C.N.R.-I.T.D. LEGO A/S C.R.E. H.L.K.

Construction kits made of Atoms and Bits

research findings & perspectives

an esprit i^3-Experimental School Environments project

Construction kits made of Atoms and Bits

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Introduction

This document has been produced for the conclusion of the CAB project. For this reason, its principal aims are the following:

- to summarise that which has taken place during the thirty months of work
- to focus on the outcomes of the research.

Given these aims, the discussion will be developed by all four partners of the CAB research consortium (ITD, LEGO, CRE, HLK) and, consequently, the following points will be examined:

- the hardware and software developments
- the pedagogical and educational aspects of the research.

Though the CAB project has reached its temporal conclusion, the indications that have emerged from the research will remain alive as both guidelines for technological development (hardware and software), as well as possibilities to enrich the educational environments and experiences (in Italy and in Sweden).

We feel that this is an extremely positive outcome of the project, as it offers to those who have been directly involved, as well as to the wider public, important meanings and opportunities for continuing to carry out research on the relationship between technology and education.

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1.1. Introduction

> "*Animated toys occupy a special place in children's lives. They are intriguing because they do things. Sometimes they even seem to have a mind of their own, and many are responsive to a child's solicitations. In all cases, objects that behave are treated differently from inert toys.*
>
> *Obviously, toys need not be animated to behave in our imagination. In their pretence play, children endow things with life all the time, blurring the boundaries between animate and inanimate. … .*
>
> *Yet toys that actually behave elicit novel ways of exploring relational issues, like agency and identity. They engage our minds because of their ambiguous nature (between animate and inanimate). They intrigue us because of their relative autonomy (responsive but with a "mind" of their own), and because of their singular form of intelligence (a "mind" that can surprise us). Their hybrid nature makes it possible to play out the fine line between objectifying minds and animating things, and come to grips with the hardships that identity formation involves. … .*
>
> *People's ability to treat fictional characters as if they were real and to personify things is important because its puts empathy and creative imagination at the service of intelligence.*"
>
> (Edith Ackermann, 2000)

In the CAB project we have investigated the use of cybernetic construction kits by young children. Using a cybernetic construction kit, children can observe the behaviour of one or more robots interacting among themselves and with the environment, they can influence their behaviours, and modify them by reprogramming and reconfiguring their buildings blocks. The key assumption is that children learn by doing and that the available tools influence what it is possible to learn. Hence a cybernetic construction kit should enrich children's learning process.

Since we assume a relationship exists between what one can learn and the available materials, the properties of a construction kit are crucial for the possibilities of enhancing children's learning experience and creativity. Building with a cybernetic construction kit entails mastering simultaneously a variety of skills: mechanical assembly of pieces, wiring of components, and programming the final behaviour. The age of the chosen target audience makes all this a challenging endeavour. Our approach has been to explore the possible design solution by starting with an existing kit designed for an older age group and using an adult tutor as a mediator to elicit from judicious field testing the essential properties of a kit for young children.

In the two years of this project we have faced many problems with this approach. One of the key problems is that a construction kit must be a coherent system, and providing incremental changes in some of its components makes life more difficult during field testing. A strong indicator of this problem was the reliance on more stable versions of the kit, i.e. one that provides assembly, programming and instructions that fit together.

Only at the end of the project was a kit for young children taking shape. This prevents us from testing the basic assumptions, especially in the area of children's creativity and learning experience.

One important property of a construction kit with an ongoing play and learning value is that is should be easy enough for four-year-old children to use and yet still be challenging for eight-year-olds, i.e. construction kits that children can grow with: to put it another way, a construction kit with "low threshold" and "high ceiling." The field testing has helped us exemplify what this means for young children. Examples of low threshold are simple reactive constructions like the vehicle built by a seven-year-old girl at Landsjöskolan school which follows sound or the elements of the "living" tree project devised by a group of five-year-old children at the Villetta Infant School. An example of high ceiling is the "monsters" and "city defenders" project at the Neruda Infant School, involving several mobiles robots that exhibit goal-oriented behaviour coupled with randomness.

Reflecting on early work on cybernetic construction kits at MIT, Ackermann (2000) states that: *"It would not occur to many children to take apart a creature to see what is inside. Instead, they take their creature as is and explore its ways of evolving in its surrounds. Optimising their 'dance' with the creature allows children to learn about its ways of being and relating to the child's solicitations. The children's purpose, in other words, is to converse rather than construct, to mutually attune rather than break down, to empathise rather than analyse. Relating to artificial creatures as if they were partners enables people to explore the dynamic of exchanges, the patterns of give and take and the degrees of mutual influence so characteristic of human transactions*". One important result of the CAB project has been that of enabling children, under controlled circumstances, to construct cybernetic creatures. Lately one group of five-year-old children using a prototype CAB programming environment at Villetta Infant School defined themselves as robot programmers after managing to build and program simple reactive creatures. Both side of the coin, exploring and constructing, are important and need more field testing with children.

1.2. The CAB kit

Our cybernetic construction kit entails four basic components:

- sensing the environment;
- acting upon it;
- constructing a skeleton that enables sensing and acting to become part of an autonomous "creature";
- controlling the relationship between sensing and acting.

So, the construction kit is characterised by a mechanical assembly system, a set of sensor and actuators, a central control unit (the programmable brick), and a programming environment. In the following we will briefly describe each component and use sample projects, coming from the field testing, to illustrate its actual use by young children.

1.2.1. The structure of the kit

The programmable brick (see Figure 1) is the most noticeable component of the kit: it provides both control and power supply to all constructions. The programmable brick can control up to three sensors and three actuators, and can communicate with other bricks by exchanging messages. Moreover, these bricks can be programmed to specify a construction behaviour. Sensors enable a cybernetic construction to interact with the environment. The available sensors (light, temperature, sound, touch, etc.) implicitly determine the range of explorations, types of construction and programming strategies one might develop. Finally, actuators allow a construction to move, grasp, talk, light up…

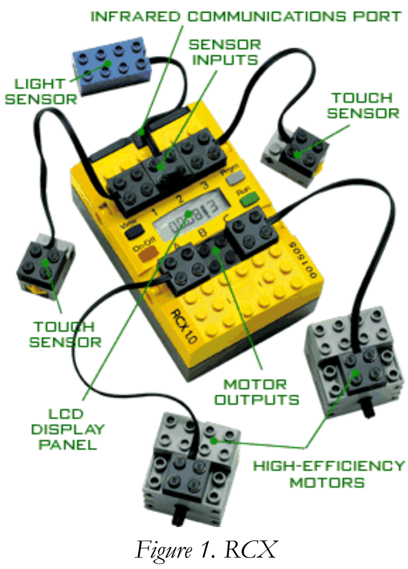

Figure 1. RCX

To assemble the sensors, actuators and programmable brick for a meaningful purpose, one needs to build at least a solid skeleton and provide the means for distributing and transforming the available mechanical energy. LEGO has developed a range of mechanical construction systems that one can use. The most powerful of these systems is LEGO Technic, which we adopted to obtain maximum flexibility. To make the system accessible we developed task specific sub-assemblies.

Although this structural characterisation of the kit might seem obvious to the developers, it proved hard for the teachers and very difficult for children. The field testers reported that: "***the structural complexity of the material seemed to be difficult for the children to manage****: also when they tried to construct objects or vehicles that could function autonomously, in the end their products were extremely rough and primitive, certainly far removed from these children's actual construction skills and abilities with regard to the complexity of the mechanical system*" (CRE, 1999).

As for the kit's sensors and programmable bricks, the field testers observed that: "*During the moments of exploration of the material or playing with the cybernetic objects constructed by the adults, almost all the children noted the particularity of the* ***physical form of the sensors****, formulating intelligent and creative hypotheses which were only in part relevant or pertinent to their* ***functions****. The children carried out extensive explorations with interest and attention, intuiting in various ways the* ***connection between the sensors and the behaviours of the various objects****, even though the* ***possibility of autonomously and creatively managing the reaction of the sensors by means of programming seemed quite beyond their imagination***" (CRE, 1999).

The challenge to make the construction kit not simpler but readable by children still holds true. We are trying to tackle this problem by an extensive redesign of the kit components, aimed at making the underlying structure emerge through a consistent use of "transparency" in the redesign of the kit. In particular, active kit components (sensors and actuators) should reveal their inner functioning.

1.2.2. Programming environment

To let young children deal with the "programming" of their constructions we have designed and prototyped a visual programming environment based on "behaviours", "conditions" and "actions".

Children should be able to program a construction incrementally by adding or removing a behaviour. Inside a "behaviour" there are two types of primitive constituents: "actions" and "conditions". Actions are commands to the brick, e.g. turn right, while conditions are tests that are either true or false (e.g. is the light sensor seeing darkness?).

Conditions and actions are combined into rules of the type: if "condition", then do "actions".

Children can define action rules by manipulating jigsaw-like tiles in a visual programming environment. To build a rule, children arrange condition and action tiles in a line, placing one condition on the left followed by one or more actions. This spatial ordering reflects the way sentences are built in languages where one writes and reads from left to right. A list of action rules constitutes a behaviour, each of which is executed as a separate parallel process.

The issue of granularity is relevant from the software component perspective. Here we have to strike a balance between ease of use and simplicity on the one hand, and flexibility and generality on the other. Furthermore, software components are potentially much more configurable and adaptable than hardware ones, thus they add a whole dimension to the design space: children can easily play with example programs, explore their structure and components, modify their appearance and refine their behaviour; the collaborative approach to these activities calls for an accurate definition of the structure and services offered by the software development environment.

The most general and all-encompassing entity we deal with is the *project*, a collaborative effort undertaken by children and adults aimed at developing a scenario where one or more constructions exhibit meaningful behaviour. Structurally, a project consists of a set of one or more individual p-brick constructions. Although a simple project might consist of just one construction, in general a project can include many constructions, which can belong to different microworlds and whose behaviour might vary considerably. In general, a project describes a society of programmable agents interacting with one another and with the environment.

Consider, for instance, the cybernetic adventures project described in Section 1.3 Sample Projects: it contains two distinct construction types, the *monster* and the *defender*.

A *microworld* is a partially specified construction type that defines a set of persistent software components pertaining to a particular area of application and capturing its peculiarities in order to provide users with already developed, easily reusable half-fabricates. Within a microworld certain assumptions may hold true, e.g. in the *Vehicles* microworld one can assume the presence of two motors and a chassis. A microworld can also pose constraints on the sub-set of the available hardware components that are allowed in building a construction, and on its default initial configuration. Once you have declared that your construction is an instance of, say, the *Vehicle* microworld, you automatically have access to a set of predefined behaviours, conditions and actions; if, for instance, your physical layout includes two light sensors, then you can seamlessly install behaviours such as "follow the line" or "follow the light."

A *construction* is an instance of a specific microworld. The construction inherits from the microworld all its features and extends them by the definition of new features or by re-definition of the inherited ones. All the assumptions valid for the microworld are also valid in the construction that instances it. A construction includes both hardware and software aspects: it provides a program definition and a physical layout. For instance, a *monster* agent is a *vehicle*, and as such it inherits from the *Vehicle* microworld some relevant traits: two motors, the ability to follow a line using light sensors, etc. Providing these built-in features smoothens the learning curve and reduces the cognitive gap entailed in designing specific behaviour, such as looking for enemies, getting to the city centre, etc.

A *program* is a set of co-operating behaviour components. It controls the construction's reactivity towards the environment by co-ordinating the behaviour components. During the normal execution of a program, its behaviours are executed concurrently. In its simplest form, a program consists in a single behaviour. For instance, the "follow the sound" vehicle described in Section 1.3 Sample Projects relies on a single behaviour component, which implements a simple reactive pattern: if the microphone senses some predefined noise level, turn on the motors for a while. More complex patterns can emerge from the composite interaction of distinct behaviour components: in the "follow the line" model two behaviour components control respectively the left and right motor-light sensor pairs . Each component states "turn on the motor when the light sensor *reads* a bright colour, turn it off when the reading is dark"; the fact that the construction can *steer* and follow a black line on the ground is not immediately predictable by examining the single component in isolation, it just emerges from the *combination* of two cooperating components.

A *software component* is either a behaviour, an action or a condition: we have used this term to collectively indicate all the reusable entities that children can import from other projects, like modify, rename etc. A software component may be either transient or persistent across sessions; it is endowed with a name and an icon that represents it in the user interface; name and icon can easily be changed to meet localisation needs and to accommodate the representations that children themselves invent for the story they are building.

A *behaviour* is a self-consistent software component (i.e., one you can test in isolation) that identifies a cause-effect relationship between some inputs and some outputs of the program. The relationship is expressed as one or more rules involving input control in the form of a condition, and output control in the form of some actions. During the normal execution of a behaviour, its rules are checked (and possibly fired) sequentially. As a special case, a behaviour can contain no conditions: this represents an unconditioned behaviour, consisting only in a sequence of actions.

A good example of behaviour, one worth examining in some detail, is named "avoid obstacles". This behaviour obviously requires a vehicle, plus two touch sensors. The implicit assumption is that the construction implements a proper touch sub-assembly, such as the one described in Figure 2. Here the default motion is linear: when no obstacles are present the touch sensors are released, and both motors have to run at the same speed and in the same direction. If the vehicle bumps into some obstacle, the touch sensor on the side involved is switched on, then the vehicle has to back up for a while, turn to the side opposite the obstacle, and restart linear motion.

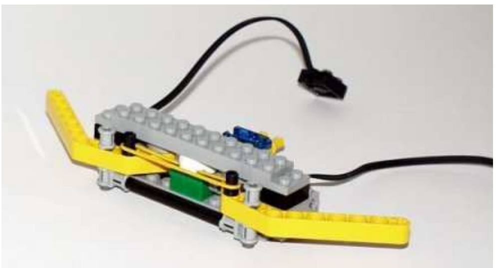

Figure 2. The touch-sensor sub-assembly

Figure 3 shows the user interface of the behaviour editor in the definition of *avoid obstacles*: it hosts two rules, one for the left touch sensor, and the other for the right one[1].

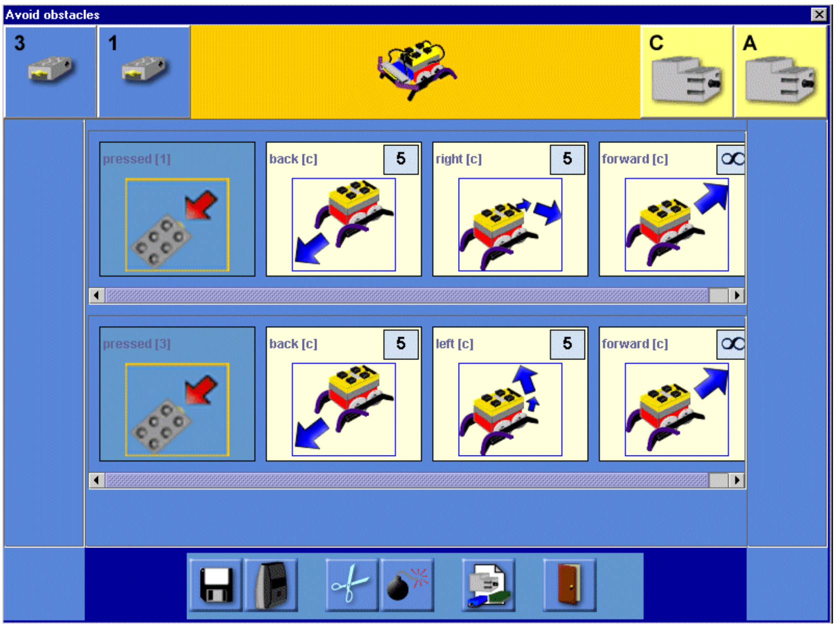

Figure 3. The "avoid obstacle" behaviour

A *rule* links one condition to a sequence of actions. A condition represents some constraint on the input, and when it holds true the sequence of actions is executed. In the special case of an unconditioned behaviour (i.e., a behaviour that does not depend on inputs), its "rules" collapse into a list of sequentially executed actions.

A *condition* is an abstraction of the reading of an input value. A condition can only assume two states: true or false, depending on the value read by the RCX from one of the attached input devices. Two examples of condition are represented in Figure 3: here touch sensors are involved, and the behaviour editor lets the user include in the rules conditions of the kind "sensor is pressed" and "sensor is released". Other sensor types require the condition to encapsulate a threshold, such as "light sensor has read a bright light".

In some cases the input value does not come from a sensor that returns some physical measure, but from a virtual device that notifies the program of some event: a message received from another construction, a time-out elapsing, a variable value that has exceeded some limit. In all these cases the abstraction offered

[1] This behaviour actually co-operates with a "move" behaviour and takes control (and priority) over the latter whenever an obstacle is in the way.

by the condition model protects the user from the specific implementation issues and offers a uniform interface for the creation of rules and behaviours.

An *action* is an abstraction of a command imposed on the RCX or on an actuator connected to it. Actions can be simple or composite. A simple action is represented atomically in the Construction Kit: its internal structure can be neither defined nor explored through the user interface. Simple actions are usually built-in. Conversely, a composite action is a collection of simple actions built by the final user using an ad hoc editor of the CKPE. The component simple actions are usually executed in sequence, with the exception of the random action, a special case where only one component is selectively executed, on the basis of a random choice. Figure 3 again shows a variety of actions, all related to motors. An important aspect to note is that actions can be parametric: users can specify a numeric value that represents some parameter controlling action execution. For instance, the "go back/forward" and "turn left/right" actions require the specification of duration: in these cases the numeric parameter represents the duration of the action. It is also possible to specify an indefinite duration ("forever") or a run-time random value. The action abstraction also encapsulates virtual output devices, i.e. devices that do not correspond to any physical actuator but represent some RCX internal feature: sending messages, playing sounds and melodies, setting timers and variables, starting and stopping behaviours, etc.

To support an operational understanding of the kit parts, the software allows the children to inspect the functioning of individual components. For example, they can understand how a light sensor works by exploring how it reacts to the environment. Built-in conditions for the light sensor provide three possible readings: dark, normal light and bright. Children can use these conditions to construct a simple behaviour that associates different sounds to each light condition. Once this behaviour is downloaded into the programmable brick, the children can move around in the environment and explore the light sensor's response.

The inspect mode for motors provides a number of movement primitives for immediate testing. The children might execute each individually, combine one or more and repeat them.

For example, one might select a combination of forward and right movements to be executed randomly; the vehicle will then perform a random walk. The children can store this combination as a user-defined primitive called "random walk" to be used later on.

1.3. Sample projects

Here we use children's projects to illustrate the construction kit in actual use and thus provide a tour of the kit's possibilities. Even though the programming environment prototype has only recently been introduced to children, and has been used only for the "Giving other life" project, we will use it to illustrate all the following examples.

1.3.1. A cybernetic pet

At the i3 conference in Jonköping the CAB project hosted a hands-on lab with children from the local field-testing schools. A girl from Landsjöskolan school built a vehicle that moves forward when it "hears" a sound. The vehicle's behaviour is a very simple reaction to stimulus; if the sound sensor detects a loud noise then the vehicle moves forward. This simple follow-sound vehicle enabled its author to give an impressive performance, playing with a new kind of pet that would move to the rhythm of clapping hands or stamping feet.

1.3.2. "Giving other life"

This is a project originated in the 1999/2000 school year at the Villetta Infant School: "from a group of five and six-year-old children who wished to help a large branch that had broken off from a tree following a heavy snowfall. The children were well aware that they could create 'another kind of life' for the plant, which had been sheltered in the school foyer. The children positioned the digital tools and materials in relation with the sensors and actuators they thought were best suited to allow the different subjects to communicate, and with other languages and materials (paper, wire, clay, structures built with recycled materials, etc.) that are a common feature of school life. The children's narration was the bond that held together the different levels at which the research was being conducted, constructing meanings, even provisional ones, and identifying new questions to be investigated" (CRE, 2000).

This year another group of five- and six-year-old children is extending the project by adding a dialogue between a bird on the tree and its robot friend. It's wintertime and food supplies are scarce. The bird asks for the help of a robot baker-boy that will bring crumbs to the tree. Once there, the robot will notify its friend, who will come down with the help of a bird elevator.

This project encompasses three constructions: a vehicle on the floor and two animated ones on the tree. The children solved a number of problems like programming the vehicle to carry the food and go to the tree and establishing how many robot steps are needed to move one tile on the floor, thus enabling conversion of a distance measured in tiles into a numeric parameter for the vehicle forward primitive.

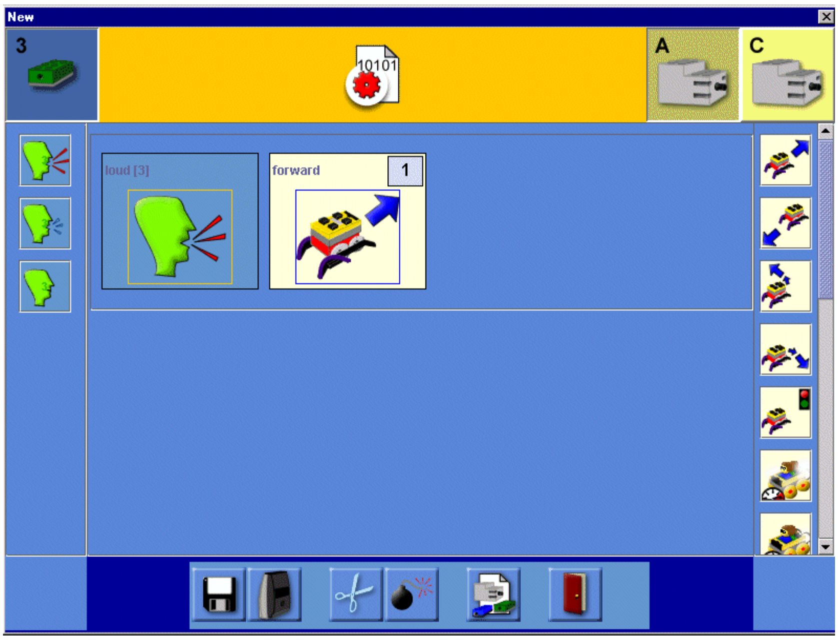

Figure 4. The robot reacts to noise

To solve the communication problem between the bird and the robot, different approaches were investigated. Initially, the children thought of recording and playing back the voices of the bird and the robot and using a sound sensor to detect the dialog (Figure 4). Since the microphone reacts to any noise, this first solution was prone to errors; once the robot was tried out in the actual noisy place where the tree is located, the bird's voice was not the only sound that triggered the robot's response. Inspecting the programming environment, the children identified a solution based on the message communication features of the RCX and kept the recorded messages as audio feedback. In this way the bird could call the robot by touching a sensor (Figure 5). The robot now reacts to a message sent by the bird through the infrared device; Figure 6 shows how the children modified the robot behaviour from reacting to sound to reacting to a message. The third construction, the elevator, is in charge of responding to the robot once the food is present. The mechanical assembly of the elevator proved too difficult for the children, thus requiring adult assistance. This is the first project where children used an early version of our programming environment and were able to program their construction.

