A Basis for Self-reconfiguring Robots using Crystal Modules

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Abstract

We discuss a basis for creating self-reconfiguring robots and instantiate it for Crystal modules. Crystalline robots consist of modules that can aggregate together to form distributed robot systems. Crystalline modules are actuated by expanding and contracting each unit. This actuation mechanism permits automated shape metamorphosis. We describe the Crystalline module concept and its physical implementation. We prove that Crystalline robots are general self-reconfiguring robots.

1 Introduction

Self-reconfiguring robots have the ability to adapt to the operating environment and the required functionality by changing shape. They consist of a set of identical robotic modules that can autonomously and dynamically change their aggregate geometric structure to suit different locomotion, manipulation, and sensing tasks. A primary design goal for a self-reconfiguring robot is to allow the robot to assume any geometric shape. This goal is different from that of other types of shape-changing robots, which may only take one of a small number of shapes.

There are two basic types of self-reconfiguring robot systems: *heterogeneous* and *homogeneous*. In a heterogeneous system, the modules may be different. In a homogeneous system all the modules are identical.

In this paper we propose a new approach to homogeneous self-reconfiguring robot systems, which uses a module called a *Crystalline Atom* inspired by muscles and amoebas, and which is actuated by expansion and contraction. By expanding and contracting the neighbors in a connected structure, an individual module can be moved in general ways relative to the entire structure. This basic operation leads to new algorithms for global self-reconfiguration planning. Crystalline robot systems can realize a wide range of geometries; for example Figure 1 shows snapshots from a simulation in which a dog-shaped object transforms itself into a couch-shaped object.

In a previous paper [17] we presented the concept of a Crystalline module and described a planner for Crystalline robots which we used to generate simulations of self-reconfiguration. In [18] we describe the mechanical design of Crystalline Atoms, a robot system composed of 10 Crystalline Atoms, and some experiments with this system. In this paper we describe a general theoretical basis for self-reconfiguration and show that Crystalline Atoms satisfy sufficient conditions for a self-reconfiguring robot system.

2 Related work

We are inspired by pioneering work in self-reconfiguring robotics. In [2], Fukuda et al propose a cellular robotic system to coordinate a set of specialized modules. Several specialized modules and ways of composing them were proposed. In [21] Yim studies multiple modes of locomotion that are achieved physically by manually composing a few basic elements in different ways. This work also presents extensive examples of locomotion and self-reconfiguration in simulation. In [10, 23, 20, 11], Murata et al consider a system of modules that can achieve planar motion by walking over one another. The reconfiguration motion is actuated by varying the polarity of electromagnets that are embedded in each module. More recently [12] this group developed a twelve DOF module capable of three-dimensional motion. In [13] Chirikjian et al describe metamorphic robots that can aggregate as two-dimensional structures with varying geometry. The modules are deformable hexagons. This work also examines theoretical bounds for planning the self-reconfiguring motion of such modules. In [9] we have shown a constant-time reduction between robotic molecule structures our group has designed to

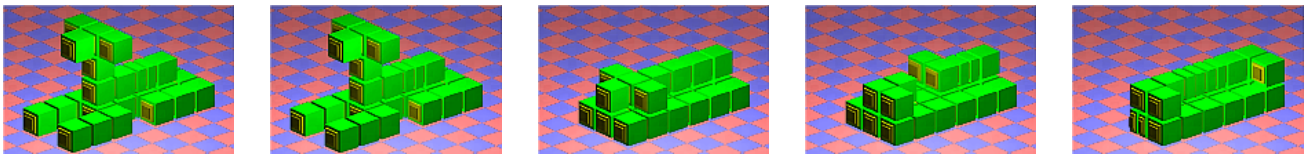

Figure 1: Five snapshots from a simulation using Crystalline robots. The initial configuration (on the left) is a dog-shaped object. The final configuration (on the right) is a couch-shaped object. The middle images show intermediate steps in the transformation from dog to couch. The planning for this transformation was done manually. Note that some Atoms are left in a compressed state so that the volume of the final shape is less than the volume of the initial shape.

support self-reconfiguration [7, 8] and metamorphic robots [13].

