Floatiles: Self-Assembly Based On Cheerios Effect and Aperiodic Monotiles

Georgii Karelin[1]

[1] Okinawa Institute of Science and Technology, 1919-1 Tancha, Onna-son, Kunigami-gun, Okinawa, 904-0495, Japan
georgii.karelin@oist.jp

Abstract

This project aims to create an affordable macroscopic physical experiment using simple principles to explore pattern formation and dynamics. Combining the Cheerios effect, a well-observed phenomenon in fluid dynamics, with the geometric concept of aperiodic monotiles makes it possible to observe the self-assembly of complex structures from identical elements. Aperiodic monotiles are unique geometric shapes with a notable property: they can tile an infinite plane without forming a repeating pattern. The specific geometric properties of the monotiles influence the resulting formations. Perturbations can increase the complexity of clusters and make them evolve and interact with each other. This setup facilitates the self-organization of patterns on the liquid surface.

Cheerios effect: examples in nature

Floating objects on a liquid surface tend to come together due to surface tension and buoyancy (Fig. 1 and 2). This phenomenon is known as the Cheerios Effect (Vella and Mahadevan, 2005) because those breakfast cereals clump together. It can be used for self-organization (Whitesides and Grzybowski, 2002) of small floating objects as an active matter. In nature, this aggregation happens with, for example, common duckweed *(L. minor)* and fungal spores (Iliff et al., 2022), mosquito eggs (Loudet and Pouligny, 2011), rafts of fire ants (Ko et al., 2022), and nematodes (Gart et al., 2010). Structures can resemble diffusion-limited aggregation simulations Witten and Sander (1981, 1983); Vicsek (1984). This project is a simple macroscopic physical experiment that can be later used for constructing complex systems with emergent properties, such as the self-replication of structures (Penrose, 1958; Virgo et al., 2012; Freitas Jr, 1980, 2004; Kriegman et al., 2021; Taylor and Dorin, 2020).

Geometry: aperiodic monotiles

The shape of the emergent pattern depends on the shape of the floating particles (Miyashita et al., 2009). Initial trials using regular plastic bottle caps resulted in simple hexagonal grids due to their circular shape. Other shapes can lead to more complex patterns, even if the shape is always the same. Modifying the shapes of the floating objects allows

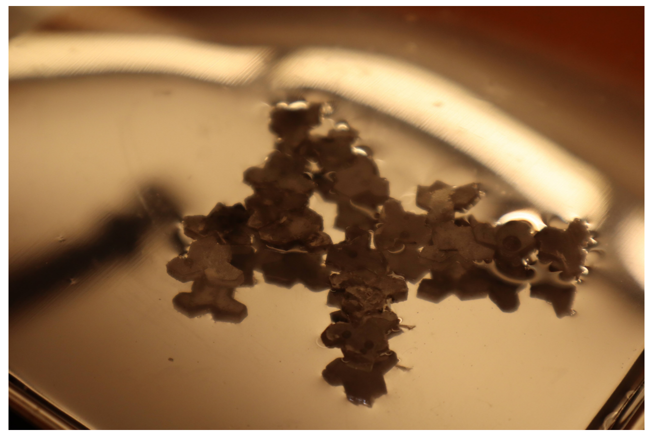

Figure 1: This illustrative photograph shows one of the conducted self-assembly experiments. Cheerios effect – the capillary force of attraction between floating hydrophobic (made from was) small (less than a centimeter) tiles leads to the predictable aggregation of the irregular raft. Tiles are based on the Hat shape. This experiment provides minimal examples of open-ended evolution and teleological behavior. The wax tiles had been moved to one side of the container for photo, but the aggregation is mostly self-organized.

