becomes increasingly relevant and effective ..... " (STARR 1976, 5).

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[20] A significant difference between the two approaches lies in the information processing mode adopted by the two approaches, and in the fact that SIMON & LANGLEY use heuristic methods (LANGLEY et al. 1987) whereas in FORRESTER's system everything is explicitly given an algorithmic character in terms of LEVEL and RATE variables enmeshed in feedback loops.

[21] A past president of TIMS (Harvard University-based Institute Of Management Science, a pioneer and professor in the field of Management Science education at the post-graduate tertiary level.

STARR was expressing a sentiment and a strong conviction about the predominantly scientific roots, the cross-curricular perspectives and the educational versatility and potential of the techniques and methodologies developed and adopted in Management Science problem-solving and education, while acknowledging and advocating FORRESTER’s System Dynamics as featuring prominently amongst these (STARR in WEST CHURCHMAN & MASON 1976).

FORRESTER's System Dynamics represents a development within Management Science education - as practised at the Sloane School Of Management - Massachusetts Institute Of Technology. The field formally known as Management Science, is applied science based on mathematics and on physical, biological and behavioural sciences, and encapsulates some of the most significant scientific approaches to business problem-solving (ROBERTS 1978).

The particular methods adopted in Management Science are primarily concerned with understanding behaviour of complex organisations, and are used to furnish corporate decision-makers with realistic evaluations of alternative courses of action aimed towards specific goals and to help shape their decisions accordingly.

We contend that Management Science techniques [22], due to their pragmatic application, can be seen to bear strong relation and influence

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[22] Additionally, four major areas have contributed heavily to the conception and evolution of Management Information Systems (ROSENBERG 1992):

- Managerial Accounting;
- Operations Research;
- Management and Organisation Theory;
- Computer Science.

upon the thematic nature of this exploration, particularly in that they are essentially intended to help provide answers to three basic management questions:

- "Where are we heading ?,
- Where should we be heading ?, and
- How will we get there ?" (HERTZ 1969,1).

We consider that questions of such nature to be instrumental – in a pragmatic sense - in instilling and stimulating a spirit of cross-disciplinary scientific discovery, and can be seen to be significant in the course and context of learning/instruction of application-oriented scientific reasoning as well as in the social context of science learning.

Since quantitative evaluation of the consequences of proposed action is considered the key contribution of Management Science to the executive decision-maker, concepts and techniques derived from Systems Engineering (originally called Operations Research), in particular, have been brought to bear upon management, business and organisational problems. The discipline of Operations Research is concerned with determining optimal decisions by using mathematical models and procedures in a systematic and specific way (ROSENBERG 1992) and

> ".......... is usually conducted with the aid of computer modelling; models may be hypothesised and fitted to experimental data or experimental data may be analysed to derive a model. Once a model is available, the effects of changes in the operations under study can be developed and predicted in a quantitative way." (OXFORD DICTIONARY OF COMPUTING 1983).

Systems Engineering draws on systematic methods and is chiefly concerned with determining optimal decisions by using mathematical models and procedures in a systematic and specific way (ROSENBERG 1992). The concept "model" in conjunction with a "systemic" viewpoint and computing facilities here also form the underlying features of Systems Engineering.

In adopting a system’s approach, one is in effect concerned with connectedness and wholeness (VON BERTALANFFY 1968, KRAMER and DE SMIT 1977) and, by its nature, a system’s view of a problem also cuts across disciplinary boundaries in an effort to understand a problem from an integrated vantage point.

The essence of a scientific education-oriented system’s approach is expressed by RAMO in the following manner:

> "The systems approach is a technique for the application of a scientific approach to (complex) problems. It concentrates on the analysis and design of the "whole", as distinct from the components or the parts. It insists on looking at a problem in its entirety, taking into account all the facets and all the variables, and relating the social to the technological aspects; (RAMO 1973, 2539).

At this stage of our deliberations, we regard that two curricular-oriented and implementation-oriented aspects to the introduction of a systems' perspective into a program of Scientific Studies can be considered potentially productive (MANDINACH 1989):

- the heuristic value of a systems' perspective provides a scientific analysis technique that can be successfully implemented as an instructional strategy to develop cross-curricular scientific themes within (and to address problematic parts of) the curriculum, or to address particular topics already mandated in the curriculum, but without risk of adding load to course content;

- the systems perspective can be used to facilitate instruction of low- as well as high-ability students.

Additionally, in this study, we regard the integration of some carefully selected key ideas and principles underlying Management Science methodologies – incorporating Systems Thinking, elements/perspectives of Social Science and computer-oriented problem-solving - as manifested at University-level education into pre-University Scientific Studies as a viable attempt to provide learners with, and/or to give them the opportunity to appreciate, an alternative, broad-based but potentially powerful, way of promoting scientific thinking and gaining insights into the aspects of the process of scientific discovery which will be most productive in cross-disciplinary problem-solving.

From an somewhat different - but clearly not unrelated in the intrinsically scientific as well as scientific-educational sense - Management Science perspective, the focus of a System Dynamics study, however, is not a system but a problem within the system (RICHARDSON & PUGH 1981); consequently, System Dynamics assumes a deep substantive knowledge of the problem (ROBERTS et al. 1983). The problems addressed from a System Dynamics perspective were also formally - i.e., for strictly academically-oriented applications - characterised by two basic features (RICHARDSON & PUGH 1981):

- they are dynamic - they involve quantities that change over time;
- they involve the notion of feedback.

Originally, but primarily from the Management Science viewpoint (ROBERTS 1983), the System Dynamics modelling and problem-solving philosophy adopted the ancillary belief:

- that a system's behaviour (time history) is principally caused by the system's structure, and
- that a system is viewed most effectively in terms of its common, underlying flows instead of in terms of separate functions.

Management Science and educational - secondary as well as university-level - applications of the System Dynamics Methodology has shown that it is possible to represent comprehensively the dynamic behaviour of economic systems (FORRESTER 1961, 1969, 1976, ROBERTS 1978), social issues (FORRESTER 1969, 1973, MEADOWS et. al. 1973), biological processes (ROBERTS 1983), dynamic processes (CRAEMER 1985), environmental systems and issues (BOSSEL 1985, FISCHLIN 1991, MEADOWS 1992), and physical processes (BETHGE & SCHECKER 1992) in much the same way as the time-varying behaviour of engineering-cybernetic systems, i.e., as an information feedback control system and whose behaviour can be specified by a series of differential/difference equations; (FORRESTER 1961, 1968).

Thus appreciation has developed for the heuristic value of systems thinking as a scientific analysis technique, and the creation and manipulation of models is recognised as a powerful educational technique that results in different mental representations of a subject.

Through cross-disciplinary contextual tools, conceptual frameworks and generic structures, i.e., ones that are not strictly mono-disciplinary and dogmatic, since Management Science encompass diverse academic disciplines, this will also enable the potentially effective development of a scientific problem-solving environment (referred to later in this chapter and treated again in CHAPTER 4) and attitude towards the learning of scientific method.

2.5 The System Dynamics Methodology - Underlying Principles, FORRESTER's Educational Perspectives and the Learning of Scientific Computation

In order to deal more effectively - than Systems Engineering techniques did with the broader top-management problems in industry, and in order to provide a foundation of theory for Management Science (Management Science education) - in the manner Physics is seen to provide the framework to the technological professions - FORRESTER pioneered the field of Industrial Dynamics - as System Dynamics was called at its inception (FORRESTER 1961, 1968) [23].

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[23] FORRESTER initially went to the Sloane School Of Management

> " ..... for the planned purpose of searching for and developing the linkages which might exist between engineering and management education ..... " (FORRESTER 1968, 398).

FORRESTER introduced the discipline of Industrial Dynamics - published as a book (FORRESTER 1961) - as a simulation approach [24] to problem-solving, and one which was based on a theory of structure of systems.

Most frequently, however, the impact of standardised Management Science techniques on secondary education has been limited almost entirely to the use of "simulation gaming", usually non-computerised. Such educational use of simulation (and serious games) formed part of a major "contemporary" shift in the pattern of learning and teaching which took place in the late 1960s/early 1970s (TANSEY 1971) - to mark a shift towards heuristic, individual, active and small group learning (and as distinctly removed from received authority, passivity and class teaching !).

With particular reference to pre-college/pre-university education, which FORRESTER suggests is

> "compartmentalised into separate subjects that, in the real world, interact with one another. Social studies, physical science, biology and other subjects are taught as if they were inherently different from one another, even though behaviour in each rests on the same underlying concepts" (FORRESTER 1992, 6),

and in which FORRESTER argues - and it is an attitude that one who is confronted with the status quo in curricular development issues and practice readily tends to subscribe to - that a curriculum is taught

> "from which students are expected to synthesise a perspective and framework for understanding their social and physical environment"; (FORRESTER 1992, 6).

It is to be recognised that such specialisation can be of hindrance in that it may lead the science learner into adopting and implementing a narrow, reductionist approach, and one which does not always, or necessarily,

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[24] "With simulation available as a procedure for exposing the behaviour of a model of a system, it became fruitful not to concentrate on mathematical methods but on the fundamental nature of structure in systems." (FORRESTER 1968, 399).

instil a satisfactory sense of science or of scientific knowledge. However, through the provision of communication and interactive links between disciplines, and with members of other disciplines, we believe that this obstacle can be overcome to a significant extent. The very nature of cross-disciplinary and/or inter-disciplinary scientific thinking enlists the implementation of a more versatile communication mechanism than is provided by methods underlying reductionism. In this respect, we consider that the methodological principles, tools and environment implied in System Dynamics comprise a potentially powerful breakthrough in which a way of thinking and methods of one discipline can be used to investigate problems in another field. This would lead to a view of the dimension of integrated science as having a structure of common basic concepts which make up a unified framework, the elements of which can be identified in the various disciplines [25].

FORRESTER's pre-university educational interests are derived from his dissatisfaction with the fragmentary nature of traditional science education and its disregard for the aspects of complexity in scientific problems. Like FORRESTER, we - instructor and learner - see a need for a systems perspective in addressing the aspect of complexity that does frequently surface in a science curriculum that is, otherwise, predominantly reductionistic-oriented.

FORRESTER, adopting the perspective of a Management Science educationalist, seeks to reform the process of learning and teaching of science at the pre-university level in response to feelings that society's needs for such scientists were not being properly served. FORRESTER claims that System Dynamics has the potential to promote all kinds of educational relevance and effectiveness in that it

> " ..... offers a framework for giving cohesion, meaning and motivation to education at all levels ..... " (FORRESTER 1992, 1),

through the consideration and direct treatment of the time dimension, i.e., dynamic behaviour, that is common to all systems - physical science, biological, natural, environmental and social; (FORRESTER 1992).

The standpoint that is taken here is that System Dynamics applications should follow the same approach but adopt, however, a modified view of FORRESTER's sentiments in that we regard System Dynamics to have potential in the promotion and the acquisition of particular scientific

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[25] The search for unifying principles is old; philosophers such as ARISTOTLE and scientists including EINSTEIN believed in the unity of the universe and tried to discover unifying laws in nature (BLUM 1994).

inquiry and/or scientific reasoning experiences that could also lead to a more profound appreciation of the scientific enterprise.

A relatively recent view of learning now guiding theory - and one appropriately adaptable here - characterises the learner as an active inquiring agent (WINNIE and BUTLER 1994). Characterising the learner as 'inquiring' emphasises the central role played by hypothesis framing and testing as the student takes part in the instructional environment. Towards the adoption of this particular perspective, three forms for representing knowledge are also distinguished - declarative, procedural and tacit. Declarative knowledge is descriptive knowledge and closely tied to the concepts of schema and analogy. Procedural knowledge, on the other hand, underlies the processes that students perform such as organising materials and the surrounding environment, i.e. algorithms - which yield reliable outcomes - are distinguished from heuristics. Tacit knowledge is knowledge that the learner possesses and that is accumulated through experience (WINNIE and BUTLER 1994).

To provide the strategy/procedural knowledge (WINNIE and BUTLER 1994), i.e., cognitive procedures that students can use to construct and refine the conceptual knowledge, inherent in the Systems Dynamics Methodology, and to develop the strategy knowledge itself, one may look to FORRESTER summary of his notion of the general nature of structure as recognised in all dynamic systems, and outlined in terms of four hierarchies (FORRESTER 1969, 12):

- ❖ Closed boundary around the system.
- ❖ Feedback loops as the basic structural elements within the boundary.
    - ♦ LEVEL (state) variables representing accumulations within the feedback loops.
    - ♦ RATE (flow) variables representing activity within the feedback loops.
        - ➢ Components of a Rate variable:
            - Goal;
            - Observed condition;
            - Detection of discrepancy;
            - Action based on discrepancy.

Essentially, the basic structure of a System Dynamics model consists of a set of reservoirs, LEVELS, that are interconnected by (information) flows. The flows are governed by decisions that control the RATES of flow. Inputs from outside the model come from sources, and outputs from the model go to sinks. Information can flow from any LEVEL of the model or from sources. According to the theory underlying System Dynamics, literally all system relationships can be expressed and analysed in terms of only these two types of variables: state variables - LEVELS, and flux variables - RATES (ROBERTS 1978).

And, correspondingly, the values of all variables are computed at each time-interval also from just two types of equations (FORRESTER 1968, ROBERTS 1978, RICHARDSON & PUGH 1981) – the LEVEL Equations and the RATE Equations.

- LEVEL Equations represent various accumulations and determine the way in which levels change from one interval to the next [26] ;
- RATE Equations represent the instantaneous flow to or from a LEVEL and determine the way in which the rates change from one interval to the next.

Frequently, however, in System Dynamics, it is not always possible to define the model entirely in terms of LEVELS and RATES that can be expressed by the given equation forms. AUXILIARY variables can be introduced to collect information on which decisions depend; such variables are, therefore, algebraically substitutable into the following RATE equations and are structurally part of the associated RATE equation. Where this information is about the consequences of past decisions, feedback control exists within the model. AUXILIARY variables allow the introduction of further intermediate AUXILIARY equations which can be used to clarify main, complex/complicated formulations. AUXILIARY equations represent explicit algebraic computations and, unlike LEVELS and RATES, have no standard form. Although it is conceivable that one could write a model without using AUXILIARY equations - formulating all RATE equations solely in terms of LEVELS and constants - the resulting model listing would probably be unreadable and/or some of the information in the model would be inaccessible.

The three types of equation LEVEL, RATE and AUXILIARY are indicated by L, R, and A, respectively, with the equation number. The LEVEL, RATE and AUXILIARY variables are defined and combined in a series of algebraic and first-order difference equations in such a way that they

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[26] Seen in a Physics/Mathematical context, they can be considered to conceptually represent and synthetically perform the operation of integration.

represent the structure and dynamic behaviour of the system (digitally and substituting for the differential equation form). This step includes the assignment of values to all coefficients , the establishment of the initial conditions of the LEVELS and the determination of the solution time-interval. A complete System Dynamics model description, therefore, consists of LEVEL - L, RATES - R and AUXILIARY - A equation statements, CONSTANTS - C and INITIAL - N values for the LEVELS.

In identifying the scientific nature, the intrinsic/inherent problem-solving characteristics and the pragmatic tenets of LEVEL-RATE formulations, it is observed that modelling in terms of such a LEVEL-RATE (and AUXILIARY) analytical process, which also helps to ensure a common understanding of various interpretations in different applications - and which is fundamental to the System Dynamics problem-solving procedure - is markedly reminiscent of KUHN's pragmatic notion of "paradigm" [27].

In the first place, KUHN claimed that the theoretical and experimental work in natural science takes place within frameworks or paradigms which are identified, at least in part, in a sociological manner (KUHN1970) KUHN claims that:

> "In its established usage, a paradigm is an accepted model or pattern ..... it is an object for further articulation and specification under new and more stringent conditions ..... Paradigms gain their status because they are more successful than their competitors in solving a few problems that the group of practitioners has come to recognise as acute"; (KUHN 1970, 23).

Regarded in an educational context, therefore, such a paradigm can be considered to have a broad cognitive and evaluative scope as well as having social significance as the defining characteristic of a particular community of scientists. When scientists adopt a paradigm, they do so because of the social, political and ideological preconceptions prevailing in the community to which they belong (GOWER 1997). Science learners placed in this situation become exposed to – and, consequently, are made to consider or to question – those systemic preconceptions and cross-disciplinary viewpoints.

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[27] Normal science does not involve finding any fundamental new laws at all, but simply applying laws that are already known or developing subsidiary laws that fill in the dominant paradigm. KUHN, in attempting to characterise paradigms both as exemplars of scientific achievement and the disciplinary values built from them, made telling points about the structure and growth of scientific knowledge.

The following section is intended to expose the underlying concepts and principles of the declarative and procedural characteristics of relevant strategic knowledge as underlying the formulation of hypothesis using Systems Dynamics. This would serve to elaborate the scientific problem-solving dimensions characterising the System Dynamics methodology. The tacit knowledge is conceptualised to be stimulated by the pragmatic component of the System Dynamics methodology, particularly through the notion and aspect of value-base.

2.6 Systems Thinking, Cybernetic Science Principles and the Aspect of Modelling Purpose in the System Dynamics Methodology

LUDWIG VON BERTALANFFY - the founder of General System Theory - posited principles of system structure and behaviour, and presented five propositions which define the major objectives of General System Theory (VON BERTALANFFY 1968) - and which we consider to have significant meaning/value to general and integrated, holistic (viz. non-reductionist) and systems-oriented science education. As their principal characteristics can be considered to be the provision of:

- general integration in the natural and social sciences;
- integration centred in a general theory of systems;
- a means for aiming at exact theory in the non-physical fields of science;
- unifying principles running vertically through the universe of the individual sciences;
- integration of scientific education.

All the major crucial problems facing the society today - population explosion, ecological pollution, dwindling agricultural, fishing and energy resources, industrialisation and urban deprivation - focus attention on the systemic nature of the earth’s resources and demand a more systemic perspective - a perspective that will recognise the aspirations and value judgements by all who will be affected by decisions concerning real-world issues.

Consequently, seen within an educational context, a significant task of scientific research becomes to find laws describing whole classes of systems - and not only unique systems. By its nature a system's perspective of a problem cuts across disciplinary boundaries as defined in many traditional sciences (VON BERTALANFFY 1968). System's thinking - potentially - enables the development of a common language that make it possible for scientists - and correspondingly, science learners - in different disciplines to communicate with one another, and can also provide insight into the methodology for a holistic approach.

In science learning one can be led to appreciate that systems thinking has tremendous potential because it compels learners to think of events and phenomena in a structured way in order to isolate and analyse the impact of various factors; it leads learners to realise that they can discover and adopt general principles that govern many complex systems. This, in turn, suggests the direct integration of systems thinking into other content areas and promotes the notion of a cross-disciplinary perspective and approach to analysing problems.

In order to maintain an interdisciplinary approach, BOULDING, an economist, had already regarded and suggested the development of a certain framework of coherence as the overriding task of General System Theory. We choose to mention the framework since it addresses and highlights the aspect of system structure that has distinct instructional ramifications. He proposed two means by which General System Theory could be structured (BOULDING 1956):

- based on empirical observation, to isolate those common features or phenomena and use to construct general models.
- based on the definition of hierarchical structures, which could be built by
    - modelling process with different levels of abstraction;

- problem-solving processes with different steps.

At about the same time that engineers began to think in terms of Systems Engineering, and the pioneers in SYSTEMS THEORY began to consider implications outside biology and engineering, NORBERT WIENER in 1948 sketched the outlines of the field of scientific inquiry - CYBERNETICS - in which he proposed that the same organising principles and concepts lie at the base of biological, engineering, social and economic systems. The fundamental structure and concepts of the System Dynamics Modelling Methodology were created by merging key ideas from Systems Thinking, Cybernetic Science and Management Science.

BOULDING's second proposal led him to propound a theoretical-hierarchical classification according to nine levels of complexity, with each successive higher level embodying all the preceding levels (KRAMER & DE SMIT 1977):

- LEVEL 1 - Static Structures - the Framework level.
- LEVEL 2 - Simple Dynamic Structures - the Clockwork level.

- **LEVEL 3 - Cybernetic Systems - Thermostat level.**

- LEVEL 4 - Open Systems - the level of the Cell.
- LEVEL 5 - Lower Organisms - the Plant level.
- LEVEL 6 - Animal level.
- LEVEL 7 - The level of Man.
- LEVEL 8 - The level of Socio-Cultural systems.
- LEVEL 9 - Symbolic systems.

We have chosen to highlight LEVEL 3 since this is the level within which we consider that key aspects of scientific computation, together with the concepts and method, have the most relevant environment in order to be manifested with validity in a scientific and curricular context.

In an interdisciplinary science educational context, such classification gives an impression of the gaps in scientific knowledge. These gaps are subsequently studied with the assistance of models. BOULDING states that adequate model representations are made at the first three or, at the most, four levels (KRAMER & DE SMIT 1977).

The underlying aspect in the application of a Systems and a Cybernetic perspective is the adoption of a systematic study of communication and control in organisations of all kinds and is, therefore, a conceptual scheme on a grand scale. CYBERNETICS (WIENER 1954, ASHBY 1956) is formally an established study of communication and control in organisations of all kinds and is, therefore, a conceptual scheme on a grand scale. Partly because of this, Cybernetic Science does not draw an absolute distinction between the living and non-living. Reference to animal and machine promises a general structure of systems, and Cybernetic Science cuts across and bridges various disciplines.

In formal terms, and in a purely social-scientific context and in related scientific activity, cybernetic modelling has the potential to link the control of social systems to flows of information to different participants, and it provides a language/discipline for thinking about adequate levels of control, adaptability and the susceptibility of systems to/over control, instability and failure when subsystems are improperly configured.

Thus - and here again regarded in an educational context - in addition to its connections with classical science, CYBERNETICS is closely related to SYSTEMS THEORY, which in turn is closely connected with ways of thinking that are also prominent in economics, ecology and the study of evolution.

Within such a context, SEYMOUR PAPERT also extends the study of CYBERNETICS to education and proposes CYBERNETICS as a "kernel of knowledge" that is only intended as "a staging area for making connections with other intellectual areas including (among others) biology, psychology, economics, history and philosophy"; (PAPERT 1993, 181). In line with this thesis, in which we hypothesise that essentials of CYBERNETICS possess a combination of appropriateness with richness of scientific content relevant to pre-university science education we, like PAPERT (1993), consider CYBERNETICS

> "as a new subject which I see as a more valuable intellectual area for young people than those that have been sanctified by school ..... and whose outlines will emerge gradually ..... and the problem of situating it in the context of School and the larger learning environment will best be broached when we have it in front of us" (PAPERT 1993, 181).

Since CYBERNETICS possesses a combination of educational appropriateness with richness of scientific affiliations, the learner can be placed in a position to regard knowledge as coming to be valued for being useful, and for being of a kind that can be shared with others (PAPERT 1993). Also, since it is based on serious ways of making the best use of limited knowledge, PAPERT (1993) considers this aspect as a way of turning science into used knowledge with epistemological implications:

"CYBERNETICS as a subject would share the general epistemological fallout that comes from the fact that it is used rather than simply learned, but has some specific epistemological implications of its own; (PAPERT 1993, 183).

A key feature characterised in an aspect of engineering - i.e., one that is implied in servomechanism theory, and one characterised in an aspect of biology - i.e., one that is implied by the concept of homeostasis, contributed

- the system's perspective to problem-solving, and
- the notion that 'feedback' is crucial to control in systems.

PAPERT regards the concept of feedback that underlines the field of CYBERNETICS as providing a powerful educational principle and one that is remarkable in that

> "it is also generative: It can be used to understand many situations, and some in very surprising ways. It is rich in intellectual jokes and comic or paradoxical situations; (PAPERT 1990, 195).

Through aspects of CYBERNETICS and SYSTEMS THINKING, we do consider that the provision of such basic organisational knowledge - procedural and diagnostic knowledge for describing a particular class of problems – in compliance with the prime criterion of **Concilience** - would also provide a means by which the student could learn to appreciate and to interpret the scientific concepts in a more meaningful manner and in a way which would add coherence to the her/his inherent conceptual knowledge.

2.6.1 The Systems' Perspective, Dimension and Environment for Science Learning/Instruction

In the empirical world around us, various sets of **entities** defined in WEBSTERS DICTIONARY as:

> “something that have objective or physical reality and the distinction of being and of character“,

can be considered as a **system** or an **aggregate**. The difference is that in a system it is significant that the parts are arranged and in an aggregate the parts are added (ANGYAL 1969).

In developing a formal **system model**, the operation of abstraction entails conceiving a system as part of a “larger whole“ eliminating all but the significant attributes from the entities in a system, and defining the interaction between system and **environment** in time and space. A system that does not react with its environment is referred to as a **closed system**. Consequently, the notion of a demarcation, a **system boundary**, between the system and its environment can also be conceived.

The way two or more entities depend on each other is a **relation**. **Structure** deals mainly with the relations recognised in the system and takes into account the following three notions:

- the set of relations,
- the positional value - defining the arrangement of the entities with respect to one another within the system as a whole, and
- the dimensional domain - which distinguishes systems from one another by virtue of their dimensional, viz., space and time, properties.

Dynamic behaviour takes into account the system’s time evolution or patterns of change and introduces the concept of **state**.

Such provision of basic organisational knowledge - introductory information at a higher level of abstraction or generality (AUSUBEL 1968) - in the form of short statements written at a more general and abstract level than is included in the specific content of the information to be learned, can be presented in a language familiar to the learner and may contain visual information relative to the subject matter.

For General Systems and Cybernetic Systems, such organisers provide the means and format for generating the logical relationships among the various elements within the system and, and as it is to be seen, are at the roots of the procedural and diagnostic knowledge characterising System Dynamics concepts and methodology.

2.6.2 The Cybernetic Perspective, Dimension and Environment for Science Learning/Instruction

The spirit of CYBERNETICS - being a science of systems - is such that it is an approach for recognising and treating problems that are common to a wide range of phenomena and scientific disciplines (WIENER 1961). This enables CYBERNETICS to be regarded as part of general system theory concerned with one principal aspect of the behaviour of the system **control** through **feedback**.

System implies class of systems and CYBERNETIC SCIENCE addresses manifolds of relations where a number of components interact with each other and produce an **effect**. Patterns of interrelationships, referred to as networks, can be represented in graphical form, interconnections or network representations. When viewing systems as networks, one comes across **circular relationships**: the analysis and design of **closed loops** in the network, of circular flows of **cause-and-effect relationships** are aspects that characterise CYBERNETICS.

The recognition of closed loops, **mutually causal relationships**; leads to the concept of **feedback** - the underlying feature of CYBERNETICS. In its most general sense, feedback is used to describe a closed loop.

In the more limited sense, feedback is short for **feedback control**. Control [28] implies variation in some of the conditions that affect an outcome. **Self-**

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[28] Scientific method is very much concerned with understanding behaviour and predicting behaviour, and as a result of this, also controlling behaviour. The concept of control poses the question as to why the system behaves the way it does rather than in some other way (ASHBY 1964). The advance of science implies the increase of (selective) control we have over our environment.

control implies that the self is capable of varying certain conditions in such a way that it controls its own outcome.

Science also has to take into account a system's teleology - **purpose** and **goals**, and that *control* has, in a sense, a normative implication. Control for what purpose ? What is to be achieved? CYBERNETICS addresses **purposive behaviour** involving feedback control. Purpose implies the system's disposition to select that behaviour pattern which is likely to attain a **goal**. The goal is defined as a state in the system's environment with which the system seeks to attain a particular relationship or which it seeks to affect in a certain way by its output.

A basic requirement for a system to be able to identify and achieve its goal is **information** about that part of the environment which contains the goal and the system's relation to that environment.

Adaptation and **learning** are the capabilities that increase the viability and quality of performance of a system that is not exhausted in mechanistic properties, including animal, human and social systems. Learning implies the system's capability for improving its performance under constant environmental conditions. Adaptation implies the capability for maintaining or improving its performance under changing environmental conditions.

2.6.3 Modelling Purpose and Resources - Educational Value-Base

We perceive that a fundamental objective of model construction in relation to meaningful/pragmatic science learning is to give the subject or topic of interest a form as well as a structure and configuration, particularly, one that is determined by a purpose that the learner can relate to, identify with and that will stimulate and/or revitalise her/his tacit learning. Such a purpose entails a value-base, i.e., establishing the foundation/basis upon which the entire modelling effort can be made to rest and to develop, and the educational environment of it must also create the particular educational value-base that gives meaning and direction to the whole endeavour.

In addition, we contend and still maintain – and in so doing identify with FORRESTER's long-past sentiments - that the gap between science and society – viz., scientists and social leaders – has indeed become and remained large primarily because:

- scientists as a rule, do not always consider society's complex problems as their prime responsibility;

- the social imperatives of these particular problems often come in conflict with their objectives as well as their selective and systematic modes and manner of investigation;

- the training of scientists and engineers is, generally, not compatible with the instilling of purposes of value in education. (LEBEL 1982, 119).

The provision of appropriate learning and instruction resources and contexts are also, consequently, effected through a clearly defined purpose, as are curricular objectives. With respect to our science's epistemology and its social context, a value-base, therefore, explicitly stipulates certain assumptions about what is scientifically and socially, and consequently, educationally desirable.

Since growth in the world during the past fifty years has created (and apparently still continues to create) such an undesirable situation along with increasing concern about the future of society, and it is established and accepted that nearly all contemporary social problems whether of national or global dimension are interrelated, exceedingly complex and so difficult to formulate, it is imperative that these problems require analysis and solution at the world level. Such problems have persistently challenged both the scientific and non-scientific community, but could seldom be resolved by the politician, scientist, engineer or economist in isolation.

Thus, to accommodate the insufficiency for the commonly-held notions of scientific problem and a scientific solution when truly critical issues that the situations propose to both the intellect and to the conscience, we subscribe to ALEXANDER KING's suggestion that curricular deliberations over the objectives that must be set and which determine the direction that science programs should follow must be resolved within the awareness that:

- ♦ course content should be conceptualised in terms of human-oriented problems rather than purely and simply in terms of the fundamental principles of science;

- ♦ the approaches adopted should have applications in different disciplines, drawing upon - whenever possible - the pure, applied and social sciences;

- an examination of the interrelationships between science and the social/cultural aspects of the scientific environment to be undertaken;
- more emphasis to be placed in developing skills associated with decision-making while maintaining the importance of inquiry and problem-solving skills. (KING 1985).

We interpret this as validating – from a different, “value-base” perspective - the cross-disciplinary, systems and social science-oriented approach that we are advocating towards scientific problem-solving.

Therefore, our acceptance of the idea of a contextually-grounded, experience-based, and socially-constructed nature of scientific knowledge, in conjunction with the social responsibility of scientists and technologists - viz., communication with the public, concern and accountability for risks and pollution, 'whistle blowing" - features predominantly within our notion of value-base. In relation to this, AITKENHEAD & RYAN (1992) identify six components [29] which collectively form a schematisation by which the influence of science/technology on society bears upon the external and internal sociology of science.

To this end we regard those conceptual and methodological details adopted in World-Modelling as concerted attempts to encompass the essential features underlying the external sociology of science, and locate them within the internal sociology of science through the employment System Dynamics as the linking factor.

A World Model was, by its very nature, to be the broadest possible form of modelling, and developing a World Model was to be the most difficult task a model-maker were to undertake (MASON 1976). The purpose of a World Model was, at its conception, to provide policy makers with an organised representation of the world, and the World Model-maker had to exercise the highest degree of judgement in the construction of her/his model. It is within such a moral responsibility - and one that cannot be taken lightly - that we regard lies the intrinsic pedagogic value and the social/scientific orientation of a World Modelling enterprise.

Although the concept of World Modelling now only commands historical and academic significance with respect to its value to science and to the solution of world problems, we contend that the reference to, and

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[29]

- Influence of Society on Science/Technology
- Influence of Science/Technology on Society
- Influence of School Science on Society
- Characteristics of Scientists
- Social Construction of Scientific Knowledge
- Social Construction of Technology

introduction of, such a pragmatic notion in science education at the secondary- school level will serve to significantly enhance the value-base of model-construction. Such a value-base can be initiated through the social/historical significance of the World Model provided by the CLUB OF ROME [30] - an association of about 100 prominent scientists, scholars and industrialists from fifty three nations - whose purpose is to

> "foster understanding of the varied but interdependent components - technical, economic, political, natural and social - that make up the global system in which we live" (WEST CHURCHMAN and MASON 1976, 1) [31].

The CLUB OF ROME sought to build a large-scale computer model which would provide some insight into some of the world's problems. In his WORLD DYNAMICS , FORRESTER (1971) attempted to understand and model world problems from the perspective of a dynamic-feedback system.

WORLD DYNAMICS indicated that a methodology exists to study the predicaments of the human race and illustrates quantifications of the interrelationships among population, food production, natural resources, capital investment, pollution and natural resources. The book describes - on an equation - by - equation basis - the less-than-fifty equations model and discusses the results obtained from the model runs. FORRESTER was commissioned to apply his methodology to the problems of unchecked growth in the world. The model that was used

> "is a formal, written model of the world. It constitutes a preliminary attempt to improve our mental models of long-term, global problems by combining the large amount of information that is already in human minds and in written records with new information-processing tools that mankind's increasing knowledge has produced - the scientific method, systems analysis and the modern computer"; (MEADOWS et al. 1973, 21).

The effort culminated in a first report - and later published as a book - entitled THE LIMITS TO GROWTH - A REPORT FOR THE CLUB OF

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[30] This was founded in April 1968 ago by Italian industrialist AURELIO PECCEI to set out to do something about the world "problematique". This is a term for a cluster of intertwined problems which together produce world-wide symptoms of a general but little understood "malaise". PECCEI claimed then that the most crucial task was to understand this malaise.

[31] The initial prospectus of the CLUB OF ROME was called "The PREDICAMENT OF MANKIND - QUEST FOR STRUCTURED RESPONSES TO GROWING WORLD-WIDE COMPLEXITIES AND UNCERTAINTIES".

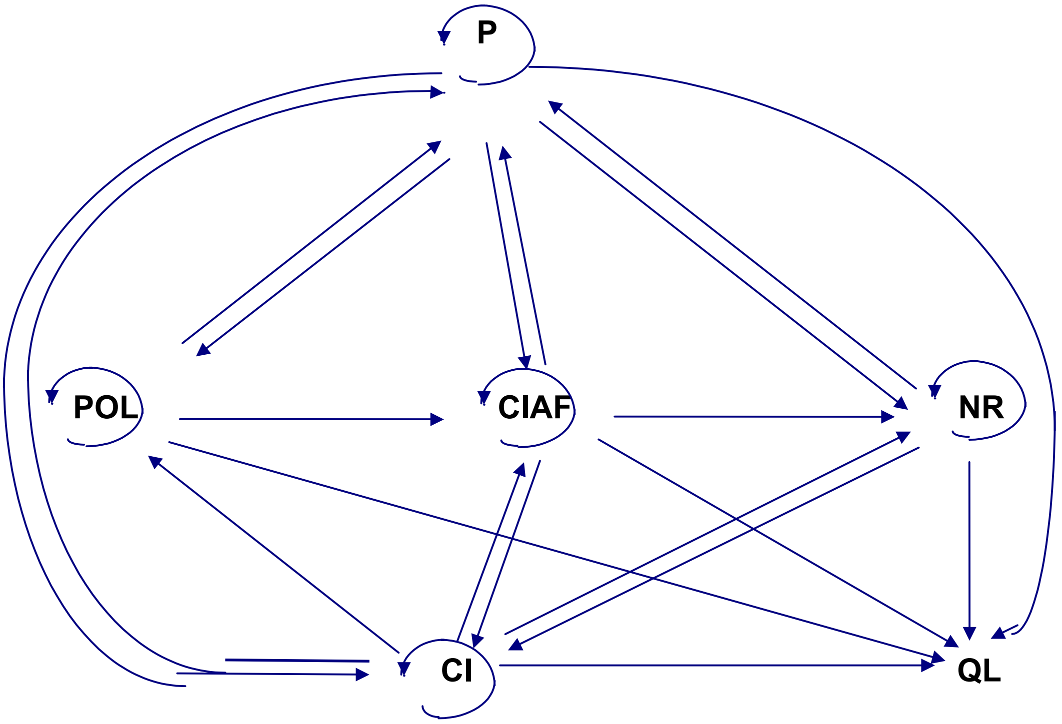
ROME's PROJECT ON THE PREDICAMENT OF MANKIND (MEADOWS et al., 1973).

Such a pedagogically-oriented model conceptualisation is not significantly different from the notion of model as we imply in this thesis. The description above serves to relate the relevance of the concept of World Modelling to our understanding of value-base while adopting our appreciation of the methodological principles and tools employed. Because of its widespread distribution (it was translated into more than thirty languages and, by 1993, more than ten million copies had been printed) THE LIMITS TO GROWTH has, consequently, been the subject of much study and has attracted widespread controversial interest and debate, while also being generally considered and acknowledged to be based on one of the better thought out social models. Few scientific reports since CHARLES DARWIN's Origin Of The Species have stirred so much popular debate and certainly few science efforts have ever created such widespread academic interest at all levels (MASON 1976).

Basically, therefore, one can represent the World - as in the original WORLD 3 (MEADOWS et al., 1973, 1992) model, and which we elect to introduce at this stage as bearing particular significance in the further development (Chapter 2) of this work - as having:

- several LEVELS,
- flows that transport the contents of one LEVEL to another,
- decision functions that control the RATES of flows between LEVELS, and
- information channels that connect the decision functions to the LEVELS; (FORRESTER 1961, 67-72).

And thus with particular reference to the WORLD Models (FORRESTER 1971; MEADOWS et al., 1972, 1992), the diagram **Fig 2.1** below (FISCHLIN 1991) can be implemented as a learning/instruction-oriented example to initialise a conceptualisation, treatment or discussion of the relations between various LEVELS pertaining to Quality of Life [32] - **QL** -in the World in terms of the System Dynamics methodology.



P - Population
POL- Persistent Pollution
CIAF - Capital Investment in Agricultural Fraction
NR – Non-renewable Natural Resources
CI - Capital Investment Output
QL - Quality of Life

Fig. 2.1 The WORLD 3 Model

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[32] The fulfilment of material needs, a sense of ecological well being - through the air we breathe, the food we eat, the environment we live in and the social relations that constitutes the fabric of our lives - and confidence in the future is the underlying theme in the "Science For The 90's" course (CHAPTER 4).

- Population, Persistent Pollution, Non-renewable Natural Resources, Industrial Capital Investment in Agricultural Fraction and Capital Investment Output are five of the LEVELS in the World Models.

- Birth Rate and Death Rate, Pollution Generation Rate, Resource Usage Rate and Food Consumption Rate, and Industrial Capital Investment Rate are the RATES considered significant in the World System.

Although the THE LIMITS TO GROWTH Model was very crude - it used educated guesses for many important data, and oversimplified matters by over-grouping many variables into aggregates - educationally, the model fares reasonably well by our selected criteria of **Originality** and **Simplicity** in the Quality of a Model since:

1. It is one of the most original and ambitious studies ever attempted in the Social Sciences;

2. The model reflects the reality of the situation as it is rooted in the model learner's everyday experience, and is consistent with the world as s/he understands it.

Neither, could it be claimed that the model could tell one how good the assumptions are. MEADOWS et al. suggest that:

> "A dynamic model deals with the same incomplete information available to an intuitive model, but it allows the organisation of information from many different sources into a feedback-loop structure that can be exactly analysed. Once all the assumptions are together and written down, they can be exposed to criticism, and the system's response to alternative policies can be tested." (MEADOWS et al. 1973, 122).

This aspect, we consider, is significant in the preliminary stages of model construction - for elucidation, explanation and hypothesis generation - and enables the appreciation of the importance of structure (or the lack of it) and information (or the lack of it) in modelling to be established.

Originally, the WORLD 1 (THE LIMITS TO GROWTH) - and later again the WORLD 3 (BEYOND THE LIMITS) - models were constructed to test implications of different assumptions, since different assumptions yield different conclusions. The arguments that were presented in these cases were not over the models themselves - it was validated for the purpose for which it was conceived (WEST CHURCHMAN and MASON 1976) - but over which assumptions should be used to give reasonable projections of the future. Projections from the THE LIMITS TO GROWTH

Model attacked, and continue to attack, some of the fundamental tenets of modern society but there can also be, and there was, intense debate over the validity of the model (WEST CHURCHMAN and MASON 1976).

Twenty years later, THE LIMITS TO GROWTH was updated, completely rewritten and reissued as BEYOND THE LIMITS (MEADOWS et al., 1993).
It can be claimed, however, that both the THE LIMITS TO GROWTH and BEYOND THE LIMITS Models can make outstanding contributions in raising issues and generating a great deal of thought and work which are destined to put into better perspective the search for what man's goals ought to be, and suggest ways to improve her/his understanding of how to achieve them.

Both THE LIMITS TO GROWTH and BEYOND THE LIMITS reports have been acknowledged for their way of addressing the world's current problems and the respective issues confronting both scientist and non-scientist alike - and for calling for a unified course of action. In order to be vigilantly aware of the possible consequences of existing trends, and if only to ensure that they do not continue in their present trends. With reference to “THE LIMITS TO GROWTH“, KING advised that

> "Cassandra type forecasts as that of THE LIMITS TO GROWTH are useful in provoking and thus raising the level of awareness so that policies may be devised to ensure that the trend curves may be diverted and forecasts proved wrong. ..... The need then is for education is to become anticipative and prepare young for life and work in a new type of society which is emerging and not melting before our eyes;" (KING 1985, 237-238).

The sociological significance, as well as of the scientific-educational value of the uniqueness of the ideas emerging from THE LIMITS TO GROWTH and BEYOND THE LIMITS Models is not simply (for learners) to believe in the models but to suggest improvements to them and, eventually, to work towards the development of other more sophisticated models. Also, particularly for the learner, simplicity is rooted in one's everyday experience. Since the THE LIMITS TO GROWTH and BEYOND THE LIMITS Models reflect the reality of the situation as the reader (learner) sees it, they are consistent with the world as s/he understands it; simpler models also requires fewer special assumptions.

Ecology is the study of the equilibria and the dynamics of populations of living entities within given environments. If we extend the notion of ecology to comprise all the dimensions of occurrence in our environments, it becomes possible to say that we are confronted with a problematique which is ecosystemic in character.

We consider the notion of balance or equilibrium as one that appropriately and conceptually describes the value content of an ecosystem, and a point from which one could embark in a scientific survey. Consequently, the idea of ecological balance seem to qualify as an appropriate value-base of this study.

From an instructional as well as a learning viewpoint, therefore, THE LIMITS TO GROWTH and BEYOND THE LIMITS Reports provide the impetus for such a value-base since they have tremendous potential and resourcefulness in stimulating provocative thinking and discussion, in becoming a way of learning and teaching about the world's problems and in the quest for the re-establishment of the many-dimensional dynamic balance that seems to have been lost.

The approach and findings in THE LIMITS TO GROWTH and BEYOND THE LIMITS“ can help to put the learning of science into some kind of historical and social context, i.e., encourage the learner to think, and to realise what it is to work with science. Seen from the point of view of this particular survey, therefore, both THE LIMITS TO GROWTH and BEYOND THE LIMITS serve the dual purpose of being valuable scientific reference reports and a scientific vindication of the System Dynamics methodology. In a manner that the learner can relate to, the reports provide invaluable educational material and the models serve as intellectual resources – providing examples and themes - in the learning/instruction of the model-building and model-validation phases.

2.7 A System Dynamics Oriented Problem-Solving Schema for Scientific Computation

Both higher-order thinking skills and problem-solving skills require development of a level of understanding beyond basic knowledge. With respect to the nature of our study of System Dynamics, we make reference to KINTSCH & GREENO (1985) who provided appropriate evidence that supported the importance of the relationship between understanding and problem-solving ability, and of the need for an internalised conceptual representation upon which the problem-solving process can operate.

KINTSCH & GREENO (1985) noted that such a relationship, viz., analogical inference, is a mapping between relations in two domains. In this respect, one domain must be familiar to the learner, and this serves as a vehicle for understanding the target domain. Reasoning by analogy involves the comparison between the familiar and the new domains (KINTSCH & GREENO 1985). The focus of an analogy is on certain relationships; the distinction between literal similarity and shared relations between the two domains becomes critical in understanding what the analogy is.

The importance of sound conceptual models in problem solving and higher-order thinking was further supported by MAYER (1992). One of the three [33] major issues which MAYER has summarised in the design of an effective program for teaching problem-solving again bears particular relevance in our study of the significance of the System Dynamics framework, namely, that problem-solving can be taught in a general, domain-free context in the hopes of promoting transfer across many domains or within the context of specific subject domains MAYER (1992).

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[33] The other two are

- that problem-solving can be taught as a single, monolithic ability that can be strengthened through training and exercise, or as a collection of smaller component skills that can be specifically taught;
- that problem-solving can be taught as emphasising the product of problem-solving or as the process of problem-solving.

MAYER'S perspective suggests to us that problem solving is the process of figuring which set of past experiences best relates to the problem at hand. The problem solver must interpret the new situation based on the schema selected and then act upon that match to find a solution.

From the above considerations we now explicate and demonstrate the development of a rational scheme centred around **Analogy** - our fourth criterion with respect to model-quality - that we consider has the potential for internalising and organising the preliminary knowledge for the understanding of the scientific problem-solving and computational nature of the System Dynamics methodology.

2.7.1 A Cybernetic-Oriented Problem-Solving Schema for Scientific Computation Process

In formal terms - and in a manner which we consider provides the intrinsic educational component - we regard that the currently most relevant and significant objective of a System Dynamics study is not so much on forecasting, as was initially and traditionally intended in the academic milieu at the graduate/post-graduate level (ROBERTS 1978, RICHARDSON & PUGH 1981), but rather in the employment of a (also learning/instruction-oriented) problem-solving technique for identifying more efficiently those parameters and structural relationships whose precise values aid in the decision-making process.

Flow diagramming tools, mathematical modelling and computer simulation based on formal and quantitative computer models, which were developed to fit the methodology, constitute a predominant and most visible feature of such a so-called System Dynamics approach. Further formal flow-diagramming and equation-writing techniques to represent relationships were also created for the penultimate steps of System Dynamics. Initiating the DYNAMO compiler and the simulation program constituted the ultimate stage in the System Dynamics problem-solving methodology.

Using the conceptual tools referred to above, the logical functioning of a mechanically simple "computational device" such as the thermostat-controlled toast-maker or water-level control can be used to illustrate and to develop the concept of a computational device/scheme for carrying out the well-defined sequence of operations and, subsequently, which can be exploited and extended to illustrate and aid the understanding and instruction of our chosen concept of an algorithm.

