Microworlds for Ecology Explorations:
From DigitalSeed to Biosphera in fostering children's understanding of plant biology

by

Mauro Cherubini

Submitted to the Department of Education, Saint Patrick's College
Dublin City University
in fulfillment of the requirements for the
Master of Arts in Education by research

Supervisor: Dr Hugh Gash

May 2004

I hereby certify that this material, which I now submit for assessment on the program of study leading to the award of Master of Arts by Thesis/Research is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ______________________________

ID No.: 52101860

Date: 15th of January 2004

This thesis was typeset using LaTeX[1].

[1] See http://www.latex-project.org/

Abstract

The essence of this study is the idea to use the human ability to notice patterns in the environment, alter these patterns and observe the consequences, as the key manipulatory experiences to grasp some ideas about plant biology. Some of the findings here contained show a positive impact of this framework in children's interaction with plants. In addition, observations suggest that plant's fragility and slow reaction to stimuli are factors responsible for children's misconceptions and lack of interest in them. Two solutions found here will be described in terms of their design and evaluated. They are the DigitalSeed and the Biosphera, for each of which, an interplay between virtual reality and physical elements will constitute the strategy to facilitate development in children's representations. The former highlights the concept of life cycle enabling the learner to "physically" feed a virtual seed; the latter enables the learner to define a "growth program" for a virtual plant bound to an actual plant. A key aspect of the design is the use of physical and virtual avenues of discovery, freeing the user to interact with the system, following non-linear paths of interaction, and testing multiple possible futures of the "plant story". The main value of this work will rest in the design domain because no systematic study has been completed on the long–term impact of this technology on children's understanding of plant biology.

Acknowledgments

I would like to thanks several colleagues that helped during the workshops and in the general discussions of the ideas. I want to thank Kathleen Biddick, Fulbright Fellow, for thinking and helping through the workshops and Jamie Rasmussen, Hervé Gomez, and all our colleagues from Everyday Learning group for supporting us during the workshop activities. I want to thank Graham Toms for the beautiful plant animations used in the initial interface. Finally, I want to thank Niall Winters and Jamie Rasmussen for the help in building the software interface and the framework in which this thesis have been developed.

For the development of the DigitalSeed project, I would like to thank: Brendan Donovan, for the PIC programming; Matthew Karau and Brian McDonald, for help in designing the electronic board; Mike Ananny, for the theoretical advice; James Condron and Steven Hughes, for help in debugging the electronic board; Valentina Nisi, for the art work; and Hervé Gomez, for the important discussions about the workshop design. Also I would like to thank Anna Lometti, St. Patricks College and California State University, Chico, for help in the workshop assessment, and Bakhtiar Mikhak, MIT Media Lab, for the important advice on the iPAQ-sensors interfacing. I thank the children for sharing their ideas with us.

Finally, I want to thank Michael Cahill for the invaluable help in building the prototypes, and all the people at MLE that is a really exciting place to be part of. A special thanks to Glorianna Davenport and Emma Coyle that were so kind to me when I could not speak a single word of English.

1st June 2004, Carol Strohecker cannot appear on the title page as she was not the university supervisor. However, I want here to emphasise strongly Dr. Strohecker's role as research supervisor and mentor of this work, as MLE Principal Investigator at the Everyday Learning group. Without her continuous support and direction this study could have not taken place. To her, all my gratefulness for her advice and human support.

I want to dedicate this work to my father and my mother, for being supportive during these two years of intense and "crazy" work, carried out mostly on the AerLingus flight EI505/2 between Rome and Dublin.

Above all, I want to dedicate this work to Roberta, my wife, who loved me beyond any human capability even when life was so incomprehensible and fast we could not understand what was happening to us. With love,

Mauro

"... As a consequence of man's having the faculty to apprehend patterns external to himself and the capability of altering those patters, interesting changes in the conscious relationship of man to universe are now multiplying in evidence."[2]

Buckminster Fuller, *Education Automation*

[2]Picture source: http://www.bfi.org .

Contents

List of Figures

List of Tables

Chapter 1
Introduction

"... many children come to science classes with ideas and interpretations concerning the phenomena that they are studying even when they have received no systematic instruction in these subjects whatsoever. Children form these ideas and interpretations as a result of everyday experience in all aspects of their lives: through practical physical activities, talking with other people around them and through the media."

Rosalind Driver, *Children's Ideas in Science*

Image from Verey (1980)

Chapter 1

Introduction

A shift of control

We live in a complex world. The powers that propel society and the speed at which changes are happening are at an increasingly faster rate. Over the last few years a shift of control (Strohecker, 2003) has occurred in the way individuals learn. Nowadays, with the diffusion of the Internet, people are enabled to access multiple sources of information and documentation. Learning is part of this revolution because people want to take charge of their own development. The old paradigm of *transfer of knowledge* is broken, people can now structure their learning process, deciding modalities and timing, deciding the way they want to explore a concept and how to relate concepts in their own cognitive grid (Papert, 1982). We register a shift in the way old disciplines are presented to and accessed by people: Internet, satellite TV, specialised reviews, journals. Moreover, for individuals the control of their own learning is becoming a necessity consequent on the speed at which old jobs are converted into new forms of employment.

With these new possibilities offered by new communication channels and the resulting access to information, people can increasingly take charge of knowledge about their own well-being and the well-being of the environments in which they live. In addition, this new awareness produces a change of view in the way people perceive their role in the world. In fact, with this shift of control comes shifts of responsibility, which may lead in turn to the emergence of a new awareness of one's personal responsibility in regard to environmental pollution, politics and social position.

In this context, new representational strategies can translate information, so that people can understand it in their own ways and thereby, contribute to this changeover. This thesis, in fact, is just an attempt to look at simple tasks, like plant keeping, from the new perspective of *knowledge construction*. New strategies of representing plants and their surrounding environment will be here proposed. This work can be considered as an attempt to use new technologies; new media to stimulate and support this shift of control.

From the outer world to the inner environment of one's room

The goal of this thesis is not to concentrate on macro systems of instruction, but on very concrete examples in which informal learning can make a difference in the way people learn. For this reason, during my work at MLE, I concentrated on the plant keeping activities that everybody does in a house environment, trying to support the exploration of the plant ecosystem as inscribed in the bigger house-room-ecosystem.

The room in which a person lives can be abstracted as a self-contained environment with proper dynamics and inhabitants. Temperature, humidity level and light conditions are perturbed as in the outer world. People living in the room are also contributing to the perturbation of this environment: breathing, for instance, increases the humidity in the room, the human body emanates heat affecting the temperature levels in the room, finally the light bulbs present in the room and/or windows can modify the light conditions.

Any pet living in the room is going to be part of its ecosystem. A plant is not different from an animal, it has different internal dynamics but it is nevertheless a living being: its biology does not allow the plant to modify the temperature directly, but it influences the humidity level and so, indirectly, the temperature conditions.

The health of the plant reflects the life support conditions of the room environment. If the plant is not healthy this may reflect a bad oxygenation of the room, or severe conditions of light, heat and humidity. There is a concrete correlation between the room–system and the plant–system, because usually a room is 10-30 m^2, and walls and windows provide sufficient insulation from the external world. Subsequently, as a first approximation I considered a room environment as a self–contained ecosystem, with its own proper dynamics, and I tried to simplify the exploration of the plant organism inscribed in its world.

In fact, it is usually difficult to understand how environmental variables affect a plant's life, or, at least, how to tune and control these conditions to provide the best environment for our green friends. We know, from oral tradition, that we have to give water to the plant and that we need to keep the plant warm and in the right light conditions, but this is usually it. Conversely, the variables' interactions are usually complicated, sometimes in good light conditions we do not get the best growth results, because the way the variables' effects mix and influence the plant's growth are difficult to predict.

This thesis seeks to intervene precisely in this context, trying to provide a framework, a technology and a tool which can help in the exploration of 'variables affecting a plant's growth', in keeping plants, and above all in constructing a personal knowledge of these phenomena.

A plant's world: limits of an interaction with a plant

When we interact with a plant we experience several dynamics which I consider as limiting to the learning experience with the plant. Firstly, you cannot manipulate the plant with too much energy because of its fragility. Is not possible, for example, to shake the plant, or to throw the plant, etc., without causing severe damage to its integrity. In this sense the manipulative experience you can have with the plant is reduced (see Eyster and Tashiro (1997), or Sowell (1989)). Secondly, plants are slow in responding to climatic/environmental changes. This impacts upon the way a learner builds cognitive connections between a perturbation on the ecosystem and the corresponding effect on the life of the plant, which is, in turn, the corresponding qualitative and empirical approach to the exploration of the plant's biology. Thirdly, a plant is in itself a complex world. Lots of environmental factors intersect to generate non-linear forms of growth. Using empirical observation to grasp the underlying laws and connections is not usually enough.

Several variables interact at the same time to generate the outcome of a plant's life. Modelling these variables is not an easy task for research and, especially, for empirical observation. Lots of simplifications are needed in order to concentrate on the core concepts driving the growth of a living organism. Technology can be at hand to simplify our understanding of this process, providing the computational power needed to isolate conditions, speeding up these mechanisms, and keeping track of the outcomes. This was specifically the task this work sought to undertake.

A new media for exploring the plant's world

One of the aims of the Biosphera and the DigitalSeed projects is to expand human potential in the observation of a plant's life. In fact, these microworlds I have designed, support the learner, the user, during the observation of the plant, enabling a *comparison* between different sets of inputs into and outcomes from the ecosystem of the plant. Another mayor feature of this system is to speed up the biological processes of the virtual alter-ego of the physical plant for real-time observation, and finally this technology allows the user, for manipulation and exploration purposes, to reverse processes that are usually unidirectional. This kind of investigation is not possible with unaided human capabilities, so technology is considered throughout this work as a tool for sustaining human exploration, allowing new kinds of enquiry.

Biosphera and DigitalSeed are new media, in the sense that they support 'new' human abilities, the ability, for example, to observe invisible phenomena, to speed up biological processes and to make comparisons that are usually impossible to carry out. Another purpose of this thesis is to provide a stimulus to the research in this field, and also to use these new media, these new technologies as research tools, to study deeply the cognitive experiences people have during their interactions with plants and the kinds of understanding they can gain with new tools supporting them.

An outline of this work

It is not my intention, in this work, to make claims about the scientific effectiveness of the technology usage proposed in this thesis. Rather, this work has to be considered as a report of an experimental design exercise emerging from two years of study and research at Media Lab Europe. The proposed solutions, in fact, have not been tested longitudinally to draw firm scientific conclusions.

The second chapter describes an interaction scenario for the usage of the Biosphera system, trying to give the reader some examples of how and when this technology can be used and for which purposes. This chapter also gives me the opportunity to discuss a matrix of cognitive experiences the user can have while comparing plants grown within the system to plants grown outside the system (or two plants grown inside the system at two different environmental conditions).

The third chapter will discuss the theoretical background of this work, giving support to the current status of research on hypotheses raised. These sections will analyse all aspects of human interaction with plants and evaluate the research questions and claims collected during the literature survey.

The fourth chapter will illustrate the design of two implemented microworlds: the DigitalSeed and the Biosphera system, explaining how technical solutions chosen are related to the theoretical study described in Chapter 3, and how the design is going to support the hypotheses.

The fifth chapter will detail how the design proposed in Chapter 4 is born from collaboration with several groups of children, who have participated at some design sessions at MLE, and how their ideas stimulated the design of the final objects. In addition, this chapter will seek to report the historical evolution of the projects through several stages of development.

The last chapter will draw some conclusions from the entire work, and indicate some future developments.

Biosphera system: a first glance

This section will present the Biosphera platform, one of the two systems which were constructed through the two years of my work at MLE and that are documented in this work. In the following chapters, in fact, I will refer many times to this system, therefore it will be easier for the reader to have some knowledge of the system to which refer to.

In short: *Biosphera is an enclosed microworld in which people can change conditions and observe perturbations in the ecological system. A computer interfaces with sensors and actuators to enable detection and control of environmental parameters such as light, temperature, and moisture in the physical world. A simulation in the virtual world enables projections beyond the time scale required for real plants growth. This interplay of virtual representations and perceptual accessibility supports experimentation and learning about biology, chemistry, and dynamic systems.*

The Biosphera system has two main, inter–linked components, a physical dome and a virtual world. The physical component is required to house, and experiment with, the actual plant. The physical component I constructed is a tabletop-sized, plastic, transparent dome. It constitutes the physical interface, and it is represented in figure 1-1. This dome is fully equipped with light, heat and humidity sensors to monitor the changing environmental variables. To modify the conditions, the dome is equipped with fibre-optic lighting, heaters, fans, and a small irrigation system.

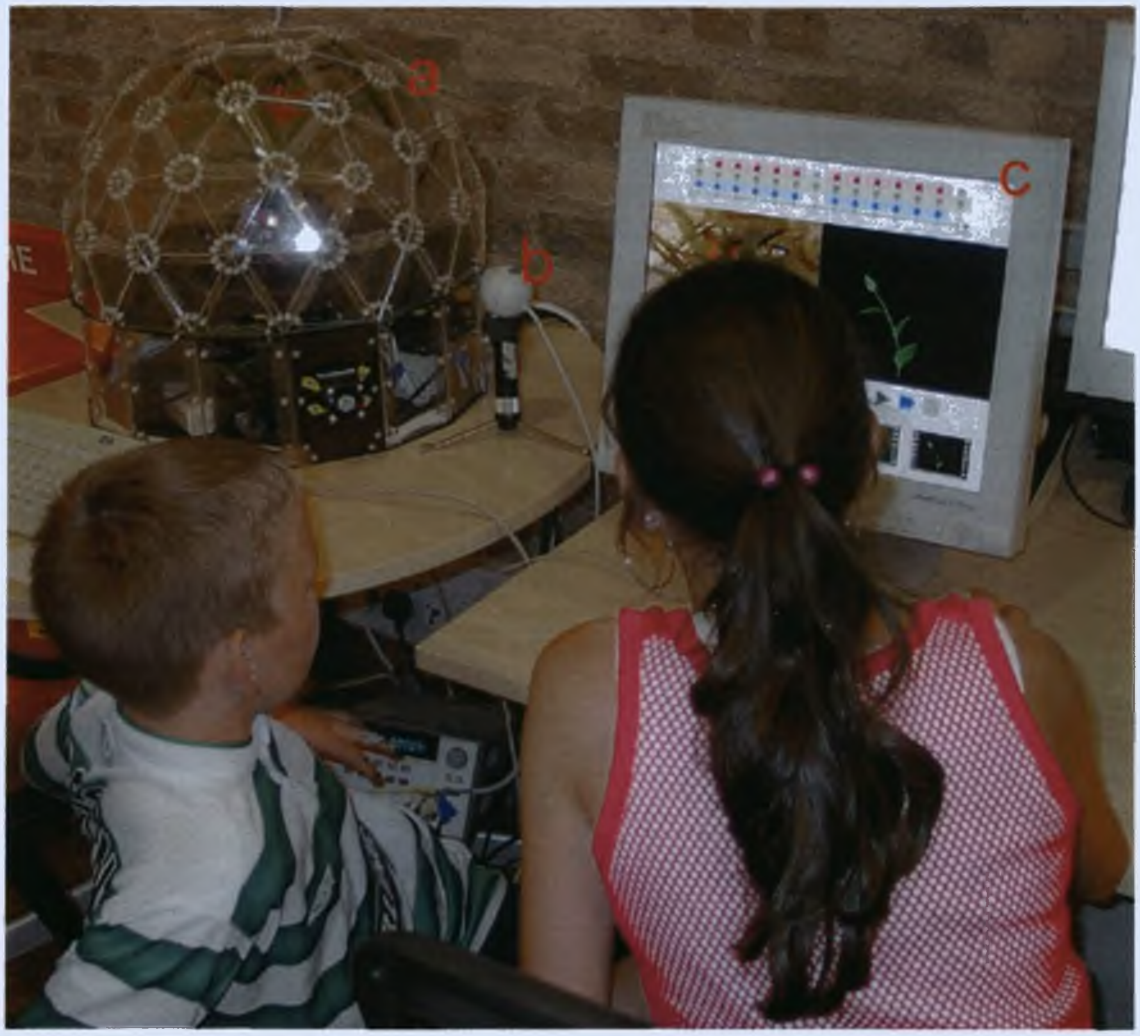

Figure 1-1: The Biosphera platform configuration. (a) dome/terrarium which can host an actual plant, (b) a webcam which record a *time*–lapse video of the growth of the plant, (c) PC running the Biosphera software with the simulated plant

The second component of the Biosphera design is a virtual world, running on a PC and connected to the physical dome, which is represented in figure 1-2. The timeline in (a) enables the user to define the environmental program executed by the hardware dome. Each variable is symbolised in this timeline (Heat → radiator; Light → sun; Humidity → drop). The timeline is composed of 15 tiles, so that each tile corresponds to two days in the life of the plant (total is 60 days). I tried to reduce the number of possible combinations between the variables, rendering discrete the variable's influence on the system in the logical term "on/off", meaning the average daily presence of such variables as above or under the mean value. Clicking any variable causes the variable to switch fro, the "on" state to the "off" one. Using this control, the user can set the growth program for the plant. The result of the execution of this program can be controlled by the simulation pane in (d). This window shows, in real time, the effect of the programmed set of variables on the growth of the virtual plant. Dragging the tile string (a) on the webcam image (b), taken from the hardware interface, causes the Biosphera subsystem to complete, over a longer period of time, the growth program set by the user. Dragging the simulation results over/from one of the free spots in (e) results in the save/load function being activated.

Figure 1-2: The Biosphera software. (a) The timeline giving access to the environmental program of the three variables, (b) a time–lapse video from the dome, (c) the simulated virtual plant, (d) simulation controls, (e) load/save spots

Chapter 2
Interaction scenario

"The development of an organism ... may be considered as the execution of a "developmental program" present in the fertilized egg. ... A central task of developmental biology is to discover the underlying algorithm from the course of development."

Aristid Lindenmayer, *The Algorithmic Beauty of Plants*

Image from Verey (1980)

Chapter 2

Interaction scenario

In this chapter, I will outline an example of use for the Biosphera system and provide a description of how it works. The scenarios used will be, for the most part drawn from reality. Sometimes, the scenarios will be hypothetical, to introduce potential future expansion or to describe possibilities offered by this design which were not necessarily implemented in the prototype we worked with. in presenting the workings of the Biosphera, all the examples described are fictional, although they are based on observed interaction patterns.

2.1 Interaction design: the cycle

In this section, I will describe how our potential user, David, is going to interact with the system. I envision two interrelated timelines through the narrative: the timeline of the user and the timeline for the plant. The former relates to the progress of the user in learning about the interface, plant biology and system dynamics; the latter relates to the life of the plant, which evolves over time following a cyclical path. These two timelines are related, because when the child is progressing through the evolution of the plant he is also learning about the powerful ideas (Papert, 1980) underlying plant biology, in addition to how a multivariate system —such as the surrounding environment— is going to influence it. While progressing though the plant's life, the user is also learning about the interface, and how the features of the interface can be used to support the experience.

2.1.1 [seed stage]

David comes to the Biosphera with no clues as to what this object is about. He can see that it is a kind of greenhouse, with strange things and wires attached to it. The interaction he has with this object is natural, intuitive because the functions of the system are self-evident. This dome connects in some way to a computer, in which software is running, displaying some colored icons and frames. David decides to start, and so he picks up a bean seed from a box, pots it in the provided container, and puts the pot in the dome (see figure 2-1). Afterwards, he seals the dome and initiates the software, clicking the program icon on the computer desktop. The software initiates. David can see a grid in the top part of the screen, with three rows and 14 columns. Each column has three icons in it, one for each row: a radiator, a light bulb, and a drop of water (see figure 4-9). These icons appear black and white. Instinctively, David clicks with the mouse over one of the tiles. Suddenly, he realizes that when clicked, an icon becomes colored. A consecutive click restores the b/w color. A sound plays every time he clicks over an icon.

Figure 2-1: The hardware interface

2.1.2 [germination]

After messing around with the tiles, he decides to stop. Nothing happens. He tries to click on the arrow under the grid, then on the empty frame below, with no results. Then he tries to click on the triangle icon below the empty frame, and this time, something starts moving. A green bar starts coloring along the line and, at the same time, a bean plant starts growing in the empty frame. He is very surprised to see the results of his actions on the screen. He wants to understand exactly how it works.

Figure 2-2: The initial software interface

2.1.3 [growth]

David believes that the sequence of tiles is connected in some way with the growth of the bean. So, he decides to start from there. He changes something in the sequence and then he tries again. This time, the bean plant seems to be different. He cannot be sure exactly how, but it seems different. David looks at the empty frames under the simulation pane and starts wondering what their functions are. He decides to try to drag the simulation window over there and this time, something happens: a screenshot of the plant story is taken, while a smaller version of the sequence of tiles, which generates the simulation, appears above the saved plant story (see figure 4-9). David realises that using these free spots, it is possible to save and load a plant story. He decides to use this function to investigate whether the set of tiles produces different outcomes. He saves the two stories in two different save positions, and then, one at a time, he reloads the two movies and observes small differences. Finally, he finds that the second sequence produces better growth, because the resulting second plant is bigger than the first. He is intrigued as to understand why this difference occurs. He has a feeling that the difference is connected with the different combination of tiles, but he is not sure how it works. He starts studying the sequence to see if the iconic code of each tile can help him. He believes that the radiator icon is connected in some way with the temperature factor. In the same manner, he believes that the light bulb icon is connected with the light and the drop icon is connected with the water. His first combination of tiles looks like figure 2-3, and his second combination of tiles is reported in figure 2-4. He thinks that the second bean plant is bigger than the first because there was more sunshine in the environmental program of the second plant. Comparing the two resulting plant movies, he can see the differences in growth, but he is still not completely sure.

Figure 2-3: David's first tiles combination

Figure 2-4: David's second tiles combination

2.1.4 [maturation]

On the right hand side of the simulation pane, he can see a video taken from the webcam installed inside the Biosphera. At the moment, the camera is just showing the image of the pot. Nothing is happening there. But he thinks that if the image is there, there must be a reason for it. He tries to click on the image, with no results. Then he looks at the icons on the right hand side of the cam image. There are three icons there, the same icons he can see in the tiles above. He thinks that in some way these icons are showing what is happening in the physical Biosphera. He tries to click on them with no results. Then, he tries to click on the play icon under the cam image, and this time something does happen: the physical dome activates. Some subsystem must have been activated, because there is a noise coming from the Biosphera. On the screen he can see that the green bar is still under the first column on the grid. This seems to indicate that it is executing that icon set. In addition, he can see a countdown running on the left-hand side of the timeline. David infers that the Biosphera is executing a growth program on the physical side, and that there are two months left to complete it: in fact, the software interface shows 14 sets of tiles (see figure 4-9) and the timeline goes from 0 days to 60 days, so, he concludes, each tile set should be 4 days of life of the plant. Suddenly, it starts raining inside the dome. After a while the rain stops. David is happy with this, and he decides to leave the computer executing the program. Before leaving the software, he tries to drag the cam image over one of the free spots under the simulation pane. Immediately, the program starts taking pictures every hour to build a time-lapse video. This is indicated by the background sound of a camera, and by a rotating film strip icon close to the used film spot.

2.1.5 [seedling]

After two weeks, the plant is still growing (every set of tiles correspond to 4 days of life of the plant). The program is now executing the fourth tile/column in the grid. David can see a sprout coming out of the physical pot, which is similar to the virtual alter-ego in the simulation pane. This convinces him that the simulation model in the software is accurate, but it does not show him why the second environmental program he ran resulted in better growth (because of the sunshine). For this reason, he decides to investigate further, setting up another experiment in which he can stress the sunny situation he wants to be tested, against a standard situation in which the plant is following an ordinary growth pattern. So, he sets up two simulations, with two corresponding environmental programs. The simulation, however, does not seem to provide the results David had expected. He cannot be sure that the simulation is working. So, he decides to apply the sunny program to a new physical bean.

2.1.6 [death]

After another two weeks, the actual bean growing inside the Biosphera seems to be aligned with the predictions the software made before starting the growth sequence; in fact comparing visually the actual plant with its virtual alter-ago, David can see the same structure and hight. He is surprised, because this contradicts what he had envisioned. So, he comes back to his first question: why did the two simulated bean plants grow differently with the two different growth sequences? He thinks that maybe the difference is not due to the sunshine, but to the fact that the first plant has more water in the first days of its life, which may result in an advantage against the second plant. This idea stimulates David's curiosity, so he wants to verify it immediately. He starts a new simulation in which, this time, he wants more water in the first days of life, against another plant with the average value of daily water. This time the simulation seems to confirm David's prediction: in fact, the virtual plant with more water in the initial days is visually bigger than the second. He is still interested in seeing how much water is important in a plant's life, so he decides to run another simulation, giving more water to the plant. Again, the plant grows larger than before. Again, David gives more water to the plant. This time, the simulation reveals a reduction in growth. David realizes that it is possible to increase the quantity of a variable too much. Too much of a certain variable may produce the same negative effect as the under-provision of the same variable. Following this exploration of the environmental variables' impact on the bean plant, David discovers that beans like a lot of water in the germination phase and less water during the maturation phase. Using the same comparative technique, David can find the best growth conditions for the bean plant and test them in the actual Biosphera.

2.2 Possible scenarios

Running the Biosphera system, the user can experience different situations in which his/her expectations do not match with the evidence presented by the system. This may lead to particular strategies or activities, which the user may adopt to resolve the discrepancy. Every activity is an exploration, in which the user is challenged to find explanations that may solve the cognitive impasse in which s/he may find her/himself. In this section, I will describe three possible scenarios that emerge from the interaction with the Biosphera.

2.2.1 Growth race

David and Anne are using Biosphera. Anne is watching her bean plant growing in the simulation pane when she sees a flower in the simulated plant. David wonders why his plant does not have a flower. They conclude that David's plant is not as developed as Anne's plant. Anne is very proud of her environmental program. David wants to develop a better program, so he starts to think about improvements in his program that may result in better growth for his plant. He starts adding more water during the germination phase, because he thinks that this may improve that part of the growth process. Then he starts thinking about the other two factors. Heat and Light should remain at the average level during the first period, he thinks. Then, he increases the heat level and the light exposure to provide more energy to the plant. He tests this solution, but ... no flower. Again, he tries to change something in the combination of the middle tiles to see if this will have beneficial effects. He tries to reduce the heat exposure and to improve the humidity somewhat. This time, he can see the bud of the flower. He is on the right track. He realizes that every time he raises the temperature, the growth seems to be reduced. So the heat above a certain level may be a limiting factor, he thinks. He needs to solve this problem. Maintaining the heat at a certain value, while alternating good conditions of light and humidity. Yes, this time the bud opens and the flower is fully visible.

2.2.2 Debugging the simulation

Anne wants to grow a bean plant up to the flower stage to give to her Mum as a present. She sets a program and then activates the dome to execute that program. After two weeks, she comes back to the system, and although she can see that there is a flower in the virtual plant, she cannot see the same flower in the actual plant. Obviously, the model underlying the simulation is not accurate, because there is a visible difference between the virtual and the physical plant. She wants to ascertain why this is happening. She decides to come back to the environmental program she initiated. Then, she opens the Biosphera status history, which logs all the climatic change inside the dome. She compares what was happening in the physical space with what she wanted to happen. She notices a change, which happened two days before. The temperature she set in the dome was high, whereas the temperature she got was low. She cannot explain why this happened, so she decides to ask her mother if someone touched the dome. Her mother says that two days before she was cleaning Anne's room, so she left the windows open all day. Anne knows why the growth program failed ... now.

2.2.3 Finding the "guilty" factor

David wants to grow some tomatoes and lettuce, so as to be able to make a sandwich at the end of the process. He sets up an environmental program to grow these plants as quickly as possible. So, he selects a plentiful amount of water, temperature and light exposure. The resulting simulation says that the plants should reach full growth in two weeks. He is happy with that, so he starts the program. After two weeks, he comes back to the Biosphera and realises that the plants are only halfway to full, completed growth. The model seems to have failed in its prediction. David is intrigued as to what the factor or factors responsible for the error in the simulation were. He decides to open up the Biosphera, and just after raising the top of the dome, he can smell stale air. He realizes that something happened while the program was running which modified the quality of the air. He opens the sensor-readings history, where he can verify that the temperature was higher than the one imposed during the previous week. Then, he opens the simulation parameters tweaking pane (see figure 2-5), where he can find all the factors in the simulations responsible for growth. He is convinced that the rise in temperature was due to an underestimated influence of external light on the dome. So he acts on the slider, augmenting that particular factor's influence on the definition of overall growth. He runs the simulation again, but after two weeks the resulting growth still appears complete. After further investigation, he decides that the factor responsible for the error must not be listed there. So, he decides to use the question mark slider to impute the error to an unknown or not monitored factor. Finally, he runs the simulation again, and this time there seems to be a match between the simulated plant and the actual plant in the dome.

2.2.4 Plant-keeping

Mark has two beautiful cacti on his desk. He is very proud of his plants. Sometimes, though, he finds that their color is not really a vibrant green, but seems somewhat pallid. He wants to discover why, so he decides to use the Biosphera system to monitor and take care of his plants. He sets up an environmental program, with little water and a high level of heat and light exposure. Then, he places one of his cacti inside the dome and initiates the program in the computer. After a month, he comes back to the Biosphera program to see what happened. He checks the environmental log, which

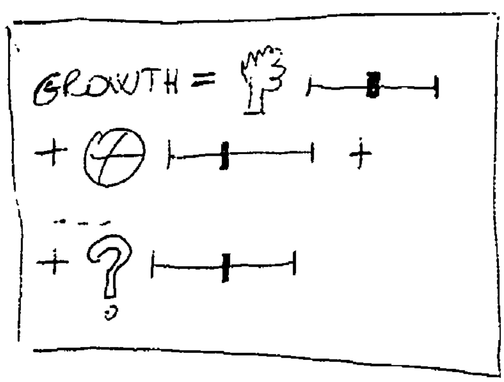

Figure 2-5: A sketch of the simulation parameters tweaking pane

reports all the sensor readings. The program seems to have been respected during the time period in question. In fact, looking closely at the plant inside the dome, he can already see that the color is different, a more intense green, than the color of the plant outside the dome. He thinks that this is related to the heat and light conditions, which are kept constant inside the dome (unlike Mark's room, where the other cactus is). He tries to stress this situation a little to see if his hypothesis is correct, so he programs another set of tiles inside the software, increasing the heat and the light exposure. Day after day, the difference between the internal plant and the external plant are more accentuated. After a month, the plant inside the dome produces a flower.

2.3 Cognitive experiences

Using the Biosphera platform, the user may explore four different cognitive experiences. The system is designed to stimulate visual comparison between two different entities (i.e., "1" and "2" of picture 2-6). From this contrast the user may confirm his/her expectations –or not. To reach this comparative point, the user is required to define one of the four different settings described below.