The robot proposed in this paper is different than the previously proposed modules in its actuation capabilities, which lead to new types of self-reconfiguration planning algorithms. The high-level idea of a shrinkable module that can be a cell in a reconfigurable system has been presented by Tanie et al as the patent [19].

3 The Crystalline Module

The Crystalline module is a mechanism that has some of the motive properties of muscles, that can be closely packed in 3D space, and that can attach itself to similar units. We chose a design based on cubes with connectors to other modules in the middle of each face. The idea is to build a cube that can contract by a factor of two and expand to the original size (see Figure 2). We wish to effect compression along all three principal directions (e.g., x, y, z) either individually or in parallel. We call the module an *Atom*, and each connector a *bond*.

Crystalline Atomic modules can be constructed in both two and three dimensions. In two dimensions, Atoms are square; in three dimensions they are cubic. For our initial experiments, we constructed a two-dimensional implementation. Figure 3 shows the physical prototype.

3.1 A Physical Implementation

The two-dimensional version of the Crystalline Atomic module was created based on the CAD designs shown in Figure 4. We describe the details of this implementation in [18]; here we only give an overview.

The module has an expansion/contraction ratio of 2. In this implementation, all four Atom faces are tied together and actuated by a single motor, i.e. they must all be simultaneously fully extended or fully

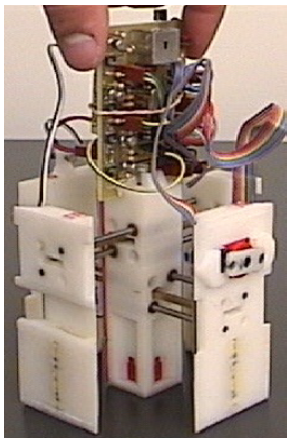

Figure 3: The physical prototype for the Crystalline Atom.

contracted[1]. Each face of the module contains part of a connection mechanism. Two out of the four faces[2] have active connection mechanisms. The other two faces have passive connection slots. Together, these provide a key-and-lock system for forming rigid connections with adjacent modules.

The entire unit can be realized with three degrees of freedom: one to expand/contract the faces of the Atom, and two for the active connectors. All three degrees of freedom can be implemented with binary actuators.

Since Atoms are not designed to rotate relative to one another, the use of two rather than four connectivity degrees of freedom leads to no mechanical limita-

[1] An implementation with independently controlled faces would be only slightly more versatile.

[2] The active connection mechanisms are situated on adjacent faces, which allows any lattice of Crystalline Atoms to be fully connected.

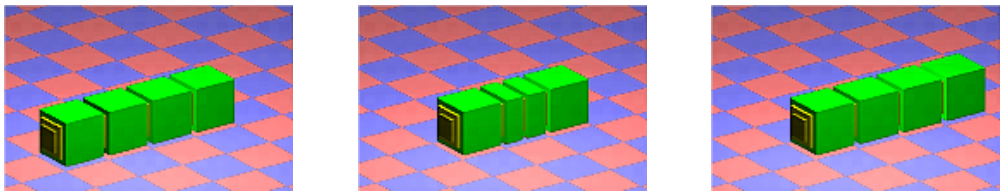

Figure 2: Three snapshots from a simulation of locomotion using Crystalline robots. The left image shows the initial state. The middle image shows the robot after shrinking two modules in the direction of motion. The right image shows the robot after relaxing the shrunk modules in the direction of motion. Notice that the entire structure moved forward one unit, in an inchworm-like fashion.

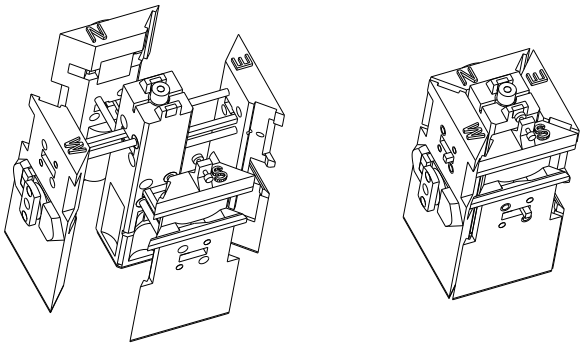

Figure 4: The mechanics of a 2D Atom actuated by complimentary rack-and-pinion mechanisms. The Atom is 4 inches tall (not including electronics, which are not shown, and which increase the height to 7 inches). When expanded (left), the Atom occupies a 4 inch square; when contracted (right) the Atom occupies a 2 inch square.

tions. Every inter-Atomic interface of a structure will have one active connection mechanism, as illustrated in Figure 5.

