CRYSTAL FORMING ROBOTS ON OVERHEAD

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The following paper presents a robotic system that makes the process of crystal growth tangible. The background of this work are the early experiments from Gordon Pask on building a chemical computer as a learning system and my own interest in brain plasticity. With the help of software simulation the idea of a learning structure that grows and modifies its own perception of the environment is illustrated. The robotic implementation of the growth process is a first step towards making such a process tangible.

1. INTRODUCTION

The topic of this paper are systems of simulated crystal growths and my current research on creating a tangible system of a simulated crystal growth process: *crystal forming robots on overhead*. The background of this quest is my interest in autonomous learning systems and brain plasticity. The process of neural growth and the process of crystal growth are fundamentally different in their details. But as Gordon Pask has shown with his work on chemical computers, on a more abstract level crystal growth may serve as a model for autonomous learning (Pask 1958). The key analogy in his experiments on learning with chemical computers was the circular relationship of perception and learning: how the perception of the environment shaped the outcome of the growth process and how the growth process itself shaped the way the environment was perceived.

The complexity of the nervous system and of our psyche is through a large part due to that circular relationship. Humans are exposed to the world through their senses and it is without doubt in large parts the world that shapes the way our brain is organized. There are numerous examples for this fact, the most prominent are the insights about the cortical organization of the sensory motor system that follows a topographic organization, thus reflecting the structure of how the world is perceived (Sanes and Donoghue 2000). At any time this nervous tissue is plastic, which means that increased activation of a sense will lead to a growing representation in the brain and, vice versa, reduced activation leads to a shrinking representation. Learning to juggle, for example, leads to the growth of those brain areas associated with hand-eye coordination (Driemeyer *et. al.* 2008). But learning to juggle not only affects the skill of juggling, as it modifies significantly the structural organization of the brain it also affects other skills. For example children that learn to juggle show an increased ability for doing mental rotations (Jansen *et. al.* 2011).

A crucial aspect in this example is however that whether we learn to juggle or not depends on our own decision. We thus always actively inscribe ourself in the process of synaptic growth. As Catherine Malabou argues in What to do with our brain (Malabou 2009)

> *It is precisely because – contrary to what we normally think – the brain is not already made that we must ask ourself what to do with it, what we should do with this plasticity that makes us, precisely in the sense of a work: sculpture, modeling, architecture.*

Such questions, about the general structure of learning, about systems that are in a continuous state of becoming, that sort of sculpt themselves into being form the general background of the proposed systems. Even though these systems are far from doing cognition, they provide us with a sense of what it means when a system's growth process is coupled in a circular way to the environment, of what it means when a system has the capacity for autonomous learning.

Gordon Pask was himself active at the interface of art and technology (Pask 1968). As a matter of fact till today he inspires both artists and scientists. The artwork *Roots* by Roman Kirschner is a beautiful example for an artwork based on his ideas on chemical computation (Trogemann 2010). In times when computer simulation of learning processes was almost impossible because of the lack of computing power, Gordon Pask used chemical computation as metaphor for and as simulation of biological systems. He went as far as to use chemical computation "to grow an ear" (Cariani 1993), a device that could differentiate two tones of 50 and 100 Hz. Till today he is the source of inspiration for a number of scientific and artistic projects. However, to my knowledge, few of his experiments could be fully replicated.

I focus on a simpler example Pask gives in his paper *Physical Analogues to the Growth of a Concept* (Pask 1958). Here he proposes a system that he calls a self-building assemblage that has the capacity of learning. This system was based on a ferrous sulphate solution and connected to a current-limited electrical source. When current was applied, ferrous threads would grow between the electrodes. The most interesting aspect of this system was that the growing structure itself was one of the electrodes and would thus modify the force field distribution that contributed to the structure of growth. If one interpreted the grown structure as a sensing element of the electrical field potentials the system was growing its own sensorium.