As represented in figure 2-6, four different comparisons are possible. The first basic comparison is made by opening two different simulation panes, and giving these two instances two different sets of environmental conditions. This kind of experience might bring the user to an understanding of the plant biology, but only through relying on the growth algorithm used in the simulation (see figure 2-6/(a)). The second possible comparison involves using the dome. This time, the comparison is between the virtual plant and the physical one. Using this method, the user might counter-proof the validity of the simulation growth algorithm (see figure 2-6/(b)). The third method consists of comparing a physical plant, which grows on a defined environmental program, and another physical plant which grows outside the dome, following the room environment. Using this kind of comparison, the user can gain an understanding of plant biology by using the external plant as a control (see

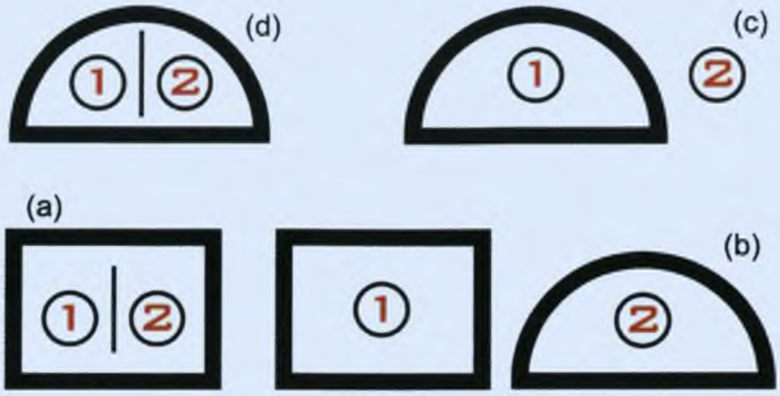

Figure 2-6: (a) A direct comparison of two virtual plants. Two instances of the simulation pane are created (i.e., two plant movies) and compared. (b) A comparison between the virtual plant and a physical plant inside the dome. (c) The comparison between two physical plants. One of them is inside the dome; the other is a control plant exposed to ambient conditions. (d) The comparison between two physical plants inside the dome, which are exposed to two different environmental conditions, imposed by the user.

figure 2-6/(c)). The fourth method consists of using a diaphragm inside the physical dome. In this way, it is possible to set up two different environmental conditions in the two different sections, so that the same plant can be grown with different environmental conditions. This might prove useful when the room environment cannot provide an appropriate space for particular kinds of experiments. Also, this kind of set-up can be used to assess the impact of a single factor on the plant's biology (see figure 2-6/(d)). A summary is reported in table 2.1.

It is also important to note that these cognitive experiences may be combined, to both prove the growth model and explore plant biology and the multivariate system. In fact, engaging in particular kinds of exploration, it may be possible to combine two or more of the above methods in order to make hypotheses and observe results.

TYPE OF COMPARISON	FEATURES	PROOF
(a) Two virtual plants	Plant biology and multivariate system. Highly interactive.	The growth model is not verified.
(b) A virtual plant and a physical plant	Growth model. Interaction restricted.	The growth model can be verified.
(c) Two physical plants. One is inside the dome, the other outside.	Plant biology and multivariate system. Interaction restricted.	The growth model is not verified. The external plant is used as a control for the running experiment.
(d) Two physical plants, both inside the dome.	Plant biology and multivariate system. Interaction restricted.	The growth model can be verified.

Table 2.1: Summary of possible comparison techniques and related features

Chapter 3
Theory / Rationale

"It's hard to think about thinking unless you're thinking about thinking about something"

Seymour Papert, *Mindstorms*

Image from Verey (1980)

Chapter 3

Theory / Rationale

This chapter details how previous research is connected with this thesis. I will describe the basis of this work and how these ideas are connected with the design solutions we have found. First, I will describe why I chose this particular methodology and implementation strategy; and what are the bases from which I started. This chapter leads into the next one, which will focus on design. Four major research fields have contributed to the development of my ideas and design solutions. I started from studies on *children's early ideas on plant biology*, because I was interested in how children develop and retain misconceptions, and because I wanted to focus on the Key ideas[1] underlying plant growth and life cycle; at the same time, while progressing through this study about plant biology, I realised that the environment surrounding the plant has a central role in affecting how the plant develops and dies. For this reason, I started to become interested in *multivariate systems*, a particular field of studies that investigates the comprehension of many variables interacting in the same dynamic system. Along with these studies and with our empirical observation (see Gash and Cherubini (2002)), I realised how influential *Time* is in the understanding of plant biology. Section 3.3 will deal specifically with this point. As a last point, I followed *Papert's constructionist theory* of informal learning, where the person 'learns by doing' through playful explorations (Papert and Harel, 1991; Kafai and Resnick, 1996).

A child's world is very different from our own. It is populated by ideas and schemes derived from sensory experience and initial living situations. This fact influences their interactions with the environment and their learning experiences. This is what Rosalind Driver defines as "alternate frameworks" (Driver, 1983, p. 33):

> ... pupils may have some strongly held ideas or beliefs about the phenomena they

[1] I use this term as synonymous of Papert's "powerful ideas" (see (Papert, 1980)), extending this concept in the meaning of a core ideas which give access to a broad number of other ideas. In this sense a Key idea is a node of a cognitive net of other ideas.

> study in science lessons. These ideas influence the observations pupils make in their experiments, as well as affecting the explanations they give for them. They can also persist in a range of situations and be persistent to change.

Many studies have been carried out to prove that this personal knowledge, in some classical literature addressed as *wrong*, can be productive in reformulating the everyday ideas which generate it (Smith et al., 1993). From this new perspective, misconceptions are not misinformation, but can be seen as a starting point from whence to locate a transformational process (Driver et al., 1994b).

3.1 Children's understanding of plant biology

Children have a number of misconceptions about plant life. Most of these misconceptions are due to the child's previous experiences and egocentric nature. Many different studies have found that it is difficult for children to understand how a plant grows, or how the environment affects the plant's metabolism. There are many conceptual issues related to plant reproduction, photosynthesis and the plant's respiration (Driver et al., 1994b). This section will highlight recent studies in this field and systematise underlying *key ideas*, dividing the material into two different groups: how children perceive both the external a-biotic/outer factors, and the biotic/inner factors in respect of the plant's growth.

3.1.1 Responding to the environment

This section will focus on children's ideas about the effect of the environment on the life of the plant, how they think about plant biology, and how they consider the plant in regard to the environment in which it grows and develops.

Light, Heat and Humidity are three central factors for plant growth. Children perceive all of them as factors connected in some way with this development, although the modality and proportions by which they impact are uncertain in their vision. In addition to this point, the object's behavior is frequently chosen as a criterion for life judgments (Driver et al., 1994b, p. 41):

> Many studies report that people of all ages identify things as living by the characteristic of movement and particularly that of movement following stimulation. However, the application of the criteria of sensitivity and movement can lead children to categorize as 'alive' certain inanimate objects ... Using movements and response as criteria of life leads children to exclude plants from category 'living'.

This point, in connection with the delay a person can experience while interacting with a plant, may influence the comprehension resulting from this interaction. Russell (1990, pp. 20-21), reported results on children being asked to draw "a plant" in the place where it would grow best, and to show everything it needed:

> There is a suggestion that the location in which children choose to place the plant varied with age. Infant and lower junior children seemed equally likely to put the plant inside or outside the building... Infant children mentioned only three conditions: water, soil and sun, with few referring to all three. By the lower juniors [2], some discrimination between the light and heat which are provided by the sun was in evidence, and this was much more marked in the upper juniors where 'light' became a more common response than 'sun'. The number of conditions mentioned by children increased steadily with increasing age though the most commonly mentioned remained water, soil and sun/light/warmth. ... There was very little mention of air or plant food at any age, and no mention at all from the infants. Nearly all mention of plant *food* was in relation to indoor plants so this condition might be related to the greater experience older children are likely to have had in caring for pot plants.

Light: source of energy, petrol of photosynthesis

Different studies also report that children of this age do not think of light as a physical entity existing in space (Guesne, 1985, pp.10-32), but rather as a source, or an effect, or a state:

> ... The first two children here identify light with its source, the third identifies it with its effect (the luminous patches produced on the ground by the sunlight), instead of considering it (as the physicist does) as a distinct entity, located in space between its source and the effect it produces. Light is also something defined as a state: 'Light is a brightness... which comes depending on the weather; it's lighter one day than another' (Lionel, 14 years). this definition is similar to the 'light-effect' one.

We can see how this notion of "Light in Space", dissociated from its source and from its effects, can be considered as a Key idea, a necessary prerequisite to touch upon problems in optics.

Most children aged between 9–14 recognise light as an important factor for the life of the plant, although they think of photosynthesis as a substance rather than a process (CLIS, 1987), or a kind of plant respiration (Tamir, 1989). Also, while the presence of light is always interpreted as good for the growth process, the absence of light is not recognised as important for particular moments of the plant life cycle (Roth et al., 1983). Wandersee (1983) found that school students have an understanding of growth towards the light, indicating an understanding of phototropism.

For this age group (11 to 13 y.o.), these concepts do not seem to be connected in as uniform and coherent an explanation as they are for grown-ups.

[2] Russell is referring to the British system.

Heat: condition for growth

Recent studies report that pupils (up to 16 y.o.) think of cold (or heat) as an entity which has the properties of a material substance (Clough and Driver, 1985). They do not think of hot and cold as part of the same continuum. In the same study (Clough and Driver, 1985), researchers found that simple understandings of heat transmission are 'known' but not explained. This study is synergic with the findings of studies on energy transfer processes (Erickson, 1977; Clough and Driver, 1985) in which a kinetic-molecular type of explanation is not spontaneously used, producing several misconceptions for the underlying mental model.

Erickson and Tiberghien in Driver et al. (1985), comment on the differences between the physicists' and pupils' interpretation of heat when considering the choice of a container to keep drink hot or ice cold for as long as possible:

> The first difference which is often found is that pupils do not take into account all the systems which interact (including in this case the ambient air); secondly, they do not redescribe the systems using parameters of state (or by interaction parameters) – in this case temperature. Most often they describe or interpret situations in terms of:
>
> - events: it is heating, it cools, etc.;
> - properties that they have ascribed to the object: the substance of the object, or the fact that is cold, hot, solid, hard, thick, etc.; and
> - function of the object: it has been made to perform a specific function, e.g., for drinking cofee or keeping food, etc.

Heat is also recognised as an important factor for plant growth, although second grade students, in recent research (Russell and Watt, 1990), refer mainly to natural sources (the sun) as effective for the growth process, not explaining the reason why heat is important. This might be related to the difficulty children have in recognising heat as energy, and energy as the 'petrol' for the photosynthesis.

Humidity: the invisible factor

I believe that humidity is the most difficult environmental factor to conceptualise because of its intangibility and relatively minor effect on human perception. Some recent studies report that one of the hardest aspects of the water cycle to understand is that water vapor and drops have weight and undergo free-fall (Bar and Travis, 1991). On the plant biology side, researchers found that children conceptualise water as food for the plant (Wood-Robinson, 1991; Russell and Watt, 1990). A recent study (Wood-Robinson, 1991) summarised the findings of several studies concerning children's ideas about plants, highlighting how many students thought that plants take in water as food. Many of them thought that a possible way into the plant's body is through leaves, and that water must be assimilated in this way (Driver et al., 1994b).

Factor interaction: the missing piece

It is not clear for children how these environmental variables interplay and affect a plant's life. Most children think that there is a strong relation between the water in the soil, the light shining on the plant, and its growth, although the heat factor is not always mentioned. In addition, these factors come into play in a mixed fashion, so that it is very difficult to think about a pure heat emitter or a pure light emitter. This fact reflects on the way children think about these variables, because I believe that if these variables are not cognitively separated, it is difficult to look at them and think about possible ways in which they could interact. What we know from physics about how these variables interact is due to some Key ideas that we master, such as, for example, the wave nature of light and heat, that are just energy waves with different wavelengths but belonging to the same spectrum. From a constructionist point of view you cannot operate on these variables unless you think of them as separated entities. For example, Wiser and Carey (1983) demonstrated that the reason why it is so difficult for children to understand the difference between heat and temperature [3] is because the two entities are not nowadays culturally separated, and because they were always treated as the same concept in the past. Similarly, I think it is difficult for children to think about heat and light because culturally we often conflate them in the effects they produce and in the sources which produce them. So, it is difficult for children to understand that an increase in light is not going to affect the heat in the environment, but is going to increase the overall temperature because it carries more energy. In the same way, increasing or decreasing the heat is not going to affect the light conditions in the space. On the other hand, humidity is affected by the temperature, because evaporation/condensation is a function of the energy level in the environment.

3.1.2 Growth

Growth as a criterion of Life

Driver et al. (1994b) found that growth and development were volunteered as criteria for life in the case of plant examples much more frequently than in animal examples, possibly because alternative criteria such as movement were available for animals. In addition, in the same study, Driver found that holding a Key idea on reproduction does not help in classify seeds and eggs as 'living' (p. 36):

> However, some children believed that eggs and seeds are not alive even when they held

[3] Heat is the kinetic energy of atoms (extensive); Temperature is the measure of a thermal status of something (intensive).

that living things develop only from living things.

The meaning of "growth"

Carey (1985) has reported on several studies of young children's conceptions of human growth. For pre-school children it appears that growth just means "getting bigger", and is explained in term of intentional human activities (i.e., eating, birthday). All the pupils interviewed defined growth, as applied to a tree, in terms of getting larger. Only a few mentioned development.

Germination and growth of a bean

Russell and Watt (1990), on pp. 44-56, interviewed a group of children (lower-upper juniors), with the question 'What do you think is happening within the bean (seed)?'. Responses most frequently mentioned the effect of water on the 'mug' bean, but less often than had been the case with the broad bean. Only a minority of responses clearly indicated that the water was actually taken into the seed. Some responses referred to a reorganisation of material. Enlargement of some kind was mentioned overall. All the juniors (11-12 y.o.) recognised water as a necessary condition for the growth of the mug bean. In addition, children were able to identify fewer conditions, on average, relating to the growth of the mug bean than the broad bean. Some responses referred to air as being a necessary condition for the growth of the bean. Children questioned about when growth occurs answered mostly that growth occurs continuously, or when external conditions are available, but also a great number of the children interviewed did not have a proper answer for the question. In addition, a few of the children answered that growth occurs in the child's absence, or only during a particular moment of the day/season/calendar.

3.1.3 Life cycle

Previous research by Hickling and Gelman (1995) showed that young children may not appreciate the cyclical nature of the growth process, whereby a seed grows into a plant, which in turn produces new seeds. It may be that rather than viewing growth as a causal, generational process (i.e., seed → plant → seed), younger children see it as discontinuous (i.e., seed → plant, plant → seed). White (1997) defines the tendency to judge that effects of a perturbation at a particular locus in an ecosystem weaken or dissipate as they spread out from that locus as *dissipation effect.* This may be the case in the children's understanding of food webs and the general life cycle.

3.1.4 Nutrition

Driver et al. (1994b) reported on children's ideas about food. Pupils appear to consider food as anything useful taken into an organism's body, including water, minerals, and, in the case of plants, carbon dioxide or even sunlight. Bell (1985) summarised the findings of several studies indicating that many secondary school students of varying ages have alternative ideas about plant nutrition to the currently accepted scientific ideas. These alternative ideas appear to be characterised by:

- different meanings for everyday words like 'food' and for technical words such as 'chlorophyll'
- a view of external sources of food for plants, rather than food being made internally
- alternative conceptions of the basic concept embodied in the idea of photosynthesis, for example, gaseous exchange, energy, particles

In addition, students' understanding of the function of food, may be restricted to a superficial 'to stay alive'. They may have little understanding of the role of energy in the maintenance of plant metabolism. Also, students may be confused or have little understanding of the relationship of the process of photosynthesis with other physical and chemical processes carried out by plants, for example, water uptake and respiration.

Plant nutrition

The universal and very persistent intuitive conception, identified in all studies with subjects of all ages, is that plants get their food from their environment, specifically from the soil; and that roots are the organs of feeding. The growth of a tree is attributed to the food it has taken, which is assumed to contain and supply energy.

3.1.5 Photosynthesis

In the case of photosynthesis, research suggests that although children do not possess prior knowledge directly related to photosynthesis itself (Barker and Carr, 1989), they do have many separate but relevant prior views about plant activities and materials. They ascribe a variety of functions to leaves, e.g., absorbing water and sunshine, and they have ideas about the importance of fertilisers, plant growth, and plant products like wood, although the origin of wood is difficult for children to explain. They also have views about multiple sources of energy for plants, and sometimes believe that plants make direct use of solar energy in vital processes. They usually think that plant food is absorbed material (Wandersee, 1983).

3.1.6 Death

Carey (1985) summarises research results concerning death, which identifies three phases. In the first stage (age 5 and under), children have no concept of the cessation of biological function and death is seen in terms of a separation, which is neither final or inevitable. In the second stage, the children recognise the finality of death but sees death as being caused by an external agent, e.g., guns, knives. In the final stage, which occurs around 9 or 10, death is seen as an inevitable biological process.

3.2 Multivariate systems

In a multivariate system several variables can change their value at the same time. To understand these systems an observation is usually required, conducted in a scientific setting, in which the learner has to manage several techniques, by which one or more factors can be isolated to test the relationship between the factors. In order to access such techniques, the user has to master some Key ideas about causality, such as "mutual influence", and "domino effect". In this section, I will describe some of the research conducted on this theme.

3.2.1 Children's understanding of Causality

In a multivariate system, understanding how the variables interact means understanding complex causality relations. Keselman and Kuhn (2002) describe a software-based system to enhance children's understanding of multi-variable causality. Their findings suggest that children perceive a variable as causal, in one instance, and non-causal in another, depending on the situation. The software they designed presented a situation in which children had to explicitly differentiate between the variables they considered to be causal and non-causal. I want to argue that multiple frameworks can be used by children, depending on the available raw perceptual data (Taber, 2000).

Another interesting study explained how children can acquire a domain-general processing strategy, called the Control of Variables Strategy (CVS) (Chen and Klahr, 1999), in which the learner should change one variable at a time, keeping all others equal. While worthwhile results were obtained, this method cannot be applied in our situation, as several variables can be changed simultaneously or in situations where it is not possible to maintain all but one of the variables at a fixed value.

Nonetheless, (Grotzer and Basca, 2000) described several other causal strategies that children need to grasp in order to create a deeper understanding of the ecosystem (domino, cyclic and mutual causality). They support the idea that teaching the embedded causal structure whilst teaching the factual content enhances the learning process. I argue that time is related to the understanding of these causal structures, so that if children cannot have a real-time experience, the learning experience may not take place. In addition, I believe that hidden causes are responsible for lots of misunderstandings, and are related to the grasp of causal structures.

3.2.2 Developing probabilistic decentralised thinking

Most people have what Resnick (1994) defines as *centralised or deterministic mindset.* This results in the difficulty many people have understanding phenomena such as the population variations within an ecosystem; economic fluctuations, and, of course, multivariate systems, which present many different variables interacting at the same time with different patterns. Following Resnick et al. (1998), I believe that it is important to support children in developing a decentralised way of seeing the world and inquiring into complex phenomena.

3.2.3 Children's understanding of bar charts and line graphs

Graphic representations of quantitative information are often imposed on children. In most formal learning situations, children are taught to use standard conventions and rules to represent causal relationships. Children coming from such experiences often report alternative frameworks in how such representations work. Aberg-Bengtsson and Ottosson (1995) showed a crucial difference in the perception of graphical representation, where the graphics are seen either as a number of separate, countable entities or as a proportional, measurable whole. It can be argued that the latter stance presupposes a certain grasp of the principle of coordinates; at least as far as the line graphs are concerned, whereas bar charts may be understood without the use of coordinates.

One of my design goals is to give the user the opportunity to experience and feel the relations among the variables. The built interface developed in this present project should privilege the exploration of "forces" and the "directions" of different variables interacting at the same time. Just as scrolling down one of the wires of a spider web gives the idea of how the structure reinforces itself lessening the stress upon all the junctions, so this interface should give the user an insight into the relations between environmental variables.

3.3 Time

3.3.1 Time: Flow or Variable?

The basic assumption of our scientific culture is that time is not a variable because you cannot modify it. This basic concept is reflected in every model we build and in the way we expect children to learn things. Several studies have been carried out trying to understand how children perceive time (Piaget, 1970; Friedman, 1990a; Montangero, 1996). Our idea is that time constraints reflect how children learn about environmental conditions and plant growth. In fact, if a child has to wait a week to see the effect of watering on a seed, s/he may lose the point of the relation between the humidity level and the germination process. This is also confirmed by recent research (Russell and Watt, 1990), where results highlight that children sometimes think growth happens only during the night. I believe this is also due to the time-lapse factor required for the interaction with the plant.

In our pilot study (Gash and Cherubini, 2002), we realised that there is a strong connection between the environmental variables perception and time (see 4.3). In fact, time plays a fundamental role in understanding causal connections. In natural phenomena we observe delays between actions and effects, and in most cases these kinds of relations are difficult to grasp. Children, like adults, use information about sequence (temporal order) to infer causal relations (Piaget, 1970; Friedman, 1990a).

3.3.2 Arrows of Time

An important part of human's knowledge of the physical world is our understanding of how objects and materials are affected by a wide variety of actions. To interpret the myriad events that we witness, we must have general representations of many such processes. A particular subset of dynamic events or "arrows of time", are common in everyday experience and include such events as the motion of pouring a liquid and breaking an object into pieces, or even slower events such as the life cycle of a plant.

Friedman (2003) showed that children are sensitive to the anomaly of backward presentations of such events, judging this anomaly to be magic. As in, for example, a video of a person holding a glass with juice in it, raising the beaker almost to the pouring position above a glass. The juice was pouring from the raised glass to the bottom in the forwards video whereas it was moving from the bottom to the raised glass in the backwards video. Children were more likely to predict the forward effects shown in the corresponding videotapes than the backwards effects.

In my design, I will try to allow the user to explore the time arrows as they relate to the plant's growth. I will give the user the possibility of exploring this particular event and manipulating the direction and speed of the event of growth.

3.3.3 Diachronic events

Of the changes that occur in time, there is one that is particularly relevant to children, namely, the phenomenon of growth. Children know perfectly well that the concept of growth may be applied to plant life. Montangero (1996) demonstrates that children's conceptions of a simple evolutive phenomena, such as the growth of a tree, change between the ages of 7–8 and 11–12:

> What evolves with the increasing age of the subjects is the variety and nature of the changes they depict. Young children, primarily at age 7 but also sometimes up to the age of 9, imagine that a single aspect – or a very restricted number of aspects – changes with time. In contrast, children aged 11 or 12 imagine that a whole set of transformations take place in the course of time. The criterion of development which I propose observing in order to trace this evolution relates to the morphological changes involved in tree growth.

This research has shown that the development of diachronic thinking is characterised by the ability to imagine qualitative changes in time which complement the essentially quantitative changes depicted by children.

The Biosphera design will amplify the visual display of the qualitative aspect of the growth, allowing *reversibility*, changing the direction of the growth story, and *serialisation*, showing successive states of the tree in an order the children can customise.

3.4 Constructionism

Learning is an active process in which learners construct new ideas or concepts based upon their current/past knowledge. The learner selects and transforms information, constructs hypotheses, and makes decisions, relying on a cognitive structure to do so. Cognitive structure (i.e., schema, mental models) provides meaning and organization to experiences and allows the individual to "go beyond the information given". This section will report on the constructionism approach I followed in developing this thesis.

3.4.1 Microworlds: incubators for knowledge

Papert (1980) described a Microworld as a "place," where the common language is the theme of the Microworld (i.e., Mathematics, Physics, etc.), where the thinking about that particular theme could hatch and grow with particular ease. The Microworld is an incubator, its design makes it a "growing place" for a specific species of powerful ideas or intellectual structures. There are two design criteria to keep in mind whilst developing a Microworld:

1. Let the learner acquire a concept of the laws of the Microworld's theme by working with a very simple and accessible instance of such laws.

2. Design the Microworld so that all necessary concepts can be defined within the experience of that world.

From Mathland to Plantland

From Papert (1980, p. 6):

> The idea of "talking mathematics" to a computer can be generalised to a view of learning mathematics in "Mathland"; that is to say, in a context which is to learning mathematics what living in France is to learning French. ... Experiences in Mathland, such as entering into a "mathematical conversation," give the individual a liberating sense of the possibilities of doing a variety of things that may have previously seemed "too hard".

In the same manner, my design will try to build a "Plantland", a microworld where the common language is plant biology.

3.4.2 The Magix series

Ackermann et al. (1997) in her papers about the *Magix* series, defined some contructionist principles which are also applicable in my design. First of all, the learning environment I want to design should contrast with the instructional character of most software and hardware for learning. My design will try to highlight a constructive and dialogic style of interaction. In the Biosphera design, the child shares control with other children, in contrast with most educational packages in which the system tries to guide and "teach" the child.

In addition, the system I want to design does not impose, as Ackermann et al. suggested (p. 4), a prescriptive sequence of activities or topics. Instead, it would allow the learner to "initiate a dialog and respond by generating the unpredictable emerging effects and providing suggestions for further experimentation."

3.5 Other approaches

Several other researchers have tried to find a technological solution to allow the exploration of plants' biology. I will report here only some of the most representative. The descriptions below are taken from the Internet sites referenced.

The approach I followed differs from those here described because they are solely simulations. I believe that giving access to the model underneath the simulation, has an enormous learning value and therefore our solution aims to open the model to the user, using an innovative approach that is not a mere simulation but that can be defined as a "representation". Moreover, my design has been inspired by the telegarden project described below, from which I took the idea of keeping the real plants close to the virtual model may have a strong impact on the understanding of the biological processes because it reinforces the connections from the model to the phenomena and vice versa. On the contrary, the projects here described operate a detachment from reality, offering, in many cases, modeled versions of reality which are difficult to grasp.

3.5.1 Telegarden

The telegarden installation allows WWW users to view and interact with a remote garden filled with living plants (see figure 3-1 and figure 3-2). Members can plant, water, and monitor the progress of seedlings via the tender movements of an industrial robot arm. Internet behavior might be characterised as "hunting and gathering"; the purpose was to consider the "post-nomadic" community, where survival favors those who work together (Bekey et al., 1996).

Figure 3-1: Tele-Garden Interactive Organic Art Installation. In the center of the circular garden is an adept robot. Overhead you may notice the light needed for plant growth that slowly revolves around the garden (image from the Telegarden Internet site (Bekey et al., 1996))

This interface gives the user the possibility of dealing "virtually" with a real plant, keeping tracks of the environmental changes. However, although of great interest, this project did not solve the time-delay issue I raised above.

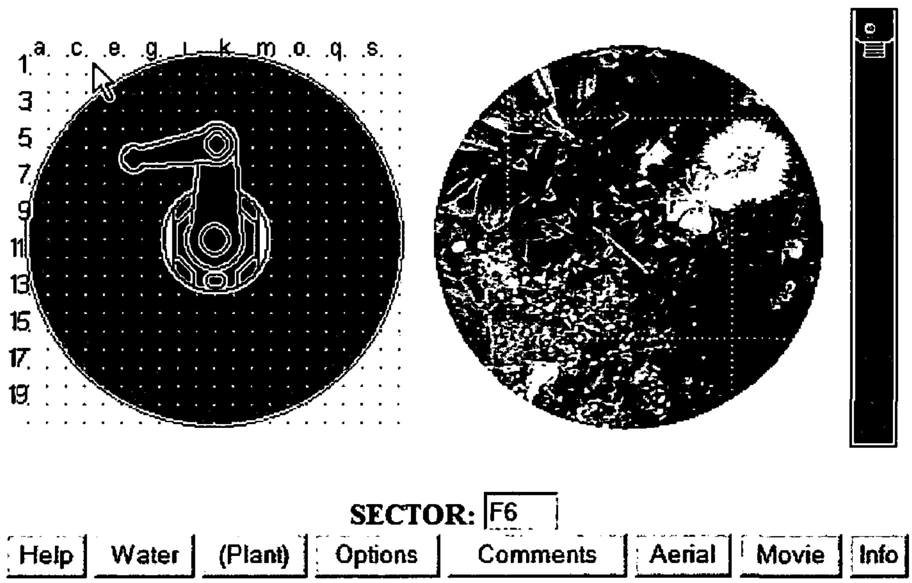

Figure 3-2: This is the default member setup in the garden. The robot schematic is on the far left, followed by the camera image with the zoom bar on the far right. By clicking on the robot schematic the user can quickly command the robot to move to that spot (image from the Telegarden Internet site (Bekey et al., 1996))

3.5.2 Nerve Garden

Nerve Garden is a biologically-inspired multi-user collaborative 3D virtual world available to a wide Internet audience. The project combines a number of methods and technologies, including L-systems, Java, cellular automata, and VRML. Nerve Garden is a work in progress designed to provide a compelling experience of a virtual terrarium exhibiting properties of growth, decay and energy transfer reminiscent of a simple ecosystem (see figure 3-3). The goals of the Nerve Garden project are to create an on-line "collaborative A-Life laboratory" which can be extended by a large number of users for purposes of education and research (Damer et al., (September, 2003)).

Nerve garden is a simulation world, in which the user can play with different ideas about plant biology. Although of great visual appeal and great back-end design (VRML [4]), this interface is a black box, in which the model and the rules of competition that drive the simulation are not accessible to the user.

[4]Virtual Reality Markup Language, see http://www.vrml.org.

Figure 3-3: Nerve Garden VRML interface with control panel. Using a separate pane is possible to create a new kind of plant using a restricted number of variables. Then is possible to plant this new species on the Nerve island, where it is possible to follow the evolution and the competition of the plant among all the other species (image from the project Internet site (Damer et al., (September, 2003))

3.5.3 SimLife

The producers of SimLife refer to it as "The Genetic Playground." The game allows users to explore the interaction between life-forms and environments. Users can manipulate the genetics of both plants and animals to determine whether these new species could survive in the Earth's various environments. Players can also create new worlds with distinctive environments to see how certain species (earth's species or their own) fare within them (MAXIS, 1992).

SimLife, like much other software, is merely a simulation, in which the model is not fully accessible to the users. Most of the understanding the user gets of the rules of the simulation are inferred empirically by the user through trials and errors. From a cognitive standpoint I argue that the framework implemented in SimLife is not structured nor redundant enough to sustain the cognitive exploration of the biological concepts targeted in this research.

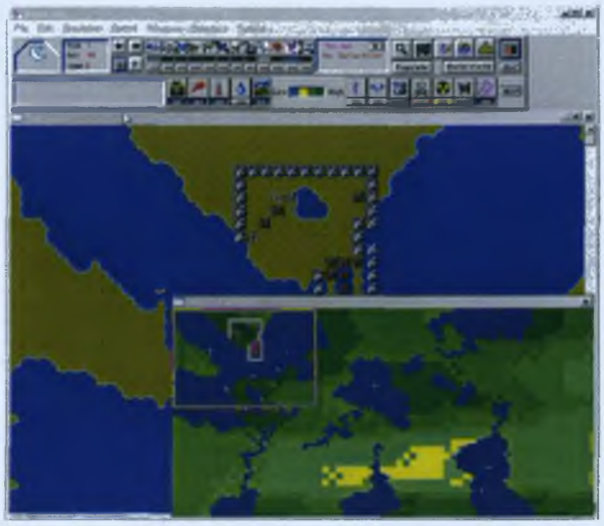

Figure 3-4: A screenshot from SimLife interface. Using the icons in the command bar is possible to perform some actions in the world map, adding biological entities to certain parts of the map and observing the emergence of their interactions and development

3.5.4 The garden with insight

The Garden with Insight garden simulator is an educational simulation that uses weather, soil, and plant growth models to simulate a simple garden in an open-ended microworld setting. You can plant vegetables and grow them to learn more about plants, the soil, the weather, gardening, and science (Fernhout and Kurtz, 1999).