The expansion/contraction degree of freedom is implemented with a rack-and-pinion mechanism. A vertically mounted pinion at the center of the core mates simultaneously with all racks. The racks are rigidly mounted to the rear of each face. Racks from opposing faces are mounted off-center and racks from adjacent faces are staggered vertically so that they do not overlap at the center of the core. The pinion is driven by a gear motor. Spinning it in one direction extends the racks, which causes the Atom to expand. Spinning in the other direction retracts the racks which causes the Atom to contract.

The connection mechanisms are based on a *channel and key* concept. The passive face contains a deep horizontal channel on its outer surface. Pockets are built into the upper and lower inside surfaces of this channel at the center of the face. A bar (the "key") is attached to the output shaft of a small gearmotor. At one position of the motor, the key can slide horizontally through the channel of the passive face without obstruction and the connector is freed. At another position, the key is rotated so that it extends into the pockets of the passive face and the connector is bonded.

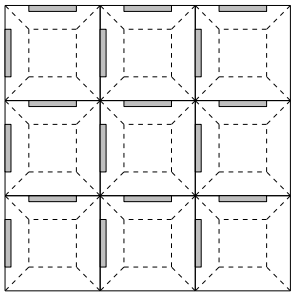

Figure 5: A schematic tiling of 9 compressed Atoms. Note that every inter-Atomic interface contains exactly one active connection mechanism (dark rectangles).

The connection mechanisms are designed to be misalignment tolerant and correcting. This allows adjacent units which are not precisely aligned to bond, and in the process to become better aligned. Some correction for flexibilities and other inaccuracies in the rest of the mechanics is thereby provided.

Each Atom contains an on-board processor (Atmel AT89C2051 microcontroller), power supply (five 2/3 A Lithium batteries), and support circuitry, which allows both fully untethered and tethered operations. Atoms are connected by a wired serial link to a host

computer to download programs. For untethered operations, an experiment specific operating program specified as a state sequence is first downloaded over a tether. When the tether is removed, an on-board IR receiver is used to detect synchronization beacons from the host.

When fully contracted, the Atom is a square with a 2 inch side. When fully expanded, the Atom is a square with a 4 inch side. The height of the Atom is 7 inches and its weight is 12 ounces.

3.2 Primitive Operations for Crystal Modules

Crystalline robot systems are dynamic structures: (1) they can move using sequences of reconfigurations to implement locomotion gaits; and (2) they can undergo shape metamorphosis. The dynamic nature of these systems is supported by the ability of individual modules to move globally relative to the structure.

The basic operations in a Crystalline robot system are:

- `(expand <atom>, <dimension>)` - expand a compressed Atom in the desired dimension (x, y, or z)
- `(contract <atom>, <dimension>)` - compress an expanded Atom in the desired dimension
- `(bond <atom>, <dimension>)` - activate one of the Atom's connectors to bond with a neighboring Atom in the structure
- `(free <atom>, <dimension>)` - deactivate one of the Atom's connectors to break a bond with a neighboring Atom in the structure

4 A Basis for Self-reconfiguration

In this section we use the terminology of Yim, who in [21] defined a reconfigurable system to be *unit modular* if it is homogeneous. Most existing self-reconfiguring robot systems are based on a unit-modular approach. In particular, the system discussed in this paper is unit modular.

The primary design goal for a self-reconfiguring robot is to allow the robot to assume any arbitrary geometric shape in a dynamic fashion. The geometric, mechanic, and kinematic structure of a unit-modular system define its specific approach to self-reconfiguration. We observe that a system composed of a specific unit module is self-reconfigurable if the unit module satisfies two properties as stated by the following theorem.

