COMPUTATIONAL MODELLING IN SCIENCE EDUCATION: A STUDY OF STUDENTS' ABILITY TO MANAGE SOME DIFFERENT APPROACHES TO MODELLING

by

Arion de Castro Kurtz dos Santos

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Doctor of Philosophy of the University of London

Department of Science Education
Institute of Education
20 Bedford Way
London WC1H OAL

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ABSTRACT

This research is an exploratory study with 6th form students about their ability to use some different approaches to computational modelling.

It involves a survey through an individual questionnaire about causal diagramming and mathematical knowledge, which aims at characterizing the students' model building capability.

Also, it includes an intensive study with pairs of students doing exploratory and expressive tasks using two modelling systems: IQON and STELLA.

Data was gathered through written notes from observation, written answers given to questionnaires and data recorded in the computer.

Overlapping questionnaires connected the survey and the intensive study. Comparisons between the use of causal diagrams and IQON were carried out.

Results show that students in some cases replace variables by objects, events and processes, though this seems to depend on the problem. There is evidence of semi-quantitative reasoning, which tends to be complex and its nature and frequency seems to depend on subject matter. It is natural even in quantitative tasks and may depend on gender and background.

To use/make computational models it is important to reason in a semi-quantitative way, to imagine the world in terms of variables, to understand about rate of change, to think at a system level and to understand causation in a system. Results support the use of IQON, which allows the student to think rather freely about a system. STELLA's structure and metaphor obliges the student to think about rates. Evidence of the difficulty of thinking about rates in a formal mathematical way is presented.

Students seem to articulate analogies according to their scientific backgrounds, and to use their own ideas. They tend not to invoke reality to interpret models, but have a well defined conception of the relationship between model and reality.

Results suggest that 6th form students can undertake valuable work with both computational systems.

To my wife Sílvia
and my daughters
Luísa and Larissa

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I would like to thank the group of researchers of the Tools for Exploratory Learning Project, of which I have been a collaborator, for providing me with an earlier version of IQON. As a physicist who appreciates the potential value of computational modelling systems, I decided, from the very beginning, to link my research to "Tools" and, therefore, I came to use a terminology similar to that of the project. I hope this study will be useful to the "Tools" project as additional information concerning older students working with semi-quantitative and quantitative modelling tools.

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CHAPTER 1 - MODELS, MODELLING AND COMPUTATIONAL SYSTEMS

1. 1. INTRODUCTION

With modelling now figuring prominently in the National Curriculum, the efforts made over the past decade to develop computer systems to help teachers and pupils build computer models now have to be converted into curriculum practice.

This work presents an analysis of what is involved in developing computational models of real situations, and in learning the important general features of classes of models, so as to provide a guide to practice.

This research is about modelling, particularly, computational modelling using modelling systems. It is a practical exploratory study with sixth form students involving data collection through a general questionnaire about modelling and intensive studies where students work with the computer. It tries to give an account of the students' ability to manage some different approaches to modelling; namely causal diagrams and a pair of computational tools: IQON and STELLA.

1. 1. 1. MODELS AND MODELLING

To understand nature, through observation of natural phenomena, people have since ancient times looked for regularities and have developed models that can be understood as the codification of these regularities. Through models, humans have attempted to dominate nature and develop technology. The evolution of Science was based on the construction of models and, from them, the development of theories.

Neelamkavil (1987) suggests that models can be classified as physical models, symbolic models and mental models (see figure 1. 1). Physical models are representations of physical systems and are made of tangible components. They are described by measurable variables. Physical models can be subdivided into static (wax statues, models of cars, for example) and dynamic models (LCR circuit to study car suspension systems, for example). Symbolic models can be subdivided into Mathematical and nonmathematical models. Mathematical models can be subdivided into Dynamic models and static models. Dynamic models are generally described by differential or difference equations. It is these last that this research mainly concerns.

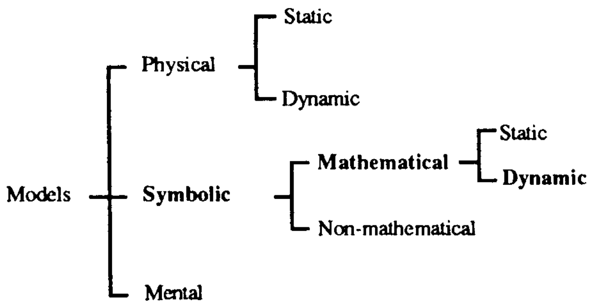


Figure 1. 1 - Classification of models.

Neelamkavil adds that modelling is the process of establishing interrelationships between important entities of a system. For each modeller there exists a base model (modeller's view or image of the real system) from which a simplified specific model is built. By experimenting with this simplified model it is hoped to enhance the understanding of the base model and also of the real system characterized by this model. He points out that the ability to build models by selecting the smallest subset of variables that adequately describe the real system is a very important quality of a good modeller. He adds that skill in modelling depends also on experience, expertise, intuition, judgement, foresight, and imagination. The building of a mathematical model of an object is based on a specific way of looking at the object - i.e., at "reality".

Skovsmose (1988) points out that the conception of reality must be so structured in our thinking that patterns can be identified. In his opinion we have (1) to select elements from reality, which are conceived as important, and (2) to decide what relationships among these elements are to be considered important. These two fundamental selections are interpretations of "reality". This means that a model is not a model of "reality" as such, but a model of a (conceptual) system, created by a specific interpretation based on an elaborated theoretical framework.

1. 1. 2. KINDS OF COMPUTATIONAL TOOLS

Bliss and Ogborn (1989) presented a classification of kinds of tools as Quantitative, Semi-quantitative and Qualitative. They considered as Quantitative modelling systems and spreadsheets; as Semi-quantitative as an approximation STELLA (however, it really is a quantitative tool) and the Alternative Realities Kit; and as qualitative, story maker, Linx, adventure game shells.

In this review I will describe some quantitative modelling systems (DMS, CMS and STELLA), spreadsheets and a semi-quantitative modelling system (IQON).

1. 1. 3. EXPLORATORY AND EXPRESSIVE LEARNING MODES

Bliss & Ogborn (1990b) proposed that there are two different but complementary ways of using a computer tool - the exploratory and expressive learning modes. In the exploratory mode, the students explore a model already put in the computer. In this case they explore representations, developed by the teacher or researcher, which may be different from their own. In the expressive mode, the students develop their own models of a domain, presenting their own representations of the "reality" being modeled.

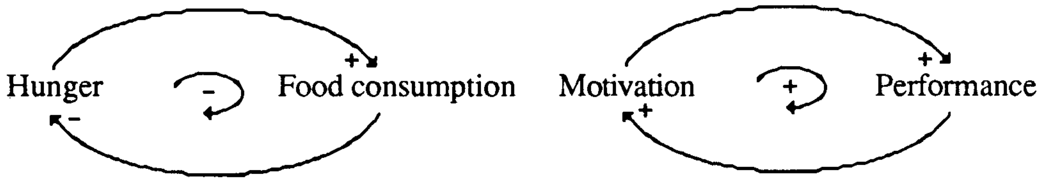
1. 2. DYNAMIC MODELLING

Perhaps the most systematic accounts of dynamic models have been produced in the system dynamics framework (Forrester, 1968). Roberts at al (1983) provide a comprehensive introduction to the concept.

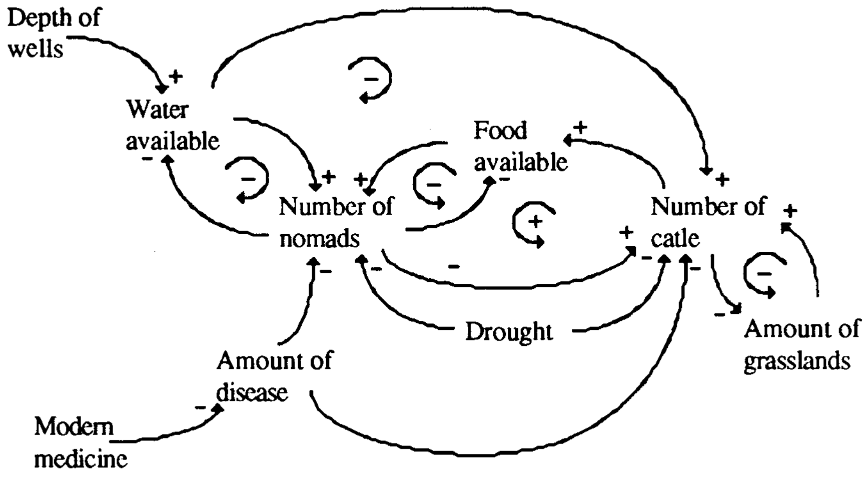
1. 2 .1. CAUSAL DIAGRAMS

According to Roberts (1983) causal thinking is the key to organizing ideas in a system dynamic study. We can represent the sentence "food intake influences weight" by an arrow diagram such as **food intake** --------->$^{+}$ **weight** from cause to effect. The positive sign (+) means that an increase in food intake increases the weight of a person. A negative sign (-) means influence in the opposite direction [1] .

There are two kinds of closed loops. Negative loops seek to stay the same, resisting change, such as the feedback process (a) presented in figure 1. 2 below, while positive self-reinforcing loops generate run-away growth or collapse, such as the feedback process (b). It is possible to have very complicated positive and negative closed loops, to show causation in a real system, as for example the Sahel (c). It is the causal structure which in the end will tie any formal system of equations to the underlying reality being modelled.



a) Example of negative feedback process.   b) Example of positive feedback process.



c) The tragedy of the Sahel.

Figure 1. 2 - Causal - loop diagrams.

---

[1] ——— + ▶ { If the cause increases, the effect increases; If the cause decreases, the effect decreases.

——— – ▶ { If the cause increases, the effect decreases; If the cause decreases, the effect increases.

1. 2. 2. FEEDBACK AND SYSTEM THINKING

A key element of the system dynamics method is a search to identify closed, causal feedback loops. The emphasis on causal loops can be a powerful tool to help define a system's boundary, and to sort out what should and what should not be included within the study of a social, economic or other system.

Roberts (1983) points out that one way to clarify the representation of a system is to focus on circular chains or causal-loops.

> "Within a causal - loop, an initial cause ripples through the entire chain of causes and effects, until the initial cause eventually becomes an indirect effect of itself".
>
> Roberts (1983).

She argues that the most important causal influences will be exactly those enclosed within feedback loops. In her opinion, by limiting the attention to closed loops, the number of factors or variables to be included within a system's definition can be drastically reduced to a manageable level and, more important, attention can be focused on those variables that are most important in generating and controlling social and economic problems.

The working of closed-loop processes generates dynamic behaviour patterns (see section 2. 5) and causal-loop diagrams are fundamental to express these processes.

Causal-loop methods can provide much insight into a system's structure, but it is often difficult to infer the behaviour of a system from its causal-loop representation. It is necessary to move from a causal-loop representation to a computer simulation model, traditionally first developing a flow diagram. Causal-loop diagramming is basic to the development of models using DYNAMO (Roberts, 1983), and STELLA (Richmond, 1987) [see section 1. 3].

Checkland (1989) points out the importance and ubiquity of what control engineers call the process of feedback, specifically the transmission of information about the actual performance of any machine (in the general sense) to an earlier stage to modify its operation. Usually, in <u>negative</u> <u>feedback</u> the modification is such as to reduce the difference between actual and desired performance, as when the increasing speed of a steam engine causes the flying pendulum of the governor (one of the oldest devices for automatic control invented by Watt, 1788) to reduce the steam supply and therefore lower the speed. <u>Positive</u> <u>feedback</u> induces instability by reinforcing a modification in performance, as when a conversation between two people in a crowded room is conducted in louder tones as their output, increasing the general noise level, makes it harder and harder for them to hear each other. Checkland points out that examination of situations in which excessive feedback causes oscillatory hunting about the desired state led researchers to recognize the essential similarity between hunting in mechanical or electrical control systems and the pathological condition ('purpose tremor') in which the patient, trying to perform some simple physical act, such as picking up some object, overshoots and goes into uncontrollable oscillation.

1. 2. 3. CAUSAL - LOOP DIAGRAMS AND MENTAL MODELS

Forrester (1968) considers that mental models of dynamic systems are ill-defined, not easy to communicate, and that the imprecise nature of language can be used to hide a clouded mental image from both the speaker and the listener.

He argues that mental models cannot be manipulated effectively and that it is not possible to manage in the mind all the facets of a complex system at once. He states that we tend to break the system into pieces and draw conclusions separately from the subsystems, and that such fragmentation fails to show how the subsystems interact.

Forrester adds that by constructing a formal model, our mental image of the system is clearly exposed.

Concerning the fact that it is not possible to have perfect information about a Physical or Social system, in terms of description of reality, Forrester states that

> "Models are then to be judged, not on an absolute scale that condemns them for failure to be perfect, but on a relative scale that approves them if they succeed in clarifying our knowledge and our insights into systems".
>
> Forrester (1968).

For Forrester, when a system is reduced to causal-loop diagrams and mathematical equations, it can then be examined and communicated to others, and we can compute the temporal evolution of variables, so that we can hope to understand reality better.

Roberts (1986) points out that causal-loop diagramming allows a person to communicate, with a few words and arrows, his or her theory of the underlying structure of a problem. She thinks that causal-loop diagramming also aids students in expressing their current level of understanding of a situation, sometimes referred to as their mental model.

Mandinach (1989) shares the same view that the creation and manipulation of models is increasingly recognized as a potentially powerful teaching technique that results in different mental representations of a subject.

Richmond et al. (1987) consider that a causal - loop diagram is really a way of using a closed-loop language to express a mental model created by what they call "laundry list thinking" (the student makes a simple list of the relevant variables necessary to describe the system, as first step in the construction of a causal diagram).

1. 3. USING COMPUTERS

1. 3. 1. LANGUAGES AND MODELLING SYSTEMS

It is possible to find, in the University of London Library, 327 references to problem solving using a computer language - the majority (305) being about BASIC (Beginners All-purpose Symbolic Instruction Code). This probably shows that BASIC is the most widely used language for teaching. There are, approximately, ten times more books about problem solving using BASIC than books about problem solving using other languages such as Pascal, Fortran and Prolog, together.

It is worth mentioning, to exemplify them, some authors who have worked with models written in computer languages. Marx (1984a and 1984b), presents some games designed to teach topics related to Science as, for example, Radioactivity, Chemical Reaction and the Replication game (cell automaton), besides exploring Chaos. He presents a collection of programs written in BASIC.

Crandall (1984), describes equation solving and modelling with graphics, using examples from Mathematics, Chemistry, Physics and Biology. To follow the book, and to get graphical output, the student will need to implement certain lengthy procedures.

Becker and Dorfler (1989) provide large programs, which must be typed into the computer to give graphical output for applications concerning dynamical systems and fractals.

Nowadays, there is a growing tendency to involve computers in the modelling process. However, computer implementation can be very tedious if the knowledge of a programming language is involved.

When analysing the programs presented in these books one is impressed by the fact that only a few lines of code contain the mathematical equations that represent the model which is being studied. The other lines are there to define input and output for the program, especially graphics.

A disadvantage of using such a language for teaching Science, through problem solving, is the fact that the students have to know the principles of programming and to master a specific high level language first (including procedures that must be used to obtain graphs). Besides mastering the language they have to be familiar with the hardware and software.

Computational tools have been developed to ease the exploration of models, and to make the modelling process more accessible to students. These tools can be classified as quantitative and semi-quantitative (see Table 1. 1.).

Quantitative	DMS, CMS, STELLA and Spreadsheets
Semi-quantitative	IQON

Table 1. 1 - Examples of quantitative and semi-quantitative computational tools.

In these systems, the students need not worry about writing code to define graphical output, which demands knowledge and time. The idea is that they should only manipulate icons or write equations and numbers, as needed to define and run the model, and the computer will produce graphs automatically.
The tools presented in table 1. 1 will be discussed in more detail below.

1. 3. 2. CELLULAR AUTOMATA

Ogborn (1990) discusses Cellular automata as a type of computational model, pointing out that the idea of a cellular automaton was derived from Von Neumann, one of the best known instances being Conway's Game of Life[2]. In a cellular automaton, the next state of each individual cell is determined by its present state and by the present state of the neighbouring cells, according to a strictly deterministic rule. Within this framework Von Neumann proved the possibility of a self-reproducing cell automaton in 1953.

A cellular automaton consists of a large array of cells, each of which has a small finite number of states. The state of a cell changes in relation to its own present state and those of its immediate neighbours. Thus the rule for evolution of the system of cells is a local rule, which is the same everywhere. A cellular automaton is a discrete version of the scientific concept of a field.

Toffoli and Margolus (1987) point out that cellular automata can model not only general phenomenological aspects of our world, but also the laws of physics itself. Their approach has been used to provide extremely simple models of common differential equations of physics. They show that the rule may be chosen so that such a system can model for example the diffusion of particles, the propagation of a density wave through a system of particles, the growth of a dendritic crystal, and the interaction of populations of predators and prey.

The rule for its behaviour is a rule about the objects in the system and their relationship to nearby objects. The system is visible to someone watching the evolution of the model, as some pattern of behaviour of the assembly of cells.

Marx (1984 b) presents examples of educational programs, written in BASIC, which use the cellular automaton idea. Cellular automaton-like simulations have direct applications in teaching. One obvious example (Ogborn, 1990), is the predator and prey class of

---

[2] John Horton Conway of Cambridge University created a cellular automaton with the following properties:
1. the law of the game is simple;
2. most junk configurations disappear soon;
3. some structures survive;
4. some structures perform unexpected evolution.
In Conway's Game of Life each cell is either dead (empty) or live(full). Its fate is influenced by its state and by the states of its four neighbours:
Law I. BIRTH: a cell will be born if the empty place has 3 neighbours.
Law II. SURVIVAL: a live cell will survive to the next generation if it has 2 or 3 neighbours.

problems, in which predator cells eat prey cells when they are nearby, or die if they do not eat. Both predator and prey cells can breed new ones of their kind, if there is room.

> "The rules for this problem can be very simple and intuitive, though the problem formulated as a differential equation may be very difficult to solve".
>
> Ogborn (1990).

Other problems such as population growth or radioactive decay can be modelled in the same way. Ogborn argues that such models have the great advantage that the objects one is talking about are directly represented on the computer screen. The behaviour of the whole system is represented by the pattern of behaviour of the objects, not as values of system variables.

Cellular Automata will not be studied in this research. However, it is important to mention the idea because these computational systems (or programs) are capable of describing dynamic systems, as well. I decided to present the Cellular Automata to make it clear that dynamic systems are not necessarily only described by variables and mathematical relations, but can function at the level of objects and rules.

1. 3. 3. SPREADSHEETS

Spreadsheets are computational commercial tools [such as Lotus 123 or Visicalc (for IBM computers) or EXCEL (for IBM and Macintosh)], which have recently been used in research and teaching in Science Education.

Bolocan (1986) introduces EXCEL as a (then) new, sophisticated spreadsheet package that includes graphics, data base functions, and a macro programming language. A Spreadsheet is a sheet of boxes. Numbers are placed in the boxes, which are organized in rows and columns to create tables of numbers. Electronic spreadsheets enable us to change any factor and immediately see how this change affects our table. It is possible to write functions to perform complex numeric calculations or text manipulations. The macro command language makes it possible to write programs that control EXCEL spreadsheets and to create an interface between inexperienced users and a complex EXCEL spreadsheet application.

Osborn (1987) was one of the first to discuss the possibility of using Spreadsheets as a teaching tool in Science. People working in The Computer Based Modelling Project at the Institute of Education University of London have been using EXCEL to develop models to explore topics in Mathematics and Science, for example, "Population Change" and "Heat Flow".

Customised spreadsheets using EXCEL were explored in the Tools for Exploratory Learning project (Bliss & Ogborn, 1990b) for quantitative tasks and were made to appear as user-friendly as possible. Brosnan (1989 and 1990) presents very interesting examples of the use of spreadsheets in Chemistry teaching.

About spreadsheets Ogborn (1987) emphasized that in most of them, one must refer to a cell by its coordinates and calculate cells by expressions such as "A2*B3", which do not carry the meaning of the calculation. Brosnan (1989 and 1990) pointed out as a complicating factor the fact that one has to start by writing equations, and can not visualise the processes being modelled, as in STELLA.

Spreadsheets are important because they can be used as quantitative modelling tools and make possible work with iteration. I decided to give a brief account of Spreadsheets because they have been used in modelling and are the basis of the Cellular Modelling System which will be described in section 1. 3. 4, below.

1. 3. 4. THE DYNAMICAL MODELLING SYSTEM (DMS) AND THE CELLULAR MODELLING SYSTEM (CMS)

As CMS was used in the pilot studies (see chapter 4) and its construction was inspired by DMS and spreadsheets, and since expectations concerning the use of CMS and DMS are discussed in chapter 3, both systems will be introduced here.

Its not the aim to present here an extensive account of these systems. More details about DMS can be found in Robson, K. & Wong, D. (1985), and about CMS in Holland, D. (1988).

1. 3. 4. 1. The Dynamical Modelling System (DMS)

The Dynamical Modelling System is a general purpose tool that makes possible work in both expressive and exploratory learning modes (see section 1. 1. 3). Ogborn and Wong (1984) pointed out that in educational programs the model is hidden from the student, or if not hidden can at most be modified within strict limits, usually by changing parameters. DMS can be thought of as having an empty slot waiting for a model to be written in BASIC and inserted, the rest being occupied with graphics and with facilities for editing models. DMS was designed to help those who know little of computer languages and little calculus. DMS presents a program editor, a slot waiting for a model and a graph plotter as represented in the figure 1. 3 below.

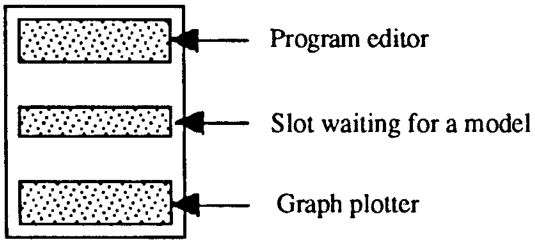


Figure 1. 3 - DMS structure.

Figure 1. 4. shows a possible model and graph for a harmonic oscillator in DMS. Notice that it is possible to see only two modes at the same time. The model has another mode called VALUES where the initial values of variables, and constants, are defined.

MODEL

a = F/m
dv = a*dt
v = v+dv
t = t+dt
dx = v*dt
x = x+dx
F = -k*x

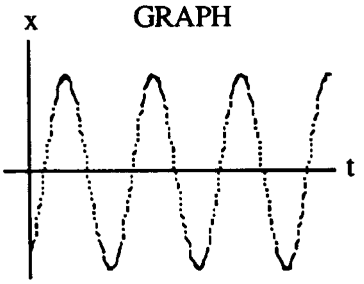


Figure 1. 4 - Model equations and graph in DMS for a harmonic oscillator.

DMS is included because historically it was developed prior to CMS, program which was used in one of the pilot researches (see section 1. 3. 4. 2., below).

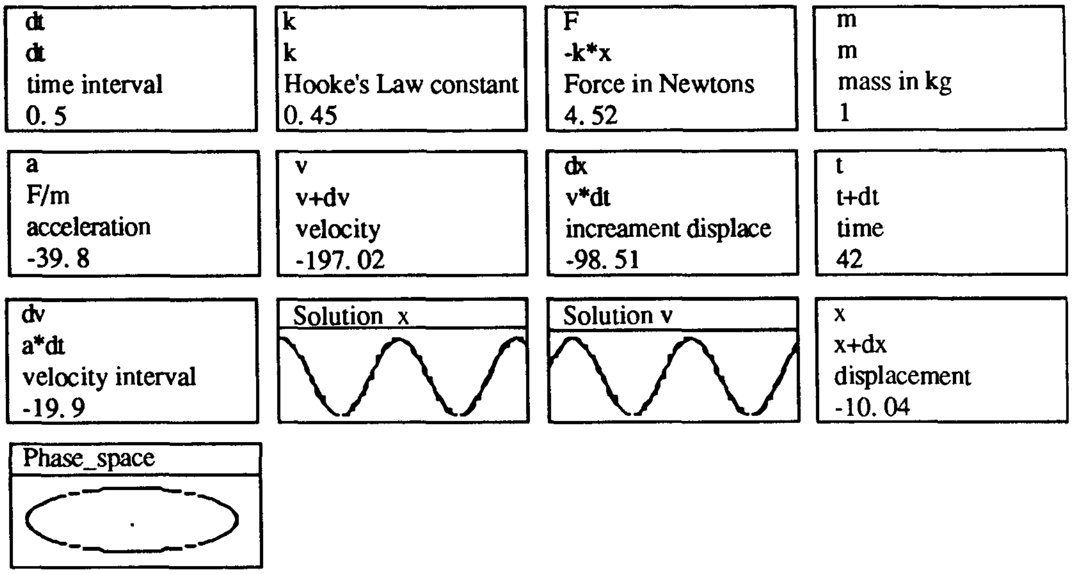
1. 3. 4. 2. The Cellular Modelling System (CMS)

Like DMS, the Cellular Modelling System (Holland & Ogborn, 1987) is a general purpose tool that makes possible work in both expressive and exploratory learning modes.

The basis of the system is a spreadsheet of calculating cells, similar to the cells of a commercial spreadsheet, as presented in section 1. 3. 3.

After identifying variables and proposing mathematical equations to be used to describe a situation, when using CMS the user must define a cell corresponding to each variable which will be calculated by the model. For example, CMS makes it possible to define a cell for the total time **t** which will be calculated by the equation **t = t + dt**, where **dt** is the time interval, which is defined by another cell (see figure 1. 5). The user can write the equation that will calculate each cell as a function of other cells of the model.

It is possible to define calculation cells and graphical cells. When using the system, one is either telling it what to do, or watching it work out results when running. In the calculating mode, the content of cells is worked out and displayed cell by cell, starting at the top left of the screen. Figure 1. 5 shows a possible CMS model for the harmonic oscillator, as it appears on the computer screen.



dt dt time interval 0. 5	k k Hooke's Law constant 0. 45	F -k*x Force in Newtons 4. 52	m m mass in kg 1
a F/m acceleration -39. 8	v v+dv velocity -197. 02	dx v*dt increament displace -98. 51	t t+dt time 42
dv a*dt velocity interval -19. 9	Solution x	Solution v	x x+dx displacement -10. 04
Phase_space			

Figure 1. 5 - CMS model for harmonic oscillator.

The calculation can run continuously, calculating and recalculating the entire spreadsheet, or it can be set to pause to be inspected. The pauses can be either after each interaction, or after any pre-determined number of interactions.

The mathematical equations, which describe a model, must be written in a BASIC - like form. There are available in the system algebraic, arithmetic and other functions. In effect, the system is an array of functions (in the computational sense), each having a name, parameters and yielding a numerical value.

Ogborn (1987) claims that CMS deals with a wide class of problems: most differential equations and finite difference models. It provides the user, whether pupil or teacher, with a powerful set of possibilities, but does not tell the user what to do with these possibilities.

> "... this feature encourages the gradual building up of models from simple and inevitably inadequate beginnings, to more complex and less inadequate later versions, so that the pupil may play some part in the actual development of theory, being less a passive spectator as theory is unfolded . . .".
>
> Ogborn (1987).

In his opinion

> "Such programs should be seen in the context of the existence of a number of computer modelling languages, which may offer more power at the cost of greater complexity".
>
> Ogborn (1987).

Ogborn (1987) stated that the Cellular Modelling System was developed, in the hope of making modelling accessible to younger pupils than those for whom the Dynamic Modelling System was suitable.

1. 3. 5. DYNAMO

Roberts at al. (1983) introduces the DYNAMO simulation language (DYNAMO is an acronym for DYNAmicMOdels). Like the computer language BASIC, DYNAMO is used to direct the computer in the computations it should perform. Unlike BASIC, DYNAMO is not a general-purpose language. It is a special-purpose language to aid in building computer models. DYNAMO, which bases itself on Forrester's principles of systems (see chapter 2, section 2. 2.), eases the task of building and running models.
Suppose we want to model a temperature change. The development of the model of a cup of tea cooling, could start with a causal-loop diagram as in figure 1. 6.

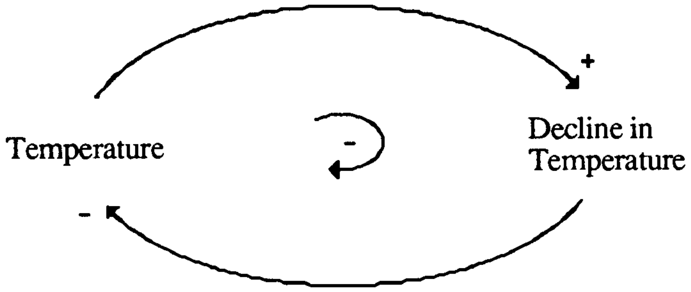


Figure 1. 6 - Causal - loop diagram for the temperature change.

The diagram says that a decline in temperature reduces the temperature, and that the lower the temperature, the smaller the decline.
Based on the causal-diagram one has to develop a flow diagram of the temperature change as in figure 1. 7.

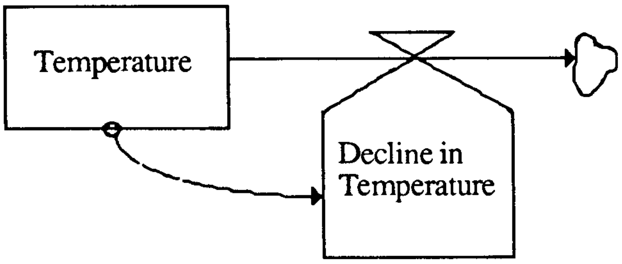


Figure 1. 7 - Flow diagram of the temperature change - not physically realistic (no thermal capacity).

The flow diagram helps in showing the nature of variables (whether rates or levels) and the dependence between them.
Through the flow diagram one can identify how the equations for rates and levels must be written to be run in DYNAMO.
For example, part of a DYNAMO program might be

```
* TEMPERATURE CHANGE
L TEMP.K = TEMP.J + (DT)(-DECLINE.JK) DEGREES
N TEMP = 80
R DECLINE.KL = DIFF.K/T  DEGREES/MINUTE
C T = 12 MINUTES
A DIFF.K = TEMP.K - ROOMTP DEGREES
C ROOMTP = 20  DEGREES
.
.
.
```

being written in a syntax which distinguishes rates, levels and initial values.

When modelling with DYNAMO one has to know what the equations of the model are and how to write the equations in the system. DYNAMO makes it possible to print values of variables, and plot graphs of variables against time.

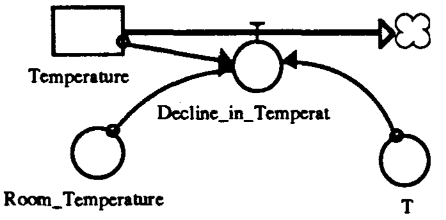
DYNAMO is available for the APPLE microcomputer and for most mini and mainframe computers. It is historically the precursor of STELLA, one of the modelling systems chosen to be used in the research, which will be presented in the next section.

1. 3. 6. STELLA

STELLA (Structural Thinking Experimental Learning Laboratory with Animation) (Richmond et al., 1987) is a computer tool which was a natural evolution of the DYNAMO environment. Developed for the Apple Macintosh computer it is a quantitative modelling tool that uses a metaphor of pipes, valves and tanks.

In STELLA a tank ▦ (stock, level) represents a quantity which can increase or decrease, from some starting value. It is convenient to represent the variables related to accumulations during the passage of the time by tanks (or stocks). A tap ⧖ (rate) connected to a tank decides how quickly the amount in the tank is changing. Several taps can be connected to one tank. Quantities represented by ○ (convertor) can be constants, or can be calculated from other quantities.

STELLA makes possible the construction of a model through the linking of these basic objects and, unlike DYNAMO, the user does not have to think about what lines of program to write. S/he has to write algebraic relations but the system converts these into program lines. STELLA allows a graph to be plotted of any variable against any other, and against iterations, and generates a table of data. Figure 1. 8 presents in STELLA the diagram, equations and graph for the same tea cooling model shown before in DYNAMO.



Temperature = Temperature + dt * (-Decline_in_Temperat)
INIT(Temperature) = 80
Decline_in_Temperat = (Temperature-Room_Temperature)/T
Room_Temperature = 20
T = 12

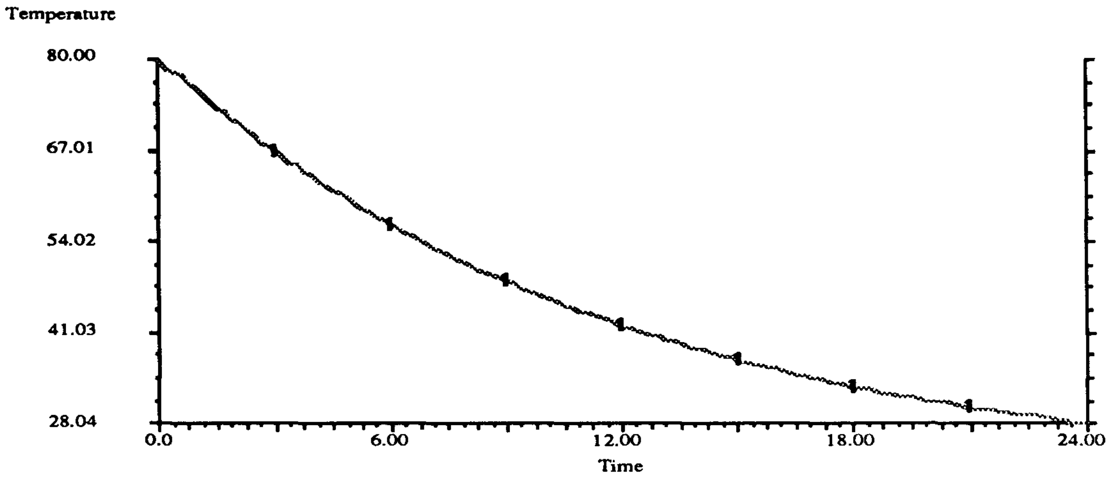


Figure 1. 8 - Diagram, equations and graph for the STELLA model of tea cooling - not physically realistic (no thermal capacity).

STELLA is a very flexible tool. The animated diagram, graphs, table and equations are all accessible. The graph pad allows work with five different graphs within the same model.

In STELLA the physical systems that can most easily be modelled are those directly associated with its visual metaphor, such as hydraulic systems. An obvious example of these systems is a "leaky tank", having its flux controlled by a valve. In this system, STELLA would show the water level decreasing, during the running of the model on the computer. Of course, not only hydraulic systems can be represented through STELLA's metaphor.

The visual metaphor is of a tank , leading to the expectation that an empty tank represents zero, and that negative values cannot exist. In the underlying metaphor, however, a "tank" can contain negative values, and the relation between the values in it and the picture on the screen is chosen by the user.

There are many physical processes that can be represented in STELLA which have no direct representation in the visual metaphor. For example, momentum could be represented by a tank, and its variation by the level change in the tank. Obviously, the variation of the momentum in time, which represents the force, would have to be expressed by a valve (see figure 1. 9).

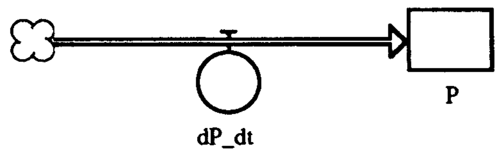


Figure 1. 9 - Momentum represented by a tank and the force by a valve in STELLA. Remember that F=dP/dt.

Due to its visual metaphor, I argue that STELLA is <u>not</u> suitable for modelling any kind of situation in any kind of subject. It makes the system inflexible if someone is interested in developing activities mainly in Physics, for example (see section 3. 3. 2.).

1. 3. 7. WHAT DMS, CMS AND STELLA HAVE IN COMMON

CMS, DMS and STELLA make possible work with quantitative dynamic models, perhaps the best known kinds of model, at least in Science. The user has to formulate how the important variables that describe a system change in time, as a result of the values of other variables and constants. The rules for the evolution of a system, expressed by differential equations, are thus the rules for computing the next value of each variable. These systems iteratively solve finite difference equations that are discrete approximations to differential equations. The difference equation for WATER VOLUME in a leaky tank, for example, is

WATER VOLUME $_t$ = WATER VOLUME$_{t-\Delta t}$ - Δt*(OUTFLOW RATE)
where
OUTFLOW RATE = - CONSTANT * f(WATER VOLUME)
and
WATER VOLUME $_{t=0}$ = any suitable value

The simplest solutions may use Euler's method, though other methods also may be provided for. See section 2. 7. 3. for a detailed description of the Leaky Tank problem. When using these systems the student does not need to know how to solve a differential equation analytically.

The computer can generate graphical or tabular output and the modeller must interpret the solutions through such output. These multiple linked representational systems (see Fey, 1989 and 1990) make it possible to move quickly between iconic or algebraic representations of the model, and graphic and tabular representations of the solution.

1. 4. MODELLING WITH COMPUTERS AT A SEMI-QUANTITATIVE LEVEL

1. 4. 1. ON ANIMATING CAUSAL DIAGRAMS - IQON

The researchers linked to the "Tools for Exploratory Learning" project (Miller, R., Brough, D. and Ogborn, J., 1989) proposed to develop a semi-quantitative tool, and made it clear that this would require fundamental thinking about the nature of the primitives and how these might be implemented. Ogborn (1990) presented what he called a semi-quantitative model, as in figure 1. 10 - a causal diagram that shows relationships and the directions of their effects.

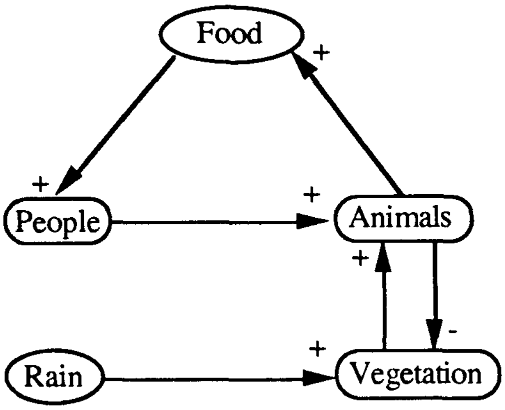


Figure 1. 10 - Semi-quantitative model.

Bliss & Ogborn (1990a) presented the reasons and justification for choosing the causal - loop representation as a starting point for developing a representational formalism for semi-quantitative modelling. According to them, causal - loop diagrams are a common starting point for those engaged in the business of mathematical (i.e., quantitative) modelling. One of their motivations for developing a semi-quantitative modelling environment, was that it can serve as a pre-cursor to mathematical modelling. They added that causal - loop diagrams can be used to represent complex systems and are easily extendible. This makes them a useful utility when engaged in "real life" problems and tasks. The symbolism employed in such diagrams seems to reflect a natural intuition about many systems. Causal - loop diagrams only give a limited indication of the likely algebraic structure of expressions.

Ogborn presented the idea of building modules that represent quantities where one says nothing about absolute values, but recognises change. He pointed out that a model could be built out of linking together identical modules and that links should transmit positive or negative influences, from the output of one module to the input of another. At each iteration the inputs to each module would have to be summed, and added to its current value. Ogborn suggested, based on the mathematics of Neural Networks, an updating rule for a module to run as a dynamic model. The current value a(t) of a module becomes a(t+1), when weight w_j is given to the input $i_j(t)$ from the jth module, where:

$$a(t+1) = a(t) + \sum_j w_j i_j(t) * [1 + a(t)] * [1 - a(t)]$$

The output from a module is just its value a(t), and the strengths and signs of links are given in the weights w. The reason for the non-linear response function

$$[1 + a(t)] * [1 - a(t)]$$

was to limit the range of values of a quantity to between plus and minus one, since without it the value could rapidly go off to infinity.

Ogborn discussed an alternative approach that would make models relax to a stable configuration, through the modification of the iteration rule to

$$a(t+1) = a(t) + \sum_j w_j i_j(t) * [1 + a(t)] * [1 - a(t)] - k * a(t)$$

exactly the form of the rule used in parallel distributed networks, in the relaxation approach to modelling the brain.

The researchers intended to define, in addition, a simple graphic modelling facility, for pupils to see qualitative interactions at work, without having to consider the exact functional relations between variables. The models developed through the new tool would work with "hidden numbers".

Ogborn (1990) argues that when trying to understand a situation, one often has too little knowledge to form an exact quantitative model, but one does often have a reasonable semi - quantitative idea of the working of a system, and could make such causal diagram (which he named a semi - quantitative model) where one could show relationships and the directions of their effects. Following that discussion he presents some aspects of the prototype of the semi-quantitative tool, developed by the "Tools for Exploratory Learning" project, and some hypotheses and proposals. He argues that the way pupils learn models is far from ideal, because they first learn functional relations between quantities (Newton's laws, etc.) and, after that, develop advanced mathematics. He argues that perhaps one should reverse the normal order, beginning with semi-quantitative models, learning from them about variables and causal relations, then later seeing how the use of well - defined relationships in similar models can give more precise answers, in numerical simulations. His proposal is to concentrate from the beginning on form, "defined at first loosely and then more precisely".

Briggs (1989), developed in Hypercard, a prototype of a semi-quantitative modelling tool, called BOX MODELLER. It used the metaphor of filling and emptying tanks, but some pilot work with children showed that this metaphor was not suitable, because an empty tank implies a zero or rest level, rather than a 'much lower than normal' level.
Miller et al. (1990) introduce **IQON** (Interacting Quantities Omitting Numbers) - the semi-quantitative modelling tool, based on BOX MODELLER, implemented in SMALLTALK, and having two kinds of primitives: a continuously-valued variable or 'box' that can take a range of values above or below a 'normal' level and 'negatively and positively affects' links to represent relationships that imply incremental change. Figure 1. 11 shows the iconic representation of boxes and links.

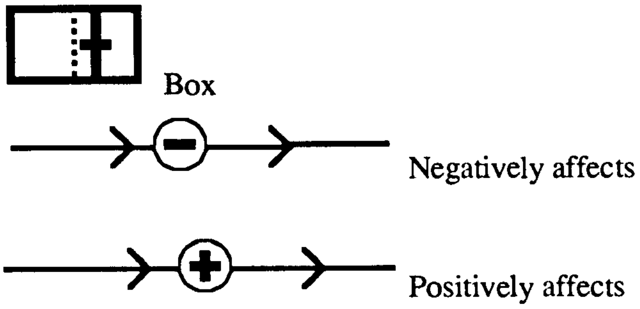


Figure 1. 11 - Iconic representation of boxes and links. Primitives in IQON.

The authors hope that thinking about systems and variables can be made accessible to people, particularly younger children, who could not yet cope with quantitative simulation, but for whom such a system might be a bridge to more quantitative modelling.
Finally, the authors recognise that although IQON can be used to model a variety of systems, it does not represent properly some important types of continuously - valued parameters. But, they proposed some extensions of the tool to deal with these.
They add that the "rough and ready" models resulting from such an environment may not be precise and accurate - they may be ambiguous in some respects - but should be a useful aid in supporting the user's own reasoning about the domain in question. The inevitable limitations of a system might even serve as a motivation for more traditional mathematical modelling later.
Their approach has thus been to develop an environment that provides computer processing of causal - loop diagrams. Constructing causal - loop diagrams involves identifying system variables, and assigning the (somewhat ambiguous and vague) directional relations "positively affects" or "negatively affects" to pairs of them.
IQON's primary task is to interpret causal - loop diagrams in a consistent way, to construct an underlying dynamical mathematical model whose behaviour (roughly) corresponds to the modeller's original intentions. The "affects" links in a causal - loop diagram are ambiguous, and offer only a limited indication of acceptable mathematical

relationships between variables in a particular model. But an analysis of dynamic modelling shows that these individual causal relationships are generally one of two basic types, which are "gradual" and "immediate" effects. A gradual effect influences the way a variable's value is changing in time, whereas an immediate effect influences the actual value of a variable itself. In mathematical modelling, gradual effects correspond to expressions describing a variable's rate of change, whereas immediate effects correspond to functions defining one variable in terms of others. This is the same idea about levels (accumulation) and rates in DYNAMO or STELLA, discussed before.

1. 4. 2. A MODEL FOR THE GREENHOUSE EFFECT IN IQON - AN ILLUSTRATION

Figure 1. 12 presents a model for the Greenhouse Effect in IQON, as it appears on the computer screen. Notice the boxes that represent the main variables which describe the situation. "Energy radiated", for example, is the amount of energy radiated or reflected back into space from earth. "Land clearance" is the amount of land cleared for building and agriculture and "Sun's radiation" is the amount of energy reaching the Earth from the Sun. The meaning of the other boxes can be easily understood.

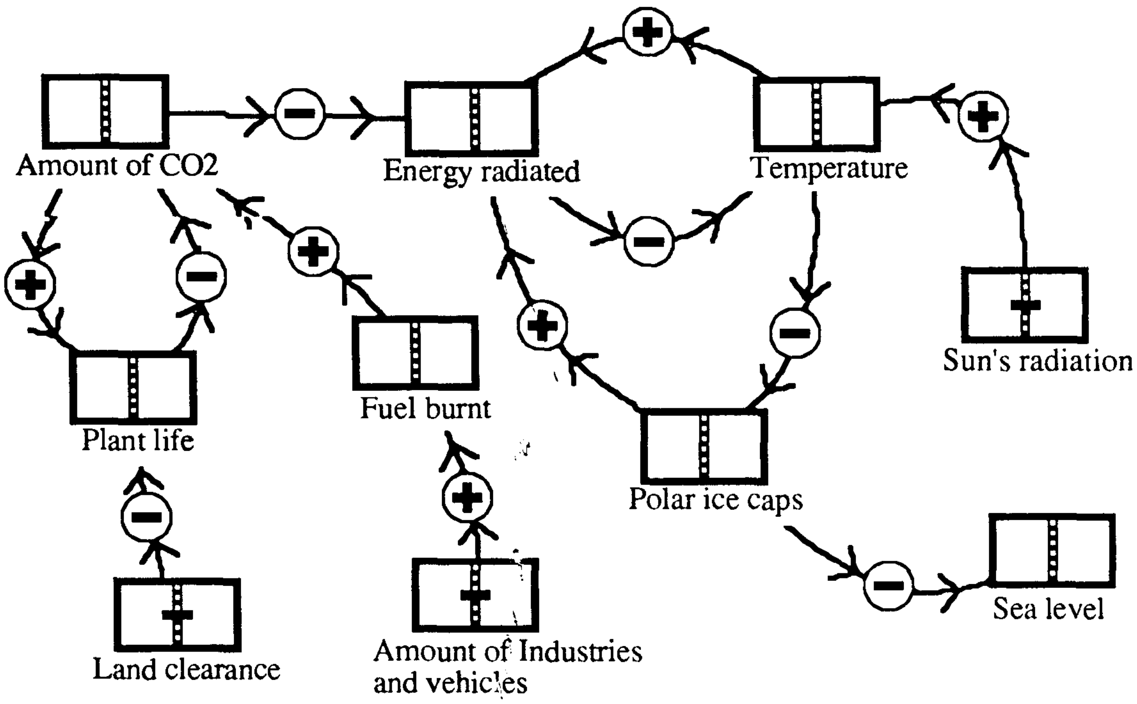


Figure 1. 12 - IQON model for the Greenhouse Effect - an example.

CHAPTER 2 - THEORY OF MODELLING AND A MODEL OF LEARNING ABOUT MODELLING

2. 1. INTRODUCTION

The purpose of this chapter is to present the theories which were used to inform the research.

I will present a brief account of Forrester's Principles of Systems and Forbus' Qualitative Process Theory (QP), and will draw a parallel between both theories. I will also present some ideas about causation and association, derived from Bunge.

Finally, I will present my ideas about dynamic behaviours and kinds of models, and a model for teaching and research into computational modelling.

2. 2. FORRESTER'S PRINCIPLES OF SYSTEMS

Consider a tank that is being filled with water. The height of the water is a level. The level depends on the accumulation produced by the past flow of water, but the level is not determined by how fast water is being added at the present instant. A large stream into an empty tank does not imply a full tank, and an already filled tank is not affected if the flow ceases entirely (Forrester, 1968).

Forrester considers that there are two fundamental types of variable elements within a loop -- the levels, and the rates. Levels (states) and the rates (actions), except for constants, are sufficient to represent a feedback loop.

The level variables accumulate the flows described by the rate variables. The level equations perform the process of integration. The rate variables tell how fast the levels are changing. They determine, not the present values of the level variables, but the slope (change per time unit) of the level variables. Forrester argues that the rate equations are the policy statements that describe action in a system, that is, the rate equations state the action output of a decision point in terms of the information inputs to that decision. The rate variable does not depend on its own past value, nor on the time interval between computations, nor on other rate variables (Forrester, 1968). Thus to Forrester an averaged rate is a system level variable, not a rate variable. The true rate is the instantaneous action stream that is being averaged.

Because some interval of time is necessary to measure and transmit information about any rate, Forrester argues that no rate at one instant can depend on other rates at the same instant. He points out that rates do not act directly on other rates but only by first being averaged (and these averages contain accumulations or integrations and involve level variables), so that the beginner should strictly avoid any rate - to - rate coupling in a model. The value of a rate variable should depend only on constants and on present values of level variables.

Forrester (1968) considers that a feedback system has a closed loop structure that brings results from past action of the system back to control future action (see chapter 1, sections 1. 2. 1 and 1. 2. 2). He presents the basic structure of a feedback loop as in figure 2. 1, and explains that

> "the feedback loop is a closed path connecting in sequence a decision that controls action, the level of the system, and information about the level of the system, the later returning to the decision-making point".
>
> Forrester (1968).

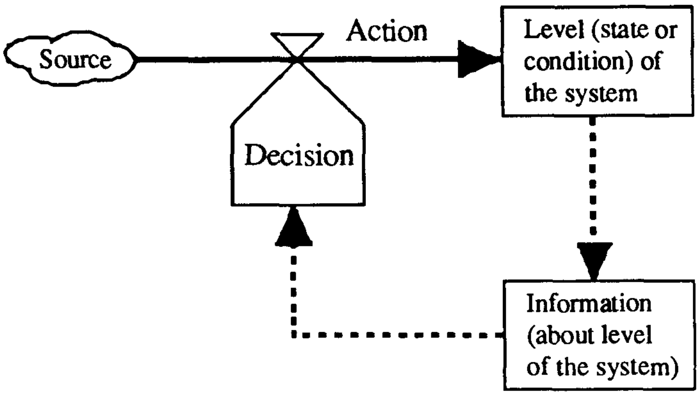


Figure 2. 1 - Forrester's feedback loop.

He adds that

> " the available information, as it exists at any moment, is the basis for the current decision that controls the action stream. The action alters the level of the system".
>
> Forrester (1968).

Forrester argues that whether a system should be classified as an open system or a feedback system is not intrinsic to the particular assembly of parts, but depends on the observer's viewpoint in defining the purpose of the system.

2. 3. FORBUS QUALITATIVE PROCESS (QP) THEORY

Qualitative Process Theory (QP) is an AI theory in 'Qualitative Physics'. Only some QP ideas are discussed in this section.

2. 3. 1. QP, QUANTITIES AND OBJECTS

The representation of how things change is a central problem in common sense physical reasoning. In Physics, *dynamics* describes how forces cause changes in physical systems. For any particular domain, a dynamics consists of identifying the kinds of "forces" that act between the classes of objects in the domain and the events that result from these forces (Forbus, 1985 based on Forbus 1982).

Forbus argues that reasoning about the physical world requires reasoning about the kinds of changes that occur and the effects that result. He considers qualitative descriptions important because they show the results of reasoning with incomplete information, and this information generally only allows one to propose alternatives rather than a single prediction.

In Qualitative Process theory (QP) the continuous parameters of an object, such as mass, temperature, and pressure, are represented by quantities, and a quantity consists of two parts, an amount and a derivative (intuitively the time derivative), each of which are numbers. Higher-order derivatives can be expressed constructing quantities whose amount is equal to the derivative of the original quantity.

Forbus points out that objects can come and go, that their properties can change dramatically, and that some of the changes depend on values of quantities. For example, when the amount of water in a tank becomes zero we can consider that the water (object) has gone, and when a spring breaks it does so at a particular length.

2. 3. 2. PROCESSES AND QP TENETS

Qualitative dynamics is a theory about the kinds of things that can happen in a domain. Forbus claims that such theories are organized around the notion of physical processes. It is possible to predict how a situation will change and evolve over time if we use processes to describe what is happening in the situation.

Qualitative Process theory (QP) includes in its ontology of common sense physical models the notion of a physical process. Forbus understands processes as including for example boiling, flowing, and stretching, all processes that cause changes in physical situations. To Forbus, the collection of active processes constitute the description of "what is happening" in any situation. Thus, processes represent activities that are occurring in physical situations. A physical process acts through time to cause changes, and the central assumption of the QP theory is that

> "only processes directly influence quantities and that functional dependencies are the causes of indirect changes".
> Forbus (1985).

Thus processes provide the mechanisms of change. This is introduced as the *Sole Mechanism* assumption:

> "all changes in physical systems are caused directly or indirectly by processes".
> Forbus (1985).

To Forbus what distinguishes a process is that it has *influences*, that is, a set of quantities that it directly affects. A changing quantity is said to be influenced directly or indirectly by a process or processes. If a process P influences some quantity Q and some other quantity R is qualitatively proportional to Q (represented by $\mathbf{R} \propto_{Q+} \mathbf{Q}$ - meaning that there exists a function which determines R and is increasing monotonic in its dependence on Q), then we say that P indirectly influences R.

Forbus adds that as a consequence, the physics for a domain must include a vocabulary of processes that occur in that domain. This is the specification of the dynamics theory for the domain.

> " A situation is described by a collection of objects, their properties, the relations between them, and the processes that are occurring ".
> Forbus (1985).

2. 3. 3. CAUSAL REASONING IN FORBUS' QP THEORY

Forbus points out that causal reasoning is specially important for understanding physical systems. It has been noted that in causal reasoning people do not use equations in all possible ways, and that

> "only certain directions of information flow intuitively correspond to causal changes ".
> Forbus (1985).

Forbus proposes the *Causal Directedness Hypothesis* :

> "changes in physical situations which are perceived as causal are due to our interpretation of them as corresponding to direct changes caused by processes or to propagation of those direct effects through functional dependencies ".
> Forbus (1985).

Causality requires some notion of mechanism, and processes are the mechanisms which directly cause changes (Forbus, 1985).

2. 3. 4. DESCRIPTION OF GENERAL DOMAINS

Many important kinds of change are not strictly physical, for example in Economic and Social systems. Forbus and others such as De Kleer and Brown (1983) for example, have described simple physical systems, for which the "right answers" are more or less evident. But their aim is broader. Forbus argues that a full theory of action should have Dynamics as the most approachable subset.

Bhaskar et al. (1990) considers as the greater challenge for qualitative physics and artificial intelligence the description of systems where the underlying Physics knowledge is not yet understood or computed.

2. 3. 5. FORRESTER'S PRINCIPLES OF SYSTEMS AND FORBUS' QUALITATIVE PROCESS THEORY

Forrester's Principles of Systems present levels and rates as the main kinds of variables needed to describe a feedback or dynamic system. As we have seen in chapter 1, STELLA (and DYNAMO) is based on Forrester's principles because it presents as basic elements stocks, flows and convertors. In consequence, a convenient way of looking at variables is trying to recognize what could be represented as levels or rates. It would be wise to make this distinction when drawing a causal-loop diagram for the situation, and a good way is try to think of a quantity as composed of a level (stock) and a corresponding rate (flow) as in figure 2. 2.

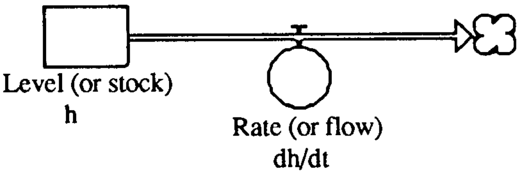


Figure 2. 2 - Flow diagram representing a level (or stock) and its corresponding rate (or flow).

When describing a system, the aim would be try to recognize pairs of stocks and flows that should be linked together, producing a series of coupled differential equations, of the following form

$$\frac{dy1}{dt} = f1 (y1, y2, ... , t)$$

$$\frac{dy2}{dt} = f2 (y1, y2, ... , t)$$

which model the situation.

The flow diagram makes possible work at a semi-quantitative level, as well. Without worrying about defining equations, the user can make a complete, if possibly still ambiguous, representation of the system, on the computer screen or on paper.

The conception of variables as levels and rates, by itself, can be used as a framework for analysing entities used by students when developing diagrams in STELLA, causal diagrams and even IQON models. Like Forrester's principles, Forbus QP theory promotes some similar thoughts about the analysis of entities in models, as we will see below.

To Forbus, a quantity consists of two parts, an amount and a (time) derivative, each of which are numbers. This pair of amount and derivative, corresponds to Forrester's pair level and rate. Hence, the interpretation of one of Forrester's diagrams (as in STELLA) and the QP assumptions seem to show that both approaches appear to be able to represent semi-quantitatively the same situations.

The main aspect of Forbus' QP theory seems to be the concept of <u>process</u>, as causal action.

Thus both QP theory and Forresters' system dynamics suggest that we should look for amounts and derivatives in students' causal diagrams. Besides that, the diagrams could present explicit representations of processes affecting quantities. For example, in the diagram below, the process of Heating is being shown as responsible for changes in Temperature.

Heating ----------> $^+$ Temperature

Forbus considers that the existence of objects may be dependent on values of some quantities. This suggests looking to see whether students, in reasoning about dynamic systems, find themselves using objects as entities in diagrams, instead of the expected quantities.

2. 4. CAUSATION AND ASSOCIATION

The aim of this section is to present some of Bunge's ideas concerning causation and association, which seem to me to be very much related to the ideas of Forbus.

2. 4. 1. BUNGE'S IDEAS ABOUT THE CAUSAL PRINCIPLE

Bunge (1979) initially defined the causal principle as

If C, then E,

and pointed out that C and E could be read as designating "singulars belonging to any classes of concrete <u>objects</u> - <u>events</u>, <u>processes</u>, conditions and so on, ...".

He added that C and E should refer to a limited number of features, and not to the unlimited richness of real events. In his opinion, it might be appropriate to consider C and E as "kinds of free variables".

Bunge considered that the relation between the two variables should hold always, for all values of the variable - the causal connection is supposed to hold universally. Consequently he restated the causal principle as

If C, then E always,

Bunge discussed the *conditionalness* of the causal principle, since *If C* states the clauses or conditions for the occurrence of E, and the *asymmetry, or existential succession* principle that the cause is existentially prior to the effect, but need not precede it in time (though there may be a time delay between C and E).

Bunge points out that one possible objection to considering the last definition as an adequate description of the causal bond could be that it does not account for the uniqueness of the causal bond (a one-to-one correspondence between C and E). That is, multiple causation is allowed, since C may denote any of the sufficient causes for producing the effect E, as shown in the figure 2. 3 below.

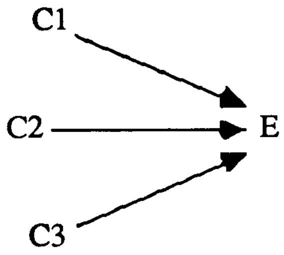


Figure 2. 3 - Multiple causation.

Bunge avoids the possible objection adding *uniqueness* to the causal bond and states the causal principle again, this time as

If C, then (and only then) E always.

One could argue that, when dealing with systems of interacting entities, multiple causation will often be present, since the same effect can be obtained from different causes. For example, for the case of a tank of water, the flow of water is affected, at the same time, by the pressure of water and by the size of the hole.

Bunge comments that giving values to the variables C and E is a way of seeing whether the singular propositions are causal or not. He presents as examples "wars cause worries" and "red apples are sweet", and says that the former proposition is clearly causal, while nobody would accept that the quality redness would cause sweetness. He argues that both propositions fit the Humean formula *If C, then E always* and that this means that it "is not specific enough to be considered as an adequate conceptual reconstruction of the causal bond".

Bunge comments that a law of correlation is not a causal law, because it does not state that "a given entity (or change in it) is *produced* by another entity (or change in it), but just that the two are regularly associated" (or go together). He adds

> " the genetic, productive element is absent - and this productivity is chiefly what renders the cause-effect connection essentially unsymmetrical".
>
> Bunge (1979).

He thus adds *production* and presents a new and now in his opinion adequate formulation,

If C happens, then (and only then) E is always produced by it,

and explains that the proposition means that every event of a certain class C produces an event of a certain class E.

Bunge considers the following concepts as essential components of causation and that they are included in the previous and last proposition: *conditionalness* ; *uniqueness ; one-sided dependence* of the effect upon the cause; *invariability* of the connection, and *productivity,* or the generative nature of the link.

2. 4. 2. BUNGE AND FORBUS

I argue that one-sided dependence on the effect upon the cause, which means that a link can be read in one direction only, is concerned with the idea that "only certain <u>directions of information flow</u> intuitively correspond to causal changes". (Forbus, 1985).

For example, the link

size of the hole ---> + how fast the water drains out

suggests that, for a given set of initial conditions, the size of the hole is responsible for the flow of water. For a rigid tank, it does not make sense to suppose that the flow of water would be responsible for changes in the size of the hole. The flow of water is a function of the size of the hole, and not the other way around. Then, following Forbus, one could say that there is a certain direction of information flow.

However, the link

volume of water ---->+ depth of water,

is an association, and could be read in both directions. It makes sense to say that depth of water could be calculated from the volume of water and that the last could be calculated from the former.

In addition, the productivity of the link, I argue, is concerned with the idea that only processes are the <u>mechanisms which directly cause changes</u> (Forbus, 1985).

In the previous examples, there is a causal connection between the size of the hole and the flow of water. Changes in the size of the hole, which would involve an action of some kind (a process), will <u>produce</u> changes in the flow of water. However, volume and depth of water are not produced by each other, they are correlated - there is no production, they just go together.

Finally, there is production, as well, when effects of processes are transmitted, through functional dependencies, to other parts of a system. For example, changes in depth of water affect the pressure of water at the outlet, which will affect instantaneously the flow of water. One could say that the effect of the process responsible for changes in depth of water ("opening a tap to put water in the tank", for example), for a given set of initial conditions, is transmitted through functional dependencies ultimately affecting the flow of water.

2. 5. USE MADE OF THESE IDEAS

The ideas of Forrester, Forbus and Bunge were used in this research to produce guidelines for what to look for in student's construction of models. The research did not test these theories, nor does it rest on them as foundations. Rather, they provide a vocabulary for looking at how students work with modelling tools.

2. 6. DYNAMIC BEHAVIOUR AND KINDS OF MODEL

This section introduces a general map of dynamic behaviours and examples of models, which was used as a framework for choosing the kinds of tasks which would be sensible to use with students.

It is common to find in the mathematics teaching literature an emphasis on teaching modelling through case studies (e.g., see James & McDonald, 1981; Burgues & Wood, 1984). The problem is to know what case studies to choose and how to develop them, if one's purpose in teaching is not merely to give a few samples of computational modelling, but is rather to teach students systematically how to make computational models and how to choose between kinds of model. Such an orientation is necessary if one is teaching modelling in the context of teaching Science or Technology.

I shall argue that one way of choosing between models is to have them show a good range of kinds of dynamic behaviour.

Dynamic behaviour, is the pattern of change in a system over time. It is shown by the graphs of key system variables plotted against time (Roberts et al., 1983).

Aiming to begin making choices about what to do in the research in terms of tasks and questions to be asked, a review of examples in literature of modelling suggests distinguishing the six generic types of dynamic behaviours:

Linear Process;
Build-up Exponential;
Exponential Growth;
Exponential Decay;
Logistic Process plus chaos and
Oscillations.

Table 2. 1 shows some differential equations and possible graphical outputs. They cover the majority of problems found in Science Education.

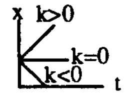
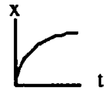
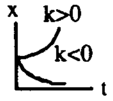
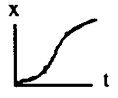
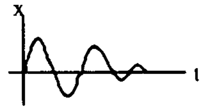
	Linear process	**Build-up exponential**	**Exponential growth and decay**	**Logistic process**	**Oscillations**
Differential Equation k,M,m,b constants	$\frac{dx}{dt} = \pm k$	$\frac{dx}{dt} = k(M - x)$	$\frac{dx}{dt} = \pm kx$	$\frac{dx}{dt} = kx(1 - \frac{x}{M})$	$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0$
ORDER	1	1	1	1	2
LINEAR	YES	YES	YES	NO	YES
Possible graphical solution					

Table 2. 1 - Differential equations and possible graphical solutions.

Figure 2. 4 shows examples of models and how each case relates to the generic dynamic behaviours. It is a general map which suggests a broad spectrum of possible kinds of activities to be developed in modelling. These activities were selected by a criterion of analogy between mathematical structures (equations and dynamic behaviours) (see table 2.1).

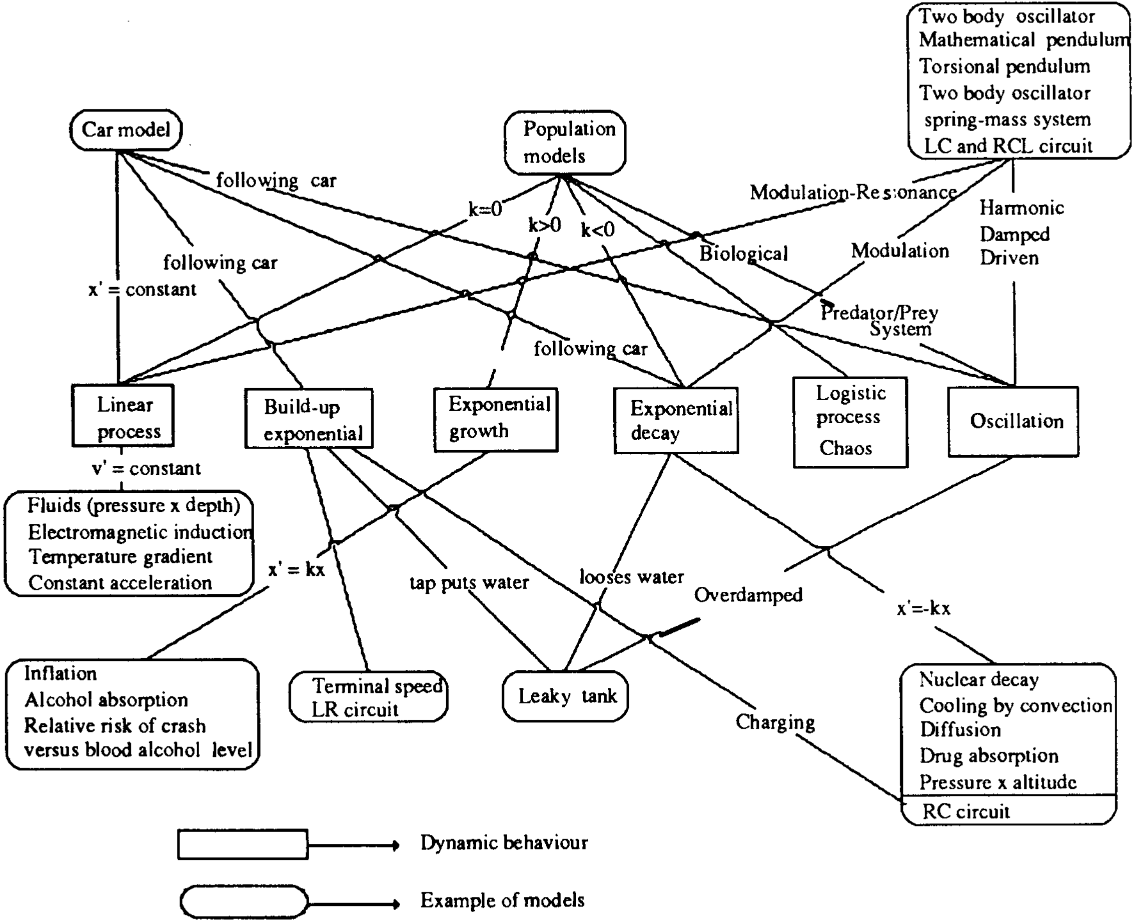


Figure 2. 4 - General map of activities showing dynamic behaviours for kind of model and some differential equations.

As it would not be possible to work with all the examples of models shown in figure 2. 4, I decided to choose some examples that could be considered at an intuitive level - that is, examples about which students should have some previous knowledge, from instruction or everyday experience. I thought that this would make the tasks or questions more motivating for the students. For that reason I decided not to involve "electrical" models, and to initially restrict the examples to the ones shown in table 2. 2.

Table 2. 2 presents dynamic behaviours for part of the models used as bases for questions in the main questionnaires of the research and in intensive study tasks (for details of these questions and models see Appendix I.1 - questions 13, 14, 15, 16, 19, 20 and Appendices III. 1 and III. 2). However, the instruments and the research design will be explained in detail in chapter 5.

Model x Pattern	Two cars in a stream of traffic	Leaky tanks	Population models	Pendulum
Linear	√		√	√
Build up	√	√		
Exponential Growth			√	
Exponential Decay	√	√	√	√
Logistic			√	
Oscillation	√	√	√	√

Table 2. 2 - Dynamic patterns for some kinds of model.

The table shows explicitly where analogies between models can be explored in terms of mathematical structure and graphical output. For example, in a Population model, we have as possible graphical output a linear process, an exponential growth, an exponential decay, a logistic process and oscillations (biological models). On the other hand, exponential decay appears in Two cars in a stream of traffic, Leaky tanks, Population models and Pendulum. Oscillation happens in Two cars in a stream of traffic, Leaky tanks (through overdamped oscillations), Population models (biological models), and Pendulum.

2.7. A MODEL FOR TEACHING AND RESEARCH INTO COMPUTATIONAL MODELLING

2.7.1.THE NEED FOR AN INSTRUCTIONAL MODEL FOR COMPUTATIONAL MODELLING

Since the research concerns the use of computer modelling systems, I felt the necessity to try to define a model for teaching and research into computational modelling. The idea was to have initial guidance for

(1) planning the work with students,
(2) defining the questions to ask in the research and
(3) defining the structure and content of instruments to be developed.

I took as a starting point, developing it for the case of computational modelling, a seven stage model of mathematical modelling (Open University 1981; Burgues & Borrie 1981), as shown in Figure 2. 5 (the ideas in this section were presented in Kurtz dos Santos, A. C. & Ogborn, J., 1992, included in Appendix XII).

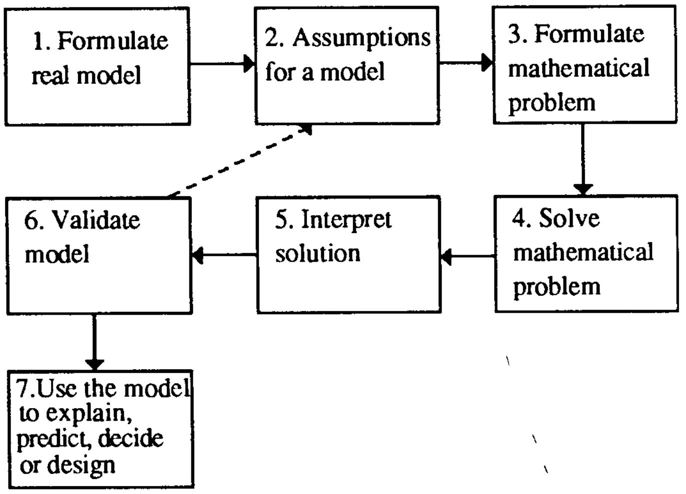


Figure 2. 5 - The mathematical modelling process. The seven stage framework.

My framework goes beyond the model of Figure 2. 5 in a number of respects. First, I will regroup some of its elements, and analyse some of them in greater detail, paying attention to some important interconnections. Secondly, I will develop it by introducing a second level: where Figure 2. 5 concerns the level of creation of a given model, I add a second level of learning *about* modelling, through the construction of a series of models. Thus I will present both a framework for the computational modelling process and a framework for generalizing from particular models. The two frameworks are of course related. Thirdly, I will analyse stages 1, 2 and 3 of Figure 2. 5 in terms of the use of *causal diagrams*.

2. 7. 2. THE MODEL IN OUTLINE

Figure 2. 6 shows the seven stages of Figure 2. 5 regrouped into five areas A-E

Area A	*Choice of system to be modelled*
Area B	*Mechanisms of causation, identification of variables*
Area C	*Type of model required*
Area D	*Generation of output from model*
Area E	*Interpretation, checking, validation and use*

These areas apply to the level of the construction of a given model. To them in Figure 2. 6 I add a further area (see figure 2. 7), belonging to the second level of learning about models:

Area F	*Generalise, learn structures*

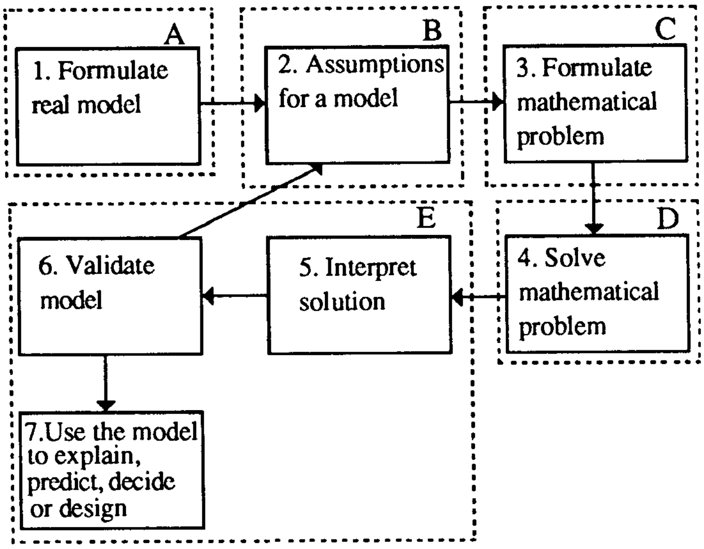


Figure 2. 6 - The model of Figure 1 regrouped in five areas.

Figure 2. 7 shows these areas developed in greater detail, with interconnections between them. I will first discuss what Figure 2. 7 suggests about teaching strategies at the level of constructing a model (areas A to E), and then what may be said about learning about modelling (area F).

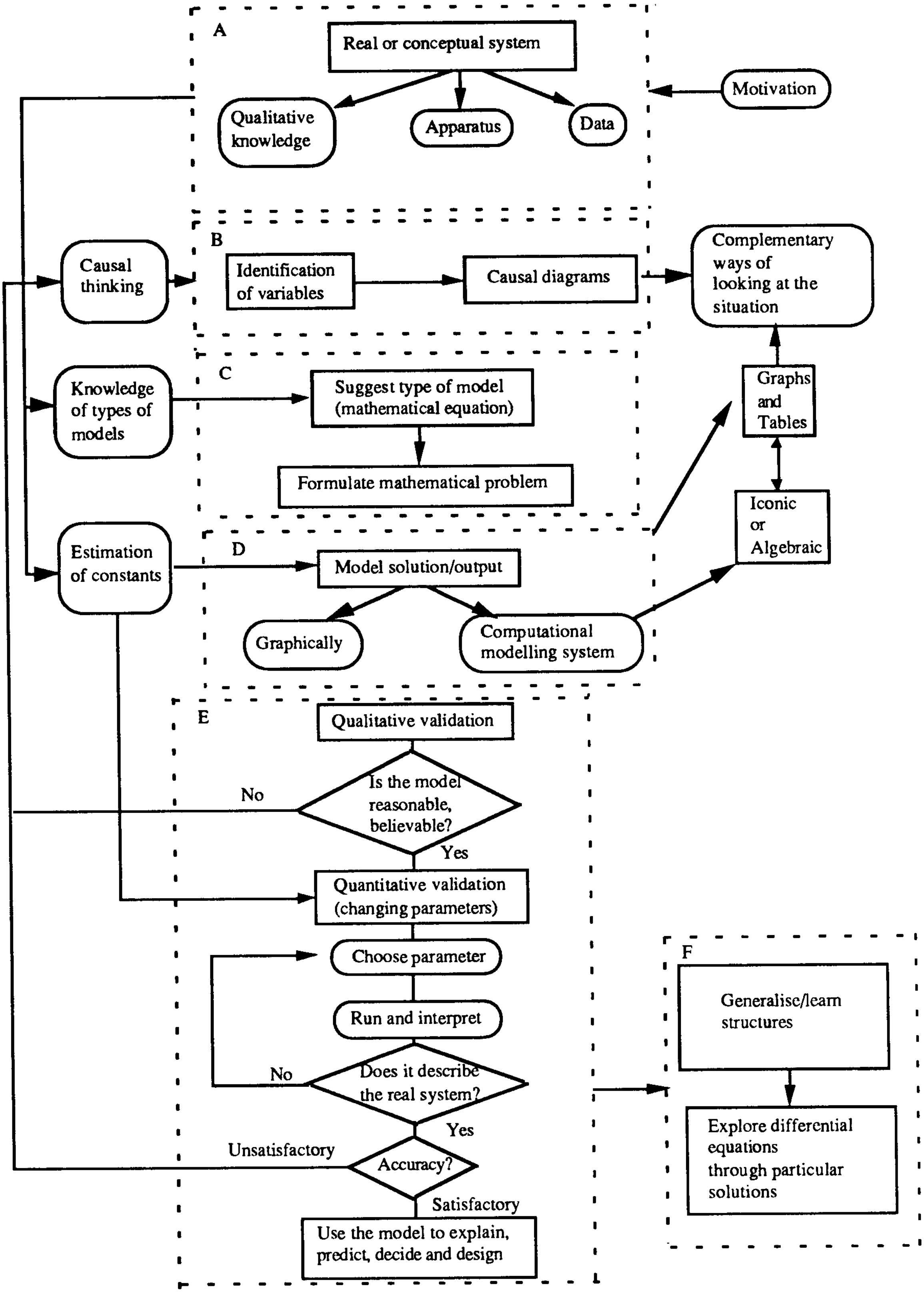


Figure 2. 7 - Framework for teaching and research into computational modelling.

2. 7. 3. MODEL CONSTRUCTION

Area A *Choice of system to be modelled*

It is common to pretend, for instructional purposes, that a system to be modelled is chosen purely for the sake of understanding it better, without regard to how it might be modelled. Yet this is rarely so. In the first place, the system may have been chosen just in order to exemplify some important and general type of model. In the second place, it is scarcely possible to delimit and define a system for analysis without having any idea about how it will be modelled.

At the same time it is important to begin from a secure base in observed phenomena. Much of the empirical knowledge of the system at this stage will be qualitative, in that quantitative formulations depend on later stages being achieved, such as variables being isolated and relationships postulated. This suggests an emphasis on simple experimental work aimed at a qualitative understanding of the system: what happens and what affects what happens. And this relates to motivation: to an idea as to what any model would need to try to account for.

Area B *Mechanisms of causation, identification of variables*

The qualitative understanding of the system from area A now needs to lead to an analysis of causation in the system, so that variables and relationships can be isolated. Here it is appropriate to work with *causal diagrams.*

To illustrate their use in developing a model, suppose we are modelling water draining through a hole from a tank. A causal-loop diagram, in terms of cause-and-effect relations among the variables, might look (Mandinach, 1989) like Figure 2. 8.

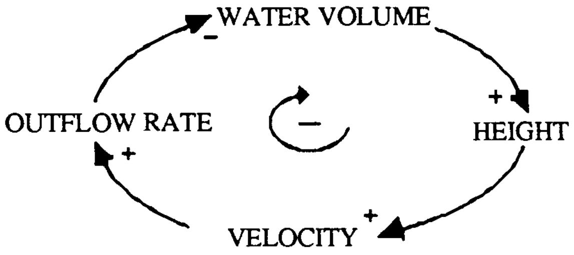


Figure 2. 8 - Causal loop diagram of a leaky tank.

This diagram says that the OUTFLOW RATE is responsible for the decrease in the WATER VOLUME. It says that the greater the WATER VOLUME, the greater the HEIGHT of the water; that the greater the HEIGHT, the greater the VELOCITY at the outlet; that the greater the VELOCITY, the greater the OUTFLOW RATE; and finally that the greater the OUTFLOW RATE, the *less* the WATER VOLUME. Thus overall, the feedback loop is *negative.*

Such a diagram begins to show what variables to define and what relationships will be required. Thus the OUTFLOW RATE will have to be calculated from the VELOCITY of the water at the outlet, which is a function of the HEIGHT of the water in the tank, which itself depends on the WATER VOLUME. Thus the diagram shows that the OUTFLOW RATE should be able to be expressed as a function of the WATER VOLUME.

Such a diagram mixes rates and amounts. While the OUTFLOW RATE produces a continual decrease in WATER VOLUME, the WATER VOLUME and HEIGHT of water simply “go together”. Nor are all the relationships truly 'causal'.

Area C Type of model required

Suppose potential relationships between variables have been identified as being required. The next step is to formulate these as well defined mathematical equations, often differential equations. In the example of Figure 2. 8, the diagram suggests a model of the form:

OUTFLOW RATE = - CONSTANT * f(WATER VOLUME)

where f is some function. It takes some knowledge of kinds of model to see that this is a differential equation, and that it is of first order. It takes further knowledge to see that such models are related to exponential decay. Such knowledge may suggest trying the simplest exponential decay model

$$\frac{dV}{dt} = -kV.$$

Students cannot be expected to have such knowledge of types of models when first engaging in the modelling process. But such knowledge of types of models is nevertheless fundamental, and part of teaching about modelling is necessarily teaching about types of model (see figure 2. 4 and table 2. 1).

In fact, of course, this model may well not fit data at all well. A better approximation for the function f is likely to be

$$f = \sqrt{\text{WATER VOLUME.}}$$

The square root arises if the velocity of water coming from the hole is

$$\text{VELOCITY} = \sqrt{2*g*\text{HEIGHT}}$$

where g is the acceleration of gravity, and if the tank has uniform cross-sectional area, so that

$$\text{HEIGHT} = \frac{\text{WATER VOLUME}}{\text{AREA}}$$

The model can then be written as

$$\frac{dV}{dt} + k\sqrt{V} = 0$$

where k is a constant to be estimated from the radius of the hole, the area of the tank and the acceleration of gravity.

Area D Generation of output from model

Despite the value of the computer, there are arguments for initially solving differential equations by hand, graphically (Nuffield Advanced Physics 1985, 1986). But this does take time. If the work is being done with quantitative modelling systems such as CMS, DMS or STELLA (see chapter 1, section 1. 3.) what is involved is iteratively solving finite difference equations as discrete approximations to differential equations (see section 1. 3. 7.).

Area E *Interpretation, checking, validation and use*

Validation is both qualitative and quantitative. Thus the first question to be asked is whether the qualitative behaviour of the solution is appropriate: does it rise or fall when it should, for example? This leads to the question whether the causal structure of the model is reasonable or believable.

Quantitative validation looks at the quantitative behaviour of the model. It is necessary to choose parameters, to run and interpret the model and, finally, check if it describes the real system adequately. If after adjusting parameters, the model still fails to describe the system, then we may have to think again about its qualitative behaviour, and the modelling process may have to be begun again. In the case mentioned previously, the simplest model of water flow from a tank at first appears to be qualitatively correct, but is quantitatively wrong, leading to a re-design of the model.

There are the same two levels of use of a model to explain or predict. At a qualitative or semi-quantitative level, one may be able to account for such features as increasing or decreasing rates of growth, oscillation, phase lag or lead, etc. At a more quantitative level, with a well tested model, one may be able to make quantitative predictions, for example of a period of oscillation or a time to decay.

2. 7. 4. GENERALISING FROM PARTICULAR MODELS

I now turn to area F in Figure 2. 7, which concerns the different level, not of model construction but of learning about different types of model. Figure 2. 9 elaborates this area, suggesting an iterative process through which a student learning to model may pass from particular cases to a successively broader view of the process and to a more general set of competencies.

The student may need to start with imitation, that is, to begin with pre-defined problems and models, copy them into the system, run them, and evaluate the models through reflection about their structure and output. Later the student may begin to generalise some behaviours of the model (e.g. oscillation or decay). By looking at different examples with the same model structure, and the same broad behaviour, the student may begin to group models into types (e.g. those in which the rate of change is proportional to the present amount). This process would need to be repeated with new types of model, constructed through variations of earlier ones (e.g. decaying oscillation from pure oscillation).

I drew attention to the necessity in model construction for this kind of knowledge of types of model, when discussing area C. This knowledge tells one what kind of result a given kind of model could possibly give, without building it. It is the lack of such knowledge which is one reason why imitation is often a necessary starting point in learning about models.

The final goal of learning about models is what I have called in figure 2. 9 'modelling in the mind'. Modelling in the mind is to take a physical situation (for example the movement of the branches of a tree on a windy day) and identify directly how it could be successfully modelled (a first attempt could be to try pure oscillation, and a second attempt to consider a superposition of oscillatory motion and a random component).