The garden with Insight project utilises an approach similar to my own. It is, however, a simulation, and does not allow the user to fully test the model on which it is based. In addition, the interface design is sometimes too cryptic (see figure 3-5, 3-6, and figure 3-7)[5].

3.5.5 BioBLAST

BioBLAST (Better Learning Through Adventure, Simulation and Telecommunications) is a multimedia curriculum supplement for high school biology classes. Based on NASA's Advanced Life Support research, the program offers students both traditional and computer-based research tools to study the interdependent components of a bioregenerative life-support system (BLiSS) for long-term space habitation (University and NASA, 2000). Student tasks are presented as part of an adventure mission at a virtual lunar research station. The mission culminates with students testing their own BLiSS designs using the BaBS (Build a BLiSS System) simulator, an integrated modeling

[5]These pictures were captured as screenshot directly from the software

system (see figure 3-8).

BioBlast is a web simulation interface, which presents a limited amount of variables affecting the growth of some plants in a "growth chamber". Although based on scientific data, this project present the classical limitations of the simulation, with the resulting difficulty of grasping the model that drives the animation, and which brings the user to adopt a "trials and errors strategy" instead of an active thinking process.

3.5.6 Logal Science Explorer

The Logal Science Explorer Series provides students with comprehensive coverage of key concepts in biology, chemistry, and physics through computer simulation activities. Users develop problem-solving skills as they form hypotheses, manipulate variables, generate and collect data, analyse relationships, make conclusions [6].

3.5.7 L-systems

L-systems are here presented as last example, although, they differ from those above because L-systems are mathematical models used to represent the plat's evolution, and, in this context, cannot be categorised as other approaches for plant's biology exploration. However, I listed them here because I used them a lot in the software algorithm of this project.

Lindenmayer systems, or L-systems for short, are a particular type of dynamic, symbolic system, with the added feature of a geometrical interpretation of the evolution of the system. They were invented in 1968 by Aristid Lindenmayer to model biological growth (see figure 3-9 and figure 3-10). A Lindenmayer system consists of a starting string of symbols from an alphabet, and has repeated transitions applied to it, specified by a list of transition search-and-replace rules. The limiting geometry of even very simple systems can be an extraordinary fractal [7] (Prusinkiewicz et al., 1995; Prusinkiewicz and Lindermayer, 1990).

---

[6]See the manufacture Internet site at: http://www.riverdeep.com

[7]Natural definition: a geometric figure or natural object that combines the following characteristics: a) its parts have the same form or structure as the whole, except that they are at a different scale and may be slightly deformed; b) its form is extremely irregular or fragmented, and remains so, whatever the scale of examination; c) it contains "distinct elements" whose scales are very varied and cover a large range. (Source: http://www.mrob.com/pub/muency/fractaldefinitionof.html)

3.6 Connections

3.6.1 Representations versus Simulations

There is an important distinction to be made regarding the design of the virtual world, between simulation and representation. In my vision, science education must accurately pass beyond reality, and reality must be the witness and the meter to judge the accuracy of our model. I want to use sensor readings to incorporate something of the physical world into our virtual world, so that we are not simulating but representing reality. Model and phenomena must be kept together.

Beyond the 'seduction of simulations' (Starr, 1994), I believe that virtual representations are powerful environments, able to give great insights about the real world, as long as they remain closely defined by the physical world. I believe that the ability to visually compare is a powerful approach to learning underlying models, as it allows the child to overcome black box assumptions (Resnick et al., 2000), and feel encouraged to understand and explain biological processes.

3.6.2 Physical manipulatives

Manipulative materials play an important role in children's learning. In fact, pupils may explore deep mathematical and scientific concepts through direct manipulations, comparisons, and the physical feedback they can get from playing with tangible objects/toys. Following Resnick et al. (1998), as children build and experiment with these manipulative materials, they develop richer ways of thinking about things, and although this is always applicable, there are many concepts that are very difficult to explore with these traditional tools, such as concepts related to dynamics and systems. My approach consists, in accord with the cited study, in technologically enhancing traditional toys and forms of interaction with domestic objects, in order to enhance these deeper explorations.

3.6.3 Aesthetic

In accord with Resnick et al. (2000), I think that the aesthetic of the scientific design should be considered more carefully. In fact, through the simple form of the objects, it is already possible to achieve an idea of the object's working principle, of the philosophy behind the form. Quoting Resnick (p. 4):

> Most MBL (microcomputer-based lab) and home science activities pay little or no attention to the aesthetics of the instrumentation, or the ways in which instruments are integrated into their surroundings; and on those few occasions when home science activities do pay attention to aesthetics, they tend to do so in a way that stresses

> post-hoc decoration (e.g., the exterior of a home telescope may be painted after the instrument is constructed).

I tried to incorporate this concept in the design of the Biosphera. In fact, the dome, which is based on Buckminster Fuller's design is aesthetically transparent in representing the idea of Life support (see section 4.6.7 and 4.8.5).

3.6.4 Transparency

I define Transparency in accord with Strohecker and Slaughter (2000): we display visualisation of algorithms, calculations, and processes whenever possible; we represent constituent properties of objects, often in ways that facilitate users' modification of them; and we provide multimodal feedback. The opposite of a "transparent" design is defined by Resnick as (Resnick et al., 2000, p. 2):

> ...But, at the same time, these black boxes are "opaque" (in that their inner workings are often hidden and thus poorly understood by their users) and they are bland in appearance (making it difficult for users to feel a sense of personal connection with scientific activity).

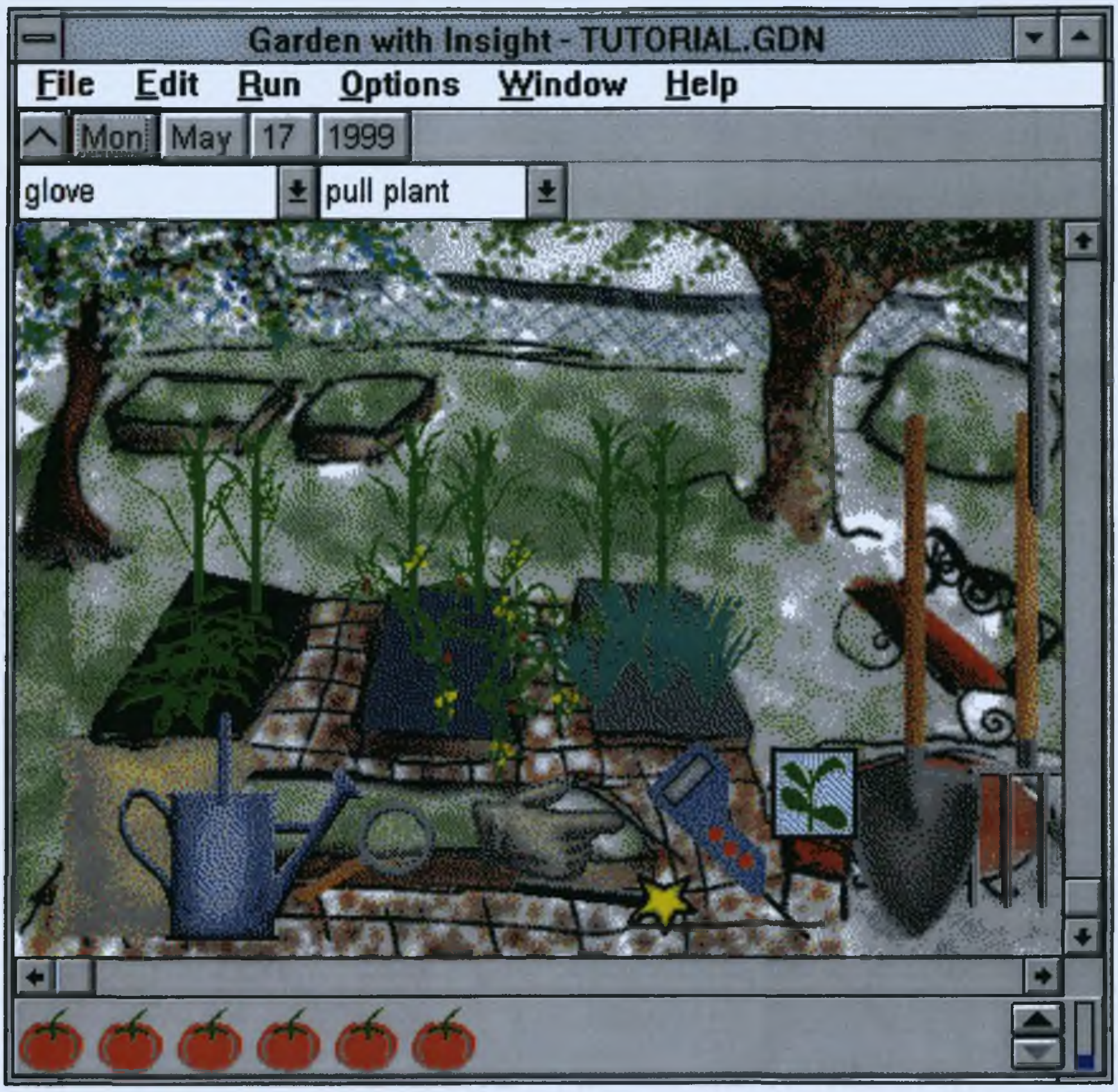

Figure 3-5: A screenshot from the Garden with insight's software interface. The commands are iconised as garden tools, which the user can move around the screen to perform maintenance operations to the garden

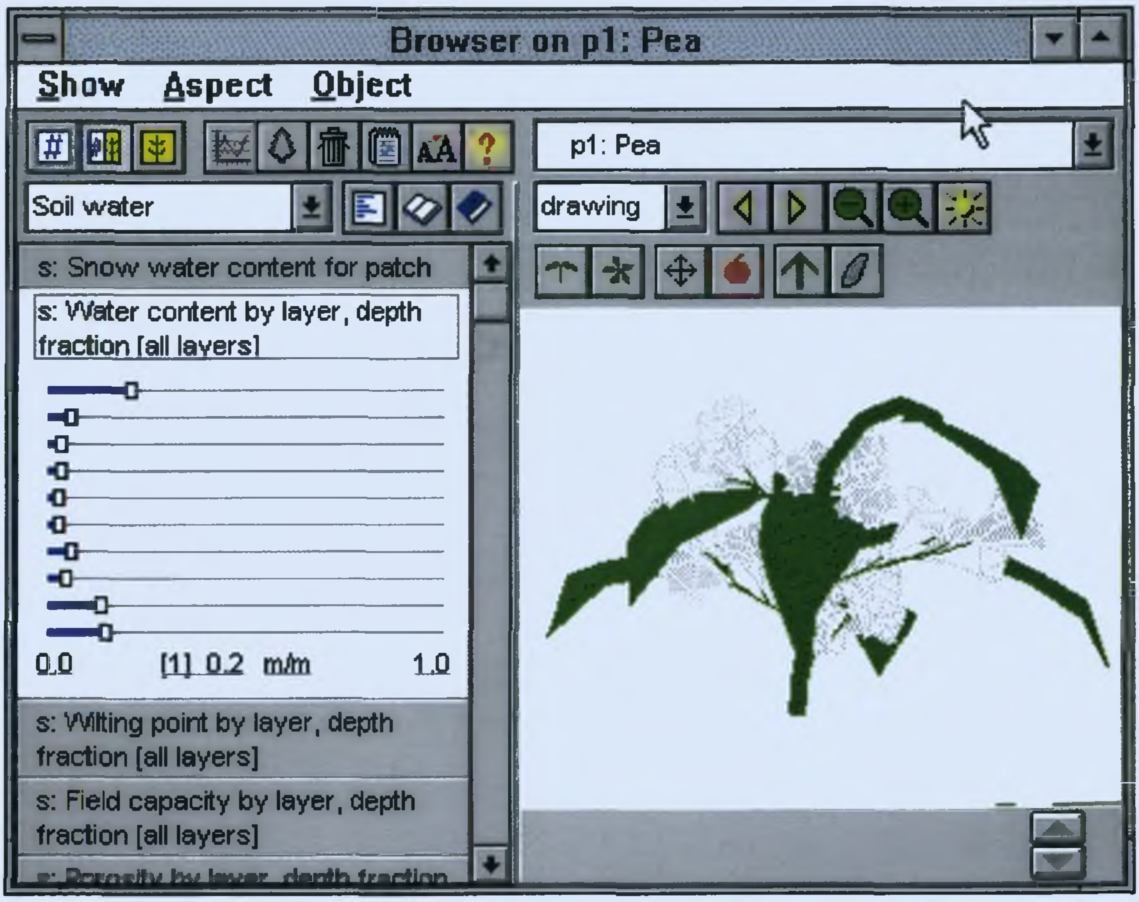

Figure 3-6: Using the simulation browser, the user can access all the parameters of the simulation

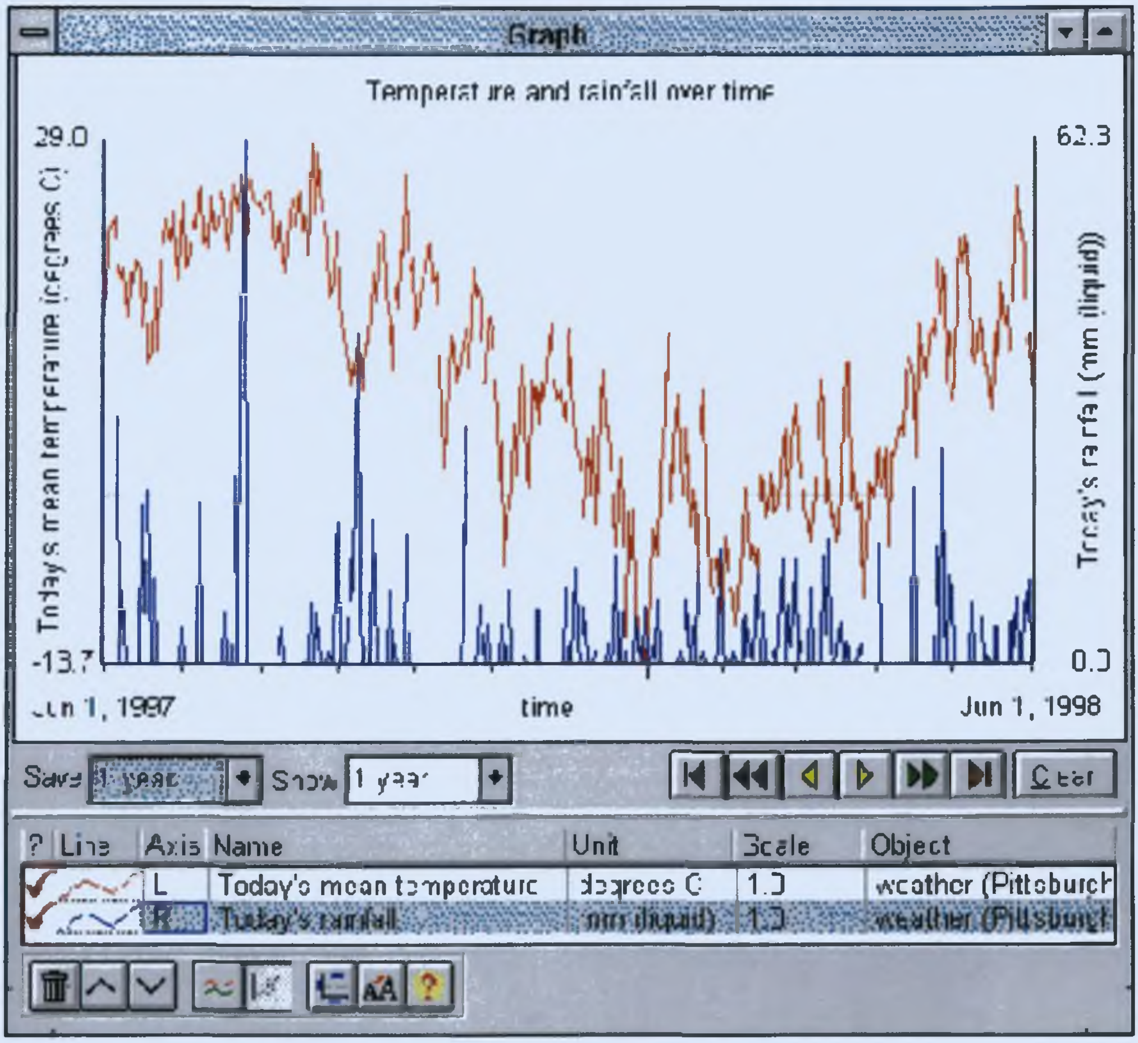

Figure 3-7: The graphic representation of the interface helps the user to visualise the environmental conditions

Figure 3-8: Plants play a vital role in the lunar base–refreshing the air, purifying the water, and providing food for the crew. As part of their BioBLAST mission, students will adjust plant growth conditions in environmentally - controlled growth chambers to achieve crop production sufficient for their crew's food, water, and air. (Source: http://www.cotf.edu/BioBLAST/project.htm)

```
9
45
10
AB
A = [F[+FCA][-FCA]]
B = [F[^FCB][&FCB]]
C = '(0.7071)
@
```

Figure 3-9: The formalism of the L-systems helps us to move from the structural representation of the plants (right in the picture) to a mathematical model that we can manipulate in a virtual environment (left in the picture). Image source: http://www.xs4all.nl/ cvdmark/tutor.html

Figure 3-10: Comparison between a microscope picture of a fern gametophyte Microsorium linguaeforme (left) and a simulated model using map L systems (right). (Source: The algorithmic beauty of plants (Prusinkiewicz and Lindermayer, 1990))

Chapter 4

Design

"Synergy means behavior of whole system unpredicted by behavior of any of the system's parts when it is considered only by itself."

Buckminster Fuller, TETRASCROLL, 12

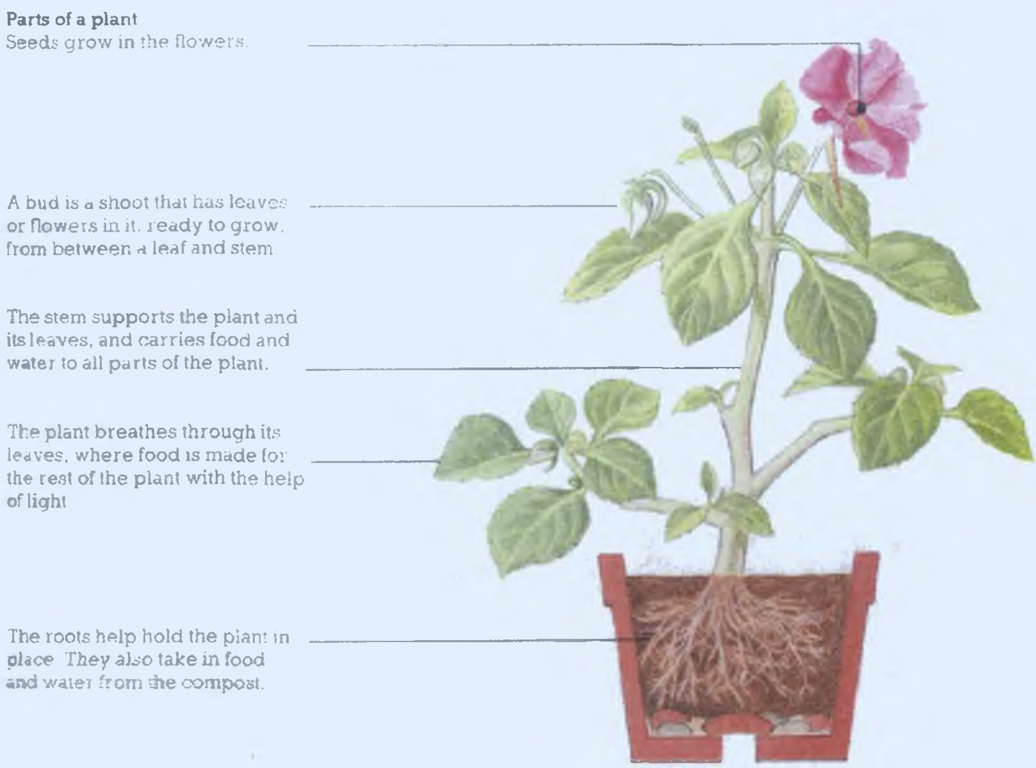

Image from Tarsley (1980)

Chapter 4

Design / Implementation

This chapter will present the implementation of the design solutions announced in the previous chapter. The ideas presented here follow a temporal order, and are relevant to the development of the design right through the history of the Biosphera project at MLE.

This design process started two years ago, with the literature review of the major research presented in the previous chapter. This analysis culminated with the definition of a group of key ideas, which will be presented in section 4.1. Simultaneously, these key ideas have been tested through a series of workshops with children, the results of which will be presented in chapter 5.

This observation and recognition led me to develop and design a technological solution called "DigitalSeed", a physical box which displays the story of a Seed that grows according to the weather conditions surrounding the box. Subsequently, I evaluated how this toy could eventually affect the way children perceive the relation between seeds and plants –one of the issues recognised as crucial. This workshop highlighted some of the limits to the DigitalSeed design, which brought me to another solution, called "Biosphera".

The Biosphera project passed through several stages of development, in which both the hardware and the software have been redesigned to better accommodate ideas taken from the literature and direct observation. This design process will be documented in the last part of this chapter.

The development of this project, and of this thesis, directly follows my personal and professional growth at MLE, and reflects all the doubts, mistakes and corrections which I have experienced during my work.

4.1 Literature study and direct observation: Key ideas and design solutions

The Key ideas found in the literature study presented in the previous chapter are reported in the following tables. Following the different age groups to which each description refers, I decided to divide the content in two different tables. It is also important to note that the ideas presented occurred in the workshop we did with very young children (4, 5 y. o.), which is described in the next chapter.

This first table (4.1, 4.2, 4.3) summarizes commonly held views by comparing adults and childrens thinking (4, 5 y. o.). The table also provides a form for thinking through important relationships among the ideas. For each category, I bore in mind the question of what concept/s would be needed in order to understand the idea. Discerning these relationships would help to articulate the conceptual structure of the domain, which would in turn help in building the environment. This is simply an initial foray into a complex analysis which I hope to pursue further, yet it suggests that the concept of *cycle* could be an important foundation for many of the other ideas. I do not consider this concept necessarily as a precursor, as it seems that any of the related categories might lead to it just as it might lead to them. Nevertheless, the frequency with which the concept of cycle appears in this exercise reveals its importance.

In this second table (4.4) I will report the Key ideas for a different age group (11 to 13 y. o.). Again, I will make a comparison between the children's view and the adult's understanding of the same idea. This group of ideas have been tested through direct observation, as described in the next chapter. As a last consideration, I won't try to find relations as I did before, because these ideas are much wider that those in the previous table and the links among them can be multiple.

4.1.1 From the Key ideas to the design solutions

I grouped the ideas reported above into functional blocks. Then I sketched design solutions that could assist in the exploration of the ideas contained in the block. The results are shown in table 4.5. Two objects resulted form this analysis. The first one, in temporal order, is the DigitalSeed (DS), a virtual plant growing into a physical plastic cube. The second is the Biosphera (BS) platform, a transparent, table-sized dome able to host an actual plant. Both solutions resolve the impasse generated by the time-delay I introduced in section 3.3.; the transition from the first to the second occurred after reflection upon the design of the DS and its subsequent limitations. In fact, as I will explain later (4.4), the DS allows only a finite number of states to play with and this results in a forced path of exploration which is in contrast with Papert's definition of microworld (see 3.4.1). Both solutions accept from the user a definition of the environment as input and give, as output,

Table 4.1: Key ideas and their relation (1 of 3)

CATEGORY	ADULTS' UNDERSTANDING	CHILDREN'S CONCEPTION (4-5 Y.O.)	RELATION
Origin of the seeds	The seed is inside the fruit of the plant	Seeds are made by humans or can be found in nature in a non-specified place	CYCLE
Origin of the plant	A plant is born from a seed in the adequate environmental conditions	A plant is always there	RELATION WITH SEEDS
Growth of the plant	When the seed grows, it changes its properties and becomes the plant	The plant does not grow, or it keeps becoming bigger and bigger	CYCLE
Relation between seed and plant	The seed is the plant not yet born. It will become the plant in the right environmental conditions	Seeds are *food* for the plant	CYCLE
Flowers and fruits	Flowers and fruits are part of the chain between plant and seed	Flowers, fruits and seeds are not related	CYCLE

Table 4.2: Key ideas and their relation (2 of 3)

CATEGORY	ADULTS' UNDERSTANDING	CHILDREN'S CONCEPTION (4-5 Y.O.)	RELATION
Roots	Roots are on the base of the plant, where the plant takes in nutrients	[Roots are not conceptualized.]	FOOD OF THE PLANT METABOLISM
Placement of the seed in order to grow	The seed must be under the soil with the right humidity	Under the plant or into the flowers, or into the plant	ORIGIN OF THE PLANT
Species and relations with seeds	An apple seed can generate only an apple tree	You can grow an apple tree from a tomato seed	CYCLE
Environmental conditions responsible for the growth	There must be light, water, soil and the right temperature	Water, sunshine	CYCLE
Cycle	A plant will follow its own cycle from the seed to the mature plant to the newborn seed	[Cycle is not conceptualized.]	[This seems to be the foundation concept.]

Table 4.3: Key ideas and their relation (3 of 3)

CATEGORY	ADULTS' UNDERSTANDING	CHILDREN'S CONCEPTION (4-5 Y.O.)	RELATION
Psychological, Human features	A plant is a living thing without psychological features	A plant can be sad, happy, sore, etc.	[This category seems to be singular.]
Being alive	A plant is alive because it generates from another plant, it grows and it can reproduce before dying	Yes, because it goes up, or no, because it cannot move	GROWTH OF THE PLANT
Time of growth	A plant grows in weeks/months	It can grow in 5 minutes	CYCLE
Food of the plant/metabolism	Water, minerals	Just water	ENVIRONMENTAL CONDITION
Number of plants and number of seeds	1:1	Many to one, one to many	CYCLE

Table 4.4: Key ideas for K12 compared to adult's view

CATEGORY	ADULTS' UNDERSTANDING	CHILDREN'S CONCEPTION
Life-cycle	Discontinuous phenomenon	Continuous phenomenon
Growth	Getting bigger	Qualitative and quantitative change
Responding to the environment	Water and sunshine should be present for growing. There is no clear idea of a growth dynamism	Any perturbation in the environment produces a qualitative and quantitative effect on the plant
Nutrition	Water, minerals, carbon dioxide or sunlight are considered food for the plant	All these components sustain photosynthesis which produces food as glucose
Photosynthesis	Plant food is absorbed material	Plant food is glucose produced internally using CO_2 and Light

a simulation of the growth of the virtual plant. Whereas this manipulation of the environmental variables is a good deal more limited in DS, it is a key concept which I used in the design of BS, where the user has much more freedom in combining the variables. In both cases, DS and BS offer a complete Life-cycle of the plant.

Table 4.5: Functional blocks of Key ideas and design solutions sketched

BLOCK	IDEAS GROUPED	DESIGN SOLUTION
Cycle	Origin of the seeds; Growth of the plant; Relation between seed and plant; Flowers and fruits relation; Species relation; Time of growth; Matching between number of plants and number of seeds; Life-cycle as continuous phenomenon	Virtual plant which grows faster; Reduction of time delays; complete Life-cycle, manipulation of environmental conditions
Growth	Growth; Time delays; Causal relations	Virtual plant which grows faster and responds to the environmental conditions
Responding to the environment	Single factors affecting the growth of the plant; Environmental factors interaction; Causal relationships	Virtual plant which responds immediately to the environmental perturbations
Nutrition	Role of environmental components on the plant's growth; plant metabolism; Photosynthesis	Virtual plant on which it is possible to test different growth conditions

4.2 Children's common conceptions

Two main workshops have been organised for the Biosphera and DigitalSeed projects: one was held in 2002 in Howth in the north of Dublin (see section 5.1.1) and the second in 2003 at MLE. Both workshops tried to make observations with children on the topics which emerged from the literature study. In both cases the results set back the design of the objects. The next chapter will mainly report on these two workshops and the analysed results.

4.3 The DigitalSeed

In this study, I consider how constructivism could inform learning about an aspect of life sciences –the cyclic nature of plant growth. My goal is not to conduct a psychological study of developmental stages or phases, but to provide an environment in which children can explore concepts and eventually be in contact with their own conceptual growth. I do not want to force children to follow a specific path, or teach them a piece of pre-ordained ecology curriculum. Rather, I want to provide them with a playful way to experiment with plants and seeds in the world of plant growth. On the basis of children's conceptions, I designed and built a model of a plant's life cycle, which they then critiqued. Here I review our eliciting and representing of ideas related to germination, growth and pollination. This is a qualitative pilot study combining results of clinical interviews with an iterative design process, to produce an interactive toy with physical and virtual components (see Hanna et al. (1997)). I regard the children's varying understandings of plants origins' and growth as being potentially reflective of good reasoning within their relatively constrained realms of experience, and inevitably useful in their learning processes (Smith et al., 1993). Their imaginative responses inspired my representations and the interactivity design.

4.3.1 The toy design

The Digital Seed (DS) is born from the idea that an interactive computational device could help children to explore the ideas listed above. I started from the problem of the time required for a real plant to grow. Obviously, moving into a virtual world would be the easiest solution, but in this case I would have to renounce all the tangible features of a real plant and the subsequent richness of the learning environment that this would produce. Finally, I moved our design into a space between these two extremes. Without pretending to have all the features of a real plant, I selected the tangible aspects that I wanted to preserve in relation to the virtual world. I decided to maintain:

1. Water: a tangible element that children conceptualize as being responsible for the beginning of growth and for the maintenance of the health of the plant.
2. Temperature: an invisible condition for the growth of the plant that the children did not address.
3. Light: corollary to sunshine. This dimension is also very important for the growth of the plant, and was understood by most of the interviewed children.

A fundamental part of the learning environment is the interplay between these factors. In all the phases of the growth of the plant there is not just one factor that encourages growth, it is the combination of necessary conditions which must be realised. Humidity, temperature and light exposure are fundamentals for life: they have to be present at the same time and in the right proportions.

The physical interface

In the physical domain, I wanted a robust interface, with adequate dimensions, to support actions involving water, light, and changes in temperature, and which would be waterproof and shock resistant. I decided to use an iPAQ Pocket PC^{TM}[1], situated within a plastic cube with sensors and apparatus, as the computational unit. Compaq's iPAQ is a PDA[2] that is easy to use and yet powerful enough to do serious processing of sensor data (see Laerhoven (2001)). I used environmental sensors as a bridge between the real world and the virtual world, to acquire quantitative differences in environmental conditions around the iPAQ. This acquisition process occurs through an interface board with a PIC[3] microcontroller and a multiplexer. Essentially the PIC reads the sensors though the multiplexer and sends back the readings to the Pocket PC using the ASCII format over the serial line. I have 5 pairs of light and temperature sensors, one for each face of the cube excluding the base. I decided to use a flow sensor instead of a humidity sensor, because I need to appreciate differential readings, not just an absolute value, and even more importantly because the commercial humidity sensors cannot be used in direct contact with water. Thus, the flow sensor allows children to pour liquid directly into the cube, thereby "watering" the virtual seed. I also incorporated a clap sensor[4] and an accelerometer[5] for further interactions (see figure 4-1).

