Distributed Computing Column 66
Algorithmic Foundations of Programmable Matter
Dagstuhl Seminar 16271

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Programmable matter is a term denoting a collection of small and simple computing entities that can work together to change their characteristics and accomplish a task. Variations of this idea have been considered in widely disparate communities. In summer 2016, a Dagstuhl seminar devoted to this topic brought together researchers from the algorithms, robotics, and distributed systems communities. The seminar was organized by Sándor Fekete, Andréa Richa, Kay Römer, and Christian Scheideler, who have contributed an overview for the current column. Their contribution consists of a description of the purpose of the workshop, and a concise summary of all the talks given. The topics range from computer systems to algorithmic theory to DNA-computing to caterpillars, just to name a few. The distributed computing community has touched on this area in the past, but new fascinating problems have surfaced, and the article gives us a convenient set of pointers to them.

Many thanks to Sándor, Andréa, Kay, and Christian for their contribution!

Call for contributions: I welcome suggestions for material to include in this column, including news, reviews, open problems, tutorials and surveys, either exposing the community to new and interesting topics, or providing new insight on well-studied topics by organizing them in new ways.

Algorithmic Foundations of Programmable Matter
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Abstract

In July 2016, the Dagstuhl Seminar 16271 considered "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 the Dagstuhl seminar was to bring together researchers from the algorithms community with selected experts from robotics and distributed systems in order to set a solid base for the development of models, technical solutions, and algorithms that can control programmable matter. Both communities benefited from such a meeting for the following reasons:

- Meeting experts from other fields provided additional insights, challenges and focus when considering work on programmable matter.
- Interacting with colleagues in a close and social manner gave many starting points for continuing collaboration.
- Getting together in a strong, large and enthusiastic group provided the opportunity to plan a number of followup activities.

1 Executive Summary

Programmable matter refers to a substance that has the ability to change its physical properties (shape, density, moduli, conductivity, optical properties, etc.) in a programmable fashion, based upon user input or autonomous sensing. The potential applications are endless, e.g., smart materials, autonomous monitoring and repair, or minimal invasive surgery. Thus, there is a high relevance of this topic to industry and society in general, and much research has been invested in the past decade to fabricate programmable matter. However, fabrication is only part of the story: without a proper understanding of how to program that matter, complex tasks such as minimal invasive surgery will be out of reach. Unfortunately, only very few people in the algorithms community have worked on programmable matter so far, so programmable matter has not received the attention it deserves given the importance of that topic.

The Dagstuhl seminar "Algorithmic Foundations of Programmable Matter" aimed at resolving that problem by getting together a critical mass of people from algorithms with a selection of experts from distributed systems and robotics in order to discuss and develop models, algorithms, and technical solutions for programmable matter.

The aim of the seminar was to bring together researchers from the algorithms community with selected experts from robotics and distributed systems in order to set a solid base for the development of models, technical solutions, and algorithms that can control programmable matter. The overall mix worked quite well: researchers from the more practical side (such as Julien Bourgeois, Nikolaus Correll, Ted Pavlic, Kay Römer, among others) interacted well with participants from the theoretical side (e.g., Jennifer Welch, Andrea Richa, Christian Scheideler, Sándor Fekete, and many others). Particularly interesting to see were well-developed but still expanding areas, such as tile self-assembly that already combines theory and practice (with visible and well-connected scientists such as Damien Woods, Matt Patitz, David Doty, Andrew Winslow, Robert Schweller) or multi-robot systems (Julien Bourgeois, Nikolaus Correll, Matteo Lasagni, André Naz, Benoît Piranda, Kay Römer).