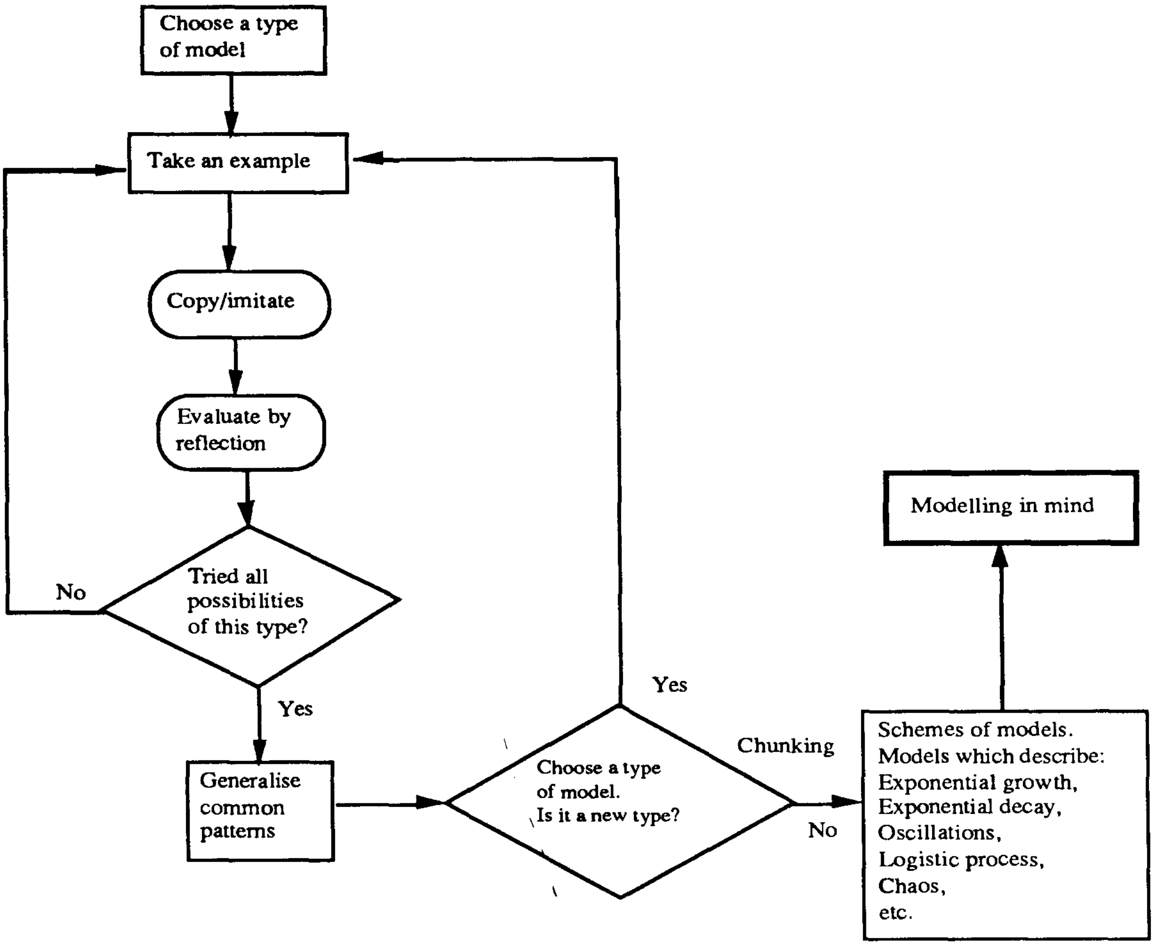
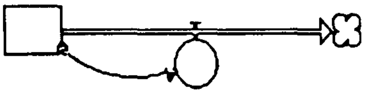


Figure 2. 9 - Framework for generalising from particular models.

Applying the framework for generalising from particular models

There follows a simple example of how the framework of Figure 2. 9 might be used in planning teaching about simple first order equations.

<u>Choose a type of model:</u> models where rate of decrease of an amount is proportional to that amount can be represented in STELLA as follows:



Take an example: Leaky tank.

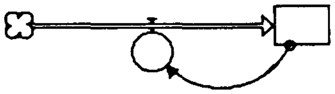
Copy/Imitate: construct the model in the computational system. The teacher gives equations and parameters to describe the real system.

Evaluate by reflection: the students will have to look at the model running, at equations, graphs and tables and data. They will need to move between representations to understand the situation.

Have you tried all possibilities of this type? There are many others, such as cooling by convection, radioactive decay, diffusion etc. Repeat for other examples (see figure 2. 4, chapter 2).

Generalise common patterns: all situations can be described by a differential equation of the kind $\frac{dX}{dt} = -kX$ (k constant > 0) with exponential decay solution.

Choose new type: rate of increase related to present amount, represented in STELLA by:



Take an example: bacteria breeding

Have you tried all possibilities of this type? Other examples are economic inflation and alcohol absorption. Repeat for other examples.

Generalise common patterns: all situations are described by a differential equation of the kind $\frac{dX}{dt} = kX$ (k constant > 0) with exponential growth solution.

2. 7. 5. USE MADE OF THIS THEORY

In the research, it was not possible to design complete sequences of teaching about modelling as suggested by this theoretical account. However, ideas from the account were used to select and organise the tasks that were used.

CHAPTER 3 - CLAIMS AND RESEARCH RESULTS

3. 1. INTRODUCTION

The first purpose of this chapter is to present a survey and review of claims that people make about the use of computational modelling systems and causal diagrams, so as to identify particular questions to be addressed in the research (see chapter 5).
These claims will also give some guide lines about what to expect in terms of students' performance when using computational modelling systems and causal diagrams, so as to provide bench marks for evaluating the work done by students.

3. 2. CLAIMS

3. 2. 1. ADVANTAGES OF USING COMPUTERS

O'Shea and Self (1987) assert that the most widely used technique of computer-assisted learning is the simulation, a program that models some process or system that is made available to the student in the hope that, by studying the performance of the program, s/he will gain insights into whatever process or system is being modelled. The student's role is usually more than that of mere spectator, often being responsible for providing inputs for the program, and deciding some strategy for using it, and, through these, being able to 'experiment' with the modelled system. Sometimes, but more rarely since it presumes programming knowledge, the student may modify the program to investigate its consequences. O'Shea and Self consider that the particular advantage of the computer is that it is a powerful and flexible device for controlling simulations. They argue that the physical sciences are largely concerned with the development and use of mathematical models, and that the complexities of the models are often beyond the ability of a student. They add that computer implementations of models can make them usable by a student, who may, in this way, gain some understanding of the principles underlying them.

> "Often a computer simulation may serve to remove complications that could obscure the more important principles to be understood".
>
> O'Shea & Self (1987).

In addition they suggest that

> "...a computer simulation may be the only way to provide a student with safe, inexpensive view of certain phenomena, such as nuclear reactions, or space travel. Such simulations may be made more effective by capitalising upon the computer's ability to generate special displays, ...".
>
> O'Shea & Self (1987).

Borcherds states that

> "...The increasing availability of computers with graphics displays is making a considerable impact on the teaching of undergraduate Physics: not just in the way it is taught, but also in what is taught . . .".
>
> Bocherds (1987).

Ogborn considers that

> "... a further advantage of the computational modelling is because real world complexities could be introduced with often little penalty. In writing the force for the oscillator as F= -k*x - b*v we introduce viscous damping into the problem, with damping constant b. The computer could find the solution no more difficult, though the analytic solution would be now appreciably harder to obtain. Make the dependence of force on velocity more complex still . . . and analytic solutions are out of reach of most school and many college students, but the computational solution is not . . .".
>
> Ogborn (1989b).

About graphs, Ogborn adds

> "... A further educational advantage of computational models is that it is very easy to look at plots of various variables. Phase space is normally treated as a territory best kept out of by many students, but plotting v against x for an oscillator is natural and simple . . .".
>
> Ogborn (1987).

Bork (1987) considers as an advantage of the use of computers, the fact that individual differences among students can be taken into account. He thinks it important to give different students different amounts of time to go through the learning material. He adds that computer-based instruction allows the student to control the pace of an individual learning sequence, and the general pace of the course, and can provide a choice of content even within a single course.

Wedekind (1988), states that many results of research on natural, social, or economic systems were worked out on models of these systems, and that it would be logical, then, to regard modelling as an integral part of Science teaching. He adds that students should have not only theoretical knowledge about modelling but also practical skills in the development, testing, validation, and analysis of models.

He states that computer simulation programs have proven to be valuable tools in teaching about theoretical models, especially when these programs use the possibility of graphical visualization. He thinks that many models in Sciences are characterized by a high degree of complexity, abstraction, and mathematization, but that the graphic capabilities of computers, their computational speed, their interactive dialogue, and the variation of parameters, possible for this kind of tool, can make possible the production of more concrete learning material.

The normal process of making a computer simulation of reality, includes the translation of this reality into differential (or difference) equations to describe the dynamic system. After this step, to get the model into operation, it is necessary to write the equations in a programming language to put in the computer. This activity could be difficult for whoever would be constructing the simulation. Nowadays, for Computer-Aided Model Building, researchers have developed tools that do not presuppose programming knowledge, but allow the user to concentrate on the original task (see section 1. 3. 1).
Some authors (for example, Fey and Kaput) have emphasized the possibility of working with equations, graphs and tables when using the computer. Fey (1989 and 1990) writing about multiple representations (the use of computer tools which make it possible to change quickly from diagrams and equations to graphs and tables, and vice-versa), points out that they are helpful and that the ability to translate an idea from one notation to another is an indicator of meaningful knowledge, adding that there is a promise that, using such an approach, students will be able, with modeling tools like STELLA (see section 1. 3. 6), to see much more challenging problem solving material.

> "Nearly everyone hopes that ready access to graphs will enrich student understanding of algebraic forms, giving visual images of symbolic information".
>
> Fey (1989).

Kaput also considers that computer numerical, graphic, and symbol manipulation tools offer students multiple linked representations for the abstract ideas and relations embodied in algebraic expressions. Computer tools allow users to shift quickly from one representation to another, or to view several representations simultaneously. They provide both the opportunity and the challenge to choose the form that is most insightful. Kaput argues that one reason why the idea of an algebraic variable has been so difficult for students to learn is that its alphanumeric representation is so implicit and that, for this reason, the user must " in a real sense, supply the variation". But when working with graphs

> " ... to provide the variation, all the user needs to do is trace a finger, or in another way, follow along the graph, to provide the temporal variation that it has captured and frozen in place".
>
> Kaput (1989).

However, he adds that

> "students in first and second year algebra course are primarily arithmetic creatures ... and that significant teaching and prompting are needed to get them to use graphically represented information".
>
> Kaput (1989).

Thompson (1989) argues that the idea of multiple - linked representational systems appears to be powerful, but that we have little idea of the actual effect their use has on students' cognition. He points out that there is preliminary evidence that their use has a positive effect on skill, quoting Greeno et al (1985), Lesh (1987) and Thompson & Thompson (1987) in support.

3. 2. 2. TRANSFERENCE OF THE UNDERLYING STRUCTURE OF A PROBLEM

Jerome Bruner (1960), suggested that one key element of problem solving is understanding the underlying structure of the subject under study.

Forrester (1968) points out that a structure (or theory) is essential, if we are to effectively interrelate and interpret our observations, in any field of knowledge. To Forrester, without an integrating structure, information remains a hodgepodge of fragments, and without an organizing structure, knowledge is a mere collection of observations, practices and conflicting incidents. He writes about the importance of structure in education and devotes a whole page to quoting Bruner.

Barclay & Roberts (1986) suggest that the true pedagogic reward, recognized by researchers such as Bruner for some time, is the ability of students to identify the underlying structure of a problem and to transfer this understanding to other problem areas. They think that

> "modeling the same phenomenon in several different disciplines will hopefully strengthen the perceived value to problem-solving skills of identifying the underlying structures that cause the observed behaviour ".
>
> Barclay & Roberts (1986).

It is important to point out that "modelling the same phenomenon in several different disciplines" is what is behind the map presented in figure 2. 4, in chapter 2. The framework for teaching and research into computational modelling (figure 2. 7) and mainly the framework for generalizing from particular models (figure 2. 9), includes the idea of schemes of models, obtained through work with different kinds of models.

Roberts (1986) agrees with Forrester that system dynamics is a method to study the underlying structure of complex systems to ease problem solving, and to test Bruner's ideas further, has developed curriculum material. She considers the causal-loop diagram as the tool for expressing the underlying structure of an observed behaviour over time. About the contributions that system dynamics can make to teaching she writes that

> "If one agrees with the arguments Bruner makes for teaching the underlying structure of a discipline, clearly system dynamics provides a powerful set of tools to accomplish this".
>
> Roberts (1986).

3. 2. 3. LIMITATIONS OF CAUSAL LOOP DIAGRAMS

Richmond et al. (1987) present thoughts about the limitations of the Causal-loop Diagramming (chapters 1 and 2).

They think this approach has the practical advantage of being simple to learn and easy to implement. Causal - loop diagrams also can be very effective for communicating how simple closed loop processes work. But, causal - loop diagrams are in their opinion significantly limited in their ability to undertake serious analysis of feedback systems. As such, they point out that it is essential to move beyond causal - loop diagramming to a more rigourous language.

They identify three other limitations. First, causal - loop diagrams are drawn on paper or blackboards. "There's no computer standing behind the diagram to bring it to life" [this is exactly what IQON (chapter 1, section 1. 4) is intended to do - it brings causal - loop diagrams to life]. That is, in looking at a causal - loop diagram, you have to "do the simulation in your head", to produce the associated dynamic behaviour.

Second, the inability to incorporate quantitative information further limits the utility of the causal - loop diagram as a language for tying structure to dynamic behaviour. It is not possible to shed much light on delays and shifts in dominance.

Third, reliance on "words and arrows", to represent relationships, can lead to some erroneous deductions about dynamic behaviour. Causal diagrams make no distinction between things that flow and things that accumulate.

Richmond et al. argue that by recognizing the distinction between stocks and flows, the structural diagramming language provides a far more rigourous framework than causal - loop diagrams, for linking structure to dynamic behaviour.

Similarly Roberts et al. (1983) point out that the flow diagram is a more detailed representation of the feed-back loop than is the causal - loop diagram. The causal - loop diagram ignores the distinction between a rate of flow and a cause - and - effect link not involving a rate of flow. The flow diagram calls explicit attention to this distinction. They think the main reason for moving from a causal - loop representation to a flow diagram is to provide additional insight into the behaviour a proposed model generates over time. They say that it is necessary to express each model relationship in equation form, and that the translation from a verbal description of each model relationship to a statement as an equation often requires a good deal of ingenuity.

3. 3. RESEARCH RESULTS

3. 3. 1. THE USE OF DMS

Wong (1987) presents descriptions of extended case studies in secondary schools using the Dynamic Modelling System (see section 1. 3. 4). Wong considers that DMS encourages thinking about fundamental principles and is a program for teaching about the structure of knowledge. He adds that it makes it possible for the student to "do - think":

that is, to try out some adjustments to the model, run the model, and then reflect about the numerical and graphical outputs, and to "think - do": that is, to use DMS to test a hypothesis, first deciding about the modifications that should be made, and then to try out the modifications changing parameters or equations in the computer model.

Wong commented that some students said that although they had been taught a specific topic before, it was only after modelling with DMS they really understood it. Wong set homework that involved the use of "DMS cards". The homework took students from the idea of analogy between fundamental mechanical and electrical relationships, to the idea of analogy between mechanical and electrical systems, which were made up of those relationships. Another worksheet drew the distinction between analytic and dynamic models, looking at them in terms of differential equations and their solutions.

One of Wong's conclusions was that the class had learnt how to use dynamic models in answering familiar questions, but had not learnt how to apply them to unfamiliar ones. Attitude questionnaires showed that students were generally favourable to DMS. It was considered enjoyable to use and, they thought, aided understanding.

Related to problem solving, the areas of interest that arose were:

(1) problem - representation, which concerns the translation and categorisation of problems into a form that is more easily processed and

(2) "chunking" of principles, in which they are organised so that they are used at the appropriate time.

DMS provides evidence of "chunking" within the structure of different models. It can help to show those features that make two systems analogous, as for example, the electrical and mechanical models as follows:

```
Vr = I * R          Fv = -K * V
Vl = E - Vr         F = Fd + Fv
I ' = Vl/L          A = F/M
dI = I ' * dt       dV = A * dt
I = I + dI          V = V + dV
T = T + dT          T = T + dT
```

One outcome of Wong's thesis was that the group taught using DMS freely chose to attempt to answer in an A-level examination a question involving describing the uses of differential equations, although they were a non-mathematical group. This outcome suggests that after teaching with DMS, non-mathematical students became more confident about differential equations.

Wong claims that the full power of DMS comes first through modelling and not simulation. And secondly, through dynamic modelling as opposed to analytic modelling.

Wong found evidence of what he called "computational thinking", that is, being capable of developing a model using the BASIC formalism, without the necessity of working in the presence of the computer. He considered that the computer was in principle dispensable, but that it checked and corroborated the mental processing that students carried out. In his opinion DMS was a feedback device that had the advantage of being precise in its arithmetic calculations.

It is interesting to point out that what Wong calls "computational thinking" is basically what I call 'modelling in the mind' (see chapter 2, section 2. 7. 4.).

3. 3. 2. SOME RESULTS OF THE MAIN RESEARCHES USING CAUSAL-LOOP DIAGRAMS AND STELLA

Barclay & Roberts (1986) describe a project that began with an intensive four week course for 16 high school students. The purpose was to get a sense of how easily fifteen-year-olds could handle the proposed activities combining system dynamics, computer modelling and applied mathematics. STELLA was used for modelling.

The teaching approach included students building their own model, modifying an existing one, and analyzing a complicated model. According to the general evaluation students had little or no trouble mastering the hardware and software tools. On the other hand, they had to struggle to understand the ideas of system thinking, to use causal - loop diagrams, and to use levels and rates to model more than just the simplest systems, but, by the end of the fourth week, had made impressive progress.

Students actively discussed the difference between rates and levels among themselves, with no prompting from the teacher. They also recognized that different problems shared the same underlying structure and showed substantial improvement in questions dealing with causal - loop diagrams. According to the authors this gain was predictable, because students spent a good deal of class time drawing positive and negative causal - loop diagrams to help them understand particular types of models. They showed substantial gains involving graphing and graph interpretation, although the graphing skills tested by the questions were not explicitly taught during the course. The authors argue that some transfer of skills, particularly in the area of graphing and graph interpretation, had taken place.

The authors noted that students were satisfied with their models if the shape of the generated graphs looked right, even though the scale of the graphs was incorrect.

They remark that analysing a problem using causal-loop diagrams represents a synthetic level of thinking. Once mastered, these tools give the user a way of grasping complex, interconnected, real problems. The authors argue that over the years it has become clear that people of all ages, from as early as kindergarten, and of all backgrounds, can master these tools.

Mandinach (1987) introduced the STACI Project (in U.S.A.) whose aim was to examine the cognitive demands and instructional consequences of learning from a system thinking approach, and from using simulation modelling software. She presented a study whose purpose was to test the "potentials and effects of using the systems thinking approach in existing secondary school curicula to teach content specific knowledge as well as general problem solving skills". The study also examined the effectiveness of using STELLA.

Existing instruments were used to measure ability, content knowledge, and higher order thinking skills. An instrument was developed to assess knowledge of system thinking. Two courses were given. In one students developed their own models, were given existing ones and were asked to alter particular parameters to examine the effects on the entire system. In the other, they were given textbook problems to solve using system analysis. According to Mandinach these approaches were likely to produce different cognitive outcomes in terms of content knowledge and problem solving skills. She argues that

> "manipulating parameters in an existing model may promote inquiry skills (e.g., understanding of causality and variation), and may influence directly the acquisition of content knowledge - by contrast, model building may be less explicitly related to content knowledge acquisition, yet may promote more general problem-solving skills".
>
> Mandinach (1987).

According to Mandinach (1987) in biology and chemistry, more complex causal - loop structures were developed than in general physical science. The teacher reported that General Physical Science curricular topics did not lend themselves to simple feedback relationships. Biological science, of all the subject areas, lent itself most readily to a system approach. Feedback was discussed briefly at the beginning of the year and again at the end during the introduction to STELLA modeling. But, the teacher reported that time constraints limited the discussion.

In assessing students' reactions to system thinking, the teacher indicated that students appeared initially interested in learning the concepts and discussing simple causal diagrams. Difficulties arose as complexity was introduced. Not all students could follow the connections between loops.

Mandinach points out that although the relations among the variables were specified in causal diagrams, and that they had understood how to quantify numerical variables, students still had difficulty with the less quantifiable parameters.

She concludes that students could learn system ideas and apply them to scientific problems at varying levels of complexity and sophistication, but that because the Science curricula were not totally covered, it was impossible to make definitive statements about the impact of the systems approach on acquisition of content knowledge.

Mandinach (1988a) argues that the system thinking approach necessitates the student's engagement in high-order thinking skills, and that the processes of construction of STELLA models "require students to exhibit self-regulated learning process".

Corno and Mandinach (1983) defined self-regulated learning as student's active acquisition and transformation of instructional material. It is related to Metacognition, generally defined as an individual's knowledge about that person's own cognitive processes (Flavell, 1976 and 1979). For them, the

> "learner must be able to evaluate and supervise their own cognitive behaviour through the use of self-regulation ... Self-regulation is viewed as a normative ideal that few students use consistently ".
>
> Corno and Mandinach (1983).

Mandinach could classify students as self-regulated or recipient. She found that the most common level of cognitive engagement among Physics students was self-regulation and for Chemistry students recipient. For her the Physics students were more cognitively adapted to the assigned tasks.

Mandinach reported slight ability and gender differences in levels of cognitive engagement. She found interaction between gender and ability, and gender differences in Physics - Females were more likely to be self-regulated than males and less likely to be recipient.

Mandinach (1988a) argues that the System Thinking approach is not applicable to all problems encountered in Science courses. But it is possible to apply it in Biology, in such topics as Life: Common Characteristics, Cell Structure and Function, Principles of Heredity and Plant Nutrition. In Chemistry, it can be applied to topics such as Reaction Rates and Chemical Equations, Environmental/Social Problems and in General Physical Science (G. P. S) in topics such as The Nature of Science, Laws of Motion, Properties of Matter and Compounds and Bonding, Waves, Light and Colour, Electricity and Electricity and its uses. This restriction in curriculum is because System Thinking is useful when describing dynamic systems that evolve in time. Therefore Biology seemed the most suitable subject in which to follow this approach, and the example that was most often considered is a population model, which shows an interaction between populations of rabbits and foxes, for example.

According to Mandinach (1988a) all the 6 students, who took both Physics and system thinking as a strategy for analysing the dynamics of historical and current events, highlighted that STELLA could be used for Physics problems, but cautioned that the System approach was not appropriate for all Physics problems and that they needed to have sufficient understanding of Physics for the approach to make sense. Without the content knowledge, students could not apply STELLA as a problem solving tool.

STELLA was reported to have helped several students to visualize problems. STELLA, through visual representations, made ideas more easily understandable, more tangible, and connected to real-world phenomena. Mandinach argues that the low ability students focused on STELLA's capability to enhance learning through visual representations and internal calculations, explaining:

> "it was as if these students perceived that the computer was shortcircuiting some of their cognitive processes by performing some to the problem solving. One student noted that ... 'It figures out the math for you and lets you see how it works.' ".
>
> Mandinach (1988a).

Traditional methods were seen as more useful and efficient for simple problems: the system approach was considered more effective for complex and dynamic problems.

3. 4. SUMMARY OF CLAIMS, RESEARCH RESULTS AND EXPECTATIONS

From this brief account of research and development, it is possible to identify a number of claims and research results concerning the following topics:

1) Computers and computational modelling systems (DMS and CMS);
2) Multiple-linked representational systems;
3) Calculus and differential equations;
4) Graphs and graphical visualization;
5) Transference of underlying structure of a problem;
6) Causal-loop diagrams;
7) System thinking (STELLA and the Macintosh computer);
8) The modelling process.

Based on these claims it is possible to define some expectations concerning work with causal diagrams and computational modelling systems (see table 3. 1).
Some of these expectations may reflect just the personal opinion of the authors and are, of course, disputable. They might not be related to the use of computational modelling systems at all and also may depend on the kinds of tasks developed. Students are able to draw causal diagrams only for situations which they have some knowledge about. On the other hand, expectations concerning gender (15) and background (16) seem to be independent of the kinds of tasks developed.
The table will serve as one of the sources of research questions (see chapter 5). Also, it will give some rough indicator to compare findings reported in chapters 8, 9, 10, 11 and 12.
Since the research concerns sixth form students working with causal diagrams, IQON and STELLA, I shall use these expectations, together with the answers given by teachers for a questionnaire about opinions concerning the tasks using the modelling systems, to evaluate their performance on tasks.
The research design and questions are presented in detail in chapter 5.

1) After the understanding of the situation being modelled, we should expect no trouble in mastering the mechanics of the construction of diagrams in IQON, STELLA and the Macintosh computer (e.g. selection of primitives, mouse events and the use of pull down menus).
2) We should expect students to easily master the syntax of BASIC code when using modelling systems as DMS or CMS. Consequently, we should expect them to be capable of mastering the similar syntax of equations generated in STELLA.
3) We should expect students with modest command of mathematics, after the understanding of the situation being modelled, to successfully use the iconic representation as a way of thinking about systems - STELLA through visual representations makes ideas more easily understandable and connected to real-world phenomena.
4) We should expect problems in understanding of graphs generated by the modelling systems, due to possible deficiency in interpreting graphs.
5) We should expect much trouble in understanding of rates and levels.
6) We should expect no problem in learning causal loop diagramming as a technique, regardless age or background. However, not all students will be able to follow the connections between loops, when complexity is introduced. Complement: Causal diagrams are not runnable. There is not a computer program to bring it to life.
7) We should expect the recognition that different problems share the same underlying structure.
8) We should expect students to be able to identify the underlying structure of a problem and transfer the understanding to other problem areas.
9) We should expect much difficulty in translating a verbal description into an equation.
10) We should expect at the end some gain involved in graphing and graph interpretation.
11) We should expect difficulties when defining values to less quantifiable parameters in STELLA. For example, when developing a model for "controlling body weight through diet and exercises", it would be difficult to give a value to a rate called "energy used up per day".
12) We should expect some positive effect of the use of multiple-linked representational systems.
13) Even working with very simple STELLA models, we should expect some understanding about calculus and differential equations, because STELLA makes step by step computation - which is considered a good way of looking at the solution of differential equations, and uses the ideas of rate of change and integration.
14) Some topics will be more suitable to be developed through the use of causal diagrams than others. Consequently, we should expect students to develop more complex causal loop structures in General Topics than in Physics.
15) We should expect gender effects concerning the work with system thinking.
16) We should expect Physics students to be more cognitively adapted to the system thinking approach .

Table 3. 1 - Summary of the main relevant expectations for the research.

CHAPTER 4 - PILOT RESEARCHES

4. 1. INTRODUCTION

The aim of this chapter is to present a personal account of five initial pilot studies, and to show the contribution of each to the definition of the final research.

I carried out the following five pilot studies:

1) Characterization of entities in modelling through causal-loop diagrams. A preliminary analysis;

2) Pilot work with IQON;

Both pilot studies 1 and 2 generated unpublished reports.

3) Application and analysis of a Questionnaire About Modelling, first and second parts;

4) Pilot Work with causal diagrams, IQON and Cellular Modelling System (CMS) and

5) Pilot work with IQON and STELLA.

4. 2. CHARACTERIZATION OF ENTITIES IN MODELLING THROUGH CAUSAL-LOOP DIAGRAMS. A PRELIMINARY ANALYSIS

I presented 10 questions to students in a questionnaire where I asked for a causal explanation and a causal diagram for each situation (Kurtz dos Santos, 1989a). The situations were:

1) Two cars in a stream of traffic;
2) Leaky tank;
3) Leaky tank with a tap putting in water;
4) The swing;
5) Inflation in Britain;
6) Population model: predator- prey system;
7) Diet;
8) Supermarkets;
9) Motorways and
10) Greenhouse effect.

With these questions I hoped to see if the students could give reasonable causal explanations, and could identify or select variables and draw a causal diagram. It was applied to 9 student teachers of the Institute of Education.

The main outcome of this pilot research was that students in general did not conceive variables as levels and rates as I was expecting. Besides that, the results seemed to show that some students give non-variable-ized descriptions as causal explanations - that is, explanations based on objects and events instead of variables, for example.

Some differences were found related to the kind of activity and the student's background, as well. These results gave me some clues as how to analyse causal diagrams drawn by students. Besides, the entities used by them could be identified within a framework defined by Forbus' Qualitative Process theory - recognizing entities as processes, events, objects or quantities (as discussed in chapter 2, section 2. 3.).

Results suggested that there is a previous step that must be followed in a System Thinking approach when teaching and working with modelling. The identification of entities as variables is not at all obvious and suitable work with events, processes, quantities and objects may better respect students' previous knowledge.

This first pilot work was very helpful for choosing questions for the development of a general questionnaire about modelling, and gave me ideas about how to analyse causal diagrams, and even IQON models developed by the students.

4. 3. PILOT WORK WITH IQON

Following pilot work with IQON reported (Kurtz dos Santos, 1990) 12 hours of activities using IQON with 4 students (GCSE level, with poor grades in their exams) at a Sixth Form College in Tower Hamlets.

The research was done using two students working, simultaneously, with one computer. The sequence of activities was repeated later with another pair:

Day 1 - Teach IQON.

Task - Controlling the traffic: good and bad effects.

Day 2 - A Questionnaire about Models.

Task - Controlling CO2 in the air.

Day 3 - Expressive activity about "keeping fit".

Task - Changing answers to Questionnaire about Models.

Data was obtained through observation, questionnaires developed by people from the Tools for Exploratory Learning Project ("Traffic", "CO2" and "Keeping fit") and the Questionnaire about Models developed by me (see chapter 5, section 5. 5. 4).

This Pilot work was designed to get some data for the Tools for Exploratory Learning Project, concerning the use of IQON with older children. Also, it gave me some experience with the computational system IQON and with British students, and helped me to test the viability of some research questions. It was a first opportunity to apply some instruments (the Questionnaire about Models - see Appendix II.3) and helped me with some ideas about what it would be reasonable to do with students in a intensive study format. This pilot study gave me some clues about how to observe and record the *student - modelling system* interaction.

4. 4. APPLICATION AND ANALYSIS OF THE QUESTIONNAIRE ABOUT MODELLING, FIRST AND SECOND PARTS

A first version of this questionnaire was applied to 10 A - level students of the same school as in 4. 3. This questionnaire was based on the instrument developed for the pilot work about "characterization of entities" reported in section 4. 2. However, I added another part about relevant mathematical skills needed to engage in the modelling process (see final version of this questionnaire in Appendix I.1 and I.2).

The results gave me information about how to analyse and improve the questionnaire. The main conclusion was that I should give some minimum instruction about causal-loop diagrams, before asking the students to draw causal diagrams for situations.

4. 5. PILOT WORK WITH CAUSAL DIAGRAMS, IQON AND THE CELLULAR MODELLING SYSTEM (CMS)

My initial thoughts in this pilot work were to do something with the same structure of the 'Tools for Exploratory Learning Project' material. That is, to give exploratory and expressive tasks in which the student would be supposed to answer 'what happens if' and 'why' questions, besides criticising the model.

The activities were undertaken in two Catholic Sixth Form Schools in Haringey. The tasks were[3] :

1) Harmonic Oscillator - Exploratory task using IQON.
2) Harmonic Oscillator - Exploratory task using CMS.
3) Two cars in a stream of traffic - Drawing a causal diagram.
4) Two cars in a stream of traffic - Expressive task with IQON.
5) Two cars in a stream of traffic - Exploratory task with CMS.
6) Two cars in a stream of traffic - Exploratory task with IQON and CMS.

My aim was to get some data about students working with models (expressive and exploratory learning modes) using a quantitative modelling system (CMS) and the semi-quantitative modelling system IQON.

I worked with pairs of students, but with each answering his/her own work sheet.

The basic problem was the large number of questions asked, which made the tasks too long. Despite that, I could interpret students' answers to 'what happens if' and 'why' questions, which were answered using the computational systems.

The expressive task about 'two cars in a stream of traffic' using CMS was very difficult. Although they were working together, one helping the other, the maximum they could do, was a very simple model that added to a constant the speed of one car.

After having problems in trying to use different hardware (since CMS runs on IBM and IQON runs on Macintosh computers), I decided to use STELLA and IQON in the

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[3] I will not either present the original tasks here or give a detailed account of these tasks, because the final versions of the questionnaires used in the main research were based on these tasks.

research, because both used Macintosh computers, and have related graphic interfaces. This decision obliged me to redesign the tasks. This pilot study helped me to define what it would be reasonable to use as a group of tasks in the main research. I realized that the tasks should be more motivating, and that for this purpose they should involve real and current issues, and not only problems related to Physics.

4. 6. PILOT WORK WITH IQON AND STELLA

This Pilot study was designed to the activities using IQON and STELLA. It was developed with two students working for a period of 8 hours.

I had now learned that any research with students using such tools would require a considerable time with each student. This raised practical questions about access to students. Negotiations with schools indicated that three sessions of about one hour each would be the maximum I could expect, so the research was designed to fit with in this framework of time.

As I knew our meetings would be limited to 3 sessions of about 60 minutes for each pair of students, in the final data collection, I had to redesign the initial proposed tasks with IQON and STELLA. Besides that, my idea was to design some material where I could still get something useful for the research, if any students gave up after the first meeting. I could not afford to obtain results only in the final session.

The first idea was to introduce some newspaper texts to serve as motivation. The students, using the texts, were to think about the situation, and model it in a computational system. I decided to include expressive problems about the greenhouse effect, rat war and diet and weight loss (see Appendices II.1, II.2 and III. 1). However, this study showed that to define equations and values for the expressive task "diet and weight loss" was difficult, consequently it was decided that STELLA in the main study would be used only as a drawing tool.

I had to shorten the material so as to be able to introduce and use STELLA in one session of 60 minutes. I decided to remove the 'Harmonic Oscillator - Exploratory task using STELLA', which I had initially thought about keeping in the final version of the research. It would be very difficult if the student did not have specific knowledge about the topic. Taking out these questions, opened the possibility of using the tasks with Sixth Form students of the first year, which would simplify the sampling.

4. 7. PILOT STUDY AND THE DEFINITION OF A STRUCTURE FOR THE RESEARCH

After carrying out these pilot studies it was possible to define a structure for the research. The research is a study of students' ability to manage some different approaches to modelling.

It consists of practical exploratory research with two modelling systems: IQON and STELLA, and with causal diagrams. Students are given exploratory and expressive tasks to work using the Macintosh computer.

The main research has two parts: first a larger scale survey using a questionnaire and, second, an intensive individual work with pairs of students (see research design in chapter 5).

The research involves first and second year sixth form students taking any of the following A - level subjects: Physics and Economics. See chapter 8 for a description of the sample used in the survey and chapter 10 for the sample used in the intensive study.

CHAPTER 5 - RESEARCH QUESTIONS, DESIGN AND INSTRUMENTS

5. 1. RESEARCH QUESTIONS

5. 1. 1. INTRODUCTION

There are three sources of questions for this research:

Source 1 - the model for teaching and research into computational modelling (chapter 2, section 2. 7);

Source 2 - expectations (shown in table 3. 1, chapter 3);

Source 3 - results from pilot studies (presented in chapter 4).

The framework (source 1) suggested some general and specific questions.

The literature review suggested some other questions which were not addressed by source 1, and gave ideas about sampling.

The pilot studies helped in crystallising some specific research questions which originally came from source 1.

I propose the definition of one overall research question (about work with computers), split into three general research subquestions. These general subquestions can be split into specific research questions.

I propose, also, a second overall research question about modelling, which will be explained below. The two overall research questions are complementary to one another.

5. 1. 2. GENERAL RESEARCH QUESTIONS

The present research is about students' ability to manage some different approaches to modelling. Consequently, the first general question is

Can sixth form students achieve success or some valuable work with (certain) computational modelling systems ?

The first general question can be split into three general subquestions:

1. What is required for students to use / make computational models ?

2. How good are (certain) modelling systems as tools for making models ?

3. How is students' thinking about / with models related to their other knowledge ?

The second general research question, related to modelling is

What can be said about the model building capability of sixth form students, without using the computer ?

5. 2. DECISIONS - WORK WITH IQON, CAUSAL DIAGRAMS AND STELLA

For answering the general questions some decisions were made: -

1. to work with quantitative and semi-quantitative modelling, because there are (a) tools that deal with these kinds of modelling and (b) good psychological reasons for promoting semi-quantitative reasoning (e. g. Forbus 1982, 1985).
2. to choose IQON and STELLA, for practical reasons. Both run in the Macintosh computer.
3. to involve causal diagrams because:
   - the literature about STELLA claims they are important;
   - they make possible the link to quantitative models and
   - they offer a possibility of comparison with IQON models.
4. to work with causal diagrams, IQON and STELLA in an intensive study format with exploratory and expressive tasks. Because modelling tasks take time, work with a small number of students.
5. to complement the intensive study with a survey about abilities and knowledge needed for modelling. Involve a larger number of students. Find out about computer experience, causal diagramming and Mathematics.
6. to link two studies by a subset of the main instrument used in the survey.

5. 3. SPECIFIC RESEARCH QUESTIONS

5. 3. 1. INTRODUCTION

Table 3. 1, in chapter 3, shows a summary of the main relevant expectations one might have, concerning work with causal diagrams (possibly IQON) and STELLA. One expectation is that students with a modest command of Mathematics could use modelling systems as IQON and STELLA successfully. This suggests that it is possible and useful to work with first year sixth form students.

The claim that causal diagrams are not runnable, the difficulties of using them, the limitations of causal-loop diagrams and the existence of IQON, made me propose as part of the research some comparisons involving runnable and non-runnable diagrams (IQON models compared with causal diagrams).

The use of causal diagrams, IQON and STELLA raises obvious questions about the students' conception of variables, since to use these systems students have to select (or identify) variables and think about how they are related or connected.

The work with STELLA, in particular, raises questions about the influence of the strong visual metaphor (of tanks, taps and pipes) on the way students think about variables. One could argue that students would feel obliged to think about some variables as rates, since tanks (levels) must be connected to other tanks through rates (see figure 5. 1 below).

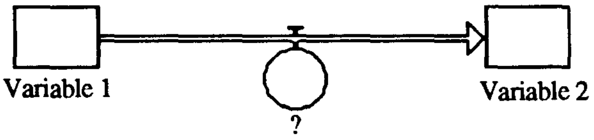


Figure 5. 1 - Linking variables using a rate in STELLA.

Causal diagrams and the work with IQON and STELLA, in expressive and exploratory learning modes, suggest an exploration of the engagement of students in genuine semi-quantitative reasoning.

Claims numbers 7 and 8 (table 3. 1, chapter 3) made me decide to try to explore the issue of transference of the underlying structure of a problem.

Other questions are inherent in the use of computer modelling systems and were based on the ideas developed in pilot researches (as described in chapter 4) concerning the use of IQON and STELLA.

For answering the general question I will propose some specific research questions related to each general subquestion (numbers 1, 2, 3).

5. 3. 2. SPECIFIC RESEARCH QUESTIONS FOR EACH GENERAL SUBQUESTION

Each general subquestion will be addressed through specific questions related to

- Semi-quantitative reasoning;
- Comparison of IQON versus causal diagrams;
- Entities and structure of models;
- Understanding of STELLA models;
- Problems of metaphor;
- Specific difficulties when using modelling systems;
- Recognition and transference of structure;
- Relation to reality;
- Criticism of models;
- Student's conception of models and dynamic behaviours.

1. <u>What</u> <u>is</u> <u>required</u> <u>for</u> <u>students</u> <u>to</u> <u>use / make</u> <u>computational</u> <u>models</u> ?

1. 1. Semi-quantitative reasoning

1. 1. 1. Will students engage in semi-quantitative reasoning when drawing causal diagrams ?

1. 1. 2. How well does the student think about a current issue when understanding a causal diagram or exploring an IQON model ?

1\. 1. 3. How well does the student use the causal diagram or IQON model when making predictions ?

1\. 1. 4. How does the student explain in his/her own words what the causal diagram or IQON model is describing ?

1. 2. IQON versus causal diagrams

1\. 2. 1. How do answers for questions involving a causal diagram differ from answers given for the same questions involving an IQON model ?

1\. 2. 2. How do causal diagrams and IQON models differ for expressive tasks ?

1\. 2. 3. Is working with IQON better than working with causal diagrams, for promoting thinking about systems, and for assisting later work with STELLA ?

1. 3. Entities and structure of models

1\. 3. 1. Can the student identify (select) variables? What sort of entities do they use to model and how do they use the entities when modelling?

1\. 3. 2. What can be said about the entities used and the final structure of causal diagrams and IQON models ?

1\. 3. 3. What can be said about the entities used when making a STELLA model?

1. 4. Understanding of STELLA models

1\. 4. 1. How good is the student's understanding of STELLA models ?

1\. 4. 2. How does the student explore a more elaborate model in STELLA ?

1\. 4. 3. After having worked with STELLA, can students think of variables as tank or flow giving the corresponding unit of measure ?

1\. 4. 4. After having worked with STELLA, how well do they understand a STELLA diagram for a new situation ?

2. How good are (certain) modelling systems as tools for making models?

2\. 1. What can be said about how the IQON formalism constrains, or not, the way a student thinks about systems and variables ?

2\. 2. What can be said about the influence of STELLA's metaphor on the way the student thinks about variables ?

2\. 3. How did the student manipulate IQON and STELLA models ?

2\. 4. What are the student's specific difficulties when using IQON and STELLA ?

3. How is students' thinking about / with models related to their other knowledge ?

3. 1. Recognition and transference of structure

3. 1. 1. Is the student able to recognise situations that could be modelled with the same (STELLA) structure ?

3. 1. 2. How does the student transfer the knowledge acquired through the work with STELLA models, in an accustomed context to other area ?

3. 2. Relation to reality

3. 2. 1. Will the student think about the real system and use his/her own ideas when drawing a causal diagram ?

3. 2. 2. How does the student relate to reality what happens in a model ?

3. 3. Criticism of models

3. 3. 1. How does the student criticise causal diagrams and IQON models ?

3. 4. Students' conception of models

3. 4. 1. What can be said about the student's conception about models ?

3. 4. 2. Did the student change his/her conception after having worked with computational modelling systems ?

3. 5. Ideas about dynamic behaviours

3. 5. 1. How well does the student choose patterns (graphs) corresponding to written situations ?

4. Additional questions

4. 1. Social interaction and attitude towards the activities

4. 1. 1. What is the interaction between students, researcher and written material ?

4. 1. 2. Can I find hints of attitude towards the activities ?

4. 2. Comparison between intensive study and large survey

4. 2. 1. How do students, from the intensive study and the large survey, differ concerning causal diagrams, entities and mathematical knowledge ?

5. 4. RESEARCH DESIGN

Figure 5. 2 presents a schematic representation of the research design. Notice that the main intensive study, where students work with causal diagrams and models in IQON and STELLA, is supported by a Questionnaire about Modelling, and a questionnaire about "Teachers' Opinions". The data collected from the "Questionnaire about Modelling", besides being a survey about the model building capability of students, without using the computer, was used as control for the data collected by the instrument "Ideas about modelling" in the intensive study. "Ideas about Modelling" is a subset of the "Questionnaire about Modelling" and consequently has some common questions which will make it possible to look for differences between students who have or have not worked with the computer. These instruments are described in section 5. 5, below.

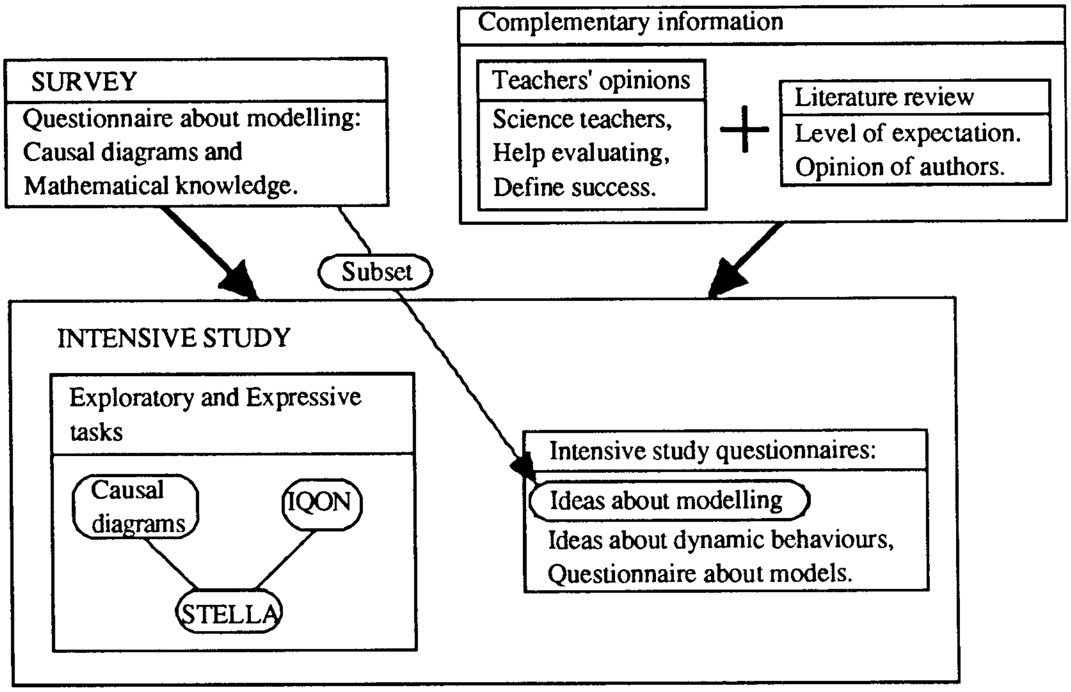


Figure 5. 2 - Scheme presenting the research structure. Notice that there is a general questionnaire about modelling, an intensive study using computers where "Ideas about modelling" is a subset of the general questionnaire. There is a comparison between causal diagrams and IQON models. There is also a teachers' questionnaire and a literature review.

There is a comparison in the intensive study between the work with causal diagrams and the work with IQON.

Schematically one could represent the research design, as one with treatments and measurements. The treatments would be:

X1 --> the work involving IQON;

X2 --> the work involving causal diagrams;

X3 --> the work involving STELLA;

The 'measurements' would be:

O1 --> IQON related tasks;
O2 --> Causal diagrams related tasks;
O3 --> STELLA related tasks;
O --> Questionnaire about modelling;
O' --> Ideas about modelling;
O'' --> Ideas about dynamic behaviours;
O4 --> Ideas about models.

The design, for the intensive study, can be considered as a Multiple Intervention Design with treatments and measurements. For each class involved, pairs of students were selected for work with IQON and STELLA or causal diagrams and STELLA (see scheme below).

$$\begin{array}{l} X_1O_1O_4 \ldots X_3O_3O_4O'O'' \text{ (IQON + STELLA)} \\ \hline X_2O_2O_4 \ldots X_3O_3O_4O'O'' \text{ (Causal diagrams + STELLA)} \end{array}$$

From the point of view of the research as a whole, the design can be considered as a kind of quasi-experimental scheme, with the intensive study (involving computers) being the experimental group, and the large group research (through questionnaire and not involving computers) a kind of control group. Here $X_{1/2}$ means treatments X_1 or X_2 and $O_{1/2}$ means measurements O_1 or O_2.

$$\begin{array}{ll} X_{1/2}O_{1/2}O_4 \ldots X_3O_3O_4O'O'' & \text{(Computer - intensive study)} \\ \hline O & \text{(No computer - survey)} \end{array}$$

5. 5. QUESTIONNAIRES

This section introduces some of the questionnaires used in the research.

5. 5. 1. QUESTIONNAIRE ABOUT MODELLING

Through the scheme presented in section 2. 6, for choosing the questions to be asked, and using the model presented in section 2. 7, it was possible to define some main steps and skills involved in the modelling process. My aim was the design of a "Questionnaire About Modelling" (Appendices I.1 and I.2) that would make it possible to survey the model building capability of Sixth Form students. The questionnaire was designed in two parts, following from the decision about surveying causal diagramming and Mathematical knowledge. The first part is basically about variables and the drawing of causal diagrams and the second part is about the relevant mathematical knowledge needed to engage in modelling.

Besides an initial survey about the use of software and hardware, the main cognitive demands of the questions of this questionnaire, designed to be applied on a fairly large scale, are presented in table 5. 1.

Questionnaire about Modelling - First Part
Experience with Software: 1. Experience with Hardware: 2.
Creativity in defining causal-links: 3, 4, 5, 6, 7, 8. Graphical interpretation of causal diagrams: 9. Graphical interpretation of a text: 10. Graphical interpretation of a physical situation: 14, 15. Reading and interpreting a causal diagram: 11, 12. Identification of variables in physical situations: 16a. Selection of variables in physical situation: 13a, 20a. Drawing causal diagrams for physical situations: 13b, 16b, 20b. Identification of variables and construction of causal diagrams for general situations presented through short texts: 19a, 19b, 17, 18.
Questionnaire about Modelling - Second Part
Construction and interpretation of a graph for data: 21a, 21b. Knowledge of the equation for proportional relation: 22. Pictorial solution of a problem: 23. Knowledge of mathematical equations corresponding to a pattern: 24, 25. Knowledge about differential equations and what they can represent: 26, 27, 28. Understanding pieces of computer programs: 29, 30, 31.

Table 5. 1 - Cognitive demands and number of the questions, for each part of the Questionnaire about Modelling.

Concerning the second part of the questionnaire, questions 27 and 29, 28 and 31 are related, since the differential and difference equations, and expected graphs, describe the same dynamic behaviours. Question 23 and questions 29, 30 and 31 are related as well, since the procedure that should be used to solve 23 is similar to the procedure that should be used to solve 29, 30 and 31 (see Appendixes I.1 and I.2).

5. 5. 2. IDEAS ABOUT MODELLING

"Ideas About Modelling" (Appendix IV) is a questionnaire which is a subset of the "Questionnaire About Modelling" but also has two questions (6 and 7) about the use of STELLA. "Ideas about Modelling" was designed to link the intensive studies with the survey research, and to get some data to complement the evaluation of the work with STELLA.

5. 5. 3. IDEAS ABOUT DYNAMIC BEHAVIOURS

"Ideas About Dynamic Behaviours" (Appendix V) is a questionnaire used in the intensive studies where the students had to choose the graph (dynamic behaviour) which could describe dynamic (and non-dynamic) situations presented through sentences. The questionnaire asks for the best graph and others that could describe the same situations. The questionnaire explores whether the students who were engaged in activities with the modelling systems were able to recognize dynamic and non-dynamic situations, besides giving a suitable graphical output.

5. 5. 4. QUESTIONNAIRE ABOUT MODELS

"Questionnaire About Models" (Appendix II.3), for the intensive study, was designed to get some data about the students' conception of models. This questionnaire (see example of questions in figure 5. 3 below) was applied after the first session and again at the end of the last session, where the students were asked to change answers if they thought it was necessary.

	agree	partly agree	partly disagree	disagree
1) If the model predicts things wrongly it must be wrong.	☐	☐	☐	☐
5) Only a very small part of reality can be understood through models.	☐	☐	☐	☐
9) A model should try to reproduce reality in all its complexity	☐	☐	☐	☐

Figure 5. 3 - Examples of questions - Questionnaire about Models questions: 1, 5, 9.

5. 5. 5. TEACHERS' OPINIONS

"Teachers' Opinions" (Appendix VI) was designed to serve as a bench mark to help evaluating students' performance in the intensive tasks. It asked teachers to evaluate explanations and models developed by students.

5. 6. INTENSIVE STUDY TASKS

The scheme presented in chapter 2 (figure 2. 4) was the framework for choosing the quantitative tasks which it would be sensible to use in the intensive work. Due to limitations in time, the group of tasks had to be a subspace of the general map which charts the full range of dynamic behaviours. Following this line, I decided to choose *Leaky Tanks* and *Two cars in a stream of traffic*, as the main kinds of models related to Physics to explore. Unlike the latter, the former is close to STELLA's metaphor.

Concerning the semi-quantitative tasks with causal diagrams and IQON models, I decided to introduce some current issues (Greenhouse Effect and Rat War) which might be motivating.

In Appendices II.1, II.2, II.3, III. 1, III. 2, IV and V, the instruments (work sheets and questionnaires) used in the intensive tasks involving the work with causal diagrams, IQON and STELLA are given. Each question or group of questions was designed to answer the specific research questions presented in section 5. 3.

Figure 5. 4 shows the structure of intensive tasks:

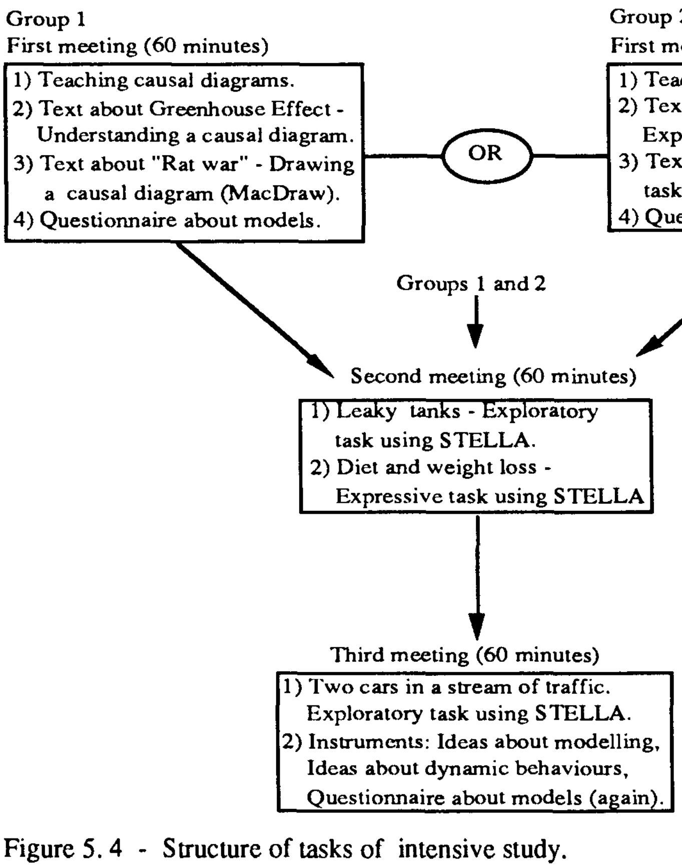


Figure 5. 4 - Structure of tasks of intensive study.

The first STELLA exploratory task, which also aimed to teach STELLA, was designed to be based on a familiar context - work with "leaky tanks", a physical situation which students have got some intuitive ideas about and could have worked on formally in Science courses.

Students using IQON learned the Macintosh that way. Students doing causal diagrams learned it using MacDraw to draw causal diagrams - basically the use of the mouse and pulling down menus, since both groups were supposed to work with STELLA in the second and third sessions.

These tasks followed the model for teaching and research into computational modelling (section 2. 7), particularly the framework for generalizing from particular models (presented in figure 2. 9, chapter 2) - starting with a "one tank" system and finishing with a "three tanks" system (see Appendix III.1). Like the STELLA activities, the IQON teaching tasks were based on "embryonic model building", as well. By "embryonic model building" I mean a succession of tasks starting with an embryonic (very simple) model, which corresponds in STELLA to one leaky tank, and finishing with more complicated systems, such as the "three tanks" or the "two cars" tasks (see Appendices III. 1 and III. 2).

Causal diagrams and IQON tasks are described in chapter 6. STELLA tasks are described in chapter 7.

5. 6. 1. WORKING IN PAIRS

De Corte (1990) claims that social interaction through active participation in peer-directed groups is beneficial for students. Other researchers point out the advantage of working in pairs from the point of view of learning. Sutherland (1989) refers to constructive working partnerships, for example.

In the intensive study tasks it was decided to have students working in pairs using one Macintosh computer. The justification for this is based on the exploratory nature of the research. Students through social interaction with their peers could perhaps go further in terms of performance in exploratory and expressive modelling tasks, giving more reliable information concerning their ability with different approaches to computational modelling.

5. 6. 2. THE ROLE OF OBSERVATION

As the students would work with the computer, it was necessary to collect observational data on this work. My decision was to define a schedule for systematic observation (see Appendix VII) and, with a notebook, to record everything I thought was relevant for the research.

After each session, I went through the schedule, filling the grid with the main aspects which were written and others that I could remember. The notes and the schedule complement each other, and both assist in interpreting the written answers given by students. Based on the schedule, I could register the interaction between *student - computer, student - peer, student - researcher* and *student - written material*.

I was concerned to observe the interaction of the student with the computer model, the operation with the model, kind of reasoning followed, entities used, interaction with peer, interaction with researcher, hints of attitude towards activity, interaction with written material, mastering of the knowledge involved, level of criticism about the model and written material, level of interaction with the model, opinion about the work in general, development of expressive tasks and specific difficulties when using the tool.

Besides the written notes and written answers given, data recorded in the computer (causal diagrams, IQON and STELLA models) was also used.

Making written notes has the advantage of giving time afterwards to try to understand how students were thinking. The disadvantage is that it was not possible to arrange other people to check the interpretation (see in Appendix XI a photocopy of a sample of these notes).

5. 6. 3. INTENSIVE STUDY TASKS AND THE NATIONAL CURRICULUM

The intensive study tasks are consonant with the *Recommendations for statements of attainment for Information Technology Capability* - National Curriculum (1990) Levels 4 to 10, which expect the students to:

- understand that a computer model is a set of instructions to be followed in a pre-determined sequence;
- use the computer model to detect patterns and relationships, and how the rules governing the model work;
- use information technology to explore patterns and relationships, and to form and test simple hypotheses;
- investigate and assess the consequences of varying the rules within a simple computer model;
- design, use and construct a computer model of a situation or process;
- use software to represent a situation or process with variables, and show the relationship between them;
- evaluate computer models;
- decide how to model a system, and design, implement and test it, justify methods used and choices made.

CHAPTER 6 - THE WORK WITH IQON AND CAUSAL DIAGRAMS

6. 1. INTRODUCTION

The aim of this chapter is to describe IQON, and the way it was taught to students, together with details of the expressive and exploratory tasks used. Finally, I will present the way causal diagrams were taught, and the tasks involving understanding and drawing causal diagrams.

6. 2. IQON

6. 2. 1. HOW IQON WORKS

Figure 6. 1 shows a model for the Greenhouse Effect in IQON (the same as in figure 1. 12, chapter 1 - section 1. 4. 2.), as it appears on the computer screen. Notice the button functions at the top of the screen.

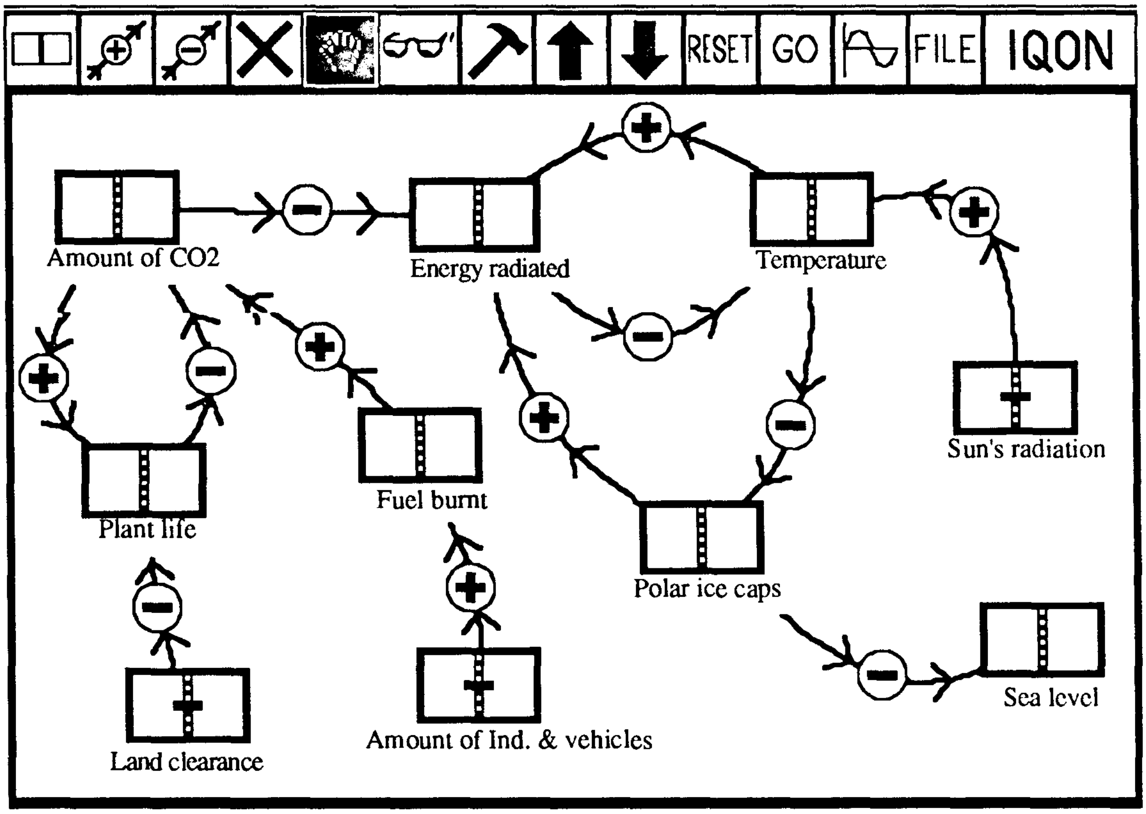


Figure 6. 1 - IQON model for the Greenhouse Effect.

From left to right, the box function is used to add a new box to the model. A box represents a variable. The positive arrow button adds a positive link between two selected boxes. The negative arrow button adds a negative link between two selected boxes. The X button, deletes a selected link or box and its associated links. The hand button, changes the position of a selected box or link. The glasses button makes it possible to look "inside" a box to see a comment about it, or also to change the comment and/or name of the box. The hammer, clamps or un-clamps a selected box (see figure 6. 2). The arrows up and down, alter the strength of a selected link or increase/decrease the level of a selected box. The RESET button, reinitialises the model to start a new run. The GO button animates the model starting from its present state. The graph button calls up a graph of the behaviour of a selected box during the last run. The FILE button provides options for external file handling, starting new models and quitting IQON. Finally, the IQON button (selected while pressing), makes it possible to alter the step, speed or damping of the current model.

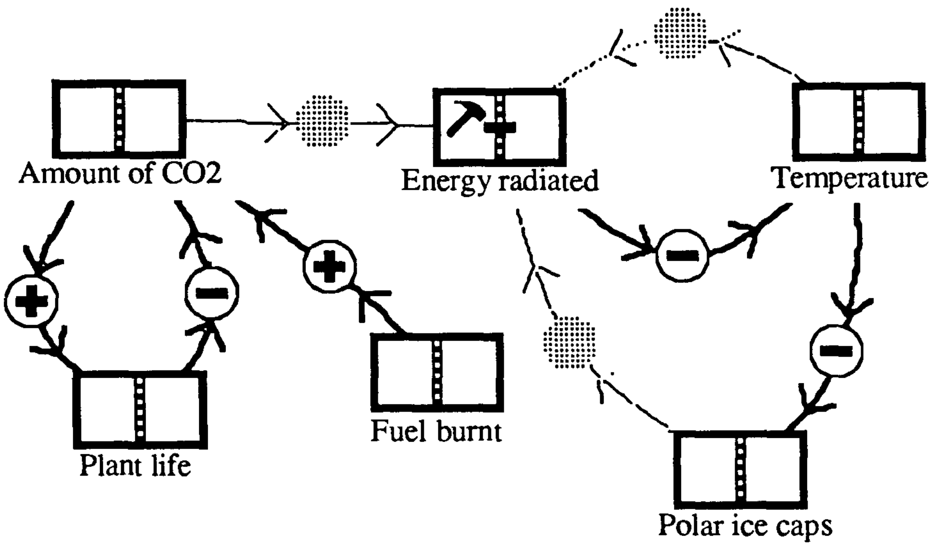


Figure 6. 2 - Part of the model presented in figure 6. 1 with the box for "Energy radiated" clamped. Notice that all arrows coming to this box are disabled. This tool makes possible to isolate parts of the model to analyse the behaviour of specific sub-systems.

6. 2. 2. ALTERING STEP, SPEED AND DAMPING

The IQON function makes it possible to alter semi-quantitatively, Step, Speed and Damping. It is important to point out that Damping, also Step and Speed are properties of the system being modelled, as a whole (See chapter 1, section 1. 4. 1 about the mathematics of IQON).

6. 2. 3. ALTERING THE STRENGTH OF LINKS

The up and down arrows can also be used to alter the strength of a selected link. This makes possible to work with different positive (+ ✚ ✚) and negative (– ▬ ▬) links. In figure 6. 3, for example, there is a small negative influence of *Plant life* on the *Amount of CO2* but there is a large negative influence of the *Amount of CO2* on the

Energy radiated. There is also a large positive influence of the *Temperature* and a small positive influence of *Polar ice caps* on the *Energy radiated*.

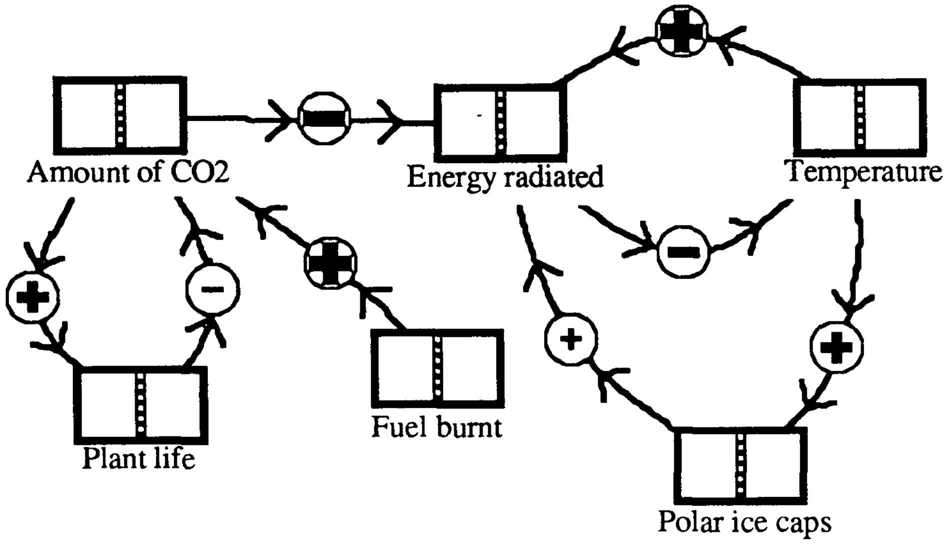


Figure 6. 3 - IQON allows three semi-quantitatively different negative and positive links. This feature allows comparison of stronger positive/negative influences with weaker positive/negative influences, for example, for one box.

6. 3. TEACHING IQON

In chapter 5, section 5. 6, the structure of the intensive study was described, including a scheme showing what was involved in the three meetings of 60 minutes each. IQON was taught only during the first meeting (with Group I) and the teaching phase took about 15 minutes. Appendix II.2 shows the four "exercises" that were designed for teaching IQON.

They started with one box (selected and named by me) on the screen (see figure 6. 4) - *how tired you get*, and the students were asked to observe how I made the operation of selecting and naming the box. They were asked to think about variables that could affect *how tired you get*, and to consider how these variables could affect one another (see exercise 1).

Figure 6. 4 - First box for teaching IQON.

After thinking about the situation the students were asked to observe how I worked in exercise 2, which considered *how hard you work* as the only variable that affected positively *how tired you get* (figure 6. 5).

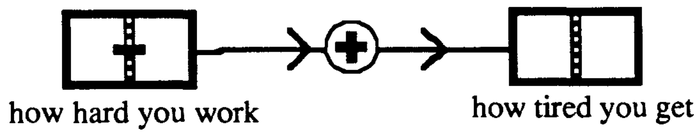


Figure 6. 5 - A positive link for teaching IQON.

I showed the students what happened to *how tired you get* when we considered low and high levels (below and above the normal level) of "working hard", and how to obtain the graph for the temporal change of *how tired you get.*
In exercise 3 the students constructed themselves the improved model (adding *how keen you are* and *how strong you are* - see figure 6. 6), by imitation (see framework in figure 2. 9, chapter 2) in the computational system, and tried different combinations of "high" and "low" values of the variables.

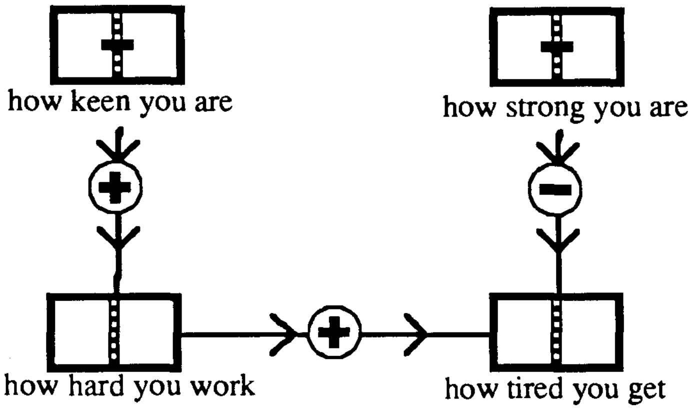


Figure 6. 6 - Improving the model presented in figure 6. 5, for teaching IQON.

In this exercise I emphasised the negative link between *how strong you are* and *how tired you get* , and what would happen to the "tiredness" for both low and high levels of "being strong".
I asked the students, before running, to make predictions about what they thought would happen.
Finally, I asked them to change the model, by themselves, to a loop diagram for *how hard you work* and *how tired you get* (see figure 6. 7) and, before running, to tell me what they thought would happen. After making predictions, I asked them to test those predictions, running the model and asking for graphs.

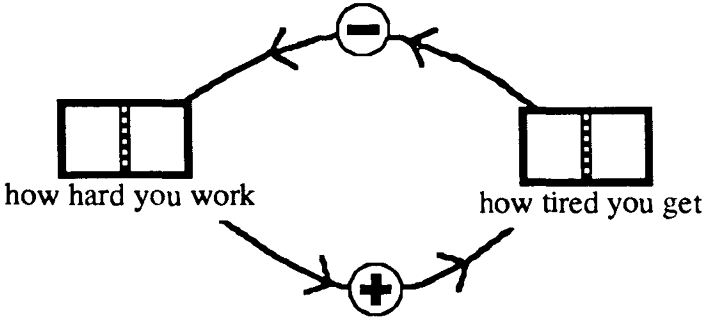


Figure 6. 7 - An oscillatory system in IQON, for teaching IQON.

Behind the teaching scheme are the ideas of *imitation* and *embryonic models* (see section 5. 6). Imitation happened in teaching, when the student initially followed what I had done before as a way of making, naming and linking boxes.

Embryonic models are those corresponding to situations made simple for teaching purposes only. These situations could be modelled in IQON by the simplest kinds of structures - two boxes linked through a positive or a negative link (see, for example, figure 6. 5 above).

In exercise 3 (figure 6. 6) and 4 (figure 6. 7), I asked the students to make predictions before running the models. This was a way of making sure that they had understood the representation, and to give them a chance to test their hypotheses about the situation that was modelled. In exercise 4, in particular, before running, if they did not understand what the loop was doing, I emphasised the oscillatory pattern of both levels.

6. 4. EXPLORATORY AND EXPRESSIVE TASKS USING IQON

As stated briefly in section 5. 6, I decided to introduce some current issues to help with motivation. The current issues chosen were one related to the Greenhouse Effect topic and the other related to an explosion of the rat population in London (Barnet). As a way of introducing the students to the topics, I used texts. For the exploratory task, it was "Global warming worries heightened by mildest winter for 330 years", by Greg Naele, Environment Correspondent - The Daily Telegraph, December 15, 1989 (see Appendix II.2). After reading this text the students worked with the model presented in figure 6. 1 above, answering three written questions of the kind,

a) Make the amount of industries and vehicles high.

What happens to the temperature?

Why?

The exploratory task finished with three questions about their opinion of the model:

d) Explain in your own words how the model tries to show how "global warming" can happen.

e) In what ways do you think the model is accurate?

f) In what ways do you think the model is not good enough?

These questions were designed to get some data on the level of criticism students had about the model.

For the expressive task I used part of the article "Barnet fights a losing rat war", by Greg McIvor - Times Group Newspaper, April 12, 1990 (see Appendix II. 2). After reading the text the students were asked to model the situation by themselves, using IQON.

6. 5. WORK WITH CAUSAL DIAGRAMS

In this section I describe the work with Causal Diagrams (Group II), which was an alternative to the work with IQON (see chapter 5, section 5. 6). The work with causal diagrams followed the same structure as the work with IQON described above.

6. 5. 1. TEACHING CAUSAL DIAGRAMS

The work with causal diagrams started, in exercise 1 (see Appendix II.1), with one variable "how tired you get", and the students were asked to think about and write down some variables which could affect "how tired you get", and to consider how these variables could affect one another.

Exercise 2 presented the causal diagram, as in figure 6. 8

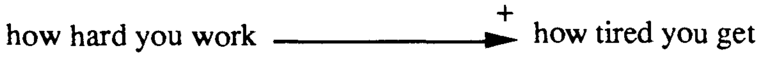


Figure 6. 8 - Causal diagram for exercise 2. Compare to figure 6. 5, for working with IQON.

and asked students to consider an increase and a decrease in "how hard you work" and to think about what would happen to the "tiredness".

Exercise 3 asked the students to try to understand the following causal diagram (figure 6. 9) and say what the diagram said would happen if the person was very keen and very strong.

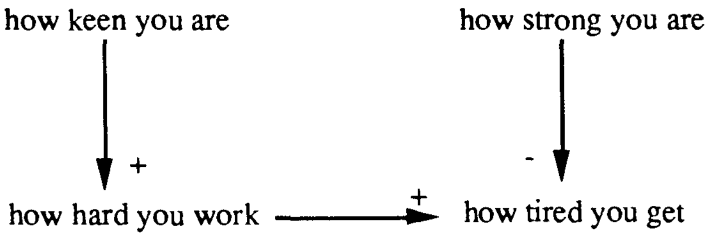


Figure 6. 9 - Causal diagram for exercise 3. Compare to figure 6. 6, for working with IQON.

Exercise 4 asked the students to try to understand the following causal diagram including a loop (figure 6. 10) and to say if you worked hard, what would happen to your tiredness, and what effect that would have on "how hard you work".

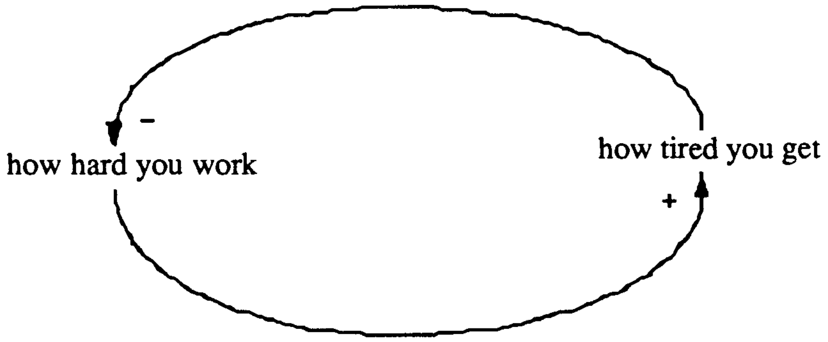
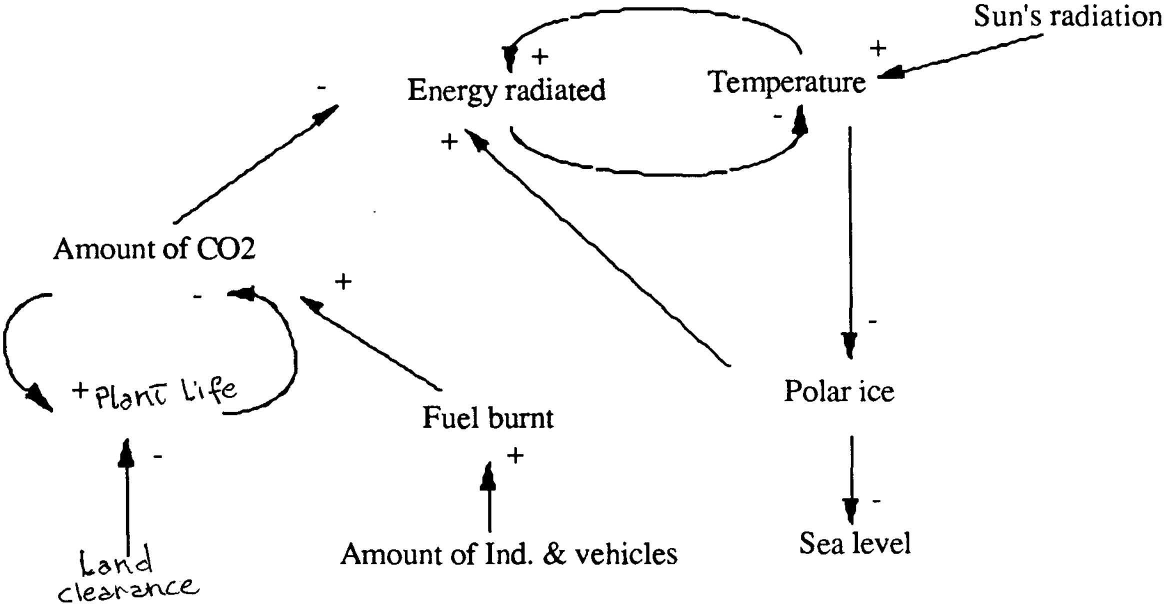


Figure 6. 10 - Causal - loop diagram for exercise 4. Compare to figure 6. 7, for working with IQON.

6. 5. 2. UNDERSTANDING AND DRAWING CAUSAL DIAGRAMS

The texts "Greenhouse Effect" and "Rat War" used with IQON (section 6. 4) were also used here. Figure 6. 11 shows the causal diagram for the Greenhouse Effect which was given, with the list of relevant variables.



Explanation of the meaning of variables

Land clearance = Amount of land cleared for building and agriculture.

Fuel burnt = The amount of coal, oil and other fuels being burnt.

Plant life = The amount and vigour of plant life, specially forests.

Amount of CO2 = Amount of Carbon dioxide in the air.

Temperature = The overall average temperature of the Earth. How warm the climate is.

Energy radiated = The amount of energy radiated or reflected back into space from the Earth.

Sun's radiation = The amount of energy reaching the Earth from the Sun.

Sea level = The overall sea level.

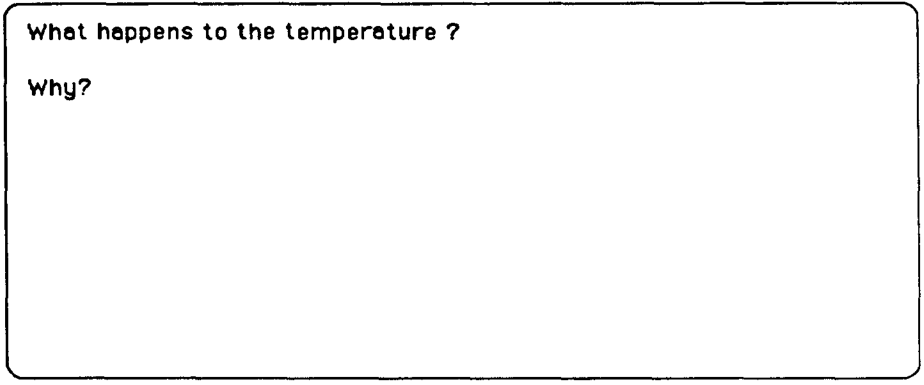
Polar ice = The amount of snow and ice on the Earth, specially at the poles.

Amount Ind. & vehicles = Amount of industrialisation, and vehicles in use.

Figure 6. 11 - Causal diagram for the Greenhouse Effect with list of relevant variables.

After reading the text and inspecting the causal diagram, students were asked three written questions parallel to those used with IQON, one of which was:

a) Suppose that the amount of industries and vehicles increases.



What happens to the temperature ?

Why?

Like the tasks using IQON, the exploratory task finished with three questions about their opinion of the model:

d) Explain in your own words what the causal diagram says about how "global warming" can happen.

e) In what ways do you think the causal diagram is accurate?

f) In what ways do you think the causal diagram is not good enough?

For the expressive task about drawing a causal diagram to describe the "Rat War", I decided to make the students use MacDraw, as a way of getting used to the Macintosh computer, to assist later work with STELLA.

CHAPTER 7 - WORK WITH STELLA

7. 1. INTRODUCTION

As we have seen before, IQON is a program that does not require the student to think about the status of the entities used to model a situation. In other words, the student is allowed to mix entities, which can be represented as rates and amounts in a model, and still have an approximate behaviour and corresponding graphical output which may be qualitatively right or wrong. STELLA is different. Now the student has to think from the start about rates and levels, in order to describe a situation at all (see in section 5. 3 a discussion about rates in STELLA).

This chapter describes the tasks (given in full in Appendix III.1 and III.2) used in the intensive study with STELLA (see chapter 5, section 5. 4, the research design).

7. 2. SECOND MEETING: TEACHING STELLA

STELLA is a relatively complex program to master. A wide range of functions are provided, and there are many operations to learn. It seemed clear that the students in the intensive study would not have enough time to master the system fully. The limitation in time was a crucial factor for designing the teaching phase, which suggested the idea of a training step from which other tasks would follow naturally. For this purpose, I decided to start with a model of a tank leaking water. A leaking bottle (figure 7. 1) was demonstrated to the students, who observed what happened to the level of water, and to the appearance of the water jet. The leaking water was collected in another tank.

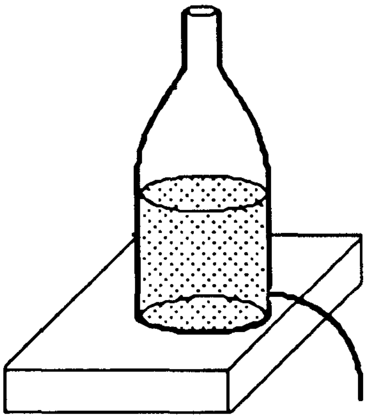
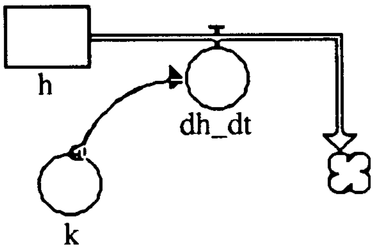


Figure 7. 1 - The bottle with water used for demonstration.

After observing the phenomenon students where guided through the initial teaching tasks in which values (see table 7. 1), obtained from a real experiment, were given, together with a STELLA model to explore (figure 7. 2).

h (cm)	**Mean time (s)**
11	6.5
10	17.3
9	29.0
8	41.3
7	53.7
6	67.7
5	83.5
4	101.0
3	120.7
2	146.5
1	179.7

Table 7. 1 - Real data presented to students.



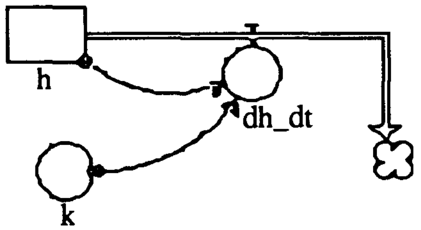
□ h = h + dt*(- dh_dt)
INIT (h) = 11
○ dh_dt = k
○ k = 0. 0926

Figure 7. 2 - First STELLA model to explore.

I showed how STELLA represented the problem, "opening" the main variables and revealing the equations, and then explaining what the group of equations represented. I then asked them to think if there was anything wrong with the model. Did it fit the real data presented in the table ? Students were asked to provide a written answer to give me an idea of their level of understanding.

Deliberately, this model does not describe the data well. It gives a linear decrease of height and in the end negative values for height.

After this was noticed, a different model was shown in which the rate of change of height is proportional to height (figure 7. 3).



☐ h = h + dt*(- dh_dt)
INIT (h) = 11
○ dh_dt = k * h
○ k = 0. 00841

Figure 7. 3 - Second STELLA model to explore.

This model did not give negative values for height, and is qualitatively valid (see section 2. 7. 3 about validation), but still does not describe the data accurately.

I asked the students if they could think of any way to improve the model further. If not, I told them that one way would be to change the equation for the rate, making it proportional to the square root of height (see section 2. 7. 3. for an explanation).

Following these tasks I showed the students how to model the situation in figure 7. 4, with two tanks.

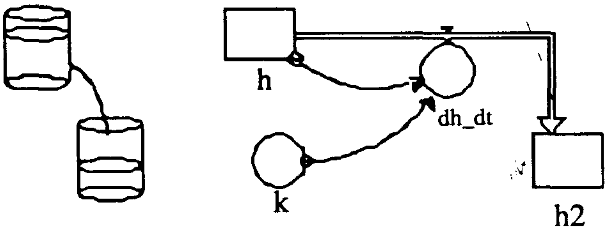


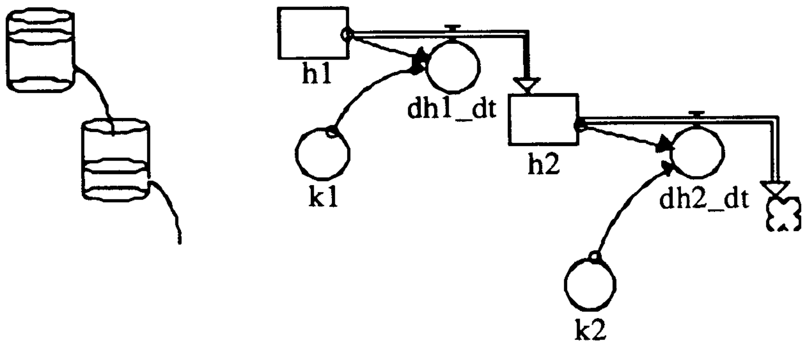
Figure 7. 4 - Two tanks system and model.

I asked them to pay attention to the way I added the extra tank, and to the way I modified the graph and table to show both heights versus time.

To help deal with scales, I provided a pre-defined scaled box for the height of water in the second tank.