I packaged this equipment inside a cubic plastic box. I used two funnels, one on the top of the box, the other on the bottom, to divert the water flow through the flow sensor. An opening around the screen allows illustration of the story of the seed. Temperature sensors and light sensors are positioned on each face of the cube, enabling detection of changes in the direction of the light and the location of the principal heat source (see figure 4-2 and figure 4-3).

The virtual interface

The software interface of the Digital Seed displays the story of an apple seed as a sequence of still illustrations, which play as a slow animation (see figure 4-4). Each image in the sequence is a bitmap; a transparent background allows the characters/illustrations to be placed in layers. The story of the seed begins before germination. In order to grow, the seed needs particular quantities of light, water, and temperature, dispensed at an even rate. Children can experiment with the sensors in

[1]Copyright Hewlett-Packard, see http://www.hp.com
[2]PDA is the acronym of Personal Digital Assistant, an handheld.
[3]PIC is the acronym of Programmable Interrupt Controller, a tiny electronic processor.
[4]A clap sensor is an acoustic sensor that is sensitive to noise and vibrations.
[5]A sensor sensitive to fast variations of position.

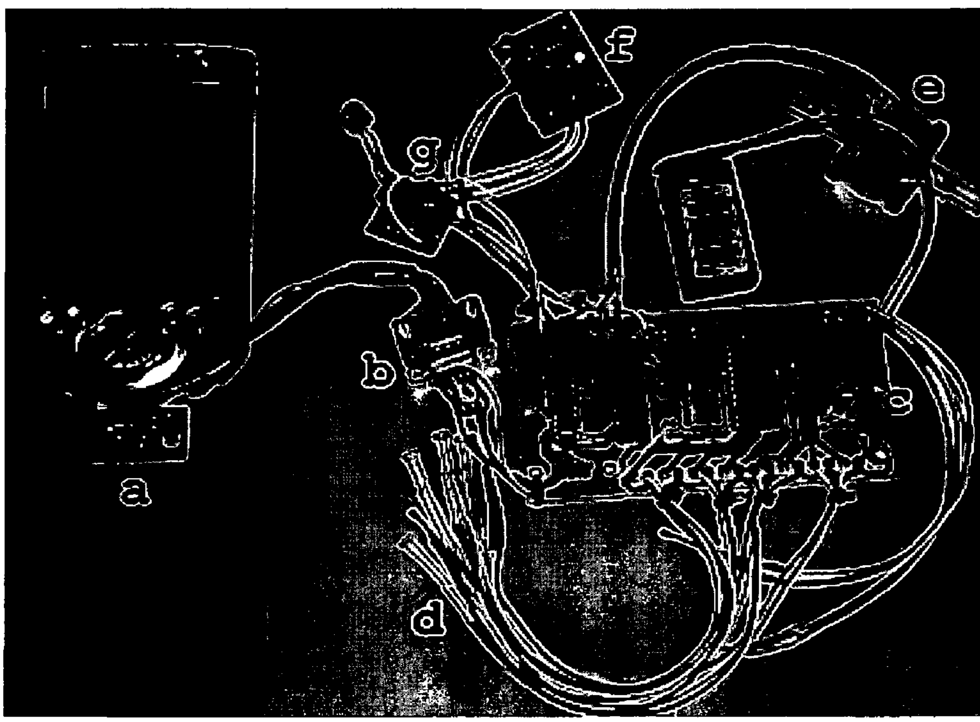

Figure 4-1: Sensors interfacing with the iPAQ. (a) iPAQ Pocket PC, (b) serial connection with the board, (c) interfacing board, (d) temperature and light sensors, (e) flow sensor, (f) clap sensor, (g) accelerometer. The circuit board measures 5 cm by 12 cm

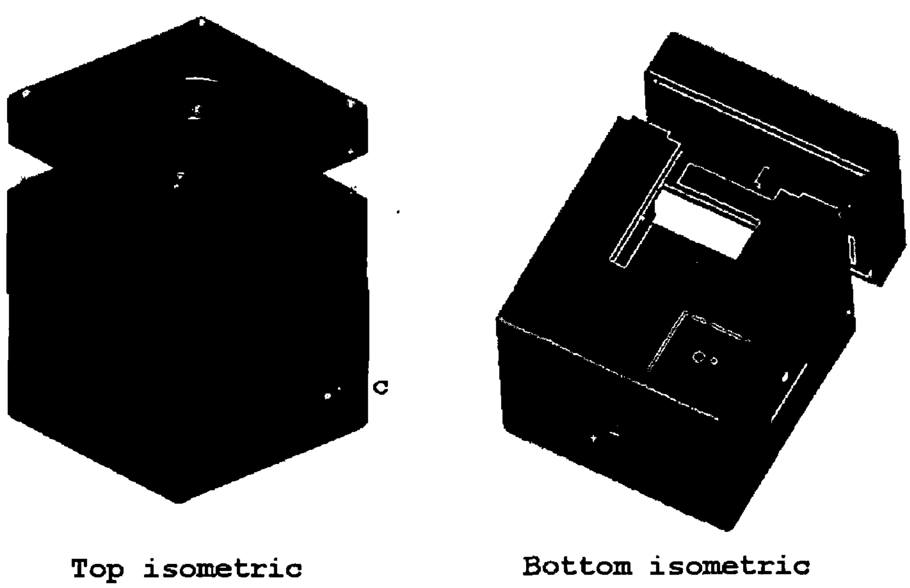

Figure 4-2: Representation of the external interface. (a) Funnel for water drainage, (b) window for the iPAQ display, (c) holes for light and temperature sensors, (d) small funnel for the exit of the water

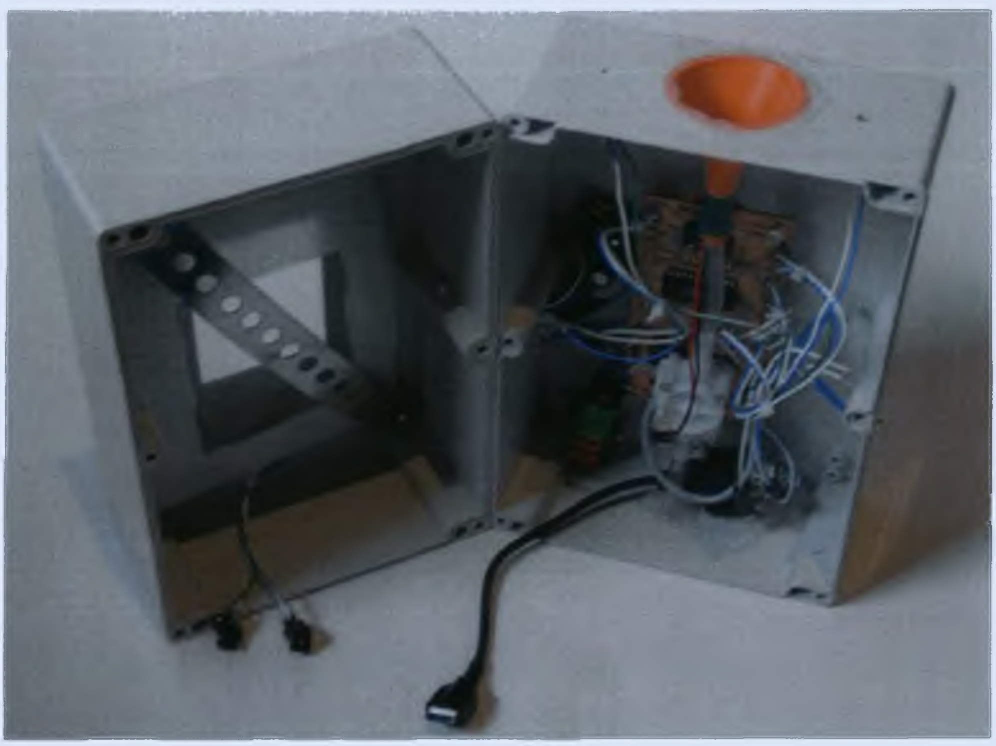

Figure 4-3: DigitalSeed plastic box. On the right hand side are visible the circuitry and the funnel for measuring the water flow

order to generate favourable or unfavourable "environmental conditions". If the plant receives too little or too much of any stimulus it will become visibly unhealthy. To encourage experimentation, the plant is robust enough to withstand serious mistreatment and only dies after extreme abuse. The software interface of the Digital Seed implements a Finite State Machine, or FSM. The FSM is a more concrete instantiation of the state map shown in figure 4-5, including animations based on sensor input or plant state, such as clouds and rain or a pollinating bee. The program was written in Microsoft eMbedded Visual Basic 3.0 using the Pocket PC 2002 SDK[6].

Figure 4-4: The software interface layout

The interaction between virtual and physical

I wanted to represent the plant's complete life cycle, but in a definite and reasonable amount of time, in order to maintain interest and interactivity. There are 12 healthy stages of growth with which the child can interact. The entire life cycle plays out in about 15 minutes. The software states correspond to three general conditions (depending on the environmental conditions): present in the right quantities, not enough present, and too much present. The sensors are continually polled to decide which state transitions are warranted. During the life of the plant, I also include some other animations to enrich the environment and to introduce some other concepts (see figure 4-5).

For an example of a state transition, see figure 4-6, in which the virtual plant moves from a healthy state to an unhealthy state. This state transition could be caused by a lack of water. I take the liberty of exaggerating dimensions within the virtual world, in order to show each stage of growth optimally and to take advantage of the elasticity inherent in virtual representations (see figure 4-7). For example, at the end of the cycle we zoom in on the fruit and then on its internal seeds. Among the representations are a sun that follows the main source of light around the box, a bee that pollinates the flower, and a bird that tries to eat the apple but can be scared away by loud noises.

[6]See http://www.microsoft.com/windowsmobile/

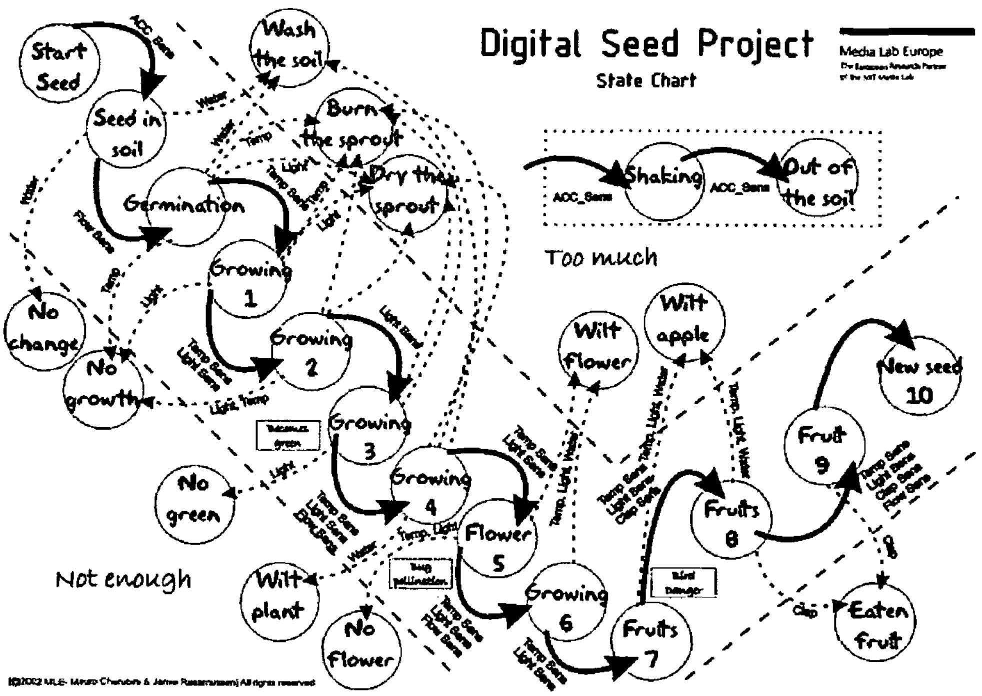

Figure 4-5: Software state chart

Figure 4-6: On the left, the sick state. On the right, the healthy state of the plant.

Figure 4-7: Some frames of the sequence of the growth in the healthy state

4.3.2 Getting the Key ideas interactions into the design

The primary focus of this design is to illustrate continuity between the stages of growth, emphasising the cycle that joins them: a plant is born from a seed, produces a seed that can give life to another plant, and so on. Flowers, fruits and seeds are all parts of this cycle, part of the reproduction of the plant. The roots of the plant were initially hidden under the soil, but after the first workshop, I decided to show them, as if the child was watching a cross–section of the terrain in which the plant is living. I put the seed under the soil to illustrate the placement of the seed within appropriate environmental conditions for growth. The design also addresses species relationships, by maintaining the continuity between seeds and plants of the same kind. Controlling environmental conditions is fundamental to the interaction design.

4.3.3 Interaction with the Toy

I worked with children interacting with the Digital Seed in a setting and manner similar to the first workshop, though this time the objects included a plant, the DS, some crayons, the toy, a mug of water and a flashlight. While there are shortcomings with the DS in its present form, I felt the childrens reactions provided important feedback for the next phase of my work.

Interactions with the toy revealed that the proportions of the illustrated seed from picture to picture (e.g., figure 4-7) were affecting childrens understandings of the depicted situation. Also, the children did not understand our representation of the camera effect of "zooming in" on a particular part of a scene. The illustrated events are represented with just a few frames, which produce a crude animation without "dissolves" between stages of plant growth. While it was clear that the children enjoyed the animation, it did not always clearly represent the changes as the plant transformed from one stage to the next. At the end, for example, some of the children thought that the tree had simply "disappeared" and that a seed had appeared in its place.

The first sequence was particularly interesting, because the children seemed surprised by the transition from seed to plant. This picture shows the seed germinating a sprout, something they would not likely have imagined. They seemed to maintain a distinct separation between the seed and the plant. Also, the design of the section of the terrain seemed not to help the children to conceptualize the presence and function of the roots. Some of them referred to the roots as "sticks" or "leaves" that grow under the soil. The design of the pictures is an important issue that emerged vividly from the follow-up workshop. In fact, sometimes the meaning of the pictures seemed to be uncertain. For example, we used a brown colour to express the "unhealthy" state of the wilted flower. Some of the children did not recognize this meaning.

This prototype is large, heavy and fragile, so the children tended to shy away from it just as they were drawn to the pictures. This inhibited direct manipulation of the box, the water and the lamp. The mechanism designed to save the apple from the bird was hand clapping, though the interface does not suggest this and the children did not guess it. In fact, they did not interpret the bird as a threat. A final point is that I think that the starting point with the DS should be the childs starting point, that is the plant, as the children more often had problems in relating the seed to the plant than the plant to the seed.

4.4 DigitalSeed evaluation: a way to the Biosphera

I regard childrens ideas not as being systematised in stages, but as differing and changing over time and across culture . I am not looking for an absolute truth, but I am trying to build an environment in which children can experiment with their ideas, an environment in which it would be possible to perform operations among many states and particular objects. This interplay is informed and inspired by love for a specific idea or domain; for example, the concept of life-cycle in this study. I think of knowledge as experience, and experiencing as defining ones own boundaries and curriculum (see also Peacock (2000)). The work reported here only begins to suggest the richness of interactivity that I am striving for. My next designs will support an indefinite number of computational states, perhaps using a simulation paradigm, and will display carefully coordinated representations in the interface, including images, sounds and tangible input devices. In fact, I realised that this software design prescribes discrete cause and effect relationships between each picture and the next. Because it anticipates a single sequence of events, interactions are limited. One of the goals of the next design, the Biosphera, will be to allow a deeper manipulatory experience through the interaction with the interface.

4.5 The Biosphera platform

The Biosphera project aims to give children an environment in which to experiment with some of their ideas on plant growth, the life cycle and how environmental variables affect a plant's life. I realised this environment with two parts: one physical and one virtual. I choose this particular design because I wanted to give users a feeling for the accuracy of the simulation model behind the virtual representation.

4.5.1 The hardware interface

A table–top sized Plexiglas dome constitutes the physical interface, in which the user can place a real plant (see figure 4-12). This dome is fully equipped with sensors and actuators able to monitor some chosen environmental conditions and modify them. I designed this shell to keep separate the space in which the plant lives and the external world. In this way, it is possible to modify environmental conditions with a relative effort in terms of spent energy. Therefore the sensor readings are rendered both possible and more accurate, being as they are separated from external disturbances. The user is able to access the internal part of the dome at the beginning of the interaction and every time s/he wants to start over. In this initial stage of development, and for the cognitive framework I am targeting, I decided to sense and affect three parameters: Light, Heat and Humidity . This is the minimal set of information required to support and understand the plant's condition. In fact I am using the two parts in a concurrent way: the information collected in the physical dome is transferred into the virtual world (running in a PC) and used to trigger the representation of the plant avatar (the virtual plant). The avatar and the real plant are usually aligned, but the avatar evolution may proceed forward and backward in real time depending on the user's will.

I tried to utilise the advantages from both extremes of this design solution: while the physical plant is a clear "witness" to the accuracy of our simulation model, the virtual interface gives us the possibility of circumventing some physical limitations, such as the time required for the plant to respond to external stimuli. In this way one is able to interact with the plant in real time, follow a non–linear path of interaction, and test multiple possible futures for the story of our plant. This last option give the user the opportunity to test a certain environmental plan for the variables and observe the corresponding results. Testing many hypotheses also gives the user the chance to access, reversing the assumptions, the single factor responsible for a certain result.

Time, in the virtual world, is a parameter and not a flow. Growth (or un-Growth) on the virtual side happens in real time, while on the physical side it takes its natural length and direction. The algorithm of the program on the virtual side, takes care to spreading the action the user performs in real time over a longer period of time. Instead of a mere Simulation (see Starr (1994)) we would rather think about representation not just a pre-defined model, pre-determined and separated from the physical world. In our vision, Science Education must pass through the reality, and reality must be the witness and the meter to judge the accuracy of our model, as in the scientific method. We want to use sensor readings to incorporate something of the physical world into our representation, so that we are not simulating any more, but representing reality. Model and phenomena must be kept together. For example, the understanding that comes out of the underlying data set in a data visualization application cannot be considered separately from the model on which the application is based (something equals something else). Beyond the seduction of simulations, we believe that virtual representations are powerful environments, able to give great insights about the real world, as long as they remain closely defined by the physical world. In our design choice, the user can access if the model is wrong just by visually evaluating the validity of the virtual representation against the real plant when the two are aligned. Losing this match would mean coming back to black box assumptions and losing the great value of giving the learner/user access to the model underlying the simulation (see Resnick et al. (2000)). This particular design is in Papert's tradition of "Objects to Think With" (Papert, 1980). In fact, while watering a plant in the classical fashion does not provide any interesting information without a huge delay, the Biosphera can reply in real time and tell the user what that water is doing to the plant.

4.5.2 The software interface

The main aim of the Biosphera project is to create a learning environment where children can create their own knowledge about multi–variate systems. In my case, I chose plant media as an accessible exemplar, utilizing a virtual world, which enabled children to control the temporal domain. Significantly, in this world they are free to construct and develop a number of scenarios, envisaged as their own "plant movies". These movie stories may be saved for future work, and evolve over a timeframe chosen by the child. The particular outcome (e.g., the rate of plant growth, whether the plant flowers or withers etc.) is a direct result of the child's actions. My design focused on developing a virtual world, that emphasised creating and contemplating variables and the relationships that can occur between them. In common with other microworld designs, my design focuses on the core characteristics of a phenomenon (Edwards, 1998), in our case Light, Temperature, Humidity and Time. It was important that, in the virtual world, emergent effects were easily generated by constructive interaction. Figure 4-11 shows my initial design.

Constructive interaction occurred using the "Simulation Parameters" panel where the child was able to choose which combination of variables and, significantly, for how long to apply them in the virtual world. The child can see the results displayed in the simulation window and choose whether to save them for later contemplation. Additionally, if the child is happy about their knowledge of the interaction between parameters affecting the plant's growth, s/he can decided to apply the changes to the enclosed physical dome containing a real plant. In this way, the child is actively creating his/her own knowledge about the relationships between variables in a complex system. The above paragraphs describe the development of a virtual world designed from an adult's perspective. Based on the core ideas and questions generated by this design process, I felt that I was at a stage where I could gain significant insight into the design criteria for children by actively involving them in the design process of a second prototype virtual world.

4.6 Design solutions

From the theoretical group of studies named in chapter 3 and from the workshop findings reported in the next chapter, I designed this environment, trying to find technological solutions that would support children during their exploration. In my designed solution, I tried to build an environment in which it is possible to iterate on the same problem with different starting conditions, developing multiple stories and comparing them. My unique approach consisted of maintaining a multi-modal approach to the design, keeping the actual plant as a counter-proof method for the simulated reality. Therefore, I designed the variable's control system, described in point 4.6.6 below, to explore the variable's effect on and interaction with the story system described in point 4.6.5 below (see figure 4-9/(b)), to "debug" experiments and test causality relations; and finally I followed the approach described in point 4.6.4 below to free children from time constraints. The resulting initial software and hardware interfaces are represented in figure 4-8 and 4-9.

4.6.1 Hardware: physical interface

I designed the Biosphera as an "object to think with" (Papert, 1980). It has two main, inter–linked components, a physical dome and a virtual world. In conceiving this design, the physical component was required to house, and experiment with, the biological world under examination. The physical component I constructed was a tabletop-sized, plastic, transparent dome. It constituted the physical interface, as shown in figure 4-8. This dome is fully equipped with light, heat and humidity sensors to monitor the changing environmental conditions. To modify the conditions, the dome is equipped with fibre-optic lighting, heaters, fans, and a small irrigation system. I designed the dome as a shell, to separate the space in which the plant lives from the external world. In this way, it is possible to modify environmental conditions within a closed system, free from external disturbance. Naturally, the user can access the internal part of the dome should the need arise. Of course, this must occur before running any experiments, so as to maintain the integrity of the results acquired. The physical plant exemplifies the emergent, inter–related phenomena resulting from the child's control of the dome's environmental factors. That is to say, the child can witness and learn from the plant's health and its progress over time. The particular outcome (e.g., the rate of plant growth, whether the plant flowers or withers, etc.) is a direct result of the child's actions.

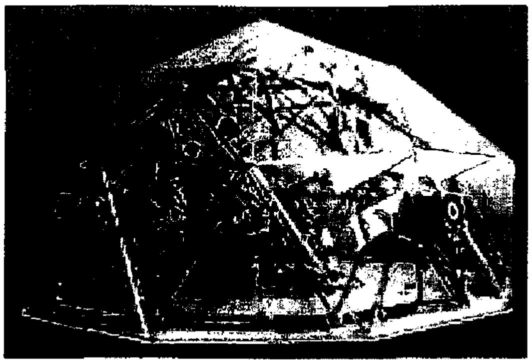

Figure 4-8: The physical interface. Heating/cooling units are visible on both sides. Photograph by: Arash Kaynama

4.6.2 Software: virtual interface

A second component of the Biosphera design is a virtual world, running on a PC and connected to the physical dome. It was designed to overcome some constraints associated with the physical dome –in particular, those associated with time. A basic assumption of our scientific culture is that time has to be conceptualised as an irreversible flow. Several studies have been carried out, attempting to understand how children perceive time (Piaget, 1970; Friedman, 1990a, 2003; Montangero, 1996). In my case, I designed the Biosphera's virtual world to enable children to construct and develop a number of scenarios, envisaged as their own "plant movies". These movie stories evolve over a timeframe chosen by the child, and may be saved for future work. The availability of this option allows the child to contemplate and reflect upon his/her choices and decide whether or not to apply their changes in the physical dome. A second advantage of having control over the temporal domain is that there is less chance that children will forget the relationships between variables that they may build while interacting with the virtual world (Friedman, 2003). Our initial software interface is represented in figure 4-9. I tried to reduce the number of possible combinations between the variables, rendering discrete the variable's influence on the system in the logical term "on/off", meaning the average daily presence of such variables as above or under the mean value. The tiles set in (a) represent all the possible combinations the user can get from the variables on the system. Using a drag & drop mechanism, the user can set the monthly program using the string of empty tiles in (b), which is composed of 15 tiles, so that each tile corresponds to two days in the life of the plant. The execution of this program can be controlled by the timeline in (c), or by dragging the tiles string over the simulation pane (d). This window shows, in real time, the effect of the programmed set of variables on the growth of the plant, and it is driven by a growth algorithm[7]. Dragging the same string on the webcam image (e), taken from the hardware interface (figure 4-8),

[7]WIMOVAC: http://www.life.uiuc.edu/plantbio/wimovac/

causes the Biosphera subsystem to complete, over a longer period of time, the growth program set by the user. Dragging the simulation results over/from one of the free spots in (f) results in the save/load function being activated. Icons on the tile set were chosen according to the outcomes of the initial workshops (see section 5.1.2).

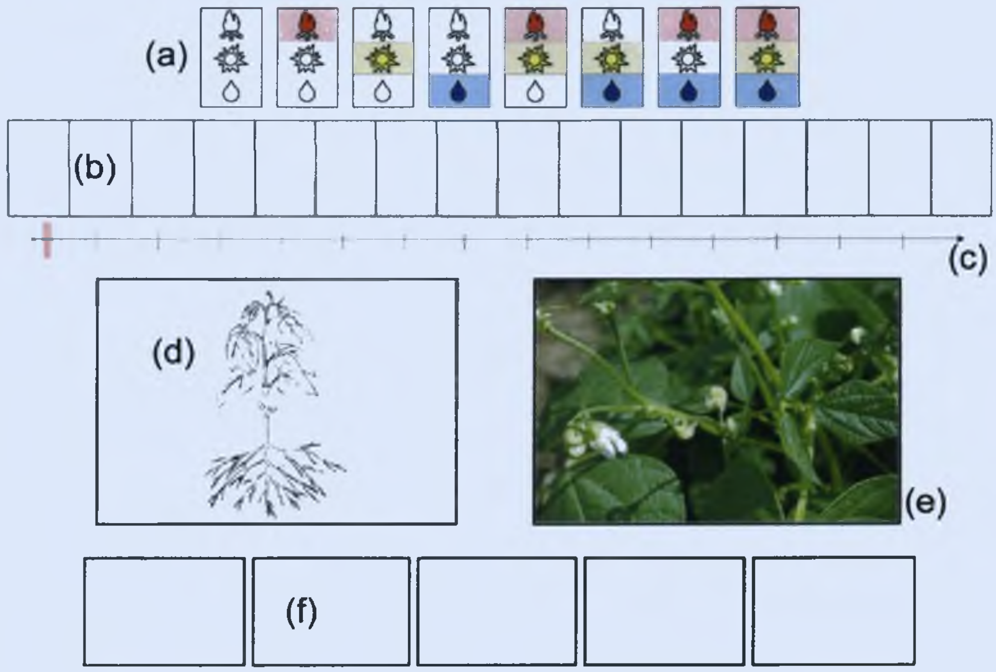

Figure 4-9: The initial software interface

4.6.3 Representation versus simulation – using actual plants

I want to use sensor readings to incorporate something of the physical world into our virtual world, so that I am not simulating but representing reality. Model and phenomena must be kept together (Starr, 1994) to overcome black box assumptions (Resnick et al., 2000). I designed a Plexiglas dome, which can host a single plant. This physical object is equipped with sensors and actuators able to control environmental conditions (see figure 4-8).

4.6.4 Time as variable – using virtual reality

I want to use time as a variable of the system, something that can be changed, because plant growth and changes in environmental conditions are time-based and because projections in time are the basis for interacting with the simulation. So I envision in our virtual world a timeline that should represent the position of the system at a certain point in time ((c) on figure 4-9). This position can be changed. The user can browse the timeline, and modify the system variables on any point along the timeline. This is connected with point 4.6.5 and 4.6.6 below. Therefore, the user should be able to perform an action on the system and observe the effect in a short amount of time. This should enable the cognitive connection between action and effect, which should result in deeper understanding and give the user access to the causal relations. The virtual side takes full advantage of the computer's computational power to circumvent the physical limitations of reality. Here the user is able to browse the timeline of the plant's life (e.g., we can grow the plant in a minute)(see figure 4-9). Moving the timeline (c) produces an immediate effect on the virtual alter-ego of the plant shown in (d). I chose this linear design instead of a circular one, for example, because I believe that it is more compatible and usable with regard to the "movie" metaphor I am trying to adopt (a movie is represented as a linear sequence of frames). This choice, along with many others, is an initial representation and I will see through experimentation how people engage with the concepts, whether this representation is helpful, and how other representations of time could support such engagement.

4.6.5 Multiple Scenarios – stories technique

Because causal relations are so difficult to grasp, I want to give the user the ability to experiment with different scenarios. Each scenario is connected with a different set of environmental conditions ((b) on figure 4-9), which, at a certain point in time, generated it. Comparing the results of different scenarios, it is possible to formulate hypotheses about the factors determining the results obtained from interacting with the system. These hypotheses may be the object of further explorations as starting conditions for new scenarios, with results, which may or may not validate the hypotheses. Inside the software interface, it is possible to tailor many different stories for the plant, testing different futures or pasts. Every story can be saved and compared with the others ((f) on figure 4-9). Thus Biosphera is a platform for experiments. The user can build his/her own knowledge, making hypotheses and "debugging" them (Papert, 1980).

4.6.6 Variables in the system – visualization system

My design focuses on developing a virtual world that emphasises creating and contemplating variables and the relationships that can occur between them. In common with other microworld design, my design focuses on the core characteristics of a phenomenon (Papert, 1980), in our case Light, Temperature, Humidity and Time are the key variable. Using the pane (b) of figure 4-9, the user is able to visually select, at a specific point in time, a certain combination of the variables in the system.

4.6.7 Aesthetic of the design – Biosphera as a terrarium

The Biosphera Design was taught with particular care to the aesthetic in accord with (Resnick et al., 2000). In fact, I designed the Biosphera as a furniture object for a child's room: this because in order to keep the evolution of the plant the child has to have access to the object for a consistent amount of time. For this reason, I privileged the captivating form of the dome and its transparency: to keep the object interesting to look at and through.

4.7 Design development

The Biosphera project did not follow a major redesign because it did not undergo a systematic longitudinal study. The hardware only had one major redesign, to assimilate some intuitions we had playing around with the system. For this reason, the differences between the hardware of version 1.0, represented in figure 4-10, and version 2.0, represented in figure 4-12, are minimal. On the contrary, most of the work has been carried out on the software design, trying to incorporate more and more of the findings or insight we had during this study. Section 4.7 will focus on this point in particular. In details, the first dome I built, was 70 cm of diameter and was made with glued Perspex[8] triangles, which resulted in a fragile structure. In addition, the object was too big for a desk environment, and also the power required for the environment control was too much, potentially exposing children to dangerous electrical shock. For these reasons the hardware redesign involved mainly mere ergonomic issues, trying to reduce the dimensions of the dome (now 50 cm), and the power required by the subsystems. Section 4.8.1 will deal with this point specifically.