We see that such "a computational procedure comprising well-defined sequence of operations" (PENROSE 1990, 22) is (scientifically and computationally) particularly appropriate since it is also of the kind underlying System Dynamics formulations. PAPERT perceives the pragmatic discovery that the "principle of the thermostat can be used to design machines that behave as if they are following goals" to be fundamental to processes in modern technology (PAPERT 1993,194).

PAPERT, in addition, considers that ways could be found to pursue such a discovery process that could lead to valuable discussion among children of epistemological and psychological principles, and that this could be an intriguing and exciting way to engage with an important body of knowledge (PAPERT1993). We attempt to illustrate through our subsequent analyses and deliberations that there is strong evidence to support this viewpoint.

The algorithm illustrating and describing, respectively, such a procedure is straightforward:

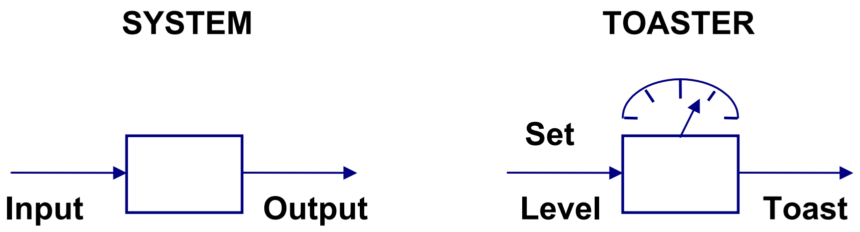


Fig. 2.2 **Input causes Energy (in the form of heat) to flow from the Electrical Heating Mechanism to the Bread.**

- Step 1 - the device registers whether the temperature level is greater or smaller than the setting/desired level - input;

- Step 2 - which in turn is determined by the degree of 'desired darkness' - output;

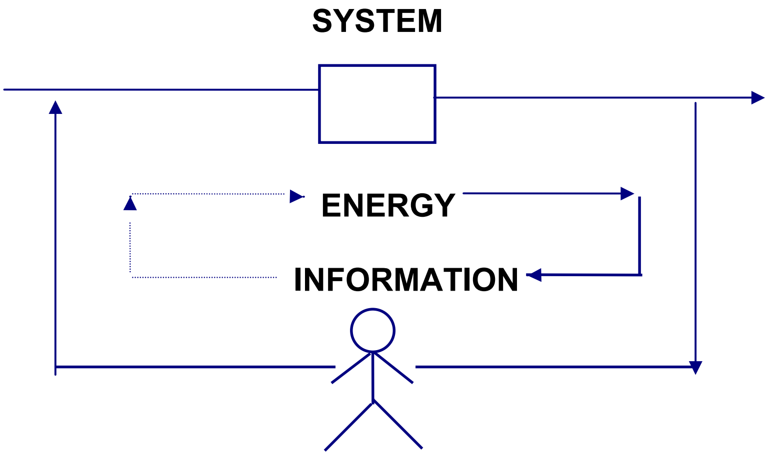
- Step 3 - and then it arranges that the circuit be disconnected in the former case and connected in the latter.

The inclusion of Step 2 modifies open-loop control - Step 1 and Step 3 - to closed-loop control through information-feedback.

Philosophically, in appropriating the concept of feedback, the algorithmic procedure described above shows one aspect of a large range of behaviours and possesses epistemological implications that is softer and more pluralistic. With respect to a learning environment, PAPERT regards this essential feature of such "cybernetic thinking" as

> "..... making the student's affective relationship to such work as more intimate (PAPERT 1993, 182) ..... epistemologically different in that it used a different way of thinking ..... creating an epistemology of 'managed vagueness' ..... and a serious study of ways to make best use of limited knowledge"; (PAPERT 1993, 185).

With respect to instruction, this state of affairs may be depicted in the following diagram which would serve as a pictorial layout (description plus intention) of the verbal algorithm above and, with further development, as communication link in an intermediate stage towards a computation-oriented algorithm.



<u>Fig. 2.3</u> Closed-Loop Feedback Control introducing Energy and Information (Cybernetic) Notions.

Such an implicit "Cybernetic Abstract Structure" can be viewed as a schema or a frame[34] (PIAGET 1966 [35], MINSKY 1975, HOLLAND et al. 1986) and provides an abstract categorisation for the problems; for the learner, this structure may become explicit in the course of using the schema.

HOLLAND et al. also argue that schema induction is a major contributor to successful transfer across remote problem domains, and that induction of an explicit schema facilitates transfer (HOLLAND et al. 1986). For expert problem solvers (for the instructor), solving a routine problem can be thought of as a process of retrieving an appropriate problem schema and providing it with problem-specific parameters.

Technically, however, a perfect analogy does not exist in the sense that two different domains cannot be completely identical and there are, therefore, limitations to any analogy. Nevertheless, with respect to the learning of an intrinsically scientific concept, we regard that recognising both the similarities and differences with a fully developed analogy can be essential and instructionally valuable in developing a clearer and more complete understanding of a concept [36]. In particular, because HOLLAND et al. support the view that problem solving through analogical inference must be viewed as an integral part of the overall process of model construction (HOLLAND et al. 1986), we, consequently, regard the provision of such a domain-specific framework to provide the novice with a powerful technique and procedure for assimilating or improving the understanding of new information.

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[34] An abstract structure common to problems can be viewed as a schema. A schema represents an abstract category of which specific analogues are instances. HOLLAND et al. 1986).

[35] PIAGET (1966) - in a different context – had earlier described discovery as the spontaneous reorganisation of earlier schema which are accommodated into the new situation through reciprocal assimilation.

[36] Inductive mechanisms can invoke the use of an analogous source model (if one is needed and is available), and they can continue to improve an imperfrct target model beyond the point at which the analogy itself “runs dry“;(HOLLAND et al. 1986, 300).

2.7.2 Relating EULER's Method and the Cybernetic Metaphor to Develop the Characterisation of Scientific Computation

In mathematical terms, the basis of most conventional models of natural phenomena is most precisely characterised by the differential equation. And, therefore, since its introduction towards the end of the Seventeenth Century, it has been the backbone of scientific theory and has been used as the universal tool to describe dynamic systems. An appreciation and a basic understanding of differential equations - and of the nature of calculus - for engineering and physical science students at the tertiary level, consequently, remains beyond challenge.

The classical approach to investigating dynamic systems also uses differential equations as the modelling framework. Such equations give the relation between certain quantities and their rates of change. Complete solution to linear differential equations, in terms of standard mathematical functions, are occasionally obtainable.

For non-linear differential equations, however, the standard EULER's method - which is based on discretisation [37]– can be exploited and developed to formulate an extrapolation scheme/technique for developing solutions. The differential equations of the model are replaced by corresponding finite difference equations which are solved at each time step. The time paths of the system variables are evaluated by progressing through time in discrete, equal-sized steps. The time step used is sufficiently small for there to be effectively no change in rates of flow during it.

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[37] For continuous systems, the clock advances smoothly. Knowing input and state defines the output completely. In deterministic systems, a complete knowledge of the output can be completely described in terms of its input, whereas in stochastic systems only the probability of occurrence of a certain output can be estimated. Digital simulation in the computer starts with a discretisation of the time variable and the transformation of differential equations into algebraic ones. Discrete systems are defined by changes in the state of the system occurring periodically.

In his manner, therefore, essentially any scientific system, event or process which can be described in terms of arithmetical, algebraic or differential equations can be modelled in terms of difference equations - functions are replaced by flows within the system under consideration. We consider this modelling approach to be convenient and appropriate in providing a legitimate means for the description, for the significance and for characterising the form of the differential-equation. In addition to this, such a utility, when implemented on a computer, essentially constitutes digital simulation. Digital simulation as applied to scientific processes starts with a discretisation of the time variable and the solving of difference equations. Inasmuch as differential equations have the reputation of being difficult among the less mathematically-inclined engineering or physical science student, the need to use them as an immediate tool towards digital simulation, subsequently, disappears as computers shoulder much of the work in solving these equations.

From didactical and epistemological standpoints, the outcome of the simulation, however, is to be seen in the light of obtaining information and learning about the system's generic properties. That is, the model's features and modelling details are educationally paramount, rather than the model's real-world manifestations at this stage.

Consequently, when integrated within the context of the Cybernetic metaphor developed by FORRESTER (1968), we regard that EULER's method provides both an instructional mechanism and the learning tools/environment by which our concept of scientific computation may be introduced, characterised and further developed [38].

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[38] For the learner not familiar with such mathematical aspects as differential equations and the EULER discretisation process, the burden of such mathematics is placed squarely on the computer and the learner is only required to appreciate/acknowledge the mathematical processes underlying computation. Consequently, we do not regard computation as a vehicle for introducing such mathematics to non-mathematically inclined learners. The mathematically-inclined student who has a firm grasp of the difference equation and its basic formulation, on the other hand, could be in a position to appreciate the mathematical nature of digital computation and appreciate its relationship to the simulation process.

Considering the case of the distance, speed and time relationship in the dynamics of motion, for example, Mathematics/Physics Didacticians are convinced, however, that difference equations of the form

$$\mathbf{X(n+1) = X(n) + V \,.\, \Delta t}$$

where $X(n+1)$ is the new position (cf. NEW LEVEL in System Dynamics),
$X(n)$, the previous position (cf. OLD LEVEL),
V is the speed, (cf. RATE) and
Δt is the time interval,

are visually more appealing and meaningful and, consequently, educationally more conducive than the standard differential equation form, In the following subsections, we demonstrate how the algorithmic nature and the logical and descriptive statements of System Dynamics formulations can also be made explicit and meaningful in this context thus furthering the understanding of the process leading to (an appreciation) of scientific computation.

2.7.2.1 Characterisation of the Open-Loop Control - Cause-And-Effect - Process (1)

The Open-Loop Control Process may be conceptualised in terms of the flow of water into a tank that takes place at a constant RATE, R. Changes in the system are observed through the LEVEL, L of the water. R, in turn, is "governed" by the setting in a valve connected to the inflow, and is external to the system. This is represented schematically below.

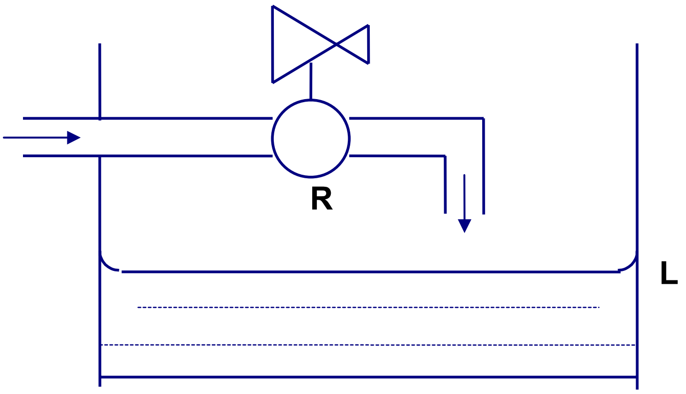

Fig. 2.4 **Cause-And-Effect Schematisation of the Open-Loop Control Process -1**

In the preliminary source schematisation above, conceptual learning - through such a pragmatic and syntactic characterisation of the process –

V = dX/dT.

is provided and/or enhanced by the notional structure mechanism for the reasoning schema, and whose secondary purposes would serve:

- to offer a metaphor to convey understanding that relates to the process and,

- to supply the contextual framework for the relevant System Dynamics concepts, formulations and terminology.

In terms of a System Dynamics Causal-Loop Diagram, a representation of the system's process is simply described by

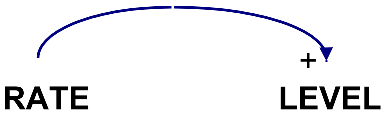

Fig. 2.5 **Causal-Loop Diagram of the Open-Loop Control Process - 1**

Such a pragmatic-reasoning, causal construct for recurring types of relations in the real world, and their construction is an innate human attribute which, although existing at a purely abstract level, is independent of any content domain and can be further developed to include multiple-cause relationships (HOLLAND et. al. 1986).

System Dynamics further enables the illustration of the dynamic (time-varying) characteristics of the process through LEVEL-RATE Flow diagrams, with the cloud-like symbol representing sources and sinks, and the RATES and LEVELS being pictured as stylised valves and tubs to emphasise the analogy between accumulation processes and the flow of a liquid (RICHARDSON & PUGH 1986).

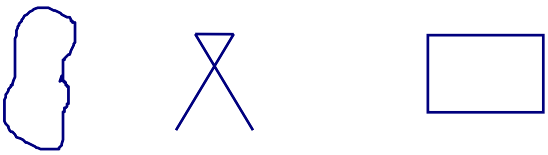

Fig. 2.6 **LEVEL-RATE Diagram of the Open-Loop Control Process - 1**

The mathematical basis of such a diagram is that **L** is the accumulation of the rate of change, **R**[39]**.** The initial step to this mathematical model is :

$L(t) = L(0) + R * \Delta t$[40].

The System being modelled is considered to be controlled by information feedback, i.e., the System is composed of feedback loops within which are the LEVELS and RATES variables. Within such a System Dynamics formulation/program, however, is incorporated the algorithm for the process described by the difference equation(s), and this algorithm can then be regarded to serve as the basic principle for describing the computational process.

From a curricular/didactical - viz., instructional perspective, two[41] particular aspects of the notion of computation can become apparent:

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[39] Thus when considered in a purely mathematical context, a RATE is represented by the derivative of a LEVEL, and since System Dynamics relates LEVELS to RATES, a System Dynamics model is, therefore, observed to be actually a set of differential equations.

[40] Thus when considered in a purely mathematical context, a RATE is represented by the derivative of a LEVEL, and since System Dynamics relates LEVELS to RATES, a System Dynamics model is, therefore, observed to be actually a set of differential equations.

- The resulting equations thus constitute, in effect, an algorithm that determines the value of a quantity at the end of an interval given a value at the beginning. Through the application of this algorithm repeatedly for successive intervals, the approximate variation of the quantity with time can be found. Smaller intervals will yield more accurate results. The calculation required for each interval is reasonably straightforward to appreciate, but it must be repeated several times by iteration to achieve an acceptable degree of accuracy, and this is clearly most appropriately undertaken and executed by the computing facilities of the computer.

- In the algorithm [42], a RATE can be determined from the derivative of the LEVEL function, and thus implicit in the notational scheme is a simple integration formula [43].

The structure of the underlying phenomenon may be examined by a simplified representation of the system, viz., simulation, and incorporating EULER's technique:

---

[41] Such an operation defines an integrator (FORRESTER 1968) which is the fundamental dynamic component for continuous systems. Whatever time-function that comes in is integrated and the result appears as output, i.e., the input is the derivative of the output. This particular aspect of computation can be used to illustrate that the primary mathematical operations governing computer simulation are, in effect, elementary algebra and integration.

[42] which FORRESTER calls “rectangular integration algorithm” (1968).

[43] As such, concepts from integration and differential equations - which are more oriented towards graphical representation than symbolic ones - are made more accessible through a need-to-know basis rather than through traditional axiomatic approaches. The underlying structure of the algorithm is cast in terms of LEVEL-RATE computational statements in which the content matter of differentiation and integration are developed in an exploratory manner. This allowed FORRESTER to claim that it was much easier and much more natural for the student to deal exclusively with the process of integration and to make no reference to differentiation. Differentiation was seen as a mathematical artificiality which does not have a real life counterpart (FORRESTER 1968).

$$\mathbf{L\ \{new\} = L\ \{old\} + L\ \{added\},}$$

$$\mathbf{L\ \{added\} = R * \Delta\ t;}$$

Using System Dynamics notation, this is expressed as

L LEVEL NOW = LEVEL BEFORE + (RATE OF CHANGE * ELAPSED TIME)

Therefore, by specifying rules that describe change and the dynamic nature of the phenomenon in terms of

- variables that characterise the system and change over time,
- relationships among the variables that are connected by cause-and-effect feedback loops, and
- the status of one or more variables that affects other variables, it becomes possible to construct and simulate a model of the system's behaviour [44] .

2.7.2.2 Characterisation of an Open-Loop Control - Cause-And-Effect - Process (2)

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[44] FORRESTER - in questioning the aspect of a differential-equation description of a system here calls attention to the fact that nowhere in nature does the process of differentiation take place, and that no instrument measures derivatives - manages to leave differential equation formulations out of a System Dynamics simulation altogether. The basic idea underlying such an analysis is stated as:

" .... an integration method that employs estimated past and/or future values of output and derivative in an effort to better estimate their present values;" (FORRESTER 1961, 68).

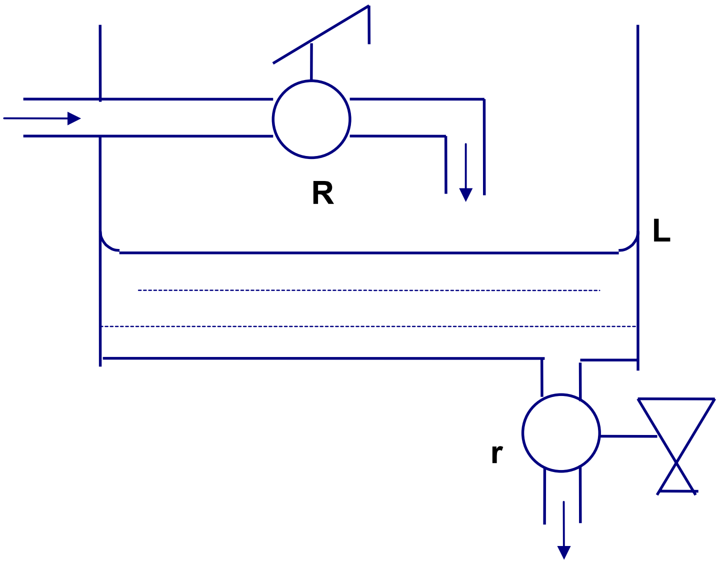


Fig. 2.7 **Schematisation of the Open-Loop Control - Process 2**

Through a hole in the tank's bottom water flows out at a (different) constant RATE **r -** (outgoing rate) - changing LEVEL **L. L**, consequently, now becomes the accumulation of the net flow **(R - r) -** (incoming rate - outgoing rate) **-** in a given time, and is constant. The corresponding situation for this system is depicted below.

The system behaviour is illustrated using a Causal-Loop Diagram as shown below.

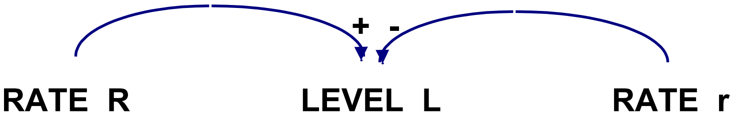


Fig. 2.8 **Causal–Loop Diagram of the Open-Loop Control Process - 2**

The LEVEL-RATE representation of the situation depicted above may be shown as below.

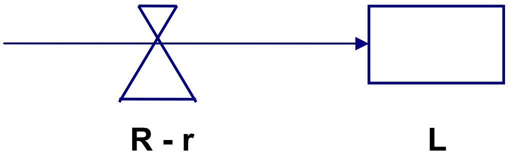


Fig. 2.9 **LEVEL-RATE Diagram of the Open-Loop Control Process - 2**

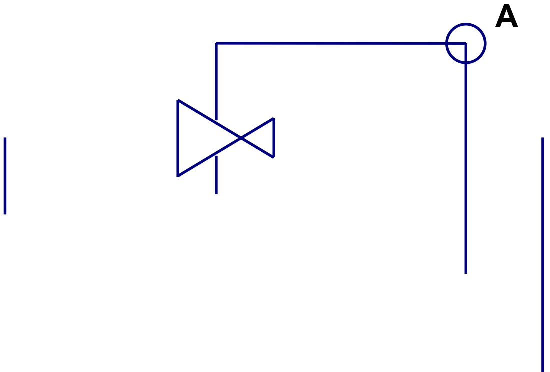
To simulate this new system, DYNAMO formulation incorporating EULER's technique gives:

L {new} = L {old} + {R - r} * Δ t;

Using DYNAMO notation,

L LEVEL NOW = LEVEL BEFORE + {INRATE - OUTRATE} * {ELAPSED TIME}

2.7.2.3 Characterisation of the Closed-Loop Control - Feedback-Control - Relationship



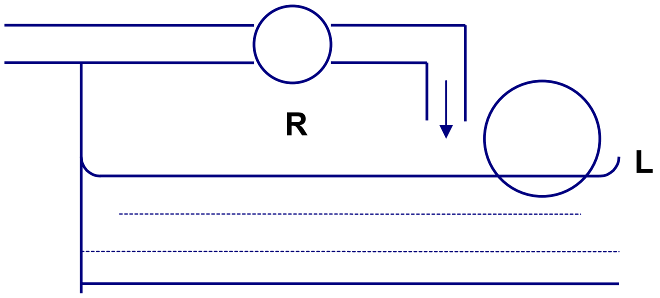


Fig. 2.10 **Schematisation of the Feedback-Control Process**

The flow-rate into the tank is regulated by the position of the valve, and the valve's setting, in turn, is being controlled by a float. Like FORRESTER who regards this as

> " ..... a simple feedback system for water level control will be used as a basis for exercises in flow diagrams, consistency of measure, time graphing, that accumulation process represented by a level variable, and computation of successive levels of a system ..... "; (FORRESTER 1968, W2, 2-3),

we may use the mechanism illustrated above as a basis to initiate in the learner familiarity with the way in which a dynamic feedback system functions, and whose structure can subsequently be developed into the more comprehensive flow diagrams and equations (FORRESTER 1968). The causal-loop diagram is initially modified to take into account the aspect of feedback in the following simple manner:

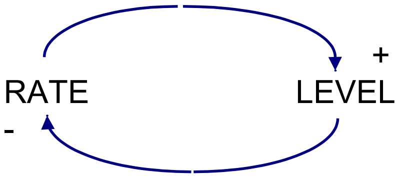


Fig.2.11 **Causal-Loop Diagram of the Feedback-Control Process**

As a first step towards introducing the auxiliary function – to take into account the contribution and consequence of the float action – the LEVEL-RATE Flow Diagram takes then the following form:

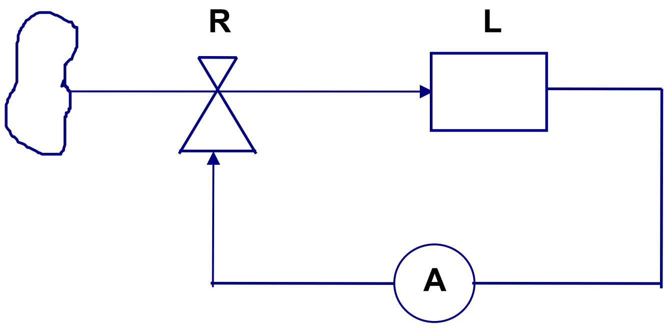


Fig.2.12 **LEVEL-RATE Diagram of the Feedback-Control Process**

The LEVEL-RATE Flow Diagram infers more reliability into some of the dynamic implications of the feedback structure. The present water level is an accumulation of all the past flow rates; the next water level is determined by the present water level. The flow rate is maximum when the tank is empty and tends to zero as the tank fills up.

The equations describing this feedback system in DYNAMO are, finally,

L LEVEL NOW = LEVEL BEFORE + FLOW RATE * ELAPSED TIME

R FLOW RATE = CONSTANT * DIFFERENCE NOW

A DIFFERENCE NOW = MAXIMUM LEVEL - LEVEL NOW

Such a system represents the simplest "negative feedback", goal-oriented, self-regulating – like homeostatic or temperature-regulating systems (GOODMAN 1983) - structure. Formally, the four basic elements that constitute such a negative feedback process are :

- the desired state (GOAL),
- the discrepancy (DIFFERENCE),
- the action (RATE),

- the system state (LEVEL).

Altogether, these variables form a dynamic feedback system, expressed in terms of simultaneous equations.

In the final analysis, simulation - using a DYNAMO compiler - is used to examine the structure of the system in question. This is performed by altering characteristics of variables and assessing their effects on other variables and the system. Over time variables change and cause other variables and their interactions to change as well.

It has been found (GREENO 1980) that the computational analogue of thinking partly depends on general purpose procedures, but rather more on skilful use of specific knowledge that has been retrieved from memory. However, the knowledge has to be highly structured or well organised for retrieval to be efficient. The Dynamic-Feedback-Cybernetic-Systems thinking outlined above, and one that underlines System Dynamics, can be seen to meet the criterion by providing the required domain-specific framework. The knowledge structure so retrieved is not simply and merely the necessary, basic information but, as we observe in later developments, serves as a procedure for processing other data structures. Novices tend to lack domain-specific knowledge and SIMON (LANGLEY et al. 1987) suggests that good-problem solving performance requires that the problem-solver has large amounts of domain-specific knowledge organised into chunks or sub-routines.

3 The COMPUTATION COMPONENT of Scientific Computation Literacy

3.1 Key Issues in Science Education and Educational Computing

Through our formally defined and problem-solving-oriented notion and concept of computation in application to science, the computer can be considered not only to have radically influenced the nature of scientific problem-solving, but we regard also that such a problem-solving capacity does, consequently, radically alters what it means for science learners to learn about solving scientific problems. From the three meanings of computation (outlined in CHAPTER 1), we adopt here the notion of Scientific Computation to be primarily a means of obtaining information of specified scientific content/quality - and not simply a means of obtaining numerical answers to scientific problems, viz., numerical analysis - using the capabilities of the computer. Within such an educational context of "computation towards further understanding, computers can be regarded, consequently, to have also significantly affected the hold and the influence of the formal theoretical and experimental approaches of scientific method on the scientific education process - and manifested in traditional science learning, instruction and curriculum design - by providing the third aspect, the computational approach. Such an approach, however, we consider is not necessarily to be introduced as an extension of either theoretical or experimental approaches, but can constitute an independent mode of scientific research. We analyse in this chapter the significance and potential of this mode of scientific research to science learning and instruction, and the dimension it adds to the understanding of scientific method together with some implications upon context-related computer literacy issues.

In the field of educational computing, while some educators continue to argue that pre-college students should learn how to use computers, and others assert that only a preliminary knowledge of the function of computers is necessary, a third faction are firmly of the opinion that students should learn to program them. And of those who believe that students should be taught programming, some argue that it should be taught for its own sake and others argue that it should be taught for the cognitive skills it develops (SCAIFE and WELLINGTON 1993, KOZMA 1994). A viewpoint of programming as an instructional activity, and of programming just for the intellectual challenge of programming or for exercise/practice in programming, perhaps extreme but which we consider to be worthy of note in our context of computing, is taken by G. SOLOMON who claims that:

> "it is interesting to note that the only people in the world - as far as I know - that program for the sake of programming, with no other purpose in mind, are grade school students"; (SOLOMON in POLIN, L. 1992 (b), 8).

The current view of programming as a discipline - in which the goal of a project is given in advance and where emphasis is placed upon the product - also has a profound influence on computer science education at the tertiary level (HARVEY 1991). Thus programming in such a context may claim status as a discipline or subject of study in its own right, and in this respect the activity of programming can undoubtedly be considered intellectually absorbing and educationally rewarding.

Through our analyses, however, we address this “no significant academic purpose in mind“ viewpoint, which is essentially characterised as a consequence of educational claims of contributions of programming to mathematics learning, and which is influenced by curricular issues and computer literacy requirements through computer studies, viz., through programming as an instructional activity. For those not subscribing to formal Computer Studies, we contend that it does reflect the uncertainty, and questions the intent and relevance, of the role of programming in pre-university education, particularly in the light of current and continuing computer software and hardware developments.

3.2 Programming Basis of PASCAL, LOGO and DYNAMO

Bearing such notions and perspectives of computer programming in mind, we explore and analyse the programming and computer simulation environment featured in DYNAMO - and against the background of the strongly contrasting language PASCAL and the LOGO computing environment - in a scientific educational light, and attempt to appreciate the computer oriented scientific problem-solving learning potential and instructional features of the scientifically-oriented computational activities underlying System Dynamics. In particular, we examine the potential of DYNAMO’s computational features in providing some educationally desirable aspects of programming that are inherent and valued in PASCAL, and in providing a learner-oriented/learner-friendly environment that is claimed for LOGO.

In general, programming languages are designed to control and effect the insertion and the processing of data, and the presentation of the outcome, and must, consequently, include instructions to:

- input and store data of numeric and other types;
- output stored data of various types;
- assign values to specified data items;
- execute instructions in a sequence determined by the current value of data items;" (WOODHOUSE and McDOUGALL 1986, 137).

An algorithmic viewpoint and approach are required in a computational process when the problem at hand requires a numerical answer which is of significance for subsequent work either within or out of the main mathematical content. An algorithm being a precise description of how to solve some specific problem, the notion of algorithm [45] forms a fundamental concept in scientific computation.

We summarise DAVIS and HERSH's (1986) interpretation of complete Scientific Computation (which they also identify as 'numerical analysis of scientific problems as practised by expert scientists') - and which comprises the strategy of computation as well as the evaluation of what has been accomplished - to consist of:

1. the formation of algorithms;
2. error analysis (including truncation and round-off error);
3. convergence (and rate of convergence) study; and
4. comparisons of algorithms - to judge the relative utility of different algorithms in different situations.

but DAVIS and HERSH are prompt to point out that:

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[45] An algorithm here - and also seen primarily from an instructional angle - is interpreted to be a set of instructions specifying a sequence of operations which will give the answer to any problem of a given type (PYLYSHYN and BANON (1989).

> "the pure algorithmic spirit would be content with steps 1 and 4 only - to try them out in typical problems and to see how they work. ..... A good algorithm can be used, even if we have no direct proof, but only computational experience will tell us that it is good." (DAVIS and HERSH 1980, 186).

Since an algorithm is comprised of constructions, an understanding of the algorithmic process requires the awareness and appreciation of the combined actions of the contained constructions. Educationally, but particularly adopting an instructional viewpoint, using algorithms can be employed as a means of building the learner's understanding of programming semantics and of the problem-solving process involved in programming and, subsequently, such an intellectual exercise of algorithm development should lead the student to a better understanding of the problem and towards an acquisition of the important high-level skill of developing the sequence of steps by which a problem is to be solved (SOLOMON 1986).

In general, the process of converting the problem into a computer simulation program was traditionally reviewed as indicated below.

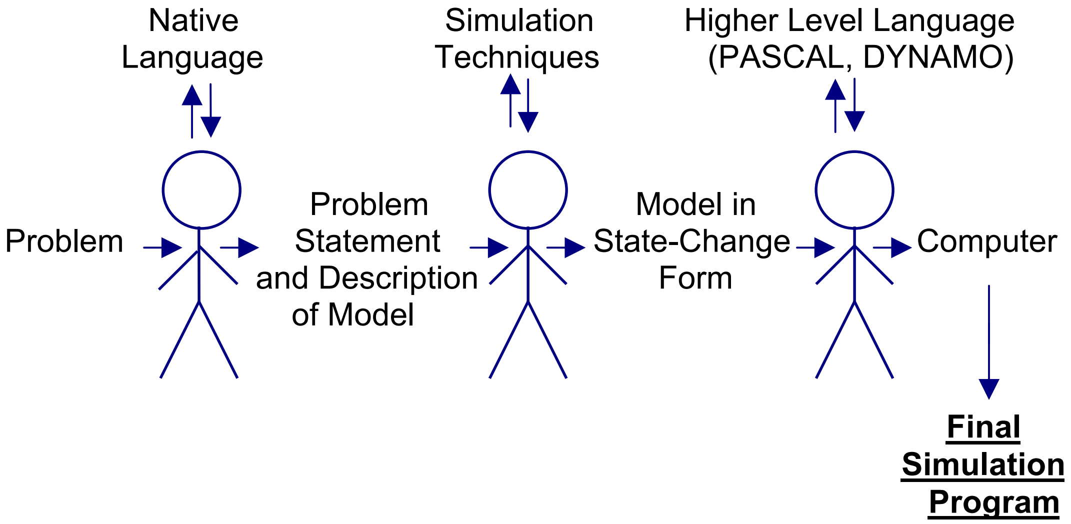

Fig. 3.1 **Conversion of a Problem into a Simulation Program – Standard Procedure**

Such a configuration can also be applied to an algorithm-based programming language of which DYNAMO is a case - to a significant extent.

Conventional approaches to implementing algorithms, however, tend to describe the action of existing steps in isolation, and usually no attempt is made to rationalise the selection of those constructions that are used. Moreover, and in the purely programming sense, since algorithms are abstract representations of programming logic, difficulties may also be encountered in thinking at the level of abstraction required. The introduction of the computational concept of model - along with employing examples of models used in different disciplines - allows algorithm design to be equivalent to, or to come close to, model building. This very feature underlines model-construction and, as we see later, model-testing in System Dynamics.

With respect to the underlying aspects and features of programming, we recognise that both PASCAL and LOGO require different levels of educational commitment - which include, in particular, a reasonable amount of time to learn and a degree of ongoing use to remember. The following two sections (and subsections) consider this by contrasting aspects of the programming elegance of PASCAL, the simplicity of the LOGO programming environment and the DYNAMO programming pragmatism. Part of the analyses is carried out implementing a simple, tried-out Predator-Prey Ecological model (CRAMER 1985, HILTY and SEIDLER 1991).

3.2.1 PASCAL

PASCAL (JENSEN and WIRTH 1978) was invented by NIKLAUS WIRTH of ETH in Zurich, and designed to be comparatively straightforward to learn – it was/is acknowledged for its consistent, logical and systematic approach and it avoided machine-oriented details. Further developments of PASCAL command widespread acceptance from academic circles (particularly in advanced Computer Science courses) as languages that exploited fundamental programming concepts and for their emphasis on structured programming and are, sometimes, also strongly recommended for applications in introductory Computer Science courses. It is expected that programming practice with PASCAL, which contains the right concepts explicitly in its syntax and vocabulary, should tend to inculcate those concepts in the user’s thought processes and habits of problem analysis and programming.

PASCAL was originally developed, therefore, primarily for the teaching of programming concepts - amongst a variety of other motives - and without any specific area of programming application in mind. It was designed, additionally, to be a general-purpose language and embodies understanding of good techniques for algorithm design and expression; it provides a wide range of data structures and permits the programmer to define further, new data structures (WOODHOUSE & McDOUGALL 1986). Thus PASCAL can be very useful - and recommended in computer science courses - where data structures are required to be studied in depth.

PASCAL does possess a rigid set of rules, however, and these rules must be followed rigorously. Computational ideas such as "procedural and recursive thinking" as well as "algorithm formulation" are imbedded in PASCAL (SOLOMON 1986). Problem-solving techniques in the style of POLYA (1973) - breaking problems into simpler components - can be applied through PASCAL's capability for characterising the problem's components in procedures. PASCAL's 'portability' and the standard nature of its (viz., Turbo PASCAL) implementation also make it a preferred medium for even further conceptualisations and developments of programming ideas and programming practice in education (FORD 1990).

3.2.2 LOGO

Characterising the programming language LOGO is the LOGO environment - comprising LOGO microworlds [46] (PAPERT 1992) - and the programming culture which can evolve from such an environment.

LOGO was conceptualised/created by SEYMOUR PAPERT and was designed to enable very young children to control the computer's output and thus to discover for themselves basic computing principles such as procedural description, iterative algorithms subroutines and recursions.

In LOGO, the language and operating system are integrated so that one instruction produces a 'miniature program'. PAPERT's belief is that while children explore and experiment in the LOGO environment and solve problems they encounter, they can develop skills of systematic thinking

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[46] GOLDENBERG has defined a microworld as:

> “a well-defined, but limited, learning environment in which interesting things happen and in which there are important ideas to be learnt.“ (GOLDENBERG 1982, 210).

and learn such "powerful ideas" as procedural thinking, concrete and formal operations, problem decomposition and debugging through discovery learning in a microworld. As problem-solving experience accumulates, it is expected that systematic thinking will give way to intuitive understanding of concepts and to formulation of rules and strategies for solving problems (PAPERT 1980, 1993).

At the extreme, the LOGO movement represents an ambitious attempt to foster general thinking skills by teaching programming. The findings on LOGO's effectiveness are, however, mixed. Some findings (PEA et al. 1987, SINGH 1992) conclude that LOGO has not lived up to PAPERT's expectations, while a number of studies report cognitive gains following LOGO training in particular problem-solving activities (LAWLER 1985, SINGH 1992). Attempts to explain both aspects speculate that learners may think more specifically in terms of the structure of the problem under consideration rather than the language being used to solve it. Transfer effects have been more evident, however, in highly structured situations where the learner's attention is drawn explicitly to the principles s/he is unconsciously applying, rather than in the open, exploratory PAPERTian mode (SINGH 1992).

LOGO is the result of a movement [47] against the dominant paradigm of computing in education, namely, the delivery of content, and rallies around the particular educational theme of "constructionism". PAPERT (1980, 1993) has described constructionism as empowering students to be novice epistemologists : young scientists, not simply consumers of the analysis of the work of established scientists. Constructionism - in PAPERT’s view - poses the questions:

> "How can one become an expert at constructing knowledge ? What skills are required? Are such skills the same for different kinds of knowledge ?" (PAPERT 1993, 143).

It is our contention that an approach towards promoting - and providing the conditions for - computational intuitionism and constructivistic science learning in a computer-based environment can be provided by the computational features of the System Dynamics methodology. We subscribe to the educational principle that learners may experience the construction of knowledge by using the cognitive and social/cultural tools

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[47] and is a position we have also elected to adopt.

of the discipline they are studying (PAPERT 1980, 1993). Teaching that is conducive to constructionist learning, it may consequently be interpreted, provides assistance to learners by instruction in the means by which people in scientific disciplines investigate their field, in what constitutes evidence and knowledge, and how to communicate about these.

With respect to the learning/instruction of the concepts and process Scientific Computation, we propose as a prelude to our analyses that System Dynamics through DYNAMO has the potential to provide one such formal system and that it comprises an environment which contains important and powerful methodological tools that brings important ideas and aspects of different scientific fields together. Moreover, we recognise that such a scientifically-based approach to learning as can be described as constructivistic, in contrast to the more traditional and objectivistic-oriented approach to school science.

3.2.3 DYNAMO

Although the System Dynamics approach is essentially language free, the special-purpose programming language DYNAMO - an acronym for DYNAmic MOdels - has been associated with System Dynamics from the beginning (RICHARDSON and PUGH 1981). To increase the applicability and ease of a programming language, special-purpose programming dialects provide sophisticated forms of programming instructions to facilitate the achievement of the specific goals which have been established. DYNAMO was designed to simulate feedback systems – the language itself contains functions and features that aid in the conceptualisation and formulation of dynamic models.

One of the penultimate steps to be implemented in the System Dynamics methodology is the conversion of the model equations into a program that is suitable for solution on the computer. This requires:

- checking that the components are compatible with one another;
- coding the mathematical equations in the DYNAMO language;
- developing a simulation control program.

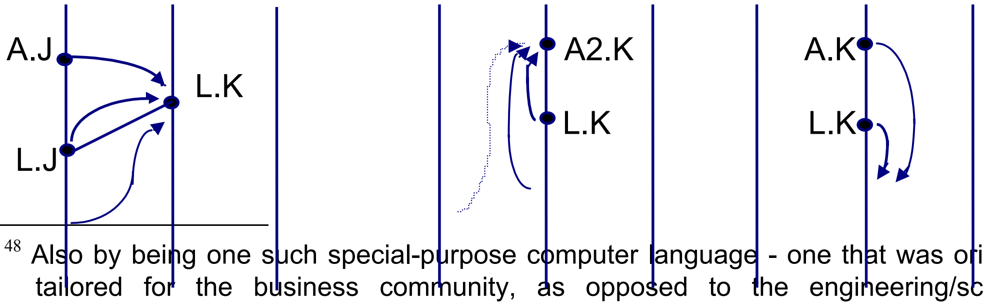
The equations in DYNAMO comprise:

- LEVEL, RATE and AUXILIARY Equations - preceded by the letters L, R and A, respectively - which constitute the basic building blocks of a System Dynamics model;

- The Supplementary Equations - preceded by the words PRINT and PLOT - are used to couple the model to the printed or plotted results.

- The CONSTANT and INITIAL VALUE Equations - preceded by the letters C and N, respectively - define constants and initial values.

The notational scheme allows a DYNAMO model to be specified as a network of components and, most conveniently, reflects a difference equation approximation, i.e., the notational scheme is patterned after the actual computational method that is used to calculate the results [48].



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[48] Also by being one such special-purpose computer language - one that was originally tailored for the business community, as opposed to the engineering/scientific community (FORRESTER 1968, RICHARDSON and PUGH 1981) - DYNAMO can be shown or interpreted - through instruction and applied use - to be structured and formulated in terms of linear or non-linear difference equations as applied to specific, simplified physical/engineering and mathematical phenomena should the need arise.

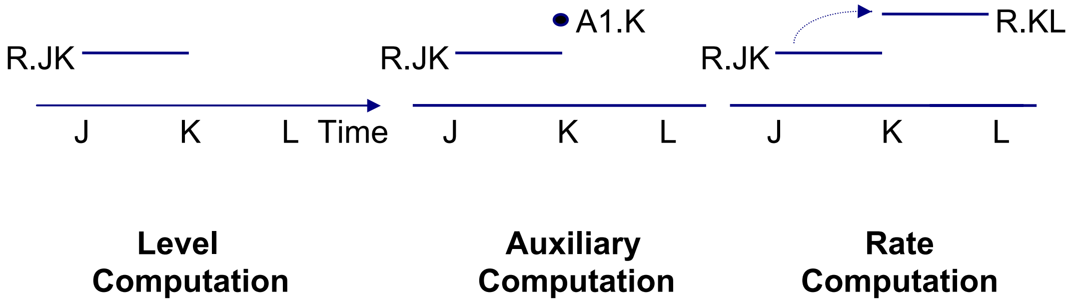

Fig. 3.2 **LEVEL, AUXILIARY and RATE Computational Schemes**

Within the LEVEL and RATE equations, the letters "J", "K" and "L" are used to indicate the time steps:

.K denotes the present time,

.J denotes the preceding time,

.L denotes the next time,

.JK denotes a rate of flow between times J and K,

.KL denotes a rate of flow between times K and L,

DT denotes the computation time interval that separates the time steps.

Initially, the LEVEL at time .K - L.K, is computed from the LEVEL at time .J - L.J, from the AUXILIARIES at time .J - A.J and from the RATES during the time interval .JK - R.JK. Then the AUXILIARIES at time .K - A.K are computed using values of LEVELS at time .K - L.K, of AUXILIARIES at time .K - A.K, and of RATES in the interval .JK - R.JK. Finally, the RATES in the time interval .KL - R.KL are computed from the RATES in the time interval .JK - R.JK and the AUXILIARIES and LEVELS in the time .K - A.K and L.K. The model equations are thereby solved in a recursive manner over the planned time interval.

We note that by introducing the semantic categories LEVEL.K, RATE.KL and DT [49], the semantic structure is shown to consist of the logical dynamic dependence between the variables; this can have the effect of making the syntactic representation for the prevailing semantic structure easier to appreciate and to apply.

The form of structuring essentially serves to make the model compatible with the DYNAMO compiler. DYNAMO is, therefore, fundamentally a programming system where programming is performed by functional specification at a very high level, and by the alteration of parameters rather than by detailed coding or by the manipulation of machine-oriented terminology. Given the data in the specified form, the DYNAMO compiler (RICHARDSON and PUGH 1981) - which is in the "compile and go" format:

- checks the given equations for logical consistency - i.e., checks and translates the model into machine language;
- solves the system of equations - i.e., runs the model;
- tabulates the data and plots the results graphically;
- reruns the model with parameter changes.

The machine code is never saved, the user works exclusively in the source language and does not need to know anything about the execution language. Seen from the learner's angle, therefore, since DYNAMO carries the burden for calculating, recording and displaying mathematical equations describing the relationships between variables and the values of the variables under simulation conditions, this amounts to the provision of an icon-based tool kit for creating, managing and exploring dynamic systems rather than of programming tools as such.

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[49] which also comply with the notion of dimensional consistence, a noteworthy aspect that can be mentioned and elaborated in the course of instruction.

3.3 Application to the Predator-Prey Ecological Model

Although computer programming skills are important, one must attain a reasonably high degree of mastery of all the skills to achieve and to claim a level of competency in programming. This is not an impossible task and can often be an exciting one. However, we contend that it is best undertaken and accomplished as a separate activity, and not as an integral part of the Physics/Science/Mathematics lesson.

As a contrast to the acquisition of programming skills, the following features - summarised and modified from ROTH (1975) - may serve to provide guiding principles and instructional perspectives within which a systems simulation model may be constructed and its educational value tapped and, subsequently, assessed.

- Division of the system into conceptually simple logical subsystems;

- Use of diagrams to illustrate the structure of the system and relate and subsystems.

- The inclusion of pertinent information.

- Model simplicity and the use of standard terminology.

- Structural and computational accuracy.

More immediately, however, these simulation features may serve to contrast and to indicate the degree to which scientific computational notions are promoted by the programming features and program-construction steps in PASCAL, LOGO and DYNAMO and applied to the Predator-Prey Ecological system as described by the LOTKA-VOLTERRA model.

3.3.1 Basic Assumptions of the LOTKA-VOLTERRA Model

For the case rabbits and foxes, a modified form of the LOTKA-VOLTERRA system enables the development and formulation of a simple and elementary Predator-Prey model in terms of the following assumptions,

- ❖ the preys' increase-rate is proportional to the number of prey;

- ❖ the preys' decrease-rate is proportional to the number of predator-prey encounters, i.e., to the arithmetical product - predators * prey ;

❖ the predators' increase-rate is proportional to the number of predator-prey encounters, i.e., to the arithmetical product - predators * prey;

❖ the predators' decrease-rate is proportional to the number of predators.