7. 3. TASKS INVOLVING LEAKY TANKS WITH STELLA

The first task was to explore a model of a related situation, where the second tank also leaks (figure 7. 5).



```
h1 = h1 + dt * ( -dh1_dt )
INIT(h1) = 30
h2 = h2 + dt * ( dh1_dt - dh2_dt )
INIT(h2) = 0
dh1_dt = k1*h1
dh2_dt = k2*h2
k1  = 0.5
k2 = 0.5
```

Figure 7. 5 - Two tanks with water, with the second tank leaking water, and the model in STELLA .

The students were asked to run the model and to answer the two questions:

a) What happens to the level of the second tank?

Why?

b) What happens if you increase k_2 ?

Why ?

Figure 7. 6 illustrates the graphical output for this model.

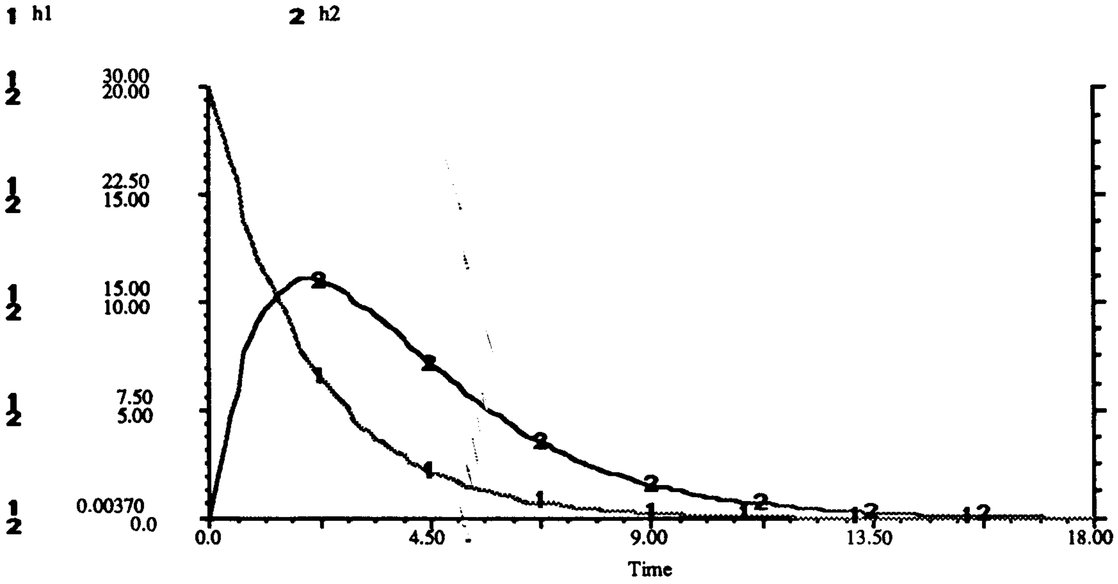


Figure 7. 6 - Graphical output for the initial conditions of the model presented in figure 7. 5.

From this point I acted only as an observer, recording what they did using the schedule for observation (see section 5. 6. 2).

The same process was repeated with a three tank system (figure 7. 7). A predefined box was again provided for the new variable (height of water in third tank).

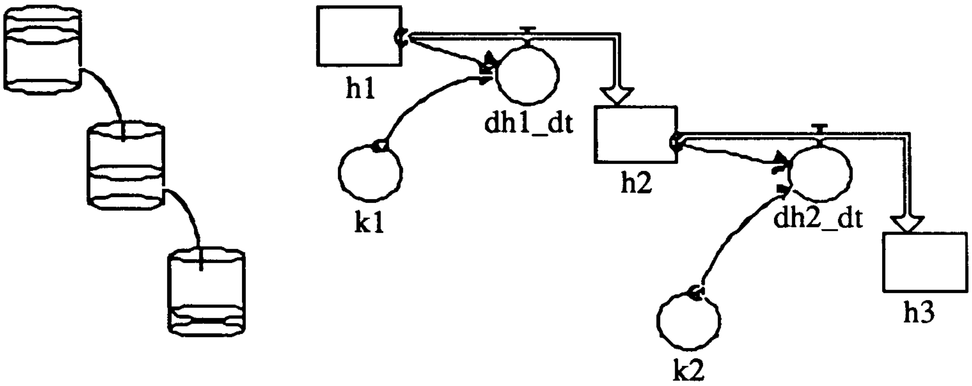


Figure 7. 7 - The three tanks system and model.

They answered the following questions:

c) What happens to the level in the third tank ?

Why ?

d) Could the same model be used for another problem which is not about leaking fluids at all ? Suggest one if you can.

7. 4. DIET AND WEIGHT LOSS - EXPRESSIVE TASK USING STELLA

The expressive task set concerned diet and weight loss. The main points to be investigated were the entities chosen, which entities were considered as levels or rates, and the structure of the model. It was also important to see how far they could transfer the metaphor of tanks used previously, to describe this situation (see research questions in chapter 5).

The starting point was the following text

If you regularly take in more calories in food than you lose in moving about and in heat losses, then you grow fatter and heavier. But the heavier you are, the more effort you need to move around, so you do not go on for ever getting fatter, but stop at a heavier weight.

They were asked to make a STELLA model which could be used to experiment with the effects of over-eating or of dieting, on body-weight.
Because pilot results showed that to define equations and values for "diet and weight loss" was difficult (see chapter 4, section 4. 6), STELLA in the main study was used only as a drawing tool. By the word <u>model</u> here is meant just a structure of TANKS, TAPS and pipes ("the plumbing"). The models developed by students are thus not runnable.
Figure 7. 8 shows a STELLA diagram which would be reasonably acceptable, to be used as a guide when interpreting students' models.

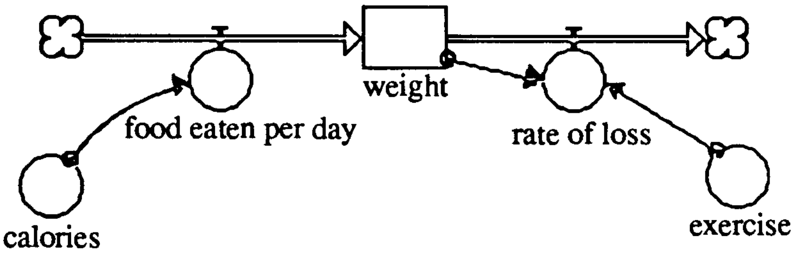
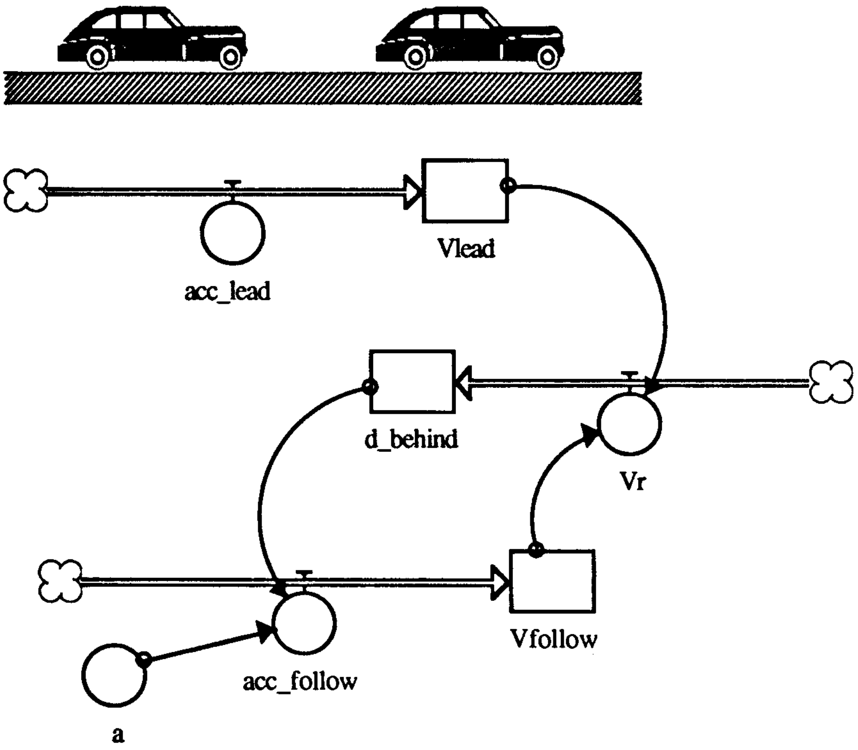


Figure 7. 8 - Diagram used as reference for analysing the diet and weight loss models in STELLA.

7. 5. THIRD MEETING: TWO CARS IN A STREAM OF TRAFFIC - EXPLORATORY TASK WITH STELLA

In this meeting the students were given a complex model for two cars in a stream of traffic to explore, as presented in figure 7. 9.

This is a hypothetical model and does not precisely correspond to any real situation. The students could run the model, observing the change in levels of boxes, and ask for graphs of any variable as function of time.



```
d_behind = d_behind + dt * ( Vr )
INIT(d_behind) = 0
Vfollow = Vfollow + dt * ( acc_follow )
INIT(Vfollow) = 20
Vlead = Vlead + dt * ( acc_lead )
INIT(Vlead) = 40
a = 5
acc_follow = IF d_behind > 0 THEN  +a ELSE -a
acc_lead = 0
Vr = Vlead - Vfollow
```

Figure 7. 9 - Two cars in a stream of traffic. Hypothetical situation and model.

Students were asked to read the equations, thinking about the situation being described. In particular I explained to them the line that defines the acceleration of the following car, which uses an IF THEN ELSE function.

The following drawing (figure 7. 10) for thinking about the situation was presented,

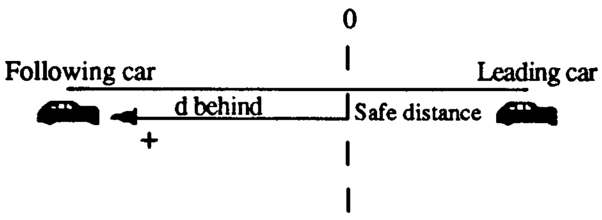


Figure 7. 10 - Drawing showing the distance behind and the safe distance for two cars in a stream of traffic.

with the explanation:

The model represents as boxes (levels) the Velocity of the following car (Vfollow), the Velocity of the leading car (Vlead) $\{\frac{m}{s}\}$ and the Distance behind (d_behind) {m}. As rates the acceleration of the following car (acc_follow), the acceleration of the leading car (acc_lead) $\{\frac{m}{s^2}\}$, which was considered zero, and the relative velocity (Vr) given by Vlead - Vfollow.

The equations shown in figure 7. 9 produce an oscillatory graphical output for d_behind versus time (see graph 1, in figure 7. 11). Also, the graph for acceleration of the following car versus time (3) is constant (positive or negative) and, consequently, the graph for velocity of the following car versus time (2) is linear (increasing and decreasing).

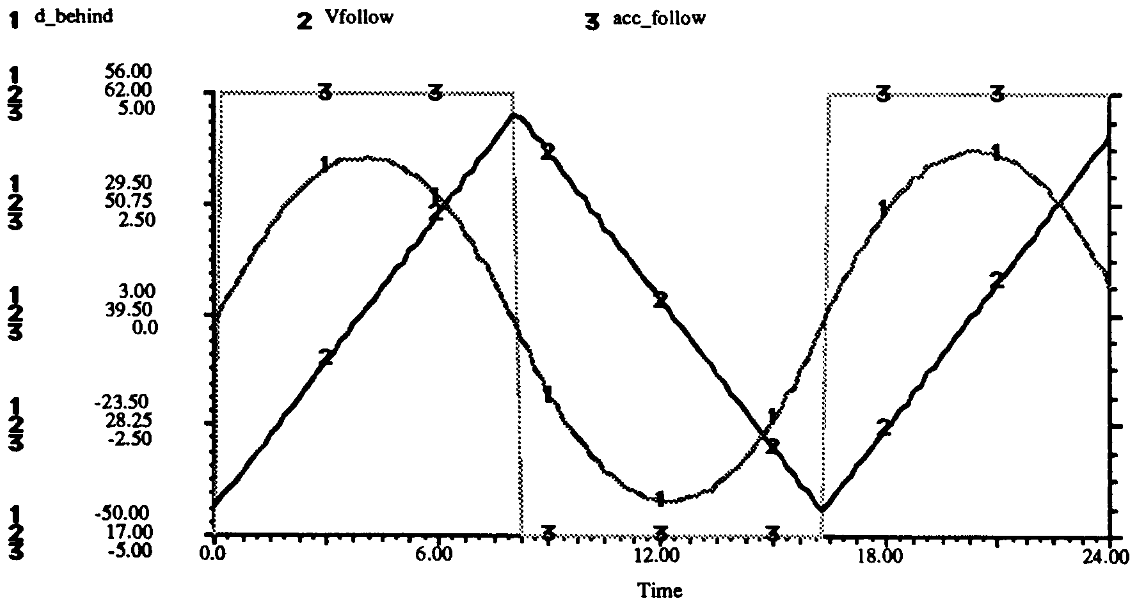


Figure 7. 11 - Graph of the main variables for the two cars in a stream of traffic model.

These written questions were then answered:

1) What happens when the model is run?

2) Could this happen in reality? Why/Why not ?

3) Why does the model in the computer behave this way ?

4) Can you think of any other situation which behaves like this ?

7. 6. DYNAMIC BEHAVIOURS EXPLORED

The STELLA models presented in this chapter produce some of the dynamic behaviours shown in figure 2. 4. These are linear, exponential decay, build-up exponential and oscillation.

The leaky tank model shown in figure 7. 2 has a rate of change constant and, consequently, gives a linear decreasing pattern for height of water versus time. Making the rate of change proportional to height of water, the model produces an exponential decay pattern (see figure 7. 3). The height of water of a second tank added to the leaky tank system (as in figure 7. 4) increases at a decreasing rate, since its rate of increase is proportional to the height of water of the first tank, which is decreasing. As a result the dynamic behaviour of its level of water is a build-up exponential. Considering that the second tank also leaks, the water level of the second tank now depends on the rate of change of the first and second tanks, simultaneously. The resultant pattern of the level of the second tank is critically damped (see figure 7. 6). This system will never oscillate.

For the two cars in a stream of traffic model (in figure 7. 9), the dynamic behaviour of d_behind is oscillatory, while the dynamic behaviour of the velocity of the following car is linear (increasing and decreasing).

CHAPTER 8 - EXPERIENCE WITH HARDWARE AND SOFTWARE, CAUSAL LINKS AND DIAGRAMS AND EXPLAINING A PHYSICAL SYSTEM.

ANALYSIS OF THE QUESTIONNAIRE ABOUT MODELLING, PART I

8. 1. INTRODUCTION

In chapters 8 and 9 the general research question

What can be said about the model building capability of sixth form students, without using the computer, concerning (a) work with causal diagrams and (b) the relevant mathematical knowledge needed ?

will be addressed, together with at least partial answers to the following specific questions:

Will students engage in semi-quantitative reasoning when drawing causal diagrams ?

Can the student identify (select) variables ? What sort of entities do they use to model and how do they use the entities when modelling ?

Will the student think about the real system and use his/her own ideas when drawing a causal diagram ?

These and the other research questions are shown in chapter 5, sections 5. 1 and 5. 3.

8. 2. FRAMEWORK FOR ANALYSING FREE RESPONSE ITEMS

8. 2. 1. THE PROBLEM

In free response items in the first part of the Questionnaire about Modelling (see Appendix I.1.), students were asked to

-suggest causes of effects;
-suggest effects of causes;
-select causal factor from a list;
-make links between cause and effect and
-draw causal diagrams.

Six questions asked for one out of two entities in a causal link, and for a suitable sign for the link, as in the example below (figure 8. 1)

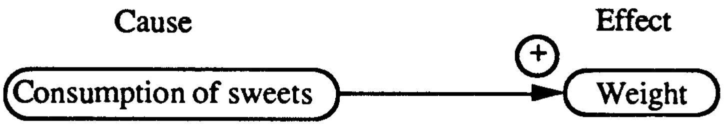


Figure 8. 1 - Example of causal link, questions 3 to 8.

Three questions asked for an effect given a cause, and three the reverse, as below (figure 8. 2).

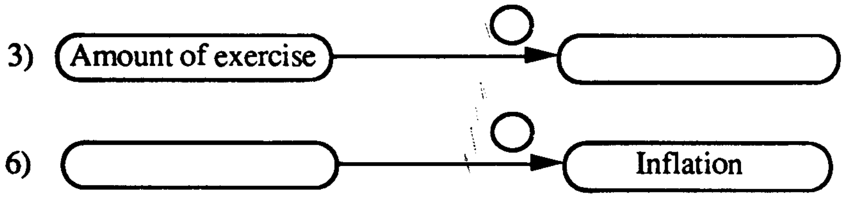


Figure 8. 2 - Questions 3 and 6, showing examples of causal links asking for an effect of amount of exercise and for a cause of inflation.

Questions 13 and 20 are related to Physics and are about a leaky tank and a swing. They were designed with a parallel structure. They present a list of entities to be chosen as variables to describe the situation and to be used when constructing a causal diagram. Students were asked to cross out the items which were of no use at all in making the diagram. In these questions, students were not free to choose entities and had to select them from the list. Some of the entities of the list were previously classified as Quantities or "Other than quantities".

Unlike questions 13 (Leaky tank) and 20 (the Swing), in questions 16 (Two cars in a stream of traffic), 17 (Motorways), 18 (Greenhouse Effect) and 19 (Rabbits and Foxes) students were free not to give quantifiable variables as entities in causal diagrams (see Appendix I.1). In all these questions the heading presents some initial thoughts to guide students to generate their causal diagrams.

8. 2. 2. THE FRAMEWORK OF ANALYSIS OF CAUSAL LINKS

The framework, in figure 8. 3, describes aspects of students' answers on four dimensions:

1) the nature of the entities invoked;
2) the nature and status of the links used;
3) the structure of the causal diagram and
4) the mechanisms used to explain the system.

The network in figure 8. 3 follows the systemic network conventions in Bliss, Monk and Ogborn (1983). Selections are made from all systems following a bracket. One selection is made from a system following a vertical bar.

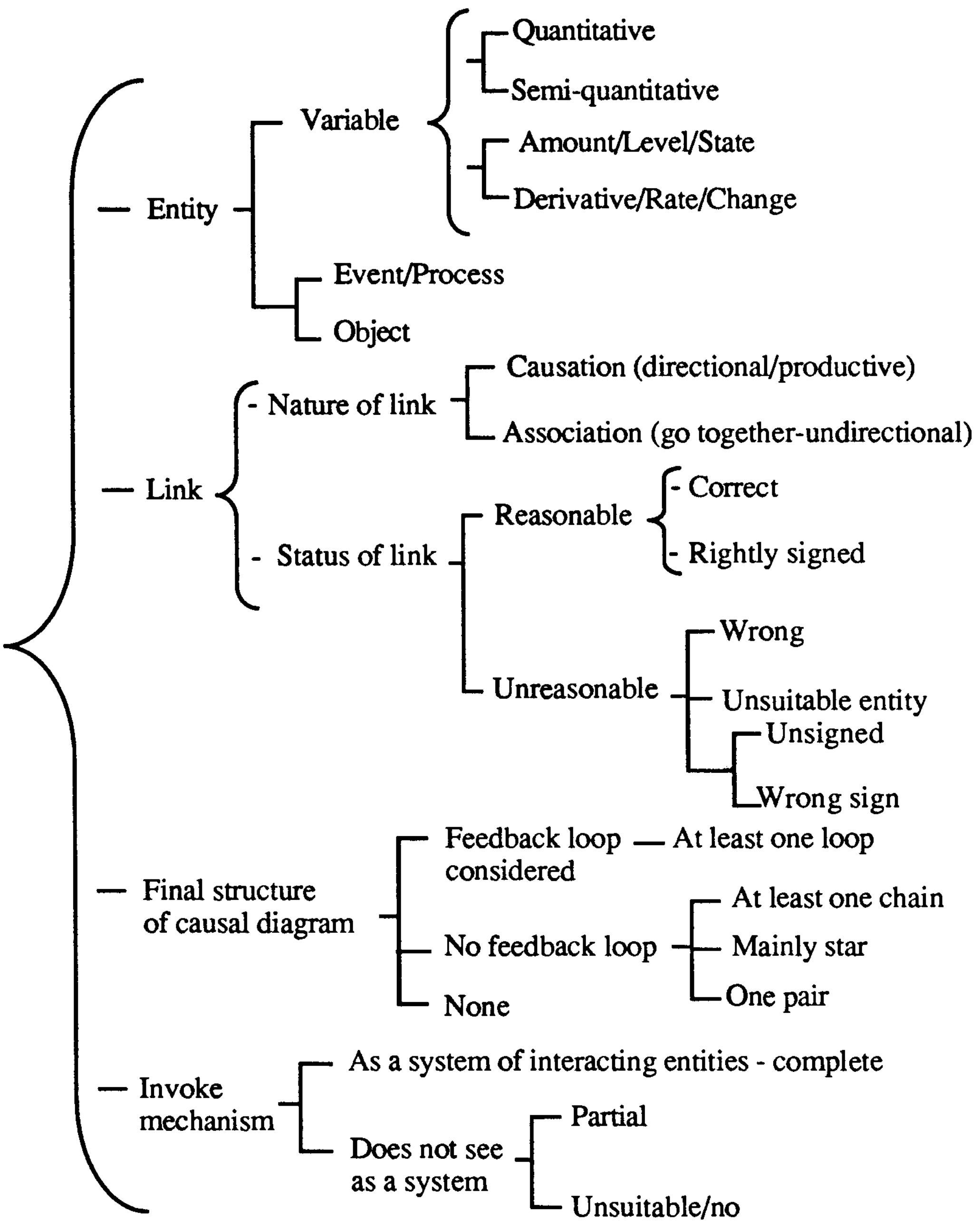


Figure 8. 3 - Framework for analysing data of large survey and intensive study.

8. 2. 2. 1. Classification of entities used

The network describes entities as

- an amount or level of some quantifiable variable, for example weight or height.

- a rate/change of some quantifiable variable, for example, loss of weight, less height or interest rate.

- an amount or level of some nonquantifiable variable, for example, fitness or amount of awareness and

- a rate/change of some nonquantifiable variable, for example, less leisure or greater fitness.

A **Process**, following Forbus, is an action of some kind. For example, 'eating' is a process and it can be more or less intense or active, in other words, there is more or less of an action. Other examples are: burning fuel, eating grass and reproduction.

An **Event** is something that just happens, for example, starting eating or stopping eating. It is localised in time and is not considered in terms of any sort of quantity. Examples of events are: car moves away, foxes die and rabbits survive.

It was not always possible to distinguish an entity as an event or process, in which case entities which could be considered as an event or process were put in one category named **"event/process"**.

We have an **Object** when the "variable" is seen as a thing or a person. Examples of objects are: Bob (name representing a person), Earth and Channel Tunnel.

8. 2. 2. 2. Reasonable links

I decided to use as an indicator of whether a link is reasonable or not in a causal diagram its nature and status. The framework uses Bunge's ideas of directional/nondirectional and productivity, for analysing the nature of the link as Causation or Association (see section 2. 4). The status of the link is also assessed as being reasonable or unreasonable. A link is reasonable if it indicates the correct direction (production) or association between two entities and if it is correctly signed. A link is unreasonable if it indicates a wrong direction or association between two entities. It is unreasonable, as well, if it has got at least one unsuitable entity, is unsigned, or has the wrong sign. The judgment about what should be considered a correct/wrong direction/association, a wrong sign and an unsuitable entity will depend on the situation being modelled.

As examples of unreasonable links, for describing a Leaky tank, we have:

1) Flow of water ------> + Size of the hole,

indicates a wrong direction since, for a rigid tank, it will never happen (see discussion in section 2. 4);

2) Size of the hole --------> - Flow of water,

has a wrong sign since size of the hole will positively affect the flow of water;

3) Size of the hole --------> Flow of water,

has no sign and

4) Size of the hole -------->+ Density of water,

might have Density of water as the unsuitable entity.

Reasonable links can be composed of semi-quantitative variables, events/processes and objects as well, but have to make sense. For example, both the links

rabbits ---------> + foxes

and

number of rabbits --------> + number of foxes

were considered reasonable, even though the first link might be interpreted as composed only of objects, and the second of quantitative amounts.

8. 2. 2. 3. Structure of causal diagrams

The structures of the causal diagrams produced were divided into two groups: those which contained **at least one feedback loop** and those which did not. Whether the links were reasonable or not, students who used at least one feedback loop, in principle, were identified as possibly thinking at a system level. Evidently, in an extreme case, it would still be possible to have a feedback loop composed entirely of unreasonable links. Because of this, the structure and the fraction of reasonable links were analysed together. Amongst the causal diagrams which had no feedback loop, it was possible to order structures as **one pair**, **mainly star** ["laundry list thinking" (see section 1. 2. 3)] and **at least one chain**, see structures in figure 8. 4 below.

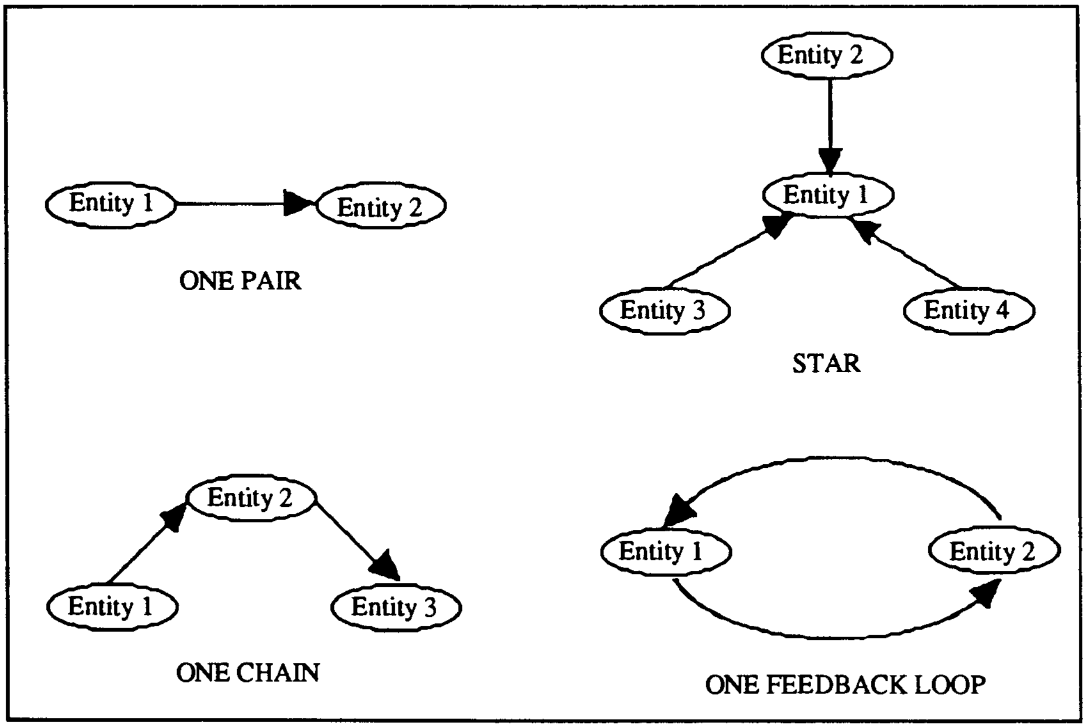


Figure 8. 4 - Possible structures of causal diagrams.

I hypothesize that developing causal diagrams, composed of reasonable links, having 'at least one feedback loop' involves more elaborate reasoning than developing causal diagrams which have 'at least one chain' (a sequence with a minimum of three interacting entities). I hypothesize, as well, that developing causal diagrams that have 'at least one chain' involves more elaborate reasoning than developing causal diagrams which are 'mainly star' or 'one pair'. As a consequence, I decided to adopt the following score scheme to classify structures of causal diagrams:

none --> 0

one pair --> 1

mainly star --> 2

at least one chain --> 3

at least one feedback loop --> 4

8. 2. 2. 4. Invoke a mechanism

The last dimension of the framework presented in figure 8. 3, will be discussed later, in section 8. 6.

8. 3. THE SAMPLE USED FOR THE QUESTIONNAIRE ABOUT MODELLING

The Questionnaire about Modelling first and second parts, described in section 5. 5, was applied in London, in 4 Schools, to 48 students, 45 of whom also completed the second part. In Kent, it was applied in two schools, to 25 students, 22 of whom also completed the second part. Thus for London and Kent together, the questionnaire was applied to 73 students 67 of whom also completed the second part.

The majority of the students were 17 years old, taking at least Physics A-Level.

Table 8. 1 shows the geographical location of the schools, the number of students per school and the total number of students, for each part of the questionnaire.

Location	School	1st Part nº of students	2nd Part nº of students
London	A	6	6
	B	13	13
	C	7	7
	D	22	19
	Total London	**48**	**45**
Kent	E	15	15
	F	10	7
	Total Kent	**25**	**22**

Table 8. 1 - Location, label of school and number of students for each part of the Questionnaire about Modelling.

Schools A, B and C are located in North London, and school D is located in South East London. School D is a VI form College. Schools A, B and C are comprehensive. School E is a Technical School and F a Grammar School for Boys. All schools offer regular A - Level courses in many subjects.

It was not possible to make a random selection of subjects, so the selection of students was based on their willingness to participate in answering the questionnaire.

Differences between schools were analysed with respect to previous experience with software and hardware (questions 1 and 2, Questionnaire about Modelling, Part 1 - see

Appendix I. 1) and mathematical knowledge (Questionnaire about Modelling, Part 2 - see Appendix I. 2).

Kent schools did not differ from one another concerning the overall scores in mathematical knowledge and experience with hardware and software. London schools did not differ from one another concerning mathematical knowledge, but school C for girls presented a significantly smaller mean score for experience with software. The comprehensive school B presented a significantly larger mean score for experience with hardware. Schools A, B and D did not differ for experience with software and schools A, C and D did not differ for experience with hardware.

In view of the minor nature of any differences, in what follows Schools A, B, C and D in London are analysed together, with the analysis of Schools E and F in Kent kept apart.

8. 4. EXPERIENCE WITH HARDWARE AND SOFTWARE - LONDON AND KENT

Questions 1 and 2 were designed to survey the experience of students with software and hardware. Previous experience with specific types of software and hardware may be an important factor for developing model building capability. Besides characterizing the experience students have with software and hardware, the aim will be to relate this survey with achievement in Mathematics and model building using causal diagrams.

One could argue that it is necessary to know exactly what kinds of activities have been done with the computer in class. However, the simple data collected here may give some reasonable indications.

Chart 8. 1 shows experience with software and hardware, for London and Kent. (Experience was scored as two for use of two or more items, one for use of one or two and 0 for no use).

In general, London and Kent seem to have a reasonable experience with hardware and software, with the smallest mean score being due to London (about 0.50 for software, which corresponds to one or two types used).

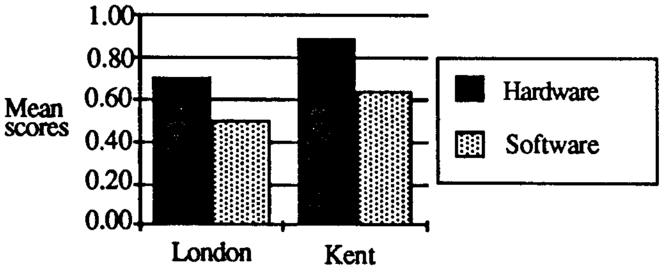


Chart 8. 1 - Experience with Hardware and Software - London and Kent.

Chart 8. 2 shows the fraction of students who have used **not any, one or two**, and **more than two**, types of software and hardware, for London and Kent.

London and Kent differed significantly for use of hardware ($\chi^2 = 5.7$, 1df, with continuity correction, considering Not any and 1 or 2 as one category) at 0.05 level. In general, Kent students had used a significantly larger number of types of hardware.

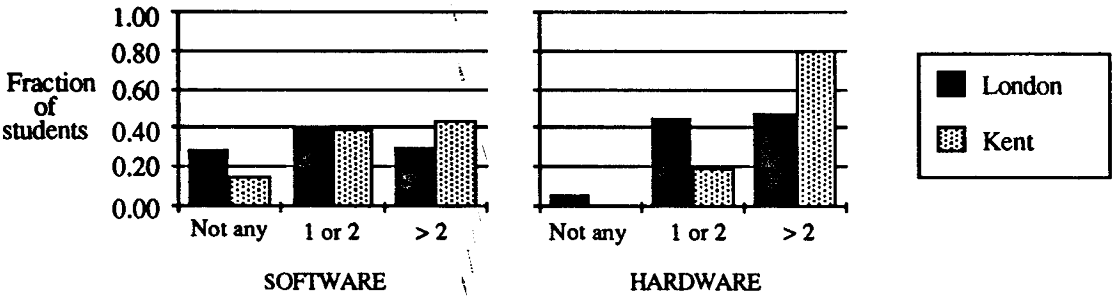


Chart 8. 2 - Fraction of students by number of software and hardware used, for London and Kent.

Chart 8. 3 shows that the most used type of software, for London and Kent, is the computer language BASIC. In second place comes the application Spreadsheets.
London and Kent did not differ concerning the use of BASIC and Spreadsheets, but there is a noticeable difference in favour of London, concerning the use of Pascal, and, in favour of Kent, concerning the use of LOGO.
Few students had any experience with Prolog, and only one student had used DMS.
Under "others", students indicated the language "C" (5 responses), and Assembler (1).

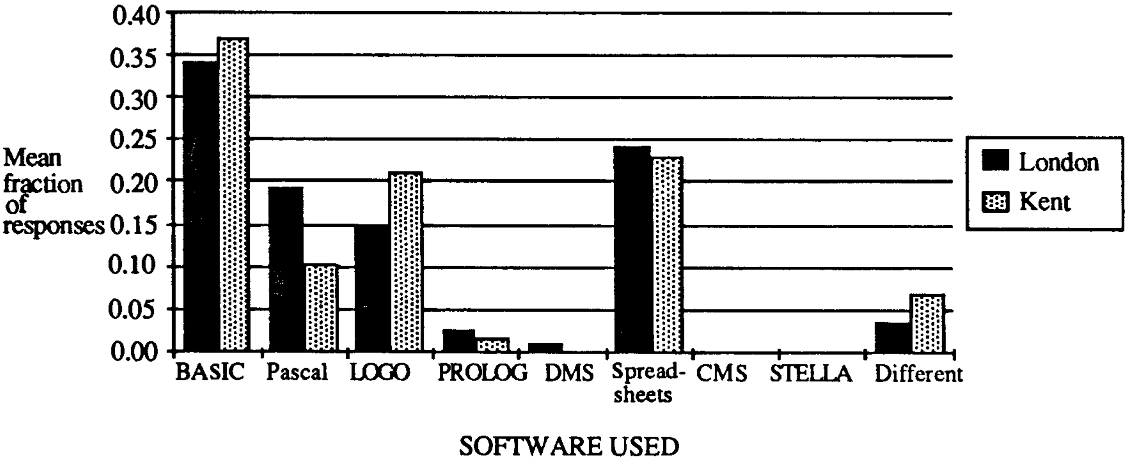


Chart 8. 3 - Specific software indicated - London and Kent.

Chart 8. 4 shows that there is a wide range of experience with different types of computers in London and Kent. In general, they present a very similar pattern for hardware used, the most common being the BBC computer, followed by the Nimbus. There is a small difference between London and Kent concerning the use of BBC and IBM.
The experience with Macintosh computers is minimal. Only very few students had used Macintosh computers before.

There is a noticeable difference between London and Kent concerning the use of other hardware. Types given were Sinclair (2), Spectrum (11), Atari (8) and ZX81(5).

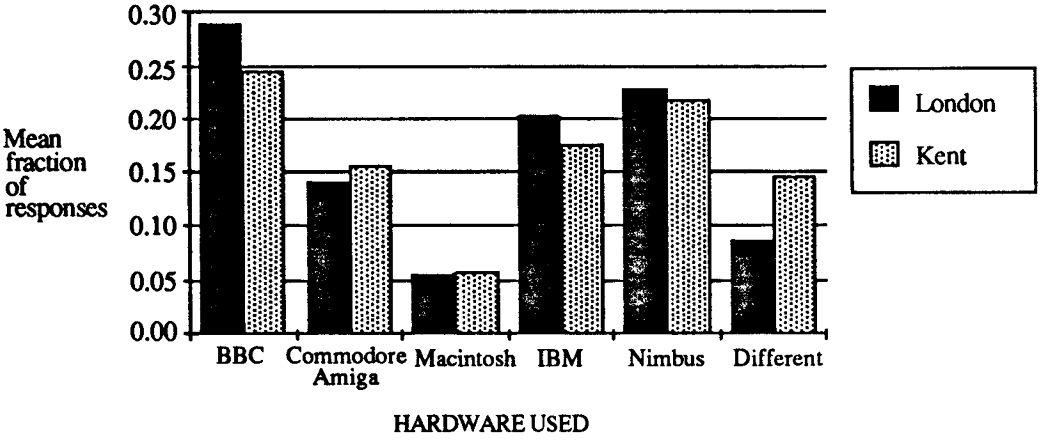


Chart 8. 4 - Specific hardware indicated - London and Kent.

These results indicate that BBC computers and BASIC seem to be the most used combination of software and hardware in schools.

8. 5. SIMPLE CAUSAL LINKS AND INTERPRETATION OF CAUSAL DIAGRAMS

After a brief introduction to causal diagrams, there were six questions (3 to 8) about causal links (see section 8. 2. 1), one question about graphical interpretation of a text (10) and three questions about interpretation of causal diagrams (9, 11 and 12).
Besides the characterization of answers, one of the aims of these questions was to help students with the necessary knowledge of causal diagramming as a technique, for them to be able to draw causal diagrams for more complex situations.

8. 5. 1. SIMPLE CAUSAL LINKS

Each question gave either a cause or an effect, and asked the student to propose, respectively, its effect or its cause.
The analysis will look at how well students could propose any cause or effect at all, at how reasonable their ideas were, and at what kinds of entities they proposed.
Aiming to get a score which could reflect the students' performance in the whole group of six causal links (questions 3, 4, 5, 6, 7 and 8, together), each set of answers was coded showing the number of slots filled and the number of slots (or links) which were reasonable.
Chart 8. 5 shows the mean fraction of slots filled and of reasonable links for the whole group of 6 questions. In general, students were able to propose an entity for each causal link and to construct a causal link that made sense.

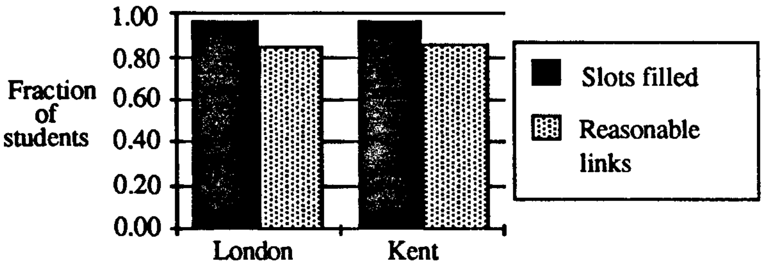


Chart 8. 5 - Mean fraction of slots filled and reasonable links, for questions 3, 4, 5, 6, 7 and 8, together, for London and Kent.

To achieve a reasonably reliable classification, the initial set of categories in section 8. 2. 2. 1 was modified and simplified until agreement could be reached with a second rater. "Variables as quantitative amounts and rates" were put together as **quantities**. Also, "variables as semi-quantitative amounts and rates" were put together as **semi-quantities** and events, objects and processes as **others**.

Chart 8. 6 shows the fraction of students who used **Quantities, Semi-quantities** and **others**, in their causal links, for each question.

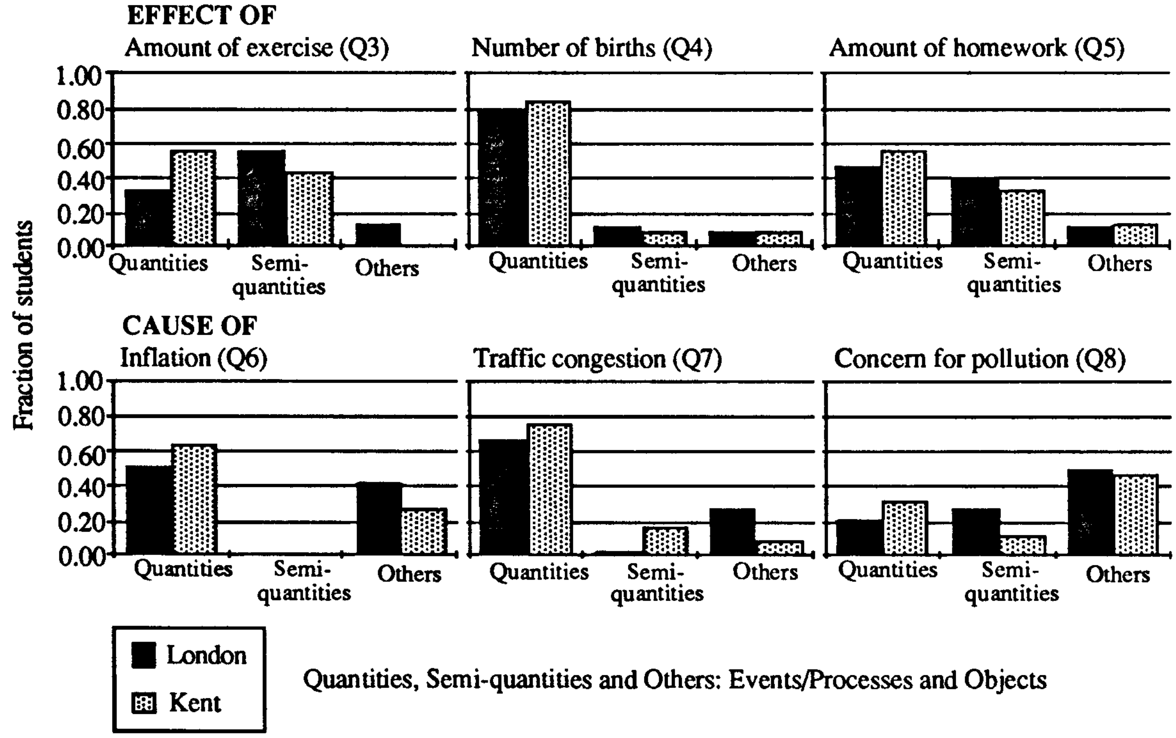


Chart 8. 6 - Fraction of students who have used Quantities, Semi-quantities and Others in causal links for questions 3, 4, 5, 6, 7 and 8.

Questions 4 and 7 asking for an effect of number of births and for a cause of traffic congestion had the largest fraction of students who used quantities. For question 4 the commonest entity was "population", and for question 7 the "amount or number of cars" and the rate/change "more cars".

Question 6 and 8, for causes of inflation and concern for pollution, were responsible for the largest fraction of students who have used "others". Maybe due to lack of knowledge about inflation and pollution, some students were not able to think of proper variables to use in causal links.

Questions 3 and 5, for the effect of amount of exercise and homework, respectively, were responsible for the largest fraction of semi-quantities. The most used semi-quantities for effect of amount of exercise were "fitness" and "health", and the most used quantity was "weight". For amount of homework the most used semi-quantity was "knowledge", and the most used quantities were related to time as, for example, "free time".

Differences between London and Kent were very small for effect of number of births and amount of homework and for cause of inflation and concern for pollution. Kent students used quantities slightly more often than London students, who slightly preferred semi-quantities or (for inflation and concern for pollution) "others". Differences were noticeable for effects of amount of exercise and cause of traffic congestion. For effect of amount of exercise London students were responsible for noticeably larger fractions of semi-quantities and "others", while Kent students were responsible for a larger fraction of quantities. For cause of traffic congestion Kent students were noticeably responsible for a larger fraction of semi-quantities, and London students for a larger fraction of "others". The difference for effects of amount of exercise was <u>not</u> statistically significant ($\chi^2 = 3.24$, 1df, with continuity correction, considering semi-quantities and "others" as one category) at 0. 05 level.

8. 5. 2. CAUSAL DIAGRAM, TEXT AND GRAPH

Question 9 gave a simple positive feedback causal loop diagram, linking the entities CRY and DEPRESSED, for the student to interpret, and to draw the associated dynamic behaviour on a graph of one of the main variables against time.

Answers were coded according to the kind of graph drawn. The possible scores, for question 9, were

0 no/wrong answer,
1 a graph with upward slope
2 graph has an upward curvature and upward slope (see figure 8. 5 below).

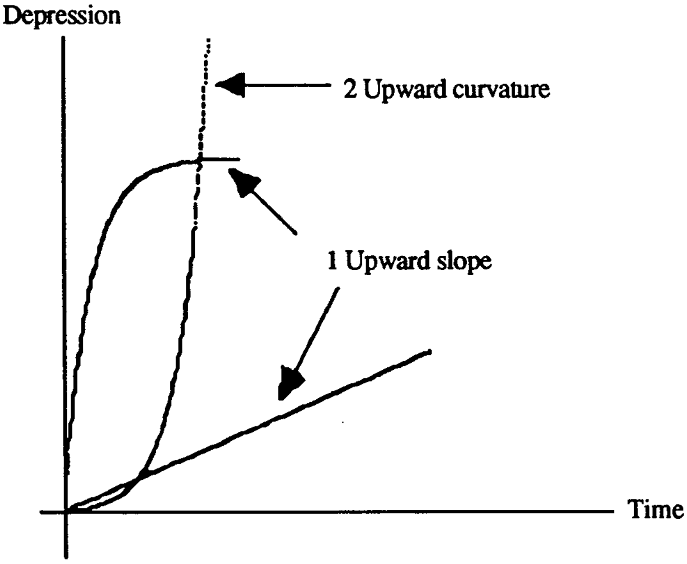


Figure 8. 5 - Kinds of graphs drawn by students and corresponding scores for question 9.

Question 10 gave a short text about a student who prepares for an examination - the more she prepares, the better her performance, up to a point, after which more work does not improve her test score. The question asked students to identify variables, choose the best shape of graph which might represent the situation and to allocate the variables to axis *y* and *x* (see Appendix I. 1).

Answers were coded according to the following score scheme:

0 no/wrong answer,

1 the choice of  (*c*) as the correct graph,

plus 1 for the correct identification of variables and

plus 1 for the correct allocation to axis *y* and *x* . Consequently, the possible total scores for the item, are: 3, 2, 1 and 0.

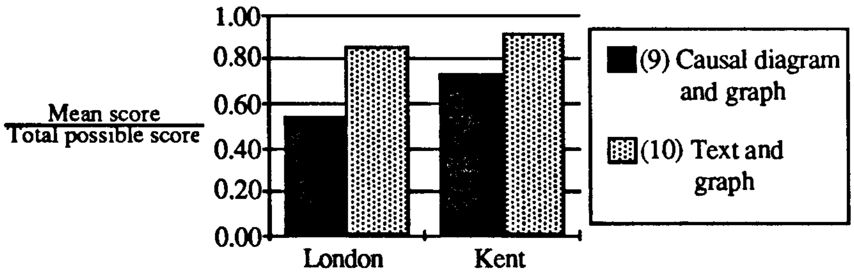


Chart 8. 7 - "Mean score per total possible score" for London and Kent in questions 9 and 10.

To compare achievement in questions with different maximum scores (2 for question 9 and 3 for question 10), a mean score as a fraction of the maximum possible score was defined.

Chart 8. 7 shows the mean score per total possible score for London and Kent in these questions. In general, students scored well in both questions, for London and Kent. The minimum mean score was about 0.50 of the possible total (which corresponds to a mean score 1), for London, for question 9. There was a significant difference between London and Kent, in favour of Kent ($t = 2.69$, 71df), at 0.05 level.

The difference between London and Kent was not statistically significant for question 10, but the trend for question 9 was maintained.

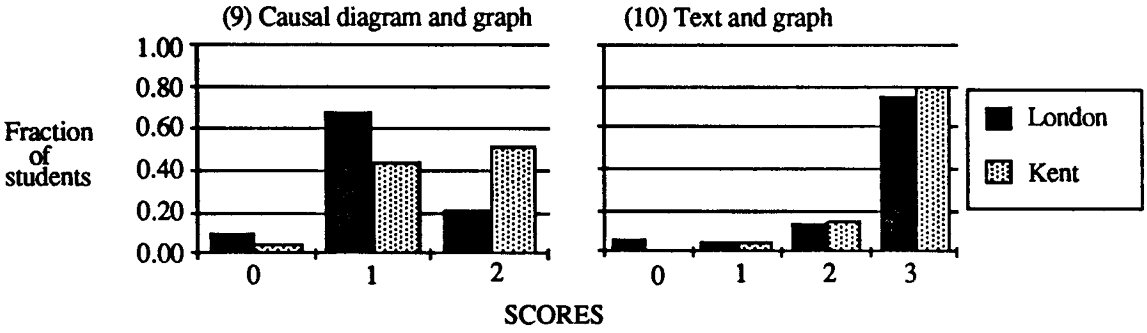


Chart 8. 8 - Fraction of students by score, for London and Kent, in questions 9 and 10.

Chart 8. 8 shows, for questions 9 and 10, for London and Kent, the fraction of students who got scores 0, 1, 2 and 0, 1, 2, 3, respectively.

In general, for question 9, the majority of London students drew a graph with an upward slope (score 1). Only about a fifth of London students, and roughly half of the Kent students, drew a graph with an upward curvature (score 2). Differences between London and Kent, for question 9, were significant ($\chi^2 = 6.\ 03$, 1df, with continuity correction, considering scores 0 and 1 as one category) at 0.05 level.

For question 10, the majority of London and Kent students gave a completely correct answer (score 3).

8. 5. 3. CONTROLLING WEIGHT AND POLLUTION

Question 11 gave a causal diagram showing how a person's weight affects and is affected by other things (see figure 8. 6). Seven related true/false subquestions were asked.

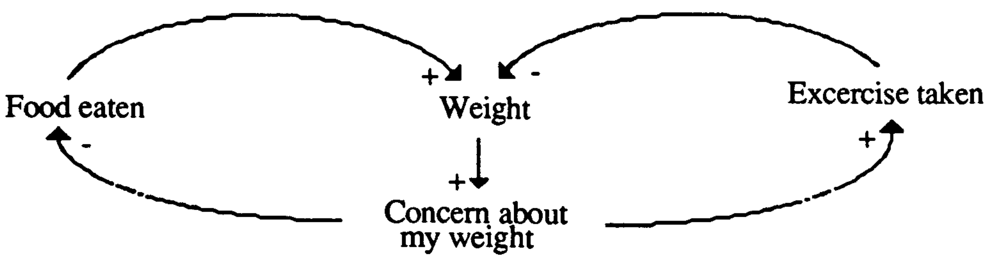


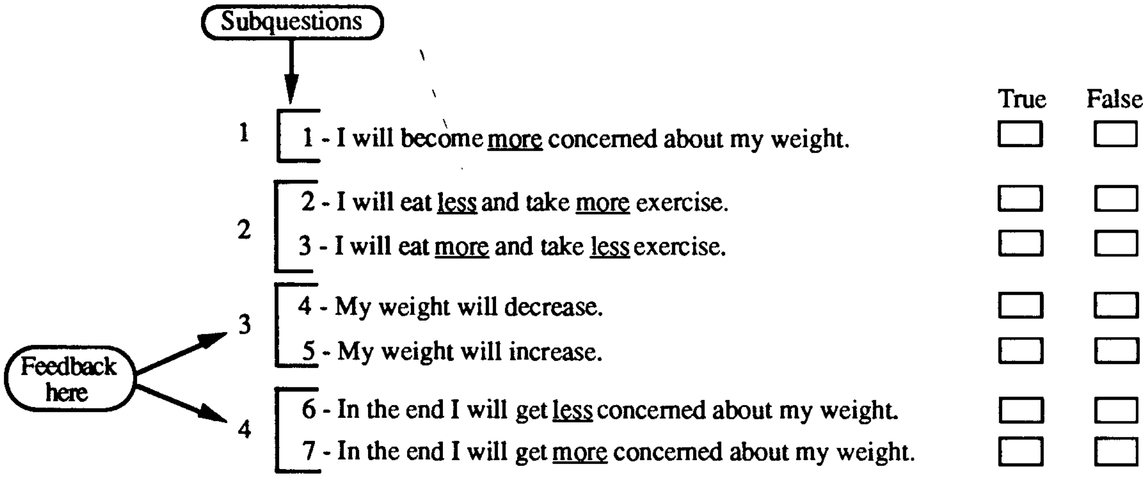
Figure 8. 6 - Causal diagram showing how a person's weight affects and is affected by other things.

Question 12 was of the same nature, with five subquestions, but about "controlling pollution" (see Appendix I.1.).

Both questions gave causal loop diagrams for the students to interpret. The aim of the questions was to see if the students could understand what the causal diagram was representing and to see also, if they could manage the loops - that is, predict the behaviour of entities involved in a feedback loop.

8. 5. 3. 1. Reasonable answers

The maximum number of reasonable answers was 4, for question 11, and 3, for question 12, since subquestions of same nature, for the purpose of data analysis, were grouped together. For example, see figure 8. 7 below, for question 11, subquestions *2 and 3* , *4 and 5* and *6 and 7* were grouped together. Each group of two related subquestions was counted as one group only.



1 - I will become <u>more</u> concerned about my weight. ☐ ☐

2 - I will eat <u>less</u> and take <u>more</u> exercise. ☐ ☐

3 - I will eat <u>more</u> and take <u>less</u> exercise. ☐ ☐

4 - My weight will decrease. ☐ ☐

5 - My weight will increase. ☐ ☐

6 - In the end I will get <u>less</u> concerned about my weight. ☐ ☐

7 - In the end I will get <u>more</u> concerned about my weight. ☐ ☐

Figure 8. 7 - Scheme showing how answers for question 11 were analysed.

Chart 8. 9 shows the mean fractions of reasonable answers, and those which got the effect of feedback right (see discussion below), for London and Kent, for questions 11 and 12.

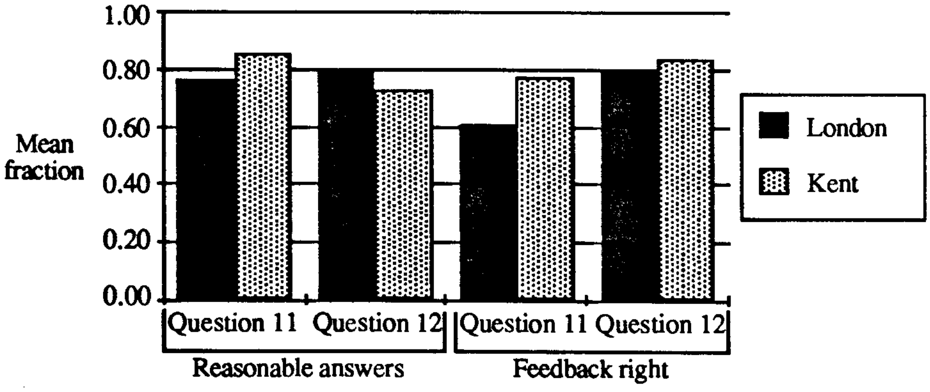
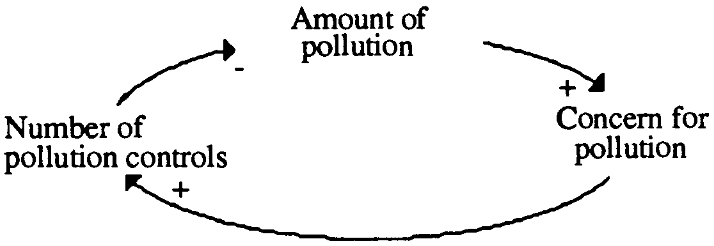


Chart 8. 9 - Mean fractions of reasonable answers and feedback right for London and Kent, for questions 11 and 12.

In general, students presented a large number of reasonable or right answers for groups of subquestions. The minimum mean fraction was about 0.7. These results suggest that students seemed able to follow the connections between entities in causal diagrams without much problem.

8. 5. 3. 2. Feedback right

Question 12 shows the following causal diagram (figure 8. 8) and considers initially that the amount of pollution is high.



True False

3 - In the end the Amount of pollution will increase. ☐ ☑

Figure 8. 8 - Causal diagram for controlling pollution and subquestion three.

Subquestion 3 asks about what will happen in the end to the amount of pollution. To answer this question the student may think first that the concern for pollution will increase, which will make the number of pollution controls increase, which, eventually, will make the amount of pollution decrease. Then the student is coming back to the variable which was initially changed - here, amount of pollution.

It was possible to isolate for questions 11 and 12 the items responsible for "closing" the loop (feedback). For question 12 there were two subquestions (numbers 3 and 5) with feedback for *amount of pollution*. For question 11 there were two subquestions with feedback for *weight* (numbers 4 and 5) and two for *concern about weight* (numbers 6 and 7). To be counted as getting the feedback correct, students had to come back to the entity that was originally changed. If the student answered correctly the related pair of subquestions, s/he has been considered as correctly following the feedback loop.

Chart 8. 9 shows that, in general, students had a large mean number of feedback loops correctly described, with minimum score 0.60, due to London, in question 11.

No significant differences between London and Kent, for reasonable answers and feedback right, were found.

Chart 8. 10 shows, for question 11, the fraction of students for group of subquestions with feedback right. London and Kent had the same fraction of students with no feedback right.

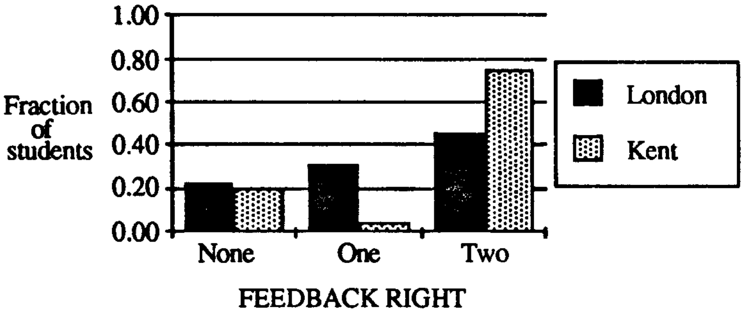


Chart 8. 10 - Fraction of students, for London and Kent, per groups of subquestions with feedback right, for a person controlling his/her weight (Question 11).

However, a significantly larger fraction of Kent students was responsible for *two* groups of subquestions with feedback right ($\chi^2 = 8.3$, 2df) at 0.05 level. Despite there being no significant difference concerning means for feedback right, a larger fraction of students in Kent got right both subquestions involving feedback.

Roughly half of the students in London, and a quarter in Kent, had at least one feedback wrong, which suggests that these students had some difficulties when explaining the entities involved in feedback. This may mean that their basic level of reasoning with causal diagrams was "following chains", and not "closing loops", in this particular question.

For question 12, the majority ($\approx$ 0. 80) of London and Kent students got right the only group of subquestions about feedback.

8. 5. 4. AN OVERALL SCORE FOR INTERPRETING CAUSAL DIAGRAMS

An overall score for achievement in interpreting causal diagrams and defining causal links (questions 3 to 11) was constructed. The aim of this score was to reflect whether the students, after a brief introduction about causal diagrams (see page two of the Questionnaire About Modelling, Part 1), were ready to engage in the construction of causal diagrams for the main tasks (Leaky tank, Two cars in a stream of traffic, Motorways, Greenhouse Effect and Rabbits and Foxes).

The overall score included the fraction of reasonable causal links (questions 3 to 8), the mean scores for graphical interpretation of a causal diagram (question 9) and text (question 10), and the mean scores for reasonable answers for reading and interpreting a causal diagram (questions 11 and 12).

The construction of this overall score was justified by the fact that the questions correlated positively. The correlations were not large, a result explicable in terms of the fact that many students obtained the maximum score on several items.
The overall scores (maximum one) are presented in table 8. 2 below.

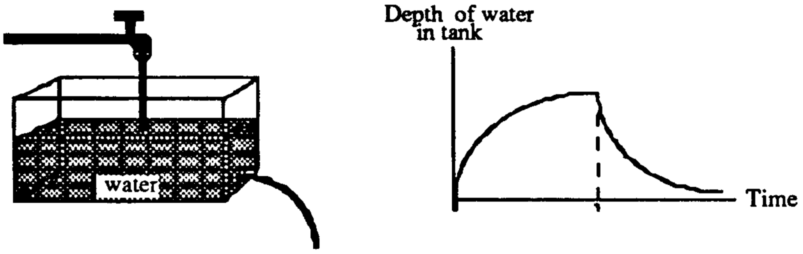
	London	Kent
Mean	**0. 82**	**0. 85**
St. dev.	0. 15	0. 13
Nº stud.	48	25

Table 8. 2 - Overall score (max 1) for interpreting causal diagrams (questions 3 to 11).

Students got very good overall scores in the initial questions about causal diagrams. This result supports the validity of later questions asking for causal diagrams (this result is also in accordance with expectation 6 in section 3. 4, table 3. 1 - that we should expect no problem in learning causal loop diagramming as a technique ...).
No differences between London and Kent were found.

8. 6. EXPLAINING A PHYSICAL SYSTEM

In questions 14 and 15 students were asked to explain, from reading a graph, what was happening in a physical situation - a leaky tank with a tap putting water into it (see questions in figure 8. 9 below).



(14) What do you suppose is happening between time equal to zero and time equal to 1 ?

(15) What do you suppose is happening to time greater than 1?

Figure 8. 9 - Questions 14 and 15 about a leaky tank with a tap also putting water into it.

I decided to check the fraction of students who used variables and who presented rates in and out explicitly in their explanations.

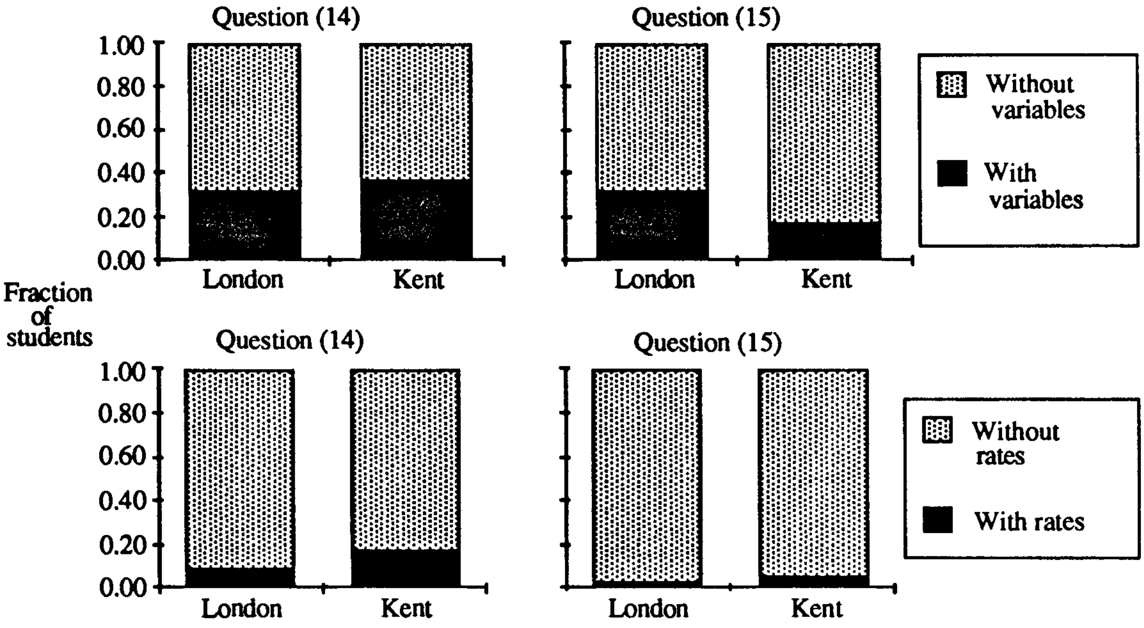


Chart 8. 11 - Fraction of students who were able to explain using variables and using explicitly rates in or out, for London and Kent.

Chart 8. 11 shows that, in general, for London and Kent, for questions 14 and 15, students tended not to use variables or rates in or out explicitly in their explanations. Less than about a third of the students used variables in their explanations. An example of an explanation involving variables is
"water depth decreases with time".
The others (about 0.70) gave explanations using events, in terms of what happened to the object tank or water. Examples are:
"no more water is being added therefore the tank empties out";
"the water entering the tank from the tap is greater than the water leaving the tank through the hole " and
"the hole of the tank is kept close as the water is being collected".
For both questions very few students mentioned explicitly in their explanations the rates in or out (this result is in accordance with expectation number 5 in section 3. 4, table 3. 1 - we should expect much trouble in understanding of rates ...).
An example involving explicitly rates in and out is
"rate of flow from the hole > rate of flow from the tap => tank is emptying".
As a way of knowing whether students saw the situation as a system of interacting entities or not, **mechanisms** they provided in explanations were classified. Three kinds of mechanisms, for explaining changes in the water level, were identified:

1 - **tap** (or related entity) **and** **hole** (or related entity) as responsible;
2 - just **tap** (or related entity) **or** **hole** (or related entity) as responsible and
3 - **no or unsuitable** mechanism (those that did not make any sense).

Students who used mechanism 1 were considered as potentially seeing the situation as a system of interacting entities. Students who used mechanism 2 were considered as not doing so.

I hypothesize that 'seeing as a system' reflects a higher level of perception of the situation. Consequently, for evaluating the kind of mechanism used, I defined the following score scheme:

See as a system: **tap** (or related entity) **and hole** (or related entity) responsible ----> 2;

Does not see as a system: just **tap** (or related entity) **or** **hole** (or related entity) responsible ----> 1;

No mechanism or **unsuitable** mechanism ----> 0.

Chart 8. 12 shows the fraction of students who used a specific kind of mechanism, for London and Kent.

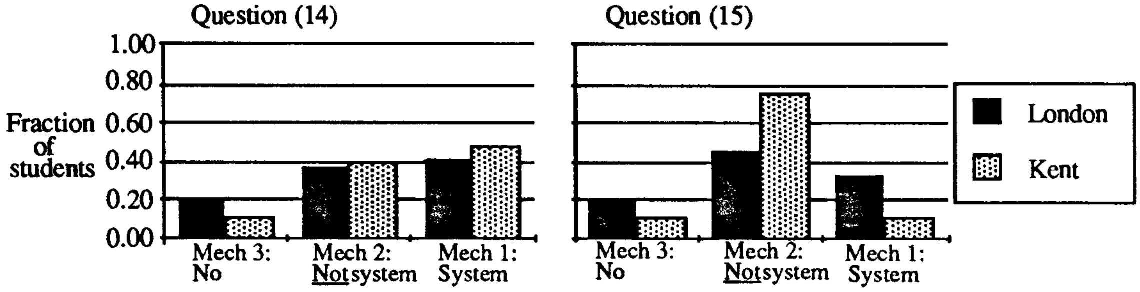


Chart 8. 12 - Fraction of students per kind of mechanism, for questions 14 and 15, for London and Kent.

For question 14, roughly 0.40 of the London students, and half of Kent students saw the situation as a system of interacting entities.

For question 15, about half for London, and two thirds for Kent, did not see the situation as a system. London and Kent differed significantly in the proportion of students that used different kinds of mechanism in their explanations ($\chi^2 = 6.258$, 2df) at 0.05 level.

The difference can be explained because questions 14 and 15 are related. Students from Kent, after giving a suitable explanation for question 14, just explained what happened to the tap, ignoring the hole, maybe to avoid repeating themselves. They usually answered, for example, "the tap has been closed". Thus this result may be an artefact of the question.

We saw in section 8. 5 and we will see again later (in sections 8. 6 and 8. 9) that in a variety of other problems students use events and objects in place of variables, and that this varies with the nature of the problem.

8. 7. ENTITIES USED IN CAUSAL DIAGRAMS FOR THE LEAKY TANK AND THE SWING TASKS

The analysis will look at the number and kinds of entities students chose to use in causal diagrams, at the way students considered "time" in causal diagrams, and at the kind of causal diagrams drawn. Besides that, I will be looking at which entities were seen as causal factors, for describing the situation, and the number of reasonable links used. Differences between London and Kent will be reported.

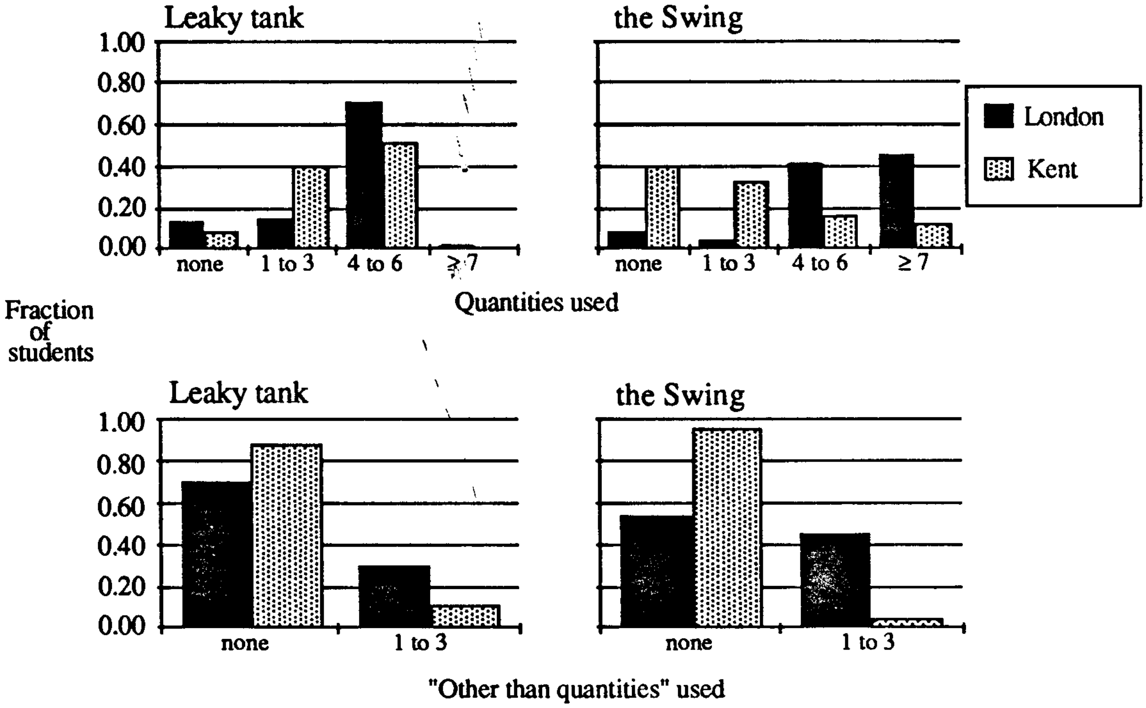


Chart 8. 13 - Fraction of students by number of Quantities and "Other than quantities" used in causal diagrams for the Leaky tank and the Swing, for London and Kent.

The leaky tank (question 13) and the swing (question 20) tasks are presented in Appendix I. 1.

Chart 8. 13 shows that, for the leaky tank task, about two thirds of London students used 4 to 6 quantities in causal diagrams. The same was done by roughly half of the Kent students. About 0.40 of the Kent students used between one and three quantities.

The majority of London and Kent students did not use any "other than quantity", but about a third of London students used one to three "other than quantities".

For the Swing task, the majority of the Kent students used a maximum of three quantities while the majority of London students used between 4 and 7 quantities. Almost all Kent students did not use any "other than quantity", while almost half of London students used one to three "other than quantities".

For the Swing task, London and Kent differed significantly concerning the number of quantities ($\chi^2 = 23.7$, 1df, collapsing the groups in *0 - 3* and *≥4* quantities used) and "other than quantities" (p = 0. 0001 - Fisher[4]) used, at 0.05 level. London students used a significantly larger number of quantities and "other than quantities" in causal diagrams. Kent students constructed causal diagrams with smaller numbers of quantities and avoided "other than quantities".

No significant differences for the leaky tank task, for the use of "Other than quantities", were found, but the pattern for the swing task was maintained.

8. 8. USE OF TIME AS A VARIABLE FOR THE LEAKY TANK AND THE SWING TASKS

As **time** was an entity listed among those to be chosen from, when drawing causal diagrams, for questions 13 and 20, it is interesting to see the fraction of students who used it as an active entity. For example, one of the most commonly used links involving time as an active entity, for the Leaky tank, was

Time ----------------> ⁻ Depth of water,

which describes an association, since **time** does not cause changes in depth of water.

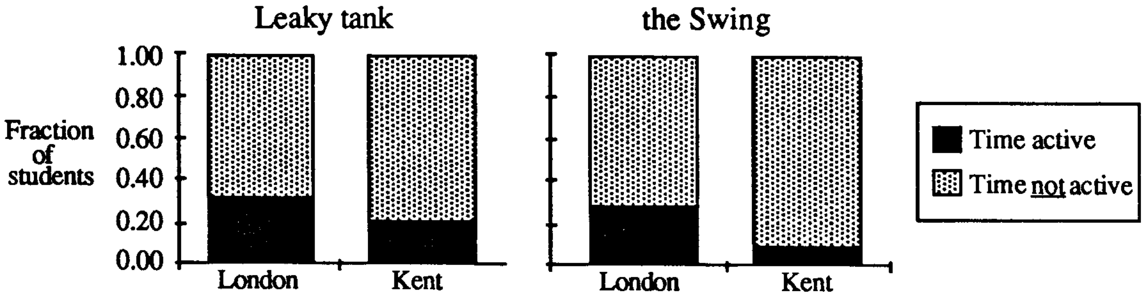


Chart 8. 14 - Fraction of students who considered time as active and not active in causal diagrams, for London and Kent.

Chart 8. 14 shows that, in general, students did not much use time as an active entity in their causal diagrams.

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[4] The Fisher exact test (see Siegel, 1988) was used in 2 x 2 tables when N (number of cases) ≤ 20 or when the smallest expected frequency was less than 5.

In both cases, London students used time as active more often than Kent, but only for the swing task the difference was noticeable but <u>not</u> significant at the 0.05 level.

8. 9. ENTITIES SEEN AS CAUSAL FACTORS FOR THE LEAKY TANK AND THE SWING TASKS

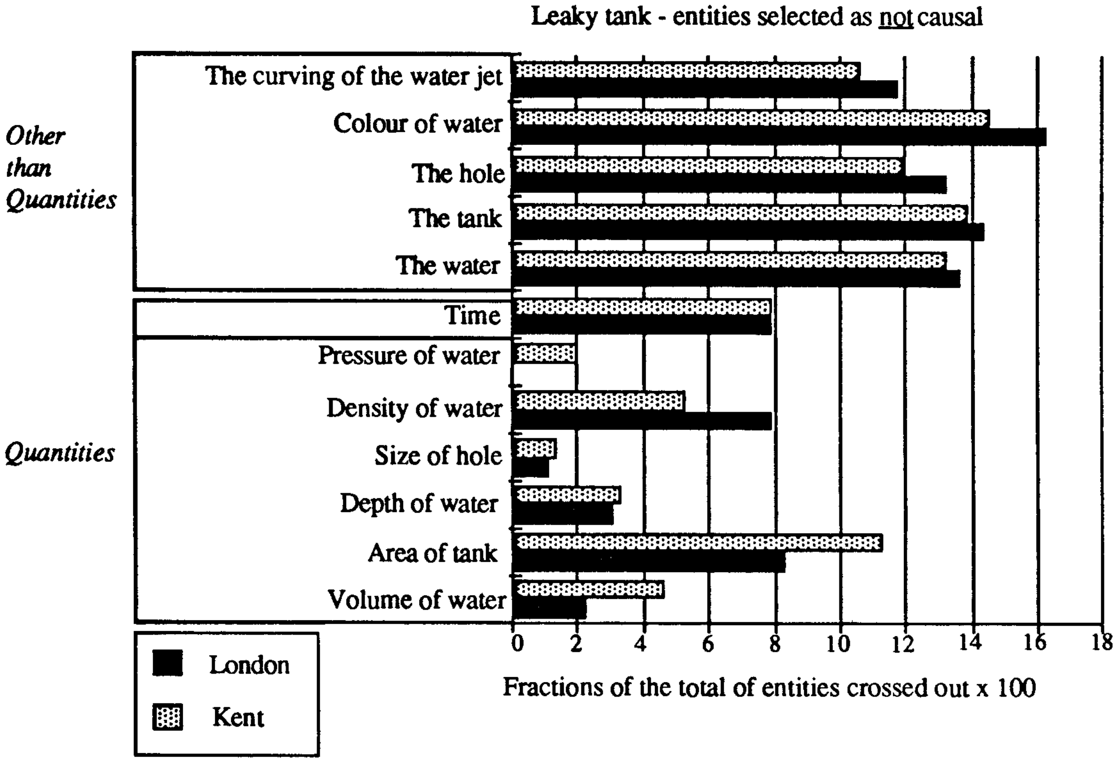


Chart 8. 15 - Entities selected as <u>not</u> causal for the leaky tank task - question (13), for London and Kent.

Chart 8. 15 shows the entities classified as quantities and as "other than quantities". Students tended to avoid "other than quantities", and preferred to use in their causal diagrams, mainly the following quantities:
size of hole;
pressure of water;
depth of water;
volume of water;
density of water.
The distributions for London and Kent were very similar.

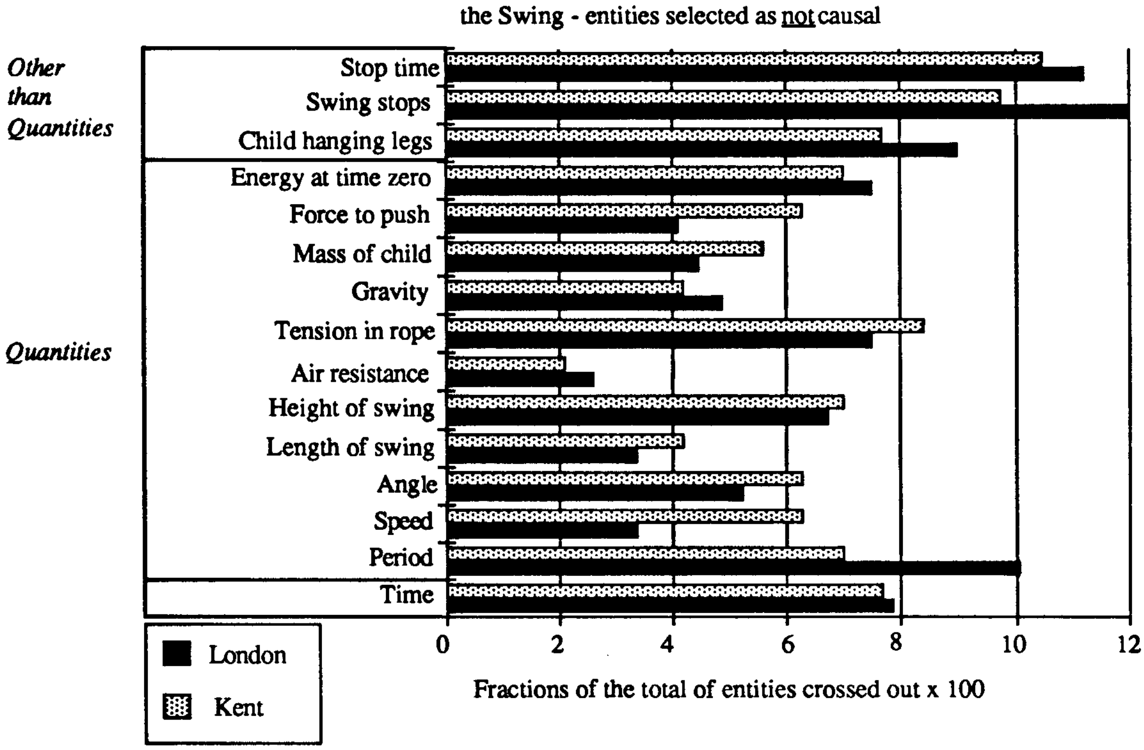


Chart 8. 16 - Entities selected as not causal for the swing task - question (20), for London and Kent.

Chart 8. 16, like the previous one, shows fractions for the swing task. Students again tended to avoid using "other than quantities", but less noticeably than before, and preferred to use the following quantities:
air resistance;
length of swing;
gravity;
mass of child;
force to push.
Again, the distributions for London and Kent were very similar.

8. 9. 1. A BRIEF DISCUSSION ABOUT CAUSATION

For a pendulum, the main factors actually responsible for causation in the system are:
a) gravity;
b) air-resistance and
c) external action.

Gravity is responsible for the swinging of the swing. Air resistance is responsible for it slowing down. External action is responsible for starting it going.

We also know that if we increase the length of a swing its period will increase, since length (L) and period (P) are related by $T\alpha\sqrt{L}$. However, L and P just go together - the link between the variables is not in fact causal. This makes the swing problem relatively difficult from the point of view of causal diagrams since there are both different kinds of causation at work, and non-causal determining relations to consider.

8. 10. KINDS OF LINKS USED IN FOUR TASKS

"Two cars in a stream of traffic" (question 16), "Motorways" (question 17), "Greenhouse Effect" (question 18) and "Rabbits and Foxes" (question 19), are causal diagramming tasks which are presented in Appendix I. 1.

Here students had to propose their own entities for causal diagrams. It would clearly be useful to be able to analyse the kinds of entity or links which students spontaneously proposed. This proved difficult to do, because

(a) responses were often inexplicit,

(b) it was only possible to judge the nature of an entity if one looked at what it was linked to (it could even be true that the same entity was treated as a variable in one of its links and as an object in another).

For these reasons, no reliable classification of entities alone was found. However, it was possible to achieve a good reliability of classification of pairs of entities and their links. Two other raters agreed with at least 80% of the classifications.

A sample of causal diagrams drawn by students, for each task, with the classification written over the link is presented in Appendix VIII.

It would have been very interesting to distinguish quantitative and semi-quantitative variables. However the only reliable discrimination was the use by the student of some term strictly implying an amount. This seemed in practice arbitrary - there is no reason for the student to be so explicit. For this reason the classification distinguishing quantities and semi-quantities was collapsed.

Following the framework (figure 8. 3) links involve variables as *amounts (a)* and *rates (r)*, and non-variables as *events/processes (e)* and *objects (o)*.

During the data analysis I felt the necessity of including an extra entity: *qualitative variable (q)*, which appeared as a qualitative property of objects (e.g. colour of cars). Consequently, considering that the symbol **-->** means "affects", links were classified as

<u>Variable-ized</u>:

aa - amount --> amount;

rr - rate --> rate;

ra (ar) - rate <--> amount.

<u>Partly variable-ized</u>:

qr, qa (rq, aq) - qualitative variable <--> (rate or amount);

or, oa (ro, ao) - object <--> (rate or amount);

er, ea (re, ae) - event <--> (rate or amount).

<u>Non-variable-ized</u>:

qe, qo (eq, oq) - qualitative variable <--> (object or event);

oe, eo - object <--> event;

ee - event --> event;

oo - object --> object.

Chart 8. 17 shows, for London and Kent, the percentages of these kinds of links used in Rabbits and Foxes, Two cars in a stream of traffic, Motorways and Greenhouse Effect tasks.

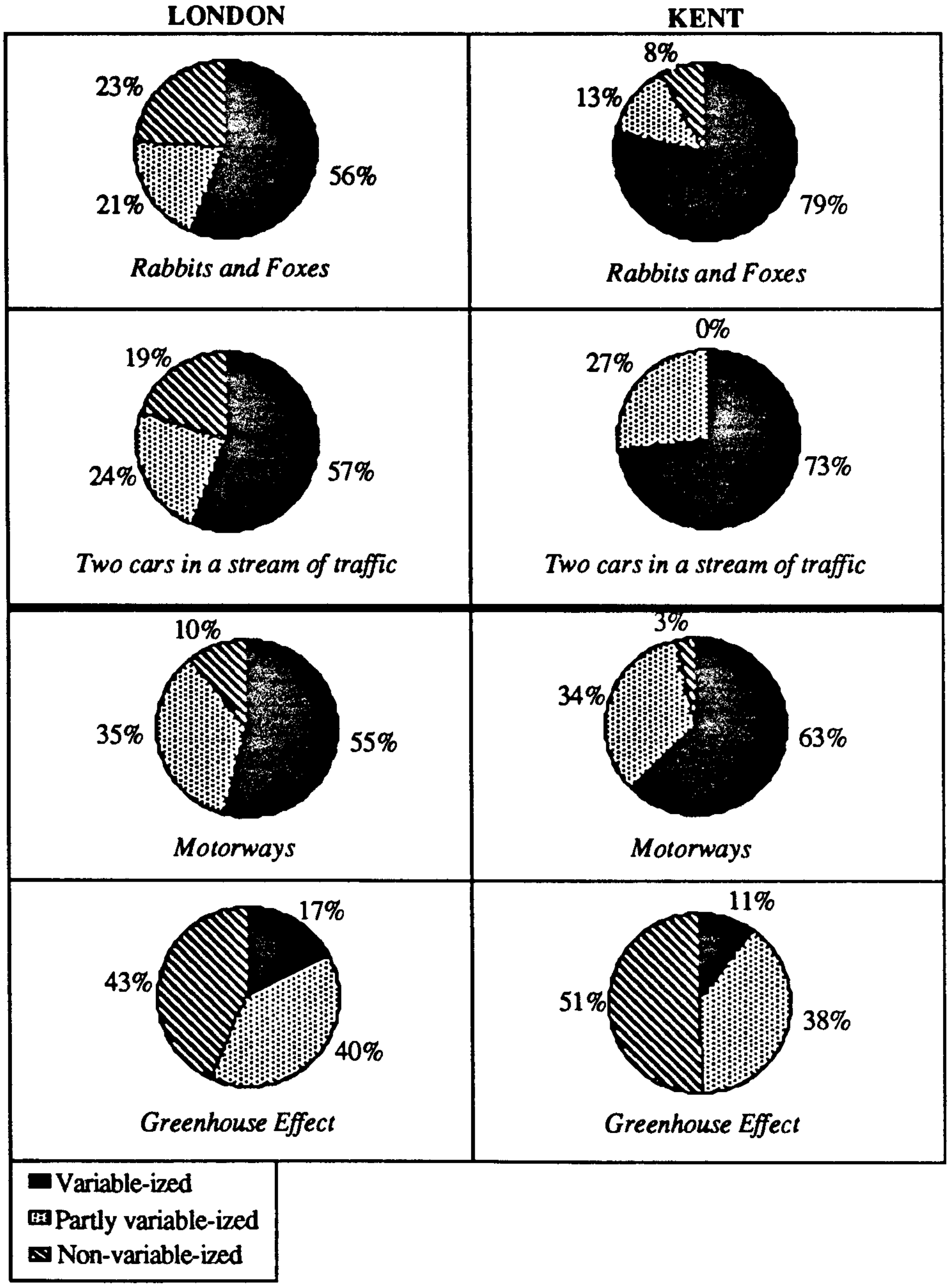


Chart 8. 17 - Kinds of links used for "Rabbits and Foxes", "Two cars in a stream of traffic", "Motorways" and "Greenhouse Effect", for London and Kent.

