

**Self Assembling Magnetic Tiles**

by  
Jessica A. Rabl

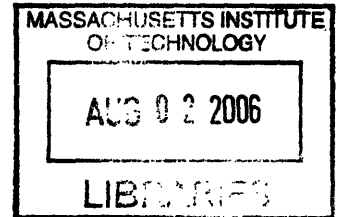
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Jessica A. Rabl

Submitted to the Department of Mechanical  
Engineering on May 12, 2006 in Partial Fulfillment  
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Bachelor of Science in Mechanical Engineering

## **Abstract**

Self assembly is an emerging technology in the field of manufacturing. Inspired by nature's ability to self assemble proteins from amino acids, this thesis attempts to demonstrate self assembly on the macro-scale. The primary focus of the thesis was to improve the design of magnetic tile self assembly. By constructing a flexible chain embedded with permanent magnets, self assembly is achieved through magnetic interaction. Theory has shown that such a chain is capable of self assembling into any 3D shape without self-intersection. The 3D shape created by the chain is predetermined by the sequence of the tiles.

For this thesis, two chains were manufactured, each self assembling into one distinct shape. One chain self assembled into a sphere while the other self assembled into a '3-leaf clover'. An important characteristic shared by the two chains is that they both were constructed from 48 tiles that had the same proportion of north-pole and south-pole facing magnets. The difference between the two 3D shapes created is a direct result of the magnet tile sequencing, only.

To connect the tiles, two different types of connectors were designed: one rigid and one flexible. The rigid connector design was able to stabilize the chain geometry; however some joints displayed excessive rotational friction. Additionally, the chain was not robust and was easily broken if dropped. When the chain was manufactured using flexible connectors, the amount of friction in the joints was significantly reduced. However, the chain lost geometric stability since the flexible connectors could not overcome some torsion forces created by the magnets.

Ultimately, this thesis provided supporting data for the theoretical arguments concerning the ability of a flexible chain to self assemble into arbitrary 3D shapes. By predetermining a sequence of magnetic tiles, it can be known with certainty what shape the chain will assume. This thesis furthered the understanding of the mechanisms of self assembly, providing groundwork for the eventual application on the nano-scale.

Thesis Supervisor: Joseph Jacobson

Title: Associate Professor of Media Arts and Sciences

## 1. Introduction

Self assembly is a concept that originates in biology. Within the cellular nucleus of eukaryotic cells, DNA holds the genetic code for protein assembly. Proteins are formed by the strategic folding of amino acid chains. Often referred to as the “building blocks of life”, there are twenty different amino acids utilized by the cell in protein synthesis.<sup>1</sup> Nature’s ability to assemble and fold amino acid chains into a protein is the motivation for bringing self-assembly into a manufacturable context.

Current manufacturing technologies are primarily based upon an assembly line technique, where a work piece is moved through a series of machines that transform raw materials into finished goods. While effective, this system is wholly dependent on external inputs to create the finished product. The principle of self assembly seeks to remove some of the dependence on external assembly processes, replacing them with preprogrammed assembly features that complete production. As an emerging field of manufacturing technology, self assembly falls under the wider umbrella of “digital fabrication”.

Digital fabrication describes the use of patterned printing in the construction of physical systems.<sup>2</sup> Various software packages already exist in the market with which a user can design and dimension parts for assembly. With the digitally created file, these parts are fabricated using machines such as laser cutters and water jets. The next step in this technology is to digitally fabricate parts that are embedded with information useful for assembly purposes.

The purpose of this thesis is to design, manufacture, and demonstrate physical models of 3D self assembly on a macroscopic scale. To achieve this, a flexible chain has been digitally fabricated and imbedded with permanent magnets. The chain is composed of individual plastic tiles that are connected by either a hinge joint or a flexible connector. The magnetic forces at each joint are the preprogrammed information controlling assembly. Therefore, specific 3D shapes are created through the proper sequencing of the magnetic tiles. Each unique sequence of magnetic tiles will create only one unique 3D shape.

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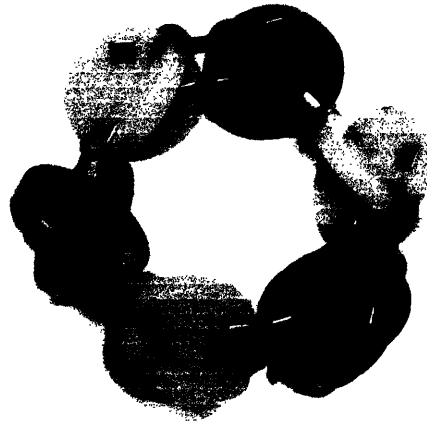
<sup>1</sup> William K. Purves, et al., *Life: The Science of Biology*, 7<sup>th</sup> edition (Sunderland, MA: Sinauer Associates, 2004), page 39.

<sup>2</sup> “Call for Papers, DF 2005, International Conference on Digital Fabrication Technologies,” (The Society for Imaging Science and Technology, 2004-5), <http://www.imaging.org/conferences/DF2005/index.cfm> (accessed April 20, 2005).

## 2. Theory

The purpose of this thesis is to demonstrate programmable self assembly in 3 dimensions. To accomplish this, chains of magnet-impregnated tiles will be programmed to self assemble into various predetermined shapes. The final shape of the chain will be dictated by the geometry of the tiles and the magnetic interactions at the tile joint. An extensive theoretical proof of 3 dimensional self assembly has been set forth by Dr. Saul Griffith in his Ph.D. thesis.<sup>3</sup>

The geometry of the chain is based upon the formation of hexagonal voxels consisting of twelve tiles each. A voxel is the 3 dimensional equivalent of a pixel. The voxels, discussed in more detail in the following sections, are stacked and interconnected to form arbitrary shapes. Figure 1 shows a typical voxel used in this thesis.

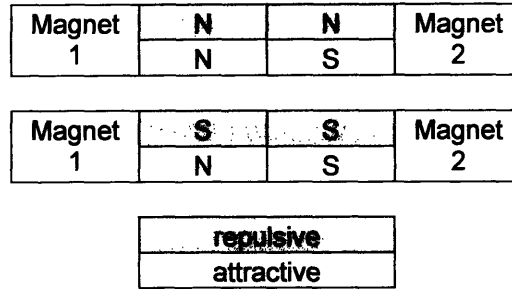


**Figure 1:** The 3D shapes created in this thesis are based upon the geometry of a hexagonal voxel.

The force necessary to drive the self assembly was provided by magnetic interactions at the joints of the chain. The magnets used were permanent magnets, therefore each magnet had distinct North and South poles. An attractive force results when a North and South pole interact; conversely, a repulsive force results when two North poles interact or when two South poles interact. At each joint there is one set of magnets exhibiting an attractive force and one set exhibiting a repulsive force. Figure 2 shows the possible combinations of magnetic interactions.