In a set of software simulations based on the diffusion limited aggregation algorithm I replicate a single experiment and I take these simulations as a proof of concept that crystal growth may help study the interplay of a growing structure and its environment and thus shed light on mechanism of learning.

The aim of this paper is to go beyond software simulation and to develop a tangible system, that allows for experimenting with growth. The idea of using robots is thus that the whole process of crystal formation is taken to a macroscopic level that is much easier to observe in detail. It is like watching the crystallization process through a microscope. The other reason to use robots as an experimental platform is that they offer the potential to link them electronically and to connect them to behavior. Such robots that have the ability to self assemble into larger structures have of course a long history in robotic research, see (Groß and Dorigo 2007) for an overview paper and see the works by Penrose (Penrose 1959) for an early reference. However, using very simple solar powered robots to study and make tangible growth processes themselves is a new approach.

2. SIMULATING GORDON PASKS LIQUID ASSEMBLAGE

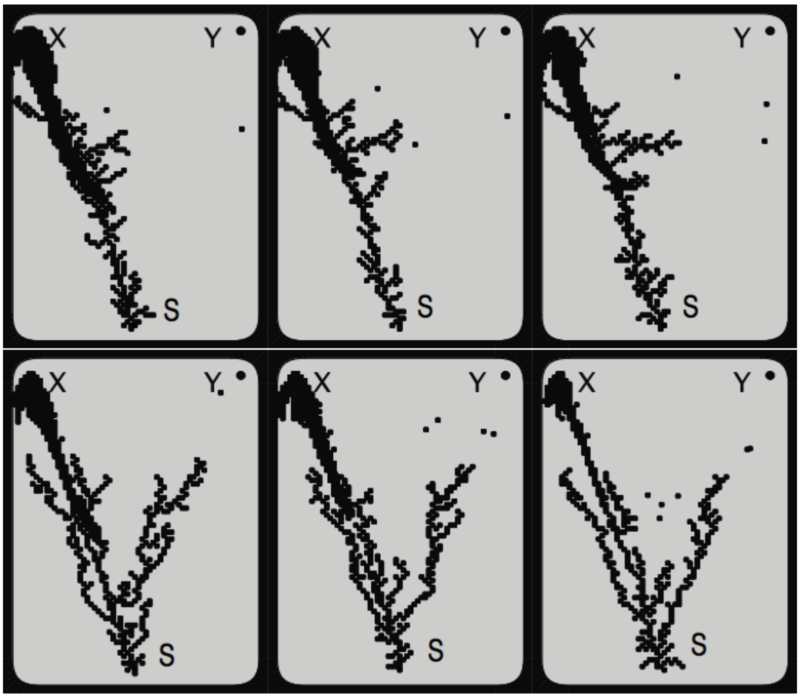
In Gordon Pasks setup what he refers to as the assemblage is an electrolyte solution where two anodes are placed at positions X and Y, that define a force field between them and a single cathode S. He then analyzes two different regimes. He argues that if initially point X has more positive potential than Y, the thread will grow in direction of X and that if at some moment in time the potential at Y is set to equal value the thread might bifurcate and split into two branches. If after this bifurcation, the initial parameters for X and Y are re-established, the behavior of the system will now be very different, because it has already formed a thread towards Y. He argues that the behavior after bifurcation can not be predicted from the observations of the system before the bifurcation. From this observation he concludes

> *Thus an observer would say that the assemblage learned and modified its behavior, or looking inside the system, that it built up a structure adapted to dealing with an otherwise insoluble ambiguity in its surroundings.*

For simulating the force fields created by the different potentials that are defined by the electrodes, the diffusion limited aggregation algorithm (Witten and Sander 1983) is modified. In the standard algorithm the diffusion process of particles is simulated with a random walk and the aggregation is computed just based on neighborhood relations. The aggregate is initialized with a starting seed. Whenever a particle hits the neighborhood of the seed or an already aggregated particle it stops moving and becomes part of the structure. In the original algorithm no force fields are defined.