For both London and Kent, "Rabbits and Foxes", "Two cars" and "Motorways" were the tasks where students used the largest percentage of variable-ized links. In particular, the most used kinds of links were *amount* affecting *amount*, for "Rabbits and Foxes", *rate* affecting *amount* (or *amount* affecting *rate*) for "Two cars" and, for "Motorways", *rate* affecting *rate*, for London, and *amount* affecting *amount*, for Kent.

The Greenhouse Effect task had the largest percentage of non-variable-ized links, the main kind being *event* affecting *object* (or *object* affecting *event*). Amongst the tasks, the percentage of variable-ized links for the "Greenhouse Effect" was the smallest.

The Greenhouse Effect task had the largest percentage of partly variable-ized links, with Motorways next. For all tasks London and Kent students had almost the same percentages of partly variable-ized links.

For all tasks but the Greenhouse Effect London students were responsible for the largest percentage of non-variable-ized links, and Kent students for the largest percentage of variable-ized links. These results suggest that Kent students thought more about the situations in a variable-ized way. The kind of link used by the student seems to depend on the kind of situation being modelled. For example, for the Greenhouse Effect task, the majority of the links used were partly or non-variable-ized, which means that finding suitable variables for modelling this situation was not a simple task.

The results found here are in accordance with those for causal links (section 8. 5 - Chart 8. 6). In the first, the largest category of causes which students proposed for "Concern for Pollution", was "other than variables". We notice that, in agreement with this, the largest percentage of links in the "Greenhouse Effect" are non-variable-ized.

The largest category of effects which they proposed for "Number of births", was *quantities*. In agreement with this, the largest percentages of links in the "Rabbits and Foxes", are of the kind *amount --> amount.*

The largest category of causes which students proposed for "Traffic congestion" was *quantities*. In agreement with this, "Two cars in a stream of traffic" and "Motorways", had large percentages of variable-ized links.

Kinds of entities and links used seem to depend on the kind of situation being modelled. Some situations will be more suitable than others, to be described in terms of variables.

It is worth having a closer look at the category *Variable --> Variable* which provided the largest fraction of links used.

Chart 8. 18 shows the fraction of students by number of variable-ized links, for London and Kent.

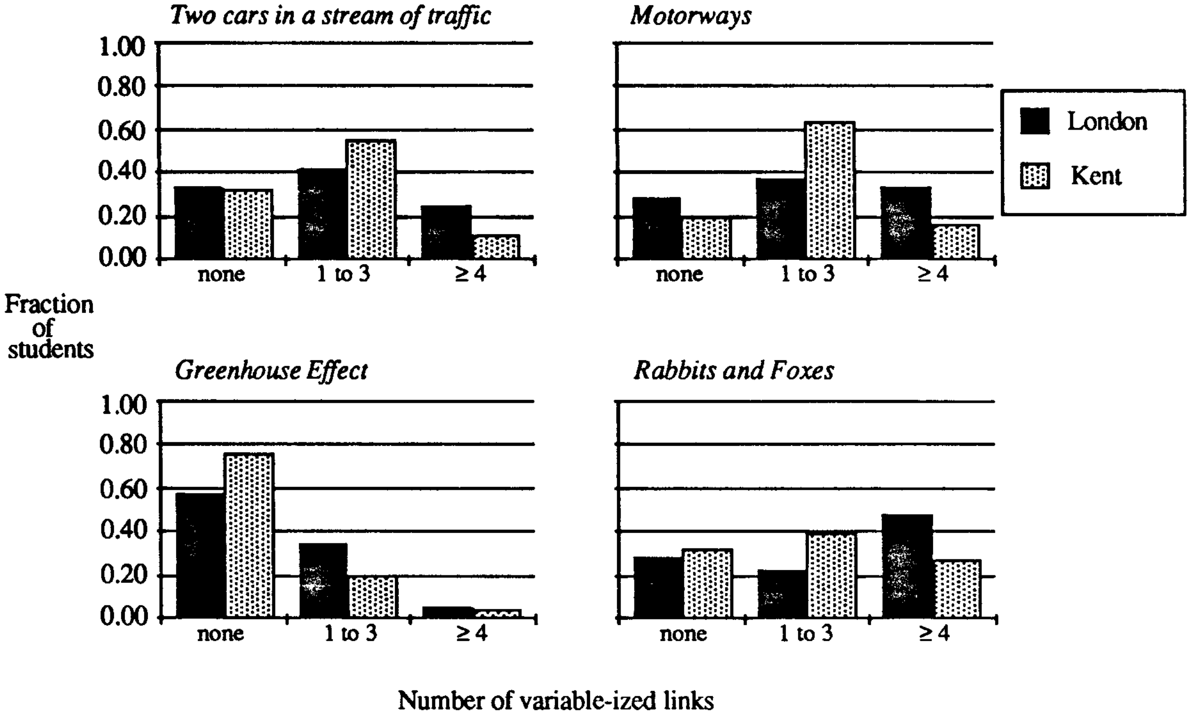


Chart 8. 18 - Fraction of students by number of variable-ized links, for London and Kent.

The majority of both London and Kent students produced a maximum of three variable-ized links in each diagram. The Greenhouse Effect task shows the largest fraction of students with no variable-ized links. "Rabbits and Foxes" was the task where a larger fraction of students used more than 4 variable-ized links. The distributions for "Two cars" and "Motorways" were very similar.

Because the "Greenhouse Effect" was the task with a noticeably larger number of partly variable-ized (one of the two entities seemed like a variable) and non-variable-ized links, it is interesting to show (in Chart 8. 19) the distribution of students for these kinds of links.

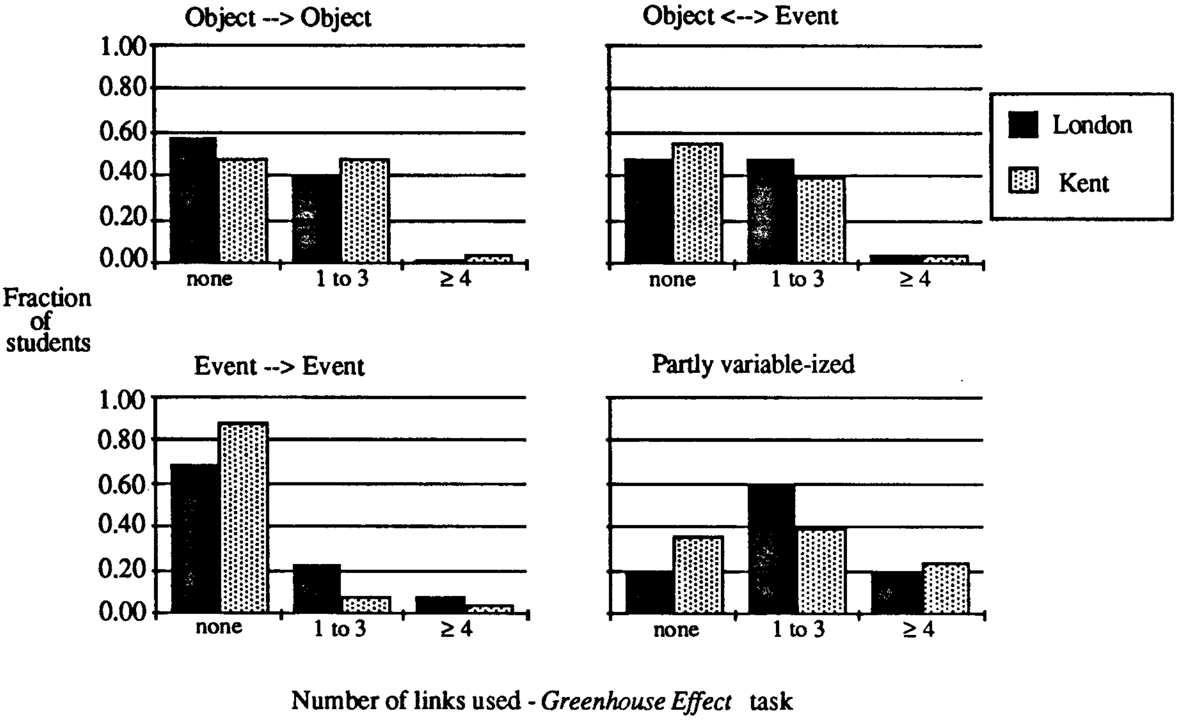


Chart 8. 19 - Fraction of students by number of non-variable-ized links, for the Greenhouse Effect task, for London and Kent.

In general, a noticeable fraction of students used one to three non-variable-ized links. Roughly half of them used no links of the kind *Object --> Object* and *Object <--> Event*. The distributions for *Object --> Object* and *Object <--> Event* were very similar, but only very few students used *Event --> Event* links. Students, in general, tended to use partly variable-ized links. This suggests that they were at least attempting to use variables.

8. 11. ENTITIES USED IN ONE TASK

For the "Two cars" task, when constructing the causal diagram, some students tended not to use entities related to interactions between the cars such as the distance between cars, or the velocity of the following and leading car. These students included in their causal diagrams entities related to traffic conditions such as, amount of traffic on the road, number of stops or quality of road surface.

Chart 8. 20 shows the mean fraction of *interacting* and *traffic related* entities for the two cars task, for London and Kent.

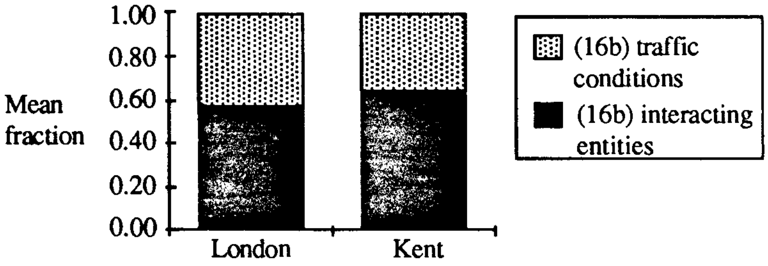


Chart 8. 20 - Mean fraction of entities related to "traffic conditions" and "interacting entities", for the two cars task, for London and Kent.

The majority of the entities used in causal diagrams, for London and Kent, were *interacting* ones, though a substantial minority used variables related to traffic conditions. London and Kent did not differ significantly.

8. 12. STRUCTURE OF CAUSAL DIAGRAMS

Chart 8. 21 shows the fractions of students giving different kinds of causal diagrams, for the Leaky tank, the Swing, Two cars in a stream of traffic, Motorways, Greenhouse Effect and Rabbits and Foxes tasks, for London and Kent.

In all tasks except the Swing, loop diagrams were the most frequent, followed by chains, which indicate some level of system thinking. The Swing was clearly difficult (this result is in accordance with expectation 14 in table 3. 1 - we may expect students to develop more complex causal loop structures in General Topics than in Physics). See also the earlier discussion of causes of motion (section 8. 9. 1).

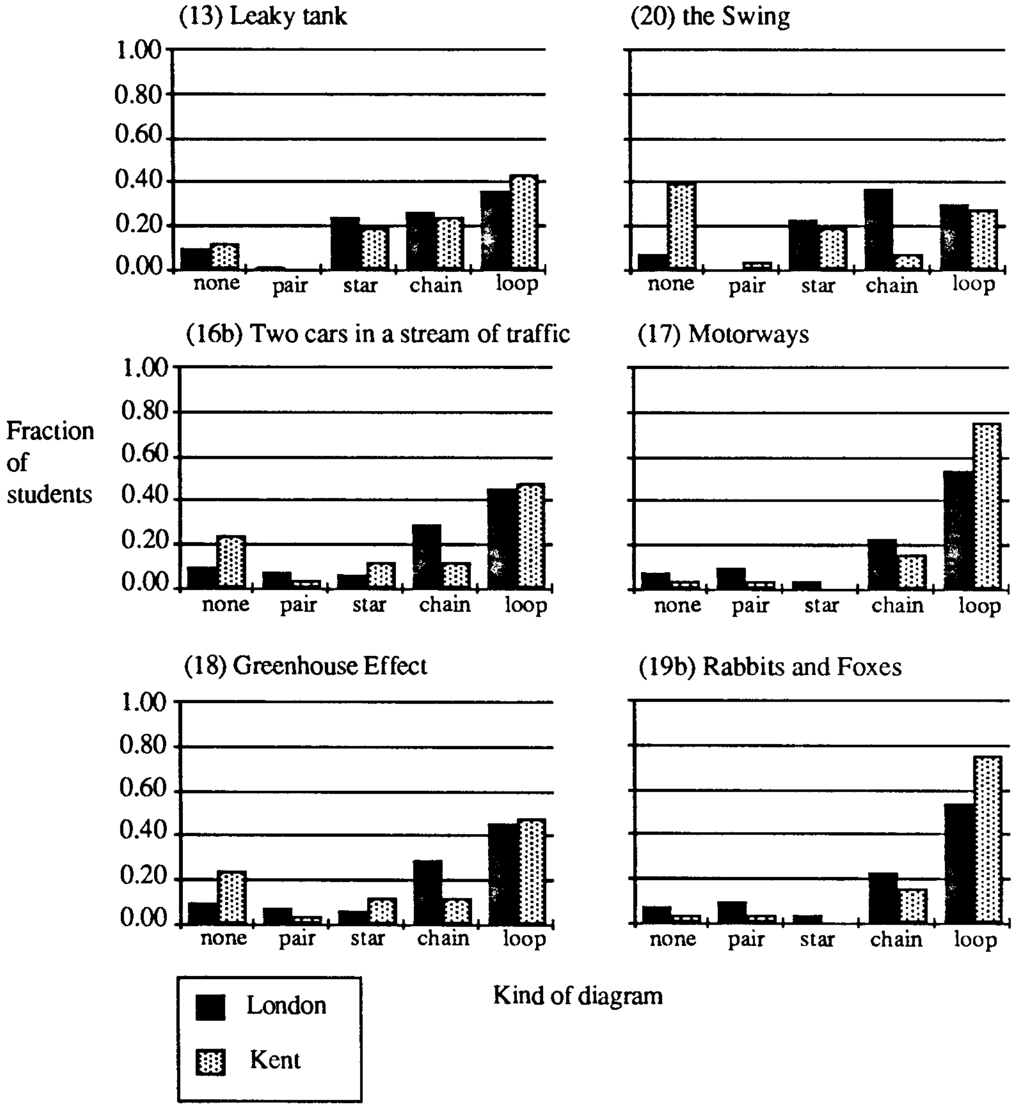


Chart 8. 21 - Fractions of students by kinds of causal diagrams, for each task, for London and Kent.

8. 13. CRITERIA FOR JUDGING REASONABLE LINKS

Appendix IX shows, for all tasks, models against which to judge diagrams constructed by students. The models show the links that were considered reasonable. For example, in the model for the Leaky tank task (see figure 1 in Appendix IX), there is one main negative feedback loop responsible for the decreasing in *depth of water*, since the pressure is a function of the depth of water. The density of water affects the pressure, and the *size of the hole* affects *how fast the water drains out*. Volume and depth of water are associated, and go together, and *time* is associated to changes in volume of water, depth of water and pressure of water.

8. 14. ANALYSIS OF REASONABLE LINKS

Chart 8. 22 shows the mean fraction of reasonable links - the fraction of links given which also appeared to be reasonable (see section 8. 2. 2. 2), for the Leaky tank, the Swing, Two cars in a stream of traffic, Motorways, Greenhouse Effect and Rabbits and Foxes tasks, for London and Kent.

Motorways, Rabbits and Foxes, and Greenhouse Effect were the tasks where students used the largest mean fractions of reasonable links. Two cars, Leaky tank and the Swing were those with the smallest fractions of reasonable links. These questions are related to Physics, and involve some specific knowledge, to be properly solved.

There are small differences, in favour of Kent, for Motorways, Two cars and Leaky tank and in favour of London, for Rabbits and Foxes, Greenhouse Effect and the Swing, but they are not significant at 0.05 level.

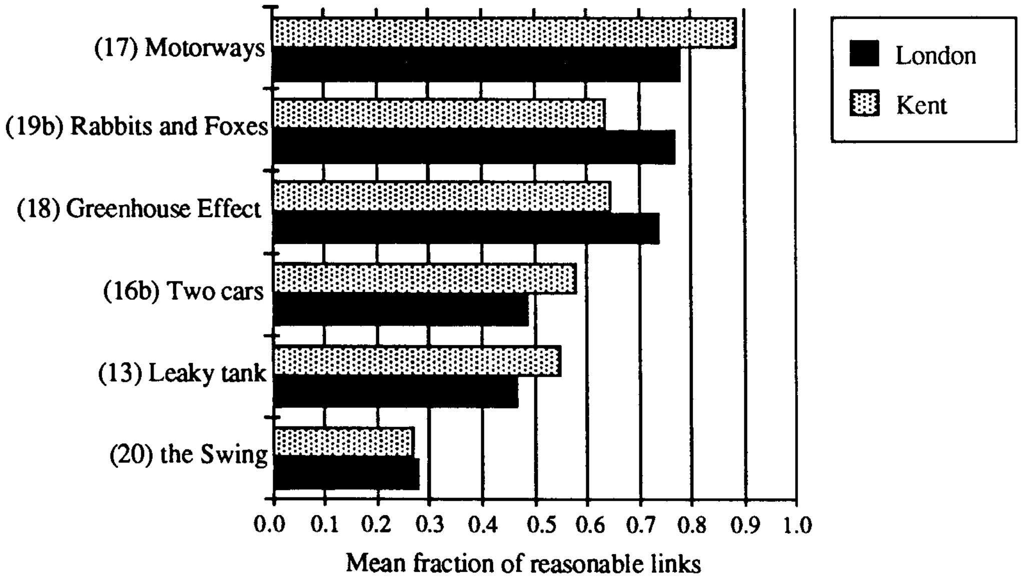


Chart 8. 22 - Mean fraction of reasonable links, for each task, for London and Kent.

Chart 8. 23 shows the fraction of students classified in four different categories of numbers of reasonable links, namely, *none* , *1 to 3* , *4 to 6* and *≥7* , for each task.

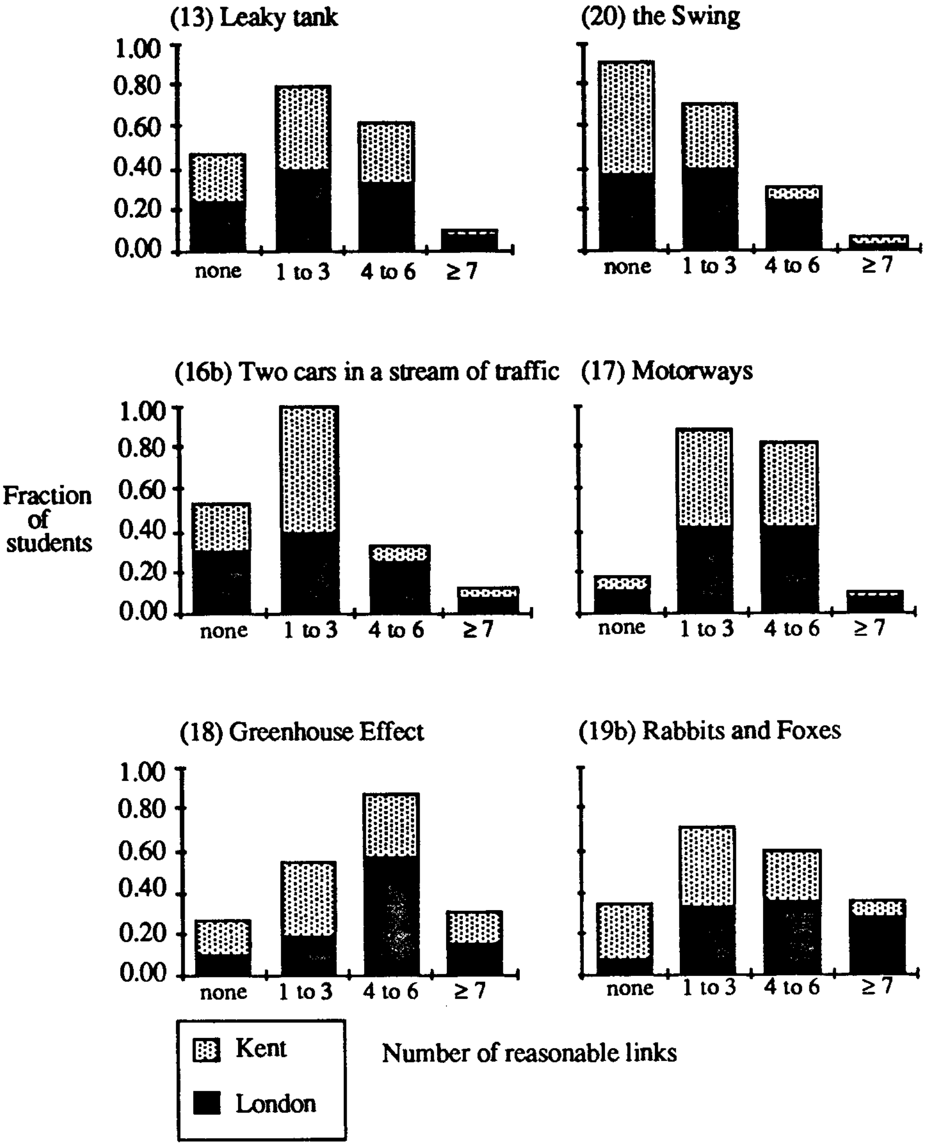


Chart 8. 23 - Fraction of students classified in four different categories of numbers of reasonable links - none, 1 to 3, 4 to 6 and ≥ 7, for each task, for London and Kent.

Chart 8. 23 shows that, Motorways, Greenhouse Effect and Rabbits and Foxes are the tasks with the largest fractions of London students for *4 to 6* and *7 or more* reasonable links. The same is the case for Kent students for Motorways and Greenhouse Effect tasks.

For the Swing task, about half the students, in Kent, had no reasonable links. This was the largest fraction of students with no reasonable links.

Motorways, Greenhouse Effect and Rabbits and Foxes are the cases with the smallest fractions of London students for no reasonable links. Again, the same was true for Kent students for Motorways and Greenhouse Effect tasks.

As was found for kinds of entities and links used, the number of reasonable links students can propose or choose seems to depend on the kind of tasks proposed.

8. 15. CAUSAL VERSUS NON-CAUSAL DIAGRAMS

A document with examples of diagrams drawn by students for the Leaky tank, Motorways, Two cars in a stream of traffic, Greenhouse Effect, Rabbits and Foxes and the Swing, is available on request. In the document there are examples of the most causal and the least causal diagrams, for each question. Some comments about the diagrams are now made below.

By the 'most causal' is meant the one which contains the largest number of *directional /productive* reasonable links, and by the 'least causal' the one that contains the largest number of unreasonable links (see framework in figure 8. 3). Diagrams classified as the least causal were those where the students do not use proper variables or do not think properly about the linkage between them.

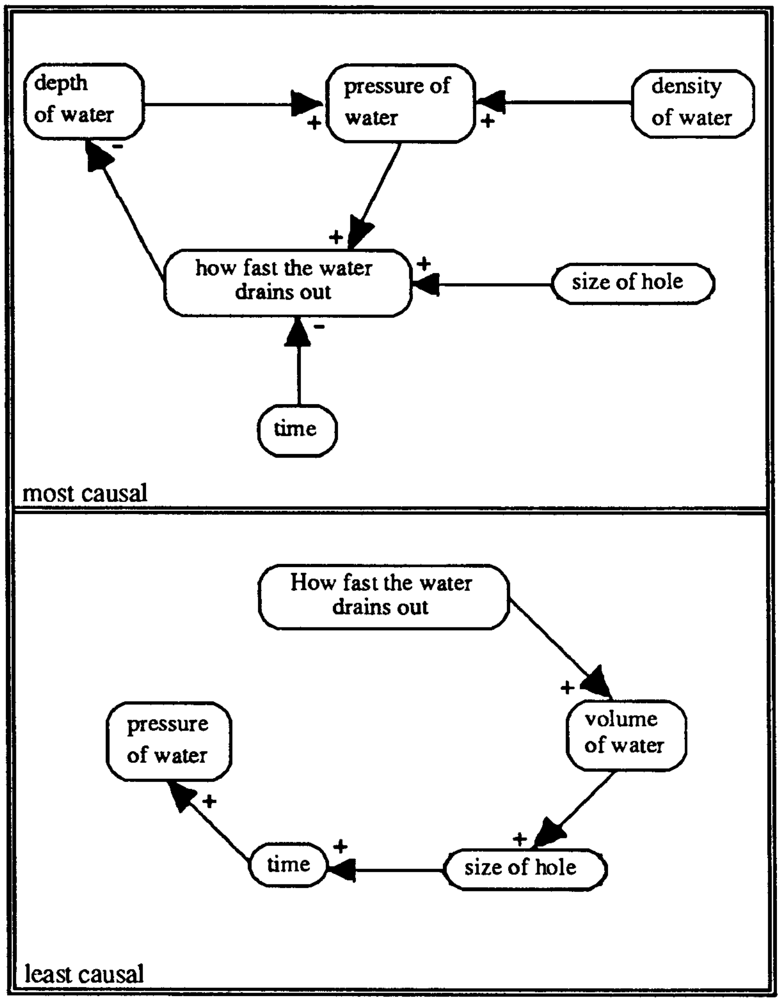


Figure 8. 10 - The most and least causal diagrams for the Leaky tank.

For the Leaky tank task, for example, the most causal diagram in figure 8. 10, has one link between time and *how fast the water drains out*, which is an association, since time does not *produce* anything (see previous discussions in section 2. 4). The other links are purely causal. The least causal has links with completely wrong directions, and even wrong entities. For example, it is not possible to imagine that the size of the hole would affect time.

8. 16. RELIABILITY OF GROUPS OF QUESTIONS ABOUT CAUSAL MODELS

I decided to estimate a reliability coefficient as a way of getting an idea about how consistent students were in using reasonable links, quantities, variable-ized links and causal diagram structures.

The coefficient of reliability was calculated using

$$r = \frac{k}{k - 1} \left[1 - \frac{\sum s_i^2}{s_t^2} \right]$$

where

k represents the number of questions,

s_i^2 is the variance of student scores on a particular question,

$\sum s_i^2$ is the sum of these question variances and

s_t^2 is the variance of the total test scores (Ebel, 1979).

Questions 13 (Leaky tank), 16b (Two cars), 17 (Motorways), 18 (Greenhouse Effect), 19b (Rabbits and Foxes) and 20 (the Swing) all concern aspects of making causal diagrams. The main aspects are, the number of reasonable links used, the kinds of diagram drawn (structure) and the number of variable-ized links used (for this aspect Leaky tank and the Swing were <u>not</u> included - see previous discussions). Scores for reasonable causal links (Questions 3 to 8 - see section 8. 5. 4) and number of quantities used in the Leaky tank and the Swing tasks were included, as well.

The reliability, for London and Kent, for this group of questions is presented in table 8. 3.

Reliability	London	Kent
Nº of items	19	19
Nº of students	48	25
r	0. 93	0. 90

Table 8. 3 - Reliability for Causal links, “Leaky tank”, “Two cars”, “Motorways”, “Greenhouse Effect”, “Rabbits and Foxes” and “the Swing”, concerning the number of reasonable links used, the kinds of diagram drawn, the number of variable-ized links used (“Leaky tank” and “the Swing” <u>not</u> included), and number of quantities used (only Leaky tank and the Swing tasks).

In general, for both London and Kent, the coefficient of reliability was very high. This result suggest that students, in general, were very consistent in the way they defined causal diagrams for the situations, particularly in terms of the number of reasonable links, quantities, number of variable-ized links and kind of diagram used. This result suggests, that maybe there may be a factor to be associated with causal diagramming. This will be explored through factor analysis (see chapter 9, session 9. 6).

8. 17. SUMMARY OF CHAPTER 8

8. 17. 1. EXPERIENCE WITH COMPUTERS

London and Kent students have a reasonable experience with software and hardware, but Kent students have used a significantly wider range of hardware. BBC computers and BASIC seem to be the most used combination of software and hardware in schools. Only very few students have used Macintosh computers.

8. 17. 2. SYSTEM THINKING

In general, for questions 3 to 8, students were able to select an entity and construct a causal link that made sense. They were very creative in choosing entities for causal links. In questions 4 and 7 most students used quantities; in questions 3 and 5 semi-quantities were popular; and in questions 6 and 8 "other" kinds of entities were common. The choice of an entity as quantity, semi-quantity or "other" seems to depend on the nature of the question asked.

Students were able to interpret a causal diagram and a small text in questions 9 and 10, respectively. Kent students tended to do better.

For questions 11 and 12, in general, students had a large mean number of feedbacks right. They were able to interpret causal diagrams but roughly half of them in London and a quarter in Kent, for question 11, partly or totally misinterpreted the behaviour of particular entities - those involved in feedback. Despite there being no difference concerning means for number of feedback right, a larger fraction of students in Kent got both subquestions involving feedback right.

Students got very good overall scores in the initial questions about causal diagrams. This result supports the validity of later questions asking for causal diagrams.

In general, for explaining a physical system (questions 14 and 15), less than half of the students saw the situation as a system of interacting entities. About two thirds of the students did not use variables in their explanations and preferred to explain in terms of objects and events. This result is in accordance with the findings for causal links and kinds of links used. The majority did not use rates explicitly in their explanations.

8. 17. 3. THE LEAKY TANK AND THE SWING

For both tasks students tended to avoid "other than quantities", but for the Swing task less notably than for the Leaky tank.

In general students did not use time as an active entity in causal diagrams.

For both tasks, Kent students tended to use a smaller number of entities and tended to avoid using "other than quantities". London students tended to use a larger numbers of entities and "other than quantities".

There was a noticeable difference, in favour of Kent, for the Swing task, concerning avoiding the use of time as an active causal variable.

8. 17. 4. TWO CARS IN A STREAM OF TRAFFIC, MOTORWAYS, GREENHOUSE EFFECT AND RABBITS AND FOXES

For both London and Kent, "Rabbits and Foxes", "Two cars" and "Motorways" were the tasks where students used the largest percentage of variable-ized links. "Greenhouse Effect" had the largest percentage of non-variable-ized links.

Kent students were more able to think about the tasks in a variable-ized way. Also, the kind of link used by the student seem to depend on the kind of situation being modelled, which is in accordance with the findings for entities used in causal links (questions 3 to 8).

For the "Two cars" task, more *interacting* entities than *traffic related* entities were used in causal diagrams, for London and Kent.

For the "Leaky tank" and the Swing tasks the majority of students were spread among mainly star, at least one chain and at least one loop.

For "Motorways", "Greenhouse Effect" and "Rabbits and Foxes", the majority of Kent students were able to construct causal diagrams with at least one feedback loop. The same was true for London students for "Motorways" and "Rabbits and Foxes" tasks.

The "Leaky tank", "Motorways", "Greenhouse Effect" and "Rabbits and Foxes" seemed the kinds of tasks where students could best develop thinking at a system level.

"Motorways", "Rabbits and Foxes", and "Greenhouse Effect" were the ones where students used the largest mean fractions of reasonable links. "Two cars", "Leaky tank" and "the Swing" were the ones with the smallest fractions of reasonable links. For the Swing task about half of the students in Kent had no reasonable link.

"Motorways", "Greenhouse Effect" and "Rabbits and Foxes" are the ones with the largest fractions of London students giving large numbers of reasonable links. The same is true for Kent students for "Motorways" and "Greenhouse Effect" tasks.

Students were very consistent concerning the work with causal diagrams, particularly in terms of the number of reasonable links, quantities, number of variable-ized links and kind of diagram used. There may be a factor associated with causal diagramming.

CHAPTER 9 - MATHEMATICAL KNOWLEDGE. ANALYSIS OF THE QUESTIONNAIRE ABOUT MODELLING, PART 2

9. 1. A GENERAL SCORE FOR MATHEMATICAL KNOWLEDGE

It was possible to construct an overall score (out of 10) for the part of the questionnaire about Mathematics (see Appendix I. 2). This overall score was obtained by finding the arithmetic mean of the scores for each question, for each student. The number of students, mean scores and standard deviations are shown in table 9. 1 below

Mathematics	London	Kent
Nº of students	45	22
Mean	**4. 86**	**5. 63**
Std. deviation	1. 84	2. 69

Table 9. 1 - Overall scores for the Questionnaire about Modelling second part, for London and Kent.

Thus overall scores were in the region of 50% of the maximum.

Despite the difference in favour of Kent, London and Kent did not differ significantly in the overall means (t = 1.37, 65 df) at 0.05 level.

9. 2. AN ANALYSIS FOR EACH QUESTION

Chart 9. 1 shows the mean fractional score for each of these questions.

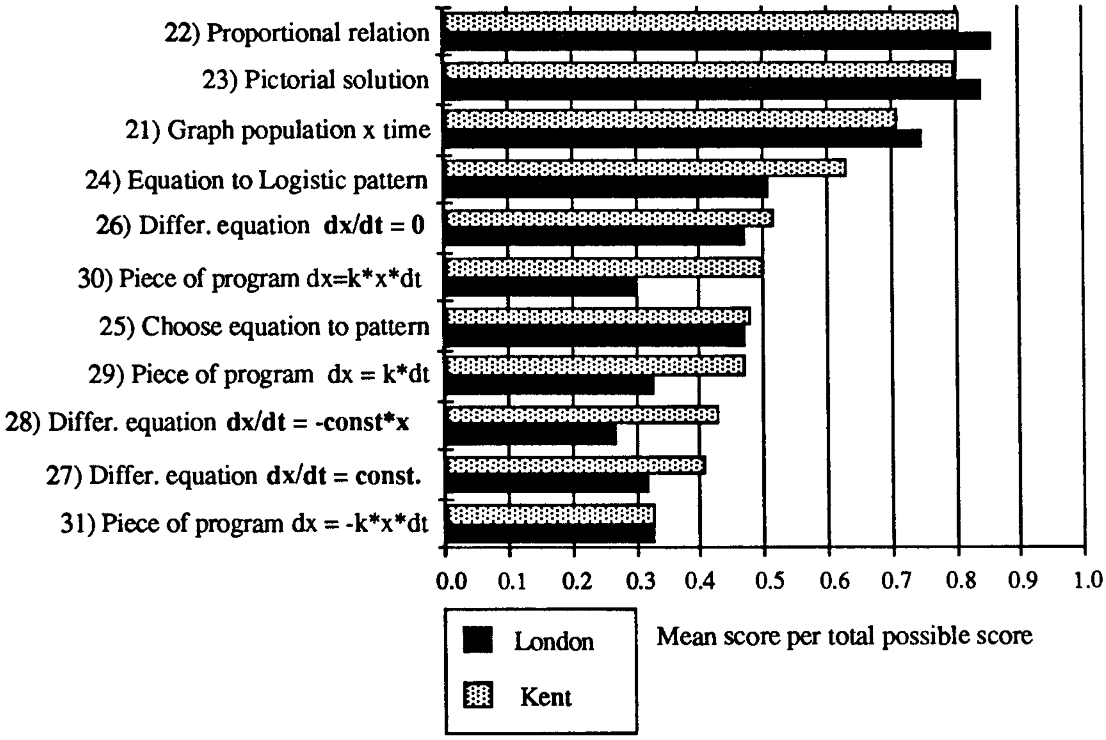


Chart 9. 1 - Mean fractional score for each question of the Questionnaire about modelling second part, for London and Kent.

In general students had good mean scores for questions 21 (graph for population versus time), 22 (equation for proportional relation), 23 (pictorial solution to a problem) and 24 (equation for a graphical pattern). Scores were not so good for questions involving differential equations and pieces of computer program. The score was also not so good for question 25 (association of mathematical equations to graphs).

Question 23 (pictorial solution) presents a problem where the students have to calculate, for each year, 10% of the total amount (A) in a bank, at the beginning of the year, and add the result (0.10 * A) to the total amount already in the bank (A = A + 0.10 * A). The large scores achieved may mean that students should be able to understand the procedure involved in calculating a difference equation as the computer does.

For question 21 (graph of population versus time) students could manage to get a simple graph from data in a table format. For questions 22 (proportional relation) and 24 (equation for a graphical pattern), students knew the equation for the proportional relation and could associate a graphical pattern to a mathematical equation.

There were significant differences between London and Kent, in favour of Kent, concerning the scores in questions 29 and 30 (pieces of computer programs) [t = 1.8 and t = 2. 3, 65 df, respectively] at 0.05 level.

These results suggest that despite there being no significant difference between the overall means, for London and Kent, for the whole questionnaire, Kent students seemed to have scored better for pieces of computer programs. This result is in accord with the fact that Kent students presented a larger experience with hardware and software, as reported in section 8. 4.

9. 3. RELIABILITY OF QUESTIONS ABOUT MATHEMATICS

The reliability of this set of questions was estimated as a way of getting an idea about how consistent students were in answering questions about the mathematical knowledge needed for engaging in the modelling process. The coefficient of reliability was calculated as in chapter 8, section 8. 16. Table 9. 2 shows the coefficient of reliability for the questions about Mathematics.

Reliability	London	Kent
Nº items	11	11
Nº students	45	22
r	0.75	0.89

Table 9. 2 - Reliability of mathematics questions.

The reliability of mathematical questions, was high for Kent and reasonably high for London, but not as high as for questions about causal diagrams. Thus students were reasonably consistent in answering the questions (21, 22, 23, 24 and 25), about graphs and patterns, and the questions related to differential equations and pieces of computer programs (see chart 9. 1).

9. 4. DISTRIBUTION OF STUDENTS BY SCORE

Charts 9. 2 and 9. 3 show the distribution of students by score for each question about Mathematics. Chart 9. 2 shows that there is a large fraction of students with maximum score 2, particularly in questions 22, 23 and 24. In question 21, the largest fraction of students had score 2, and less than 0.40 of them got the maximum score. In question 25 the distribution of students was roughly similar for each score.

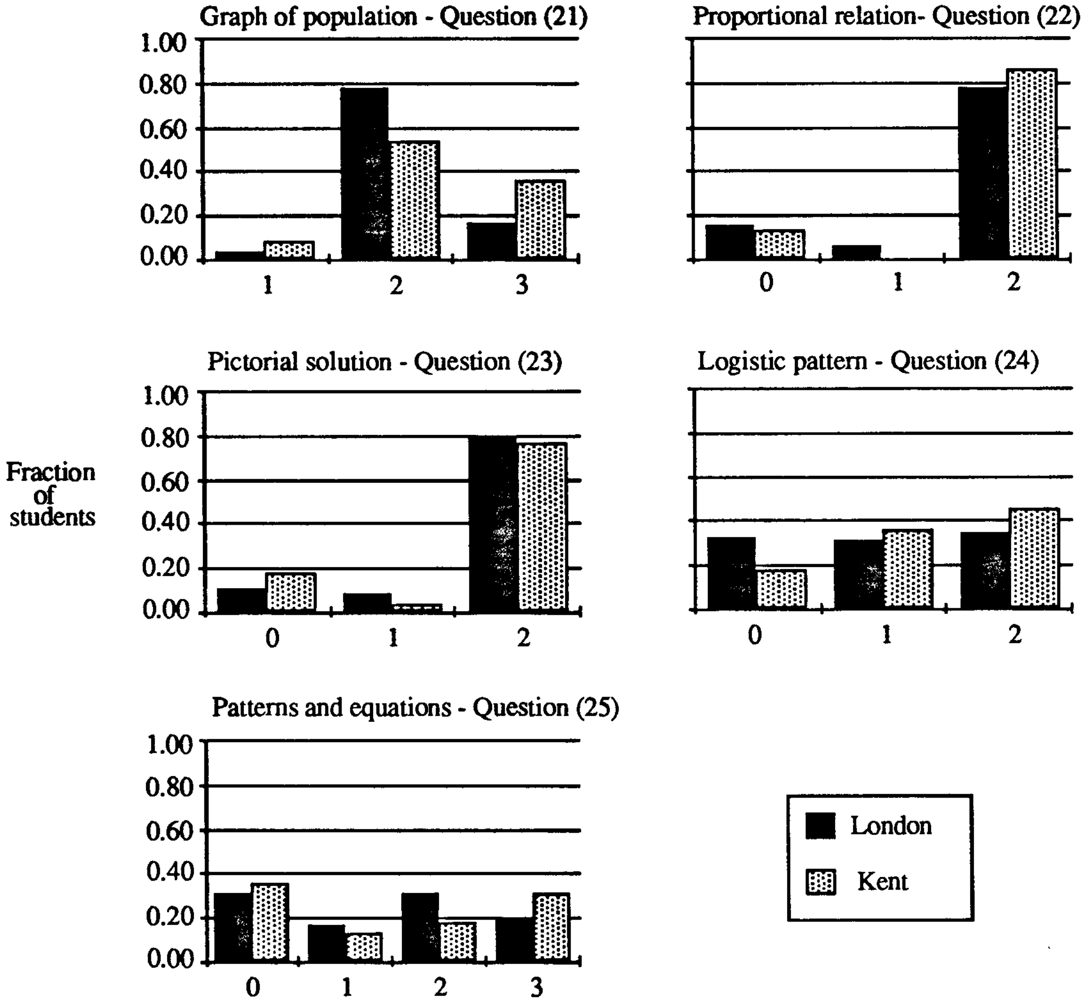


Chart 9. 2 - Fraction of students by score for initial questions on Mathematics.

Chart 9. 3 shows, in general, a large fraction of students with score zero in questions about differential equations (26, 27 and 28), which shows why the general mean scores for these questions in Chart 9. 1 were low.

The distribution was different for pieces of computer programs (29, 30 and 31) with a few Kent students having the maximum score 3, which is the main source of the significant difference found.

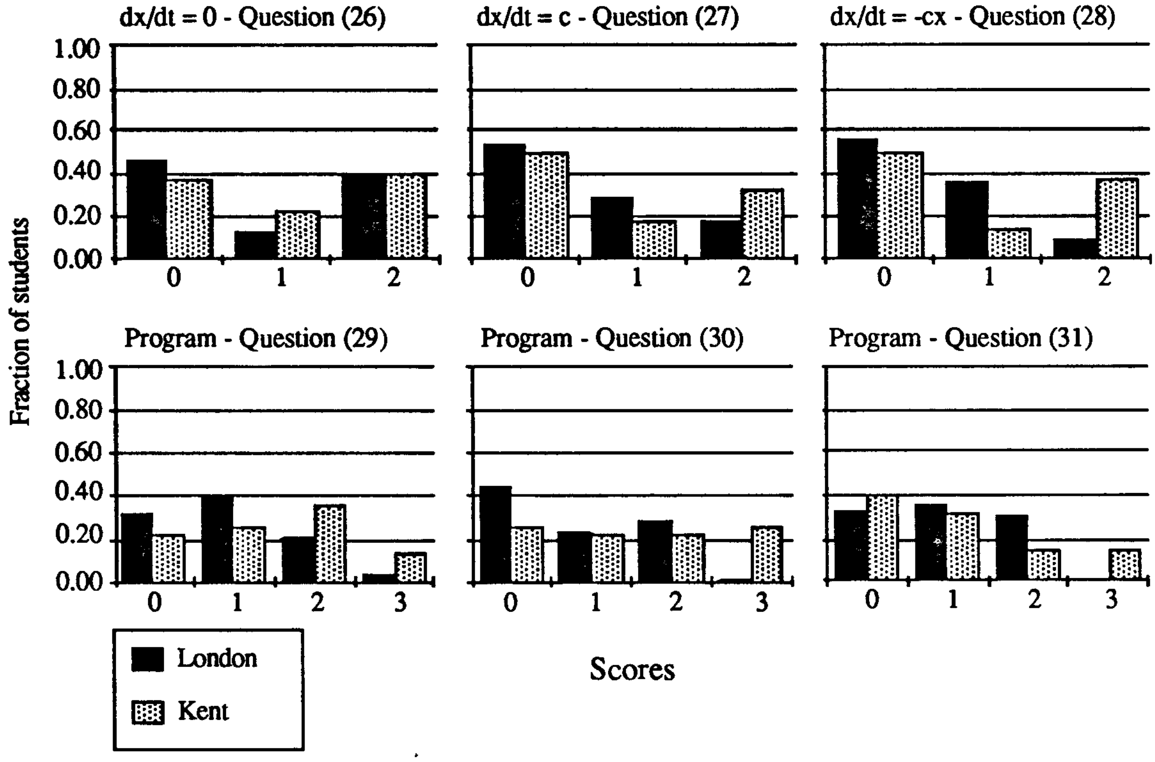


Chart 9. 3 - Fraction of students by score for differential equations and pieces of programs.

9. 5. POSSIBLE RELATIONSHIPS BETWEEN DIFFERENT PARTS OF THE QUESTIONNAIRE

Tables 9. 3 and 9. 4 were designed to get an impression of possible relationships between different parts of the questionnaire. These tables are based on the full set of correlation tables presented in Appendix X. Table 9. 3 looks at correlations between use of hardware and software, with mathematics and use of causal diagrams.
Because the Greenhouse Effect was the task with a noticeably large number of partly variable-ized and non-variable-ized links (see charts 8. 18 and 8. 19), I also decided to look at correlations involving links of the kind *event --> event*, *object --> object*, *object <--> event* and the partly variable-ized ones (e.g. *event --> amount*) for this particular question. See tables 10, 11, 26, 27 and 28 in Appendix X.

Correlations	London		Kent	
	Software	Hardware	Software	Hardware
Mathematics	Very weak in general T4 AP X	Very weak in general T4 AP X	**Moderate** 6 about 0.4 T5 AP X	Weak 1 about 0.4 T5 AP X
Reasonable links	Weak 3 about 0.3 T6 AP X	Weak 2 about 0.3 T6 AP X	Very weak T7 AP X	Very weak T7 AP X
Variable-ized links	Very weak T2 AP X	Weak 2 about 0.3 T2 AP X	Weak 2 about 0.3 T3 AP 10	Very weak T3 AP X
Kind of diagram	Weak 2 about 0.3 T8 AP X	**Moderate** 1 about 0.5 and 2 about 0.3 T8 AP X	**Moderate** 3 about 0.4 T9 AP X	Weak 1 about 0.4 T9 AP X
Non-variable-ized links - Greenhouse Effect	Very weak T10 AP X	Very weak T10 AP X	Very weak T11 AP X	Very weak T11 AP X
Partly variable-ized links - Greenhouse Effect	**Moderate** 1 about 0.4 T10 AP X	Very weak T10 AP X	Very weak T11 AP X	Very weak T11 AP X

Table 9. 3 - Description of main correlations involving experience with software and hardware - London and Kent. Key: - T4 AP X means table of correlation number 4 in Appendix X, for example.

Overall, table 9. 3 does not point to much correlation between experience of hardware or software, and performance in the various groups of questions. However, for London, students with larger experience with software used more partly variable-ized links in the Greenhouse Effect task. Students with larger experience with hardware were able to construct more elaborate diagrams. For Kent, students with larger experience with software were those who did better at Mathematics questions, and who were able to construct more elaborate diagrams.

Correlations	Mathematics		Reasonable links		Variable-ized links	
	London	Kent	London	Kent	London	Kent
Mathematics	**Moderate** Few about 0.5 Majority≤0.4 Several ≈ 0.2 T12 APX	**Strong** Several >0.6 T13 APX	**********	**********	**********	**********
Reasonable links	Weak and negative in general. Several ≈ -0.2 Few ≈ -0.3 T22 APX	**Strong some cases** Few > 0.6 Several between 0.4 and 0.6 Majority<0.3 T23 APX	**Strong some cases** Majority between 0.4 and 0.6 T16 APX	**Strong some cases** Majority between 0.3 and 0.6 T17 APX	**********	**********
Variable-ized links	Very weak in general T14 APX	**Strong some cases** Few >0.5 Several ≈ 0.3 T15 APX	**Moderate** Majority between 0.3 and 0.65, but only one about 0.65. T18 APX	**Moderate** in general **Very strong** 3 cases ≈ 0.8 T19 APX	**Moderate** 3 cases ≈ 0.4 T18 APX	**Moderate** 2 cases ≈ 0.4 T19 APX
Kind of diagram	**Moderate** negative mainly for pieces of program. Few between -0.3 and -0.5. T24 APX	**Strong some cases** mainly for initial questions. 2 cases ≈ 0.8. Few > 0.6 Few between 0.4 and 0.6. Majority≤0.4 T25 APX	**Moderate** in general but **strong some cases** (≈ 0.6) T16 APX	**Moderate** in general but **strong some cases** (≈ 0.6) T17 APX	**Moderate** Majority between 0.3 and 0.5 T20 APX	Weak in general. **Moderate** and **strong** some cases 3 ≈ 0.5 and 1 ≈ 0.6 T21 APX
Non-variable-ized links - Greenhouse Effect	Weak 1 case ≈ 0.3 T26 APX	**Moderate** 1 case ≈ -0.4 (ee) and (30) program. T27 APX	**Moderate** 1 case of 0.44 (eoe) T28 APX	**Strong** 1 case = 0.54 (oo) T28 APX	**********	**********
Partly variable - ized links - Greenhouse Effect	Very weak 1 ≈ -0.5 T26 APX	**Moderate in 2 cases** 2 ≈ 0.4 **strong in 1 case** 1 ≈ 0.6 T27 APX	**Moderate** 1 case = 0.37 T28 APX	**Strong** 1 case = 0.64 T28 APX	**********	**********

Table 9. 4 - Description of main correlations involving Mathematics, reasonable links, variable-ized links, kind of diagram, non-variable-ized and partly variable-ized links. Notice that T12 AP X means table of correlation number 12 in Appendix X, for example. Also, (ee) means event --> event, (eoe) event <--> object and (oo) object --> object.

Table 9. 4 looks at correlations between groups of questions in the questionnaires. It shows a number of reasonably strong correlations between performances on groups of questions.

As would be expected from the data on reliability, correlations within questions on Mathematics are strong (Kent) or moderate (London). Similarly, correlations within questions on reasonable links, variable-ized links, and kind of diagram, are generally strong or moderate (least so in Kent for kind of diagram).

Relations between Mathematics and other groups of questions are all strong or at least moderate for Kent students, but not for London students, where some correlations are even negative.

Relation between reasonable links, variable-ized links and kind of diagram are broadly moderate in strength, both for London and Kent.

Correlations between reasonable links, and in the Greenhouse Effect, non-variable-ized links and partly variable-ized links are moderate for London and strong for Kent.

9. 6. SEARCHING FOR A STRUCTURE

The Questionnaire about Modelling was designed with two main components: semi-quantitative or qualitative reasoning and mathematical abilities. Maybe there are others, such as, identification of variables, graphical interpretation, understanding of causal diagrams and causal links, computer programs and equations (see section 5. 5 the cognitive demands).

The high reliabilities obtained for the questions on Mathematics and causal diagramming make it interesting to look for factors underlying the test.

A factor analysis, for London and Kent together, for reasonable links, use of quantities, kind of diagram, variable-ized links and scores in mathematical questions, suggests that there are two large factors, the rest involving only 2 or 3 variables. Even though there were not large correlations between factors the oblique solution seemed the easiest one to interpret. See in table 9.5 the loadings for factors. **Bold** means that the factor loading is greater than 0.50.

	Factor1	Factor2	Factor3	Factor4	Factor5	Factor 6	Factor 7	Factor 8	Factor 9
(16b)Variab.	059	-010	**806**	-016	-066	-045	037	015	-078
(17)Variab.	391	-123	151	006	-308	144	043	322	234
(18)Variab.	-079	071	095	009	**754**	025	058	136	006
(19b)Variab.	134	014	329	017	228	-177	-041	-005	306
(13)Quant.	**565**	-019	-007	144	344	125	105	189	-342
(20)Quant.	-089	-092	038	**776**	066	002	134	288	-226
(3-8)Reas.	151	-005	-003	**733**	-187	-006	-014	161	001
(13)Reas.	031	-002	017	-285	232	093	093	**597**	009
(16b)Reas.	085	-018	**733**	-078	067	001	-087	125	-063
(17)Reas.	**678**	003	024	004	-183	081	-162	158	162
(18)Reas.	038	003	-002	052	188	-002	-006	141	**574**
(19b)Reas.	007	003	353	238	032	033	049	365	354
(20)Reas.	-076	065	003	249	-004	-127	-076	**796**	048
(13)Kind	-001	081	-095	158	-032	**832**	043	-042	075
(16b)Kind	**755**	-022	013	-063	-058	-053	-063	-006	-092
(17)Kind	213	-122	**523**	322	084	-113	044	-244	048
(18) Kind	**764**	048	010	064	-015	-133	094	-188	-075
(19)Kind	**573**	176	-043	107	192	-078	061	-006	243
(20)Kind	112	-027	036	**675**	131	073	024	-034	029
(21)popul.	-076	065	003	249	-004	-127	-076	**796**	048
(22)propor.	-008	**538**	-184	232	156	153	-442	-018	101
(23)pictor.	232	**508**	057	195	-243	-018	046	-136	-188
(24)logistic	-003	133	-061	002	114	020	**824**	-094	103
(25)pattern	-039	**742**	137	-086	-009	-001	134	-007	-021
(26)$\frac{dx}{dt} = 0$	-102	**668**	-058	-239	-174	024	179	079	357
(27)$\frac{dx}{dt} = c$	051	**725**	-157	064	242	192	149	152	-111
(28)$\frac{dx}{dt} = -cx$	009	**536**	-109	001	146	252	-182	339	-305
(29)k*dt	169	**663**	-049	-107	072	427	-162	-036	052
(30)k*x*dt	-015	405	010	097	061	068	-052	-042	-241
(31)-k*x*dt	011	216	-056	-202	007	**799**	104	-041	075

Table 9. 5 - Oblique solution reference structure - Orthotran/Varimax - Questionnaire about Modelling.

Where

(13) - Leaky tank;

(16b) - Two cars in a stream of traffic;

(17) - Motorways;

(18) - Greenhouse Effect;

(19b) - Rabbits and Foxes;

(20) - The Swing and

For Mathematics see Appendix I.2.

Also

Variab. means number of variable-ized links

Quant. means number of quantities;

Reas. means number of reasonable links and

Kind means kind of diagram constructed (if pair, chain, star or loop)

Factor 1	17.5%
Factor 2	15.0%
Factor 3	10.9%
Factor 4	12.0%
Factor 5	6.6%
Factor 6	11.4%
Factor 7	6.7%
Factor 8	13.0%
Factor 9	7.0%

Table 9. 6 - Proportionate variance contributions of each factor (Oblique).

Factors 1 and 2 have a very low correlation (0.117), and together contribute about 33% of the total variance (see table 9.6).

Figure 9. 1 shows clusters in the factor space defined by Factors 1 and 2.

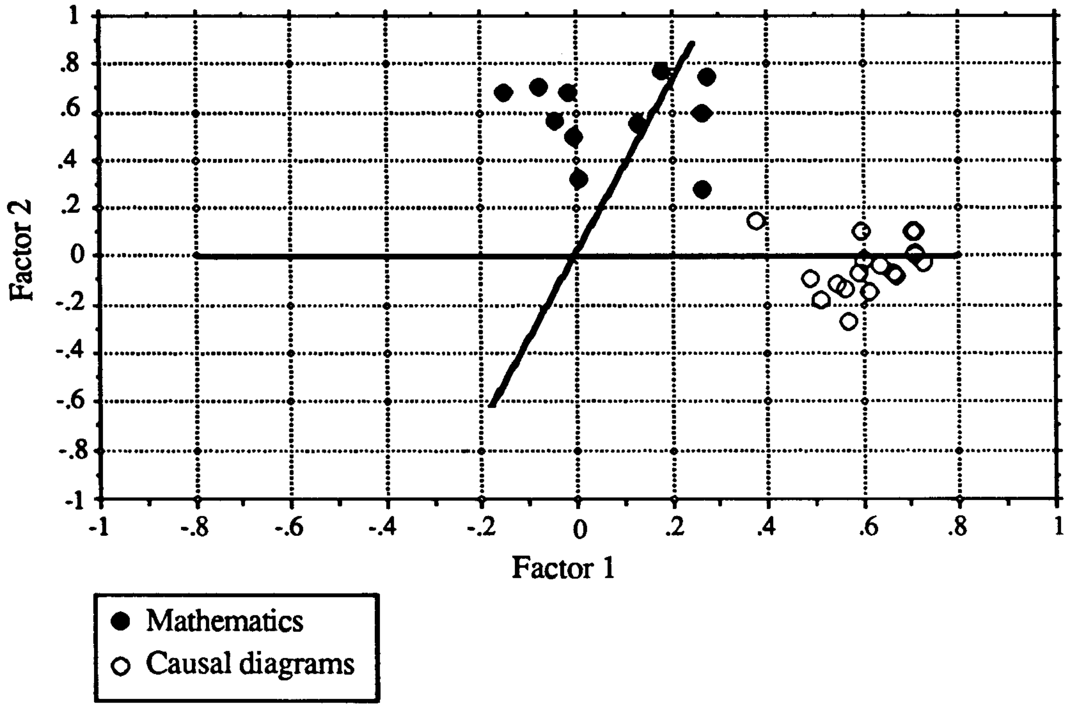


Figure 9.1 - Transformed Oblique Plot of Factor 1 versus Factor 2 - Questionnaire about Modelling.

The average of variable complexity (Oblique) is 2. 173, which means that many items depend on more than one ability. There is evidence of subject matter dependence.

9. 6. 1. INTERPRETATION OF FACTORS

Factor 1 could be interpreted as the **Semi-quantitative or qualitative reasoning** needed to be able to construct a causal diagram for a situation. Factors 3 and 4 seem to be specialized versions of qualitative reasoning (Factor 1). Factor 3 is related to "Two cars" and Motorways (car related factor), and Factor 4 is a "swing plus causality" factor. Factor 5 is related to the variables used in the Greenhouse Effect.

Factor 2 is clearly mathematical and maybe can be identified as **quantitative reasoning**. It has as a specialized version Factor 6, which is knowledge about exponential decay.

No obvious interpretation of Factor 8 has been found. Factors 7 and 9 each load only on one variable, suggests more special knowledge at work.

9. 7. ANSWERING THE RESEARCH QUESTIONS

Before answering the research questions proposed at the beginning of chapter 8, it is worth summarizing findings concerning the relation between Mathematics, Computers and System thinking.

9. 7. 1. MATHEMATICS AND COMPUTERS

London and Kent presented a middling achievement (mean scores 4.9 and 5.6 out of 10, respectively) and did not differ concerning the overall mean scores in Mathematics. However, in general, students had large mean scores in the initial questions and low scores in questions involving associating mathematical equations to graphs, differential equations and pieces of programs, with a poor achievement in explaining what a piece of computer program written in BASIC code does.

Other results suggest that students:

- are able to understand the procedure involved in calculating a difference equation as the computer does;
- could manage to get a simple graph from data in a table form;
- know the mathematical equation for the proportional relation;
- could, by elimination, identify equations that did not describe the logistic pattern and
- were reasonably consistent in answering the questions about graphs and patterns, and the questions related to differential equations and pieces of computer programs.

There is evidence that **quantitative reasoning** was used mainly when students answered mathematical questions. It has as a special case knowledge about exponential decay.

Kent students seem to have scored better for pieces of programs, which is in accordance with their larger experience with software and hardware.

9. 7. 2. MATHEMATICS AND SYSTEM THINKING

Kent students with larger experience with software were the ones with better scores in Mathematics (moderate correlation). But students with better scores in Maths were the ones able to think reasonably, in a variable-ized way and to construct more complex causal structures. For the Greenhouse Effect task, they avoided using events and recognized that one of the two entities seemed like a variable.

Thus, for students to be able to engage in the modelling process, knowledge about Mathematics is seen to be important.

9. 7. 3. RESEARCH QUESTIONS PREVIOUSLY PROPOSED

Will students engage in semi-quantitative reasoning when drawing causal diagrams ?

There is enough evidence to suppose that this does happen. *Semi-quantitative reasoning* is present when the student thinks about entities for use in a causal link, and when s/he is developing or understanding causal diagrams that describe situations. The system thinking which is necessary when developing a loop structure, for example, linking entities through reasonable links, is predominantly semi-quantitative. However, semi-quantitative reasoning tends to be complex and seems to depend on subject matter - in that differences concerning kinds of entities, kinds of links, reasonable links and kinds of diagram were found amongst tasks of different natures.

Can the student identify (select) variables? What sort of entities do they use to model and how do they use the entities when modelling ?

Students can identify or select variables, but what they choose will depend a good deal on the situation posed. There is evidence that some situations are easier to describe in terms of variables, and this may be related to the complexity and dependence on subject matter of semi-quantitative reasoning.

Will the student think about the real system and use his/her own ideas when drawing a causal diagram ?

This is the question where we have least evidence in these data. However, students in general were able to construct causal links that made sense, and causal diagrams composed of a large fraction of reasonable links, mainly in general questions. These results suggest that students thought about the real system, since they could answer the questionnaire reasonably.

There is some evidence that students used their own ideas when they selected or decided about specific entities for causal links and causal diagrams.

What can be said about the model building capability of sixth form students, without using the computer, concerning work with causal diagrams and the relevant mathematical knowledge needed ?

Results suggest that students present a modest model building capability, since overall their achievement in causal diagramming and Mathematics can be considered acceptable. When working with modelling some special care must be taken concerning difference equations and dynamic behaviours. Additional work with computer code instruction will be important if using quantitative modelling systems or languages.

For using a computational modelling system the conceptualization of entities as variables is fundamental. Work with variables seems necessary, since for some situations students will tend to use spontaneously events, processes and objects instead of variables. The choice of variables as entities in diagrams is not at all obvious, and suitable work with variables seems to be an important step in a system thinking approach.

9. 7. 4. GENERALISABILITY OF RESULTS

Similarities between London and Kent are in general more striking than the differences found. In general, despite being distinct educational realities, for most aspects, London and Kent presented much the same pattern of distribution of fractions of students or scores. This suggests that results found here may be generalisable to some degree to a wider population of sixth form students.

CHAPTER 10 - WORK WITH IQON AND CAUSAL DIAGRAMS - EXPERIMENTAL RESULTS

10. 1. INTRODUCTION

In the broad survey reported in chapters 8 and 9, the model building capability of sixth form students was characterized. An analysis for students of the intensive study (listed in table 10. 1), understanding and drawing causal diagrams, working with exploratory and expressive tasks using IQON and STELLA, is now presented. Where possible, parallels between results found in the broad survey and results found here will be drawn.

The teaching phase of IQON, causal diagrams (see chapter 6, sections 6. 3 and 6. 5. 1), and STELLA (see chapter 7, section 7. 2) about exploring a leaky tank model, were not analysed. Research questions presented in chapter 5, section 5. 3 will be used as headings for the sections where appropriate.

10. 2. THE FRAMEWORK FOR THE INTENSIVE STUDY

The network in figure 10. 1 was used, together with the network described in chapter 8, figure 8. 3, as a framework for analysing the data of the intensive study. The present network adds new dimensions to the one shown in figure 8. 3.

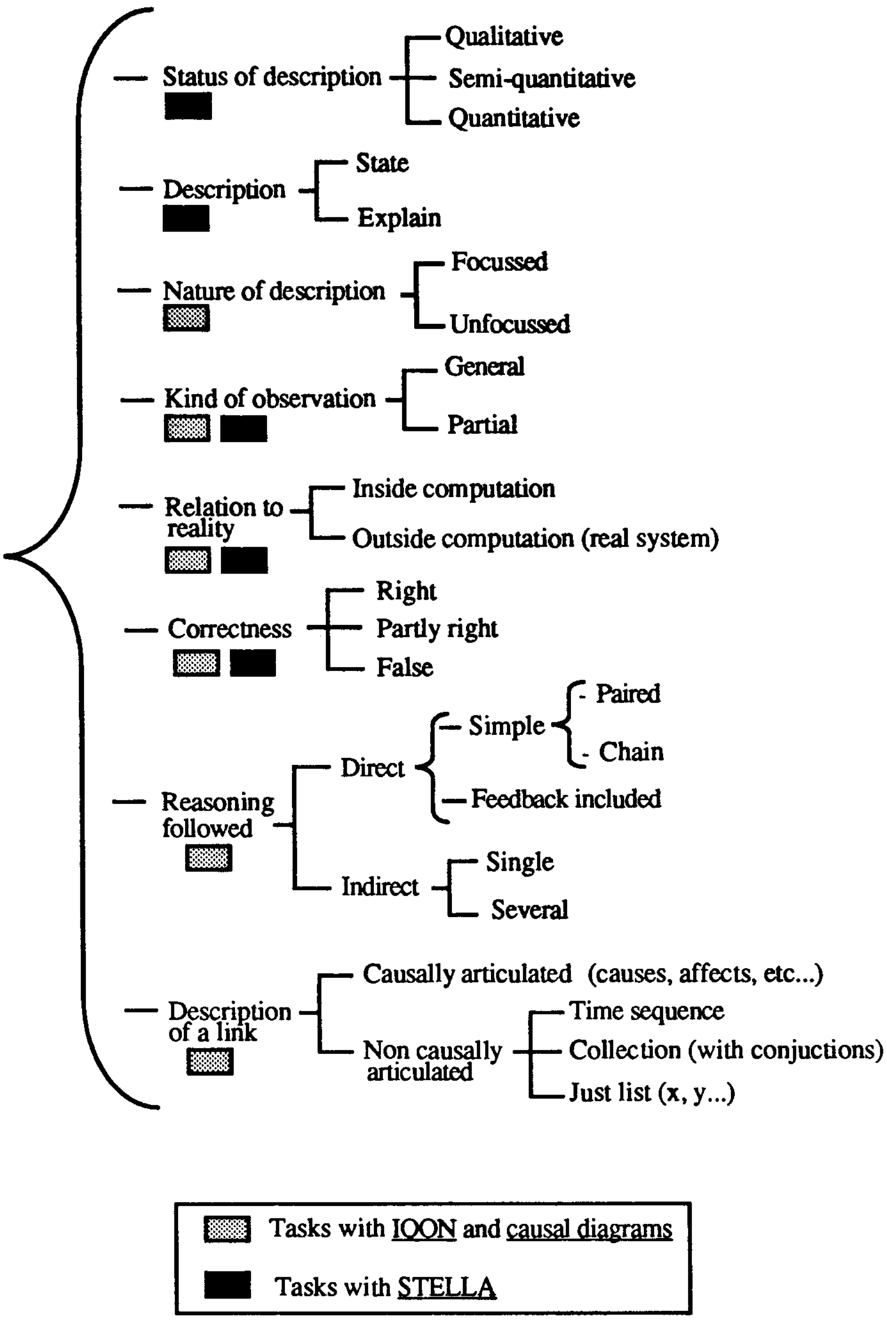


Figure 10. 1 - Framework for analysing data in the intensive study.

The framework was designed to help to classify written explanations given by students for questions concerning their work with computer models (see Appendices II. 1, II. 2, III. 1 and III. 2). Some of the dimensions were used exclusively in the analysis of the work with IQON and causal diagrams, and others in the work with STELLA.

Early versions of this network were far more elaborate. Some of the original dimensions were then collapsed, so as to achieve more meaningful groupings.

10. 2. 1. DIMENSIONS OF THE FRAMEWORK

Written explanations produced during the work with IQON, causal diagrams and STELLA were analysed according to

- kind of observation,
- relation to reality and
- correctness of explanation.

Also, in addition, for the work with IQON and causal diagrams, the analysis looked at:

- nature of description,
- reasoning followed,
- description of a link and,

for the work with STELLA, at status of description and description (state or explain).

Besides the description of entities and mechanisms used (as shown in figure 8. 3, in chapter 8), explanations were analysed in terms of the status of the description as qualitative, semi-quantitative and quantitative, and if the description given by the student was explanatory or descriptive.

The description is focussed if the explanation uses only entities which are relevant to describe the behaviour of the main dependent variable. It is unfocussed if the student describes the behaviour of entities which do not affect the main dependent variable. For example, for the Greenhouse Effect model (figure 6. 1, in chapter 6), explaining the reasons for the increase in the temperature of the Earth, by describing what happens to sea level, is unfocussed.

The kind of observation was considered general if the student saw the general pattern described. For example, if s/he wrote that a certain model represented an oscillatory pattern. It is partial or localized if the student reported just what happened to a certain number of entities in the model (e.g. "the velocity carries on increasing for a while, and then starts to decrease").

A student is thinking outside the computation when s/he gives entities which are related to the real system, and are not explicitly represented in the model. For example, when the student uses "atmosphere" or "Ozone". Even though some of these entities were in the information provided about the meaning of variables (see section 6. 5. 2, for causal diagrams) their use by the student was not obvious or immediate.

For the "two cars in a stream of traffic " task, for example, relation to reality is concerned with referring to events or objects outside the computation (e. g. " the cars seem to attempt to catch each other up").

An explanation is right if it gives the correct account for the expected behaviour of a dependent variable. It is false if the student makes the wrong prediction of what happens to the main dependent variable. An explanation can also be partly right.

The reasoning followed was considered direct and simple, when it described a chain of boxes (or entities) or pairs. For example, when predicting what happens to the temperature when the amount of industries is set to a high level, the student may write that the fuel burnt will increase, which will make the amount of CO2 increase, which will make the energy radiated decrease, which will make the temperature increase. This student clearly followed a chain of boxes (or entities). Direct reasoning can also include a feedback if the student, for example, continues and explains what happens next to the energy radiated.

The reasoning was considered indirect when the student just described what happened to one or several isolated boxes/entities in the model.

The description of a link was considered causally articulated when the student articulated linguistic indicators like *causes* , *affects* , *will lead to* , . . ., *etc* , when describing the link (e. g. the amount of Fuel burnt will cause the amount of CO2 to increase). It was considered non causally articulated when the link was described in terms of a time sequence (e. g. when amount of industries increases, the fuel burnt increases), a collection with conjunctions (e. g. amount of industries increases therefore fuel burnt increase) or just a list of entities (e. g. amount of industries increases, fuel burnt increases, ...).

I will consider the use of these linguistic clues as a possible indicator that the students were expressing themselves in a causal way, whatever kind of mechanism was used to explain the link (see below).

10. 2. 1. 1. Problems of cause in language

Draper (1988) points out that "because" can occur not only in explanations that express cause but also in those that give reasons for belief or for a speech act. Conversely, he adds that "because" and related connectives like "so" can be missing from utterances that are clearly causal explanations. In his opinion, causation is often implied by connectives like "and" and "while". Also, although "because" probably does always signal the presence of an explanation, its presence does not tell you much about what kind of explanation it is. Thus neither "because" nor the set of related connectives are reliable markers of causation.

Conscious of the problems of implying causation by linguistic indicators, I will not consider explanations which use "because" or "will cause", for example, as causal, but as articulated with links expressed in a causal language. Maybe the use of these indicators just reflects that the student is more able to express herself in writing, and not that s/he is really thinking in a causal way.

10. 3. STUDENTS INVOLVED IN THE INTENSIVE STUDY

Name	Gender	Age	Place of school	A level Background	Treatment
ELI	Female	16	North London	Economics	IQON - STELLA
PAT	Female	16	North London	Economics	IQON - STELLA
SIM	Male	16	North London	Physics	IQON - STELLA
CHI	Male	16	North London	Physics	IQON - STELLA
EDD	Male	16	North London	Physics	IQON - STELLA
NWA	Male	16	North London	Physics	IQON - STELLA
JAS	Female	17	South East	Economics	IQON - STELLA
SHA	Female	17	South East	Economics	IQON - STELLA
MEL	Female	18	South East	Economics	IQON - STELLA
PAA	Male	17	South East	Economics	IQON - STELLA
ROS	Male	17	South East	Economics	IQON - STELLA
TOB	Male	17	South East	Economics	IQON - STELLA
COL	Male	17	South East	Economics	IQON - STELLA
PAO	Male	18	South East	Economics	IQON - STELLA
JASO	Male	18	South East	Economics	IQON - STELLA
PET	Male	18	South East	Economics	IQON - STELLA
STU	Male	16	North London	Economics	CD - STELLA
MARC	Male	16	North London	Economics	CD - STELLA
JOA	Female	17	North London	Physics	CD - STELLA
ROSA	Female	17	North London	Physics	CD - STELLA
REB	Female	18	North London	Physics	CD - STELLA
COLE	Female	17	North London	Physics	CD - STELLA
NIC	Female	17	South East	Economics	CD - STELLA
DAR	Male	17	South East	Economics	CD - STELLA
ANK	Male	16	South East	Physics	CD - STELLA
PHO	Male	16	South East	Physics	CD - STELLA
MARG	Female	17	South East	Economics	CD - STELLA
TON	Female	17	South East	Economics	CD - STELLA
MAR	Male	17	South East	Economics	CD - STELLA
RIC	Male	16	South East	Economics	CD - STELLA
TUO	Male	17	South East	Physics	CD - STELLA
MIC	Male	18	South East	Physics	CD - STELLA
BRU	Male	17	South East	Economics	CD - STELLA
HAR	Male	16	South East	Economics	CD - STELLA

Table 10. 1 - List with Name, Gender, Age, Place of school, A - Level background and the treatment received - if Causal Diagrams - STELLA or IQON - STELLA, for students (17 pairs) involved in the intensive study with computer.

Table 10. 1 shows a list of students in the intensive study, shown as pairs which did IQON, or causal diagrams (CD), followed by common work with STELLA.

PLACE	AGE	BACKGROUND	GENDER	Nº of students
North	Older	Physics	Female	4
North	Younger	Physics	Male	4
North	Younger	Economics	Male	2
North	Younger	Economics	Female	2
South East	Older	Physics	Male	2
South East	Older	Economics	Male	10
South East	Older	Economics	Female	6
South East	Younger	Physics	Male	2
South East	Younger	Economics	Male	2
TOTAL OF STUDENTS:				34

Table 10. 2 - Distribution of students according to Place of school, Age, Background and Gender, for 34 students involved in the intensive study with computer.

Table 10. 2, obtained from table 10. 1, shows the distribution of students according to the main relevant variables (not including treatment). In this table 17 and 18 year old students are grouped as 'Older'. As explained below, it was impossible to avoid this undesirably uneven distribution of age, place, gender and background.

For the sample presented in table 10. 1, gender was not related to age, place of school, background or treatment. Age was not related to background and treatment, nor treatment to place of school and background. However, as shown in tables 10. 3 and 10. 4, respectively, school and age and school and background were related.

	North	South East	TOTAL
16	8	4	12
17	3	13	16
18	1	5	6
TOTAL	12	22	34

Table 10. 3 - Number of students for North London and South East London by age.

There are significantly different fractions of ages according to place of school. Table 10. 3 suggests that schools from North London had a larger fraction of 16 year-old students, and schools from South East London larger fractions of 17 and 18 (Considering 17 and 18 years old as one category, p = 0. 008 - Fisher).

	North	South East	TOTAL
Economics	4	18	22
Physics	8	4	12
TOTAL	12	22	34

Table 10. 4 - Fraction of students for North London and South East London by subject.

Table 10. 4 suggests that students from North London more often had a Physics A - Level background, and those from the South East were more often doing Economics A - Level (p = 0. 008 - Fisher).

A random selection of subjects was impossible. Students were selected according to their willingness to participate in the experiment, and as a consequence the above links of backgrounds and ages were unavoidable. It is important to keep in mind that differences in achievement between North and South East London, could be explained due to these differences in age and background.

In this study, for the purpose of data analysis, North and South East London schools were initially put together. Any differences are reported.

10. 4. PROBLEMS CONCERNING WORK IN PAIRS

In the intensive study students were intended to work in pairs on three occasions sharing one Macintosh computer. All the students worked in pairs during the first meeting (see section 5. 6, figure 5. 4) with causal diagrams or IQON. But some problems arose, after the first meeting, with 3 pairs in one school in North London, when the teacher rearranged times for further sessions, which led to some students not appearing.

Specifically:

EDD and NWA worked together with IQON and STELLA (Leaky Bottles and Diet and Weight loss), but worked individually on the "Two cars" task (STELLA) ;

SIM and CHI worked together with IQON, but SIM worked alone on the tasks with STELLA, and CHI did not do them;

MAR and STU worked together with causal diagrams, but MAR worked individually on the tasks with STELLA, and STU did not do them.

These differences in treatment will be taken into account in interpreting the data.

10. 5. DATA ANALYSIS COUNTING INDIVIDUALS

Even though students worked in pairs, for most tasks, the majority of the pairs did not engage in consistent collaborative work, and wrote their answers independently, so individual answers differed. The only exception was for the "two cars in a stream of traffic" task, where 10 pairs really discussed each question before deciding about what to answer. Since students predominantly worked independently, and because pairs were composed in some cases of students of different age and gender, I decided to analyse the data counting individuals rather than pairs, so as to get some idea of age and gender effects. However, it was a difficult decision to make.

It seems likely that answers given by people working in pairs will tend to converge rather than diverge, thus tending to reduce rather than exaggerate any age or gender effects. On tasks where students did collaborate in pairs (the expressive ones with causal diagrams, IQON and STELLA), the data are treated as pairs, however. In this case, age and gender effects can not be examined.

10. 6. WORKING WITH THE COMPUTER - GENERAL PICTURE FROM OBSERVATION

10. 6. 1. WHAT IS THE INTERACTION BETWEEN PAIR, RESEARCHER AND WRITTEN MATERIAL?

Few students decided to take the lead in the peer interaction, and in some pairs both students shared almost equally the only computer. In general, pairs started the tasks without discussing, or interacting. There were a few exchanges of ideas mainly when giving opinions about the IQON model or causal diagram (questions d, e and f). In the second session about two and three tanks in STELLA, a few students worked collaboratively, exchanging ideas. The third section "Two cars" in STELLA was the one where the students discussed most. Maybe they interacted more due to the difficult nature of the question or because they felt more relaxed since it was the last session. However, when the peer interaction happened it did seem to help the students to reach a better understanding of the models. Peer interaction always happened, for the expressive tasks "Rat War" (IQON or C. D.) and "Diet and weight loss" (STELLA), where students had to discuss and decide together what to write in the computer.

In general students did not ask the researcher questions, and the few asked were to clarify some misunderstanding of the model, or vocabulary of the text. All students read and used the written material and did not express doubts about it. One student did not know the word "spate" (see text about the Greenhouse Effect in Appendix II. 1). No criticisms of the written material were made.

10. 6. 2. CAN I FIND HINTS OF ATTITUDE TOWARDS THE ACTIVITIES ?

Students seemed in general keen to answer the questions, and just two pairs seemed not motivated to think about the first models for the leaky tank in STELLA (teaching phase - see section 7. 2). Just two students (in different pairs) seemed indifferent or negative towards the tasks in general.

10. 6. 3. HOW DID THE STUDENTS MANIPULATE IQON AND STELLA MODELS ?

Students seemed to master reasonably the Physics or general knowledge involved in the tasks with models to explore in IQON and STELLA. Just two students, in distinct pairs both with a Physics background, criticised the Greenhouse Effect causal diagram, realizing its ambiguity.

In general, students played with the models simply to answer a question, and few students even tried to change the "two cars in a stream of traffic" STELLA model without being asked.

Students in general seemed to understand equations generated in STELLA, in exploratory tasks.

10. 6. 4. WHAT ARE THE STUDENT'S SPECIFIC DIFFICULTIES WHEN USING IQON AND STELLA ?

In general, after being taught, students did not have much problem in dealing with IQON's basic functions. Similarly, students could deal with the basic operations in STELLA, although a few of them asked for help when selecting and dragging a box, pulling down menus and even defining new graphs. The use of MacDraw to draw causal diagrams seemed to have helped students with the basic operations in STELLA.

10. 6. 5. SOME INTERESTING REMARKS

Three students interpreted the STELLA model as if it were the real system. For them, the water should not pass the 'drain level', which is in fact arbitrary in the STELLA diagram.

One student said that it is easy to imagine water coming down into tanks, but not when we have to think about calories coming down into a tank. Some students said that IQON was better and easier to use.

The STELLA diagram was considered very helpful, but defining equations and understanding how they worked in the model, was considered difficult. Some students even said that it was not necessary to look at the graphs, and that the diagram alone was enough to understand the situation. The representation by icons, itself, seemed to have satisfied these students.

One student said that STELLA is more difficult because IQON allows the user to determine whether the link is positive or negative, while in STELLA the positive and negative links are determined by different structures (flow in or flow out).

10. 7. EXPERIMENTAL RESULTS CONCERNING AN EXPLORATORY TASK WITH IQON AND THE UNDERSTANDING OF A CAUSAL DIAGRAM

10. 7. 1. INTRODUCTION

Section 6. 4, in chapter 6, presents the exploratory task using an IQON model for the Greenhouse Effect. Section 6. 5. 2 presents a task about understanding a causal diagram for the same situation. Both the IQON and causal diagram models have the same structure and entities (see in chapter 6, figures 6. 1 and 6. 11).

Questions *a*, *b* and *c* are about the effect on one parameter of setting others at high or low levels (see Appendix II. 1). Questions *d*, *e* and *f* are about the student's opinion of the model.

The following research questions will be addressed:

how well does the student use the causal diagram or IQON model when making predictions ?

how do answers for questions involving a causal diagram differ from answers given for the same questions involving an IQON model ?

what can be said about the entities used and the final structure of causal diagrams and IQON models ?

how do causal diagrams and IQON models differ for the expressive task ?

how does the student explain in his/her own words what the causal diagram or IQON model is describing ?

how does the student criticise causal diagrams or IQON models ?

and

how well does the student manage an exploratory task (Greenhouse Effect) using a causal diagram or IQON?

This last question, being about an exploratory task, necessarily includes getting information about how well students understand the subject matter of the task, namely the Greenhouse Effect.

10. 7. 2. OPINION OF OTHER RESEARCHERS ABOUT THE GREENHOUSE EFFECT TASK

The causal diagram (in figure 6. 11, chapter 6) was shown to 5 teachers who answered the teacher's opinions questionnaire in Appendix VI. They were asked to rate how difficult they thought it would be for most VI form students to think about this system. Four considered the situation fairly easy and only one fairly difficult. They were asked as well to rate some explanations given by students and also to indicate how many students they thought might be capable of such an answer. This data was used to help evaluate the performance in the intensive tasks.

10. 7. 3. GENERAL PICTURE FROM OBSERVATION

10. 7. 3. 1. How well does the student use the IQON model when making predictions ?

In general students seemed to understand the IQON model for the Greenhouse Effect well, but some of them expressed doubts about what the box Energy Radiated represented. Students in general worked independently, and gave correct predictions and explanations for items about the effect on one parameter of setting others at high or low levels (see Appendix II. 1.).

Students, when predicting, seemed to reason mainly following chained interactions. Only three pairs, two composed of students with a background in Physics, gave evidence of thinking at a "system level" (in this case, being able to follow loops). Only two pairs gave evidence of thinking outside the computation, relating the model to reality. Nine pairs seemed to think exclusively inside the computation or model, that is, treating the model as the phenomenon to be analysed. The others did not give enough evidence to judge how they were thinking.

Complementary evidence can be found in the written answers to the questions (see later).

10. 7. 3. 2. How do answers for questions involving a causal diagram differ from answers for questions involving an IQON model ?

Unlike IQON, for the work with causal diagrams, five pairs made some wrong predictions, at least initially, for these items. Also, students who worked with causal diagrams tended to have doubts about the links *Polar ice* --> - *Sea level* and *Energy radiated* --> - *Temperature* (negative links, see model in figure 6. 11, chapter 6, section 6. 5. 2).

Some students seemed to persist in the misunderstanding of these links, during and even at the end of the causal diagram task.

Unlike the causal diagram, the runnability of IQON seemed an advantage for the immediate understanding of the effects of a plus or minus sign.

10. 7. 4. ANALYSIS OF THE WRITTEN ANSWERS

Finding common aspects between diverse explanations was not an easy task. It was not always possible to account for all the nuances of the data. Looking at the defined dimensions, as presented in the framework in figure 10. 1, runs the risk of overlooking the richness of the data. However, I believe that the level of analysis reached here depicts those common aspects presented by the whole group of explanations which it is possible to distinguish reliably.

The written explanations given by the students were analysed, following the framework in figure 10. 1. An equivalent kind of analysis was developed for items concerning effects on the temperature of making the amount of industries and vehicles high and the land clearance low. Also, for effect on the energy radiated of making the temperature increase. These questions were of same nature.

10. 7. 4. 1. a) Make the amount of industries and vehicles high. What happens to the temperature ? Why ?