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<sup>3</sup> Saul Thomas Griffith. "Growing Machines". Thesis, Massachusetts Institute of Technology. September 2004.



**Figure 2:** The chain bends due to the magnetic forces of attraction and repulsion.

The tiles manufactured for this thesis encompass all possible magnetic combinations. Black tiles are used to for N-N and N-S magnetic combinations. Orange tiles are used for S-S and N-S combinations.

### 3. Experimental Procedure

This thesis involved four stages of experimental procedure. First, the magnetic tiles and joints were designed and redesigned through trial and error. Once the proper design was achieved, tiles and joints were produced en masse. Following the manufacture phase, various chain sequences were assembled to observe the behavior of the self assembly. Lastly, the self assembly performance was optimized and the results were captured in .mpeg format.

#### 3.1. Apparatus

##### 3.1.1. Design

The tiles and joints were designed using SolidWorks 2003 SP3.1 and CorelDraw 10 on an IBM ThinkPad T43.

##### 3.1.2. Manufacture

The tiles and connectors were cut from acrylic sheets with a Universal Laser Systems laser cutter. The acrylic sheets used were .125" thick and either black or orange in color. Additionally, LOCTITE 495 super bonder was used to secure a pair of .125" cubic NeFeB magnets into each tile. The super bonder was applied in a fume hood using Becton Dickenson PrecisionGlide 21G1½ syringes and Henke Sass Wolf GMBH Norm-Ject 2ml (3ml) needles.



A second generation of connectors was later manufactured using flexible strips of overhead transparency cut to specification with a scissor. These flexible connectors were glued to the tiles in the same manner as the magnets.

### 3.1.3. Sequencing

This phase involved working directly with the manufactured tiles, recording the behavior exhibited by various magnetic orientation combinations. No special apparatus was used.

### 3.1.4. Self Assembly in Buoyant Media

Once a tile sequence was constructed, it was allowed to self assemble in various media. The purpose of this experiment was to optimize buoyancy and viscosity parameters. The primary medium employed was tap water, contained in a 30 gallon glass tank. Other media used included Crisco vegetable oil and CVS antibacterial hand soap, each contained in 3 gallon Aquatic Gardens Deluxe Aquarium Totes.

## 3.2. Methods

### 3.2.1. Design

The design of the acrylic tiles and acrylic connectors was based upon the work of Dr. Saul Griffith.<sup>4</sup> Within his Ph.D. thesis, he argued the theory behind his design, stating that the tiles could be sequenced to produce any 3D shape without intersection. However, the tiles he designed and manufactured had high friction connectors and the magnetic relationships between the tiles were not fully documented.

#### 3.2.1.1. Tile Size

The tiles created for this thesis are circular in shape, with a diameter of approximately 0.76". The tiles are cut from acrylic sheets with a thickness of 0.125". While these tiles are on the macro-scale, one of the long term goals of manufacture for self-assembly is to reduce the size of chain sub-units, eventually reaching the MEMS-scale. Inspired by this goal, the acrylic tiles

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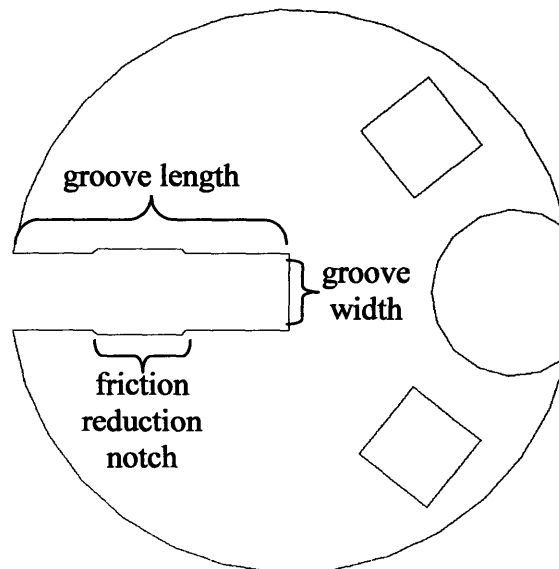
<sup>4</sup> Griffith, Saul Thomas. "Growing Machines". Thesis, Massachusetts Institute of Technology. September 2004.

manufactured for this thesis were approximately  $\frac{2}{3}$  the diameter of those previously manufactured by Dr. Griffith.

### 3.2.1.2 Tile Intersection

The tile chain is constructed by fitting together both tiles and connectors. Within the chain, two tiles are fitted together by a snap-fit along a deep groove. Important design features of the groove include its depth, width, and interaction with connectors. The groove must be deep enough so that when the tiles are pushed together, the outer edges of the tiles are flush with each other. This requires that the groove be cut as least as deep as the midpoint of the tile. Also, since the tiles interact at right angles, the groove must be wide enough so that it can accommodate the thickness of the tile.

The final design requirement involves reducing the friction between the tile and the connector. When using a laser cutter to manufacture the acrylic pieces, a small ridge forms on the surface of the acrylic sheet furthest from the laser source. This defect is not large, but when working with snap-fit tolerances, it becomes a source of significant friction. To eliminate the friction, a shallow notch is cut into the walls of the groove. Even though the ridge only forms on one side of the connector, for the sake of assembly convenience, a notch is cut into both walls of the groove. Figure 3 below shows a representative tile, highlighting the important design features.



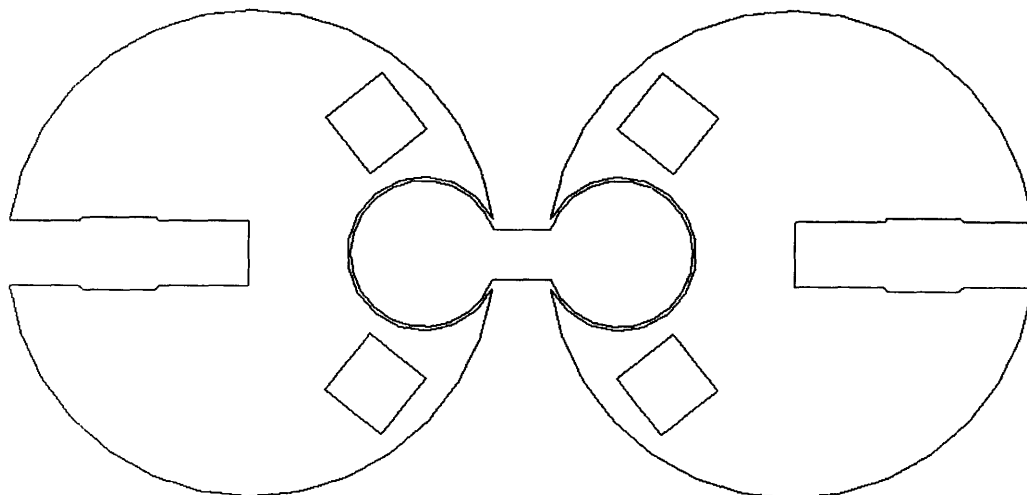
**Figure 3:** The tiles are designed for snap-fit assembly. The groove length, width, and friction reduction features are highlighted.

