Emergent Interfaces: Constructive Assembly of Identical Units

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Figure 1: Emerging helix after an experiment session.

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Abstract

In this paper, we present five types of constructive assemblies that emerge through a form-finding process resembling growth. The synthetic growth is obtained through the assembly of identical blocks performed by two competing users. Each block type gives rise to different morphologies during each assembly session depending on the user and the environment that is augmented through projection on the synthetic structure and around it. The digitally augmented tangible interface is evaluated by professionals and students in interaction design. We introduce the concept of Emergent Interfaces (EI), which proposes harnessing non-determinism, temporal design, and self-organization. This work could contribute to organic user interfaces and morphogenetic engineering.

Author Keywords

Constructive assembly; synthetic; growth; organic; morphogenesis; form-finding; tangible interface

ACM Classification Keywords

H.5.m. [Information Interfaces and Presentation (e.g. HCI)]: Miscellaneous

Introduction

Computer interfaces have evolved in recent decades from being only graphical to becoming tangible. The paradigm is shifting from seeing digital information through a screen to having the information manifested physically. The tangible user interface embodies digital information in physical space, so that physical objects "support direct engagement with the digital world" [9]. The predicted future paradigm is that of interfaces that are changeable in form and appearance. Constructive assemblies are embodiments of the programmable matter vision [7, 9, 17, 19]. They are made up of interactive units that are connected together automatically or manually to form a complex structure [17].

We adhere to Van Alstyne and Logan's hypotheses that design must harness the process of emergence, that an innovative design is an emergent design. We review natural and artificial systems that lead to emergence and examine the need for representation compared with nature's non-determinist and self-organizational processes. We propose the concept of Emergent Interfaces (EI) as an alternative approach to human-computer interaction. We explore its properties with a form-finding experiment employing identical units that are assembled into emergent organic structures through a tangible interface. This unit-by-unit assembly results in organic morphologies and exhibits growth behavior, which we call synthetic growth since we were inspired by synthetic biology research [2] and "biologically produced architecture" [15]. We explore five variations of building blocks, evaluate them using interaction design professionals and students.

Background

We consider our work a development of organic user interfaces [22] and morphogenetic engineering [6]. In this context, we emphasize emergence and morphogenesis, and point to the areas of complexity science that inspired us.

Emergence

"Emergent behavior implies a holistic capability where the sum is considerably greater than its parts" [1]. Moreover, emergence is "the process by which a set of simple rules determines complex pattern formation" [13]. Ronald et. al give examples from artificial intelligence of emergent flocking behavior from simple steering mechanisms, self-replicating structures from basic components, visual patterns in Game of Life, team behavior, social structures, ants' paths, Braitenberg vehicles, wasp nest structures, pattern recognition solutions with neural networks, and density solutions with cellular automata [16]. Furthermore, Marvin Minsky claims that the human mind "emerges from a society of myriad, mindless components" [16, 10]. In this paper, we will explore with the help of constructive assemblies how user interfaces could make use of design principles that would result in emergent morphology.

Organic user interfaces and organic architecture

Holman and Vertegaal's definition of an Organic User Interface (OUI) is a "computer interface that uses a non-planar display as a primary means of output, as well as input" [22]. The three principles for OUI design that guided our work are: input equals output, function equals form, and form follows flow (context) [8]. Parkes et. al define kinetic organic user interfaces as OUIs that embody motion to communicate information to users [13]. They predict that KOIs "may create systems that could someday reflect some of the complexity of living organisms". In this context, we have to bring up R. Brooks' subsumption architecture for controlling robots based on simple rules, able to cope in complex environments [4]. Synthetic biology research studying the