For **F** foxes and **R** rabbits at a stated point in time **t** and a period of time **Δt**[50] later, the following equations may be formulated to describe the basic system:

$$\mathbf{R(t + \Delta t) = R(t) + a * R(t) * \Delta t - c * F(t) * R(t) * \Delta t}$$

$$\mathbf{F(t + \Delta t) = F(t) - b * F(t) * \Delta t + d * F(t) * R(t) * \Delta t}$$

where **a** - **the increase factor** = rate at which Rabbit population increases in isolation,

where **b** - **the decrease factor** = rate at which Fox population decreases in isolation,

where **c** - **the prey factor** = rate at which the Fox-Rabbit encounters decreases the Rabbit population - giving **$c * F(t) * R(t) * \Delta t$** = expected number of Rabbits eaten by Foxes in a given period,

---

[50] A problem one encounters when translating the model into a programming language (like LOGO, PASCAL or DYNAMO) is that the algebraic equations cast the process as a continuous (or analogue) one. Since the computer works discretely, the concept of "Δt" is not formally significant. One simply steps through the process incrementing according to the rules at each stage. The problem is that the algebraic form is essentially static, with the increment "Δt" being a mental abstraction. The computer procedure is essentially dynamic, with the time being represented as either real-time or an artificial sequence of steps. Computer representation is algorithmic in nature, and one also has to work within the precision with which the software represents the numbers. To make the structure clearer, one would, therefore, have to recast the problem in a non-algebraic form.

where **d - the predation factor** = rate at which Fox-Rabbit encounters leads to a Fox population increase - giving **d * F(t) * R(t) * Δt** = expected increase in Fox births as a result of food supply,

and **a**, **b**, **c**, and **d** are all **positive constants.**

Adopting values for the constants taken from a study taken by BOSSEL (1989, 63-65), the equations in their intrinsic mathematical form may be written as.

$$R(t + \Delta t) = R(t) + 0.10 * R(t) * \Delta t - 0.02 * F(t) * R(t) * \Delta t$$

$$F(t + \Delta t) = F(t) - 0.25 * F(t) * \Delta t + 0.05 * F(t) * R(t) * \Delta t$$

3.3.2 PASCAL Version of the Predator-Prey Ecological Model

The general structure of a simulation algorithm, written as a self-contained module comprising four distinct stages - viz., procedure - in PASCAL, takes the form:

(i) Obtain the Simulation Parameters and Initial States;

(ii) WHILE the termination criterion is NOT met

```
            Time -----> Time  + Time Step;
            Change the State Variables and record the State of
            the System;

  (iii)  Summarise the System Behaviour;

  (iv)  Stop.
```

Towards the subsequent stage of program transformation - by stepwise refinement - in which the basic structure is maintained while details are modified, a type of "solution algorithm" allows the process to be simplified by redefining the Predator-Prey Ecological model in terms of mathematically-derived expressions. Thus, for a single-species (rabbit only and foxes only) model - reformulated and given by the equation in its standard mathematical form and, particularly, to enable an appreciation of the transition into a form amenable for PASCAL – the model equations for **rabbits** – **r** and **foxes** – **f** is given by:

$$\mathbf{r(t + \Delta t) = r(t) - \{ 0.10 * r(t) * (1 - r(t)) * \Delta t \} - \{ 0.02 * r(t) * f(t) * \Delta t \}}$$

$$\mathbf{f(t + \Delta t) = f + 0.25 * f * (r - 0.05f) * \Delta t;}$$

Stage (ii) of the simulation algorithm can be expressed and implemented as a PASCAL procedure and adopts the PASCAL format:

```
WHILE (t = t lim) DO

    BEGIN

        t := t + Δt;

        r : =  r- {(0.10 * r * (1 – r) * Δt ) – ( 0.02 * r * f * Δt )

        f new : = f + 0.25 * f * (r - 0.05f) * Δt;

        writeln (t, r, f, '*');
```

```
          END;
```

In PASCAL, the block or compound statements, which comprises a group of statements encompassed by the words BEGIN .... END, act like brackets and are used to group self-contained ideas and enhance intelligibility. [51]

To appreciate such programming elegance and to gain insight into the algorithmic significance of such a programming construct, demands the development and usage - instructionally as well as on the part of the learner - of PASCAL's language features and computational facilities. One of these - central to the development of Stage (ii) - and characteristic of some key features of PASCAL, is the provision of the control constructs for "looping" (WHILE-DO, FOR and REPEAT-UNTIL) and for decision-making (IF-THEN-ELSE). Changing the State Variables requires implementing the fundamental equations of Ecology.

Through PASCAL's syntax and construction rules, the procedure declarations and descriptive features - parameters, local and global ranges, recursion - are introduced. Finally, further refinement of Stage(ii) of the Simulation Algorithm leads to the following coding and PASCAL program outline.

```
PROGRAM (input, output);

CONST (number of months to run the simulation - t max, number of
       steps per month - n steps);

VAR (r, f new, f, t, Δt, months, i);

BEGIN (main - obtain/record simulation parameters and initial
      states);

      t := 0;

      Δt := 1/n steps;
```

---

[51] PASCAL also permits the usage of long, self-explaining names.

```
          FOR months := 1 TO t max DO
               BEGIN
                    FOR i := 1 to n steps DO
                         BEGIN
                              t := t + Δt;
                              r := r - (0.10 * r * (1 - r) * Δt) - (0.02 * r * f * Δt);
                              f new := f + 0.25 * f * (r - 0.05f) * Δt;
                              IF (r = 0) THEN
                              r := 0
                         END;
               END (for);
END;
```

Fig. 3.3 **PASCAL Version of the Rabbit-Fox Model**

3.3.3 LOGO Version of the Predator-Prey Ecological Model

Instead of taking a direct „formula translation“ approach as in PASCAL, one may use the LOGO procedure system to split the problem into distinct mind-sized components. The procedures are then used as a means of generalising from the artificial concretisation of the fox and rabbit scenario to a more general predator-prey ecological model.

The original equations can first cast be as independent (reusable) procedures:

```
To preyincrease :reproduction_factor :population
```

```
output int[52] ((1 + :reproduction_factor) * :population)
end

To preydecrease :predation_factor :prey_population
:predator_population
output int (predation_factor * :prey_population * :predator population
end

To predatordecline :decrease_factor :population
output int ((1 - :decrease_factor) * population)
end

To predatorincrease :predation_factor :predator_population
:prey_population
output int (predation_factor * :predator_population *
:prey_population)
end
```

All the procedures carry the input variables in the title line - this keeps them local. When the procedures are combined to make a particular microworld, one can, if one wishes, delete these references. This will mean that the references are accessible within the global environment and may, therefore, be manipulated by external factors. However, when developing the procedural set, one must make sure that each procedure works in isolation and test its output. Making the variables global requires that they have to be named carefully - this is not, necessarily, to be regarded as a problem because it makes the expressions clearer.

The procedure set for the rabbit population becomes:

```
To rabbitpopulation :rabbit_population :fox_population
:reproduction_factor :predation_factor
```

---

[52] The „int“ primitive is used to keep the outputs as integers. If one wants to write the word integer in full, one simply defines the procedure

```
To integer :input
output int :input
end
```

```
output int (rabbitincrease - rabbitdecrease)
end

To rabbitincrease
output int ((1 * :increase_factor) * :rabbit_population)
end

To rabbitdecrease
output int (predation_factor * :rabbit_population * :fox_population)
end

To foxdecline
output int ((1 - :decrease_factor) * :fox_population)
end

To foxincrease
output int (:prey_factor * :rabbit_population)
end
```

And for the fox population, the following procedure is added:

```
To foxpopulation :rabbit_population :fox_population
:decrease_factor :prey_factor
output int (foxdecline * foxincrease)
end
```

By running the two procedures together one can monitor the two populations. Procedures can be elaborated by adding conditional statements such as a limit for prey population and those required to keep all the results positive [53].

We can consider the special case and write it in a form that replicates the PASCAL code so that a comparison may be allowed - although adherents to the LOGO philosophy are averse to such form of coding.

```
To Predator_Prey :r f :months :steps

make „Δt 1/:steps

repeat :months [
```

---

[53] This, however, is not a feature unique to LOGO.

```
          repeat :steps [

                    make „r :r - (0.10 * :r * (1 - :r) * : Δt) - (0.02 * :r * :f * : Δt)

                    make „f :f + 0.25 * :f * (:r - 0.05 * :f) * :Δt

                    if :r = 0 [make „r 0]

                     ]
           ]
end
```

Fig. 3.4 LOGO Version of the Rabbit-Fox Model

A version more in character with the LOGO environment, however, would take the following form.

```
To Rabbits & Foxes :Rabbits :Foxes :months :dayspermonth

repeat :months [repeat :dayspermonth [make „Rabbits Rabbits make
„Foxes Foxes]]

end

To Rabbits

output :Rabbits - (0.10 * :Rabbits * (1 - :Rabbits) - (0.02 * Rabbits *
:Foxes /:dayspermonth)

end

To Foxes

output :Foxes + 0.25 * :Foxes * (:Rabbits - 0.05 * :Foxes)
/:dayspermonth
```

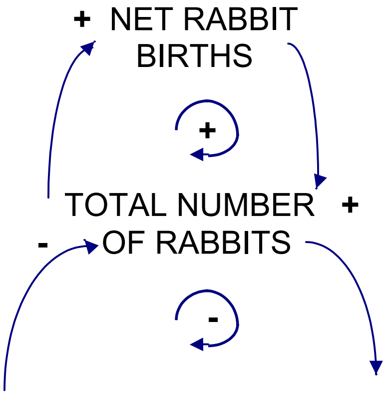
```
end
```

Fig. 3.5 Alternative LOGO Version of the Rabbit-Fox Model

The above outlined two versions of the Predator-Prey Ecological system show the versatility, extensibility and – to some – the simplicity of programming in LOGO. The concepts of local and global are made explicit in LOGO as they are in PASCAL. Both LOGO and PASCAL are designed to make explicit fundamental ideas of computer science and problem solving, and can be considered useful for learning, thinking and exploring a variety of advanced and abstract ideas. However, we contend that the rudimentary programming skills that are oriented towards problem solving are required to be developed and to be mastered – a significant demand upon time and effort - before the system to be simulated can be considered and treated.

3.3.4 DYNAMO Version of the Predator-Prey Ecological Model

Starting with a causal-loop diagram, a complete System Dynamics version of the Predator-Prey Ecological Model (modified LOTKA-VOLTERRA Model) is presented below (please refer to 3.3.1):



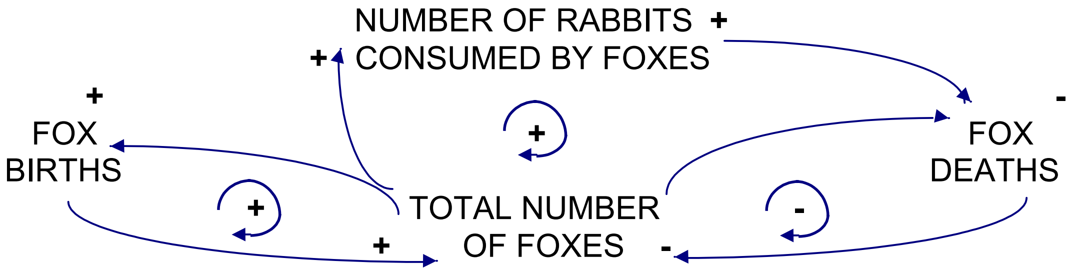
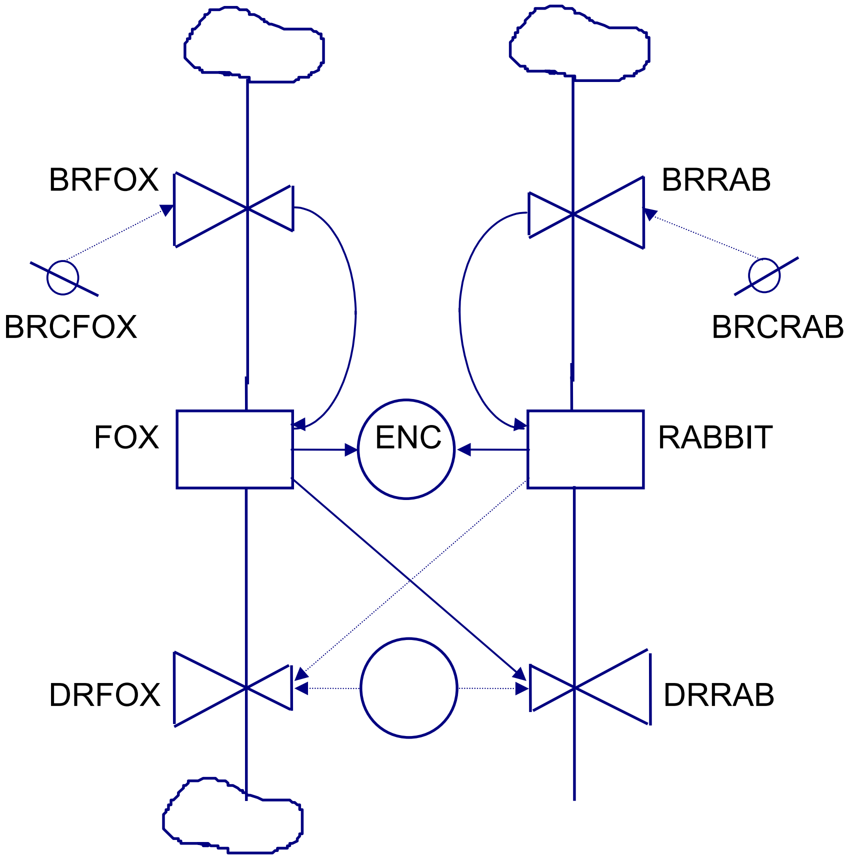


Fig. 3.6 **Causal-Loop Analysis of the Rabbit-Fox Model**

The LEVEL-RATE diagram can be given the following configuration (the original LOTKA-VOLTERRA model was, however, asymmetric):



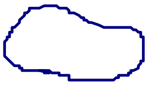


Fig. 3.7 LEVEL-RATE Analysis of the Rabbit-Fox Model

The treatment so far has, we contend, initiated and led to the development of a relatively simple (cf. PASCAL) and visible (cf. LOGO) introduction to the model. Further development of the Predator-Prey VOLTERRA model into the respective equations requires the model to be re-expressed in a manner that is directly interpreted in terms of LEVELS and RATES, and adopting the DYNAMO formulations as follows:

For the case of Rabbits (and referring to the equations in 3.3.1),

$$\mathbf{R(t + \Delta t) = R(t) + \underbrace{a * R(t) * \Delta t}_{\text{[Births]}} - \underbrace{c * R(t) * F(t) * \Delta t}_{\text{[Deaths]}}}$$

Since {a * R(t)} is equivalent to Rabbit Birth Rate - BRRAB, and

{c * R(t) * F(t)} is equivalent to Rabbit Death Rate - DRRAB,

this gives in terms of LEVELS and RATES,

L RABBIT.K = RABBIT.J + DT * (BRRAB.JK - DRRAB.JK)

R BRRAB.KL = RABBIT.K * BRCRAB
[BRCRAB = Birth **R**ate **C**oefficient For **RAB**bits]

R DRRAB.KL = RABBIT.K * FOXES.K * ENCNTR
[ENCNTR = Number (Probability) of Rabbit-Fox Encounters]

Correspondingly, in the case of Foxes (and referring again to the equations in 3.3.1) where,

$$F(t + \Delta t) = F(t) - b * \Delta t * F(t) + d * R(t) * F(t) * \Delta t$$

we have the Rabbit-Fox model in terms of LEVELS and RATES;

L FOX.K = FOX.J + DT * (BRFOX.JK - DRFOX.JK)

R BRFOX.KL = FOXES.K * RABBIT.K * FGR
[**FGR** = **F**oxes **G**rowth **R**ate Constant]

R DRFOX.KL = FOXES.K * DRCFOX
[**DRCFOX** = **D**eath **R**ate **C**oefficient For **FOX**es]

The overall situation can be considered to take the form depicted below (cf. situation depicted in **Fig. 3.1**):

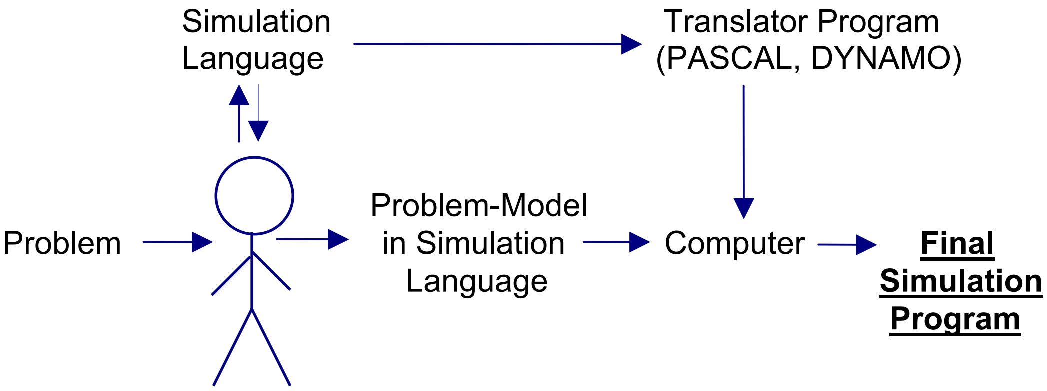


Fig. 3.8 **Conversion of a Problem into a Simulation Program – Condensed Procedure**

The language itself can be seen to become effective as an aid to problem formulation. The conceptualisation to a state-change model is facilitated and the manual step from problem statement to computer program has been removed. (Debugging may still be required but the translator program reports the errors in simulation language terms, which considerably expedites the debugging process.

Regarded in a purely educational context, the computer here can be thought of as taking on the role of a quiescent tool and resource when the occasion arises, and the learner (user) and the computational processes take turns in controlling and maintaining the thread of the activity.

A workable DYNAMO Program for the Predator-Prey Model is given below. This is followed by two simulation runs of the model. The numerical data pertaining to the runs is included in **APPENDIX C**:

```
*       PREDATOR-PREY MODEL

L       RABBIT.K = RABBIT.J + DT * (BRRAB.JK - DRRAB.JK)
R       BRRAB.KL = RABBIT.K * BRCRAB
R       DRRAB.KL = FOXES.K * PRF * ENC

NOTE

L       FOX.K = FOX.J + DT * (BRFOX.JK - DRFOX.JK)
R       BRFOX.KL = FOXES.K * RABBIT.K * FGR
R       DRFOX.KL =  MAX (0, (PRF * FOX.K - RABBIT.K)/PRF) [54]

NOTE

N       FOX = 10
N       RABBIT = 100
C       BRCRAB = 0.10
C       FGR = 0.05
C       ENC = 0.02
C       PRF = 4
```

---

[54] The MAX function in the Fox Death-Rate expression is a system-supplied logical construct - serving the function of the conditional IF-THEN procedure in PASCAL - used to select between variables based on the result of a logical test. In several DYNAMO versions, this can also be replaced by SPEC END functions. MIN, CLIP and SWITCH are also some of the other built-in DYNAMO logical functions (RICHARDSON and PUGH 1981).

```
PLOT   RABBIT = R, FOX = F
PRINT  RABBIT, FOX
SPEC   DT = 0.1/PLTPER = 0.1/PRTPER = 0.1
X      LENGTH = 10

RUN
```

Fig. 3.9 **DYNAMO Version of the Rabbit-Fox Model**

PLEASE REFER TO Page 281

<u>Fig. 3.10</u> **Rabbit – Fox Model Simulation Run 1**

PLEASE REFER TO Page 282

Fig. 3.11 **Rabbit– Fox Model Simulation Run 2**

3.4 Comparing and Contrasting Programming Language Features of PASCAL, LOGO and DYNAMO

In examining the role of programming languages in Systems Modelling, three essential aspects are considered to characterise the task and the underlying processes.

- Formally, the principles of Systems Modelling generally may be outlined in the following steps (from ROTH 1975):

    - **MODULARITY** - divide the system into logical subsystems each of which is conceptually simple.
    - **SYSTEM DIAGRAMMING** - use a high-level diagram to relate subsystems.
    - **RELEVANCE** - only include pertinent information in the model.
    - **UNDERSTANDIBILITY** - the model should be presented as clearly [55] as possible; the terminology should be standard.
    - **VERIFICATION** - check the structural and computational accuracy of the model.

- As the intention of programming is that the learner will also acquire scientific problem skills as a result of writing (and debugging) programs in a friendly, transparent language, some means of programming the

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[55] The model should be straightforward.

computer will remain a requirement for the student. DU BOULAY et al. identified two important characteristics of programming languages for novices (DU BOULAY et al. 1981, 237-249):

- **Simplicity** - the language should be syntactically simple, i.e., the rules defining the language should be uniform, with few cases to remember and without potential ambiguities.

- **Visibility** - novices should be able to view in action selected parts and processes of the "notional machine".

- Model-validation and model-verification - which is related to, and which we consider forms an essential component of, the computational process - which we treat subsequently, are additionally the two independent - but in practice not completely separable (SPRIET & VANSTEENKISTE 1982) - steps of model-testing.

3.4.1 Aspects of Program Structure

In System Dynamics modelling, the student in going through the phases of the model-building process is required to approach a problem in roughly parallel stages adopting the principles of Systems Modelling and some basic principles of structured programming:

STAGE 1 - Define the algorithm coarsely - in plain language or with some sort of code.

Problem Definition and Identification in System Dynamics involves recognising and defining the three characteristics that are fundamental to the nature of all dynamic systems:

- they involve quantities that change with time,

- that forces causing this variability can be described, and

- that important causal influences can be contained within a system of feedback loops.

STAGE 2 - Explain the parts of the algorithm that need further clarification using a structured language or a flow chart.

System Conceptualisation involves committing to paper the important influences believed to be operating within a system. The three ways adopted are

- causal-loop diagrams,
- plots of variables against time, and
- computer flow diagrams.

STAGE 3 - translate the algorithm into the programming code.

Models are represented in computer code using DYNAMO notation by first representing systems in equation form.

STAGE 4 - In „Stepwise Refinement“, the algorithm is specified at an abstract level and additional levels of detail are added in successive iterations throughout the design process.

The philosophy underlying model-building in System Dynamics is to begin with a relatively simple model which embodies those aspects of the system which appear to be of major importance in determining behaviour, and to add refinements in discrete steps. The introduction of the computational concept of model - along with employing examples of models used in different disciplines - allows algorithm design to be equivalent to, or to come close to, model building. This very feature underlines model-construction and, as we see subsequently, model-testing in System Dynamics. Conventional approaches to implementing algorithms, however, tend to describe the action of existing steps in isolation, and usually no attempt is made to rationalise the selection of those constructions that are used. Moreover, and in the purely programming sense, since algorithms are abstract representations of programming logic, difficulties may also be encountered in thinking at the level of abstraction required.

When considering language structure for scientific problem-solving in particular, it is to be expected, therefore, that the language chosen should be such that it facilitates the achievement of the scientific goals specified.

In addition to requiring a knowledge of the Syntax and Semantics of PASCAL language, the translation of the algorithm in its abstract representation requires a knowledge of the pragmatics - from the learner’s/user’s perspective, the reasons (the 'whys’), the rationales (the 'wherefores') and the goals - as well as the peculiarities of each programming construct.

Additionally, for the purpose of associating the scientific content with programming details in the context of the computation, and for facilitating and enhancing the learning of the programming constructs, it is desirable that the language involved allows the constructs to be expressed parsimoniously and elegantly.

Referring back to program development in PASCAL (3.3.2), the three main stages in writing a program in PASCAL - and also in DYNAMO - may be summarised as being:

UNDERSTAND THE PROBLEM	→	DESIGN A SOLUTION	→	CODE AS A PROGRAM
I		II		III

For the particular cases that one is involved with in System Dynamics, Stage I requires the identification of the dynamic system with feedback as the preliminary stage. Stages II and III are primarily concerned with DYNAMO formulations of the system. One observes that a programmer working with DYNAMO can said to have a considerably simplified task because s/he is relieved of the responsibility of defining the method used - the language itself has taken on part of the work.

- In adopting and applying the highly stylised DYNAMO notation, the semantic knowledge need not be acquired through instruction dealing with details of programming, or through programming experience, but can be learned generally as meaningful sets of information that are, more or less, independent of the syntactic knowledge characterising the programming language itself.

- Through the "unambiguous" - and in the programming sense, through the direct - implementation of the LEVEL and RATE (and including the ancillary AUXILIARY and Supplementary) Equations, DYNAMO allows the model-maker to describe her/his application in terms of standardised control structures - which are essentially, nothing other than algorithmic constructions and/or formulations - and using operations that are natural to the problem domain; this, therefore, avoids all computer-related details that are not essential to the problem.
- By replicating the procedure that is to be programmed in terms of LEVEL-RATE modules, the decomposition task has also been designed and systemised in such a way that the modules share a common, highly-specified control and communication structure. Such a desirable feature is also seen to underline the LOGO programming philosophy.
- Ultimately, by also allowing the programmer to focus on the problem, rather than on the program itself, DYNAMO facilitates the shift from problem to code as a direct (natural) step; this reduces the preliminaries of further mathematical formulation and programming expertise to a minimum. Further program refinements then require the specification and the writing of the control parameters and the control statements, respectively; no further development of the basic algorithm is required.

It can be seen from the formulation of the Predator-Prey problem, that the process of constructing a DYNAMO model is, in several respects, similar to the development of the PASCAL simulation program. In both instances a systematic approach was used to implement an algorithm. Both versions of the model required a high-level system description and a well-defined procedure for the implementation of the model. Representations in DYNAMO, however, offer many of the advantages of programming language-code representation, as well as the advantages of a pictorially-structured algorithm. Thus, besides such savings in time and flexibility, DYNAMO actually is a language in the more general sense, i.e., it is useful in describing a situation independent of the fact that it can be translated by a computer into machine language.

3.4.2 Educational and Didactic Aspects

In attempting to master the syntax and semantics of PASCAL, apart from not contributing to the main learning, instruction and transfer of the main computing ideas and features demands a degree of expertise and experience from the instructor. PASCAL also lacks the special features which would make it particularly efficient in any individual application area, even though it has the feature of wide applicability. Thus, although PASCAL is without doubt considered a good language to learn about and/or to know, it could always be bettered for a particular application by a more application-specific language (FORD 1990). In contrast we note the following features in algorithm formation to be observed in DYNAMO:

- Since an algorithm is comprised of constructions, an understanding of the algorithmic process requires the awareness and appreciation of the combined actions of the contained constructions [56]. Regarded educationally, but in particular when adopting an instructional viewpoint, using such algorithms can be considered to be a means of building the learner's understanding of programming semantics and of the problem-solving process involved in programming and, subsequently, such an intellectual exercise of algorithm development should lead the student to a better understanding of the problem and towards an acquisition of the important high-level skill of developing the sequence of steps by which a problem is to be solved (SOLOMON 1986). Certainly, from an instructional perspective, we regard that such DYNAMO simulation-construction software and programming features of the language itself have the potential to enable the introduction of subject matter content - computational as well as scientific - and to

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[56] Implicit in the LEVEL-RATE formulation and notational scheme is the rectangular integration algorithm - a LEVEL is the integration over time of its RATE, and a RATE is identical to the time derivative of the LEVEL associated with it. The mathematics of integration is oriented more towards graphic representation than towards symbolic ones, and recast in terms of computational statements. The mathematics of integration is oriented more towards graphic representation than towards symbolic ones, and recast in terms of computational statements.

adopt a systems analysis approach to scientific problem-solving directly and without resorting to primary computer programming details and techniques.

- Working with DYNAMO the learner's task is strictly restricted to reaching a clear understanding of the problem, and then describing the problem to the computer using suitable language statements. In addition to that, representation and specification of the procedure using symbols and equation notation that has also been made explicit in the formulation language, effectively allows the algorithm to be expressed as a procedure whose structure closely corresponds with the algorithmic sequence. Since the algorithm, and the data it processes, are thus also made clearly distinguishable to the learner - providing constructions to aid expressions of problem-solving strategies (DU BOULAY et al. 1981) - this will, eventually, also serve to enhance the debugging process.

- In adopting and applying the highly stylised DYNAMO notation, the semantic knowledge need not be acquired through instruction dealing with details of programming, or through programming experience, but can be learned generally as meaningful sets of information that are, more or less, independent of the syntactic knowledge characterising the programming language itself. Through the "unambiguous" - and in the programming sense, through the direct - implementation of the LEVEL and RATE (and including the ancillary AUXILIARY and Supplementary) Equations, DYNAMO allows the model-maker to describe her/his application in terms of control structures - essentially, algorithmic constructions - and using operations that are natural to the problem domain; this, therefore, avoids all computer-related details that are not essential to the problem. Moreover, because such DYNAMO constructs and/or constructions have a straightforward meaning that a learner/model-maker can attach to an individual procedure, this entails the requirement of "logical" simplicity in a programming language (DU BOULAY et al. 1981).

  PAPERT, in characterising LOGO (1980) puts forward the argument for such types of modularisable programs, and in interpreting PIAGET's concept of principle of "groupments", i.e., in that it "shows us the power of a specific computational principle, in this case the theory of pure procedures, that is, procedures can be closed off and used in a modular way"; (PAPERT 1980, 170).

Such modularisable DYNAMO programs also can be regarded to facilitate a systematic approach to scientific modelling and the process of debugging, and enables one to appreciate that seeing the world through computational concepts can lead into insights into familiar phenomena that have no direct connection with computers (PAPERT 1980, 1993). Providing learners with such a way to breakdown programs through ready-made concepts also makes them less formidable - the amount that the learner must bear in mind is reduced - and makes it easier for them to construct new programs - i.e., giving a sense of where to start and the kind of building blocks to construct.

Unlike the indirect procedures involved in the presentation of the problem for compilation and solution in PASCAL, DYNAMO modelling enables the problem to be approached from the onset. The functions to be carried out are specified at a very high level, rather than explicit coding and programming – a dominant feature and purpose of PASCAL.

- The learner is allowed to think more specifically in terms of the structure of the problem under consideration, rather than broadly in terms of the language being used to solve the problem; the programming of the model becomes a subsidiary activity. Also, DYNAMO can be seen to be in possession of the vocabulary, a syntax and a structure that can help the student to formulate her/his model directly, and since it is reasonably descriptive, the tendency could be considered to be for one to think in DYNAMO.

In the main model-formulation stage of scientific problem-solving with the computer, the System Dynamics methodology requires the learner to draw upon her/his own intuition, requisite knowledge and a pool of central, unifying ideas - if necessary acquired through the preliminary instructional phase - to put into effect what s/he already knows in sequencing her/his scientific reasoning. Here less emphasis is placed on the student becoming proficient at programming, and more emphasis is placed on the student in developing the computational algorithm to explore the particular problem domain. Generally, and in the purely programming context, writing a program in PASCAL requires the programmer to concentrate on the discipline of programming and a conservative technique, i.e. on the correspondingly low-level details of precisely encoding the symbolic information rather than on the meaning. Additionally, the sequence of events in a computation is emphasised rather than on their meaning.

In contrast, DYNAMO focuses attention on high-level issues of semantic functionality and the implementation of the language, minimising the time spent on syntax and machine representation issues, but exploiting the potential of the computer as a powerful responsive tool while providing powerful images of programming. The syntax, semantics and pragmatics of DYNAMO form the fundamental building blocks of the language itself. This we believe should nurture a a degree of interest in programming at a pre-university stage where the exploration of some computer programming is featured. The LOGO dialect also provides many of the same high-level mechanisms along with a user interface that is less intimidating to a novice programmer.

In addition to the above features, an essential learning aspect that makes DYNAMO-based simulation different from alternative modes of processing and assimilating scientific information is its straightforward, scientifically-interactive nature and mechanisms. That is, the mode in which the computer and learner take turns in communicating messages to each other focuses on the science-learning through the scientific-modelling and model-testing and environment, but without usurping control from the learner. While the learner is able to acquire the key ideas with respect to the modelling procedures in a structured, independent manner, the teacher is able to draw the link between the heuristics of DYNAMO, scientific reasoning and the conceptual ideas embedded in System Dynamics.

Through her/his interaction, the learner determines - following some guided thought - what will appear on the terminal, and the simulation run and tabulated results and graphical output provoke further scientific reaction from the student. The instruction/learning is therefore driven by responses given at the terminal, and the interaction environment allows the learner to be an active participant in the model building process as the simulation progresses.

3.5 Simulation and Learning of Scientific Computation

Generally, computer simulation modelling of a system can be viewed as a flexible, iterative, problem-solving process that includes the formulation of a problem, the development of a mathematical simulation model and, finally, the employment of the simulation to arrive at potential solutions to the problem. This may be presented schematically as shown below (after MANETSCH et al. 1971):

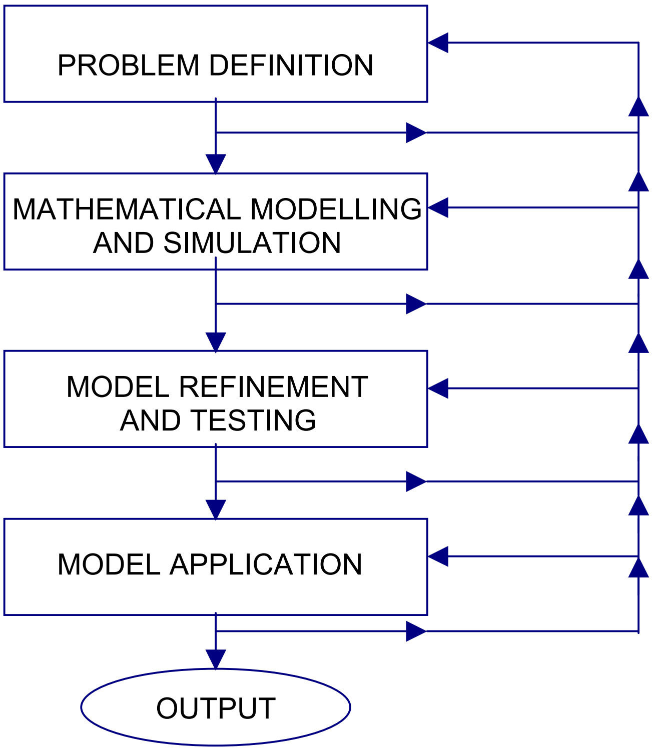

Fig. 3.12 Stages in Computer Simulation Modelling of a System

Formally, and particularly in modelling, computer model testing involves two distinct, independent steps - termed credibility validation and verification - which, in practice, are not always entirely separable (SPRIET and VANSTEENKISTE 1982):

- **Credibility Validation** - which enlists
    - Conceptual Model Validity and
    - Parameter Validity

  - determines whether correspondence exists between the system being modelled and the operating model. It, therefore, requires detailed examination of the internal structure of the model, and of the data used for the estimated parameters.

- **Verification** - which implies the aspect of debugging - ensures that the programming and the implementation of the conceptual model is correct. This is the iterative process of:
    - running the model on the computer;
    - evaluating the output - with respect to intuitive correctness and theoretical and/or mathematical consistency;
    - searching for and correcting errors in the program.

It is our contention that within the sphere of validation, the learner would not benefit overtly through her/his operating in a PASCAL or DYNAMO environment since at this level of computational activity syntactic and semantic details play a secondary role and assume significant prior knowledge of programming detail. However, model verification is significantly facilitated in DYNAMO mainly through its operational features and special-function characteristics.

In order to categorise and interpret the computational activities in the System Dynamics methodology within current strictly computer-oriented learning and related computer literacy issues, we resort to KEMNIS et al. (1977) - CHAPTER 1, who adopted a learner's perspective and identified the four educational paradigms of student interaction with the computer:

- the instructional paradigm,
- the revelatory paradigm,
- the conjectural paradigm, and
- the emancipatory paradigm.

The "instructional" paradigm draws on the ideas of programmed learning, and is manifested in Drill-And-Practice, Rote-Learning and Instructional Dialogue approaches (SOLOMON 1986, SCAIFE and WELLINGTON 1993). The overall aim is to teach a learner a given piece of subject matter, or to impart a specific skill.

Within the "revelatory" paradigm,

> "the computer acts as a mediator between the student and a hidden model of some situation", RUSHBY 1979, 28)

and guides a student through a process of learning by discovery: content, key concepts and related theory are expected to be revealed by progress through the software (WATSON 1994).

The "conjectural" paradigm involves increasing control by the student over the computer, and centres on the student learning by allowing her/him to articulate, manipulate and test her/his own ideas and hypotheses. This suggests the use of a form of modelling.

The "emancipatory" paradigm hinges on the function of the computer as a labour-saving device, i.e., serving purely as a tool for the learner's convenience, and relies on the distinction between 'authentic' - that which is desirable and purposeful - labour, and 'inauthentic' - that which is considered unnecessary and irrelevant - labour. Within this paradigm, the computer is only partly involved in the learning process (SCAIFE and WELLINGTON 1993).

DRIVER and SCANLON (1989) regard the development of an enhanced understanding of difficult concepts in science to be possible through the revelation and conjecture of simulations. Since we regard the application of DYNAMO to have the potential to transfer the inauthentic labour of programming, calculating and presentation to the computer, thus leaving the learner to focus on the intellectually creative task of devising and exploring the model, we focus on the computing activities featured in System Dynamics Modelling and Simulation in the light of these last two paradigms - the revelatory and the conjectural - exclusively.

3.5.1 Aspects of Validation, Verification and Modification

For the learner of scientific modelling, the context for Credibility Validation and Verification is suggested by an interactive computer environment, and one that is regarded as being particularly effective when building, testing and obtaining runs of a scientific model if and when modifications to the model structure may frequently be required (SCAIFE & WELLINGTON 1993). To facilitate an appropriate interactive environment in which experimentation with the model may be effected, the essential features and implications of an interactive learning activity that are suggested are (SCAIFE and WELLINGTON 1993):

- Action/active learning;
- Choice - the learner has a choice over the learning engaged in;
- Control - the learner has control over her/his learning;
- Responsibility - the onus for learning rests on the student - largely as a consequence of the first two aspects above.

In addition, GOODFELLOW asserts that

> "..... if the purpose of an experiment is to change the model of reality in the learner's mind, it is best changed by the learner her/himself." (GOODFELLOW 1990, 47).

This implies the selection of themes, subject matter, and content - in addition to the mechanism - that the instructor will find easiest to identify with. Also based on the goals which they adopt, self-regulated learners develop a plan for action grounded in prior knowledge. A central feature of this plan is obtaining feedback by monitoring immediate products against goals. Incrementally, the learner modifies knowledge, motivational beliefs, goals and strategies in response to that feedback. Thus interaction with the task evolves strategically based on dynamic engagements involving the learning, the task and the events that transpire during learning; (WINNIE and BUTLER 1994).

In the initial stages, considering our theme of Predator-Prey modelling, determination of the constants - adopted in the LOTKA-VOLTERRA equations, which can be undertaken as a science activity/exercise, is determined from a careful analysis of the internal structure of the system and through the calibration of the purely scientific parameters of the model by relating these to the real-world state of affairs.

Such credibility-testing – formally involving the underlying parameter-validity and conceptual-validity examination as required/performed by experts – can be seen to be scientifically important and educationally productive as it requires a clear line of scientifically-qualified thinking between analysis and decision-making. It also provides the rationale for modelling in this particular form and for providing meaning for the entire exercise, i.e., how does one know that the prediction made by a simulation model will infer more reliability than prediction made by some other method (e.g., by judgement or through experience). It is to be appreciated, however, that such an absorbing, albeit time-consuming exercise also involves a significant proportion of computational activity and could, therefore, require a large numerical dimension to the activity. The value of this can only be seen in the light of the purpose of the particular activity.

In validating and verifying a System Dynamics model, the user/learner does effectively engage in an interactive and responsive conversation with the model. S/he first summons and runs the updated and edited model. A specified time plot for any period of interest is entered and displayed on the screen. Inspection of time plots and discovery of unexpected variable behaviour raises questions. Closer inspection of the model's structure and assumptions may produce concrete explanations - inaccurate model equations and/or unjustified model hypotheses and assumptions and/or unrealistic model parameters - for the unexpected behaviour.

The student's role becomes more than that of a mere spectator since s/he is responsible for providing new inputs to the program after deciding on some strategy of use, i.e., the simulation is programmed by describing the constraints that must exist between parts of the system. S/he is then required to make a decision and so shifts to the edit mode and types in desired changes. Experiencing the consequences of her/his decision or indecisiveness, s/he is compelled to make a selection amongst competing values, and to weigh the consequences of one response against the others in determining the acceptability of those decisions. While the student is thus making full use of this capacity for discovering relations, s/he is effectively making and testing hypotheses. These hypotheses could be considered to be reflecting internal schemata and hypotheses-testing, consequently, implies the exploration of implications of those schemata. Clearly, the educational value and scientific significance of hypotheses-testing also depends on the quality of the simulation program.

3.5.2 DYNAMO Simulation And Debugging - Interactive Mode Learning

Although human interaction is mainly by means of the spoken word, mainstream education is based on the criterion that non-verbal communication can augment the message in a powerful, less conscious manner. In the field of science especially, visual illustrations tend to be abstracted into diagrams and, in physical sciences, a significant portion of this abstraction takes the forms of graphs. In a similar vein, the learner is in a hypothetical position to interact scientifically with a computer through its synthetic laboratory and interactive graphics facilities, and the computer can be regarded as providing a scientific discovery learning medium as well as environment.

In DYNAMO simulations in particular, the problematic situation can be seen to drive the learning when there is incoherence between the learner's description and the behaviour on the screen. A channel is provided in which technology can enable communication through the manipulation, experimentation and experiencing the use of ideas. The learner's inquiry involves noticing different problematic aspects and constructing new relationships among them. This is also what we observe to correspond to DEWEY's notion of inquiry (Section 1.3), which means a practical activity that transforms the situation into one, regarded primarily from the learner’s angle, that is more clearly articulated, unified and comprehensible, and in which directions for successful action are now clear.

With reference to Section 1.3, inquiry seeks a controlled transformation that produces coherence, meaning and a clear path for action. Importantly, inquiry requires noticing new features in an experience, and restructuring the relationships between the features. DEWEY's particular notion of inquiry flowed from his conception of a problematic experience (1938a, 1938b). We choose to reflect on such a perspective here as we interpret this broad view of the category of technology and of the specific details of the way technology supports collaborative inquiry learning to be currently relevant and, therefore, to be given renewed significance in a manner that is particularly meaningful and edifying – particularly to the instructor - when associated with the type of problem-solving context associated with computer simulation. The teacher's role in interactive-mode learning changes from knowledge transmitter to learning facilitator since the learner takes responsibility for her/his own learning. Such transformation of roles requires that the instructor take some risks, relinquish control and alter some instructional strategies to facilitate and/or enhance learning. This also implies that the teacher may not be able to anticipate every question or solution suggested by the learner.

An activity whose prominence has been unquestionably raised by a computing is the process of locating and removing the source of known errors in a system. PAPERT describes such a technique whereby LOGO programs, as procedural descriptions, are constructed, tested and modified essentially as "debugging"; and regards the activity in which processes are constructed by descriptions and the manner in which these descriptions can undergo modification as a powerful computational idea (SOLOMON 1985). The function of debugging is to localise a failure, and inclines the programmer to focus more on the process and less on the results; this culminates in the further characterisation of the problem since further analysis and deeper understanding is required.

Debugging is clearly by no means confined to computer procedures and can be productively extended to other activities. Since scientific problem solving also involves the exploration of alternative hypotheses, as well as the search for new relationships and recurrent regularities in the problem-solving environment, the relationship between programmer or learner and her/his program can be regarded to be practically identical to that between a scientist or science learner and her/his theory. Debugging consists of the process of diagnosis and repair Diagnosis involves the use if strategies of model, plan, process and code diagnosis. Repair is made by correcting or completing the program. Consequently, we regard the aspect of model-testing in scientific computation to be analogous to a scientific debugging process.

In a the re-run of a System Dynamics model, the DYNAMO simulation program is run once more and model behaviour is compared with the previous run. If the behaviour is no longer unexpected, the learner gains insight and confidence in her/his hypothesis generation skills, her/his account of the problem and her/his subjective analysis with respect to the problem. If the unexpected behaviour still persists, s/he is compelled to re-examine her/his own implicit assumptions and/or hypothesis and modify them for greater reliability.

Thus by extending the learner's engagement with aspects of knowing s/he finds problematic DYNAMO simulation procedures and debugging facilities have the potential to enhance scientific problem-solving and computation skills within our context of Scientific Computation. In the end, a simulation model becomes a specific computational tool, and simulations that test scientific aspects of model structure can be powerful laboratory tools for generating insight and understanding.

3.5.3 DYNAMO and the Computer as a Scientific Tool

We adopt the standpoint here that the computer's presence as a scientific tool and its potential to contribute to the scientific discovery process is not just as an opportunity but a potentially powerful means to enhance science education. A believed necessary precondition for new technology to be regarded as models of success is their acceptance as convivial tools (FISCHER 1981). Such tools were originally characterised by ILLICH (1973) as being intrinsic to social relationships; the individual relates her/himself to her/his society through the use of tools that s/he actively masters, or by which s/he is passively acted upon. To the degree that s/he masters her/his tools, s/he can investigate the world with her/his meaning; to the degree s/he is mastered by her/his tools, the shape of the tool determines her/his own self-image. Convivial tools are those which give each person who uses them the greatest opportunity to enrich the environment with the fruits of her/his vision.

According to ILLICH, tools foster conviviality to the extent to which they can be easily used , by anybody, as often or as seldom as desired, for the accomplishment of purpose chosen by the user. ILLICH did not mention computers and/or computer-based tools explicitly, but they have the potential to be tools for conviviality through such resources. The computer's peculiar role and properties applied to our current context of controlling and running simulations, account for its ability for being a powerful and flexible scientific tool in the hands of a learner.

Long before this, DEWEY also located the place of technology in a central place in inquiry; he viewed inquiry as a productive craft, and technology as the tools of the craft. He points to specific functions that often require technological support for inquiry to proceed: continuous engagement with the problematic situation, focus and context, communicative action and experimental doing and undergoing; (DEWEY1938a, 1938b). Identifying features and constructing relations are the operations by which the problematic situation is transformed from a problem to a coherent communication.

A unique additional perspective that bears particular significance on the educational function and meaning of computer tools in the context of this study can be derived from the theory of VYGOTSKY (1978). The theory originally proposes that learning results from interaction that accompanies assisted performance as the student is helped to accomplish a meaningful task. These task-oriented, assisted interactions are mediated by social/cultural signs or cognitive tools. With particular reference to the application of such tools, learning occurs when the student successfully internalises or appropriates the tool-mediated actions.

At the heart of the matter is his Zone of Proximal Development, a learning zone functionally defined as the difference between what a learner can do alone and what s/he can do with help, and which

> "enables us to propound a new formula, namely that the only 'good learning' is that which is in advance of development (VYGOTSKY 1978, 89).

This is, consequently, the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined by independent problem solving under adult guidance or in collaboration with more capable peers, (i.e., assisted performance). VYGOTSKY speculated that learning occurs when the learner successfully internalises or appropriates the tool-mediated actions.