Most of the development of this project concentrated on the design of the virtual interface, where different solutions have been sketched and a few implemented. Figure 4-11 represent the initial software design we chose, to show the features of the Biosphera project and to start a brainstorming process about possible visual display solutions. This initial interface presented three big buttons with three corresponding icons: a sun, a thermometer and a raining cloud. The associated meanings were: light, temperature and moisture (soil and air). The timeline is just under the buttons. This was the central control in the simulation window. Acting on this timeline would have result in a transformation of the plant status towards the point in time of the life of the plant selected on the timeline. The central part of the window, in fact, is taken by a tridimensional representation of a potted plant, which was going to animate slowly and grow or regress according to the selected point in time. Pressing one of the variable's buttons corresponded with setting the value for that variable, ON=above and OFF=below the mean value of the simulation, for the whole length of the simulation. This resulted in 9 possible combinations of variables and 9 different outcomes for the

[8] A plastic transparent material.

simulation of the growth of the plant. In addition the connection with the physical Biosphera was already presented; the button "Apply Changes" was, in fact, designed to send the same combination of variables selected into the simulation pane, to the actuators of the Biosphera. Also, the pane "Current Status" contained the sensor readings from the Biosphera. Lastly, the Simulation movies was trying to anticipate the idea of giving the user the possibility of saving the current status of the work.

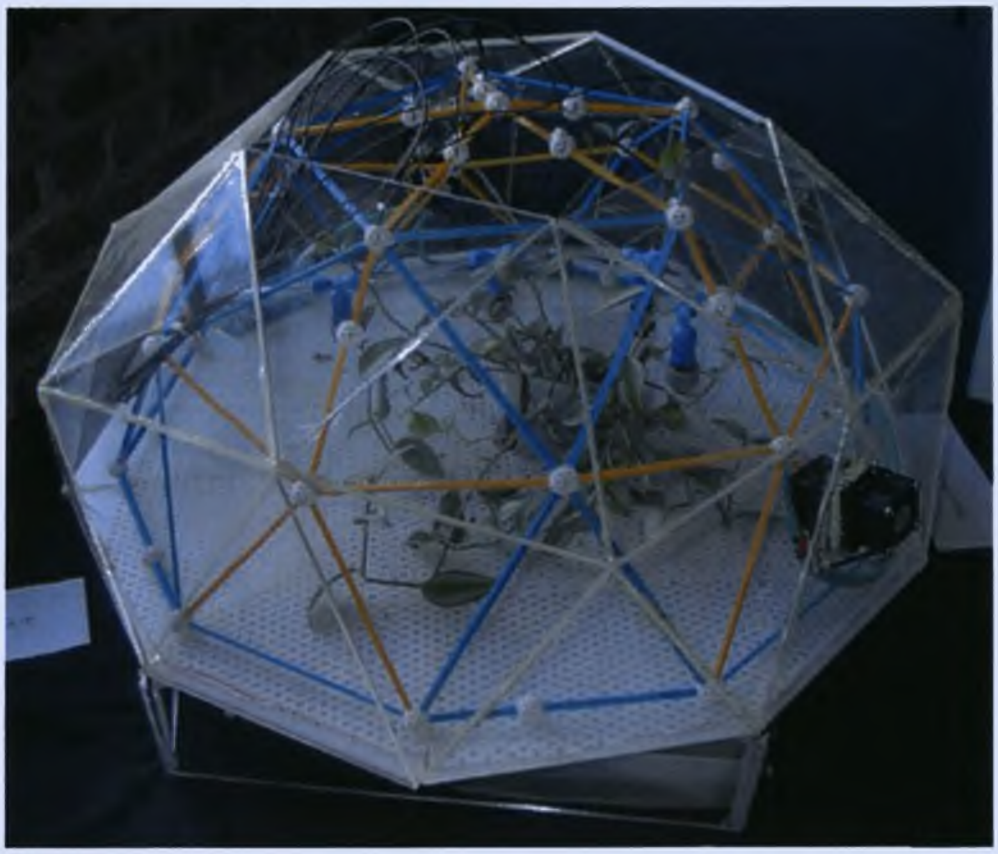

Figure 4-10: The initial Biosphera hardware interface. Version 1.0

Development of the software design

The software interface underwent major redesign steps during the last months. Most of these corrections and adjustments have been introduced to simplify the learnability of the interface and to incorporate new insights I had studying this matter. The things I sought to represent are:

1. The changeability and the current value of each variable in the system, so that the user can have an idea of the variable's status

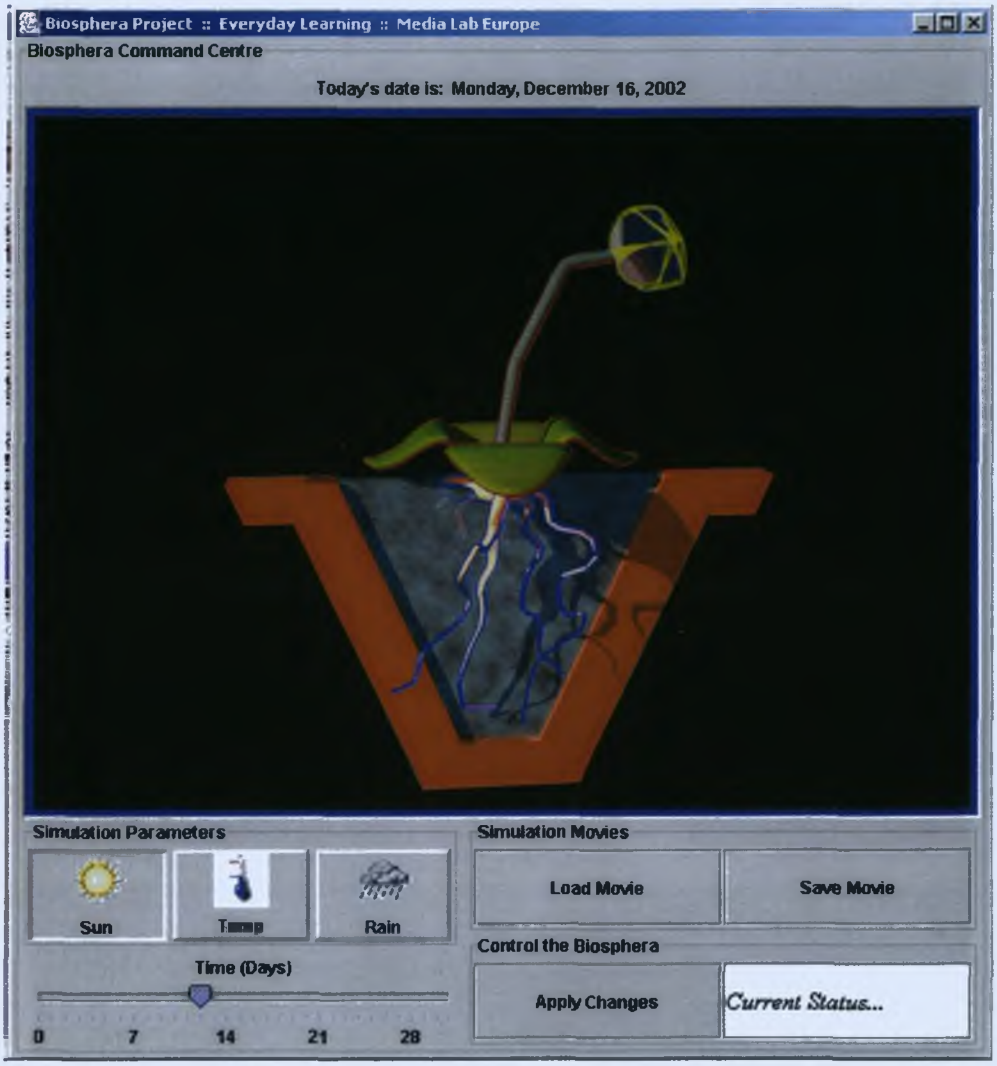

Figure 4-11: The initial Biosphera software interface

Figure 4-12: The new Biosphera hardware interface. Version 2.0

Figure 4-13: The new Biosphera software interface

2. Interactions between each variable: how the variables affect each other and the system

3. Projected (wanted) value and instantaneous (current) value: you cannot always get what you *want* from the system, and also it is impossible to have it immediately because there is a system inertia which affects the way the system reaches the wanted value (e.g., one cannot bring the Biosphera temperature to 100°C for the phisical limitations of the device and even for acceptable in range temperature, the device takes a large amount of time to reach it).

4. Definition of the wanted value in time (daily and monthly basis): this is a kind of timer, with which the user can program the Biosphera in time

The first interface I designed is represented in figure 4-14. Here a circle represents a single variable, and a big circle represents the whole system. The position of each of these circles with regard to the center of the system dictates the value that each variable has in the system. The closer the variable is to the center of the system, the greater the influence on the system. This first attempt, in fact, merged the control and the sensor readings from the Biosphera in one single visualization system: moving one of the circles ((a) or (b) or (c) of figure 4-14) produces an effect on the position of the other variables/circles, giving an idea of how the variables are interconnected and offering a control to the user, but also the position that each variable has is the direct reading from the sensor inside the Biosphera. So, each action on the position of one of these variables/circles, s/he forces the moved variable/circle to split, generating a secondary circle ((d) in figure4-14). This duplicate circle is the wanted value, whereas the original circle is the actual value. Eventually, according to the system dynamic, this duplication is going to be re-absorbed when the actual value reaches the wanted value.

This circle visualization layout was designed to work as part of a timeline view, represented in figure 4-15, offering the user the ability to create multiple stories in accord with the configuration of several variables. This timeline view uses different colors to differentiate between past, present and future ((b), (e), and (f) of figure 4-15). The user can insert a modification point along the timeline ((c) of figure 4-15), creating a secondary timeline and so on. Using the simulation window, it is possible, at the end, to visualise the cumulative results of all the changes ((g) of figure 4-15).

One of the most interesting aspects of this design was that the user could set the variables on an analogical continuum, not being forced to operate two logical levels (ON, OFF of the interface described in 4.7) or a discrete number of states. Afterwards, I realised that these two approaches are both extreme, and both presented difficult aspects to grasp. For this reason I tried to work on a different approach: the clock design first, and later the tiles design. However, some of the elements of these initial approaches still survive in the final version of the software.

The clock design is based on the general idea of the watch display. In fact, if you select a point in this space, you can describe this point with an angle Φ and a radius D (see figure 4-16). If the

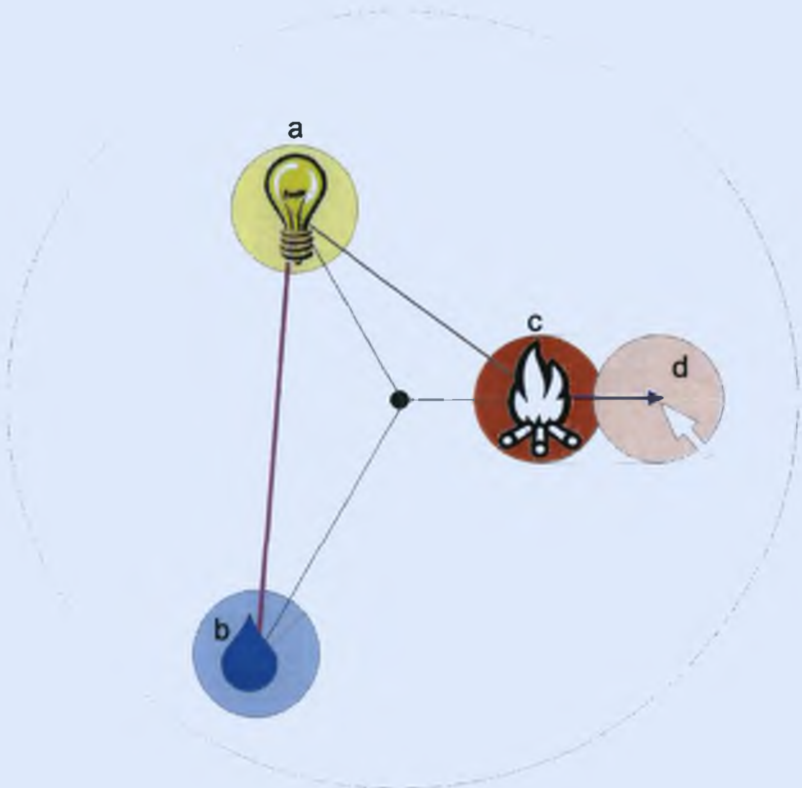

Figure 4-14: A circles interface layout

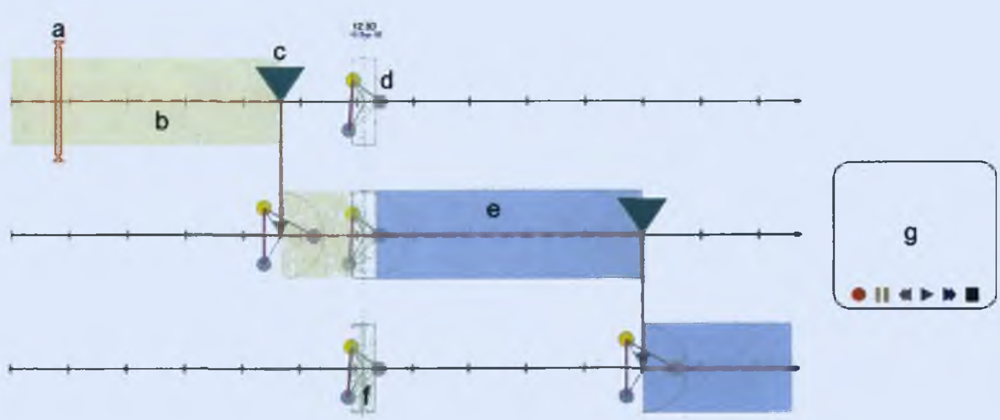

Figure 4-15: A timeline view of the circle interface layout

angle corresponds to a certain time and the radius is the value for the variable, every point in this space can set the variable's value in time. Selecting two points, the user can isolate a sector which corresponds to a variable's trend between two points in time. For example, in figure 4-17 the user set the first variable's value at 1.15 and the second at 3.00. The values in between are interpolated by the program on a linear basis. This means that between 1.15 and 3.00 the variable will modify its value between D1 (which is the radius at 1.15) and D2 (which is the radius at 3.00).

Figure 4-18 represents this clock design concept applied to the whole interface. The three variables are placed on the left–hand side of the screen while the rest of the space is left to the simulation pane, below which there is the timeline. Acting on this control, the user can browse the simulation. This design presents the limitation of being unable to modify the variable's value in a long period of time: the user can decide the variable's value in the interval of 24 hours, but it is not possible to modify the variables in a weekly or monthly basis. In other words, it is not possible to control the variables for a long period of time as, for instance, the length of development of the plant. For this reason, I moved to the tiles design described next. As a last point, for this design I developed a comparison pane, with which the user can place several plants together and set different environmental conditions for each plant, activating a visual comparison between the simulations. Figure 4-19 represents such a pane, in which the shared timeline acting on all the windows simultaneously is visible.

The last attempt I made is very similar to the implemented design. This approach uses the metaphor of the tiles as a card, that can be dragged in a solitaire–like environment. Figure 4-20 represent the first sketch of this last approach. The "time period" is a fixed width, corresponding to some amount of time (1 month in our choice). The time period is broken up into a series of chunks. In our first version, there will be a fixed number of constant-width chunks (15, but just 8 in figure 4-20). Using 15 chunks for 1 month, each chunk corresponds to the environmental conditions for roughly two days. I allow the user to specify a binary state for each of the three variables: Light, Temperature, and Humidity. This is done by selecting one of the eight possibilities in the form of a "domino". The dominoes are placed one-by-one into the chunks until the whole period is filled. The system then calculates what that set of dominoes amounts to for each of the three variables. The three resulting numbers are fed into WIMOVAC-derived equations [9], yielding a "growth".

The movie is activated by dragging and dropping the collective time period onto the simulation window. There is also a webcam view of the physical biosphere. Dragging and dropping the collective time period onto the webcam view will apply the sequence to the biosphere actuators. The final design is represented in figure 4-9.

One last design point involved the choice of the icons to represent light, heat and humidity. My first choice resulted from the workshop we did with children about quantitative visual displays for

[9] see section 4.8.2 for a description of the WIMOVAC equations

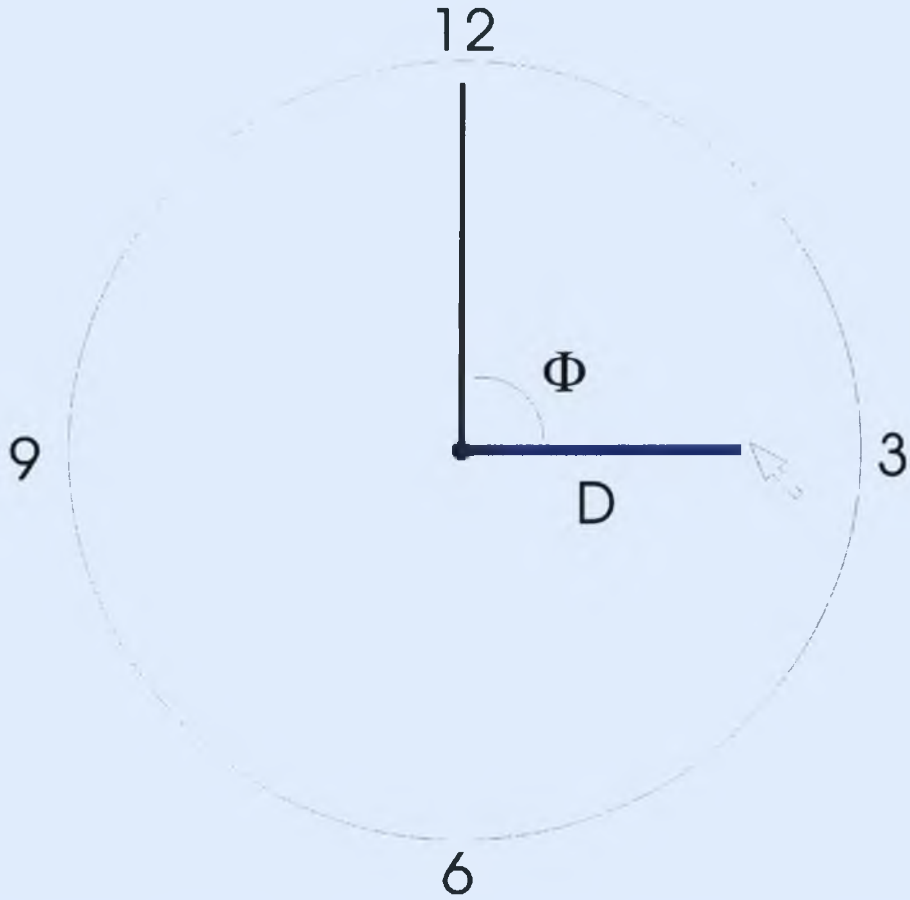

Figure 4-16: The clock design rationale: you can describe any point in the clock space with an angle Φ and a radius D

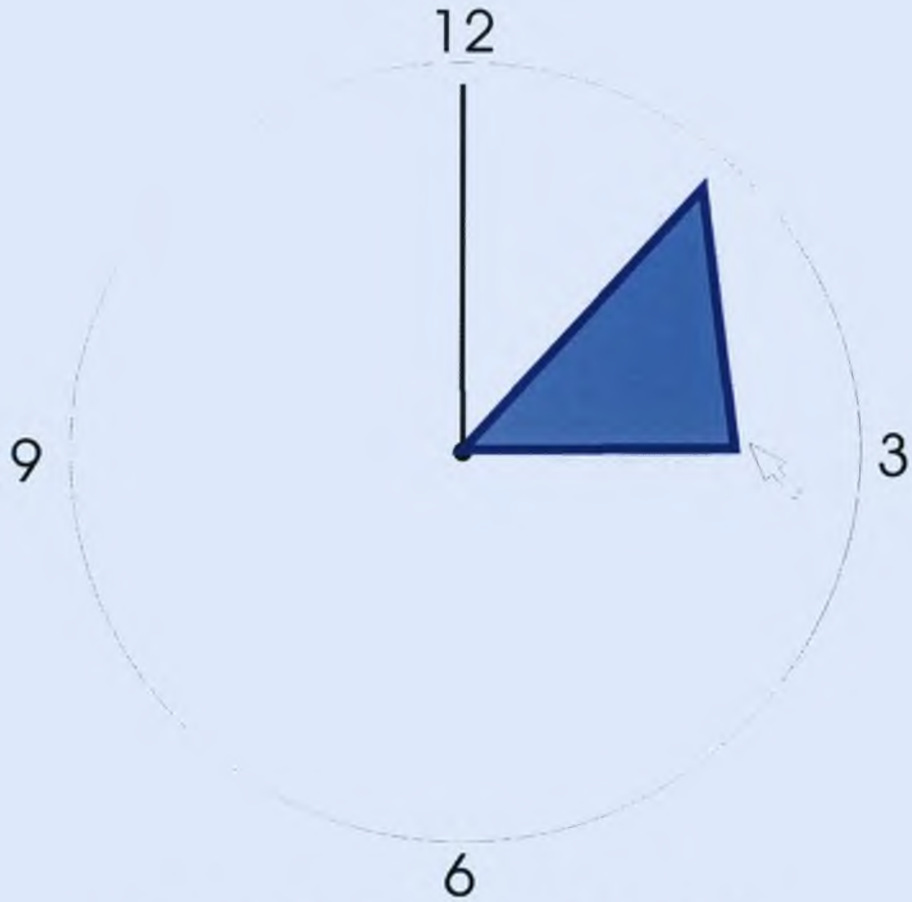

Figure 4-17: A variable is set in the clock interface

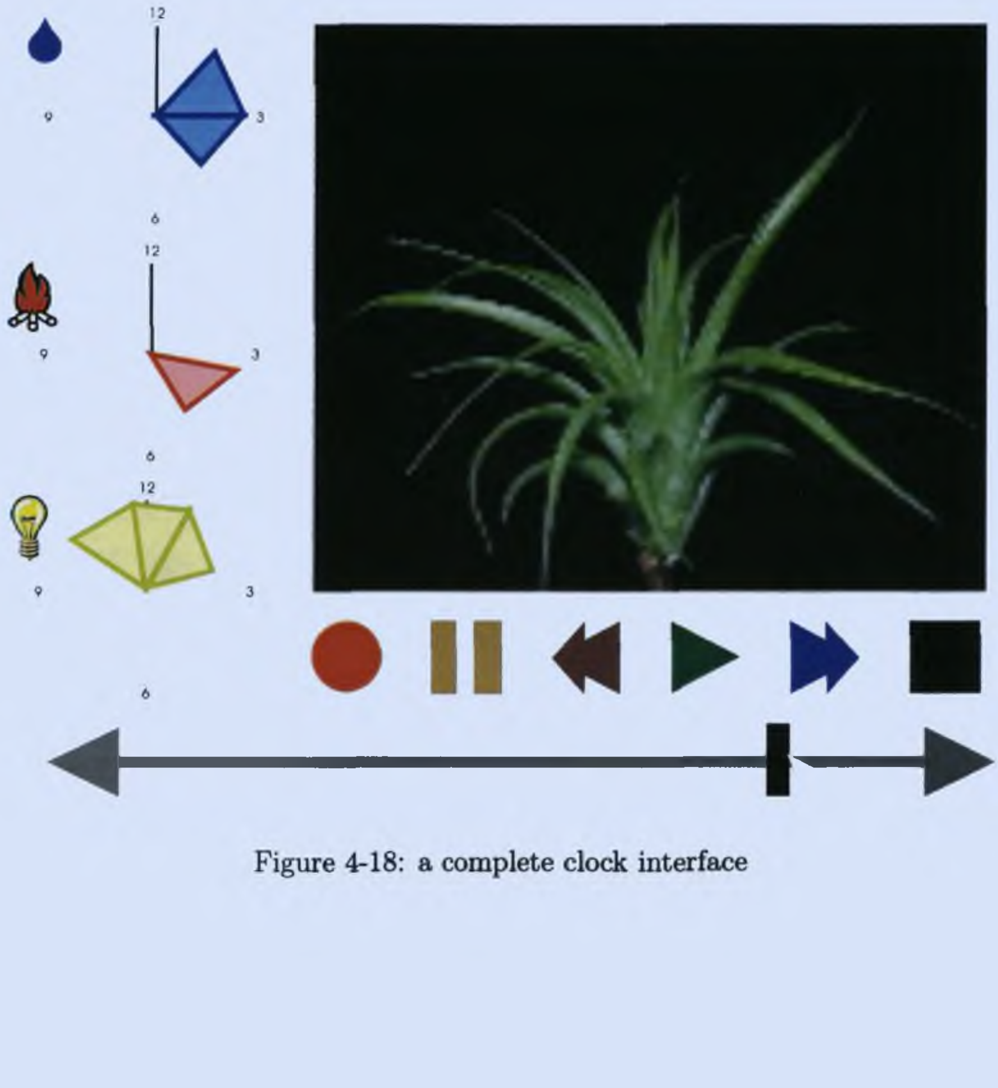

Figure 4-18: a complete clock interface

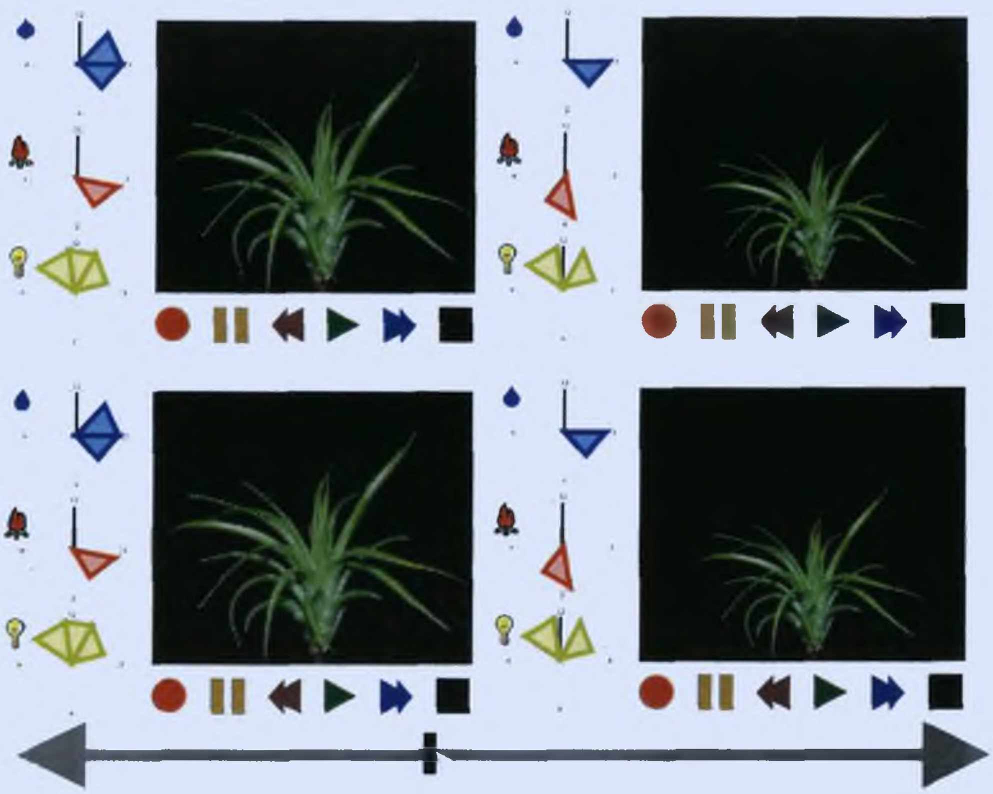

Figure 4-19: A comparison of 4 different situation in the clock interface

Figure 4-20: The tiles design sketch

these variables (see next chapter): the sun for the light, a fire for heat and a water drop for the humidity (see figure 4-21). In the final implementation, however, I decided to substitute the fire with a radiator and the sun with a light bulb. This choice is mainly due to the fact that both the sun and the fire are heat and light sources, whereas the light bulb and the radiator are much more "clean" emitters, giving rise to less confusion. The final icon set is represented in figure 4-22.

Figure 4-21: The initial icons set

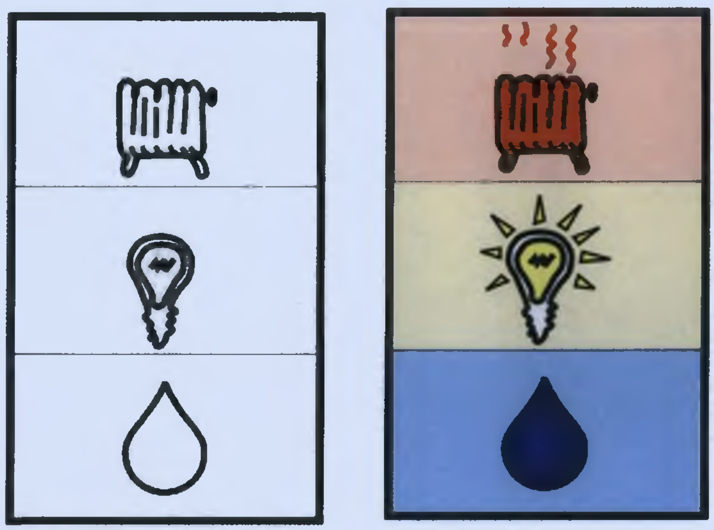

Figure 4-22: The reviewed icons set

4.8 Engineering solutions

In this section I will detail the engineering solution I implemented to realise the prototype.

4.8.1 The Biosphera dome

My unique approach consists in building a physical object to think with. I designed a shield capable of sustaining life and limiting the numbers of factors responsible for growth. this accomplished two things: first, I can sense the environment to monitor the factors I selected (temperature, humidity, light); second, I can modify these factors. My approach therefore takes advantage of the computational power of a PC interconnected with the biosphera. Inside this virtual domain, in fact, I can simulate a wide range of possibilities, and above all, I can circumvent such natural laws as the time required for the plant to grow. This interaction between the physical and the virtual gives us the possibility of taking advantages from both extremes: firstly, I am not just simulating but "representing" nature; secondly, I can display multiple futures for my plant.

I have realized the physical interface: a tabletop air–tight Plexiglas dome, as shown in figure 4-12. There are two Peltier junction units, which provide air temperature control (see figure 4-23). There is a rainfall subsystem, with a micro-sprinkler and a humidifier for soil moisture and humidity control (see figure 4-24). Some optical fibres provide light control inside the shield. Finally there is a rack of environmental sensors tracking the changes inside the dome. The water is completely recycled. An external web cam, represented in figure 4-25, records a time lapse video of the physical plant, providing a comparison image in the virtual interface (see figure 4-9/(e)).