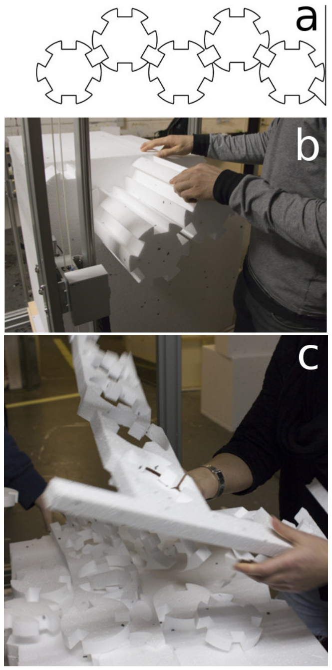

Figure 2: Block fabrication process for the unit with 6 cogs: a) design of the units given to the CNC hotwire cutter machine as a curve, b) cylinders being removed from the styrofoam block, and c) sliced cylinders resulting in the units.

evolution of morphology through interaction with complex environments shows that the morphological complexity of virtual organisms is influenced by the complexity of the environments in which they evolve [2].

Organic Architecture proposes combining the aesthetics of nature with modern architecture by balancing planar geometries with nature's irregular shapes [8, 24]. More recently, Ramirez-Figueroa et. al propose an approach to developing new materials derived from synthetic biology [15]. One potential application is to "grow buildings by programming cellular organisms to fabricate and deposit material into architecturally relevant patterns" [15].

Complexity of natural and artificial systems
Based on nonequilibrium physics and dynamical systems theory, Nicolis and Prigogine laid the foundations of complexity science and realized that physical processes like "instabilities and fluctuations are ultimately responsible for the amazing variety and richness of the forms and structures we see in nature" [14]. They illustrate examples from chemistry, materials science, electromagnetism, and biological systems that reveal similar patterns in both organic and inorganic matter and note that "many fundamental processes shaping nature are irreversible and stochastic" [14]. A. Turing investigated the chemical processes behind morphogenesis and phillotaxis. Referring to a system of chemical substances responsible for morphogenesis, which involves reacting and diffusing through biological tissues, he notes: "although it may originally be quite homogeneous,[it] may later develop a pattern or structure due to an instability of the homogeneous equilibrium, which is triggered off by random disturbances" [20]. These insights about patterns were obtained by exploring and understanding the underlying physical laws of nature.

Another approach is to explore the completely digital emergent patterns. S. Wolfram researched the digital world of elementary cellular automata by visualizing the patterns with the help of a computer [23]. The patterns seemed to be randomly changing after a sequence of homogeneity (e.g. rule 110[1]). These patterns were *computational irreducible* since they emerged from simple programs with great diversity of behavior that is impossible to predict without running them [23]. By studying complex systems and spontaneous pattern formation through random and repetitive processes, Doursat et al. propose a programmable self-organizing design, *Morphogenetic Engineering* [6]. This field lies at the border between natural and artificial systems, promising more architecture, less randomness (than in nature) and more self-organization, and less design (than in artificial systems). The following "dynamic processes" were considered representative for the reviewed artificial systems: constructive, coalescing, developing, and generating. Although this field emphasizes self-organization, emergence is not considered a central characteristic.

We can view the emergent structures presented in this paper as a result of running similar programs; not on a computer, but in a digitally augmented physical space through growth by the assembly of identical three dimensional units. Ronald et. al identified key elements of complex systems: computational undecidability, self-organizing phenomena, and sensitivity to initial conditions [16]. These characteristics guided our work.

Block design and growth
In this research, we aimed to design identical units as building blocks that would emerge and grow into a

[1] http://mathworld.wolfram.com/Rule110.html

Figure 3: Five variations of blocks with all openings connected to identical blocks. These were the starting structures for the experiment.

complex organic structure. Inspirations were the elementary particle-particle interactions from nature [14] and cellular automata [23], but on a human scale. The building blocks needed to be robust enough to sustain a structure as high as a person and as wide as the projected surface that would be used to augment the structure and the physical space around it. They had to fit in one hand, be able to be assembled quickly and easily, and be able to be attached and detached rapidly. Several designs and materials were considered for the building block. Early prototypes were made out of cardboard and then styrofoam in the shapes of a cutout quadratic block, a cutout cylinder, hexagonal and octagonal prisms, and a dodecahedron.

