Algorithmic Foundations of Programmable Matter

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─── **Abstract** ───

This report documents the program and the outcomes of Dagstuhl Seminar 23091, "Algorithmic Foundations of Programmable Matter", a new and emerging field that combines theoretical work on algorithms with a wide spectrum of practical applications that reach all the way from small-scale embedded systems to cyber-physical structures at nano-scale.

The aim of this seminar was to bring together researchers from computational geometry, distributed computing, DNA computing, and swarm robotics who have worked on programmable matter to inform one another about the newest developments in each area and to discuss future models, approaches, and directions for new research. Similar to the first two Dagstuhl Seminars on programmable matter (16271 and 18331), we did focus on some basic problems, but also considered new problems that were now within reach to be studied.

1   Executive Summary

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Algorithmic Foundations of Programmable Matter is an area that aims at designing models and algorithms for materials that can change their physical properties in a programmable fashion or based on external stimuli.

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This was the third successful Dagstuhl Seminar on this topic, following seminar 16271, which brought together a number of algorithmic core topics, and seminar 18331, which helped to identify a number of particular challenges. In this third seminar 23091, we continued and extended these first steps, in particular, by considering systems with many small components (such as in physics), very large structures (such as in space), and very complex structures (such as in biology).

Despite having to deal with a number of pandemic and post-pandemic issues (which led to the cancellation of the originally planned seminar 21091 in March 2021), we were able to benefit from a broader range of interaction, including digital preparation: We ran an online event over two half days (accounting for time zones from Japan to the US), bringing together the originally planned group of attendees with additional interested and motivated colleagues. This not only helped to maintain the community spirit and keep in touch about ongoing developments, but it also helped to identify the most motivated members of the community. This preparatory event was successful in the following ways.

- Participants worked out a refined format for preparing joint work on new research problems.
- Participants of the digital meeting demonstrated their great commitment to attend: At the end of the second day (i.e., after 8h of online interaction spanning 11h of time difference), the number of live participants was still at 43, i.e., basically undiminished.

This turned out to be extremely helpful for the organization of the renewed seminar 23091, in particular with respect to participation: Despite the inevitable late cancellations due to illness or other unforeseeable emergencies, there was a total of 38 in-person participants.

Another key feature of the seminar was to again make use of the interactive electronic tool coauthor[1], which allowed exceptionally intensive and interdisciplinary collaboration throughout the week, allowing dynamic formulation and development of research problems, ideas, progress and formulation of results. Thus, coauthor greatly facilitated the work done during the seminar, enabling not just identification of, but also dynamic research work on a number of new topics.

On the content side, a number of research areas were brought together, with theoretical connections to the areas of *Distributed Computing*, *Computational Geometry*, and *Self-Assembly*. In addition, a number of application areas provided further directions, including *Swarm Robotics* with their methods for dealing with systems composed of many individual components that together form complex and reconfigurable structures; *Engineering and Physics*, with a variety of technologies and applications for developing flexible and innovative materials and constructions; and *Biomolecular applications* with a spectrum of real-life scenarios.

Overall, we brought together a combination of established experts from the mentioned areas. On the senior level, participants included a number of leading authorities who are established in more than one of the mentioned topics; on the junior level, we had a good selection of highly talented scientists who will continue to advance the field by specific contributions.

Making use of the excellent experiences during the previous seminar, the seminar started with a plenary introduction of all participants, their research areas and their specific challenges and expectations for the seminar. This was followed by a number of plenary sessions, in which experts gave overviews over broad developments and specific open problems.

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[1] https://github.com/edemaine/coauthor/

- Amira Abdel-Rahman gave an excellent survey over the challenges and perspectives of using self-replicating hierarchical robotic swarms in application areas such as space missions.
- Dan Halperin gave an overview of geometry at the service of robotics, ranging from snapping fixtures to multi-robot coordination.
- Damien Woods gave an introduction to practice and theory of self-assembly using synthetic DNA, and then went on to give an overview of work going on in the wet lab, covering a range of different practical topics.
- Kay Römer described scalable real-time localization for robotic ensembles, providing insights into practical hardware considerations.
- Benoît Piranda gave an overview of ongoing work on both the development of real-world Catoms (as a powerful model for producing programmable matter platforms), as well as their simulation and visualization.
- Tom Peters (with support by both Irina Konstitsyna and Christian Scheideler) described the state of the art and ongoing challenges in the amoebot model.