Because the tiles are snap-fit at right angles, the two circular tiles roughly form a sphere. When the tiles are properly fit together, the chain consists of two-tile spherical subunits bridged by connectors.

### 3.2.1.3. Connectors

Connectors were located between every spherical subunit and were designed to allow the chain to bend. Two different types of connectors were designed: a rigid acrylic connector that relies on relative motion between the connector and the tiles and a flexible plastic connector rigidly fixed to the tiles.

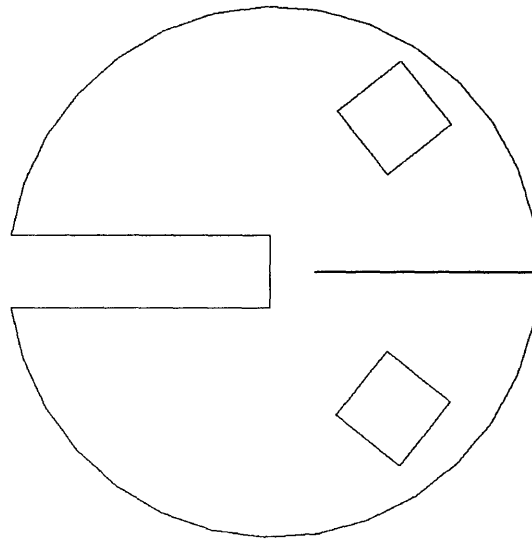
The rigid acrylic connector design was based on the tile connectors manufactured by Dr. Griffith. The shape of the connector consists of two circular sections connected by a narrow straight section. The tiles were designed to interact with the rigid connectors via a circular cutout in the tiles. Each circular section of the connector fits inside the circular cut out of one tile, thereby connecting two tiles with one connector. Figure 4 below show two tiles and one connector.



**Figure 4:** The connector consists of two circular sections bridged by a straight section. The circular ends of the connector fit into the circular cut outs of the tiles.

The flexible connectors consisted of overhead transparency plastic cut by hand into 0.85” by 0.1” strips. The plastic used had a thickness of 0.004”. To accommodate the geometry of the

flexible connectors, the tile was modified to eliminate the circular cutout. Replacing the circular cutout, a slit was cut into the tiles that penetrated the outer diameter by 0.32". The width of the slit was 0.015". This thickness is significantly larger than the width of the plastic strip; however it was not possible to reduce the width since the laser cutter has a minimum beam thickness of 0.015". Also, the friction reduction notch was eliminated because there is no rotational motion of the connector relative to the tile. Figure 5 shows a tile modified for the flexible connector.



**Figure 5:** The tile cutout is modified from a circular shape to a deep slit to accommodate the flexible connector.

### 3.2.1.3. Magnets

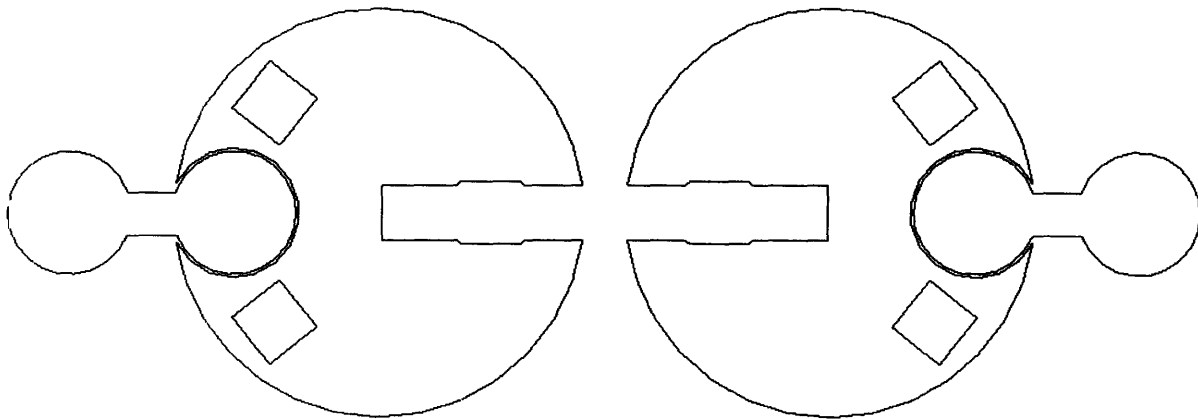
A pair of Neodymium Iron Boron (NeFeB) magnets was embedded in each tile. The magnets measured 0.125" on each side and were fit into the square holes cut into the tile on either side of the connector cutout. The holes measured 0.117" on each side. The holes were designed smaller than the actual magnets because of the laser cutter diameter of 0.015". The laser diameter resulted in an effective length of 0.132" for each side of the magnet hole. This allowed the fit between the magnet and the tile to be slightly looser than press-fit.

### 3.2.2. Manufacture

The tiles and rigid connectors were manufactured from 0.125" thick acrylic tiles using a laser cutter. The laser cutter was set to cut at 1000 pulses per inch (PPI), 20% power, and 1% speed. The tiles and connectors were cut in a single pass. At these settings, it took approximately 15 seconds for each tile to be cut. The connectors took approximately 7 seconds each. Once all the tiles were cut, the magnets were glued into place by hand.

In total, four different types of tiles were manufactured based upon color and magnetic polarity of outward facing magnets. The four types were: black tiles with two north-facing magnets, black tiles with one north-facing and one south-facing magnet, oranges tile with two south-facing magnets, and orange tiles with one north-facing magnet and one south-facing magnet.

When a chain is assembled using the rigid connectors, the connector must be placed in the circular cutout of the tile before the tiles are snap-fit, as was shown in Figure 2. To obtain the snap fit, two tiles were arranged as mirror images of each other, with their grooves along the horizontal axis, facing inward. Figure 6 shows the necessary tile alignment.