The seminar program started with a set of four tutorial talks given by representatives from the different sets of participants to establish a common ground for discussion. From the robotics and distributed system side, Nikolaus Correll and Julien Bourgeois gave tutorials on smart programmable materials and on the claytronics programmable matter framework, respectively. From the bio-engineering side, Ted Pavlic gave a tutorial on natural systems that may inspire programmable matter. From the algorithmic side, Jacob Hendricks gave a tutorial on algorithmic self-assembly. In the mornings of the remaining four days, selected participants offered shorter presentations with a special focus on experience from the past work and especially also open problems and challenges. Two of the afternoons were devoted to discussions in breakout groups. Four breakout groups were formed, each with less than 10 participants to allow for intense interaction. Inspired by a classification of research questions in biology into "why?" and "how?" questions presented in Ted Pavlic's tutorial, the first breakout session was devoted to the "why?" questions underpinning programmable matter, especially also appropriate models of programmable matter systems (both biological or engineered) suitable for algorithmic research. The second breakout session towards the end of the seminar was devoted to a set of specific questions given by the organizers that resulted from the discussions among the participants, they included both research questions and organizational questions (e.g., how to proceed after the Dagstuhl seminar). After each of the two breakout sessions, one participant of each of the four breakout groups reported back the main findings of the discussions to the plenum, leading to further discussion among all participants. One of the afternoons was devoted to a hike to a nearby village, where the participants also visited a small museum devoted to programmable mechanical musical devices.

The seminar was an overwhelming success. In particular, bringing together participants from a number of different but partially overlapping areas, in order to exchange problems and challenges on a newly developing field turned out to be excellent for the setting of Dagstuhl - and the opportunities provided at Dagstuhl are perfect for starting a new community.

Participants were enthusiastic on a number of different levels.

- Meeting experts from other fields provided additional insights, challenges and focus when considering work on programmable matter.
- Interacting with colleagues in a close and social manner gave many starting points for continuing collaboration.
- Getting together in a strong, large and enthusiastic group provided the opportunity to plan a number of followup activities.

The latter include connecting participants via a mailing list, the planning and writing of survey articles in highly visible publication outlets, and a starting point for specific scientific workshops and conferences.

Participants were highly enthusiastic about the possibility of another Dagstuhl seminar in the future; organizers are keeping the ball rolling on this, so it is quite possible that there will be more to come.

2 Overview of Talks

Claytronics: an Instance of Programmable Matter

Julien Bourgeois (FEMTO-ST Institute - Montbliard, FR)

Programmable matter (PM) has different meanings; they can be sorted depending on four properties: *Evolutivity, Programmability, Autonomy and Interactivity.* The talk presented the Claytronics project, which is an instance of PM, evolutive, programmable, autonomous and interactive. In Claytronics, PM is defined as a huge modular self-reconfigurable robot. To manage the complexity of this kind of environment, the speaker presented a complete environment including programmable hardware, a programming langage, a compiler, a simulator, a debugger and distributed algorithms.

A Markov Chain Algorithm for Compression in Self-Organizing Particle Systems

Sarah Cannon (Georgia Institute of Technology - Atlanta, US)

One can model programmable matter as a collection of simple computational elements (called particles) with limited (constant-size) memory that self-organize to solve system-wide problems of movement, configuration, and coordination. In recent work with Joshua J. Daymude, Andrea Richa, and Dana Randall, the speaker focused on the compression problem, in which the particle system gathers as tightly together as possible, as in a sphere or its equivalent in the presence of some underlying geometry. More specifically, a fully distributed, local, and asynchronous algorithm was presented that leads the system to converge to a configuration with small perimeter. The corresponding Markov chain-based algorithm solves the compression problem under the geometric amoebot model, for particle systems that begin in a connected configuration with no holes. The talk gave a brief overview of Markov chains, described the Markov chain and why it achieves particle compression, and showed how it leads to a fully distributed, local, and asynchronous protocol each particle can run independently. Furthermore, it was discussed how Markov chains might be amenable for use in other programmable matter contexts.

Algorithm Design for Swarm Robotics and Smart Materials

Nikolaus Correll (University of Colorado - Boulder, US)

Programmable Matter is a conjunction of a discrete program and continuous matter. Where the line between the two needs to be drawn is currently unclear. One approach is to abstract matter to the point where it can be treated exclusively by discrete models. Another approach is to think about individual elements becoming so small that they are captured by continuous physics such as fluid dynamics. In this tutorial, a hybrid automata model was explained that consists of a discrete network of computers, which can sense and actuate on a continuous material that the network is integrated in. Here, communication not only happens through the network, but also in the material itself via sensor/actuator coupling. This approach was illustrated using a series of robotic materials including a sensing skin, a shape-changing beam, and a modular wall that can recognize gestures. These systems demonstrate a number of algorithmic challenges ranging from networking, distributed control and optimization, and programming. At the same time, each instance illustrates that material properties strongly influence algorithmic design and vice versa.