MARGOLIS, in focusing his efforts on the identification and investigation of learning contexts and tools argues that computer tools must be based upon and reflective of learners' thinking rather than simply embody the ideas under study. This then allows learners to construct models of their own initial understandings for direct comparison and manipulation (MARGOLIS 1990a). According to MARGOLIS (1990b), the key mechanism of such transformations is the system of transition from the action with the computer models to the action with the object and back again

The basic System Dynamics formulations, and computer implementations of these formulations in DYNAMO, theoretically, have the potential to provide learners with the means for thinking and for communicating about the topic under consideration, and thus can be regarded to serve the same function as the psychological tools that VYGOTSKY refers as critical to learning activities. The computing activities and simulation runs allow learners to create external representations of their understandings and to examine them, manipulate them, apply them and confront their limitations. In this way the computer functions as a bridge between concept and learner. Accepting a view of assisted performance as a significant mechanism of learning, we recognise and acknowledge that a DYNAMO environment possesses the following three essential characteristics with respect to its function as a learning tool adapted to the classroom:

- The learner performs a whole, meaningful task, not a sub-skill:
- The tool carries some of the burden of the task - it scaffolds the elements the learner cannot accomplish alone:
- The tool allows increasingly complex versions of the task by turning back some of the task burden to the learner.

Hence the tool must function as a bridge between knowledge or concept and the learner, being accessible to the learner while retaining the knowledge or conceptual level. With respect to potential success in problem solving through the provision of guidance which draws the learner's attention to the principles and rules underlying the problem, DYNAMO simulation makes provision for such form of guidance through feedback facilities and simulation runs, and this may significantly facilitate problem solving since it

- redirects the learner's attention to the essential scientific features of the computation;
- requires the learner to verbalise the rules or principles associated with the computation;
- stimulates the recall of similar classes of scientific computational problems.

Such interaction with the computer looks for deeper, enduring effects of technology - which PAPERT (1980) refers to as a culture - rather than surface effects of procedural convenience. The finding of bugs in

DYNAMO models focuses on model flaws within the - LEVEL-RATE-AUXILIARY - simultaneous equations, forming a flexible, experimental exercise and does not solely become a large part of the student's programming experience.

Also, a System Dynamics model is developed in pieces, and in an iterative process that seeks to improve model formulation on a number of successive planes. Thus System Dynamics' Algorithm refinement procedures provide ways to investigate the model characteristics repeatedly by the provision of stable, long-term access to the problematic situation, and to direct focus on specific attributes while nonetheless retaining the broader context of the model.

By subjecting the problematic situation to inquiry by means of computer-based simulation, the System Dynamics program - in conjunction with DYNAMO's editing, compiling and run facilities - enables the student to test different parameters to probe and perturb the problem, and to try to test (newly) postulated solutions. The students can, therefore, make predictions from their emerging concepts and test their serviceability. This enables the student to gradually transform her/his perception of the problem. Thus, the experiential and experimental dimension of learning about Scientific Computation is achieved by scientific inquiry as occurring not merely in the head, but importantly occurring in the experienced world. The four features considered to involve scientific problem-solving with the computer primarily in a scientific and computational education context:

- Synthetic Experiment,
- Mathematical Tool,
- Simulation Technique, and
- Programming Problem,

are also seen to be the inherent features of problem-solving with System Dynamics and DYNAMO.

As a scientific tool, the computer can be considered to have made a significant impact to the extent that its use has freed the science learner from unnecessary tedium and from having to master low-level computing skills before getting involved in more interesting and more rewarding computational-oriented issues, and to the extent that the learner is in a position to mindfully exploit that opportunity.

4 EMPIRICAL STUDIES

This chapter outlines three empirically-conducted and didactically-oriented surveys - **STUDY 1 – Part 1 & Part 2, STUDY 2** and **STUDY 3** - of three separate and distinct aspects of instruction-based implementations of System Dynamics whose combined and primary purpose is to allow an assessment to be drawn of the degree to which System Dynamics could constitute - principally from the learners' perspective - a more meaningful addition to the learners' scientific studies programmes. The secondary function of **STUDY 2** but, particularly of **STUDY 3,** is to provide an indication of the manner in which the students' scientifically-oriented epistemological commitments and views, i.e., of the concurrent views of knowing and learning about science of a group of selected students, are modified as a result of their interaction with elements of the System Dynamics Methodology. This would subsequently serve to substantiate any relationships that might exist between such commitments and the validity of implementing System Dynamics in their course of scientific studies, and thus to indicate the type of learning epistemology at this functional level of science education that System Dynamics would be compatible with. Altogether thirty-two pupils (including eight pupils who constituted a control group) were involved in the three surveys.

4.1 Empirical Studies, General Curricular Background and the Student Population

The empirical survey – comprising the three studies **STUDY 1** - **Part 1** and **Part 2, STUDY 2** and **STUDY 3** and the subsequent analytical surveys - was undertaken with the assistance of altogether thirty two, pre-university pupils from Internationale Schule Hamburg e.V..

4.1.1 Curricular/Scholastic Background Of the Empirical Studies

The students involved in all three studies were all between seventeen and nineteen years of age and were, invariably, college/university-bound students in their final (pre-university) years at Internationale Schule Hamburg e.V..

Internationale Schule Hamburg e.V. is a Kindergarten-to-Grade 12 independent school offering a traditional primary-school and secondary-level programme in English up to and including the pre-University stage, and whose academic programme is primarily designed to serve a predominantly mobile, multinational population.

The United Kingdom-based International General Certificate of Secondary Education (IGCSE) functional up to Grade 10, and the pre-university International Baccalaureat (IB) curricula and examination syllabi determine the structure - and set the academic achievement standards and norms - of the programme at the secondary and pre-university levels, respectively, at Internationale Schule Hamburg e.V..

A particularly striking feature that also characterises the student population at Internationale Schule Hamburg e.V., consequently, is the national as well as the cultural diversity; fifteen separate nationalities were represented in the three groups concerned with this research. Another significant feature is the student's length of stay at the school, which averages between three and four years.

All the thirty-two students who participated in all empirical aspects of this study had attended the school for at least two years and were involved in completing the penultimate stages of their chosen programmes of study. The choice of this stage of their education can, therefore, be considered to be optimal with respect to their suitability and participation in this study. Environmentally, the most striking instructional/learning feature at the 11/12 Grade level is the relatively small, but fluctuating class size (averaging eight-to-ten students) giving rise to an intimate, relatively non-rigid but intensive learning environment.

All the members of the three study groups commanded varying degrees of proficiency in spoken English, including conversing skills and communication habits significantly constrained by cultural and social influences as well as previous educational experiences. Thus written responses to questions and to a questionnaire - in preference to formally-conducted interviews - were chosen as primary information sources for evaluation. This mode was also generally considered to be more conducive and appropriate as a means of conveying the students' impressions and opinions. Indeed, preference for this mode of response was expressed by invariably all the students themselves and, therefore, the questions for **STUDY 3** were constructed to also allow statistical inferences to be drawn that would supplement interpretation of the qualitative information obtained.

4.1.2 Overview of STUDY1, STUDY 2 and STUDY 3

STUDY 1 comprised didactically-oriented appraisals of four selected examples of System Dynamics applications,

(i) two of which were used in instruction and whose treatment of the principles of the underlying aspects applied constitute **Part 1** of this particular study, and

(ii) two project-mode applications (comprising project-outlines that formed the framework of two International Baccalaureat Extended Essays).

These appraisal procedures were primarily intended to test the conceptual basis and to assess the potential of particular schemes to incorporate System Dynamics into normal science-study programs that involved both collective (classroom) learning and independent (project-based) learning, respectively.

For **STUDY 2 – Pilot Study**, a course on Computer Modelling and Simulation based on System Dynamics was introduced and taught to a group of twelve pupils in their final two years at Internationale Schule Hamburg e.V.. Through the analyses and interpretation of a qualitative, empirical survey that was subsequently conducted, a preliminary indication of the degree of acceptance and of the scientific reasoning educational potential of System Dynamics within the respective science programme would be assessed.

As an additional aspect to such an indication, the impression/modifications such a course made upon the pupils' original epistemological inclinations could be assessed.

STUDY 3 comprises a more-detailed, data-oriented qualitative and analytical investigation - based on responses to a questionnaire examined primarily in the light of didactical considerations but supplemented with statistically-acquired information - with the experimental group of ten students (four girls and eight boys).

For this study, an "appreciation-oriented" series of sessions on and about the essential features and applications of the System Dynamics Methodology was initially conducted as a formal, open-inquiry, and after-school activity with the ten students. The analyses and interpretation of this aspect of the empirical survey would serve to provide a preliminary indication of the degree of acceptance, and of the scientific reasoning educational potential, of System Dynamics. This would then be contrasted with appreciation of aspects of scientific method acquired through their participation in the Theory Of Knowledge studies.

4.1.3 Classification Of The Student Population in STUDY 2 and in STUDY 3

In the analyses and discussion of the information obtained and, particularly, in order:

(i) to assess more closely any modifications in the students' epistemological commitments , and

(ii) to identify a rational explanation for any such (or no) modifications,

it was decided to classify all the subjects according to the following epistemological tendencies:

- 1. objectivistic,
- 2a. modified objectivist - inclined towards constructivism, or
- 2b. constructivist.

A clear distinction between the last two groupings is, however, difficult to establish so that generally we refer only to two predominant groups - objectivists and constructivists. We should note, nevertheless, that a transition within constructivist thinking can and does exist.

Such a classification was based on our knowledge and impressions of the pupils which were acquired - and formed - through the regular science learning sessions, through consultation with teaching colleagues, and which were substantiated through informal conversation with the pupils themselves.

4.1.3.1 Overall Pupil Classification

In general, our preliminary classification of the thirty-two pupils under study (including **SHOKO K.** and **MARCO P.** from **STUDY 1**) at Internationale Schule Hamburg e.V. reflects the assignment of a general tendency towards a constructivistic epistemology with the objectivists holding a distinctly strong position with regard to aspects of science learning. This can be gleaned from the responses given by the groups under study to the question/questionnaire, respectively, employed in the surveys. Around 39% of the students - about 42% in the pilot-study group, approximately 50% of the experimental group and around 25 % of the control group - were thought to demonstrate objectivistic conceptions on matters regarding the nature of scientific knowledge and its relation to truth. This is, consequently, depicted in the manner shown in the Table below.

Objectivist	**Modified Objectivist / Constructivist**	
SHOKO K. **MARCO P.**		
MYRA D. **DETMAR v H.** **TRACY H.** **RAHIM K.** **YURI P-B**	**ALISTAIR D.** **CORD H.** **CAMILLA K.** **ANGELIQUE Z.**	**JESPER B.** **JACQUELINE H.** **HANS H.**
LENNARD H. ** **THOMAS M-J.** **NIKHIL G. **** **GORO K. **** **NOA F. ****	**ISABEL C. **** **JEPPE Z.**	**JUN O.** **MARK v T.** **LIESBETH S.**
ANNEMARIE P. **CHRISTIAN T. ****	**ARIANE A.** **BEN O. **** **NATHALIE S.**	**FRANK A.** **ISABELLE v H-K** **ADI K.**

Table 5 – Overall Objectivist and Modified Objectivist/Constructivist Pupil Classification

The criterion used to guide such a classification for **MARCO P.**, **SHOKO K.** and the **Pilot Study Group** was value judgement based on our impressions of these twoo pupils, on outcomes gathered from scholastic performance – primarily from homework, from classroom interaction and from periodic tests – and from consultation with colleagues. The principal criterion, however, that was employed to establish and substantiate such a classification for the **Experimental Group** as well as for the **Control Group** was the status of Question 19 in Section 3 of a questionnaire (please refer to **APPENDIX A**).

A high ranking (i.e., a placing amongst the top five) allocated to the role of the teacher was taken to indicate adherence and application to canonical science learning ideals and beliefs and the consideration given to the prominent position of the teacher within such learning (reference can also be made here to **Tables 9, 10, 11** and **12)**. The students who subscribed to such a standpoint are indicated by the <u>**</u> next to their name in **Table 5** above, and put together in **Table 6** is an indication of the relative position of this ranking for the students concerned and taken from both the experimental and control groups.

	STATEMENT NUMBER – Ranked First to Fifth from Left to Right					
ISABEL C. **(2)**	BEFORE	#11	#**19**	#20	#10	#5
	AFTER	#17	#5	#11	#18	#3
LENNARD H. **(4)**	BEFORE	#20	#**19**	#5	#10	#7
	AFTER	#20	#**19**	#1	#6	#7
NIKHIL G. **(6)**	BEFORE	#10	#20	#**19**	#4	#5
	AFTER	#20	#10	#8	#13	#1
GORO K. **(7)**	BEFORE	#6	#5	#20	#12	#**19**
	AFTER	#4	#3	#13	#6	#1
NOA F. **(8)**	BEFORE	#2	#**19**	#10 (#7)	#8	#17
		#2	#**19**	#1	#7(#10)	#13
BEN O. **(15)**	BEFORE	#2	#**19**	#14	#18	#6
	AFTER	-	-	-	-	-
CHRISTIAN T. **(18)**	BEFORE	#**19**	#20	#16	#10	#8
	AFTER	-	-	-	-	-

<u>Table 6</u> - Selected Members of Experimental and Control Group giving prominence to Statement 19.

In the light of the predeeding considerations, 71% of the objectivists and 17% of the constructivists indicated a high level of importance to the function of instruction in their science learning, suggesting a link between an objectivistic epistemology and the role of the teacher at this level of learning.

4.1.3.2 GROUP I – Members of STUDY 2 - Pilot-Study Group

Objectivist	Modified Objectivist/ Constructivist	
MYRA D. DETMAR v H. TRACY H. RAHIM K. YURI P-B.	ALISTAIR D, CORD H. CAMILLA K. ANGELIQUE Z.	JESPER B. JACQUELINE H. HANS H.

Table 1 – Pilot-Study Group

The students for this study comprised a group of twelve students taking part in the 11/12 Grade "Science For The 90's" scientific studies course. "Science For The 90's" was designed for a mixed-ability intake of students who elected not to participate in the pre-university International Baccalaureat pure science (Biology, Chemistry and Physics) disciplines offered at Internationale Schule Hamburg e.V. at both Higher Level (HL) and Subsidiary Level (SL). Essentially, 'Science For The 90's' strives towards an experiment or activity-based and society-oriented scientific literacy course, whose underlying objective is to increase awareness of the influence of science in society.

At the time of the study, the students in this group had all participated in the General Certificate Of Education (up to an including 10th Grade) Biology and/or Chemistry and/or Physics courses offered in a formal environment at Internationale Schule Hamburg e.V.. These students are also significantly less mathematically-oriented, and elected to tackle either of the mathematics courses:

- Computer-based Mathematics, or
- (International Baccalaureat) Subsidiary Level Mathematical Studies

offered at this level. The large majority (eight) of these students were also undecided about their post-school academic aspirations, whereas the remaining four elected to pursue Liberal Studies courses in the U.S.A. Consequently, it was clear that none of the students elected to pursue pure science or technological disciplines as courses of specialised study on entry into tertiary education.

4.1.3.3 GROUP 2 - Members of STUDY 3, Experimental Group and Control Group.

The students in these two groups comprised ten and eight, respectively, 17-19 years-old, highly-motivated and university-bound students who made up approximately half of a graduating group in their final semester at Internationale Schule Hamburg e.V.. These students, who were also taught for several years by - and, consequently, they were very well-known to - us, were selected for their openness, their diversity of commitments and their independently conceived views of their science learning, although their experiences were constrained by a curriculum based on formal scientific knowledge. The students' individualistic views and commitments could - at this particular stage - be considered to be firmly formed and established and, therefore, the use of these views and commitments to form the basis of an evaluation can also be justified.

These students were also considered - mainly through their academic performances in the International General Certificate Of Education and by virtue of their candidacy for the exacting International Baccalaureat Diploma and through their interim performance/achievements - to command above-average ability to learn and to master the concepts of canonical science, respectively, and were currently also focusing on the achievement of high marks to meet the stringent university requirements for the further studies of their choice. The primary functional role of the teacher - at this particular stage of their pre-university preparations - therefore becomes essentially that of one who provides the necessary guidance that will lead to the achievement of high scores in the formal, ultimate examinations. All the groups in this study were also characterised by such atypical science-classroom compositions at Internationale Schule Hamburg e.V..

Generally, all the International Baccalaureat science courses at the Internationale Schule Hamburg e.V. are conducted in a traditional, lecture-oriented fashion - with practical aspects and experimental methods forming essential components of the programmes - also as prescribed by the traditional North American Programmes of Study and the standardised British Examining Boards and Syllabi. Consequently, no attempts were made to make the teaching /learning environment for the System Dynamics sessions overtly and significantly different from normal.

Internationale Schule Hamburg e.V. has also always been comprehensively and extensively provided with the current-architecture computing facilities in their entirety, and access to the computers is open to all pupils. Specific computer-based activities such as word processing, multi-media projects, graphic program utilisation and data management are incorporated in the Grades 1 - 9 curriculum; instruction takes place in the Computer Laboratory and is conducted by a Computer Studies Specialist.

The eighteen pupils comprising the experimental and control groups were generally adept at word-processing skills, which they acquired for writing their Extended Essay - required for obtaining the International Baccalaureat - as well as through other essay writing assignments in their course work. In conjunction with their respective science programs and projects, they have also become well-versed in the use and functionality of data logging and spreadsheet display and analysis - particularly, for displaying and analysing data obtained experimentally, and from other secondary sources, in both tabular and graphical form. Additionally, half the group possessed their own laptops.

At the time of the study, the eighteen students had also covered approximately three-quarters of their prescribed, two-year science program including the scientific component of the International Baccalaureat Theory Of Knowledge (TOK) course - program details are given in **APPENDIX B**. The ten students in the experimental group are listed below along with their countries of origin and including their pre-university and tertiary-level preferences, respectively, their scientific and mathematical inclinations, and their scientific/non-scientific interests and academic aspirations.

1	**JUN O.**	Japan	Biology (HL), Mathematics (SL).	Both **JUN** and **ISABEL** do not intend to pursue a pure/applied science-oriented courses of study at the Tertiary Level. **JUN** was considering taking up Psychology, and **ISABEL** was contemplating taking up Law Studies.
2	**ISABEL C.**	Germany	Biology (HL), Mathematical Studies (SL).	

3	**MARK v T.**	U.S.A.	Biology (HL), Chemistry (SL), Mathematics (SL).	**MARK** did not intend to pursue a pure/applied science-oriented course off studies at the tertiary level. Strongly inclined towards Liberal Studies.

4	**LENNARD H.**	Canada	Chemistry (HL), Physics (HL), Mathematics (HL).	All four, **LENNARD**, **THOMAS**, **NIKHIL** and **GORO** intended to pursue Pure or Applied Science courses of study at universities in the U. S. A., Denmark, U.K., and Japan respectively.
5	**THOMAS M-J.**	Denmark	Chemistry (HL), Physics (HL), Mathematics (HL).	
6	**NIKHIL G.**	India	Chemistry (HL), Physics (HL), Mathematics (HL).	
7	**GORO K.**	Japan	Chemistry (HL), Physics (HL), Mathematics (HL).	

8	**NOA F.**	Israel	Chemistry (HL), Physics (HL), Mathematics (HL).	**NOA** intended to take up Medical Studies in Israel

9	**LIESBETH S.**	Holland	Physics (HL), Mathematics (SL).	**LIESBETH** intended to pursue Systems Science/Engineering at University in Holland.

10	**JEPPE Z.**	Denmark	Physics (SL), Mathematics (SL).	**JEPPE** intended to pursue Economic Science at University in the U.K..

<u>Table 2</u> – Pupils of the Experimental Group: Pupil Number, Name, Country of Origin, Science & Mathematical Courses (HL/SL ≡ Higher Level/ Subsidiary Level) and Future Aspirations.

Prior research findings have indicated that students at this particular level of school science learning predominantly adhere to an objectivistic epistemology. EDMONDSON (1989) characterised seven and two of ten males in a freshman college Biology course for majors as objectivists and constructivists, respectively. On the other hand, she reported one and five of eleven females as falling into the same respective categories. According to SOLOMON (1991), 62% of 17-year old British students thought that scientific knowledge is certain in the context of experiment or of a science learning environment (laboratory).

The students in the Experimental Group and in the Control Group, respectively, are - employing the same criteria/value judgements used for the pilot study - therefore classified according to their epistemological commitments in the following manner:

Objectivist	**Modified Objectivist/ Constructivist**	
LENNARD H. (4) **THOMAS M-J. (5)** **NIKHIL G. (6)** **GORO K. (7)** **NOA F. (8)**	**ISABEL C. (2)** **JEPPE Z. (10)**	**JUN O. (1)** **MARK v T. (3)** **LIESBETH S. (9)**

Table 3 – Pupil Classification - Objectivist or Modified Objectivist/ Constructivist - Experimental Group; (Figures in brackets indicate number allocated to pupil)

Objectivist	**Modified Objectivist/ Constructivist**	
ANNEMARIE P. (16) **CHRISTIAN T. (18)**	**ARIANE A. (11)** **BEN O. (15)** **NATHALIE S. (17)**	**FRANK A. (12))** **ISABELLE v HK. (13)** **ADI K. (14)**

Table 4 – Pupil Classification - Objectivist or Modified Objectivist/ Constructivist - Control Group; (Number in brackets indicate number allocated to pupil)

4.2 STUDY 1

The two parts of **STUDY 1** - conducted under two separate modes of learning and applications of the System Dynamics Methodology - are outlined as:

(i) **STUDY 1 – Part 1** which followed an instruction-based and didactically-oriented survey of the basic scientific principles and methodological features of System Dynamics conducted with twelve pupils, and

(ii) **STUDY 1 – Part 2 -** which was based on two independent-learning and project-based applications of System Dynamics, and undertaken by two students – **MARCO P.** and **SHOKO K.** - as part of their formal program of studies.

4.2.1 STUDY 1 – Part 1

Starting with two different examples of varying complexity that we chose and consider,

(i) from an instructor's perspective, to fit in smoothly within the context of the various disciplines of secondary school science and

(ii) lend themselves well to suit the interest and entire ability range of the students involved,

learners are introduced to elements of the System Dynamics methodology that allow them to relate to and help them to maintain a significant degree of relevance with respect to their conventional science learning experiences; viz.,

- **Example *1*** - The Cooling Of A Hot Liquid (Physics), and

- **Example *2*** - The Spread Of Flu In A Specified Population (Social Biology), As such, an attempt is made in which it can be exemplified and illustrated how, in the course of instruction and learning, the LEVEL-RATE paradigm - initially introduced through the “Toaster“ and “Water Tank“ structuring schemes - in conjunction with System Dynamics terminology can be exploited and further developed towards greater articulation and specification.

It may be generally construed that, regardless of the complexity of the feedback system, or regardless of the interconnectedness of the variables or how intriguing the dynamics may be in examples at this particular learning/instruction level, the computation scheme takes the form of a standardised procedure. We consider the structure of such a procedure to be amenable both to learning and instruction.

These two particular examples were selected mainly to illustrate the cross-disciplinary characteristics as well as the pragmatic nature of System Dynamics analysis. In so doing, two such scientific problem-solving environments amenable to conventional Upper Secondary School science learning are considered that have the potential to be smoothly incorporated into a conventional program of scientific studies. These two examples were also considered to be particularly suitable for the entire student population involved in the survey, thus allowing for development and versatility.

4.2.1.1 The Construction and Running of a System Dynamics Model

Generally, the System Dynamics Modelling Approach - also formally regarded as a theory of system structure that also permits the analyst to represent interactions governing behaviour of complex systems graphically and mathematically (RICHARDSON and PUGH 1981) - involves two distinct , formally articulated stages:

- the "Model Conceptualisation" stage, and
- the "Model Evaluation" stage.

Adopting a primarily instruction-oriented approach, the strategy then to follow when formulating a System Dynamics model can be summarised (from ROBERTS et al. 1983, 229) formally as:

- Begin the analysis of the problem using Causal-Loop diagrams;
- Formulate the Flow diagrams;
- Write the corresponding equations;
- Simulate the model on the computer using the equations.
- Explore consequences of alternative assumptions on running model.

Within such a standardised strategy exists a potential instruction-oriented prescription and a set of procedures, viz., "construction set" (PAPERT 1993, 142), for the scientific process that is essentially non-abstract and one that attaches importance to the role of constructions while also offering the learner an additional sense of the nature of method-based scientific activity [57]. Such a standardised procedure allows, not only appreciation or acknowledgement of scientific method, but also provides a structure that learners may commit to memory and access at the onset of the modelling activities.

Theoretically, the approach also focuses on problem understanding and, consequently, problem formulation and representation through analysis and, ultimately, on the formulation of hypothetical models which can be tested against reality. System Dynamics claims, and we argue justifiably, to providing both the scientifically-creative and reality-testing approach as well as the environment that is characteristic of analytical science (PAPERT 1993). We contend, however, such science learning is not to be found in conventional secondary-school scientific problem-solving programmes. We examine the presence of these features in the following sub-sections.

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[57] PAPERT, in making reference to PIAGET's "science of the concrete" and LEVI STRAUSS's "stage of concrete operations" - as distinguished from modern science - asserts that all learners are able to resort to "concrete thinking" implied in such a construction-set methodology, and this forms the basis of constructionism (PAPERT 1993). LAWLER also sees several advantages in adopting this image since it is a central characterisation of human activity and behaviour (LAWLER 1985).

In common with standardised (Physics and/or Physical Science) learning and instruction, several features with model conceptualisation can be regarded to crystallise:

- The learner is in a position to establish a self-determined conceptual basis to the task – formed from prior knowledge and personal interest in the subject area. The instructor serves to elicit students' ideas.
- Learning means restructuring, developing and/or improving understanding established so far.
- Novice and expert take turns in developing scientific problem-solving formulations and procedures.

4.2.1.2 Analysis of Model Conceptualisation Phase - Implementing Examples *1* and *2*.

This particular stage involves an initial abstraction process - verbal and visual description of the model, or the phenomenon - which comprises three phases:

- ♦ Phase 1 commonly begins with the Causal-Loop Feedback diagrams employing unidirectional cause-and-effect arrows which are used to depict the structure of the system, and which are further developed

  (a) to identify those interactions that create and maintain the behaviour that is of interest and

  (b) to define the system's boundary.

- ♦ Phase 2 involves the charting of the LEVEL-RATE (and AUXILIARY) Flow Diagrams - using the tools of flow diagramming [58] .
- ♦ Finally, in Phase 3, the LEVEL-RATE (and, when necessary, the AUXILIARY) Equations are explicitly formulated.

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[58] The resemblance to block diagrams that represent graphically the interconnection relationships between elements - circuits or functional units - of a computer system (Dictionary of Computing 1983) is not coincidental.

Such abstract thinking, inherent in a methodology which allows one to stay close to concrete situations but one in which the purely essential features are isolated from the details of concrete reality, is seen here to be consistent with the idea of scientific method that adheres to a constructivist and/or constructionist (see **1.4**) point of view. Abstract thinking, in which one is required to isolate pure essential factors from details of concrete reality, enables the learner to acquire a more profound sense of the theoretical process of the initial stages of formal scientific activity.

Within a science learning context, PAPERT also distinguishes between a "science of the concrete" and "analytical science" as manifested in traditional school science programs (PAPERT 1993). In doing so, we see that PAPERT is suggesting a platform and attempting to establish a computation environment (System Dynamics, STELLA II) in which the computer is introduced as a tool – in contrast to conventional laboratory facilities - that simply but significantly extends the range of opportunities that learners or novice scientists can engage in activities but particularly those with scientific content.

4.2.1.2.1 Phase 1 and Phase 2 Application to Example *1*

In order to hypothesise and to communicate the underlying structure of the system that is causing and maintaining the problem, System Dynamics initiates the analysis with a visualisation of the model through a Causal-Loop diagram, a diagram which shows the consequences of all the major cause-and-effect relations. Such visualisation of a preliminary framework provides a cognitive link - "symbolic realisation" and "generalised tools" (LAWLER 1985, 187) - between the concrete world and the preliminary mathematical and abstract concepts needed for the subsequent development of the equations used to describe the behaviour of the system in question. By its very derived nature, conventional science education does not, generally, formally advocate and stipulate such a procedure to be an essential feature of the scientific problem definition and identification process in scientific modelling instruction and learning.

The Cooling of a Hot Liquid can be considered to be a common, first-order feedback process [59].

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[59] FORRESTER regards a first-order feedback process corresponds to a system having a first-order linear structure (1968); this aspect may have educational ramifications and interpretations for the mathematically-inclined learner.

The Causal-Loop Representation of Temperature and Cooling Rate is given below.

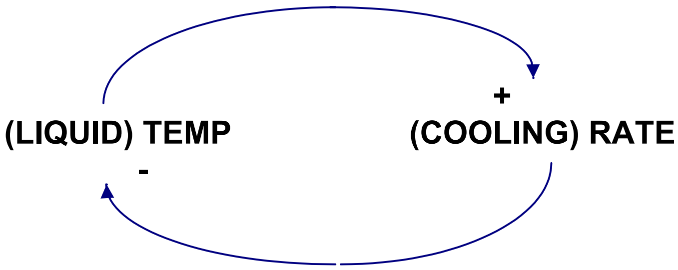

Fig. 4.1 Causal-Loop Diagram for the Cooling of a Hot Liquid

Through such an illustration, which we consider not to be overtly abstract, the learner is given the opportunity and a conceptual or schematic tool that enables her/him to distinguish between an everyday perspective of a physical phenomenon and a purely scientific perspective. In general, we found this to be predominantly the case with the subjects in **STUDY 1**. Teaching pragmatic reasoning schemas such as the causal schemas and methodological principles in System Dynamics, is the sort of thing that formal education claims to do, and frequently does, rather proficiently. Unlike in the teaching of logic and some types of empirical rules, learning through such instruction can amount to "swimming downstream" educationally (HOLLAND et al. 1986).

For both the students involved in **STUDY 1** [60] Causal-Loop analysis centred round further examples taken predominantly from elements of Biology, Environmental Science and Physics.

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[60] For the students in involved in **STUDY 2**, Causal-Loop analysis centred round further examples taken predominantly from elements of Biology and Environmental Science.

In the evolving discussions a distinct outcome was that both **MARCO P.** and **SHOKO K.** were readily able to recognise the scientific nature and to acknowledge the conceptual basis of such analyses [61].

For further and more detailed structuring, i.e., particularly in order to achieve/provide additional insight into the time-evolving (dynamic) behaviour generated by the preliminary model, (as well as) to sketch out the implications of hypothesised system relationships and, finally, for the subsequent mathematical documentation of the model, System Dynamics requires one to move on to LEVEL-RATE "flow Diagrams".

The corresponding LEVEL-RATE diagram for the Cooling of a Hot Liquid is given as a simple straightforward structure as indicated below.

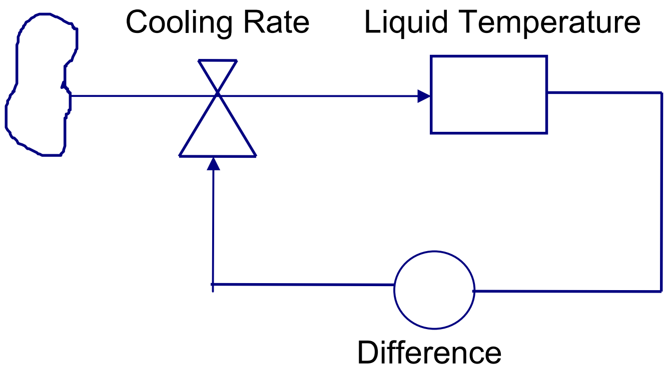

Fig. 4.2 LEVEL-RATE Diagram for the Cooling of a Hot Liquid

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[61] Most of the pupils in **STUDY 2** had difficulties in coming to terms with the scientific dimension of such a procedure (as well as the conceptual basis of such a dimension). Consequently, they showed puzzlement and scepticism. This could be attributed to their common, ingrained misapprehension of the science learning they had experienced so far. Thus the successful establishment of such Causal-Loop analysis amongst members of this particular group was, relatively seen, time-consuming albeit eventually fruitful. Later we observe that, as was to be expected, the **STUDY 3** group also encountered very little difficulty in appreciating the analytical significance of Causal-Loop structuring. Whatever difficulties arose could be attributed to the fact that a detailed study of the essentials of the System Dynamics Methodology was not a major instructional component of the course.

In **Fig. 4.2** above, the newly-defined Auxiliary variable - DIFF(erence) - clarifies the Flow Diagram, and is the difference between Liquid Temperature and Ambient Temperature.

NEWTON's Law Of Cooling states that the rate of cooling of a liquid is directly proportional to the difference in temperature between the liquid and the ambient temperature. With the aid of such a structure-oriented, graphic model-building system provided by Causal-Loop and LEVEL-RATE schematisation, the learners were not limited to pure verbal characterisations and are given the opportunity to explicitly formalise the qualitative descriptions (providing relevant parameters, interdependence and magnitudes).

The mathematical relationship are now required to be elicited in a form that would expose the mathematical nature while maintaining the structural (LEVEL-RATE) description of the problem. An appropriate System Dynamics and DYNAMO formulation of this statement would be:

```
R      CLRATE = K * (LQTEMP - AMTEMP)
```

In the statement above,

LQTEMP represents the Liquid temperature (degrees Celsius);

AMTEMP represents the Ambient Temperature of surrounding (degrees Celsius);

CLRATE represents the Rate of cooling (change) of liquid temperature (degrees Celsius per minute);

K is the Proportionality coefficient for Newton’s Law (/minute).

In a conventional Physics session, and one adopted during this study, this example involves the carrying out of a straightforward physical experiment - followed by tabulation and graphical illustration of the results obtained - and then estimating or assessing the correspondence between the system’s features and parameters and those obtainable from the experiment. An approximation and significance of the constant **K** - the coefficient of cooling - is then calculated.

When attempting to identify the mathematical significance behind such a computational statement, students with knowledge of elementary integral calculus and NEWTON's Law Of Cooling may be led to recognise and appreciate this situation as one in which integration and/or experiment could be used to find the length of time needed for the liquid to cool. This could then be used to obtain a numerical value for the coefficient of cooling – **K**. This was observed to be clearly the case with **MARCO P.** and **SHOKO K.** [62].

The connection between the simulation experiment and the respective runs and the actual experiment, and the significance of simulation was nevertheless established. The opportunity to exploit the potential and the manner in which Theory, Experiment and Computer-based Modelling complement also presented itself ideally through the implementation of such an investigation.

4.2.1.2.2 Phase 3 (Stage 1) Analysis Applied to Example *1*

This phase concerns the development of an even more elaborate abstract representation and requires the conversion of the verbal description into a form suitable for running the model on the computer.

The formal documentation of the model requires the writing of logical statements as a set of first-order difference equations in a format required by the DYNAMO (RICHARDSON & PUGH, 1981) and STELLA II (1990) compiler and simulator programs (see CHAPTER 3).

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[62] Again, as we see later in the survey, this was also the case with practically all the pupils involved in **STUDY 3**. This was in effect tried out in **STUDY 3** but due to the weight attached to such an exercise, a significant degree of success amongst the not-so-ardent mathematicians could not be gleaned from the discussion after the execution of the experimental procedure. Students not possessing the requisite knowledge, however, needed only to acknowledge the significance of a proportionality constant. No attempt was made to exploit this avenue with the pupils in **STUDY 2**; the mathematical demands made were considered to be unnecessary and beyond the scope of their mathematical studies program.

Finally, the DYNAMO statements describing this model [63] were formulated as:

L LQTEMP.K = LQTEMP.J + DT * (CLRATE.JK)

R CLRATE = DIFF.K/ K

A DIFF.K = LQTEMP.K - AMTEMP

N LQTEMP = 90 .... "initialising" equation setting the starting temperature.

C AMTEMP = 20 .... stipulates the constant ambient temperature.

C K = 30 .... gives a value for the cooling constant.

The time-scripts **.J**, **.JK,** and **.K** - although not always required in some versions of DYNAMO - help to communicate precisely how the computation described is carried out. The symbol **DT** is used to represent the length of elapsed time between J and K (past and present) or K and L (present and future), and replaces **Δt.** Some puzzlement was expressed at the choice of these symbols, but the acknowledgement of the idiosyncrasies and characteristics of computer jargon, added with the element of logic, made such use acceptable.

A System Dynamics computational sequence solves the initial cooling rate by iteration - i.e., the repetition of one set of instructions often with changed variable values at each instruction and one which gives legitimate approximations that are made acceptable by shortening the iterated time interval, are a feature of the DYNAMO compiler program - which itself is reflected in the underlying algorithm and

clarified by DYNAMO formulation; the computer-based simulation runs can be explained to represent the performance of the hypothetical or "synthetic" experiments. For **MARCO P.** and **SHOKO K.**[64], the mathematics of iteration was familiar and recognition of the DYNAMO compiler process was relatively easily appreciated.

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[63] We decide (rather arbitrarily) to compute every half minute say. Initially, **LQTEMP = 90, AMTEMP = 20** and the cooling constant **K = 30.**

[64] Also, as is to be observed later, for most of the pupils involved in **STUDY 3.**

Using this program, the indications were that, in general, the ten students in the empirical survey (**<u>STUDY 3</u>, 4.4**) were convincingly able to weigh and assess the correspondence between the values obtained, along with the (exponentially-characterised) graphs of the simulation runs, with those they had obtained performing the actual experiment – this involved Sessions 6, 7 and 8. They were thus in a clearer position to acknowledge the simplicity, applicability and to appreciate the effectiveness/(non-effectiveness) of such a simulation experiment, and its relation/value to the actual experiment carried out.

In general, it may be claimed a positive trend in the true appreciation and/or acknowledgement of the value of a simulation experiment could be drawn – in most of the cases, perhaps, for the first time.

Additionally, the high mathematical component of many Physics topics has (traditionally) been a source of difficulty to most of the students in the survey. Physics teachers are, however, reluctant to remove the elegant mathematical notions such as exponential growth and decay - that are applicable to many branches of the sciences - from instruction since this would leave behind an unsatisfactory residue of inadequately-defined concepts and ideas. We contend, nevertheless, that the above example may serve to expose/convey an appreciation - through a mathematically-unconventional procedure - of the (concept and some) characteristics of exponential decay to students both with limited as well as with polished mathematical ability, but without directly resorting to canonical methods of elementary integral calculus.

4.2.1.2.3 Phase 1 Application to Example *2*

The dynamics of an infectious disease within a population lends itself particularly well for treatment with System Dynamics, particularly amongst those science learners showing a strong leaning towards Pure and Social Biology and away from the Physical Science topics that formed part of their early science learning. This aspect of implementation of the System Dynamics methodology was, therefore, exploited and formed [65] .

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[65] This was also imolemented with the Predator-Prey Model and the LIMITS TO GROWTH Report – part of the Science For The 90's programme with the pupils in **<u>STUDY 2</u> – Pilot Study** (**4.3**).

For the initial analysis of the dynamics of an epidemic resulting from an infectious disease, the students may consider the population in three blocks (or aggregates), each block having a LEVEL (state) which is influenced by RATES of change in the LEVELS.

- Block 1 - Susceptible Population - **SUSP**; Infection Rate - **IR.**
- Block 2 - Infected Population - **INFP**; Recovery Rate - **RR.**
- Block 3 - Immune Population - **IMMP**; Immunity-Loss Rate - **LR.**

Through careful planning and well-articulated guidance on the part of the instructor, this stage of the analysis may be initiated with a reasonable degree of success – problems (particularly with the pupils in **the Pilot Study**) arise mainly in the stating and defining of the respective (LEVEL-RATE) parameters and the learner may be led into these invariably reasonably smoothly.

Although there are no precise laws governing the RATES, as there was for the liquid cooling problem (***1***), the students could be called upon collectively and intuitively (combining a deductive with an inductive approach) to adopt or develop an empirical approach to calculate values for the RATES. Based on further intuitive reasoning - e.g., the more Susceptible people there are that are exposed to the epidemic, the higher the Infection Rate would be, and the Infection Rate in turn should decrease the number of Susceptible people - the students are now in a position to postulate and formulate a number of different relationships (leading to an initiation of formula-construction) relating the RATES to the corresponding LEVELS.

BRUNER (1986), in reference to such type of scientific intuition required in the analysis of a situation in which different factors affect each other and the explorations of possible interventions, claimed that it is the intuitive mode that yields hypotheses quickly and that strikes on combinations of ideas. Moreover, it is the value of intuitive thinking that is particularly valued and stressed by mathematicians, biologists and physicists in their respective areas:

> "Intuitive thinking characteristically does not advance in careful well-defined steps. Indeed, it tends to involve manoeuvres based seemingly on an implicit perception of the total problem"; (BRUNER 1986, 239).

Development of the Causal-Loop and LEVEL-RATE schematisations involved in the dynamics of an epidemic altogether involved a significant amount of intuitively-oriented discussion and interaction [66], resulting in constructive cross-disciplinary science interactivity and learning. Such hypothesised, intuitively-developed relationships can also be freely and diagrammatically expressible, as in the manner shown below, and these could later be modified and entered into the mathematical model and confirmed empirically.

The (final version) Causal-Loop Diagram for the Epidemic Model takes the form shown below.

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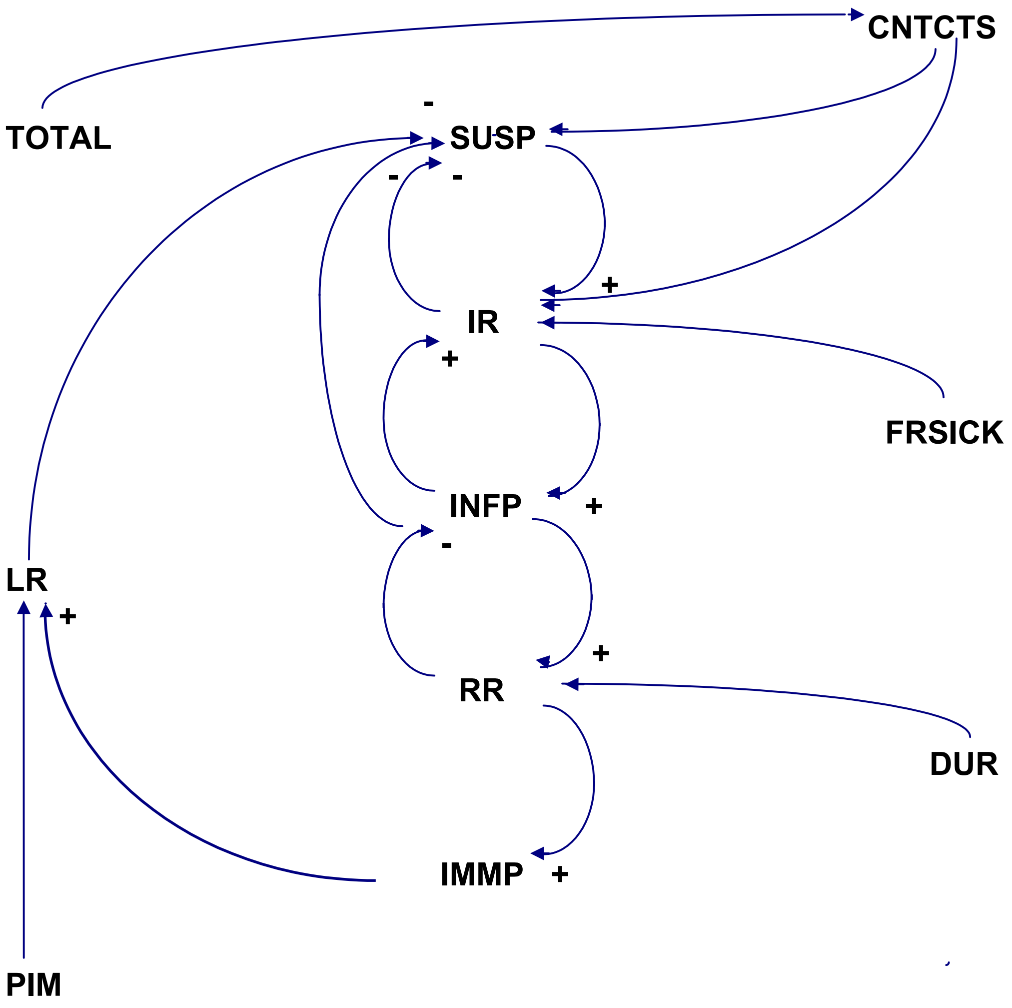
[66] For practically all the members in **STUDY 1** - as well as for the members of **STUDY 2** (**Pilot Study**) and **STUDY 3** - the problem was a novel situation. While the individuals in **STUDY 1** and **STUDY 3** were involved in the exploration and discussion of the finalised versions of the Causal-Loop and LEVEL-RATE diagrams, both diagrams were elaborately developed in the course of instruction with the **Pilot Study** group.



TOTAL - Total Population,
CNTCTS - Susceptibles Contacted Per Infectious Persons Per Day,
FRSICK - Fraction Of Contacts Becoming Sick,
DUR - Duration Of Disease,
PIM - Period Of Immunity.

Fig. 4.3 Causal-Loop Diagram for the Dynamics of an Epidemic

4.2.1.2.4 Phase 2 Application to Example *2*

The following LEVEL-RATE Flow Diagram for the Flu Epidemic Model was – through exploration, discussion and guidance - constructed and is depicted below. This generally, however, turned out to be a lengthy, drawn-out but necessary procedure involving a great deal of elaboration for eventual effective assimilation. The formulation of the problem in terms of LEVELS and RATES serves to illustrate the central feature of the problem and determines the next step of the procedure. Again here, the final version was carefully managed through instruction and applied guidance – to avoid undue time consumption and to allow for smooth transition to the next stage.