We decided on five design variations of the building block similar to a cogwheel made out of a cylinder slice, because this design i) supported the robust and rapid addition and removal of a block, ii) was quick to manufacture, and iii) enabled the emergence of organic structures. After initial experiments, we decided to manufacture and explore this block design by having all the possible number of cogs at that scale between three and seven (Fig. 3). Every building block could be connected to between three and seven other identical blocks, depending on the number of cogs. The cogs were all equally spaced on the circle circumference, with the openings' dimension between the cogs always the same size. See the example with six cogs from Fig. 2a and the other variations from Fig. 3. Our experiments showed that the structure's robustness would be influenced by the height of the cogs or depth of openings. The shape of a unit was designed in Rhino as a cylinder slice with a diameter of 12cm and a height of 2cm (Fig. 2a), so that they fit best in the hand. The material chosen was styrofoam. The 12 cm diameter, 60 cm high cylinders were cut of styrofoam blocks using a CNC hotwire cutting machine (Fig. 2b). These cylinders were then cut again into 2cm high slices (Fig. 2c). In total there were five block types of 50-60 units each that could be assembled by pushing them together at their openings (Fig. 3). After several tests in building horizontally and vertically, we concluded that a good way to explore the "structure space" was to have as little time available as possible and to compete against an opponent.

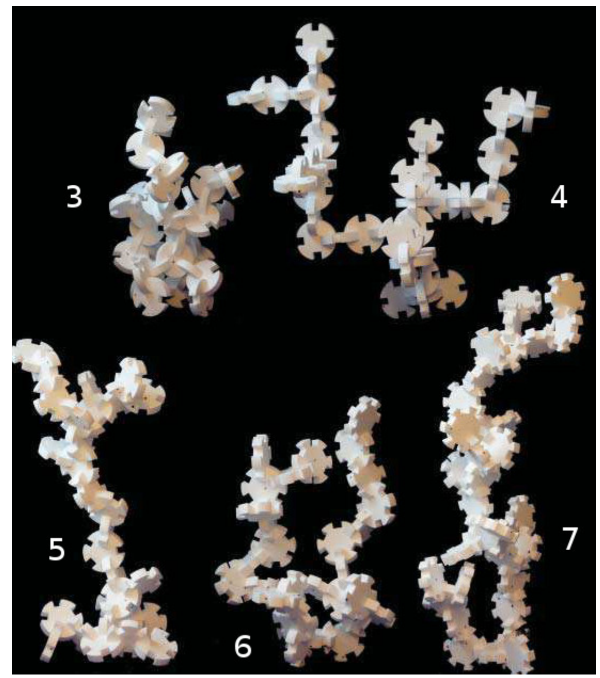

Figure 4: Five variations of blocks with the number of openings varying between 3 and 7 developing into structures.

Synthetic growth experiment

We decided to create the experiment as a two-player game; each player building with the same block type but

Figure 5: Experimental setup and two participants completing questionnaires near the structures they had just created. The Kinect-projector system is attached to a tripod. Structures are built on the triangular base plates. A poster with the game rules is attached at the bottom of the tripod.

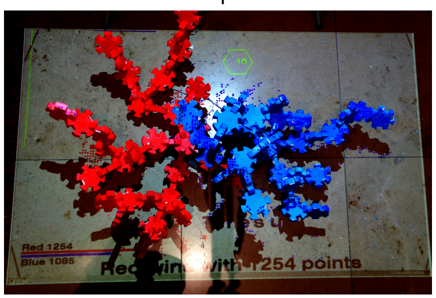

Figure 6: Top view of the resulting structures at the end of a game. The score is shown at the bottom left. The bottom centre shows time, the winning player and points. A green hexagon is visible at the middle top. Black points are projected onto the blue structure in the middle showing that the user should build in that area in order to balance it.

with a different color. Half of the units were blue; the other half red.

Hardware

To enable processing of geometry and augmentation of structures and environment, a Kinect-projector system was suspended on top of the scene using a tripod (Fig. 5). The calibration of the Kinect-projector system was done with a toolkit developed in Processing and described in previous work [12]. The calibration consisted of correcting the projection skew and distance of the RGB-depth mapping received from the Kinect and carefully aligning it to fall exactly on the objects and surfaces of the scene. In this way, we could know exactly where the colored point clouds of the geometry were in the scene and project accurately on and around the structure.