Dynamic Networks of Computationally Challenged Devices: the Passive Case

Yuval Emek (Technion - Haifa, IL)

Motivated by applications in biology and nano-technology, the trend of applying the "distributed computing approach" to networks of message passing devices with weak computation (as well as communication) capabilities is gaining momentum. So far, most of the advances have been made under the assumption that (1) the network is static; or (2) the dynamic behavior of the network is dictated by devices that can actively control their own motion. In this talk, some research questions were discussed that are related to such networks that undergo dynamic (adversarial) topology changes in which the devices only play a passive role.

Algorithms for Robot Navigation: From Optimizing Individual Robots to Particle Swarms

Sándor Fekete (TU Braunschweig, DE)

Planning and optimizing the motion of one or several robots poses a wide range of problems. How can we coordinate a group of weak robots to explore an unknown environment? How can we ensure that a swarm of very simple robots with local capabilities can deal with conflicting global requirements? And how can a particle swarm perform complex operations? It was demonstrated how an appropriate spectrum of algorithmic methods in combination with geometry can be used to achieve progress on all of these challenges.

The Amoebot Model

Robert Gmyr (Universität Paderborn, DE)

The speaker envisioned programmable matter consisting of systems of computationally limited devices that are able to self-organize in order to achieve a desired collective goal without the need for central control or external intervention. The formal investigation of programmable matter is based on the Amoebot model. In this talk, a brief introduction to this model was presented. Furthermore, an overview of the work on three central problems was given, namely shape formation, coating, and leader election.

Dances with Plants: Robot-supported Programmable Living Matter

Heiko Hamann (Universität Paderborn, DE)

Besides standard self-reconfiguring modular robotics and self-assembly, robots can also be mixed with other components to form heterogeneous systems. For example, combining natural plants and distributed robot systems offers new approaches to programmable matter. Instead of applying methods of synthetic biology, the idea here is to make use of natural plant behaviors to control them. A second example is self-organized swarm construction of possibly actuated structures. These approaches offer unique advantages, such as growth of additional material for free, environmental safety, and simplicity, despite their limitations in flexibility concerning possible structures and potential for reconfigurations.

Introduction to Modeling Algorithmic Self-Assembling Systems
Jacob Hendricks (University of Wisconsin - River Falls, US)

This talk introduced theoretical tile-based models of self-assembly. First the definition of Winfree's abstract Tile Assembly Model (aTAM) was given, which was developed to study DNA-based molecular building blocks. The talk proceeded with examples of specific tile assembly systems, such as binary counters and Turing machine simulators, as these demonstrate the possibility of algorithmic self-assembly. A discussion of a few specific topics in the field followed. These topics included non-cooperative self-assembly, various models of self-assembly, common benchmarks for determining the capabilities and limitations of models, simulation as a means of comparing models, and finally, the notion of intrinsic universality. Topics were selected to provide a bird's-eye view of a theoretician's considerations about modeling self-assembling systems using tile assembly models.

Advantages, Limitations, Challenges of Tendon-Driven Programmable Chains
Matteo Lasagni (TU Graz, AT)