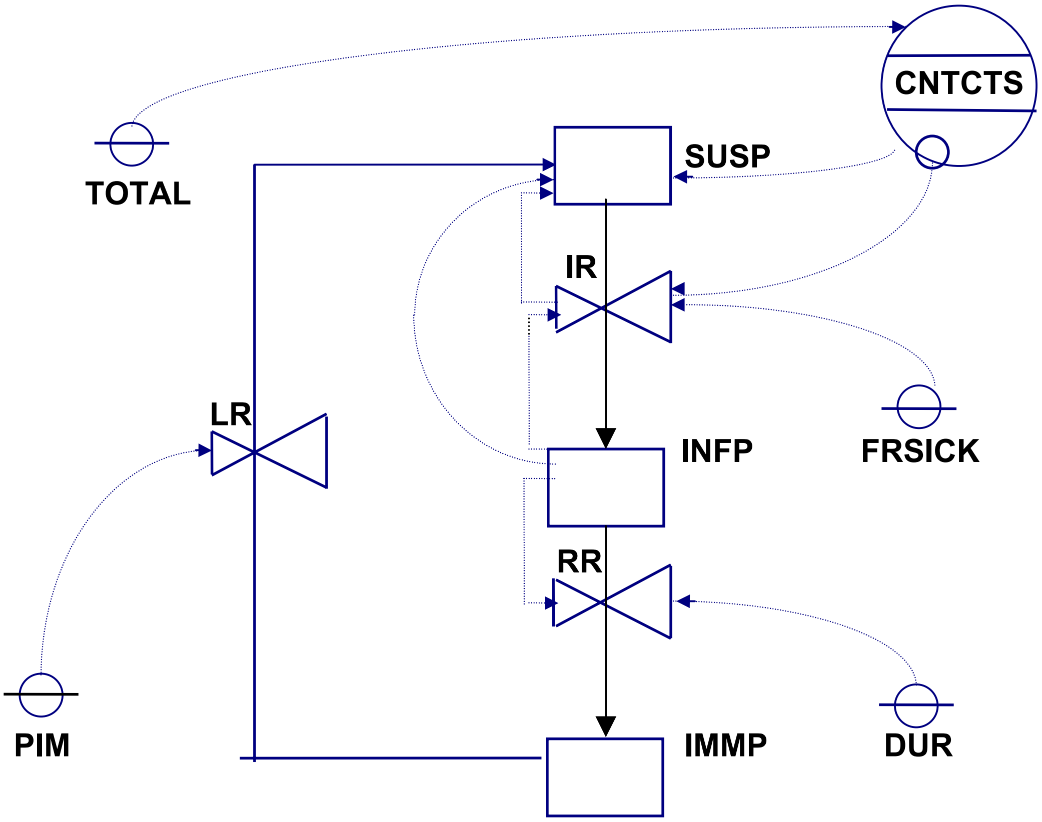


Fig. 4.4 LEVEL-RATE Diagram for the Dynamics of an Epidemic

System Dynamics flow diagrams, when regarded as alternatives to written explanatory statements, show the accumulations, flows, their relationships and the dynamic nature of the system schematically but with relatively fewer features. Such flow diagrams explicitly show LEVELS and RATES, and make distinctions between "physical flows" – normally indicated by solid arrows, and "information links" - indicated by broken lines.

Such stylised diagrams are also brought close to the quantified form; and since they constitute the intermediate stage prior to mathematical formulations, they consequently serve to bridge the gap between mathematical equations and causal-loop diagrams. This aspect attributes to flow diagrams the characteristics of structure diagrams, and provides the mechanism to move from a visual stage of scientific thinking to the subsequent descriptive scientific computational procedure of mathematically formulating the (LEVEL-RATE) equations. Thus, System Dynamics flow-charting can be seen to form a comparatively-easy, visualised and functional representation of feedback systems. Being essentially LEVEL-RATE flow diagrams that show the system's structure in terms of LEVELS and RATES, and in the process enable one to infer more reliably some of the dynamic implications of the feedback structure represented, System Dynamics flow diagrams invariably always cover the same familiar concepts and chunk information.

Such a scientific schema's principal implication for learning is that new information can also be presented in a way that can ensure maximum contact with prior knowledge. They stress the procedural aspect of knowledge and also serve as matrices for asking specific questions - and not for the presentation of propositional or verbal knowledge (JUNG 1985). This aspect was also clearly observable almost uniformly with the individuals in **STUDY 1** [67].

Such a schema approach also emphasises the importance of (not only of general but also of) specific knowledge (MINSKY 1975). Thus problem solving with the schema approach avoids elaborate exploration and evaluation of alternate methods for the solution of a particular problem. On the basis of vague similarities with the problem, a new problem is tackled with the procedure associated with the familiar problem, relying on debugging knowledge for making the procedure fit the new case.

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[67] This was also to be observed with the group in **STUDY 3**, but particularly more so among the more mathematically-inclined members, whose interest in System Dynamics was also more pronounced.

KROHN (1983) found, in addition, that the graphic structure of flow diagrams aided problem-solving, and that performance was optimal when the flow diagrams were consistent with reading patterns. In this respect, System Dynamics flow charts require and enable the learner not only to understand the LEVEL-RATE equations but also to define the sequence in which they will be used. Consequently, it could also be argued that in the course of instruction [68] or in the debugging of a program, flow-charting a System Dynamics program can be more useful in a problem-solving or learning context after the program has been written and before it is rewritten [69].

4.2.1.2.5 Phase 3 (Stage 1) Analysis applied to Example *2*

Primary features of the LEVEL-RATE structure "schematisation" (i.e., Flow Diagram) and the DYNAMO statements of the mathematical relationships describing the Flu Epidemic Model demonstrate how the structuring facilities of System Dynamics extend the paradigm further into a cross-disciplinary context.

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[68] We found that the instructional strategy one can generally employ is straightforward explanation and elaboration of the diagram features, and it is one that could be predominantly based on the provision of several examples from the different science disciplines.

[69] Surprisingly, practically all the students involved in the preliminary (**Pilot Study**) survey conducted, and described (**4.3**), also expressed no inherent scepticism on encountering these visual features of System Dynamics, and, eventually, most also encountered relatively few difficulties at mastering these particular diagramming aspects of the System Dynamics methodology; additionally, most found the visual simplicity of both Flow-Diagramming and the subsequent LEVEL-RATE equation-formulation phase novel, meaningful and appealing.

For the Flu Epidemic model, the LEVEL Equations are:

L SUSP.K = SUSP.J + DT * (LR.JK - IR.JK)

L INFP.K = INFP.J + DT * (IR.JK - RR.JK)

L IMMP.J = IMMP.J + DT * (RR.JK -LR.JK)

The corresponding RATE Equations are:

R IR.KL = INFP.K * CNCTS.K * FRSICK

R RR.KL = INFP.K/DUR

R LR.KL = IMMP.K/PIM

The infection rate **IR** is the product of **INFP.K, CNCTS.K** and **FRSICK. INFP** is the infected population and **FRSICK** gives the probability of a new infection when an infected person comes in contact with a **SUSC**eptible person; **CNCTS.K * FRSICK** gives the expected value of the number of new people infected each day).

The recovery rate **RR** is calculated as the ratio of the infected population, **INFP**, to the duration, **DUR**, of the disease, and is based on the infected population at the time .**K**).

The rate of loss of immunity **LR** is the ratio of the immune population, **IMMP** to the period of immunity, **PIM**).

Finally, and subsequently, the qualifying AUXILIARY equation is given by:

A CNCTS.K = TABLE (TABCON, SUSP.K/TOTAL, 0.1,0.2)

This equation states that the number of susceptible people, **SUSP.K**, contacted per day are to be found in a table of numbers called **TABCON**. A second equation fills in the information about the dependent variable **TABCON**.

T TABCON = 0/2.8/5.5/9.5/10

This TABLE function is also an AUXILIARY statement that captures a non-linear relationship, thus avoiding the development of elaborate mathematics to describe the variable interrelationships within the model.

From studies in Learning and Discovery – admittedly, however, from primarily adopting an instruction perspective - HOLLAND et al. suggest that teaching techniques would select and make use of analogies between scientific problems and everyday problems. In the case of problem solving, analogy is used to generate rules applicable to a target problem by transferring knowledge from a particular, selected source domain that is better understood (HOLLAND et al. 1986). Since an analogy is a shared structure of relationships between two domains, and not just a list of attributes in common, critical reasoning skills are employed to resolve conflicts between new information and previous concepts.

Problem-solving by analogy involves four basic steps which interact in many ways and, therefore, need not be carried out in serial order:

- Constructing mental representations of the sources and target;
- Selecting the source as a potentially relevant analogue to the target;
- Identifying components that play corresponding roles in the two situations;
- Extending the mapping to generate rules that can be applied to the target in order to achieve a solution; (HOLLAND et al. 1986, 292).

From the perspective of the instructor, these four steps offered a useful conceptual organisation scheme as well as an instrument in the choice of problems and/or examples; compatibility between aspects of the System Dynamics methodology and the above four steps was found to be strong.

HOLLAND et al. further argue strongly that problem-solving by analogy provides a general context for theoretical discovery, and that analogy is the primary means of theory construction; many discoveries take place when problem-solving leads to the association of a new problem domain with already understood ideas (HOLLAND et al. 1986). In effect, we can see this feature to be present in the general nature, structure and adaptability of the LEVEL-RATE constructions and formulations, and to be serving towards the conceptual organisation of the underlying algorithm supporting the LEVEL-RATE statement.

The development and constructions of the following two further examples - **MARCO's** and **SHOKO**'s projects - may serve to demonstrate the ramifications of deploying such models as the Cooling Of A Hot Liquid and Flu Epidemic in the course of instruction.

4.2.2 STUDY 1 – Part 2: Project-Mode Applications of System Dynamics

Subject to further examination and analyses are the following two examples,

- **Example *3*** - **MARCO**'s International Baccalaureat Project on Yeast Population (Biology), and

- **Example *4*** - **SHOKO**'s International Baccalaureat Project on Chemical Kinetics (Chemistry),

both undertaken as projects by two (then seventeen-year old) graduating students at Internationale Schule Hamburg e.V., and submitted as a component [70] of the International Baccalaureat Diploma requirements, are included to demonstrate the versatility and adaptibility of System Dynamics within a school's Scientific Studies program.

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[70] An (investigation-based) “Extended Essay“ and the “Theory Of Knowledge“ studies form ancillary and essential components, and are required for the awarding, of the International Baccalaureat Diploma.

Both projects exemplify solo efforts by which the rudimentary skills and the requisite knowledge were introduced and expertise was acquired in a relatively short - less than three hours - time, with the respective proficiency levels being achieved independently and with minimal guidance, and that culminated in successful implementation of System Dynamics to complete the tasks within the stipulated time span of forty-five hours. These project-mode efforts throw light upon the high degree of success with which System Dynamics modelling and simulation - undertaken as a supplementary activity and in conjunction with experimental work - may be successfully implemented. Also, as was indicated, this was achieved with minimal disruption among the more able students at the secondary school level in the ongoing course of their studies. The students' positive reactions to their involvement with System Dynamics are given at the end. Examples of selected key features of these efforts are included in **APPENDIX E1** and **APPENDIX E2**.

4.2.2.1 Phase 1 and 2 (Stage 1) Analysis applied to Example *3* - MARCO's Project

Experimentally, and conducted at the Upper Secondary School level, the development of a Yeast Population Ecosystem is an easily observable and, therefore, ideal phenomenon for investigation because (as formally postulated by **MARCO** at the initiation of the project):

- Yeast Cells are not mobile,
- dead cells are easily distinguishable (using Methyl Blue solution) from living ones, and
- the amount (Molar Density) of the Alcohol produced is readily estimated as it stands in direct proportion to amount of the Sugar solution present.

Therefore, through the comparison of actual experimental data with that obtained through computer-based simulation of the system under the same parametric conditions, examining the degree of validity of biological modelling (and simulation experiment) - as well as the limitations of the effort - becomes feasible. This, in effect, has been performed and forms the essence of **MARCO**'s completed International Baccalaureat Diploma Project (International Baccalaureat - Extended Essay).

In a parallel manner, BETHGE & SCHECKER (1992) explain how the analysis is readily extendable and applicable to the principles of the Mass-Spring (Simple Harmonic) System and Displacement-Velocity-Acceleration (Kinematic) Systems employing STELLA (1990) - which has its roots in System Dynamics.

The Causal-Loop diagram and the LEVEL-RATE diagram, respectively, formulated independently by **MARCO** in depicting the dynamics of a Yeast culture in a Sugar solution - taking into account growth and decay of Yeast Cells in solution - are given in the two diagrams below. **MARCO** (and **SHOKO**) needed and asked for minimal guidance in the formulation of the two diagrams. Basic technical issues were needed to be resolved – and these could also be obtained from a DYNAMO handbook, but he (and **SHOKO**) had mastered the conceptual basis of these two diagramming procedures from instruction. Both **MARCO** and **SHOKO** frequently worked together on their projects.

The Causal-Loop diagram was given the following form.

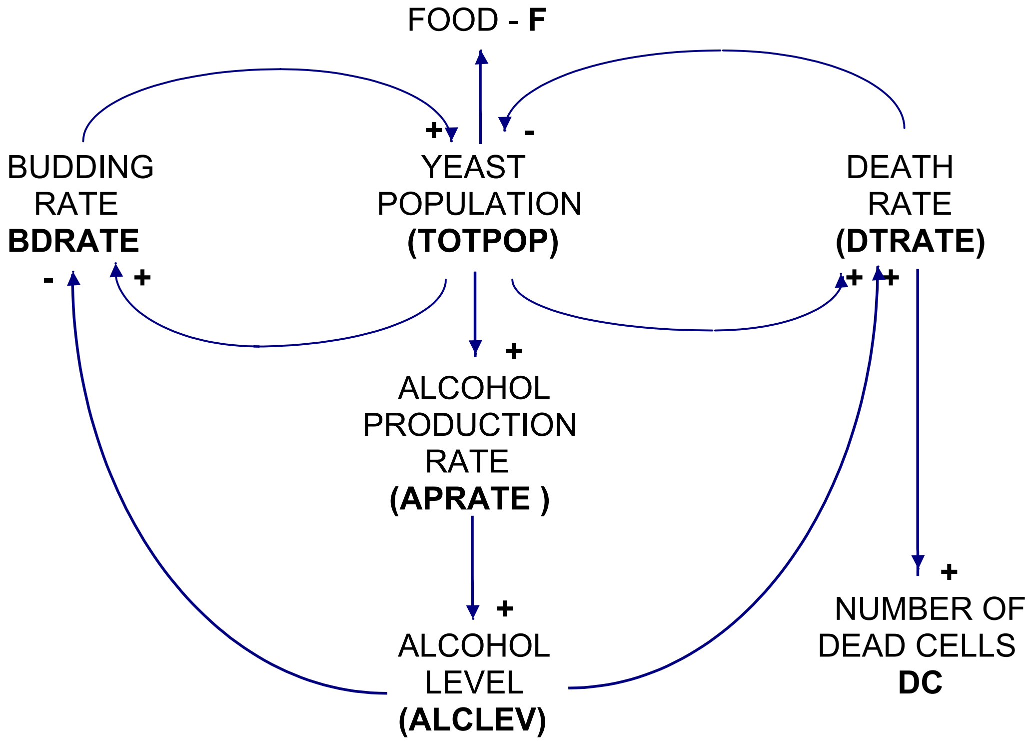
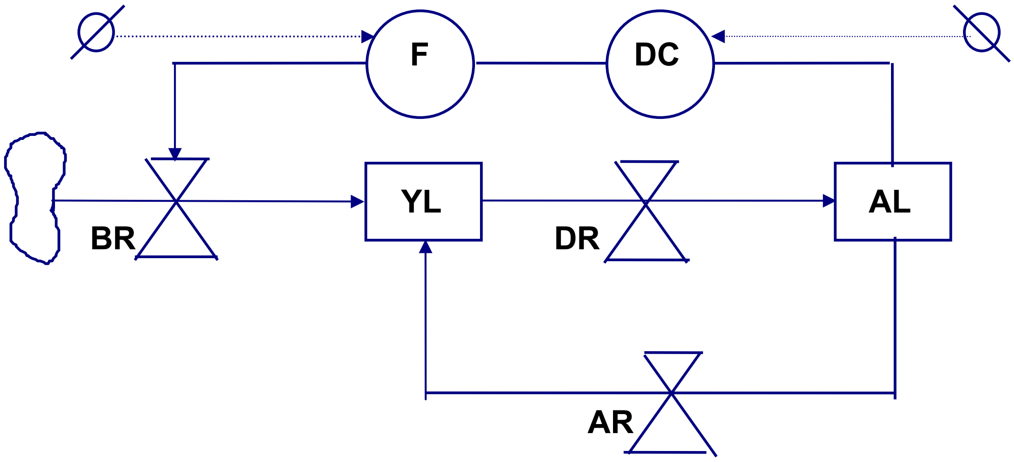


Fig. 4.5 Causal-Loop Diagram for MARCO’s Yeast Population

The corresponding LEVEL-RATE diagram was assigned the following form.



Figs. 4.6 LEVEL-RATE Diagram for MARCO's Yeast Population

4.2.2.2 Phase 3 (Stage 1) Analysis applied to Example *3*- MARCO's Project

The DYNAMO LEVEL, RATE and AUXILIARY Equation statements for the Yeast Population Ecosystem were formulated by **MARCO** in the following three sets of DYNAMO equations:

L TOTPOP.K = TOTPOP.J + DT * (BDRATE.JK - DTRATE.JK)

R BDRATE.KL = TOTPOP.K *BUDFR.K

A BUDFR.K = (ALCON - ALCLEV.K) *CONSTA

L ALCLEV.K = ALCLEV.J + DT * APRATE.JK

R APRATE.KL = TOTPOP.K *PRODFR.K

A PRODFR.K = (ALCON - ALCLEV.K) * CONSTB

L CLDEAD.K = CLDEAD.J + DT * DTRATE.JK

R DTRATE.KL = ALCLEV.K * TOTPOP.K * CSK

Examples of the main results from **MARCO**'s completed project are included in **APPENDIX E1**.

4.2.2.3 Phase 2 and 3 (Stage 1) Analysis applied to Example *4* - SHOKO's Project

Chemical Kinetics covers techniques and methods related to the study of evolving chemical phenomena, whether it is a question of simulating a reaction, or of identifying its parameters or for optimising it. Reaction Kinetics studies require both careful experimental measurements and careful processing of the results if reliable values of rate coefficients are to be obtained. Using the methodology of System Dynamics, some problems in Reaction Kinetics at upper secondary-school/pre-university Chemistry level can be investigated and studied without reverting to simplifying hypotheses.

Although students may acquire understanding of a particular chemical system from their interactions with a model, they do not necessarily acquire the understanding of the potential of systems modelling generally as a tool or heuristic for thinking about the problems. It may then be argued that to do so would require the opportunity to actually construct a working model of such a system.

In the investigation of the various factors that affect a reaction rate, the standard reduction-oriented approach requires that one single factor be varied while the other factors are kept (or assumed) constant. However, in actual systems where often more than one factor changes during the on-going process, such as in highly exothermic reactions - here, the temperature and concentration do not vary independently of - but in relation to each other, a reduction-oriented approach presents difficulties in selecting the factor dominant in influencing the reaction rate.

In this particular case of Chemical Kinetics, **SHOKO** speculated that applying System Dynamics to such systems enlists a holistic or systems approach, which permits the combination of various factors to influence the rates simultaneously and continuously in a simulated environment, as well as the prediction of the dominant factor.

Simulation of such reactions requires the determination of the evolution of the products and the intervening reactants from a knowledge of the kinetic model, and a specification of the initial concentrations and rate constants. Changes in concentration can be determined by computer simulation, and conclusions about the properties of the real phenomena can be drawn. This forms the basis of **SHOKO**'s project.

To initiate the analyses, the "simple case" - the Dissolution of Candy in Water at different Temperatures – was considered and **SKOKO** formulated the following equations:

L VOL.K = VOL.J + DT * DECRT.JK

R DECRT.KL = CONST * AREA.K

A AREA.K = 4 * π * EXP((2/3) * LOGN (3 * VOL.K/(4 * π))

As a further development, i.e., for the "complex case" - where combined factors influencing Reaction Rates in the reaction of Zinc with Hydrochloric Acid are considered - the ARRHENIUS Equation -

Rate = A exp (- E/RT) S^m $(H+)^n$

- **A**, **E**, **m** and **n** are constants to be determined experimentally, and **R** is the Universal Gas Constant -

is employed, and the following sets of DYNAMO equations were formulated:

For the amount of Zinc in Hydrochloric Acid:

```
L    AMT.K  =  AMT.J - DT * DECRZ.J

R    DECRZ.KL  =  {A*EXP(-E/(R*TEMP.K)*AREA.K} *
                  {EXP[POWER*LOGN(HCONC.K)]}

A    MASSZ.K  =  I MASSZ - MOLAR * (IMATZ.K)

A    AREA.K  =  2 * EXP(0.5*LOGN(π*MOLAR*AMTZ.K*HEIGHT/DENST))

A    HCONC.K  =  ROT.K/VOLUME
```

For the Hydrogen Ion Concentration:

```
L    PROT.K  =  PROT.J + DT * DECRP.JK

A    DECRP.K  =  2 * DECRZ.JK
```

For the Temperature:

```
L    TEMP.K  =  TEMP.J + DT * INCRT.JK

A    INCRT.K  =  [(-1)*HEAT.JK/(MASSA*SHCAP)] - [(FACTOR *
                 (TEMP.K - ROOMT)]

A    HEAT.K  =  ENTHALP * DECRZ.K
```

SHOKO selected the following data in her simulation runs for the Zinc-Acid reaction:

Time = 30 minutes
Mass of Zinc = 19.8 g
Amount of Zinc reacting = 0.164 mol
H^+ concentration = 6.2 mol dm^{-3}
Temperature = 301 K
Area = 10.104 cm^2
Rate for H^+ = 20.319 x 10^{-3} mol min^{-1}

Further essential features of **SHOKO**'s project and examples of computer results are included in **APPENDIX E2**.

4.2.3 MARCO's and SHOKO's Reactions - Secondary (to STUDIES 2 and 3) - Assessment of the Potential of System Dynamics

MARCO's and **SHOKO's** projects using System Dynamics demonstrate two contrasting attitudes towards tasks undertaken. While **MARCO's** approach may be considered minimalist, albeit thorough, **SHOKO** exploited the full modelling, simulation and experimental dimensions of the System Dynamics methodology and her Chemistry project to promote her interest in Chemistry and Computational procedures. Indeed, **SHOKO** developed her experimental programme to accommodate features of System Dynamics that were initially considered to be time-consuming and elaborate. **MARCO** was content to keep his involvement with his project according to the time allocation suggested, and did just enough to ensure completeness. These aspects are reflected in the contrasting sophistication of their respective DYNAMO simulation programmes (**APPENDIX E2**). **MARCO's** and **SHOKO's** undertaking of their respective projects was at the teacher's (project-supervisor/dissertation-submitter) suggestion in response to their request for topics for investigation as part of their IB Diploma programme – they were made familiar with System Dynamics through informal/social interaction with pupils taking part in the **Pilot Study**.

In independently formulating their respective equations, both **MARCO** and **SHOKO** - both considered to be clear objectivists in our study - resorted to purely constructivistic scientific thinking and were able to function in an environment conducive to constructivism as well as objectivism. PAPERT (1993) considers such constructivistic thinking as important for discovery in computing environments since it calls for the appropriation and the usage of the needed specific and organised knowledge - mental construction - that was, indeed, provided with minimal instruction.

The teacher (project-supervisor/dissertation-submitter), fully aware that the project was intended to be student-centred, only transmitted the initial introductory knowledge and merely acted – on the odd occasion – purely as a facilitator. System Dynamics' methodological features do enable such a view of supervision/instruction, which was particularly compatible with the constructiivistic nature of the subsequent programming culture.

As an instructional vehicle for presenting what one may consider to encompass essential characteristics of a problem-solving methodology, System Dynamics also enables the instructor to approach a topic without trepidation or apprehension about the unknown. This is because the applications being relatively content-free - the scheme does not directly relate to standard science or mathematics instruction but is minimalist by nature - thus offer an interdisciplinary, middle-ground approach to problem-solving. For the both learner and the instructor, the computer serves as a scientific tool for exploration and the computer culture does not demand programming know-how but soft-approach skills (TURKLE 1996) that take advantage of purely computational computing. **MARCO** comments:

> *"This was a very satisfying involvement in two contrasting aspects of scientific investigation - experiment and theory; and I am glad to have had the opportunity to work on this theme before taking up further studies in the biological sciences at university."*

SHOKO, through the supportive environment of her Chemistry studies, developed a much more subjective relationship towards programming than **MARCO** did. She tended to project herself into the events and details in the program, achieving a much more intimate connection with her programs. **SHOKO** comments:

> *"I enjoyed working on this project, as I was interested in the reaction rates and what would happen to them if there was more than one factor affecting them (not discussed in textbooks !). The System Dynamics Methodology provided a good opportunity to investigate this question, and it will be interesting to continue the research in more depth and in many other situations."*

MARCO's positive reaction can be understood when observed within the constraints and context of the traditional program and the subjective, functional approaches adopted in his Biological studies. Manifestations of the formulation of hypothesis and hypothesis validity - rather than hypothesis formulation and validation themselves - which are at the heart of the scientific process are emphasised.

While the formal instruction and learning materials were based upon an objectivistic view of nature, science and knowledge - which **MARCO** [71] generally subscribed to - **MARCO** here clearly and adventurously chose and had no reservations/misapprehensions in adapting to a constructivist orientation to this particular Biology learning environment.

This particular involvement with System Dynamics provided him with an opportunity to redirect some of the emphasis placed in his Biology program, to orient them in a more meaningful context and, consequently, to enhance his science learning. **MARCO'**s program can be seen to exemplify an attitude towards programming in which the aim is to achieve mastery over a formal system, to cause the objective world of the computer to behave in a desired manner, and to control a piece of the external world.

At the time of this study, **SHOKO** [72] was ranked the top student (with **MARCO** following closely) in the final-year, pre-university graduating class and, although always having been a very independent student, held and commanded a distinct objectivist epistemological position. A central feature of **SHOKO**'s Chemistry instructional and learning experiences at this level was "the adoption of a thoughtful, systematic approach to problem-solving, with models (and limitations of models) as a major emphasis;" (ZUMDAHL 1993, xi). **SHOKO**'s favourable constructivistically-oriented comments about her involvement with System Dynamics arise, presumably, from her being able to easily, comfortably and meaningfully venture into unknown territory and yet to stay within the constraints of a rigid, scientific program of studies and one with which she was most familiar and comfortable with.

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[71] **MARCO P.** was working towards meeting stringent requirements needed for study at a prestigious university.

[72] **SHOKO K.** had intensive and high-level musical commitments outside normal school, and was contemplating a professional musician (concert pianist) career

4.3 STUDY 2 – Pilot Study

For this **Study**, a course on Computer Modelling and Simulation based on System Dynamics was introduced and taught to a group of twelve pupils in their final two years at Internationale Schule Hamburg e.V.. Through the analyses and interpretation of a qualitative, empirical survey subsequently conducted, a preliminary indication of the degree of acceptance and of the scientific reasoning educational potential of System Dynamics within the respective science programme would be assessed. Additionally, the impression/modifications such a course made upon the pupils' epistemological inclinations could be gleaned.

4.3.1 Course Essentials Related To STUDY 2

The course - comprising thirty-five hours spread over nine weeks - on Computer Modelling and Simulation and that was based on System Dynamics was introduced into the pre-university "Science For The 90's", inter-disciplinary science course offered at Internationale Schule Hamburg e.V., and taught to a group of five girls and seven boys in their final two years at the school.

Since ecological awareness and the societal context of science formed the primary thematic features of this particular course, extracts form LIMITS TO GROWTH - A REPORT FOR THE CLUB OF ROME's PROJECT ON THE PREDICAMENT OF MANKIND (MEADOWS et al. 1973), and frequent references to the Report and the System Dynamics Modelling package (RICHARDSON & PUGH 1982) were found to be appropriate; they provided the main resources and material for instruction and activities, respectively.

At the end of the course, the following question was set in the final portion of an examination focusing on the concepts and the methodology characterising System Dynamics that they were formally exposed to, viz.,

> **"Explain, as clearly as you can, what you see as the merits and problems in learning about System Dynamics within the "Science For The 90's" programme ?"**

The answers given – replicated and summarised in **APPENDIX D** - were analysed and interpreted in the light of the character judgements and impressions of the academic capabilities that were formed of the individual pupils - mainly in the course of instruction, but also through formal and informal consultation with colleagues and through informal, out-of-classroom conversation with the individuals themselves.

The analyses and interpretation of this aspect of the empirical survey would serve to provide a preliminary indication of the degree of acceptance and of the scientific reasoning educational potential of System Dynamics within the respective science programme at Internationale Schule Hamburg e.V..

4.3.2 Analyses and Discussion of Responses from STUDY 2 (APPENDIX E) - Qualitative Evaluation of Pilot Study.

In retrospect, the lessons and the course in its entirety were conducted in an atmosphere occasionally (but vividly !) characterised with periods of tension, disharmony, dissatisfaction and bewilderment interspersed, however, with more frequent periods where the educational outcomes were (also clearly) significantly more desirable and satisfyingly constructive – both on the part of the teacher and on the part of the pupils themselves. It could be speculated that the presence of such contrasting features could, on the whole, be attributed towards the novelty of integrating such scientific thinking into their science learning and/or the relative absence of expertise - but the distinct presence of a large measure of enthusiasm - on the part of the instructor in handling the innovative features of System Dynamics.

Generally, the following three points may be drawn from a study of the responses given and regarded in the light of classroom interaction and experiences during the conduction of the sessions.

1. Although most of the pupils did generally express some measure of scepticism or mixed feelings towards the institution of the topic of System Dynamics as part of their scientific studies - and in particular, with reference to the question posed - over half the group responded with distinct enthusiasm towards the integration of the unit on System Dynamics into the 'Science For The 90's' course.

> *"Science was not really my favourite subject. .... It is, however, interesting to study about the problems in the world and how to solve them, which is very difficult because I had never thought about them and it is nice to learn how to study about them. .... "* **JACQUELINE**;

> *"The System Dynamics course .... does help me to have a better understanding of how a scientist goes about solving major problems ...."* **ANGELIQUE.**

> *"I think that a topic like this will give one a deeper insight into many different fields and applications that we have not touched upon before. A topic like this can be useful in any sort of job in the future. I can see almost only merits in a topic like this. ...."* **JESPER.**

The scepticism that was expressed during lesson time – and which in part could be gleaned from some responses –

> *"Science was not really my favourite subject. ...."* **JACQUELINE**.

> *" The problem is that the topic is so new.....* (it may not have had time to develop fully)........... " **JESPER.**

> *"I liked this topic because it was very different,* (but it is also a bit strange)." **YURI.**
>
> *" .... Even though "LIMITS TO GROWTH" is an important topic, and I think it should be brought up, it should be taught in a different form."* **DETMAR.**

> *" .... Some of the present problems may come up with their own solution. I think we should just let things be."* **MYRA;**

> *" .... I am not a very good student when it comes to science and, definitely, very shy when it comes to talking in class."* **CAMILLA;**

could be attributed partly to the unconventional and unusual nature of this type of science learning that they were confronted with at this particular stage of their schooling, and in part also due to a number of 'revolutionary' features of the form of science presented through the System Dynamics Methodology, which were observed to contribute towards some puzzlement and difficulty in understanding. Generally, however, modification of the students' initial attitudes and reservations - which were influenced and shaped by their epistemological commitments and scepticism and prevalent during the early sessions - was noticeably positive.

Compatibility between their responses to the question set at the end of the examination and their epistemological commitments could also be drawn. This, in turn, may lead us to interpret that System Dynamics could subsequently have been regarded and accepted as a structured approach to dealing with scientific issues and problems in a manner most of them could appreciate, relate to and consider as being significantly more meaningful - in a manner unlike the influences of their previous science learning.

> *"When studying a topic like System Dynamics, I found that it taught you a better way to look at problems. "* **ALISTAIR;**

> *" .... this particular course looks closer at real-world problems and not only at scientific formulae as in Physics, Chemistry and Biology"* **CORD*;***

> *" It was, more or less, the first science course that I could relate to and it was fun." ...."* **HANS.**

It was noted that once the sessions were underway and both the essence and nature of System Dynamics were established, they were able to (begin to) appreciate the value of learning of science in the light of the non-canonical, alternative science/scientific perspective offered by learning about System Dynamics. They needed a certain amount time to appreciate and acknowledge this form of presentation and learning about aspects of scientific method.

2. Within the context of a value base - and with respect to related issues referred to in the LIMITS TO GROWTH Report - and in adopting a more pragmatic perspective, positive reactions were to be noted. It was considered that:

> *"What I liked about this course is that one learns a lot about matters that everybody should learn today. .... "* **HANS;**

> *"System Dynamics taught you what causes these problems, and that there is not only one problem within a problem, but many interrelated problems. "* **ALISTAIR;**

> *"I think the topic of System Dynamics would help us understand the dangers of pollution much better, and how to solve such problems; and the problems that we do not know or have heard about. It teaches us how to make life for our children, or the future generation, better and more comfortable."* **RAHIM.**

Since they were now able to give aspects of their own, innate scientific knowledge an identity and configuration, they were also now able to relate to and recognise a value in their involvement with this type particular kind of science learning. This could have, in part, been due to the unusual instructional approach, learning environment and the comparatively unconventional but formally acceptable presentation of science.

The seven pupils, **ALISTAIR**, **ANGELIQUE**, **CORD**, **JACQUELINE**, **JESPER**, **HANS and RAHIM,** also mentioned in 1 and 2 above, generally participated actively in the formulation of the problems under study and the accompanying discussions. It was evident, however, that their on several occasions their conceptual grasp of the elements of System Dynamics and their individual interpretations of the information to be extracted from the LIMITS TO GROWTH Report did not exhibit the same degree of scientific commitment or were not unilaterally shared.

Additionally, since these pupils did not directly associate the scientific nature and characteristics of System Dynamics with their currently negative experiences of the nature of science, the concepts and methodology of System Dynamics propose a potentially smooth integration of new material and content into their scientific studies programme pitched at such a pre-university level.

3. There were, however, aspects of System Dynamics that students felt distinctly at unease with and had difficulties coming to terms with,

> *".......... At the beginning, I thought that this was a very nice subject, but now I have found that it looks much easier than it really is."* **JACQUELINE;**

> *" .... this business with feedback control, exponential growth, system and so on. It was brand new for me and it was some kind of an adventure to find new ways of looking at things. .... I know we have a lot of problems in the world, but do we need to know that this kind of work to come to an answer ?" .... "* **YURI;**

> *"Using computer diagrams, charts or graphs may help us deal with problems of the future, or help us prepare for them, which may be our solution. But depending too much upon these graphs, diagrams or charts may lead us away from letting us deal with the present problems which are now rising."* **MYRA;**

or considered may have been suffering from a lack of instructional expertise:

> **"** (The problem is that the topic is so new) *..... it may not have had time to develop fully........... "* **JESPER;**

> **"** (I liked this topic because it was very different)**,** *but it is also a bit strange. .... But I still do not know why you taught us this topic or this kind of science "* **YURI.**

JACQUELINE in particular, but also **YURI , MYRA** and **JESPER** to a certain extent, were expressing strong reservations and apprehensions about some of the mathematical and computational aspects that were introduced – which they found relatively difficult to grasp and that they, perhaps, had hoped to avoid learning - and they believed, in contrast to the rest of the course, they would have difficulties coming to terms with.
Three students, **ANGELIQUE, YURI** and **TRACY,** although believing that System Dynamics' perspectives and methods were meaningful and effective in provoking, and in helping them to develop their scientific thinking and analytical capabilities as well as in stimulating scientific argument, felt uncomfortable, however, with the nature, content-structure and manner of presentation of the subject material as well as with the new and unconventional approach by which they were required to apply these themselves to the content and tasks. They indicated that the study of System Dynamics was not one of those science learning options they were readily willing to accept and/or apply themselves to.

4.3.3 Summary and Concluding Remarks

Generally, for most of the pupils , learning about the elements of System Dynamics did, subsequently, begin to become more smoothly acceptable than learning those aspects of the conventional science that had previously been rigidly and formally prescribed - aspects they had all previously found difficult to identify with and with whose nature and demands they, undoubtedly, encountered problems in coming to terms with.

However, three particular students - **DETMAR, MYRA** and **CAMILLA** - demonstrated strong apprehension towards the institution of System Dynamics, and on several occasions betrayed a strong (emotional) rejection of some aspects and demands of the course, particularly those that pertained to discussion and verbal manifestations with controversial, society-oriented issues; they would argue rarely and reluctantly took part in discussion. These sentiments are strongly expressed in their answers which also reflected objectivistic tendencies towards science learning. These reactions can be interpreted as a reluctance or an inability on the part of these students to assert themselves or their personalities in issues pertaining to the kind of socially-oriented problematic situations they were confronted with during the sessions. Additionally, since these students were not required to conform to expectations and no norms were presented for their behaviour, they received little comfort from the presentation of content matter and were unable to receive a sense of security from learning about, or their experiences with, System Dynamics.

On closer observation, it was also noticeable that these particular, objectivistic science learners, felt distinctly uncomfortable - and were occasionally overwhelmed - with the novelty and approach of System Dynamics, the manner and mode in which it was presented and the sociologically/politically oriented treatment of the issues presented in the LIMITS TO GROWTH Report.

Generally, however, the indications were that, within a group of students whose academic inclinations - both at their current pre-university and aspiring tertiary levels - have alienated them from the rigid approach and content of the canonical science that they have so far been subjected to up to their current pre-university stage, System Dynamics has the potential not only play a significant role in contributing towards their scientific literacy and their appreciation of aspects of scientific method, but could potentially also equally significantly modify their attitudes towards science learning in a positive manner.

These aspects were to be noticed most clearly amongst those learners we consider as subscribing towards a modified objectivistic or constructivistic epistemology of science learning. In three (out of ten) cases, nevertheless and contrary to expectation, interaction with the System Dynamics methodology and applications can be construed to have been contra-productive.

Finally, it could be strongly speculated that that, amongst the more academically-aspiring and more highly-motivated, scientifically-inclined learners, System Dynamics has the potential to achieve a degree of acceptance and significance with respect to science learning, and to be more appreciated and acknowledged as an aspect of scientific method.

4.4 STUDY 3

The primary function of the questionnaire in general was to enable the identification of any modifications - and, when possible, to provide an indication of the extent of these modifications - in the students' epistemological commitments and their concurrent views of knowing and learning science resulting from their interaction with elements of the System Dynamics Methodology.

The formulation of the questionnaire would serve to elicit qualitative as well as statistical inferences. At the onset of the survey the fact that the post-test inquiry would contain (virtually) identical questions to those to be found in the pre-test questionnaire was withheld from the students. On both occasions the pupils were given limited but a mutually agreed-upon period of time (of one week) to provide the required information. The students were, however, made fully aware of the nature and purpose of the inquiry, and participated in the project with forthright willingness, total application, and absolute candour.

4.4.1 Course Essentials Related To STUDY 3

Altogether ten, eighty-minutes, once-weekly sessions were allocated (and available) for the sessions on System Dynamics and, throughout the ten sessions attendance was 100%. The time allocation and frequency for the sessions was identical to that given to the Theory Of Knowledge course of lessons. A breakdown of the sessions is given below.

SESSION 1	Introductory Session. The Reductionist and the Holistic Approaches to Scientific Problem Solving. The System Dynamics Method and the contribution of FORRESTER.
SESSION 2	Elements of System Dynamics Methodology. Essentials of Cybernetics and of Systems and Feedback Thinking. Causal Loops and (Information) Feedback.
SESSION 3	The "LIMITS TO GROWTH" and the "BEYOND THE LIMITS" Reports.
SESSION 4	System Dynamics Flow Diagrams and the LEVELS and RATES Formulations and Equations.
SESSION 5	Computer Programming Issues, The DYNAMO Language and DYNAMO Programming.
SESSION 6	Experimental Investigation of Newton's Law of Cooling - The Coffee Cooling Experiment.
SESSION 7 & SESSION 8	Conducting of Coffee-Cooling Experiment and Computer Simulation of Coffee-Cooling using (micro-) DYNAMO.
SESSION 9	Running the Predator-Prey and Flu Epidemic Models.
SESSION 10	Concluding Session. Discussions on System Dynamics Implementation in current programme.

The source of data for this study was the information collected from written responses to pre-test and post-test questionnaires given to the students to complete before the start of the sessions and at the conclusion of the sessions, respectively. Descriptive statistics and inductive information from t-test and Cluster Analysis comparisons on selected sections of the questionnaire were used to supplement the written qualitative information obtained and these were, subsequently, integrated into the analyses and discussions.

As an adjunct, occasional and informally-conducted, outside-classroom discussions with the ten individuals of the experimental group also provided secondary information content that was used to support and/or supplement the data formally acquired. The control group, formed from the other eight (also) graduating International Baccalaureat Diploma students, was employed primarily for the statistical analyses.

4.4.2 Characteristics of the Questionnaire

The pre-test questionnaire was made up of three sections; the post-test questionnaire which was identical to the pre-test questionnaire, except for the inclusion of a fourth section and also had **Theory Of Knowledge (TOK)** in Section 2 replaced by **System Dynamics** (please refer to **APPENDIX B**).

Section 1 of the Questionnaire - to be found in **APPENDIX A** - comprised seven questions. The questions were formulated such that the character, style and quality of the answers submitted to these questions on the nature of science would initially serve to allow an interpretation of the students' perceptions, appreciation, and/or interpretations of the status of their current scientific knowledge to be obtained. Such conceptual knowledge pertaining to the nature of science was assumed to be enhanced by their participation in the scientific component of the Theory Of Knowledge course, this latter aspect forming a compulsory part of their International Baccalaureat Diploma programme.

The content, aims and objectives of this particular Theory Of Knowledge component and pertaining to selected aspects of Epistemology [73] (AITKENHEAD & RYAN 1992) are outlined in **APPENDIX B**.

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[73] Nature Of Scientific Knowledge

- Nature of observations.
- Nature of scientific models.
- Nature of classification schemes.
- Tentativeness of scientific knowledge.
- Hypotheses, theories and laws.
- Scientific approach to investigations.
- Precision and uncertainty in scientific knowledge.
- Logical reasoning.
- Fundamental assumptions for all science.
- Epistemological status of scientific knowledge.
- Paradigms vs. coherence of concepts across disciplines.

The information acquired, which was highly interpretative but appeared to substantiate our prior interpretations of the students' epistemological inclinations, was then used as the underlying criterion to categorise the students according to our previously-stated objectivist, modified obectivist (inclined to constructivism) and constructivist-oriented groupings.

Further comparison of these answers with the nature and quality of those answers submitted (post-test), i.e., after exposure to the concepts and methodology of System Dynamics, would also allow any modifications in the students' notions and interpretations of the formal, underlying context of their science learning and in their appreciation of the meaning and value of the scientific knowledge that they have acquired to be assessed.

The purpose of Section 2 was to elicit/provide more substantial qualitative information - which, in part, was enhanced by quantitative, statistical inferences from data. The changes in the students' self-perceived scientific and computer-oriented expectations of the knowledge acquired in their scientific studies prior to and after the sessions on System Dynamics would then be inferred.

The students were asked to assess twenty categories of their personal possible scientific-oriented and computer-oriented appreciation of scientific knowledge on a five-point scale ranging from 1 = "Of No Use" to 5 = "Extremely Useful". Again, in the categories, an attempt was made to utilise only those selected key concepts, overall objectives' statements and terminology that the students were familiar with from their science and Theory Of Knowledge sessions, those that were extracted from Scientific Literacy and Computer Literacy Syllabi guidelines, and those that also formed the basis and were inherent in the System Dynamics Methodology.

The twenty statements formulated were articulated and phrased so as to enable the students to characterise the nature and objectives of their (expected) current scientific knowledge and to enable them to reflect upon and to express their scientific thinking and/or scientific reasoning capabilities with minimal or no difficulty. It is also supposed that responses to these statements would enable one to elicit the students' reactions to the influence of computers in their science learning so far, and of the contribution of the Theory Of Knowledge/System Dynamics towards their current scientific epistemologies.

The statements themselves may be divided into 3 sub-composition groups:

- Statement Group 1 – i.e., statements #**2,** #**3,** #**4,** #**5,** #**9** - comprises (predominantly) System Dynamics (Scientific and Computational) Notions
- Statement Group 2 – i.e., statements #**1,** #**6,** #**7,** #**8** , #**10,** #**16,** #**17** – comprises (predominantly) Scientific Literacy Notions
- Statement Group 3 – i.e., statements #**11,** #**12,** #**13,** #**14,** #**15** - comprises (predominantly) Computer Literacy Notions

Section 2 of the questionnaire is duplicated below for reference.

The contribution of the lessons to my appreciation of:

#**1. the "scientific method" has been** **1 2 3 4 5**

#**2. the common, interdisciplinary principles characterising the pure sciences (Biology, Chemistry, Physics) has been**

1 2 3 4 5

#**3. the difference between the "reductionist" and the "holistic" scientific approaches has been**
1 2 3 4 5

#**4. the significance of cause-and-effect feedback process and thinking has been**
1 2 3 4 5

#**5. the impact of scientific knowledge on environmental issues has been**
1 2 3 4 5

#**6. the significance of the "making of a scientific model" in scientific investigations has been**
1 2 3 4 5

#**7. the significance of the "testing of a scientific model" in scientific investigations has been**
1 2 3 4 5

#**8. the significance of scientific problem-solving has been**

1 2 3 4 5

#**9. the significance of scientific decision-making has been**

1 2 3 4 5

#10. the significance of scientific experimentation has been

1 2 3 4 5

#11. the significance of formulating a scientific algorithm has been

1 2 3 4 5

#12. the significance of the process of scientific computation has been

1 2 3 4 5

#13. the role of the computer as a scientific tool has been

1 2 3 4 5

#14. the significance of a simulation experiment has been

1 2 3 4 5

#15. the role of the computer in imparting scientific knowledge has been

1 2 3 4 5

#16. the structure of scientific knowledge has been

1 2 3 4 5

#17. the relationship between human problem-solving and scientific problem solving has been

1 2 3 4 5

#18. The social/collaborative aspect of scientists working together has been

1 2 3 4 5

#19. the role of the teacher in imparting scientific knowledge has been

1 2 3 4 5

#20. the "fun" aspect of doing/learning science has been

1 2 3 4 5

Finally, the questions in Section 3 would serve to elicit answers - which were also subsequently employed to substantiate the findings in Section 1 - that would provide an indication of the influence of the sessions on System Dynamics upon changes in the students' own original attitudes and epistemological commitments and priorities, i.e., their self-perceived scientific-learning priorities and values.

The responses were, subsequently, also used to provide an indication of the degree of receptivity - which could be used to serve as an indicator of the curricular potential - in introducing System Dynamics formally into a conventional program of Scientific Studies.

4.4.3 Analyses and Preliminary Evaluation of Responses to Section 2

Before considering the implications of the study in some detail, it is essential to note that the results of the study may still depend, to a significant extent, upon the idiosyncratic interpretations of the questionnaire statements by the individual students. Moreover, the students were not interviewed to probe for reasons for their views or to check for their comprehension of the statements or understanding of the various terms used. However, familiarity with the terminology and with the formulation of the question statements was assumed since similar terminology and/or phrasing also constituted the core of the scientific component of their particular scientific discipline(s) and of their Theory Of Knowledge studies.

Also to be considered is that, characteristically, the students' views of knowing and learning in the various science subjects (Biology and/or Chemistry and/or Physics) at this stage of their education are also established, and that they have also developed definite patterns of learning. Thus, it is to be expected that when they encounter a learning context which does not fit their expectations, it might adversely affect them (EDMONDSON 1989). This particular aspect, and the degree to which it was or was not manifested, was exploited to provide an assessment of the potential and role of Scientific Computation as they perceived it – and primarily through the mechanisms of the System Dynamics methodology - if integrated into a conventional Scientific Studies program.

