Abstract
After more than a century of domination by neo-Darwinian theory, biological thought is beginning to give increasing recognition to developmental theory. Amongst other reasons, this recent widening of perspective is grounded on the incompleteness of the neo-Darwinian perspective in providing models for the invention of novel forms or species and individual development. Evolutionary design theory has drawn much of its inspiration from evolutionary biology and consequently shows analogous flaws. This paper demonstrates an adoption of biological developmental theory to the field of design theory in order to fill the corresponding gap. As natural developmental processes are based on the development of cellular units, which form composite structures, this paper employs the cellular model as a means for the development of a corresponding design and construction theory. The discussion of this approach includes possible linkages between morphologic and behavioral attributes of tissues with implications for self-assembly, growth, healing and self-reproduction of man-made structures.

1 Introduction
Owing to the interrelation of phenomena such as variation, adaptation, selection and hierarchical orders with creative innovation, many close and loose parallels have been drawn between biological evolution and man-made design during the past centuries. Since the discovery of DNA as the carrier of genetic information during the 1940s and 50s, Neo-Darwinism, the synthesis of evolutionary theory and genetic theory, has long remained unchallenged and has provided a significant paradigm for designing and reflections on designing. Since the pioneering of genetic algorithms in the 1970s [see Holland, J. H. (1992)], evolutionary design and related fields such as generative design, have come to represent major streams within contemporary design theory, which – due to their comparatively high degree of formalizability – have a particular relevance in the computer aided design context. The Neo-Darwinist model has come under increasing criticism for a number of reasons. These reasons include its implicit assumption that population and individual levels were evolutionary independent and its treatment of selective processes largely as ‘black boxes’ [for more detailed discussions see Wallace, A. (1997), p. 10 and also Kauffman, S. A. (1993), p 16 ff.]. In the biological field, this criticism has led to the synthesis of evolutionary and developmental biology – an approach biologists have informally dubbed “Evo-Devo”. This area of research examines the genetically instructed developmental pathway from zygotes to fully developed organisms and ultimately studies the interaction of matter and the self-evaluation of matter as information for the purpose of substantial and behavioral development. Based on this important extension of the ‘generative’ paradigms in biology, we believe that reason is given to re-consider evolutionary design’s emphasis on the neo-Darwinian paradigm. While evolutionary design has previously mainly focused on the mechanisms of variation and selection [the latter one being the far more difficult challenge, see Fischer, T. and Herr, C. M. (2001)], the following pages will take a closer look at the developmental path from genotypes to phenotypes [see illustration in Langton, C. G. (1996),...
The cellular structure of organisms allows mechanisms that are still largely unavailable to artificial design such as autonomous growth, healing and reproduction. If applied to the design and construction of man-made structures, such mechanisms would yield a significant potential. Theoretically, they could complement evolutionary design theory and contribute the missing developmental view of design. Evolutionary approaches to the generation of variations (genetic algorithms etc.) could be complemented by variance generation driven by developmental interaction with environments (“epigenetic algorithms”). Applied to practical building and construction, the extent of required human labor could be reduced and development could take place where human workers cannot go. Buildings might literally be enabled to “grow” by themselves. And [as Konrad Zuse has envisioned as early as 1957 [see Zuse, K. (1993), p. 201]] something on the scale of a subway system or larger could be “planted” rather than built, even through a pin hole. Potential applications in other fields range from nanotechnology to space colonization.

On the way towards introducing such ideas to man-made design, we need to identify the processes, mechanisms and algorithms required for cellular development. This undertaking brings up three fundamental questions:

• How can matter self-evaluate as information (as for example cells are capable of evaluating DNA molecules)?
• How can such information self-evaluate as configurations of matter at a larger scale (as for example cells are capable of protein synthesis and cell proliferation)?
• How can these two processes interact with each other to generate developmental and evolutionary design processes?

Answers to these questions can only be found if basic differences between natural and artificial design and development are taken into account. The most fundamental of these differences is that artificial design until the present day is virtually exclusively based on external blueprints (plan here, product there) whereas “blueprints” in Nature are incorporated into the cellular building blocks of its designs [see also “The Problem of the Blueprint” in Frazer, J. H. (1995), p. 11]. In our attempt to answer the above questions, we therefore adopt the natural model of cellular incorporation of morphologic and behavioral blueprints.

On the following pages, we will identify strategies for incorporating developmental design descriptions into cellular atoms of composite design products, based on findings in developmental biology, and present some resulting aggregated tissues, modeled in a software tool designed to emulate cellular developmental processes.

