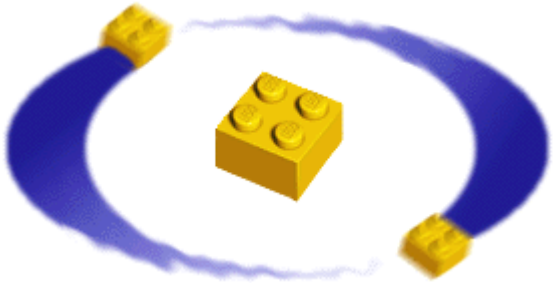

C o n n e c t e d W o r l d s

- The Future of Digital LEGO -

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Introduction

This paper describes the geatest, largest, most amazing toy known to humankind. It is a vision to bring LEGO successfully into the world of digital toy design. While relying on the company's fruitful past, this vision lays down a practical plan, and a research foundation, for a highway to the future of digital LEGO toys. The vision is based on an approach called **play-oriented design**.

Play-oriented design is design that emphasizes the user in free play. In stead of other issues, we put the user at the forefront of our effort -- free play is play where the direction and events is dictated primarily by the player. Providing means to open ends, this approach supports peoples' imagination and triggers their creativity. It allows players to expand their knowledge and enhance their skills within a wide variety of domains and tasks. The elements of play-oriented design are {1} **modularity**, {2} **modality richness**, and {3} **layered compatibility** between levels of abstraction. No one item of these three is more important than the others - together they make for one of the most powerful recipies for toy design imaginable, an idea we refer to as **Connected Worlds**.

Before dealing in greater detail with the implications of Connected Worlds to the vision of digital LEGO, we will now look a little closer at the elements of play-oriented design.

Modularity

The most important feature in any LEGO software product should be end-user modularity: Its modularity must support - in the strongest possible way - ideas and fantasies. While this may seem an obvious statement to make about physical LEGO bricks, in the software world it is easy to get distracted and stray from this immensely important principle. Thus, principle number one is {1} **Users can freely construct and play with the digital LEGO toy**.

Modality Richness

Physical toys are three-dimensional, graspable objects. They have absolute size and they make a different sound every time they fall - they even have a particular taste. This is modality richness. Some of these features are difficult to duplicate in cyberspace. Absolute size, for example, has very little meaning in the digital domain. Taste is also difficult to address. But there are other features that fall in the modality category that can be taken advantage of instead. A lot of current software is

modality-poor because it doesn't take advantage of the information that lies in the the history of user actions. At the simplest level, these include keyboard activity, mouse movements, sound input and even video camera input. But one can also make assumptions about the skill levels of users, what their interests is and how they approach problems, tasks and play. Principle number three is {3} **Use as many modalities as possible** to improve the modality-richness of the product.

Layered Compatibility

The studs on physical LEGO bricks provide a kind of generality that allows most bricks to hook up to most other bricks. These constraints are very important for abstracting away and combining the concepts of "stickiness" (the bricks stick together with just right amount of force) and "fit" (two bricks fit together in many, but limited, ways). This abstraction results in one of the world's most flexible, and fun toys.

The digital domain is much more flexible than the physical. Therefore it is even more important to make abstractions and set constraints. These constraints, like the stud, will allow various parts of a toy to hook to other parts -- i.e. they make them compatible. But what does layered refer to? Physical LEGO bricks allow us to construct objects. Digital LEGO bricks could allow us to do much more: design organisms, construct chemicals, devise perception mechanisms, run simulations, etc. In fact, digital LEGO bricks in all these different domains may not end up looking anything like bricks at all. But with an abstract notion of "stud" at each level of abstraction the layers become compatible with each other. When we have multiple domains compatible at muliple levels, we have Layered Comaptibility.

Principle number three is {3} **Any object in the LEGO tool suite should be compatible with the levels above and below it**. This principle is at the heart of **Connected Worlds.** The rest of the paper will focus on various aspects of the Connected Worlds idea.

Connected Worlds

There are many abstractions we can make about structures in the world. The LEGO brick is an example of an abstraction made in the Physical Domain, especially well suited to construction of static, physical objects. In the digital world, the starting point should also be the physical LEGO brick.

The brick allows us to build structures with 500-1000 elements, e.g. buildings and cars -- at a reasonable level of detail. From this level we can move outward, to buildings that form cities, to cities that make countries, to countries that make a globe, to globes that make solar systems, to galaxies, to universes. We can also move down, from the brick to the chemicals, from chemicals to atoms, from atoms to electrons, neutrons and positrons, etc. etc.