10. 7. 4. 1. 1. General profile of the explanation

Table 10. 5 shows that roughly half of the explanations presented a kind of mechanism, referred to entities of the real system (for example, atmosphere, Earth, planet, Ozone, space, air) and followed a chain of boxes/entities. Two reached the wrong conclusion (that the temperature would decrease) and 31 gave focussed descriptions (of boxes/entities which were relevant for answering the item).

Students who did not follow a chain, when giving the explanation, in general had problems in explaining links which involved the box or entity *Energy radiated.* This result is in accordance with the observation data of students using models to make predictions (see above).

There will be other results which suggest that some students had problems in thinking about the real system.

Dimensions of framework	IQON	C. D.	TOTAL
Gives any kind of mechanism	7	11	18
Uses entities of real system	7	11	18
Follows a chain of boxes/entities	7	10	17
Reaches false conclusion	1	1	2
Gives focussed description	15	16	31
Causally articulated links:			
none	0	3	3
less than half	2	2	4
half	5	4	9
more than half	4	8	12
all	5	1	6

Table 10. 5 - Number of students (maximum 16 for IQON and 18 for causal diagram) for each dimension of the framework for explanations for effects on temperature of making the amount of industries and vehicles high, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Concerning causally articulated links used, only 6 explanations were completely articulated with links expressed in a causal language. For example, "more fuel burnt will cause more CO2...". (my emphasis). The others had at least one non-causally articulated link. For example, "Number of vehicles increases, fuel burnt increases...". Just three explanations were completely articulated with links expressed in a non-causal language.

In general explanations were very limited concerning mechanisms given. One example of an explanation rated as very good is

> "It goes up.
> Industry and vehicles increase, so amount of fuel burnt must increase. An increase in burnt fuel means and increase in CO2. More CO2 means less radiation energy deflected off the earth..., *as it cannot so easily penetrate CO2*. If less energy is radiated, *when the form of energy is heat, then if it is trapped* the temperature must rise". (STU)

The mechanisms in *italic* (my emphasis) were given to explain the causes of increase in temperature. One mechanism explains the reason why more CO2 will cause less radiation reflected. The other, explains that if the energy is heat and is trapped them the temperature will rise.

An example of a poor explanation is

> "Increases.
> Because less energy is radiated. Industries + vehicles increases so more fuel is burnt. More CO2 thus less energy radiated". (REB) (my emphasis).

REB described the links between variables with conjunctions so and thus. She does not explain the link between Fuel burnt and Amount of CO2. She does not give any mechanism.

Kinds of mechanisms given are presented in table 10. 6 below.

Mechanism given	IQON	C. D.	TOTAL
Related to the production of CO2	3	5	8
Related to the effect of having a high level of CO2	3	3	6
Industries and vehicles producing/burning more fuel	1	1	2
Action of Energy radiated increasing temperature	0	2	2
Only a slight amount of CO2 is absorbed by plant life	1	0	1
The Earth will begin to warm up (there is no let off in temperature)	0	1	1
Total number of mechanisms	8	12	20

Table 10. 6 - Main kinds of mechanisms used in explanations for effects on temperature of making the amount of industries and vehicles high, for the Greenhouse Effect exploratory task.

The main kinds of mechanisms given were related to the production of CO2, with 8 cases. An example is "Industries and vehicles produce more fuel. Fuel when burnt provides CO2 " (my emphasis). In second place, with six cases, are those related to the effect of having a high level of CO2. An example is "CO2 stops energy returning back to space" (my emphasis). Other examples of these kinds of mechanisms are, respectively, "burning of plant life used for energy " and "Amount of CO2 damaging the Ozone". Plant life, despite being a box in the model, is not linked to fuel burnt. Also, there is no representation for Ozone in the model.

Other kinds of mechanism are also presented.

It may be interesting to note that 18 students were responsible for 20 mechanisms, which gives a mean of about one mechanism per explanation. This result indicates that students in general were very limited in giving mechanisms. As mechanisms were given to justify causation in a system, since they were usually expressed as an action of some kind (Forbus), this result may mean that students' causal thinking in the Greenhouse Effect task was unsatisfactory. This seems to agree with the large number of non-causally articulated links in explanations. Also, it agrees somehow with results from the survey where students had problems in thinking causally in questions related to Physics (Leaky tank and the Swing) and general questions (Greenhouse Effect, Rabbits and Foxes and Motorways). However, in general tasks they could use noticeably larger fractions of reasonable links, which may indicate that their causal reasoning was more successful in these tasks (see sections 8. 9. 1, 8. 12 and 8. 14).

The use of mechanism is related to gender (p = 0. 00003 - Fisher) and age (p = 0. 02 - Fisher) for students who worked with causal diagrams.

Table 10. 7 suggests that a larger fraction of 16 years old male students gave mechanisms.

C. D.

	Female	Male	TOTAL
Give mechanism	0	11	11
Do not	7	0	7
TOTAL	7	11	18

C. D.

	16	17-18	TOTAL
Give mechanism	6	5	11
Do not	0	7	7
TOTAL	6	12	18

Table 10. 7 - Gender and age effects for mechanism. Explanations for effects on temperature of making the amount of industries and vehicles high, for the Greenhouse Effect exploratory task with causal diagrams.

As background and gender and background and age are not related (for causal diagrams), effect of background is not an alternative explanation. This suggests that there is a genuine gender effect in favour of male students, concerning giving mechanisms. There will be other results to support this.

Unfortunately, I do not have a good explanation for why 16 year old students tended to give mechanisms when working with causal diagrams.

No other significant effects were found.

10. 7. 4. 2. b) Make the land clearance low (reforestation). What happens to the temperature? Why?

10. 7. 4. 2. 1. General profile of the explanation

Table 10. 8 shows that the majority of the explanations presented a kind of mechanism and followed a chain of boxes/entities. Students who did not follow a chain, when giving the explanation, in general had problems interpreting the Energy radiated. This result is in accordance with the findings for question *a* (see above). 13 students (4 for IQON and 9 for causal diagrams) used entities of the real system, five reached a false conclusion and 27 gave focussed descriptions. Just one student (EDD), who gave a focussed description, included a feedback, going further than necessary in his explanation.

Dimensions of framework	**IQON**	**C. D.**	**TOTAL**
Gives any kind of mechanism	7	14	21
Uses entities of real system	4	9	13
Follows a chain of boxes/entities	14	14	28
Reaches false conclusion	1	4	5
Gives focussed description	11	16	27
Causally articulated links:			
none	1	6	7
less than half	4	7	11
half	2	1	3
more than half	4	2	6
all	5	2	7

Table 10. 8 - Number of students (maximum 16 for IQON and 18 for causal diagram) for each dimension of the framework for explanations for effects on temperature of making the land clearance low, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

As in section 10. 7. 4. 1. 1, these results add a little further to the evidence that relating model to reality might be problematic.

Concerning causally articulated links used, only seven explanations were completely articulated with links expressed in a causal language. The others had at least one non-causally articulated link. Seven explanations were completely articulated with links expressed in a non-causal language.

As for question *a*, explanations were very poor concerning mechanisms given. One example of a good explanation is

> "It goes down.
> If less *land is cleared for development*, *more room is available* for plants which will increase. Plants *photosynthesise CO2 to produce oxygen*. The oxygen production would mean the reduction in the level of CO2 in the atmosphere. *CO2 which prevents the Earth deflecting the sun's radiation* will decrease, more energy will be radiated off the Earth and the temperature will drop". (STU)

The mechanisms in *italic* (my emphasis) were given to explain why the amount of plants increases, why the level of CO2 decreases and why the temperature drops. An example of an explanation that has no mechanisms given is

> "Due to the land clearance the plant life decreased causing the amount of CO2 to decrease, therefore causing the temperature to decrease". (JASO) (my emphasis).

JASO got the right conclusion that the temperature would decrease. However, his reasoning was wrong since he considered that the plant life would decrease. He did not consider reforestation (as solicited). Also, he avoided the explanation of the Energy radiated. Even though he expressed the links between variables in a causal language, the explanation is not completely convincing.

The main kinds of mechanisms given are presented in table 10. 9 below.

Mechanism given	IQON	C. D.	TOTAL
Related to action of plants (by photosynthesis) reducing CO2	3	11	14
Related to action of reforestation increasing number of plants	1	2	3
Related to action of Energy radiated cooling Earth	1	3	4
Related to action of CO2 working like a blanket	1	2	3
Building give out more heat	0	1	1
Increase polar caps occur falling sea levels	1	0	1
Total number of mechanisms	7	19	26

Table 10. 9 - Main kinds of mechanisms used in explanations for effects on temperature of making the land clearance low, for the Greenhouse Effect exploratory task.

The main kinds of mechanisms given were related to the action of plants (mainly through photosynthesis) reducing CO2 and producing Oxygen, with 14 cases. In second place, with four cases only, were ones related to the action of Energy radiated cooling the Earth. Other kinds of mechanisms are also presented.

As in section 10. 7. 4. 1, results for causally articulated links and mechanisms given add to the evidence that students' causal thinking was unsatisfactory.

Use of mechanism and gender are related (p = 0. 01 - Fisher).

Table 10. 10 suggests that a significantly larger fraction of male students, who worked with causal diagrams, gave at least one mechanism. As background is not related to gender, like in section 10. 7. 4. 1. 1, it does not account for the difference. This result adds a little further to the impression that there is a genuine gender effect.

C. D.

	Female	Male	TOTAL
Give mechanism	3	11	14
Do not	4	0	4
TOTAL	7	11	18

IQON

f	16/North	17-18/South	TOTAL
<0.5	0	5	5
≥0.5	6	5	11
TOTAL	6	10	16

Table 10. 10 - Effects of gender for mechanisms and fraction *f* of causally articulated links. Explanations for effects on temperature of making land clearance low, for the Greenhouse Effect exploratory task with causal diagrams and IQON, respectively.

The same table suggests that a noticeably larger fraction of 16 year old students from North London (p = 0. 06 - Fisher), who worked with IQON, had larger fractions of causally articulated links. However, as background is related to age and place of school, these results may just reflect that students with an Economics background (the older ones from South East London) were unsuccessful in giving causally articulated links. On the other hand, there was an advantage to students with a Physics background (the younger ones from North London). These results seem to agree with expectation 16, in table 3. 1, chapter 3 (we should expect Physics students to be more cognitively adapted to the system thinking approach). There will be several other cases indicating an advantage to students with a background in Physics.

No other significant effects were found.

10. 7. 4. 3. c) Consider that the temperature increases. What happens to the energy radiated? Why?

10. 7. 4. 3. 1. General profile of the explanation

Table 10. 11 shows that the majority of the explanations:

- presented a kind of mechanism;
- did not use entities of the real system;
- gave mainly focussed descriptions;
- did not generalise the pattern;
- reached a partly right conclusion and
- followed boxes/entities, pairs and at least one chain.

Dimensions of framework	IQON	C. D.	TOTAL
Gives any kind of mechanism	8	11	19
Uses entities of real system	1	5	6
Gives focussed description	8	14	22
Generalises	3	3	6
Correctness:			
Reaches a right conclusion	5	2	7
Reaches a partly right conclusion	6	14	20
Reaches a false conclusion	5	2	7
Reasoning:			
Follows at least a loop	4	3	7
Follows at least a chain	8	5	13
Follows only boxes/entities and pairs	4	10	14
Causally articulated links:			
none	3	6	9
less than half	1	1	2
half	5	0	5
more than half	4	1	5
all	3	10	13

Table 10. 11 - Number of students (maximum 16 for IQON and 18 for causal diagram) for each dimension of the framework for explanations for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

The explanations were not very successful concerning the description of the observed pattern. Students could report that the Energy radiated first increased and then decreased, because it could be directly observed on the computer screen (in IQON), but they could not provide a convincing argument to explain this behaviour. To describe correctly the pattern it would be necessary to account for the main feedback loop (*Energy radiated* <-> *Temperature*), which the majority did <u>not</u> do. These results may suggest that students had some problems of thinking at a system level, since they just followed pairs, isolated variables and chains. Notice however that, in the survey, chapter 8, section 8. 12, the task about the Greenhouse Effect was one of those where students did develop loop diagrams, indicating some level of system thinking. It may be interesting to note that students from the survey misinterpreted the behaviour of entities involved in feedback (see section 8. 5. 3. 2). These results may indicate that students had difficulties in thinking at a system level. System thinking no doubt involves causal thinking. Consequently, these results support the view already presented that students' causal thinking in general was unsatisfactory.

Concerning causally articulated links used, 13 explanations were completely articulated with links expressed in a causal language. This result may represent an improvement concerning the number of causally articulated links for items *a* and *b*. This may be because students had started to get used to elaborating a written answer.

The others had at least one non-causally articulated link. Nine explanations were completely articulated with links expressed in a non-causal language.

Mechanism given:	**IQON**	**C. D.**	**TOTAL**
Concerning the kind of relationship expressed by sign of link	3	4	7
Concerning heat	0	2	2
Concerning equilibrium between different actions in the model	1	1	2
Action or possible action on Energy radiated	4	3	7
Temperature increase causing polar ice to melt and sea level to rise	1	0	1
Total number of mechanisms	9	10	19

Table 10. 12 - Main kinds of mechanisms used in explanations for effects on the energy radiated of making the temperature increase, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Like the previous results (for items *a* and *b*) rather few mechanisms were given in explanations (19 students gave 19 mechanisms, which gives a mean of one mechanism per explanation). This adds to the evidence that students had problems with causal thinking.

Mechanisms could be grouped as shown in table 10. 12. The main kinds of mechanisms used were the ones concerning the kind of relationship expressed by the sign of the link (7 cases), and the ones which described an action or possible action on Energy radiated (7 cases). An example of the first case is "the arrow at the top indicates for the energy radiated to increase". In this case the positive arrow appears as responsible for the change in energy radiated. For the other case "so with no ice caps to reflect off, the radiated energy is used up and so Energy radiated decrease".

An example of those concerning heat is "more of the heat is used to heat the extra water". Other kinds of mechanisms are also presented.

The following three explanations illustrate the complexity of the written answers given by students.

> 1) "If the temperature increases then this would mean that less energy is being radiated. This would suggest an ***inverse relationship*** between the energy radiated and the temperature. As a result of a temperature increase the amount of energy radiated must be decreasing. However, the model would seem to suggest that if the temperature is already increasing then the amount of energy radiated increases in proportion. This would suggest a *proportional relationship* between temperature and the energy radiated". (MARC)

MARC realised the ambiguity of the causal diagram. He knew that an inverse relationship between Energy radiated and Temperature would be expected from the previous running of the model in items *a* and *b* . However, if the Temperature is already high and Energy radiated is at the "normal" level, it is reasonable to expect, due to the positive link, an initial increase in the level of Energy radiated. MARC saw the loop as contradictory. The *inverse/proportional relationship* in *italic* (my emphasis) for him worked as the mechanisms to explain changes in Energy radiated.

> 2) "It keeps increasing and decreasing.
> As the temperature is high the energy radiated increase, but then that leads to a fall in the temperature which then leads to a decrease of energy radiated. This goes to increase the temperature because energy radiated *has a negative relationship* with temperature". (PAT)

PAT working with IQON followed twice the loop *Energy radiated <-> Temperature* when giving her answer. She generalised the pattern when she wrote about the existence of a negative relationship, but her explanation was circular. The *negative relationship* in *italic* (my emphasis) works as the mechanism to explain the increase in temperature.

> 3) "Decreases.
> Increase in Temperature reduces amount of polar ice. Reduction in amount of polar ice results in decrease in Energy radiated. As the direct effect of Temperature on Energy radiated is that increase in Temperature increases Energy radiated, and increase in Energy radiated results in decrease in Temperature - equilibrium reached *this equilibrium will resist decrease in Energy radiated* due to polar ice decreasing. But there will still be an overall decrease". (MIC)

MIC working with causal diagrams realised that the temperature affects directly the Energy radiated (positive link) and indirectly through polar ice caps, and that the resultant behaviour of the Energy radiated would have to be the resultant of both distinct effects. In this explanation the non-equilibrium between actions on different parts of the model is the mechanism for explaining the behaviour. See mechanism in *italic* (my emphasis).

Some interesting effects were found.
Use of mechanism is related to place of school ($p = 0.02$ - Fisher). Kind of observation is related to age and place of school (both, $p = 0.04$ - Fisher).
Table 10. 13 suggests that a significantly larger fraction of North London students, who worked with causal diagrams, gave at least one mechanism. A significantly larger fraction of 16 year old North London students, who worked with IQON, was able to generalise the pattern. A noticeably larger fraction ($p = 0. 06$ - Fisher) of 16 year old North London students, who worked with IQON, gave focussed descriptions. A noticeably larger fraction ($p = 0. 05$ - Fisher) of female students, who worked with causal diagrams, used only entities of the model.

C. D. p = 0. 02	**North**	**South East**	TOTAL
Give mechanism	6	5	11
Do not	0	7	7
TOTAL	6	12	18

C. D. p = 0. 05	**Female**	**Male**	TOTAL
Model	7	6	13
Reality	0	5	5
TOTAL	7	11	18

IQON p = 0. 06	**16/North**	**17-18/South**	TOTAL
Focuseed	5	3	8
Unfocussed	1	7	8
TOTAL	6	10	16

IQON p = 0. 04	**16/North**	**17-18/South**	TOTAL
General	3	0	3
Partial	3	10	13
TOTAL	6	10	16

Table 10. 13 - Effects of place of school, gender and age for mechanisms, relation to reality, nature of description and kind of observation. Explanations for effects on the Energy radiated of making the temperature increase, for the Greenhouse Effect exploratory task with IQON and understanding of a causal diagram.

However, as in section 10. 7. 4. 2. 1 differences in favour of 16 years old and North London students might be explained because they have a Physics background, since for the work with IQON background is related to age and place of school. As in sections 10. 7. 4. 2. 1 and 10. 7. 4. 1. 1 background is not related to gender, and again it does not account for the difference. This result adds to the evidence of a genuine gender effect, which seems not able to be explained by other factors. It may be interesting to note that gender effects appeared only for the work with causal diagrams but not IQON. Male students seemed better in giving mechanisms and thinking about the real system. This result seems to agree with expectation 15, in table 3. 1, chapter 3 (we should expect gender effects concerning work with system thinking).

Treatment and correctness of explanation are related (p = 0. 02 - Fisher).

Chart 10. 1 shows that, independently of gender, age, place of school and background, about two thirds of students who worked with IQON gave answers which were clear cut, either right or wrong, the majority of the students who worked with causal diagrams gave in-between, that is partly right answers. Not having seen the model running, it seems that students working with causal diagrams were less clear about the whole system.

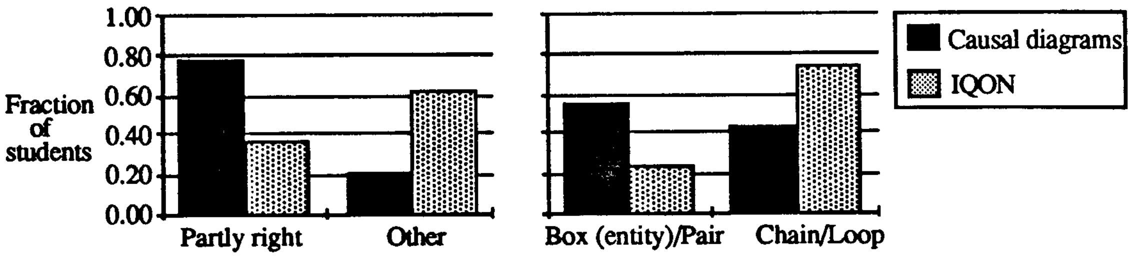


Chart 10. 1 - Correctness of explanation and reasoning followed, according to kind of treatment used - explanations for effects on the energy radiated of making the temperature increase, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

The same chart shows that students who worked with IQON when explaining tended to follow chains of boxes or loops (p = 0. 06 - Fisher).

A place effect was found for the use of causally articulated links. A significantly larger fraction of causally articulated links was given by North London students (p = 0. 02 - Fisher), who worked with causal diagrams (see table 10. 14).

C. D.

f	North	South East	TOTAL
< *0.5*	0	7	7
≥*0.5*	6	5	11
TOTAL	6	12	18

Table 10. 14 - Effect of place for fraction *f* of causally articulated links. Explanations for effects on the energy radiated of making the temperature increase, for understanding a causal diagram for the Greenhouse Effect.

For this case background and place of school are not related and because of that background is not an alternative explanation. The same was true for the place effect found for mechanisms, for students who worked with causal diagrams (in table 10. 13). Unfortunately I do not have a good explanation to account for these place effects.

No other effects were found.

Questions *d* , *e* and *f* asked about the student's opinion of the model.

10. 7. 4. 4. d) Explain in your own words how the model tries to show how "global warming" can happen

Answers were classified according to two main trends:

specific - the ones where the student made clear that the main things responsible for global warming were at least one, or a combination, of the following variables - land clearance and amount of industries and vehicles.

non-specific - the ones where the student did not specify particular variables as being responsible, and gave a kind of general description.

These trends correspond to different levels of perception of the model.

Examples of these kinds of answers are, respectively,

> "the causal diagrams show that the main causes of global warming are land clearance and industry and vehicles. If both of these causes were reduced, the effects of global warming would also decrease " (JOA)

and

> " the model shows how various changes in the environment can affect other aspects. It shows the chain reactions caused by various ecological changes. The model then shows what the actual effects are by showing the increase/decrease in temperature". (ROS)

Table 10. 15 shows that a little over half the students gave specific answers.

Kind of answer	IQON	C. D.	TOTAL
Specific	3	16	19
Non-specific	13	2	15
Number of students	16	18	34

Table 10. 15 - Specific and non-specific answers for explaining in their own words how the model tries to show how "global warming" can happen, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

The table shows that roughly the other half gave non-specific answers.

Kinds of answer and treatment are related (p = 0. 0001 - Fisher).
Chart 10. 2 shows that non-specific answers were given by the majority of students who worked with IQON.

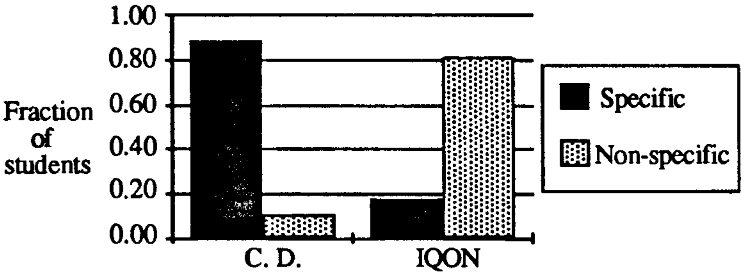


Chart 10. 2 - Specific and non-specific answers according to kind of treatment used for explaining in their own words how the model tries to show how "global warming" can happen , for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Students who worked with the causal diagram had to make the simulation in their own minds and, maybe, due to that, were sure that global warming was caused by specific variables that they had to mentally alter. On the other hand, students who worked with IQON, having seen the model running and showing the effects on several boxes on the screen, preferred to give a non-specific description to account for the complexity of the

situation. These results suggest that students who worked with IQON had more problems in expressing in their own words their understanding of a complex model.
No significant differences were found for place of school and background.

10. 7. 4. 5. e) In what ways do you think the model is accurate?

Table 10. 16 shows the main kinds of answer given for question *e*.

Kinds of answer	IQON	C. D.	TOTAL
Focus on *clear* variables of the model	11	8	19
Gives a *vague* description of model's structure	1	7	8
Model shows changes in output of variables	3	0	3
If we take each part separately not as a whole	0	1	1
If one can understand signs	0	1	1
Rise in one does not cause rise in other	1	0	1
It is not accurate in any way	0	1	1
Number of students	16	18	34

Table 10. 16 - Kinds of answers for ways in which students think the model is accurate, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Students in general considered variables and links and correct structure as the main factors to judge a model as accurate. For them, the model is accurate if it describes reality well. However, it was possible to differentiate two main kinds of explanations given to justify accuracy - one, where the student considered *clear* variables (land clearance, fuel burnt and amount of CO2) as responsible for effects on temperature and, the other, where the student did not consider any variable and gave a *vague* description of the model's structure. Example of the first kind of explanation, focussing on variables, is

> " The diagram is accurate, because it shows how land clearance and burning fuel increase carbon dioxide and how that increase affects the temperature and the sea level, it all links together ". (MAR)

Examples of the second kind of explanation, giving a *vague* description of the model's structure, are

> "It is accurate in that no one part of it is able to be taken out, decreased or increased without a significant effect on the other parts. A complicated two way chain reaction ". (STU)
> "It has many different factors which may affect the temperature of the Earth ". (ROSA)
> "It shows the effect of each stage of the global warming process and gives positive and negative effects in relation to the interaction of the different factors". (TON)
> "In general the causal diagram is fairly explanatory; it shows us the basic effects of global warming and what dangers it can cause when certain parts increase or decrease". (BRU)

Table 10. 16 shows that the majority of the students was divided between answers focussing on *clear* variables (19) and giving a *vague* description of the model's structure (8).

For the purpose of finding effects, answers were grouped as *clear*, *vague* and *others*. For students who worked with causal diagrams, place of school and kinds of answers are related (p = 0. 01 - Fisher).

	North	South East	TOTAL
Clear and others	1	10	11
Vague	5	2	7
TOTAL	6	12	18

Table 10. 17 - Effect of place of school, for ways in which students think the causal diagram for the Greenhouse Effect is accurate.

Table 10. 17 suggests that a significantly larger fraction of North London students, who worked with causal diagrams, gave *vague* answers. This may indicate that the idea of accuracy of a causal diagram did not make much sense for them. Maybe because they did not know what to write, they gave a *vague* answer. There is also some evidence from observation that some students who worked with causal diagrams could not understand what was meant by "accurate" in that context.

As in section 10. 7. 4. 3, background is not related to place of school (for causal diagrams) and I do not have a good explanation to account for this place effect.

No other significant differences were found.

10. 7. 4. 6. f) In what ways do you think the model is not good enough?

Table 10. 18 shows the main kinds of answer given for question *f*.

Kinds of answer	IQON	C. D.	TOTAL
Model is limited	7	3	10
Quantitative aspect is missing	2	7	9
Model is difficult to understand	0	6	6
Model is good enough	3	0	3
We have to rely on Scientists	2	0	2
Model should work in reverse	1	0	1
The model as a whole is not good	0	1	1
Can' t think	1	0	1
Does not make sense	0	1	1
Number of students	16	18	34

Table 10. 18 - Kinds of answers for ways in which students think the model is not good enough, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

An example of the most frequent kind of answers, for the causal diagram being limited is

> " it only concentrates on two causes of the Greenhouse Effect, when many things contribute to it. So in this respect it is over simplified ". (JOA)

For the quantitative aspect being missing, for the causal diagram, an example is

> " it doesn' t show whether the relationships between each of the factors are equal. It may need a lot of land clearance increase to cause the same amount of CO2 increase which only needs a small amount of industry and vehicles increase ". (ROSA)

In this category were put together answers where students explicitly wrote that numbers were missing (5), and the ones were they complained that the weights of the effects should be specified (4).

For the model being difficult to understand, for the causal diagram, an example is

> " It is accurate in the sense that if one can understand the positive and negative signs, it is OK but it is confusing. Common sense and background knowledge is used ". (ANK)

Table 10. 18 shows that the majority of the students were divided amongst answers which considered the model limited (10), that the quantitative aspect was missing (9) and that the model was difficult to understand (6). For the purpose of finding effects answers were grouped as *model is limited*, *quantitative aspect is missing*, *difficult to understand* and *others*.

Kinds of answers and treatment are related (p = 0. 01 - Fisher).

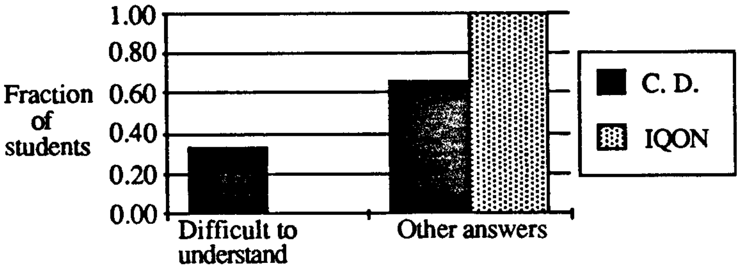


Chart 10. 3 - "Difficult to understand" and "other answers" according to treatment. Ways in which students think the model is not good enough, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Chart 10. 3 shows that, independently of age, place of school, background and gender, a significantly larger fraction of students who found the model difficult to understand, worked with causal diagrams. Students who worked with IQON tended <u>not</u> to find the IQON model difficult to understand.

Some noticeable effects of treatment and place of school were found.

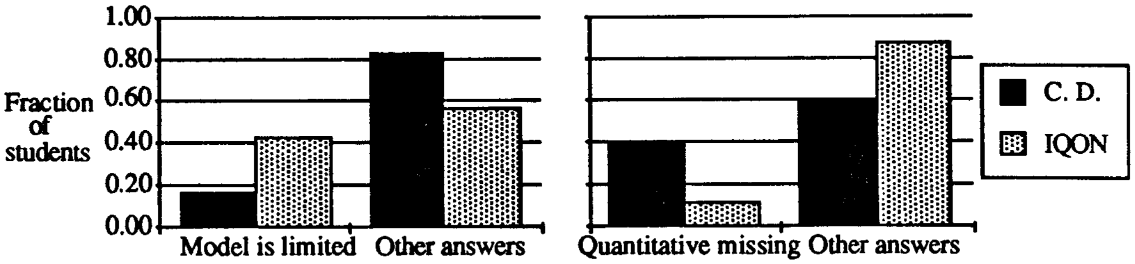


Chart 10. 4 - Kinds of answers according to treatment. Ways students think the model is not good enough, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Chart 10. 4 shows that a noticeably larger fraction of students who worked with IQON tended to consider the model limited (p = 0. 09 - Fisher). A noticeably larger fraction of students who worked with causal diagrams tended to consider that the quantitative aspect was missing (p = 0. 09 - Fisher). These results might mean that students who worked with IQON were more capable of criticising the model and did not feel so uncomfortable about the fact that IQON does not use numbers.

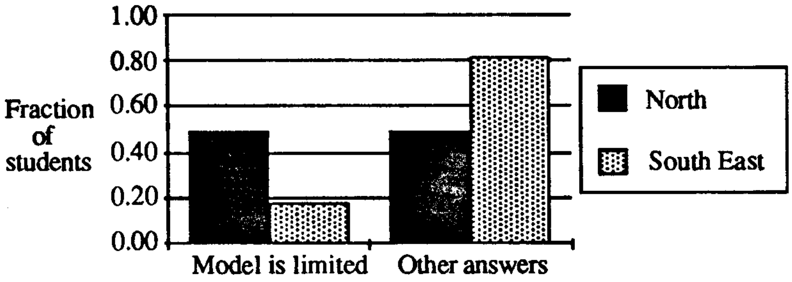


Chart 10. 5 - Kinds of answers according to place of school. Ways students think the model is not good enough, for the Greenhouse Effect exploratory task with IQON and understanding a causal diagram.

Chart 10. 5 shows that a noticeably larger fraction of students who considered the model limited were from North London (p = 0. 06 - Fisher).

To explore this place effect further a two-way ANOVA was carried out on this data, and a complex pattern emerged (see table 10. 19). The table shows that the main factor is gender, however there is a place effect and a place-gender interaction. This may mean that male North London students tended to consider the model limited. It may be interesting to note that gender effects were found before.

Source	df	Sum Sqr	Mean Sqr	F - test	**P value**
Place of school	1	0. 742	0. 742	4. 505	0. 0422
Gender	1	0. 840	0. 840	5. 105	**0.0313**
Interaction	1	0. 742	0. 742	4. 505	0. 0422
Error	30	4. 938	0. 165		

Table 10. 19 - ANOVA table for kinds of answers.

Background definitely is not an alternative explanation. No significant effect was found for age.

10. 8. EXPERIMENTAL RESULTS CONCERNING AN EXPRESSIVE TASK USING IQON AND THE DRAWING OF A CAUSAL DIAGRAM

In chapter 6, sections 6. 4 and 6. 5, the expressive task with IQON and the work with causal diagrams were presented. For both tasks students were given a text to read and asked to model the situation using IQON or causal diagrams (see text "Barnet fights a losing rat war" in Appendix II. 1 and II. 2).

A document with causal diagrams and IQON models developed by pairs of students is available on request.

Links were classified following the criteria used in section 8. 10, in chapter 8.

10. 8. 1. EXPECTATIONS FROM TEACHERS

As for the Greenhouse Effect, four out of five teachers considered this situation as fairly easy for VI form students to think about.

10. 8. 2. KINDS OF LINKS USED

The models developed by the pairs were composed predominantly of reasonable links. Unlike the exploratory tasks (see previous sections) and Physics related tasks (see chapter 8), this result suggests that students in general did not have problems with causal thinking for this system.

Table 10. 20 shows the number of kinds of links used by 17 pairs of students who worked with IQON and causal diagrams.

Kinds of links used	IQON	C. D.	TOTAL
Variable-ized	30	2	32
Partly variable-ized	18	37	55
Non-variable-ized	5	31	36
Number of links	53	70	123

Table 10. 20 - Number of kinds of links used - Expressive task using IQON and the drawing of a causal diagram.

Chart 10. 6 shows the corresponding percentages for each kind of link.

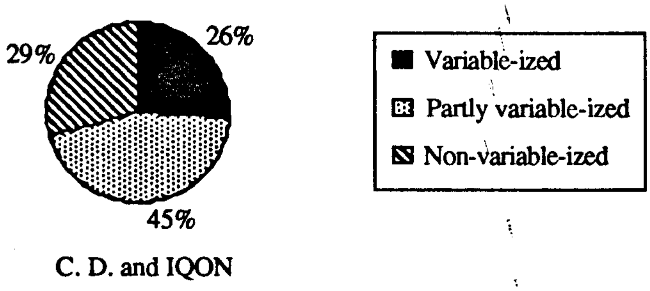


Chart 10. 6 - Percentage of kinds of links used - Expressive task using IQON and the drawing of a causal diagram.

Only about a third of the links were variable-ized.

The only kind of variable-ized link found was *amount* --> *amount* (with 32 cases), which indicates that, for this situation, students who thought in a variable-ized way, conceived boxes as always representing an amount of something. The most frequent kinds of links that followed were the partly variable-ized ones

amount <--> *event /process* (26) and

amount <--> *object* (24).

Kinds of links used and treatment are related ($\chi^2 = 42.5$, 1df).

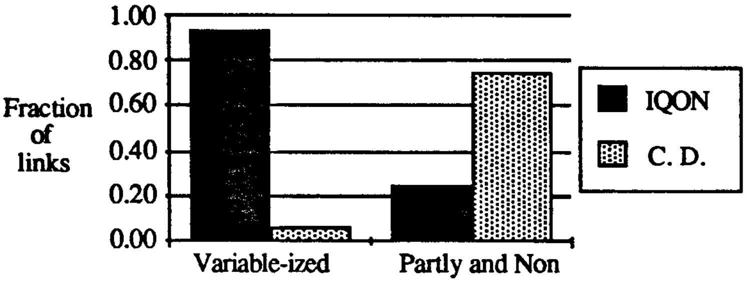


Chart 10. 7 - Kinds of links used and treatment - Expressive task using IQON.

Chart 10. 7 shows that IQON models presented a significantly larger fraction of variable-ized links. This result suggests that maybe IQON helped students to think of entities as variables. On the other hand, students who worked with causal diagrams could not go as far as amounts.

No effects of background and place of school were found for IQON and causal diagrams, separately.

10. 8. 3. STRUCTURE OF THE MODEL

Models were classified, as shown in table 10. 21, according to the structure presented.

Structure of model	nº of pairs	fraction
Two feedback loops	4	0. 23
One feedback loop	3	0. 18
At least one chain	6	0. 35
Mainly star	4	0. 24
TOTAL	17	1. 00

Table 10. 21 - Structure of the diagrams - Expressive task using IQON and the drawing of a causal diagram.

Seven pairs developed a complex structure with at least one feedback loop. The others (10) developed a star shaped diagram or model composed of at least one chain of four entities. Roughly half of the pairs were classified as thinking at system level.

There is a weak relation between the structure of the diagram and treatment (p = 0. 12 - Fisher).

Table 10. 22 shows that maybe students who worked with IQON tended to construct more elaborate models (with loops) than those who worked with causal diagrams (star and chain). There is some indication that IQON, due to its runnability, puts the students in a better position. Being able to run the model and check its behaviour, the student can improve it gradually, getting better developed structures. Students who worked with IQON produced thinking at system level, since they managed the loops.

Structure of model	IQON	C. D.
STAR AND CHAIN	3	7
LOOP	5	2
Number of pairs	8	9

Table 10. 22 - Structure of the diagrams and treatment - Expressive task using IQON and the drawing of a causal diagram.

No significant differences were found for place of school and background, for IQON and causal diagrams, separately.

10. 9. ANSWERING THE RESEARCH QUESTIONS

10. 9. 1. HOW WELL DOES THE STUDENT USE THE CAUSAL DIAGRAM OR IQON MODEL WHEN MAKING PREDICTIONS ?

In general students seemed to understand the IQON model for the Greenhouse Effect well. They made correct predictions for items about the effect on one parameter of setting others at high or low levels. When predicting, they seemed to reason following chained interactions. Few gave evidence of thinking at a system level and outside the computation. Some students when working with causal diagrams were less good.

10. 9. 2. HOW DO ANSWERS FOR QUESTIONS INVOLVING A CAUSAL DIAGRAM DIFFER FROM ANSWERS GIVEN FOR THE SAME QUESTIONS INVOLVING AN IQON MODEL ?

In general, there was a clear disadvantage concerning the use of causal diagrams. Students who used causal diagrams had doubts about links and predicted wrongly. They found the diagram difficult to understand and could not generate the correct dynamic behaviour. For exploratory tasks, they gave partly right descriptions and considered only isolated entities and pairs in their explanations. They criticised the diagram because it missed numbers. They seemed to have presented a lower level of criticism of the model. The idea of accuracy of causal diagrams did not make much sense for them, since they tended to give a 'vague' description of the model's structure (see 10. 9. 6).

Students who worked with IQON did not feel so uncomfortable about the fact that IQON does not use numbers. For exploratory tasks they tended to give correct descriptions and followed a chain/loop in their explanations. Also, they tended not to consider the

Greenhouse Effect model difficult to understand and considered it limited. Nonetheless, students who worked with IQON when explaining in their own words (see 10. 9. 5) tended to give non-specific descriptions, which may indicate that they had problems in understanding a complex model.

10. 9. 3. WHAT CAN BE SAID ABOUT THE ENTITIES USED AND THE FINAL STRUCTURE OF CAUSAL DIAGRAMS AND IQON MODELS FOR A CURRENT ISSUE?

The majority of the links were composed of at least one variable, which may indicate a reasonable level of achievement. Roughly, half of the pairs could develop a feedback structure.

10. 9. 4. HOW DO CAUSAL DIAGRAMS AND IQON MODELS DIFFER FOR THE EXPRESSIVE TASK ABOUT A CURRENT ISSUE ?

Unlike causal diagrams, IQON seemed to have helped students to think in a variable-ized way and to develop more elaborate structures.

10. 9. 5. HOW DOES THE STUDENT EXPLAIN IN HIS/HER OWN WORDS WHAT THE CAUSAL DIAGRAM OR IQON MODEL IS DESCRIBING ?

Students gave answers which suggested that there were two different levels of perception of the model. Half considered the main responsible for global warming at least one, or a combination, of specific variables. The other half gave non-specific answers where the student did <u>not</u> specify those variables as responsible, giving a general description. Students who worked with IQON tended to give non-specific descriptions, which may indicate that they had problems in explaining in their own words a complex model (see 10. 9. 2).

10. 9. 6. HOW DOES THE STUDENT CRITICISE CAUSAL DIAGRAMS OR IQON MODELS ?

Concerning <u>accuracy</u>, for the Greenhouse Effect exploratory task with IQON and understanding a casual diagram, the majority of the students were divided between answers focussing on 'clear' variables and giving a 'vague' description of the model's structure. Students who worked with causal diagrams tended to give 'vague' descriptions (see 10. 9. 2).

Concerning <u>criticisms</u>, the main ones were:
- model is limited;
- quantitative aspect is missing and
- model is difficult to understand (for causal diagrams only).

About half of the students could reach a reasonable level of criticism of the model or causal diagram.

10. 9. 7. HOW WELL DOES THE STUDENT MANAGE AN EXPLORATORY TASK (GREENHOUSE EFFECT) USING CAUSAL DIAGRAM OR IQON?

Teachers in general considered the causal diagram for the Greenhouse Effect fairly easy for sixth form students to think about. Despite that, results suggest that students in general seemed to give unsuccessful explanations mainly concerning the number of mechanisms given, the use of entities of real system, and causally articulated links. These results suggest that the causal thinking in these tasks was difficult. Students tended not to see the situation as a system and mechanisms in general were concerned with actions on/of CO2 and Energy radiated.

10. 9. 8. WHAT CAN BE SAID ABOUT HOW THE IQON FORMALISM CONSTRAINS, OR NOT, THE WAY A STUDENT THINKS ABOUT SYSTEMS AND VARIABLES?

The majority of the links used by students involved at least one variable. The only kind of variable-ized link found was *amount* --> *amount*, which indicates that, for this situation, students who thought in a variable-ized way, conceived boxes as always representing an amount of something.

IQON seemed to have helped students to think in a variable-ized way and to develop more elaborate structures. It seems that IQON gives a more malleable environment for constructing causal diagrams.

10. 9. 9. OTHER INTERESTING EFFECTS

North London students who worked with causal diagrams:

- gave mechanisms (for effect on the energy radiated of making the temperature increase);
- gave causally articulated links (in the same task) but
- gave 'vague' answers for accuracy.

Male North London students tended to consider the model limited.

Also, mechanisms were given by 16 year old students (for effect on temperature of making amount of industries and vehicles high) and male students (for effect on temperature of making amount of industries and vehicles high and making the land clearance low).

Females used only entities of the model (for effect on the energy radiated of making the temperature increase). A larger fraction of Males used entities of the real system. These seemed to be genuine gender effects.

North London 16 year old students who worked with IQON:

- used causally articulated links (for effect on temperature of making the land clearance low);
- made generalisations (for effect on the energy radiated of making the temperature increase) and
- gave focussed descriptions (for the same task).

Since background is related to age and place of school, for the work with IQON, it may be accounting for these effects. However the numbers are too small to be absolutely sure.

CHAPTER 11 - WORK WITH STELLA - EXPERIMENTAL RESULTS

11. 1. HOW GOOD IS THE STUDENTS' UNDERSTANDING OF STELLA MODELS ?

This chapter presents an analysis for students of the intensive study (listed in table 10. 1, chapter 10) of the work with exploratory and expressive tasks using STELLA.

11. 1. 1. A) WHAT HAPPENS TO THE LEVEL OF AN INTERMEDIATE TANK? WHY?

Students were first given a STELLA model for the two tanks system to explore (see figure 7. 5, in chapter 7, section 7. 3). After running the model students were asked three questions. This section is concerned with the analysis of the written answers about what happens to the level in a second tank when the first drains in to it, but it also drains. Following the framework presented in chapter 10, answers were analyzed in terms of the status of the description, if qualitative or semi-quantitative, the kind of mechanism used by the students, the kind of entities used in explanation and the relation to reality of reasoning when exploring the model.

Table 11. 1 shows numbers and fractions of students for status of description, kind of mechanism and relation to reality (problem of modelling metaphor).

	nº stud.	fraction
Status of description:		
Qualitative ("rises and falls")	23	0.70
Semi-quantitative (say how)	8	0.24
Does not explain	2	0.06
Kind of mechanism:		
Complete simultaneous action	5	0.15
Incomplete simultaneous action	8	0.24
Separated action	6	0.18
Partial action of entity 1	8	0.24
Partial action of entity 2	5	0.15
Unsuitable/no	1	0.03
Modelling metaphor:		
Interpret literally (reality)	7	0.21
Does not (model)	26	0.79
Total of students	33	1.00

Table 11. 1 - Status of description, kind of mechanism and relation to reality - 'What happens to the level of the second tank?'.

The majority of students gave a qualitative description, only stating that the level of water "increases and decreases". Only 8 students gave a semi-quantitative description stating for example that "the level increases rapidly and then slowly decreases ".

It may be interesting to note that despite the fact that the models were quantitative answers were predominantly qualitative and semi-quantitative. Maybe semi-quantitative (or qualitative) reasoning (see chapter 9) is natural even in quantitative tasks. There will be other cases to support this.

11. 1. 1. 1. Kinds of mechanisms identified

The following kinds of mechanism were identified:

- complete simultaneous action;
- incomplete simultaneous action;
- separated action;
- partial action of entity 1;
- partial action of entity 2 and
- unsuitable/no mechanism.

The category *complete simultaneous action* describes cases where the student described the reason why the level first increases and then decreases. In this case the student points out the simultaneous action of the input and output rates. An example of this kind of mechanism is

> "dh1/dt of first tank is, initially, high compared to dh2/dt and so h2 rises. After a certain time dh1/dt decreases and dh2/dt increases until they are equal, the maximum h2. After this dh2/dt is greater than dh1/dt and so level of h2 slowly decreases". (TUO)

An example of an explanation giving a mechanism classified as *incomplete simultaneous action* is:

> "The 1st tank's volume decreases. The 2nd tank's volume increases but it's rate of output is slower than 1st tank. It fills up to a certain height". (ANK)

In this case the student explains only why the level increases, recognizing the simultaneous action of the rates of input and output. However he does not explain the decreasing in the level of water, giving an incomplete description.

A *separated action* means that the student considers that the level increases because of an action due to tank 1(or related entity) and that the level decreases due to an action on tank 2 (or related entity). For example

> "The level increases because it is being filled from tank 1. It then decreases because it is being drained from tank 2".(PAO)

A *partial action of entities 1 or 2* describes the cases where the student considers only what happens to tank 1 (or related entity) or tank 2 (or related entity). An example of a partial action on the second tank is

> "The reason for this is that there is another outlet releasing water from the second tank". (BRU)

I hypothesize that students who considered in their explanation any kind of simultaneous action saw the situation as a system of interacting entities (systemic view of the situation), and that students who considered separated and partial action, or gave an unsuitable/no mechanism, did not.

The main mechanisms identified were *incomplete simultaneous action* (8 students) and *partial action of entity 1* (8 students), but there is an almost equal distribution of students for each kind of mechanism.

Only 13 students can be thought of as seeing the situation as a system of interacting entities, whilst 20 did not. This result seems to agree with the one for explaining a leaky tank (section 8. 6) where students tended not to see the situation at a system level. Also, students in general tended not to think at a system level in questions related to Physics (see chapter 8). Difficulties in system thinking are also reported in section 10. 7. 4. 3 concerning the explanation of feedback. System thinking involves causal thinking and, consequently, these results add to the evidence that students' causal thinking in general was unsatisfactory.

Chart 11. 1 shows the distribution of students according to the way they saw the situation and according to background.

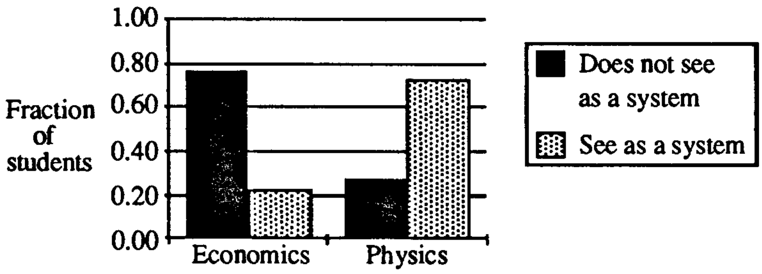


Chart 11. 1 - Systemic view and background - 'What happens to the level of the second tank?'.

Systemic view and background are related (χ^2 = 7.679, 1df). It was thus students with some background in Physics who more often described the situation as a system of interacting entities, showing a higher level of perception of the situation (see section 8. 6). Notice that some results in chapter 10 pointed out an advantage to students with a background in Physics. This result adds a little further to the evidence that background matters.

11. 1. 1. 2. Entities used in explanation

	nº stud.	fraction
Entities in explanation:		
rate1	10	0.30
rate2	8	0.24
level1	5	0.15
level2	13	0.39
drainage level	5	0.15
pressure	4	0.12
water	18	0.55
tank1	15	0.46
tank2	14	0.42
hole/tap	2	0.06
Total of students	33	1.00

Table 11. 2 - Entities used in explanation - 'What happens to the level of the second tank?'.

The articulation of variables in explanations may indicate whether the student was able to imagine the world in terms of variables.

Table 11. 2 shows a complete list of the entities that students used in explanations. These entities can be classified as variables (rates, levels and pressure) and objects (water, tanks and hole).

The objects water, tank 1 and tank 2 were the entities most used in explanations, and level 2 and rate 1 were the variables most used. However, students used larger fractions of objects than variables in explanations, and about a third used rates. These results are in accordance with those found in "explaining a physical system" in chapter 8, section 8. 6, where students tended not to use variables in explanations. Also, they seem to agree somehow with results in the survey, where students tended to use objects as entities in causal diagrams (see, for example, section 8. 10).

Chart 11. 2 shows the number of variables used according to the student's background.

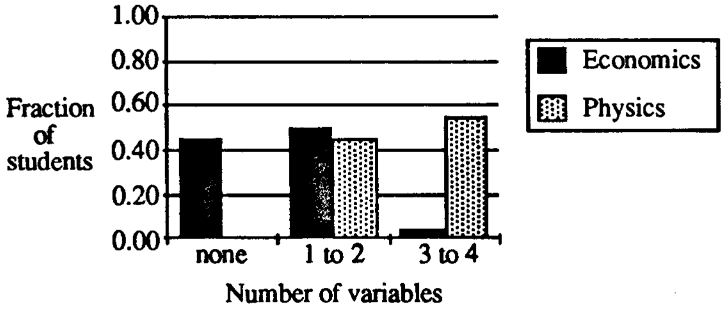


Chart 11. 2 - Number of variables used according to the student's background.

Students with some background in Physics were those responsible for a significantly larger fraction of variables in explanations (p = 0. 007 - Fisher, considering only two categories: "none" and "at least one variable"). This result supports the view that background matters.

No significant differences were found for treatment, gender, age and place of school.

11. 1. 1. 3. Problem of STELLA metaphor

Seven students (3 doing Physics and 4 Economics) when playing with the model were worried about what happened to the water when it reached the level of the pipe drainage which appeared to be shown on the screen. Unlike the others, they were thinking outside or beyond the computation or model, interpreting the screen simulation more literally than is intended in STELLA.

11. 1. 2. B) WHAT HAPPENS IF YOU INCREASE THE RATE OF FLOW OUT OF THE TANK? WHY?

Question b asked the students to increase k2 which governed the rate of flow out of the tank and write what happened to the model.

	nº stud.	fraction
Kind of mechanism:		
Complete simultaneous action	3	0.09
Separated action	8	0.24
Partial action of entity 2	22	0.67
Entities in explanation:		
rate of change	9	0.27
flow of water	2	0.06
level/amount of water	4	0.12
pressure	1	0.03
rate and level	7	0.21
rate and pressure	3	0.09
nothing	7	0.21
Total of students	33	1.00

Table 11. 3 - Kinds of mechanisms and entities in explanation - ' What happens if you increase k2?'.

11. 1. 2. 1. Kinds of mechanisms identified

Answers were classified according to a specific kind of mechanism used, as shown in table 11. 3. The most common kind of mechanism was related only to the action on the rate of the second tank. This result agrees with the one in section 11. 1. 1. 1 and adds a little further to the impression that students had difficulties with causal thinking and in thinking at a system level. Examples of explanations giving a mechanism classified as *partial action of entity 2* are

> " the water will leave h2 quicker.
> k2 is the rate of change and if its increased the rate at which the water will leave h2 will be faster" (ELI)
>
> and
>
> " the water level in tank 2 doesn't go as high and the whole process is speeded.

> Because the higher the constant the higher the rate of change (0.5*h2 < 2*h2)". (ROSA)

In these cases the students focussed only on the increase of the rate of change as being responsible for the water leaving the second tank faster.

An example of an explanation giving a mechanism classified as *complete simultaneous action* was

> "The 2nd tank doesn't fill up as far and then it empties.
> The rate of flow from the 2nd tank increases. So the water will flow from the 1st to the 2nd tank when the rate of flow in the 1st is high. Gradually, the rates become equal and then the 2nd, faster than the 1st, so the 2nd tank will then empty more quickly than the first ". (COLE)

COLE considered that, even though the rate of the second tank has changed, the final behaviour was determined by both rates acting simultaneously.

Example of an explanation giving a mechanism classified as *separated action* is

> " If k2 is increased then the level in tank two decreases at faster rate, the peak level is smaller than when k1 was smaller.
> This occurs because the water entering h2 leaves at a much quicker rate therefore, the level starts to go down quicker which means that the water from h1 does not accumulate as much". (SIM)

SIM recognises that the change in k_2 made the level of tank two decrease at faster rate. However, he describes what happens to tank 1 as well, but not connecting the final behaviour to a simultaneous action of both rates.

Kinds of mechanisms used are not related to treatment, background, age and place of school.

11. 1. 2. 2. Variables used in explanations

Table 11. 3 also shows the entities used in explanations. There is a substantial number of students (9) who used only the rate of change in their explanations. Seven considered rate of change and level of water, three rate of change and pressure of water and two the flow of water. Thus 12 students did not involve the rate of change in their explanations, despite their previous work with STELLA. Of these, 7 did not use level of water or pressure, in their explanations. They considered only time or the objects tank, water and hole. Only RIC considered the variable pressure in his explanation, and four considered the level of water.

Chart 11. 3 shows the use of rates according to the place of school, background, gender and age.

Use of rate and place of school (p = 0. 002 - Fisher), background (p = 0.02 - Fisher), gender (p = 0. 01 - Fisher) and age (p = 0. 02 - Fisher, considering 17 and 18 as one only category) are related. Use of rate and treatment are not related.

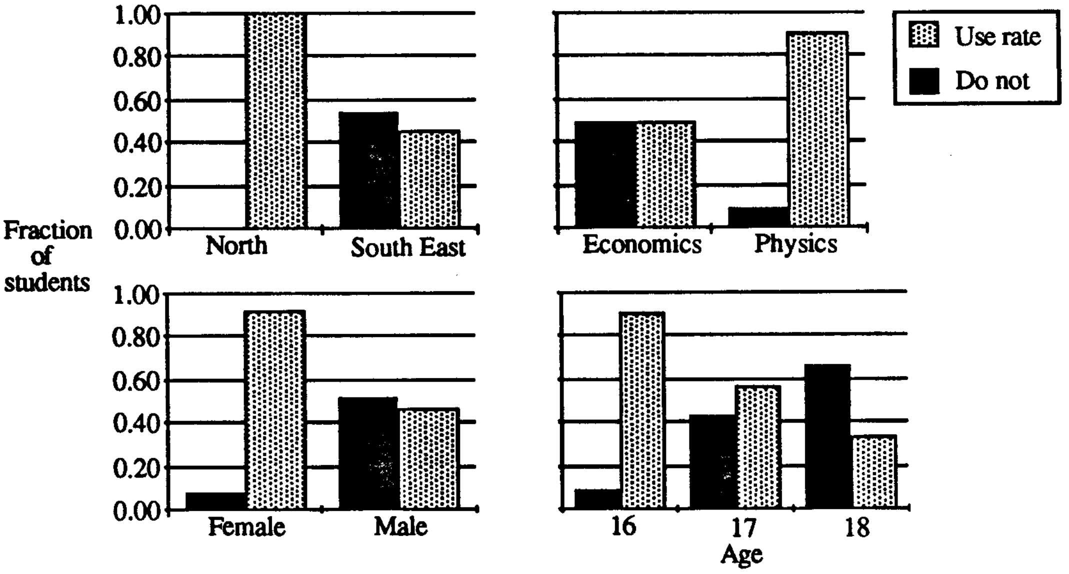


Chart 11. 3 - Use of rate in explanation according to the place of school, background, gender and age - 'What happens if you increase k2 ?'.

In general students used rates in their explanation. However, older male Economics students from South East London, tended not to use rates in their explanations.

Rates were used in explanations by:

- all North London students;
- almost all Physics students, and about half of the Economics students;
- almost all female students, and about half of the male students;
- almost all 16 year olds.

Older students tended to use rates less in their explanations.

These results again support the view that background is important. Like the work with IQON and causal diagrams (see chapter 10) a genuine gender effect was also found. But it may be interesting to note that these effects are in opposite directions. While male students were better in working with causal diagrams, female students seemed to be better when exploring STELLA models. Unfortunately, I do <u>not</u> have a good explanation for this. Like the work with IQON and causal diagrams, place and age effects were also found. A further exploration using two way ANOVAs confirms the existence of these factors and indicates <u>no</u> interaction among them. Also, it points out that the most important factors are place of school and gender, with an advantage to North London and Female students. Unfortunately, I do <u>not</u> have a good explanation for why North London students were better than South East London students.

Use of level/Amount of water and use of Pressure are not related to gender, age, place of school, background and treatment.

11. 1. 3. C) WHAT HAPPENS TO THE LEVEL IN THE THIRD TANK? WHY?

The problem now concerned the addition of a third tank to the two-tank system worked in questions *a* and *b* (see in chapter 7, figure 7. 7). Students had to answer what happened to the level in the third tank.

	nº stud.	fraction
Status of description:		
Qualitative ("it raises")	24	0.73
Semi-quantitative (say how)	7	0.21
Quantitative	1	0.03
Does not explain	1	0.03
Kind of observation:		
Complete	6	0.18
Partial	25	0.76
Not compatible with phenomenon	1	0.03
None	1	0.03
Kind of mechanism:		
Action of water filling tanks	19	0.58
Action of tanks emptying	8	0.24
No tap so it collects water	2	0.06
Unsuitable/no	4	0.12
Entities in explanation:		
rate 2	2	0.06
rate increases level 3	4	0.12
level/amount 1	2	0.06
level/amount 2	3	0.09
level/amount 3	6	0.18
h (not specifying)	1	0.03
pressure	2	0.03
water	18	0.55
tank 1	21	0.64
tank 2	25	0.76
tank 3	25	0.76
tanks (without specifying)	5	0.15
hole	11	0.33
Total of students	33	1.00

Table 11. 4 - Status of description, kind of observation, Kind of mechanism and entities in explanation - ' What happens to the level in the third tank ?'.

Table 11. 4 shows that, in general, for question *c*, students gave qualitative descriptions and made a partial observation of what happened in the model. The most common kind of answer for the behaviour of the level in the third tank was "it rises". One example of a complete semi-quantitative description is

> "it increases rapidly then the rate of increase decreases slightly until it stops".

Qualitative descriptions were in general partial, but there was only one case of a partial semi-quantitative description. This was due to NIC who wrote

> "the 3rd tank increases steadily".

This result adds a little further to the impression that semi-quantitative (or qualitative) reasoning is natural even in quantitative tasks (see section 11. 1. 1).

The most common kind of mechanism found was *action of water filling tanks*, and a typical explanation was

> "the first tank fills the second tank which in turn fills the third tank".

An example of *action of tanks emptying* is

> " this is as h1 empties out into h2 which then empties out all into h3 to fill up the 3rd tank".

This mechanism is very similar to *action of water filling tanks*. The combination of both mechanisms will embody the majority of the students.

The most used entities in explanations were the objects Tank 3, Tank 2 and Tank 1, Water and Hole. Few students used levels and rates. This result is in accordance with the findings for question *a*, and with findings reported in chapter 8. They support the view that imagining the world in terms of variables may be problematic for the student.

Some interesting interactions were found. Status of description is related to place of school (p = 0. 03 - Fisher), gender (p = 0. 04 - Fisher) and background (p = 0. 03 - Fisher).

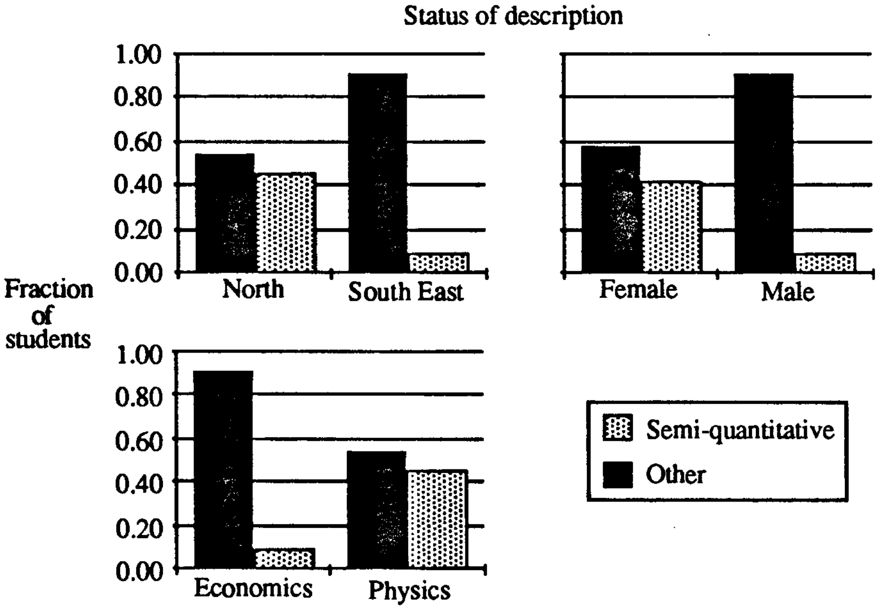


Chart 11. 4 - Status of description for place of school, gender and background - ' What happens to the level in the third tank ?'.

Chart 11. 4 shows that male Economics students from South East London tended to give mainly qualitative descriptions. Semi-quantitative descriptions were given predominantly by:
- about half of the North London students;
- about 0. 40 of the female students and
- by about half of the Physics students.

Status of description is not related to treatment.

Further analysis using two way ANOVAs indicate that the main effects are background and gender, showing no interaction between these factors. These results support the view that background is important and agree with gender effects previously found. Also, these results suggest that semi-quantitative reasoning may depend on gender and background, as well.

Kind of observation is related to place of school and background (p = 0. 05 - Fisher).

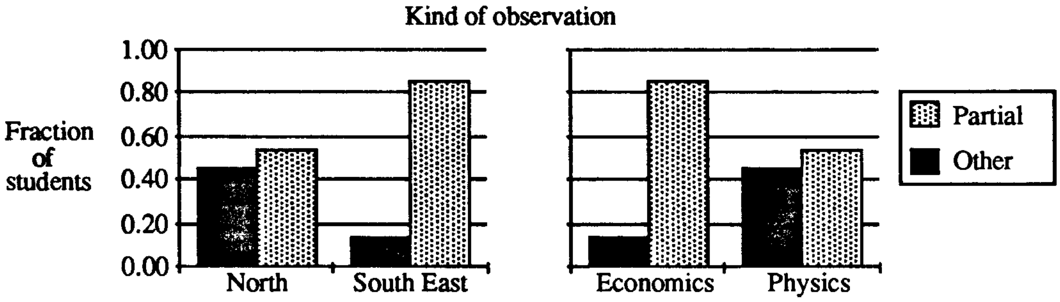


Chart 11. 5 - Kind of observation for place of school and background - ' What happens to the level in the third tank ?'.

Chart 11. 5 shows that partial observations were common mainly amongst Economics students from South East London. "Other" observations were common amongst about half of Physics students and students from North London. This result lends further support to the view that background is important.

Kind of observation is not related to treatment.

No significant differences were found for kinds of mechanism and entities used.

11. 2. HOW DOES THE STUDENT EXPLORE A MORE ELABORATE MODEL IN STELLA?

Students were given a complex hypothetical model for two cars in a stream of traffic to explore (see figure 7. 9, in chapter 7, section 7. 5) Four general questions about the model were asked.

11. 2. 1. WHAT HAPPENS WHEN THE MODEL IS RUN?

Chart 11. 6 shows the fraction of students in the intensive study who, after playing with the "two cars" model, gave different kinds of explanations for the question "what happens when the model is run?". Different explanations were classified according to status and kind of description, kind of observation, relation to reality and correctness (see in chapter 10 the framework for the analysis).

Semi-quantitative here must be understood as opposed to quantitative. The answers were long, and it was difficult to differentiate semi-quantitative and qualitative descriptions. In this question the distinction was collapsed.

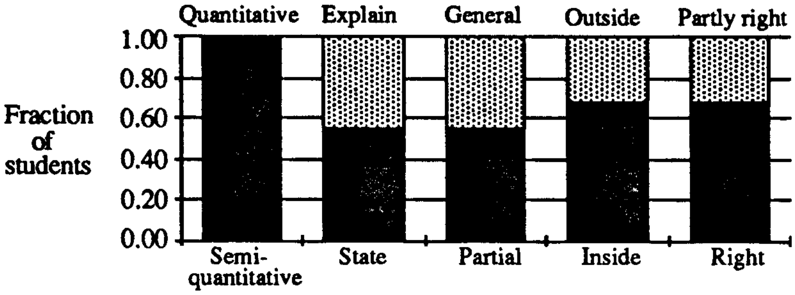


Chart 11. 6 - Characterization of explanations given 'what happens when the model is run?'.

Students, in general, gave correct semi-quantitative descriptions of the situation, in the terms of the computation, just stating without explaining their partial observation (e.g. "if d_b increases v_f will increase"). These results support the view that semi-quantitative reasoning is natural even in quantitative tasks and that relating model to reality is problematic. Also, they suggest that explanations were often unsatisfactory, derived from partial observation.

About a third gave partly right descriptions, referred to events or objects outside the computation, and explained a general pattern (e.g. "there is oscillation").

An example of a correct description, outside the computation, where there is a kind of generalisation, is

> "when the model is run the cars seem to attempt to catch each other up (distance) but then the front car would pull away. This leads on to something similar again - much like a 'cat and mouse' battle". (MARC)

MARC uses a 'cat and mouse' battle as a very concrete analogy for generalising what happens in the model. Also when articulating this analogy he was thinking outside the computation or model.

An example of a correct partial description, inside the computation is

> "when the model is run the distance behind increases, and the velocity of the following car increases as well. When the distance decreases, the velocity carries on increasing for a while, and then starts to decrease ". (NWA)

NWA just described what he saw happen on the screen. He described what happened to variables of the model in a limited running time interval and did not generalise the pattern. Significant difference was found concerning background.

C. D.

	Economics	Physics	TOTAL
Partial	4	0	4
General	5	8	13
TOTAL	9	8	17

Table 11. 5 - Kind of observation and background for students who worked with causal diagrams.

Table 11. 5 suggests that a larger fraction of students with background in Physics who worked with causal diagrams was able to generalise the pattern described by the model ($p = 0.\ 05$ - Fisher). This result, like others, is further evidence that background matters.

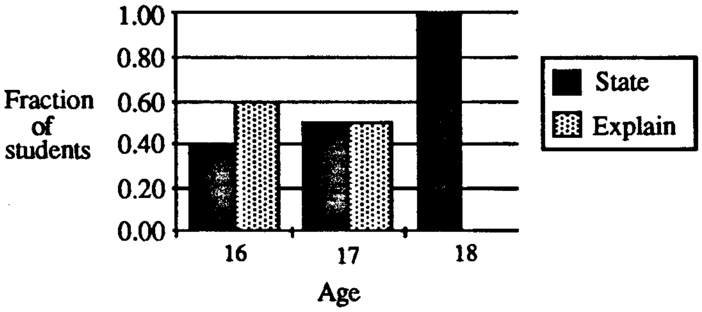


Chart 11. 7 - Age and kind of description.

Chart 11. 7 shows that 0.60 of the 16 y.o (6 students) tended to explain their answers. However, all 18 y.o. (6 students) stated without explaining. The chart shows that older students tended just to state without explaining their answers. As age and background are related, this result might be just reflecting that older Economics students tended to state their answers. This is also further evidence that background matters.

Kind of description and relation to reality are <u>not</u> related to treatment.

11. 2. 2. WHY DOES THE MODEL IN THE COMPUTER BEHAVE THIS WAY?

For question 3, answers were classified as:

- the equations, the *way* the *model is programmed*;
- *model is limited.* It is a very simplified description of reality;
- *function of the model* (e.g. " the computer shows this to give an idea ...".);
- *no* external or *other action* (e.g. " because there is <u>no</u> obstacle to stop the ...".) and
- *action of entities* (e.g. " because of the relative velocity ").

Chart 11. 8 shows the fraction of students for each kind of answer.

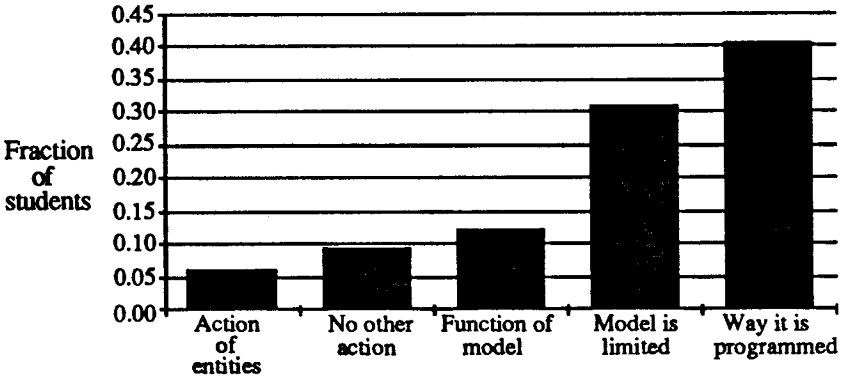


Chart 11. 8 - Kind of answer given for 'why does the model in the computer behave this way?'.

The most frequent kinds of answers were *way it is programmed* with 0. 40 of the students, and *model is limited* with about a third of the students. It may be interesting to note that when judging an IQON model about a third of the students could realise its limitations (see section 10. 7. 4. 6).

An example of the first kind of answer is

> " It was programmed to act in this way. It is simulating a possible situation in reality". (ELI)

Students who gave this kind of explanation seemed not to have reflected very much to answer the item. It seemed the most obvious kind of answer to give.

An example of the second kind of answer is

> " Because the equations do not take into account that a real driver would, after reaching a safe distance, maintain a constant speed and not decelerate". (ANK)

ANK was able to criticise the model arguing that it is limited. For him the equations do <u>not</u> take into account what happens in reality. This explanation is much more elaborate than the previous one.

Function of model, no other action and *action of entities* were the least frequent. Examples are, respectively,

> "the computer <u>shows</u> us this <u>to give an idea</u> about how the mathematics in the car driving is possible to predict", (RIC)

> "the model in the computer has <u>no obstacles</u> in the way and keeps on running over and over" (PET)

and

> " the model behaves this way because the <u>relative velocity acts</u> as a time-lag between the acceleration or deceleration of the following car ". (my emphasis in each case) (SIM)

RIC focussed causation on purpose of the model. He did not answer what was asked. PET clearly confused the model with the real objects. SIM, having a Physics background, gave a very interesting explanation focussing on the relative velocity. Only very few students could give explanations involving action of entities.

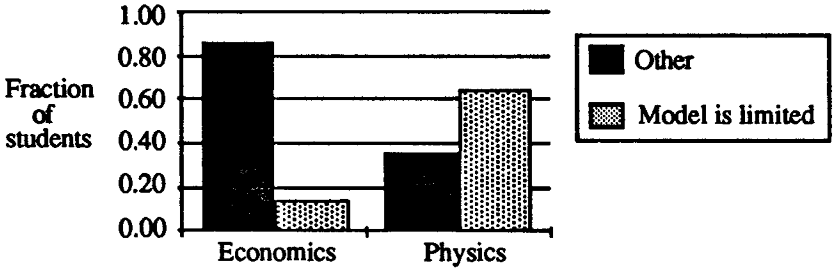


Chart 11.9 - Model is limited and background.

No interactions between gender, age, place of school and kinds of answers were found. However, background and thinking that the model is limited are related (p = 0. 007 - Fisher). Chart 11. 9 shows that a larger fraction of Physics students considered that the model is limited. This result supports the view that background is important.
Kind of answer given and treatment, gender, age and place of school are not related.

11. 3. HOW DOES THE STUDENT RELATE TO REALITY WHAT HAPPENS IN A MODEL?

11. 3. 1. COULD THIS HAPPEN IN REALITY? WHY/WHY NOT ?

Chart 11. 10 shows that , in general, about half of the students wrote that the situation can happen in reality. The majority gave a convincing explanation and all students gave evidence of thinking outside the computation.

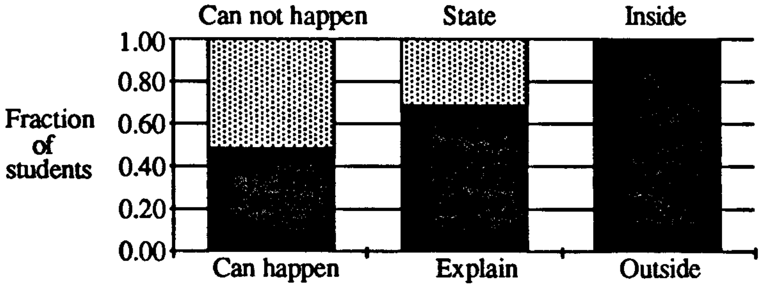


Chart 11. 10 - Kind of answer given, description and relation to reality - 'Could this happen in reality?'.

Example of answer which considered that the situation can not happen is

> " no, because drivers accelerate to get approx. safe distance from leading car and keep a constant speed whereas the program does not keep constant speed and is always decelerating and accelerating ". (ANK)

This explanation argues that the model is limited.

An example of an answer which considered that the situation can happen is

> "yes, the cars could catch each other up and pull away --> such as in everyday life on the roads or motorracing". (MARC)

This explanation just describes the pattern presented in the model.

Chart 11. 11 shows the kinds of arguments used by the students.

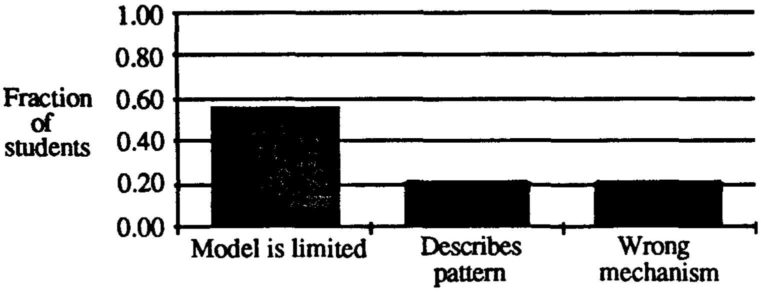


Chart 11. 11 - Kind of argument used when answering 'could this happen in reality?'.

Roughly half of the students used an argument which is concerned with the model's limitation. These students were roughly the ones who considered that the situation could not happen in reality. About a fifth of the students just described the pattern, and the same fraction gave a wrong mechanism.

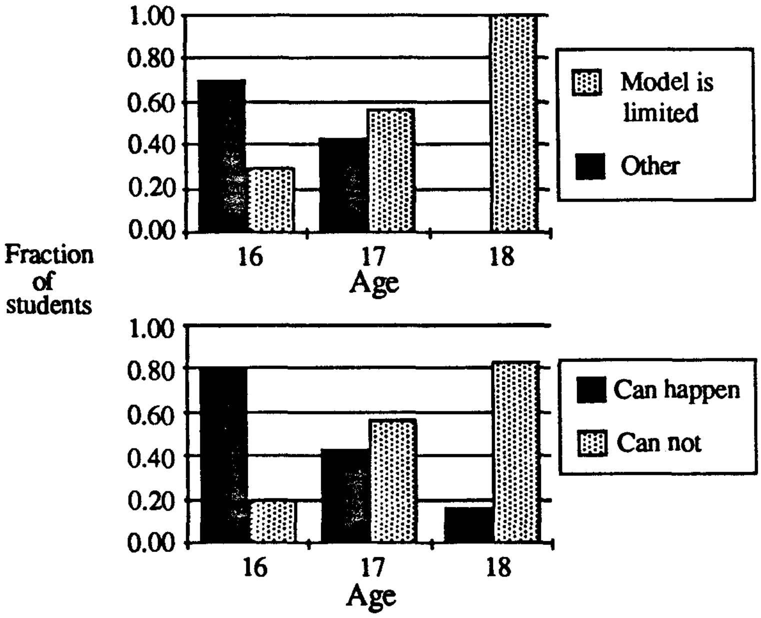


Chart 11. 12 - Kind of argument and age, kind of answer and age.

Kind of argument and age are related (p = 0. 05 - Fisher, considering 17 and 18 as one category).

Chart 11. 12 shows that, unlike 17 and 18 years old, the majority of the 16 years old tended to use other (less good) kinds of argument in place of "model is limited".
Kind of argument is not related to treatment, gender, place of school and background.
The same chart shows that, unlike 17 and 18 years old, the majority of the 16 years old tended to consider that the situation can happen in reality. Older students tended to criticise the model more ($p = 0.03$ - Fisher, considering 17 and 18 as one category), realizing its limitations.
There is no relation between the kind of answer given, treatment, background, gender and place of school.
Kind of description is not related to place of school, background, gender and age.
For these results, background is not an alternative explanation. It may be that older students have more previous experience and because of that were more able to criticise the model.

11. 4. CONCLUSIONS: EXPLORATORY TASKS

11. 4. 1. Systemic view

In general most students did not see the leaky tank case as a system. Only Physics students tended to see the situation as a system.

11. 4. 2. General pattern

Results suggest that there was some advantage for female, Physics, North London students, concerning the use of rates, semi-quantitative descriptions and making generalisations.

11. 4. 2. 1. Use of rates in leaky tank case

In general students tended not to use rates in explanations. Rates were used by 16 year-old, Physics, female and North London students.

11. 4. 2. 2. Generalisations

The majority gave partial descriptions (two cars) for "what happens when the model is run?". The majority of Physics students (two cars) who worked with causal diagrams made generalisations.

11. 4. 2. 3. Semi-quantitative descriptions

In general, for the leaky tanks, despite the fact that the STELLA models used numbers, the answers were qualitative or semi-quantitative. For the "two cars" task, answers for "what happens when the model is run?" were semi-quantitative.
Semi-quantitative descriptions were given by about half of female, Physics and North London students.

Semi-quantitative descriptions were not given by male , Economics and South East London students.

11. 4. 3. Explanations

11. 4. 3. 1. For the leaky tank case

Explanations were often unsatisfactory, derived from partial observation and used only entities inside the computation. In general students tended to use larger fractions of objects than variables in explanations. The ones given by Economics students from South East London were based on partial observation.

The majority of Physics students used a larger number of variables.

11. 4. 3. 2. For the "two cars" case

About half of explanations for "what happens when the model is run?" were unsatisfactory (they just stated) and derived from partial observation. The majority were correct and used entities inside the computation. But the ones given by older Economics students were less satisfactory. The ones given by younger Physics students were satisfactory.

For "why does the model in the computer behave this way?", about half answered "the way it is programmed" and a third "because the model is limited". The majority of Physics students considered the model limited.

For "could this happen in reality?" half considered it could, and the majority explained and used entities outside the computation. Half used "model is limited" as an argument to justify that it could not happen in reality. Older students were more critical considering that the model is limited and that the situation could not happen in reality.

11. 4. 4. Relating to previous research

Results indicate in general an advantage for Physics students concerning work with STELLA models. Similar background effect was found for the work with IQON and causal diagrams, as well. This may be related to expectation 16, table 3.1 (we should expect Physics students to be more cognitively adapted to the system thinking approach). Some results are related to expectation 15 (we should expect gender effects concerning the work with system thinking). See in chapter 3, section 3. 3. 2, report of differences between Physics and Chemistry students concerning cognitive engagement in system thinking tasks. Also, slight ability and gender differences in levels of cognitive engagement showing an advantage to female students (Mandinach, 1988)

11. 5. IS THE STUDENT ABLE TO RECOGNISE SITUATIONS THAT COULD BE MODELLED WITH THE SAME (STELLA) STRUCTURE ?

In chapter 3, section 3. 2. 2, the issue of transference of the underlying structure of a problem was discussed. It was pointed out that modelling the same phenomenon in several different disciplines might help learning about such schemes of models.

In the *three tanks* task, and in the *two cars in a stream of traffic* task, questions explored if the students were able to suggest situations which could be modelled with the same STELLA structure.

Answers were classified according to the subject matter proposed and kind of description used.

Students in general were able to suggest situations which could be modelled with the same STELLA structure, for both tasks. This result is in accordance with expectation 7 in chapter 3, table 3. 1 (recognition that different problems share the same underlying structure).

For the 'three tanks' task the majority used Economics related situations (see table 11. 6). The same was true for about half of the students in the 'two cars' task (see table 11. 7). For both tasks the majority were able to propose correctly a similar situation which could be modelled with the same structure. Only about a third of the students merely stated an answer without explaining it.

	nº stud.	**fraction**
Subject of answer:		
Physics related	7	0.21
Economics related	19	0.58
Social related	4	0.12
Physics and Economics related	3	0.09
Kind of description:		
Explain	21	0.64
State only	10	0.30
Do not explain	2	0.06
Total of students	33	1.00

Table 11. 6 - Three tanks system - 'Could the same model be used for another problem which is not about leaking fluids at all? Suggest one if you can'.

Examples of Physics related answers, for the *three tanks* task, are

> "Kinetic and potential energy of a car going down a hill, heating of a house" (EDD) (he just states)
> and
> "rate of change of atoms resulting from nuclear decay of an element and the subsequent decay of it's decay product to a third element ...". (MIC)

EDD just stated his answer. He did <u>not</u> show how Kinetic and Potential Energy or heating of a house could be related to the three tanks structure. MIC could use his Physics knowledge about nuclear decay process to make an analogy with the three tanks system. He thought that what happens to the atoms is someway similar to what happens to the water.

An example of an Economics related explanation is

> "Tank 1 could be an amount of government money. Tank 2 could be a model of a department such as the health service and the water could represent money given by the government to the health service. Tank 3 could represent the hospital who receive money from the health service department". (COL)

COL could specify a correspondence between tanks and entities in his Economics related model.

An example of a Social related explanation is

> "To find the number of people in an area in a tube station. h1 is where the train is full then people get off. h2 is the platform filling up then people leaving through turnstiles and h3 is outside. This could be used for safety reasons". (ROSA)

Like COL, ROSA besides making a correspondence between level of water and number of people added a purpose for having the model.

Only 3 students with an Economics background gave answers having any reference to subjects other than Economics.

	nº stud.	fraction
Subject of answer:		
Physics related	4	0.13
Economics related	15	0.47
Diet related	2	0.06
Similar case (e.g. race)	8	0.25
Economics and similar case	2	0.06
Physics and similar case	1	0.03
Kind of description:		
Explain	23	0.72
State only	9	0.28
Total of students	32	1.00

Table 11. 7 - Two cars in a stream of traffic - 'Can you think of any other situation which behaves like this?'.

For the *two cars in a stream of traffic* task, examples of explanations related to Economics are

> "When more people buy houses, prices will increase, therefore less people can afford houses and so prices will decrease" (JOA)
>
> and
>
> "... the result of high inflation might cause interest rates to rise or vice versa...". (MARC)

Both JOA and MARC depicted the oscillatory pattern of the 'two cars' model to give their answers.

Only 4 students with a background in Physics (ANK & PHO and TUO & MIC) gave Physics related answers as, for example,

> "The motion of an object which is in simple harmonic motion", (TUO) (he just states)
> and
> "Electrons bump into atoms when accelerated by a p.d. which slow it down but accelerates again to reach velocity required by p.d". (ANK)

TUO just stated his answer. He used the sentence "simple harmonic motion" to embody the oscillatory behaviour of the 'two cars' model. ANK with a Physics background could use his knowledge to give a good answer. For him, the electron will behave like the following car when decelerated by atoms and accelerated by the electric field.

8 students suggested a situation very similar in kind to the one previously modelled, for example,

> "In some cases, pedestrians walking behind one another on the street. If there is a slow person in front of you - you will slow down/increase d behind accordingly". (ELI)

Two students suggested a diet related situation like

> "A person may become hungry and eat too much. He then has to cut down on the amount of food eaten but may decrease this too much so he become hungry". (ROS)

ROS made an analogy between the oscillatory nature of 'hunger' and the oscillatory pattern of the model.

A few students gave examples which mixed different subjects.

For the three tanks task, <u>subject of answer</u> and <u>background</u> are related (for Physics and Economics related answers, p = 0. 03 and p = 0. 002 - Fisher, respectively). Chart 11. 13 shows that the majority of the Physics related answers were given by Physics students, and the majority of Economics related answers were given by Economics students.

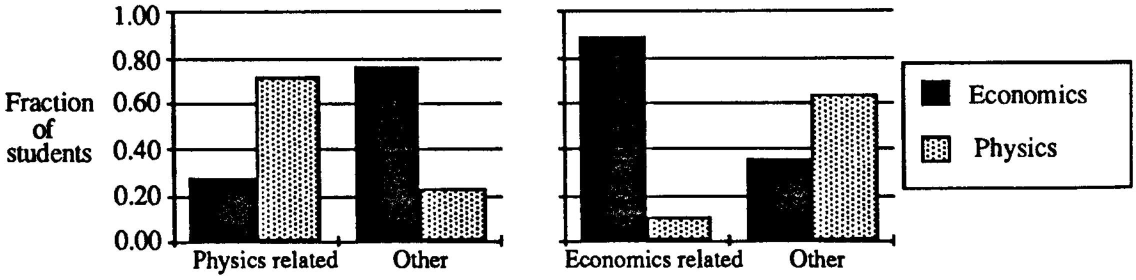


Chart 11. 13 - Subject of answer and background for the three tanks task.

This result indicates that students when thinking about models tended to articulate analogies according to their backgrounds. Also, it adds to the evidence that background matters.