Further presentations were given by Jo Ellis-Monaghan (on DNA self-assembly), Sándor Fekete (describing work on coordinating large ensembles of particles at extreme dimensions, from space to targeted drug delivery), Timothy Gomez (on two-handed self-assembly), Christian Scheideler (on reconfigurable circuit extension), and Giovanni Viglietta (describing programmable matter from fractal formation to genetic programming).

Extending precedent, we put particular emphasis on sessions and presentations that were focused not only on previous and ongoing work, but also on coming challenges, by running a considerable number of open problem sessions. A variety of open problem sessions were headed by Amira Abdel-Rahman (path planning for assembly and reconfiguration), Yuval Emek (self-stabilizing chemical reaction networks), Dan Halperin (minimum number of control alterations), Tanja Kaiser (open-ended evolution), Maria Kokkou (leader election with faults), Irene Parada (fast parallel reconfiguration), Nicolas Schabanel (DNA origami and experiments), Cynthia Sung (self-folding structures), and Ryuhei Uehara (slide-and-pack puzzles).

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3 Overview of Talks

3.1 Self-Replicating Hierarchical Robotic Swarms

Amira Abdel-Rahman (MIT – Cambridge, US)

We introduce the self-replication of hierarchical robotic swarms made by robotic swarms. This is accomplished by discretizing their construction from a feedstock of primitive building blocks that are simultaneously simpler than prior reconfigurable robotic modules and can be composed to create a wide range of functionality. The motivating application is the assembly of high-performance (high specific modulus and strength) cellular structures, for which the swarms function as a combined material-robot system. The discretization significantly simplifies the swarm's navigation, error correction, and coordination. Such a system can build serially, can grow exponentially by building more robots, and can grow hierarchically by building larger robots. We present an algorithm for this novel path-planning problem to compile a shape into a swarm to construct it, show an experimental design of the building block basis set, and model the scaling tradeoffs.

3.2 Some open questions from DNA self-assembly

Jo Ellis-Monaghan (University of Amsterdam, NL)

This talk gives a brief overview of three areas in DNA self-assembly, with emphasis on open problems, including:

- Self-assembly for flexible armed tiles, and also geometric tiles for example in the octet truss.
- Identifying reporter strands for verifying experimental results.
- The problems and possibilites of knotted scaffolding strands in DNA origami.

3.3 Space Ants: Episode II – Coordinating Connected Catoms

Sándor Fekete (TU Braunschweig, DE)

How can a set of identical mobile agents coordinate their motions to transform their arrangement from a given starting to a desired goal configuration? We consider this question in the context of actual physical devices called Catoms, which can perform reconfiguration, but need to maintain connectivity at all times to ensure communication and energy supply. We demonstrate and animate algorithmic results, in particular a proof of hardness, as well as an algorithm that guarantees constant stretch for certain classes of arrangements: If

mapping the start configuration to the target configuration requires a maximum Manhattan distance of d, then the total duration of our overall schedule is in O(d), which is optimal up to constant factors.

3.4 Unique Assembly Verification in Two-Handed Self-Assembly

Timothy Gomez (MIT – Cambridge, US)

One of the most fundamental and well-studied problems in Tile Self-Assembly is the Unique Assembly Verification (UAV) problem. This algorithmic problem asks whether a given tile system uniquely assembles a specific assembly. The complexity of this problem in the 2-Handed Assembly Model (2HAM) at a constant temperature is a long-standing open problem since the model was introduced. Previously, only membership in the class coNP was known and that the problem is in P if the temperature is one ($\tau = 1$). The problem is known to be hard for many generalizations of the model, such as allowing one step into the third dimension or allowing the temperature of the system to be a variable, but the most fundamental version has remained open.