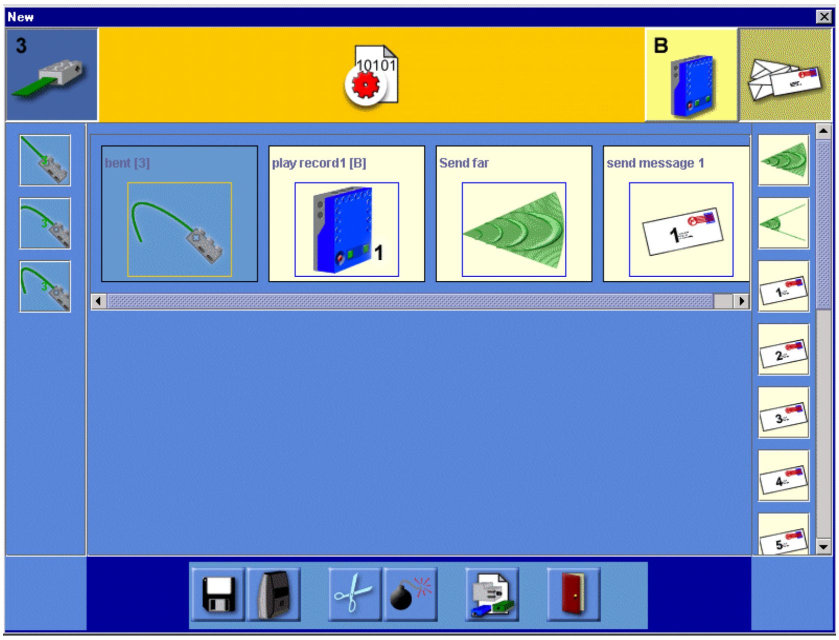

Figure 5. The bird calls the robot

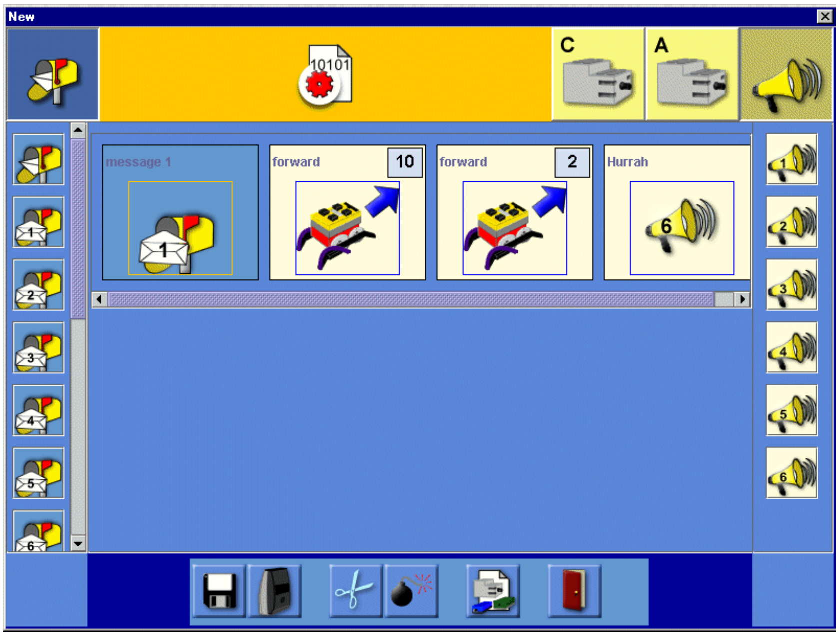

Figure 6. The robot reacts to a message

1.3.3. "Cybernetic adventures"

Over a number of years one class of children had been showing considerable interest in monsters; this provided the opportunity to work around the idea of constructing a scenario where the different identities of the single cybernetic subjects and the characteristics of the context would allow the creation of a 'possible life'. This life would develop and evolve according to the frequency and quality of relations between the 'actors' (monsters or defenders of the city).

This project comprises four vehicles: two monsters and two city defenders. The monsters attack the city and win if one is able to enter it. The monsters lose if they fall into one of the traps built by the city people. Outside of the city, the defenders can detect an approaching monster since monsters carry a flashlight. The defenders look for light and try to push the monsters away from the city gate.

This project involves several mobile robots that exhibit a goal-oriented behaviour coupled with randomness.

The goal of the monsters is to enter the town, that of the defenders is to locate the monsters. The monsters can locate the gate by following a trail that points to it, the defenders look for light. The children arranged the trail and the initial position of monsters and defenders in such a way that the outcome of the battle wasn't predictable. The evolution of each game was dependent on the randomness arising from robots clashing or bumping into obstacles placed on the battle field. Both monsters and defenders were equipped with touch sensors and an "avoid obstacle" behaviour to enable the game to proceed while maintaining a certain degree of randomness.

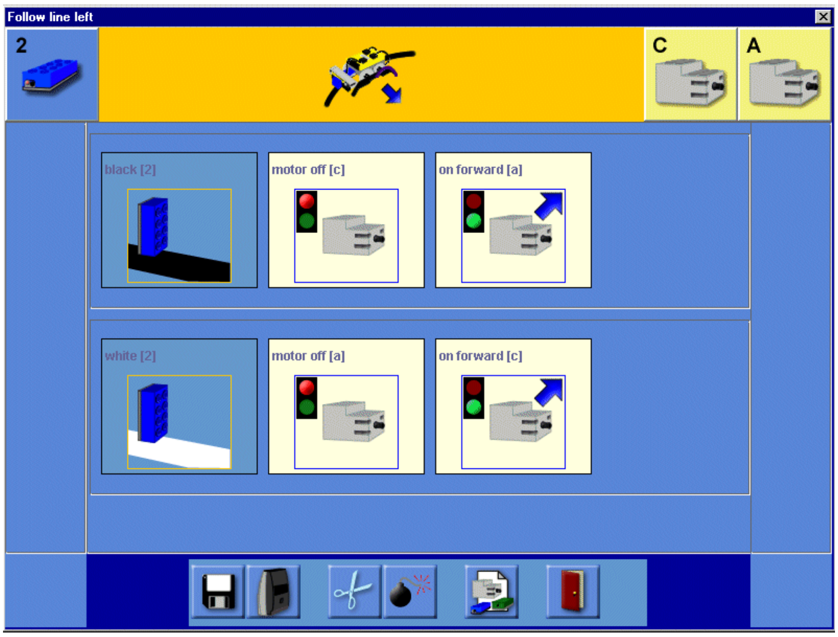

Figure 7. "Follow the line" behaviour

This project proved a challenge for both children and adults, as it required the development of non-trivial behaviours like the one described in the following. To follow a trail, i.e. segments, one needs to modify the "follow the line" (Figure 7) behaviour to make sure that at the end of the trail the vehicle continues moving in the current direction while still being able to follow the next piece of the trail when it comes across another one. The standard "follow the line" algorithm we provide oscillates across the track edge. The oscillation has a characteristic frequency: by monitoring how much time is spent in turning left or right, one can determine if the vehicle has lost the track because it has reached the end of the segment.

By adding a behaviour that monitors the time spent in the transition between dark and light, as detected by a light sensor, the "follow the line" behaviour is controlled by the "follow the segment" behaviour (Figure 8). In our programming environment we can control behaviour execution via the "start" and "stop" commands. A timer is reset whenever the light sensor detects either the white or the black colour; if a timeout occurs, this means that the sensor has "lost" the track, i.e. it no longer oscillates across the black/white edge. This event is captured by the third rule, which states: *if a timeout occurs, stop the "follow the segment" behaviour and revert to linear exploratory movement.* Note that in the action sequence of this rule we first have to start another behaviour (number 3 in figure) and then stop the "follow the line" (number 1) and the timeout monitor (number 2, the current active behaviour), otherwise the start command will never be executed.

To complete our job we need to modify the "move forward" behaviour to make the robot search for a dark spot. Initially the robot activates the "move and look for trail" behaviour; when it succeeds, the construction switches to the "follow the segment" behaviour, and then reverts to the previous one once the trail is lost.

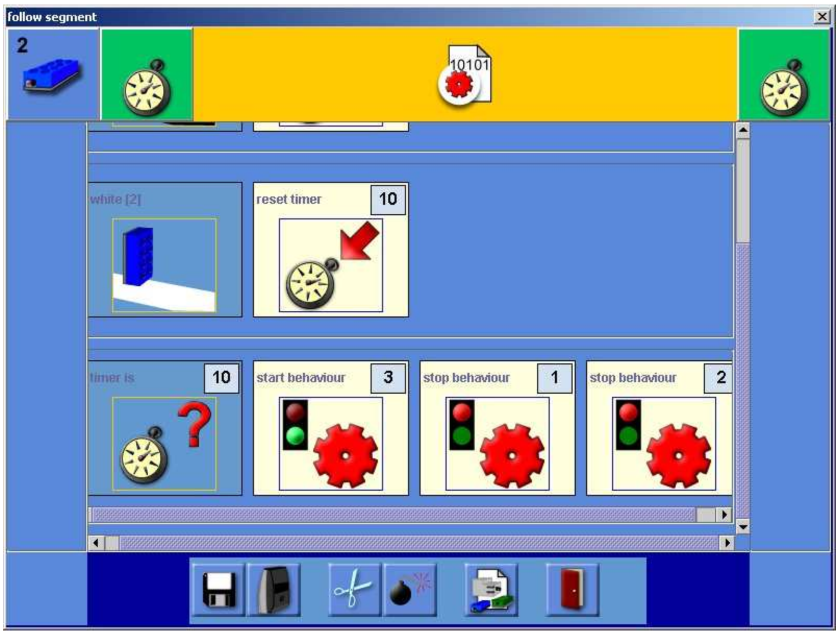

Figure 8. "Follow the segment" behaviour

As this project shows, the Construction Kit can deal with problems whose complexity probably exceeds the children's capabilities of planning and identifying the details of the required behaviours. However, in the actual project the children were able to discuss and propose creative approaches, dealing with the behaviour as a whole. In our programming environment one can mix existing behaviours, but the problem of synchronizing concurrent behaviours remains: this can be addressed either via the explicit control of the robot state (start/stop command), as in the previous example, or via a priority mechanism (Martin, 2001). Both these approaches require further experimentation with children and detailed analysis of their theories of control before being incorporated at the children's interface level.

1.4. Different styles of comprehension

Building and programming small robots might be feasible for eight-year-old children, but does the construction kit idea work with four-year-olds? Clearly, four-year-olds were not expected to perform at the same level as older children. Generally, so-called *intelligent toys* provide young children with responsive devices they can interact with. The responsiveness of these devices is completely pre-defined by adult toy designers; what's more, children are not supposed to take them apart and modify their respective behaviour. These intelligent toys reinforce the current tendency towards "opaque design": most video games are very rich in their range of interaction, but opaque in terms of their inner working.

Providing children with working examples of devices is an obvious strategy. However, a construction kit ought to allow them to take apart and modify any construction. The level of complexity will depend on age, know-how and support from more experienced builders. Edith Ackermann (1991) describes children interacting with functioning cybernetics artefacts as "playing the psychologist" and children building and programming as "playing the engineer". Regardless of the role to be played, the first goal that needs to be achieved is facilitating comprehension. Comprehension of the construction kit and its elements is a prerequisite to meaningful creation or modification. The child must be able to foresee possible actions and operations with the construction kit.

The epistemologists Papert and Turkle investigated the processes of comprehension and problem solving approaches and found no uniform methodology. With the term *Epistemological Pluralism* they described two dimensions in problem solving and construction strategies: planning and tinkering (Turkle and Papert, 1991).

The idea of "many methods to comprehend" can be found rephrased in terms of educational practice in the philosophical considerations underlying the Reggio Emilia pre-school system and are referred to as the "hundred languages" that children use to express themselves and explore their world (Edwards et al., 1998).

In the following, the different styles of comprehension are briefly outlined with respect to the CAB construction kit design. Then, CAB measures and strategies are described that support different learning styles and different ways of exploring existing constructions. Underlying all of these design modifications and extensions is the objective of improving the subjective sense of control that the children attain in working with the CAB construction kit; this helps comprehension and thereby establishes a sense of understanding the system.

1.4.1. The Planning Style

In the "comprehension through planning" style, the curious mind tries to map out an area completely and systematically. Every detail is taken in and all aspects at the same level of detail are, a priori, equal. The key to success in terms of comprehension is to understand the whole by first understanding all the parts. The knowledge is thorough but not economical, and therefore the more complex the system is.

The Planning Style is already well supported by traditional construction materials. Here, a complete map of any construction is always available since it is either provided in the building instructions or internalised during the building process where it is formed by active design. Children can start "from scratch" and create their own constructions according to a plan in their mind.

On the other hand, the CAB programming environment can be understood and used by those that can comprehend it in all its levels. Level by level, increasingly complex programs can be put together, from project to construction to behaviour. Starting with simple behaviour users can gradually add complexity in much the same way as their physical constructions gradually become more complex – step by step.

1.4.2. The Tinkering Style

In the "comprehension through tinkering" style the curious subject is content to explore the "immediate neighbourhood" and speculate about what lies beyond, then maybe sets off in the most promising or most interesting direction. The area is never mapped. Rather, it is internalised and remembered by landmarks. Landmarks are chosen according to the criteria that are personally and subjectively most relevant. The key to success in terms of comprehension is making sense of the landmarks and dynamically building a coherent system connecting them. The knowledge is most detailed in those areas that have been the most relevant in the past.

The exploration starts with an existing complex system. If this system is a construction's behaviour then tinkering might start with the addition, modification or removal of parts of the behaviour, observation of the change in overall behaviour, reversal of the steps if necessary or otherwise manipulation of some more.

In the case of the existing programming environment, support for tinkering may imply that behaviour construction is starting from an existing default behaviour that is gradually manipulated, re-manipulated and re-formed. For instance, as soon as children connect two motors to the programmable brick, the default behaviour could be "go straight for a while"; adding a knob, the children might control how long "a while" should be. The existing programming environment does already implement such functionality at the level of behaviours.

Alternatively, support for tinkering could also mean that a more complex internal state is introduced to the RCX. This would mean that even with no explicit behaviour defined by the child, the construction would already expose a degree of autonomy. Using the programming interface, the child could then influence these internal states, i.e. emotions, to find out more about the hidden tacit laws that govern the behaviour of the construction.

While the open-ended nature of a construction kit means that the freedom to construct anything from scratch must remain intact, it could be helpful to offer reference points, i.e. example constructions, for those children that prefer tinkering to planning. In any case, is it the firm belief of the CAB developers that supporting many different styles of comprehension is a crucial step towards a truly open-ended and widely accessible construction kit – for atoms and bits.

1.5. Improving sense of control

This chapter describes several ways to improve the subjective sense of control that young children have when interacting with the construction kit and, thereby, ways to make the material more age-appropriate.

In his work on optimal experience, Csikszentmihalyi (1990) provides guiding principles on how to avoid frustration on the one hand and boredom on the other. He stresses that one must make sure that expectations and challenges match skills. The sense of control is one of the main ingredients of such optimal experience, as only through personal assessment can a task be perceived as "within one's reach".

Behaviour construction will be perceived as "fun" when the CAB tools allow the child to respond to any given design challenge, whether internally or externally motivated. Any problem will be perceived as interesting as long as the means to respond to the challenge and solve the problem are transparent.

For the design of a powerful and usable construction kit it is important to make clear which tools are available and what can be done with them. The more a child feels in control of the construction kit the better he or she will be able to utilise it and the more enjoyment will be gained from the construction activity.

Issues central to the achievement of improved controllability and usability are described in the following. Many of these issues have emerged in discussions with the teachers during and after the field tests.

1.5.1. Component granularity

As we have seen earlier, there are many ways to approach an unknown object, many ways to explore it, investigate it, many ways to comprehend its qualities and properties. Some may try to understand what exactly is happening by decomposition into smaller parts, understanding the small parts and then making sense of the whole. Others may playfully explore the external parameters of an object, thereby trying to discover regularities and making sense of the laws that govern the behaviour of the object. Many may try a combination of the two.

Regardless of how an object is approached, in the world of construction kits all objects are composed of a number of smaller objects - smaller components.

A typical behaving and moving object, i.e. one made of Lego bricks, contains some parts that are essential for its stability, some that provide extra abilities and some that are pure decoration meant to give the construction a certain character.

The usefulness and especially the usability of any construction set very much depend on these basic components. Usefulness can be defined as all the things a tool might potentially be used for. Usability, on the other hand, can be defined as the degree to which a tool can be utilised with regards to its full potential. The usability of a construction kit depends on a number of aspects: What functionalities are provided by its components?; How well can these functionalities be communicated?; How can the components be used together so that a combination of simple functionality lets us create completely new, maybe more complex functionality?

The question of the proper granularity of components is posed as how much functionality should be encapsulated in the single components that make up the construction kit. This question is relevant both in terms of hardware (play material) components (i.e. sub-assemblies) and in terms of software (programming) components (i.e. actions, conditions, rules). Looking at the CAB materials, granularity affects actuators just as much as sensors. It pervades every design aspect of the construction kit, regardless of whether they are made of atoms or bits.

One example may serve to illustrate both aspects, virtual and physical: the flower.

In order to build a flower with petals that open and close, one could start construction using single Lego Technic elements (see Figure 9). The mechanical complexity would be quite high as all petals should open and close in a synchronised way. The synchronisation mechanism would need to be connected to a motor that would drive the opening/closing motion. The connection between the motor and the petal mechanism may require a set of gears to gain enough torque to move the petals and some gears to direct the rotation coming from the motor to the petal mechanism.

If one looked at the finished flower now it would be obvious that the construction could be decomposed into functional parts: a motor cradle, a power transmission and direction module, a petal mechanism module and decorative elements that give the flower its identity. Decomposing the construction into sub-assemblies would allow reuse of these basic mechanical modules in other contexts.

One could also look at the flower and deem the whole endeavour too hard for the age group and provide a finished pre-fabricated flower with all necessary mechanisms encased.

In any of the three cases, the chosen granularity would have a strong influence on the child's construction activity (in the last case one could argue that a construction activity was no longer in place) and on the requirements concerning the child's ability.

Figure 9. A flower made of Lego Technic elements

Just as there would be implications for the play material, there would also be implications for the usability of the software. In order to program the flower to open its petals one could have a command available to "turn the motor on for 3 seconds" (Figure 10). On the other hand, one could have a more specific command to "open the petals" (Figure 11) for the pre-fabricated flower.

In this example it can be seen that the usability is directly related to the degree of specificity – more specific means more usable. At the same time, it can be seen that the usability comes at the expense of open-endedness and evocativeness. The more the pieces suggest "flower!" the unlikelier it is that a child will build something different.

From a CAB standpoint, it seems that a modular approach integrating different levels of granularity is the most promising compromise.

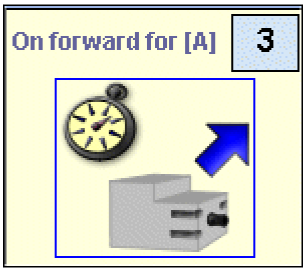

Figure 10. The "motor on forward" command

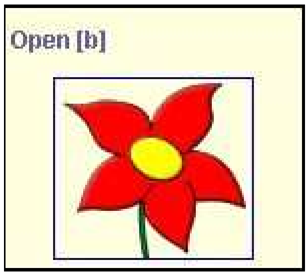

Figure 11. The "open flower" (petals) command

It can be concluded that granularity determines to a large extent how much sense of control is given to the child. As mentioned earlier, unless the cooperation of single components as well as their respective functionality are communicated in a transparent and thus understandable manner, the construction kit will not be able to support children's creativity in the way the CAB project has set out to do.

1.5.2. Enriched Acting

A cybernetic construction should be able to react actively with the environment in a variety of ways. Motors are a natural solution not only for building vehicles but also for animating constructions.

The world of gears and wheels that Papert described in Mindstorms (Papert, 1980) is not the only one we might address: sound output, both recorded and synthesised, can turn the pre-set interaction with voice-endowed dolls from passive fruition into active construction. Playing with light patterns (Resnick et al., 1998) as components of a cybernetic construction, or building musical instruments based on inexpensive MIDI chips, might open up interesting new perspectives for children's interaction with construction kits (Askildsen et al., 1999).

The construction of a behaving object requires a reasonable combination of functional components, a stable skeleton and decorative additions. To provide the best possible set of basic components in a construction kit a balance needs to be achieved in the component granularity that provides a maximum freedom in what can be constructed and at the same time a minimum intrinsic complexity in building and combining. It is the trade-off between specific/powerful and generic/open-ended components.

The benchmark material that the CAB project investigated and that was based on the LEGO Robotics Invention System (RIS) was heavily biased towards the generic.

For reasons of age-appropriateness, a compromise was sought between the powerful LEGO Technic building system (see Figure 12) and a more specific architecture (see Figure 13) that is more limiting and restricted yet much easier to comprehend and construct with. In discussions following the various field tests it was stated that the benchmark system in itself was not appropriate. Most objects had to be designed and constructed by the teachers, thereby deflating the personal meaningfulness of the constructions. For future developments, it was therefore stated, the building would have to be simplified without giving up too much open-endedness. The trade-off poses the biggest dilemma in the evolution of the play material. In a perfect world, flexible granularity would allow quick building of the construction's skeleton, which would hold all the functional components together that contributed to the behaviour qualities. In the beginning, the children would be able to build and experiment quickly and roughly – almost like an outline of a drawing. Later on in the process, they would be able to refine and define in more detail their designs, filling the gaps with the characteristics of their very own creations/constructions.

In order to make their constructions capable of expressing their intentions and reactions, the children need modules that can provide more than one mode of expression, i.e. motion, melodies, sounds and light patterns.

Going beyond the "world of gears and wheels", several modules had already been developed for the second field-testing phase, which facilitated better expressiveness. But those sub-assemblies were only the beginning of an investigation that must be taken further in the future.