Subsequently, however, statements #**1,** #**6,** #**7,** #**8,** #**16** and #**17** – pertaining to Scientific Literacy **SL**, and statements #**11,** #**12,** #**13,** #**14** and #**15 -** pertaining to Computer Literacy **CL,** respectively, were subjected to more detailed and concerted analyses since they were considered to be specifically relevant to those scientific reasoning and scientific computational issues, respectively, of primary interest in this study. The remaining questions, however, were considered relevant in that they were instrumental and functional in setting the scientific computational context and the scientific educational environment for the questionnaire.

4.4.3.1 Analyses and Evaluation of a Statistical t-test applied to Responses to Section 2

As a first step in the analysis of the data acquired, information on t-test comparisons on pre-test and post-test results of the **Experimental Group** and the **Control Group**, respectively, are contained in the tables below. As competing hypotheses we formulate the following two statements:

Null Hypothesis:	Knowledge and/or Experience of the mechanisms of System Dynamics Methodology does not influence specific Scientific Literacy and Computer Literacy notions.
Experimental Hypothesis:	Knowledge / Experience of the mechanisms System Dynamics Methodology influences specific Scientific Literacy and Computer Literacy notions.

Statement Number/Type – SL/CL	t-Value	2-Tail ** Probability
#1- SL*	- 3.4	0.01
# 8-SL*	- 2.9	0.02
#11-CL*	- 4.0	0.00
#12-CL*	- 2.6	0.03
#17-CL*	- 2.7	0.03
#13-CL *	- 6.0	0.00
#15-CL*	- 3.5	0.01
#6-CL	- 1.9	0.09
#7-SL	0	1.00
#14-CL	- 1.9	0.10
#16-SL	- 0.9	0.40

Table 7 – t-Test - two-tailed, matched samples - Data for the Experimental Group

Although ordinal (and not metric) data was presented, and the samples each had less than 30 values, a two-tailed t-test (matched samples) was chosen because the alternative hypothesis was not considered to be having a specific direction. The pre-test and post-test answers form a pair for each pupil and the samples are, therefore, matched. The standard deviation was also not known and so needed estimating. A comprehensive tabulation of the statistical analysis in included in **APPENDIX F1**

.

The information that may be gleaned from the above comparison of the before and after System Dynamics results show that a significant increase in the mean results was seen at the $t > 0.05$ level in the statements marked by the * . At this level the critical value is given as 2.2.

We were, therefore, in a position to reject the Null Hypothesis. Consequently, the results may be taken to imply that exposure to - and interaction with - the mechanisms of the System Dynamics methodology, at the very least, does indeed lead to an awareness and/or an acknowledgement and/or an appreciation of

- key Scientific Literacy concepts, i.e. namely those pertaining to scientific method (#**1**), scientific problem solving (#**8**), the formulation of scientific algorithms (#**11**), the process of scientific computation (#**12**) and the relationship between human problem solving and scientific problem solving (#**17**), and

- specific Computer Literacy notions, i.e., the roles of the computer both as a scientific tool and in its capacity to impart scientific knowledge (#**13** and #**15**).

Contrary to expectation, however, no distinct outcomes were to be derived with respect to the structure of scientific knowledge (#**16**), the making of a scientific model (#**6**) as well as the testing of a scientific model (#**7**) - in particular, through simulation. An appreciation of these aspects were not considered by most members of the group to be initiated or brought out by System Dynamics.

An interpretation of this occurrence here is that the type of computer-oriented modelling and computer-based model-testing as featured in the System Dynamics methodology, was not clearly regarded to bear direct correspondence to the conventional scientific modelling and scientific model-testing notions and procedures that the students were, up to now, exposed to and have come to interpret as part of their scientific knowledge.

In sharp contrast, however, is the information obtained in relation to #3.

Statement Number/Type – SL/CL	**t-Value**	**2-Tail ** Probability**
#**3-SL***	**- 10.9**	**0.00**

Here, all students regarded the "difference between the reductionist and holistic scientific approaches" not only to be distinctly illustrated – and, we contend, also to be pragmatically manifested - by the System Dynamics Methodology, but that the methodology also firmly established the appreciation of a distinction and the presence of a difference between two approaches in scientific endeavours - the reductionist and the holistic - one not brought out so vividly before in the context of their particular science learning.

With respect to the Computer Literacy aspects - #**11, **#**12, **#**13, **#**14 and **#**15** - knowledge of System Dynamics and the structure of the methodology can be regarded to have had a distinct influence upon the manner in which they perceived the concept and function of computation and the role of computers in the scientific enterprise.

The following features that arose in the context of instruction and discussion within System Dynamics may be of significance when it comes to assessing outcomes:

- Generally, in algorithm development one is unable to resort to any particular method or implementation technique to assist in the task, and the understanding and development of an algorithm can, as a consequence, become the hardest part of programming. The System Dynamics methodology entails initial discussion of the problem, this leading to a general discussion of the algorithm, its scope and its purpose. Such a procedure as a means for discussing algorithms and for the purpose of promoting algorithmic thinking was employed with the experimental group during the sessions on System Dynamics. The individual steps of the algorithm were first systematically explained. Each step discussion usually revolved around a description of the processing actions of the algorithmic constructs. For most of the students, this form of explanation was quite adequate since they were able to recognise the actions of the algorithms without teacher direction in the first place. For some students, knowledge of the separate actions of the constructs did not lead to understanding of the algorithm, and explanations were necessary so that the students could see and understand the relationship and connection between the individual steps. This was achieved - reasonably smoothly - through description of the steps in a sequential fashion and with implementation of analogies.

- Through DYNAMO’s language features - syntax, semantics and pragmatics - the essence of computation is easily established in the course of the collaborative non-verbal activity. That is, the learner communicates ideas about the LEVELS and RATES, CONSTANTS and INITIAL VALUES by making gestures with reference to the information on the computer screen. Moreover, s/he links notions and metaphors with actions on the screen in order to constrain the meaning of and RATES within a computational context.

In summary, and from the analysis of the results in Section 2 of the Questionnaire , the following Scientific Literacy notions and Computer Literacy aspects can be extracted and observed to have achieved a significant degree of awareness and relevance after the course on System Dynamics:

- The appreciation of scientific method.
- The nature of scientific problem-solving and its relationship to human problem-solving.
- The difference between the reductionist and the holistic (system's) approaches in scientific enterprise.
- The importance of formulating a scientific algorithm and the essence of the process of scientific computation.
- The roles of the computer as a scientific tool and as a vehicle for transporting and eliciting scientific knowledge.

t-test comparisons on pre-test and post-test results of the **Control Group** as well as the **Experimental Group** are contained in the table below.

Statement Number/Type – SL/CL	**t-Value**		**2-Tail ** Probability**	
	CG	EG	**CG**	EG
#1- SL*	**- 0.4**	-3.4	**0.69**	0.01
#3-SL	**-1.9**	-10.9	**0.10**	0.00
# 8-SL*	**2.2**	-2.9	**0.06**	0.02
#11-CL*	**0.3**	-4.0	**0.80**	0.00
#12-CL*	**0**	-2.6	**1.00**	0.03
#17-CL*	**1.4**	*-2.7*	**0.22**	0.03
#13-CL *	**0.7**	-6.0	**0.52**	0.00
#15-CL*	**0.6**	-3.5	**0.60**	0.01
#6-CL	**0.6**	-1.9	**0.56**	0.09
#7-SL	**0.6**	0	**0.60**	1.00
#14-CL	**0.5**	-1.9	**0.63**	0.10
#16-SL	**0**	-0.9	**1.00**	0.40

Table 8 – t-Test Data – Comparing Control Group Data - CG with Data From Experimental Group - EG

On inspection, and as was to be expected, no statistically significant outcomes or implications could be extracted from the part of the control group responses as tabulated above. The critical value at the t > 0.05 is given as 2.3 for the statements marked by the * . This allows us to imply that their not being exposed to an alternative, innovative science learning experience like System Dynamics, viz., no change in their learning experiences, these particular students generally maintained the status quo with respect to their science learning attitudes and knowledge, and no significant modifications in their epistemological commitments could be identified.

4.4.3.2 Analyses – incorporating Cluster Analysis - of Answers in Section 2 in Conjunction with Answers in Section 3

In an attempt to draw a relationship between the students' scientific tendencies and/or their inclinations/epistemologies - according to their responses - on an Objectivistic-to-Constructivistic scale, and the influence System Dynamics may have exercised over modifying these inclinations, compatibility matching between the following two instruments were employed:

1. a pre-test and post-test Hierarchical Cluster Analysis - using the WARD METHOD for cluster classification (See Appendix) - on all twenty questions - and

2. interpretative and inductive information, comprising in part information obtained from the answers to Section 1 of the Questionnaire (in the case of the experimental group) and partly upon our knowledge and judgement of the individual student's epistemological commitments.

In Section 3 of the Questionnaire, the pupils were asked to rank the top five aspects of their science learning experiences they believed or considered to be of most significance. They were asked to use Section 2 to make their selection, requested to justify their selection and, if possible, the ranking. In general, however, they found this last part to be too cumbersome to deal with and this aspect was, therefore, given low weighting in the ensuing analyses.

Additionally, the students' responses to Section 4 are incorporated into this analysis to further complement the information on the students' modified scientific tendencies and/or their inclinations as a result of interaction with the System Dynamics Methodology. In subsequent analyses, interpretations to the answers to these two sections would serve to suggest the manner in which - and possible reasons for which - System Dynamics may have influenced the students in modifying their priorities of their own science learning.

Cluster Analysis was employed to enable us to speculate upon and/or to identify more closely any preliminary indications of modification in the students’ epistemological inclinations – and thus to establish a viable criterion - as a result of their experience of the System Dynamics Methodology. The pre-test and the post-test Hierarchical Cluster Analysis (see **APPENDIX F2**) employing all the questions and all students yielded the following classification.

	Student Number	
All Questions	**EXPERIMENTAL GROUP**	**CONTROL GROUP**

	PRE-TEST	POST-TEST	PRE-TEST	POST-TEST
CLUSTER 1	**6 8 10**	**4 5 6 7 8**	**12 15**	**12 15 16**
CLUSTER 2	**1 2 3 4 5 7 9**	**1 2 3 9 10**	**11 13 14 16 17 18**	**11 13 14 17 18**

Table 9 – PRE-TEST and POST-TEST CLUSTERS - Experimental (Pupils 1 to 10) and Control (Pupils 11 to 18) Groups

At this particular stage of the analyses, and since the principal criterion that was used was primarily to identify homogeneity in characterisation of their learning experiences as a consequence of either exposure or absence of exposure to System Dynamics (explicitly defined scientific literacy and computational literacy) concepts, it was considered necessary to consider the second and third clusters only.

The post-test, two-cluster solution indicated the presence of two distinctly different aspects of epistemology within the experimental group as a result of interaction with System Dynamics which, on inspection, also bears a noticeable degree of compatibility with our earlier objectivist as distinct from modified-objectivist to constructivist categorisation [74].

Although no clear-cut trends are indicated by these instruments, some striking aspects are worth identifying - particularly with respect to the manner in which their priorities of the students of the experimental group were modified - which one can attribute to the influence of knowledge acquired as a result of interaction with System Dynamics.

In the light of the above classification, the answers to SECTION 3 - which are summarised below,

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[74] This would seem to suggest that knowledge and/or appreciation of System Dynamics had made a more profound impression upon those students adopting an objectivistic epistemology and contemplating a scientifically-oriented course of studies in future than on those who were not. No comparably significant re-ordering of clusters was observed to occur in the control group.

		STATEMENT NUMBER – Ranked First to Fifth from Left to Right				
LENNARD H. (4)	BEFORE	#20	#19	#5	#10	#7
	AFTER	#20	#19	#1	#6	#7
THOMAS M-J (5)	BEFORE	#20	#16	#8	#1	#6
	AFTER	#6	#7	#10	#4	#18
NIKHIL G. (6)	BEFORE	#10	#20	#19	#4	#5
	AFTER	#20	#10	#8	#13	#1
GORO K. (7)	BEFORE	#6	#5	#20	#12	#19
	AFTER	#4	#3	#13	#6	#1
NOA F. (8)	BEFORE	#2	#19	#10/#7	#8	#17
	AFTER	#2	#19	#1	#7/#10	#13

Table 10 - RESPONSES TO SECTION 3 – Objectivists: Experimental Group

		STATEMENT NUMBER – Ranked First to Fifth from Left to Right				
JUN O. (1)	BEFORE	#20	#17	#18	#9	#5
	AFTER	#20	#17	#18	#5	#7
ISABEL C. (2)	BEFORE	#11	#19	#20	#10	#5
	AFTER	#17	#5	#11	#18	#3
MARK v T. (3)	BEFORE	#20	#5	#8	#18	#9
	AFTER	#1	#16	#8	#6	#7
LIESBETH S. (9)	BEFORE	#20	#5	#1	#8	#10
	AFTER	#20	#5	#6	#4	#13
JEPPE Z. (10)	BEFORE	#17	#2	#8	#6	#7
	AFTER	#17	#6	#8	#9	#7

Table 11 - RESPONSES TO SECTION 3 – Constructivists: Experimental Group

It can be construed that for both the constructivists as well as objectivists of the experimental group, most showed signs of varying degrees of modification in certain aspects of their epistemological commitments while maintaining their former positions in others; only four (two objectivists and two constructivists) demonstrated distinctly radical modification. Further insight into the reasons for their educational priorities, values and preferences, together with possible interpretations are subdivided and submitted in the following manner:

(i) results and interpretations - objectivists;

(ii) results and interpretations - constructivists.

4.4.3.2.1 Results and Interpretations - Objectivists

This group comprised three students **(NOA**, **LENNARD** and **THOMAS)** considered to be the most capable and most intensely involved in their scientific studies. All five students in this group, however, shared a generally very positive attitude towards science - with respect to their current involvement with Chemistry, Physics and Mathematics all at Higher Level, and all five contemplating further involvement with scientific studies at the tertiary level - and they all maintain, in varying degrees, that the value of scientific knowledge is relative to the framework of the scientist and the era in which s/he lives. Experimentation in their science learning is used in the context of applying aspects which they already understand or for interpretative efforts order to understand the conceptual underpinnings of the topic or subject. Their respective involvement with (International Baccalaureat) Higher Physics and Chemistry demand a substantial portion of experimental work. **NOA**, **LENNARD** and **THOMAS,** in particular, generally appeared content with traditional Physics and Chemistry learning/teaching - using material directly from the book and with experimental elaboration; teacher guidance is sought and her/his resolution of the problems is requested.

The three students . **NOA**, **LENNARD** and **THOMAS, also** found some comfort in aspects of reductionist thinking which are exact, precise and rigid. This, however, did not make it problematic for them to comply with the system's viewpoint implied in the System Dynamics methodology. All five also acknowledge the existence and influence of an external reality; society and culture affect the output and creative proposal of scientific work.

While **NIKHIL**, **GORO** and **NOA** also hold that the attitudes of the scientists are affected by their social environment, they also began to realise that knowledge may also be significantly affected and influenced. These three students were able to distinguish between anthropomorphic formulations and factual explanations, and they believed that System Dynamics formalisms and formulations facilitated comprehension of several scientific concepts, and fostered a realistic, non-mythical understanding of the process of science.

The LIMITS TO GROWTH and BEYOND THE LIMITS studies and reports provided an insight into the interaction between science and aspects of society. For three members of this particular Group - **NIKHIL**, **GORO** and **NOA** - System Dynamics played a significant role in two key aspects:

(i) in their appreciation and acknowledgement of the computer as a scientific tool and as a scientific-learning tool, and

(ii) in elucidating aspects of scientific method.

GORO regarded computation as the ultimate stage in some types of scientific activities,

> *" .... The computer can be very useful when we know how to put it to use .... Computation is the final stage in the scientific process and comes in when actual figures and relationships are to be worked out .... ".*

NIKHIL saw value in computer modelling and in simulations of particular scientific processes. Computational processes

> *" .... speed up the scientific process as well as providing an organised overlook and clarity to the entire process .... ".*

NOA emphasised the importance of specific prior knowledge and therefore felt comfortable with some aspects of System Dynamics but not with other, viz., she could relate to 'holistic' thinking but not with the 'interdisciplinary' and 'computational' emphasis.

NOA, in particular, firmly believes that a student must acquire a substantial amount of preliminary scientific knowledge and basic scientific skills through a mastery of the concepts and methods of canonical science before s/he is able to 'think scientifically'.

In her post-System Dynamics responses, however, **NOA** recognised and associated the role of computers and computation as the involvement with and the interaction with mathematical aspects of scientific processes. Accordingly all three - **NIKHIL**, **GORO** and **NOA** - recognised an essential and obvious need for further (scientific) computational and computer-based (scientific) activities to be incorporated in their science learning programme.

For **NIKHIL**,

> *" .... Scientific problem-solving employing scientific method is the beauty in science. ....It provides a disciplined and organised approach to the problem. .... This forms the basis of, and is necessary for, practising science."*

GORO - due to his particular engineering and ecologically-oriented interests - associated "conscious scientific thinking" in conjunction with "logical thinking" through System Dynamics, and regarded the System Dynamics Methodology - through the aspects

> *" .... of sharing ideas .... holistic thinking and systems modelling .... and .... taking into account of feedback.......... ",*

as providing a coherent framework for implementing (and learning about) cross-disciplinary problem-solving scientifically. **GORO** viewed computation as a logical stage in scientific problem-solving, and that it constitutes the foundations on which further knowledge is enhanced or is to be acquired.

In **THOMAS**' view, group work - which he sees to be exemplified and entailed in System Dynamics problem-solving practice - in scientific endeavour is motivating and offers the opportunity to arrive synergistically at new ideas, solutions, understanding or meaning. He favours multiple viewpoints as they tend to encourage criticism and reflection, and because more versatile and complex solutions can be arrived at more rapidly.

THOMAS, **NIKHIL** and **LENNARD** who also believed that group work supports and enhances meaningful learning - the three of them having collaborated and worked closely together as fellow pupils during the past six years - valued System Dynamics-type of group discussions for their potential for negotiation of meaning, and for arriving at shared understanding.

Additionally, the notion of scientific method and aspects of scientific modelling became more significant to most of the members of this group (possibly, by some kind of inductive inference). For **LENNARD,**

> *" .... Formation of a model, verification of the model and hence a formulation of a scientific theory is the 'old' way of deriving novel ideas. System Dynamics also applies the process of science, but the objective is not to develop a new theory, but to solve the problem that is being analysed."*

Thus, with respect to the dimension offered by LIMITS TO GROWTH and BEYOND THE LIMITS Reports and studies, **LENNARD** saw a major drawback of his current scientific knowledge and scientific problem-solving capabilities in the absence of a distinct "social-human" component, i.e., in the lack of anthropocentric orientations and anthropocentric-oriented explanations, in his science learning. To **LENNARD**, scientific laws and theories ought to go hand in hand with human existence, that scientific endeavour should be driven by the scientist's commitment to the betterment of society. LIMITS TO GROWTH and BEYOND THE LIMITS provided these. **LENNARD'**s views on this aspect were particularly strongly expressed.

System Dynamics made aspects of scientific method and the notions of the making and the testing of a scientific model - viz., scientific reasoning - more meaningful and relevant to **LENNARD** as well as all the other members of this particular group. Thus the knowledge arising out of interaction with the System Dynamics methodology was more compatible with his way of thinking.

Also, both to **LENNARD** and **THOMAS**, the Holistic Approach - which to **THOMAS** also encompassed the sharing of ideas with other scientists - and Feedback Thinking inherent in System Dynamics, and when applied to scientific problem-solving, added a new dimension to scientific reasoning and to the scientific process. These two students in particular articulated their responses most elaborately and filled both the questionnaires (but in particular, the post-test one) most comprehensively and painstakingly.

Their responses and the general reactions to the courses on System Dynamics can thus be regarded as one that was received by all five in this group with most constructive criticism and acclaim. They saw System Dynamics as a means of entering a world of scientific enterprise that they conceptualised for themselves not only in a scientific manner but also in the social, communal sense.

In sharp contrast, the responses of the Control group objectivists - required to be submitted in the pre-test questionnaire only - yielded the following information.

	STATEMENT NUMBER – Ranked First to Fifth from Left to Right				
ANNEMARIE P. (16)	#20	#13	#10	#9	#8
CHRISTIAN T. (18)	#19	#20	#16	#10	#8

Table 13 - RESPONSES TO SECTION 3 – Objectivists: Control Group

For the above two serious students of science, involvement in their scientific studies is characterised by a traditional scholastic attitude and application towards learning and the acquisition of scientific knowledge.

4.4.3.2.2 Results and Interpretations - Constructivists

Generally, the five students in this group initially possessed significantly lesser positive attitudes towards the canonical science they were so far exposed to. Unlike the group of objectivists, this particular group's involvement with, and their choice of, their respective science subjects did not go significantly further than conveniently and optimally fulfilling conditions set for acquiring the International Baccalaureat Diploma; their involvement with conventional scientific studies was to end with their time at school. Central to these five students' reservations on science learning are the notions of exactness and absoluteness that they believed was fundamental to science. The scientific endeavours that they encountered so far in their science lessons have little purpose directed towards society and are not driven by scientists' commitment to man's benefit. Society does not necessarily prescribe to scientists, through its institutions of learning, what it wants them to look for.

JUN, LIESBETH and **JEPPE** harboured a resentment of the simplistic and naively absolutist conception of the nature of scientific problem-solving and the development of scientific theories. This conception - in relation to these particular issues - had not been radically modified after their System Dynamics experience.

However, **LIESBETH** and **JEPPE**, and to a lesser degree **JUN**, seemed to give priority to their analysis of knowledge, to the characteristics of items or bodies of knowledge that they were confronted with, independently of their attitudes, beliefs or other subjective states in the light of their interpretation of the concept of scientific modelling that was presented through System Dynamics.

Again, in contrast, the responses of the Control group constructivists - required to be submitted in the pre-test questionnaire - yielded the following information.

	STATEMENT NUMBER – Ranked First to Fifth from Left to Right				
ARIANE A. (11)	#5	#10	#20	#17	#9
FRANK A. (12)	#13	#18	#15	#4	#7
ISABELLE v HK. (13)	#17	#18	#1	#10	#20
ADI K. (14)	#2	#3	#18	#13	#20
BEN O. (15)	#2	#19	#14	#18	#6
NATHALIE S. (17)	#2	#1	#10	#6	#7

Table 14 - **RESPONSES TO SECTION 3 – Constructivists Control Group**

From an examination of the data tabulated above, it may be construed that generally, a rigid, traditional approach to the acquisition of scientific knowledge science learning was not one that these pupils felt comfortable or at ease with. These pupils seemed to value the collaborative nature in scientists working together, involvement in experiment and interdisciplinary themes, i.e., traditional aspects of science education that we did not directly associated with objectivism.

With regard to

- the nature of the scientific enterprise and
- the social context of science,

answers of all the five students - **JUN, ISABEL, MARK, LIESBETH** and **JEPPE -** to both their Pre-System Dynamics and Post-System Dynamics questionnaires revealed short, descriptive, definition-type responses placing their scientific epistemologies strictly within the boundaries of school science.

With respect to scientific reasoning and its relation to scientific problem solving,

ISABEL

> *" .... The nature of scientific thinking helps me to see things in a different dimension. .... However, this does not contribute to my career aspirations .... "*

and **JEPPE**

> *" .... I will not pursue a scientific career but the nature of scientific thinking has opened my eyes for this way of thinking in solving a wide range of problems ...."*

Although their responses generally indicated that System Dynamics had not significantly modified or influenced their impressions of the scientific enterprise, this was not clearly seen to be so with respect to the computational aspects and the social context. Both **JEPPE** and **ISABEL** indicated, however, to possessing fewer misgivings than before (prior to being exposed to System Dynamics) about the influence of scientific thinking upon their general problem-solving notions; and both **JEPPE** and **ISABEL** treat knowledge as something outside rather than inside their minds or brains.

For **ISABEL**, scientific processes and scientific methods offer certain "systematic and algorithmic" procedures - that are devoid of human feelings or emotions - and therefore can, within clearly defined limits, contribute to the solution of "humanistic and non-scientific" as well as scientific problems.

JEPPE - referring to the issues raised in the “LIMITS TO GROWTH“ and “BEYOND THE LIMITS Reports“ - was now willing to accept and appreciate a more pragmatic and meaningful perspective to the application of the formal and theoretical aspects of scientific modelling and testing than was obtained previously from his participation in traditional science lessons.

For the four students - **JUN, ISABEL, LIESBETH** and **JEPPE** - computational processes in science, on the other hand, took on a distinctly more significant meaning, as did the role of computers in the scientific process.

> *".......... Computational processes make life easier in terms of organisation and working with results ....".* **- ISABEL.**

> *".......... Computational processes represent rational, logical thinking, but in a wider perspective and in a way that is superior to the human thinking process. This makes the computer a very useful tool for gathering scientific knowledge ....".* **- JEPPE.**

> *".......... Computational processes and Information Technology enable the analysis and estimation of problems of a large magnitude like population ....".* **- JUN.**

> *".......... Computational processes involve the making and testing a model through the formation of mathematical equations and running them on a computer to test them, and thus are significant for the process of science ....".* **- LIESBETH.**

All four retained a constructivistic position with regard to this, viz., a full characterisation of computation would include a standardised characterisation of the theoretical propositions, skills and techniques that it involves. Nonetheless, one could imply from their answers, there was no indication amongst this group of students that the learning of computation and/or the appreciation of Information Technology was considered a necessity or priority in their science learning.

This could lead one lead to form a clear distinction between these students' willingness and their mindfulness of the role of the computer as a scientific tool - namely, that it cannot be assumed that because these students were mindful of the information and assistance available in the tool, they were willing to readily engage in computer-based computational activities in the course of their scientific studies.

With regards to the social context of science and its priority upon their acquisition of scientific knowledge, familiarity with System Dynamics helped to establish an appreciation of the notion of a "value-base" very firmly with three out of four of this particular group of students.

JUN and **LIESBETH** recognised the value, practicality (implying the usage of computers and computational processes) and the necessity of applying the methodologies of science to ecological and social-medical problems.

MARK, the most articulate constructivist, while ready to appreciate and acknowledge the success of scientific methodologies, does not always identify with the intrinsic nature of scientific enterprise, and regards it as only as one of several possible - albeit successful - ways towards the understanding of nature. For **MARK**,

> *"The nature of scientific knowledge is unique .... conforms to consistent methodological process .... and is quite different from knowledge human beings have acquired in non-scientific ways. ....".*

True to character, **MARK** subscribes to the constructivist view that what exists is a product of what is thought. To **MARK**, society and culture affect the output and creativity of scientific enterprise and influence the interaction between a scientist and his social environment.

MARK, who also likes to try out new things in science and to explore with the tools and concepts of the subject-matter, regarded the educational potential of System Dynamics in its interdisciplinary role, in bringing about the interrelationships among, and the interdependence of, the different aspects of scientific thinking.

To **MARK** - in his post-test answer to Question 3, Section 1 - through the processes of science, which "undoubtedly include scientific method", one can provide sufficient evidence to support a scientific theory.

For these five students, through System Dynamics, the discipline of science ceased to be a formality and an adjunct activity; they became more appreciative of the scientific enterprise and acknowledged an influence it could now exercise on their particular academic inclinations and aspirations.

4.4.3.3 Preliminary Evaluation of STUDY 3

With respect to the specific Scientific Literacy and Computer Literacy issues, one could speculate that the impact of System Dynamics upon the scientific knowledge of this particular experimental group was, to a large extent, consistent with their epistemological commitments.

All students who were considered as subscribing (in varying degree) towards an objectivistic epistemology in science learning regarded the significance of scientific method with a new perspective. As was to be expected, this view was shared, however, only exceptionally by the constructivists.

In likewise manner, appreciation of aspects of the making of a scientific model and the testing of a scientific model were seen to be readily indicated by most of the objectivists but generally by a minority of the constructivists.

There was also an indication was that some constructivists joined the objectivists in appreciating aspects of scientific problem-solving and human problem-solving manifested in the System Dynamics Methodology.

The analysis also indicated that with notable exceptions, i.e., by the self-professed non-scientists /non-technologists - all acknowledged the role of the computer as a scientific tool and, therefore, its capability and value in imparting scientific knowledge.

4.4.3.4 Interpretations of Answers from Section 3 in Light of the Answers from Section 4

The analyses and interpretations in the above-mentioned sections do not provide a unitary picture that could be summarised along one single dimension. However, with respect to the concepts and mechanisms of System Dynamics, there are features and impressions which all students share, regardless of their epistemological commitments.

“The relevance of the System Dynamics Methodology towards the meaning of scientific thinking to me is that the methodology helps me to understand the problem, or focus on the root of the problem, even though the problem issue can be very complicated. .... System Dynamics can be quite useful in Biology because Biology is related to social issues.“ **- JUN.**

“I found learning about System Dynamics very interesting, although it was actually not completely new to me; it did emphasise the holistic approach to solving problems irrespective of their nature. .... My appreciation of ‘scientific thinking’ was not really influenced by these lessons, because we got taught only the basics of System Dynamics, which is not enough to affect my way of life or approach to science. This goes also for my appreciation of scientific method. .... It would be a good idea to integrate System Dynamics into our science lessons.“ **ISABEL.**

“I believe that learning about the System Dynamics Methodology would be an advantage in Biology and Geography lessons since I can understand how one can apply the system’s approach to problems. But I do not really see how one can use the methodology in science - this is because I still do not know all that much about it. I think it would be best to integrate it into our Theory Of Knowledge course where it would be possible to develop a general understanding of the methodology and so the student would appreciate as a way of thinking.“ **JEPPE.**

“Although we only touched upon the System Dynamics Methodology, I believe that System Dynamics has the potential to be a significant part of the scientific processes in the future. It entails certain aspects that are both similar to and different from scientific method, but its advantage is that it takes into account every aspect and factor when solving a problem. Since this methodology is only useful to scientists and experts who have the knowledge to utilise it, it should be integrated it our science learning program at an elementary level.“ **MARK.**

“The System Dynamics Methodology made me think of science in a different way. Learning science in school is trying to remember laws

> *and equations, while one should actually learn how to solve a problem."* **LIESBETH.**

Invariably all the students above strongly indicated, however, that System Dynamics can/did bring a considerable amount of scientific meaning and significance (including valuable knowledge) into conventional science-learning environments. They differed only - apart from their commitments on the dimensions of epistemology - upon the degree to which they believed that this could be meaningfully, perhaps effectively, implemented and achieved.

To **JUN**, **ISABEL** and **JEPPE,** who clearly held on to a constructivistic view of nature, of science and of scientific knowledge acquisition, scientific knowledge is a matter of course. To a large degree, they also hold some aversions to the mathematical and computational aspects of science which, consequently, impede their motivation for further involvement with the Pure Sciences. For these three, science is linear and unidimensional, to be learned using the textbook as reference and the teacher as guide.

ISABEL saw difficulties in either trying to find a role for, or logistically "to fit" System Dynamics into her current program of studies. Nevertheless, both **ISABEL** and **JUN** found it easier to articulate and to characterise their scientific impressions and to articulate their thoughts in answering (particularly Section 1) the second time round, i.e., after the System Dynamics sessions - this would indicate a significant tendency of System Dynamics' structuring notions to clarifying and/or illuminating aspects and notions of scientific processes and method.

JUN, **ISABEL**, **JEPPE and MARK**, however, recognised and acknowledged some significant potential and value for System Dynamics in a modified Scientific Studies program. In effect, **JUN**, **ISABEL** and **MARK** were made to reflect upon and to report that aspects of System Dynamics had positively influenced their tacit scientific knowledge accumulated previously. **LIESBETH** was not forthcoming with either outright positive or negative impressions.

While **MARK** subscribed strongly to constructivistic thinking, **LENNARD, NIKHIL** and **THOMAS** distinctly prefer objectivistic learning environments. However, were System Dynamics to be integrated as a formal course within their program of studies, it would be enthusiastically received by all the four of them.

The three **LENNARD, NIKHIL** and **THOMAS** regarded it as encouraging the type of creative thinking and understanding they associated with science. They recognised that inclusion of the System Dynamics methodology into their science-learning program would raise the possibility to exercise greater control of what to investigate and, therefore, encourages emancipatory interests in their science learning.

> *"The reductionist approach to science does not allow ideas and processes to be transferred to social issues. Only the science that is done for the human being and his welfare are applied, such as pollution control and manufacturing efficiencies. System Dynamics can assess social issues through scientific method. By development of causal-loop diagrams, different components affecting the preliminary problem can be introduced. Hence the relationship between these can be methodically assessed using the computer."* **LENNARD.**

> *"Most of the scientific knowledge acquired during school tends to get forgotten and not carried over after time at school. Learning practical scientific thinking, on the other hand, would enable one to use such science in other fields. In this context System Dynamics comes in useful. It is, however, important to build a solid fundamental base of scientific knowledge before applying it to the real world. System Dynamics does this and, through the use of computers and computing is very useful for general problem solving even though it may not be directly related to scientific problem solving as we know it."* **NIKHIL.**

> *"The impression that I got from the System Dynamics sessions is that we could apply the knowledge acquired in our regular science classes to social, economic and environmental problems with the help of very powerful concepts. .... We saw very clearly how we can use System Dynamics to predict, to change factors - through the rabbit-fox problem - but it was very difficult to see how we could use it to discover new theories. .... One can use rates and amounts to express knowledge in different branches of science but with a common language so that we can see how they relate and interact. .... Perhaps this may be the way one could discover new knowledge."* **THOMAS.**

For **NIKHIL** System Dynamics provides the unique opportunity at this level to be involved with scientific problem-solving with a computer;

nevertheless, he distinguishes (and recognises a difference) between solving school-science problems with the help of computers from Scientific Computation. For these three students **LENNARD**, **THOMAS** and **NIKHIL**, a congenial and social aspect of learning is group work, and three or four minds thinking together are undoubtedly better than one mind thinking by itself; thus, they recognised and welcomed the potential of the emergence of alternative hypotheses, interpretations and discussions to becoming the keys to resolving issues, and the role of a System Dynamics study in complementing co-operative learning and in promoting co-operative skills (WATSON 1991). This sentiment was most forcibly expressed in **THOMAS**'s post-test responses.

All three also considered scientific reflection, which plays a very important part in their learning since it allows them to think creatively and to make connections to real-life applications of the concepts and ideas they learned, to be realisable through System Dynamics.

> *“System Dynamics gave me the approach and enabled me to be conscious about, to deal with and to use the sublime knowledge that I already had. “* **GORO**

> *“Through System Dynamics I had a greater appreciation of what science is really all about. More emphasis on methods of fields of knowledge was made and not so much on facts. This enables you to see what you are learning with a broader view. .... I also appreciated the significance of computers and programming. I do not think that System Dynamics should be taught as a separate subject, but it is essential that scientific method and how scientists work should be formally treated.“* **NOA.**

GORO, **NIKHIL** and **NOA** also share a markedly objectivistic attitude to learning science. While, **NIKHIL** and **NOA** recognised significant potential in the integration of selected, key aspects of System Dynamics as a way of enhancing their scientific education, **GORO** tended to be relatively constrained with their positive reactions.

All the constructivists (except for **JEPPE**) indicated that they were able to appreciate the cross-disciplinary, scientific characterisations of the methodology, i.e., the potential extensions and applications of the methodology into the various 'sciences'. Consequently, they were also able to regard science not just as being compartmentalised into Physics, Chemistry or Biology, but also having in common a cross-disciplinary scientific way of thinking. However (except for, perhaps, **MARK**), cross-disciplinary science-learning through System Dynamics was not held to be of particular significance or importance to this group.

On the basis of the information gathered from the questionnaire - as well as from informal conversations with the students - and from the flow of the sessions, it may be claimed that knowledge of the mechanisms of System Dynamics appear to have a significant, distinctly positive, influence upon

- their understanding/recognition of scientific method,
- their understanding/appreciation of scientific modelling,
- their appreciation of the computer as a scientific tool, and
- their appreciation of the collaborative/social aspects of scientific enterprises.

From an analysis of the information, the structuring principles inherent in the System Dynamics methodology could be seen to be instrumental in establishing a conceptual bases for delineating features of scientific method. Scientific modelling issues took on more significance, as did the acceptance of the role of the computer as a tool for learning and thinking scientifically.

A clear appreciation and/or acknowledgement of the computer as a scientific tool was indicated. With reference to the aspects of computing and computational activities - the latter of which introduced a mathematical dimension - in System Dynamics, in particular, an "unsettling" factor was observed to be shared among the non-scientifically inclined members of the group, viz., **JUN**, **ISABEL**, **MARK** and **JEPPE**.

However, they could be seen to more comfortably relate to the humanistic and social applications of the System Dynamics Methodology and this could be indicated by the degree with which features of and interaction with System Dynamics modified their priorities. A positively concrete comprehension, however, as well as an appreciation, of the concept of "computation" and the computational aspects of science learning was also evident from the observations, but most clearly among the more "scientifically-oriented and mathematically-oriented" students.

System Dynamics also seems to have provided the means to providing a clearer resolution between the 'systems/holistic' and 'reductionist' approaches to scientific investigations.

Uniformity of results derived from the answers to the questionnaire submitted by these four students was, on the whole, not distinctly evident - due, in most part, to the localised, isolated nature of the data source. However, these particular students’ perception of science as a way of thinking and as a way of looking at/solving problems, and not always and necessarily as three separate independent disciplines, was clearly being sharpened. This was particularly observable from the improved quality and nature of the answers provided.

Generally, all the students described their experience of the methodology of System Dynamics - presented in this particular manner - and its potential integration into a Scientific Studies program in a distinctly positive light, irrespective of their epistemological commitments. This would seem to suggest that their knowledge of the nature of System Dynamics was instrumental in contributing significantly or making modifications to their scientific epistemology. They also all indicated, in favourable terms, that they had encountered an alternative way of thinking in science and of doing science in, what could be construed to be, a (more) meaningful way. Discussion of "causal-loop" analysis and feedback processes revealed that, apart from the concept of "homeostasis" introduced in Biology, feedback process thinking, viz., teleological reasoning, as presented through System Dynamics had been a missing element in their scientific thinking, had not been appreciated as a powerful scientific tool, but this dimension was now made available through System Dynamics.

System Dynamics was also powerful in its socio-scientific dimension, and had cross-disciplinary experiential and social assets. Also, System Dynamics had significant motivational value, seems to lead to a better understanding and appreciation of the scientific enterprise, and science to them took on a broader perspective. This features as the most distinct preliminary outcome of the survey.

4.5 Concluding Remarks

From the results and analyses presented above, the potential of successful integration of System Dynamics into a Scientific Studies programme is observed to be extremely good, since the degree of receptivity was distinctly positive. Amongst a group of academically-oriented students exhibiting strong scientific and/or technological orientations and interests, a clearer and closer identification with the underlying principles and mechanisms of the System Dynamics methodology, than amongst those harbouring non-scientific university and/or professional aspirations, is to be observed.

In contrast, for those pupils whose involvement with aspects of the canonical science through their formal programmes of study - and as prescribed by traditional syllabi - has not met with the desired degree of success, System Dynamics has been acknowledged as being able to offer a scientific environment and scientific methodology that a significant number of these particular students can identify with.

From a learning perspective, those strongly academically-oriented science students subscribing towards an objectivistic epistemology clearly favoured, and were observed to regard the integration of System Dynamics within their scientific studies - viewing this as contributing significantly towards their scientific and computer literacy - in a more positive light than those students adopting a constructivistic standpoint. On the other hand, the integration of System Dynamics within a formal Scientific Studies program - particularly for learners who do not harbour strong scientific and mathematical inclinations and aspirations - can be a means of meeting specified, higher-level Scientific Literacy and Computer Literacy objectives. The appreciation and/or acknowledgement of scientific method is generally recognised as an inherent feature in the application of its methodology.

The clear indications are also that in a computer-based, cross-disciplinary instruction context, the mechanisms of System Dynamics/ DYNAMO have the potential to function as scientific tools for conviviality (ILLICH - see Chapter 3) par excellence through the use of their formulation capabilities, information processing and communicating resources.

5 Summary and Discussion

As first step in this study, Scientific Computation Literacy was conceptualised and developed as a means of achieving - in a meaningful, purposeful and comfortable manner, and primarily from a learner's perspective - specific Scientific Literacy and Computer Literacy objectives. The scientifically-oriented characteristics and computer-based resources of the System Dynamics methodology were suggested to provide the mechanisms by which our notion of Scientific Computation Literacy may feasibly be promoted.

A preliminary requirement that needed to be met was the establishment of the significance of scientific computation in the curriculum, i.e., the domain and processes encompassing Scientific Computation Literacy, the educational issues inherent in the learning of the scientific content and the computational features underlying our notion of scientific computation, and the role of System Dynamics within such mechanism. The following diagrams - Fig 5.1 and Fig 5.2 - define our domain of Scientific Computation Literacy and illustrate the structural features of how the mechanisms of System Dynamics were conceptualised and developed to achieve the objectives of Scientific Computation Literacy, respectively.

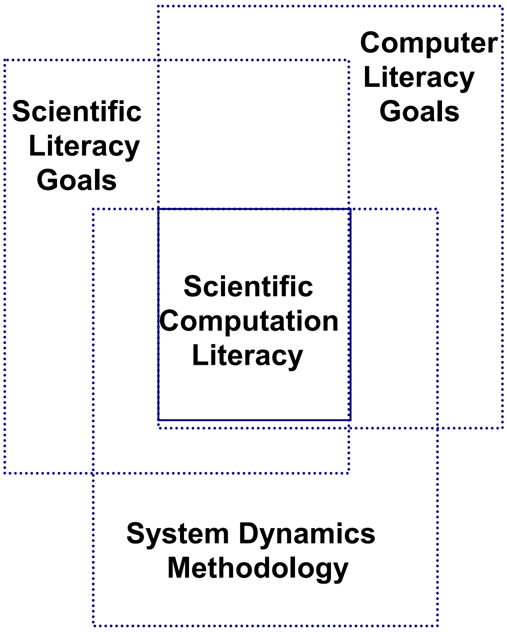

Fig. 5.1 The Domain Of Scientific Computation Literacy

In **Fig. 5.2**, 1 outlined the operating domain within which traditional Scientific Literacy and Computer Literacy objectives - pitched at our particular (pre-university) level - may be defined, and which was to be modified to include the notion of Scientific Computation, the interaction with System Dynamics and the development of Scientific Computation Literacy. The appreciation and/or promotion of scientific reasoning and algorithmic thinking skills are considered desirable goals within Scientific Computation Literacy. 2 designates the path taken by the “Glass-Box“ approach hypothesised and adopted in this study in contrast to 3 - the path considered to be taken by the “Black-Box“ approach and underlying systems such as STELLA, MODUS and others. A particular learning environment envisaged in terms of the objectivistic-to-constructivistic inclinations of science learners was conceptualised to assess the degree of receptivity of System Dynamics in science learning. These particular features of the study characterised the content of CHAPTER 1.

In CHAPTER 2, the parallels between the scientific component of System Dynamics and aspects of scientific method were explored in an intuitive and tacit basis. Scientific problem-solving was shown to be promoted through the development of constructive and intuitive intellectual strategies and on the organisation of information that are inherent in System Dynamics. The framework for such organisation, drawing on elements of systems thinking - in contrast to reductionism that characterises much of current science education - and upon structuring principles derived from elementary Cybernetic science metaphors and techniques, was observed to provide the process and the interlocking concepts as well as a solid support for diversity.

The development of an educational value-base was considered in the light that any innovation in science education, seeking to provide learners with intellectual abilities and social values relevant to the scientific world of the future, encourages respect for nature and society and precludes the pursuit of ideas that could possibly be dangerous in their wider context. As such is suggested a scientific methodology that looks at the whole as well as the parts, and at qualities as well as quantities, and one that cultivates the intuitive as well as the analytical way of pursuing knowledge.

The resources provided by the “LIMITS TO GROWTH“ and “BEYOND THE LIMITS“ reports - based on information acquired through application of System Dynamics - were seen as appropriate and significant in this respect. Scientific reasoning skills are, consequently, regarded to have significant potential for development through the learning and adoption of an alternative approach, and further research to assess the magnitude of such potential may be of particular interest.

In CHAPTER 3, computational skills have the potential to be acquired through the model-verification, debugging and model-validation procedures that form the rudiments of the computer simulation procedure. The role of the computer as a tool and as a synthetic laboratory, the activity of programming and the domain over which the programming language DYNAMO operates is clearly defined. In contrast to PASCAL and LOGO, DYNAMO - being a special-purpose, functional-programming language - provides an environment which offers a good chance of exposing the algorithmic and the computational sequences - and, thereby, narrowing down the problem-solving task - and which is created through the employment of a communication system which is simple to learn, easy to use and designed for the task. The underlying algorithms and their formulations are tried out through concrete examples form Biology, Chemistry and Physics. Here again, a scientific computation culture, in which algorithmic thinking processes can be promoted through the conjunction of programming activity and manipulating and visualising scientific data - in distinct contrast to the shifting of the focus of the computer culture from programming to the manipulation of simulations - characterises the computing environment; further research as to the extent to which this can be realised could also provide valuable information.

In the attempt to assess the degree to which involvement with the mechanisms of System Dynamics - presented as an adjunct to a regular scientific studies program - can influence pre-university science learners' personal attitudes towards computer-oriented science learning and their epistemological commitments, the empirical surveys in CHAPTER 4 indicate that no distinct visions could be gleaned. There were, however, clear indications to suggest that:

- amongst learners harbouring a negative or unhappy association with conventional science education, System Dynamics has strong potential to revitalise their involvement with science learning and to modify their attitudes towards science in a particularly positive manner;

- particularly amongst academically-oriented learners, specific scientific literacy notions - scientific method and scientific problem-solving through modelling in particular - and computer literacy objectives - such as the appreciation of computer as a tool and the significance of the computational process - were made significantly more visible and/or, respectively, more appreciative as a result of interaction with System Dynamics; some clearly acknowledged the role of computers in making inductive solutions possible or easier.

- academically- and scientifically-oriented learners - in particular those subscribing to an objectivistic epistemology - consider the intrusion of System Dynamics as a potentially powerful influence and a significantly positive development in their scientific studies.

We regard that the principal contribution of the studies in chapters 2, 3 and 4 has been to demonstrate the potential and role of System Dynamics in providing the learner/instructor of Scientific Computation with a skeleton/structure which can be fleshed out for acquiring deeper insight into rudiments of scientific method and of the significance of the process of computation in the application of scientific reasoning. We also regard the potential of System Dynamics to be productively integrated into any scientific studies program at a pre-university level as high. Finally, a further contribution of this thesis has been to highlight the non-changing role of a specific aspect of computer literacy but the continued modification of some scientific literacy objectives.