Theorem 1 *A unit-modular robotic system is self-reconfiguring if its unit modules have the following two properties:*

1. **structure formation***: groups of unit modules can be assembled into arbitrarily shaped rigid structures.*
2. **module relocation***: in every structure composed of unit modules, some unit module can be relocated to each location on the surface of the structure without human intervention.*

Proof: The first property ensures that any geometric structure can be aggregated from some collection of modules. In general, the geometric structure of the module will determine a three-dimensional grid pattern that will approximate the desired structure to within some resolution. For example, a cube-shaped module like the one described in this paper can be packed as any geometric shape subject to the approximation resolution given by the size of the cube. In general, this property is not valid for arbitrary geometric shapes. For example, even a simple shape such as a regular tetrahedron fails to satisfy this property because it does not pack in three dimensions.

The second property provides for shape metamorphosis in a general way: given a starting structure S and a goal structure G, it makes it possible to construct G from S incrementally. At any point in the process, some module in S can be relocated without human intervention anywhere on the structure—specifically, it can be placed as part of the structure of G. Thus, it is possible to relocate modules from places in S to places in G until G has been fully assembled. □

Corollary 2 *A robot system based on the Crystalline module is self-reconfiguring.*

In the following two sections we prove this result by arguing that the Crystalline Atom satisfies the conditions of Theorem 1; thus the Crystalline Atom can be the basis for a self-reconfiguring robot system.

4.1 Structure Formation with Crystal Modules

Since Crystalline Atoms are cubic in three dimensions and square in two, they can be packed tightly to approximate any three dimensional structure (or two dimensional structure.) In such a packing we can bond all inter-Atom interfaces shared by two Atoms,

thus creating a solid structure which we call a Crystal. Figures 7 and 1 show examples of creating three-dimensional structures by packing Atoms. We then have the following result:

Theorem 3 *Any two- or three-dimensional solid structure that allows a cell decomposition where the size of the grid is the size of an individual Atom can be approximated using Crystalline Atoms. The approximation error depends on the size of the Atom.*

Thus, by manipulating the size of the Crystalline Atom in the mechanical design phase, we can use this module to represent any solid geometric shape to an arbitrary precision. This idea is analogous to reducing the aliasing error on a raster display by increasing the resolution of the display.

4.2 Relocating a Module on a Crystal

Crystalline module motion is controlled by attaching one Atom to a neighboring Atom and actuating the expansion or compression mechanism (as shown in Figure 6.) An individual module can not relocate without help; however, by contracting and expanding a group of modules in a coordinated way, Atoms can move relative to a structure.

Unlike all other proposed unit modules [21, 10, 12, 13, 7, 8] which can relocate only by traveling on the surface of a structure, Crystalline Atoms can be relocated by traveling *through* the volume of a Crystal. This interesting property of Crystalline robots is illustrated in Figure 7. The goal is to move the Atom on the surface of the cubic Crystal to some other location on the surface. Instead of propagating the module along the surface of the large cube (which would require a number of operations linear in the size of the cube) it is possible to reach the goal using a *constant* number of internal operations. That is, the number of operations remains constant independent of the size of the cube and no matter how the start and goal locations are oriented relative to each other.

The algorithm for module relocation is as follows. First, the module is pulled inside the cube by contracting two internal Atoms (see Figure 8). The two contracted Atoms are selected to be on the supporting line for the start location and adjacent to the intersection of that line and the supporting line for the goal location. Next, two more Atoms are contracted. These Atoms are selected to be on the supporting line for the goal location and adjacent to the intersection of that line and the supporting line for the starting location. The four contracted Atoms are selected so that a void is created at the intersection of the two supporting lines. At this point, the first pair of contracted Atoms are expanded into the void. Finally, the second pair of contracted Atoms are expanded in the direction of the goal, pushing along an entire column of Atoms. The end result is an Atom at the location of the goal. Note that the Atom popped at G is not the same as the Atom that originated at S[3]. Since all units are identical, it does not matter which actual unit pops out at the goal; what is important is the overall shape transformation. Thus, using this algorithm, an Atom can be relocated in *constant* time on any convex Crystalline structure[4].