Figure 12. Lego Technic building system, age 7+

Figure 13. Action Wheelers building system, age 4+

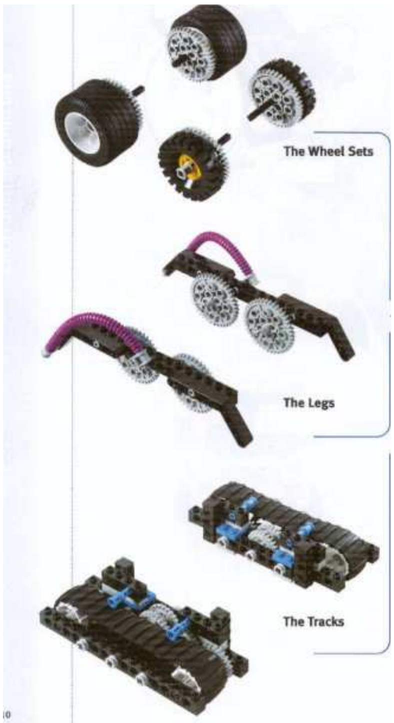

Figure 14. Wheels, legs and belts

Figure 15. A vehicle chassis

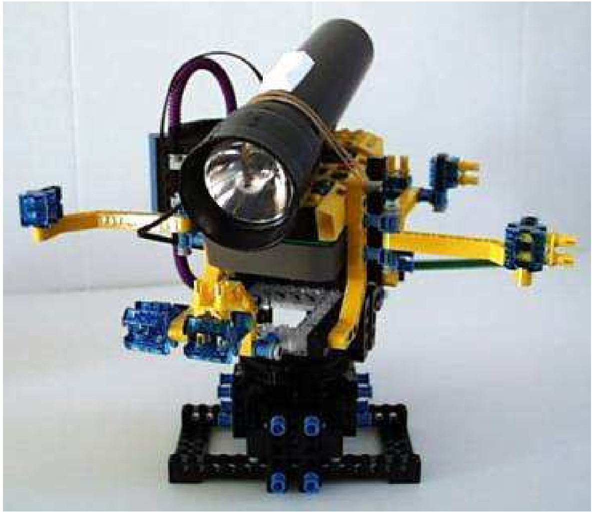

Figure 16. A cradle for the RCX that can turn

As a point of reference, a simpler mechanics system will need to be developed that extends the ideas illustrated by the two sub-assemblies provided in the second field testing phase. The chassis for vehicles (see Figure 15) already modularised several kinds of motion, i.e. using legs, belts or wheels (see Figure 14). The Kinetic Sculpture base (see Figure 16) provided vertical rotation and a cradle for the RCX brick. Many horizontal and vertical rotation motions could already be implemented in this way. Figure 17 shows an example of a module that provides oscillating motion. A better mechanics system for younger children should not start at the level of gears and axles. Instead, it should abstract the different types of motions and make them combinable.

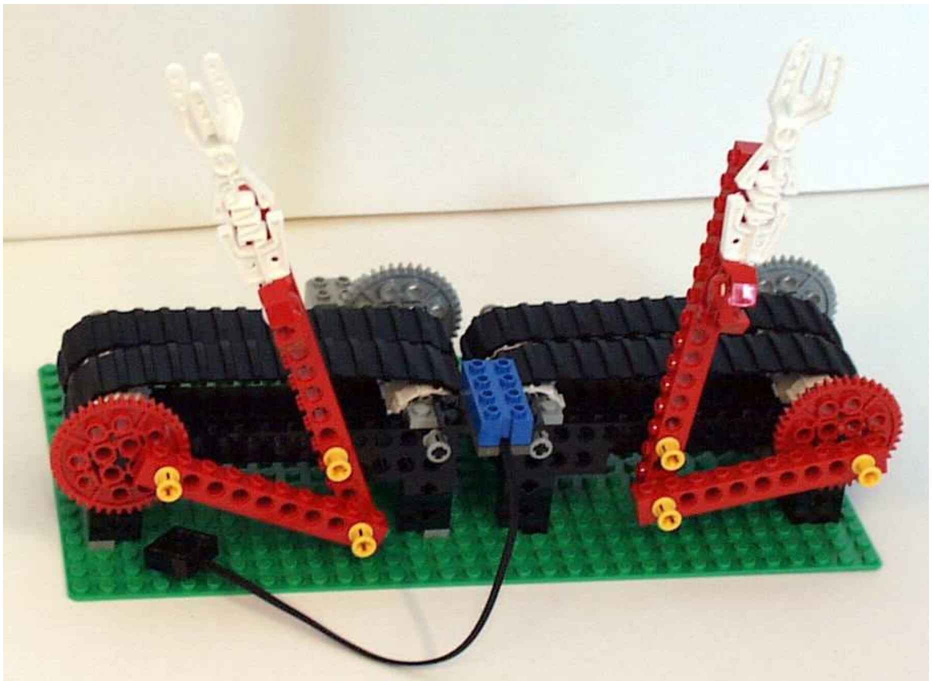

Figure 17. A modular mechanism for oscillating (waving) motion

For sound feedback the programming environment already provided a melody maker. Melodies could thus be introduced for expressing states/emotions of constructions. The playback unit added general sound effects but in the field tests revealed some weaknesses concerning usability. The connection between the hardware and the software representation was too disparate. Nevertheless, the playback unit displayed a strong potential and was frequently picked up and used by the children to give constructions speech.

The domain of music is both motivating and highly expressive. Unfortunately the current hardware capability excludes MIDI support, thus hindering exploration of this context. The "melody editor" provided in the programming environment (see Chioccariello et al., 2001) is still too abstract (it assumes musical notation knowledge) and does not support the interplay of tinkering and planning. Current research at MIT (Martin et al., 2000; Weinberg, 1999) points to ways of incorporating MIDI devices in a construction kit. The question remains as to whether we should head in this direction by integrating proper music hardware and software components and building blocks, and whether the behaviour/action/condition paradigm would still work.

1.5.3. Animated "smart bricks"

One limitation of the material often mentioned by teachers during the field tests was that there was no way to explore the sensor and actuator components without programming. The components had no way of communicating their functionality to the children. A tactile exploration of the material was difficult and the only clue as to the function of a component was visually through its form. Following each phase of field testing, discussions regarding a number of design proposals for more evocative and communicative materials and design led to gradual improvements in the form of the construction kit's components. Yet, a far greater improvement would be to make the sensors and actuators themselves – the "smart bricks" - actually active and allow them to be used independently, i.e. a noise sensor (microphone) could glow with differing intensity depending on the volume of noise it picked up. The idea is to have LEDs arranged in a line, acting as a mini graphic equaliser display (similar to those found in car stereo systems). The child would be able to observe the LEDs' response as he/she made different sounds. This would give a more concrete level reference. The child would be able to relate a level of noise to a visual readout on the microphone. Such an approach would in any case be a step forward from the current abstract numerical representation of sensor values.

The LEGO Scout brick has a similar kind of direct feedback already integrated into its architecture. It makes clever use of light diodes and simple sounds for direct feedback. If it were equipped with similar detection capabilities, the programming environment could sense which components are currently connected and on which ports. Then the layout level could be automated or completely eliminated.

1.5.4. Auto-detection of active components

As it now stands, the RCX and therefore the programming environment do not "know" which sensors and actuators are connected to them. The programming environment asks the child to re-create the physical layout on the screen in order to filter the programming components, i.e. actions or conditions. Then, the only ones displayed are those that can be used in connection with the present sensors/actuators.

This step inhibits a more immediate and more integrated use of default behaviours, as the earliest point at which the programming environment can suggest existing behaviour is after the layout has been re-created in the software.

An improvement in the CAB construction kit that would encourage and support tinkering would be to detect active components automatically as they are attached to the RCX. Then the programming environment could either suggest a behaviour to be added or expose a default behaviour automatically, as happens with the Scout (i.e. touch sensors automatically trigger a sound when triggered). This would result in a tighter integration of physical and behaviour design as the two processes would be more closely intertwined than they currently are. It would also naturally support the "Tinkering Style" of comprehension as the constructions could be outfitted with behaviour right away and then explored and interacted with by the child.

1.6. Sharing and reflecting

In this section the importance of embedding the system in a social and historical context is stressed. Reflection is the centre of discussion - reflection on the child's own work, the evolution of the child's work and, on the other hand, reflection on work by other children. These issues have also been addressed in the research on Distributed Constructionism (Resnick, 1996), which entails and investigates discussion about constructions, sharing of constructions and collaboration on constructions.

1.6.1. Common repository

The objective of this proposal is to support the requirements of programming in social settings where programming is no longer considered a solo activity. Children constantly work in different settings, they build on their own, they gather to build in groups and, given the opportunity, they might build in a larger community. The CAB construction kit of the future should support all of these settings. It should be as easy to share behaviour pieces stored in a common repository as it is to share Lego bricks in a pile on the floor.

A common repository is a shared collection of digital pieces. A group of users, a small group in a classroom or a larger online community, can collect their behaviour components (in CAB: projects, constructions, or behaviours) in the repository. These components are made accessible to all users and can be freely retrieved, modified and eventually re-submitted. A common network repository can become an inspirational as well as a social medium.

Judging from observations in the context of the CAB project, most collaborative efforts involve a small group of children working in a supportive learning environment. The results of this work should be exchangeable with other groups. They will mostly consist of projects, executable programs, but also of documentation, annotation, etc.

1.6.2. Supporting social context

Project work is always embedded in a context – a domain context, a social context and a historical context.

To support "reflecting", it is necessary to support discussion of a given project's development. In this context, integration with children-oriented documentation is crucial.

The focus is on the meta-cognitive aspects of the process, the aspects that prompt the children to think about their thought and development processes.

A history mechanism should be implemented at two levels: a more rudimentary history that allows for read-only inspection of project "snapshots" and a full-fledged history support including versioning. With the latter, the children could revert to a previous stage/version of a project and pursue an alternative course of action.

A checkpoint snapshot of the software environment is created whenever a behaviour is either saved (explicit check-point) or downloaded (implicit). We expect reasoning on breakdowns, i.e. what did not work, to be captured in the implicit checkpoints.

While the programming environment's history function supports a historical context, as well as children's reflections on their own thought processes and breakdowns, a common network repository could give insight into the ideas that sprang from other children's minds and therefore provide a wider social context. Because it encourages reflection on the work of others, it challenges children to shift their perspective (Ackermann, 1996) and analyse in one way or the other, planning or tinkering, the workings of an existing component.

1.6.3. Fostering documentation

A network repository makes documentation meaningful. The degree of documentation is crucial for successful re-use of components. Observations in the schools of Reggio Emilia show that documentation can and should become an integral part of any design process and project.

As a reward, a wider audience will take notice of the children's results. When, in earlier research, the children saw their work being published to a larger audience, sociological aspects were observed that indicated a motivational boost was produced.

A common repository with well-documented components is consequently a powerful tool for the "tinkerer". It offers a range of components of varying complexity that can be taken out, manipulated and tinkered with.

In the software environment special functionality is provided to deal with documentation. From within a project it is possible (at various granularity levels) to access documentation pages in HTML format that are stored either locally or on the Internet.

1.6.4. Software Integration

In order to integrate a network repository into the programming environment, a few additions would need to be made to the existing prototype. As it is, the software is structured in different layers: the project layer, the construction layer, and the behaviour layer. A repository should be able to store items from all of these levels, thereby providing re-use at different granularity levels.

Shared behaviours (sets of rules) could be proposed when "new behaviour" is selected. This feature would be similar to an already present feature, which selects and proposes local behaviours when they are recognised as applicable. Constructions (sets of behaviours with a common layout) and projects (sets of constructions) could be integrated in similar ways.

1.7. Future visions

A cybernetic construction kit design requires consistent integration of its software and hardware components. In this project ITD was responsible for the software side, LEGO for the hardware. We have worked as a joint team on both aspects; the above co-authored sections are the result of this process. Even though the CAB project is reaching its completion we do not think that we have completed our investigation on cybernetic construction kits for young children. In the previous sections we have outlined the design of a third generation kit as it emerges from the field test carried out. Here we propose visions of possible future work from the perspective of a research institute (ITD) and that of a toy company (LEGO).

1.7.1. ITD's perspective

The landscape of children's toys has dramatically changed with the advent of "animated" toys, objects that do things and appear to have a mind of their own. Some of these toys are virtual: they live on a computer screen. As Edith Ackerman (2000) puts it "*toys that actually behave elicit novel ways of exploring relational issues, like agency and identity. […] Their hybrid nature makes it possible to play out the fine line between objectifying minds and animating things, and come to grips with the hardships that identity formation involves.*"

Some educators have expressed their concern about possible negative effects of these new toys on children's development. Similar concerns have been raised about TV or video-games. We have little difficulty with the idea of a child sitting in front of the television watching cartoons, playing with a "smart toy" or a video game for hours on end. At the heart of the problem is our ambiguous relationship with the products of the consumer society. As parents, we are happy to allow a video game, a smart toy, or the television to act as baby-sitters, but worry about the effects of dependence or undesirable content. However, adults seldom ask youngsters if they would like to create their own cartoons or build robots, because they assume that such activities are the preserve of specialists.

In our project we assume that children are indeed interested in building their own "animated" constructions and "programming" their behaviours; we relying on an image of a competent child capable of pursuing difficult projects for extended periods of time in the presence of a supportive learning environment.

During the course of this project both the children and the adults involved have adopted the view that "the sky is the limit", enabling us to continue our investigation in spite of the many difficulties arising from the inadequacies of the materials used in the field testing. Nevertheless, at the end of our investigations we can point to evidence that young children are interested in cybernetic constructions, capable of designing their behaviours, and even of "programming" them.

However, we cannot assess how these new building materials enhance children's learning. Only at the end of the project were we capable of designing a construction kit for young children that should enable them to explore the material freely and autonomously (without the need for external "experts") while engaging in motivating projects.

In this section we will speculate on the possible future directions of our work. To this end before looking forward we will step back to the beginning of the Logo project at MIT in the late sixties and seventies and revisit work and issues that are still relevant.

One might claim that Logo became successful with children thanks to the "turtle", at that time a floor robot tethered to the computer. The turtle robot allows children to think about robot programs using their own body, by putting themselves into the robot's shoes and "walking" through a Logo program. To enable young children to program the turtle, Radia Perlman and Danny Hillis (Perlman, 1976) built an innovative interface called the "slot machine". By inserting cards in colour-coded racks, the children were able to build a turtle program by manipulating physical objects instead of virtual ones.

We feel that the current programming interface of the construction kit is still too complex and abstract for young children. A possible improvement might be a tangible programming environment (McNerney, 1999) where behaviours, conditions and actions are themselves physical manipulative components of the kit.

This could be accomplished by building "smart" tiles that contain electronics components capable of storing the information necessary to assemble a program for the programmable brick. The memory component can be overwritten to redefine the meaning of a tile. The connection parts should enable a tiles "dock" to recognize current configuration of all the docked tiles and communicate to the programmable brick the corresponding program. The tiles dock should also communicate with a computer to connect the physical interface with the visual one.

The benefits of a tangible interface are twofold:

- it enables a small group of children to build programs together - this is difficult using a screen-based programming environment because only one child at time can be in control of the mouse or keyboard (Suzuki and Kato, 1995);
- children can take advantage of the dexterity of their hands - in a graphical user interface objects are manipulated via a mouse or other suitable pointing devices.

Given the age of our target group even small advantages should not be underestimated. A tangible version of the programming environment developed for CAB could realize the vision of mixing Atoms and Bits in a very concrete and child friendly way. Manipulating Lego bricks and behaviours tiles on the floor simultaneously, children might manage to build an animated construction. The computer would offer distinct advantages, for example in storing previous work or exchanging behaviours at a distance, but would not be required to start a project. Creating a new action, composed of existing ones, and giving it an icon and name is easily done by drawing it with pencil and paper and attaching it to the newly composed action. The need for a context switch between a layout editor and a behaviour editor present in the current software would disappear. As a matter of fact, the physical construction *is* the layout and co-exists with its behaviour definitions. Both can be manipulated and evolve while changes immediately take place. We still envisage the need for a computer when a new set of primitive actions and conditions needs to be built for the project at hand. Inspecting a behaviour to see how it has been built also requires a computer; it allows the sharing of behaviours at a distance and means children are not forced to leave their behaviour definitions intact on the floor beyond a project time frame.

In the course of the CAB project we have discussed the relationship between simulated worlds and actual worlds. In principle a child should be able to construct an object and then build its behaviour or vice-versa. However, agents in a real world have to take into account physical laws while virtual ones can ignore them. For example, virtual objects can disappear from one place and reappear in another; a virtual playground can be co-operatively built and shared at a distance, a physical one is local and co-operation occurs in one place. Attempting to simulate the real world within a virtual computer world is possible, but increases the conceptual complexity of the task. Our belief is that both are important and complementary, but they should capitalise on their relative strengths. Looking at a problem from different perspectives and building an object with different materials is beneficial to learning, but the end results are different.

We see our future work encompassing both aspects by providing a single common structure of behaviours, conditions and actions as the structural elements to control both virtual and concrete agents.

The CAB project has shown that, in a supportive learning environment, children can indeed design and build animated construction behaviours. To this aim, we proposed and prototyped a visual programming language that is not general purpose but rather attempts to gain simplicity and power by incorporating knowledge of the construction types and the specificity of the project at hand. Further investigation into the types of constructions and projects that suit children's creativity is needed. Moreover, the shift from interacting with virtual objects to manipulating tangible ones should enhance children's creativity and autonomy, by allowing them to explore the kit freely while being less dependent on adult support.

1.7.2. LEGO's perspective

As we are discussing future visions and speculations about future directions, we would be well advised to point out the questions to which we are seeking answers. The questions driving the CAB project's research were manifold. Seen from the viewpoint of the LEGO's company, a toy manufacturer and developer of new play and learning materials and concepts, the core objectives that have been pursued within CAB are two, namely to:

- provide behaviour as an additional dimension of construction;
- provide tools to sculpt and manipulate behaviour.

There are many other objectives and questions involved, especially with regard to child development, epistemology and learning, but we will focus on the questions mentioned from the perspective of a provider of materials and tools.

We shall start by focusing on the appeal of the materials. As they should motivate children to start a quite elaborate construction project, our materials naturally ought to be interesting, evocative, and engaging enough to capture their attention for quite some time. How can we achieve qualities for the material that will motivate the children in this way? Which contexts do the children relate to and find personally meaningful and do these contexts allow them to direct the construction process themselves? Personally meaningful projects are those that provide an intrinsic motivation, i.e. are based in the child's desire to express or to explore.

Some contexts were explored in the classrooms of our CAB partners - mainly theatre and storytelling scenarios as well as animated physical creatures. These categories may be considered interesting and engaging for the children as they allowed a high degree of expression and exploration. They fostered active and creative play. Future investigations will need to seek out other areas and contexts that motivate children, so that our play materials can be tested and benchmarked to discover whether the material helps the children self-direct their constructive play in whatever context they choose.

How can our play materials empower children to construct in a self-directed and intrinsically motivated fashion?

How can we help them mentally grasp the potential lying in the material and how can we help children decode the functionality and use?

The starting points for such investigations have been documented in this booklet. The construction of personally meaningful objects led to the conclusion that objects often came either from storytelling contexts or that "intelligent" objects were made that the children could personally relate to. Explorations of possible further developments were fuelled by the ambition to support many different approaches, many different ways of thinking and reasoning, in order to get a mental grasp of the materials.

One encouraging result from the project we can now state is our belief that the project's initial objectives and hypotheses regarding relevance to young children were valid and reasonable. Furthermore, we can say that the issue is no longer **whether** behaviour should be a new construction medium and **whether** we should provide tools to craft it. The question for the future will be much more **how** we implement the tools and **how** behaviour can be tied in with those construction materials that can be sensually and physically explored.

For more than two years, we have investigated a lot of **whether** and a little **how,** while using benchmark material that was not age-appropriate to start with. But we developed and evolved the material so that it should allow the combination of behaviour and physical construction. In this booklet, now, we have presented proposals for changes to existing CAB play material. These changes embodied what could eventually constitute a third-generation prototype of a behaviour construction kit. But in those two years we have already identified the issues to be resolved next. Relevant problematic areas of software and hardware improvements were discussed and outlined.

In more than one respect, finding the right package size for basic components was identified as the central issue for further developments. Both for behaviour construction and also for the physical building system we experimented with differing degrees of specialization. Should a component providing motion consist of a bare motor, a motorized set of legs, or a complete chassis? Should a condition in the programming environment describe a lighting situation in terms of subjective perception (dark and bright), in terms of luminosity, or in another way? While a number of re-design proposals were made to modularise building-components as well as programming components, future research will certainly have to explore these issues further in order to strike the best compromise between usable and useful.

To go beyond finding a single compromise, future research should investigate how we could achieve degrees of specialization that adapt to the child's skill level as it progresses. We can foresee that for the components of the behaviour construction kit true open-endedness will require interfaces to define and re-define its functional base components. Here we see the possibility to support the child at different levels of expertise with different levels in the kit that build upon one another. In addition to providing a low threshold to behaviour construction – the focus of CAB - we also need to look for directions to supply a high ceiling that allows personal growth and skill development in connection with the kit and that allows a smooth and gradual transition.

A second problematic issue arose that needs to be resolved in the future in order to make the material more accessible –allowing the children to get a mental grasp on the components. The internally discussed approach to improvements was to supply more transparency. By improving transparency we intended to give more insight into the dynamics, functionality, and interactivity of the components. Finding the right degree and mode of transparency will be a big challenge in the future. Within the project group we discussed several methods of achieving more functional transparency through exterior design changes as well as concept and software supplements that should put stronger emphasis on immediate feedback and trackable functionality of components. Such dynamic explorations of feedback would need to take the place of the sensual experiments in physical construction. Where the consequence of physical constructions can immediately be felt and experienced, the behaviour components and their respective combination remain opaque and mystical. We see more transparency as the most promising direction to resolve this problem of mental grasp of our construction kit material.

But transparency and package size, topics we elaborated earlier, are not the only issues with regards to components. The very character of the components' functionality is at the heart of discussions that have often circled around the merits of the abstract. The claim of many researchers is that abstract components give way to the most open-ended construction environment. We believe that a big challenge in future digital material is to find the right balance between abstract and concrete.

The LEGO® brick itself is a good example of how abstract pieces can be put together to form a concrete object. They have little trouble conveying functionality, possibility and combinability. Mirroring this process in digital terms is an ideal we strive for. In terms of software, no adequate metaphor is currently available that could play the role of the LEGO brick. Exploration of software components is not yet as straightforward as is the case with the LEGO bricks. The consequence is that in current design considerations concrete elements are favoured over abstract ones because they inherently expose their functionality and possibility better. The trend, which we observe and concord with, is towards domain-orientation and contextualised non-general-purpose systems.

Only when adequate metaphors are discovered that allow experimentation with combination and re-combination of abstract digital manipulatives (Resnick et al., 1998) must this current tendency towards the concrete be reconsidered.

For us, all future directions regarding the CAB results have one greater objective in common. For the LEGO Company any further development from here on must be concerned with the task of bringing the materials from a professional environment into a family setting. Within the CAB project outstanding results were achieved and observed in the nurtured environments of the test schools in Sweden and Italy. These field tests were important in showing that there exists a foundation that future developments can build upon. They confirm that the ambition to include digital manipulatives (Resnick et al., 1998) in the play materials even for young children is reasonable and highly relevant.

But in order to extend the behaviour construction kit for a school setting to a stand-alone product, used by a child on his/her own or preferably with parental support, many steps need to be taken towards improvement in the motivational, transparency and comprehension aspects of the material. For us, that is the general vision for the future: to find out much more about the relationship between children and cybernetic objects and to allow children to explore them self-directed and self-contained in a learning environment involving parents and educators.