The first modification to the original algorithm is that the movement of the particles is not defined in cartesian but in polar coordinates. This makes it much easier compute a directional force. The second modification is the introduction of a directional force that acts upon the particles. This force is defined by the growing structure that set an attractive force. In addition to this directional force a random force is defined that follows a Gaussian distribution around the direction of the attractive force. To compute the attractive force of the growing structure on a particle each element of the growing structure sets an attractive force in its own direction. The overall force is then obtained by integrating all forces. The single force of one element on the particle is defined by the distance of the particle with respect to that element of the structure. The further apart the smaller the attractive force. This way of computing the direction for the moving particles is based on the dynamic systems approach to navigation (Schoener and Bicho 1997). The forward speed of a particle may be computed independently, and follows a simple rule: The closer a particle gets to the structure, the slower it speed.

Fig. 1 The top row shows simulation results of three different runs for the regime with constant source distribution 84% of the particles come from location X and only 16% from Y. The bottom row shows three simulations runs with a switch of the distribution to 50% from X and Y after time t1 and again switch back to the original distribution after time t2.



When it hits the structure it stops moving and aggregates to it. As more particles aggregate the force field is modified, because each new element contributes a new force that will be integrated. With this set-up it is now possible simulate Gordon Pask's setup and to compare the two different regimes. The difference in positive potential of a source X versus a source Y is modeled through the distribution of particles they release.

In the first regime 84% of the particles come from source X and 16% come from source Y (see Figure 1 for the spatial setup). In this first regime over the full time of the experiment the distribution is not changed. In the second regime the experiment starts with the same distribution of 84% and 16%, but then switches after some time t1 to an equal distribution of 50% from source X and 50% from source Y and finally after time t2 it switches back to the initial distribution.

What the simulations (Figure 1) clearly show is that in the second regime a bifurcation happens early on, when the switch to the equal distribution happens (lower part of the figure). Two threads one directed toward the source X and the second directed towards the source Y grow. As a result of this bifurcation the thread leading towards Y is so close to the source that after switching back at time t2, particles coming form source Y are rather attracted towards this thread, so that it now continues to grow. In the first regime where most particles come from source X, only small degenerate subthreads towards Y develop and they appear late in the process. What is also remarkable is that while each of the simulations produces locally very different results, the overall shape within a regime looks very similar over different trials. These effects are all very well reproducible.

3. SIMULATING GROWTH WITH HARDWARE

The basic idea of simulating crystal growth with hardware is to render tangible the processes of self-organization and autonomy. The two ingredients of the diffusion limited aggregation algorithm are two processes, the diffusion process of a random walk and the clustering process that leads to the aggregation. The idea of crystal forming robots on overhead is to realize these two processes with small robots. These are based on the overheadbots, which are small solar powered robots that work with the so-called suneater circuit as it has been developed by Mark Tilden.

3.1. OVERHEADBOTS

The overheadbots are little solar powered robots that are placed on the overhead projector. They use the light that comes from the overhead projector as their source of energy and they are fully autonomous. They have been shown in different configurations at diverse media art festivals and premiered at the festival *The Art of the Overhead* in 2005 (Gansing 2013).

With a small solar panel the light energy from the overhead projector is converted to electrical energy and used to charge up a capacitor. A small electronic circuit monitors the amount of energy and whenever a critical level is reached a discharge is triggered that drives a small vibration motor. This cycle of charging the capacitor and discharging it through a motor creates a rhythmic pattern. The overhead projector forms a sort of habitat for the overheadbots, once it is turned on they work fully autonomous. Similar to real particles the overheadbots diffuse and without a physical border on the screen of the overhead projector, it is only a matter of time till they are all off the screen where there is no more energy supply.

3.2. CRYSTAL FORMING OVERHEADBOTS

In order to have the potential for forming patterns on the overhead projector the overhead robots need to be as tiny as possible. To this end instead of using a standard solar panel, a custom made solar module that consists of 9 photodiodes (actually very tiny solar cells) is used. Using this custom made solar panel the robots measure only two by two centimeters. To create the additional attractive force the overheadbots are equipped with a rectangular frame that holds 4 neodymium magnets, one for each side (see Figure 3).