But that's not all. The computer allows us to add behavior - functionality - to our bricks. LEGO Technic is very well suited to behavior, or animation, that allows us to see gears and wheels in action. This works well for exploring, for example, principles of gear reduction and electric motors. But it doesn't allow its users to play with function as it appears in our solar system, in the form of gravitational fields, or function as it appears in biology, in the form of cell divisions and multi-celled organisms. However, in a computer these options become available and are very viable as worlds to expand the LEGO spirit into.

What is needed to make it work is an abstraction of the fundamental priniciples of ***function*** at each of these levels, just like the studs are an abstraction of the concepts of "fit" and "stickiness" at the construction level. The three main worlds that have been identified as relevant to LEGO toys are {1} The **Physical World**, {2} the **Living World** and {3} the **Mental World**. Each of these connect

together in certain ways in the real-world; currently, our scientific knowledge of the world limits what we can say about these connections. (At some point, for example, we may find out how neurons can cause mental events.) We will therefore prbably be better off -- and will be able to do the more amazing things -- if we keep the worlds abstracted from each other when making new digital LEGO toys. Precisely how will become apparent in the follwing paragraphs. But we already have a precident to the idea of abstracted worlds, and it provides a natural place to start moving into the world of digital LEGO: The LEGO brick itself.

The PHYSICAL World: Starting with the LEGO Brick

The traditional plastic LEGO brick is a simplification and abstraction of construction in the real-world. But the range of objects buildable with this principle is limited to non-mechanical, solid structures. By adding a few, slightly more spcialized elements, LEGO Technic allows for construction of mechanically functional toys that also are compatible, in terms of their constructional abilities, with the studded brick. With digital LEGO, the opportunity to represent mulitple levels of construction detail is enormous: I can play with bricks, building houses, cars, airplanes and so forth; I could play with a whole city, where the basic construction elements are buildings, streets, traffic and high-voltage powerlines; I could play with a country, where the basic construction elements are cities, highways, weather and powerplants; I could play with a planet, where there are elements like water, land, atmosphere, etc. At each of these levels the details below and above are masked, yet their functionality needs to show through: We want the houses' appliances to run when playing with buildings; we want electricity in the cities when playing with powerplants; we want powerplants to output energy (and waste) when playing with a planet.

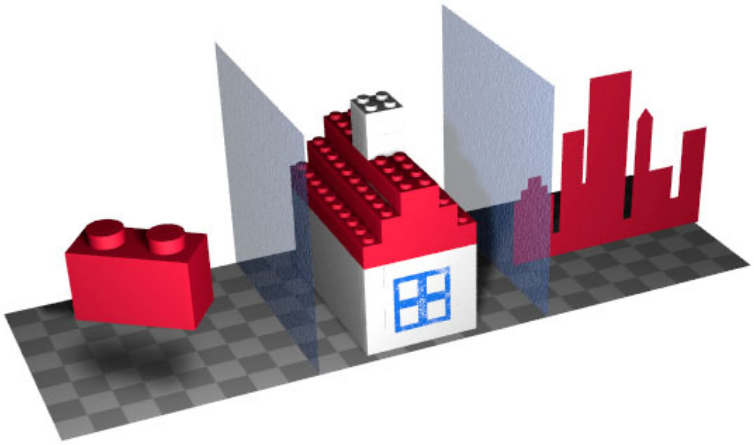

Figure 1. In the **Construction World**, moving between levels of abstraction allows us to use various elements - a brick, a house, a city - as the basic construction "block". When building with bricks, you can make houses; when bulding with houses you can make cities; when building with cities, you can make countries.

Compatible Elements in the Physical World

To make this possible, our task is to find common features that allows elments on various levels of scale, as well as between domains, to be used together in a seamless fashion. For example, when playing with a city one can run a water pipe to the city's water intake that comes with the city's building blocks. When water from the dam is hooked to this intake, water automatically becomes available in all the citie's houses. If you now enter one of the houses in the city, there is also a water intake, but especially for the house, with lower pressure. Now you can run water pipes into the bathrooms and the kitchen. When you hook the pipes to the house's water intake, simulated water flows into the bathtub. Hidden from view is now the city's water intake - this is part of the mechanism of detail hiding. Yet if you go from playing with the house back to the city abstraction level,

disconnecting the city's water intake will now stop the water in the bathtub from running.

The following elements have been identified as being common across several levels of representation in the Physical World:

- Building blocks (bricks, houses, cities, countries, planets, solar systems ...)
- Transmission of energy.
- Transmission of data.
- Transmission of matter (liquids, gasses).
- Motion control (motors, muscles, pneumatics, planetary movements, etc.)