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1.9. ITD & LEGO: CAB organisational structure

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2.1. Introduction

In this section dedicated to the CAB research carried out in the Reggio Emilia Municipal Infant-toddler Centers and Preschools[2] and, for certain aspects, also conducted in a first and a second grade class of a primary school[3], we will attempt to reconstruct by main points the semantic map that has accompanied our activity during the two years of research.

We can briefly underscore certain general aspects that have characterised the project.

We are clearly aware that schools can and should be directly and actively involved in projects that affect the future and offer children the opportunity to build new forms of learning within contexts that are topical and relevant to contemporary life. Today it is absolutely necessary to take schools out of isolation and establish a close collaboration between schools and other subjects, such as the world of industrial production and that of digital technologies.

Further incentives should be given to this very important aspect precisely in order to encourage and give different forms to the idea of school as a laboratory of ongoing research, as a place of bio-technological evolution, a place that can get away from the disciplinary fragmentation by which it is often characterised.

Therefore, the proposal made by the European Union with the Esprit - ESE Programme (Experimental School Environments) was opportune, as this programme falls within a context of research aimed at promoting the creation of innovative instruments and environments based on information technology for children aged four to eight. By providing for the active involvement of the protagonists of the school (children, teachers, and parents) in the development of new educational technologies, this programme has stimulated the scholastic world to re-think its role and to participate in effecting change proactively.

Another important aspect of this programme is to take indications directly from the world of young children, stimulating it to be not just a context of play but also of thinking and proposal-making that could orient certain new developments in digital technology.

We therefore examined the encounter between children and programmable construction kits with the aim to develop innovative materials, test a method of research appropriate to the age of the children, and investigate how and what children learn within contexts that develop around technological objects that can be made to interact intelligently with the environment by means of suitable programming.

In rethinking the school environment in light of the development of digital technology, while aiming to situate the children's play with the programmable construction kits in a significant context[4], it was indispensable to make recourse to theories familiar to the educational sphere (theories on cognitive development, individual and group learning, play and playing, …) and place them in relation to less familiar, though extremely stimulating, areas of study (cybernetics, neuroscience, information technology, …).

Within this process of interactive flow between familiar and less familiar areas of knowledge, between official culture and culture constructed in the encounter between the adults' knowledge and the children's knowledge, the concepts that have traversed the research as a whole have come together, which we summarise briefly in this document.

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[2] Pablo Neruda, 8 Marzo, and Villetta are the three preschools involved in the project with children from four to six years old (one class participated in the project continuously for two years).

[3] Italo Calvino is the state-run primary school involved in the research with one class (the same class, in the first and second grades, worked on the CAB project for two consecutive years).

[4] The objectives of the CAB research stated in the Project Programme are:

- to experiment with and validate a methodology that favours the interaction of the children with the computer through the use of cybernetic construction kits;
- to favour the approach to and use of cybernetic objects by children aged 4 to 8 in multiple contexts (and not just in separate laboratories).;
- to investigate how children's knowledge-building processes are structured when they encounter and experiment directly approaches to multimedia and three-dimensional construction of cybernetic objects.

As regards the choice of the research methodology appropriate to the age of the children involved in the project, we will briefly discuss this point here.

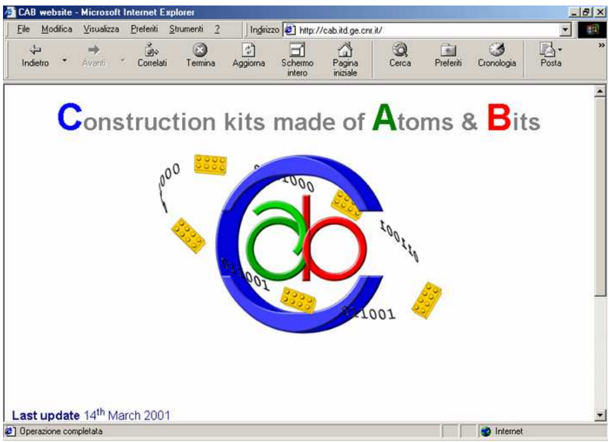
*Right from the beginning we discarded the idea and the structure of comparative research, as such a method would require repeatable contexts and problem situations that could be proposed to different groups, chosen and predefined by the adult, as well as a controlled number of variables of modification of the initial context. We therefore chose an approach we called "sensitive research" (*this concept is discussed in detail in the section "Sensitive research" on page 38).

The aim was thus to identify a strategy that would make it possible to follow, step by step, not only the learning but also the non-learning, the reasons for these difficulties, to what extent this could be attributed to subjective aspects of the children and to what extent it is attributable to the object itself. Consequently, modifications were made to the tools as the work progressed (in process).

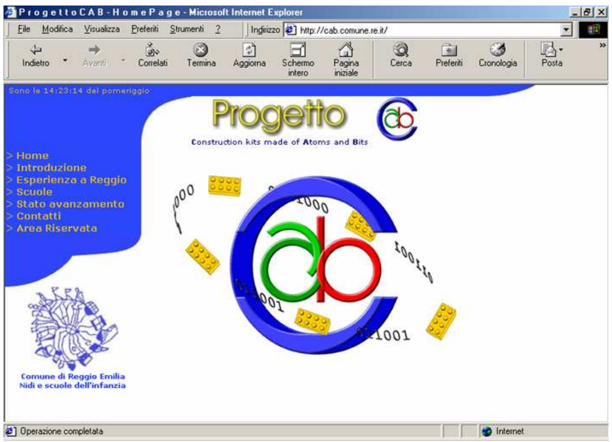
This meant working in close collaboration with ITD and LEGO, and also making use of a procedure that was sensitive to the ways and rhythms with which the children proceeded. This type of research could not follow either the experimental or the comparative procedure, but was based on a systemic approach; that is, it was aimed at observing the relationships and interactions between the children and the construction kit, among the children themselves, between children and adults, and examining the extent to which these relationships modified the learning taking place and the object itself.

With this approach, we have investigated individual and group learning strategies (i.e. how learning is constituted in different ways), rather than the quantitative existence of learning phenomena. We have attempted to disclose a part of the processes, the moments, the places, and the dynamics of children's learning that can take place in the daily life of the school, which can itself play an active part in the continuous invention of the signs and languages of the school community.

In this document we attempt to provide a summary of meanings and experiences extensively documented by the teachers by means of multimedia languages (observations, digital images and video, construction of a Web site in English and a specific site for the Reggio Emilia experience in Italian, deliverables for monitoring the development of the research, reports on the meetings among the partners and meetings with the parents for sharing thoughts and ideas…).



Home page of the CAB Web site (English)



Home page of the specific site for the CRE experience (Italian)

2.2. The cultural contexts of the adults and the children

The world in which we live today is characterised by a strong mixing of natural objects, cultural objects, and digital technologies which are transforming the natural objects, the cultural objects, and the technologies themselves, as well as the relationships between these elements.

Instruments (digital and others) and materials exist in a fluid space that is not rigidly defined in relation to functions or to formal codes; each one certainly has its own specific nature but can assume other identities in relation to the experiences involved and to the intensity and quality of the connections.

The knowledge of digital technologies held by the teachers, and by adults in general, is highly differentiated.

In the municipal preschools of Reggio Emilia, the widespread use of computers, printers, digital cameras, scanners, graphic pads, and video projectors coexists with that of other technologies (slide projectors, overhead projectors…) that are commonly and frequently used in daily didactic work.

It is important to underscore that these instruments are not neutral but, indeed, have an extraordinary capacity to intervene in and on the environment to favour and/or limit the construction of knowledge-building structures and of relationships.

They are also instruments designed with specific qualities and for specific functions, which stimulate and require competencies, and are approached by the teachers with different strategies and methods.

The teachers have asked themselves how they could nurture the culture and experience of the school by bringing in an awareness of the currently debates in regard to:

- the multisensory dimension, which recasts the idea of sensoriality and of reality, overcoming the dichotomy between virtual/artificial reality and material/concrete reality to open the way for a new concept of "matured reality", which keeps together the different elements and the different interpretations contained therein;
- the ability to look at things from different viewpoints, to interconnect them and interpret them;
- the central importance of interdisciplinary approaches;
- the awareness that the subject who acts and thinks, whether adult or child, exists as a "person" in his or her wholeness, with his or her own interests, experiences, with his or her own body, rooted in a social, biological, material, and cultural context;
- a new approach to knowledge and to the learning process that takes into account and connects concepts such as:
    - ◊ serendipity, as the art of transforming apparently insignificant details into indications that enable one to reconstruct a story;
    - ◊ the investigative approach directed on issues of our times;
    - ◊ the relationship between declarative and procedural knowledge;
    - ◊ designing relationships as the ability to formulate and relaunch hypotheses, with a firm grasp of the possibility of flexible connections between parts that may even be very distant from each other and apparently entirely separate;
    - ◊ living and pondering the idea of "semantic aura", as a possible zone of research generated by continuous transmutations under way in various spheres (cultural, technological, social, etc.).

To better understand the lines of possible development of the research, the teachers have also examined new issues elicited by the specific nature of the CAB research.

They have explored the world of artificial intelligence, which has always investigated how one learns to learn, how knowledge evolves, how to operate with a "fuzzy" logic, i.e. a flexible logic that can adapt to the search for understanding, and considers how to develop new interfaces that are intelligent and sensitive to the relationship with the user and can state the procedures clearly and make them accessible. We feel we can claim that the identification of codes of access to digital communication is facilitated by reference to images that are now shared by the adults and the children alike.

In the CAB research, these aspects emerged frequently as questions posed by children and adults, or as problems to put forward to the partners involved in the area of hardware and software development. It is clear that the children sometimes touched upon, and other times directly encountered, concepts that for a number of years have engaged researchers, research centres, and universities, and they tried to express intuitions, doubts, and interpretations that are temporary and partial.

It is also clear that the application of any technology has always transformed the world and our way of conceiving it and living in it. Children breathe an atmosphere characterised by many kinds of links (cause-effect, mechanical, communicative, connective, etc.), which have been greatly strengthened (from both the quantitative and qualitative points of view) but at the same time have been dematerialised.

As educators, we thus asked ourselves where and how children encounter technologies that not only can be used with skill and competence but can also be revealed and therefore be at least partially comprehensible.

A difficult question emerges: How can a school make this world which is impalpable, yet so powerful, easier to reveal, interpret, and grasp?

Following the research carried out with the children, we feel we can highlight certain developments in the strategies of approach and in the processes involved in comprehending the digital technologies which emerged in quantitatively and qualitatively different forms as the research progressed.

2.2.1. The first year of research

The first year made it possible to link and interweave all the cultural inputs and those specifically tied to the characteristics of LEGO MINDSTORMS. This period was crucial for implementing an active process of acculturation for adults and children regarding the limitations and "attractions" suggested by the range of specific possibilities of the programmable construction kits.

The children demonstrated a high level of interest and attention toward the world of digital technologies that surrounds them, expressing doubts but also basically maintaining an attitude of faith and openness.

*"**Computers** are things that make your memory work..."*

"They have special games"

"With the computer you can buy clothes, too..."

"If a mother has a baby in her tummy, you can see it with the computer!..."

"Computers work if you put the diskettes in them, because inside there's the programme of the computer."

"My computer can understand and remember things, because it has a brain inside the box, it's square..."

"Computers draw, write, and erase, but they can teach you to write, but they don't learn like children do because they don't have a brain and memory."

"They don't think, because they don't have a mind."

*"There are toy **robots**, not real ones."*

"If you make them they become real."

"Robots are toys, they're made of lots of pieces, then there has to be a button that maybe if you press it then it talks, it walks, it changes."

"Some robots have a wire, some of them have batteries, and some of them the children make them walk."

"There are also some robots that don't have a face, they don't walk, but they do other things like eating...cleaning..."

"You can build them but you have to put the transmitter inside, so they can understand the messages."

At the end of the first year, we could already see how the construction kits were able to captivate the children's interest. Curiosity, pleasure, and enthusiasm are qualities that distinguished their attitude in the initial approach to these materials. But the characteristics that helped the children most to gradually discover the complexity of these instruments were their desire to understand, tenacity in searching for solutions, and intelligence in interpreting.

Though the children came up against a high level of complexity in recognising the functions and the relationships among the various pieces, they compared ideas, theories, and knowledge, imagining and shaping possible contexts in which they could develop their research and thus suggesting possible didactic projects and knowledge-building paths, as can be seen from the examples below.

Example 1

Experimentation of the operation of a robot-vehicle on a platform that reproduces the map of a city.

"I think he doesn't know how to go on our map. He falls down and breaks."

"He's afraid, because he doesn't like white, he likes black..."

Example 2

Exploration of relationships between the environment and a tree branch which has become an 'agent' by means of a light sensor, a tape recorder, a microphone, and two motors from the Lego Mindstorms kit.

"...It's the tree that's talking!"

"If we push the red and green buttons the programme comes on."

"This is a robot sensor, it's the robot's eye."

"And maybe these [the tape recorder] are the buttons for making the tree talk!"

"Try it!"

"It should be the programme… Maybe it's magic, maybe to make it talk you need the programme."

"The sunlight has come all the way there on the sensor!

"And this tape recorder said: 'It's so hot – the sun is coming!"

Example 3

Exploration of a robot carrying an audio sensor to which a "light chain" was associated, so that the lights lit up in relation to the intensity of the audio input.

"He feels the wind! Look! He turns on the lights when he feels it."

"I have an idea! What if we told the robot a joke? Do you think he would laugh?"

"Come on, let's try! I'll start..."

"The red lights turn on and off."

"So he's laughing, too."

"Because there's a microphone inside."

"I think so, too, that there's a microphone that transmits our laughing like this a lot of times: Ah, Ah, AH… and the robot turns on the lights."

As can be seen in the examples given above, the experience has contributed to developing an environment that can retain findings (documents, objects…) and memories, and represent the state of the culture developed by the children themselves around the new technologies. This enabled the children, from the very first year of work and then with increasing strength and awareness those who entered the research in the second year and for several months of the third year, to have a bio-technological-cultural context that was more favourable to the development of a more highly evolved form of learning.[5]

[5] This aspect will be discussed in more detail in the section "Revealable complexity."

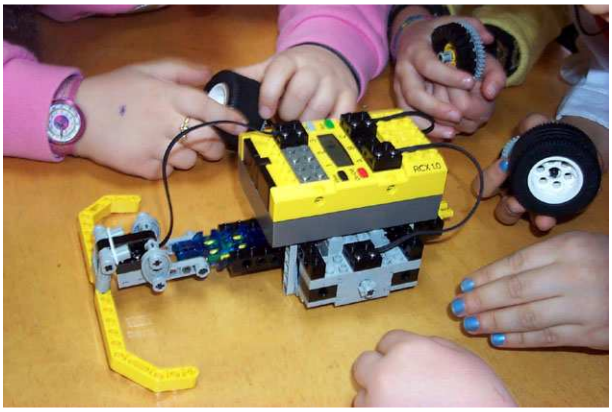
2.2.2. The second year of research

During the second year, we saw an increased awareness on the part of the children as regards the possibility of being “authors and creators” of cybernetic subjects (thanks to the possibility to determine these subjects’ characteristics of behaviour and interaction), and therefore to be the “conductors” of situations and contexts designed by the children themselves.

Example

A group of children designs a “living system”, a cybernetic scenario composed of a city that some “monsters” want to conquer, while the “defenders” of the city have to prevent this.

The metaphorical "life" of the system is determined by the quantity but above all the quality of the interactions between the protagonists.



For this reason, the need to design and create the identities of the “robotic creatures” and the physical environment of the scenario in a way that is consistent with the characteristics of the construction kit, constitutes the essence of the learning challenge that the children are attempting to confront.

However, there was often difficulty in being able to reconcile a way of designing and thinking that belongs specifically to the children and the limitations of a programming environment that was still not particularly open to these qualities.

In the final months, we thus focused on the development of a software environment that would, in a more flexible way, be able to hold the “traces” of the knowledge-building processes that the children were constructing. By “traces” we mean not only the collection of the various projects identified and developed, but also attempts that were just barely sketched out, which in order to take shape needed to be compared with others and a procedure for trial and error.

The possibility to keep a memory of these processes becomes the fundamental premise for the construction of knowledge and awareness in both children and adults, because it constitutes an invaluable instrument of design, revisiting, and sharing, and therefore of learning.

2.3. Sensitive research

We have done a great deal of reflection on how to qualify this research, which examines topics with very young children that could be considered "for grownups", in order to delineate the values-related, conceptual, and theoretical references, and which aims to receive input for innovation precisely by means of trying to interpret the thoughts and ways of thinking of the children themselves.

First of all, priority was given to the need to have a respectful attitude toward the children that would be curious about the field of research but also critical and self-critical.

We thus adopted the idea of a project approach that would:

- lend itself to being structured over time in relation to the developments of the research itself;
- entrust a central role to documentation as a procedure for understanding;
- consider the close transformational dialogue[6] between educational theory and practice to be crucial;
- foresee moments of pause;
- stress the importance of listening to the thoughts and the 'temporary theories' expressed by the children, interpreted as possible new questions rather than answers;
- identify interpretation as an essential component to be placed in relation to comprehension and knowledge, without, however, confusing them;
- express clearly that the most significant part of the result is represented by and in the process that accompanies the experience rather than by and in the final outcome.

Below we will see an example of a situation in which the role of the teachers, of documentation, and of time contribute to the construction of an attitude of research that is respectful of the children.

This was the starting situation: at the beginning of the research, a group of children encountered a number of robot-vehicles. The following day, using the documentation prepared by the adults, the children revisit the experience.

Their objective is to hypothesise solutions for the construction of a track for the robots on the platform that reproduces the map of a city. This track must have characteristics that take into account the identity and the perceptual and sensory qualities of the robots.

"The strange machines that we saw yesterday."

"I remember that when you press number 5, the one with the eyes, it went on the black track, it went forward, it turned… If we want to make it go on our block platform there has to be black on the road."

Research that is therefore *sensitive* to the age and to the elaborations mapped out by the children, to the different learning contexts, to the potential developments of the software and hardware.

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[6] Gergen, K.J., (2000) - *Verso un vocabolario del dialogo trasformativo* - Pluriverso 2/2000 pp. 100/113

Research that is sensitive to flexibility, because it is capable of adapting to the needs of the children, the adults, and the time frame of the project; at the same time, research that is sensitive to rigour, as it can maintain a memory of the thoughts, actions, and interpretations.

2.3.1. Research as a strategy for building learning

The attitude of research is a fundamental point to be considered and reflected upon, as in our educational experience it represents a strategy of approach and understanding for adults and children alike.

In the encounter with new technologies, the attitude of research is seen as all the more necessary as a knowledge-building strategy for opening and building relationships between children and adults, with different motivations and responsibilities, who are all engaged in an effort to understand a still little known phenomenon.

In order to take this approach, it was essential to define a position with respect to:

A. strategic thinking
B. the approach to the design problem
C. the role of the adult
D. the relationship between the construction of individual learning and the individual or group contexts in which it takes place

A. By strategic thinking we mean a close and interlocutory relationship between:

   ◊ the formulation of interpretive theories
   ◊ the development of design strategies
   ◊ experimentation and modifications
   ◊ the reformulation of the initial theories
   ◊ progressive re-design
   ◊ the assessment of the outcomes
   ◊ self-assessment of one's own processes.

   This way of thinking searches for coherence between different parts, maintains the relationship of 'what happens' and 'what is learned' with 'how it happens' and 'how it is learned', underscoring the continuous process of self-learning of adults and children.

B. By approach to the design problem, we mean a way of designing that presupposes the possibility to identify multiple paths and multiple solutions with respect to problem situations.

   It is interesting to consider the idea that there is not a single solution to be reached and that, at the same time, there are clear constraints to be kept in mind.

C. As regards the role of the adult-teacher, we have based ourselves on the idea of a cultural mediator, who is capable of revealing the structures of approach and of connection that the children identify or can identify.[7]

D. We have also given priority to the choice of group contexts (5-6 children) as the place in which individual learning takes place in a more flexible, articulate, and complex form.

   Individual learning that is constructed in a group context can be built on:

   ◊ the meeting of multiple points of view,
   ◊ the comparison with different strategies of thought and action,

[7] This aspect will be further developed in the section "Revealable complexity."

◊ the possibility to take proper account, in our project designs, of the gap between the various "mental models" that the children are constructing and limitations which are often in "conflict" with each other.

We are clearly aware that each group explores, constructs, and structures a more advanced knowledge, where the single individuals reach levels on the cognitive plane that would be unthinkable in an individual approach.

In their research, the children experience moments that are engaging and exciting; they know how to participate in a process for constructing something new, together with the adults and the other children, and they develop the awareness of creating relationships between 'traditional' knowledge and the emerging strategic and content-related aspects of the project.

2.3.2. Research and learning: theoretical reflections

In the course of the CAB research, the children had the opportunity to enquire, to put themselves to the test, and to learn with respect to complex issues such as:

- recognition and conceptual and semantic mastery of the technology of the sensors;
- the identification of problems related to computer programming;
- the transfer of explanatory theories formulated in relation to one element or system to another element/context; for example, when the children work with the sensors they acquire a deeper understanding of how their own senses work, they investigate the functioning of their own brain, movement, and so on;
- the intuition of the idea of a 'living system' and identification of the qualities and problems that characterise such a system;
- the ability to create a relationship between designing subjects and/or scenarios inhabited by multiple subjects and programming the subjects/scenarios hypothesised;
- the possibility to 'capture' the sense of artificial life, proceeding by modifying the simulations to test other hypotheses;
- the recognition and use of error and/or chance to highlight unforeseen aspects;

and on familiar questions such as:

- decoding alphanumerical codes;
- the use of multiple languages, instruments, and materials in the sense of design, construction, and communication;
- the development of strategic abilities tied to resolving problems of stability, solidity, and equilibrium of constructions created using the LEGO bricks and other materials;
- the capacity to act and reflect on one's own actions;
- the development of relational skills in the group work;
- the capacity to compare one's own point of view with those of others.

In addition, we feel that it is important to underscore the possibilities for knowledge-building and learning that are created by the contexts constructed with kits such as LEGO MINDSTORM in relation to:

- the development of systemic thinking and a systemic approach, but especially the access to 'thinking about systems' as a dimension of metacognition
- the development of predictive thinking
- the construction of 'metaphors of living and sensitive intelligences', where metacognition and imagination, animism and narration, intersect.

In designing and constructing "autonomous cybernetic subjects" (those which the relevant literature defines as "agents"), the children were called upon to produce hypotheses and think in depth about:

- the "knowledge" that the robots should have
- the robots' methods *(and possibilities)* of interaction with the environment and with other beings, human and cybernetic

In the following example, we will see a number of programming interfaces created by the children to design robot relationships and behaviours in the environment.