Fig. 2 A series of photographs of a clustering sequence, it took approximately 20 minutes for the final structure to build. fully autonomous. Similar to real particles the overhead bots diffuse and without a physical border on the screen of the overhead projector, it is only a matter of time till they are all off the screen where there is no more energy supply.

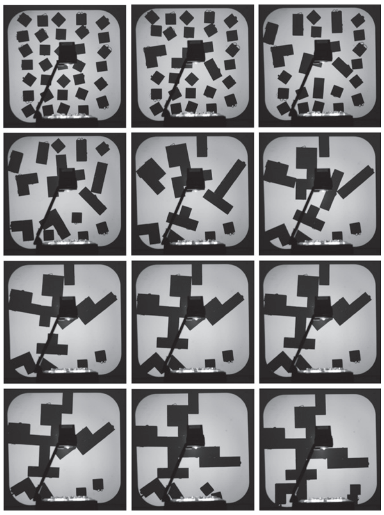
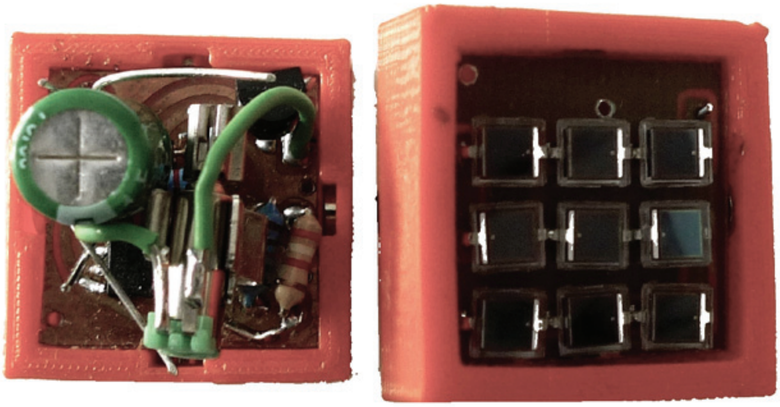


Fig. 3 The left side shows the top view of a crystal forming robot with the electronics and the motor, the right side shows the bottom view with the custom made solar panel.



When two robots with matching polarity come close to each other this attractive magnetic force will form a local cluster. Unlike the standard diffusion limited aggregation algorithm there is not a single seed but each particle is a potential seed for the growth of a structure. Once a cluster is formed the robots start to move together, the trigger of one motor also physically agitates the other robot. However as the cluster grows the overall movement amplitude becomes small smaller and smaller, because the total weight of the structure increases. Figure 2 shows an exemplary run, initially the robots are equally distributed on the screen. After some time the first local clusters of two or three robots appear. Then larger clusters form, only two robots stay separate. In the final frame the three larger clusters all have joined into a single structure.

4. CONCLUSION AND OUTLOOK

The software simulations of Gordon Pask's early experiments show that using the process of crystal growth uncovers interesting couplings between growth processes and the environment they appear in. Such processes act as metaphors in understanding our own processes of learning that have a similar signature in that a learning also may alter the way we perceive the world.

The overheadbots form structures that look very similar to those observed in simulations of crystal growth. Even though there is no global force field but only local attractions between robots of opposed polarity, global patterns may emerge. Sometimes a local sub-cluster remains isolated but always one large structure builds up. Instead of looking through a microscope to watch particles aggregate as during the observation of real crystal growth this process is scaled to the size of little robots and again magnified with the help of the overhead projector.

In order to connect the growth of the structure to functional changes, currently I am working on adding contact points to the side of the robots, so that when they touch an electrical connection between them is created. With these contact points it will become possible to grow electrical connection and to plug those connections to behavior of the robots. As a matter of fact there is clearly the potential to use such robotic systems to simulate interesting aspects of learning where growth affects behavior and behavior affects growth.

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