In this paper, we prove the UAV problem in the 2HAM is hard even with a small constant temperature ($\tau = 2$), and finally answer the complexity of this problem (open since 2013). Further, this result proves that UAV in the staged self-assembly model is coNP-complete with a single bin and stage (open since 2007), and that UAV in the q-tile model is also coNP-complete (open since 2004). We reduce from Monotone Planar 3-SAT with Neighboring Variable Pairs, a special case of 3SAT recently proven to be NP-hard. We accompany this reduction with a positive result showing that UAV is solvable in polynomial time with the promise that the given target assembly will have a tree-shaped bond graph, i.e., contains no cycles. We provide a $\mathcal{O}(n^5)$ algorithm for UAV on tree-bonded assemblies when the temperature is fixed to 2, and a $\mathcal{O}(n^5 \log \tau)$ time algorithm when the temperature is part of the input.

3.5 From snapping fixtures to multi-robot coordination: Geometry at the service of robotics

Dan Halperin (Tel Aviv University, IL)

Robots sense, move and act in the physical world. It is therefore natural that understanding the geometry of the problem at hand is often key to devising an effective robotic solution. I will review several problems in robotics and automation in whose solution geometry plays a major role. These include designing optimized 3D printable fixtures, object rearrangement by robot arm manipulators, and efficient coordination of the motion of large teams of robots. As we shall see, exploiting geometric structure can, among other benefits, lead to reducing the dimensionality of the underlying search space and in turn to efficient solutions.

3.6   Fast communication in amoebot systems

Tom Peters (TU Eindhoven, NL), Irina Kostitsyna (TU Eindhoven, NL)

The concept of programmable matter envisions a very large number of tiny and simple robot particles forming a smart material that can change its physical properties and shape based on the outcome of computation and movement performed by the individual particles in a concurrent manner. We use geometric insights to develop a new type of shortest path tree for programmable matter systems. Our feather trees utilize geometry to allow particles and information to traverse the programmable matter structure via shortest paths even in the presence of multiple overlapping trees.

3.7   How to manage the movement of robots with VisibleSim to achieve locomotion and self-reconfiguration

Benoît Piranda (FEMTO-ST Institute – Montbéliard, FR)

This presentation introduces VisibleSim a behavioral simulator for distributed robots placed in a regular 3D lattice. I first present our programming model and then show a video that introduce VisibleSim, presenting the several robots that can be simulated, with different shapes and capabilities (change color, move from one cell of the lattice to another one...). VisibleSim is a C++ project that allow to observe the effects of running the same program in all the robots, in order to debug, capture picture and video from the simulation. The second part of the presentation shows step by step how to write an application code (BlockCode) for VisibleSim to displace a line of 4 SlidingCubes. Using our online generator which generate a runnable skeleton of the application from a formular, for your application the code that must be added is very limited to get a quick result. Finally in the third part of my presentation, I have presented an application of self-reconfiguration developed with VisibleSim applied on 3D Catoms robots which are placed in a Face Centered Cubic lattice and are able to roll to neighbor to change their position in the grid. We first define meta-modules made of 10 modules, and the basic process to dismantle, transfer and assemble these meta-modules. Using VisibleSim, we evaluate an algorithm that compute a distributed version of the Max-Flow algorithm to compute a set of separated paths between sources (Meta-module that must be removes) and destinations (connected meta-modules that must be added), and finally moves modules along these paths.

3.8   Scalable Real-Time Localization for Robotic Ensembles

Kay Römer (TU Graz, AT)

For controlling the movement of swarms of robots or drones, the positions of the robotic entities need to be tracked at sub-decimeter level. This entails a number of research challanges, (i) minimizing the overhead for the infrastructure needed to support tracking such as the number of reference anchors (ii) scaling to a large number of densely deployed robotic elements (iii) supporting a high update rate for positions in the order of hundrets to thousands of position fixes per second, and (iv) robustness in harsh environments, for example due to obstacles blocking the line of sight between anchors and robotic elements. In this talk we present two results to address these challanges using Ultra-Wide-Band (UWB) communication. In the first solutions, a single anchor supports localization by exploiting the reflections of the UWB signals from the walls. In the second solution, multiple anchors submit UWB pulses quasi simultaneously to allow robotic entities to localize themselves with just a single UWB message reception operation, thus supporting scaling to an arbitraty number of robotic elements and more than 1000 position updates per second.

