

# **Reconfigurable Kinetic Polygons: An Approach to Designing 2D Kinetic Tessellations**

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## **Abstract**

In this research, we discuss underlying geometries and overlaid patterns as principles of kinetic design, and consider how designers might generate a wide variety of kinetic patterns. We also present three approaches to designing kinetic polygons with a scissor mechanism. Finally, as a means of better understanding the kinetic design process and motion composition in general, this work presents a series of reconfigurable magnetic kinetic modules named L8 that offer numerous kinetic compositions, and it presents authentic fabrication process of L8 blocks.

## **Introduction**

In general, most of the existing research and practice relevant to motion design do not consider motion itself, nor do they present a comprehensive kinetic design methodology. Therefore, the existing body of literature on motion design does not provide sufficient insight for those seeking to learn about its complexities, compositional character, possible configurations, or the general composition of movement.

The full depth of the motion design process cannot be understood by theory alone. Therefore, to better understand the design process and relationships that craft motion composition, we present a series of reconfigurable kinetic tessellations that offer a variety of kinetic compositions. In exploring kinetic tessellations, we explain certain fundamental design aspects of kinetic patterns, as well as the following:

- 1- The principles of kinetic design, such as underlying geometries and overlaid patterns;
- 2- Design principles of kinetic polygons with scissor linkages; and the
- 3- Potential of reconfigurable kinetic tessellations.

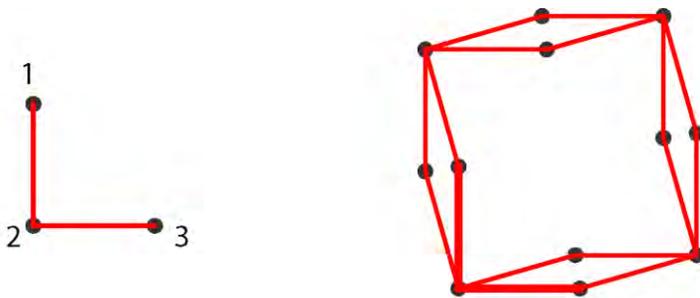
## **Principles of Kinetic Design: Underlying Geometries and Overlaid Patterns**

Motion has a strong bond with geometry because at its core, motion is the spatial transformation of one geometric configuration into another [1]. The underlying geometry of any kinetic structure can be described as the geometry of motion. It is a fundamental element in geometric thinking and the general concept of motion. Motion geometry traces the positions of different components to reveal the relationships among them.

Every kinetic design has three main components: kinematics, materials, and behaviors. Kinematics refers to the geometry of motion without consideration of the causes of that motion. It deals with the geometry of motion on its own, isolated from the forces associated with movement [2]. Kinetics, by comparison, is the study of the causes of motion. Each kinetic design has three fundamental design parameters, including kinematic, or the geometry of motion; material, or the

physical properties; and behavioral, or time-based control of motion. In this research, the main focus is on kinematics. In developing kinetic tessellations, the primary category of knowledge the designer must master is kinematic knowledge.

There are three main elements in kinematic design: 1) linkage, 2) joint, and 3) point of connection to the ground [3]. Linkages are rigid bodies that transfer force through a kinetic structure. Joints are the connections between bodies that define constraints on the movement of the kinetic structure. Finally, points of connection to the ground are the static points of reference for the entire kinetic structure. In this research, we explore kinetic tessellations with one degree of freedom.<sup>1</sup> For example, in Figure 1, the red “L” shapes are linkages and the black dots are joints. In the depicted kinetic polygon, any of the joints could be considered the points of connection to the ground.