The idea of shadow as a language and form of communication, perhaps suggested by the communicative method through the display of the RCXs, is probably taken into consideration by the children because it embodies strong concepts of digital communication such as variability, but also based on the possibility that shadows have to be flexible, temporary, modifiable, and above all, as the children say, *"you can't hold it in your hand"*.

"I know how to make a programme, I'll show you. To make a machine learn things, you have to show it the letters, the numbers for learning to count. Then if we want to make him follow a track, he has to learn to know the road, so you make him a black track so he gets used to seeing it and then he learns it… You also have to put wheels on that means he has to move, he has to move on the wheels…"

In practice, the children found themselves directly faced with the question of "what to do" in order to enable their "cybernetic creatures" to "learn" and "understand". The situations exemplified briefly below offer an effective testimony.

"We want him to obey our orders: go forward, stop, turn..."

"If we connect him to the computer, he'll do everything we tell him to..."

"There's an invisible ray that goes and gives the commands… it says them to his head… no, to his LEGOs!"

"This is a map. The robot needs it because he's a robot made with LEGOs so he can only understand the words if you draw them!"

This is particularly important because we are dealing with subjects that are "autonomous" and animated, not so much because they are capable of physical movement in the space but, rather, because they are experienced by the children in a dimension of metaphorical recognition of life, and are therefore full of emotions and "affective" involvement.

Here we are implicitly close to the thinking of Edith K. Ackermann when she affirms *"children's ability to engage in pretense play and to endow objects with a life of their own. Taking on other people's views, changing one's stance in the world, and animating things… are powerful heuristics by which children use empathy as a lever for cognitive growth."*[8]

In summary, with respect to complex dynamic systems, we have seen that the use of the cybernetic construction kits has offered important possibilities in terms of the development of metacognitive abilities, also for preschool children, favouring the structuring of thinking and learning abilities.

It is not easy to define the level and quality of learning achieved, and perhaps it would be naive and ungenerous to confine the richness of the experiences and processes expressed to a matter of manifestly acquired behaviours and skills.

Certainly we can state that the children have acquired skills and competencies as concerns the learning content described in this section, in addition to having nurtured their curiosity and desire to investigate further.

2.3.3. Research as transits between different learning experiences

The context

A group of children is trying to understand how and when a robot-vehicle can take bread to the birds in the feeding platform under the branch.

"The robot starts off when he hears the birds saying they're hungry." - Francesca

"The robots can hear with the microphone, so if we put the microphone on the robot, he can hear the birds go 'cheep, cheep' when they're hungry." - Nicolò

"He gets to the feeding platform and then stops." - Alex

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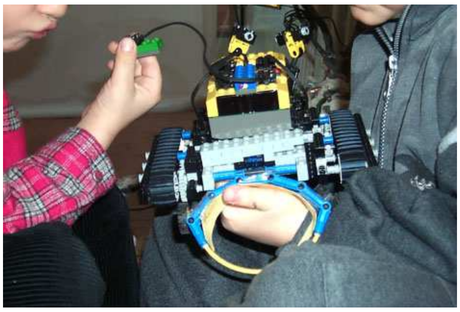
[8] "Enactive Representations in Learning: Pretenses, Models and Machines" - Ackermann, E., 1997

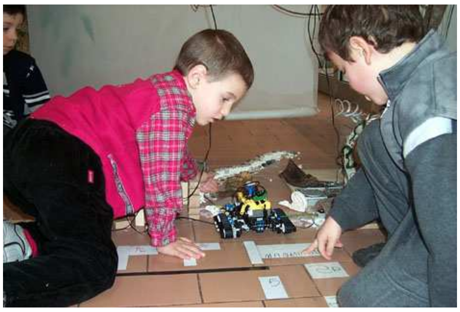
"And the bird that's hungry comes down to the feeding platform and eats the bread… To make the robot go to the feeding platform we have to programme it: go forward... turn left… turn around… stop." - Alessandro



The problem

The children identify the constructive and functional methods of a robot whose task is to take bread to the birds on the branch, and they design the robot's behaviour.

The robot has to start off when it receives the verbal message of the children that imitates the birds' chirping. The microphone the children have situated on the robot will receive this message.



The value of error

The children's expectations come up against the potentials and restrictions of the technology: the generic nature of microphones that pick up all the background noise makes it necessary for the children to modify their design.

Every noise picked up by the microphone on the robot makes it start off, causing it to go beyond the point of encounter with the bird.

"He got it wrong! He stopped and then started again!" - Alex

"Maybe he didn't understand what he had to do?" - Alessandro

"Maybe he got confused… Yes, he gets sort of confused like we do when we don't understand something very well." - Nicolò

"Maybe he didn't understand because he heard the cheep-cheep too soft… Let's try making it louder!" - Alex

The children have understood that the problem is linked to the method of communication between the microphone and the environment. Together with the teacher, they conduct a number of trials to modify, within the programming environment, the intensity of the microphone's listening capacity.

These attempts do not lead to the desired results, as the robot starts off again each time it picks up a noise.

At this point a problem situation arises: how can we resolve it?

Will the children be content with things as they are or will they seek alternatives?

It is the second hypothesis that wins out; the children seek help from their friends to develop possible strategies.

There is a suspension, and they take time to think and reflect...

The adoption of an idea

During the assembly, the children share with their classmates their idea of the "bread-carrier" robot and the problems they have encountered.

These are daily moments that offer the children and adults the opportunity to build relationships that are open to receiving the thoughts of others and evaluating them in order to give suggestions and support, and, at the same time, to feel part of a project in which each can offer his or her own knowledge.

The children evoke consolidated learning that has taken place in their daily life.

"The robots send each other messages like we do, when we want to say to a friend something like: "Do you want to be my friend?" Or: "Do you want to go with me to the Campo di Marte to play?"" - Eleonora

"We draw them or write something with the computer, then we put them in the message boxes of our friends or on the diskettes..." - Laura

"But maybe the robots use secret codes..." - Nicolò

"What is a code?" - Teacher

"A code is something that helps you understand another thing." - Nicolò

"Their code could be made of gears or electricity..." - Tommaso

"And what kind of codes do you use?" - Teacher

"In our messages we use a code that we understand. If I make a message for my friend Alessandro, because I know that he knows the printed letters, I use a code of printed letters if I want him to understand; for Tommaso, though, who doesn't know many letters, I put some drawings and just a little bit of writing!" - Nicolò

After having already experimented with verbal communication with the robot, the children hypothesise other forms of communication and make reference to their concrete experience, which is the daily exchange of messages with their friends created either on paper or in digital format.

In the construction of a message, the communicative intention of the sender is in relation with what the receiver knows and with the reciprocal expectations among friends, generating different communicative qualities.

Each child has his or her own mailbox for receiving messages from friends.

Solutions

Together with the children, we agree on the need to find another system of communication in the software that will make it possible to realise their project.

In the their exploration of the software, the children recognise the icons that evoke the idea of mail:

"I think the mail gives us a suggestion." - Tommaso

"These might be the messages that the robots send." - Nicolò

"And the mail for the robots goes in the box." - Alex

"Maybe you can write a message..." - Alessandro

"You need a message that's kind of secret, that we don't hear but the robot hears it and understands it, so then he starts off." - Alex

"Instead, with the tape recorder, which is an important thing, we'll make the clay bird talk, because he doesn't have a voice!" - Nicolò

"I'll talk into the tape recorder myself but it's like it was the bird's voice." - Alessandro

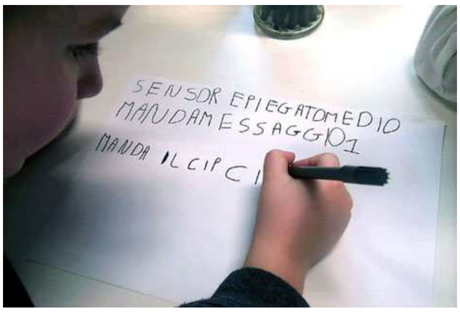
The initial project is in part modified, at this point including a second robot and new conditions for activating the relationships between the branch and the "bread-carrier" robot.

"We need another robot, who's his friend and sends him the message to start off..." - Nicolò

"I think when the bird that's on the branch touches the bend sensor, the message starts… a message made of cheep-cheep." - Alessandro

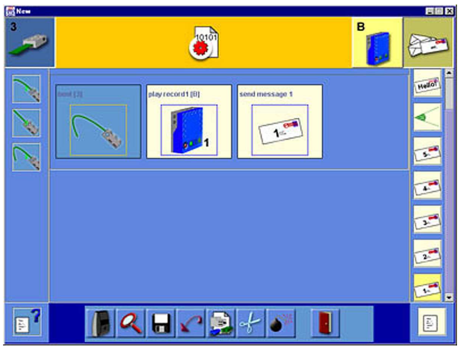
"But do we hear it too?" - Alex

"If we record it we'll hear it, but to make the bread-carrier robot hear it, so he doesn't get confused, he has to hear it with the microphone, but in another way..." - Nicolò



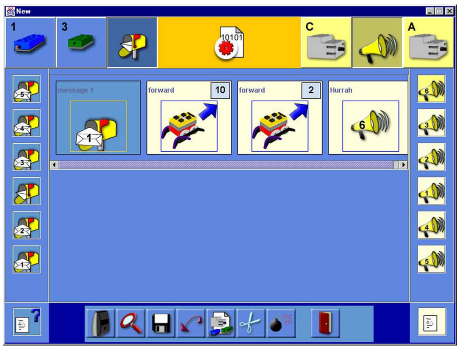
Metaphors

The children's thoughts return to another medium and another language for giving shape to their first programming hypotheses and at the same time, they feel the need to transfer them, translating them into the language of communication of the robots.



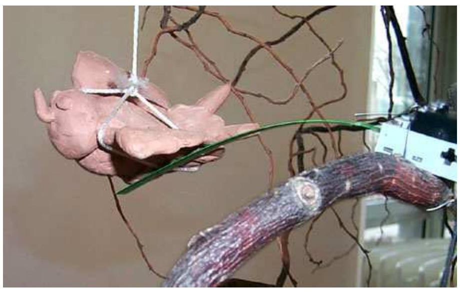
This is the programming of the "robot-friend", in which at a certain degree of bending of the bend sensor, the tape recorder emits a sound to call the “bread-carrier” robot, to which a message in the form of an infrared signal is associated.

This is the programming of the “bread-carrier” robot which, when it has received the start-off message, must move forward for the time necessary to reach the feeding platform. At the moment in which it reaches the tray, it emits a sound that signals its arrival.

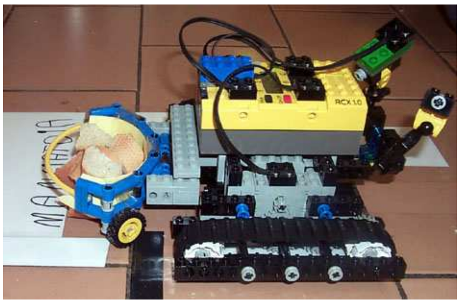


The test

The group of children arrange a test of the programming of the two robots...



A bird touches the bend sensor...



...and immediately the "bread-carrier" robot starts off and goes to the tray.

Then the bird comes down from the nest and...

...it can finally eat!

The success of the animation, which took place through relationship and communication, gives the children enormous satisfaction.

This satisfaction is manifested not only by expressions or gestures of joy, but also through verbal expressions that probably declare the children's awareness that they have learned something in such complex contexts.

"We've become robot programmers!"

"We discovered some secrets: one is that the robots, with the envelope and the mailbox, can talk to each other."

2.4. Keywords

In this section we offer some reflections using a number of "keywords" to trace the possible meanings explored and developed by the children and adults in the sphere of this research.

Using this method we hope not only to provide some outcomes of the research but also to highlight new possible lines of innovative research, which this theme could stimulate in the educational field.

We will therefore discuss:

- bio-technological environment
- revealable complexity
- connection as communication
- nomadic memory

2.4.1. Bio-technological environment

In our research, we have upheld the idea of school as an environment that is not indifferent to the processes of knowledge-building, an environment in which these processes are activated and/or enacted.

We have tried to dwell within the idea of an environment that acts as an accomplice and co-participant, that can be modified and can provide a context for knowledge-building.

In particular, the research has underscored the productiveness of an environment that is capable of changing, of integrating traditional technologies, digital technologies, natural objects, materials, and symbolic codes. We have defined this environment as "bio-technological" to underscore its aptitude for creating relationships between and different ways of accessing knowledge and interconnecting them, with an ecological and ecodisciplinary perspective.[9]

Listening to the children, what clearly emerged was that many of them tried to inhabit different space-time dimensions with familiarity; they kept in mind the different contemporary aspects; they connected places that are geographically and conceptually distant; they explored and interwove different languages and media.

The children showed an extraordinary ability to assume the concept of interface as a "relationship between" and to decode different symbolic codes. Through their play, they were able to handle and organise thought, emotion, and action.

When they used instruments and materials capable of eliciting broad and open links, they transformed the identity of those instruments and materials, changes that were stimulated by the experiences that were taking place and by the intensity and the quality of the connections they imagined or experimented with.

Therefore, it seems that an important indication that emerged from the research is that of designing, equipping, and inhabiting the environment, favouring the identification of situations in which there is a strong degree of "cross-fertilisation" between different dimensions (natural, artificial, digital, technological, etc.)

Learning that develops in an environment conceived in this way aims at keeping together the theoretical development and the understanding of the practical application of the concepts, and gives a new meaning to part of cognitive epistemology that is based on the reciprocal relationship between theory and practice.

2.4.2. Revealable complexity

As has been true in the history of people who have contributed to creating new technologies and the disciplines within which they work, we feel that the problem—for children as well—is not to construct complex digital technological objects by moving through all the phases in isolation; rather, the problem is having the opportunity to design, think, and "model" complex systems and giving them a communicable form.

In the course of the research, children and adults did not search for simplification, but tried to understand and confront complexity, viewed as a network of connections between hardware, software, and environment, also infusing these three factors with affective dynamics, imaginative capacities, and desires.

The way the children proceeded within this complexity was modulated as a continuous connection between the understandings acquired as they went along, in terms of the use and possibilities of the kit, and the desire to push themselves farther, giving shape to their mental images and searching for new ones.

For the children, this became a strategy for measuring the potentials of the material, but also for bringing out other possible paths of knowledge, venturing in unexplored directions.

At times it seemed that the children were taking us off track, and we had difficulty finding coherence between their mental images and the realisation of this images.

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[9] Edgar Morin, La testa ben fatta, Raffaello Cortina editore, Milano, 2000

The children also used narration to give shape to their thoughts rather than the identification of technical/technological solutions.

However, when the children, together with the adults, were able to find solutions through the "orchestration" of the various technological possibilities, imagination, and narration, we noted the following:

- the desire of the children themselves to set new objectives, relaunching other ideas and desires;
- a growing motivation based on a desire to "become experts"; that is, to learn more and to confirm their own knowledge by putting themselves to the test again;
- a growth in the children's ability to effect an interplay of understandings and desires, technology and imagination, mixing specific knowledge (on the use of sensors and actuators, etc.) with broader and more abstract ideas and mental images.

The conversation that follows offers us a significant example of orchestration between the various technological possibilities, imagination, and narration:

We could write the name of each child at the starting line, because that way the robot will know who his master is. *(Elisa)*

The robot **starts when he hears** the birds saying they're hungry. *(Francesca)*

Then **he has to stop** and **pick up the bread**: either we load it or he picks it up by himself. *(Corinna*)

Yes, he starts off with the empty basket and then there's a brick that says "Stop to pick up the bread for the birds." *(Elisa)*

Then with the light sensor **he can see the white, black, or green line**; instead, the one that follows the light sees straight ahead. *(Nicolò)*

Maybe **he recognises the picture** of the bread. *(Elisa)*

Or else he could have the sensor that **follows the light.** *(Corinna)*

He should start only when the birds are hungry. *(Corinna)*

Robots **can hear with** the microphone, so if we put the microphone on the robot he can hear the birds go "cheep, cheep" when they're hungry. Then he starts off. Then when we see him going near the feeding tray, **he has to turn.** *(Elisa)*

He could turn with the light. *(Corinna)*

Or when the robot sees a green signal, he has to turn. *(Alessandro)*

Then **he has to go fast** when the birds are hungry, like in the new programme... I'd put the bread halfway down; he has to follow the road to get there, a black line or a green line because **he knows them**. He gets to the bread but he doesn't stop, he picks it up without stopping and he keeps on going. **He gets to the feeding tray** and he stops when he sees the light that's inside the feeding tray. *(Nicolò)*

I'd put the bread for the birds near the starting line. The robot follows the road, when he gets to the bread **he raises the blue thing** and picks it up. To get to the feeding tray we have to programme him: **go straight on, go left, turn...** but the robot only moves when there's lots of light, when he gets to the feeding tray it has to be dark so he stops and gives the bread to the birds. The feeding tray has to be black, that way he'll stop and he'll leave the bread there. If we make a noise with the tape recorder, the birds will hear it and come get the bread: like "poom, poom, tick, tick, cheep, cheep"... **The robot could also say** "Come on little birdies, your food's ready here on the ground." *(Francesca)*

And it needs this one, too, the temperature sensor, because that way the robot **feels and if it's cold** he takes the food to the birds, but before he gets to the feeding tray he has to hear the "cheep, cheep" with the microphone. *(Alessandro)*

While the children looked to the technology to provide answers that would give shape to the challenges they launched, they found some possible meanings and attributed a stronger identity to the work being carried out by using other languages, narration in particular. This certainly stimulated their motivations, interest, thoughts, and enthusiasm.

In this long process of research, an important role was played by the context that accepted the complexity and tried to make it "revealable". In this sense, the various strategies adopted were crucial:

- the multimedia documentation (digital images, written observations, interpretations of both adults and children…), placed at the disposal of the children for revisiting; i.e. for a comparative re-reading of their experience;

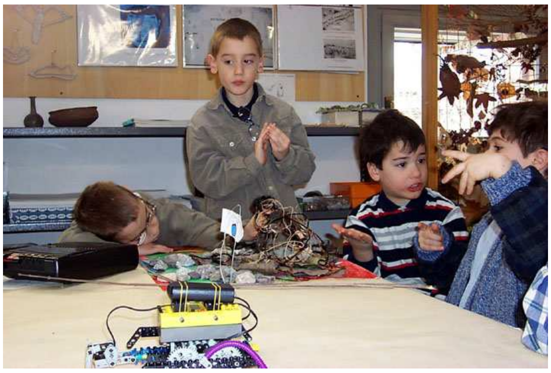
- the traces of memory (products, drawings, photographs, etc.) left by the children in the work space, objects which also contributed to the progressive enrichment of the environment;

- the use of instruments such as the video projector to construct "zones of dialogue" among the children, zones that are difficult to create around the small monitors of the computer;

- the creation of contexts able to stimulate interpretations, intuitions, hypotheses, visualisations, and relationships;
- the use of multiple languages for hypothesising, designing, and representing complex systems, and making them visible;
- the identification of hardware and software as powerful instruments that help to make the complexity not simple but revealable.

Once again in terms of strategies, it is important to remember the interlocutory role of the adults who, during the discussions with the groups of children, often formulated generative questions that were capable of eliciting developments in thinking and further awareness.

The example given below provides effective testimony to this.



The situation was mentioned previously, and refers to the design by a group of children of a “living system”, a cybernetic scenario composed of a city that some “monsters” want to conquer, while the “defenders” of the city have to prevent this.

The children encountered a number of problems in the design phase, particularly connected to the reciprocal attraction between the antagonistic robots and between them and the physical environment of the scenario.

These problems were closely connected to the technological characteristics of the construction kit (in particular the possibility to programme the reactivity of the sensors).

To support the development of the children’s processes of thought and action, the teacher proposed a series of question that progressively helped them to focus on the problems and hypothesise possible solutions.

- What kind of characteristics do the “monsters” and the “city defenders” have to have?
- How can you make the monsters understand that the place they have to go toward is the city? And how can they get there?
- What has to be attractive about the city to make the monsters want to go there *(characteristics that can be recognised by the robots’ sensory apparatus)*?
- And what characteristics do the monsters have to have so that the defenders recognise them and try to stop them?

2.4.3. Connection as communication

Communication was a fundamental theme to consider in exploring and developing an idea of programming that was close to the children, and in order to reveal this idea and make it more tangible. Even though at times the children’s questions around this issue remained open (or in any case they found temporary answers that were modified as they went along), the research became the occasion for encountering, experimenting, testing oneself, and framing possible programming structures.

“I’m drawing the world, that way F3 can know, when he gets there, what the world is.”

“I drew the arrows; they’re for telling him to go straight and turn.”

“We made a metre stick, too, that’s for measuring the track. Then we’ll tell him how long it is.”

“First you have to give the commands, that way he understands how we talk… we’ll write them for him.”

“…we’ll tell them to him… after that he’ll remember them.”

“But is it possible that one day he’ll learn our language and he can talk to us? Does he have a head?”

“If he comes to the assembly with us, he’ll learn!”

To reveal the dynamics of relationship and communication between their robots, the children thus investigated:

- strategies for knowing and learning
- methods for relating
- strategies for giving identity
- giving value to the role of memory
- codes and channels of communication

The effort to know and recognise the point of view of the other became evident when the children were investigating the procedures for communicating with the robots and for communication among the robots. In this phase, the children seemed to return to communication strategies that are familiar to them, then developing others that could make sense also for their objects-subjects, and in this way exploring some of the methods that govern how the kits work.

"We can't hear them, but the robots talk through the wires, with their own language."

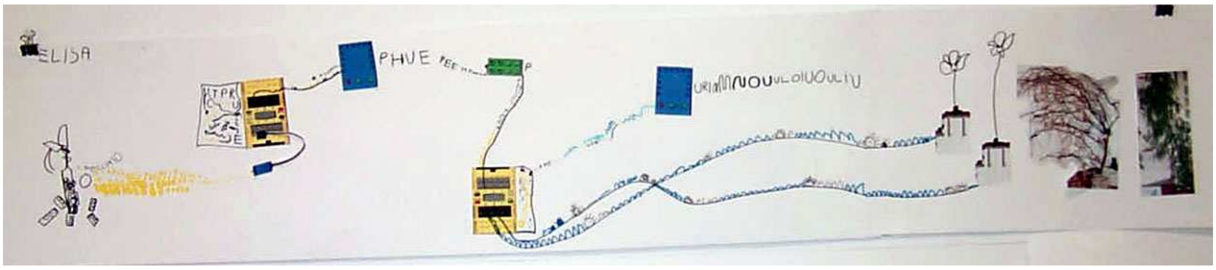
"But do you know the robots' language?"

"Wait, I just thought of something: What I thought was that the robots' language doesn't exist… we transmit it ourselves with this [tape recorder]."