A plate in a shape of a triangle with the ability of sensing pressure was developed as a base for each structure (see bottom of structures in Fig. 9). Consequently, the blue and red structures had as a base the completely connected units from the bottom images of Fig. 3, attached with double sticky tape to the pressure base plate. The pressure plate was constructed out of two wooden plates with a carbon sheet and aluminium sheets in between, connected to an Arduino. The carbon sheet acted as a resistor whose conductivity decreased when pressure was applied on top of the plate. This pressure sensing system was accurate, being able to sense when the structure was unbalanced and leaning towards one of the three sides of the triangle plate.

Software

The experiment was created in Processing and the information was projected on top and around the structure. The game logic is based on analyzing in real-time the amount of red and blue point clouds received from under projection. The winner is the player with the largest score at the end of the game. The game session lasts for 5 minutes, with a timer counting down at the projection bottom. The timer is replaced with a message informing who has won the game when the minutes are up (bottom of Fig. 6). A green hexagon appears near the structures randomly for 20 seconds, counting down. Fig. 6 shows the hexagon in the top middle of the image having 16 seconds until it disappears. If it isn't picked during this time by building on top of it, it disappears and reappears in another random place where there is no built structure. The score is shown at the bottom left of the projection using horizontal red and blue bars, with the score in numbers (bottom left of Fig. 6). The score is calculated by counting the number of red and blue points under projection, adding the bonus points that can be gathered by building on top of the green hexagons. Extra bonus points are added by building higher. The pressure information acquired with the base plate is employed by projecting black points in order to show where the user should build so that the structure becomes more balanced.

Task instructions

On the base of the tripod near the projection, a poster showed the task instructions as game rules below a "How to play" title (Fig. 9). "Red and blue compete to cover the most areas as seen from the top, like plants struggling for light from above". The task instructions were the following:

Figure 7: Two participants constructing structures during evaluation.

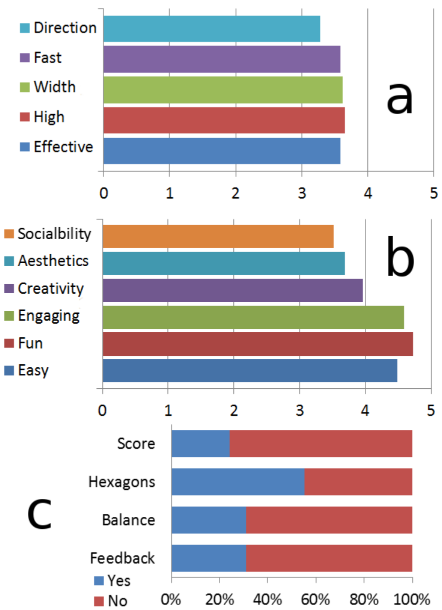

Figure 8: Charts with questionnnaire results. The questionnaire was divided into three parts: a) 5-point Likert scale questions regarding building blocks, and overall system questions that were either b) rated on a Likert scale, and c) answered with yes or no.

1. Add one block at a time
2. Pick green hexagons to get bonus points. Do so by building the structure over the green hexagon
3. If blocks break off, they will be removed from the playground
4. If you run out of blocks, you are allowed to replace one block at a time

Three tips were suggested: i) build high to get more points, ii) build over the competing structure to steal their points, and iii) use the balance indication to see if your structure is balancing; black means the structure needs more weight.

Evaluation

The goal of the evaluation was to assess human factors influencing the assembly process, namely usability and user experience of the system to obtain insights regarding the building process, and to get any additional new insights from the written comments. The evaluation was performed as part of a demonstration at a conference, so the participants were professionals or students in interaction design. The number of participants was 28, out of which 13 were females, 12 males, and 3 undeclared gender. Their age ranged between 21 and 45 (M=28.6, SD=6.1). Participants were paired, competing against each other during a five minute session. There was always a winner, except for a single time when there was a draw. The participants were given a building block with 3, 5, 6 or 7 cogs, but not the block with 4 cogs which was the most different from the rest since it yielded structures with perpendicular branches (see Fig. 4).