2 Self-Reproduction

Of the numerous potential applications and innovations the developmental approach might produce – such as artificial healing, the automatic self-repair of man-made structures – we first want to discuss one example that appears particularly intriguing in form of a thought experiment: self-reproduction. This field of study was initiated by John von Neumann in the late 1940s and aims at theoretically understanding the mechanisms and algorithms required for automated construction and ultimately and primarily for artificial reproduction. Whereas the related body of publications is not concerned with physical realization of self-reproductive designs, in this paper we follow John Frazer’s [Frazer, J. H. 1995] implicit suggestion to apply machine logic to spatial logic and to apply knowledge about reproductive machinery to architecture and design. The life cycle of a biological cell typically starts and ends with the self-reproductive act of cell division. The intervening, longer part of its life span is called the “interphase”, which has a number of sub-phases. During one of these sub-phases, the cell’s DNA code is duplicated in preparation of the forthcoming division. When the cell divides, each of the resulting two cells obtains
one of the two identical DNA copies. With respect to its central organization, this copying operation is similar to the one that John von Neumann's Universal Constructor was designed to perform.

Inspired by Turing's description of a mechanism capable of universal automatic computation, von Neumann proposed his (cellular) universal constructor, as a means for universal construction: a machine that is capable of building any other machine [v. Neumann, J. (1948), p. 550 ff.]. This theoretical reflection assumes a two-dimensional cellular automata machine that is equipped with a tape memory for blueprints and a means to translate stored blueprints into mechanical construction activity, enabling the machine to produce any machine for which a blueprint is stored inside the constructing machine's memory. As a benchmark criterion for its universality, the machine should be able to reproduce itself, provided it is equipped with a blueprint of itself (this criterion has by the way been identified as being false, as self-reproduction does not necessarily prove the ability of universal construction).

This machine however, if built and applied, would inevitably run into the recursive problem that constructing a second machine from a stored plan could only produce a copy of the machine, excluding the blueprint (as the blueprint cannot include a blueprint of itself which includes a blueprint of itself etc. in the first place). In order to overcome this obstacle, von Neumann introduced a copy operator that copies the stored blueprint and sends the copy to the newly produced machine before it is “turned loose” [for a more lengthy discussion of this problem see Arbib, M.A. (1988)]. This copying of the blueprint when duplicating [see v. Neumann (1966), p. 119] is quite similar to the DNA copying in biological cells described above. While this operation appears to be seen as a basic requirement for plan-based reproduction, we will now proceed to hypothesize a different method of automatic self-reproduction using an alternative strategy based on cellular design development.

In the course of their previous engagements in the development of haptic programming systems, the authors have become aware of the possibility of linking morphological and behavioral expression in cellular structures. Related publications [see Fischer, T., C. Ceccato and J. H. Frazer (2001)] discuss how three-dimensional cellular configurations (machine-readable model) can be interpreted as programming code, which determines the behavior of a second three-dimensional cellular system such as a Lego robot.

If the physical configurations (input programming code configuration and output sensory/motor configuration) of such a setup are merged into one single cellular entity, the result will be a robotic cellular organism, whose behavior is a manifestation of its own shape based on decentralized language interpretation. A simple example of such a machine could consist of three cells with the capability to blink, each with a differentiated identity, one of which would represent “blink”, one representing “3” and one representing “times” in a specified language. Upon connection, the cells analyze their configuration, evaluate it collectively as instructive code in an interpretation mode and then blink together three times in a subsequent runtime mode. A machine of this type needs to execute two programming languages on two levels simultaneously: A cellular scripting language defining every cell’s behavior e.g. using textual code (this is the level of Zellkalkül's cell code execution, see below) and a higher-level, "metabolic" language evaluating spatial configurations of cells as instructions for the entire organism. This higher-level physical language is executed by or “on top of” the low-level textual language. For example, it can map a spatial dimension of cellular configurations on the temporal dimension of a programmed procedural behavior.

We believe a more complex variant of such a machine could be built, which would evaluate its shape as instructions to build a second machine formally identical to itself. The resulting reproduction process would produce a new machine, which includes (or manifests) the blueprint for its own reproductive action stored in its physical shape. In this case, a single global copying of a machine blueprint is not necessary. The functionality of such a type of machine is not necessarily limited to self-reproduction. As is the case with other programming languages, its cellular language can provide for non-evaluated code (or morphologic) elements, conditional branching and different run levels to allow additional functions.
not necessarily related to reproduction. In fact, the reproductive apparatus of this machine could constitute merely a small portion of larger structures which are designed to perform primary structural, behavioral, aesthetic etc. functions (similar to the design of natural organisms). The cellular metabolic programming method presented here must not be confused with the “cellular programming approach” of Sipper [Sipper, M. (1997), p. 73 ff.] who discusses non-uniform two-state cellular automata with no metabolic coding functionality.