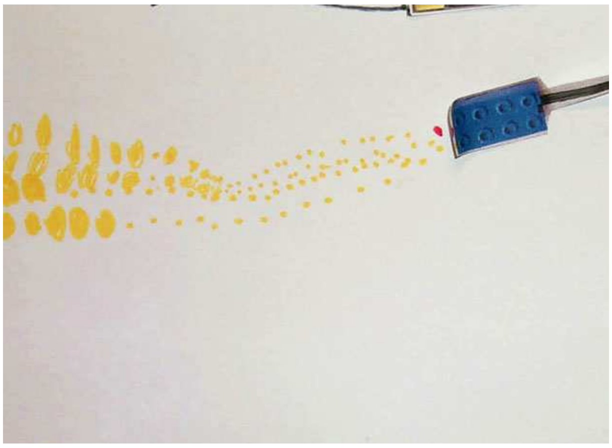
The children's idea that transformation is a condition that generates relationships between different natural and artificial worlds (real and digital) also emerges in their graphic representations of their theories.

Faced with the attempt to design and develop programming on paper for the robots that animate the branch, the children identify communication as an element and a condition that generates relationships.

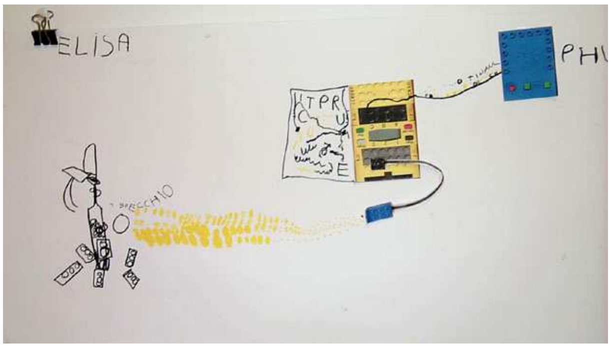
It is a type of communication that is modified and transformed based on the quality of the single sensors and actuators, but is also an idea of communication which is attentive to the variation of codes between the real and the virtual.



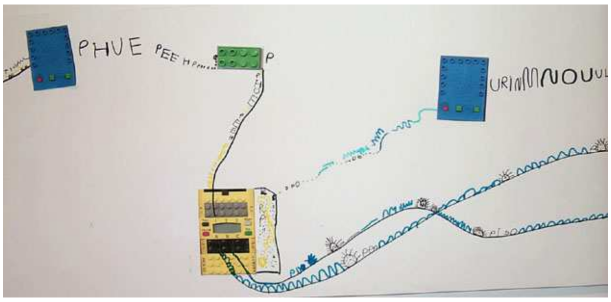
Elisa's theory represented in graphic form



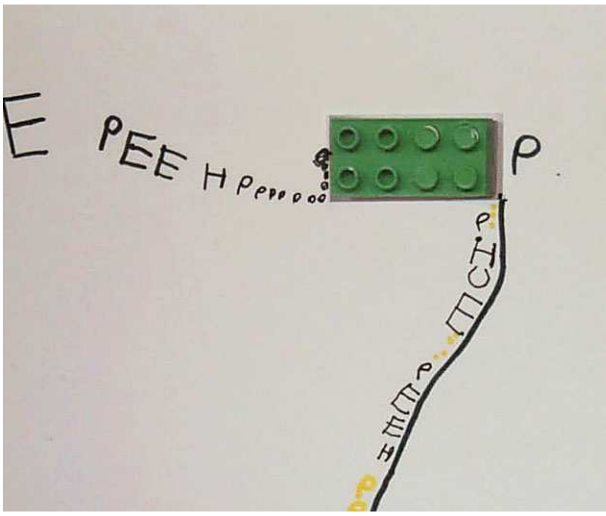
"When the light of the sensor gets to the sensor, I think it gets smaller to go into the sensor… Inside the sensor these yellow balls get little and then the light becomes a voice because the wire that connects this sensor with the RCX is working and working..."



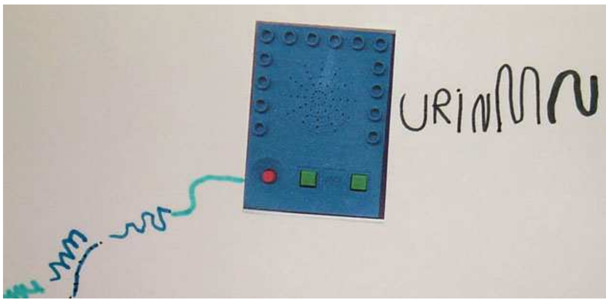
"Inside the RCX the light works and works and then gets modelled, it gets turned into a voice, then with the wire it goes out into the tape recorder..."



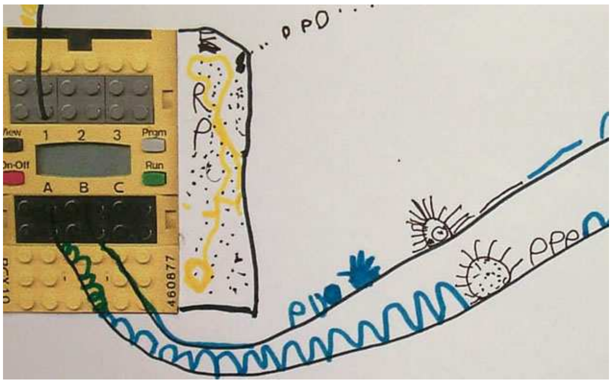
"The voice got bigger, then it gets smaller and smaller..."



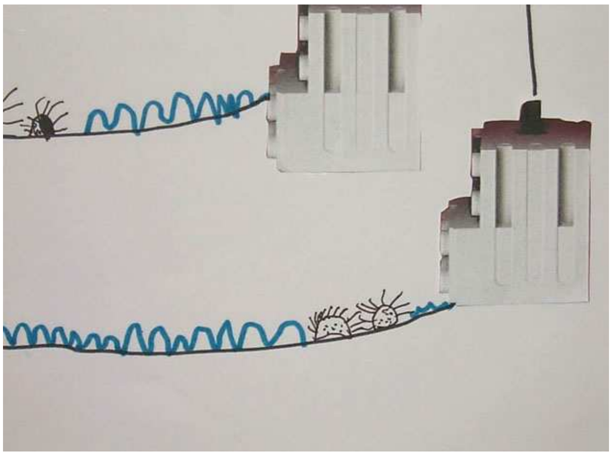
"...To get into the microphone, first it gets medium-size then smaller and smaller, and when it goes into the microphone it's still a voice – it's a really complicated job!"



"From the microphone to the RCX, the letters go from being small to large... The sunlight, when it goes in the RCX and in the tape recorder, it gets specialised; when it becomes a voice there's still a bit of the sunlight."



"...When the motors have to start to make the fans turn, in the message there's sort of like gas, or wind, it's a message of noise, of gears..."



"...There's a lot of wind in these wires, because they have to make the fans understand that they have make cool air..."

Another interesting aspect to underscore is that, in trying to create a programme, some of the children used the strategy of creating sequences, which is clearly visible in their productions on paper.

All this suggests to us once again the importance of an interface for programming cybernetic objects which should not be unidirectional but flexible, design-oriented, and open to the children's different thinking strategies.

2.4.3. Nomadic memory

Today there is an emerging idea of memory that is mobile and nomadic, which opens and is itself open to traversing and connecting universes of problems, worlds lived, and landscapes of meaning (mental, economic, professional, pedagogical, scientific, etc.).

Memory is recognised and recognisable as a structure and a place of knowledge and, as such, we find it in this research at different levels, with different meanings, perhaps with new stimuli that come to us from the children, who are so able to connect, sometimes implicitly, sometimes explicitly, the different subjective and intersubjective "memories".

The children offered us suggestions for focusing more closely on what may constitute a network culture[10], a question around which there is currently much debate, both political and economic, but which does not often involve the scholastic world.

In the CAB research, we can see at least three different levels with different significance.

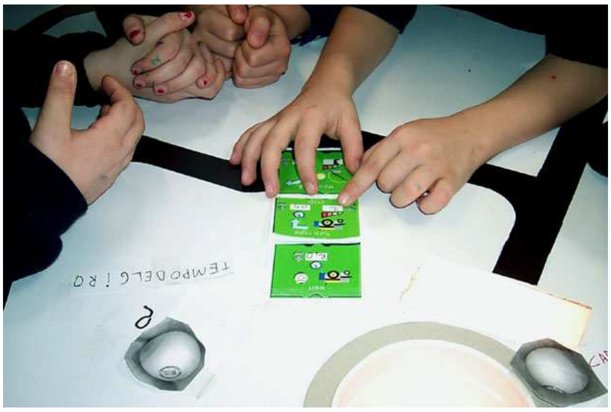
[10] Pierre Lévy, L'intelligenza collettiva, Feltrinelli, Milano 1996

2.4.3.1. The memory of the robots as an element of identity

In the construction of the various robots, the children attempted to build a memory for them. It seems that they attribute to memory the possibility of guaranteeing the originality and autonomy of the identity of their objects-subjects. To have a memory means having one's own history and experiences that are personal and unique.

2.4.3.2. Memory as a data bank for interpreting the unknown

On the other hand, in thinking and designing with the possibilities offered by the kit, the children themselves often make recourse to their memory (individual and group) of other experiences, going to "fish out" and circulate other knowledge and references that can help them to construct meanings and understandings.



For example, to identify the codes and channels of communication with the robots, the children turn to analogous knowledge and experiences encountered in other contexts, outside the CAB research:

"Our voice gets inside the head [of the robots], like in Microworlds."[11]

"But it would be good to have a remote control, like Emilio[12] *does."*

"The sensors are like the ones for bats, that send the waves…"

It seems that the children know how to make recourse to this sort of personal archive of experiences in order to develop new knowledge, but also to bring the experiences back into play and discussion to revisit and modify what they know.

3.4.3.3. The stratification of the memory of the individuals and of the group as a didactic strategy

In the experience of the municipal preschools of Reggio Emilia, one of our established didactic strategies is to leave notes and traces of the children's experiences in the environment; teachers construct panels and various types of documentation to make the memory of what has taken place visible and accessible.

This strengthens the spontaneous strategies of the children because it allows them to go back over their thoughts, to revisit what they have done, and carry out assessment and self-assessment of their work.

In the CAB project specifically, the forms of documentation used for supporting memory were:

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[11] Microworlds is a computer programme often used in the preschools.

[12] Emilio is a robot toy that is familiar to the children.

- documentation on paper containing texts (the words of the children and teachers, and drawings of the children's hypotheses), photographs and video recordings;

- digital documentation (organised on html pages), which was updated in progress as the various paths of research developed;

- a sort of 'digital photo album' organised by images, which was easy and intuitive for the children to consult and which encouraged them to revisit and reinterpret their learning experiences.

Regarding this question of memory, we feel that what emerged from the children in the course of the research is of considerable importance for the development of the idea of memory in the software.

How memory is constructed, how it is used, and how the children can change it; i.e. how it becomes a structure of knowledge, was the topic of frequent discussions with the partners.

2.5. Visions of possible futures

When we began working on the idea of the CAB project, we had many intuitions and few certainties. Starting from these, in any case, we set out a number of objectives and guidelines.

The project was therefore defined in process, as we acquired new awareness on two different levels:

- the interweaving with the activities of the partners, particularly in relation to the software and hardware development
- the creation of places for play and research where the children could encounter and work with concepts that are both familiar and innovative, such as those introduced by the sensors and their programming.

In the thirty months of work, we have carried out investigations with five- and six-year-old children, and a number of experiences with four/five-year-olds and six/seven-year-olds, always with materials that were not yet perfected and often with parts of prototypes.

Therefore, a number of questions and many curiosities remain open; rather than being concluded, the work has brought out and initiated new lines of investigation.

As regards the initial objectives, some answers emerged with clear definition. These answers stimulate us to go forward in areas of research where new alliances and solidarity can be created between the biotechnological-digital sphere and the educational experience, at the centre of which are the children, their protagonism, and their learning.

As regards the school environment, the work carried out in the CAB project proposes innovative interventions in the environment and also leads to the intuition that we could go much further if the world of technology truly initiated a close dialogue with that of school.

This dialogue would involve investments of economic and technological resources in close relation with educational and pedagogical projects.

One of our hopes is therefore that a "transformational dialogue" remains open between the different professions, where the relationship between the culture expressed by the children and the culture of the adults (teachers, electronic engineers, designers, researchers, pedagogistas, and so on) can truly generate new images and be translated into innovative materials, digital and non-digital.

The didactic methodology adopted in the research makes reference to a complex system of strategies and procedures, and involved the relational action of children, teachers, parents, researchers, and various experts as consultants and contributors.

It is way of working based on flexibility and innovative, sensitive research where everyone (adults and children) was in the condition of learning step by step.

It involved the adoption of a spiral type of logic, which keeps the differences together and attempts to maintain the central focus on the construction of meanings.

We feel that we can glimpse the possibility also for the future of an idea of school where:

the children, particularly in the small group dimension (4-5 children), share, construct, and try out a capacity for critical thinking that supports processes of assessment and self-assessment

- the work takes place in motivating contexts of play, where the play-based, emotional, and affective dimensions are indispensable parts of the construction of knowledge by children and adults;
- the way the result is achieved is just as important as the result itself, because the qualities of the process are interwoven with the fabric of its outcomes;
- the biotechnological environment can try to reveal to the children the information necessary for understanding the possibilities for using the materials they encounter (digital and other) and their meaning with different contexts;
- multimedia documentation created in process not only constitutes the memory but also becomes a reference for re-reading that can generate new questions and hypotheses to be investigated;
- digital materials are widely present in the environment and coexist with other instruments and languages in order to foster the children's action, though in a discreet, non-invasive way, in the various experiences;

- the issues raised by robotics can be approached and examined in depth in terms of the different values they can assume: ethical, psychological, aesthetic, affective, emotional, and cognitive.

We see the idea of a school that is curious, that welcomes the entry of technologies for inventing other strategies that forge new roads to the encounter with learning, in both traditional and innovative contexts.

As regards the development of the software and hardware, we feel that we have certainly seen new possibilities for creating programmable materials that would be interesting also for young children.

In terms of the hardware, its properties and the possibilities of the various specific sensors should be declared more clearly, and it should be possible for the children to sense these intuitively without their being banal or over-simplified.

The encounter with the world of design thus becomes essential for further possible changes in the materials.

The software should maintain a closer relationship between flexibility, sequence, memory, and programming of subjects in a systemic relationship.

Advances have been made in both the software and hardware, and this permits us to affirm that it is an interesting and possible road for children of this age to follow, but obviously further developments are necessary, along with investments of time and economic resources.

Looking toward the future, we sense with even greater awareness how important it is for schools to be the protagonists of these moments of advancement in research on the technological-digital world at the European level.

The CAB research is therefore concluding in the temporal sense, but certainly it has not exhausted its missions declared explicitly and implicitly in the project.

The experience has given a strong impetus for innovation to the didactic experience of the schools involved in the project, though we have been cautious not to let ourselves be carried away by easy and useless enthusiasms, and have tried to keep in the forefront a respectful attitude toward the children.

For children and adults alike, the experience has activated and perhaps accelerated a process of acculturation regarding the technology of the sensors applied to didactics, as it has made this process more explicit and visible.

This is the road we have travelled, with many possibilities not yet encountered.

The CRE group feel that we have learned, and thus gained much in our knowledge, through the experience of the CAB project.

A final hope is precisely that we can continue to discuss this experience with various international interlocutors in order to broaden the exchange and receive critical contributions and new stimuli.

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2.7. CRE: CAB organisational structure

Coordinating group

Aristodemo Spaggiari	Director - Dept. of Education CRE
Carla Rinaldi	Director - Early Childhood Dept. CRE – Project Leader
Grazia Filippi	Coordinator CRE and Contact Point Consortium CAB
Tiziana Tondelli	CRE Administrative Supervisor
Elena Bruna Giacopini	CRE Research Supervisor
Paola Cagliari	Pedagogical Consultant
Paola Barchi	Teacher/Researcher
Gino Ferri	Teacher/Researcher
Maura Rovacchi	Teacher/Researcher

Secretarial staff

Federica Ferretti

Dimer Camparini

Information Technology Consultant

Franco Bonazzi

Municipal Preschools

Pablo Neruda

Lara Bonadia	Teacher
Simonetta Bottacini	Teacher
Lara Del Rio	Teacher
Antonia Ferrari	Teacher
Mara Davoli	Atelierista

8 Marzo

Giuseppina Baroncini	Teacher
Rosanna Macchidani	Teacher
Brunella Marchesini	Teacher
Antonella Spaggiari	Teacher
Georgiana Zanetti	Atelierista

Villetta

Angela Barozzi	Teacher
Ramona Carretti	Teacher
Diletta Tirelli	Teacher
Giovanni Piazza	Atelierista

Elementary School

Italo Calvino

Anna Maria Ferrari	Teacher

and some other personnel of CRE.

In particular cases, the work group made use of outside consultants and collaborators in the legal, information technology, and the pedagogical areas.

Swedish Field Tests within the CAB Project

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3.1. Introduction

This is the concluding report from the Swedish members of the CAB project, i.e. Construction Kits made of Atoms and Bits.

The intention of the report is to give a continuous presentation of some of the most interesting and important processes during the course of the project, successively giving the first year's partial results, together with the more conclusive findings from the final stages of the project.

3.2. Research Background

The School of Education and Communication (HLK) in Jönköping has been responsible for carrying out the Swedish field tests. HLK is one of three independent Schools for research and education within the Jönköping University Foundation. At HLK, research and development is carried out in close association with the School's study programmes for Children and Youth Education, Comprehensive and Pre-School Teacher Training, and Media and Communication Studies.

For a period of more than 15 years, a number of IT projects have been successfully carried out at HLK. These projects, which have attracted much national interest, have focused on the educational use of computers among pre-school and school children. Findings show that children are both encouraged and stimulated in their work by the challenges presented by computers. Following the same lines, the LEGO material included in the CAB project have been used to introduce new challenges, where the children have been able to construct and program robots made of LEGO bricks. Within the framework of Workpackage 4 (WP4), we could foresee a number of very interesting and important questions being raised by this research project, based on the fact that children take an active approach to using computers, and that they are interested in exploring the possibilities offered by new software and hardware. However, there are still very few tools available which are specially designed for children i.e. tools that are designed to encourage and spur children to explore new possibilities, while at the same time taking an interactive approach to their activities.

3.2.1. Field Testing

Field tests have been carried out in three schools located at some distance from each other. One of the schools "Landsjöskolan", is situated in Jönköping. The second school, "Bredaryds skola", is located in Värnamo, about 70 km south of Jönköping and the third school, "Nya Varvets skola", is in Gothenburg, some 150 km west of Jönköping. These are junior- and intermediate level schools, which vary in size and number of pupils, and are located in a rural area, a sparsely populated urban district, and in the suburb of a major city. Each school has a local project supervisor and teachers taking part in the project. Both the supervisors and many of the teachers have been involved in other IT projects or networks previously initiated by HLK.

Figure 1. The schools participating in the Swedish field test

3.2.2. Project Organisation

At each of the three participating schools a project supervisor was appointed. At "Landsjöskolan" it was Staffan Claesson (recreation instructor); at "Bredaryds skola", Annica Martinsson (teacher), and at "Nya Varvets skola", Åsa Wallén (teacher) and Olof Sandström (recreation instructor). Olof has also partly been responsible for the technical side of the project. The project supervisors had the overall responsibility for the project at their respective schools, co-ordinating CAB activities, and collecting and filing all the relevant documentation. All the participating pupils, who in Autumn 1998 were 6 or 7 years old, were involved in the project for the entire project period.

Figure 2. Participators in the Swedish field test

Project leader of the Swedish field tests was Bo Gustafsson at HLK. He has, for more than 15 years, been engaged as a project leader in a number of national IT projects principally focusing on the use of computers among young school children. Dr. Jörgen Lindh, whose doctoral thesis examines computer-aided education, has headed the research activities within the Swedish field tests.

Alexander Tornberg has been responsible for the technical side of the project, the website for WP 4 and also a number of other IT projects currently run by HLK.

3.3.3. Project Research Material

Each of the participating classes was supplied with LEGO construction kits. In addition, each class had access to at least one multimedia computer, or more if required. At each school the project teachers also had a digital camera, a scanner and a video camera at their disposal. All three schools had access to the Internet, including e-mail software, the project supervisors having their own personal e-mail addresses. In February 1999, the schools had cameras installed together with the required software to be able to arrange video conferences using CU-SeeMe.

3.3. Research Questions

The following is an overall description of the Swedish CAB research process, in which the *main research issue* has been:

What will the children be able to accomplish by using the LEGO material?

Figure 3. Children at Bredaryd School participating in the project

We can distinguish three separate stages in the process of becoming aware of the full possibilities of LEGO MINDSTORMS in schools, and the kits becoming a natural component in learning situations, more or less in combination with other, traditional supports: pencils, tape-recorder, videos and so on. The three stages can also be formulated as questions:

- What will the context for LEGO MINDSTORMS be?
- How do we teach children to use LEGO MINDSTORMS interfaces (software and hardware)?
- How do we integrate LEGO MINDSTORMS into regular school activities?

These are questions we have been wrestling with in different degrees during the various stages of the project.

The implementation of the research process can be described as the following activities:

- Field work, testing the kits.
- Documentation of the tests.
- Administration of the documentation.
- Regular project meetings.
- Possible re-adjustment of the research aims.

A characteristic feature of the Swedish field test has been the geographic separation of the involved partners. The schools are far away from each other, and many of the teachers participating live far from the research centre at HLK. This demands an excellent communication network. For that reason we drew up a list of directives for documentation during the project planning stage, such as recording information and dates of observation.

It was not our intention to formulate any clear-cut hypotheses for the Swedish field test, but an overall research issue, which was:

What would children be able to accomplish by using the LEGO material?

There was, however, one hypothesis integral within the Swedish field test, from the inception:

The version of LEGO MINDSTORMS that was supplied at the start of the project should work properly when used by the target age group in a normal Swedish school environment.

The definition of "work properly" was that pupils and teachers together would be able to obtain results by their input of a reasonable amount of time and effort.

The overall research issue was categorised into a number of separate questions, partly connected to the different periods of time during the learning process, and partly having to do with various social and communicative aspects affecting the children's work with the LEGO kits.

The questions were formulated under the following headings:

- The Initial Stage
- Working with the LEGO Material
- Social and Communicative Aspects

A number of subquestions, divided into three main categories, are as follows:

The Initial Stage

- How is/should the context (be) organised? (Classroom, number of teachers etc.)
- What previous knowledge do the children possess at the start of the project?
- Of special interest here is the type of computer knowledge/skills the children already have.
- What are the children's conceptions of robots?