When the Crystalline robot structure is non-convex, a similar algorithm effects the module relocation operation in $O(k)$-time, where k is the number of concave angles in the structure. The intuition behind the generalized algorithm is to iterate the algorithm for convex substrates by making transitions at each concave angle between the starting location and the goal location. To make the presentation of the general algorithm cleaner, we now introduce some definitions and supporting results.

Definition 4.1 *A* scrunch *consists of two adjacent and connected Atoms that are contracted in the dimension normal to their connected face.*

Definition 4.2 *An* axis *is a connected string of at least two Atoms along one dimension. Two axes intersect if they have one Atom in common.*

Definition 4.3 *The Atom Connectivity Graph for Crystal C denoted by $ACG(C)$ is an undirected graph whose vertices represent the Atoms in C and whose edges represent bounded inter-Atomic interfaces in C.*

Theorem 4 *If an axis in a Crystal contains a scrunch, that scrunch can be moved to any position on the axis by the inchworm propagation algorithm illustrated in Figure 2. If one of two intersecting Axes in a Crystal C contains a scrunch, a transition can be performed to transfer the scrunch to the other axis, provided that there is sufficient surrounding structure to maintain connectedness throughout the operation.*

Proof: Let i be the axis containing the scrunch and f be an intersecting axis to which the scrunch should be transfered (see Figure 9.) Without loss of generality, suppose the scrunch is adjacent to $i \cap f$.

[3] If the supporting lines for the start and goal location in a Crystal do not intersect, two transitions will be required instead of one.

[4] This result assumes that the actuators are strong enough to push or pull any number of Atoms during these operations.

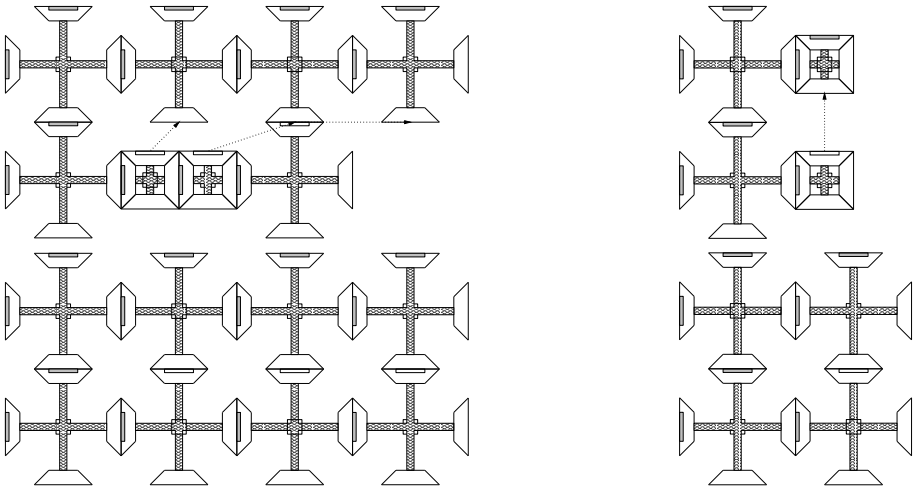

Figure 6: This figure illustrates the use of the expansion and contraction mechanism for movement. The left figure shows a compound movement with several approach trajectories represented as dotted lines. The upper half of the figure shows a configuration of 8 Atoms, with two compressed Atoms preparing to expand. The lower part of the figure shows the resulting structure after the expansion of the Atoms. The right figure shows a compound movement with a 90° approach trajectory. The top half of the figure shows a configuration of four Atoms with two compressed Atoms about to expand. The bottom half shows the structure that results from the expansion of those Atoms.

The following algorithm transfers the scrunch (see Figure 9.) A void can be created at $i \cap f$ by compressing two Atoms along f. Next, the scrunch along i can be expanded into the void. The scrunch has thus been transfered from i to f.