Compared to von-Neumann’s mode of automatic reproduction, the process described here is in a way turned “inside out” as there still is a copying process necessary at the beginning of the required cellular code scan when cells copy a representation of their spatial configuration into each of their memories for metabolic interpretation. This copying, however, is initial and massively parallel in nature, whereas the method described by von Neumann is terminal to the actual reproduction process and centralized. Von Neumann’s proposed mechanism bears strong resemblances to those employed by natural reproduction, which were discovered only a few years after von Neumann’s concept. While this concept requires computation universality as well as construction universality to achieve the self-reproduction capability, Smith [first discussed by Smith in 1968-96 and widely published in Smith, A. R. (1992)] has proven that computation universality alone is sufficient to implement a self-reproducing machine. That is, nothing beyond the scope of ordinary computation is needed. We believe that our thought experiment discussed above meets this criterion as it is composed exclusively of computation-universal cellular entities. Moreover, there is reason to assume that our architecture will yet be able of universal construction on the basis of universal computation. Putting this thought experiment into practice using Zellkalkül as soon as the ongoing development of this tool allows will be one of the future steps the authors will take in this project.

3 Zellkalkül

While developmental biology research takes a basic and analytical view of natural processes, design research primarily aims at experimental exploration and prospective planning. The toolkit required for this different perspective necessarily deviates from biological methodology accordingly. In order to experiment with developmental mechanisms, we have developed a purpose-centered non-uniform voxel automata environment named ‘Zellkalkül’. This software allows for the development of cellular structures and the behavioral scripting of cell types (“cell code”) for execution in massively parallel mode. Zellkalkül allows real-time execution of developmental algorithms and three-dimensional visual observation and analysis in real-time. It also provides for the introspective self-analysis of cellular configurations and the derivation of instructive information determining the configuration’s metabolic behavior from its physical form as discussed in more detail in the section ‘Self-Reproduction’ above.

Figure 1: The rhombic dodecahedral shape of plant cells as identified by Kieser
A cell in Zellkalkül is a unit of rhombic dodecahedral shape, allowing for isospacial close packing. This geometry is an idealization of natural cells [as identified by Kieser, D. G. (1815), see Figure 1] and appears to be of particular usefulness in three-dimensional cellular automata computing. Whereas in classical cellular automata systems cells are programmed with a globally identical set of rules, Zellkalkül allows the manual design and generative development of non-uniform automata. Its cells can be programmed individually or in groups (IDs) to execute different code scripts in different cells simultaneously. Each cell instance is equipped with a language interpreter for individual ECMA code execution (see McComb, G. [1998]). Cells are capable of performing functions like moving, splitting, differentiating, dying and scanning their adjacent neighborhood or overall cellular configurations in a completely de-centralized manner. Cells are able to manipulate text, exchange code and hence program each other at any time. Cells also possess sufficient individual memory for storing data such as cellular configuration patterns. As mentioned above, these patterns can in turn introspectively be evaluated as metabolic code, which determines behavior on the organism (as opposed to the cellular) level.

Figure 2: Screenshot of the Zellkalkül environment

4 Morphogenesis: The Ability to Express and Grow Tissues

The biological view of development focuses primarily on multi-cellular higher organisms. For the sake of consistency and illustration, we have adopted this scope of focus for the application of developmental theory to design which we propose in this paper. We will refer to composite structures composed of homologous elements – regardless of whether they are man-made or natural – as tissues. We denote the development, growth and differentiation of tissues into organs and organisms as morphogenesis.

A very fascinating question regarding cellular development arises from its ability to express local and temporal characteristics based on one persistent set of instructions: How can different cells of an organism - which all share an identical set of genetic data - express locally and/or temporally different tissues and organs? What tells a muscle cell to differentiate into a muscle cell and not as a nerve cell though its DNA is identical with that of all other cells of its organism (including its nerve cells)? Wallace A. (1997), p. 103 explains:

“Development is possible only if cells ‘know’ what to do [...]. So the key question becomes ‘how do they know?’; and the whole of developmental biology could be regarded as an attempt to answer this question.”