**Figure 1.** Linkages and joints. The linkage on the left, the whole L shape is rigid, and does not bend at point 2.

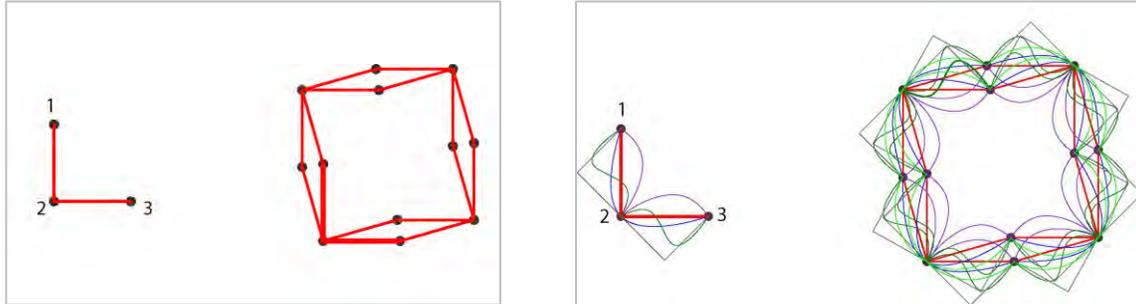
The authors of this research has coined two terms to help designers understand and design simple kinetic geometries. In any kinetic design process, there are two design efforts: the generation of an *underlying geometry* and the creation of an *overlaid pattern* [4]. The underlying geometry of any kinetic structure can be described as the design’s geometric constraints on motion. Here, the geometry of pure motion is considered without reference to force or mass. A transformation in the underlying geometry of motion outlines the relationships among elements, their arrangement, and the final layout of the motion composition regardless of certain values such as the dimensions or shapes of elements. By manipulating the positions of the endpoints and shifting the locations of the connectors where the elements intersect, a new set of motion compositions can be constructed.

In spite of maintaining geometric relationships among the various elements of a motion composition, a transformation in the geometry of each element could result in changes to the overlying geometry. The overlying geometry, however, is a secondary issue compared to the underlying geometry. Transformations in the overlying geometry are the result of manipulating the applicable ranges of values for different variables. By modifying an element’s proportions, adding additional elements, or altering the shape of an element by adding another given shape, the composition may have a familiar structure but with a different appearance, thus generating another design.

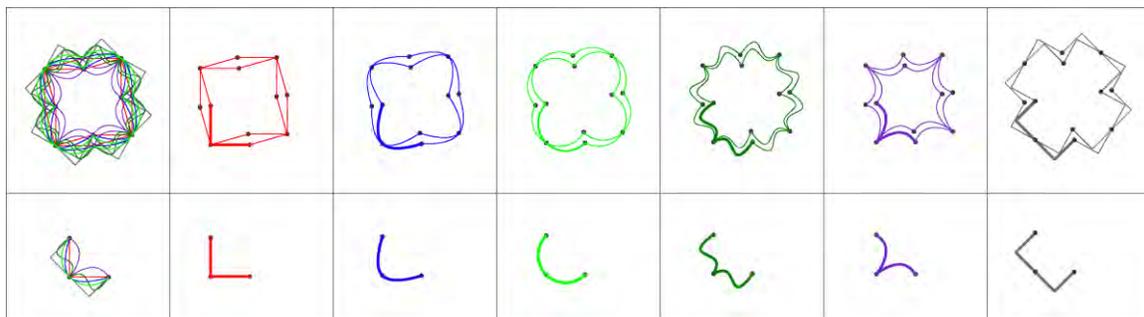
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<sup>1</sup> Degree of Freedom (DOF) is the number of independent motions that the body is allowed, or in the case of a mechanism made of several bodies, the number of possible independent relative motions among the various pieces of the mechanism [5].

In Figure 2, the left box presents the underlying geometry of a simple kinetic polygon, and the right box shows the five other possibilities of the overlaid pattern for this kinetic polygon. In other words, any linkage connecting points 1, 2, and 3 could be an overlaid pattern for this kinetic design. The geometrical integrity of this kinetic polygon will be maintained if the three points are connected with a rigid body of any shape. Therefore, the underlying geometry of motion can produce endless kinetic patterns simply by changing the overlaid design (see Figure 3).



**Figure 2:** Underlying geometry (left) and overlaid pattern (right).



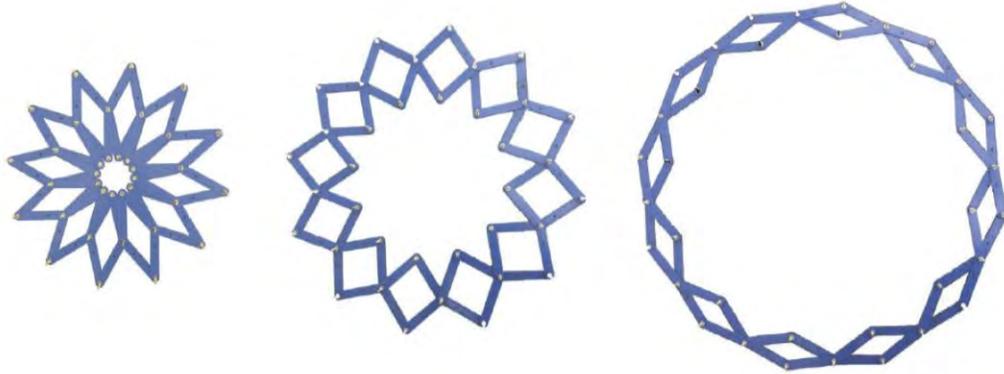
**Figure 3:** Different kinetic polygons with the same underlying geometry.