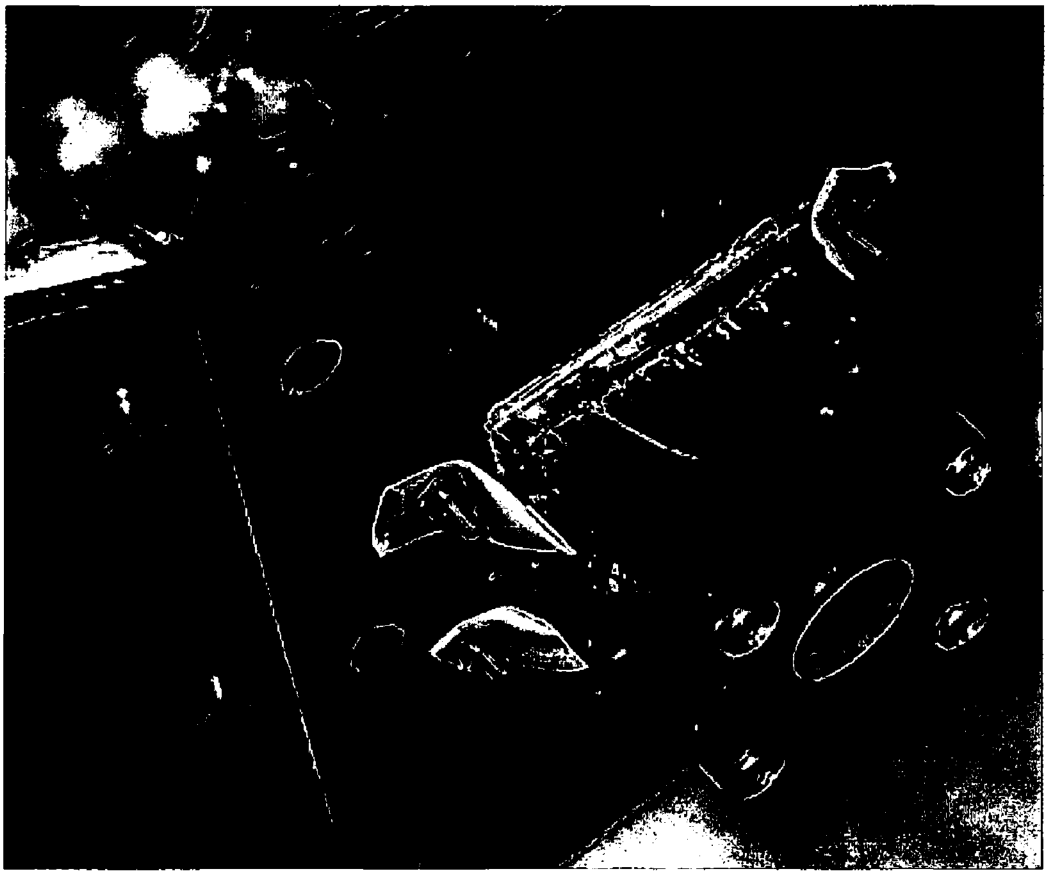

Figure 4-23: One of the fan units on the side of the Biosphera's basement

Figure 4-24: The sprinklers system in the top part of the dome

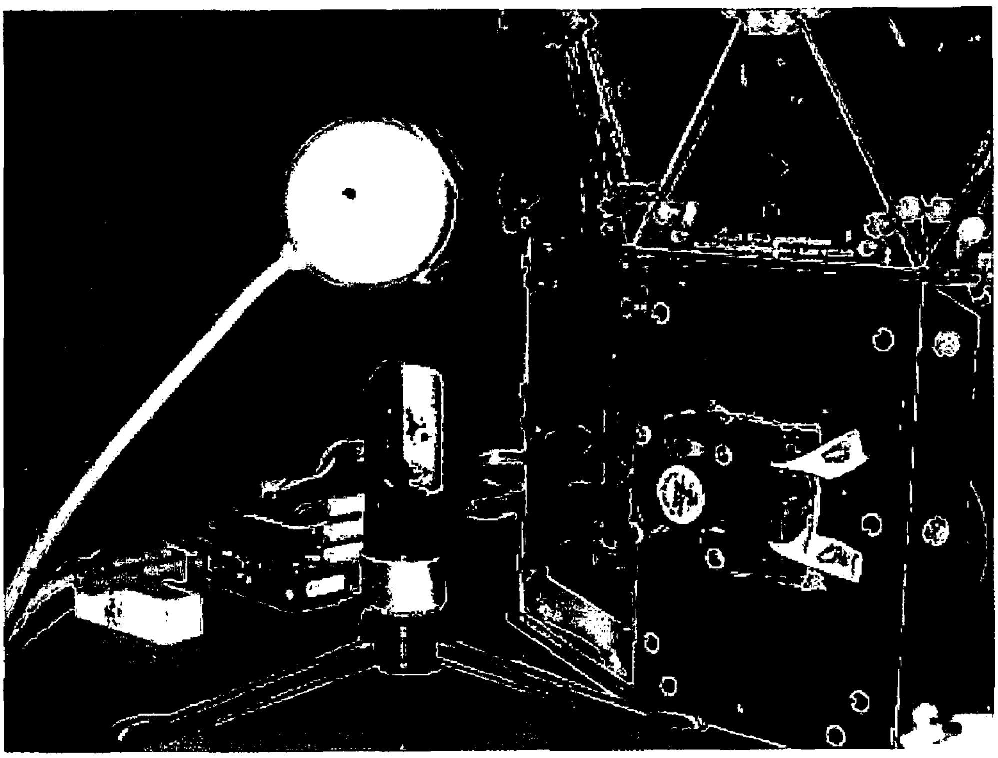

Figure 4-25: The external web cam

4.8.2 The growth algorithm

The simulation in the software interface of the Biosphera is driven by the WIMOVAC algorithm (Windows Intuitive Model Of Vegetation response to Atmospheric & Climate change [10]), developed by the University of Illinois in the US. This general model (WIMOVAC) is applicable to a wide range of vegetation and soil types and importantly it is accessible, as an experimental tool, to managers, students and experimentalists. This is a modular mathematical model of the carbon balance of vegetation and related systems, which would allow prediction of responses to climate change, and which would also allow non-specialist users to vary parameters, numerical assumptions, vegetation, climate and atmospheric variables, and to visualize their outcomes in a straightforward fashion.

This algorithm was originally developed for crop growth, so I tried to adapt it to my specific needs: a single plant, a bean plant, in a artificial environment. Following the definition of such a growth algorithm, I have extrapolated a simplified group of equations which take, as inputs, the Light, Temperature and Humidity conditions and give back, as output, the growth response of the plant. In details, the output is the photosynthetic response to light ($P(L)$), to temperature ($P(T)$) and to relative humidity ($P(H)$), which have been assimilated to growth. Equations 4.1, 4.3 and 4.6 are the functions used in the software. In these equations there are some static parameters, whose meaning is explained in table 4.6: Q_y is the Quantum Yield and is equal to 0,055; C is the Convexity and is equal to 0,9; A_{sat} is equal to 25; D_r is the Dark Respiration which is equal to 3. Equation 4.2 computes the Leaf Photosynthesis at the equalised temperature of 25°C. $P_{Leaf(T)}$ is the the Leaf Photosynthesis adjusted for temperature, so the $P_{Leaf(T,H)}$ which is adjusted for temperature and humidity.

$$P(L) = \frac{Q_yL + A_{sat} - \sqrt{(Q_yL + A_{sat})^2 - 4C(Q_yL + A_{sat})}}{2C} - D_r \tag{4.1}$$

$$P_{Leaf} = \frac{Q_yL_{500} + A_{sat} - \sqrt{(Q_yL_{500} + A_{sat})^2 - 4C(Q_yL_{500} + A_{sat})}}{2C} - D_r \tag{4.2}$$

$$P(T) = P_{Leaf} \exp \frac{(T-25)68500}{298(273+T)8,314}\sqrt{\frac{273+T}{298}} \tag{4.3}$$

$$P_{Leaf(T)} = P_{Leaf}\sqrt{\frac{273-T_{25}}{298}} \exp \frac{(T_{25}-25)65800}{8,314(273+T_{25})298} \tag{4.4}$$

$$P_{Leaf(T,H)} = P_{Leaf(T)}\frac{H_{80}}{100} \tag{4.5}$$

[10] http://www.life.uiuc.edu/plantbio/wimovac/

$$P(H) = P_{Leaf(T)} \frac{H}{100} \quad (4.6)$$

Table 4.6: WIMOVAC parameters used in the equations

PARAMETER	EXPLANATION
Quantum Yield Q_y	This expresses the efficiency with which the plant photosynthetic system uses light to fix CO_2. It's effects are particularly important at low light intensities when this is usually the limiting factor for photosynthesis.
Convexity C	This is a largely empirical factor that describes the curvature of the transition between light limited and CO_2 limited photosynthesis. Photosynthesis in the intermediate light range is most efficient when the convexity of the photosynthetic light-response curve is high.
Light saturated A_{sat}	Is the light saturated (typically 2000 $umol\ m^{-2}\ s^{-1}\ PAR$) rate of photosynthesis and gives a measured of the CO_2 limited rate of photosynthesis. In simple terms this is analogous to the amount of photosynthetic / carboxylating metabolic machinery in the plant leaf.
Dark respiration D_r	This is a measure of leaf respiration in the dark and therefore in the absence of photosynthesis. It is usually assumed to be the cost of maintenance of the photosynthetic metabolic equipment in the leaf but does not include the respiratory cost of its construction. Generally speaking Net photosynthesis = gross photosynthesis - dark respiration.

4.8.3 LACE

Lace is a package of Java classes for creating structures that can be described by collections of rules[11]. It is based in part on the work of Przemyslaw Prusinkiewicz and Aristid Lindenmayer described in their book: The Algorithmic Beauty of Plants (Prusinkiewicz and Lindermayer, 1990) and in subsequent papers by Prusinkiewicz (Prusinkiewicz et al., 1995).

An abstract form in Lace is defined by a list of symbols and a set of rules which specify how those symbols are rewritten. In almost all cases, the ultimate goal of defining an abstract form is to 'render' it as one of the familiar media types. A structure in Lace, called a domain, specifies the mapping from an abstract form to a specific representation. The key idea here is that there are aspects of form which are independent of any particular representation.

Productions are composed of a predecessor part and a successor part. The predecessor is a single symbol, possibly with some parameters. The successor is a sequence of one or more symbols. A production may have multiple successors, and which one is selected during evaluation is determined by condition expressions that may be associated with successor symbol strings.

We know what set of inputs maximizes and minimizes the simple WIMOVAC–derived equations. I equate the minimum with the start of a long time-lapse series, and the maximum with its end. In the Biosphera software I am using LACE for generating the animation of the bean plant growing (see figure 4-9/(d)). The speed and the ending point of this growth are determined by the WIMOVAC equations described in the previous section, as per a recent technique explained in a paper by Jim Hanan (Hanan, 1997).

I take $(growth - min)/(max - min)$, as giving us the growth percentage. This percentage will reflect on the length of the plant simulated growth that the user will see.

4.8.4 Interaction between hardware and software

There is a bidirectional communication channel between the hardware and the software: sensor information from the dome is transferred into the virtual world to drive the simulation. The environmental settings chosen by the user in the simulation environment are applied, at the user's will, to the physical side. The current development of the software stores the sensor readings into a log file, but no actions are taken at this point. One of the possibilities offered by this design is to apply an algorithm to this log file, capable of extrapolating the dynamics of the dome exposed to a particular environment and triggering and fine–tuning the execution of the environmental program on the physical side. In addition, taking into account the sensor readings can also redefine the theoretical growth algorithm into an empirical framework. Although I envisioned this expansion of my design,

[11] LACE has been written in Java by Chris Laurel. Please see http://www.shatters.net/ claurel/lace/index.html .

Figure 4-26: An example of virtual plant generated with LACE

the time constraint of this project prevented me from exploring these directions further.

The tower system

I am using the Tower System as a bridge between the physical Biosphera and the software interface. This system has been developed by Bakhtiar Mikhak (et al.) at the MIT Media Laboratory in Cambridge[12] (see Gorton et al. ((March 2003)). Figure 4-25 shows in the background the tower in Biosphera configuration. A description from the internet site [13]:

> The Tower is a powerful, flexible and extensible, yet inexpensive modular development system for designing and prototyping computational devices. Physically, the Tower consists of a primary Foundation layer with a central processor. Additional circuit board layers can then be stacked on top for added functionality, as a particular application requires. We have been working to create a base set of layers that perform many standard functions and will be useful for a wide variety of electronic systems. Existing modules for sensing, actuation, data storage, and infrared communication will soon be joined by ones for enhanced display output and high-speed wireless communication.

4.8.5 The dome's design: a tribute to Buckminster Fuller

The Biosphera dome was inspired by the work of Richard Buckminster Fuller (born in Milton, Massachusetts, 1985). Known by his friends as "Bucky", has undeniably been one of the key innovators in the 20th century. He is known as a philosopher, thinker, visionary, inventor, architect, engineer, mathematician, poet, cosmologist, and more. Buckminster Fuller was probably one of the first futurists and global thinkers. He is the one who coined the term "Spaceship Earth", and his work has inspired and paved the way for many who came after him. Fuller is the inventor of the Geodesic dome, and was a pioneer in utilizing basic geometical shapes in design. A key goal for Buckminster Fuller was the development of what he called "Comprehensive Anticipatory Design Science", which is the attempt to anticipate and solve humanity's major problems by providing "more and more life support for everybody, with less and less resources."

---

[12] http://www.media.mit.edu .

[13] See http://gig.media.mit.edu .

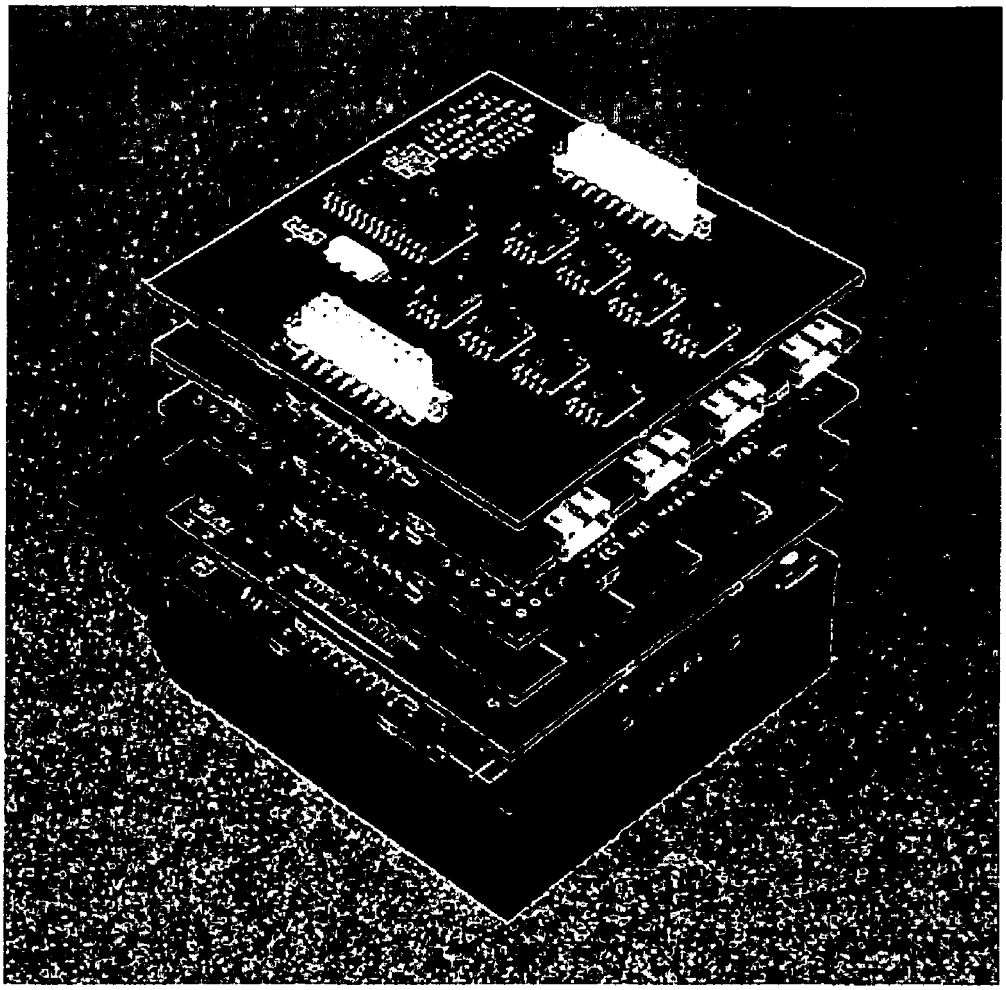

Figure 4-27: The Tower system

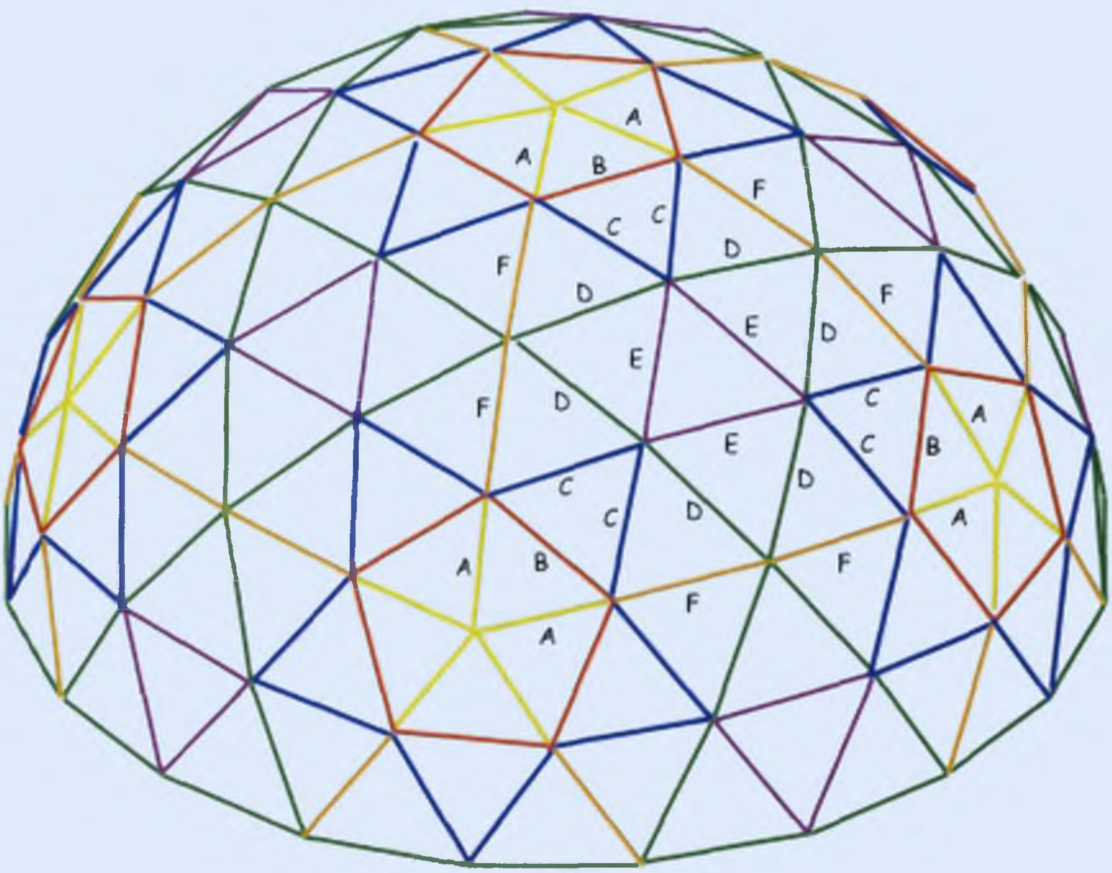

Figure 4-28: A Buckminster Fuller's Dome

Chapter 5
Evaluation

"KAEN (11): Is a stream alive?—*Yes, it goes* (il roule). —Is the lake alive?—*Yes, it is always moving a bit.*—Is a cloud alive?—*Yes, you can see it moving* (on le voit marcher).—Grass?—*Yes, it can grow.*"

Jean Piaget, *Child's Conception of the World*

Image from Wikes (1997)

Chapter 5

Evaluation

In this chapter, I will describe how the design I have worked on and reported in the previous chapter has been developed and evaluated, through a continuous interaction with potential users. For this purpose I set up several activities with children during my research period at MLE. Most of these meetings provided a framework to start developing the current design, others, more specifically, tried to evaluate that design. An important consideration is that this evaluation has not yet been completed. At the time of writing this thesis, the studies leading to progressive iterative design are ongoing. For this reason, this work should be considered as a design exercise. In the next sections, I will describe the design of the interactions I conducted for Biosphera and DigitalSeed with children. Then, I will report a synthesis of the main outcomes from these interactions.

5.1 Evaluation design

One of the targets of this evaluation was a phenomenal exploration of children's thinking as they engage with the Biosphera and DigitalSeed objects. For this reason, the structure of the meetings I organised reflected: the choice of making a direct observation of the children interacting with objects: seeds and plants in the DigitalSeed interviews, and the Biosphera platform. In addition to being observed, children were questioned, time to time, as a way to stimulate and enquiry their interaction.

5.1.1 DigitalSeed interviews

I conducted the initial cycle of interviews in a primary school near Dublin, with 15 preschool children, 4 and 5 years old, of varying gender and socio-economic status. Some of them had previous experience with gardening, though that does not ensure consistent or complete understanding of botanical processes. The materials included crayons, sheets of paper for drawings, a small box with soil, seeds of various kinds (green beans, maize, oats, apple, & tomatoes), fresh fruit (whole and cut apples (red and green), oranges, & tomatoes), plants, flowers, and pictures of vegetables, fruits, flowers, and trees (see figure 5-1). Each interview involved a child, an interviewer, a note-taker who intervened occasionally, and a tripod-mounted video camera that recorded each session. We prepared questions to frame the enquiry, but these did not dictate a sequence for the conversation and we tried to respond to the children's thinking as in the manner of the classical Piagetian interview (see appendix A). Because I am a non-native speaker of English and was working with Irish children, I sought the partnership with a native English speaker. The interviewer asked questions that seemed natural in response to each child's thinking. I designed the questions not to imply a yes/no answer or a particular avenue of response, but to reveal each child's unique reasoning. She tailored the questions during the course of the conversations, as she noticed the ways in which particular ideas or terminology did or did not seem to address or reflect the children's thinking. She tried to be unobtrusive and not to suggest answers. The children expressed themselves by speaking, gesticulating, drawing pictures, and manipulating objects. I welcomed and encouraged each kind of answer. My goal was to focus on the reasoning process behind the words and actions. Each of every individual child's communications contributed to our emergent interpretation of an overall consistency in the children's thinking.

I report in 5.2.1 the most common children's conceptions discovered in the initial cycle of interviews. The order of categories does not reflect any sequence of conversation. I have changed the children's names to protect their privacy. Most of the results find a synergic relation with Hickling and Gelman (1995), although we found reasoning on the causal mechanisms pertaining to growth to be less strong.

5.1.2 Biosphera interactions

In October 2002, I engaged a group of children from a local school in a series of interactions, with the aim of gaining a glimpse into their ideas about environmental variables affecting plant growth and how to represent them. A group of 6 children was involved in three different activities: (a) a discussion about possible ways to display Light, Heat and Humidity gradients in an interface; (b) a discussion of how these variables interact and how to represent the interaction; and finally (c) an environmental data logging activity inside the MLE building (see figure 5-4).

(a) In this first activity, I asked children to suggest both possible ways to represent the targeted variables, and a possible interface to visualise the sensor readings connected to these variables. Children were engaged in working in small groups and drawing the results of the discussion. Then, in the bigger group, every solution was evaluated, asking the kids who did not contribute to that

Figure 5-1: The interviews setting

particular drawing to describe what it meant. At the end, the best graphical representation was chosen by the larger group, based on the communication features of that particular interface.

Figure 5-2: A "circles" representation of the variables suggested by children. They chose to represent the variables with colours which are usually associated with these factors: water–blue–Humidity, fire–red–Heat, and sun–yellow–Light

(b) The second activity attempted to address the interaction between the variables. I was interested in how children think about this interaction and if they could envision possible ways to represent it. For this reason, they were presented with a series of objects connected with the sought–after variables. Table 5.1 reports the description of the used objects. Children were asked to play with some of the objects on the table. The facilitator stimulated the discussion, providing

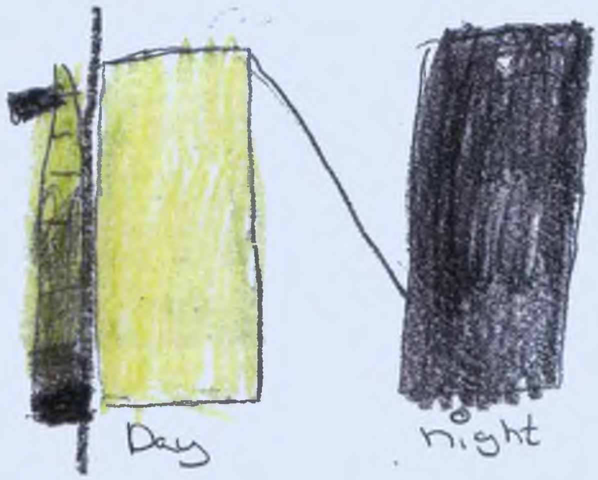

Figure 5-3: A gradient representation of Light suggested by children. Here the intensity of the colour is directly proportional to the value assumed by the variable

examples of concrete situations in their daily life in which they would find evidences of a particular factor. They had a tool to explore each factor in its essential features. They also had paper and crayons, to design and represent their own ideas. After a while, the facilitator initiated a discussion while they were drawing. The same structure was repeated for two and three variables at a time.

(c) In the last activity, kids were asked to take one cricket [1] with an environmental sensor and a 4–digits Led display (see figure 5-5). The task of this activity was to map the intensity of the variable connected with the sensor they have in the ground floor of Media Lab Europe. They could record the data in any way they wanted. Afterwards, kids were asked to reconvene in a big group and put together their results. They were then asked to represent on a general map all the data they have logged. They could use all the techniques they wanted. Following the conclusion of the representation process there was a general discussion. Facilitators asked questions to stimulate the discussion.

5.2 Findings

5.2.1 Analysis of the DigitalSeed interviews

I conducted this cycle of interviews in a primary school near Dublin, with 15 preschool children, 4 and 5 years old, of varying gender and socio-economic status.

[1]Figure 5-6 represent this device. For more information see http://cricket.media.mit.edu/ .

Table 5.1: Objects used during the interactions with the Biosphera

VARIABLE(S)	TOOL/OBJECT	EXAMPLE
Light	LED (pure Light Generator)	Sunshine; Torch; Light bulbs; colors
Heat	Hair dryer (pure Temperature Generator)	Fire; hot coffee; furnace; stove
Humidity	Mirror (visualizer); humidifier (pure Humidity Generator)	Shower; boiling water; breathe; drops; rain;
Light & Heat	Lamp (Light and Temperature generator)	Sunshine
Humidity & Heat	Boiler (Temperature and Humidity generator)	Hot coffee
Light & Humidity	Colored light diffused through steam or water (Light and humidity interaction)	Clouds
Light & Heat & Humidity	Lamp shining on a surface with water or ice (Light and Temperature humidity generator)	Greenhouse

Figure 5-4: Two kids recording humidity levels in the room

Figure 5-5: A cricket recording the temperature level in the fridge

The origin of the seeds

A seed's origin is not clear to children of this age range. We registered different conceptions of the origin of seeds: humans make them, they come from a seed box, seeds come from far away. Some children have more naturalistic conceptions: seeds can be found in the soil, or in the plants but not in a specific location. None of the children interviewed seemed to relate the seed with the fruit of the plant, even if the half-apple, with its seeds, was visible in front of them. For example, Carl's first answer assumed a non-naturalistic source:

Carl (5): Where do you think the seeds come from? *From the apple shop.* What would happen if I was unable to find the seed in the apple shop? Where do I have to go? *I think I don't know, maybe from the apples.*

Patrick (4): Where do seeds come from? *From the seeds shop.* And if I was unable to find seeds in the shop where do I have to go? *Far away.* Where do I have to go? *In England.*

Mary (4): Where do you find seeds? *You can find them under the ground. ...* How does this seed get inside this apple? *Mans just put it in there.*

Sarah (5): Where do the seeds come from? *From the packages in the shops.* Can you find them anywhere else? *Sometimes you can find them in the tree.*

Gwyneth (4): Where do seeds come from? *Under the ground.* And where? *Where flowers are.*

Cara (4): What makes the seeds? *You put them in the muck.* And then? *You need a circle.* (She traces with her finger a circular movement on the table.)

The origin of the plant

Children tend to consider the seed and the plant as distinct objects. So the origin of the plant can be uncertain as well as the origin of the seed.

Carl (5): If I would like to grow another plant like this, what will I have to do? *You will have to put in a box.* What do I have to put in the box? *You have to put a tree.* Where do I find the tree? *You will find it to the apple tree.* How does it start? *When you have a car, you have to look around for the apple tree. When you find the tree, if it is a small tree, you can put it into a box.* (Carl offers no explanation of how this or any tree would have originated. Later, he develops an elaborate story about the moon and the sun talking to the plant, which becomes sad but does not sprout any seeds.)

Renny (5): Are these plants from the ground? *No.* Where are they from? *You can get flowers in the shops.*

Growth of the plant/seed

For most of the children, growth meant just becoming bigger and bigger. They seem to lack a conception of progress through phases and a perception of qualitative differences in the morphology of the plant.

Carl (5): Let's imagine that the seed will grow. How will they grow? *They will grow bigger and bigger.* So they will keep growing bigger? *Yes.*

Relation between seed and plant

The relation between seeds and plants is not clear to the children. Some of them think of seeds as food for the plant, implying that seeds help the plant to grow. However, these children do not associate seeds with the plant's origin.

Carl (5): If I were to take this seed out of the apple, what I would do with that? *You put to the apple tree.* So here is an apple tree, where do I have to go? (He points to the base of the plant.) So I would have to put the seed on the apple. And then what would happen. *It will go up, up, up into there.* (He points to the top of the tree). Would I get an apple from that? *Yes.*

Patrick (4): What would you do with the seed to make the plant grow? *Give it water.* Can the seed grow anywhere? *Under the plant.*

Mary (4): Would I be able to use a tomato seed to grow an apple tree? *No, you can use them to grow a tomato tree.* Do I have to put the seed inside? (The interviewer points to the soil in the potted plant.) *You make the tomato grow.* With what? *With the tomato tree, and them will grow on it.* How would I get a tomato tree? *You have to buy one.* ... Do plants need help to grow? *Yes, they do.* What do they need? *You need to put many seeds into the plant.*

Cara (4): How does this became a flower? What do you do with the seed? *You put them in the flowers* (She points to the flower). And what happens to the seed? *It grows up.* And what does it mean to grow up? *It needs the dark.* Where do you find seeds? *In the apples.* ... What do you need to grow? *My breakfast.* And, what does the plant need when it gets hungry? (pointing to the seed) *This.* The seeds? *Yes.* ... Do seeds have a mummy or daddy? *Yes.* (pointing to another seed) This is its mummy? *Yes.*

Flowers and fruits

None of the children seemed to sense the sequence seed → plant → flower → fruit → seed. This is also related to the idea of progression between phases, stages or states.