Questionnaire
The questionnaire consisted of three sections (a, b, and c) presented below. Corresponding answers are shown in Fig. 8.

a) Building blocks, 5-point Likert scale (Fig. 8a)
i) How effectively can you build structures with the block? ii) Does the block support building high? iii) Does the block support building in width? iv) How fast can you build with the block? v) How well can you build in the intended direction?

b) Rating the system, 5-point Likert scale (Fig. 8b)
Is the system i) easy to learn, ii) fun to use, iii) engaging, iv) supportive of creativity, v) aesthetically pleasing, and vi) able to enhance sociability?

c) Rating the system, yes or no (Fig. 8c)
i) Does the system provide enough feedback during building? ii) Did you use balance? iii) Did you collect the green hexagons? iv) Did the score influence you during building?

Participants' comments
A user appreciated that "it was a really good experience to see that the rule of getting more light is making the structure actually become like plants in the real world". He also observed that the green hexagons "were helpful in making decisions about the direction of the structure". Another player mentioned that it was hard to focus both on building the structure and looking at the projected information. Some suggested that the feedback should attract more attention. Some users complained about casting a shadow with their bodies and not being able to see the feedback. One suggested that an additional screen or using a tabletop would be better. Regarding the gameplay, one participant suggested that having more

time and turn-by-turn could make building more social. Other suggestions included combining different block types in one structure and using magnetic blocks for the connection. The participants considered that it would be useful to have more audio support like a voice, music, or alarm clock sounds informing about the remaining time. Additionally, visual feedback, for example a picture with the structures from above, would have helped to gain a structure overview. One player noted: "I competed for space in the middle even though there was empty space on my side".

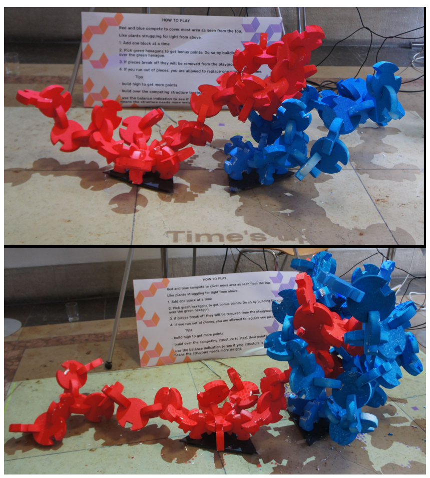

Figure 9: Synthetic structures with three cogs. The base plate can be seen supporting the structure. The poster with task instructions can be seen in the background.

Why design for emergence?

Van Alstyne and Logan identify similarities and differences between design and emergence, and argument that innovative design is emergent [21]. Based on this hypothesis, they raise the question: "how does one incorporate both design, an intentional activity, and emergence, a self-organizing principle, in the same process? The solution to this problem will reveal the secret of innovative design" and refer to the processes behind adoption and selection of certain products by the user community [21]. Besides innovation being an emergent phenomenon, employing emergence in design could lead to richer forms and behaviors.

Current technology and spaces we inhabit have a great impact on how society perceives and interacts with digital information, but also influence greatly how human beings develop. The separation between the development of environment and digital interfaces, and lack of embodiment of these two leads to decoupling and inconsistencies of physical states from the underlying representations. M. Minsky observes that "the most usual way to represent knowledge has been to first select a representation. And that's been the problem! Using any particular representation you'll soon encounter some limitation or constraint, and these will quickly accumulate until your reasoning starts to fail." [11]. Minsky proposes identifying the causes contributing to a phenomenon and assessing how much each contributes to deciding on which representation to choose [11]. However, this approach does not take into account embodying the information in the interface and still separates the representation of information from its purpose and physicality. We introduce the concept of Emergent Interfaces (EI), which proposes harnessing non-determinism, temporal design, and self-organization.