Computer-oriented prospects and, therefore, the further development of such a mode of the computational activity with respect to other relevant aspects of upper secondary school/tertiary level science learning, are being considered to remain one of the key features within the realm of the Laboratory Work Station 2005 – see **Fig. 5.3** below – which is envisaged to be forming the bases of a digitally-relevant science curriculum for the foreseeable future. Amongst the future trends with respect to Information Technology integration towards the potential enhancement of science learning, the following educational resource facilities and technical developments are immediately recognisable:

- Hardware and software becoming more sophisticated and powerful.
- The availability of Data-logging and Sensing capabilities.
- The versatility of laptops and palmtops.
- The dimension of Virtual Science Laboratories and Dry Laboratories.
- Networks as the normal in institutions.
- The Internet.

The impact and the outcomes of these on the cognitive, socio-cultural and scientifically-oriented development of the science learner and upon her/his scientific and computer literacy need to be further investigated if applications of Information Technology are to be constructively and resourcefully integrated within a digitally relevant and meaningful science curriculum.

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APPENDIX A

Questionnaire

NAME ....

International Baccalaureat (I.B.) Subject(s) - please underline

BIOLOGY	CHEMISTRY	PHYSICS
Higher/Subsidiary	Higher/Subsidiary	Higher/Subsidiary

THIS QUESTIONAIRE COMPRISES THREE SECTIONS:

SECTION 1.

In this section you are asked to lay bare your personal perceptions on the significance/quality of the "scientific" knowledge that you have acquired through your regular I.B. Higher and/or Subsidiary Level Science (Biology and/or Chemistry and/or Physics) lessons so far - and in conjunction with:

- the Theory Of Knowledge lessons (Natural Science section) - in Pre-Test questionnaire
- the System Dynamics lessons - in Post-Test questionnaire:

by answering the following open-ended questions as sincerely and as elaborately as you possibly can.

1. What do you appreciate/understand by the "nature of scientific knowledge"?
2. What do you appreciate/understand are the objectives of "scientific problem-solving" ?
3. How do you think that the "process of science" (can) lead(s) to the "development of scientific theories" ?

4. In what manner are scientific processes and scientific knowledge employed in problem-solving and decision-making in relation to social issues ?

5. What significance do "computational processes" bear upon the processes of science ?

6. What impact does Information Technology have upon the acquisition of scientific knowledge ?

7. What impact does the acquisition of scientific knowledge and the "nature of scientific thinking" have upon your aspirations to pursue a scientifically-oriented career after your time at this school ?

SECTION 2.

In this section you are asked to give a personal assessment of the contribution made by:

- the regular International Baccalaureat Science and Theory Of Knowledge lessons - in Pre-Test questionnaire
- the regular International Baccalaureat Science and System Dynamics - in the Post-Test questionnaire

towards your comprehension and/or understanding of the following selected aspects of scientific knowledge. Read each aspect carefully. If you think/believe that the contribution of the lessons was of NO USE to you circle the number 1. Circle 2 if the contribution is believed to have been SLIGHTLY USEFUL. If the contribution is believed to have been USEFUL, circle 3. If the contribution is believed to have been VERY USEFUL, circle 3. Circle 5 if the contribution is believed to have been EXTREMELY USEFUL.

The contribution of the lessons to my appreciation of:

1. the "scientific method" has been	1	2	3	4	5
2. the common, interdisciplinary principles characterising the pure sciences (Biology, Chemistry, Physics) has been	1	2	3	4	5

3. the difference between the "reductionist" and the "holistic" scientific approaches has been
1 2 3 4 5

4. the significance of cause-and-effect feedback process and thinking has been
1 2 3 4 5

5. the impact of scientific knowledge on environmental issues has been
1 2 3 4 5

6. the significance of the "making of a scientific model" in scientific investigations has been
1 2 3 4 5

7. the significance of the "testing of a scientific model" in scientific investigations has been
1 2 3 4 5

8. the significance of scientific problem-solving has been
1 2 3 4 5

9. the significance of scientific decision-making has been
1 2 3 4 5

10. the significance of scientific experimentation has been
1 2 3 4 5

11. the significance of formulating a scientific algorithm has been
1 2 3 4 5

12. the significance of the process of scientific computation has been
1 2 3 4 5

13. the role of the computer as a scientific tool has been
1 2 3 4 5

14. the significance of a simulation experiment has been

1 2 3 4 5

15. the role of the computer in imparting scientific knowledge has been

1 2 3 4 5

16. the structure of scientific knowledge has been

1 2 3 4 5

17. the relationship between human problem-solving and scientific problem solving has been

1 2 3 4 5

18. the social/collaborative aspect of scientists working together has been

1 2 3 4 5

19. the role of the teacher in imparting scientific knowledge has been

1 2 3 4 5

20. the "fun" aspect of doing/learning science has been

1 2 3 4 5

SECTION 3

Please rank the top five aspects of Science Learning that you believe or consider to be of most significance. Use SECTION 2 to make your selection, and explain the reasons for your selection - and, if possible, the ranking.

SECTION 4

Please explain what you believe has been (or to be) the actual (or potential) contribution, or relevance and significance of the System Dynamics Methodology towards the meaning of "scientific thinking" and towards your appreciation of the processes of Science and of Scientific Method. Explain this in relationship to the (possible) integration of the System Dynamics Methodology into your science learning programme.

APPENDIX - B

Theory Of Knowledge - Programme Details

- Systems Of Knowledge: Natural Science

- Why are the Natural Sciences regarded today by many people as the paradigm of all knowledge ?
- What is meant by the Scientific Method ? How is the method traditionally described in science textbooks ? Is this depiction an accurate model of scientific activity or could it be a distortion ?
- What is the role of inductive and deductive reasoning in scientific reasoning, prediction and explanation ?
- What are the various components of the context within which a scientist works ?
- How does the social context affect the questions and results of the scientific enterprise ?
- What is meant by the "paradigm shift" ?
- What role do experiments, hypotheses, models and theories play in scientific investigation ?
- What is the demarcation between scientific and pseudo-scientific knowledge claims ?
- Is scientific knowledge progressive ? In what sense ?
- What can be meant by the assertion that science as a method is self-correcting ?
- Should science be regarded as a method or a body of knowledge ?
- Is science valued largely because of its ability to predict and/or because of its technology ?

- Are the models and theories that scientists use merely pragmatic instruments or do they actually describe the natural world ?
- In what way, if any, should the methods of natural science be exemplars for the social sciences ?
- Is there necessarily a conflict between science and religion ?
- What are the moral dimensions of scientific pursuits and the application of scientific knowledge ?
- What are the consequences of scientific discoveries for politics ?
- How does language help or hinder scientific pursuits ?

APPENDIX C – Predator-Prey Model 1

```
PAGE-6      MENDES PREDATOR-PREY MODEL 1

  TIME     RABBT      FOX
  E 00      E 00      E 00

 0.0000   100.00    10.000
 0.1700   109.66    21.334
 0.3400    90.89    43.680
 0.5100    48.88    67.756
 0.6800    19.34    75.926
 0.8500     7.47    71.448
 1.0200     3.26    62.967
 1.1900     1.66    54.190
 1.3600     0.99    46.199
 1.5300     0.67    39.221
 1.7000     0.50    33.229
 1.8700     0.42    28.123
 2.0400     0.38    23.789
 2.2100     0.36    20.119
 2.3800     0.37    17.014
 2.5500     0.40    14.392
 2.7200     0.45    12.178
 2.8900     0.52    10.310
 3.0600     0.62     8.736
 3.2300     0.76     7.411
 3.4000     0.95     6.297
 3.5700     1.21     5.362
 3.7400     1.55     4.580
 3.9100     2.03     3.929
 4.0800     2.67     3.391
 4.2500     3.54     2.950
 4.4200     4.74     2.597
 4.5900     6.37     2.324
 4.7600     8.59     2.126
 4.9300    11.62     2.006
 5.1000    15.74     1.972
 5.2700    21.32     2.045
 5.4400    28.81     2.271
 5.6100    38.72     2.740
 5.7800    51.46     3.649
 5.9500    66.97     5.438
 6.1200    83.48     9.142
 6.2900    94.98    17.051
 6.4601    89.34    32.426
 6.6301    61.05    53.007
 6.8001    30.35    66.145
 6.9701    13.31    66.943
 7.1401     6.13    61.209
 7.3101     3.19    53.669
 7.4801     1.90    46.233
 7.6501     1.28    39.509
 7.8201     0.96    33.629
 7.9901     0.79    28.565
 8.1601     0.71    24.237
 8.3301     0.68    20.556
 8.5001     0.69    17.433
 8.6701     0.74    14.789
 8.8401     0.82    12.553
 9.0101     0.95    10.666
 9.1801     1.12     9.076
```

```
PAGE-7      MENDES PREDATOR-PREY MODEL 1

  TIME     RABBT      FOX
  E 00      E 00      E 00

 9.3501     1.37     7.738
 9.5201     1.70     6.616
 9.6901     2.14     5.679
 9.8601     2.75     4.899
```

APPENDIX C – Predator-Prey Model 2

```
PAGE-7     MENDES PREDATOR-PREY MODEL 2                                RUN-RERUN

   TIME    RABBT      FOX
   E 00     E 00     E 00

 0.0000   100.00   10.000
 0.1700   118.01   10.732
 0.3400   135.58   13.427
 0.5100   145.64   19.013
 0.6800   138.70   27.542
 0.8500   114.12   34.917
 1.0200    87.16   35.183
 1.1900    70.17   29.200
 1.3600    63.66   21.885
 1.5300    64.79   16.023
 1.7000    71.68   12.139
 1.8700    83.49    9.959
 2.0400    99.73    9.207
 2.2100   119.30    9.916
 2.3800   138.95   12.641
 2.5500   150.97   18.561
 2.7200   143.82   28.148
 2.8900   115.80   36.802
 3.0600    85.43   37.053
 3.2300    67.09   30.094
 3.4000    60.39   21.935
 3.5700    61.66   15.618
 3.7400    68.81   11.527
 3.9100    81.06    9.241
 4.0800    98.07    8.391
 4.2500   119.06    8.956
 4.4200   141.14   11.494
 4.5900   156.46   17.406
 4.7600   151.21   27.894
 4.9300   120.40   38.493
 5.1000    85.44   39.532
 5.2700    64.65   31.741
 5.4400    57.06   22.554
 5.6100    57.99   15.578
 5.7800    64.97   11.129
 5,9500    77.18    8.629
 6.1200    94.49    7.586
 6.2900   116.50    7.881
 6.4601   141.07    9.984
 6.6301   161.13   15.367
 6.8001   161.22   26.168
 6.9701   129.83   39.395
 7.1401    88.65   42.782
 7.3101    63.42   34.601
 7.4801    53.86   24.103
 7.6501    53.79   16.118
 7.8201    60.02   11.067
 7.9901    71.60    8.200
 8.1601    88.50    6.059
 8.3301   110.76    6.774
 8.5001   137.27    8.226
 8.6701   162.82   12.494
 8.8401   172.65   22.365
 9.0101   146.53   38.095
 9.1801    97.97   46.510
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PAGE-8     MENDES PREDATOR-PREY MODEL 2

   TIME    RABBT      FOX
   E 00     E 00     E 00

 9.3501    64.73   39.326
 9.5201    51.30   27.212
 9.6901    49.24   17.639
 9.8601    54.03   11.571
```

APPENDIX D

STUDENTS' RESPONSES - PILOT STUDY

(1) JESPER B. - Sweden.

"I think that a topic like this will give one a deeper insight into many different fields and usages that we have not touched upon before. A topic like this can be useful in any sort of job in the future. I can see almost only merits in a topic like this. .... The problem is that the topic is so new that it may not have had time to develop fully. .... Since I, most probably, will be studying Business Administration in the future, I think that this is a suitable topic, and it was fun and interesting."

(2) ALISTAIR D. - South Africa.

"When studying a topic like System Dynamics, I found that it taught you a better way to look at problems. It taught you what causes these problems, and that there is not only one problem within a problem but many problems. .... I do not understand the follow-up question - I do not think there are any problems."

(3) MYRA D. - Philippines.

"Using computer diagrams, charts or graphs may help us deal with problems of the future, or help us prepare for them, which may be our solution. But depending too much upon these graphs, diagrams or charts may lead us away from letting us deal with the present problems which are now rising. Some of the present problems may come up with their own solution. I think that we should just let things be."

(4) CORD H. - Germany.

"In my opinion, this particular course looks closer at real world problems and not only at scientific formulae as in Physics, Chemistry and Biology. These three subjects are interesting in their own way; we can study about a wider variety of subjects, like computers, which we would never be able to study in any of the main (science) courses."

(5) HANS H. - Germany.

"What I liked about this course is that one learns a lot about matters that everybody should learn today. .... It makes a lot of things clearer and better to understand. .... It was, more or less, the first science course that I could relate to and it was fun."

(6) DETMAR v H. - Germany/USA.

The problems and merits that I can see so far in studying about System Dynamics is that it is confusing in many aspects. Even though the "Limits To Growth" is an important topic, and I think it should be brought up, it should be taught in a different form."

(7) JACQUELINE H. - Holland.

"Science was not really my favourite subject. .... It is, however, interesting to study about the problems in the world and how to solve them, which is very difficult because I had never thought about them and it is nice to learn how to study about them. .... At the beginning, I thought that this was a very nice subject, but now I have found that it looks much easier than it really is."

(8) TRACY H. - USA.

"I think that this is a good topic, but there is not enough written work. .... There must be a lot of discussion but, in my opinion, also more written work."

(9) CAMILLA K. - Holland.

"This topic is not one of my favourites since we do not do anything that makes any sense to me. If we could do something like cooking or energy, it would be more interesting. I am not a very good student when it comes to science and, definitely, very shy when it comes to talking in class."

(10) RAHIM K. - Iran.

"I think the topic of System Dynamics would help us understand the dangers of pollution much better, and how to solve such problems; and the problems that we do not know or have heard about. It teaches us how to make life for our children, or the future generation, better and more comfortable."

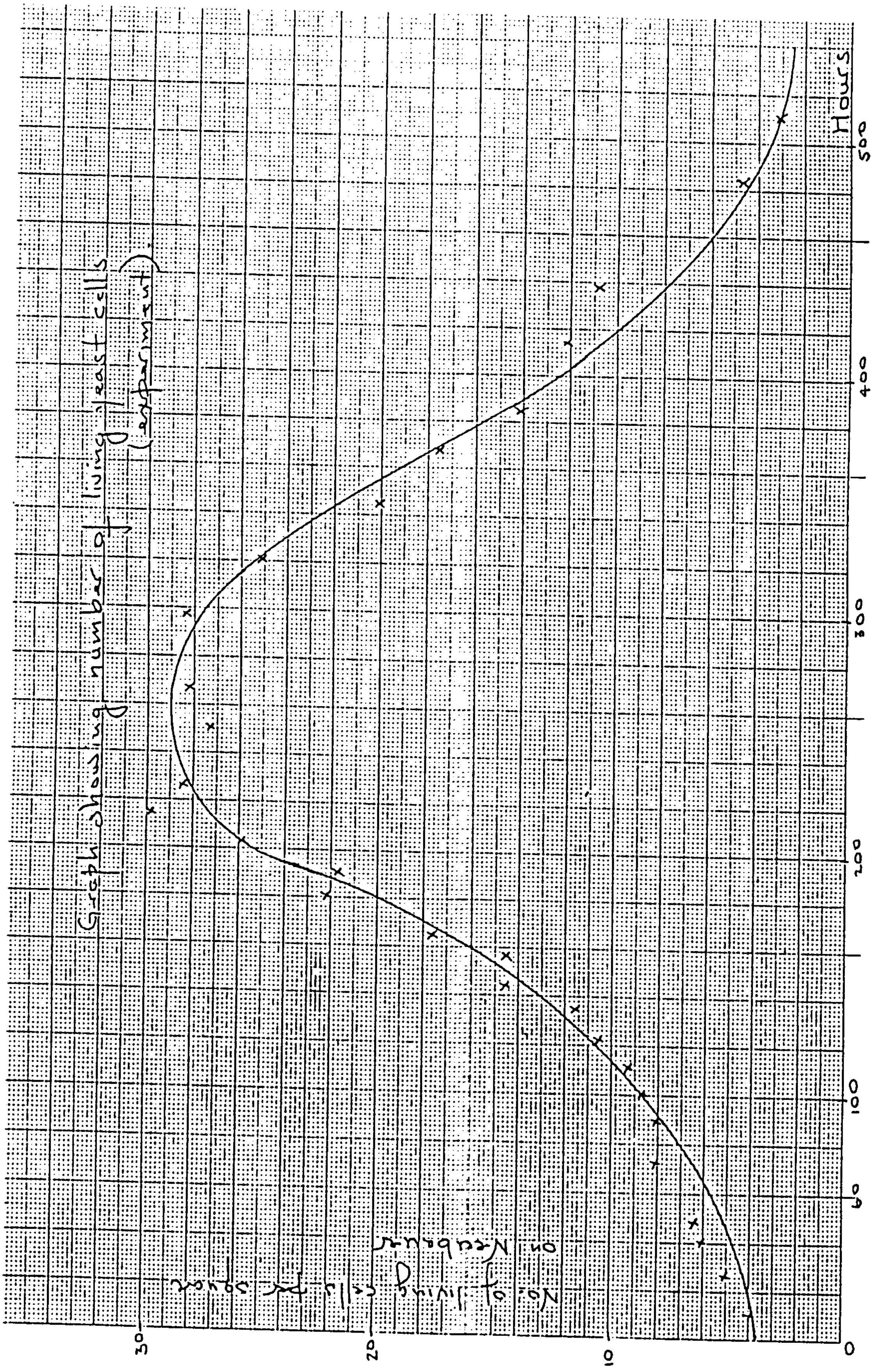
(11) YURI P-B. - Germany.

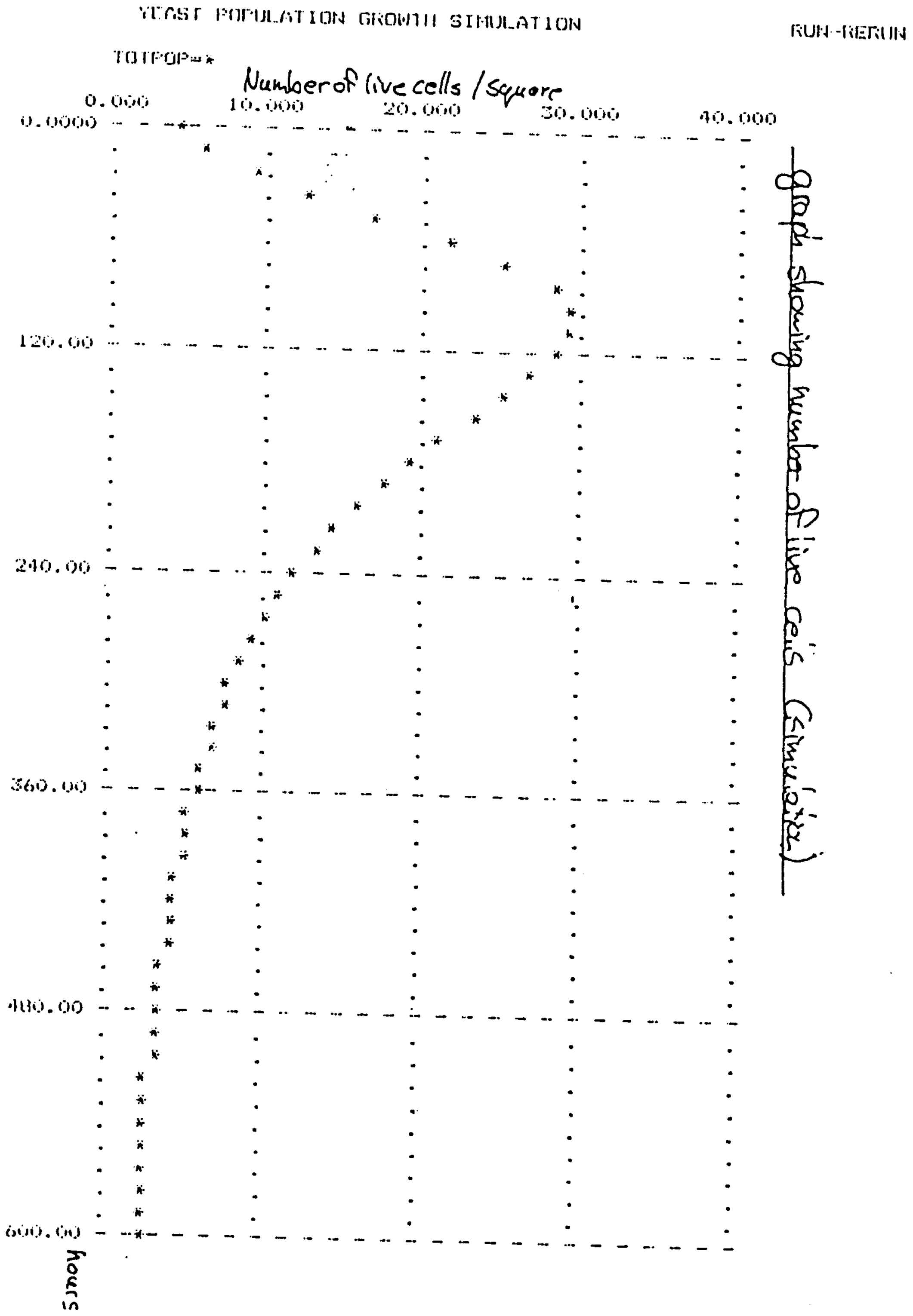
"I liked this topic because it was very different but it is also a bit strange. .... It is relatively interesting even though it was not as easy as I first thought. .... It was even the first time that I had heard about this business with feedback control, exponential growth, system and so on. It was brand new for me and it was some kind of an adventure to find new ways of looking at things. .... But I do not know why you taught us this topic or this kind of science, as I will not deal with this later on in life. I know we have a lot of problems in the world, but do we need to know that this kind of work to come to an answer ?"

(12) ANGELIQUE Z. - USA.

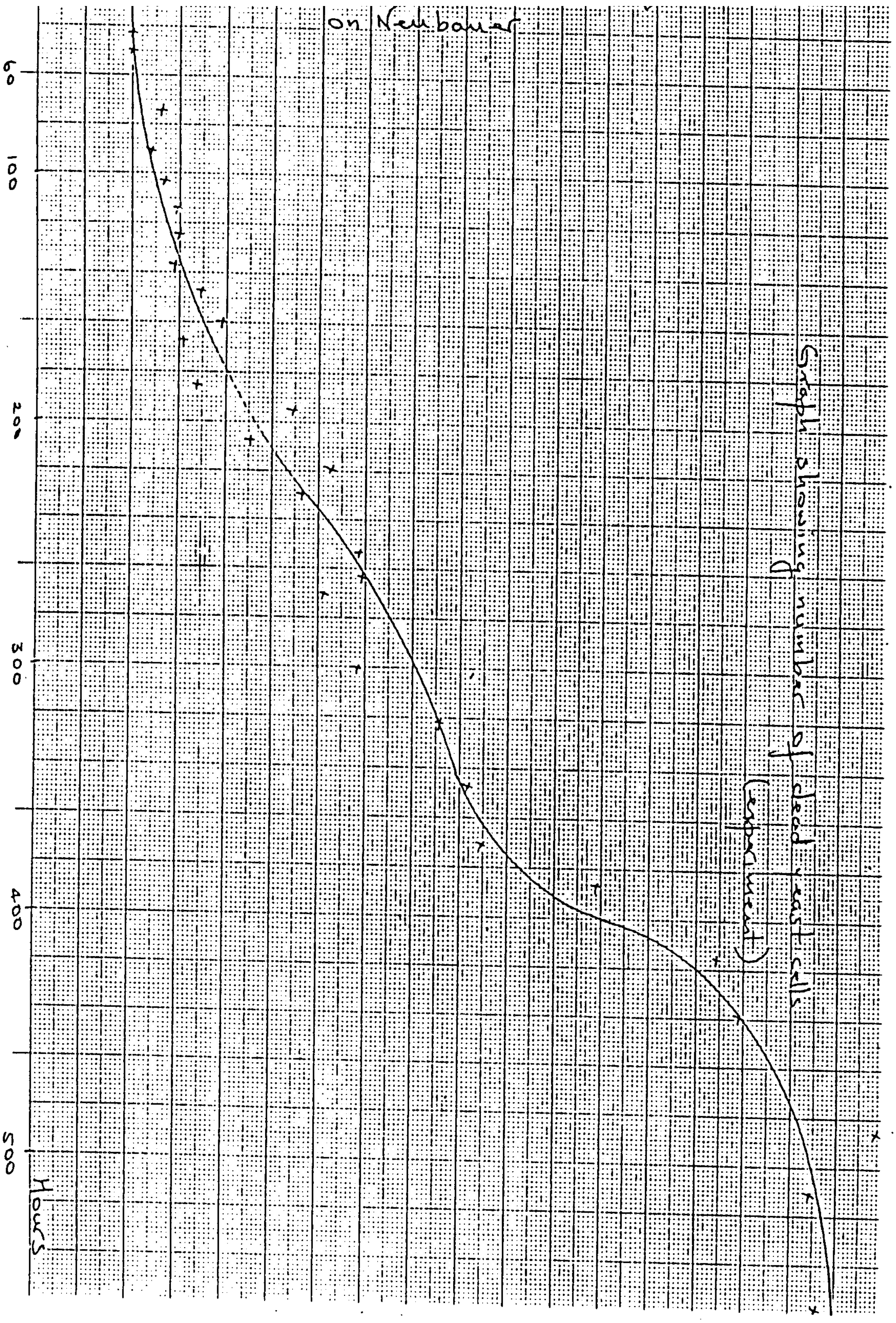
"The System Dynamics course is very confusing for me. It does help me to have a better understanding of how a scientist goes about solving major problems, but it is very hard to understand. It was a very good class though and it helped me a lot."

APPENDIX E1 - Experimental Outputs, Working Models and Simulation Runs – MARCO's Project


Graph showing number of living yeast cells (experiment)
No. of living cells per square on Neubauer
Hours
0
10
20
30
0
60
100
200
300
400
500

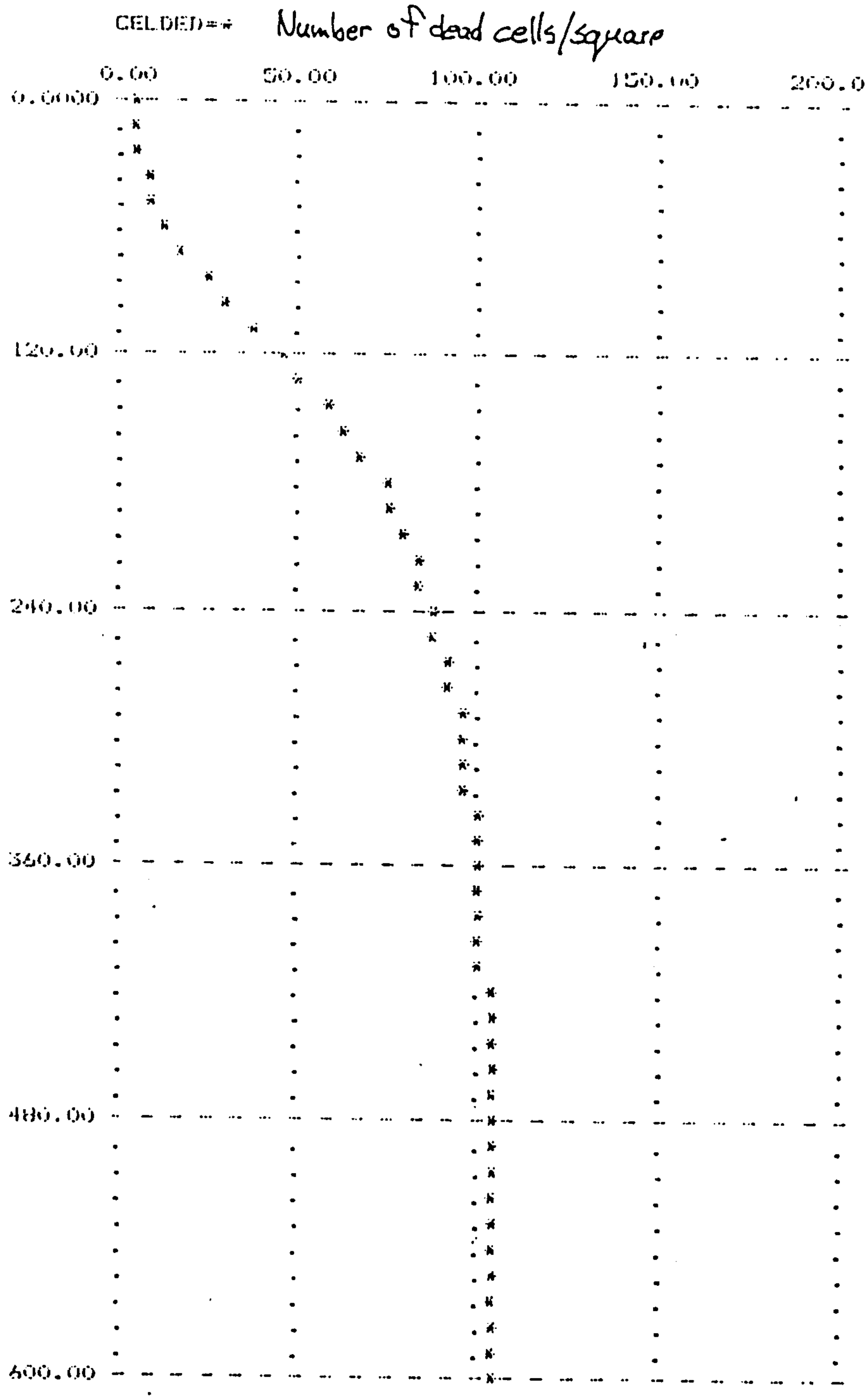


graph showing number of live cells (simulation)

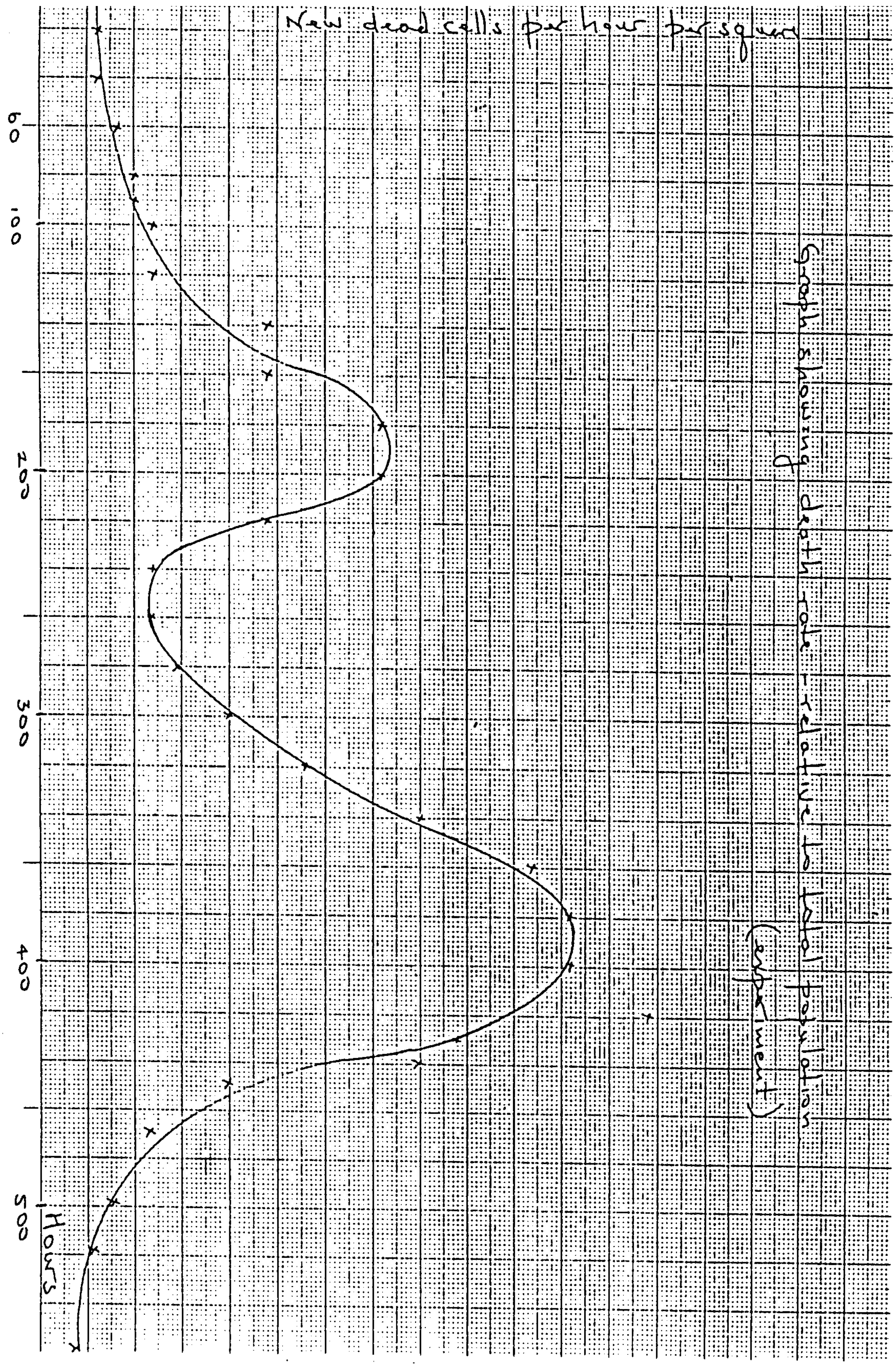


Graph showing number of dead yeast cells (experiment)

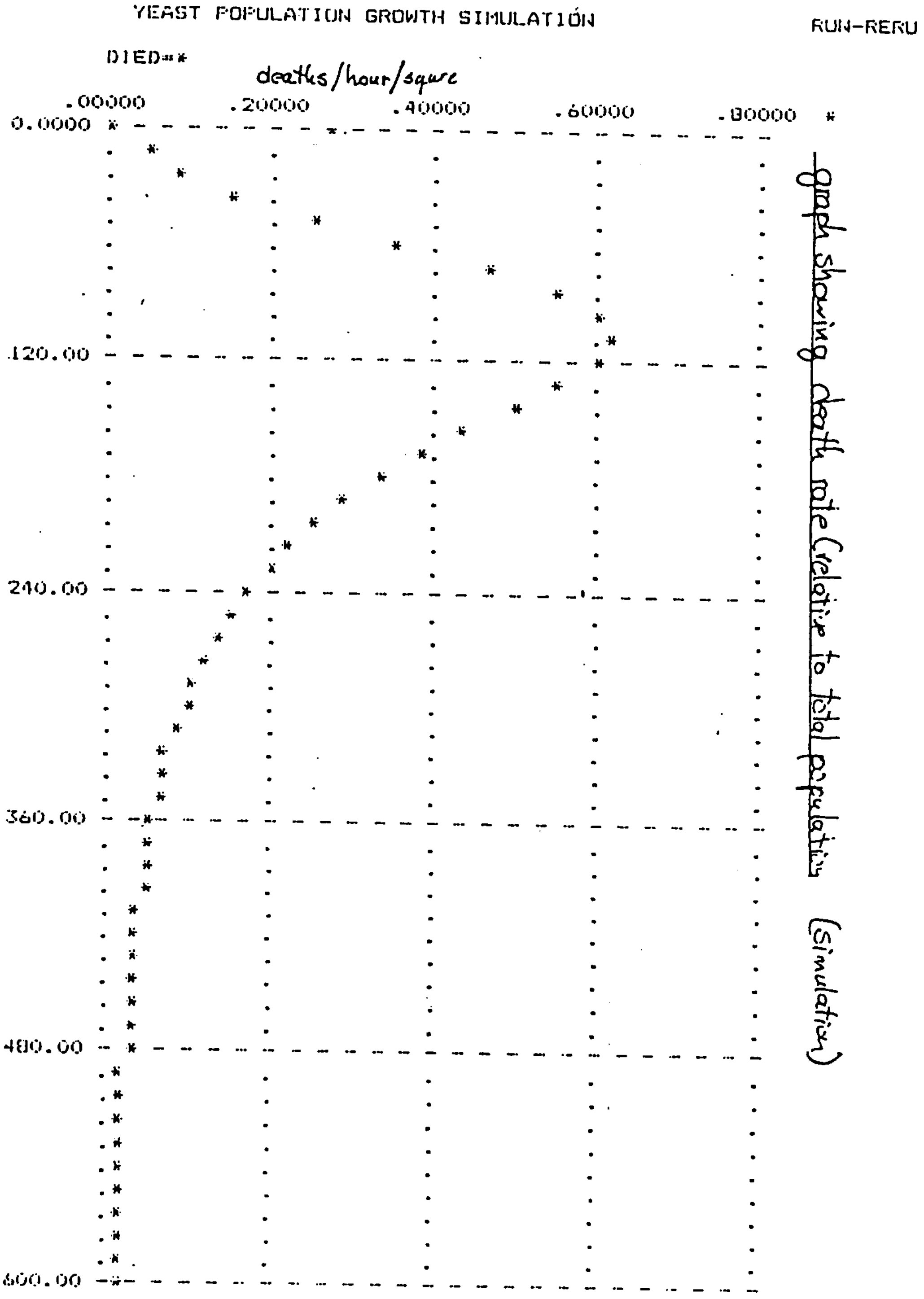
YEAST POPULATION GROWTH STIMULATION RUN RERUN



graph showing number of dead cells (simulation)



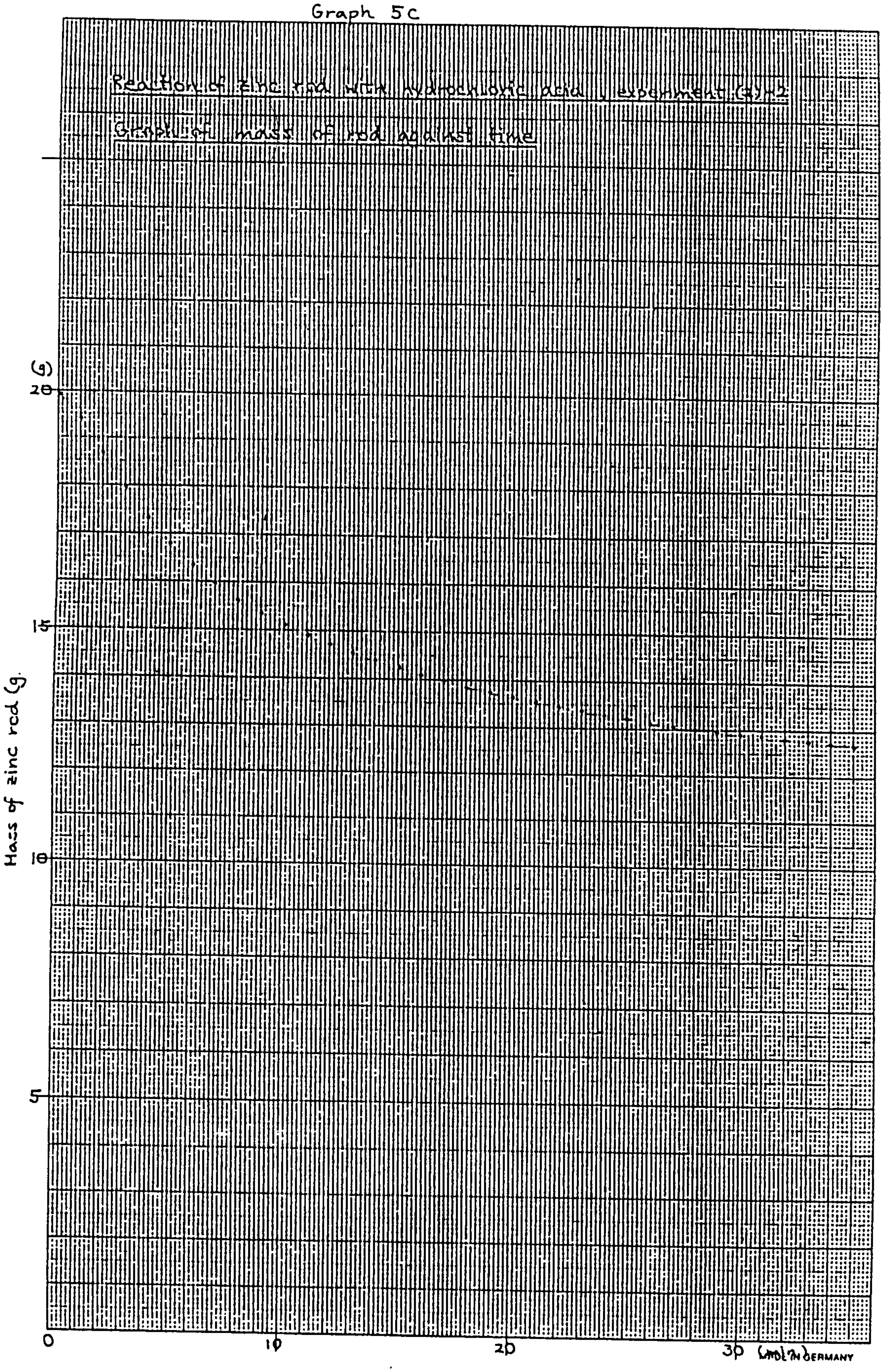
Graph showing death rate relative to total population (experiment)



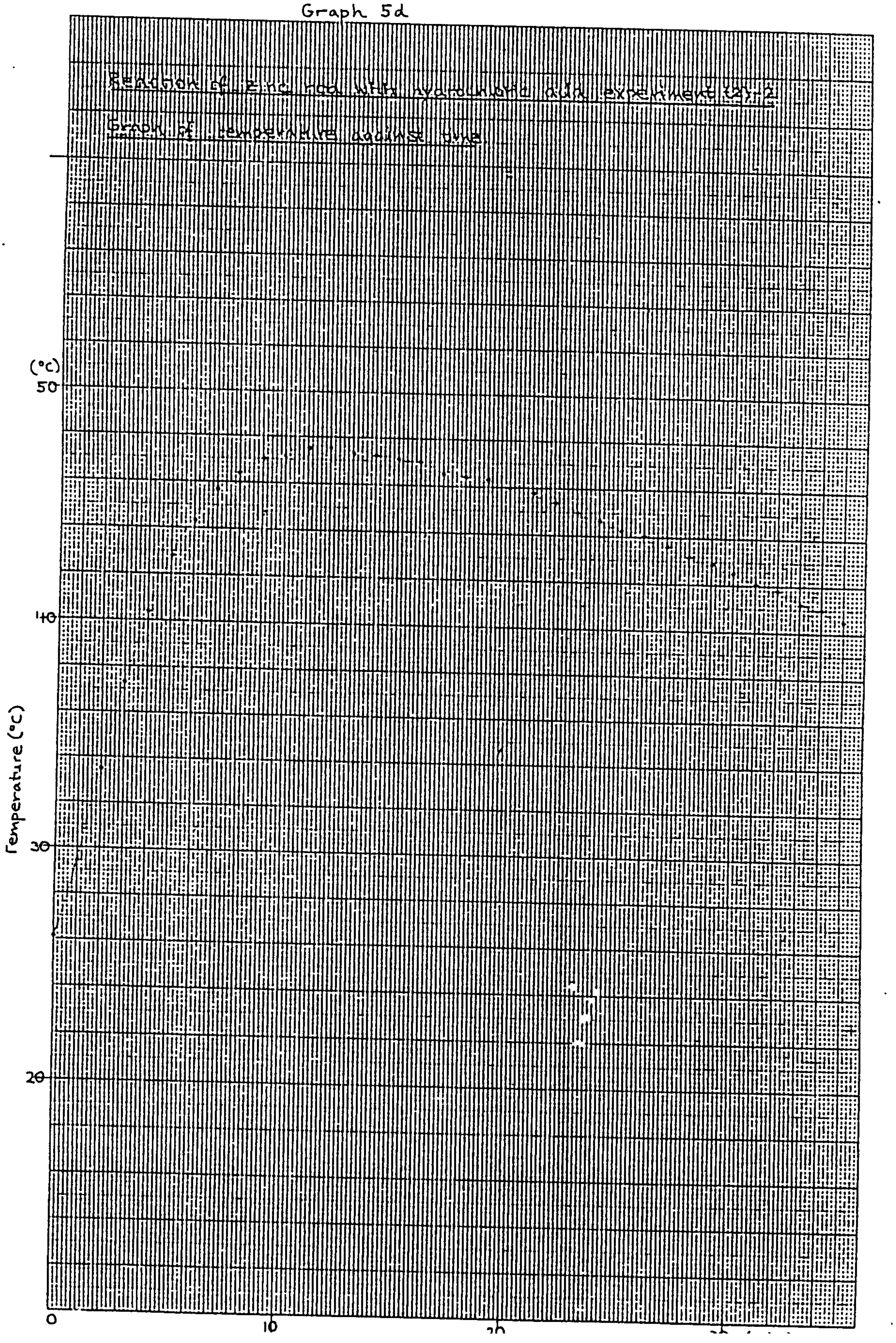
graph showing death rate (relative to total population) (simulation)

APPENDIX E2 - Experimental Outputs, Working Models and Simulation Runs – SHOKO's Project

Graph 5c


Reaction of zinc rod with hydrochloric acid, experiment (a)-2
Graph of mass of rod against time
Mass of zinc rod (g)
(g)
20
15
10
5
0
10
20
30 (min)
MADE IN GERMANY