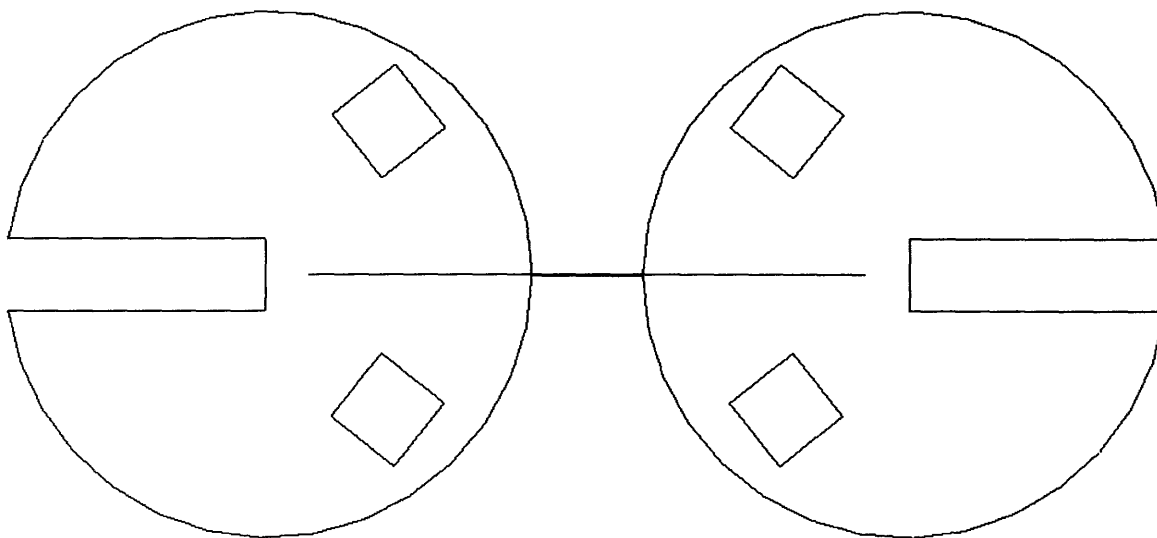


**Figure 6:** The tiles must be aligned with the grooves facing each other, as shown. Then, one tile is rotated 90° about its horizontal axis. Snap fit is achieved by sliding the two tiles together along the grooves.

Then, one tile is rotated 90° about its horizontal axis. Pushing the tiles together creates the snap-fit. For proper chain alignment, the tiles must be pushed together until the outer edges of both

tiles are flush. This process is continued until the desired chain length is created. The magnetic orientation of the tile added to the chain determines the direction that the chain will bend at that connection point. The method to order the magnetic orientation of the tiles is discussed in the next section.

The assembly characteristics of the chain using flexible connectors are slightly different than that for the rigid connectors. For the rigid connectors, the connector is added immediately before the two tiles that form the spherical subunit are joined. Each subsequent connector is added as the chain grows. For the flexible connectors, the connectors are still added before the two tiles that form the spherical subunit are joined. The difference lies in the fact that the connector must be glued into its slot before the two tiles are snap fit together. The gluing of additional tiles can be done as the chain is growing; however, the tiles and connectors take at least 30 seconds to dry and need to dry on a flat surface. These requirements are more easily satisfied if the connector is glued into its two adjoining tiles before the chain is assembled. Figure 7 shows two tiles connected by a flexible connector.

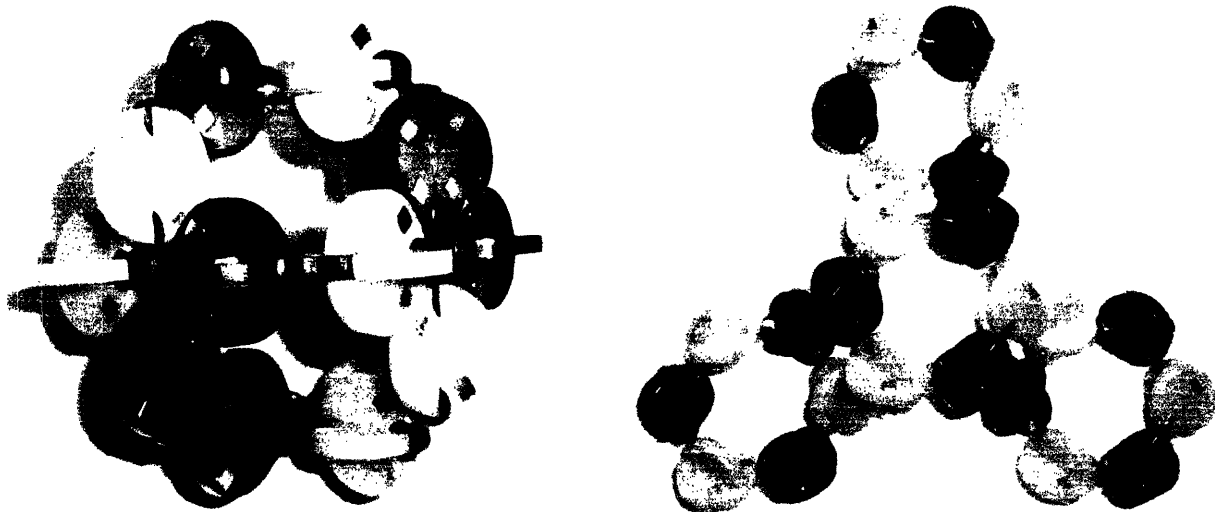


**Figure 7:** A flexible connector is used to connect two tiles. The connector should be glued into place between the two tiles before the chain is assembled.

Therefore, the most time effective assembly technique is to glue each connector into its two adjacent tiles, and to complete this process for all the tiles that will be used in the chain. Once the flexible connectors have dried in place, the chain can be assembled via snap-fitting.

### 3.2.3. Sequencing

The tiles and connectors have been designed to form a chain that bends according to the magnetic orientation at each connector joint. To demonstrate the ability of such a chain to self assemble into a predetermined shape, two shapes have been chosen to construct and discuss in depth. The chosen shapes are shown in Figure 8, and will be referred to as a sphere (left) and a 3-leaf clover (right).



**Figure 8:** The two shapes that will be discussed are the sphere and the 3-leaf clover, respectively.

The significance of these two shapes is that they are distinctly different, yet both constructed from the same combination of tiles. The only differences between the chains are that the sequencing of the tiles is different and the type of connector employed is different. The sphere utilizes rigid connectors while the 3-leaf clover utilizes flexible connectors.

The sphere and the 3-leaf clover both consist of a chain of 48 tiles. The tiles are evenly split among the 4 different types of tiles available: 12 black tiles with two north-facing magnets, 12

black tiles with one north-facing and one south-facing magnet, 12 orange tiles with two south-facing magnets, and 12 orange tiles with one north-facing magnet and one south-facing magnet.