Object-Oriented Physics

Common to all levels in the Physical World is the principle of "object-oriented physics" - the inherent nature of our world: An object such as a ball, made of soft rubber, is "bouncy". This quality of "bounciness" is part of the ball - it does not come from an external power that looks at the ball, determines that it should bounce, selects the right equations and applies them to the ball. No, the "bounciness" is inherent in the fabric of rubber, and rubber is what the ball is made of. (This is essentially why the object-oriented paradigm in programming is so popular.) By using object-oriented physics as a model for objects in a virtual world, the world can be constructed in a very modular, economical and, above all, expandable way. This is the way digital LEGO objects in the physical world should be modelled.

But there are other sides to the world that scientists are just beginning to scratch the surface of, and that is what we refer to as the "Living World" and the "Mental World".

Extending the Vision: New Worlds

The structures that can be built with the traditional LEGO bricks and Technic bricks are still very limited considering what a computer can make happen: They are limited in {1} dynamic action range (e.g. speed, power and autonomy), {2} scalability (could you build a transportation device with as much detail as a real car, or a city with 100.000 houses?), and {3} domain (even LEGO Technic is strictly limited to the mechanical domain, leaving out the biological, social, chemical, to name a few). One can think of this task as generalizing the idea of the stud to other forms of media; data, power, DNA, nurons, biology, sociology, etc. By finding the equivalent of studs for these domains, and within levels of details of these domains, we can begin to create the worlds largest and most powerful toy.

The key to moving successfully between levels in action range, scalability and topics, is keeping an element of constance that allows the different representations to be used together. When designing software systems at multiple levels of detail and abstraction, each level should be compatible with the one above and below it. This allows incremental development of each level, yet ensures that all elements of a system to be compatible with each other as we go along.

At a quick glance, making sure that each level is compatible with the one below and above may not seem such a difficult task. But because of shear complexity, modelling everything in detail and then running simulations of **everything** *all the time* - no matter which level the player is constructing at - will simply not work. Finding common threads or concepts that work at each level (as the studs on the LEGO bricks work for various sizes of bricks and constructions) may prove to be more difficult than it looks. It is therefore crucial that the model adopted for this task is clear, concise and flexible. Addressing the problem as three related "Worlds" provides an answer to this question. We have already looked at the Physical World. Now, let's address the remaining two, the Living World and the Mental World.

The MENTAL World

The Mental World as we know it from everyday life manifests itself as thinking, talking, acting beings. Some beings with mental powers are less capable in the language arena than we are, for example cats and dogs, and others are totally incapable of speech understanding and generation, like hamsters and rabbits. Yet something in their bodies makes them act intelligently. This "something" is the nervous system which connects their sensors - eyes, ears, tactile information - to their muscles.

The most familiar real-life manifestation of mental phenomena is already available in the LEGO line of toys: the human and animal figure. These are interesting because they are the level at which the most important actions happen in our lives: We have parents that raise us, we have teachers that teach us, we have pets that we feed, friends that we play with, etc. Thus, when selecting a level to start developing toys in the Mental World the most natural one is the individual, personal.

Making it possible for a child to construct the functional underpinnings of an animal or a human-like figure is not a trivial task, but just like the LEGO brick in the Physical World, it is the obvious starting point. From there we can go in each direction of detail: Multiple human figures become groups; multiple groups become societies - in the other direction a mind reduces into perception processes, motor processes and decision processes; a perception process reduces into recognizing features in images, etc. etc.

Starting at the Individual Level: Advantages

Beginning to model at the individual level as outlined above has four important advantages: {1} By taking the individual as a starting point we begin with a level that is very familiar to everyone. {2} It is also one that linguistics and psychology research can contribute to the most. Choosing this level as the starting point will {3} allow us to create virtual characters and playpals that can interact with children and grown-ups at the most familiar, personal level, and {4} provide a platform for expansion into other levels, such as dogs, cockroaches and fantasy creatures with new and unheard-of abilities, as well as societies of such creatures, all the way up to human societies with collections of creatures with all sorts of abilities and interests.

In order to enable children (of all ages) to play with the elements of mental phenomena, we need a LEGO-like mind model that serves as the basis for autonomous social characters and playpals. Fortunately, precursors to this model are already in existence.