Working with the LEGO material

- What difficulties with familiarisation does the LEGO kit present?
- What learning levels occur during familiarisation with the LEGO kit?
- What methods do children use when they construct mechanical objects, such as robots?
- Do children plan their work in advance when they construct and build LEGO objects or do they plan during the time they build their robots?
- What skills and abilities do children possess or develop, when gaining an increased awareness of real mechanical things, e.g. cog wheels?
- How do children react to programming mistakes they have made, and how do they solve these problems?
- What do children choose to do first: build the model or program the robots?
- How do they develop their technical knowledge and skills?
- How is work with the LEGO material connected to other subjects at school?

Social and Communicative Aspects

- How does social interaction between the children influence their activities with the LEGO material?
- What is play and what is teaching? Is it possible to separate these activities/should they be separated?
- Are there any significant differences in how girls and boys work with the material?

It should, however, at this stage be emphasised that this was an open agenda, allowing for additional questions to be raised in the course of the project.

Of these issues, several could also be subdivided. Some of the questions raised above already overlap each other and could even merge at a later stage.

3.4. Research Methodology

The present research project can be identified by the following keywords:

Explorative: The essential element of the CAB project is the development of new knowledge and to find new learning methods.

Hermeneutic: The hermeneutic spiral is sometimes used to describe the process of developing new knowledge. Our aim has been to create a better and more true-to-life picture of the research object, while at the same time gaining a deeper understanding of the research context.

Qualitative: The data and/or information we have collected, can, to a large extent be described as the gathering of observations, or textual descriptions of various educational or teaching situations. However, this does not exclude the fact that some of the collected data is of a quantitative nature.

Participant observation: Primary data, to be analysed at a later stage, has been collected by the teachers working together with the children. The importance of this is that it is those closest to the children and know them very well, who have made the observations, which cannot be stressed enough.

The most important task for both teachers and researchers involved in this project has been to document and report the research experiments and findings as thoroughly as possible by providing detailed descriptions of cognitive processes and concepts developed by the children. In this way, the collected information should make it possible to understand how children act, think and accept new challenges, and how they seek and find solutions to problems that arise.

The purpose of data collection has been to successively create a picture of the way children develop their knowledge. This method of generating knowledge from empirical textual descriptions within a specific area, is sometimes called Grounded Theory.

The project supervisors documented their observations in the form of diary notations, photos, videotapes etc. The submitted documentation were filed and stored for subsequent analyses for the research findings, parts of which have been given the form of monthly multimedia presentations on our website.

Eventually, all the information was stored in a database created using FileMaker Pro. The database included the name of the observer, the date, the school, the type of observation, and the name of the enclosed file. Searches can thus be carried out using any of the above data.

In order to simplify the process of documentation and data collection, it was decided to provide the three schools with digital cameras. Pictures could then automatically be stored on disks and short video sequences could be recorded. These were stored on disks and so the process of submitting pictures became considerably easier.

A detailed presentation of the various methods used in the course of this project, together with a brief description of each method follows:

Direct observation combined with Check List or Observation Chart

- a means of assistance when making observations, i.e. if you know what events or aspects to study and therefore will be able to follow a pre-formulated questionnaire

Videotaping

- video recordings create a relatively complex picture of the interface between the user and the computer. This is, however, dependent on the quality of the taped material

Interviews

- structured interviews (including pre-formulated questions) and unstructured interviews (flexible, no pre-constructed questions)

Questionnaires and surveys

- limited questions with a number of given alternatives
- open-ended questions without any given alternatives

In addition, standardised questionnaires have been used to study general factors and to analyse dependent variables.

3.5. The First Year of the Project

The introduction of the LEGO material to the children was a very interesting stage in their process of learning. When starting the project we had a choice of possible approaches to the introduction of the material:

1. Provide the children with detailed instructions of how to build specific models.

2. Do not provide the children with any instructions at all.

3. Suggest some examples of constructs to be made from the LEGO material, but otherwise let their sense of discovery determine their work.

Underpinning each of these strategies was a pedagogic/didactic approach, which can be commented as follows:

Strategy 1 was contrary to the very nature of these experiments with teachers giving detailed instructions, i.e. against the idea of appealing to the children's sense of joy when exploring new ground. This strategy was therefore not chosen.

Strategy 2 was possible. Research findings in the U S involving children 9-14 years old show that many children are able to handle the material themselves. However, it is somewhat unrealistic to expect that pre-school children in general should be able to perform such tasks. Thus, choosing this strategy would be dependent on the age of the children.

Strategy 3, giving a short introduction to the material, which focused on discussing possible prototype models or metaphors, seemed to be entirely realistic. In this case the children's imaginative worlds are used as a starting point, developing pictures the children would already know. One possible approach was to try to identify human needs, and to find means of fulfilling these by the creation and production of models or robots.

To summarise, strategies 2. and 3. could be considered as possible paths to follow. In this situation, it could have been tempting to have the different schools choose different strategies and to perform a comparative study. However, the number of participating classes was probably to small for such a comparative study.

Thus, the suggested approach focused on Strategy 3 as presented above. This meant that the teachers gave the children a short introduction to the material, together with some ideas as to how the material could be used for building models. The extent of this introduction was adjusted according to the children's age or level of maturity.

Initially, we worked with several groups of pupils (from grade one and upwards) from the three schools, so that we could observe the work of pupils of various ages. We also wanted to see if children in year 2 found it easier to use the material. We wanted to involve several teachers in the project for two reasons. Firstly, we wanted to see if "ordinary" teachers and pupils could handle the material properly. Secondly, we wanted to avoid limiting the knowledge of the LEGO material to one teacher and thereby increasing our dependence on that person. The first year of the CAB project was characterised by the great efforts devoted to establishing a good organisation, both in the work within the schools and in other activities that formed part of the project.

3.5.1. Some conclusions from the initial research

- The children found it easier to construct robots than to program them.
- The children had difficulties in learning how to use the program for working the robots.
- Teachers found it very difficult to supervise the project sessions and to document their observations at the same time.
- Using LEGO MINDSTORMS often created complex learning situations.
- In many cases, girls found it easier than boys to concentrate on learning how to use the project software.

Experiences from the first year can be separated into two groups, the first concerning contextual issues, and the second material issues.

Context

By context we mean the total environment in which the field tests take place. In this concept we include factors such as localities, computer/technical equipment, access to personnel, and schedules, but also teachers' resources (time, knowledge about the material etc.), and the individual children's characteristics.

We found increasing difficulties in learning situations where there were:

- too large and too many groups of children in one class,
- too many activities going on in the classroom,
- when working with LEGO MINDSTORMS had to compete with other activities,
- not enough teaching staff,
- length of lessons too short.

We found differences in progress referring to the children's characteristics (age, capabilities, gender etc.)

Material

By the concept of material we cover the entire LEGO MINDSTORMS kit, i.e. both hardware and software, in which hardware is the mechanical parts, and software the equipment for programming the robots. We found some mechanical problems, i.e. connecting the LEGO kits, and difficulties in application of the programming activities because of problems with the interface.

3.6. Revised Research Objectives

Our point of departure during the first period of the project was to offer a minimum of help to the children, supporting them only when they were faced with major problems. This added a certain element of excitement:

- What was considered to be a minimum of help?

Our impressions were that the children encountered some serious problems when building their LEGO models, especially during their programming activities.

Our conclusion was that *the material supplied in the first version was not sufficiently self-instructive*. We therefore decided in a slight shift of strategy.

Our initial studies showed that our original hypothesis that the version of LEGO MINDSTORMS supplied at the start of the project would work when used by the target age group in a normal Swedish school environment was inaccurate. It was therefore discarded in favour of the other one.

As a result it was decided, in late spring 1999, to change the aims of the project as follows:

- To limit the number of pupils in each group, as well as the number of groups.
- To concentrate more on helping the children understand the various parts of the software.

Some of the difficulties found when working with the LEGO MINDSTORMS interface, were:

- The use of the English language was a limiting factor; there should have been a Swedish speaker.
- Texts had to be exchanged by graphic symbols.
- It was difficult to connect details to the RCX (especially to the motors, which often fell off when driving).
- New components, especially more appealing to girls (for example wings), should be added, as well as a larger range of colours.
- It was frustrating, but perhaps necessary, having to reload the software if the batteries fell out, which frequently happened as the RCX easily came apart.

The above was summarised as a list required for the development of the first version of the construction kit, i.e. the development of new components, and a revised version of the software provided.

3.7. New Components and New Software

The new material was introduced in November 1999 to complement the previously used material within the CAB project. The following additional components were given to each of the participating schools:

- 2 bend sensors
- 2 microphones
- 2 tape recorders
- 1 IRB (Infra Red Beacon)
- 2 sets of semi-fabricated parts in green boxes

In addition, a new Swedish version (1.5) of the LEGO MINDSTORMS software was presented.

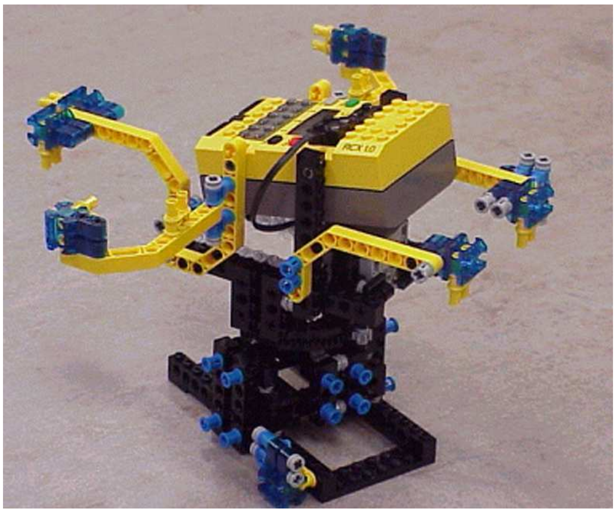

Figure 4. One of the new semi-fabricated components

The new components added functions in two major respects:

- The new sensors allowed greater possibilities for the RCX to communicate with the outside world.
- The semi-fabricated parts acted as instigators and initiators for module construction.

During this period, teachers at the project schools experienced some problems when using the new material and the program. Some of these problems were mutual, some experienced by individual schools. An overview of the comments of each of the local school coordinators is given below.

3.7.1. Reaction to the new hardware

One of the difficulties experienced throughout the period was the programming of the new sensors. In some cases there were even problems in understanding how to use them. One example is the IRB unit, which the teachers could not understand until the ITD was consulted in January 2000. When the functions of the IRB were finally understood, most of these units appeared to be out of order. Thus, we have not been able to use them very much.

Gradually, teachers learnt to program one or two of the sensors, e.g. the microphone and the bend sensor. The tape recorder caused problems, as there was, for quite some time, only one program for this.

There have been some additional requirements voiced as to the LEGO material. Concerning hardware, the requirements are to have additional cog wheels in different sizes. Another requirement is to have an RCX attachable charger. This would be very time-saving, as it takes a long time to dismantle and reassemble the constructions when changing batteries. There is also a risk that the microcode can be erased.

One great disadvantage has been not to be able to achieve exact and precise movements, caused by the limitations of the time-settings. It would have been of great advantage to be able to set these in 1/100 sec; or, having more exact and reliable motors.

3.7.2. Reactions to the new software

The new version was mainly tested at Bredaryd school, resulting in the following experiences:

- The pupils have found the manual and the program texts easier to understand.
- Some problems remain in understanding the various commands, as these are still in English.
- The Constructopedia included in the new manual has been a tremendous help to the pupils in their construction work.

However, there are explicit requirements to have the instructions and commands translated into Swedish.

3.8. Creating Scenarios/Microworlds

One important feature in the activities during spring 2000 was the creation of so-called scenarios or microworlds. This concept was defined by Chioccariello, Manca & Sarti (2000) as ”a microworld cuts a piece of the world out; it is a limited and closed world where laws and possibilities are allowed and others are not” (p.2).

In this respect, the Swedish field test has been inspired both by CRE (and their implementation of the “city scenario“); and by the discussions at the January meeting in Billund.

One important source of inspiration was the presentation given by Carla Rinaldi in Billund, discussing the concept of “agency“, with the purpose of animating or giving life to microworlds and constructing actions/interactions between artefacts. The final definition, decided at the Billund meeting, was as follows:

- “Agency” is “something” that reacts to any circumstances in which it finds itself. It seems to have "life-like" behaviour. Agents act like living creatures and react similarly in typical situations. According to Repenning, Ioannidou & Ambach (1998), agents are characterised by the fact that they can be programmed to perceive and act in response to certain impulses.
- Agents can also react to inputs from other agents. This is one of the main ideas of building scenarios, in which several robots can interact with each other. By creating situations where cybernetic constructs can interact, a micro world context can be constructed, i.e. so-called microworlds. It is assumed that the creation of microworlds will appeal to the children, and make them interested in contributing their own ideas to the creation/construct.

Within the concept of ”agency” some further benefits are:

- Personality. Can give an emotional relationship from the children to the agents.

- Adds a living, dynamic element to LEGO material.
- Can give a sense of independence to "communities", in which several agents interact with or against each other.
- The agent can take care of simple or routine tasks, such as domestic work.
- Can help children to distinguish between man and machine (in those cases where the agent does not possess qualities similar to humans).

But there were also disadvantages in connection with the concept of agency:

- Risks that children can become passive in their relation to the agent.
- Social risks in that children may relate to agents rather than other children.

Thus, one major change of strategy was made before commencing the spring research activities in 2000: *scenarios* were introduced as a basis for the children's group activities. Local project co-ordinators, together with their pupils, discussed and decided various scenarios to be realised, i.e. presenting a framework for the children's creative thinking and the realisation of their ideas.

A very short résumé of the ideas behind the three scenarios created in spring 2000 follows:

<u>Bredaryd School</u>

The group decided to construct a railway with a level-crossing barrier, which would come down when the train passed, and that the IR beacon should signal crossing cars to stop, and then start again.

<u>Landsjö School</u>

The children drew a scenario of a "city environment" where they tried to include all the various suggestions: roads, streams and houses etc.; places where they thought there would be movable devices.

<u>Nya Varvet School</u>

The boys decided that they wanted to build a city environment including a car that would be able to stop at a petrol station. Some of them started by constructing the car, attaching light sensors so that the car was able to follow the road. Some boys also constructed the road, using a large sheet of paper and black tape.

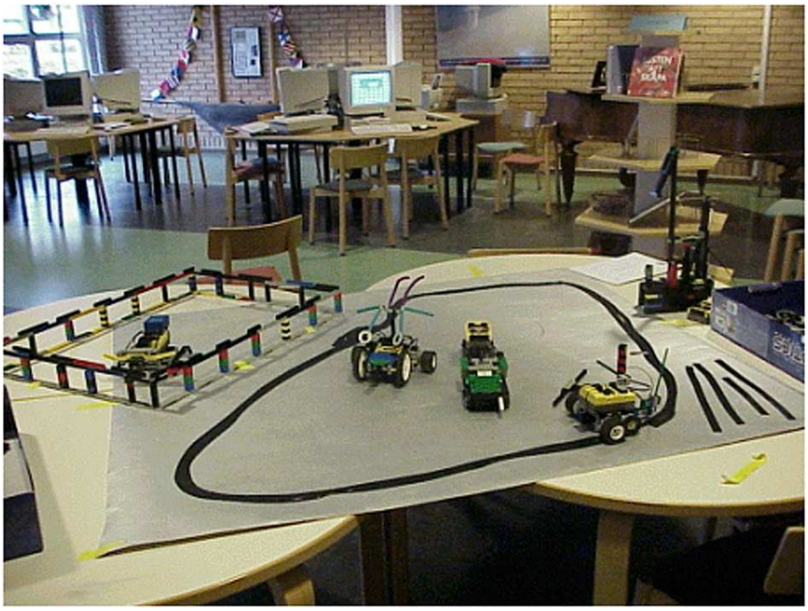

Figure 5. One of the scenarios in spring 2000; a city like appearance

The following section presents some of the views and comments emerging from the idea of a scenario in the Swedish field test activities during spring 2000.

3.8.1. Feed back from the local coordinators spring 2000

These are a few of the responses and comments from the local co-ordinators based on some questions on the project activities carried out in spring 2000. The questions were formulated to generate answers of a more comprehensive nature.

3.8.1.1. Most positive aspects as experienced by the children

- The children have been active in describing their robots.
- Most of the time, the children had great fun during their building activities.
- The children (particularly girls) like to improve their earlier constructs.

3.8.1.2. Most negative aspects as experienced by the children

- Some children were very disappointed when their ideas were not included in the final scenario.
- Organisational difficulties, for example continuity in the construction activities.
- There have been frequent distractions, for example other activities imposing on the time available.
- Too much control, making the separate groups dependent on each other.

3.8.1.3. Building of scenarios as experienced by the children

- The children found working with scenarios a new aspect of the LEGO material.
- The building of scenarios creates a closer similarity to real life.
- Many exciting ideas emerged.

3.8.1.4. Knowledge development among the children

a) Programming abilities

- The children are generally not adept at programming.
- Girls are generally somewhat better at programming.
- The children found the programming easier when they could work freely.

b) Building models

- The children learnt how to follow a set of instructions.
- The children are now able to build other objects than vehicles.

c) Understanding the interaction between software and bricks

- The creation of a scenario has been a major influence in giving the children a better understanding of the connection between software and bricks, as they have to make sure that the various objects do not interfere with each other.
- Difficulties come from the fact that things do not turn out as expected.

3.8.1.5. Most positive aspects as experienced by the teachers

- The scenario has meant a big step forward; it was a joy to see how the children acquire new skills.
- To be able to help the children to realise their ideas.

3.8.1.6. Most negative aspects as experienced by the teachers

- Having to reschedule from time to time, due to changes in the work situation.
- The new material (the sensors and pre-fabricated bricks) did not engage the children as much as had been expected.

Wishes for the future project activities

- Having more time for project activities.
- Intensifying contacts/discussions between the Swedish field test partners.
- Formulating explicit project goals for longer periods.

Future project organisation

- Two local school coordinators will be working with new groups of children.
- One coordinator will continue working with the same group of children.

Wider effects

- Lack of any real interest from other school staff in spite of reminders.
- Colleagues sometimes ask questions, but only to a limited extent.
- There is a certain amount of interest among older children at school.

3.9. "Pedagogical" Scenarios

It was decided to continue working with the concept of scenarios during the autumn term 2000. In contrast to the spring term activities, the scenarios were to be based on a specific pedagogical content, the idea being that each school was to focus on a preferred subject, perhaps as part of the school's regular curriculum, but trying a different pedagogical approach with the use of the LEGO material. The following is a presentation of the results of this new approach, and the pedagogical content, as applied by the different schools, together with the teachers' conclusions from this stage of the CAB project.

3.9.1. Bredaryd School

Scenario

The pedagogical idea presented to the children included a visualisation of the concepts of "half" and "double" using the LEGO material, followed by the children ”teaching" these to their younger peers. In order to be able to test the children's level of understanding, they were encouraged to describe their scenarios/activities in their own words.

Implementation

These were the children's suggestions:

1. A scenario in which two robots would move forward and stop after a set distance; one of the robots restarting to complete the same distance once more. By fastening a felt-tip pen onto the robots to leave visual traces, it would be possible to show the distance covered by each robot.
2. This scenario utilised the lamps included with the LEGO material. The children suggested that two green lamps would light, followed by two red lamps, and then two green lamps again.
3. Using two cars, one of them was to be programmed to complete a semicircle, while the other one completed a full circle.
4. The fourth scenario included sounding an RCX for, for example, 2 seconds, another RCX for 4 seconds etc. However, this was never implemented.

Two groups used the distance scenario; one of the them applying a felt-tip pen to show the completed distances. To begin with, one of the cars, which was intended to go around in a full circle, was made only to go in a semicircle, subsequently completing the full circle in order to find the best possible way of visualising the concepts of half and double (Figure 6).

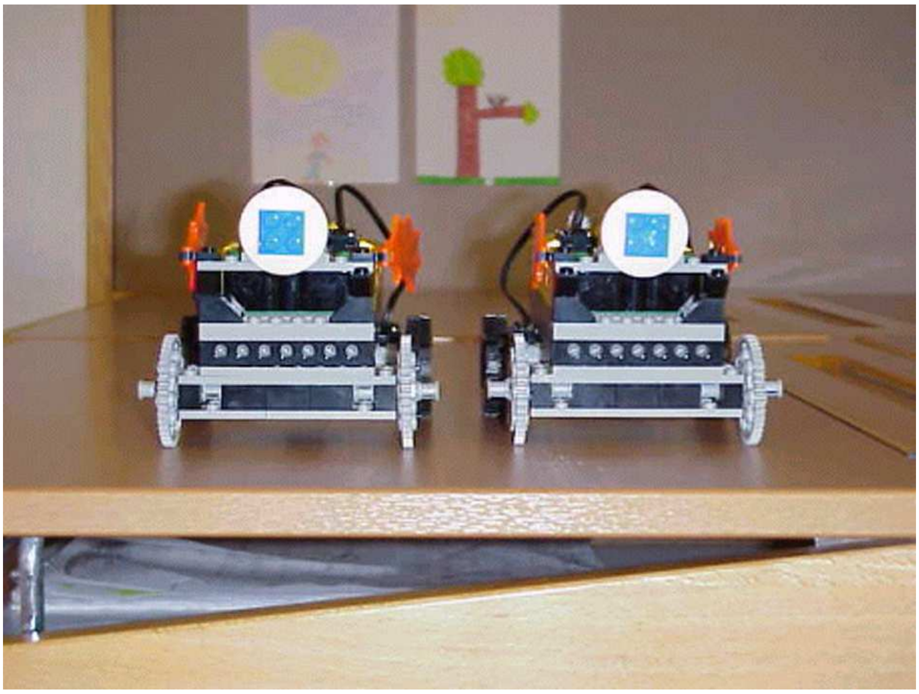

Figure 6. The cars completing a full circle and a semicircle

The children were then given the task of "teaching" the concepts to three groups of six-year-old children, "questioning" them afterwards to check their understanding. The two concepts were visualised by pen traces. All three groups were successful, showing that they had understood the concepts.

At a later stage, a test was carried out including all the third-grade children. The results of the CAB group were significantly better compared to those children not involved in the LEGO project.

Conclusions

The children presented a number of ingenious ideas of how to visualise and demonstrate the two concepts, and were successful in the implementation of these. As they were not allowed to use numbers, only to explain their scenarios in their own words, they had to think the task through carefully, and gave the distinct impression that they had gained a good grasp of the two concepts.

Assembling and programming their constructs did not present any major obstacles to the children. On the contrary, any difficulties encountered were mainly caused by the robots' erratic behaviour from time to time due to unreliable battery levels etc.

3.9.2. Landsjö School

Scenario

At this school, the idea of using a "pedagogical scenario" included the task of encouraging the children to construct and programme robots that would be able to draw pictures.

Implementation

The teacher started by showing a picture which had been made at a previous conference held in Jönköping, encouraging the children to think about how it might have been made and by whom. They soon suggested that it must have been made by some kind of machine, commenting that "children cannot draw such straight lines and perfect circles".