Shannon (4): What is a seed? *A seed is ... you have to put it into the ground and then is a flower.*

Rose (4): What will this seed grow into? *A flower.*

Roots

Most of the children interviewed did not mention the presence of roots and their function for the life of the plant.

Sarah (5): Why do plants sit in the ground? *Because they have to, till they grow.* Then what happens? *Some apple will grow on the tree.*

Placement of the seed in order to grow

Most of the children who recognized the seed as responsible for the origin and/or nourishing the growth of the plant were still not clear about where to put the seed so that it will mature or increase in size. They thought they should put the seed into the flower, or that the seed grows under the plant, which does begin to suggest an idea of a relation with the soil. In addition, they did seem to understand some need to access the plant as it grows.

Mary (4): Where do you have to put the seed to get it to grow? *Maybe around the plant in a circle.* How do you get the seeds to grow? *They need water.*

Species and relation with seeds

Most of the children did not have a clear idea of the relation between a certain kind of plant and its seed. So, for them it is possible to grow (whatever "to grow" means for them) an orange tree using an apple seed, an apple tree using a tomato seed, etc.

Carl (5): If I was to plant this tomato seed, would I be able to get an apple? *Yes you could.*

Patrick (4): Would I be able to use an apple seed to make an orange. *Yes.*

Mary (4): Would I be able to use the apple seed to make a tomato tree? *Maybe because the seed colour is the same of the apple.*

Environmental conditions responsible for the growth

Children consider water to be an important factor in the growth of the plant. Most of them also consider the light (sunshine) as an important factor. Not one addressed invisible conditions for growth, such as temperature and the presence of circulating air.

Patrick (4): What do plants like? *Water.* Do plants like anything else? *No.* Do you think plants like morning or nighttime? *Morning.* Why? *Because they like sun.*

Mary (4): Can a seed grow anywhere? *Yes, they grow wherever they have to grow.* Can a seed grow on this piece of paper? *Yes, it just needs water.* Can the seed grow in this pot? *Yes, it will grow longer.* Why? *Because I had plants before.*

Cara (4): Do you think that this plant likes the morning or the nighttime? *The nighttime.* Why? *Because makes some sleep.* What would happen if I put this plant in the dark all the time? *It gets dead.* Does this plant need light? *Yes.* Why? *It gets bigger.* So, what does it need, light or darkness? *Light.* ... What do these plants need to grow? *Water, they need to grow.* Do they grow by themselves? *Yes.* How come? (She puts the plant into the soil.)

Season, cycle and death

They do not anticipate a significant difference in the plant during the course of a year, but most of them do recognise the winter as the period in which the plant is sleeping. The children did not correlate progress in plant growth with the seasonal cycle. Plants, for them, seem to be "always" there with the same shape and size.

Patrick (4): Where do seeds come from? *From the seeds box.* Where do you find the seeds box? *Far away.*

Shannon (4): What does the plant look like during the wintertime? *They are dying.*

Psychological, human features

The children often spoke about the plant anthropomorphically, for example as sad, happy or sore. They understand the difference between plants and humans in terms of what is missing: the plant does not have legs, so it cannot go to the bathroom; the plant does not have a mouth, so it cannot eat; the plant feels sore if it loses a leaf.

Patrick (4): Do you think this plant is alive? *No, because is not moving.* How do plants move? *They grow.* How do they grow? *They grow up.* ... Do plants feel hungry? *No.* How come? *Because they don't have a mouth.* How do they get food? *From the pot.* What is in the pot that feed them? *Nuts.* What do the nuts do. *Nuts make plants grow.* Do you see nuts on this table? *Yes* (He points to the seeds from the green bean pod.) ... Do plants breathe? *No, because they don't have a mouth.*

Sarah (5): Does a plant feel a touch? *Yes.* How come? *Because it just moved.* So if the plant moves it means that it felt that? *Yes.*

Renny (5): If I were to touch it, would the plant know? *No, because it doesn't have eyes.*

Being "alive"

We wanted to investigate the concept of being "alive", according to whether the plant possessed the following attributes: growth, reproduction, feeding, and breathing. Most of the children related the concept of "being alive" with the idea of motion (see Turkle (1984)). Therefore, a plant is not alive because it does not have legs or hands. Other children think that a plant is alive if its leaves point toward the sky and conversely, dead if the body of the plant points to the soil.

Mary (4): Do you think that this plant is alive? *Yes, because is going up.*

Time of growth

Carl (5): How long does it take the seed to grow up? *It takes 5 minutes.*

Food of the plant, metabolism

Most of the children were certain about the fact that plants drink water, but uncertain about whatever food plants may consume. Often this is identified with rocks among the soil or, sometimes, with water itself. None of the children considered soil as a source of nutrients.

Carl (5): What tells you that the plant is breathing? *It is thinking that it is hungry.* How do you know that? *When it is hungry it has to eat these things.* What. *These things in there* (the little rocks in the soil).

Rose (4): What do plants need to grow? *Plants need plant food.*

Renny (5): What do they eat? *They eat and drink water.* ... What does this plant need to grow? *Seeds.*

Number of plants and number of seeds

Mary (4): How many plants can you get with 10 seeds? *You might have one. You have to get two seeds for each plant.*

Sarah (5): How can you make another plant? *Just putting two seeds.*

Shannon (4): If I were to plant watermelon seeds, what would I get from those? *A watermelon.* How many seeds do I need to use? *All of them.* To get how many watermelons? *One.*

5.2.2 An analysis of the Biosphera interactions

In the first activity I asked children to discuss possible ways to display humidity, heat and light in a computer interface. The starting point was that these conditions are present in the environment and affect a plant's life. I wanted to see how children could envision the variables' interaction through their graphical representation. Two of the pictures we obtained are represented in figures 5-2 and 5-3. Here, the separation of the variables into three different entities without any relation is clearly marked (figure 5-2) by distinct colours and positions on the screen space. In the second example, this condition is even more evident, because the variables are represented on three different screens, each of them varying in a continuum from full presence to total absence: a gradient (figure 5-3).

During the second activity, two groups of 6 children tried to represent Light, Heat and Humidity for an alien, a person coming from an another planet. In this exercise I wanted to stimulate their representational capabilities, asking them to use uncommon metaphors to describe the enquired variables. They started by representing different situations with different sources (e.g., Heat → oven); then they tried to represent the variables with objects with which to avoid exposure to those variables (e.g., Light → sunglasses); finally they tried representation on the functional level, through the relation of the variable to animals (e.g., Heat → growth).

In the third and last activity, I asked children to perform an environmental data log on the ground floor of the MLE building looking for Light, Heat and Humidity levels. Then I asked them to represent these quantitative data on a "map". The equipment used is represented in figure 5-6.

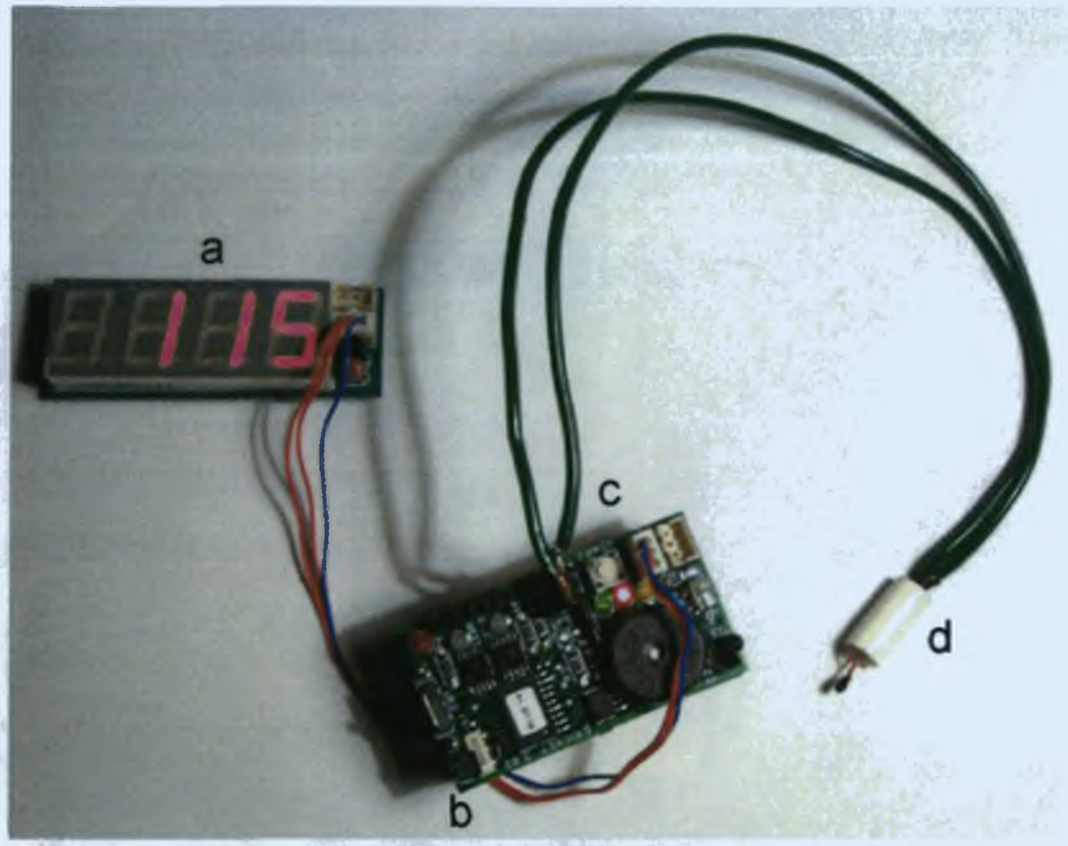

Figure 5-6: The cricket used during the third Biosphera activity: (a) 4–digit display; (b) the Cricket electronic circuit; (c) Start/Stop button; (d) a temperature sensor. The circuit board measures 3 cm by 5 cm

I found that it is extremely difficult for children to think about a single factor, because in most cases the factors are interconnected (e.g., Light and Heat are often mixed). Humidity is also a difficult concept to visualise because, in most cases, it is imperceptible to the user's domain of experience. I found them thinking about the interaction of factors, but they could not figure out what happens when you get two variables at the same time (see figure 5-4). In this particular example, the assignment was to represent on a "map" the sensor readings they were gathering around a room (see figure 5-7). They choose yellow for Light, red for Heat, and blue for Humidity. The intensity of the color was directly proportional to the sensor reading. Eventually, they took readings in the same zone of the room and the result on the map was the overlap of two colors (i.e., blue and yellow) with the emergence of a new color (i.e., green)(see figures 5-8, 5-9). They were surprised to see the green color appearing from the overlap. They could not find a meaning in the key of their map.

Figure 5-7: The map realised in the third activity (see section 5.1.2) without the interactions of variables. Children represented the factors separated with different colours

5.2.3 An interaction with the Biosphera system

The Biosphera platform has been tested with several groups of children aged between 11 and 13. As specified in the introduction to this chapter, it is not possible to provide strong arguments on the long-term impact of this technology on children's understanding of the plant biology, because an extensive study has not yet been completed. However, the observed interactions children had

Figure 5-8: The same map of figure 5-7 showing the interactions between the variables as gradients of colours overlapping a creating new colours

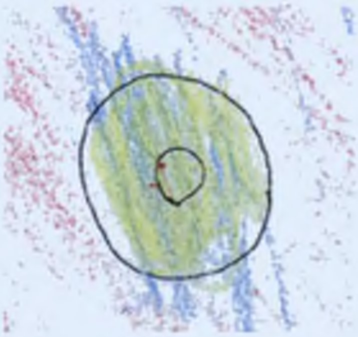

Figure 5-9: An zoom on the interaction area of figure 5-8. A green colour is resulting from the overlap of the yellow–Light and the red–Heat. The children could not find a mean for this colour.

with the object resulted in a number of interesting outcomes. I will try here to recall the context in which they originate.

In the first test I tried the system with a single user, as illustrated in figure 5-10, then I tried the system with two peers. At the beginning there was a bug in the software I was using, which caused full growth when all the icons were ON. This led to a very quick realization on the part of the children. They usually started with two or more random combinations, and then they usually tried the everything–ON combination, finally discovering the full growth of the plant. At this point they usually stopped being interested in the system, and also they could not relate the position of the changes with the timeline.

Figure 5-10: An initial interaction with the Biosphera system

In a second series of meetings, the bug was fixed. This resulted in a longer interaction with the Biosphera, and a deeper analysis of the graphic elements and the functionality of the icons. Usually they immediately discovered that the position of the changes along the timeline has a "weight" in the final outcome of the simulation, although they could not detect any relation within the variables just by looking at the interface. In fact, the variables are represented as distinct buttons. The pressure of one button is completely independent from the pressure status of other buttons. Also, the placement of the three variables in a column did not seem to affect this comprehension. They usually ended up saying that plants need: *"a little bit of everything."*

During the interaction, children found a connection between Humidity and Heat, probably because they thought that turning OFF lots of Heat buttons would also affect the impact of the Humidity on the overall growth. In fact, one of the children once said: *"if you turn off too much of water, heat is not going to be enough."*

Again in the interaction, I tired to follow the children's reasoning process to understand if they tried applying specific strategies. One of the children, for example, tried to count the number of "OFF" buttons because, he explained, *"maybe they have to be equal."* Looking at the interface, this search for the right quantity was not facilitated be the visual comparison: there was just one simulation window, and small differences in growth were difficult to appreciate.

One of the most interesting aspects of the interaction was that after a period of free trial and error, each child started to think about the plant instead of remaining concentrated on the graphic interface. The combinations offered by the tiles timeline are too much for finding the right program by chance, so, after a while, each child started to move from a reasoning on the combination to a reasoning on the plant biology. In fact, most of them tried to set up an environmental program which could respect the plant's life, giving enough water during the germination period, keeping the plant at a certain temperature, but without abusing on the conditions.

On the ergonomic level, I found that children fully understood the connections between the virtual world and the physical dome, although they could not use the dome in full for time constraints. They tried to see the effect of their program applied on the actual plant (see figure 5-11). In addition, while interacting with the virtual side, I found that the LOAD/SAVE functions were clear enough, although a direct comparison on two opposed panes would have been better.

5.3 A synthesis of the main outcomes

The evaluation presented here has partially confirmed some of the arguments raised in the thesis: (a) speeding up the biological processes of the plant results in a faster interaction which children often found more intriguing; (b) the current design of the graphical interface does net seem to support the exploration of the variable's relation, although it does seem to direct more attention to the relation of these variables with time; (c) using the virtual plant, users found themselves more comfortable in trying several environmental conditions whilst "plant keeping"; (d) the physical side of the dome has not been sufficiently tested in a full growth cycle (see table 5.2).

(a) Children experimenting with the DigitalSeed device (figure 5-13) or the Biosphera platform

Figure 5-11: A look inside the dome

Figure 5-12: Interaction with the virtual world

usually engaged in an entertaining interaction and commented positively on the experience. Specifically, children interviewed about the connections between seeds and plants seemed to modify their perception after a "real–*time*" interaction (see section 5.2.1). Speeding up the growth process helped children to map the inputs to the plant (e.g., the environmental program) with the output from the plant (e.g., the growth response).

(b) During the interaction with the Biosphera interface, I could not observe any comment or action which demonstrated a change of view on the relation between the variables arising from simply looking at the graphical elements of the interface. Instead, these changes of view have been registered, playing with the combinations of the tiles and the timelines, in the connection of the variables' influence on the growth with time.

(c) Children often engaged in "growth races", which, in most of the cases, brought them to think about the best conditions for the life of the plant. Although I could observe several different strategies in trying to reach the maximum growth, I could not systematise them in a conceptual framework because they do not seem to have common similarities.

(d) The aesthetic design of the Biosphera stimulated the children, inspiring them to execute the growth program they created on the virtual side. Unfortunately, I can not report any interesting observation on the feedback that the vision of the actual results on the physical plant could have provoked in their initial conclusions.

Table 5.2: Synthesis of the testing

ARGUMENT	DESCRIPTION	TESTING
Time lapse	The delay experienced while interacting with a plant between an action upon and a reaction from the plant itself. This delay can negatively influence the comprehension of the plant's biology and the multivariate system of the environmental factors	The usage of the DigitalSeed device proved that speeding up the process may result in a better understanding of the plant phenomena (see section 4.3.3)
Visualising the variables	The way the variables information is presented on the screen can influence the comprehension a person has about the relation between the variables	Children seem not to possess a clear idea of the relation between environmental variables (see section 5.2.2). In addition, the current design of the interface does not seem to support this comprehension (see section 5.2.3)
Variable's causality	Trying out several environmental "programs" on the plant can help the user to gain an understanding of the plant's biology and the variable's relations	Some evidence of causal reasoning has been observed in the initial interaction with the Biosphera system (see section 5.2.3)
Transparent simulation	A simulation is usually a black box. Giving the user the possibility to proof the validity of the simulation helps in understand its concepts	This feature of the system has not been tested longitudinally, so it is not possible to infer the validity of the argument (see section 5.2.3)

Figure 5-13: The interaction with the DigitalSeed device

Chapter 6
Conclusions

"... it is well to remind everyone at the onset that we are only able to get from here to there by a series of errors ..."

Buckminster Fuller, *TETRASCROLL, xxi*

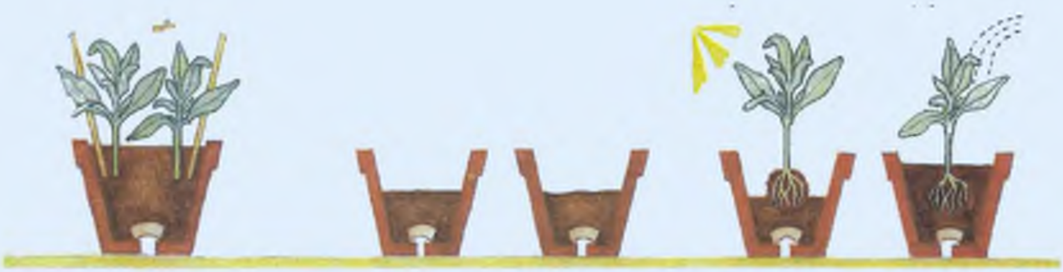

Image from Verey (1980)

Chapter 6

Conclusions

This chapter will summarise the main arguments of this work, trying to highlight how the design solutions support the arguments and how the evaluation relates to my hypotheses. It is important to state that because of the time constraints of this project and the technical problems incurred, it was not possible to complete the software interface as I designed, so a comprehensive evaluation of the Biosphera interface was not completed. For these reasons, I prefer this work to be evaluated as a design exercise rather than a complete and mature experimental work; the premises set out in this thesis may be considered a starting point for an intensive evaluation of the design solution I am proposing here, and in addition as premises for future design in this particular field.

6.1 Summary of the main arguments contained in this thesis

Table 6.1 presents the main arguments of this thesis. Three key points emerged from my study that I consider very important for developing microworlds for life science exploration: reducing the time lapse between action and reaction (a); enhancing the variable's visualisation can help in understanding the current status of the system (b); placing the variables of a multivariate system in a defined and dynamic framework can help the learner in grasping the relationship between the variables (c); giving the possibility of proofing the validity of the simulation model can help to overcome black box effect (feeling the impossibility to uncover the internal processes)(d).

(a) From the DigitalSeed workshop I realised how much the delay in a system can influence the understanding an observer has during the exploration of the same system (Gash and Cherubini, 2002). A person, a child, interacting with a plant experiences this delay all the time, and because of this different time scale s/he can make hypotheses and develop conclusions which do not conform to reality, although in most cases this interaction resolves without any interesting conclusions or considerations which is why I started to be interested in this problem.

(b) A potted plant in a bedroom is a multivariate system. Lots of variables can contribute to building a model we can use to describe what's happening to the plant. Understanding the connections among these variables is not trivial. The more complexity we add, the less understanding we achieve; the more we look for simplicity, the more complexity we discover. My personal strategy is to represent the variables in a 'synaesthetic' and multi-modal interface capable of giving the user a "feeling" for the connections. I tried to incorporate a glimpse of this idea in the circle design attempt (see section 4.7). The relation among the variables was translated into a metaphor of springs stretching between the circles. In this way the complex relations between the variables, difficult to grasp and uncommon for children, was translated into a simpler and more common object: tree interconnected circles. Moving one of the circles caused the others to move, giving a 'glimpse' of a kind of 'force/relation' between them. Unfortunately, this interface was still too complicated, with lots of visual elements that could eventually distract the user, so I moved to the tiles design, which does not present the same synaesthetic principle, but which does encourage the user to think about the variables *in time*, building the set of environmental conditions along the timeline. This may help the user in thinking more dynamically about the relations between the variables.

(c) When a scientist observes a new phenomenon, s/he tries to sketch a model that can describe it, defining a certain number of variables that can represent the main feature of this phenomenon and finally defining the relationships among the variables. For this last point, it is essential to use a very defined setting, or strategy, with which the observer can make strong conclusions about the nature of these connections. One of these strategies may consist in keeping one of the variables constant and observe the effect of this perturbation on the others. Sometimes, though, this technique cannot be applied, because it is not possible to keep a variable constant all the time, so a different framework has to be used. My argument is that it is possible, using a dynamic framework, to adapt any particular situation to the contingency of the moment, giving the user the possibility of experimenting with several strategies and making comparisons between them.

(d) SimCity and SimLife [1] are great tools for learning "rules" based scenarios. Reality can be quite different and far from simulations. My approach consists of helping the users of my microworld to critically review the results of what they have obtained in the simulation using a direct comparison with reality.

[1]Both are games by Maxis: see http://www.maxis.com .

ARGUMENT	DESCRIPTION	DESIGN SOLUTION	TESTING
Time lapse	The delay between an action to and a reaction from a plant can prevent a person from grasping the underlying causal relation in a system (section 3.3)	Using computational materials, it is possible to speed up the process without a loss in connection with reality (section 4.3)	The workshop for the DigitalSeed proved that speeding up the process of growth can have a positive effect in connecting Key ideas (section 4.3.3)
Visualising the variables	The visual representation of quantitative information can support the understanding of physical phenomena and the relations between the variables (section 3.1.1)	Several graphic solutions have been implemented to help the users during the exploration of the variables. The final prototype privileged the readability of the iconised variables in connection with the timeline (section 4-9)	Some workshops with kids helped in considering colors and colors mixing as good design elements to represent the interaction of the variables (section 5.2.2)
Variable's causality	A dynamic framework can help the user to set the variables in different situations and then compare the outcomes (section 3.2)	Running the simulation and saving the results into different "plant stories" can support such comparisons (section 4.6.5)	These features of the Biosphera have not been tested extensively, although some evidence of causal reasoning have been observed (section 5.2.3)
Transparent simulation	Understanding the model on which the simulation is based can help the user to explore the microworld (section 4.6.3)	An actual plant is kept close to the simulation for comparisons and in addition the algorithm's constituents are accessible through a "view" into the software (section 4.6.1)	These features of the Biosphera have not been tested extensively

Table 6.1: Summary of the arguments

6.2 Design synthesis

The arguments reported in the previous section refer to specific design choices in the final prototype: (a) a simulated reality can highlight and speed up the processes involving the plant; (b) merging the timeline with the variable's placement help the user to think about the variables in a dynamic way; (c) the possibility of saving the current status of the Biosphera into "story" files helps the user to compare two or more environmental settings with their relative outcomes; (d) a physical plant which grows under the same conditions as the virtual plant works as a visual comparison and proofing method of the simulation algorithm.

(a) In the final prototype of the DigitalSeed and of the Biosphera, I used a simulation in the software interface. In the Biosphera, this form of visualisation is driven by a growth algorithm, the WIMOVAC described in section 4.8.2, which describes very throughly how the plant is going to grow in a certain environmental situation. Because this representation is driven by the computer, and is free from physical constraints, it is possible to enhance the speed of the represented processes and highlight central aspects which are normally hidden and slow in reality. This is particularly useful when you want to maintain interactivity and sustain interest from the observer who is not always accustomed for calm methodical observation.

(b) From the workshops with kids described in the previous chapter, I realised that children often think about light, temperature and humidity as constant entities. It is difficult for them to conceptualise these things as variables which fluctuate across time and therefore affect the plant's growth accordingly. I argued in the third chapter that this is due to the children's tendency to think in term of centralised control of the system (Resnick, 1994). For this reason, I tried to make the connection between time and environmental conditions more evident. I designed a timeline made of "blocks" of the binary icons for the three variables (Light, Heat and Humidity, that could assume only two values: ON or OFF; see section 4.6.2). Using this timeline, the user can build the environmental program, thereby moving their attention onto defining the variables *in time*: meaning, as entities with fluctuations.

(c) One of the most important principles of the Biosphera design is to encourage and support a visual comparison between expected and current outcomes of the running experiment. This may happen entirely in the virtual side or entirely in the physical side, or between the physical and the virtual side. This ability of the system responds directly to the requirement for a dynamic framework in which the observed variables can be included, some changes operated, and the connected perturbations observed. This feature is also implemented in the "load/save" functionality of the software interface, where two environmental conditions set are saved for direct comparison (see figure 4-9).

(d) The physical side facilitates the comparison function explained at point (c). In addition, this physical part also has the mean of "debugging" the system. The Biosphera software is based on a growth algorithm, and like every model, is close to reality with a certain degree of approximation. Sometimes, the simulated reality may differ substantially from the outcome of the experiment. For this reason, the user may experience the "black box" effect, where it is impossible to understand the reasons for this difference. In this context, the physical side acts as a counter–proof system to the simulation. Every time the user want to discover the accuracy of the model, the physical side can be used (see section 2.2. In addition, a function which I have designed but not yet implemented helps the user to visualise the constituent factors of the growth algorithm (see figure 6-1). Using this pane, the user can adjust the influence of each factor contributing to the growth outcome of the simulation, and can eventually take into account the "hidden" factors not factored into the main equations (see (b) on figure 6-1).

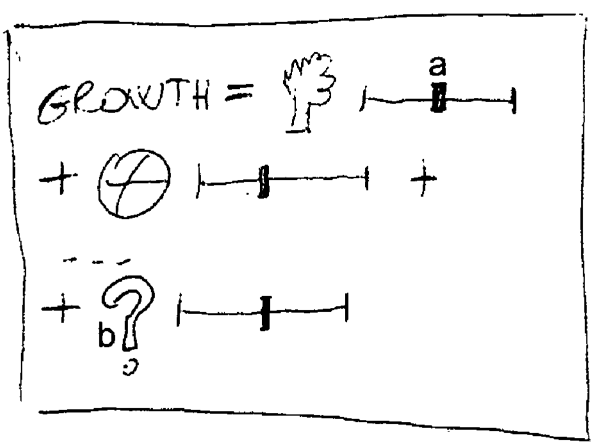

Figure 6-1: The growth pane: (a) a slidebar for "tweaking"; (b) an entry for hidden causes. Using this part of the interface, users can adjust or take into account factors affecting an observed difference between the simulated and the physical plant

6.3 Results evaluation

Points (c) and (d) of the design (section 6.2) have not been tested intensively and longitudinally. However, some workshops with kids have been carried out to assess the usability and the ergonomics of the Biosphera design, and some of the findings of the workshops analysed in Chapter 5 support the design solutions proposed in this work: (a) children using the DigitalSeed device start connecting the ideas of seed–growth–plant; (b) using the timeline of the Biosphera software interface, children start thinking about variables *in time*; (c) children using Biosphera engaged in "growth races"[2],

[2] See section 2.2.

restructuring their point of view on plant biology; (d) the dome of the Biosphera interface presented aesthetic appeal for the young users.

(a) 4 and 5 years old children used the DigitalSeed device for a certain amount of time. They were interviewed before and after the experience, and I registered a trend in their ways of talking about the connections of seeds and plants: before, they used to think about seeds as food for the plant; after, they said that plants come from inside the seeds (see chapter 5). The same concept can be applied to the Biosphera design: speeding up the process where the plant is involved can help the children to explore the connections between actions upon and reaction from the plant, and will contribute towards maintaining their interest in the topic.

(b) The design of the Biosphera timeline helped the users to concentrate on the variables in a dynamic way. In fact, because the user has to displace the variables along the timeline which was related to the simulation, they could relate every change along the timeline with a particular point in time of the life of the plant. Changing a variable in a point in the future was not the same as changing the same variable to the same extent in the past. The growth of the simulated plant was witness to this visual difference.

(c) Most of the users of the Biosphera ended up trying to grow the plant to the maximum size, and subsequently engaged in a sort of competition with their peers. In doing this, they tried to learn how to save their "plant story"[3] and how to reload it. Every time the story was reloaded, they tried to change a small amount of things along the timeline, in such a way that the changes could be "tracked" and remembered; then the changes were classified, along with the increased output they produced. The choice between bad and good changes was performed by a visual comparison, using a trial–and–error technique.

(d) Some of the children coming out of the Biosphera experience wanted to keep feeding the plant, asking for a commercial version of the dome. The aesthetic design of the dome is, in fact, suitable for a room environment, as a small terrarium.

6.4 Future work

Although Biosphera seems to be the natural evolution of the DigitalSeed design, I envision a separate development and future for each of them. Particularly, I do not consider the DS experience concluded. A good deal more has to be done to proof the impact of this technology in the long term. Lots of features and interactivity can be added to the same design, to enrich the interactivity and the functionality of these two designed microworlds as described below.

[3]See section 4.5.

6.4.1 Biosphera

This thesis presented a prototype learning environment for exploring the underlying concepts associated with botanic growth and dynamic, multivariate systems such as natural ecologies. Biosphera supports learning through an exploratory, comparative framework. The working prototype I present here promotes personally meaningful knowledge creation. A key aspect of the design is the use of physical and virtual avenues of discovery. In this way, the learner is free to interact with the system, following non–linear paths of interaction, and testing multiple possible futures in their "plant story".

In terms of future work, much has to be done on the development of the virtual world. As I specified in the evaluation section (6.3), a proper extensive study has not yet been carried out. Consequently, it is important to evaluate if the user is going to change his/her way to interact with plants in the longer term. Again, it was not possible to appreciate any evidence of multivariate understanding in this study, because of time constraints. Finally, it is important to take into account the users' ideas and opinions in order to build upon my initial designs. I hope that this will lead to new designs that are useful, attuned to and supportive of children's learning needs.

An interesting aspect which can be developed further is the "Time based visualisations". This is a way to present information in a time–dependent manner. For example, in figure 6-2, I am describing the status of the plant with a single numerical factor called: "factor K", plotted in the figure named above, against time. The scale of this horizontal axis can be adjusted for different purposes. For example, if nothing happens for a certain amount of time, the scale can be adjusted to display on screen only important events, turning this visualisation system into a diachronic table. This way of representing the information can be very powerful and informative. Another example is represented in figure 6-3, where the current status of the plant is visually compared with its past (a kind of "history") and with its future, predicted using the growth algorithm.

6.4.2 DigitalSeed

I regard childrens ideas not as being systematised in stages, but as differing and changing over time and culture. I am not looking for a general model of learning in this domain, but I am trying to build an environment in which children can experiment with their ideas, an environment in which it would be possible to perform operations among many states and particular objects. This interplay is informed and inspired by love for a specific idea or domain; for example, the concept of life-cycle in the DigitalSeed study. I think of knowledge as experience, and experiencing as defining ones own boundaries and curriculum (see (Peacock, 2000)).