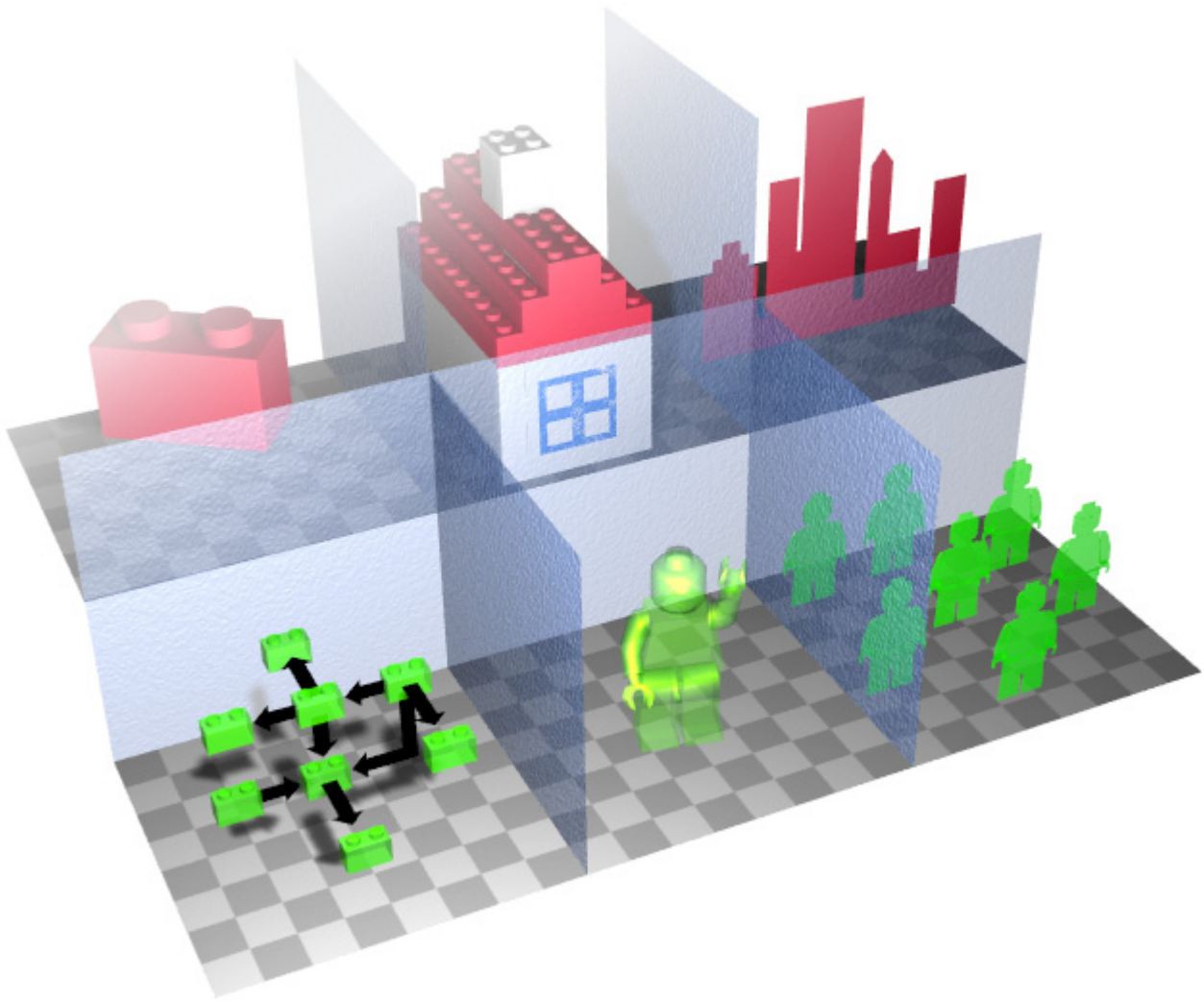

Figure 2. In the Physical World we focus on construction at various levels of abstraction. In the Mental World, the focus is on mental phenomena such as perceiving and deciding. At the basic level (green block on left) the main building element is a **mental function** (e.g. a vision module); connected together they make the brain of a character (center); moving up another level of abstraction allows us to build and simulate the activity of a whole society of interacting characters (right).

Compatible Elements in the Mental World

The following elements have been identified to be constant through various levels in the Mental World:

- Perception
- Information transmission / communication
- Information storage (memory)
- Information retrieval (memory: recognition, recall)
- Decision Making (intention / comitting to plans)
- Learning
- Planning (action scheduling)

Abstraction levels of the Mental World can be said to be societies, large groups, the family, one-on-one communication, and mental functions such as perception & decision.

The LIVING World

We have now looked at two of the more obvious worlds that LEGO might venture into in the digital domain. But the possibilities don't end there: With digital LEGO, an opportunity opens up to allow construction in the world of living organisms, including biology, medicine, and genetics, to name a few. To some degree the physical appearence of objects in these domains can be approximated by the current morphology (form and look) of LEGO bricks. Functionally, however, the current brick model falls short - it provides no hints to how to represent the function of biological structures (see list below) in the spirit of the LEGO brick studs.