Designing Emergent Interfaces

The reviewed literature contrasts two main approaches: having a representation vs. non-determinism responsible for a vast variety and richness of forms in nature [14]. Complexity science uncovered behaviors and laws leading to emergence: computational undecidability, self-organizing phenomena, and sensitivity to initial conditions [16].

Non-determinism

Science is able to model nature's phenomena and predict future phenomena, while nature seems to have rules and laws that are responsible for emergent behavior, but lacking clear goals every step of the way.
Non-determinism is important to create a rich variety of organic structures. As noted by Nicolis and Prigogine, nature's richness and variety of forms and structures are shaped by irreversible and stochastic processes [14]. A. Turing notes that morphogenesis and phillotaxis can be explained by random disturbances and instabilities [20]. In the synthetic growth experiment, non-determinism was introduced by increasing complexity in the physical-digital interaction space and supported by the process of

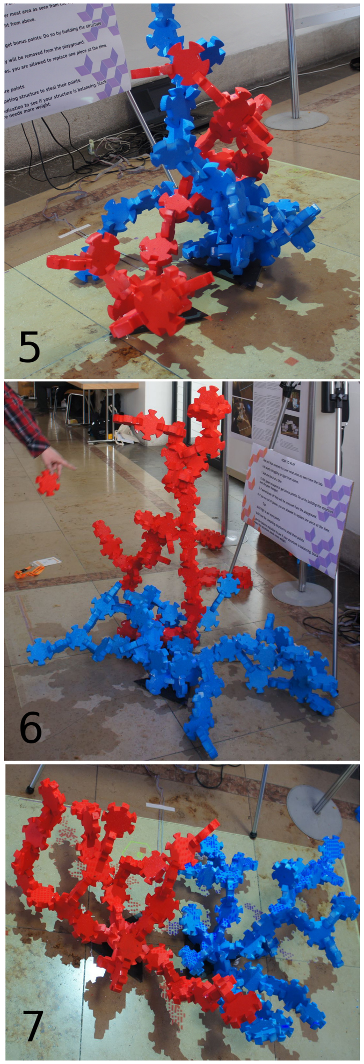

Figure 10: Synthetic structures with 5, 6, and 7 cogs. Number 5 shows a helix emerging, 6 shows the red structure expanding in height, while 7 depicts two structures expanding in width.

connecting each block to the next governed by psycho-social factors (interaction between participants and their immediate choice), geometry of matter (number of openings of a unit; other player's structure), and digital information (time available; the digitally augmented feedback; balance information; hexagons; score). The evaluation revealed that digital feedback contributed actively (hexagons), passively (score, time), and minimal (balance) to the emergent morphology.

In design, understanding the requirements and problem leads to narrowing the design space, constructing more complete assumptions and better rational solutions to a limited problem space. Non-determinism is avoided and complexity are reduced, and overcome by thoroughly studying the phenomena. But the problem can never be completely modelled, and choosing one representation will soon encounter a limitation or constraint proving insuficient in handling complexity of real-life [11]. Researchers in artificial intelligence have made great progress in modelling certain parts of the human observable phenomena and creating interfaces that perform as expected in solving a limited problem. However, predicting the complexity of real-life and the rich interaction possibilities of computing interfaces will always be limited by the representation. Brooks proposed an intelligence without representation and an architecture based on subsuming phenomena that have a lower priority [3, 4]. This approach, in our opinion, still relies on a representation of priorities. Our work proposes using non-determinism and designing interfaces that thrive on unpredicted behavior and interactions, and uses this as a resource in order to exhibit emergent phenomena.

Temporal design

D'Arcy Thompson comments on organic form generation: "Organic form itself is found, mathematically speaking, to be a function of time [...] We might call the form of an organism an event in space-time, and not merely a configuration in space " [5]. This principle inspired architecture research which proposed "growing buildings by programming cellular organisms to fabricate and deposit material into architecturally relevant patterns" [15]. Morphogenetic principles could be in "continuous negotiation between a design intent and material emergence" that would result in "biologically produced architecture" [15]. Similarly, Emergent Interfaces are designed as a function of time by developing form based on the history of that form. The interface acts as a memory, showing the past actions embodied in every growth step. In this context we don't refer only to computer interface, but also to computational materials that could be employed to create more expressive and more powerful computational machines [18].