### 3.2.3.1. Sphere

The sphere is constructed from the following sequence of tiles, shown in Figure 9: (color, magnetic orientation)

- |                |                 |                 |
|----------------|-----------------|-----------------|
| 1. Orange, S-S | 17. Orange, N-S | 33. Orange, N-S |
| 2. Orange, S-S | 18. Orange, N-S | 34. Orange, S-S |
| 3. Orange, N-S | 19. Orange, S-S | 35. Orange, N-S |
| 4. Orange, S-S | 20. Orange, S-S | 36. Orange, N-S |
| 5. Orange, N-S | 21. Orange, N-S | 37. Orange, S-S |
| 6. Orange, N-S | 22. Orange, S-S | 38. Orange, S-S |
| 7. Orange, S-S | 23. Orange, N-S | 39. Orange, N-S |
| 8. Orange, S-S | 24. Orange, N-S | 40. Orange, S-S |
| 9. Black, N-S  | 25. Black, N-N  | 41. Black, N-S  |
| 10. Black, N-N | 26. Black, N-N  | 42. Black, N-S  |
| 11. Black, N-S | 27. Black, N-S  | 43. Black, N-N  |
| 12. Black, N-S | 28. Black, N-N  | 44. Black, N-N  |
| 13. Black, N-N | 29. Black, N-S  | 45. Black, N-S  |
| 14. Black, N-N | 30. Black, N-S  | 46. Black, N-N  |
| 15. Black, N-S | 31. Black, N-N  | 47. Black, N-S  |
| 16. Black, N-N | 32. Black, N-N  | 48. Black, N-S  |

**Figure 9:** The sphere is constructed from a chain with this sequence of tiles.



### 3.2.3.2. Three Leaf Clover

The 3-leaf clover is constructed from the following sequence of tiles, shown in Figure 10: (color, magnetic orientation)

- |                 |                 |                 |
|-----------------|-----------------|-----------------|
| 1. Black, N-S   | 17. Black, N-N  | 33. Black, N-S  |
| 2. Black, N-S   | 18. Black, N-N  | 34. Black, N-S  |
| 3. Black, N-N   | 19. Black, N-S  | 35. Black, N-N  |
| 4. Black, N-S   | 20. Black, N-N  | 36. Black, N-N  |
| 5. Orange, S-S  | 21. Orange, N-S | 37. Orange, N-S |
| 6. Orange, S-S  | 22. Orange, N-S | 38. Orange, S-S |
| 7. Black, N-S   | 23. Black, N-N  | 39. Black, N-S  |
| 8. Black, N-N   | 24. Black, N-N  | 40. Black, N-S  |
| 9. Orange, N-S  | 25. Orange, N-S | 41. Orange, S-S |
| 10. Orange, N-S | 26. Orange, S-S | 42. Orange, S-S |
| 11. Black, N-N  | 27. Black, N-S  | 43. Black, N-S  |
| 12. Black, N-N  | 28. Black, N-S  | 44. Black, N-N  |
| 13. Orange, N-S | 29. Orange, S-S | 45. Orange, N-S |
| 14. Orange, N-S | 30. Orange, N-S | 46. Orange, N-S |
| 15. Orange, S-S | 31. Orange, S-S | 47. Orange, S-S |
| 16. Orange, N-S | 32. Orange, S-S | 48. Orange, S-S |

**Figure 10:** The 3-leaf clover is constructed from a chain with this sequence of tiles.

### 3.2.4. Self Assembly in Buoyant Media

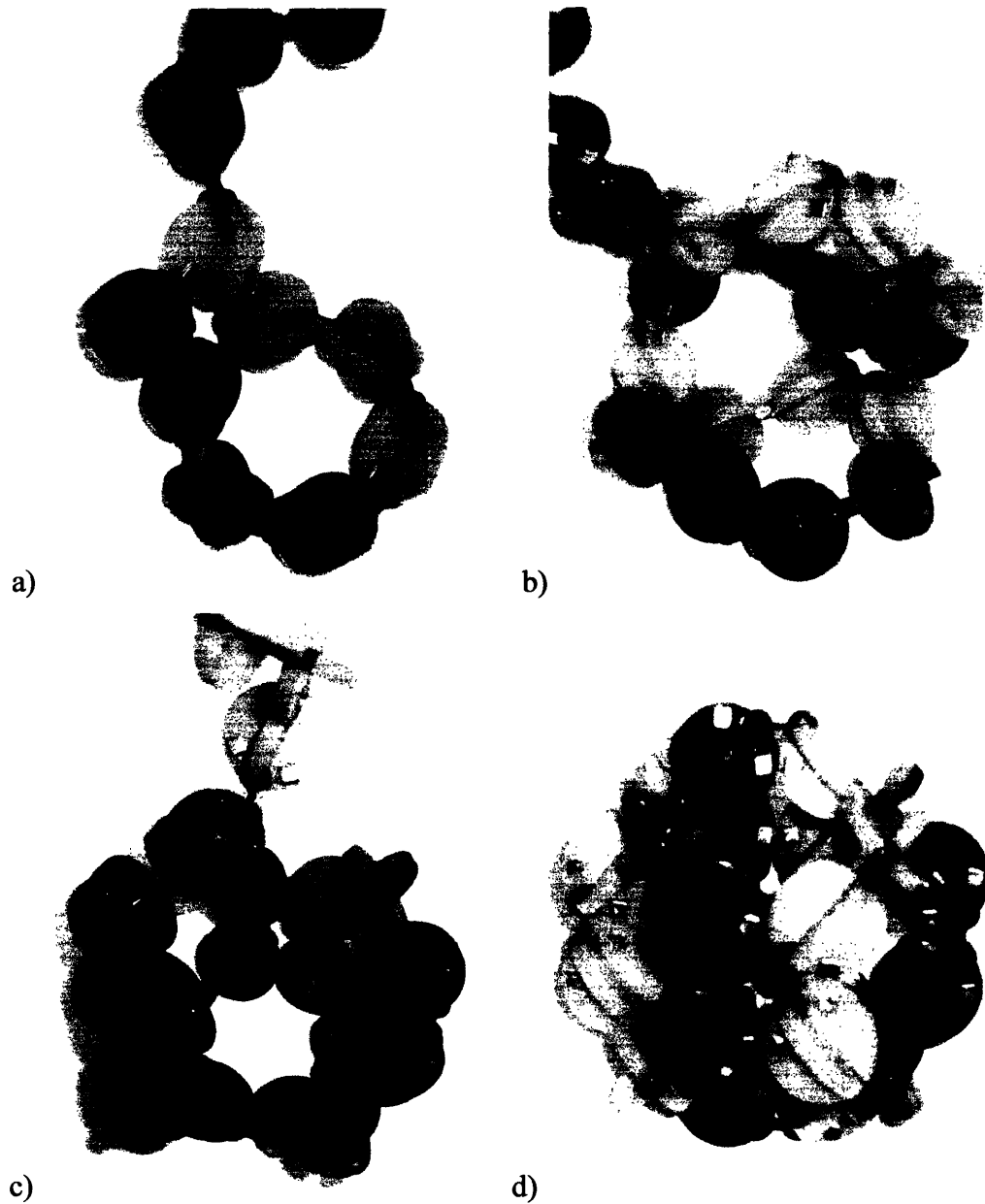
After the sphere and 3-leaf clover strands were sequenced and assembled, steps were taken to optimize the performance of the self-assembly process. It was noticed that the chain exhibited difficulty overcoming the force of gravity when attempting to assemble in the vertical direction. To counteract the gravitational force, the chains were introduced into various buoyant media. This thesis involved submerging the chains first in tap water and observing the self assembly process. Next, vegetable oil was used to provide buoyant force during self assembly. After the oil was used, the chains were thoroughly washed and dried. Lastly, liquid soap was used as a buoyant medium.