What is needed is the LEGO Technic equivalent for biological systems, medicine and genetics, but with the addtion of functional compatibility. Beyond what could be borrowed from digital LEGO in the Mental World, the task of finding functional compatibilities in the Living World is bound to borrow heavily from molecular biology, Darwin's ideas about evolution, as well as recent advances in genetic programming. The most obvious starting point for the Living World is simple evolution: Being able to merge the features of two different LEGO objects and get out a third one that is a mix between the two. The mechanisms behind such evolution have been explored in genetic programming research and can be offered as a general principle that can easily tie in with the Physical World.

Where Do We Begin?

The Living World is in many ways less LEGO-like than the Physical and Mental Worlds. Concepts like evolution and survival of the fittest are not easty to incorporate into the LEGO idea. The proposal here is that the evolution mechanisms do not affect basic LEGO elements (we could call them LEGO "atoms"), like a 2x4, but collections of those elements. This means that when I "breed" two LEGO mini figures, one with a spear and one with a sword, what comes out is not a figure with a "spord"; it either has a spear **or** a sword. Another way of saying this is that LEGO geometries and textures are not modified - just selected.

This approach has several advantages, the biggest being compatibility / stability. If we wanted for example to allow children to be able to "evolve" their new imaginative car that they built they could do so. When the car "evolves" and changes, the only thing that is modified over "successive generations" of the car are the instructions on how to fit the bricks together to make it. At each level of abstraction and in each World, evolution can be thus introduced without creating major complexity issues in "new" LEGO bricks evolving or having to fit new elements into the basic LEGO elements, etc. And there will be no risk in introducing evolution into the LEGO world because of "unknown future objects" that have to be predicted or somehow anticipated.

The approach also means that there will be a common representation for LEGO construction knowledge that can be exploited for multiple purposes. For example, building mechanisms used to automatically construct LEGO buildings can be used by evolutionary mechanisms to generate variations, and evolution can create automatic building instructions to be used in new models. A LEGO character's knowledge about how to construct a house are represented in the same way, and contains therefore compatibility with the Physical World and the Living World. Its knowledge can therefore be supplemented by new building instructions, and it can be modified by principles of evolution.

Compatible Elements in the Living World

The following elements have been identified to be constant through various levels in the Living World:

- Inheritance
- Copying

- Combining two (or more) different sets of building instructions, or recipies
- Randomization of instructions order
- "Death"
- Selection of the fittest

Conclusion

This document describes an approach that can provide the underpinnings of an expandable, modular toy, where elements at various levels of abstractions are compatible with each other. The approach is based on the fruitful history of the LEGO company; by extracting the cruical elements of its succes it gives a formula for virtually infinite expansion into the world digital LEGO toys. The traditional LEGO brick is used in a literal as well as a metaphorical way to expand on the prinicples that make LEGO toys a superior product.

A design process called play-oriented design has been outlined that emphasizes modularity, modality richness and layered compatibility for the design of all digital LEGO products. The result is the concept of **Connected Worlds**, a concept that can bring us the most amazing, most powerful and fun toy known to date.

Connected Worlds offers a toy that follows the development of a child in a unique way. When the child starts playing with digital LEGO, it brings with it what it knows about physical LEGO bricks and thus is able to understand geometric relationship in a familiar framework. But as the child grows, the digital LEGO toy grows with it, allowing for endless expansion into fields of the child's fancy.

Not only does **Connected Worlds** propose a modular toy with unlimited expansion capability from the standpoint of the consumer; it proposes a buisiness model of the same order, a model where the initial steps are small and well bounded within the history of the LEGO company. We would start by designing two levels of abstraction in the Physical World, e.g. the brick level and the city level, followed by prototyping, development and marketing of these two levels. The result will allow a valid asessment of the approach and feasibility of continued exploration into the Living and Mental Worlds, as well as expansion with in the Physical World into countries, planets and solar systems; molecules, atoms, atomic particles.

The framework presented here also allows for continued refinement of each level of abstraction. As advances are made in simulation and the power of home computers increases, well-defined interfaces between levels of abstraction allow for updates and improvements within each level without interfering with the levels it connects to. **Connected Worlds** provides the foundation for a modular, coordinated organization of software houses where one department specializes in the molecular biology level, another in artificial intelligence, a third in physics and distributed execution, a fourth in simulation of social worlds. The Connected Worlds proposal provides a foundation that enables these otherwise disparate worlds to be coordinated in *time* and *content* so that what emerges truly represent **CONNECTED WORLDS**.