Nature has a bottom-up approach, laying down the rules and building blocks as foundations and offering time as a means for emergence. Emergent Interfaces propose a similar bottom-up approach. Having simple identical units gives rise to a great diversity of organic structures that are difficult to predict without "running" them [23]. Fig. 3 shows the geometrical rules as building blocks for the various families of structures that emerged during the experiment (Fig. 9 and 10). These are an example of initial conditions that govern the growth of emergent interfaces. More generally, a temporal design approach would imply designing interfaces to the digital and physical so that its functions could grow and adapt on various timescales. Another remark concerning the time aspect would be that physical processes shaping nature are irreversible, while our design permits adding and removing blocks which make it reversible.

Design for self-organization
Nicolis and Prigogine give examples of physical and chemical systems at different scales that communicate energy from the environment and lead to self-organization phenomena, exhibiting an ordered behavior characterized by "symmetry breaking, multiple choices, and correlations of a macroscopic range" [14]. Such systems are composed out of particles and their interactions obeying simple rules. Fig. 1 shows a helix emerging during the experiment. The interactions of the blocks are given by the connections that depend on the geometrical shape of the blocks. The physical constraints are not the only rules leading to emergence. The game rules and score motivate the participants to build high and to cover each other's structure, thus creating the helix.

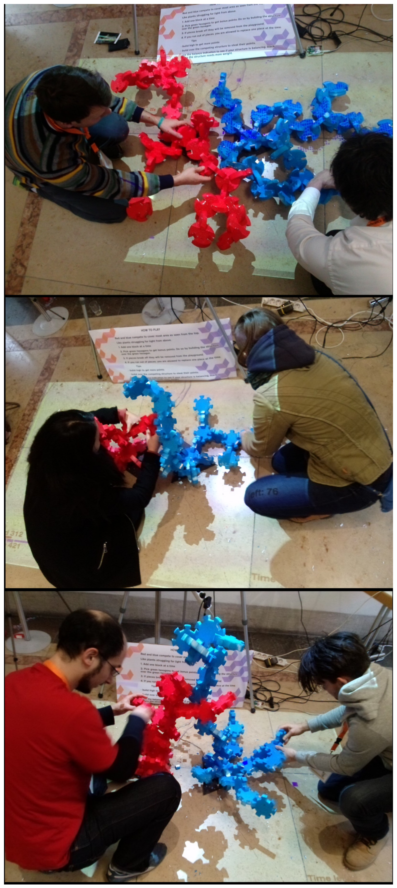

Figure 11: Participants assembling blocks during the experiment.

The relationship between the participants is embodied in the created structures, and the competition and limited time available help to explore the unique patterns of each session (Fig. 11). The five families of blocks have different characteristics. Fig. 4 shows one structure for each unit type, for example the 3 cogs unit results in structures that are very compact and have a low height; the unit with 4 cogs yields structures with perpendicular branches. The lower the number of openings, the less opportunities exist to build in the intended direction. From this perspective, the 7-cog unit supports the most building in the desired direction, while the 3-cog unit makes it hard to build in a straight line. This was reflected during the game when the 3-cog unit users wanted to pick up hexagons but were not able to go in the intended direction.

Conclusion and future work
Non-determinism, temporal design, and self-organization are physical properties of the world we inhabit. Harnessing these properties and embodying the development of the environment and digital interfaces would lead to richer morphologies and behavior. Future development would address adding motion capability to the constructive assembly unit or to another type of mobile unit designed as a hinge. An analysis tool could simulate the effects that imperfect unit assembly have on the whole structure and the variety of morphologies, and help exploring unit design. Units developed from more robust materials at smaller and larger scales could lead to interesting applications in reconfigurable robotics and biologically produced architecture. In organic user interfaces and morphogenetic engineering, emergent interfaces could suggest a way to develop more expressive and more powerful computational machines.

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