No significant differences were found for subject of answer concerning treatment, gender, age and place of school.

For the two cars task (but not the tanks task), subject of answer and gender are related (p = 0. 02 - Fisher). Independent of age, background, treatment and place of school, female students tended to give Economics related answers, as shown in Chart 11. 14.

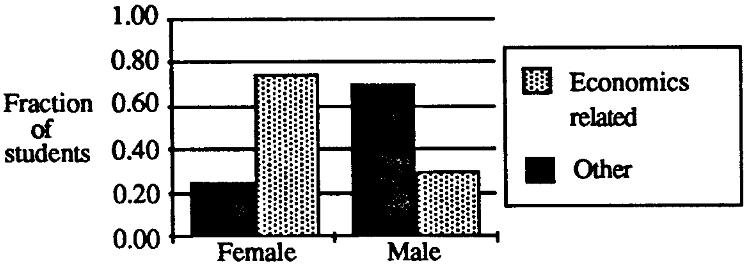


Chart 11. 14 - Subject of answer and gender for the two cars in a stream of traffic task.

This seems to be a genuine gender effect as the ones discussed in previous sections.

Subject of answer and background are related (p = 0. 01 - Fisher).

Chart 11. 15 shows that students with background in Physics gave a significantly larger fraction of answers related to Physics.

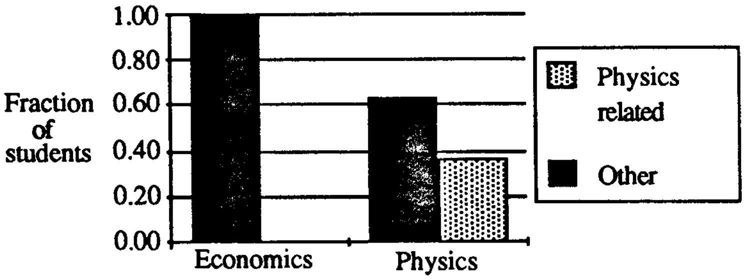


Chart 11. 15 - Subject of answer and background for the two cars in a stream of traffic task.

Like for the 'three tanks' task, this result lends further support to the view that students tended to articulate analogies according to their backgrounds.

11. 6. DIET AND WEIGHT LOSS - EXPRESSIVE TASK USING STELLA

In this section the following specific research subquestions

What can be said about the entities used when making a STELLA model ?

How does the student transfer the knowledge acquired through the work with STELLA models, in an accustomed context to other area ?

will be addressed, together with at least partial answers to the following specific questions:

What can be said about the influence of STELLA's metaphor on the way the student thinks about variables ?
and
Is working with IQON better than working with causal diagrams, for promoting thinking about systems, and for assisting later work with STELLA ?

Pairs	**Rating**	**Structure**	▤	⇐
ELI/PAT	Poor	3B2R chain	a, a, a	und.
SIM	Reasonable	3B2R chain	a, r, r	r, r
EDD/NWA	Excellent	2B2R chain-1cloud	o, a	r,p
JAS/SHA	Reasonable	3B2R chain	a, a, p	a, r
MEL/PA A	Poor	3B2R chain	a, r, a	o,p
ROS/TOB	Reasonable	3B2R chain	a ,a, a	p,q
COL/PAO	Reasonable	1B2R 2pairs-2clouds	a	r, r
JASO/PET	Poor	5B6R loop	a,o,a,a,p,p	und.
STU	Reasonable	3B2R 2pairs	o, a, q	q,p
MARC	Good	3B2R chain	a, r, p	p,p
JOA/ROSA	Good	2B2R loop	a, a	r, r
REB/COLE	Excellent	1B2R chain-2clouds	a	r, r
NIC/DAR	Good	2B2R chain-1 cloud	a, o	r, p
ANK/PHO	Good	3B2R chain	a, a, p	r, r
MARG/TON	Poor	3B2R chain	a, a, a	o,p
MARK/RIC	Reasonable	3B2R chain	a, o, p	p,p
TUO/MIC	Good	2B2R chain	r, a	r, q
BRU/HAR	Poor	2B2R loop	a, a	p, r

Table 11. 8 - Score, structure, tanks and rates - Expressive task about diet and weight loss.

Table 11. 8 shows, for each pair (or student) data about the models they constructed. Each model is given a merit rating, depending on the clarity of definition of variables, and the use of computational links (see later for a discussion of these ratings). A code for the nature of the model structure is shown, in which for example 3B2R means that it contains

3 boxes (tanks ▭) and 2 rate variables (taps ⊖). 'Chain', 'loop' and '2 pairs' describe the model's configuration (see below). The final two columns show the nature [rates (**r**) , amounts (**a**), process (**p**), objects (**o**) and qualitative variables (**q**)] of the box and tap variables. This classification follows that in chapter 8, section 8. 2. 2. 1. Observation notes were essential for helping with the classification of entities. The classification of tanks and taps was based not only on what is written in the final models developed by students. It was also helped by records kept of the path followed by students since defining the first boxes and linking them through taps, until having what was considered by them the final model (evolution of the model in time). A document with STELLA models constructed by pairs of students is available on request.

11. 6. 1. CLASSIFICATION OF STELLA MODELS

The classification of models as Excellent, Good, Reasonable or Poor, was based on the opinions of the four teachers who had answered the teachers' opinions questionnaire in Appendix VI. They were asked to rate an answer and also to indicate how many students they thought might be capable of such an answer. Based on their answers the following criteria for rating STELLA models was defined.

A model was considered excellent if it represented correctly the situation, with a chained structure similar to the pattern in figure 7. 8 (chapter 7), independently of the status of the entities involved. Also, it should indicate some functional dependencies. An example is the one from REB & COLE, in figure 11. 1. Notice that the heat loss will depend on the weight of the person and, also, the calorie intake will depend on the heat loss.

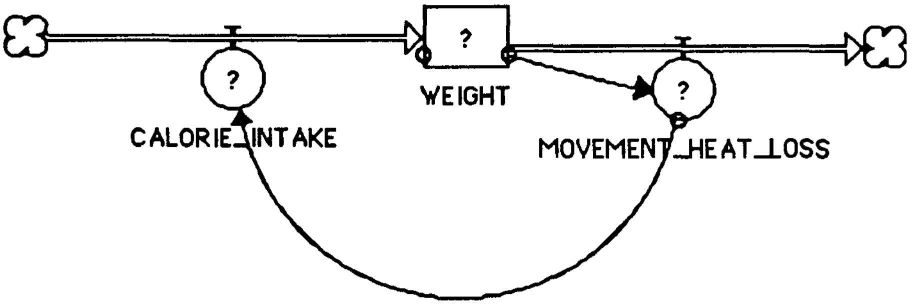


Figure 11. 1 - STELLA model for "diet and weight loss" rated as excellent - REB & COLE.

A good model could have any kind of structure but had to describe the situation correctly. An example is due to MARC, in figure 11. 2.

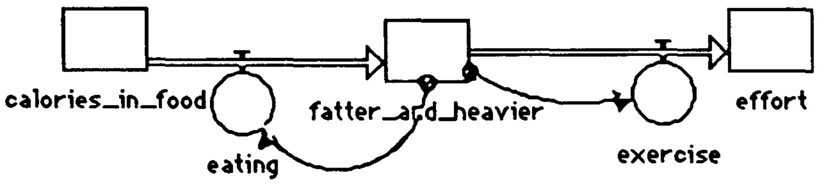


Figure 11. 2 - STELLA model for "diet and weight loss" rated as good - MARC.

In this model there is a tank for effort which will increase due to exercise. This box may represent the effort that the person is doing whilst exercising.

Models were considered reasonable which could describe correctly part of the situation. This was the case for COL & PAO, in figure 11. 3, who could describe only that food intake increases weight. The effect of energy used in the weight is unclear. To make sense it needs to be seen to act in an opposite way to food intake.

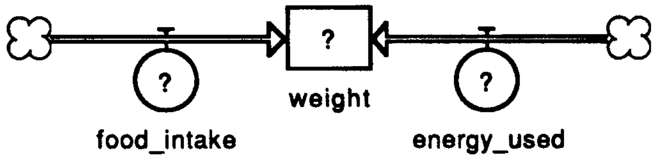


Figure 11. 3 - STELLA model for "diet and weight loss" rated as reasonable - COL & PAO.

A poor model might have a correct structure, but had wrong or undefined entities. This was the case, in figure 11. 4, for ELI & PAT who could not define the rates.

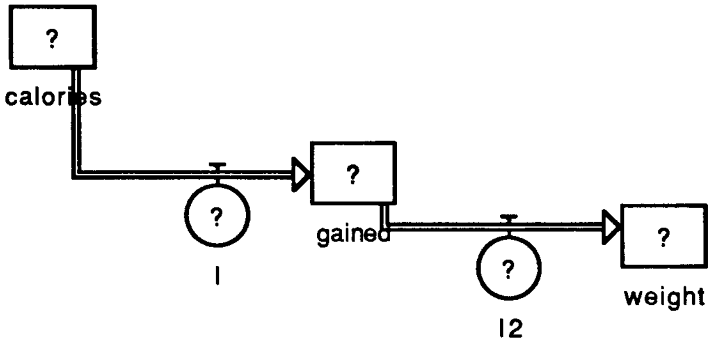


Figure 11. 4 - STELLA model for "diet and weight loss" rated as poor - ELI & PAT.

Table 11. 8 presented at the beginning of this section shows that the majority (13) of the models developed were a kind of chain, imitating the three tanks system worked in the exploratory tasks. Of these 13, five could be classified as "excellent or good". Five models had pair or loop structures. It does seem that at least at the visual level (chain of tanks) students transferred a model structure from one situation to another.

Table 11. 8 shows as well that there was a roughly uniform distribution of models classified as good, reasonable and poor. Just two models were classified as excellent.

Because some pairs contained students with different age and gender (see chapter 10, table 10. 1), these variables were not considered as sources of interaction in the analysis.

Table 11. 9 shows that a significantly larger fraction of pairs with background in Physics, independently of treatment, was responsible for good/excellent models (p = 0. 01 - Fisher). The same table shows that, independently of background, a noticeable (p = 0. 06 - Fisher) larger fraction of pairs who worked with causal diagrams, was responsible for good/excellent models. However, a closer look at the 10 pairs who worked with causal diagrams suggests that a noticeable (p = 0. 07 - Fisher) larger fraction of good/excellent STELLA models was given by students with background in Physics. These results suggest that maybe the noticeable advantage for the previous work with causal diagrams happened just because the sample was biased, since a larger fraction of students with background in Physics worked with causal diagrams (see in chapter 10, table 10. 1).

IQON and C. D.	Economics	Physics	TOTAL
Poor/Reasonable	10	1	11
Good/Excellent	2	5	7
TOTAL	12	6	18

p = 0. 01

	IQON	C. D.	TOTAL
Poor/Reasonable	7	4	11
Good/Excellent	1	6	7
TOTAL	8	10	18

p = 0. 06

C. D.	Economics	Physics	TOTAL
Poor/Reasonable	4	0	4
Good/Excellent	2	4	6
TOTAL	6	4	10

p = 0. 07

Table 11. 9 - Effects of background and treatment, for the expressive task with STELLA.

To explore the possible effect of background further, a two way factor ANOVA was carried out for scores using as source background and treatment. Table 11. 10 suggests that the main effect is indeed background (p = 0. 004). There is no effect of treatment or interaction between treatment and background.

Source	df	Sum Sqr	Mean Sqr	F - test	P value
Background	1	6. 981	6. 981	11. 846	0.004
Treatment	1	0. 519	0. 519	0. 881	0. 364
Interaction	1	0. 058	0. 058	0. 098	0. 759
Error	14	8. 250	0. 589		

Table 11. 10 - ANOVA table for effects of background and treatment, for the expressive task with STELLA.

The non effect of treatment suggests that the work with IQON and causal diagrams seemed <u>not</u> to have differed concerning the effect on the students' achievement in the expressive task with STELLA.

The larger proportion of pairs of Physics students with "Excellent or Good" models is in accordance with the findings reported in section 11. 5, for effect of background, and is further evidence that background is important.

There are <u>no</u> significant effects of Place of school.

Chart 11. 16 shows fractions of the total number of TANKS and TAPS used by students. TANKS ▤ were mostly conceived as <u>amounts</u>, followed by <u>objects</u> and <u>processes</u>. There are indications of TANKS conceived as <u>rates</u> and <u>qualitative</u> variables.

An example of TANK as amount is "weight", and as object is "Bob" (name of the person). Example of TANK as process is "work" and as rate is "change in weight".

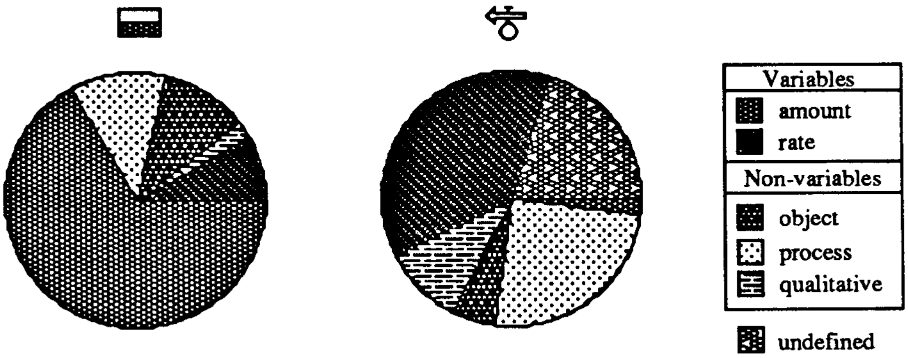


Chart 11. 16 - Fractions of the total number of TANKS and TAPS chosen in STELLA as variables, non-variables and undefined.

TAPS ⊶ were mostly conceived as <u>rates</u>, but with noticeable numbers of <u>processes</u> and <u>undefined</u> rates.

Examples of TAPS ⊶ as <u>rates</u> are "calories per day" and "food per day". Examples of TAPS as <u>processes</u> are "eating", "effort" and "activity".

These results indicate that students did not have substantial problems in thinking about variables that accumulate - TANKS. On the other hand they seemed to have more problems in thinking about suitable TAPS to link TANKS.

The existence of a noticeable fraction of <u>undefined</u> rates means that although some students knew that they were obliged by STELLA's visual metaphor to link TANKS through TAPS (and this was a surprise for some students), they did not find it easy to think about what rate would be suitable to describe the situation. STELLA in some sense puts the student in a difficult position since, in order to use it, specific knowledge about rates is needed (see in chapter 5. 3 discussion about the choice of TAPS as rates to connect BOXES).

Some interactions were found concerning background. Physics students used a significantly larger proportion of rates (p = 0.0001 - Fisher), and Economics students were responsible for undefined rates. These results show an advantage to Physics students and are in accordance with previous findings.

11. 7. CONCLUSIONS: TRANSFERENCE AND EXPRESSIVE TASK

11. 7. 1. WHAT CAN BE SAID ABOUT THE ENTITIES USED WHEN MAKING A STELLA MODEL?

In general, students did not have substantial problems with variables that accumulate. But the situation was different for TAPS, which two pairs conceived as processes and undefined variables.

It seemed to be an advantage to have a Physics background for the use of rates and to develop more elaborate structures.

11. 7. 2. HOW DOES THE STUDENT TRANSFER KNOWLEDGE ACQUIRED THROUGH THE WORK WITH STELLA MODELS, IN AN ACCUSTOMED CONTEXT TO AN OTHER AREA?

For exploratory tasks, students were able to suggest other Economics related situations which could be modelled with the same STELLA structure. Situations were consonant with students' background.

For the expressive task, it does seem that at least at the visual level students transferred a model structure from one situation to another. The majority of the pairs simply imitated a chained structure of two or three tanks (as in figure 11. 4, for example). Five did not try to imitate the tank structure, and tried to develop their own structure.

11. 7. 3. WHAT CAN BE SAID ABOUT THE INFLUENCE OF STELLA'S METAPHOR ON THE WAY THE STUDENT THINKS ABOUT VARIABLES?

STELLA's metaphor seems to have a strong influence on the way the student thinks about variables. Unlike the work with causal diagrams and IQON, where the student is free to choose entities, STELLA's structure works as a "strait jacket" which obliges the student to use the idea of rates of change (see previous discussions), demanding specific knowledge. When this knowledge does not exist, the student can not express himself with the tool, because the models will not make much sense.

11. 7. 4. IS WORKING WITH IQON BETTER THAN WORKING WITH CAUSAL DIAGRAMS, FOR PROMOTING THINKING ABOUT SYSTEMS, AND FOR ASSISTING LATER WORK WITH STELLA?

In chapter 10 there is evidence that working with IQON was better than working with causal diagrams for promoting thinking about systems. However, results described here suggest that there was no difference concerning the effect of the previous work with IQON or causal diagrams on the students' achievement with STELLA's exploratory and expressive tasks.

CHAPTER 12 - IDEAS ABOUT DYNAMIC BEHAVIOURS, MODELS AND RELATION TO RESULTS OF SURVEY

12. 1. INTRODUCTION

Students in the intensive study also answered a questionnaire at the end of the first section (*Questionnaire about Models*), which was applied again at the end of the third session (see later). Also, at the end of the third session, they did two more questionnaires: *Ideas About Modelling* and *Ideas About Dynamic Behaviours* (see chapter 5, section 5. 5).

This chapter will describe the results obtained from the application of these questionnaires. *Ideas about Modelling* makes possible a link to results from the larger survey presented in chapters 8 and 9, since it contains a subset of common questions with the *Questionnaire about Modelling* used in the survey.

12. 2. CHOOSING GRAPHS TO REPRESENT PROCESSES

Table 12. 1 shows the number of students for patterns chosen as the best graph for sentences 1 to 15 of the questionnaire "Ideas About Dynamic Behaviours" (see section 5. 5. 3). The table presents in **bold** possible acceptable patterns for each sentence.

The questionnaire was applied only to students of the intensive study. It was designed to include increasing, decreasing, oscillatory and non-dynamic behaviours. See sentences and graphs in figure 12. 1 below.

SENTENCES

1) Price change because the inflation is increasing.
2) The price is high.
3) The population is increasing.
4) The level of water is decreasing.
5) The level of water is increasing.
6) The car is stopping.
7) The swing is swinging.
8) The weight is decreasing.
9) The stone is falling.
10) The temperature is constant.
11) The swing is stopping.
12) The man hits the ball.
13) The braking distance is 20 m.
14) The radioactivity is increasing.
15) The velocity is increasing.

GRAPHS

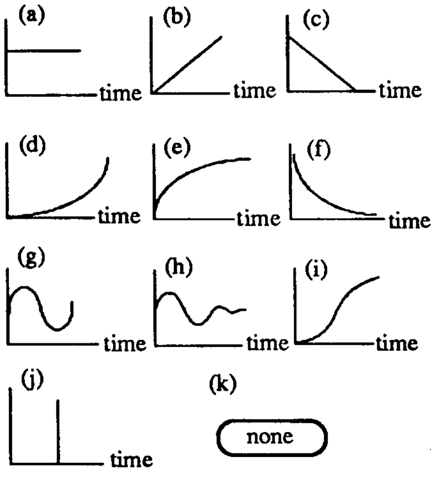
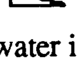
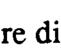


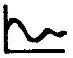
Figure 12. 1 - Sentences and graphs of the questionnaire about dynamic behaviours.

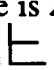
1) Prices change because the inflation is increasing.	0	16	0	6	4	0	0	0	2	0	4
2) The price is high.	10	0	0	0	3	1	1	0	1	4	12
3) The population is increasing.	1	6	0	13	4	0	0	1	7	0	0
4) The level of water is decreas.	0	0	11	0	0	20	0	0	0	1	0
5) The level of water is increas.	0	13	0	12	5	0	1	0	1	0	0
6) The car is stopping.	0	0	12	0	5	9	0	3	0	1	2
7) The swing is swinging.	1	0	0	1	0	0	21	4	0	0	5
8) The weight is decreasing.	0	0	7	1	1	19	0	2	0	1	1
9) The stone is falling.	0	2	13	1	3	3	0	0	0	5	5
10) The temperature is const.	27	0	0	0	0	0	2	0	0	3	0
11) The swing is stopping.	0	0	0	0	0	3	2	20	0	0	5
12) The man hits the ball.	1	4	2	3	7	3	0	0	1	5	8
13) The braking distance is 20m.	2	1	5	0	1	5	1	1	4	1	11
14) The radioactivity is increas.	0	7	0	12	3	0	0	1	6	1	2
15) The velocity is increasing.	0	18	0	9	1	0	0	0	3	0	1

Table 12. 1 - Number of students (maximum 32) for patterns chosen as the best graph for sentences 1 to 15 of the questionnaire "Ideas About Dynamic Behaviours".

Sentences 1, 3, 5, 14 and 15 describe increasing patterns.
A choice of a non-increasing graph for these sentences was extremely rare. The linear  and increasing rate  graphs were by far the most frequently chosen, dividing roughly equally. The linear graph  was preferred to  for "prices change because inflation is increasing" and "velocity is increasing", while  was preferred to  for "population increasing" and "radioactivity". It appears that general knowledge about exponential growth influenced this last choice.
"The level of water is decreasing" (sentence 4) and "the weight is decreasing" (sentence 8) describe decreasing patterns. "The car is stopping" (sentence 6) and "the stone is falling" (sentence 9) could describe decreasing patterns.
Choices of non-decreasing graphs were not frequent, with the exception of 5 students who chose  for describing "the car is stopping". This last result may indicate that students maybe were thinking about a graph of x versus t. For "the stone is falling", 5 choices of  may indicate the real trajectory of the stone. For these cases, the exponential decay  was by far the most often chosen. This pattern was preferred to  for "level of water is decreasing" and "weight is decreasing", suggesting that general knowledge about exponential decay influenced the choice. The linear  was preferred for "the stone is falling", while for "the car is stopping" answers were divided roughly between  and . These last choices indicate that students gave school type graphs

for the situations. For example, for "the stone is falling"  may represent v_y versus t. For "the car is stopping" the result suggests that students interpreted pattern  as a graph of v_x versus t.

"The swing is swinging" (sentence 7) and "the swing is stopping" (sentence 11) describe oscillatory behaviours. For these the majority of the choices were for patterns  and , respectively. There was a small number of choices for 'none'. Choice of increasing or decreasing graphs was very rare.

"The price is high" (sentence 2), "the temperature is constant" (sentence 10), are non-dynamic situations. They will be considered here with the statements "the man hits the ball" (sentence 12) and "the braking distance is 20 m" (sentence 13) which are less clearly able to be represented graphically. For these situations there was a noticeable choice of increasing and decreasing graphs. Seven students chose  for describing "the man hits the ball", maybe indicating the real parabolic trajectory of the ball, y versus x, or the graph of y versus t. Five students chose  and five  as graphs for "the braking distance is 20 m", maybe relating to the car is stopping situation (see before). The linear graph  was preferred, together with the option 'none' to describe "the price is high". This graph was also the most chosen for "the temperature is constant".

The questionnaire asked students to consider other graphs that could describe the sentences, besides the best one. In general the number of students who considered other graphs was very low; however it is possible to identify situations that they preferred to describe by linear patterns.

The number of students who chose the linear patterns ,  and  as the other possible graph to describe the sentences is shown in table 12. 2 below.

			
1) Prices change because the inflation is increasing.	0	5	0
2) The price is high	5	2	1
3) The population is increasing.	0	7	0
4) The level of water is decreas.	1	0	11
5) The level of water is increas.	0	8	0
6) The car is stopping.	1	0	6
7) The swing is swinging.	1	0	0
8) The weight is decreasing.	0	0	7
9) The stone is falling.	1	0	0
10) The temperature is const.	1	0	0
11) The swing is stopping.	0	0	0
12) The man hits the ball.	0	3	0
13) The braking distance is 20m.	1	0	1
14) The radioactivity is increas.	0	6	0
15) The velocity is increasing.	0	4	0

Table 12. 2 - Number of students (maximum 32) who chose linear patterns (a), (b) and (c) as the other possible graphs to describe sentences 1 to 15 of the questionnaire "Ideas About Dynamic Behaviours".

For "the level of water is decreasing" and "the weight is decreasing" there were a noticeable number of students who considered that the linear decreasing graph  could be a possible alternative pattern. The same happened for "population is increasing" and "radioactivity is increasing" concerning the linear increasing pattern . Students who had chosen an exponential pattern in their first option, tended to accept that a simple linear pattern could still be a possible output.

Table 12. 3 shows the number of students who chose acceptable patterns (see in bold in table 12. 1) for sentences.

An inspection of table 12. 3 suggests that there was no difference between students who worked with causal diagrams and IQON, in the choice of acceptable patterns [which was confirmed by Log-linear analysis, using a binomial model, for fraction of acceptable patterns out of total].

SENTENCES	C. D.	IQON
1) Prices change inflation increasing.	13	9
2) The price is high.	4	6
3) The population is increasing.	11	8
4) The level of water is decreas.	10	10
5) The level of water is increas.	10	8
6) The car is stopping.	12	9
7) The swing is swinging.	13	12
8) The weight is decreasing.	15	11
9) The stone is falling.	11	10
10) The temperature is const.	15	12
11) The swing is stopping.	12	8
12) The man hits the ball.	5	3
13) The braking distance is 20m.	6	5
14) The radioactivity is increas.	13	12
15) The velocity is increasing.	17	13

Table 12. 3 - Number of students (maximum 17 for causal diagrams and 15 for IQON) who chose acceptable patterns for sentences".

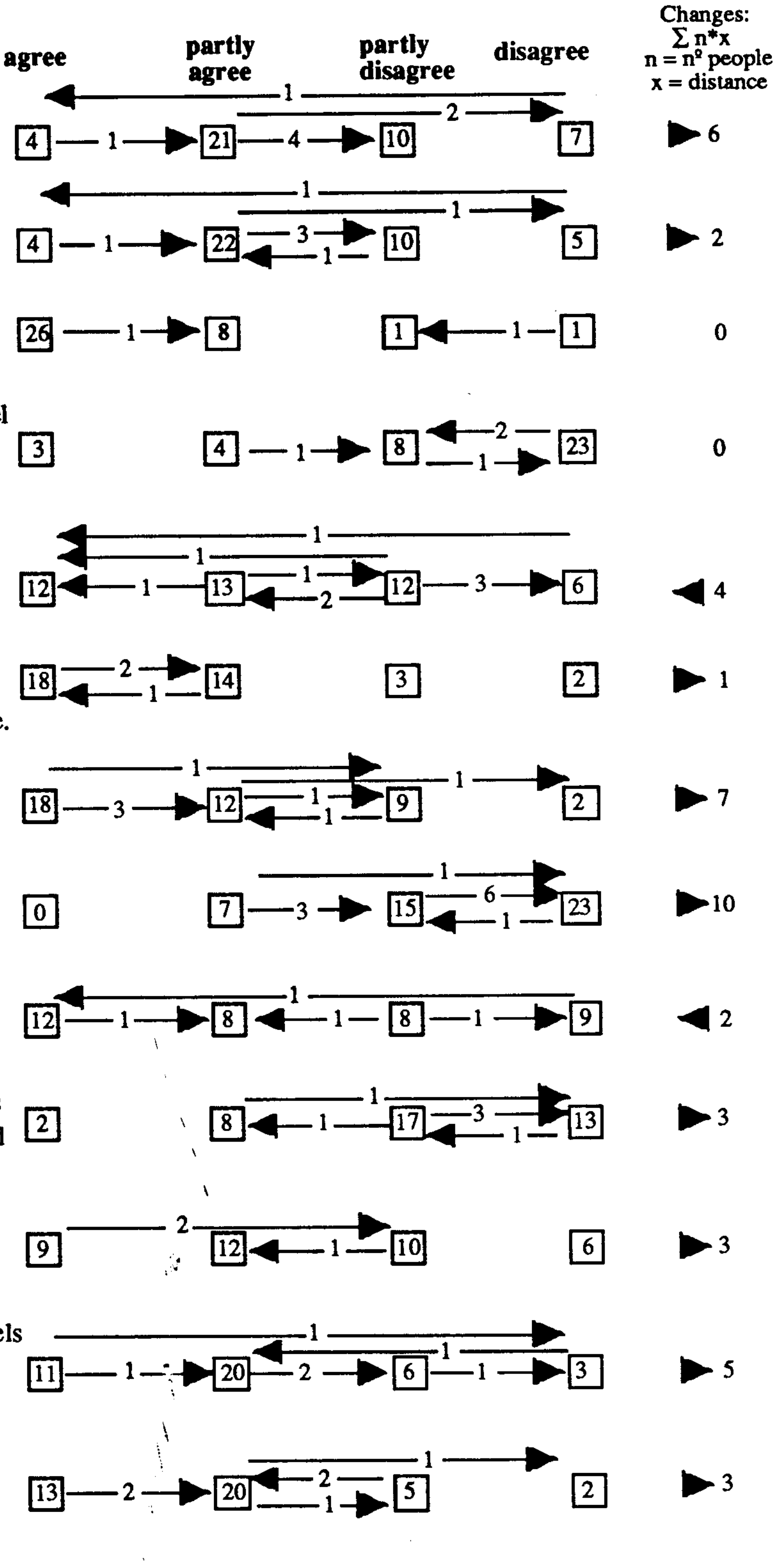
12. 3. CONCLUSIONS: IDEAS ABOUT DYNAMIC BEHAVIOURS

It seems that general knowledge of exponential decay and growth influenced the choices. Also, some students tended to give school-type graphs as answers.

The majority easily identified oscillatory situations and, after their experience with leaky tank tasks, could propose a possibly correct pattern for describing a decreasing level of water. These results suggest that students could reason at an intuitive semi-quantitative level about possible graphical outputs for situations. This adds a little to the characterization of semi-quantitative reasoning - students reasoned semi-quantitatively not only in terms of entities and structures (see chapters 8, 10 and 11), but also in terms of output (dynamic behaviour). Nonetheless, as shown in chapter 9, sections 9. 2 and 9. 4, students from survey had problems in associating mathematical equations to an exponential growth, decay and an oscillatory graphical pattern (see question 25 in Appendix I. 2).

For sentences which describe increasing (1, 5 and 15), decreasing (6 and 9) and non-dynamic (2 and 10) behaviours, there was a noticeable number of students who preferred to represent the situation using a linear pattern as the best graph. Also, for some sentences, there was a noticeable use of linear patterns as the "other" graph. These results may suggest that students tend to model situations using the simplest dynamic pattern possible. One could speculate that this happens because they simply choose the most familiar graph or have been led to expect linear graphs in such school type situations. More strongly, one might ask whether some students tend to think about nature in a linear way. This result adds a little further to the impression that students in modelling tasks tended to use their own ideas.

12. 4. STUDENTS' CONCEPTIONS ABOUT MODELS



	agree	partly agree	partly disagree	disagree	Changes: Σ n*x n = nº people x = distance
1) If the model predicts things wrongly it must be wrong.	4	21	10	7	▶ 6
2) If a model predicts things correctly it must be correct.	4	22	10	5	▶ 2
3) A model can be approximately correct.	26	8	1	1	0
4) All that matters about a model is whether it works, not whether it is true.	3	4	8	23	0
5) Only a very small part of reality can be understood through models.	12	13	12	6	◀ 4
6) A model which makes very precise (highly accurate) predictions is likely to be true.	18	14	3	2	▶ 1
7) Models represent only very simplified aspects of reality.	18	12	9	2	▶ 7
8) A model which is very simple can hardly be true.	0	7	15	23	▶10
9) A model should try to reproduce reality in all its complexity.	12	8	8	9	◀ 2
10) If a model is correct there is no difference between it and the real thing.	2	8	17	13	▶ 3
11) Using out-of-date models is unscientific.	9	12	10	6	▶ 3
12) Pure guess-work with models can be helpful for thinking about a situation.	11	20	6	3	▶ 5
13) There must be a correct model of every situation, even if we can't yet find it.	13	20	5	2	▶ 3

Table 12. 4 - Number of students (maximum 34) per choice for the questionnaire "Ideas about Models". The long arrows indicate the number of students who changed their answers in the final application of the questionnaire. The arrowheads and numbers on the right indicate direction and magnitude of "change".

Few students gave evidence of thinking outside or beyond the computation in exploratory tasks with IQON/causal diagrams and STELLA (see chapters 10 and 11). It may be interesting now to explore students' conception of the relationship between model and reality. It is hoped to get complementary information concerning 'relation to reality' and 'accuracy'.

In this section the following research questions (see chapter 5, section 5. 3. 2) will be addressed:

What can be said about the student's conception about models ?

Did the student change his/her conception after having worked with computational modelling systems ?

Section 5. 5. 4, in Chapter 5, introduces the Questionnaire About Models. It was applied after the first session and again at the end of the last session.

In general the majority of the students took a consistent and well defined view of models, and relatively a few of them changed their minds in the post-test.

Table 12. 4 shows that students consistently agreed that "a model can be approximately correct" (sentence 3). They partly agreed that "pure guess-work with models can be helpful for thinking about a situation" (sentence 12) and that "there must be a correct model of every situation, even if we can't yet find it" (sentence 13). The majority partly agreed, as well, that "if the model predicts things wrongly it must be wrong" (sentence 1) and that "if a model predicts things correctly it must be correct" (sentence 2).

Students consistently disagreed that "all that matters about a model is whether it works, not whether it is true" (sentence 4).

The majority tended to agree that "only a very small part of reality can be understood through models" (sentence 5), "a model which makes very precise (highly accurate) predictions is likely to be true" (sentence 6), and that "models represent only very simplified aspects of reality" (sentence 7).

The majority tended to disagree that "a model which is very simple can hardly be true" (sentence 8), and that "if a model is correct there is no difference between it and the real thing" (sentence 10).

Students were not consistent, with a small advantage in favour of a positive opinion, concerning the sentences:

" a model should try to reproduce reality in all its complexity" (sentence 9) and

"using out-of-date models is unscientific" (sentence 11).

In general, for each question, just a few students decided to change their answers, after having worked with models. However, some of the changes may well have resulted directly from the work with models.

To get an idea of the magnitude and direction of changes, a score was constructed using $\sum n * x$, where n is the number of people who changed their minds in the post test and x the size of change - the number of scale points jumped (possible values 1, 2 and 3). A negative number represents a change towards disagreement, and a positive number a change towards agreement. Positive and negative changes are represented in table 12. 3 by arrows to the left and right, respectively.

Sentences about simplification - "a model which is very simple can hardly be true" (number 8) and "models represent only very simplified aspects of reality" (number 7), presented the largest changes towards disagreement. After having worked with very simple models, students tended more to suppose that these models, despite being simple, could give a true description of "reality". Also, students might have been influenced by the tasks with causal diagrams and IQON models, when they worked with complicated models such as, the Greenhouse Effect and "Rat War", where many variables are involved. They may as a result have changed their minds about models representing complex aspects of reality.

Changes towards disagreement were smaller but noticeable, for "if the model predicts things wrongly it must be wrong", and "pure guess-work with models can be helpful for thinking about a situation". Students may have seen that even models which are considered correct from a structural point of view (diagram or mathematical equations) may produce predictions that do not fit properly reality - and that this is not enough reason to consider the model wrong.

The tendency towards disagreement about guess-work could have arisen from their own experience, when participating in the research.

Finally, students who worked with IQON and causal diagrams presented the same conceptions about models.

12. 5. CONCLUSIONS: CONCEPTIONS ABOUT MODELS

12. 5. 1. What can be said about the student's conception about models?

Despite having had problems in using entities of the real system in exploratory tasks, in general the majority of the students took a consistent and well defined view of models. For them, models can be approximately correct, and ones with correct structure (diagrams or equations) can make wrong predictions. It is not enough for a model just to work - it must be true. Even very simple models can be true, and high accuracy does not guarantee truth. Model and reality are entities of distinct nature, and models represent only simplified aspects of reality. Playing with a model can help with thinking about the real situation, and every situation in principle can be correctly modelled.

12. 5. 2. Did the student change his/her conception after having worked with computational modelling systems?

A few students changed their conception, but changes were especially noticeable in sentences concerning simplification (see table 12. 4). The changes may well have resulted directly from the work with computational modelling systems.

12. 6. LINKING THE SURVEY AND THE INTENSIVE STUDY

In this section the specific research question

How do students, from the intensive study and survey, differ concerning causal diagrams, entities and mathematical knowledge?

will be addressed.

Section 5. 5, in chapter 5, introduces the questionnaire "Ideas About Modelling" (see Appendix IV). The present section reports the answers given by 32 students, individually, after having worked with the computational modelling systems.

The following comparisons between intensive study and survey, aiming to make inferences about students' experience with modelling tasks, are made:

- first, independently of background, the pattern for 32 students of the intensive study will be compared to the pattern of the survey students from London;
- second, as background seems an important factor, it will be discussed how the pattern of the intensive study changes considering only students with a Physics background and
- third, comparisons between students of the intensive study with a Physics background and surveyed London students (who have predominantly a Physics background) will be carried out.

12. 6. 1. THE LEAKY TANK TASK - ENTITIES USED

For the leaky tank task, in general the choice of entities as not causal was similar to the one shown in chart 8. 15 and described in section 8. 9. As for the survey, in general, students tended to avoid "other than quantities".

Students from the intensive study and from the survey tended to use roughly the same number of quantities in their diagrams. For both studies the majority of the students used between 4 and 6 quantities (see chart 12. 1).

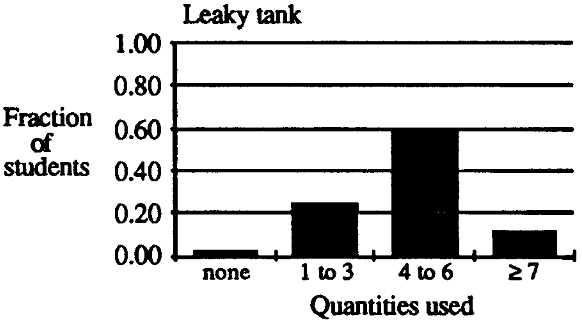


Chart 12. 1 - Fraction of students by number of quantities used, in the causal diagram for the Leaky tank task (intensive study).

Chart 12. 2 shows that roughly half of the students used 1 to 3 "other than quantities", but the difference between the intensive study and the survey was <u>not</u> significant.

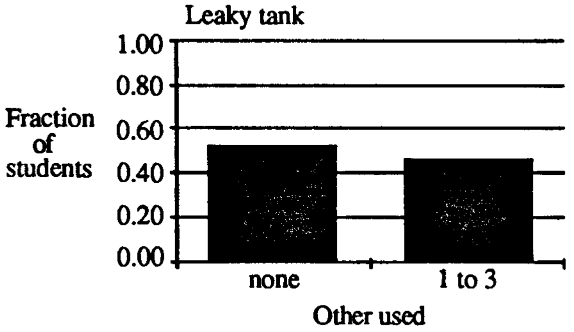


Chart 12. 2 - Fraction of students by number of "other than quantities" used, in the causal diagram for the Leaky tank task (intensive study).

Concerning the use of time as an active entity in causal diagrams, 13 out of 32 students considered <u>time as active</u>, but there was no significant difference between the intensive study and survey (see section 8. 8).

The patterns for 'quantities used', 'other used' and 'time as active' are similar for the 11 students with a Physics background, as well.

12. 6. 2. STRUCTURE OF CAUSAL DIAGRAMS

Chart 12. 3 shows the fraction of students in the intensive study giving different kinds of causal diagrams, for the Leaky tank, the Greenhouse Effect and Rabbits and Foxes.

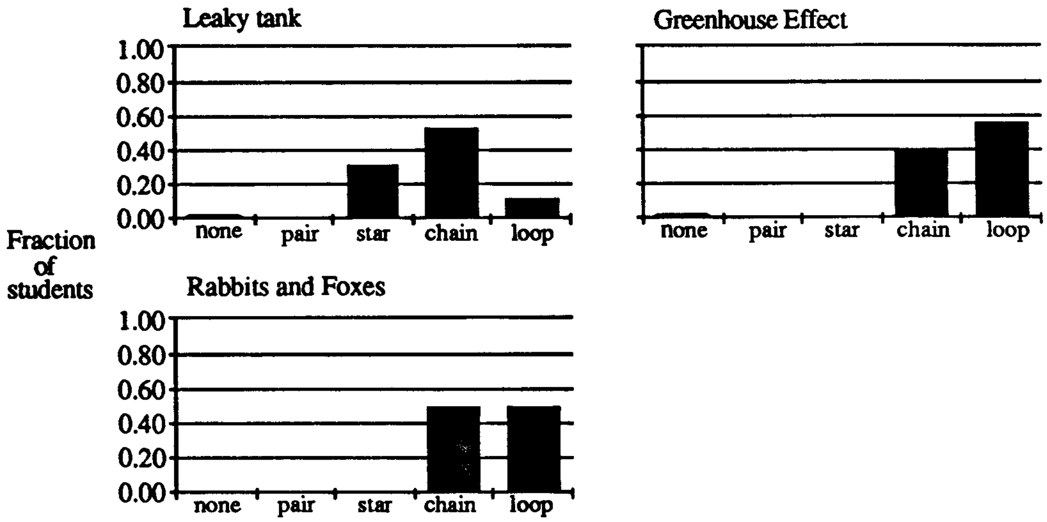


Chart 12. 3 - Fractions of students by kinds of causal diagrams, for the "Leaky tank", "Greenhouse Effect" and "Rabbits and Foxes" (intensive study).

For the Leaky tank task, star and chain structures were the most used, and just one in ten of the students constructed a loop structure. For the Greenhouse Effect task, the majority constructed diagrams composed of at least one loop.

Differences were noticeable between structures developed by students from the intensive study and survey, for the Leaky tank and Rabbits and Foxes. For both tasks, students from the survey presented a larger fraction of diagrams with at least one loop (compare to chart 8. 21, in chapter 8). This result indicates an advantage for the students from the survey concerning thinking at system level. This difference might be explained because the survey was composed predominantly of Physics students. In fact, if we consider only the 11 students with a Physics background to make the comparison, the difference between survey and intensive study, for the Rabbits and Foxes task, disappears. This result lends further support to the view that background matters. However, as the pattern for the Leaky tank did not change very much, background seems not to explain the difference in favour of the survey in this particular task. As age, gender and place of school were not considered in the survey, it is not possible to account for this difference.

In general, for the three tasks, Physics students of the intensive study constructed causal diagrams with more elaborate structures than the whole group of 32 students of the intensive study (shown in chart 12. 3). For the Leaky tank task the majority (7 out of 11) used chains. The majority (8 out of 11), for the Rabbits and Foxes and Greenhouse effect tasks, constructed diagrams with at least on loop. This supports the evidence that background is important.

No differences were found, for the intensive study, concerning treatment, place of school, gender and age.

12. 6. 3. REASONABLE LINKS

Chart 12. 4 shows that, for the Leaky tank task, about a third of the students could <u>not</u> define any reasonable link. The fraction of <u>no</u> reasonable links was smaller for Greenhouse Effect and Rabbits and Foxes. The distributions for <u>1 to 3</u> and <u>4 to 6</u> reasonable links, were very similar, but the Greenhouse Effect had the largest fraction of students (0.40) with 4 to 6 reasonable links. For the Greenhouse Effect 0. 20 of the students had at least 7 reasonable links, but this fraction dropped to about 0. 10 in the Leaky tank and Rabbits and Foxes task.

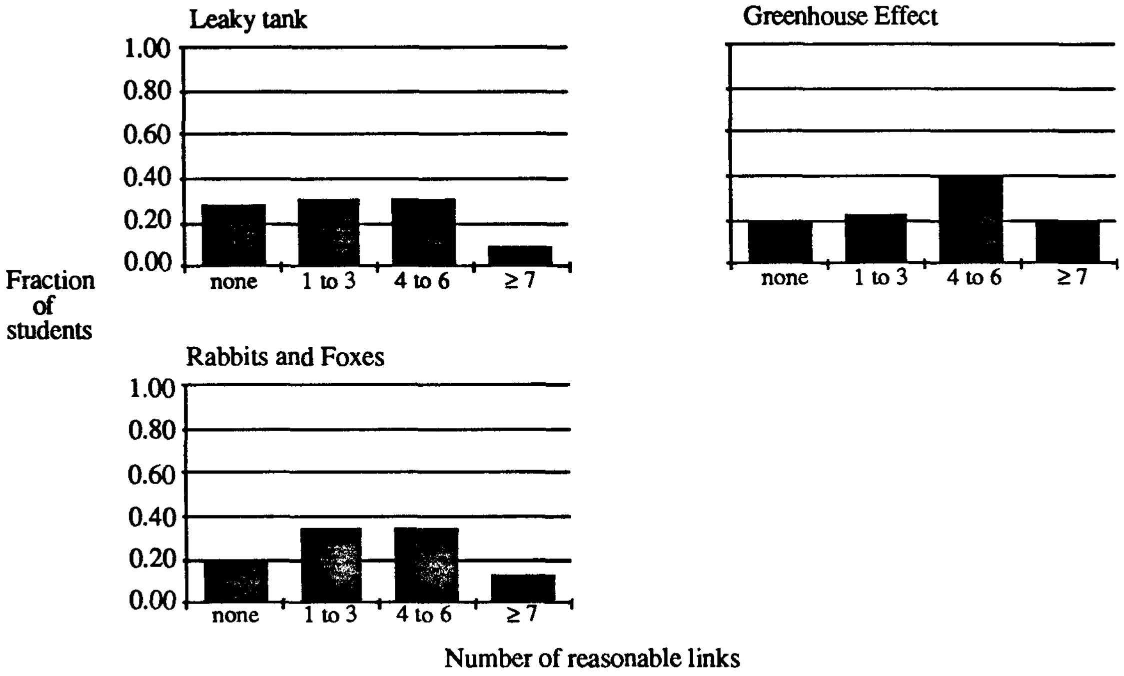


Chart 12. 4 - Fractions of students by number of reasonable links, for the "Leaky tank", "Greenhouse Effect" and "Rabbits and Foxes" (intensive study).

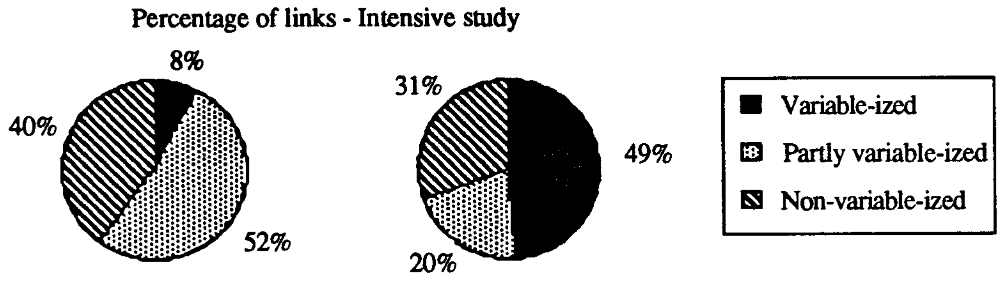
Both distributions of reasonable links, for the survey and the intensive study seem to be similar - compare chart 12. 4 to chart 8. 23 (London only), in chapter 8.

Considering only students with a Physics background, for the three tasks, they tended to use larger numbers of reasonable links than the whole group of 32 students. For the Leaky tank task 7 out of 11 used *4 to 6* reasonable links, while for the Greenhouse Effect this number was used by 8 out of 11 students. Also, comparing to the survey, there is a noticeable difference in number of reasonable links for the Leaky tank and the Greenhouse Effect tasks, in favour of students of the intensive study with a Physics background. These results may indicate that there was some positive effect of the work with leaky tanks (in STELLA) and with the Greenhouse Effect IQON model (or causal diagram) on students' understanding of causation in these systems.

No differences were found, for the intensive study, concerning treatment, place of school, gender and age.

12. 6. 4. KINDS OF LINKS

Chart 12. 5 shows that, for the Greenhouse Effect task, the majority of the links were partly variable-ized and non-variable-ized. For the Rabbits and Foxes task there were noticeable percentages of the three kinds of links. However, there is a noticeably larger proportion of variable-ized links for the Rabbits and Foxes task. For the Greenhouse Effect the most used links were of the kind *object --> rate* and *object --> amount*, and for the Rabbits and Foxes, *amount --> amount.*



Greenhouse Effect *Rabbits and Foxes*

Chart 12. 5 - Kinds of links used in the "Greenhouse Effect " and "Rabbits and Foxes" tasks (intensive study).

These results are in accordance with those of the survey (see chapter 8, section 8. 10). The intensive study and survey did not differ for the Rabbits and Foxes task, but students from the survey presented a significantly larger percentage of variable-ized links, for the Greenhouse Effect task ($\chi^2 = 10. 1$, 2df). Compare chart 12. 5 with charts 8. 17 and 8. 18, for London, in chapter 8. It is interesting to note that these results do <u>not</u> take into consideration the background of the students of the intensive study.

However, students of the intensive study with a Physics background, for the Rabbits and Foxes task, used a noticeably larger percentage of variable-ized links (see chart 12. 6) than the whole group of 32 students (see chart 12. 5). These students did <u>not</u> differ from the whole group for the Greenhouse Effect task. A comparison with the survey (London only) shows that students of the intensive study with a Physics background had a noticeably larger fraction of variable-ized links, for the Rabbits and Foxes task, and smaller percentages of non-variable-ized links, for the Greenhouse Effect task. These results suggest that the modelling tasks helped students of the intensive study with background in Physics to imagine the world in terms of variables. Chart 12. 6 shows percentages of kinds of links for students with an Economics background, as well. Notice that these students even after having worked with modelling tasks had difficulties in imagining the world in terms of variables.

These results support the evidence that semi-quantitative reasoning might depend not only on subject matter, but also background.

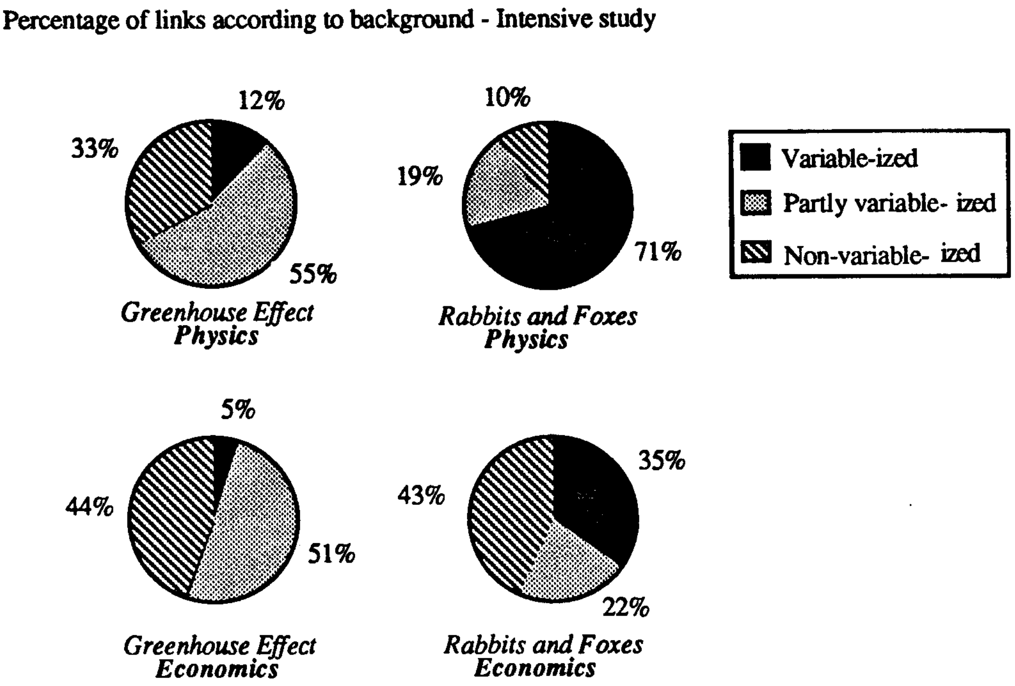


Chart 12. 6 - Kinds of links used in the "Greenhouse Effect " and "Rabbits and Foxes" tasks according to background (intensive study).

As suggested in chart 12. 6, for the Rabbits and Foxes task, use of variable-ized links and background are related (p = 0. 02 - Fisher).

Chart 12. 7 shows that a significantly larger fraction of students with a background in Physics used at least one variable-ized link.

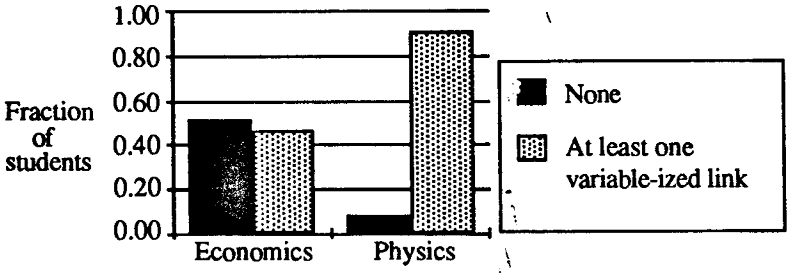


Chart 12. 7 - Background and number of variable-ized links used in the Rabbits and Foxes task (intensive study).

This result, as others, is further evidence that background really matters.

No differences were found concerning treatment, gender, place of school and age.

For the Greenhouse Effect task, use of partly variable-ized links and gender are related (p = 0. 04 - Fisher).

Chart 12. 8 shows that a significantly larger fraction of female students used at least one partly variable-ized link.

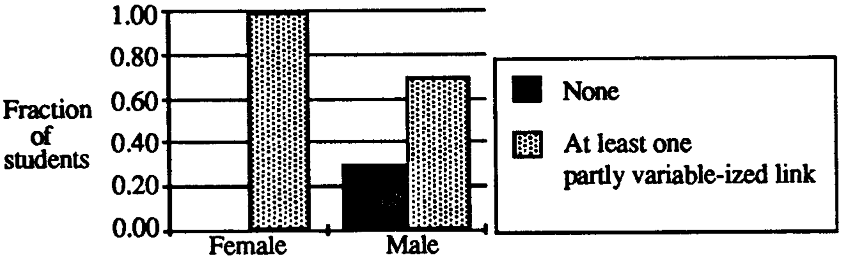


Chart 12. 8 - Gender and number of partly variable-ized links used in the Greenhouse Effect task (intensive study).

This result is further evidence that there is a genuine gender effect as discussed in previous chapters. Also, it adds a little to the evidence that semi-quantitative reasoning might depend on gender, as well.

No significant differences were found for treatment, background, place of school and age.

12. 6. 5. DIFFERENTIAL EQUATION AND PIECE OF PROGRAM

Like the survey, chart 12. 9 shows for the intensive study a large fraction of students with score zero in the question about a differential equation. Students were better in the question about the piece of program where half of them got a reasonable score.

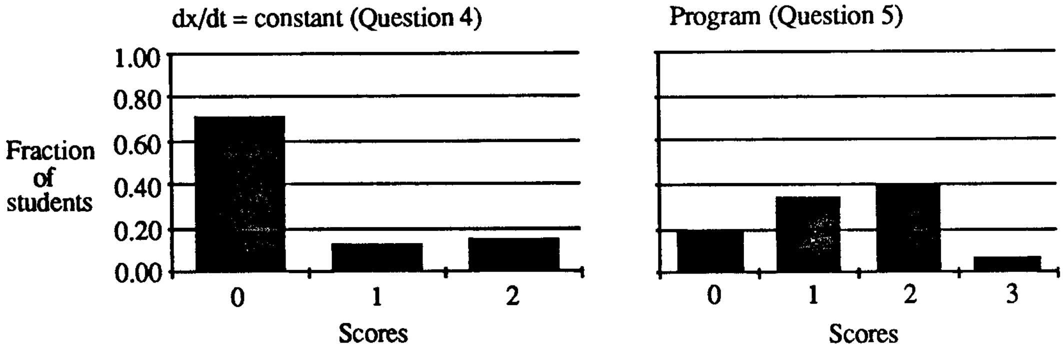


Chart 12. 9 - Fraction of students by score for the differential equation $\frac{dx}{dt}$ = constant, and piece of program (intensive study).

Independently of background students from the survey and intensive study did <u>not</u> differ significantly concerning scores in these questions, which suggests that maybe they have comparable mathematical knowledge. Relate chart 12. 9 with chart 9. 3, for London (question 27 and 29, respectively) in chapter 9.

However, considering only students with a Physics background, comparing to the survey, a noticeably larger fraction (8 out of 11) had a score 2 or more, for understanding a piece of program. This result suggests that some learning took place. Students with a

Physics background after thinking about STELLA equations for leaky tank models were able to use the idea of a difference equation in an iterative loop to answer the question. This may be related to expectation 13, table 3.1 (we should expect some understanding about calculus and differential equations).

There was no difference between students of the intensive study with a Physics background and students of the survey concerning score in the question about a differential equation, which suggests that their knowledge about mathematical representation of rates of change besides being low did not differ.

No differences were found, for the intensive study, concerning treatment, gender, place of school and age.

12. 6. 6. CONCLUSION

A question that would be reasonable to ask after making this parallel between students of the intensive study and survey is what would be expected in terms of achievement if the intensive study tasks were applied to students of the survey. Would these students generate the same pattern of scores presented by students of the intensive study? The answer for this question I believe is 'yes they would'. Students of the survey and intensive study presented similar patterns of achievement in a noticeable number of important factors. For example, in both studies, for similar kinds of tasks, students tended not to imagine the world in terms of variables, had difficulties with system thinking and causal reasoning and had a poor achievement in differential equations. These results suggest that findings for the intensive study are generalisable to a larger population of 6th form students. However, it seems that modelling tasks helped students of the intensive study with a Physics background to understand causation in the Leaky tank and Greenhouse Effect systems, to imagine the world in terms of variables and to understand difference equations in an iterative loop.

12. 7. WRITTEN TASK WITH STELLA

In this section the specific research question

After having worked with STELLA,

a) can students think of variables as tank or flow giving the corresponding unit of measure?

b) how well do they understand a STELLA diagram for a person controlling body weight?

will be addressed.

The questionnaire **Ideas About Modelling** has two questions which aimed to help evaluate the work with STELLA (see Appendix IV).

Question 6 gave six variables to be identified as tank or flow, giving the corresponding unit of measure. In item *a* the variables were credits, bank balance and debits, and in item *b* , inventory, sales and production.

Answers were coded according to the correct identification of the variable and the correct unit of measure. The possible scores, for question 6, were

0 no identification,
1 correct identification,
2 correct identification and right units.

Chart 12. 10 shows that between a third and a half of students identified variables correctly and gave right units (score 2). About two thirds achieved a score above zero.

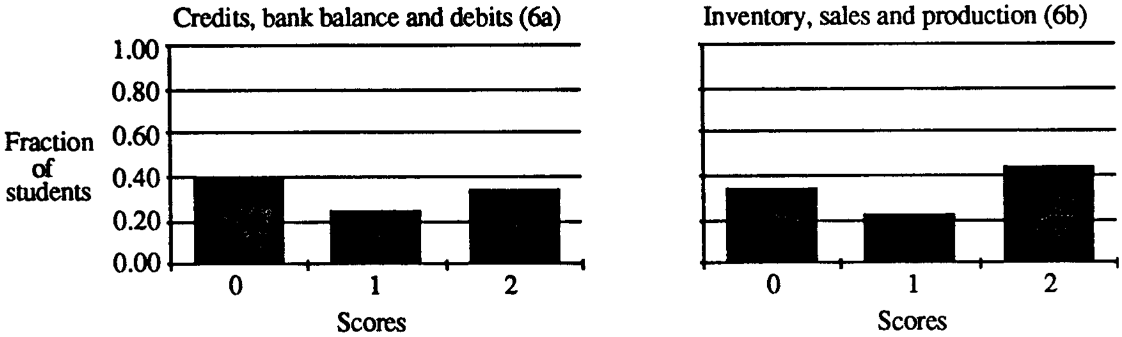


Chart 12. 10 - Fraction of students by score for identification of variables as tank, inflow and outflow, and respective units, for the intensive study (Question 6).

These results suggest that students after having worked with STELLA tasks could identify variables that flow (rates) and variables that accumulate (levels), for this situation. Nonetheless a minority could propose correct units for rates. This suggests that instruction about rates of change is needed.

Identification of a variable as tank, inflow and outflow, giving a unit of measure (for credits, bank balance and debits - question 6a), and place of school are related (considering 1 and 2 as one category, p = 0. 001 - Fisher).

Chart 12. 11 shows that North London students were significantly better in identifying correctly a variable as inflow/outflow or tank. As background and place of school are related (see in chapter 10, table 10. 4) and students with score 0 were from South East London and had an Economics background, this result may be only indicating that background matters. This result is in accordance with those described in chapter 11, and shown in charts 11. 4 and 11. 5.

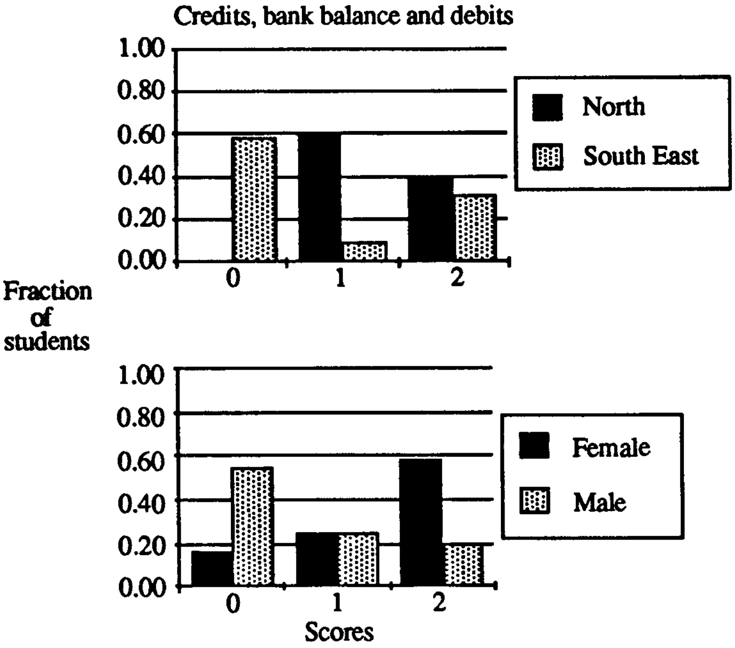


Chart 12. 11 - Fraction of students by score, for identifying a variable as tank, inflow and outflow, giving a unit of measure, according to the place of school and gender, for the intensive study (Question 6a).

Identification of a variable as tank, inflow and outflow, giving a unit of measure (for credits, bank balance and debits - question 6a), and gender are related (considering 1 and 2 as one category, p = 0. 037 - Fisher).

Chart 12. 11 shows also that female students were significantly better in identifying correctly a variable as inflow/outflow or tank, giving a correct unit of measure. This agrees with previous findings supporting the evidence of a genuine gender effect.

No effects of treatment, background and age were found.

For inventory, sales and production (question 6b), identification of a variable as tank inflow/outflow, giving a unit of measure is not related to treatment, background, gender, place of school and age.

Question 7 gave a possible STELLA model for a person controlling his body weight through diet and exercises. Item *a* asked about what influences body weight, and *b* what influences food eaten per day.

For item *a* , answers were coded:

0 wrong answer,
1 states only food or energy,
2 only food or energy saying how,
3 states food and energy,
4 food and energy saying how.

An example of an explanation which received score 4 is

> "Amount of food eaten and amount of energy used up due to exercise. The more food eaten the more weight put on. The more exercise, the higher weight loss". (REB)

Chart 12. 12 shows that the majority considered that both food eaten and energy used up are responsible for influences in body weight. Roughly half could give an explanation saying how. Students who included both entities in their explanations might be considered as seeing the situation as a system (see previous discussions for example in section 8. 6 and 11. 2). After having worked with STELLA tasks the majority could see the situation at a system level, which suggests that some learning took place.

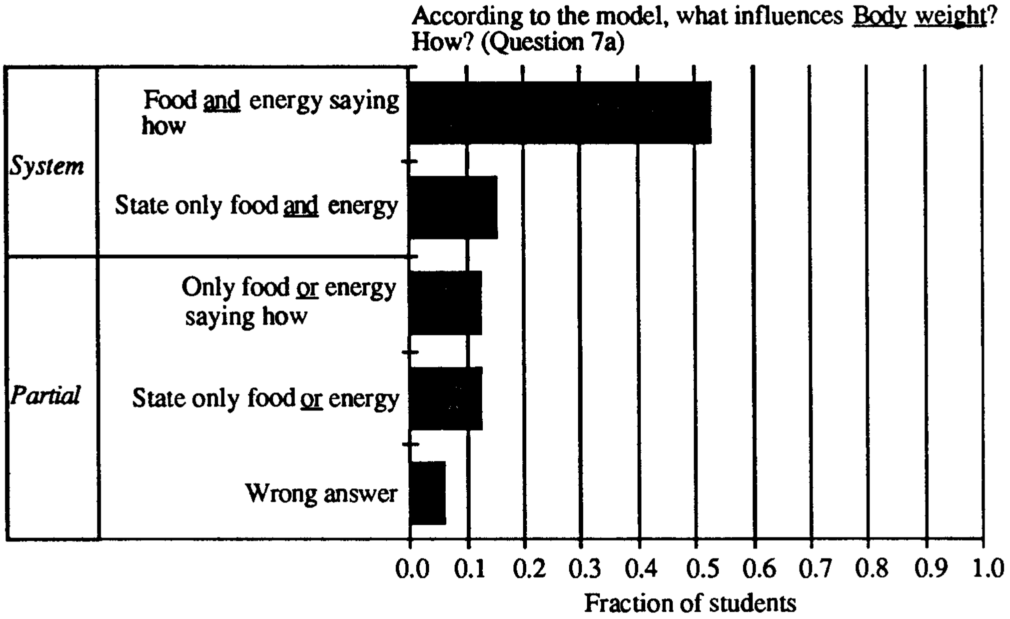


Chart 12. 12 - Fraction of students by kind of explanation, for written task about a STELLA model for a person controlling his Body weight through diet and exercises (intensive study - Question 7a).

No effects of treatment, background, place of school and age were found.

For item *b* , answers were coded:

0 no answer,

1 only states partially,

2 states partially saying how,

3 only states all variables,

4 states all variables saying how.

An example of an explanation which received score 4 is

> "Cost of food, money person has and concern about weight all influence the food eaten. If the cost of food is high and that person doesn't have much money then he will not eat as much, also if he is worried about getting fat then he will eat less". (TUO)

TUO could identify all the relevant variables and say how they affect 'food eaten'.

Chart 12. 13 shows that about 0. 40 of the students gave a complete answer (score 4) stating all variables and saying how they influence the food eaten per day. Roughly half identified cost of food, money person has and concern about weight as the main variables affecting food eaten per day. The other half gave only some of the variables involved.

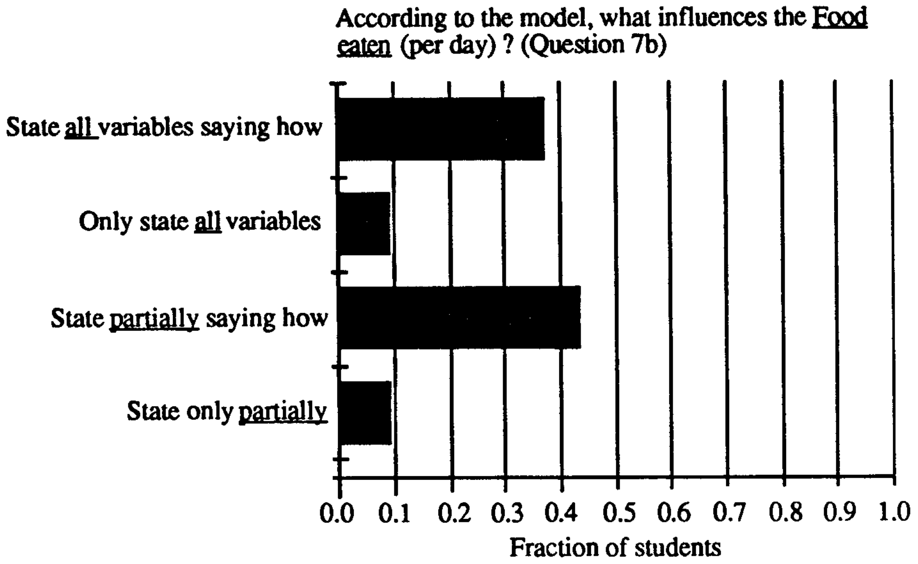


Chart 12. 13 - Fraction of students by kind of explanation, for written task about a STELLA model for a person controlling his body weight through diet and exercises (intensive study - Question 7b).

This result means that even after having worked with STELLA tasks students still had problems in understanding variables represented by 'convertors' in a model (see section 1. 3. 6). This results might be an artifact of the tasks, which in general did not involve models with variables represented by connected convertors.

Identification of variables and background are related (p = 0. 04 - Fisher).

Table 12. 5 suggests that a significantly larger fraction of Physics students, who worked with causal diagrams, was able to identify the three main variables which affect food eaten per day (which are Cost of food, Money person has and Concern about weight).

	Economics	Physics	TOTAL
Identify partly	8	3	11
all main variables	1	5	6
TOTAL	9	8	17

Table 12. 5 - Identification of variables and gender, for written task about a STELLA model for a person controlling his body weight through diet and exercises (intensive study - Question 7b).

This result adds to the evidence that background is important.

No other significant differences were found.

12. 8. ANSWERING THE RESEARCH QUESTIONS

12. 8. 1. HOW DO STUDENTS, FROM THE INTENSIVE STUDY AND THE SURVEY, DIFFER CONCERNING CAUSAL DIAGRAMS, ENTITIES AND MATHEMATICAL KNOWLEDGE ?

Independently of background there are few differences which suggest that students in the intensive study did much the same with causal diagrams, and thinking about variables and systems. Also, results suggest that maybe they have comparable mathematical knowledge.

Taking into consideration background, it seems that there is an advantage to students of the intensive study with a Physics background concerning number of reasonable links, imagining the world in terms of variables and using the idea of difference equations in iterative loop to interpret a piece of computer program. These results indicate that, for these students, some learning took place.

12. 8. 2. A) AFTER HAVING WORKED WITH STELLA, CAN STUDENTS THINK OF VARIABLES AS TANK OR FLOW GIVING THE CORRESPONDING UNIT OF MEASURE ?

The majority seemed to be able to think of variables as tank or flow, but less than half could give correct units.

North London students maybe because they have a background in Physics were better in identifying correctly a variable as inflow/outflow or tank.

Female students were better in identifying correctly a variable as inflow/outflow or tank, giving a correct unit of measure.

12. 8. 3. B) AFTER HAVING WORKED WITH STELLA, HOW WELL DO THEY UNDERSTAND A STELLA DIAGRAM FOR A PERSON CONTROLLING BODY WEIGHT ?

The majority saw the situation as a system, considering food eaten per day and energy used up as the variables which affect body weight. Roughly half of the students could identify cost of food, money person has and concern about weight as the main variables affecting food eaten per day.

Students with Physics background, who worked with causal diagrams, were able to identify the three main variables which affect food eaten per day.

12. 9. OTHER EFFECT

Female students used at least one partly variable-ized link in the Greenhouse Effect task. This result adds to the evidence that there is a genuine gender effect.

CHAPTER 13 - CONCLUSIONS

13. 1. INTRODUCTION

In this chapter the general research question proposed in chapter 5, will be answered. Also, future possible research will be suggested.

13. 2. STRUCTURE OF THE WORK

This thesis has addressed the general question

Can sixth form students achieve success or some valuable work with (certain) computational modelling systems ?

through attempting to answer three subsidiary questions:

1. What is required for students to use / make computational models ?

2. How good are (certain) modelling systems as tools for making models ?

3. How is students' thinking about / with models related to their other knowledge ?

Also, a second general question related to modelling was addressed:

What can be said about the model building capability of sixth form students, without using the computer, concerning (a) work with causal diagrams and (b) the relevant mathematical knowledge needed?

Attention was restricted to VI form students, but included students with background in Economics as well as Physics. Modelling tools selected were STELLA, and a new tool 'IQON', for making 'semi-quantitative' models (see chapter 1, section 1. 4). In parallel to a group of students who worked with IQON, a second group of students used 'causal diagrams', without the computer (see chapter 6). Both groups subsequently used STELLA, for which causal diagrams are recommended in the literature. The tasks given included both exploration of given dynamic models, and the construction of dynamic models by the student (see chapter 5, section 5. 4, for design). This work involved 34 students, working in pairs intensively for a total of about 3 hours, observed by the researcher, on specific tasks (see chapter 5, section 5. 6). In addition about 70 other comparable students were surveyed, using a pencil and paper questionnaire covering experience with computers, some mathematical and computational skills and causal diagramming tasks (see sections 5. 5. 1 and 8. 3). Students in the intensive study answered some parts of this questionnaire and additional questions about STELLA (see section 5. 5. 2), with further questions about the nature of models (see section 5. 5. 4) and about forms of behaviours (graphs) of output from models (see section 5. 5. 3).

13. 3. PREVIOUS EXPERIENCE, KNOWLEDGE AND SKILLS

Students surveyed were predominantly of Physics background. Students of the intensive study were of two different backgrounds: Physics and Economics. *Results for students of the intensive study were essentially comparable to those in the survey* (see section 12. 6. 6).

13. 3. 1. EXPERIENCE WITH COMPUTER

Previous experience with the computer may be an important factor for developing model building capability.

Very nearly all students had some experience with hardware, but a minority claimed no experience with most of the kinds of software relevant to modelling, the remainder dividing equally between having used one or two, and more than two types (40% in each group). Thus it seems that most students had at least the minimum necessary experience to work on modelling with the computer (see section 8. 4). No investigation was made of how much they had used hardware and software.

13. 3. 2. MATHEMATICAL KNOWLEDGE

The questionnaire used in the survey included questions about the construction and interpretation of graphs for data, proportional relations, pictorial solutions of a problem, mathematical equations for graphs, differential equations and comprehension of pieces of computer programs (see section 5. 5. 1 and Appendix I. 2).

13. 3. 2. 1. Achievement in Mathematics

Students in the survey presented a middling achievement in Mathematics. They did not have problems with most elementary questions, but they had low scores in questions about differential equations and comprehension of pieces of computer programs (see sections 9. 1 and 9. 2). Difference equations in an iterative loop are essentially required for describing a dynamic model. One elementary question (number 23, see charts 9. 1 and 9. 2) contained the idea of iteration, which suggests that the low scores in comprehension of pieces of programs can be explained due to misunderstanding of the difference equations. The idea of iteration may not be the problem. These results are consistent with those reporting difficulties in defining mathematical equations in expressive tasks with STELLA (see section 4. 6).

These results suggest that we should not assume that students are able to construct even simple pieces of computer programs by themselves. We can assume that their elementary mathematical competence is adequate, but should not assume that they understand differential or difference equations.

13. 3. 2. 2. Correlations

A general look at correlation tables in Appendix X (see also section 9.5) shows that there are several low correlations best interpreted, in view of the high reliability of subtests, as indicating that a complex of abilities is involved, and not a simple structure of one or two main abilities. There is some correlational evidence for the existence of "mathematical" ability since questions of mathematics are in general moderately or strongly correlated (see section 9. 5). These results were in fact confirmed by the existence of a mathematical factor which was interpreted as 'quantitative reasoning' (see section 9. 6. 1).

13. 3. 2. 2. 1. Mathematics, Computers and System thinking

The students in the survey who had larger experience with software and hardware seemed also to score better in questions about comprehension of pieces of programs. The ones with the larger experience with software also had better scores in Mathematics. Students with better scores in Mathematics were better able to think reasonably, using variables and to construct more complex causal structures, in causal diagram tasks.

Thus, for students to be able to engage in the modelling process, knowledge about Mathematics is seen to be helpful. These results are consonant with the background effect found in the intensive study. Students with a background in Physics were better in system thinking tasks, which may be because they know more Mathematics (see chapters 10, 11 and section 13. 3. 3).

13. 3. 3. EFFECTS OF FACTORS

Throughout the work, both in the survey and in the intensive study, relatively few and in general only rather small effects of background, age, gender and place of school were noticed. There were occasional differences, indicating some degree of heterogeneity amongst students. Thus, in the survey, where there were differences, they tended to be in favour of Kent students rather than London students. Nevertheless, the similarities of these groups were much more striking than any differences (see chapter 8).

In the intensive study, working with IQON and causal diagrams, a small number of minor differences were noted (see chapter 10). As might be expected, and consonant with the literature, students with a background in Physics had an advantage over those with a background in Economics in system thinking - Physics students seemed more cognitively adapted to system thinking (see section 3. 4), maybe because they knew more Physics and Mathematics (see section 13. 2. 2. 2. 1). Also, for the work with STELLA, female students had some advantage over male students, in system thinking (see chapter 11). However, for the work with IQON and causal diagram, male students had some advantage over female students concerning giving mechanisms and using entities of the real system (see chapter 10). These seemed to be genuine gender effects, not explained by other factors.

Students in the intensive study were drawn from two regions of London, North and South East and differed in age (16 - 18). There was no intention to study differences of this kind, but it was noted that when there were differences, they tended to be in favour of North London students, and younger students. However, no conclusions can be drawn from this, because the samples were biased, such that South East London students had a predominance of those with an Economics background, as did the older students. Thus any effects may well be due to this difference in background.

13. 4. WHAT IS REQUIRED FOR STUDENTS TO USE/MAKE COMPUTATIONAL MODELS ?

According to this research, to use/make computational models the following aspects seem important:

- reasoning in a semi-quantitative way;
- use of IQON;
- imagining the world in terms of variables;
- knowledge about rate of change;
- thinking at a system level and
- understand causation in a system.

13. 4. 1. SEMI-QUANTITATIVE REASONING

Semi-quantitative reasoning is natural even in quantitative tasks (see sections 11. 1. 1, 11. 1. 3 and 11. 2. 1). It is present when thinking about causally connected entities, and thus in developing or understanding causal diagrams. *Semi-quantitative reasoning tends to be complex and seems to depend on subject matter* (see section 9. 6). Students reasoned semi-quantitatively and satisfactorily when working with modelling tasks, in terms of entities, structures and output (dynamic behaviour) (see, for example, sections 10. 9. 3, 11. 6 and 12. 2). Also, there is some indication that *semi-quantitative reasoning might depend on gender and background.* Female students, and students with background in Physics were responsible for larger fractions of semi-quantitative descriptions and achieved better in system thinking tasks (see, for example, sections 11. 1. 1. 1, 11. 1. 2. 2, 11. 1. 3 and 11. 6. 1).

13. 4. 2. CAUSAL DIAGRAMS AND IQON

13. 4. 2. 1. Causal diagrams

The work with causal diagrams presented students with some difficulty. Students who worked with causal diagrams tended to present doubts about links and tended not to understand the effects of a plus or minus sign (see section 10. 7. 3. 2). In general, they gave partly right descriptions and, in explaining models, focussed only on cause-effect pairs or described the behaviour of isolated entities (see section 10. 7. 4. 3. 1). When explaining in their own words they invoked the main responsible variables that cause global warming (see section 10. 7. 4. 4) and when criticising considered that the quantitative aspect was missing (see section 10. 7. 4. 6).

13. 4. 2. 2. IQON

Students were able to use IQON successfully. The ones who worked with IQON tended to give correct descriptions (see section 10. 7. 4. 3. 1) and to follow a chain of boxes and loops in their explanations (see section 10. 7. 4. 4). They tended not to find the model difficult to understand, and to consider it limited (see section 10. 7. 4. 6).

13. 4. 2. 3. IQON versus causal diagrams

Students who worked with IQON in general achieved better in exploratory and expressive tasks. IQON, due to its runnability, seemed to have helped students to think about systems (see section 10. 8). These results suggest that work with IQON instead of causal diagrams can be recommended.

Despite IQON having provided a more malleable environment to develop causal diagrams, the work with IQON and causal diagrams seemed not to have differed concerning the effect on the students' achievement with STELLA's expressive task (see section 11. 6. 1). This result raises practical questions such as whether it is worth investing money to run causal diagrams in a computer. IQON gives an easier and a good way to use the computer, while causal diagrams are inexpensive to use. In this case, the decision should be based on other criteria such as the need for introducing computers to novices.

However, as STELLA was used mainly as a drawing tool, results concerning the expressive task are limited, because students developed only non-runnable structures (see section 7. 4). Results are not concerned with quantitative expressive tasks. Further research would have to be done to shed light on this aspect.

13. 4. 3. THE IDEA OF VARIABLE

The idea of a variable is critical for dynamic modelling. When modelling a dynamic system the student has to imagine the world in terms of variables.

Students in some cases replace variables by objects, events and processes, though this seems to depend very much on the problem. Nevertheless, given the choice students did tend to prefer variables to other entities (see section 8. 9). Unlike Physics related problems, problems about common everyday events seem not to generate variables (see sections 8. 10, 10. 8. 2, and 12. 6. 4). Independently of background, most students tended to propose the description of Economics related phenomena through structures of tanks and rates in STELLA (see section 11. 5). This suggests that general social phenomena can also be seen in terms of variables. These are just the areas where semi-quantitative reasoning is particularly appropriate.

13. 4. 3. 1 Variables in explanation

The articulation of variables in explanations may indicate whether the student was able to imagine the world in terms of variables.

Even when working with Physics related situations students tended not to use variables in their explanations. Explanations were rich in objects (see sections 11. 1. 1. 2 and 11. 1. 3). *Variables were mostly used by students with a background in Physics,* maybe because they know more Mathematics, or because they are used to thinking about variables when solving Physics problems (see sections 11. 1. 1. 2 and 11. 1. 2. 2) . Imagining the world in terms of variables should not be taken as unproblematic in any teaching and learning situation.

13. 4. 3. 2 Use of time as variable

Time will not normally appear as a variable in dynamic models. It is of special interest because dynamic models evolve in time. Normally it will not be a causal variable. It is therefore a good feature that *students tended not to use time as an active entity in causal diagrams* (see sections 8. 8 and 12. 6. 1).

13. 4. 4. THE IDEA OF RATE OF CHANGE

The idea of rate of change is fundamental to quantitative modelling of a situation and to understanding models developed in STELLA.

The idea that a variable changes seemed not to be a problem. Students were able to use this idea to construct graphs (see sections 9. 2 and 9. 4) and to develop and interpret causal diagrams (see chapter 8 and 10) and STELLA models (see chapter 11). *The problem seemed to be the representation of the rate of change of a variable as another variable in a symbolic mathematical form* (e. g. differential equation) (see sections 9. 2, 9. 4 and 12. 6. 5). Also, students of the intensive study had problems in giving units to rates (see section 12. 7). These results suggest that to engage in the modelling process some instruction about rates of change, in terms of difference and differential equations, is needed (see section 13. 3. 2. 1, before).

13. 4. 5. SYSTEM THINKING

The description of any large system will necessarily involve the interaction of several variables. The understanding of a model is related to the ability to manage all the relevant facets of a system , such as a dominant feedback loop or the simultaneous action of rates. Students who think at a system level can be considered as having a higher level of perception of the situation.

System level thinking presented students with difficulty. Students from the survey misinterpreted the behaviour of entities involved in feedback (see section 8. 5. 3. 2). Students in general tended not to think at a system level in questions related to Physics.

They could develop more elaborate structures in general questions, which might suggest that these tasks were more suitable for system thinking (see sections 8. 12 and 12. 6. 2). There was an advantage for students in the survey over those 32 students in the intensive study, on comparable paper and pencil tasks, concerning system thinking, which can be explained maybe because the survey involved predominantly students with background in Physics. In fact, students with a background in Physics tended to construct causal diagrams with more elaborate structures (see section 12. 6. 2).

Few students of the intensive study gave evidence of being able to manage loops in exploratory tasks with IQON and causal diagrams (see section 10. 7. 3).

Only students with a background in Physics were able to see Physics related tasks at a system level (see section 11. 1). However, after having worked with STELLA models, students of the intensive study could interpret a STELLA model at a system level, which suggests that some learning took place (see section 12. 7).

Unlike for exploratory tasks, in expressive tasks students could develop more system thinking (see section 10. 8. 3), which suggests that this kind of task should <u>not</u> be neglected in planning any teaching.

13. 4. 6. CAUSAL THINKING

System thinking involves causal thinking. When deciding how to model a system in terms of variables, causal links and feedbacks, one has to account for 'what causes what' and 'how'. When a student is able to link entities reasonably in a model, and when s/he is able to give a mechanism to explain a link, for example, s/he may be thinking in a casual way. Reasonable links, mechanisms and causally articulated links were all used to provide evidence of causal reasoning.

Causal thinking presented students with difficulty. Students of the survey had problems with causal thinking mainly in Physics related problems (see sections 8. 6, 8. 9. 1, 8. 12 and 8. 14). Also, the causal reasoning of students of the intensive study when working with exploratory modelling tasks was unsatisfactory (see sections 10. 7, 11. 1. 1 and 11. 1. 2).

<u>Male</u> students when working with causal diagrams tended to think in a causal way, and so did students with a <u>Physics</u> background when working with IQON. Place and age effects in favour of <u>North</u> London and <u>younger</u> students were found for the work with casual diagrams.

Students of the intensive study seemed to have managed causation in the expressive task (see section 10. 8. 2), which suggests, like in section 13. 4. 5, that this kind of task should <u>not</u> be neglected in planning any teaching. Also, there was some positive effect of the work with modelling tasks on students' understanding of how causation works in those systems (see section 12. 6. 3).

13. 5. WORK WITH PEERS

The literature gives evidence of the advantage of working in pairs from the point of view of learning. Students through interaction with their peers could perhaps go further in terms of performance (see section 5. 6. 1).