One of the first and most relevant questions when designing a shape-shifting material concerns particles topology and hence their mobility. We can distinguish between *detachable* and *non-detachable* topologies. Detachable topologies allow particles to temporarily detach from the ensemble and freely migrate to different locations in order to obtain a shape shift. In contrast, non-detachable topologies constrain particles to occupy a fixed location at which only relative displacement between adjacent particles and/or particle deformation are allowed for shape-shift. Despite the fact that detachable topologies allow the formation of literally any shape, the complex architecture to enable particle migration, generally consisting of built-in actuators and latching mechanisms, raises costs and limits the scalability of the whole system, and causes inherent problems concerning particle power supply and communication. In his work, the speaker demonstrated how a nondetachable topology can allow the formation of arbitrary complex shapes, thereby avoiding or at least limiting the above-mentioned problems. In particular, scalability and cost-effectiveness derive from the concatenation of semi-active particles without bulky built-in actuators and latches. Such particles, forming piecewise bendable chains, exploit remotely generated forces to self-actuate and hence to control the local curvature of the chain. Multiple chains can be combined to form a shape-shifting surface to support novel applications like 3D tangible displays or programmable molds. One major challenge concerns the actuation of the system. Without the support of optimal planning strategies able to schedule proper particle actuation, unbearable actuation forces might occur, for example, due to inconvenient leverage effects, with negative consequences for the system stability and integrity. Starting from the current configuration and aiming at the final target configuration, optimal planning techniques should explore the large set of possible *next configurations* where only a limited number of particles can actuate, and determine in which cases the intensity of the actuation forces is acceptable. The optimization problem involves not only a single independent chain, but applies simultaneously to all chains. Due to mechanical constraints, indeed, all chains need to actuate the same number of particles at each reconfiguration step. This calls for models able to predict the behavior of the whole system upon the application of specific control input in order to support optimal planning algorithms. Such models need to be sufficiently accurate to be consistent with reality but also computationally efficient to allow planning in reasonable time. An important question concerns the determination of an acceptable trade-off between these two aspects.

Programmable Matter for Dynamic Environments
Othon Michail (CTI - Rion, GR)

The speaker discussed two recent theoretical models of programmable matter operating in a dynamic environment. In the first model, all devices are finite automata, begin from the same initial state, execute the same protocol, and can only interact in pairs. The interactions are scheduled by a fair (or uniform random) scheduler, in the spirit of Population Protocols. When two devices interact, the protocol takes as input their states and the state of the connection between them (`on/off`) and updates all of them. Initially all connections are `off`. The goal of such protocols is to eventually construct a desired stable network, induced by the edges that are `on`. We present protocols and lower bounds for several basic network construction problems and also universality results. We next discuss a more applied version of this minimal and abstract model, enriched with geometric constraints, aiming at capturing some first physical restrictions in potential future programmable matter systems operating in dynamic environments.

Energy Harvesting in-vivo Nano-Robots in Caterpillar Swarm
Venkateswarlu Muni (Ben Gurion University of the Negev - Beer Sheva, IL)

Biological collaborative systems behavior is fascinating, urging researchers to mimic their behavior through programmable matters. These matters constitute a particle system, wherein the particles bind with the neighboring particles to swarm and navigate. Caterpillar swarm-inspired particle systems involves layered architecture with single to a predefined number of layers. Through this work, a coordinated layered particle system inspired by caterpillar swarms is discussed. In the talk, a novel design for produce-able nano-particles was proposed that uses electrodes to harvest electricity from the blood serum, energy that can be later used for swarm inter and/or outer communication, moving, coordination, sensing and acting according to a given (instructing) program. The benefit of moving and acting in a swarm is demonstrated by a design of telescopic movement in pipes (e.g., blood vessels), wherein each layer uses the accumulated speed of all layers below and moves faster, thus, mimicking the faster motion of the caterpillar swarm.

Algorithmic Design of Complex 3D DNA Origami Structures
Pekka Orponen (Aalto University, FI)

In a recent work (Nature 523:441-444, July 2015), the speaker described a general methodology and software pipeline for rendering 3D polyhedral mesh designs in DNA. In this talk, the basic idea of Paul Rothemund's DNA origami technique was given, which also underlies the speaker's approach. This was followed by a discussion of the graph-theoretic concepts and algorithmic ideas used in extending his technique from 2D patterns to 3D wireframe mesh structures. The reliability and generality of the approach was demonstrated by a number of electron microscopy images of synthesised nanostructures, including a 50-nm rendering of the widely-used Stanford Bunny model. The talk concluded by touching on the challenges of using DNA as a substrate for complex designs, and some related open questions.