## 4. Results

Video recordings were taken of the chains during the self assembly process. The following pictures show the progression of self assembly for both chains.

### 4.1 Sphere Video Frames

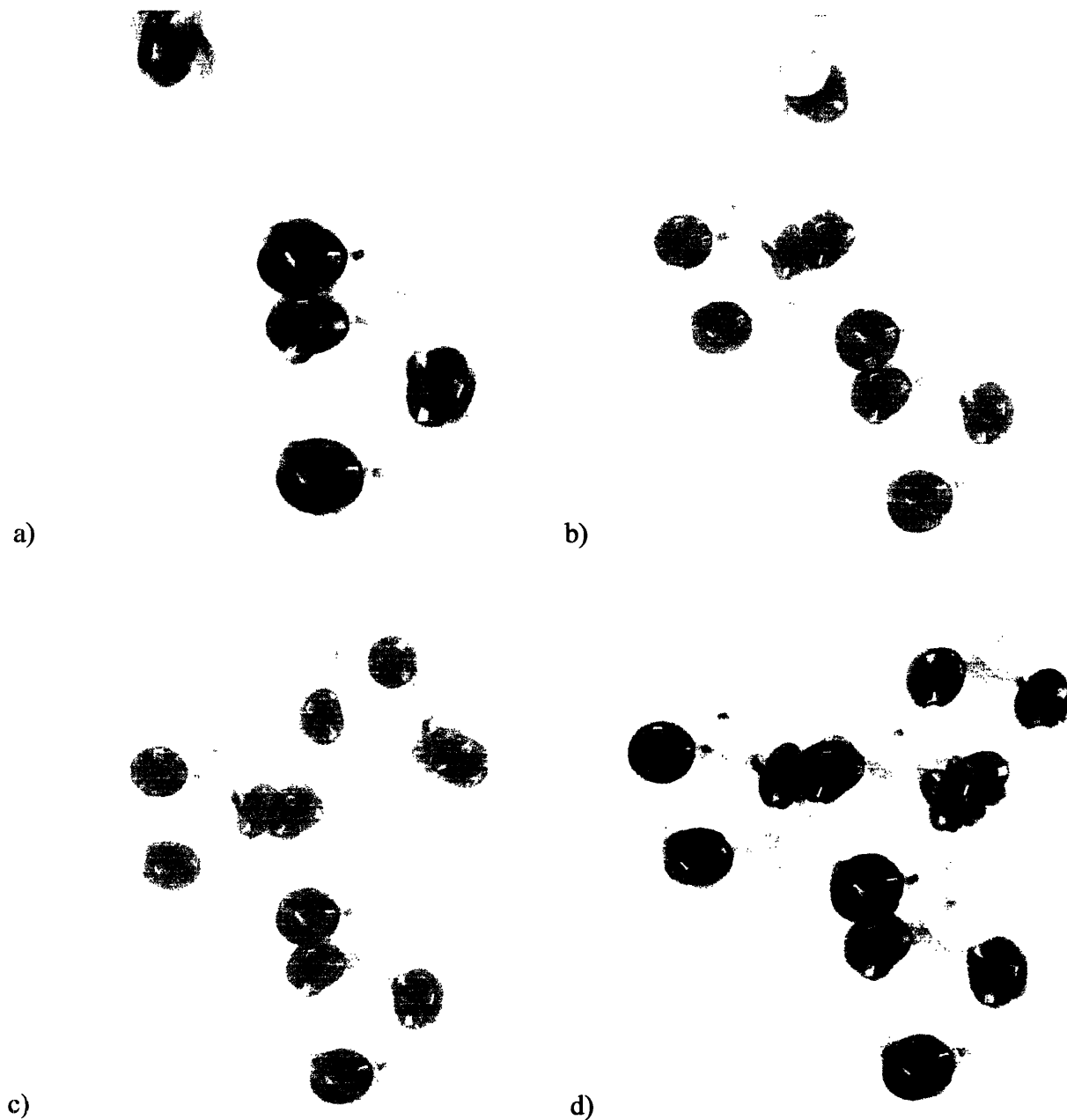
The self assembly of the chain into the sphere was captured in video format. Figures 11a through 11d show the chain in various states of assembly.



**Figure 11:** a) The sphere is beginning to take shape. b) The sphere is half formed. c) The sphere is almost complete. d) The sphere is completely self assembled.

## 4.2 Three-Leaf Clover Video Frames

The self assembly of the chain into the 3-leaf clover was captured in video format. Figures 12a through 12d show the chain in various states of assembly.



**Figure 12:** a) The 3-leaf clover is beginning to take shape. b) The 3-leaf clover is half formed. c) The 3-leaf clover is almost complete. d) The 3-leaf clover is completely self-assembled.

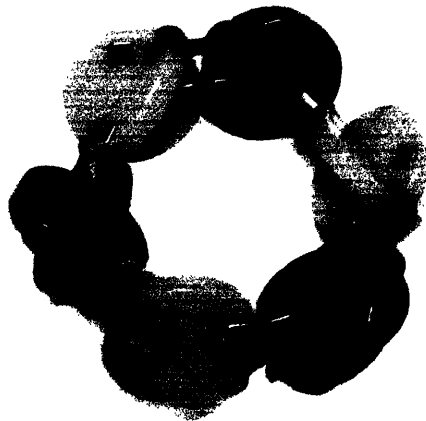
## 5. Discussion

### 5.1 Manufacturing Process

The process of manufacturing the magnetic tiles and magnets requires accuracy and precision. Because the tiles must snap fit, the tolerances are very tight. As previously mentioned, the laser cutter had a beam width of 0.015". This means that each part that was cut would have 0.0075" shaved off its outer edge (equivalent to the laser beam diameter). Since the snap fit tolerance is less than the gap created by the laser cutter, it was necessary to design the tiles such that, on paper, it appeared that they would not be able to slide together. A final consideration in snap fit tolerance was the thickness of the acrylic sheet stock. Although standard in thickness, each sheet displayed slight variations in thickness which occasionally resulted in poor snap fits. In practice, it took several generations to achieve a solid snap fit of the tiles.