Results suggest that working with peers in expressive modelling tasks can be recommended. But teachers must be careful to get a constructive working partnership. When the students do not know each other they may not work in a collaborative way. On the other hand, working together in exploratory tasks can be problematic if the students have to fill their own questionnaires - they might work individually, in their own pace (see sections 10. 5 and 10. 6. 1).

13. 6. HOW GOOD ARE IQON AND STELLA AS TOOLS FOR MAKING MODELS?

The present research is not an evaluation of IQON or STELLA. However, at least at a basic level, something must be said about these two systems.

Students can learn IQON very quickly. The teaching tasks seemed sufficient to put the students in a position to explore IQON models. The teaching and exploratory tasks may have helped students to express themselves with the tool. After being taught, students had few problems in dealing with IQON's basic functions. Similarly, students could quickly learn to deal with the basic operations in STELLA, although a few of them asked for help (see section 10. 6).

STELLA's metaphor seems to have a strong influence on the way the student thinks about variables. Unlike work with causal diagrams and IQON, where the student is free to choose entities, STELLA's structure works as a "strait jacket", which obliges the student to use the idea of rates of change. When this knowledge does not exist, the student cannot express himself with the tool, because the models will not make much sense (see section 11. 6).

Because of IQON's limitations, activities must be carefully chosen, since not any kind of system can be represented with the tool (see section 13. 10. 1). STELLA is more powerful, and so demands more extensive and specific previous instruction to be successfully used (see section 13. 10. 3).

13. 7. HOW IS STUDENTS' THINKING ABOUT/WITH MODELS RELATED TO THEIR OTHER KNOWLEDGE ?

Students when thinking about/with models seem to articulate analogies according to their scientific backgrounds, and use their own ideas. They tended not to invoke reality to interpret models, but have a well defined conception of the relationship between model and reality.

13. 7. 1. RECOGNITION AND TRANSFERENCE OF STRUCTURE

The literature considers as a key element of problem solving the identification of the underlying structure of a problem and the transference of this understanding to other problem areas (see section 3. 2. 2).

For exploratory tasks, students were able to suggest other (Economics) related situations that could be modelled with the same STELLA structure. Situations were consonant with students' background (see section 11. 5).

For the expressive task, it does seem that at least at the visual level students transferred a model structure from one situation to another. Most pairs simply imitated a chained structure of two or three tanks. A few did not try to imitate the tanks structure, and tried to develop their own structures (see section 11. 6).

Since students were able to articulate analogies, the teaching of structures of models, as proposed in section 2. 7. 4, is recommended.

13. 7. 2. RELATION TO REALITY

Relating a model to reality is an important ability, requiring the student to think about the modelled situation. *In general, for some expressive tasks, students were able to construct causal links that made sense, and their models contained a large proportion of reasonable links.* These results suggest that students thought about the real system (see sections 8. 14 and 10. 8. 2).

For exploratory tasks with IQON and understanding a causal diagram, few students gave evidence of thinking outside the computation. Written explanations were unsuccessful concerning entities of the real system (see section 10. 7. 3. 1 and 10. 7. 4).

For the work with STELLA, most explanations used only entities inside the computation (see chapter 11).

Concerning student's conceptions of models in general, students in the intensive study thought that models can be approximately correct, and that ones with a correct structure (diagram or equations) can make wrong predictions. For them, model and reality are entities distinct in nature, and models represent only simplified aspects of reality. Also, they think that playing with a model can help with thinking about the real situation, and that every situation can be in principle correctly modelled. They recognized that it is not enough for a model to work - it must correctly describe reality. Even a simple model can be correct, and accuracy does not guarantee truth - it is possible to design a highly accurate model which does not correspond to any real situation. After working with models students did not change their minds very much. The few items about which there were some changes of opinion were the ones about simplification. Some students tended to think that models can represent also complex aspects of reality, and that a model which is very simple can also be true (section 12. 4).

Relating model to reality should not be taken as unproblematic in any teaching and learning situation.

13. 7. 3. STUDENTS OWN IDEAS

This research did not aim to study in any detail students' spontaneous ideas when working with modelling. However, there is some evidence that *students used their own ideas when they selected or decided about specific entities for causal links, causal diagrams, IQON model and when explaining in exploratory tasks* (see sections 8. 5, 8. 9, 8. 10, 8. 11, 10. 7. 4 and chapter 11). *Also, when taking a consistent and well defined view of models and when tending to model situations using the simplest dynamic pattern possible - the linear pattern* (section 12. 2 and 12. 4). These results suggest that model building may have the potential for making explicit students' conceptions about models, entities and outputs.

Asking students to explain in their own words what happens in a model can be a way of making explicit their level of perception of the situation. *When explaining in their own words students of the intensive study gave answers which suggested that there were different levels of perception of the models.*

For exploratory tasks with IQON and understanding a causal diagram, half of the students considered that the main thing responsible for global warming is at least one, or a combination, of two specific variables. The other half gave non-specific answers where the student did not specify variables as responsible. Specific answers were mostly given by students who worked with causal diagrams who had to make the simulation in their minds and, because of that, were sure about what variables to mentally alter. Non-specific answers were mostly given by students who worked with IQON, maybe because of the complexity of the model - with many animated boxes on the screen (see section 10. 7. 4. 4). These results suggest that students who worked with IQON may have had problems in understanding a complex model.

For exploratory tasks with STELLA, in general, explanations were often unsatisfactory, derived from partial observation - students did not see the general pattern described. Partial observations were common amongst Economics students from South East London (see sections 11. 1. 3 and 11. 2. 1).

13. 7. 4. JUDGEMENT OF MODELS

For the exploratory tasks with IQON and understanding a causal diagram, *students in general considered variables and links and correct structure as the main factors to judge a model as accurate. For them, the model is accurate if it describes reality well.* Concerning justifications for accuracy, *the majority of the students gave answers focussing on clear variables as responsible for effects on temperature with a minority giving a vague description of the model's structure* (see section 10. 7. 4. 5).

Concerning their conception of models, students in the intensive study thought that a model which is considered accurate does not necessarily account for the truth. As pointed out in section 13. 7. 2, it is possible to design a highly accurate model which does not correspond to any real situation.

The ability to reasonably criticise a model suggests that the student has reached a higher level of understanding of the model and of what it is representing. *About half the students could reach a reasonable level of criticism of the IQON model or causal diagram.* The main criticisms were:

- model is limited;
- quantitative aspect is missing and
- model is difficult to understand (for causal diagrams only) (see section 13. 4. 2. 1).

Students who worked with IQON tended to consider the model limited. The students from South East London tended not to (see section 10. 7. 4. 6), but we noted previously that they mainly had an Economics background. Students who considered the model limited were more capable of criticising the model.

For the exploratory work with STELLA (two cars in a stream of traffic) *a minority considered the limitation of the model as the reason for its behaviour.* Physics students were more critical and considered the model limited.

Half considered the limitation of the model as a reason to claim that the situation could not happen in reality. Older students were more critical, considering the model limited and that the situation could not happen in reality (see section 11. 3).

Questions asking the student to evaluate the limitations of a model are recommended in teaching about models.

13. 8. LINKING FINDINGS AND EXPECTATIONS

In chapter 3 claims of other authors about the use of modelling systems and causal diagrams were discussed. The research was designed to get evidence about some of the expectations summarized in table 3. 1, which is reproduced in table 13. 1 below.

This section discusses under a number of different headings the relation between the findings and these expectations.

Most expectations in table 13. 1 (2, 5, 6, 7, 8, 11, 13, 14, 15 and 16) were fulfilled. Three expectations (9, 10 and 12) could not be checked because of limitations of the data. Two expectations were partly verified (1 and 4) and only expectation 3 tended to be contradicted. These results suggest that students had a general level of achievement roughly similar to what was expected from other researches.

1) After the understanding of the situation being modelled, we should expect no trouble in mastering the mechanics of the construction of diagrams in IQON, STELLA and the Macintosh computer (e.g. selection of primitives, mouse events and the use of pull down menus).
2) We should expect students to easily master the syntax of BASIC code when using modelling systems as DMS or CMS. Consequently, we should expect them to be capable of mastering the similar syntax of equations generated in STELLA.
3) We should expect students with modest command of mathematics, after the understanding of the situation being modelled, to successfully use the iconic representation as a way of thinking about systems - STELLA through visual representations makes ideas more easily understandable and connected to real-world phenomena.
4) We should expect problems in understanding of graphs generated by the modelling systems, due to possible deficiency in interpreting graphs.
5) We should expect much trouble in understanding of rates and levels.
6) We should expect no problem in learning causal loop diagramming as a technique, regardless age or background. However, not all students will be able to follow the connections between loops, when complexity is introduced. Complement: Causal diagrams are not runnable. There is not a computer program to bring it to life.
7) We should expect the recognition that different problems share the same underlying structure.
8) We should expect students to be able to identify the underlying structure of a problem and transfer the understanding to other problem areas.
9) We should expect much difficulty in translating a verbal description into an equation.
10) We should expect at the end some gain involved in graphing and graph interpretation.
11) We should expect difficulties when defining values to less quantifiable parameters in STELLA. For example, when developing a model for "controlling body weight through diet and exercises", it would be difficult to give a value to a rate called "energy used up per day".
12) We should expect some positive effect of the use of multiple-linked representational systems.
13) Even working with very simple STELLA models, we should expect some understanding about calculus and differential equations, because STELLA makes step by step computation - which is considered a good way of looking at the solution of differential equations, and uses the ideas of rate of change and integration.
14) Some topics will be more suitable to be developed through the use of causal diagrams than others. Consequently, we should expect students to develop more complex causal loop structures in General Topics than in Physics.
15) We should expect gender effects concerning the work with system thinking.
16) We should expect Physics students to be more cognitively adapted to the system thinking approach .

Table 13. 1 - Copy of table 3. 1 with summary of the main relevant expectations for the research.

13. 8. 1. 'SYNTAX' OF MODELS

Expectations numbers 1, 2 and 6 concern the syntax of causal diagrams, IQON and STELLA. Expectations 2 and 6 seemed to have been fulfilled, while expectation 1 was only partly verified. We can say that in general students could manage the mechanics of the construction of causal diagrams (and IQON models), which was a positive result. But we are not very sure what they can do in STELLA, since the evidence here is rather limited.

13. 8. 2. SUITABILITY OF TOOL

Expectations 11 and 13 are about STELLA, while expectation 14 is about causal diagrams. As a negative aspect there is some evidence that students had difficulties in quantifying parameters in STELLA (see 13. 8. 3). A positive aspect is that students seemed to have gained some understanding of difference equations in an iterative loop after having worked with STELLA tasks. Concerning expectation 14, important differences between causal structures were found for different topics (see section 13. 4. 5).

13. 8. 3. MATHEMATICS AND GRAPHIC REPRESENTATION

Expectations 3, 4, 9, 10, 12, and 13 are about mathematics, graphic representation and multiple linked representations.

There is not enough evidence to test expectations 9, 10 and 12. Evidence is rather limited for expectations 3 and 4. Expectation 3 tended to be contradicted, since in general students in the intensive study who have a modest command of mathematics (the ones with an Economics background) had more problems in using the iconic representation as a way of thinking about systems. Expectation 4 was partly verified. Surveyed students had low scores in associating mathematical equations with graphs, which may reflect a deficiency in the understanding of graphs. Also, some students in the intensive study when working with IQON and STELLA avoided asking for graphs (see 10. 6. 5). They may have avoided graphs because they felt insecure about knowing how to interpret them. For expectation 13, as pointed out in section 13. 8. 2, some learning about difference equations in an iterative loop took place.

13. 8. 3. 1. Rates

Expectations 5 and 11 are about 'rates' and were both fulfilled. Students did not have problems in understanding rates at an intuitive level, but did have difficulties when they were in a symbolic mathematical form. Students could not define values and units for rates (see section 13. 4. 4)

13. 8. 4. PROBLEM STRUCTURE, TRANSFER

Both expectations 7 and 8 seemed to have been satisfied. Students were able to propose other situations that could be modelled with STELLA structures. Also, they could transfer at least at the visual level a 'tank' structure to describe a person controlling her/his weight through diet and exercises (see section 13. 7. 1).

13. 8. 5. GENDER

Expectation 15 was fulfilled. But it is interesting to remember that there was an advantage to male students when working with IQON and causal diagrams and an advantage to female students when working with STELLA (see section 13. 3. 3).

13. 8. 6. PHYSICS BACKGROUND

Expectation 16 was also satisfied. Throughout this research there was an overall advantage to students with a Physics background in system thinking tasks (see section 13. 3. 3).

13. 9. ANSWERING THE FIRST GENERAL RESEARCH QUESTION

Results used to answer the three general research subquestions were used to answer the first general question.

13. 9. 1. CAN SIXTH FORM STUDENTS ACHIEVE SUCCESS OR SOME VALUABLE WORK WITH EITHER OR BOTH MODELLING SYSTEMS?

There is enough evidence throughout this research to say that students can do some valuable work with IQON and STELLA. Students have shown some positive achievement in expressive and exploratory tasks with causal diagrams and modelling systems, in the intensive study.

The valuable work, with causal diagrams and IQON, concerned:
- a reasonable achievement with causal diagramming in general, and with the expressive task about a current issue in IQON;
- the level of criticism of models;
- successful peer interaction mainly in expressive tasks;
- attitudes towards the tasks and
- the use of IQON.

The valuable work with STELLA, concerned:
- no substantial problems with variables that accumulate, when making a model;
- reasonable achievement in written tasks about a STELLA model for a person controlling his/her weight through diet and exercises ";
- recognition and transference of structures;

- facility with the basic operations with STELLA and
- reasonable explanations for a more elaborate STELLA model describing two cars in a stream of traffic.

Additional positive aspects were:
- general knowledge of exponential decay and growth;
- a consistent and well defined view of models and
- changes in conceptions that resulted directly from the work with computational modelling systems.

After working with IQON/causal diagrams and STELLA tasks, there was an advantage to students of the intensive study with a Physics background over surveyed students concerning understanding of causation, imagining the world in terms of variables and understanding difference equations in an iterative loop. These results indicate that some learning took place.

13. 10. SUGGESTIONS FOR FUTURE RESEARCHES

13. 10. 1. REPROGRAMMING IQON

The version of IQON used in this research does not allow the modelling of several Physics related situations. There is a restricted number of situations that could be classified as related to Physics that can be modelled with IQON. But IQON is reasonable for modelling general situations as the ones worked.

In IQON there is no distinction between quantities and rates of change. Also, the level or semi-quantitative state of a variable is responsible for the change in the level of a second variable, making impossible modelling situations in which the level or state of one box is responsible for its own variation - this means that situations which are described mathematically by differential equations of the kind $\frac{dQ}{dt}$ proportional to Q, cannot be considered. So, it is not possible to treat important problems as *radioactive decay*, *leaky tank* and others of similar mathematical structure, in IQON.

As research questions related to the development of software I propose

1) Could IQON be better?

2) Is the Mathematics of IQON suitable? How can it be improved?

3) Could we program IQON to add another primitive to represent semi-quantitatively rates of change? How should this primitive work?

4) Is the causal diagramming language used in IQON really the best way to represent semi-quantitatively systems? What alternative language could be proposed?

13. 10. 2. CONCEPTION OF ENTITIES AS VARIABLES

One of the most important aspects of this research is the conception of entities as variables. Care was taken to get the most reliable classification possible, but it is impossible to be absolutely sure about the correspondence between the word written by the student and what really was in her/his mind. An entity which was classified, for example, as a process by only reading what was written, for the student could internally mean a rate of change.

One could argue that the classification of entities as treated here is just an artifact - a problem related to language - because if you push the student when describing a situation s/he might recognize what would be classified as 'non-variable-ized entities' as the real variables needed to describe adequately a system. The characterization used in this thesis is without doubt disputable. Due to these uncertainties, the conception of entities as variables, events, processes and objects, no doubt deserves further exploration.

This research shows that this distinction seems to exist. It does not say why students tended not to use variables and has some indication of when they use it. As future research questions I propose

1) Is this distinction sensible?

2) What does the student really think? Why does the student use objects, events or processes, and when?

3) How is the use of these entities related to their other knowledge?

4) If this distinction really exists, should we use it for curriculum planning? How?

13. 10. 3. EXPRESSIVE QUANTITATIVE MODELLING TASKS WITH STELLA

The present research was very limited concerning quantitative expressive tasks, since the models constructed were non-runnable. From the point of view of exploratory and expressive tasks, working just few hours with STELLA is not recommended. There are many abilities involved in learning to model with STELLA, which should be developed in class. I propose the investigation in depth of these abilities, through the development of similar work with STELLA, spreading out the teaching and allowing more time to quantitative modelling tasks. As a possible research question I suggest

What is necessary for the student to master the construction of runnable models in STELLA?

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Appendix I. 1.

QUESTIONNAIRE ABOUT MODELLING - PART 1

Student : ______________________________

School : ______________________________

KNOWLEDGE ABOUT LANGUAGES AND MODELLING SYSTEMS

1) Indicate with ticks whether you have heard of, or whether you have used, any of the programming languages and Modelling Systems below.

	I have heard of it	I have used it
BASIC language	☐	☐
PASCAL language	☐	☐
LOGO	☐	☐
PROLOG	☐	☐
Dynamic Modelling System (DMS)	☐	☐
Spreadsheets	☐	☐
Cellular Modelling System (CMS)	☐	☐
STELLA	☐	☐

A different one (please specify): ____________________

____

2) Tick any of the kinds of computer below which you have ever used

☐ BBC.

☐ Commodore Amiga.

☐ Macintosh.

☐ IBM or IBM Compatible (eg. Armstrad).

☐ Nimbus.

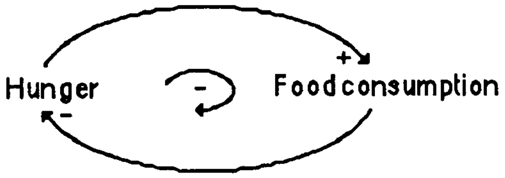
☐ A different one (please specify): ________________

____

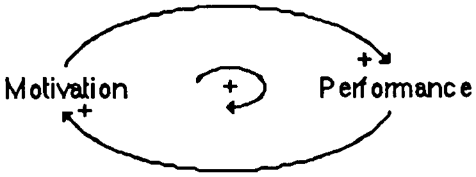
Causal diagrams

Causal thinking is the key to organizing ideas in a system dynamic study. We can represent the sentence "food intake influences weight" by an arrow diagram like **food intake --------->$^{+}$ weight**. The positive sign (+) means that the food intake affects (or influences) the weight of a person in a positive way. A negative sign (-) means influence in an opposite (negative) way*.

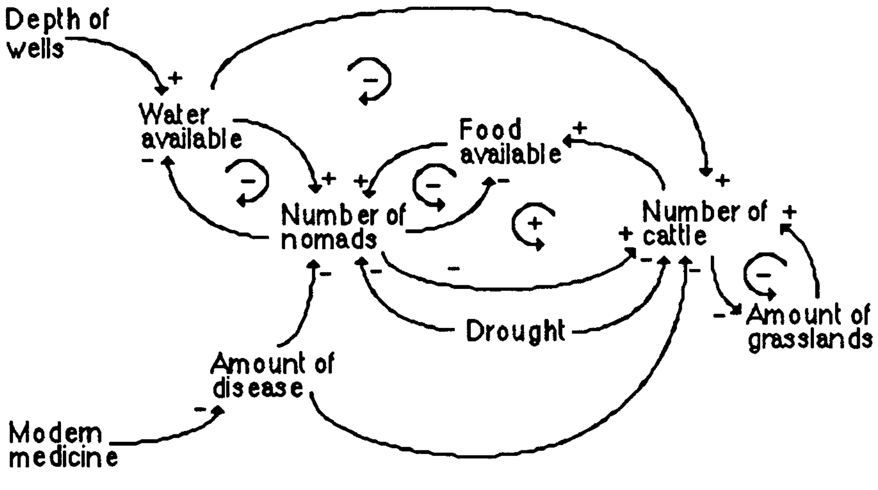
There are two kinds of closed loops. The negative, which seeks to maintain the status quo, resisting to change, such as the feedback process (a) presented below, and the positive, self-reinforcing, which generates run-away growth or collapse, such as the feedback process (b) (see symbol in the middle of the closed loops). It is possible to have very complicated positive and negative closed loops to show causation in a real system, as for example the tragedy of the Sahel (c). It is the causal structure which explains how the system evolves.



a) Example of negative feedback process.



b) Example of positive feedback process.



c) The tragedy of the Sahel.

---

* The positive and negative signs near the arrowhead indicate:

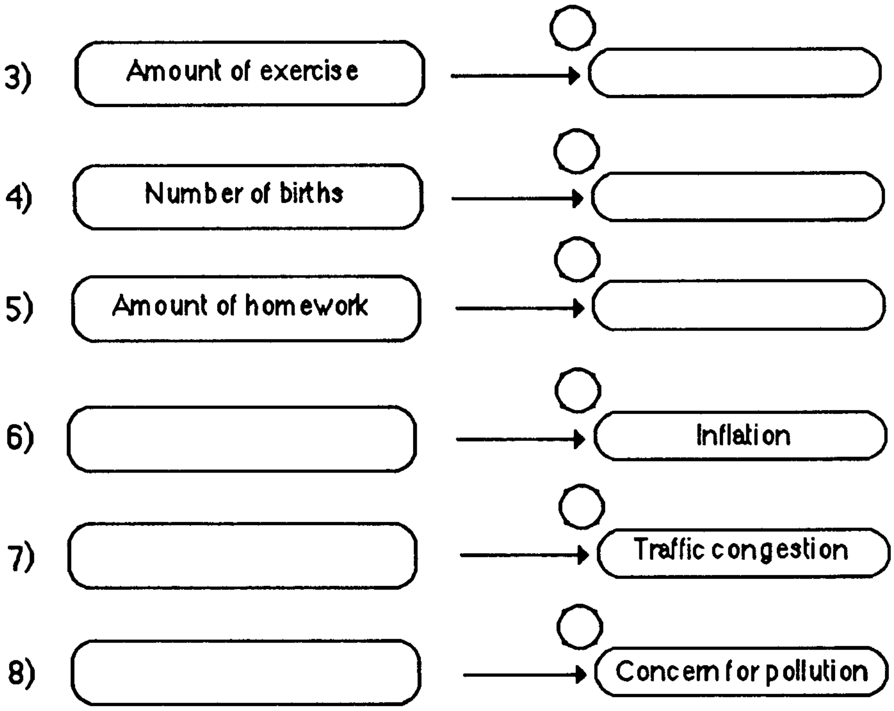
$\xrightarrow{+}$ {If the tail increases, the head increases;
If the tail decreases, the head decreases.

$\xrightarrow{-}$ {If the tail increases, the head decreases;
If the tail decreases, the head increases.

CAUSAL LINKS

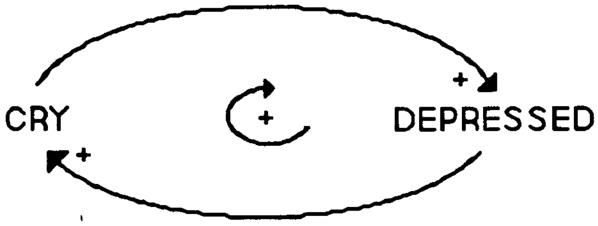
Complete the following sentences to describe a possible causal relationship between two quantities.
Indicate beside the arrow if the change in the second variable is the same (+) or opposite (-) from the first variable.

Example: Consumption of sweets causes changes in weight.

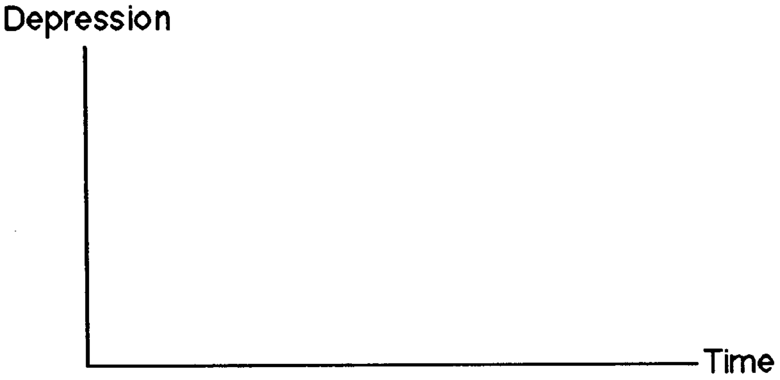


CAUSAL DIAGRAMS AND GRAPHS

9) Consider the following diagram.



This diagram says that the more I cry, the more depressed I feel, and the more depressed I feel the more I cry. If this is correct, sketch a graph showing how the amount of my depression will change with time.

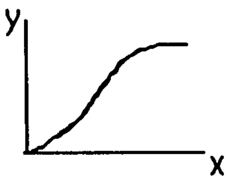


10) A student prepares for an examination. The more she prepares, the better her performance, up to a point, after which more work does not improve her test score. If this is correct, this relationship is best described by:

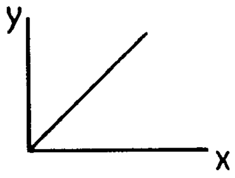
a)

b)

c)



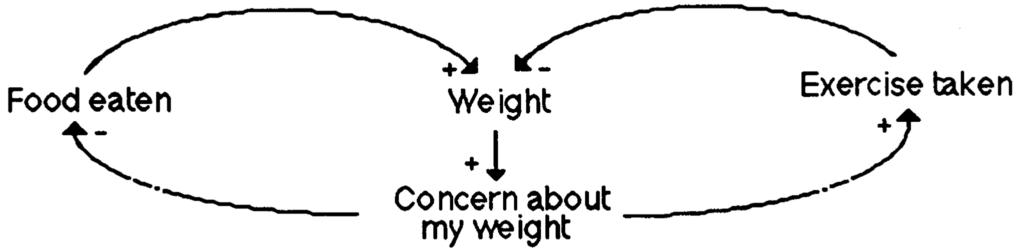
d)



What variable is plotted on axis y? __________

What variable is plotted on axis x ? __________

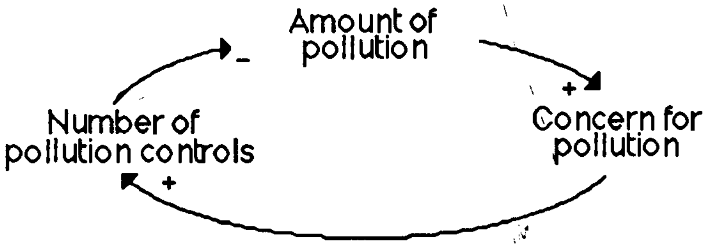
11) The diagram tries to show how a person's weight affects and is affected by other things.



If this diagram is correct, and my weight is high (overweight), which of the following will happen? Which will not happen? {please √ true or false for each}

	True	False
1 - I will become more concerned about my weight.	☐	☐
2 - I will eat less and take more exercise.	☐	☐
3 - I will eat more and take less exercise.	☐	☐
4 - My weight will decrease.	☐	☐
5 - My weight will increase.	☐	☐
6 - In the end I will get less concerned about my weight.	☐	☐
7 - In the end I will get more concerned about my weight.	☐	☐

12) The diagram tries to show the pollution control and public opinion.

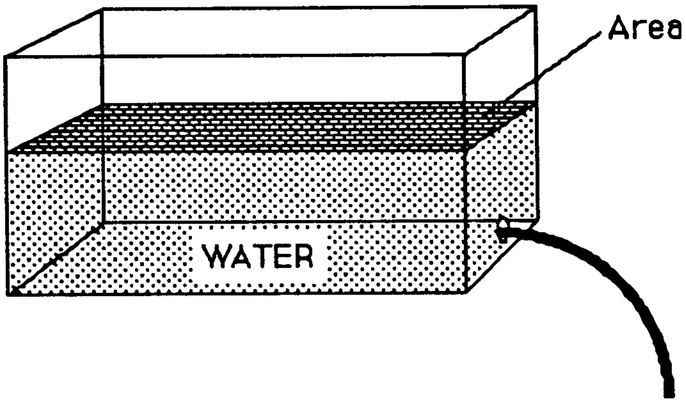


If this diagram is correct, and the Amount of pollution is high, which of the following will happen? Which will not happen? {please √ true or false for each}.

	True	False
1 - The Concern for pollution will increase.	☐	☐
2 - The Number of pollution controls will increase.	☐	☐
3 - In the end the Amount of pollution will increase.	☐	☐
4 - The Concern for pollution will decrease.	☐	☐
5 - In the end the Amount of pollution will decrease.	☐	☐

VARIABLES, PROCESSES AND CAUSAL DIAGRAMS

13) Suppose you have a tank filled with water which is draining through a hole as shown.

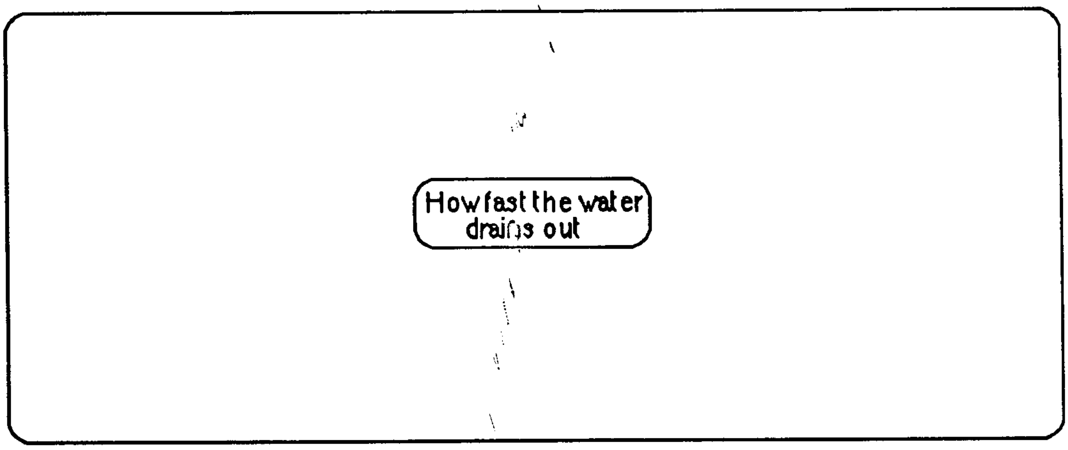


Here is a list of things some students thought should be considered in understanding what affects how fast the water drains out of the tank.

The water
Volume of water
The tank
Area of tank
Density of water
The hole

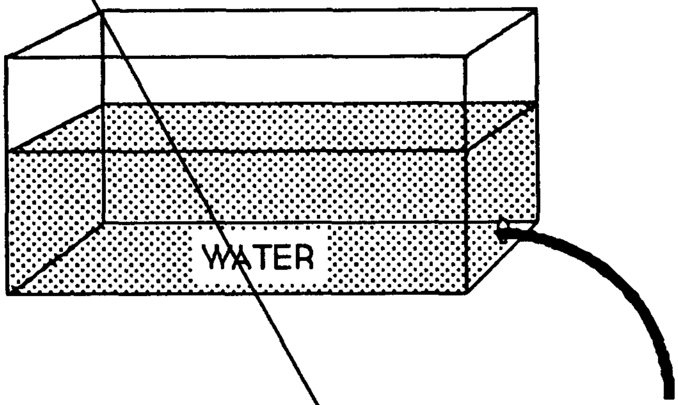
Depth of water
Colour of water
The curving of the water jet
Pressure of water
Size of hole
Time

Using only things in this list, choosing the ones which are needed, make a diagram to show what affects how fast the water drains out.



Now, in the list, cross out all the items which would be no use at all in making such a diagram.

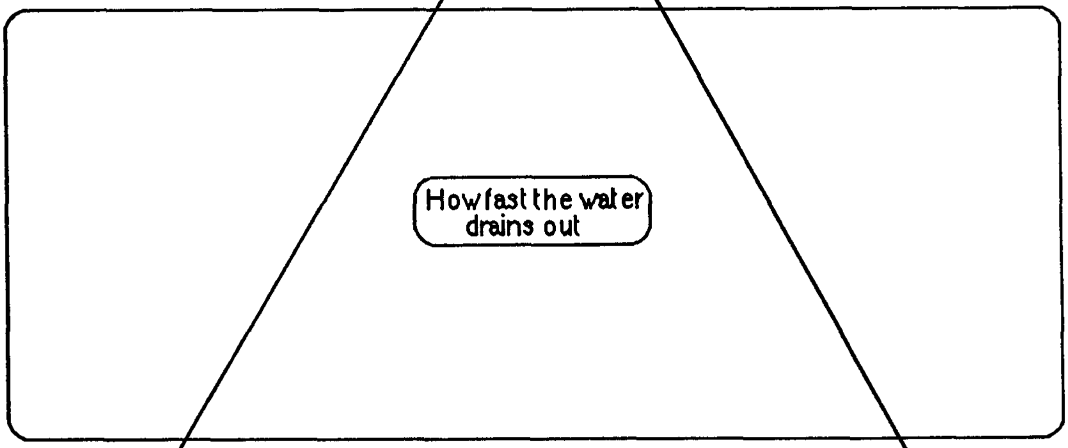
Suppose you have a tank filled with water which is draining through a hole as shown.



Here is a list of things some students thought should be considered in understanding what affects how fast the water drains out of the tank.

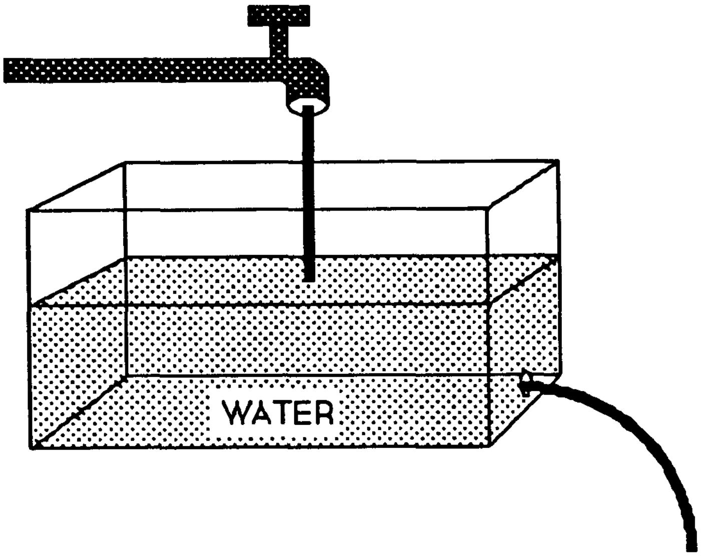
The water
Volume of water
The tank
Volume of tank
Density of water
The hole
Depth of water
Pressure of water
Outflow rate
Pressure of atmosphere
Colour of water
The curving of the water jet
Water level
Situation of hole
Size of hole
Gravity
Time

Using <u>only</u> things in this list, choosing the ones which are needed, make a causal diagram to show what affects <u>how fast the water drains out</u>.

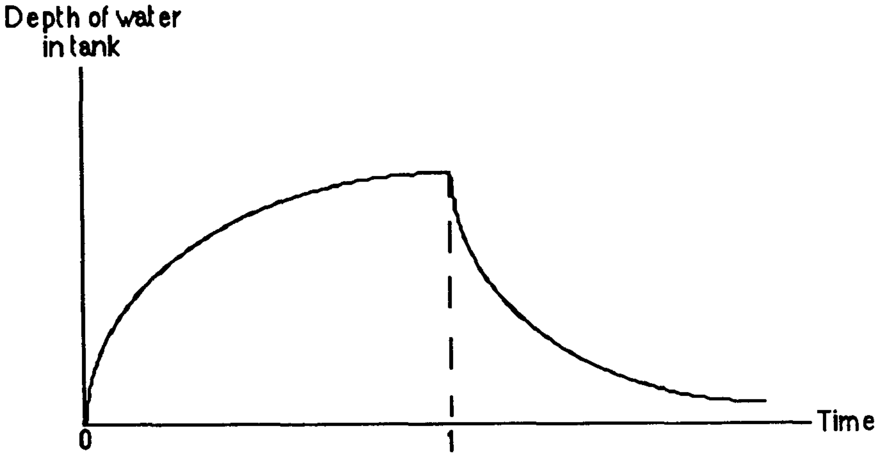


Now, in the list, cross out all the items which would be no use at all in making such a diagram.

A tap letting water into the tank is added.



The graph shows how the depth of water in the tank changes with time



14) What do you suppose is happening between time equal to zero and time equal to 1?

____

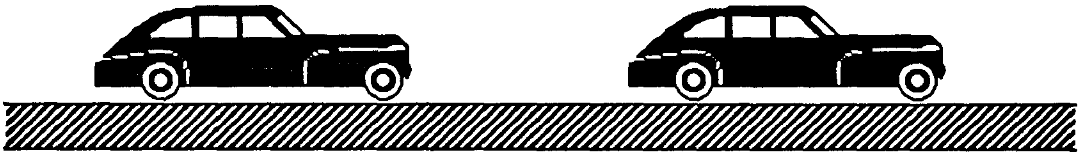
____

15) What do you suppose is happening to time greater than 1?

____

____

16) Suppose you have two cars, one leading and the other following it, in a stream of traffic.



a) What variables do you think are needed to describe the situation?

____

____

____

b) Make a causal diagram showing how these variables affect one another.

17) **Motorways.**

Some people hope that building more motorways will decrease traffic congestion. Other doubt this, and think that having more motorways actually makes the congestion worse.

Make a causal diagram which shows how building more motorways would affect congestion.

18) **Greenhouse Effect.**

CO_2 in the atmosphere 'traps' sunlight, and warms the Earth. CO_2 is added to by burning fuels. CO_2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels ...

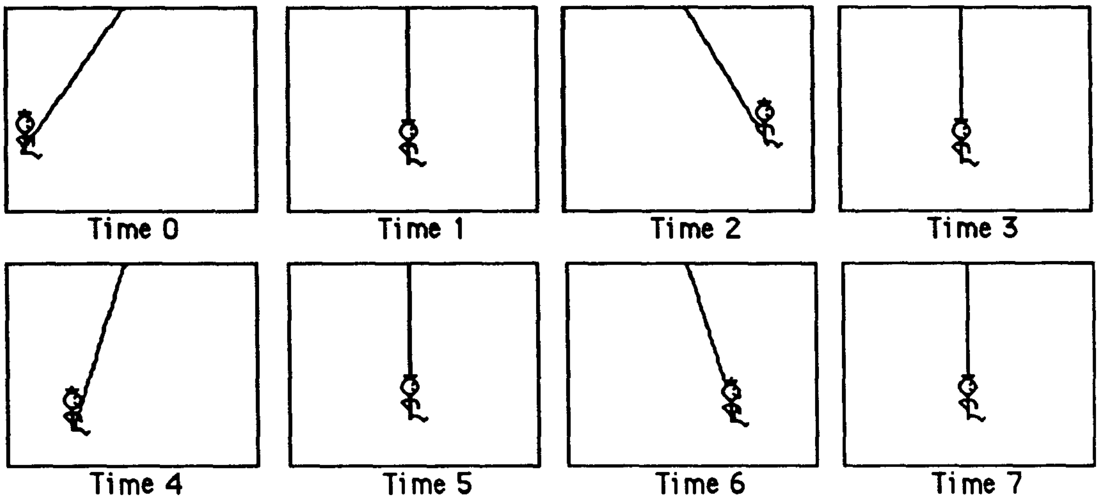
Make a causal diagram which explains this situation.

19) Suppose you want to describe the interaction between foxes and rabbits living in the same region. Suppose rabbits have plenty of grass to eat but are eaten by foxes. Both foxes and rabbits give birth, and foxes will die of starvation if there are too few rabbits.

a) What variables might be needed to describe the situation?

b) Make a causal diagram showing how these variables affect one another.

20) A child is playing on a swing, which gradually slows down and stops. The figure presents eight pictures, from time zero to time seven, showing the movement of the child.

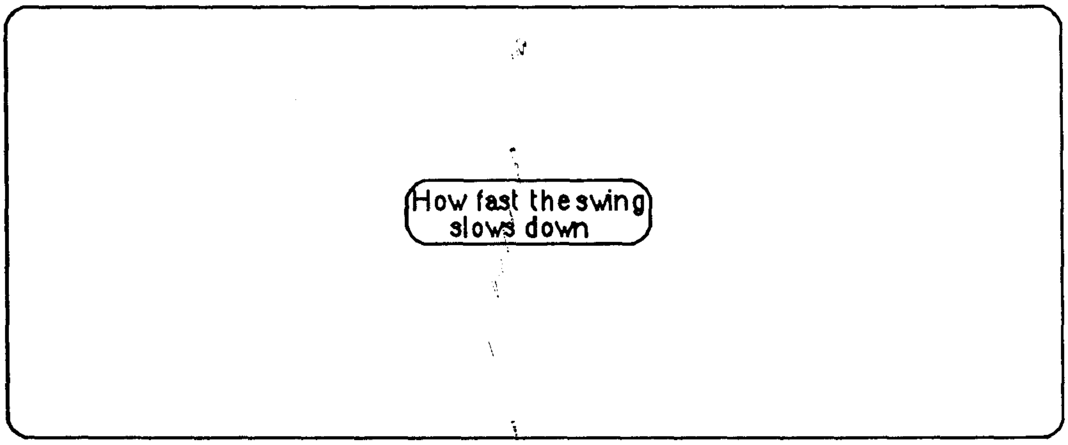


Here is a list of things some students thought should be considered in understanding what affects how fast the swing slows down.

Period
Speed
Time
Tension in rope
Child hanging legs
Angle
Height of swing
Air resistance

Gravity
Swing stops
Stop time
Length of swing
Mass of child
Force to push
Energy at time zero

Using only things in this list, choosing the ones which are needed, make a causal diagram to show what affects how fast the swing slows down.



Now, in the list, cross out all the items which would be no use at all in making such a diagram.

Appendix I. 2.

QUESTIONNAIRE ABOUT MODELLING - PART 2

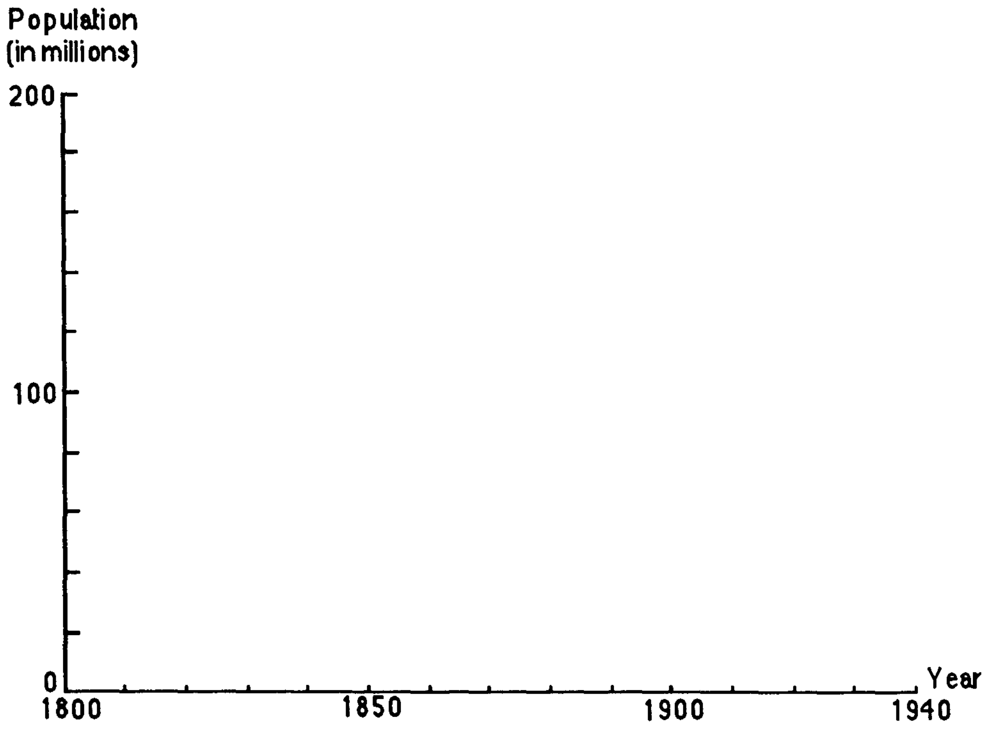
Student: ____________________________________

School: ____________________________________

21) The population of the United States is given (in millions) in the table below:

Year	Population (in millions)
1800	5.3
1820	9.6
1840	17.1
1860	31.4
1880	50.2
1900	76.0
1920	106.5
1940	132.0

a) Sketch a graph of population versus time.

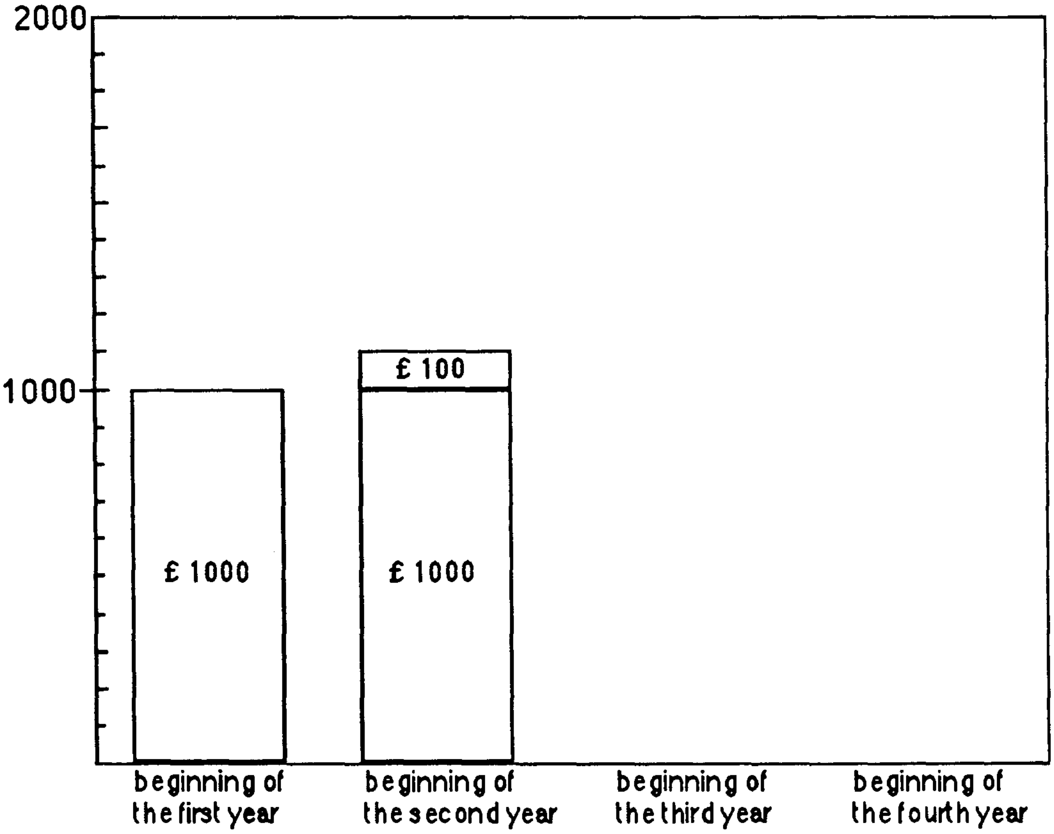


b) Describe what is happening to the population.

22) Suppose you know that "Y is proportional to X". What is the best equation that can be written for Y (consider **k** a constant $\neq 0$) ?

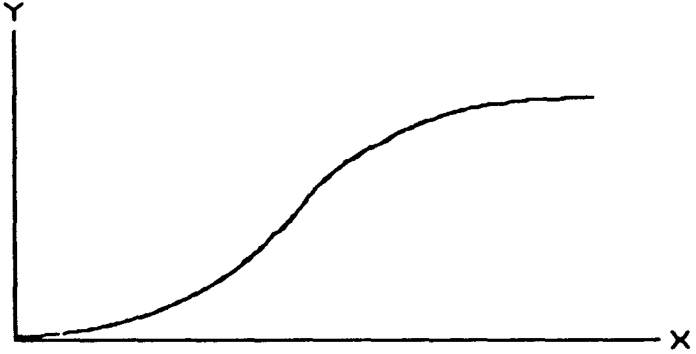
a) $Y = X$
b) $Y = \frac{k}{X}$
c) $Y = kX^2$
d) $Y = kX$
e) a different one : ________________.

23) Each year, a bank gives 10% interest on money left in the bank for that year. The picture shows the money at the beginning of the first year and at the beginning of the second year.



Draw pictures for the beginning of the third and fourth years, if all the money, including interest, is left in the bank. Add amounts of money for each year if you can.

24) Some curves can be described by simple equations.



Is this curve described by one of these equations (consider **a** and **b** constants $\neq 0$) ?

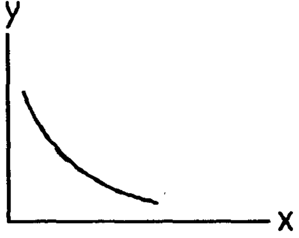
$y = a\,x$	
$y = a\,x^2$	
$y = a\,x - b\,x^2$	

Yes	No	dont know

If yes, please ✓ the equation

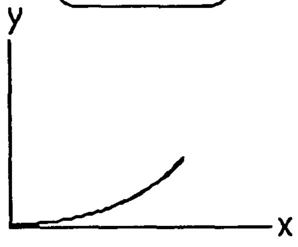
25) Which mathematical equation best describes the following relations between variables x and y?

relation 1



relation 2

relation 3



relations

	1	2	3
a) $y = a.e^{k.x}$ where a and k are constants $\neq 0$.	☐	☐	☐
b) $y = a.\cos(k.x + \beta)$ where a, k, ß are constants $\neq 0$.	☐	☐	☐
c) $y = a.e^{-k.x}$ where a and k are constants $\neq 0$.	☐	☐	☐
d) $y = a.x^3$ where a is a constant $\neq 0$.	☐	☐	☐
e) I have no idea.	☐	☐	☐

In each case **x** is some quantity.

26) If $\boxed{\frac{dx}{dt} = 0}$ how does **x** vary with time?

	✓one
x decreases exponentially.	
x increases exponentially.	
x is constant.	
x increases linearly.	
I have no idea.	

Suggest a quantity which varies like this

27) If $\boxed{\frac{dx}{dt} = \text{constant}}$ how does **x** vary with time?

	✓one
x decreases exponentially.	
x increases exponentially.	
x is constant.	
x increases linearly.	
I have no idea.	

Suggest a quantity which varies like this

28) If $\boxed{\frac{dx}{dt} = - \text{constant} * x}$ how does **x** vary with time?

	✓one
x decreases exponentially.	
x increases exponentially.	
x is constant.	
x increases linearly.	
I have no idea.	

Suggest a quantity which varies like this

PIECES OF PROGRAMS

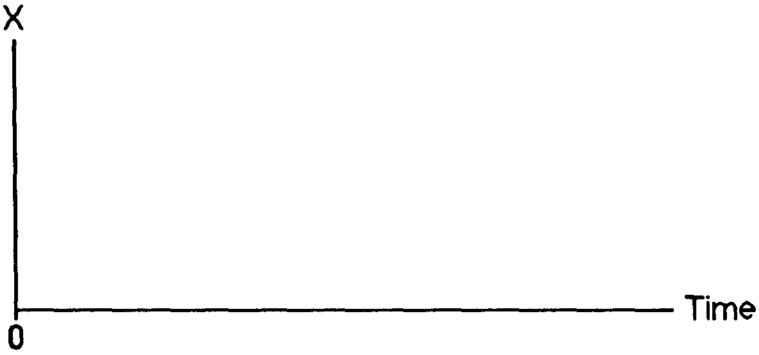
29) Here is a short computer program

```
1  X = 10
2  t = 0
3  k = 0.1
4  d t = 1
5  dX = k * d t
6  X = X + dX
7  t = t + d t
8  GOTO 5
```

Decide if each statement below about the program is true or false

	True	False
It produces as final result X = 10.1.	☐	☐
It iterates the value of X.	☐	☐
It increments the value of X with the value of t.	☐	☐
It increments the value of X with the value of k * d t.	☐	☐

Sketch a graph of X against time



30) Here is a short computer program

```
1  X = 10
2  t = 0
3  k = 0.1
4  d t = 1
5  dX = k * X * d t
6  X= X + dX
7  t = t + d t
8  GOTO 5
```

Decide if each statement below about the program is true or false

	True	False
It produces as final result X = 11.	☐	☐
It iterates the value of X.	☐	☐
It increments the value of X with the value of t.	☐	☐
It increments the value of X with the value of k*X*d t.	☐	☐

Sketch a graph of X against time

31) Here is a short computer program

```
1  X = 10
2  t = 0
3  k = 0.1
4  dt = 1
5  dX = - k * X * dt
6  X = X + dX
7  t = t + dt
8  GOTO 5
```

Decide if each statement below about the program is true or false

	True	False
It produces as final result X = 9.	☐	☐
It iterates the value of X.	☐	☐
It increments the value of X with the value of t.	☐	☐
It decrements the value of X with the value of k*X*dt.	☐	☐

Sketch a graph of X against time

Appendix II. 1

TEACHING CAUSAL DIAGRAMS

Student: ______________________________

School: ______________________________

Causal diagrams

Causal diagrams are a way of writing down very quickly your ideas about how different quantities could affect one another. Quite complicated ideas can be put into a simple picture.

So as to get used to the Macintosh computer, we want you to draw your causal diagram with MacDraw.

Let us start with one variable only.

Choose a suitable place on the screen and write "how tired you get".

How tired you get

Exercise 1

To start making a causal diagram:

1) write down some variables which affect "how tired you get".

2) consider how these variable could affect one another.

Exercise 2

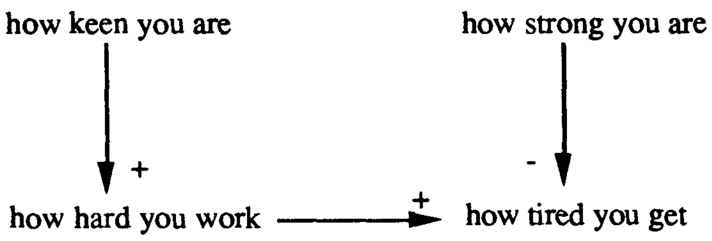
One obvious variable is "how hard you work". Link the new variable to "how tired you get" with a positive arrow.

Consider an increase and a decrease in "How hard you work" and think about what happens to your tiredness.

Exercise 3

It is possible to have very complicated causal diagrams with many variables linked through positive and negative arrows.

Try to understand the following causal diagram.

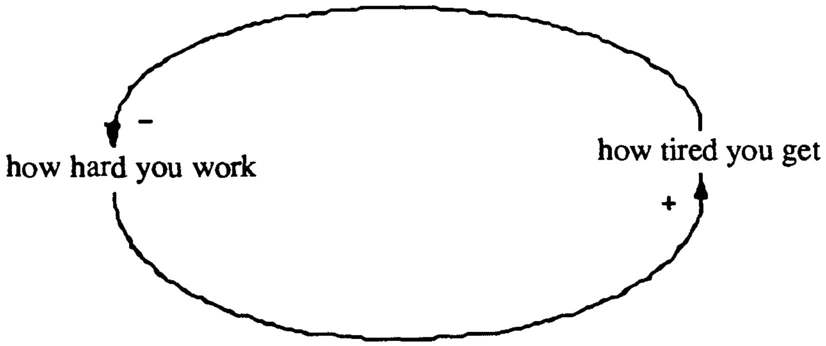


What does the diagram say will happen if you are very keen and very strong?

Exercise 4

Try to understand the following causal diagram. If you work hard, what happens to your tiredness ?

What effect does that have on how hard you work?



Text about Greenhouse Effect - Understanding a Causal Diagram

Global warming worries heightened by mildest winter for 330 years

By Greg Naele
Environment Correspondent
The Daily Telegraph

Last winter was the mildest since 1659 when records began...

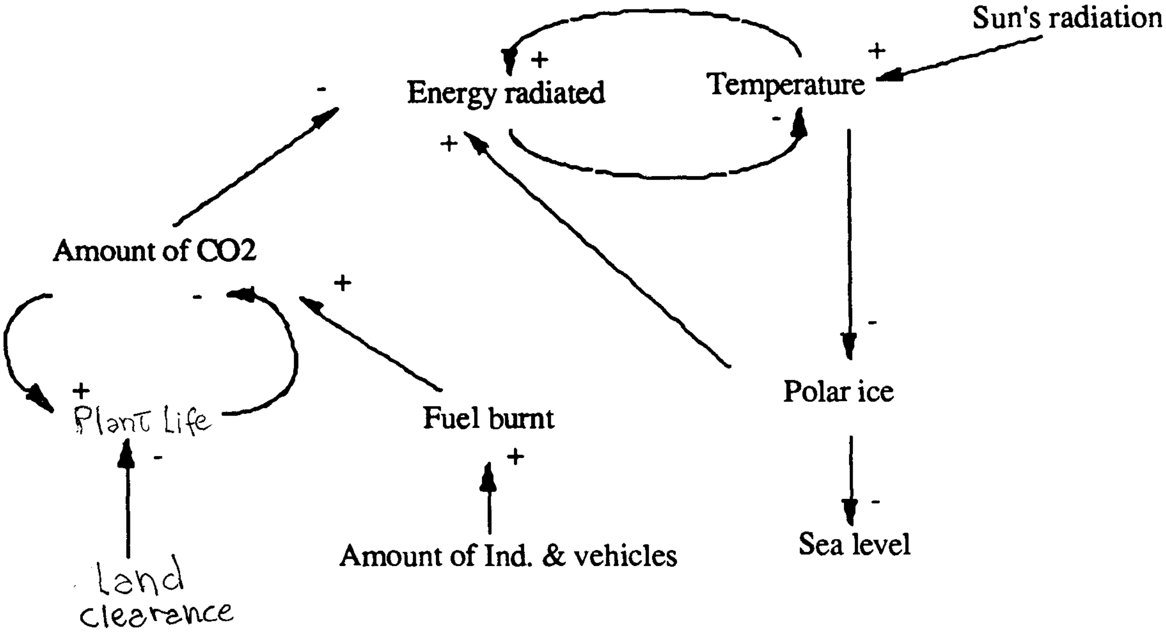
Although the scientists were cautious, their findings provide more evidence of the likely harmful effects of global warming - the greenhouse effect - with potentially profound implications for climate change, agriculture and life in Britain in the coming decades.

Dr. Melvin Cannell of the Institute of Terrestrial Ecology, who headed the investigation, said: "Last winter was consistent with predictions of climate warming".

There would have to be a spate of mild winters and unusually warm summers, he said, for there to be firm evidence of the World's climate changing because of the greenhouse effect - believed to be caused by gases, principally carbon dioxide, given off by industry and motor vehicles.

Some environmentalists believe the warmer climate could lead to the polar ice caps melting, raising sea levels and flooding low-lying regions. Higher atmospheric temperatures could bring more volatile weather.

A possible causal diagram for the greenhouse effect is presented below.



This causal diagram includes some extra variables which were not mentioned in the text.

Explanation about the meaning of some variables

Land clearance = Amount of land cleared for building and agriculture.
Fuel burnt = The amount of coal, oil and other fuels being burnt.
Plant life= The amount and vigour of plant life, specially forests.
Amount of CO2 = Amount of Carbon dioxide in the air.
Temperature= The overall average temperature of the Earth. How warm the climate is.
Energy radiated= The amount of energy radiated or reflected back into space from the Earth.
Sun's radiation= The amount of energy reaching the Earth from the Sun.
Sea level= The overall sea level.
Polar ice= The amount of snow and ice on the Earth, specially at the poles.

a) Consider that the amount of industries and vehicles increases.

What happens to the temperature?

Why?

b) Consider that the Land clearance decreases (reforestation).

What happens to the temperature?

Why?

c) Consider that the temperature increases.

What happens to the energy radiated?

Why?

NOW PLEASE TURN TO THE NEXT PAGE

Your opinion of the causal diagram

d) Explain in your own words what the causal diagram says about how "global warming" can happen.

e) In what ways do you think the causal diagram is accurate ?

f) In what ways do you think the causal diagram is not good enough?

Text about Rat War - Drawing a Causal Diagram

Barnet fights a losing rat war

Greg McIvor

Times Group Newspapers - London Borough of Barnet

Barnet is losing its war against rats.

That was the official verdict of Barnet Council's chief environmental health officer Goeff Fish after new figures showed the borough's rat population rose by ten per cent last year.

And the figures are likely to get worse after the warm winter which most rats will have survived.

...He said: “We want to discourage people from dropping rubbish because this encourages vermin. A large part of the remedy is in the hands of the public. People should be more conscious about the litter they drop”.

He said careless disposal of food and fly-tipped rubbish were major factors in the population explosion.

The borough would continue its battle against sewer rats by baiting sewers with warfarin poison, he added.

He advised people to continue taking precautions against Weil's disease - a type of jaundice which can be lethal.

The disease occurs in untreated water and is spread by rat urine.

Peter Bateman of pest control experts Rentokill believes the response from the local authorities to rat infestation is patchy and uncoordinated....

“Rats are the unacceptable face of the environment. Rats and mice carry many diseases other than Weil's disease. Both carry salmonella, for example. A mouse sheds 80 droppings every 24 hours and it is even worse with rats”, Mr Bateman added.

Using McDraw draw your own causal diagram to describe what can happen in this situation. You need not use only the things mentioned in the extract, if you think of others that could affect the situation.

Appendix II. 2

TEACHING IQON - SIMPLE MODEL BUILDING

Student: ________________________________

School: _________________________________

IQON is a computer program which deals with causal relations between variables. Each variable can be represented by a box, and boxes can be linked through positive or negative arrows. Each box has a level which represents how 'big' the variable is at that moment.

IQON does not need you to use any mathematics.

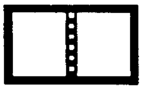
Now you are going to make some simple IQON models. They will help you learn how IQON works.

Let us start with one box only.

Choose the box symbol from the menu, pointing and clicking the mouse button. Choose a suitable place on the screen and click the mouse again. A dialogue box will ask for the variable's name.

Write "how tired you get" and press <return>.

Now you have one box on the screen. One box is not yet a model.



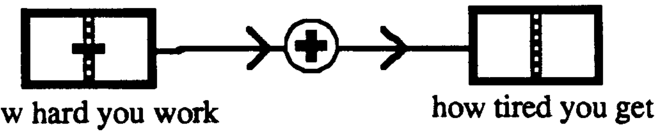
Exercise 1

To start making a model:

1) write down some variables which affect "how tired you get".
2) consider how these variable could affect one another.

Exercise 2

One obvious variable is "how hard you work". Make a new box for this, and link it to "how tired you get", with a positive arrow.

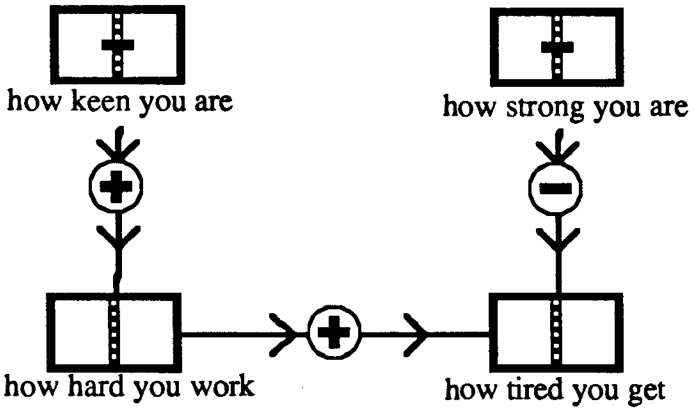


Make the level of "how hard you work" high, and see what happens to "how tired you get". Now try making "how hard you work" low, and see what happens. Ask for graphs.

Exercise 3

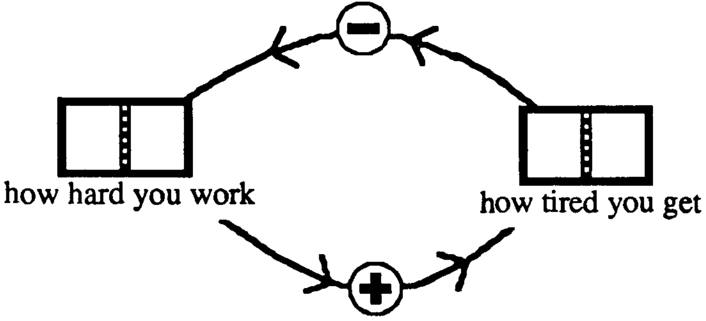
It is possible to have very complicated IQON models with many boxes linked through positive and negative arrows.

Make the model below and try it out. Try different combinations of "high" and "low" values of the variables.



Exercise 4

Do the same with the following model. Now what happens to your tiredness? Why do you think the model does this? Ask for graphs.



Text about Greenhouse Effect - Exploratory task using IQON

Global warming worries heightened by mildest winter for 330 years

By Greg Naele
Environment Correspondent
The Daily Telegraph

Last winter was the mildest since 1659 when records began...

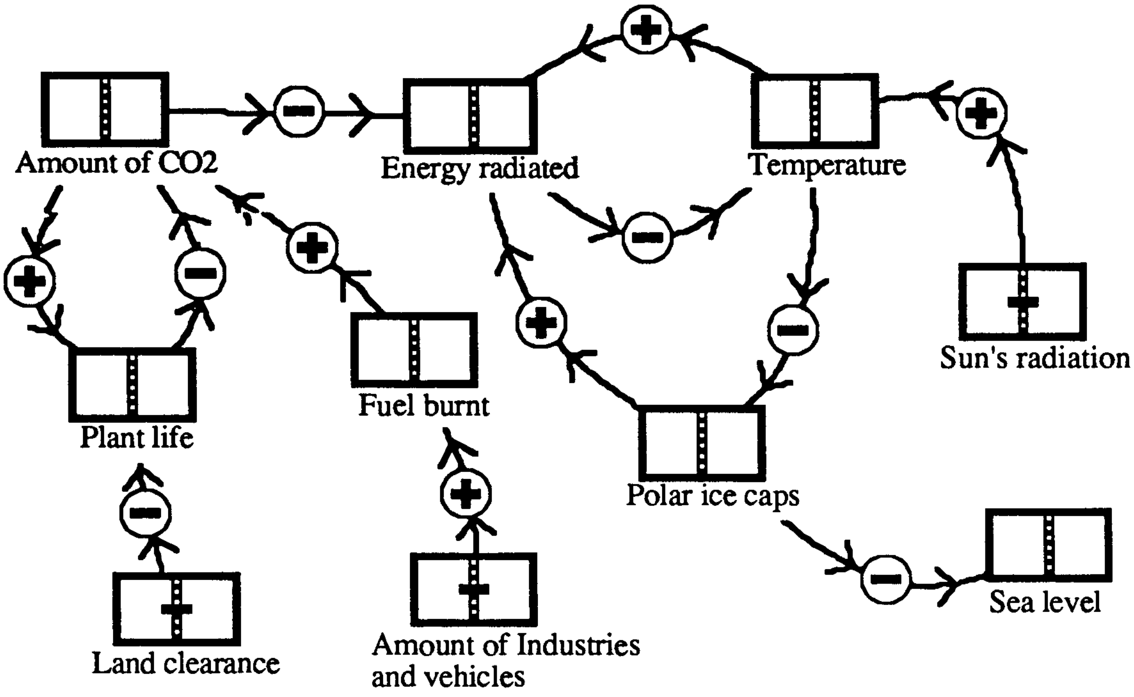
Although the scientists were cautious, their findings provide more evidence of the likely harmful effects of global warming - the greenhouse effect - with potentially profound implications for climate change, agriculture and life in Britain in the coming decades.

Dr. Melvin Cannell of the Institute of Terrestrial Ecology, who headed the investigation, said: “Last winter was consistent with predictions of climate warming”.

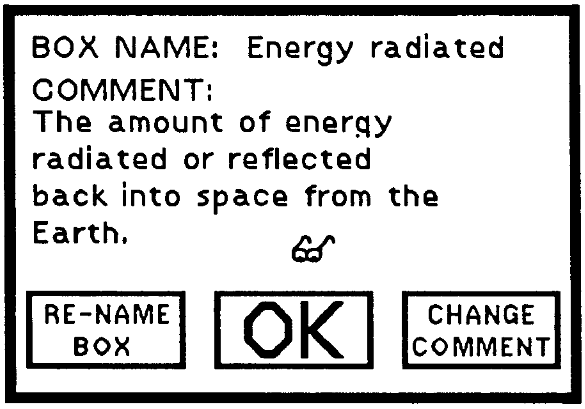
There would have to be a spate of mild winters and unusually warm summers, he said, for there to be firm evidence of the World's climate changing because of the greenhouse effect - believed to be caused by gases, principally carbon dioxide, given off by industry and motor vehicles.

Some environmentalists believe the warmer climate could lead to the polar ice caps melting, raising sea levels and flooding low-lying regions. Higher atmospheric temperatures could bring more volatile weather.

A possible IQON model for the greenhouse effect is presented below.



If you want to know more about what a box represents use the glasses tool and read the comment line. The example below is the dialogue box for the Energy radiated.


BOX NAME: Energy radiated

COMMENT:
The amount of energy radiated or reflected back into space from the Earth.

The model includes some extra variables which were not mentioned in the text.

a) Make the amount of industries and vehicles high.

What happens to the temperature?

Why?

b) Make the land clearance low (reforestation).

What happens to the temperature?

Why?

c) Make the temperature high?

What happens to the energy radiated?

Why?

NOW PLEASE TURN TO THE NEXT PAGE

Your opinion of the model

d) Explain in your own words how the model tries to show how "global warming" can happen.

e) In what ways do you think the model is accurate ?

f) In what ways do you think the model is not good enough?

Text about Rat War - Expressive task using IQON

Barnet fights a losing rat war

Greg McIvor

Times Group Newspapers - London Borough of Barnet

Barnet is losing its war against rats.

That was the official verdict of Barnet Council's chief environmental health officer Goeff Fish after new figures showed the borough's rat population rose by ten per cent last year.

And the figures are likely to get worse after the warm winter which most rats will have survived.

...He said: "We want to discourage people from dropping rubbish because this encourages vermin. A large part of the remedy is in the hands of the public. People should be more conscious about the litter they drop".

He said careless disposal of food and fly-tipped rubbish were major factors in the population explosion.

The borough would continue its battle against sewer rats by baiting sewers with warfarin poison, he added.

He advised people to continue taking precautions against Weil's disease - a type of jaundice which can be lethal.

The disease occurs in untreated water and is spread by rat urine.

Peter Bateman of pest control experts Rentokill believes the response from the local authorities to rat infestation is patchy and uncoordinated....

"Rats are the unacceptable face of the environment. Rats and mice carry many diseases other than Weil's disease. Both carry salmonella, for example. A mouse sheds 80 droppings every 24 hours and it is even worse with rats", Mr Bateman added.

Make your own IQON model to describe what can happen in this situation. You need not use only the things mentioned in the extract, if you think of others that could affect the situation.

Appendix II. 3.

Questionnaire about Models

	agree	partly agree	partly disagree	disagree
1) If the model predicts things wrongly it must be wrong.	☐	☐	☐	☐
2) If a model predicts things correctly it must be correct.	☐	☐	☐	☐
3) A model can be approximately correct.	☐	☐	☐	☐
4) All that matters about a model is whether it works, not whether it is true.	☐	☐	☐	☐
5) Only a very small part of reality can be understood through models.	☐	☐	☐	☐
6) A model which makes very precise (highly accurate) predictions is likely to be true.	☐	☐	☐	☐
7) Models represent only very simplified aspects of reality.	☐	☐	☐	☐
8) A model which is very simple can hardly be true.	☐	☐	☐	☐
9) A model should try to reproduce reality in all its complexity.	☐	☐	☐	☐
10) If a model is correct there is no difference between it and the real thing.	☐	☐	☐	☐
11) Using out-of-date models is unscientific.	☐	☐	☐	☐
12) Pure guess-work with models can be helpful for thinking about a situation.	☐	☐	☐	☐
13) There must be a correct model of every situation, even if we can't yet find it.	☐	☐	☐	☐

Appendix III. 1

LEAKY BOTTLES - EXPLORATORY TASK USING STELLA

Student: ________________________________

School: ________________________________

Consider a bottle filled with water, with a hole in the bottle (figure 1).

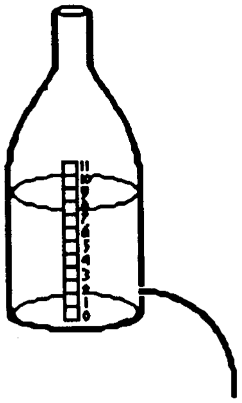


Figure 1 - Water draining out of a hole in a leaky bottle.

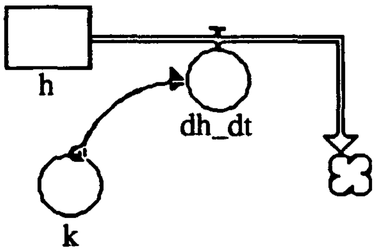
In an experiment with a 2 mm hole, the height **h** of the water changed with time as shown in table 1.

h (cm)	**Mean time (s)**
11	6.5
10	17.3
9	29.0
8	41.3
7	53.7
6	67.7
5	83.5
4	101.0
3	120.7
2	146.5
1	179.7

Table 1 - Height of water against time.

A tank ▤ (level) represents a quantity which can increase or decrease, from some starting value. A tap ⊕ (rate) connected to a tank decides how quickly the amount in the tank is changing. Several taps can be connected to one tank.
Quantities represented by ○ (convertor) can be constants, or can be calculated from other quantities.

A STELLA model to describe the situation is shown in figure 2.



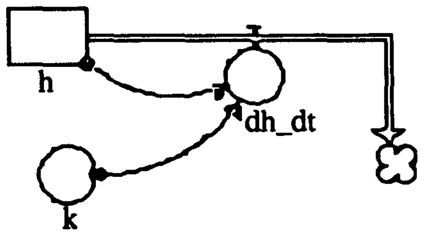
□ h = h + dt*(- dh_dt)
INIT (h) = 11
○ dh_dt = k
○ k = 0. 0926

Figure 2 - First STELLA model for the leaky bottle.

After running the model (asking for graphs and table), try to answer the questions.

a) Is there anythink wrong with this model? Explain.

Changing the STELLA model to



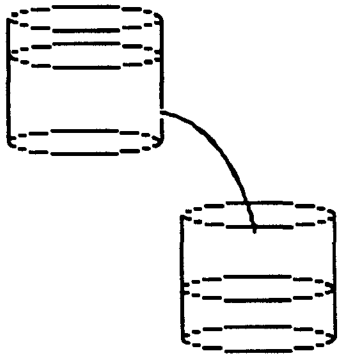
☐ h = h + dt*(- dh_dt)
INIT (h) = 11
○ dh_dt = k * h
○ k = 0. 00841

after running the model (asking for graphs and table), try to answer the questions.

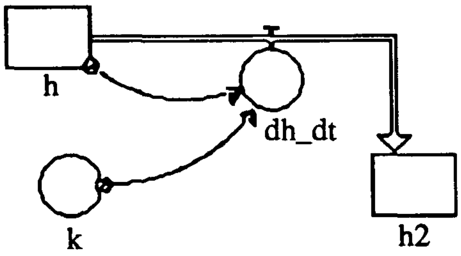
b) Is there anythink wrong with this model? Explain.

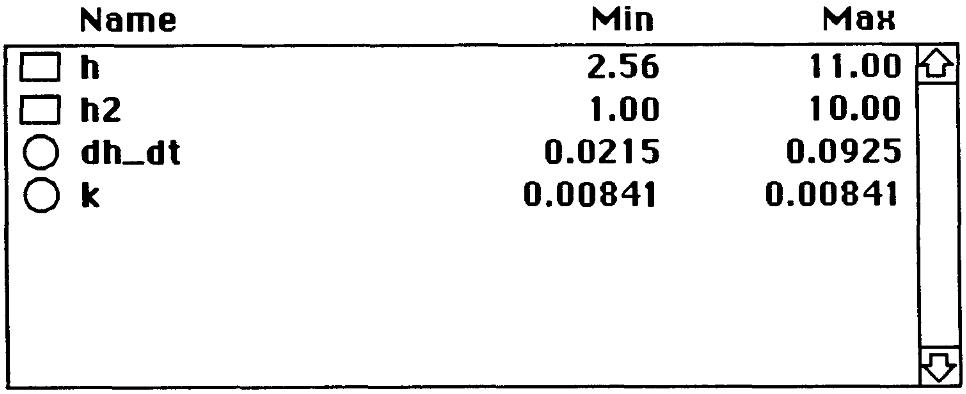
c) Can you think of any way to improve the model further?

Now I will show you how to model the following situation



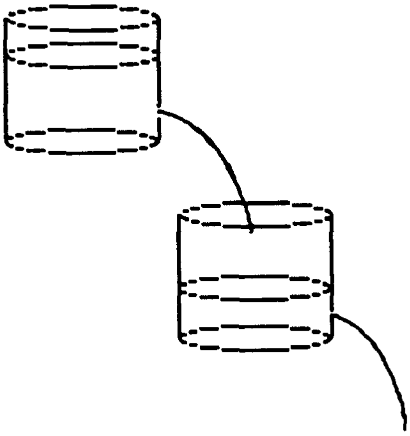
Pay attention to the way I add the extra tank and define the scales. Pay attention, as well, to the way I improve the graph and table to show h2 versus time.



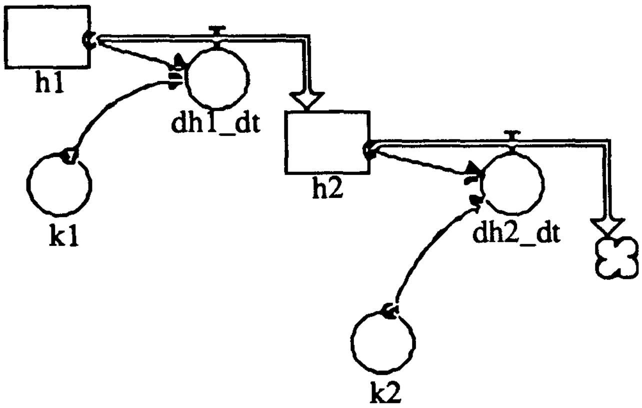


Name	Min	Max
☐ h	2.56	11.00
☐ h2	1.00	10.00
○ dh_dt	0.0215	0.0925
○ k	0.00841	0.00841

Now suppose we have two large tanks with water



A possible STELLA model to describe the situation is the following



☐ h1 = h1 + dt * (-dh1_dt)
INIT(h1) = 30
☐ h2 = h2 + dt * (dh1_dt - dh2_dt)
INIT(h2) = 0
○ dh1_dt = k1*h1
○ dh2_dt = k2*h2
○ k1 = 0.5
○ k2 = 0.5

After running the model (asking for graphs and table), try to answer the questions.

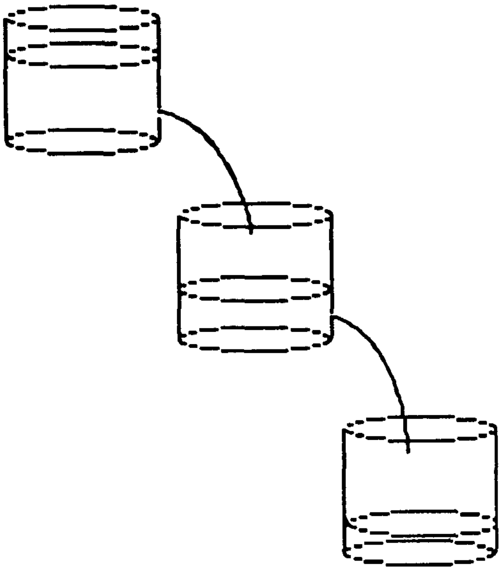
a) What happens to the level of the second tank?

Why?

b) What happens if you increase k2?

Why?

Add to the model to describe the following situation



c) What happens to the level in the third tank?

Why?

d) Could the same model be used for another problem which is not about leaking fluids at all? Suggest one if you can.

Diet and weight loss - Expressive task using STELLA

If you regularly take in more calories in food than you lose in moving about and in heat losses, then you grow fatter and heavier. But the heavier you are, the more effort you need to move around, so you do not go on for ever getting fatter, but stop at a heavier weight.

Make a STELLA diagram which can be used to experiment with the effects of over-eating or of dieting, on body-weight.

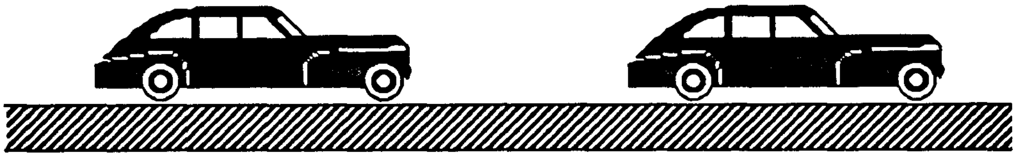
Appendix III. 2

TWO CARS IN A STREAM OF TRAFFIC

Student: ______________________________

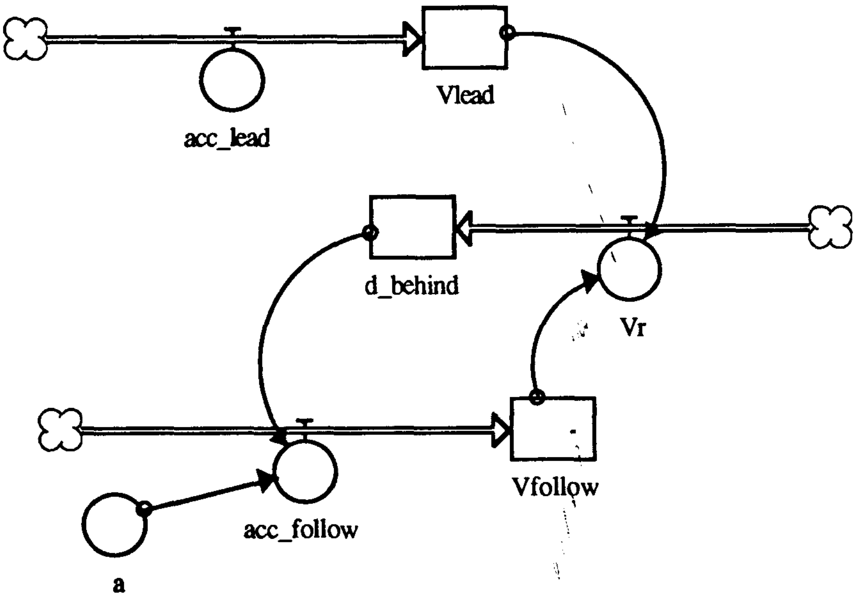
School: ______________________________

Suppose you have two cars, one leading and the other following it, in a stream of traffic.

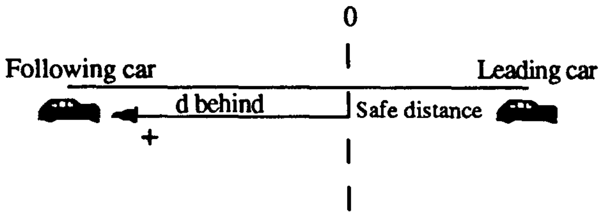


The leading car may speed up, or slow down, quickly or slowly. What do you think the following car will do as a result?

A possible STELLA model for the situation is presented on the screen.



☐ d_behind = d_behind + dt * (Vr)
INIT(d_behind) = 0
☐ Vfollow = Vfollow + dt * (acc_follow)
INIT(Vfollow) = 20
☐ Vlead = Vlead + dt * (acc_lead)
INIT(Vlead) = 40
○ a = 5
○ acc_follow = IF d_behind > 0 THEN +a ELSE -a
○ acc_lead = 0
○ Vr = Vlead - Vfollow



The model represents as boxes (levels) the Velocity of the following car (Vfollow), the Velocity of the leading car (Vlead) $\{\frac{m}{s}\}$ and the Distance behind (d_behind) $\{m\}$. As rates the acceleration of the following car (acc_follow), the acceleration of the leading car (acc_lead) $\{\frac{m}{s^2}\}$, which was considered zero, and the relative velocity (Vr) given by Vlead - Vfollow.

Play with the model and answer:

1) What happens when the model is run?

2) Could this happen in reality? Why/Why not?

3) Why does the <u>model in the computer</u> behave this way?

4) Can you think of any other situation which behaves like this?