3.9   Open Problems for the Reconfigurable Circuit Extension of the Amoebot Model

Christian Scheideler (Universität Paderborn, DE)

In my presentation, I raised a number of open problems for reconfigurable circuit extension of the amoebot model. In this extension, amoebots can set up circuits stretching many amoebots. If at least one amoebots beeps on such a circuit, all amoebots of that circuit will receive it, and otherwise no amoebot will receive a beep. When a beep is received, an amoebot cannot determine the direction it came from or the number of amoebots that beeped.

First, consider the case of rapid shape transformation. We have shown that when performing joint expansions and contractions on top of the circuit model, one can transform a line of n amoebots into a parallelogram in just O(log n) rounds [1]. However, what is the minimum number of joint expansions and contractions to get from one structure to another? Can this be computed efficiently and transformed into a distributed algorithm?

Second, consider the case of rapid energy transfer or, more concretely, the problem of repairing an amoebot structure by moving a collection of amoebots from places where they should be removed to places where they are needed. Both of these problems can be reduced to a fairly elementary problem of establishing a shortest path from one position of the amoebot structure to another (e.g., [2]). Is there a fast algorithm for constructing a circuit between these two positions representing a shortest path in the circuit model?

Third, consider the case of seed-less shape transformation. All amoebot algorithms that transform an arbitrary amoebot structure in a hexagon are based on a seed (e.g., [3]). Can we also come up with an algorithm that does not need a seed or leader to perform the transformation.

Finally, consider the situation of faulty amoebots (e.g., [4]). How can we design algorithms for shape transformation that are resilient to permanent failures of amoebots?

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3.10   Reconfigurable Circuit Extension of the Amoebot Model

Christian Scheideler (Universität Paderborn, DE)

The Amoebot model has been proposed as a model for programmable matter. However, many important issues are not captured in the basic form of this model, including rapid shape transformation, energy, fault-tolerance, and the 3D case. In my presentation, I focus on rapid shape transformation and propose a reconfigurable circuit extension of the Amoebot model for this. In this extension, the Amoebots have a constant number of so-called pins on each side that they can internally connect via wires. The connected components formed by these wires then establish circuits. Amoebots can send very primitive signals on these circuits called beeps. If an Amoebot beeps on a circuit, every Amoebot connected to that circuit will instantly notice this. However, an Amoebot does not know where the beep came form or the number of beeps. As I show, this circuit extension allows many central problems like leader election, compass alignment, and symmetry checks to be solved significantly faster than in the basic model. This will then provide the basis for synchronization which will be important for rapid shape transformation.

3.11   Programmable Matter: From Fractal Formation to Genetic-Programming Solutions

Giovanni Viglietta (JAIST – Ishikawa, JP)

Main reference Giuseppe Antonio Di Luna, Paola Flocchini, Nicola Santoro, Giovanni Viglietta, Yukiko Yamauchi: "Mobile RAM and Shape Formation by Programmable Particles", in Proc. of the Euro-Par 2020: Parallel Processing – 26th International Conference on Parallel and Distributed Computing, Warsaw, Poland, August 24-28, 2020, Proceedings, Lecture Notes in Computer Science, Vol. 12247, pp. 343–358, Springer, 2020.
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A typical approach to Shape Formation by Programmable Matter is to elect a leader and use it to coordinate and direct the whole system. This approach has some disadvantages, such as the introduction of bottlenecks and the lack of fault tolerance. In this talk, I reviewed this basic approach and I contrasted it with a recent experimental study of Genetic Programming applied to Programmable Matter.

3.12   DNA based self-assembly and robotics

Damien Woods (Maynooth University, IE)

Joint work of Cai Wood, Constantine G Evans, Abeer Eshra, Tristan Stérin, Ahmed Shalaby, David Doty, Irina Kostitsyna, Damien Woods

The talk began with an introduction to practice and theory of self-assembly using synthetic DNA, and then went on to give an overview of work going on in our lab on the following topics.