Algorithmic Foundations of Biological Matter: Faster, Cheaper, and More Out of Control

Theodore P. Pavlic (Arizona State University - Tempe, US)

For at least the past 30 years, there has been much interest in developing programmable matter solutions that have been inspired by related phenomena in nature. Visionaries in computer science from the 1980's promised that such life-like phenomena would be possible, and yet the programmable matter of today still has limited capabilities. Rather than groups of relatively inexpensive agents grouping together to form an intelligent and flexible collective matter, the automation systems we have today combine relatively intelligent individual units together into rigid and often static structures that have no ability to adapt to the surrounding environment.

To make real progress in understanding the algorithms responsible for nature's success, computer scientists and engineers need to become familiar with the taxonomy of scientific questions in biology. The outputs of biological evolution are shaped not only by adaptive value (i.e., a design objective), but also by phylogeny (i.e., structures inherited from earlier forms), ontogeny (i.e., the process of constructing the object), and the actual mechanism of action that interacts with the environment. The former of these two pressures – adaptive value and phylogeny – are the subject of the "Why" questions of biology, and those questions must always be conditioned by the ancestral environment. The latter two of these pressures – ontogeny and mechanism – are the subject of the "How" questions of biology, and those questions must always be conditioned by the modern environment. This characterization of biological questions is not unlike the ways in which computer scientists consider algorithms and their implementations – in terms of design objectives, platforms, and algorithms that operate on those platforms. However, taking the objective–platform–algorithm approach alone with biological systems obscures details about evolution and ecology that are necessary for understanding how a biological system could possibly be working and whether it is really appropriate to take such an approach with an engineered system. Additionally, taking the effort to understand adaptive value of biological phenomena can provide interesting new motivations for problems that could be solved in engineered systems, albeit using totally different mechanisms.

In this talk, a number of ideas were elaborated and complemented with various examples of biological systems that may provide useful insights when designing programmable matter that may someday finally realize a dream that has been deferred for decades.

VisibleSim: Your Simulator for Programmable Matter

Benoît Piranda (FEMTO-ST Institute - Montbliard, FR)

The speaker gave a short tutorial to write a first distributed code for VisibleSim, which is a 3D environment for distributed programs executed on distributed robots in a simulated environment. The robots are placed in a lattice, can be linked together and can move freely or in cooperation with other robots. VisibleSim can simulate many different kinds of robots but its main target is modular robots and more particularly programmable matter. It can therefore manage huge numbers of robots. It provides distributed debugging features and interactive actions to users like add or remove robots, stop, restart a simulation or tap a robot to interact with it.

On Obliviousness

Nicola Santoro (Carleton University - Ottawa, CA)

The presence of some form of persistent memory (albeit small in size) is typically assumed in "micro-level" computations (eg, programmable matter). In contrast, obliviousness (i.e., total absence of persistent memory) is a common restrictions in "macro-level" computations (e.g, autonomous mobile robots) in which the speaker has been involved. On this regards, there are two interesting research questions he shared.

- Are meaningful oblivious computations possible at the micro-level ?
- What are the precise limits of near-obliviousness (i.e., memory-size thresholds) ?

Theory and Practice of Large Scale Molecular-Robotic Reconfiguration

Damien Woods (California Institute of Technology - Pasadena, US)

The talk discussed the theory and practice of molecular robotics, describing the interest in large-scale molecular reconfiguration, where dynamic self-assembling nanostructures change their shape in response to environmental stimuli. A particular focus was on models that have the potential to be implemented in DNA: a shockingly-well understood and predictable material for nanoscale self-assembly. Specifically, the talk focused attention on questions on the *Nubot* model and on initial progress on implementing this style of molecular robotics in the wet-lab.

Distributed Coordination of Mobile Robots in 3D-Space

Yukiko Yamauchi (Kyushu University - Fukuoka, JP)

Consider a swarm of autonomous mobile robots moving in the three-dimensional space (3D-space). Each robot is anonymous, oblivious (memoryless), and has neither any access to the global coordinate system nor any communication medium. Many researchers have considered formation problems (point formation, circle formation, pattern formation, etc.) in 2D-space, and it has been shown that the symmetry among the robots determines the patterns that the robots can form. The speaker presented recent results on formation problems in 3D-space, where rich symmetry represented by rotation groups is encountered.