The answers to these questions are still far from complete. But whatever biologists understand about biological development is also of prime importance for a developmental view on cellular design. In the
remaining part of this paper we will discuss two early experimental design applications showing how tissues can express local attributes based on global code sets. This discussion requires us to move our focus away from reproduction on the cellular level to tissue and organism development. DNA, providing reproductive and developmental functionality, consists to a large extent of nongenic sequences (DNA with no or not yet understood relevance for reproduction or protein synthesis; also referred to as “junk” or “secondary” DNA). The remaining genic part can be subdivided into three groups according to the specific functions they provide [See Arthur, W. (1997), p. 42]: (1) developmental genes which are involved in the determination of body plans and the control of “downstream” developmental processes; (2) “terminal target” genes which are activated only in certain differentiated cell types (as a result of activities of developmental genes); and (3) “housekeeping” genes which are expressed in the vast majority of cells to provide basic or routine metabolic functionality. Cells communicate across short, middle and long ranges using a variety of media such as signal proteins or hormones. This communication can result in parts of individual cells’ copies of DNA being switched on or off (or to be “activated” or “repressed”). Specific activation and repression of developmental genes allows genes to synthesize locally different proteins and thus to express different tissues (differential expression).

Those types of cells, which associate with another to form tissues, do so by two distinct strategies. The more common one uses adhesion. After division, cells adhere to their neighbors (i.e. other cells and/or their surrounding extra-cellular matrix). This is the typical way by which epithelial sheets develop, which later develop into complete organs. The second strategy for tissue formation is based on migration. Cells move through the organism to assemble with cells from other locations (which might also have migrated) to change from their unicellular to a multi-cellular lifestyle and to form tissues of mixed origin.

In order to develop from a single zygote to a multi-cellular organism by differential cell expression, two basic strategies exist. Sidney Brenner, a pioneer in the field of developmental biology, has designated them the “American” and the “European” way [according to Gehring, W. (1998), p. 58]. Cells developing the American way often “may not even know” their ancestors and draw their sense of identity from interaction with their neighbors. The European way is for the cells “to do their own thing, not to talk to their neighbors very much” and to draw identity from their developmental history. Both strategies are discussed and illustrated below examining two natural case studies and simulating them using the Zellkalkül environment.

5 Development by Temporal Identity

The nematode worm Caenorhabditis elegans (shown in Figure 3 below) is a typical and well-analyzed example for the “European way” of development. There are two different sexes: hermaphrodites, capable of self-fertilization and less frequent males. C. elegans has a length of about 1 millimeter and always consists of a total number of 959 somatic cells in the adult hermaphrodite and 1,031 in the adult male (plus a variable number of germ cells). Caenorhabditis elegans’ cell lineage (the route by which all cells of the adult are derived from the zygote by cell division, see figure 4) is essentially invariant from organism to organism [see Gehring, W. J. (1998), p. 56 ff.]. Every worm develops its lineage of 959 (or 1,031) cells with a very high degree of precision. The identity of a cell, determining its fate (division, tissue expression, programmed death etc.) is a result of the cell’s position in the nematode’s cell lineage tree – the highly invariant temporal(and consequently spatial) record of cell divisions.

The first example of a developmental algorithm we present using Zellkalkül is a cellular growth model based on C. elegans’ natural lineage tree. Programming an initial artificial zygote with the known lineage history information of the natural worm allows us to “grow” a corresponding organism of 959 (or 1031) cells. This simulation generates a cell cluster based on C. elegans’ natural lineage tree and a pressure/adhesion optimization for cell proliferation. Given a cell lineage data set including spatial distribution and cell migration data, a reproduction of the nematode’s morphology can be achieved.
This mechanism of differentiating local attributes from cellular tissue grown from a single cell with a persistent code script based on temporal identity can be regarded as an answer to the basic question of how information can self-evaluate as matter.

6 Development by Local Identity

The compound eyes of the fruit fly Drosophila melanogaster (shown in Figure 6 below) are each composed of 800 hexagonally arrayed light-sensitive units called ommatidia, which are each composed of 20 cells. The individual differentiation of these cells is a well-understood example of development by local identity in the “American way” using very specific short-range intercellular communication.