1. DNA robotics: theory and implementation of the Turning Machine model (a sub-model of the Nubot model). [Wood, Kostitsyna, Woods]
2. Control of self-assembly dynamics 1: controlling growth order of tiles in self-assembly. A 32x32 canvas of tiles was given that can be grown in any order in a scaled black-wise fashion. In theory, there are a number of methods that could implement such behaviour and we've found holes to stop growth in the wrong direction to work best for us (ongoing work suggests that glue mismatches could also work). [Evans, Shalaby, Doty, Woods]
3. Control of self-assembly dynamics 2: using covers/blockers/poison to tune the rate of nucleation, including giving a method to completely suppress nucleation while allowing for seeded growth. [Rogers, Evans, Woods]
4. Thermodynamically-favoured computation: DNA origami-inspired technique to achieve thermodynamically favoured computation, leading to in-principle low/no errors. Six example finite automata have been implemented (addition, bit-parity, etc.), as well as a bit-copy system who's answer is flipped between 0 and 1 five times, each time changing the energy landscape and thus thermodynamic favourability. [Eshra, Stérin, Woods]

4.1   Path Planning for the Assembly and Reconfiguration of Structures using Neural Cellular Automata

Amira Abdel-Rahman (MIT – Cambridge, US)

In this open problem presentation, we introduced a method to learn cellular automata (CA) rules to grow and reconfigure optimal structures based on given boundary conditions and objective functions. Now that we have CA local rules to update a voxel state based on only its neighbors' state, we proposed working on the materialization of this method to be used for the assembly and reconfiguration of structures. We proposed first working on implementing distributed path planning algorithms for the swam assembly and reconfiguration of structures using the learned neural cellular automata (NCA) rules. We also proposed working on understanding the theoretical bounds of the geometries can/cannot be built using these algorithms in order to edit/update/constrain the learned NCA rules.

4.2   A self-stabilizing chemical reaction network implementation of a modular clock

Yuval Emek (Technion – Haifa, IL)

This open problem is concerned with a (discrete) CRN task referred to as self-stabilizing modular clock. For this task, let Z_k denote the additive cyclic group over the integers modulo k. We wish to build a CRN over a species set $\Sigma \cup \{E\}$ where E is a designated highly reactive external species, associated with a function $\kappa : \Sigma \to Z_k$ that maps each species $A \in \Sigma$ to a clock value $\kappa(A) \in Z_k$. A configuration over Σ in which all molecules have the same clock value is said to be synchronized. We are interested in constructing a CRN that satisfies the following properties:

1. From any initial configuration, the CRN is guaranteed to stabilize to a halting synchronized configuration.
2. The external species E reacts with all species in Σ and is not produced by any reaction.
3. If we are in a synchronized halting configuration with clock value $i \in Z_k$ and a "small" number of external molecules ("a drop") are added to the solution, then the CRN is guaranteed to stabilize to a halting synchronized configuration with clock value $i+1 \bmod k$.

It is trivial to design such a CRN operating under a fair scheduler, assuming the "usual" notion of fairness ([1]), however we are interested in the following weaker versions of fairness: (F1) Every reaction which is applicable infinitely often is scheduled infinitely often (that is, no reaction can be "starved" indefinitely). (F2) Every reaction which is applicable infinitely often is either scheduled or becomes inapplicable infinitely often (that is, no reaction can be "starved" continuously and indefinitely).

Does there exist such a CRN? For which values of k? Does the task become easier if we omit the requirement of halting configurations? Does the task become easier if we relax the "self-stabilization" requirement so that starting from an (adversarial) initial configuration, the system is guaranteed to go back to "proper operation" after a few rounds of "external species drops"?

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4.3   Minimum number of control alterations (squares in polygon, discs in curved workspace)

Dan Halperin (Tel Aviv University, IL)

Given two axis-aligned unit-square robots translating in a polygonal environment, we wish to find a collision-free motion between free start and target configurations such that at each point in time only one robot moves and that will minimize the number of alternations between the robots. What is the maximum number of alternations needed when the polygonal environment has n vertices? A lower bound of 14 alternations [Andrey Leshchenko] is shown below for a polygon with holes.