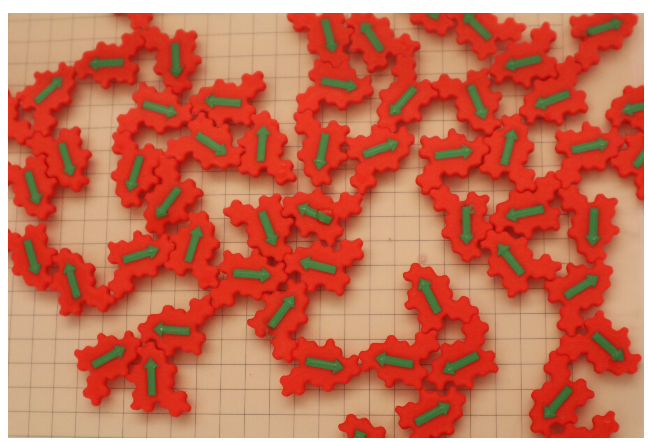

Figure 2: Example of aggregation of Spectre tiles

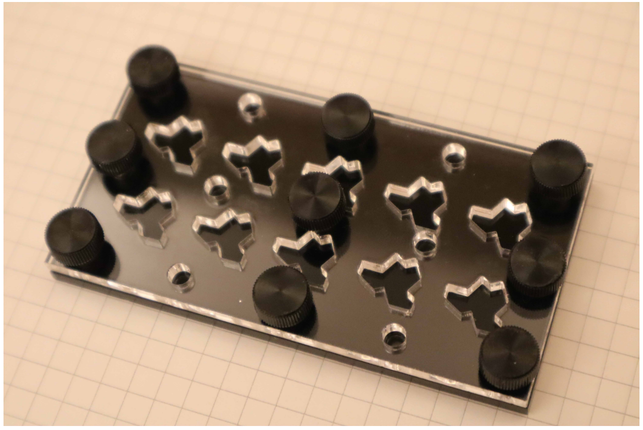

Figure 3: Laser-cutted acrylic casting for wax molding.

for control over the binding force between blocks and the creation of more irregular structures, similar to frustrations and disorder in crystals. Geometry can provide such shape. Recently discovered aperiodic monotile can cover a plane without repeats and gaps (Smith et al., 2023a,b). The Hat and Spectre were used for current experiments. Before aperiodic monotiles, an experiment in December 2022 - January 2023 utilized spiked pentagons to create complex floating structures. Regular pentagons, the simplest non-tiling regular polygons, were modified with spikes and corresponding cavities to introduce irregularities and strong capillary connections when interlocked. Notably, ten of these pentagons can form a ring resembling a gear. A separate and new idea involves exploring floating gears, as they can form self-healing connections and transfer mechanical energy between two fixed-in-space but freely rotating gears. After the literature review, it was found that (Larmour et al., 2008) used a similar approach for smaller particles to form sheets. It has also been applied for robots (Gardi et al., 2022).

Materials and production

Water was used for safety. The production process involves FDM 3D printing of hollow buoyant plastic pieces (Fig. 2). Alternatively, acrylic laser cutting can create a cast (Fig. 3) for paraffin (Fig. 1) molding. Acryl is denser than water, and it is impossible to cut floating pieces directly from it. Mixing water with glycerol may solve this issue. Wooden materials can float in regular water but absorb moisture and change shape unpredictably. Two PLA filaments (green and red) were used to create visual directional marks on each tile, simplifying visual processing and orientation analysis. A vibrational platform, built using an electric motor from a household appliance and controlled by an AC supply with a household electric transformer, introduces perturbations (Miyashita et al., 2009). A specialized table was constructed and eccentric vibrator is under development in the lab.

Agitation: effects of perturbations

The formation of patterns could be altered by introducing perturbations and non-equilibrium conditions (Thomson et al., 2023). Without that additional energy, tiles will form smaller clusters instead of more complex formations. Coalescence might be improved by applying intermediate (hormetic) perturbation, as weak and extreme agitation levels result in smaller aggregations. This is simplified toy example of antifragility (Axenie et al., 2023): patterns which formed under perturbation are ”benefited” from the stress. Agitation should be isotropic and homogeneous, which is hard to achieve. Rocking and rotation are efficient but highly anisotropic and inhomogeneous. The three available options are: (1) Vibrational motion of the whole container, (2) Wave generation by perturbation of the water surface, (3) Aeration with air bubbles. Air bubble generators, such as ”air stones” or ”bubble wands” (Riboux et al., 2010; Risso, 2018), could also create agitation but require sufficient liquid volume and height. Different amounts of liquid may have interesting effects when combined with vibrational agitation. Air bubbles on the container’s edge could prevent tiles from sticking to the boundaries. Variable agitation coupled by feedback to current pattern state can make a trivial model of open-ended evolution (Packard et al., 2019). The interplay of agitation and tiles may achieve complex behavior as in (Čejková et al., 2019; Virgo et al., 2012; Toyota et al., 2009).

Preliminary results and future plans

Examples of videos and updates on the project are available on the page: `https://karegeo.github.io/floatiles/`. Recordings of the experiment will be analyzed with specialized algorithms for pictures (Stephens et al., 2013) and spatiotemporal videos (Menon et al., 2022, 2023). Entropy is often used to analyze image complexity (Rahane and Subramanian, 2020; Larkin, 2016; El-Sayed and Hafeez, 2012). Spatial entropy analysis to measure complexity was used in (Davis and Bongard, 2022) while size of compressed videofile was used in (Aaronson et al., 2014). Automated object detection was applied in (Sayama, 2018). Some ideas on how to measure the complexity of images and videos with approaches based on entropy and neural networks could be found here (Cisneros et al., 2019; Jain et al., 2023). Mofified Active Floatiles could be used as building blocks for self-orginizing floating robots and swarms.

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