The surrounding structure required for these two steps must be such that $ACG(C)$ remains a connected graph, given that the Atomic interfaces between the compressed modules and the rest of the structure and between the void and the rest of the structure are not present. One way to ensure that this condition is met is to consider axes i and f that are surrounded by collar of modules (see Figure 9 (right)). □

Note that the construction in Theorem 4 holds for planar Crystals but it can be generalized easily to three-dimensional structures.

Figure 10 shows the algorithm for relocating an Atom on a concave structure. Figure 11 shows an instantiation of this algorithm.

Theorem 5 *Let C be a Crystal with k concave angles, S a starting Atom location on the surface of C, and G the goal Atom location on the surface of C. A relocation from S to G throuch C can be executed in $O(k)$ time.*

Proof: To analyze the complexity of Atom relocation, note that the first step of the algorithm in Figure 10 would require $O(n^2)$ time to generate an optimal path, where n is the number of Atoms in the structure. However, a non-optimal path between S and G can be found in $O(t)$, where t is the number of turns in the path. Note that $t = O(k)$. The running time of the remaining steps is $O(t)$. □

5 Discussion and Future Work

We presented the Crystalline Atom and argued that it fulfills two sufficient conditions for a homogeneous, unit-modular, self-reconfigurable robot system. The Atom is inspired by a muscle-like actuation mechanism with 3 DOFs that allow it to make and break connections with identical modules. The Atom is capable of expanding and contracting by a factor of two. This actuation mechanism supports very fast algorithms for relocating one module on the surface of a Crystal, which leads to an efficient $O(n^2)$ planner for shape metamorphosis [17]. We have described our first physical prototypes for the Atom. Our experiments [18] with a 10 unit Crystal system support these results by demonstrating self-reconfiguration for locomotion and for shape morphing.

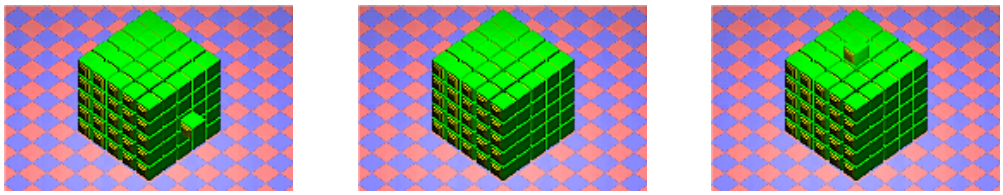

Figure 7: A Crystalline module can be pushed into the large cube and popped out at any location on the surface of the cube in constant time. The three images are snapshots from a simulation. The left image shows the initial configuration (with the extra cube located on the side face) and the right image shows the final configuration (where the extra cube is on the top face). The middle image shows the base cube where two internal modules are compressed (not visible in the figure).

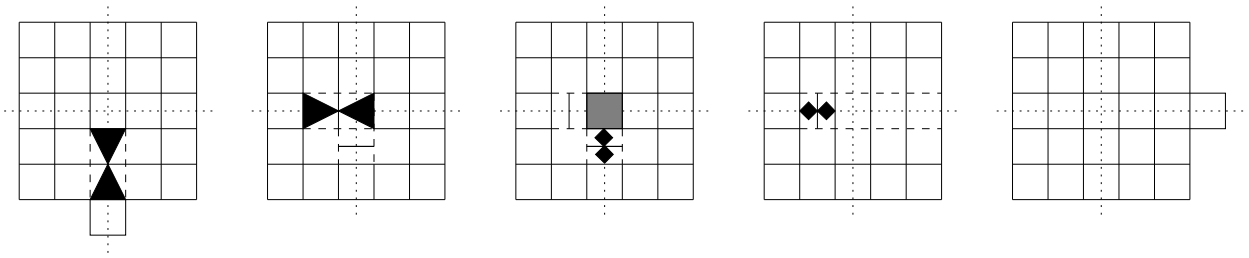

Figure 8: An internal view of the Algorithm for module relocation on a *convex* Crystal. Bow-ties mark two Atoms about to be contracted. Small dark diamonds mark two compressed Atoms that are about to be expanded. Dashed lines mark disconnected Atomic interfaces. The supporting lines for the start and goal locations are marked with dotted lines. The leftmost figure shows the initial state, where the Atom to be relocated is on the bottom surface. The rightmost figure shows the final state. The intermediate sequence shows the formation of a void at the intersecting lines between start and goal, and the expansion of an Atom into that void.