4.4   Open-ended evolution by minimizing surprise

Tanja Katharina Kaiser (Universität Lübeck, DE)

In nature, open-ended evolution has led to the continuous emergence of novel and increasingly complex artifacts. Researchers are trying to replicate this open-endedness in artificial intelligence, but it remains one of the last great challenges. Minimize surprise evolves actor-predictor pairs of artificial neural networks by rewarding only high prediction accuracy (i.e., low surprise) in the optimization process. In previous swarm robot experiments, we have shown that our minimize surprise method [2] leads to the emergence of diverse swarm behaviors and enables robots to adapt to a changing environment. In first preliminary experiments, we explore here the potential of minimize surprise for open-ended evolution in EvoCraft [1], a framework for Minecraft designed to study open-ended algorithms. So far, we have limited ourselves to a "Game of Life"-like 2D cellular automata setting and have been able to evolve different patterns. Our vision is to extend the setting to 3D and to allow the open-ended evolution of diverse entities that are capable of interacting with the environment.

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4.5 Leader election in grids with faults

Maria Kokkou (Aix-Marseille University, FR)

The leader election problem has been well studied under the Amoebot model for systems without faults. However, for systems that do contain faults the problem remains open. An interesting starting point is to determine the minimum assumptions we need to deterministically elect a unique leader even if the particle configuration contains holes and the grid contains obstacles.

The motivation for this problem comes from two possible faults. First, as a big number of particles is involved, it is possible that some particles have already crashed before the execution of the algorithm, creating obstacles within the system. The second motive comes from the possibility of faults existing in the grid itself, such as missing or damaged nodes which cannot be occupied by particles. Since obstacles restrict the ability of particles to move, an algorithm that depends on movement would need to account for an unknown number of nodes being unavailable or blocked. Furthermore, obstacles can create symmetries that do not exist in the triangular grid, such as six-symmetric configurations where a node is occupied by an obstacle and all its neighbouring nodes are occupied by competing particles.

4.6 Fast parallel reconfiguration without scaling

Irene Parada (UPC Barcelona Tech, ES)

The problem we consider is parallel reconfiguration of modular robots preserving connectivity. To guarantee fast parallel reconfiguration, the existing algorithms for modular robots need either meta-modules [1, 2] or a constant scale factor [3] (blowing up the shape size by a constant). The question is whether we can relax these conditions. More precisely, whether requiring a minimum local density of the initial and final configurations allows for an efficient reconfiguration plan.

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4.7 DNA Origami: Open Questions on Helix and Scaffold Routing; Feedback From Experiments

Nicolas Schabanel (ENS – Lyon, FR)

Helix routing consists in deciding the path followed by the DNA helices in DNA origami: it is a problem similar to coil wrapping when you want to wrap a surface with non-overlapping ribbons of fixed width. Scaffold routing is to decide the path followed by the scaffold of a DNA origami along the helices. Our experiments show that many parameters have to be taken into account to have the DNA origami fold properly. This raises the question of how to come up with an algorithmic approach to solve this issue.

4.8 When can a structure self-fold?

Cynthia Sung (University of Pennsylvania – Philadelphia, US)

Self-folding is a process through which a 2D sheet autonomously folds into a desired 3D shape. Self-folding fabrication typically involves layering rigid and active materials that allow the sheet to respond to heat, moisture, light, or other signals in a predetermined way. Designing these structures to reliably self-fold into the desired shape repeatably remains a challenge. Common approaches to "programming" the folding process involve specifying that certain folds are mountain or valley folds. However, it has been shown that a mountain-valley assignment is insufficient to uniquely determine the final 3D shape. Recent models of self-folding have considered the case where precise torques at each of the folds can be specified, but even under this model, it is sometimes impossible to control what the final 3D shape will be. We now consider a new self-folding mode, in which forces can be applied directly at each face and consider the associated questions of what can or cannot be reliably self-folded under these methods.

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4.9 Computational Complexity of Recent Slide-and-Pack Puzzles

Ryuhei Uehara (JAIST – Ishikawa, JP)

In the last decade, a series of puzzles in a new category has been developed in puzzle society. We are given a frame and a set of pieces. The goal of the puzzle is packing all the pieces into the frame. It seems that they are similar to the classic popular silhouette puzzles like the tangram. However, in recent puzzles, the frame has small entrance, and we have to find how to pack the pieces into the frame. In 2D, it can be seen as the combination of sliding block puzzle and packing puzzle. It seems that these puzzles are PSPACE-complete in general, but so far, we have no results in this framework.

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