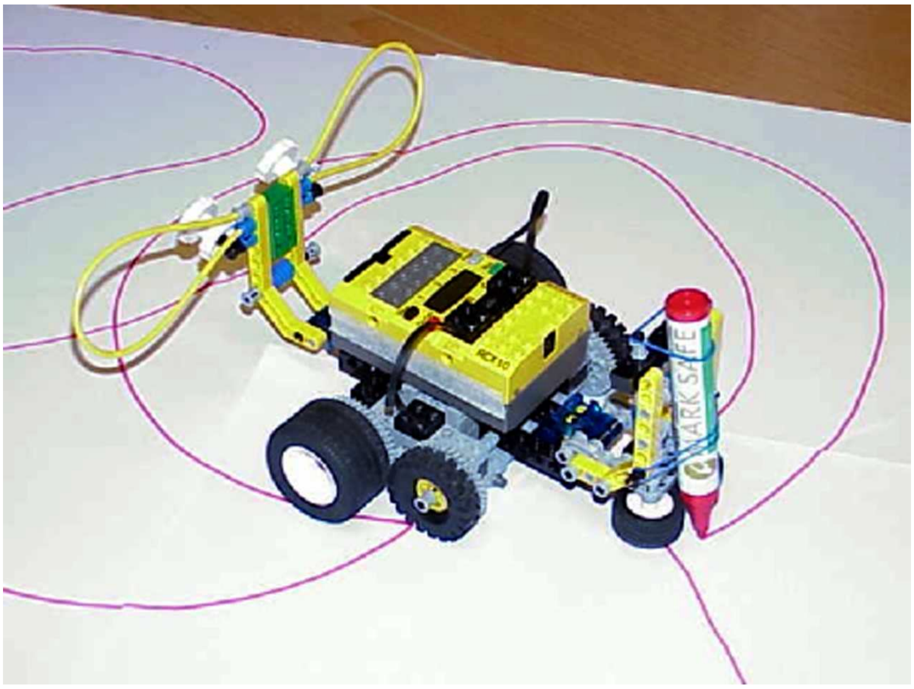

Figure 7. One of the imaginative robots made by the children

The teacher then proceeded to demonstrate how a robot, onto which a felt-tip pen had been fastened could be made to move around drawing lines on a piece of paper. The children were very encouraged by this, and eager to try to construct their own "drawing machines".

Initially, they tried to imitate their teacher's robot, but gradually they learnt to construct their own programmable cars.

The teacher explained and demonstrated how the different wheels and legs could be fitted to the constructs to produce different drawing patterns. Bumpers were added, which made the robots turn and continue in different directions when running into an obstacle, resulting in new and different drawing patterns.

The children also experimented with different colours, attaching their drawings to the classroom wall as soon as one piece of paper was finished. Together they analysed and discussed their "works of art", trying to discern different patterns.

The teacher also instructed the children how they could manoeuvre a car by using two buttons (sensors). The children were very enthusiastic and constructed several steerable cars.

To begin with, nothing happened when the children pushed the buttons, trying to make their cars move. This created a natural opening for the teacher to explain why his car could turn, explaining that this required additional programming. Using the computer, the teacher explained how to include sensors in the programming, completing his demonstration by downloading a program to one of the children's cars. The children were overjoyed on discovering that they were able to steer their cars using the sensors. The program was then downloaded to several other cars, which the children used for their drawings.

Conclusions

It turned out to be difficult to make exact drawings due to some uncertainty in the material. However, the children were offered an alternative to traditional drawings made by using pen and paper.

3.9.3. Nya Varvet School

Scenario

This scenario was focused on teaching the children the principle of cogwheels, and making speed adjustments by using different cogwheels.

Implementation

The teacher started by showing the children various speed/gear ratios by using cogwheels of various sizes, combining the biggest and the smallest wheel, turning one or the other, to give an obvious illustration. One full turn of the small wheel makes the big wheel do 1/5 of the full turn and vice versa: one full turn of the big wheel equals five turns of the small wheel. There is also the difference in resistance, depending on which axle is being turned. The teacher explained and showed this to the children, who seemed to understand the principle, although it was perhaps not crystal clear to them. One of the children, who had a 21-gear bicycle, deduced that pedalling became very heavy when using the biggest cogwheel. As the RCX was not used for this scenario, some other power mechanism was required. The teacher constructed a four-wheel-drive with one motor (Figure 8), using an additional motor that could be turned to create enough power to make the car go forward. Instructing the children about the construction of his car, the teacher encouraged them to try to build similar cars. The children started by using the "old" LEGO material which had all the various cogwheels. Two of the children needed some help putting together the axles and the cogwheels, while most of the group were able to manage on their own.

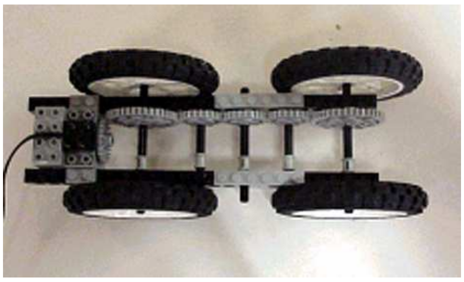

Figure 8. An example of the cogwheel principle

One of the boys attached the wheels to axles mounted directly one after the other. The teacher asked him to test the car on the table. However, the car did not go forward, as the wheels were turning in different directions. The teacher asked the boy to compare his car to another boy's which was constructed with three cogwheels and tyres on the outer wheels. The boy realised the difference himself: "You need a cogwheel between the wheels". As soon as the children realised this, they soon put their cars together including the crank mechanism.

Conclusions

The children gradually gained an understanding of the cogwheel principle and were able use various speed/gear ratios in their constructs.

3.10. The Children's Comments

"What do you think you have learnt by working with the LEGO material?" One of the teachers asked his pupils who had participated in the project this question. The children's comments fell into two categories: either positive or negative statements.

Some of the positive comments were:

I have learnt

- how to use the computer
- more about technology and how to build robots
- how the new components work
- how to deal with new challenges when solving problems
- to be more creative
- more about working with my friends
- how it feels to be in the newspapers, on TV and at exhibitions
- to believe in myself.

Some of the negative statements expressed by the children were:

- When the robots you have built break down.
- When the software does not work.
- When the batteries go flat or fall out and you have to reprogram everything.

3.10.1. Questionnaire

Towards the end of the field test, a questionnaire was submitted to all the children who had participated at some time in the different stages of the project (see appendix). Totally 78 pupils answered the questionnaire. The falling off was low, less than 5 %, that was mainly due to illness.

Most of the questions were of a specific nature with alternatives given. However, some were open questions, giving the children an opportunity to comment on their experiences.

From the answers to question 3 it is evident that most of the children enjoyed working with the LEGO material (table 1).

Table 1. How do you like working with LEGO? (question 3)

Alternative	Frequency	Percent	Cumulative percent
Great fun	67	85,9	85,9
All right	6	7,7	93,6
Boring	5	6,4	100,0
Total	78	100,0	

There is an interesting distribution of comments about the difficulties they encountered in their work. It was twice as much of the pupils who found “computer programming” to be the most difficult task, as those who considered “building robots” to be the most difficult part of their project activities (table 2).

Table 2. What do you think is most difficult when working with LEGO? (question 4)

Alternative	Frequency	Percent	Cumulative percent
Computing programming	50	64,1	64,1
Building robots	23	29,5	93,6
Both	2	2,6	96,2
No answer	3	3,8	100,0
Total	78	100,0	

In order to analyse it from a gender perspective, we made a crosstabulation of the resultat of question 4 (table 3).

Table 3. Crosstabulation of the answers of question 4 towards gender (boys and girls).

Alternative	**Boys**	**Girls**	**Total**
Computing programming	28	22	50
Building robots	8	15	23
Both	2		2
No answer	3		3
Total	41	37	78

Notice that in the group of boys, around 70 % (28/41) found it most difficult to program the computer, but for the girls it was less than 60 % (22/37). For the boys it was obviously easier to handle the mechanics.

In answer to the question if they thought they had been given enough help and assistance from their teachers when working with the LEGO material, a majority of the children replied “yes”. Taking into account that the teachers enrolled in the project often found themselves *unable* to give sufficient help and assistance, this answer is perhaps somewhat surprising.

The answers to question 6 correspond rather well with the answers to question 3: Most of the children would like to work more often with the LEGO material, other school activities permitting.

The children also commented that they learn by working with the LEGO which is evident from the answers to question 7. However, they found it more difficult to define exactly what they had learned. The children were then asked to answer an open, subsequent question: What have you learnt by working with the LEGO material?

An overwhelming majority of the children gave some very concrete examples, such as “building difficult things”, “learning how computers work”, “connecting cords to robots”, “downloading programs” etc.

Many of the children have, in fact, access to LEGO material at home. Another question was about whether the children could understand the LEGO instructions, to which their answers varied. Apparently not all children are capable of following the instructions given, which should be taken into account in the future development of the instructive material.

The concluding, open question concerned the children’s ideas of how to make working with LEGO more fun. The question was: “What would make working with LEGO more fun?”

The children gave some very concrete examples: “building more cars”, “building a real world”, “building a bigger car”, “building more roads with more difficult bends” etc.

The overall impressions from the children’s answers are:

Most of the pupils in the target group enjoy and are stimulated by working with LEGO MINDSTORMS (as examples look at Figure 9, 10 and 11). Their acquired knowledge is mostly of a concrete nature, including building and programming, rather than learning and implementing abstract ideas, such as principles and concepts. Besides, the children did not find the instructions included with the material very easy to read/comprehend.

Figure 9. Children working/playing with LEGO material at Nya Varvet School

Figure 10. Children working/playing with LEGO material at Landsjö School

Figure 11. Children working/playing with LEGO material at Bredaryd School

3.11. Teachers' Concluding Remarks

At the end of the project the coordinator of each school was asked to tell there concluding remarks upon certain issues. Here are some of the answers.

What were your initial motives for joining the project?

- I have always been very interested in learning and meeting new challenges, both, in my professional and in my private life.
- The prospect of establishing new international contacts was very attractive.

What do you think have been the most positive aspects of the project?

- I think the most positive aspect has been to see how the children have developed their problem-solving, interactive and creative abilities. At the same time, it has been useful, as a teacher, to be in a situation where one does not have all the answers.
- I think the most positive aspect is that the children have acquired new knowledge and skills which, without the project, they probably would not otherwise have gained.

What have been the most negative aspects?

- What first comes to my mind are probably the software problems we encountered during the last stages of the project.
- Another negative aspect has been the impossibility of including the project activities in my regular schedule, together with the difficulties in "selling" the project to other teachers.

What have you learned from the project (pedagogical or other aspects)?

- The experience of solving real problems together with the children, which is quite different to my usual role as a teacher.
- I have learned that when you, as an adult, build a LEGO construct, it is very important that the children can observe and learn how everything works. To put it simply: to use a pedagogical approach.

What are your comments on the support given by the school management during the project?

- The school management have taken a positive interest throughout the project, expressing a certain amount of pride in having been given the opportunity to participate in the project, and enjoying the good publicity it has created.
- I feel that the support we have received from the school management has been very strong during the entire project. I also feel that the school has benefited from my project work, even though only a small group of children has been engaged in this.

What about support from your colleagues in your project work?

- I have never had any problems in being given time off when I had to go away as part of my project work. Everyone has been tremendously understanding, covering for me 100 %.
- An amazing indifference, probably due to the fact that they had more than enough of their own work.
- Some of my colleagues adopted a wait-and-see policy, wondering whether this really was right for our school, and probably felt that I was engaged in playtime activities all day long. Others have taken some interest in the project, and have not shown any negative attitude. Only this last term have some of them asked whether we have seen any results, and when the project will end.

What are your experiences from research conducted within the project?

- It has been both stimulating and interesting to be part of a research project. To be asked supplementary questions following the submitted project documentation has been a very positive experience.
- To be involved in a research project has been both interesting and stimulating, although I found it very difficult to find the time to make both observations and notes, take pictures etc., at the same time being expected to help/instruct the children in their construction/programming activities. I would have wished for more collaboration with the research leader, and that he had made more frequent visits to observe the children working with the material.

Has the project met your expectations?

- Yes:
  - ◊ The project has been a source of inspiration to continue to work with LEGO as a pedagogical tool/teaching media. Our school has had some very positive press and media coverage, which, in turn, has lead to not only children but teachers applying for a place as a result of the progressive and enterprising image portrayed of our school.
  - ◊ The answer is “yes”, taking into consideration the expectations I had when I joined the project. These have changed during the course of the project, and perhaps the answer is no longer as categorical in all respects. For example, why was there not a more frequent dialogue between ourselves and the designers of the new software?
- No:
  - ◊ I thought that the project would have had a more wide-spread recognition within our school.
  - ◊ Parents have taken a great interest; however, my colleagues have shown less interest.
  - ◊ There have been moments when I have felt alone in my work with the project.

3.12. Conclusion

The project can be described as a long journey, its point of departure being to try to teach young children how to apply computer programming tools as a natural resource, among others, in their school environment. The CAB prototypes should be simple enough for four-year-old children to use, but still present a challenge to eight-year-olds, i.e. children should be able to grow with these construction kits.

The following is a concluding discussion concerning two crucial aspects in relation to the progress of the project within the stipulated time:

3.12.1 The CAB interface (hardware and software)

The introduction of BASIC around 1964 was based on the idea of designing a much easier programming language compared to existing ones, e.g. COBOL and FORTRAN. Consequently, Beginners All-purpose Symbolic Instruction Code, i.e. BASIC, was created by students at the University of Dartmouth College.

Since then, many new computer languages including a number of variations have been designed, most of them belonging to the same family, their instructions and commands requiring English keywords and comprising a more or less complex syntax. These languages are sometimes called traditional.

From the 1980s, efforts have been made to develop new languages that are much easier and more natural for people to learn, for example LOGO. Seymour Papert in his widely read book *MINDSTORMS - Children, Computers and Powerful Ideas*, presents an exciting future vision of education including the interaction between computers and children. LOGO has made it possible for children to use computer programming, mastering a powerful technology, and being introduced to some of the most fundamental ideas of science, mathematics and technology. The visual, graphic design of the LOGO interface was easy to understand for young children as it involved manoeuvring a turtle around the screen.

The challenge of the current project is to be able to lower this threshold even more, enabling children between four and eight years of age to be able to learn how to program LEGO material. Current research on visual programming languages is particularly focused on elementary school children.

The type of programming used for the first version of LEGO MINDSTORMS can be described as procedural programming, requiring the children to implement their ideas on their robots' successive actions in different steps or blocks. The major obstacle encountered by these young children has been to be able to transform the robots' actual behaviour on the classroom floor into abstract terms in the form of on-screen well-structured programming. The teachers have often had to intervene to assist the children in their translation of the robots' movements into an ordered structure as the children have been frustrated by not being able to manage this transformation themselves. Another - and irritating - obstructive factor has been when the teacher has not been able to help all the children due to various problems of organisation.

In the final stages of the project, new software, based on a completely different interface, was developed. In brief, this meant that the children only had to indicate on the screen what they expected to happen on the floor. The desired outcome of the activities has been the centre of attention, not the details of how this could be achieved. Thus, software development can be said to have moved from procedural programming (answering the question of how), to a declarative programming (answering the question of what). The importance and implications of this for the children's possibilities to use the software has not been investigated in detail during the time of the project, due to delays in delivery of the new software. However, it is our preliminary impression that it has simplified the children's use of the interface.

Hardware development has been very interesting following the introduction of the prefabricated robots, the idea being that when not having to start their constructs from scratch, the children should find it easier to get started. Particularly for those children who have lesser motor skills and who are not as able as their peers in putting their constructs together.

As should be evident from previous reports, the response to the prefabricated components was not overwhelmingly positive. There have been frequent comments, such as "part of the fun was missing when we no longer had to build them from scratch". And perhaps part of the very essence of LEGO material disappears if the children no longer have the possibility of starting from scratch. To be able to show the results and consequences of choosing one approach or the other, further research is required.

3.12.2. Values and benefits

As shown by this study, there is some difficulty in determining the immediate gains from a teaching point of view, although activities in connection with the so-called pedagogical scenarios, in particular, are praiseworthy. Thus, in the present situation it is somewhat difficult to see the effects of the project with regard to the possibilities of replacing or improving other school activities by the use of computer-programmed LEGO constructs.

The result and benefits from the project are, at present, more of an indirect nature, for example a possible increase of interest in science and technology as a result of the project experiments, not least among girls. Whether this interest will be of a more permanent nature as a result of their interest in the LEGO material should be a subject for further research.

This has been the primary aim of the CAB project - to be able to create new ideas and possibilities. New tools should extend and enrich the range of ideas children can explore. Insights into children's learning processes, such as studies on children's theory of control, go hand in hand with new design possibilities and further development of the construction kit.

The question whether the project activities constituted a part of children's learning or of their play has been raised during the progress of the project, both by project members and those outside the project.

The answer is perhaps both. There have been elements of play and elements of learning. To separate these is almost impossible. Presumably, one and the same activity sometimes can be described as a situation of both learning and play, depending on the perspective of the viewer. The work with scenarios in autumn 2000 was intended to include elements of learning based on the underlying pedagogical idea. The positive results, which were also supported by test results, showed the development of a learning process. Very probably these situations would also reveal an element of play. The challenge might be to be able to develop activities designated to function as learning processes while at the same time offering elements of play. Thus, it is the responsibility of the pedagogue to be able to find imaginative teaching methods and situations which combine elements of play and learning in the best possible way.

3.12.3. Spin-off effects from the Swedish field test

The CAB project has initiated many exciting and rewarding meetings and activities. Partly in the form of establishing valuable contacts with the other project partners and within the i3-net, partly in the form of further opportunities for new projects, based on the collected experience gained by working with computer controlled LEGO construction kits.

In view of this background, it was a natural development for HLK to host the arrangements of the i3 Annual Conference 2000 on 13 - 15 September in Jönköping. The conference, which was held under the name of "Building Tomorrow Today: Community, Design and Technology", was very positively received by approx. 250 delegates and visitors.

There is an increased interest in robotics in Sweden, and we feel that the CAB project is part of this process. It might be said that the PC and the Internet belonged to the 1990s, and that the first decade of the 21st century will be dedicated to robot technology! The very favourable and positive media coverage should probably be seen against this background. We have every intention to continue our dissemination of knowledge about the CAB project and the subsequent expansion and development in our country.

The October 1999 conference arranged by HLK on "Children, Creativity and the Future" will be followed by a second conference in autumn 2001, in which the CAB project will be given a prominent place on the agenda.

3.13. Future Visions

The expressed and ultimate aim of the CAB project has been research into young children's accomplishments with the use of LEGO material. Among the more implicit expectations from the project were a number of positive effects, such as:

- Creating an increased interest in science and technology among teachers and students.
- Creating a wider understanding among teachers and students of science and technology, primarily concerning complex system technology.
- Developing a comprehensive school study program, including new and exciting interactive laboratory tasks to be implemented within science and technology subjects.

The CAB project can be described as testing the limits of how early robotics can be introduced to young children. It has been a matter of some concern whether the children involved in the project would be able to learn and understand the technology involved in controlling robots by computer programming.

Comments as to some of the problems that have arisen during the progress of the project have been made earlier in this document. However, a number of very positive results were achieved, which constitute the basis of our vision.

There is every reason to ask what might be achieved in the near future:

- Perhaps an even better, improved interface?
- Perhaps new hardware, better adapted to children's abilities?

The aim of research conducted within the project has been to successively try to gain a better understanding of young children's abilities to master cybernetic material. However, part of our approach has also been to improve the material, both from the cognitive and motor skills perspective.

During the past two years, we have witnessed a distinct development in hardware and software technology. We have not, unfortunately, been able to fully explore the implications of this within the scope of this project. However, we are confident that future research will contribute in taking this development even further.

In the long-term perspective, LEGO material, in one form or another, is very likely to become an established and integral part of school activities.

For the researchers at the School of Education and Communication in Jönköping (HLK) who have been engaged in the Swedish field tests, the CAB project has resulted in many exciting and rewarding meetings and activities. Partly in the form of valuable contacts established with the other project partners and within the i3-net, partly in the form of new possibilities for further projects, based on the experience gained by working with computer controlled LEGO construction kits.

During the time spent working with the traditional construction kits, as well as the new versions developed as a result of the project research, there was an increasing confidence in the educational/pedagogical achievements and results made possible by using the material. We believe that a valuable contribution has been made to the present efforts in Sweden in increasing young people's interest in science and technology, which will eventually result in more students choosing to specialise in technical studies. Thus, HLK has concrete plans to establish Sweden's first Robotics Learning Center in spring 2001, initially in the form of a LEGO MINDSTORMS Centre. It is our ambition to create a national centre attracting many visitors, and offering possibilities for advanced studies and school projects including computer-based construction kits used in connection with interdisciplinary research activities. We hope to be able to develop the experience we have gained in the CAB project, both in the pedagogical and technical sense, with the intention of becoming nationally leading and internationally renowned in research and development within this area. These aims are to be realised through a close collaboration with business, industry and other research centres throughout the world.

We also intend to develop activities offered as part of the FIRST LEGO League (FLL), the idea of which is to form teams of young people accepting challenges to be solved using computer-based LEGO construction kits. The teams are allowed some time for preparation before they meet in competition to determine the best solution using their robots/constructs. During the next few years, information and knowledge about these exciting opportunities will be disseminated to (among others) schools, in order to arrange local and regional FLL competitions at several places in Sweden. The first Swedish FLL competition, which will be organised by HLK, is planned to be held in November 2001.

In 2002 we hope to be able to arrange a Scandinavian competition, and it would be a natural development to extend the idea to other European countries.

The CAB project has, in many respects, been a source of development and new knowledge for the Swedish field test partners. Although we are now finalising the project, it will continue to be inspirational as a starting-point for new projects and activities.

3.14. References

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3.15. Appendix

Questionnaire to pupils who had worked with LEGO MINDSTORMS

1 How many months have you been working with the LEGO material? _________ months

2 a) Are you a boy or a girl?

b) How old are you?

3 How do you like working with LEGO?

Great fun All right Boring

4 What do you think is most difficult when working with LEGO?

( ) computer programming

( ) building robots

5 Do you get enough help from your teacher when you work with LEGO?

( ) Yes

( ) No

(..) Don't know

6 Would you like to work more often with LEGO?

( ) Yes

( ) No

(..) Don't know

7 Did you learn anything new by working with LEGO?

( ) Yes

( ) No

(..) Don't know

If the answer is yes, what did you learn?

____

8 Do you work with LEGO at home?

( ) Yes

( ) No

9 Do you understand the instructions?

( ) Yes

( ) No

( ) Some of them

10 What would make working with LEGO more fun?

____

Thank you!