The tiles connected by the rigid connectors had a small notch cut out of the snap fit groove to cut down on rotational friction at the joint. This notch also had the effect of reducing the force needed to snap fit the tiles together. Because the tiles had less surface area to slide across each other, it was noticeably easier to snap fit these tiles. This notch was eliminated from the tiles connected by the flexible connectors because there was no rotational motion about the hinge. Also, since the flexible connector is fixed into the groove with glue, it was important for the connector and the groove to have maximal contact, and thus no notch.

The basic shape programmed into the tile self-assembly was a six unit ring. The ring is shown in Figure 13.



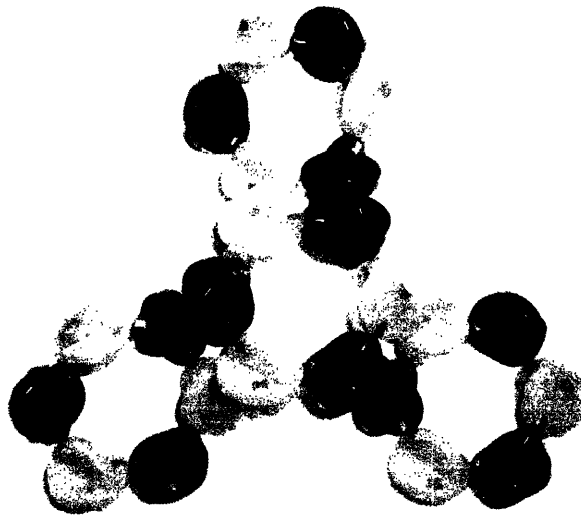
**Figure 13:** The basic shape of self assembly was the six unit ring.

The six unit ring is constructed from the following sequence of tiles, shown in Figure 14: (color, magnetic orientation)

- |                |                |                 |
|----------------|----------------|-----------------|
| 1. Black, N-N  | 5. Black, N-S  | 9. Black, N-N   |
| 2. Black, N-S  | 6. Black, N-N  | 10. Black, N-N  |
| 3. Orange, S-S | 7. Orange, N-S | 11. Orange, N-S |
| 4. Orange, S-S | 8. Orange, N-S | 12. Orange, N-S |

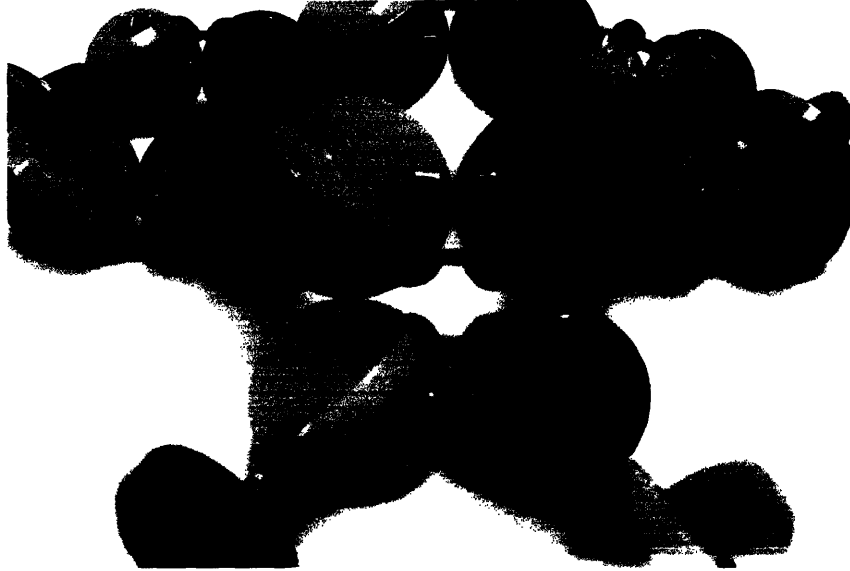
**Figure 14:** The six unit ring is created from a chain with this sequence of tiles.

The process of sequencing a shape begins with stacking the 6 unit rings. The first step is to ensure that all the rings have the same magnetic orientation relative to the table top. If one ring is upside-down, it will not stack properly with the others. Each ring is able to stack with 3 rings attaching below it and 3 rings attaching above it. The 3-leaf clover, shown again in Figure 15, is an example of a 6 unit ring with 3 other 6 unit rings stacked below it.



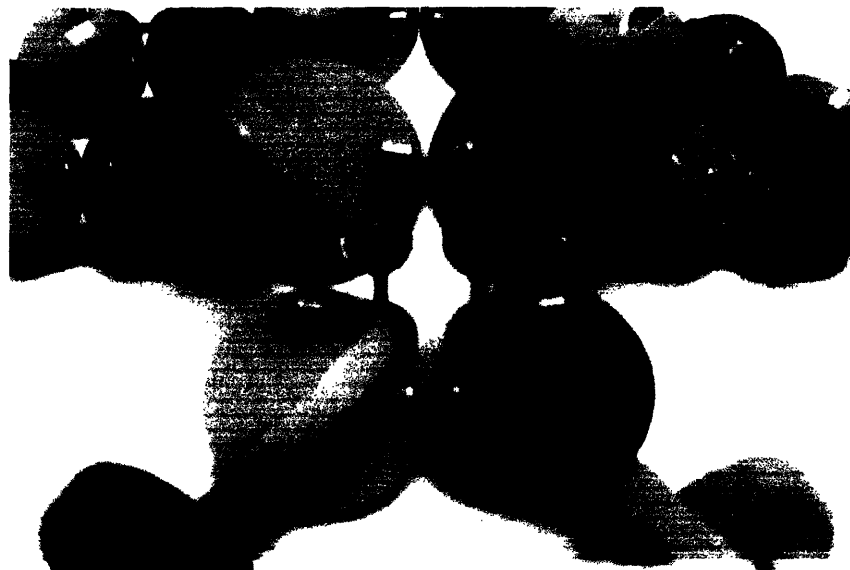
**Figure 15:** The 3-leaf clover is an example of stacking 6 units rings to create shapes.

The rings that are stacked need to be connected to each other to form a continuous chain. To accomplish this, the connectors must be reassigned from intra-ring connectors to inter-ring connector. Figure 16 shows the normal alignment of intra-ring connectors, parallel to the ground.