The work reported here only begins to suggest the richness of interactivity that I am striving for. The next developments should support an indefinite number of computational states, perhaps using a simulation paradigm, and should display carefully coordinated representations in the interface,

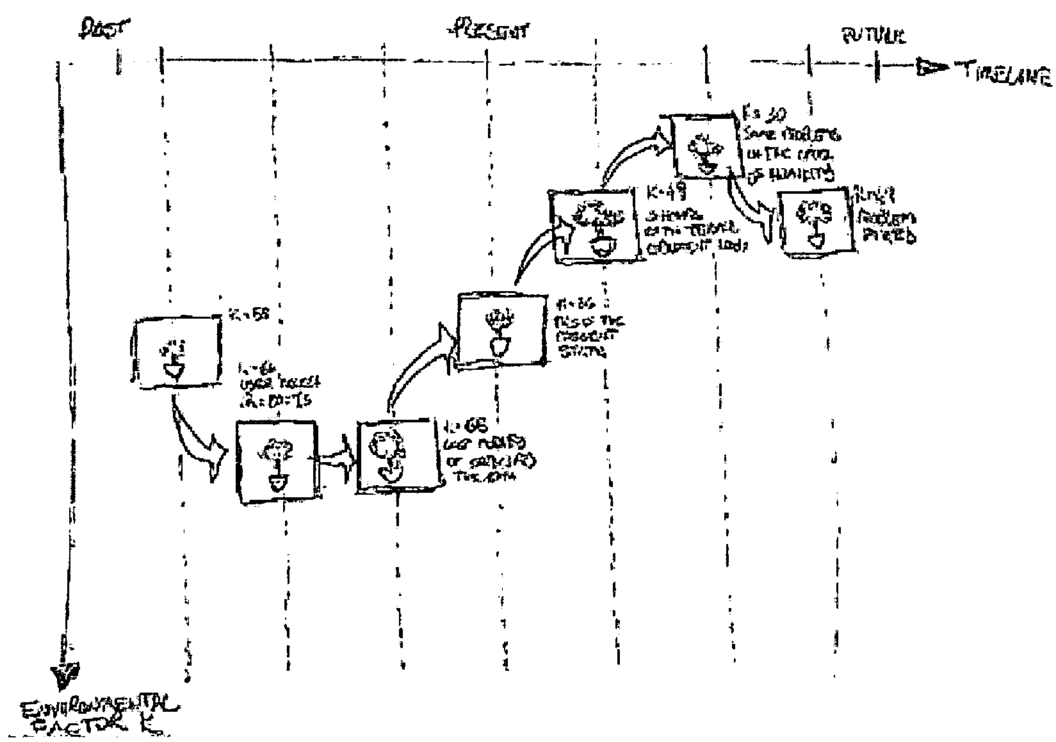

Figure 6-2: A preparatory sketch for a diachronic visualisation pane (not implemented in the final software)

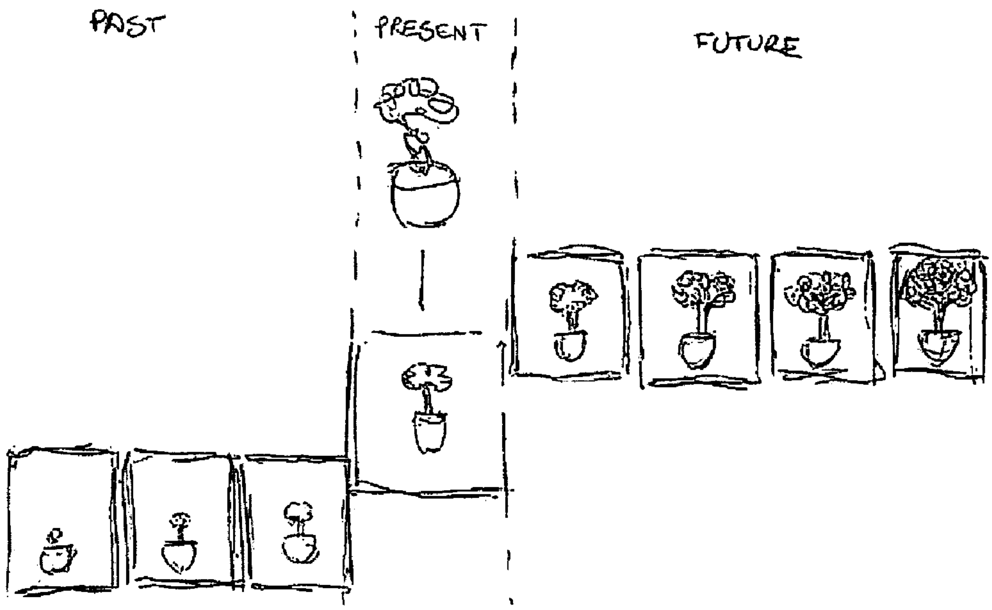

Figure 6-3: A preparatory sketch for a time–based visualisation (not implemented in the final software)

including images, sounds and tangible input devices.

In addition, lots of features can be implemented on the same design, so as to enrich its functionality and interactivity. For example, figure 6-4 shows a possible wireless interaction between two DS boxes. A flying bee can take pollen from one box, and pollinate a different box enabling the users to play with the idea of pollination. Also, using the accelerometer inside the box we can measure the "stress applied on the virtual plant", moving the plant out of the soil for more intensive abuses. As a final example, adding a gyro sensor to the design, we can detect the inclination of the pot to the plant, rendering a growth towards the sun which is not "perpendicular" to the ground, leading towards an idea of light–tropism.

6.5 Closing note: supporting the shift

In the premises of this research I referred to the work by Seymour Papert and Carol Strohecker that drove the development of the ideas contained in this thesis. Therefore, I want to wrap up referring again back to these key ideas: a) there is a shift of control in the way people learn (Strohecker), and b) people construct their learning through playful experimentations (Papert).

a) In this work I tried to demonstrate how we can change attitudes towards the way we teach and the way we expect people to learn. A change in the way we design learning systems is not

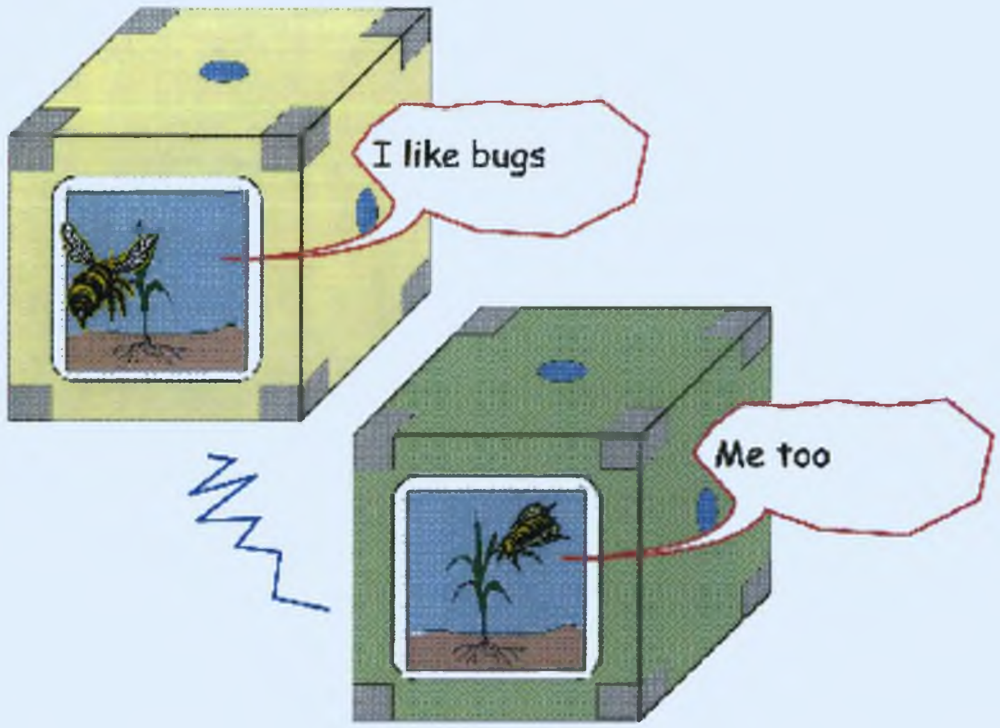

Figure 6-4: An example of a possible wireless interaction between different DigitalSeed devices. An insect takes pollen from the box on the left and pollenate the flower in the box on the right. The two boxes have to be at a certain distance to enable this operation

only possible but is desirable to match with the possibilities the society has to access information. The whole point of this work was to give an example of a possible learning system, a microworld, were free explorations where sustained and encouraged by the design. In such systems, no guidance is necessary, no teacher has to address the right concepts, but the understanding of powerful ideas is experienced spontaneously by the user, who alters the environmental patterns, observes how the changes influence the plant and reflects upon this experience. The learner is in control.

b) The learner is the actor in his/her learning process. The microworld in which the children is engaged is conceived to enable multiple points of exploration so to support different learning styles, attitudes, and/or abilities. Into the microworld, in our case: "plantland", the common language is the plant biology, like in England the common language is English by default. There is no language difficulty, no extra effort to change the mindset. Everybody can speak it, everybody can make it. Again, this particular design engages with people influencing their curiosity. Learners should be attracted by these systems because they offer them a playful environment, where no pain is required to achieve the goals and where they can constructively engage with their peers. The last consideration is that these environments support the discovery of the principles through an experimental framework. Children using such systems are in the position of experimenters: they start with some ideas, they set conditions, they observe the outcomes, they reflect on their ideas, and they start over.

As a final consideration I tried to follow aesthetic criteria while designing the systems here described. Again I believe that the way these learning systems are designed is already a criterion to engage interest and curiosity which drives learning.

There is a special beauty in plants concerning the simplicity and complexity of life in our world. I hope that this work will stimulate further research to the attention we must have in understanding, protecting and teaching the magic of our life.

Appendix A
Questions used during the DigitalSeed workshop

"Any two sides of the triangle constitute a pair of levers fulcrumed together at one end like a pair of scissors. The third side of the triangle is a rigid push-pull strut taking hold of the two adjacent lever arms.. thereby stabilizing the angle opposite with minimum effort."

Buckminster Fuller, *TETRASCROLL, 20*

Image from Wikes (1997)

Appendix A

Guidelines questions used during the DigitalSeed workshop

1. Do you think this plant [HAVE A PICTURE / OR A REAL PLANT] is alive? ... [IF YES:] how do you know? / Is it? How?
2. If I move the plant, does the plant know if I have, does the plant know it?
3. Can it move itself? How?
4. When I'm thirsty, how do I know? Do plants feel thirsty? How?
5. What happens if plants don't get enough water?
6. Does it like light? Why? Does it like more the morning or the evening?
7. Do plants feel hungry? Why? How?
8. What happens if plants don't get enough food?
9. What do plants eat?
10. Do plants go to the toilet? Why?
11. Do plants breathe? What do they breathe?
12. Do plants feel pain? If I pick a leaf, does it hurt the plant?
13. Can this plant grow? What's that like? What will happen?
14. What makes a plant happy? When is a plant happy? Sad?
15. How do plants know when to grow? How?

16. Did it grow because it wanted to?

17. Do plants need people to help them grow? [IF YES - what about trees and grass and wild flowers - do they need people?]

18. Do you grow?

19. Do you have a dog, a cat? [IF NO SKIP TO NEXT QUESTION] Does it grow? Is it different from when a plant grows?

20. What is a seed?

21. Here's some seeds [SHOW CHILD SOME SEED - ANY KIND]- how do you get them to grow?

22. Can a seed grow anywhere?

23. Tell me the story of a plant from when it begins as a seed. [ALSO CAN MAKE A DRAWING]

24. Do plants have mammies and daddies?

25. Where do seeds come from? Where do you think I found these seeds? [SAY "I FOUND THEM IN MY GARDEN IN AUTUMN"]

26. This seed came from that plant [SHOW PICTURE OF ONE KIND OF PLANT]. What will the plant from this seed look like? [SHOW TWO MORE PICTURES OF DIFFERENT PLANTS WITH THE ONE ABOVE]

27. How did they get there [in my garden]? Why were they there in Autumn?

28. What would happen if I hadn't found them?/ if they stayed in my garden? Die or grow? [SAY "LET'S IMAGINE THEY'D GROW"]

29. What happens then, once they've started to grow?

30. What does the plant look like in Spring? [DOES THE CHILD SUGGEST SOMETHING LIKE GERMINATION?]

31. What does the plant look like in Summer? [DOES THE CHILD SUGGEST THE PRESENCE OF FLOWERS AT THIS POINT?]

32. What does the plant look like in Autumn? [DOES THE CHILD SUGGEST SEED PRODUCED AT THIS POINT?]

33. What does the plant look like in Winter? [DOES THE CHILD SUGGEST SOMETHING LIKE HIBERNATION IN ANIMALS?]

34. If I got seeds out of an apple [CUT APPLE IN HALF AND TAKE OUT PIPS] - and I planted/sowed them, what would happen? Would I get an apple tree?

35. If I got seed out of a tomato [CUT TOMATO IN HALF AND TAKE OUT SEEDS] - and I planted/sowed them, what would happen? Would I get a Apple tree? Cabbage? Orange tree? Carrot? Lemon tree? Tomato plant?
36. Is there a way to get an apple tree from a tomato seed?
37. Where can I find some seeds? Where do you find them?
38. What makes the seeds?
39. Why do plants sit in the ground? Do they go into the ground?
40. What happens if plants are pulled up out of the ground? [WHY DO YOU THINK THIS IS SO?]

Bibliography

"Any two sides of the triangle constitute a pair of levers fulcrumed together at one end like a pair of scissors. The third side of the triangle is a rigid push-pull strut taking hold of the two adjacent lever arms.. thereby stabilizing the angle opposite with minimum effort."

Buckminster Fuller, *TETRASCROLL, 20*

Image from Wikes (1997)

Bibliography

L. Aberg-Bengtsson and T. Ottosson. Primary school children understanding of bar charts and line graphs: A preliminary analysis. In *6th EARLI Conference*, pages 1–20, Nijmegen, The Netherlands, August 26-31 1995.

E. Ackermann and C. Strohecker. Build, launch, reconvene: Sketches for constructive–dialogic play kits. Paper TR99–30, MERL – Mitsubishi Electric Research Laboratory, Cambridge, MA, USA, 1999.

E. Ackermann and C. Strohecker. Patternmagix construction kit software. In *CHI (Design Expo)*, 2000. Extended Abstracts.

E. Ackermann, C. Strohecker, and A. Agarwala. The magix series of playful learning environments. Paper TR97–24, MERL – Mitsubishi Electric Research Laboratory, 1997.

M. Ananny and C. Strohecker. Situated citizen photojournalism and a look at dilemmatic thinking. In *Proceedings of the Association for the Adcvancement of Computing in Education's E-Learn Conference*, 2002.

V. Bar and A. S. Travis. Children's view concerning phase changes. *Journal of Research in Science Teaching*, 28(4):363–82, 1991.

M. Barker and M. Carr. Teaching and learning about photosyntesis. part 1: An assessment in terms of students' prior knowledge. *International Journal of Science Education*, 11(1):49–56, 1989.

G. Bekey, S. Gentner, R. Morris, C. Sutter, J. Wiegley, and E. Berger. The telegarden, http://www.usc.edu/dept/garden/, (October, 2003) 1996.

B. Bell. Students' ideas about plant nutrition: what are they? *Journal of Biological Education*, 3 (19):213–218, 1985.

R. Berman. Preschool knowledge of language: What five-year olds know about language structure and language use. *Writing development: An interdisciplinary view*, pages 61–76, 1977.

M. Bers and J. Cassell. Children as designers of interactive storytellers: "let me tell you a story about myself". *Human Cognition and Social Agent Technology*, pages 61–83, 2000.

S. Carey. *Conceptual Change in Childhood.* the MIT Press series in learning, development, and conceptual change. A Bradford book, Cambridge, Massachussetts, 1985.

Z. Chen and D. Klahr. All other things being equal: Acquisition and transfer of the control of variables strategy. *Child Development*, 70(5):1098–1120, 1999.

CLIS. Children's learning in science- clis in the classroom: approaches to teaching energy, particulate theory of matter, plant nutrition. A pack of teaching materials with teacher's guide, Center for Studies in Science and Mathematics Education, University of Leeds 1987.

E. E. Clough and R. Driver. Secondary students' conceptions of the conduction of heat: bringing together scientific and personal views. *Physics Education*, (20):176–82, 1985.

V. Colella, R. Borovoy, and M. Resnick. Participatory simulations: Using computational objects to learn about dynamic systems. In *Extended Abstracts of Human Factors in Computing Systems: CHI 98*, pages 9–10, 1998.

B. Damer, K. Marcelo, and F. Revi. Nerve garden: a public terrarium in cyberspace, http://www.biota.org/papers/ngalife.htm, (September, 2003) 1997.

A. DiSessa. *Designing interaction: Psychology at the human-computer interface*, chapter J. M. Carroll (ed.) Local Science: Viewing the design of human-computer systems as cognitive science, pages 162–202. Cambridge University Press, New York, 1991.

A. DiSessa and B. L. Sherin. What changes in conceptual change? *International Journal of Science Education*, 10(20):1155–1191, December 1998.

R. Driver. *The pupil as a scientist?* Milton Keynes, Open University Press, 1983.

R. Driver, H. Asoko, J. Leach, E. Mortimer, and P. Scott. Constructing scientific knowledge in the classroom. *Educational Researcher*, 23(7):5–12, 1994a.

R. Driver, E. Guesne, and A. Tiberghien. *Children's Ideas in Science.* Open University Press, Bristol, USA, 1985.

R. Driver and V. Oldham. A contructivist approach to curriculum development in science. *Studies in Science Education*, 13:105–122, 1986.

R. Driver, A. Squires, P. Rushworth, and V. Wood-Robinson. *Making sense of secondary science: Research into children's ideas.* Routledge, London, 1994b.

A. Druin. Cooperative inquiry: Developing new technologies for children with children. In A. Press, editor, *Proceedings of CHI'99*, 1999.

A. Druin, J. Stewart, D. Proft, B. Bederson, and J. Hollan. Kidpad: A design collaboration between children, technologists, and educators. In A. Press, editor, *Proceedings of CHIí97*, Atlanta, GA, 1997.

D. M. Eagleman and A. O. Holcombe. Causality and the perception of time. *TRENDS in Cognitive Sciences*, 6(8):323–325, 2002.

L. Edwards. Embodiments of mathematics and science: Microworlds as representations. *Journal of Mathematical Behavior*, 17(1):53–78, 1998.

G. Erickson. Children's conceptions of heat and temperature phenomena. In *Symposium on 'Patterns of students beliefs - implications for science teachings'*. CCSE convention, June 1977. Fredericton.

L. S. Eyster and J. S. Tashiro. Using manipulatives to teach quantitative concepts in ecology: A hands-on method for detecting & correcting misconceptions about limiting factors in eutrophication and vegetarianism. *The American Biology Teacher*, 59(6):360–364, 1997.

P. D. Fernhout and C. F. Kurtz. Garden with insight, simulation software, http://www.gardenwithinsight.com/, 1999.

W. Friedman. *About time: Inventing the fourth dimension.* MIT Press, Cambridge, MA, 1990a.

W. Friedman. *About time: Inventing the fourth dimension*, chapter 6, The Child's Discovery of Time, pages 85–102. MIT Press, Cambridge, MA, 1990b.

W. J. Friedman. Arrows of time in early childhood. *Child Development*, 74(1):155–167, 2003.

R. B. Fuller. *Education Automation: Freeing the scholar to return to his studies.* Southern Illinois University Press, London, 1962.

H. Gash and M. Cherubini. A digital seed: designing a toy plant to facilitate cognitive growth. *The Irish Psychologist*, 29(4):49, November 2002.

T. Gorton, C.Lyon, B. Silverman, and B. Mikhak. The tower modular development system for designing and prototyping computational devices http://gig.media.mit.edu/projects/tower/, (March 2003) 2002.

T. A. Grotzer and B. B. Basca. Helping students to grasp the underlying casual structures when learning about ecosystems: How does it impact understanding? In *Proceedings of National Association for Research in Science Teaching Annual Conference*, New Orleans, April 28-30 2000.

E. Guesne. Light. In R. Driver, E. Guesne, and A. Tiberghien, editors, *Children's Ideas in Science*. Open University Press, Milton Keynes, 1985.

J. Hanan. Virtual plants–integrating architectural and physiological models. *Environmental Modelling & Software*, 12(1):35–42, 1997.

L. Hanna, K. Risden, and K. Alexander. Guidelines for usability testing with children. *Interactions*, 5(4):9–14, 1997.

A. K. Hickling and S. A. Gelman. How does your garden grow? early conceptualization of seeds and their place in the plant growth cycle. *Child Development*, (66):856–876, 1995.

K. Inagaki and G. Hantano. Young children's spontaneous personification as analogy. *Child Development*, 58:1013–1020, 1987.

N. Jewell. Examining children's models of seed. *Journal of Biological Education*, 36(3):116–122, 2002.

Y. Kafai and M. Resnick, editors. *Constructionism in Practice: Designing, Thinking, and Learning in a Digital World.* Lawrence Erlbaum Associates, NJ, 1996.

A. Keselman and D. Kuhn. Facilitating self-directed experimentation in the computer environment, November 2002.

D. Kuhn and E. Phelps. *Advances in child development and behavior*, volume 17, chapter H. Reese (ed.) The development of Problem–Solving Strategies, pages 1–44. Academic, New York, 1982.

S. Kuhn. Learning from the architecture studio: Implications for project-based pedagogy. *International Journal of Engineering Education*, 17(4 and 5), 2001. http://www.ijee.dit.ie/latestissues/Vol17-4and5/Ijee1214.pdf.

K. V. Laerhoven. Augmenting the ipaq with sensor boards via the serial port, April, 11 2001.

M. Laycock. *Bucky for Beginners: Synergetic Geometry.* Activity Resources Company, Inc., Hayward, CA, USA, 1984.

A. P. Lightman. Magic on the mind. physicists' use of metaphor. *American Scholar*, pages 97–101, Winter 1989.

MAXIS. Simlife, simulation software, http://www.maxis.com/, 1992.

A. Michotte. *The Perception of Causality.* Methuen's Manuals of Modern Psychology. Hazell Watson and Winey Ltd, London, 1963.

J. Montangero. *Understanding Changes in Time.* Taylor & Francis Ltd., London, 1996.

J. E. Opfer and S. A. Gelman. Children's and adult's models for predicting teleological action: The development of a biology-based model. *Child Development*, 72(5):1367–1381, 2001.

J. Osborne, P. Wadsworth, and P. Black. Processes of life. Technical report, Primary SPACE Project Research Report, University of Liverpool, 1992.

J. A. Palmer. From santa claus to sustainability: emergent understanding of concepts and issues in environmental science. *International Journal of Science Education*, 15(5):487–495, 1993.

S. Papert. A learning environment for children. *Computers and communication: Implications for education*, pages 271–278, 1977.

S. Papert. *Mindstorms: Children, computers and powerful ideas.* Basic Books, 1980.

S. Papert. Tomorrow's classrooms? *Times Educational Supplement*, pages 31–32, 41, March 5 1982.

S. Papert. A critique of technocentrism in thinking about the school of the future. Technical report, M.I.T. Media Lab Epistemology and Learning Memo No. 2, 1990.

S. Papert and I. Harel. *Constructionism*, chapter Situating Constructionism. Ablex Publishing Corporation, 1991.

A. Peacock. What education do you miss by going to school? children's 'coming-to-knowing' about science and their environment. *Interchange*, 31(2 & 3):197–210, 2000.

M. Peat and A. Fernandez. The role of information technology in biology education: an australian perspective. *Journal of Biological Education*, 34(2):69–73, 2000.

J. Piaget. *The Child's Conception of the World.* Routledge & Kegan Paul, London, 1929.

J. Piaget. *The child's conception of time.* Basic Books, New York, 1970.

P. Prusinkiewicz, M. Hammel, R. Mech, and J. Hanan. The artificial life of plants. In *Artificial life for graphics, animation, and virtual reality. Course notes*, volume 7, pages 1–1–1–38. ACM Press, 1995.

P. Prusinkiewicz and A. Lindermayer. *The Algorithmic Beauty of Plants.* Springer–Verlag, New York, USA, 1990.

M. Resnick. *Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Micorworlds.* MIT Press, 1994.

M. Resnick. Thinking like a tree (and other forms of ecological thinking). *International Journal of Computers for Mathematical Learning*, 8(1):43–62, 2003.

M. Resnick. The pie network http://llk.media.mit.edu/projects/pie/, (April 2003) 2001.

M. Resnick, R. Berg, and M. Eisenberg. Beyond black boxes: Bringing transparency and asthetics back to scientific investigation. *Journal of the Learning Sciences*, 9(1):7–30, 2000.

M. Resnick, F. Martin, R. Berg, R. Borovoy, V. Colella, K. Kramer, and B. Silverman. Digital manipulatives: new toys to think with. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 281–287. ACM Press/Addison-Wesley Publishing Co., 1998.

M. Resnick and U. Wilensky. Diving into complexity: Developing probabilistic decentralized thinking through role-playing activities. *The Journal of The Learning Sciences*, 7(2):153–172, 1998.

D. D. Richards and R. S. Siegler. The effects of task requirements on children's life judgements. *Child Development*, (55):1687–1696, 1984.

K. J. Roth, E. L. Smith, and C. W. Anderson. Students' conceptions of photosynthesis and food for plants. Technical report, Institute for Research on Teaching, Michigan State University, East Lansing, Michigan, 1983.

T. Russell and D. Watt. *Growth*. Primary SPACE Project Research Report. Liverpool University Press, Liverpool, January 1990.

K. Schmucker. A taxonomy of simulation software. Technical report, Apple Computer Inc., 2000. http://www.apple.com/education/LTReview/spring99/simulation/.

K. Schmucker. The "world of science" contest. http://www.apple.com/education/LTReview/spring98/contest.html, September 2002.

J. Smith, A. DiSessa, and J. Roschelle. Misconception reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences*, 3(2):115–163, 1993.

E. Soloway, W. Grant, R. Thinker, J. Roschelle, M. Mills, M. Resnick, R. berg, and M. Eisemberg. Science in the palms of their hands. *Communications of the ACM*, 42(8):21–26, August 1999.

E. Sowell. Effects of manipulative materials in mathematics instruction. *Journal for Research in Mathematics Education*, 20(5):498–505, 1989.

K. Springer and F. C. Keil. On the development of biological specific beliefs: The case of inheritance. *Child Development*, (60):637–648, 1989.

K. Springer and F. C. Keil. Early differentiation of causal mechanisms appropriate to biological and nonbiological kinds. *Child Development*, (62):767–781, 1991.

P. Starr. Seductions of sim, policy as a simulation game. *The American Prospect*, 5(17), March 21 1994. http://www.prospect.org/print-friendly/print/V5/17/starr-p.html.

R. Stavy and W. Naomi. Children's conceptions of plants as living things. *Human Development*, (32):88–94, 1989.

C. Strohecker. Whole world in their hands. *The Learning Citizen*, (6):6–8, July-September 2003.

C. Strohecker and A. H. Slaughter. Kits for learning and a kit for kitmaking. In A. Press, editor, *CHI2000 Extended Abstracts*, April 2000.

D. W. Sunal and C. S. Sunal. Young children learn to restructure personal ideas about growth in trees. *School Science and Mathematics*, 91(7):314–317, 1991.

K. S. Taber. Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education*, 22(4):399–417, 2000.

P. Tamir. Some issues related to the use of justifications to multiple choices answers. *Journal of Biological Education*, 4(23):285–92, 1989.

S. Tarsley. *The potted plant book.* Walker Books, London, 1980.

C. Tsai and C. Huang. Development of cognitive structures and information processing strategies of elementary school students learning about biological reproduction. *Journal of Biological Education*, 36(1):21–26, 2001.

E. R. Tufte. *Envisioning Information.* Graphic Press, Cheshire, CT, USA, 1990.

E. R. Tufte. *Visual Explanations: Images and Quantities, Evidence and Narrative.* Graphic Press, Cheshire, CT, USA, 1997.

E. R. Tufte. *The Visual Display of Quantitative Information.* Graphic Press, Cheshire, CT, USA, 2001.

S. D. Tunnicliffe. Talking about plants - comments af primary school groups looking at plant exhibits in a botanical garden. *Journal of Biological Education*, 36(1):27–34, 2002.

S. D. Tunnicliffe and M. J. Reiss. Building a model of the environment: how do children see animals? *Journal of Biological Education*, 33(3):142–148, 1999a.

S. D. Tunnicliffe and M. J. Reiss. Conceptual development. *Journal of Biological Education*, 34(1): 13–16, 1999b.

S. D. Tunnicliffe and M. J. Reiss. Talking about brine shrimps: three ways of analysing pupil conversations. *Research in Science & Technological Education*, 17(2):203–217, 1999c.

S. D. Tunnicliffe and M. J. Reiss. Building a model of the environment: how do children see plants? *Journal of Biological Education*, 34(4):172–177, 2000.

S. Turkle. *The Second Self: Computers and the Human Spirit.* Simon and Schuster, New York, 1984.

S. Turkle and S. Papert. Epistemological pluralism and the revaluation of the concrete. *Journal of Mathematical Behavior*, 11(1):3–33, 1992.

W. J. University and NASA. Bioblast, web simulation software, http://www.cotf.edu/bioblast/project.htm, (February, 2003) 2000.

R. Verey. *The herb growing book.* Methuen, London, 1980.

J. H. Wandersee. 'students' misconceptions about photosynthesis: a cross-age study. In H. Helm and J. D. Novak, editors, *International Seminar: Misconceptions in Science and Mathematics.* Cornell University, Ithaca, N. Y., 20-22 June 1983. 441-6.

P. A. White. Naive ecology: Causal judgments about a simple ecosystem. *British Journal of Psychology*, 88:219–233, 1997.

A. Wikes. *Lets grow a garden.* Dorling Kindersley, London, 1997.

U. Wilensky. Netlogo http://ccl.northwestern.edu/netlogo, (March 2003) 1999.

N. Winters, M. Cherubini, and C. Strohecker. Biosphera: A prototype design for learning about multivariate systems. In A. for Computing Machinery, editor, *CHI2003 Learning Workshop proccedings*, Fort Lauredale, Florida, USA, 6 and 7 April 2003.

M. Wiser and S. Carey. *Mental Models*, chapter 12, Dedre Gentner and Albert L. Stevens (eds.) When Heat and Temperature Were One, pages 267–297. Cognitive Science. Lawrence Erlbaum Associates, London, 1983.

C. Wood-Robinson. Young people's ideas about plants. *Studies in Science Education*, 19:119–35, 1991.

B. Zubrowski. Integrating science into design technology projects: Using a standard model in the design process. *Journal of Technology Education*, 13(2):19, 2002.

O. Zuckerman and M. Resnick. A physical interface for system dynamics simulation. In ACM, editor, *CHI2003 Proceedings*, Ft. Lauredale, Florida, USA, April 5-10 2003.