After metamorphosis, each of Drosophila’s two eye discs consists of a yet undifferentiated equivalence group of about 20,000 (fully identical) cells. Nevertheless, these identical cells differentiate into a clear repetitive structure of seven different types of cells which perform different functions. Two of these cell-types are so-called cone cells, which secrete an optical lens for each ommatidium, and photoreceptor cells, the actual light sensors. The interesting developmental question here is: How can nominally identical cells develop into a pattern of specialized cells?
Already half a century ago, Alan Turing [Turing, A. M. (1952)] examined this morphogenetic problem of cell differentiation in undifferentiated tissues. From a mathematical perspective, Turing considered idealized organisms in the form of rings of cells or rings of tissue, which are initially in a stable and homogenous condition. Coincidentally, these hypothetical structures were two-dimensional, as the fruit-fly's eye discs. The principles shown later in this section and the ones by Turing discussed above also apply to three (or higher) dimensional structures. Turing discusses a mechanism, which he calls reaction diffusion. Triggered by slight disturbances (such as Brownian motion), a process involving a small number of signaling substances (morphogens) is shown to be sufficient to induce the development of tissues with locally differentiated attributes (mechanical or chemical states) from initially homogenous structures.

Instead of subtle disturbances, the process of differentiation in *Drosophila*’s ommatidia is initiated by a propagated wave of signals sweeping across the eye discs. Figure 7 shows this wave at the halfway point of its way from the back to the forehead side of a disc (dark vertical band). While moving, this signaling wave stimulates every cell it makes contact with to differentiate into a photoreceptor cell named R8. Once a cell is R8, it prevents the cells surrounding it from becoming R8. As a result, R8 cells differentiate in not-too-close proximity to each other, each with a hexagonal neighborhood of cells it has prevented from becoming R8s. Each of these neighborhoods develops into one ommatidium with twenty cells. This requires the six cells directly adjacent to each R8 cell to differentiate into photoreceptor cells R1 through R6, in a subsequent step. Then an equivalence group of five again identical cells differentiates into four transparent cone cells (acting as an optical lens) plus one eighth photoreceptor cell R7. R8 sends a short-range signal to its immediate neighbors. This message can instruct any cell of the equivalence group of five to differentiate into R7. But since only one of the five cells has immediate physical contact with R8, only this one becomes the last photoreceptor cell R7 while the other four do not receive R8’s message and differentiate into cone cells.

Two *Drosophila* mutants exist, both of which fail to develop R7 cells in their ommatidia. One of them cannot produce the message that is sent from R8 to R7 and the other one's R7s are unable to evaluate R8's message. In both cases, the ommatidia develop with five cone cells and no R7 cell. One of the two mutants is hence called “sevenless”.

What makes *Drosophila*’s compound eyes particularly interesting from a developmental point of view is not only their illustration of the “American way” of development (recruitment by local inductions) but also their demonstration of the powerful morphologic and behavioral effects subtle developmental
mechanisms can have on the full organism. As each of the eight photoreceptor cells is designed to see a different segment of the light spectrum and R7 is the fly's UV sensor, both mentioned mutant types are UV blind. *Drosophila*’s attraction to light is stimulated solely by UV wavelengths and hence both mutant types are not attracted by light. This shows how the success or failure of specific intercellular messages during development can change the behavior and/or form of entire organisms.

Figure 8 shows the simulated proliferation of an initial cell (1) into an equivalence group of cells (2) in *Zellkalkül*. According to the equivalence group’s programming, this tissue develops into the wild type (3) or the “sevenless” mutant (4) with an additional cone cell (bright color) in each ommatidium. The images on the left show microscopic images of the fully developed eye (A), wild type (B) and “sevenless” mutant ommatidia (C). In contrast to the relatively complicated process underlying drosophila’s natural eye development and Turing’s mathematical reaction diffusion models, this simulation was achieved using a rather straightforward lateral inhibition algorithm.

This mechanism of differentiating local attributes from cellular tissue with a persistent code script based on spatial identity can be regarded as an answer to the basic question of how matter can self-evaluate as information.

**7 Conclusions**

This paper is an early manifestation of a new area of research, and it is important to point out that a lot of work and further research are still necessary to deploy developmental theory in man-made design and construction. In this first account we have given a discussion of the morphogenetic relationship of matter and information and shown how existing knowledge of natural mechanisms of generating spatial and temporal cell identity can be adopted in artificial design.

We emphasize the necessity of regarding the developmental view as a complement to evolutionary design theory on the pathway towards evolutionary developmental design theory in accordance with the analogous trend towards an evolutionary developmental biology. This approach will hopefully help open a “developmental” perspective on design in general and generative design in particular.

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Figure 4 was reproduced from http://www.indiana.edu/~elegans/Photo_archive/development.html.

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9 References


Distributed Agents for Morphologic and Behavioral Expression...