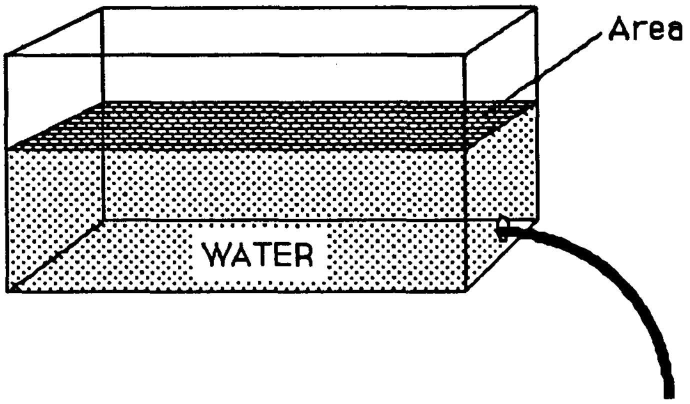
Appendix IV

IDEAS ABOUT MODELLING

Student : ______________________________

School : ______________________________

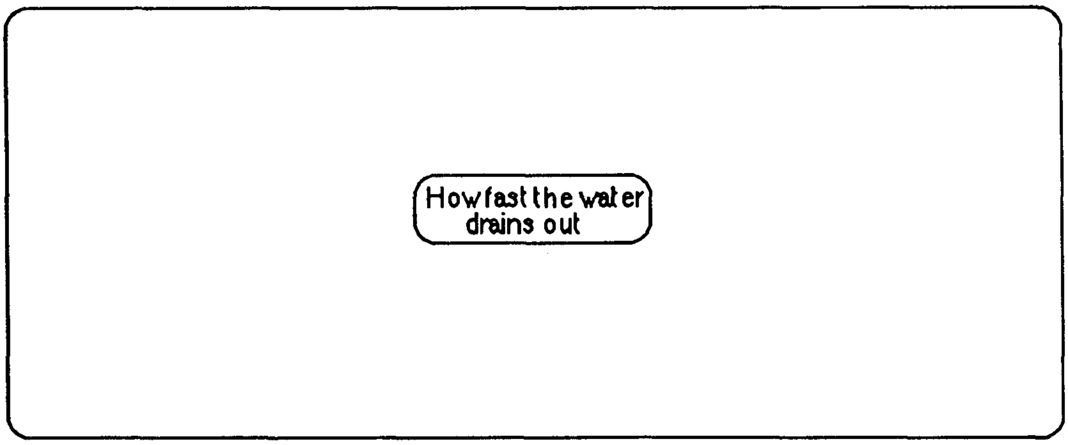
1) Suppose you have a tank filled with water which is draining through a hole as shown.



Here is a list of things some students thought should be considered in understanding what affects how fast the water drains out of the tank.

The water
Volume of water
The tank
Area of tank
Density of water
The hole
Depth of water
Colour of water
The curving of the water jet
Pressure of water
Size of hole
Time

Using only things in this list, choosing the ones which are needed, make a diagram to show what affects how fast the water drains out.



Now, in the list, cross out all the items which would be no use at all in making such a diagram.

2) Greenhouse Effect.

CO_2 in the atmosphere 'traps' sunlight, and warms the Earth. CO_2 is added to by burning fuels. CO_2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels ...

Make a diagram which explains this situation.

3) Suppose you want to describe the interaction between foxes and rabbits living in the same region. Suppose rabbits have plenty of grass to eat but are eaten by foxes. Both foxes and rabbits give birth, and foxes will die of starvation if there are too few rabbits.

a) What variables might be needed to describe the situation?

____

____

b) Make a diagram showing how these variables affect one another.

4) If $\boxed{\frac{dx}{dt} = \text{constant}}$ how does **x** vary with time?

	✓one
x decreases exponentially.	
x increases exponentially.	
x is constant.	
x increases linearly.	
I have no idea.	

Suggest a quantity which varies like this

5) Here is a short computer program

```
1  X = 10
2  t = 0
3  k = 0.1
4  d t = 1
5  dX = k * d t
6  X = X + dX
7  t = t + d t
8  GOTO 5
```

Decide if each statement below about the program is true or false

	True	False
It produces as final result X = 10.1.	☐	☐
It iterates the value of X.	☐	☐
It increments the value of X with the value of t.	☐	☐
It increments the value of X with the value of k * d t.	☐	☐

Sketch a graph of X against time

6) For each set of three variables, state whether it is most like a 'tank' (level) or most like a flow (inflow or outflow) (rate). Give the units for each variable.

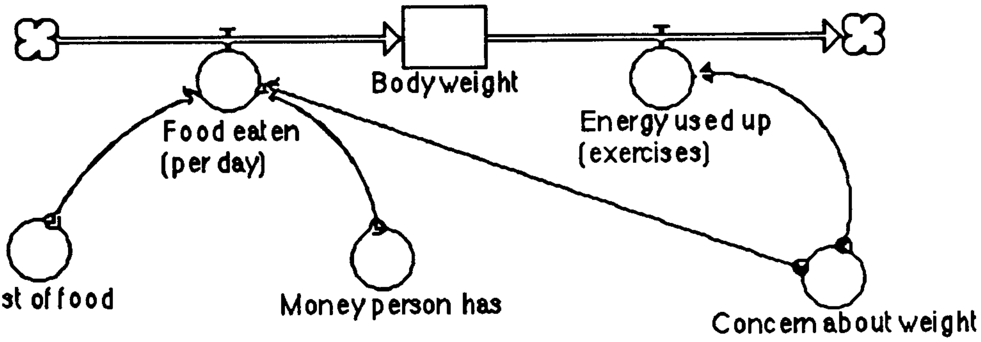
Example:

Variables	Tank or Flow	Unit of Measure
Population	Tank	Number of people
Births	Flow (Inflow)	Babies born per year
Deaths	Flow (Outflow)	Deaths per year

a) Credits
   Bank Balance
   Debits

b) Inventory
   Sales
   Production

7) Here is a model for a person controlling his Body weight through diet and exercises.



a) According to the model, what influences the Body weight? How?

b) According to the model, what influences the Food eaten (per day)?
How?

Appendix V

IDEAS ABOUT DYNAMIC BEHAVIOURS

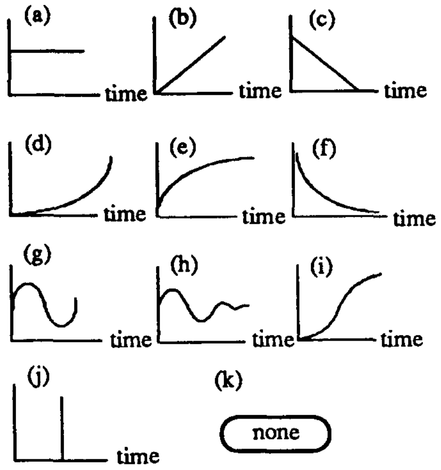
Student: ____________________________

School: ____________________________

SENTENCES

1) Price change because the inflation is increasing.
2) The price is high.
3) The population is increasing.
4) The level of water is decreasing.
5) The level of water is increasing.
6) The car is stopping.
7) The swing is swinging.
8) The weight is decreasing.
9) The stone is falling.
10) The temperature is constant.
11) The swing is stopping.
12) The man hits the ball.
13) The braking distance is 20 m.
14) The radioactivity is increasing.
15) The velocity is increasing.

GRAPHS



Sentences	best graph	Others		
1)				
2)				
3)				
4)				
5)				
6)				
7)				
8)				
9)				
10)				
11)				
12)				
13)				
14)				
15)				

Appendix VI

WORK WITH COMPUTER MODELS: TEACHERS' OPINIONS

Name: ____

School: ____

Subjects taught at A level: __________________________

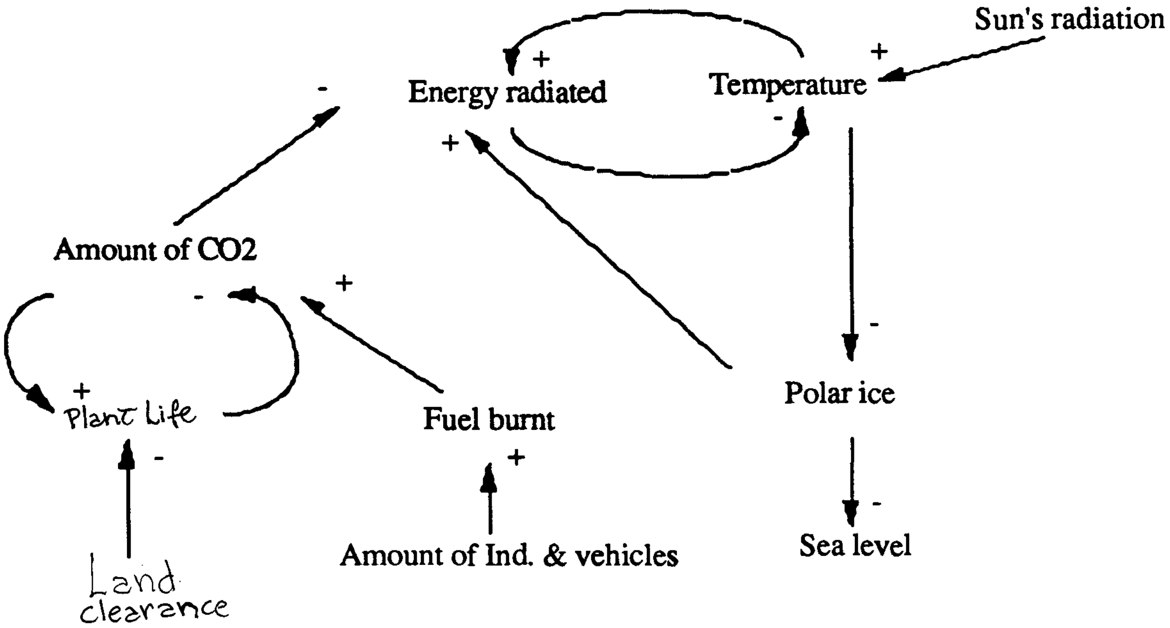
____

We are working with first year sixth form students using some computer models of real situations, and a method of thinking about models called 'causal diagrams'.

We would like to know your opinions about whether this work is likely to be useful or not for students, easy or difficult for students, and about what you think particular difficulties with it might be.

Please now read the next page, which describes what 'causal diagrams' are.

We have shown some 1st year sixth form students the following causal diagram about the Greenhouse effect.



Explanation of the variables

Amount Ind. & vehicles = Amount of industrialisation, and vehicles in use.

Land clearance = Amount of land cleared for building and agriculture.

Fuel burnt = The amount of coal, oil and other fuels being burnt.

Plant life= The amount and vigour of plant life, specially forests.

Amount of CO2 = Amount of Carbon dioxide in the air.

Temperature= The overall average temperature of the Earth. How warm the climate is.

Energy radiated= The amount of energy radiated or reflected back into space from the Earth.

Sun's radiation= The amount of energy reaching the Earth from the Sun.

Sea level= The overall sea level.

Polar ice= The amount of snow and ice on the Earth, specially at the poles.

	Very difficult	fairly difficult	fairly easy	very easy
How difficult do you think it would be for most VI form students to think about this system?	☐	☐	☐	☐

Here is what one student wrote as answer to the question

"Consider that the amount of industries and vehicles increases. What happens to the temperature? Why?"

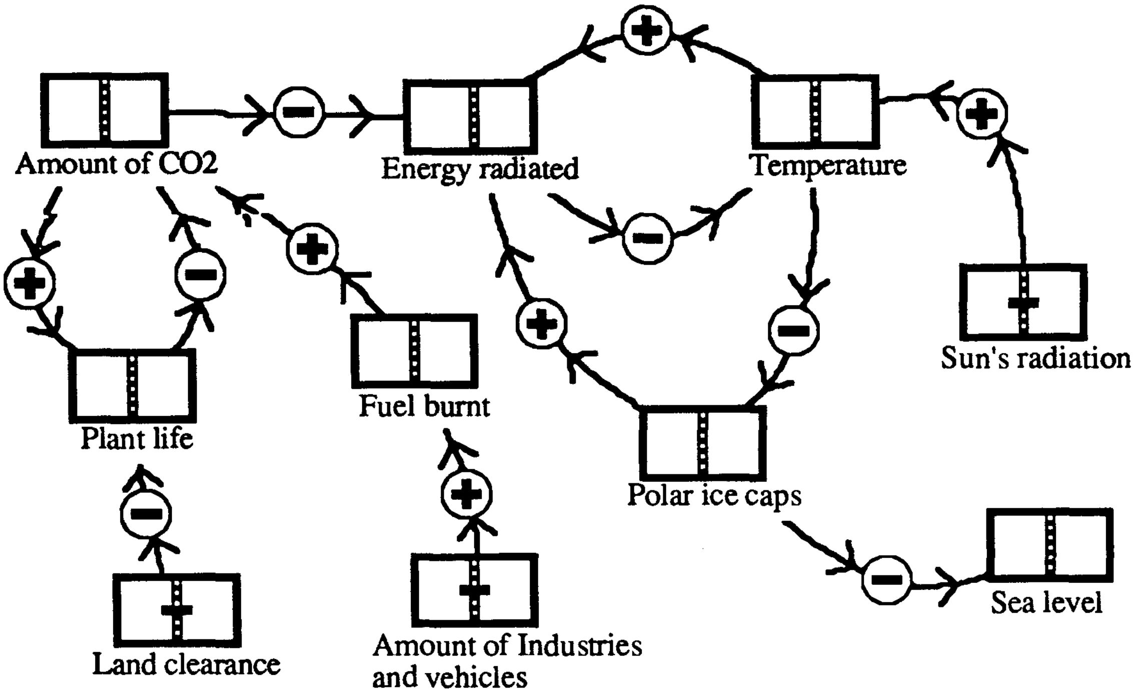
It goes up.

If the amount of industries and vehicles increases then there is an increase in the amount of fuel burnt which will lead to an increase in the amount of CO2. As a result of more CO2 the energy radiated from the Earth will suffer a decrease. Now, as less energy is being radiated the Earth will begin to warm up (as there is no let off in temperature) - therefore the temperature will increase.

	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐

Another student answered the same question working with the following IQON model for the same situation



and gave the following answer for the same question

Temperature rises.
Temperature rises because there is an increase in fuel burnt. Increase in CO2 which implies a decrease in energy radiated which therefore implies an increase in temperature.

How would you rate this answer? excellent ☐ good ☐ reasonable ☐ poor ☐

How many students do you think might be capable of such an answer? hardly any ☐ a minority ☐ a majority ☐ nearly all ☐

Another student gave the following answer

> The temperature will increase.
> As the amount of industries and vehicles increases, then more fuel will be burnt, this will increase the amount of CO2 in the atmosphere. Therefore, the energy will decrease and will make the temperature increase.

	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐

NOW PLEASE TURN TO THE NEXT PAGE

We have presented the following text for the students to make an IQON model to describe the situation.

Barnet fights a losing rat war

Greg McIvor

Barnet is losing its war against rats.

That was the official verdict of Barnet Council's chief environmental health officer Goeff Fish after new figures showed the borough's rat population rose by ten per cent last year.

And the figures are likely to get worse after the warm winter which most rats will have survived.

...He said: "We want to discourage people from dropping rubbish because this encourages vermin.

"A large part of the remedy is in the hands of the public. People should be more conscious about the litter they drop."

He said careless disposal of food and fly-tipped rubbish were major factors in the population explosion.

The borough would continue its battle against sewer rats by baiting sewers with warfarin poison, he added.

He advised people to continue taking precautions against Weil's disease - a type of jaundice which can be lethal.

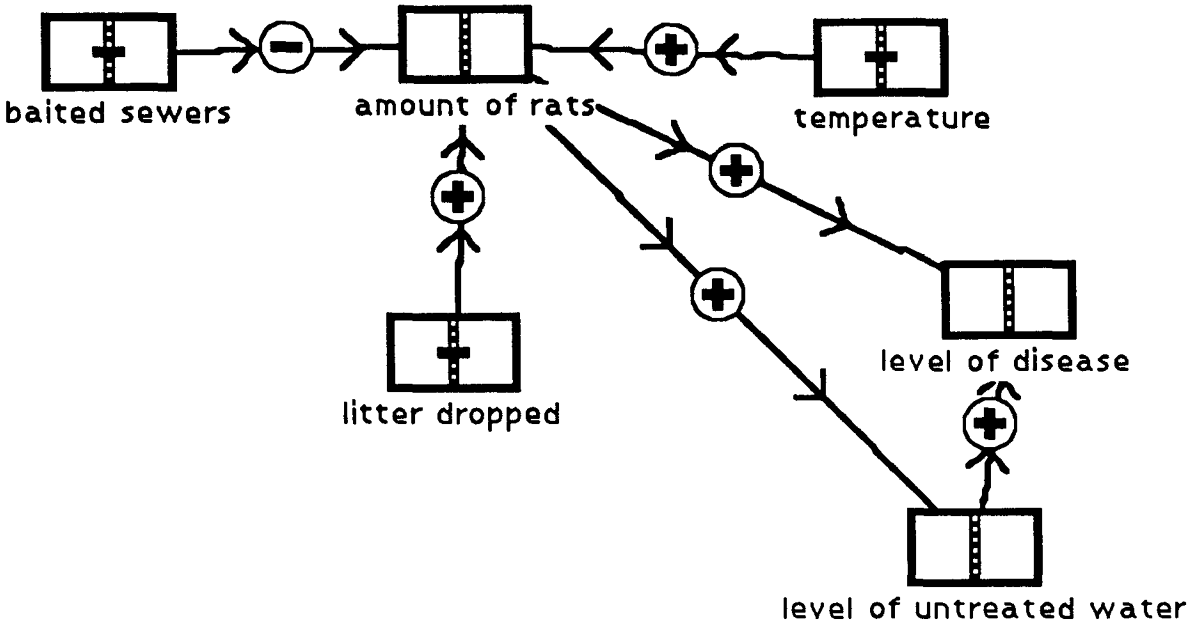
The disease occurs in untreated water and is spread by rat urine.

Peter Bateman of pest control experts Rentokill believes the response from the local authorities to rat infestation is patchy and uncoordinated . . .

"Rats are the unacceptable face of the environment. Rats and mice carry many diseases other than Weil's disease. Both carry salmonella, for example. A mouse sheds 80 droppings every 24 hours and it is even worse with rats," Mr. Bateman added.

	Very difficult	fairly difficult	fairly easy	very easy
How difficult do you think it would be for most VI form students to think about this system?	☐	☐	☐	☐

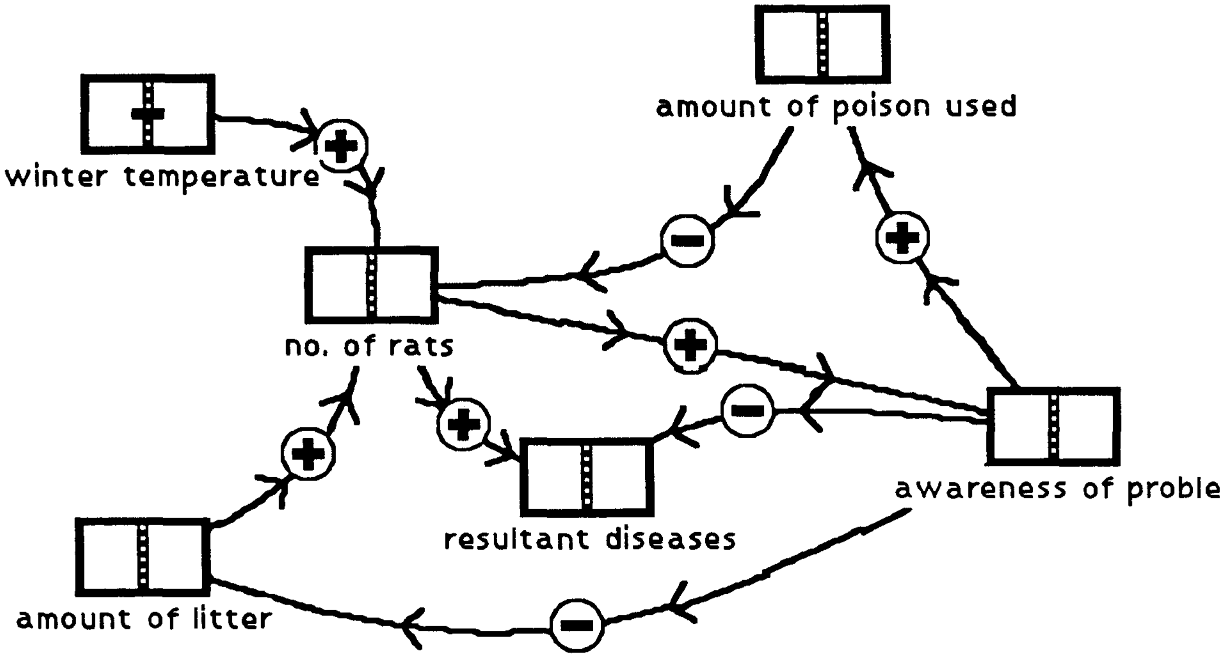
Here is what a pair of students drew as a model for the situation



	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐

Here is what another pair drew as a model for the same situation



	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐

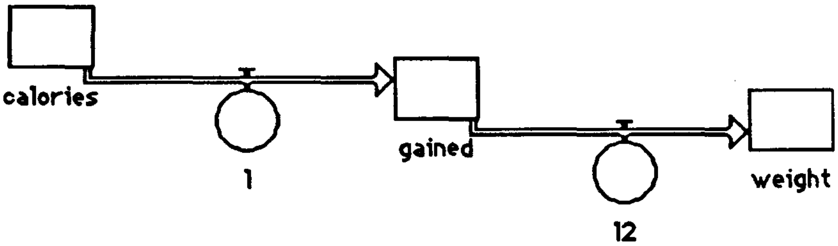
Students after developing models for the leaky tank were asked to use STELLA for modelling the following situation

Diet and weight loss

If you regularly take in more calories in food than you lose in moving about and in heat losses, then you grow fatter and heavier. But the heavier you are, the more effort you need to move around, so you do not go on for ever getting fatter, but stop at a heavier weight.

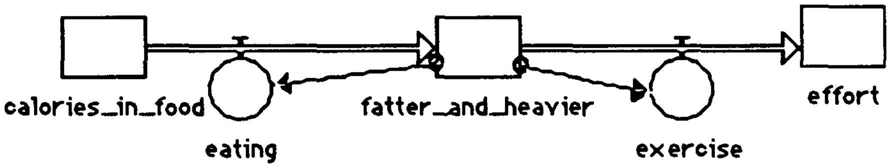
Make a STELLA model which can be used to experiment with the effects of over-eating or of dieting, on body-weight.
First draw a diagram and then try to define equations.

Here are some diagrams that students drew to model the situation.



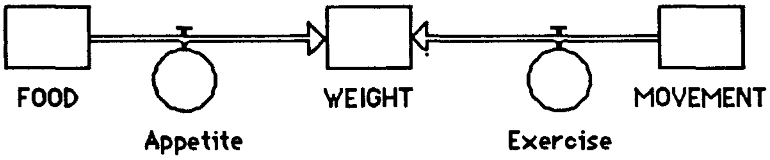
	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐



	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐



	excellent	good	reasonable	poor
How would you rate this answer?	☐	☐	☐	☐

	hardly any	a minority	a majority	nearly all
How many students do you think might be capable of such an answer?	☐	☐	☐	☐

Appendix VII

SCHEDULE FOR OBSERVATION

School:
Student 1: Subjects and level:
Student 2: Subjects and level:

ACTIVITY	√
1 - Greenhouse Effect - IQON	
2 - Greenhouse Effect - C. D.	
3 - Rat War - IQON	
4 - Rat War - C. D.	
5 - Leaky Bottles - STELLA	
6 - Diet and Weight loss - STELLA	
7 - Two Cars - STELLA	

1 - Interaction with the computer model	1	2
Seems to understand well the computer model or C.D. (pages: ___, ___, ___).		
Seems not to understand well the computer model or C.D. (pages: ___ , ___ , ___).		
Presents doubts about what a box in IQON or an entity in C. D. represents. What box or entity?		
Presents doubts about what a stock in STELLA represents. What stock?		
Presents doubts about what a rate in STELLA represents. What rate?		
Presents doubts about what a convertor in STELLA represents. What convertor?		
Works independently.		
Needs some clues to work properly. What clues?		
Does not believe in the computer model.		
Goes back to experimental apparatus or text frequently.		
Compares past and present situations well.		
Asks for graphs or tables. Which variables?		
Presents doubts about links in C. D. or IQON models.		

2 - Operation with the model	1	2
Changes other box different from expected. Which?		
Changes the dependent variable.		
Make right predictions.		
Make wrong predictions.		

3 - Kind of reasoning followed	1	2
Single box level.		
Paired interactions.		
Chained interactions.		
System level (feedback explained).		
Mentally, without externalizing		

4 - Interaction with peer	1	2
Takes the lead.		
Takes over the computer.		
Discusses some questions. What questions?		
Works independently.		

5 - Interaction with researcher	1	2
Never asks questions.		
Asks questions about the model or C. D.		
Asks questions about the knowledge needed.What?		
Confirm hypothesis.		
Asks to clarify a specific issue. Which issue?		

6 - Attitude towards activity	1	2
Keen to answer the questions.		
Indifferent.		
Negative.		

7 - Interaction with written material	1	2
Total interaction.		
Some misunderstandings. What?		
Goes back to the computer model or C. D. frequently.		

8 - Level of criticism about the written material	1	2
High. Which criticisms?		
Low. Which criticisms?		
Not observed.		

9 - Mastering the Physics or general knowledge involved	1	2
Completely.		
Enough to work.		
Not enough to work.		

10 - Level of criticism about the model	1	2
High. Which criticisms?		
Low. Which criticisms?		
Not observed.		

11 - Level of interaction with the model	1	2
Plays only to answer a question.		
Plays and tries to discover things as a way of answering questions.		
Seems not to use the model enough.		

12 - Level of mastering the system's basic functions	1	2
High without hesitating.		
Enough with some hesitancy.		

13 - Opinion about the work in general

14 - Development of expressive task

1	2
3	4
5	6

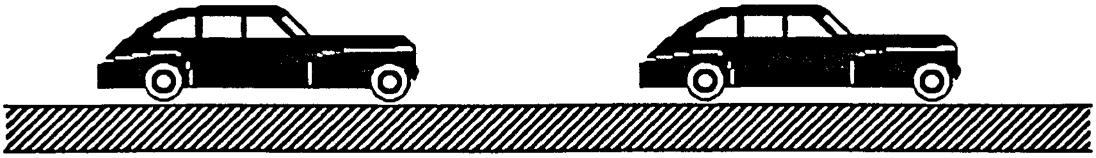
15 - What are the specific difficulties when using the tool?

16 - Additional observations:

Appendix VIII

EXAMPLES OF DIAGRAMS DRAWN BY THREE LONDON STUDENTS WITH CLASSIFICATION OF LINKS

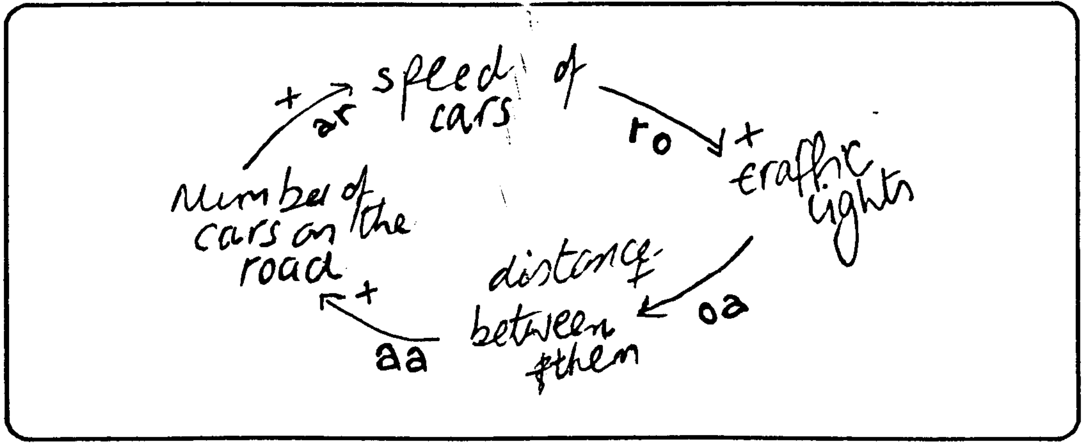
16) Suppose you have two cars, one leading and the other following it, in a stream of traffic.



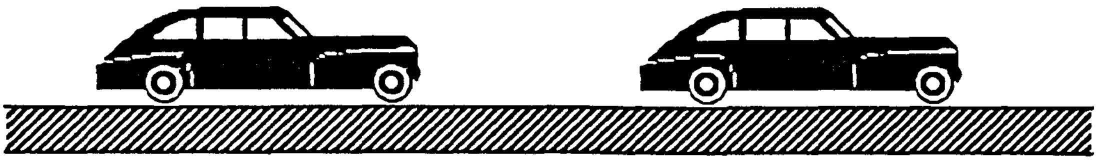
a) What variables do you think are needed to describe the situation?

Traffic lights, colour of cars, distance between them, speed of cars Number of other cars on the road

b) Make a causal diagram showing how these variables affect one another.



16) Suppose you have two cars, one leading and the other following it, in a stream of traffic.



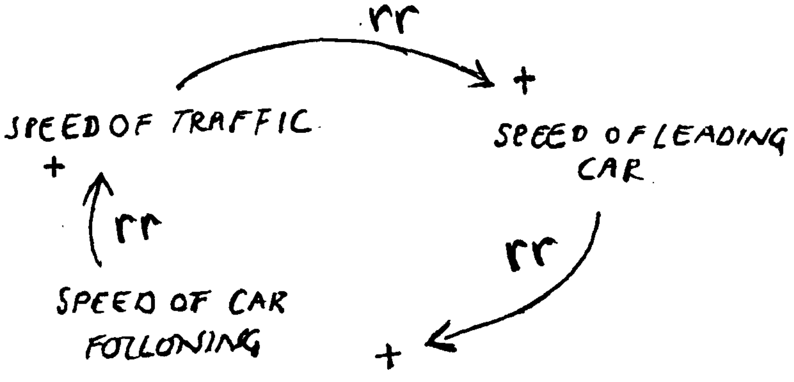
a) What variables do you think are needed to describe the situation?

SPEED OF TRAFFIC

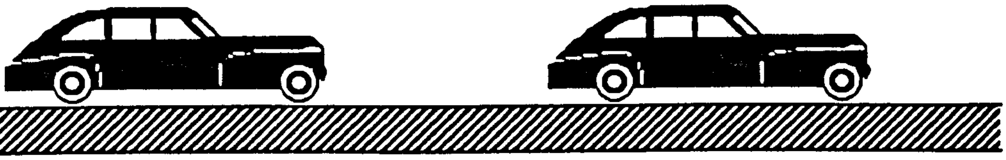
SPEED OF [illegible] [illegible] LEADING CAR

SPEED OF CAR FOLLOWING

b) Make a causal diagram showing how these variables affect one another.



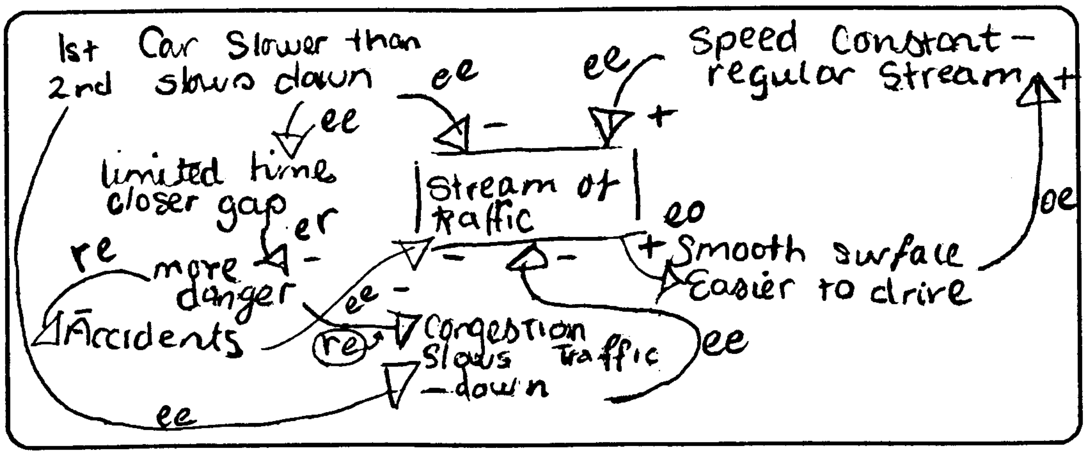
16) Suppose you have two cars, one leading and the other following it, in a stream of traffic.



a) What variables do you think are needed to describe the situation?

Speed of car, type of surface, amount of time lapse

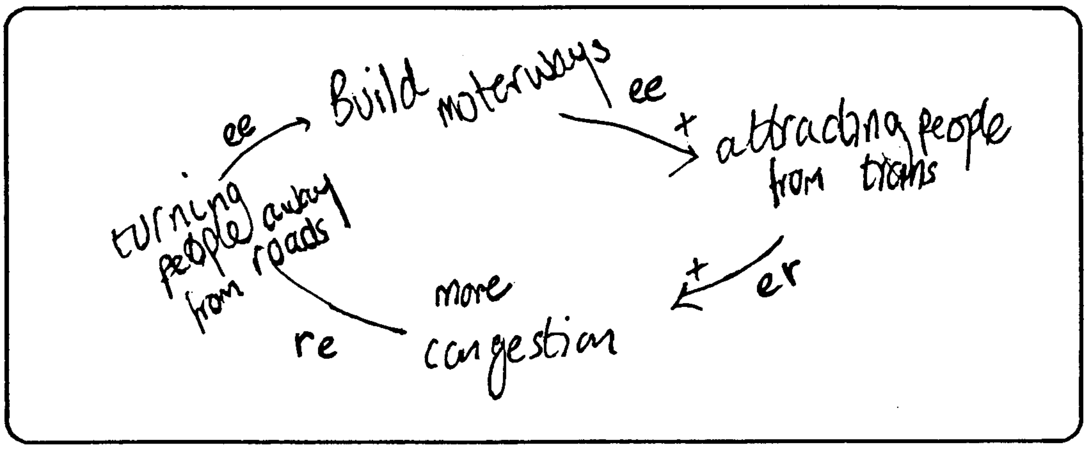
b) Make a causal diagram showing how these variables affect one another.



17) Motorways.

Some people hope that building more motorways will decrease traffic congestion. Other doubt this, and think that having more motorways actually makes the congestion worse.

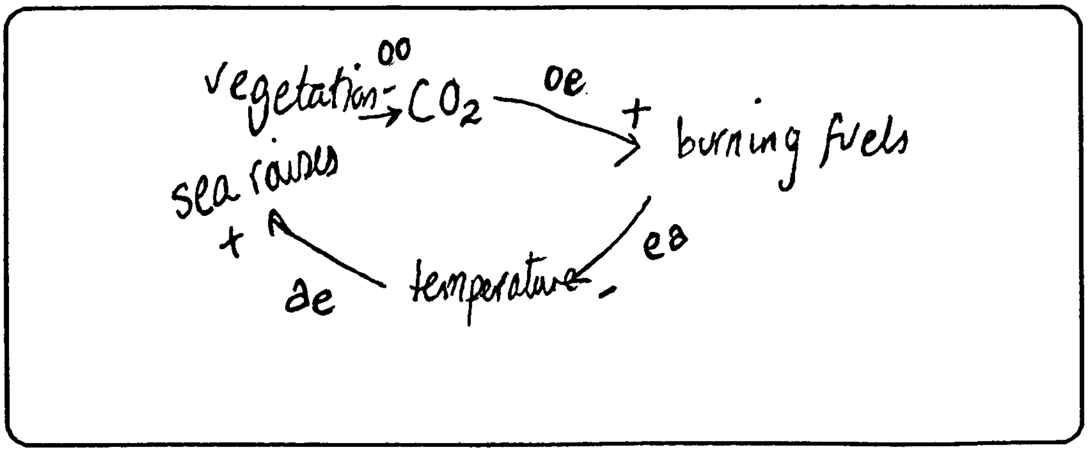
Make a causal diagram which shows how building more motorways would affect congestion.



18) Greenhouse Effect.

CO_2 in the atmosphere 'traps' sunlight, and warms the Earth. CO_2 is added to by burning fuels. CO_2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels ...

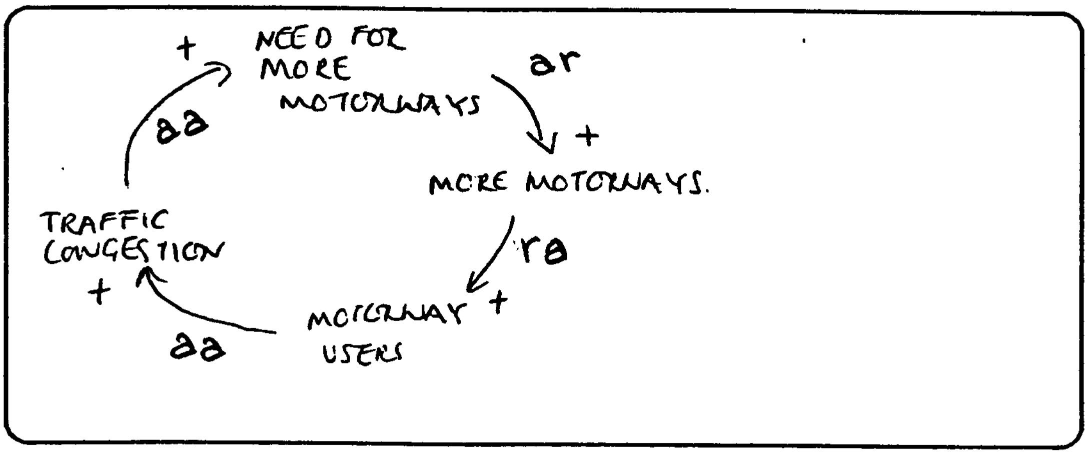
Make a causal diagram which explains this situation.



17) Motorways.

Some people hope that building more motorways will decrease traffic congestion. Other doubt this, and think that having more motorways actually makes the congestion worse.

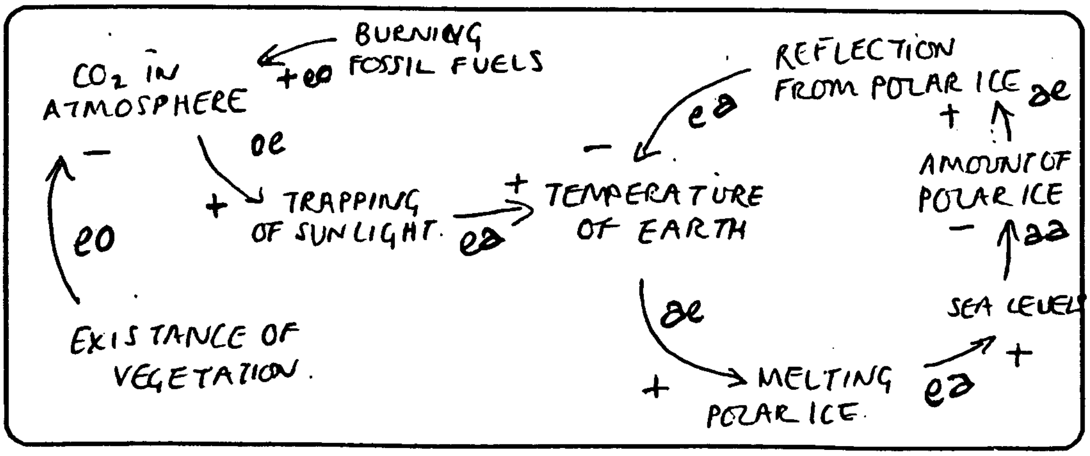
Make a causal diagram which shows how building more motorways would affect congestion.



18) Greenhouse Effect.

CO_2 in the atmosphere 'traps' sunlight, and warms the Earth. CO_2 is added to by burning fuels. CO_2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels ...

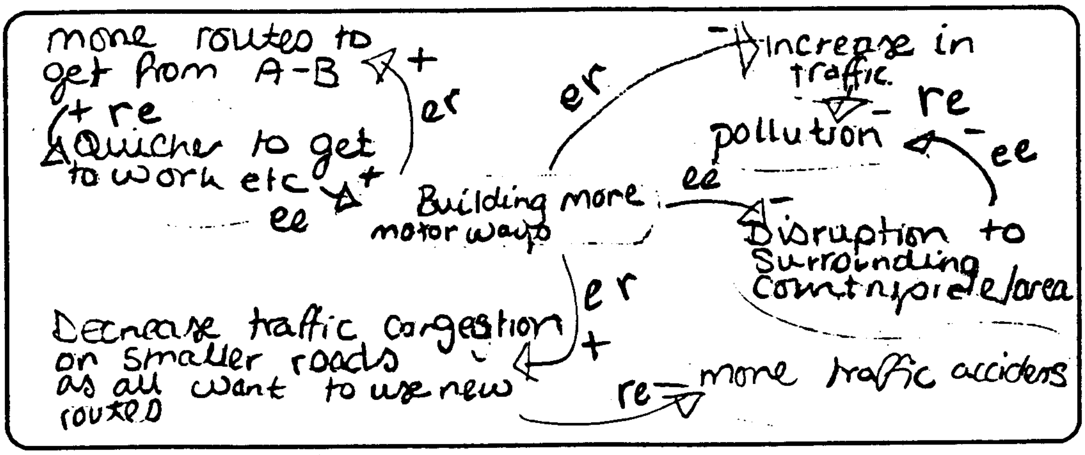
Make a causal diagram which explains this situation.



17) Motorways.

Some people hope that building more motorways will decrease traffic congestion. Other doubt this, and think that having more motorways actually makes the congestion worse.

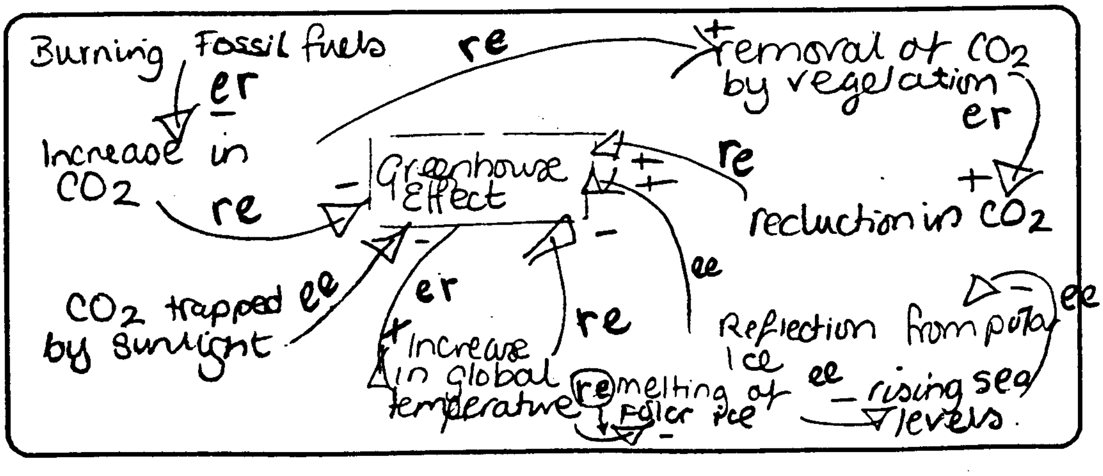
Make a causal diagram which shows how building more motorways would affect congestion.



18) Greenhouse Effect.

CO2 in the atmosphere 'traps' sunlight, and warms the Earth. CO2 is added to by burning fuels. CO2 is removed by vegetation. The Earth's temperature is reduced by reflection from polar ice, but a high temperature can melt polar ice. Ice melting raises sea levels ...

Make a causal diagram which explains this situation.

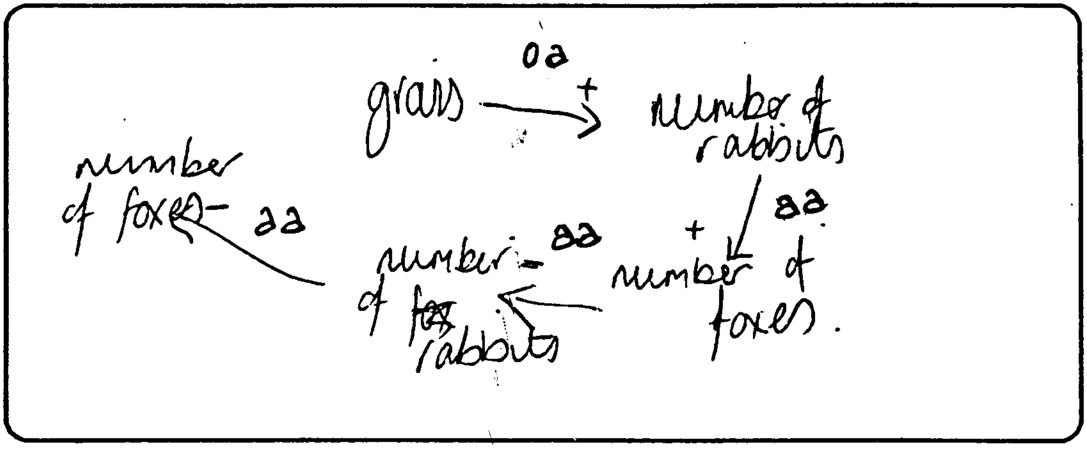


19) Suppose you want to describe the interaction between foxes and rabbits living in the same region. Suppose rabbits have plenty of grass to eat but are eaten by foxes. Both foxes and rabbits give birth, and foxes will die of starvation if there are too few rabbits.

a) What variables might be needed to describe the situation?

grass , number of rabbits , number of foxes

b) Make a causal diagram showing how these variables affect one another.



19) Suppose you want to describe the interaction between foxes and rabbits living in the same region. Suppose rabbits have plenty of grass to eat but are eaten by foxes. Both foxes and rabbits give birth, and foxes will die of starvation if there are too few rabbits.

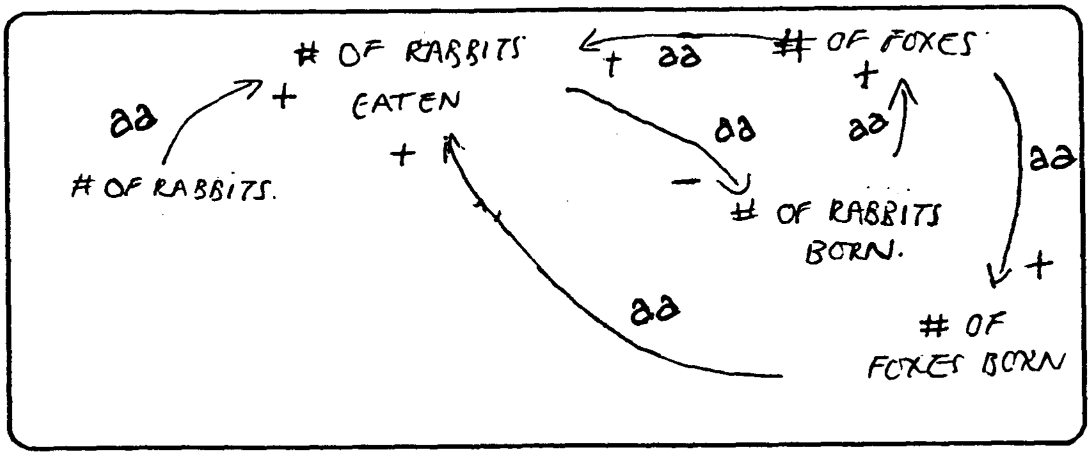
a) What variables might be needed to describe the situation?

AMOUNT OF GRASS NUMBER OF RABBITS

NUMBER OF RABBITS BORN NUMBER OF FOXES

NUMBER OF FOXES BORN

b) Make a causal diagram showing how these variables affect one another.

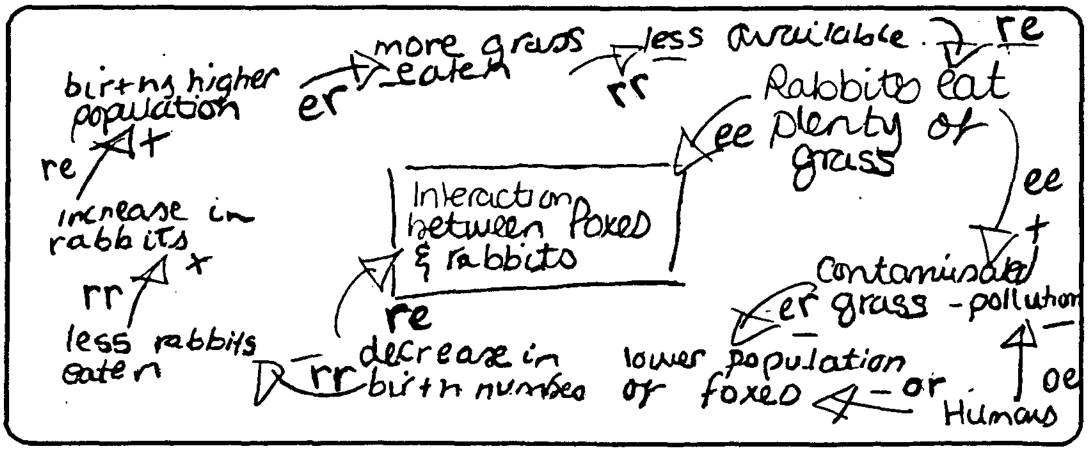


19) Suppose you want to describe the interaction between foxes and rabbits living in the same region. Suppose rabbits have plenty of grass to eat but are eaten by foxes. Both foxes and rabbits give birth, and foxes will die of starvation if there are too few rabbits.

a) What variables might be needed to describe the situation?

Size & Type of habitat, temperature or climate.
Quality of grass - pollution. Interaction
of Human beings.

b) Make a causal diagram showing how these variables affect one another.



Appendix IX

CRITERIA FOR JUDGING REASONABLE LINKS

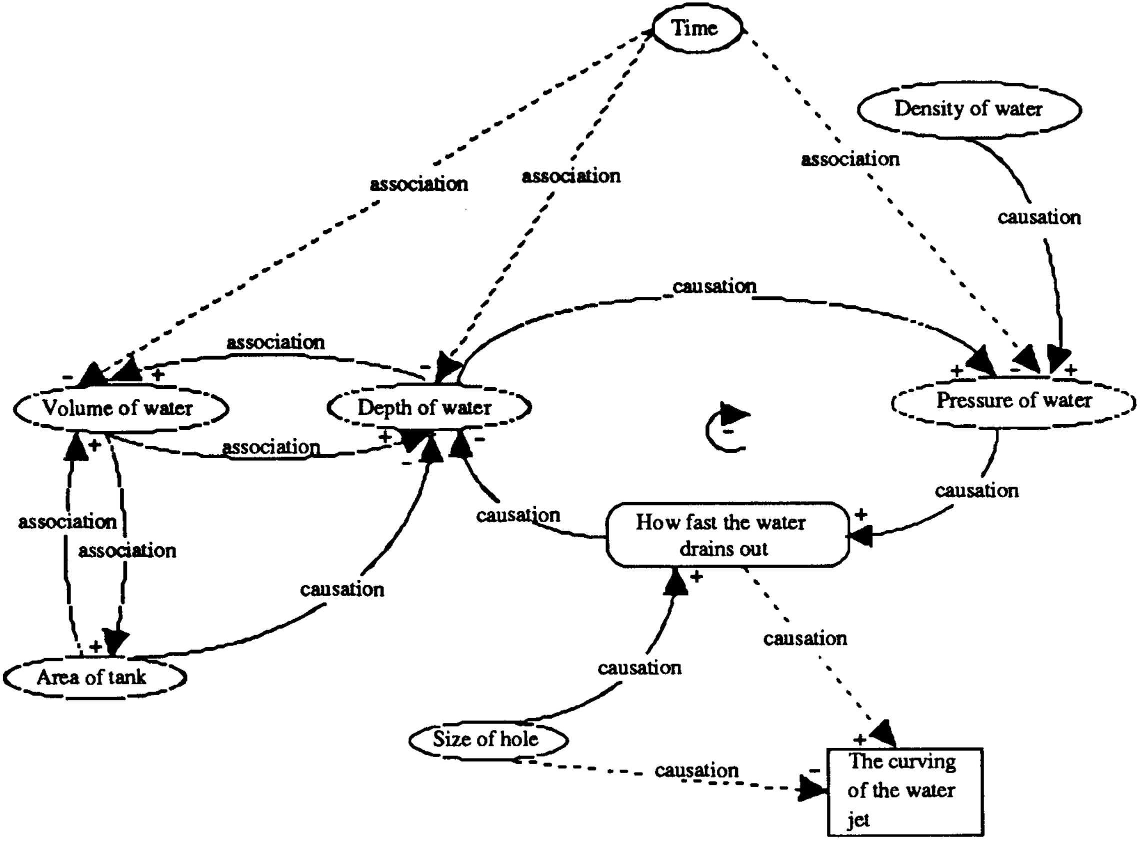


Figure 1 - Causal diagram showing possible links considered as reasonable, for the Leaky Tank task.

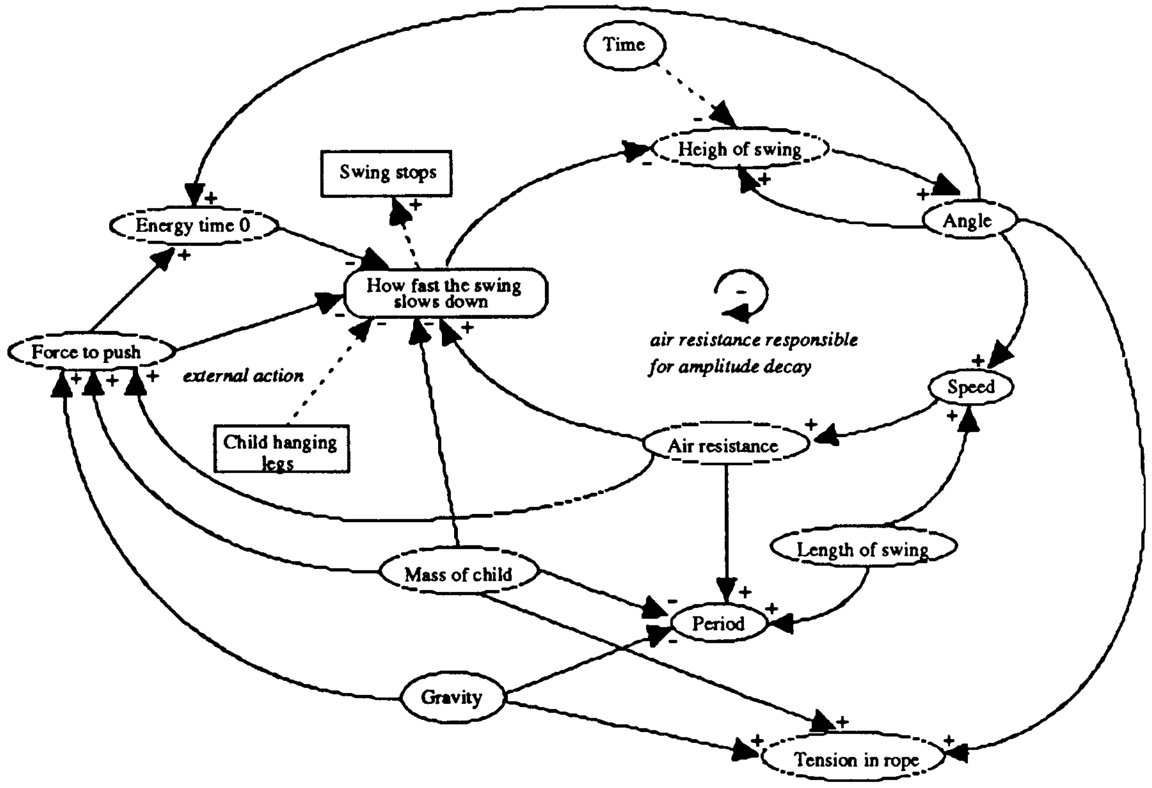


Figure 2 - Causal diagram showing possible reasonable links, for The Swing task.

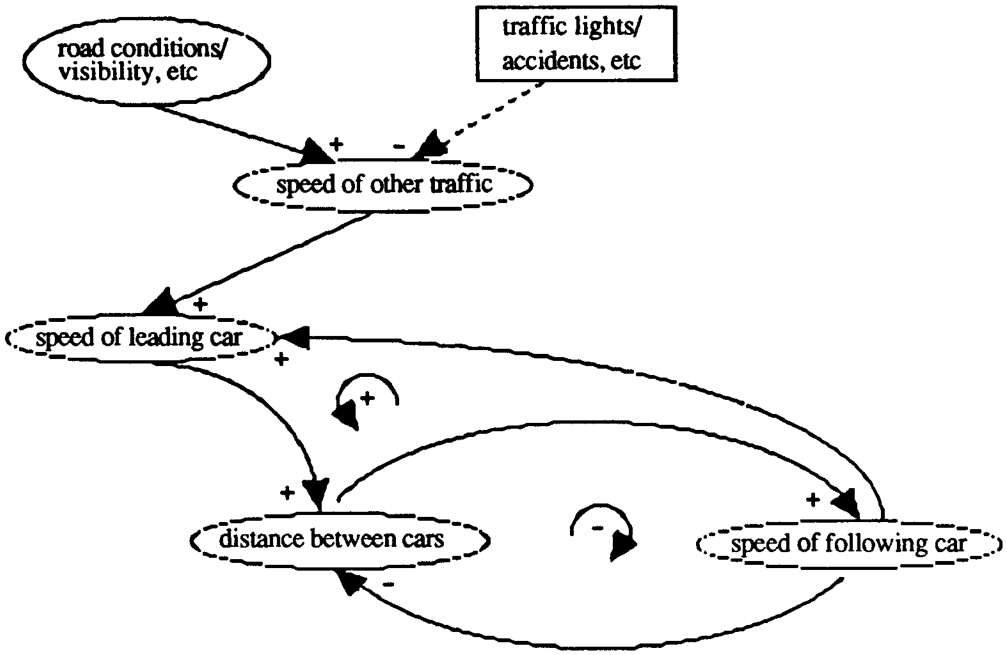


Figure 3 - Causal diagram showing possible links considered as reasonable, for the "two cars in a stream of traffic" task.

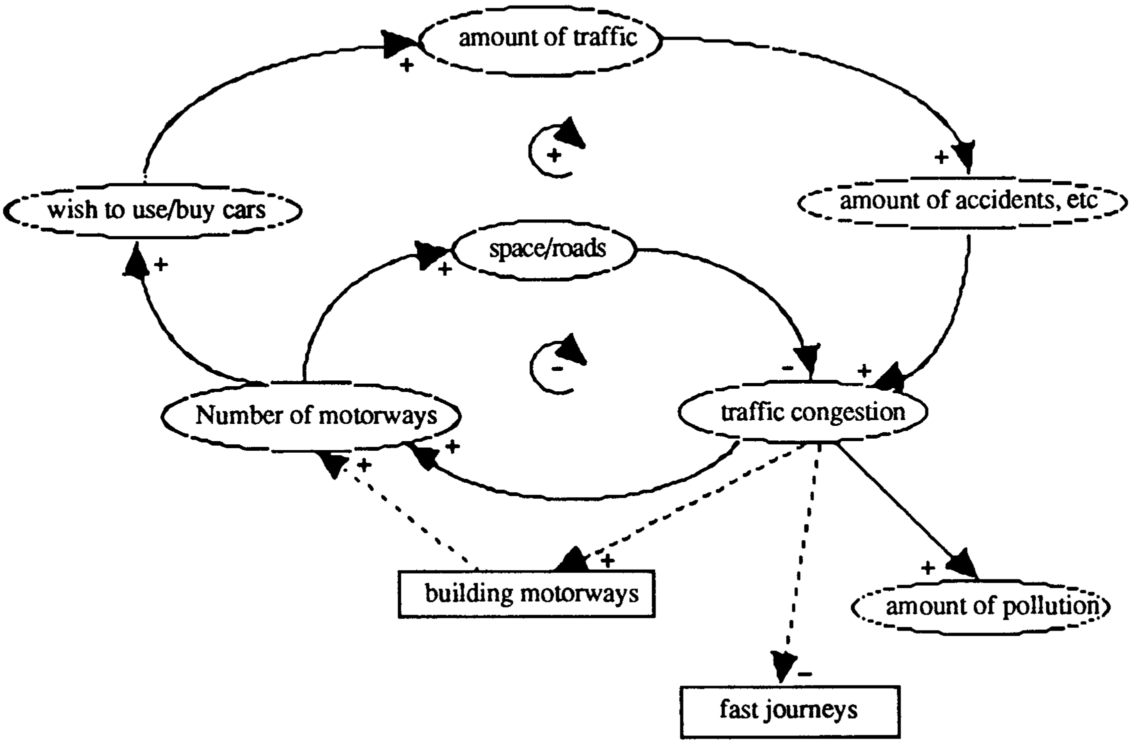


Figure 4 - Causal diagram showing possible links considered as reasonable, for the "motorways" task.

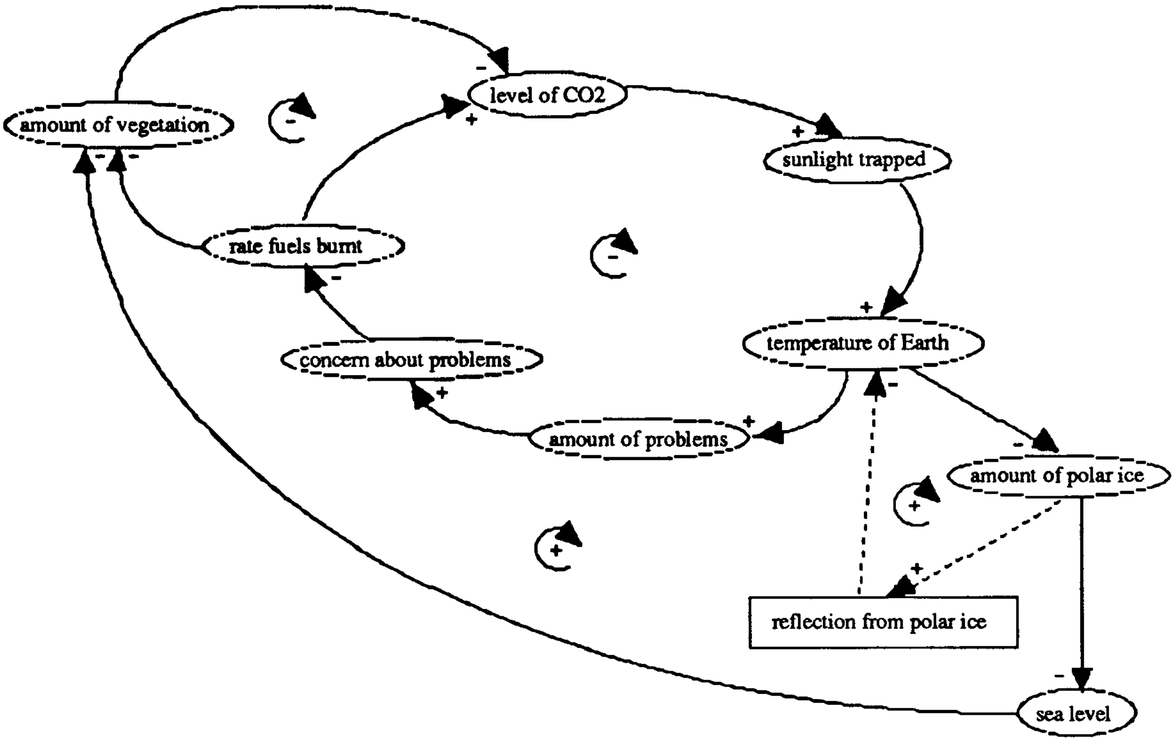


Figure 5 - Causal diagram showing possible links considered as reasonable, for the "Greenhouse Effect" task.

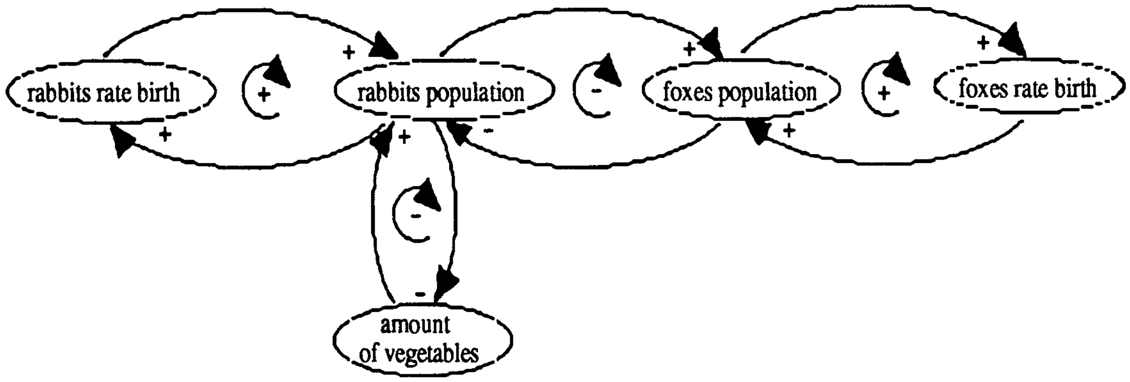


Figure 6 - Causal diagram showing possible links considered as reasonable, for the "Rabbits and Foxes" task.

Appendix X

COMPLETE SET OF CORRELATION TABLES - QUESTIONNAIRE ABOUT MODELLING

Codes:
L - London
K - Kent
2C - Two cars in a stream of traffic
M - Motorways
Gr - Greenhouse Effect
RF - Rabbits and Foxes
Bold - significant at 0.05 level

	softL	softK	hardL
softK	070		
hardL	**424**	263	
hardK	000	157	098

Table 1 - Pearson Product-Moment Correlation, for London and Kent, for experience with software and hardware.

	softL	hardL
var2CL	121	**276**
varML	172	221
varGrL	066	**260**
varRFL	141	221

Table 2 - Pearson Product-Moment Correlation, for London, for use of variable-ized links and experience with software and hardware.

	softK	hardK
var2CK	045	108
varMK	276	239
varGrK	290	056
varRFK	053	230

Table 3 - Pearson Product-Moment Correlation, for Kent, for use of variable-ized links and experience with software and hardware.

	softL	hardL
(21)graL	102	028
(22)PrL	-034	184
(23)PicL	**-395**	**-335**
(24)LogL	-141	164
(25)PattL	-082	-000
(26)0 L	006	096
(27)c L	078	-095
(28)-cxL	150	196
(29)ProL	-166	-249
(30)ProL	043	-204
(31)ProL	-069	-265

Table 4 - Pearson Product-Moment Correlation, for London, for experience with hardware and software and achievement in Mathematics.

	(1) sofK	(2)hardK
(21)graK	134	209
(22)PrK	**498**	156
(23)PicK	**425**	207
(24)LogL	353	014
(25)PattK	300	076
(26)0 K	**396**	159
(27)c K	212	169
(28)-cxK	252	**443**
(29)ProK	**403**	076
(30)ProK	**471**	204
(31)ProK	**464**	226

Table 5 - Pearson Product-Moment Correlation, for Kent, for experience with hardware and software and achievement in Mathematics.

	softL	hardL
(3-8)Reaslinks...	246	**290**
(13)reasL	222	212
(16b)reasL	**309**	**348**
(17) reasL	**329**	207
(18)reasL	**342**	250
(19b)reasL	191	160
(20)reasL	122	034

Table 6 - Pearson Product-Moment Correlation, for London, for experience with software and hardware and use of reasonable links.

	softK	hardK
(3-8) Reaslink...	143	092
(13)reasK	281	118
(16b)reasK	048	036
(17)reasK	375	303
(18)reasK	271	098
(19b)reasK	075	147
(20)reasK	098	-252

Table 7 - Pearson Product-Moment Correlation, for Kent, for experience with software and hardware and use of reasonable links.

	softL	hardL
(13) KindL	263	**385**
(16b) KindL	142	248
(17) KindL	**283**	**342**
(18) KindL	**295**	**520**
(19b) KindL	168	133
(20) KindL	123	010

Table 8 - Pearson Product-Moment Correlation, for London, for experience with software and hardware and kind of diagram drawn.

	softK	hardK
(13) Kind K	310	184
(16b) KindK	052	-073
(17) KindK	**407**	**387**
(18) KindK	340	265
(19b) KindK	**397**	304
(20) KindK	**445**	120

Table 9 - Pearson Product-Moment Correlation, for Kent, for experience with software and hardware and kind of diagram drawn.

	softL	hardL
event --> event (ee)	-068	-075
object --> object (oo)	-063	100
object --> event --> object (oeo)	-089	-068
partlyvar (e.g. event --> amount)	**388**	207

Table 10 - Pearson Product-Moment Correlation, for London, for experience with software and hardware and non-variable-ized and partly variable-ized links (Greenhouse Effect task).

	softK	hardK
event --> event (ee)	144	160
object --> object (oo)	188	-101
object --> event --> object (oeo)	174	012
partlyvar (e.g. event --> amount)	121	087

Table 11 - Pearson Product-Moment Correlation, for Kent, for experience with software and hardware and non-variable-ized and partly variable-ized links (Greenhouse Effect task).

	26)0	27)c	28)-cx	29)Pro	30)Pro
26)0					
27)c	**499**				
28)-cx	**535**	**335**			
29)Pro	**278**	260	220		
30)Pro	177	136	214	**458**	
31)Pro	028	023	192	**420**	**550**

Table 12 - Pearson Product-Moment Correlation, for London, for scores in differential and difference equations.

	26)0	27)c	28)-cx	29)Pro	30)Pro
(26)0					
(27)c	**712**				
(28)-cx	**796**	**695**			
(29)Pro	**610**	**450**	**614**		
(30)Pro	**514**	222	**534**	**778**	
(31)Pro	**545**	**540**	**615**	**619**	**714**

Table 13 - Pearson Product-Moment Correlation, for Kent, for scores in differential and difference equations.

	var2cL	varML	varGrL	varRFL
(21)graL	-116	-196	160	-097
(22)PrL	016	035	-256	-070
(23)PicL	-149	-079	-034	-146
(24)LogL	128	-126	183	-029
(25)PattL	-006	-156	-039	-176
(26)0 L	-116	-183	220	-151
(27)c L	033	-044	149	-211
(28)-cxL	-027	-215	085	-166
(29)ProL	-045	-167	047	-251
(30)ProL	-020	-268	-186	**-383**
(31)ProL	-174	-094	**-292**	-251

Table 14 - Pearson Product-Moment Correlation, for London, for use of variable-ized links and achievement in Mathematics.

	var2CK	varMK	varGrK	varRFK
(21)grK	-272	-051	162	327
(22)PrK	276	242	211	314
(23)PicK	310	**389**	279	064
(24)LogK	091	**566**	134	182
(25)PattK	-057	156	228	257
(26)0 K	-003	**631**	344	**474**
(27)c K	159	317	293	**388**
(28)-cxK	-061	**411**	**389**	**443**
(29)ProK	-179	156	**401**	029
(30)ProK	-250	301	**546**	-124
(31)ProK	-103	334	**703**	100

Table 15 - Pearson Product-Moment Correlation, for Kent, for use of variable-ized links and achievement in Mathematics.

	(13)rea...	(16b)re...	(17) re...	(18)rea...	(19b)re...	(20)rea...
(13)reasL						
(16b)reasL	**435**					
(17) reasL	**365**	**377**				
(18)reasL	**369**	**358**	**559**			
(19b)reasL	**487**	**584**	**502**	**560**		
(20)reasL	**588**	**424**	**362**	**430**	**470**	
(13) KindL	**305**	**326**	**596**	**536**	**294**	190
(16b) KindL	-063	**368**	**323**	**412**	266	075
(17) KindL	125	271	**582**	**409**	**386**	192
(18) KindL	**389**	**381**	**517**	**620**	**385**	**369**
(19b) KindL	268	125	**276**	**405**	232	187
(20) KindL	086	125	**426**	184	149	179

Table 16 - Pearson Product-Moment Correlation, for London, for use of reasonable links and kind of diagram.

	(13)rea...	(16b)re...	(17)rea...	(18)rea...	(19b)re...	(20)rea...
(13)reasK						
(16b)reasK	**433**					
(17)reasK	**591**	240				
(18)reasK	**474**	318	**599**			
(19b)reasK	**380**	**442**	376	**602**		
(20)reasK	299	141	252	228	**474**	
(13) Kind K	**603**	294	**550**	291	**390**	317
(16b) KindK	113	**560**	165	356	**389**	237
(17) KindK	270	250	**548**	**414**	223	014
(18) KindK	173	082	**447**	**625**	355	153
(19b) KindK	123	153	**507**	**546**	**588**	**429**
(20) KindK	134	-088	348	313	349	**517**

Table 17 - Pearson Product-Moment Correlation, for Kent, for use of reasonable links and kind of diagram.

	var2CL	varML	varGrL	varRFL
var2CL				
varML	**375**			
varGrL	214	021		
varRFL	**405**	242	**432**	
(13)reasL	**341**	193	**357**	216
(16b)reasL	**657**	**290**	237	**313**
(17) reasL	**303**	**467**	003	**291**
(18)reasL	192	**398**	**320**	**456**
(19b)reasL	**424**	**440**	248	**493**
(20)reasL	207	**348**	229	184

Table 18 - Pearson Product-Moment Correlation, for London, for use of variable-ized links and reasonable links.

	var2CK	varMK	varGrK	varRFK
var2CK				
varMK	269			
varGrK	083	301		
varRFK	**437**	**417**	190	
(13)reasK	313	**830**	280	**475**
(16b)reasK	**747**	312	**385**	**447**
(17)reasK	249	**667**	260	**415**
(18)reasK	240	**455**	379	**629**
(19b)reasK	**442**	**447**	169	**861**
(20)reasK	205	324	314	**380**

Table 19 - Pearson Product-Moment Correlation, for Kent, for use of variable-ized links and reasonable links.

	var2CL	varML	varGrL	varRFL
var2CL				
varML	**375**			
varGrL	214	021		
varRFL	**405**	242	**432**	
(13) KindL	**356**	**419**	089	**413**
(16b) KindL	**344**	222	132	**360**
(17) KindL	**313**	**480**	000	**471**
(18) KindL	**387**	**345**	**275**	**391**
(19b) KindL	163	259	245	**312**
(20) KindL	168	**341**	-070	161

Table 20 - Pearson Product-Moment Correlation, for London, for use of variable-ized links and Kind of diagram.

	var2CK	varMK	varGrK	varRFK
var2CK				
varMK	269			
varGrK	083	301		
varRFK	**437**	**417**	190	
(13) Kind K	**470**	**578**	074	318
(16b) KindK	**519**	148	153	238
(17) KindK	290	297	104	232
(18) KindK	-050	142	216	355
(19b) KindK	163	346	331	**516**
(20) KindK	-033	271	058	357

Table 21 - Pearson Product-Moment Correlation, for Kent, for use of variable-ized links and Kind of diagram.

	(13)rea...	(16b)re...	(17) re...	(18)rea...	(19b)re...	(20)rea...
(21)graL	-159	-083	-030	-033	-095	-051
(22)PrL	-133	-036	124	-048	029	-077
(23)PicL	-150	**-379**	-242	-219	-072	**-277**
(24)LogL	-068	-039	-123	-051	-066	-069
(25)PattL	-095	-083	050	-097	041	-132
(26)0 L	065	-064	037	038	118	012
(27)c L	238	051	199	104	089	254
(28)-cxL	044	098	065	065	-006	-105
(29)ProL	-050	-076	-147	**-318**	-173	-227
(30)ProL	006	-092	-146	-185	-065	**-343**
(31)ProL	-151	-215	-238	-212	-151	**-313**

Table 22 - Pearson Product-Moment Correlation, for London, for use of reasonable links and achievement in Mathematics.

	(13)rea...	(16b)re...	(17)rea...	(18)rea...	19b)re...	(20)rea...
(21)grK	-287	-260	000	**387**	363	067
(22)PrK	**391**	317	**486**	285	104	272
(23)PicK	370	247	292	**399**	120	-109
(24)LogK	**527**	118	**606**	273	224	**452**
(25)PattK	314	-034	095	**440**	179	079
(26)0 K	**626**	170	362	**438**	**510**	**537**
(27)c K	331	106	034	072	329	**527**
(28)-cxK	**395**	160	280	361	**453**	201
(29)ProK	056	019	169	092	263	**411**
(30)ProK	128	-041	196	180	122	217
(31)ProK	0219	-037	348	288	121	306

Table 23 - Pearson Product-Moment Correlation, for Kent, for use of reasonable links and achievement in Mathematics.

	(13)Ki	(16b)Ki	(17)Ki	(18)Ki	(19b)Ki	(20) Ki
(21)graL	-128	-129	-099	080	-026	-051
(22)PrL	146	041	362	228	028	098
(23)PicL	-268	-243	-088	-219	-073	-113
(24)LogL	-164	-116	-063	019	-139	-230
(25)PattL	**-311**	**-329**	**-285**	-082	-233	-252
(26)0 L	-150	-160	042	164	020	-238
(27)c L	078	-086	061	163	-124	098
(28)-cxL	-002	-084	-069	098	-033	006
(29)ProL	**-398**	-304	**-352**	**-347**	-248	-139
(30)ProL	**-342**	**-492**	**-420**	**-357**	**-395**	**-423**
(31)ProL	-248	**-324**	-249	**-370**	-170	-076

Table 24 - Pearson Product-Moment Correlation, for London, for scores in Mathematics and kind of diagram drawn.

	(13)Ki	(16b)Ki	(17)Ki	(18)Ki	(19b)Ki	(20)Ki
(21)grK	-285	-185	-162	183	**456**	317
(22)PrK	**418**	246	**723**	**569**	290	**416**
(23)PicK	**553**	325	**617**	**451**	143	-177
(24)LogK	**757**	357	**395**	374	304	299
(25)PattK	306	051	331	**404**	-023	004
(26)0 K	**467**	175	274	372	**398**	**494**
(27)c K	328	-109	009	-034	110	279
(28)-cxK	277	032	318	358	253	248
(29)ProK	204	242	138	291	239	226
(30)ProK	112	212	304	**464**	346	134
(31)ProK	213	131	211	353	383	217

Table 25 - Pearson Product-Moment Correlation, for Kent, for scores in Mathematics and kind of diagram drawn.

	oo	oeo	ee	partlyv
(21)graL	-135	-121	196	098
(22)PrL	231	171	197	032
(23)PicL	197	193	-143	**-536**
(24)LogL	-084	-092	073	147
(25)PattL	-047	024	067	-014
(26)0 L	245	-001	-040	001
(27)c L	-064	-084	041	160
(28)-cxL	**285**	-101	140	131
(29)ProL	-050	-179	184	-235
(30)ProL	-009	-087	-079	-079
(31)ProL	063	142	106	-123

Table 26 - Pearson Product-Moment Correlation, for London, for use of non-variable-ized and partly variable-ized links (Greenhouse Effect task) and scores in Mathematics.

	oo	oeo	ee	partlyv...
(21)grK	-111	-045	312	079
(22)PrK	161	114	137	258
(23)PicK	159	183	-335	378
(24)LogK	244	233	-316	**480**
(25)PattK	075	-036	-191	**635**
(26)0 K	250	139	-213	**481**
(27)c K	-138	-321	-123	133
(28)-cxK	106	-067	-136	373
(29)ProK	257	035	-346	160
(30)ProK	127	-044	**-396**	256
(31)ProK	120	-048	-274	108

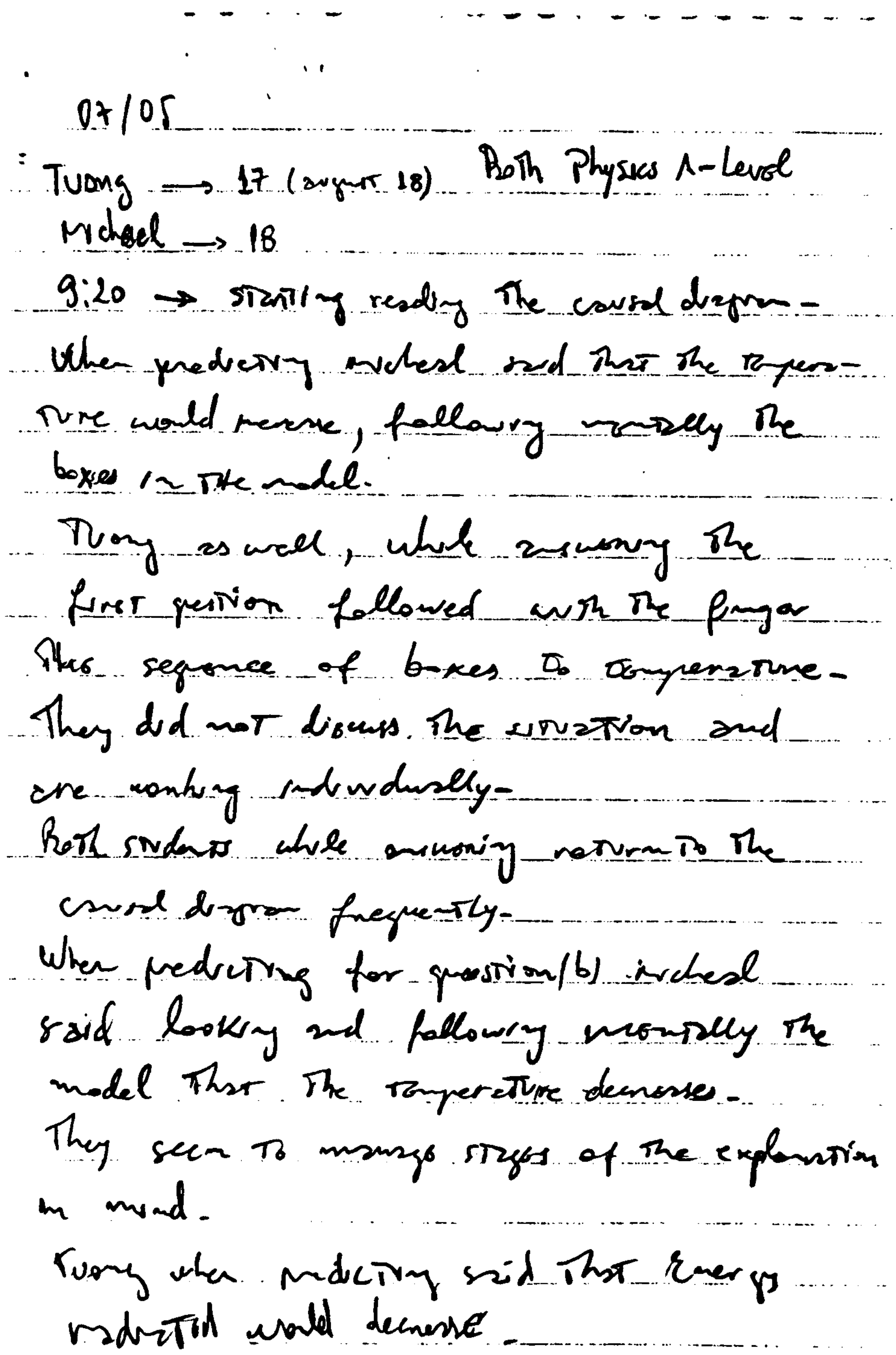
Table 27 - Pearson Product-Moment Correlation, for Kent, for use of non-variable-ized and partly variable-ized links (Greenhouse Effect task) and scores in Mathematics. See meaning of oo, oeo, ee in Table 10.

	oo	oeo	ee	partlyv
(18)reasL	-091	**435**	254	**370**
(18)reasK	**535**	185	-004	**641**

Table 28 - Pearson Product-Moment Correlation, for London and Kent, for use of non-variable-ized and partly variable-ized links (Greenhouse Effect task) and use of reasonable links. See meaning of oo, oeo, ee in Table 10.

Appendix XI

PHOTOCOPY OF THREE PAGES OF REAL NOTE TAKEN - TUO AND MIC



07/05

Tuong → 17 (august 18) Both Physics A-Level
Michael → 18

9:20 → starting reading the causal diagram.
When predicting Michael said that the tempera-
ture would increase, following mentally the
boxes in the model.

Tuong as well, while answering the
first question followed with the finger
the sequence of boxes to temperature.
They did not discuss the situation and
are working individually.
Both students while answering return to the
causal diagram frequently.
When predicting for question (b) Michael
said looking and following mentally the
model that the temperature decreases.
They seem to manage stages of the explanation
in mind.
Tuong when predicting said that Energy
radiated would decrease.

Hugh said the same but followed the variables emphasizing the polar ice, and saying that there would be an equilibrium due to the effect of polar ice and temperature

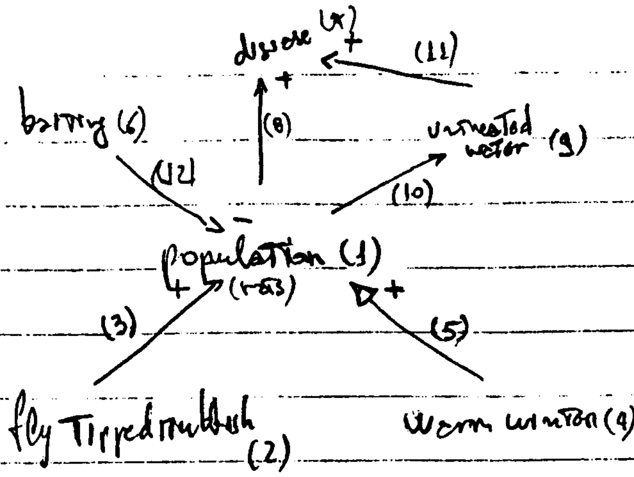
He followed Temperature → polar ice
→ En- radiated → Temperature ⟹
Energy radiated when explaining, correctly and said that there would happen an equilibrium-

Students went through the exploratory tasks individually.

Expressive Task with MacDraw -

Michael went through the text and selected the main variables to be used while Tuong just read the text.

Michael commented about fly-tipped and rubbish droped (what the difference was)



10:15 – questionnaire about models

During the teaching, Mich asked me if he should write about the pressure.

10:43 – Two teams –
Michel said that only taking into account pressure to don't behave like that – I told him that the model was taking into account pressure in the constant (K) (Embeded) They thought a lot for about 5 minutes about the situation, before answering.

Appendix XII, PAGES 352-360 REDACTED DUE TO THIRD PARTY RIGHTS OR OTHER LEGAL ISSUES

dos Santos, A. C. K. and Ogborn, J. (1992). 'A model for teaching and research into computational modelling'. *Journal of Computer Assisted Learning,* 8 (2), 67-78.