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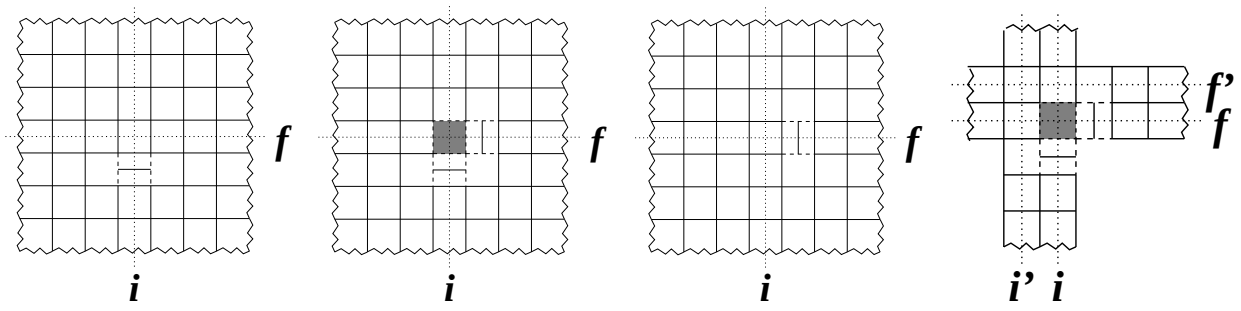

Figure 9: The scrunch transfer algorithm. The left figure shows a Crystal with axis i containing a scrunch. The second figure shows the Crystal after the creation of a scrunch along axis f. The third figure shows the Crystal after the transfer of the scrunch from i to f. The right-most figures show axes i and f in a structure that pads them with a collar of Atoms on the outside (i' and f').

Notation: C is a concave Crystal.
S is the start location on the surface of C.
G is the goal location on the surface of C.
Input: C, S, G.

Atom Relocation: Build $ACG(C)$.
Find a path p from S to G in $ACG(C)$.
Create a scrunch s along the supporting axis for S by pulling in the Atom that was in the starting location.
Drive s along p using transitions from each segment of the path to the next.
Relax s along the supporting axis for G, popping an Atom out onto G.

Figure 10: The algorithm for relocating an Atom on a concave Crystal. The Atom starts at location S on the surface of the Crystal and is relocated to G.

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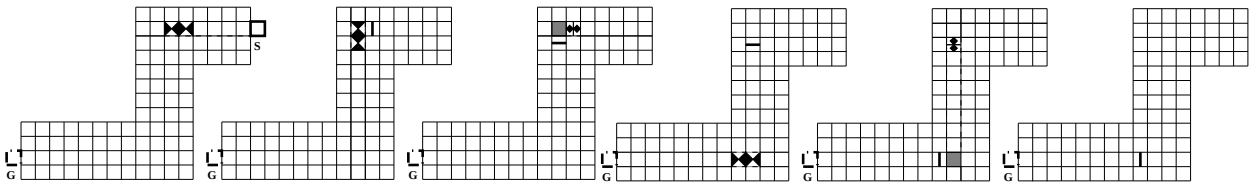

Figure 11: This figure illustrates the algorithm for relocating a Crystalline module on a concave substrate of Crystalline modules. The left figure shows the initial configuration. The relocating Atom is in the upper right corner of the structure. The goal location is in the bottom left corner. Large dark diamonds mark two Atoms about to be be compressed. Small dark diamonds mark two compressed Atoms about to be expanded. Dark lines mark compressed pairs. The second figure shows the structure after the compression of the first pair of candidate Atoms, and two Atoms preparing for the next compression. The third figure shows two pairs of compressed Atoms and a hole. The fourth figure shows the first compressed pair expanded into the hole and a candidate pair of Atoms for the next compression. The fifth figure shows the state of the structure after this compression, with the resulting hole. The right-most figure shows the structure after an expansion into the hole. At this point, the remaining compressed pair can be expanded into the goal location.

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