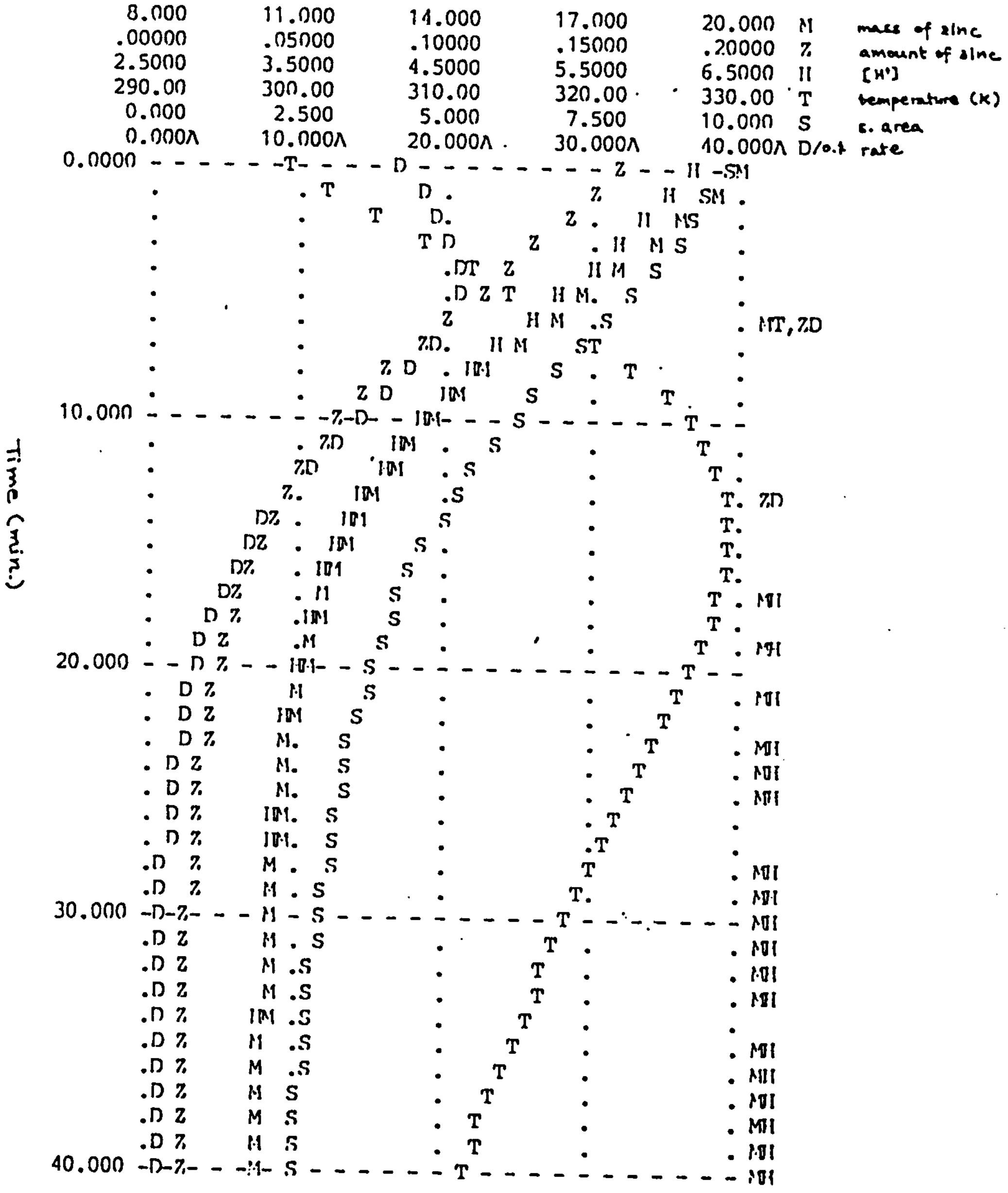
Graph 5d


Reaction of zinc rod with hydrochloric acid experiment (2)-2
Graph of temperature against time
(°C)
50
40
30
20
0
10
Temperature (°C)

Graph 6e

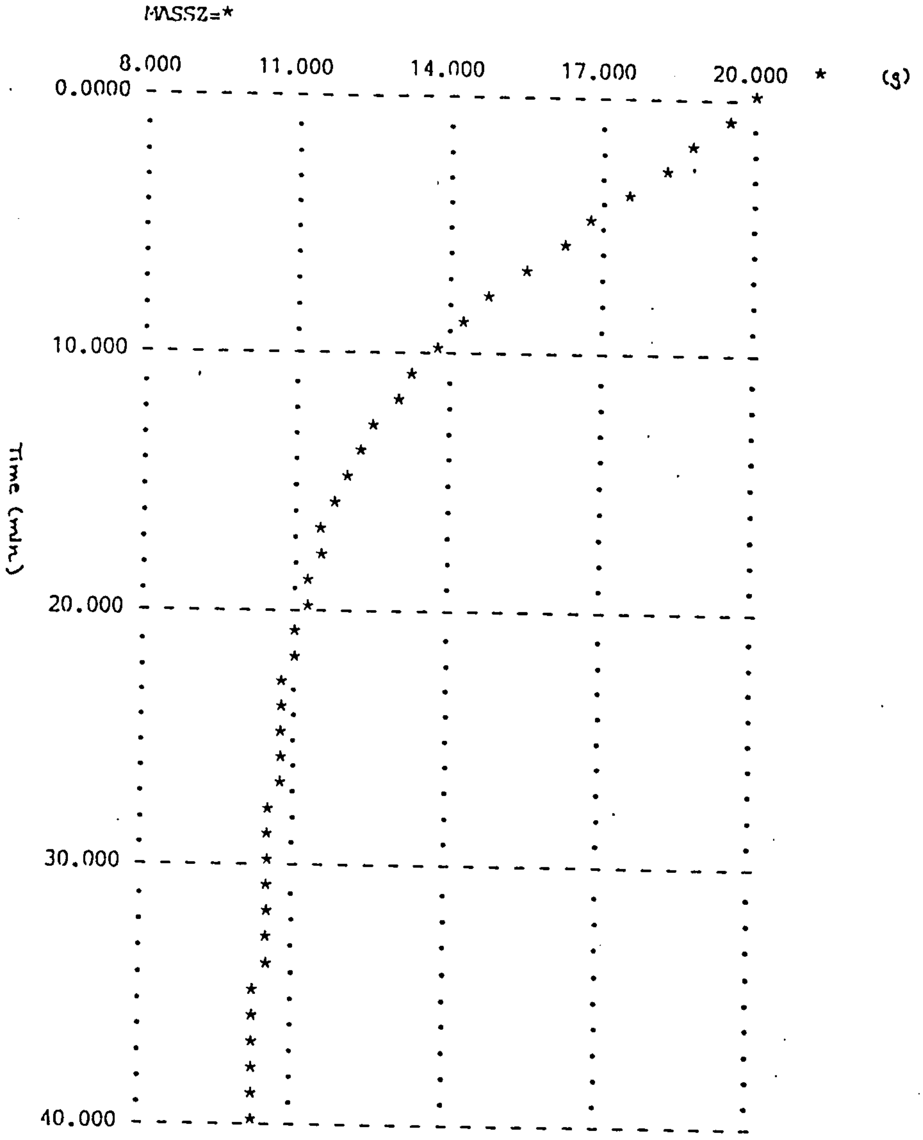
Simulation results for (2)-2
zinc-acid reaction

MASSZ=M,AMTZ=Z,HCONC=H,TEMP=T,AREA=S
DECRP=D



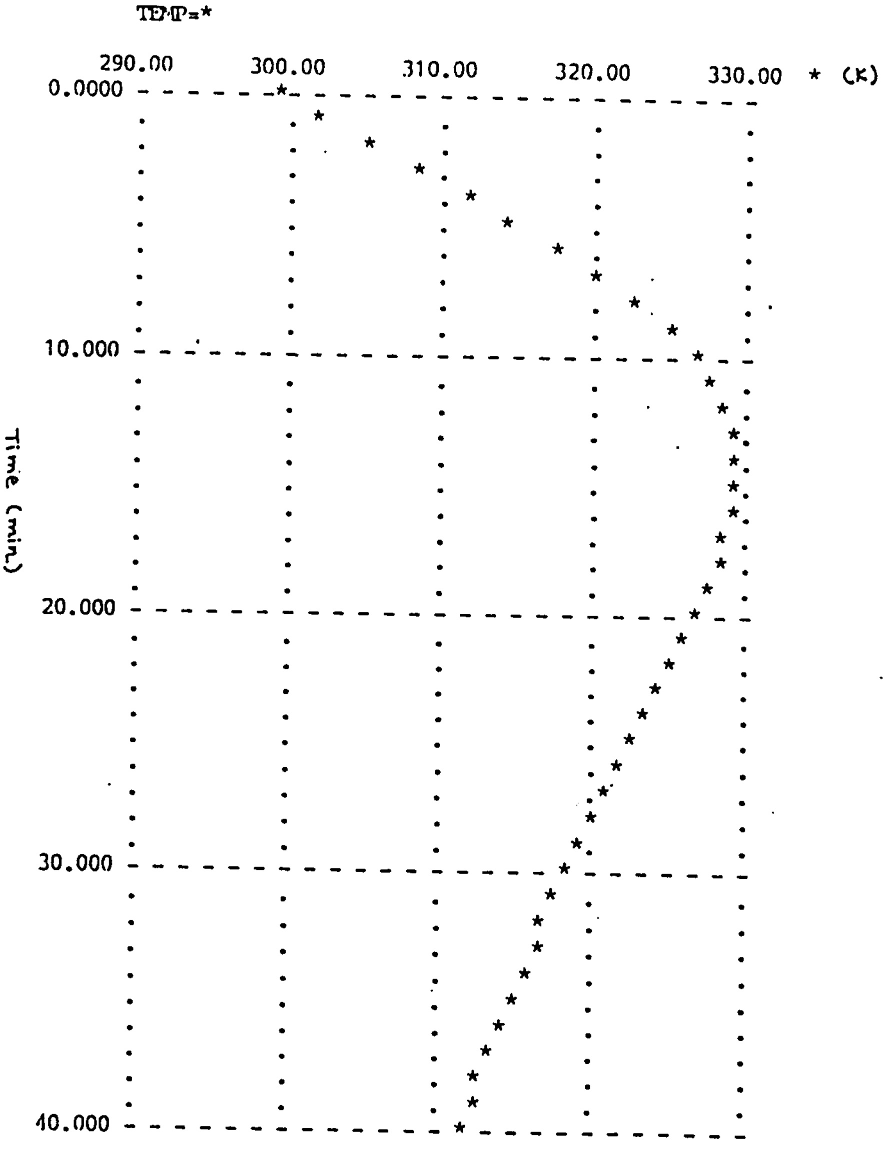
Graph 6f

(2)-2 Mass of zinc rod against time



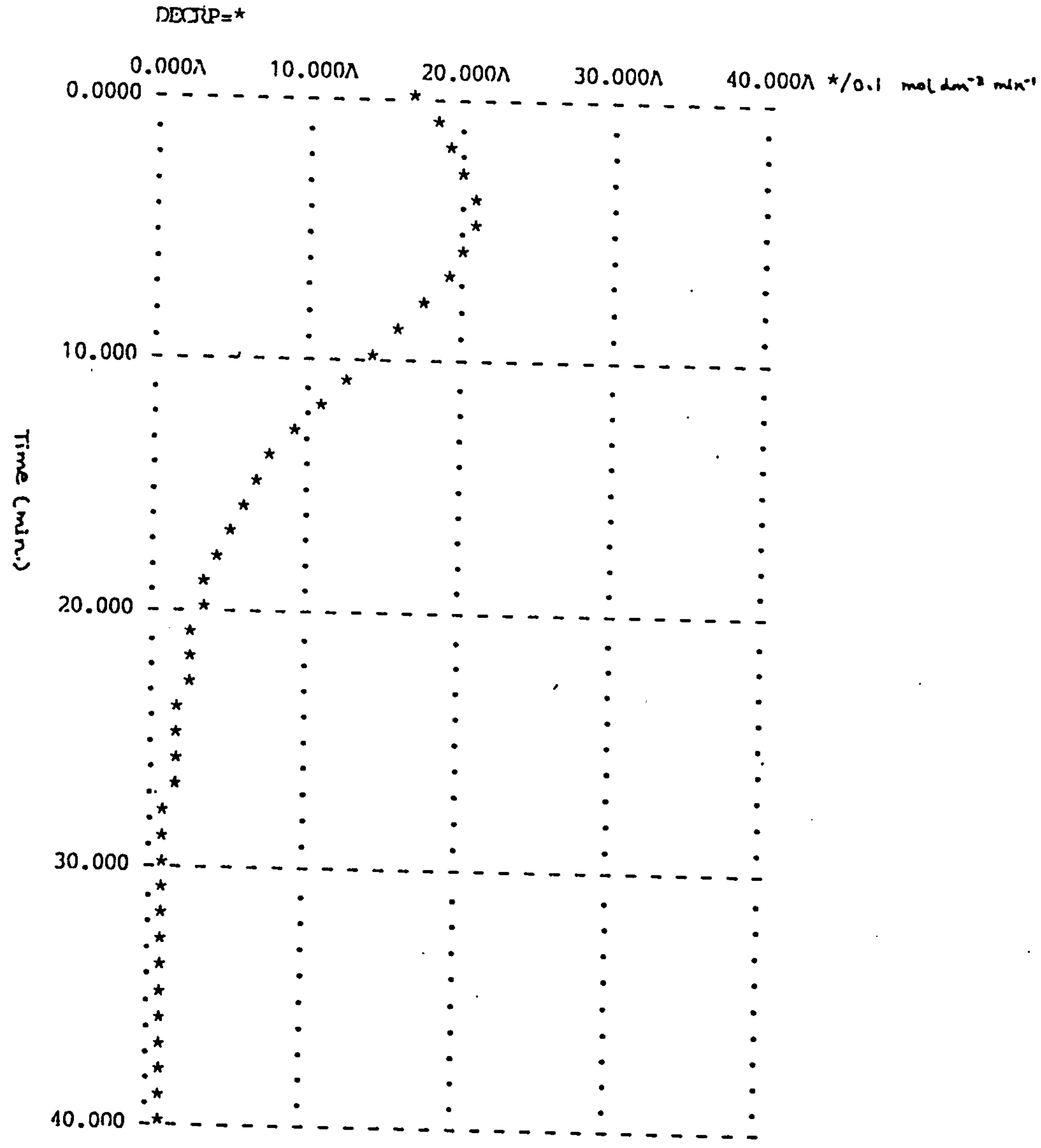
Graph 6g

(2)-2 graph of temperature against time



Graph 6h

(2)-2 graph of rate $-\frac{d[H^+]}{dt}$ against time



The results of mass of zinc and the temperature were as in *Graphs* 5 (*a*) - (*d*)[15]. In plotting the temperature, where the recorded temperatures before and after Weighing were different, the latter was plotted, as it may have taken time for the acid to acquire the new temperature.

Computer Simulation

The computer simulation[16] was carried out using the values and assumptions in experiment (1).
Further assumptions are :

i) The density and specific heat capacity of the acid were considered equal to that of water.
ii) The enthalpy change was taken for molar solution, though the acid concentration was higher and Zn^{2+} concentration lower.
iii) Effect of Zn^{2+} being produced on rate was ignored (n_t was assumed to be same as n_c).
iv) The reaction was assumed to take on all the surface under acid; bubbles produced may have reduced the area in reality.
v) The height used is the mean height. Actually, when the reaction was fast, effervescence causes more zinc above the surface to react.

At first, it was also assumed that there is no heat lost from the beaker to the surrounding. However, this gave a much too high temperature and rate of reaction near the end even for (2)-2, that the cooling factor had to be considered.

For this purpose, Newton's low of cooling was assumed to hold. Thus, at any point in the reaction,

$$\Delta T = \Delta T_{\text{due to reaction}} - \Delta T_{\text{due to cooling}}$$

where $\Delta T_{\text{cooling}} = k$ (temperature of system - room temperature)

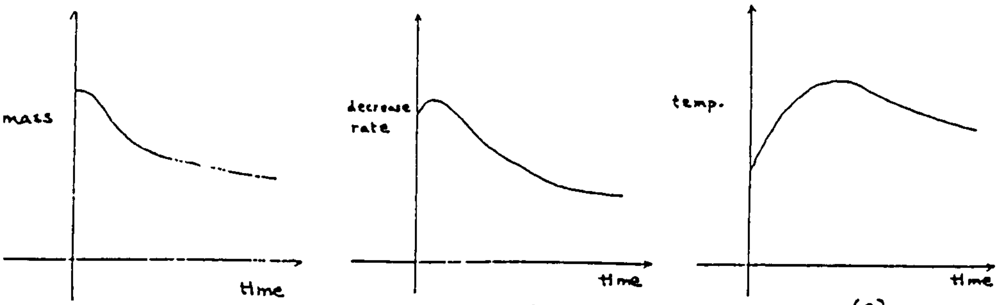
---

15) *Table of results may be found in Appendix E - 1.*

16) *For computer program for simulation, refer to Appendix E - 2.*

immediately before it decreased again (*Fig.12 a, b*). Temperature increased until the cooling factor became more dominant than the enthalpy effect (*Fig.12 c*).

Fig. 12 General trend of curves of results



(a) mass

(b) rate

(c) temperature

From the simulation graphs (*Graphs 6 a,e*), it can be seen that $[H^+]$ factor is more dominant than the area factor in determining the rate. Temperature also has a significant effect, especially at first, but as the rate starts decreasing before temperature does, concentration factor can be said to be more dominant. This is also confirmed by the fact, that at 35 minutes, there was more zinc remaining in the 2nd trial (less acid, higher maximum temperature) than in 1st trial (*Graphs 5 a,c*).

In both cases, the maximum temperature reached was higher in simulation than in experiments, and the final mass was less in the simulation. Graphs of mass from simulation and experiment matched well at first; then the mass from experiment decreased faster at first, but as the rate became smaller, the mass from simulation decreased much faster (*Graphs 7 a,c*). This may be the effect of temperature rise (*Graphs 7 b,d*), the height of the rod in reality being larger at first then smaller than the mean value (due to effervescence), and the hydrogen bubbles reducing the effective surface area of zinc. The results for the last part could be rather ambiguous, due to the many assumptions made and sources of error which would have a significant effect where the reaction rate is small.

k can therefore be calculated, since where the temperature graph flattens out (*Fig.11*),

$$\Delta T_{reaction} = -\Delta T_{cooling}$$

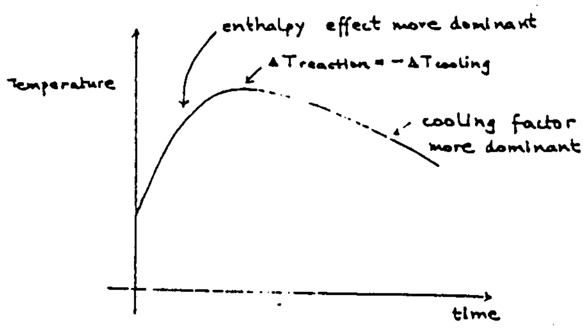


Fig. 11 Temperature curve enthalpy and cooling

1) Temperature flattens out at 40°C from 8–10 min.

At 8–10 min, 0.28g of zinc is reacted per minute.

$$n = \frac{m}{M} = \frac{0.28g}{65.4g\ mol^{-1}} = 4.28 \times 10^{-3}\ mol$$

$$\Delta H = \Delta H_r^{\circ} \times n = -152.3\ kJ\ mol^{-1} \times 4.28 \times 10^{-3} mol = -0.652\ kJ$$

$$\Delta T_r = -\frac{\Delta H}{cm} = -\frac{-0.652\ kJ}{4.18\ kJ\ kg^{-1}K^{-1} \times 0.2\ kg} = 0.780\ K$$

$$\therefore \Delta T_{cooling} = k\ (40 - 24)K = 0.780\ K$$

$$k = 0.049$$

2) Temperature flattens out at 47.5°C at 11–12 min.

$$\Delta\ mass\ zinc = 0.19\ g\ min^{-1}$$

$$n = 2.91 \times 10^{-3}\ mol$$

$$\Delta H = -152.3\ kJ\ mol^{-1} \times 2.91 \times 10^{-3} mol = -0.442\ kJ$$

$$\Delta T_r = -\frac{-0.442\ kJ}{4.18\ kJ\ kg^{-1}K^{-1} \times 0.1\ kg} = 1.06\ K$$

$$\therefore \Delta T_{cooling} = k\ (47.5 - 24)K = 1.06\ K$$

$$k = 0.045$$

The reaction was simulated to give curves as in the print out. (*Graphs 6*)[17].

The shape of the graph from the simulation fitted well to that from the experiment, especially in experiment (2)–2. The mass of zinc decreased slowly at first, then the rate increased

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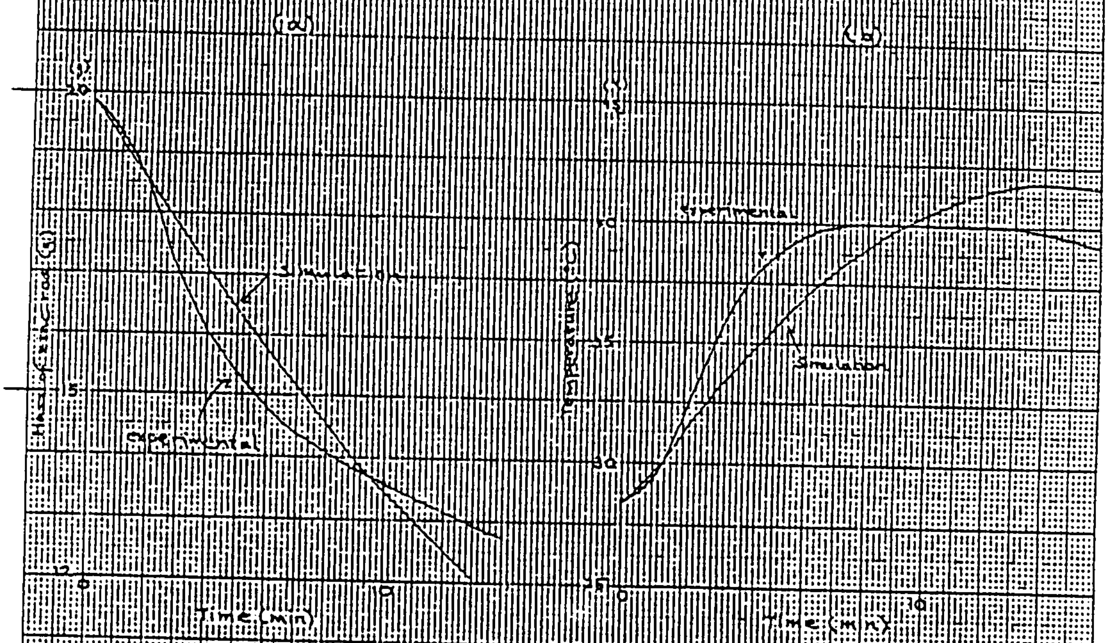
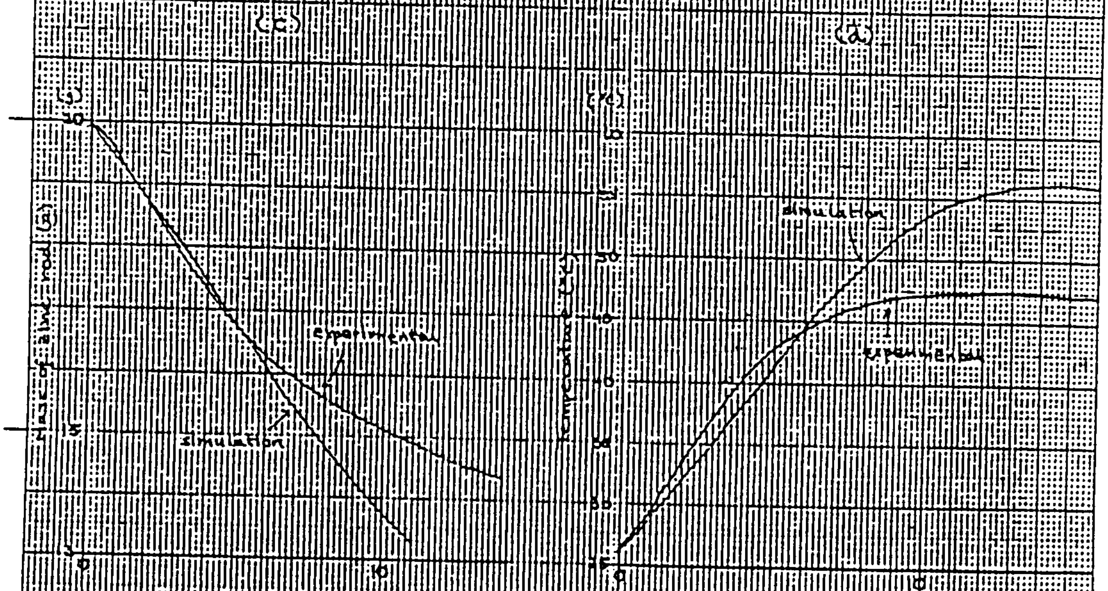
[17] *For detail refer to Appendix E – 3.*

Comparison of experimental and simulation results



(2)-1 (a) Graph of mass against time
(b) Graph of temperature against time



(2)-2 (a) Graph of mass against time
(b) Graph of temperature against time

Conclusion

The simulation could be used to predict the reaction, if not the exact accurate values, the trends and shapes of the graphs. There are still some other factors affecting the rate that were not considered here, which is shown in the discrepancy of results. Generally though, considering the various sources of the errors and the assumptions made, the results are acceptable. In the experiment, uncertainty in constants could have an effect on the prediction, since a small change in the values could make a large difference in the results (especially the E value). For this reason during the course of the simulation, the constants were slightly changed for comparison, but as the obtained results gave the most satisfactory curve, they were assumed to be valid.

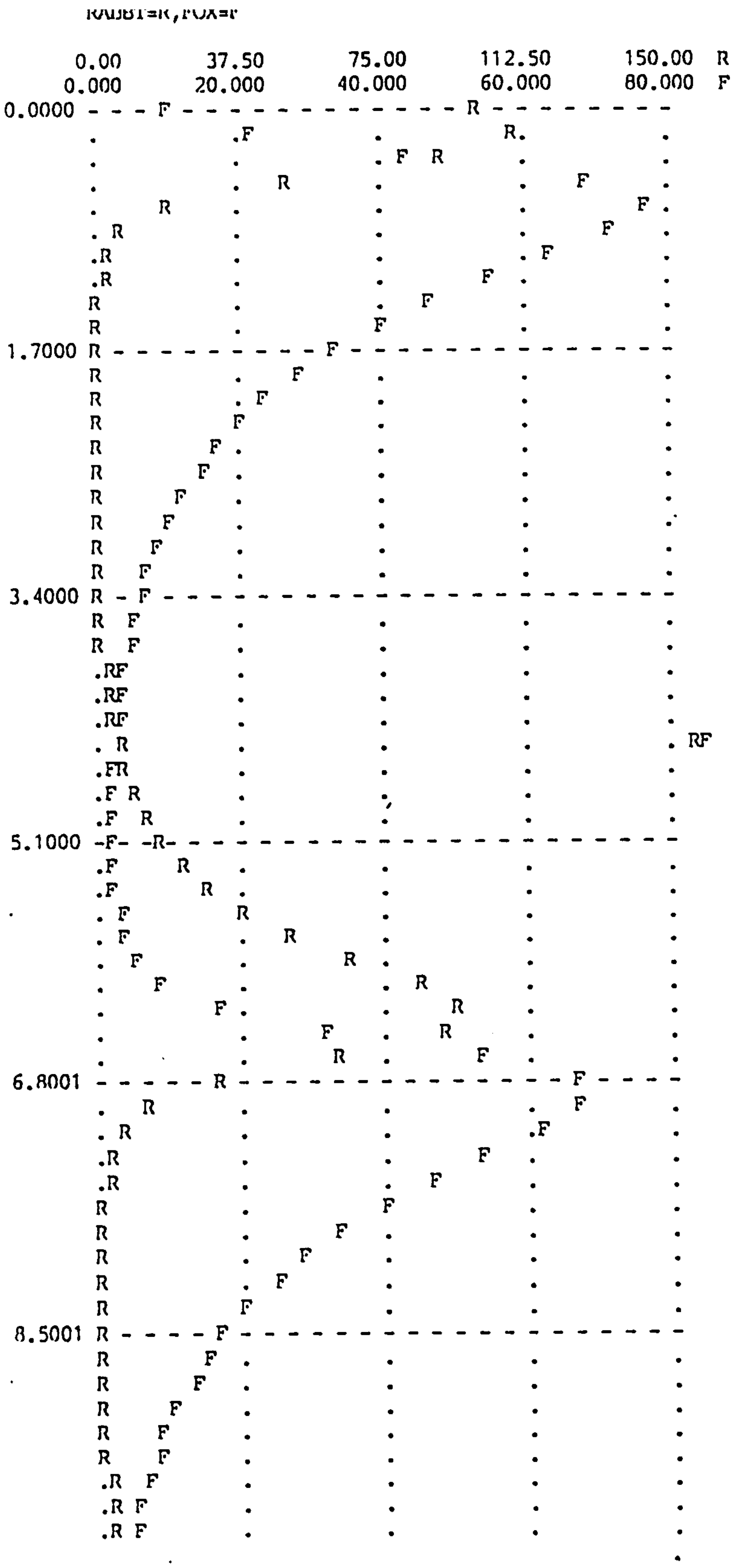


Fig. 3.10 Rabbit– Fox Model Simulation Run 1

```
       RABBT=R,FOX=F

     50.00       87.50      125.00      162.50      200.00 R
      5.00       28.75       52.50       76.25      100.00 F
0.0000 - -F- - - - - - R - - - - - - - - - - - - - - - - -
       .  F        .         R .           .           .
       .    F      .           .  R        .           .
       .       F   .           .      R    .           .
       .          F.           .   R       .           .
       .           .  F     R  .           .           .
       .           R  F        .           .           .
       .     R     F           .           .           .
       .   R    F  .           .           .           .
       .    RF     .           .           .           .
1.7000 - - F -R- - - - - - - - - - - - - - - - - - - -
       .  F       R.           .           .           .
       . F         .   R       .           .           .
       . F         .         R .           .           .
       .   F       .           .   R       .           .
       .      F    .           .       R   .           .
       .           F           .     R     .           .
       .           .   F    R  .           .           .
       .          R.   F       .           .           .
       .    R      .F          .           .           .
3.4000 - -R- - -F- - - - - - - - - - - - - - - - - - -
       .   RF      .           .           .           .
       .  F  R     .           .           .           .
       . F       R .           .           .           .
       . F         .  R        .           .           .
       . F         .         R .           .           .
       .  F        .           .    R      .           .
       .     F     .           .         R .           .
       .           F           .       R   .           .
       .           .    F     R.,          .           .
5.1000 - - - - - -R- - -F- - - -'- - - - - - - - - - - -
       .    R      . F         .           .           .
       . R      F  .           .           .           .
       .  R F      .           .           .           .
       .  F R      .           .           .           .
       . F      R  .           .           .           .
       .F          . R         .           .           .
       .F          .       R   .           .           .
       .  F        .           .   R       .           .
       .    F      .           .           R           .
6.8001 - - - - - -F- - - - - - - - - - - - R - - - - - -
       .           .    F      . R         .           .
       .           R     F     .           .           .
       .   R       . F         .           .           .
       .R       F  .           .           .           .
       .R    F     .           .           .           .
       .  R        .           .           .           . RF
       . F   R     .           .           .           .
       .F          R           .           .           .
       .F          .     R     .           .           .
8.5001 - F - - - - - - - - - - - - - R - - - - - - - - - - -
       .  F        .           .           R           .
       .       F   .           .           . R         .
       .           .   F       .     R     .           .
       .           . R     F   .           .           .
       .   R       .   F       .           .           .
       R         F.            .           .           .
       R    F      .           .           .           .
       .R F        .           .           .           .
```

Fig. 3.11   Rabbit- Fox Model Simulation Run 2

APPENDIX F1

Statement Number and Type – SL/CL		**Mean**	**SD**	**t-Value**	**2-Tail ** Probability**	**Significant Difference**
#1- SL*	Pre-Test	3.0	0.7	**- 3.4**	0.01	- 1.0
	Post-Test	4.0	0.8			
# 8-SL*	Pre-Test	3.3	1.1	**- 2.9**	0.02	- 0.9
	Post-Test	4.2	0.6			
#11-CL*	Pre-Test	1.2	0.4	**- 4.0**	0.00	- 1.5
	Post-Test	2.7	1.3			
#12-CL*	Pre-Test	2.0	1.4	**- 2.6**	0.03	- 1.2
	Post-Test	3.2	0.9			
#17-CL*	Pre-Test	2.8	1.0	**- 2.7**	0.03	- 0.7
	Post-Test	3.5	1.1			

#13-CL*	Pre-Test	1.6	0.7	**- 6.0**	0.00	- 1.6
	Post-Test	3.2	0.8			
#15-CL*	Pre-Test	1.5	0.9	**- 3.5**	0.01	- 1.4
	Post-Test	2.9	0.9			

#6-SL	Pre-Test	3.4	1.2	**- 1.9**	0.09	- 0.7
	Post-Test	4.1	0.7			
#7-SL	Pre-Test	3.7	1.3	**0**	1.00	0.1
	Post-Test	3.7	1.3			
#14-CL	Pre-Test	2.3	1.0	**- 1.9**	0.10	- 0.9
	Post-Test	3.2	0.8			
#16-SL	Pre-Test	2.5	1.1	**- 0.9**	0.40	- 0.4
	Post-Test	2.9	0.7			

Statement Number and Type – SL/CL		**Mean**	**SD**	**t-Value**	**2-Tail ** Probability**	**Significant Difference**
#3 - SL	Pre-Test	1.0	0	**- 10.9**	0.00	- 2.4
	Post-Test	3.4	0.7			

** - A two-tailed t-test was chosen because the alternative Hypothesis was not considered to be having a specific direction

Table 7 – t-Test Data - Experimental Group

Statement Number and Type – SL/CL		Mean	SD	t-Value	2-Tail ** Probability	Significant Difference
#1-SL	Pre-Test Post-Test	2.8 2.9	1.0 0.6	- 0.4	0.69	0.1
#3-SL	Pre-Test Post-Test	2.6 3.1	1.3 0.8	-1.9	0.10	- 0.5
#6-SL	Pre-Test Post-Test	3.0 2.8	0.8 1.0	0.6	0.56	0.3
#7-SL	Pre-Test Post-Test	3.3 3.0	0.7 1.1	0.6	0.60	0.3
#8-SL	Pre-Test Post-Test	3.5 2.6	0.8 1.1	2.2	0.06	0.9
#11-CL	Pre-Test Post-Test	2.3 2.4	1.0 0.9	0.3	0.80	0.1
#12-CL	Pre-Test Post-Test	2.5 2.5	1.5 1.3	0	1.00	0
#13-CL	Pre-Test Post-Test	2.8 2.5	1.8 1.5	0.7	0.52	0.3
#14-CL	Pre-Test Post-Test	2.8 3.0	1.4 0.9	0.5	0.63	0.3
#15-CL	Pre-Test Post-Test	2.5 2.4	1.5 1.3	0.6	0.60	0.1
#16-CL	Pre-Test Post-Test	3.3 3.3	1.2 1.0	0	1.00	0
#17-CL	Pre-Test Post-Test	2.9 3.5	1.3 1.1	1.4	0.22	0.6

**** - A two-tailed t-test was chosen because the alternative Hypothesis was not considered to be having a specific direction**

Table 8 – t-Test Data - Control Group

APPENDIX F2

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	1	2	20,000	0	0	2
2	1	3	31,000	1	0	3
3	1	9	39,333	2	0	4
4	1	10	50,500	3	0	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	10		9		3		2		1
1	X	X	X	X	X	X	X	X	X
2	X		X	X	X	X	X	X	X
3	X		X		X	X	X	X	X
4	X		X		X		X	X	X

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	4	6	25,000	0	0	2
2	4	8	27,500	1	0	3
3	4	5	41,000	2	0	4
4	4	7	53,250	3	0	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	7		5		8		6		4
1	X	X	X	X	X	X	X	X	X
2	X		X	X	X	X	X	X	X
3	X		X		X	X	X	X	X
4	X		X		X		X	X	X

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	13	17	23,000	0	0	3
2	12	15	34,000	0	0	3
3	12	13	57,000	2	1	4
4	12	14	80,250	3	0	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	14		17		13		15		12
1	X	X	X	X	X	X	X	X	X
2	X		X	X	X	X	X	X	X
3	X		X	X	X		X	X	X
4	X		X	X	X		X		X

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	3	9	22,000	0	0	4
2	1	2	23,000	0	0	3
3	1	10	27,500	2	0	4
4	1	3	37,333	3	1	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	9		3		10		2		1
1	X	X	X	X	X	X	X	X	X
2	X	X	X		X	X	X	X	X
3	X	X	X		X		X	X	X
4	X	X	X		X		X		X

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	4	7	2,000	0	0	3
2	5	6	9,000	0	0	3
3	4	5	14,500	1	2	4
4	4	8	33,750	3	0	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	8		6		5		7		4
1	X	X	X	X	X	X	X	X	X
2	X		X	X	X	X	X	X	X
3	X		X	X	X		X	X	X
4	X		X		X		X	X	X

Cluster

Verarbeitete Fälle[a,b]

Fälle					
Gültig		Fehlend		Gesamt	
N	Prozent	N	Prozent	N	Prozent
5	100,0	0	,0	5	100,0

a. Quadriertes euklidisches Distanzmaß wurde verwendet

b. Linkage zwischen den Gruppen

Linkage zwischen den Gruppen

Zuordnungsübersicht

Schritt	Zusammengeführte Cluster		Koeffizienten	Erstes Vorkommen des Clusters		Nächster Schritt
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	13	17	18,000	0	0	3
2	12	15	24,000	0	0	4
3	13	14	35,000	1	0	4
4	12	13	72,000	2	3	0

Vertikales Eiszapfendiagramm

Anzahl der Cluster	Fall								
	14		17		13		15		12
1	X	X	X	X	X	X	X	X	X
2	X	X	X	X	X		X	X	X
3	X		X	X	X		X	X	X
4	X		X	X	X		X		X

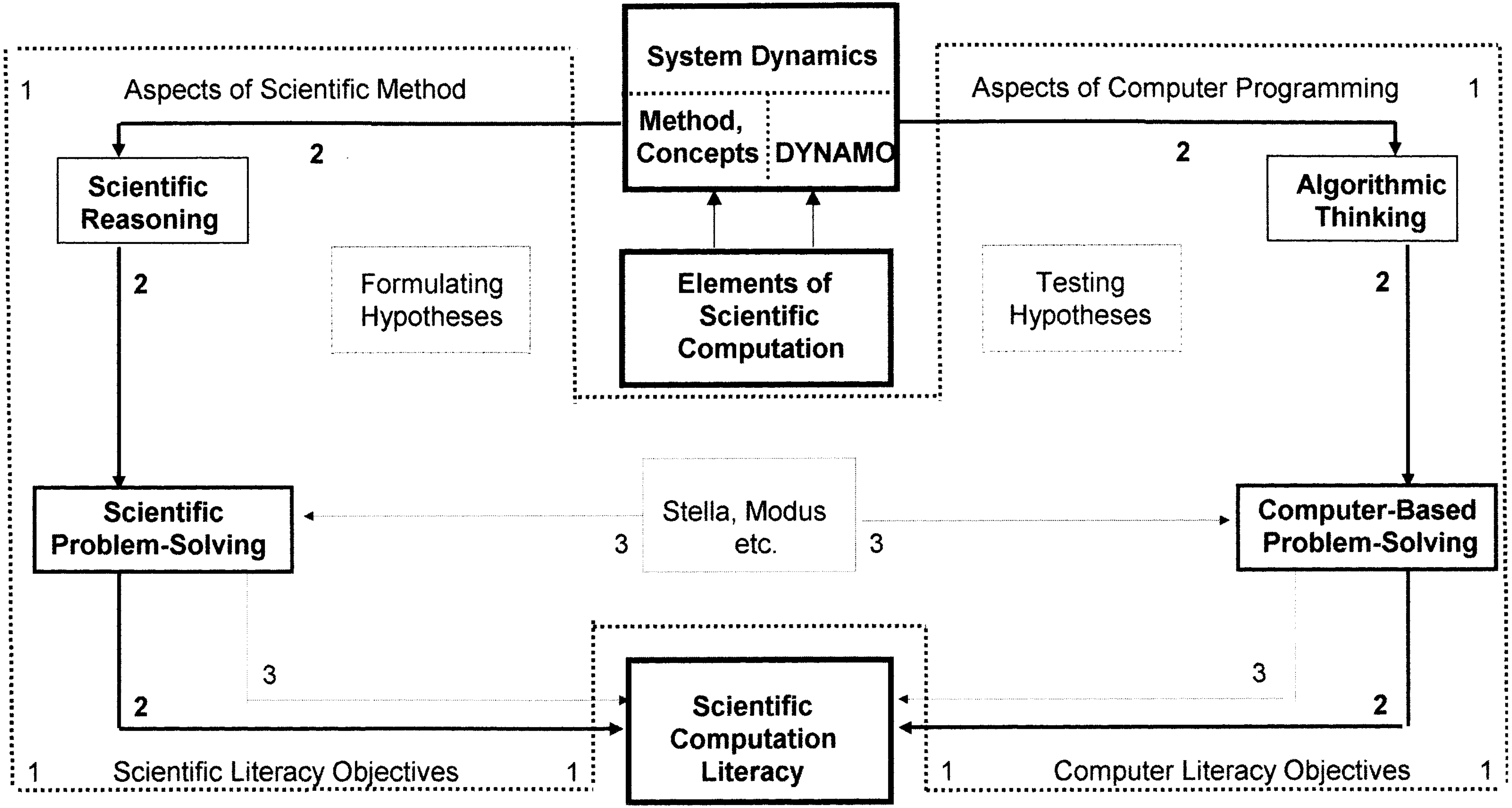


Fig. 5.2 Schematic Representation of the Development of Scientific Computation Literacy

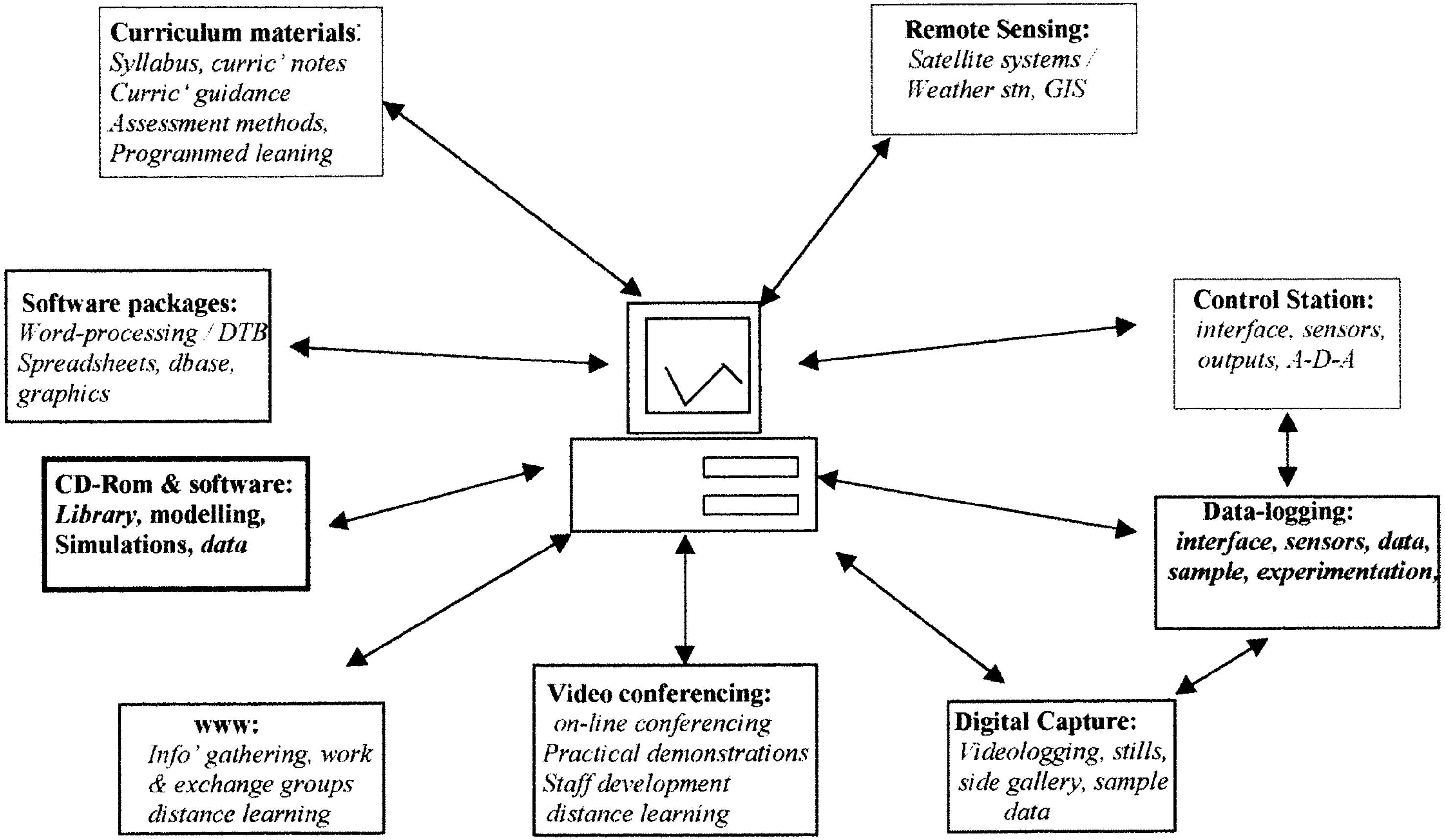


Fig. 5.3 Visualisation of Laboratory Work Station 2005

LEBENSLAUF – CV

Born 12.10.1946 in Addis Ababa. First two years of Primary School in Bombay. Later, and up to July 1964, subsequent Primary and Early Secondary schooling – up to GCE Ordinary Level (UK – external) Examinations and Ethiopian School Leaving Certificate Examinations – in Addis Ababa. Thereafter, GCE Advanced Level (Mathematics and Physics), Graduate and Post-Graduate studies, working – Department Store Sales, Hospital Orderly, City Council Librarian, Solid State Physicist and Teacher of Physics, Mathematics and Integrated Science with the Inner London Education Authority - and living in London until July 1979.

1973 - Bachelor Of Science (B Sc Honours - CNAA) IN Physics-With-Mathematics; Westminster University, London.

1976 - Master Of Science (M Sc) in Solid State Physics; Royal Holloway And Bedford New College, University Of London.

1977 - Post-Graduate Certificate in Science Education (PGCE); Institute Of Education, University Of London.

Since July 1979 married to Petra (geb. Naeve) and resident in Hamburg; children – Marco, Marcia, Piero, Paolo and Alicia. Employed since September 1979 as Teacher of Physics and Integrated Science (and sometime of Introductory Chemistry and Advanced Mathematics) at Internationale Schule Hamburg e.V..

Also, October 1986 – September 1990, registered (post-graduate) student at Universität Hamburg, Fachbereich Erziehungswissenschaft Institut 9.

ERKLÄRUNG

Ich erkläre, daß ich die Arbeit selbständig angefertigt habe, und versichere, daß ich andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.