**Figure 16:** Within a 6 unit ring, shown in the foreground, the connectors run parallel to the ground.

Connecting rings together requires disassembling the tiles surrounding the two connectors, rotating the connectors to lie perpendicular to the ground, and then reassembling the tiles. Figure 17 shows how the connectors should look after the rings have been connected.



**Figure 17:** When the rings have been connected, the connectors lie perpendicular to the ground.

The sphere is a more complicated shape, yet it was created in same way as the 3-leaf clover. By stacking rings and redirecting their connectors, a long chain was created that included the sphere, but was not limited to the sphere. Other tiles were connected in the chain, forming peripheral shapes. To separate the sphere from the rest of the chain, the connectors were unattached at the appropriate points so that only the sphere remained. Because the tile sequence of the sphere has been recorded, it is possible to construct the sphere without ever relying upon the ring stacking method.

The ring stacking method is an ideal way to create new shapes. The magnetic alignment required for this method ensures that the chain will be stable in only one configuration. That is, at each joint, the chain will only want to bend in one direction. This ensures that the chain will form the same shape every time it self assembles. The guarantee that the chain will self-assemble into the same shape every time is a fundamental principle of self assembly.

## ***5.2 Sphere and Rigid Connectors***

The self assembly of the sphere was shown in Figures 9a through 9d. The design of the chain, including the rigid connectors, was able to accomplish the task of self assembly. Issues did arise, however, when some joints were unable to overcome the rotational friction present between the tile and the connector. The primary reason for the excessive friction is poor surface quality at the tile/connector interface.

Poor surface quality results from either manufacturing defects or human error. The laser cutter used for this thesis was programmed to cut smooth edges. Occasionally, however, the heat from the laser cutter would cause the tile to fuse with the acrylic sheet after it was cut out. While easy to separate, the fusion would leave surface defects that increased friction. Also, random defects would be caused by irregularities in the laser and/or irregularities in the acrylic sheet.

There exist several ways to decrease the friction at the joint. If the diameter of the circular portion of the connector is reduced, there is more space between the tile and the connector. Issues arise, however, because the diameter of the connector must be greater than the opening of circular cut out of the tile. If the connector diameter is smaller than the opening of the circular cut out, the connectors will slip out of the tiles. In the current design, the diameter of the circular portion of the connector is 0.24” and the opening of the circular cut out is 0.17”. Therefore,

there is little room to increase the gap. Another way to reduce the friction is to increase the magnetic force at the joint by either using stronger magnets or using larger magnets. Lastly, the surface finish could be improved by investing in higher precision machinery that produces fewer defective parts.

### ***5.3 Three-Leaf Clover and Flexible Connectors***

The self assembly of the 3-leaf clover was shown in Figures 10a through 10d. The design of the chain, including the flexible connectors, was able to accomplish the task of self assembly. The flexible connectors were able to eliminate the frictional problems displayed with the rigid connectors. However, another issue developed concerning the thickness of the connector versus the geometric stability of the chain.

One of the most important variables when designing the flexible connectors is the thickness of the plastic. If the plastic is too thick, the bending moment of the connector may overwhelm the force of magnetic attraction. In this extreme, self assembly cannot occur. If the plastic is too thin, the chain will exhibit unwanted twisting about the flexible connector. Magnetic attraction forces will overwhelm the torsional strength of the plastic, resulting in the failure of self assembly. A plastic of moderate thickness must be chosen to satisfy the needs of self assembly.

In this thesis, two different thicknesses of plastic were used to create two separate 3-leaf clover chains. For one chain, the two layers of transparency plastic were used to create each connector. For the other chain, only one layer of transparency plastic was used. Experimentally, the chain using two layers of plastic gave better self assembly results. Initially, however, the double layered connections were too stiff to allow for self assembly. To correct for the stiffness, each chain was bent back and forth several times to ‘break-in’ the connector. The result for the double layer connectors was reduced stiffness and a relatively higher resistance to unwanted torsion.

### ***5.4 Self Assembly in Buoyant Media***

The ability of the chains to self assembly was tested in various media. The purpose of the testing was to determine if self assembly could be improved by submerging the chains in a fluid



more buoyant than air. The fluids tested were tap water, Crisco vegetable oil, and CVS brand antibacterial liquid soap. The tap water was contained in a 30 gallon glass tank while the oil and soap were each in separate 3 gallon plastic tanks.

The tap water was shown experimentally to be the best fluid out of the three for the purpose of improving self-assembly. The quality of self assembly in the vegetable oil was shown to be equal to that in water, however, the oil residue on the chain was undesirable. The liquid soap proved to be too viscous for self assembly; the magnets were not able to pull the tiles together before the chain hit the bottom of the tank.

Overall, if a buoyant medium is to be chosen to improve self assembly, it should have the properties of low viscosity and high density. Low viscosity is important because viscous forces act against the magnetic forces of the chain. The more viscous the fluid, the longer it will take the chain to bend at each joint. High density is necessary to keep the chain suspended off the bottom of the tank. Once the chain reaches the bottom, it is difficult for self assembly to occur against gravity. It has been shown experimentally that chains are more likely to self assemble properly if the magnetic connections occur before the chain has reached the bottom of the tank.

## **6. Conclusions**

The purpose of this thesis is to design, manufacture, and demonstrate physical models of 3D self assembly on a macroscopic scale. To accomplish this, a chain of acrylic tiles was impregnated with permanent magnets; the interactions of the magnets caused the chain to bend at each joint. The principles of magnetic attraction and repulsion made it possible to predict, and thus code, the sequence of tiles necessary to output a desired 3D shape.

Two distinct 3D shapes were programmed with the tiles: a sphere and a 3 leaf clover. The tiles that formed the sphere chain were connected with rigid connectors. The tiles that formed the 3 leaf clover chain were connected with flexible connectors. Overall, the rigid connectors were found to have some unwanted friction, but were able to sustain the desired chain geometry. The flexible connectors were able to eliminate friction at the tiles joints, but were unable to maintain geometric stability at some joints. Design improvements for future work were suggested for both types of connectors.

Self assembly characteristics of the two chains were tested in various fluid media. The goal of these experiments was to improve the quality of self assembly by providing a buoyant force to oppose gravity. Of the fluids tested, tap water proved to be the most effective and convenient medium. For future reference, short video clips were taken of the chains self assembling in a tank of tap water.

The thesis was successful in demonstrating the ability to program for self assembly on the macro-scale. The design details and specifications explained in the thesis text expand upon the work already done in the field of programmable self assembly. With every new generation of self assembly technology, manufacturing moves closer to its goal of nano-scale digital fabrication. When the nano-scale is achieved, the principles of this thesis may be applied to the programmed self assembly of cellular systems.

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