### Design Principles of Kinetic Polygons with Scissor Linkages

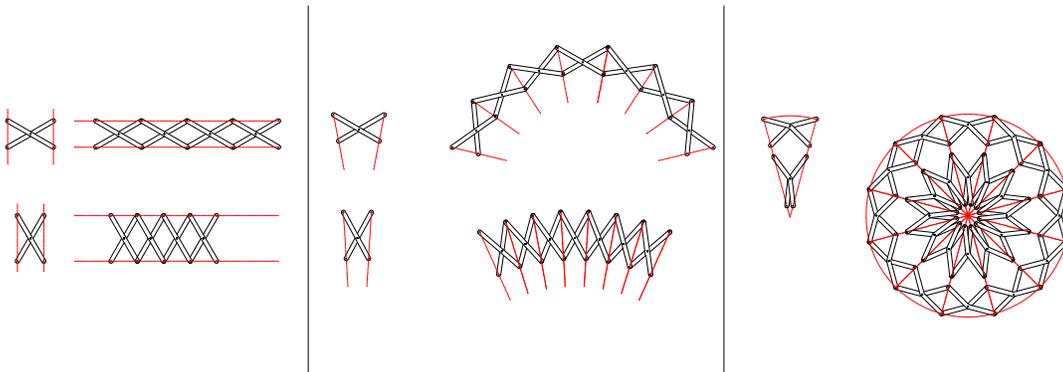
In this section, we present a methodology for designing regular and irregular kinetic polygons. The kinetic polygon is based on scissor linkages (see

**Figure 4**). An historical example of a scissor mechanism is the deployable structures of Sergio Pellegrino [6]. Later, Felix Escrib, P.E. Kassabian, Zhong You, and Chuck Hoberman all extensively expanded scissor structures [7]. Generally, there are three types of scissor linkages (see Figure 5):

- 1- Parallel scissors (center connection) that provide no curvature in the kinetic structure;
- 2- Parallel scissors (off-center connection) that provide a variable curvature; and
- 3- Angulated scissors that provide a constant curvature.



**Figure 4:** An example of a kinetic polygon.



**Figure 5:** Three types of scissor structures: Parallel scissors – center connection (left), Parallel scissors -off-center connection (middle) and Angulated scissors (right)

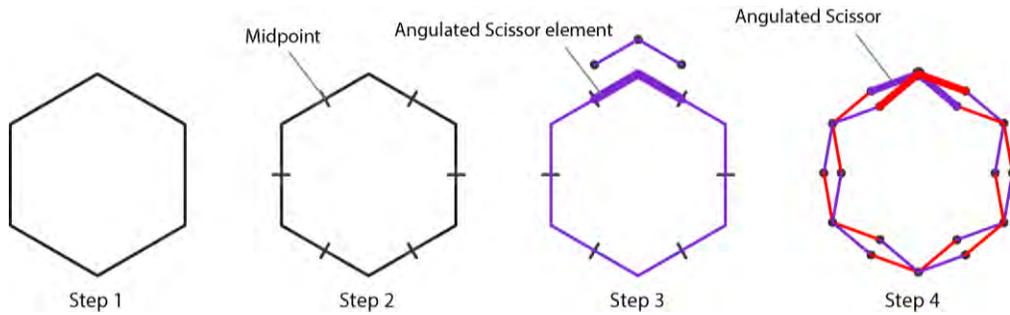
### Angulated Scissors Linkages

Angulated scissors are an alteration of the original scissor concept that consists of bending the rigid elements to achieve a desired angle and form polygonal shapes not possible with straight scissors. With angulated scissors, it is possible to design kinetic geometries for all types of regular and irregular, convex and concave polygons. The design process for kinetic polygons includes the following (see Figure 6 and Figure 7):

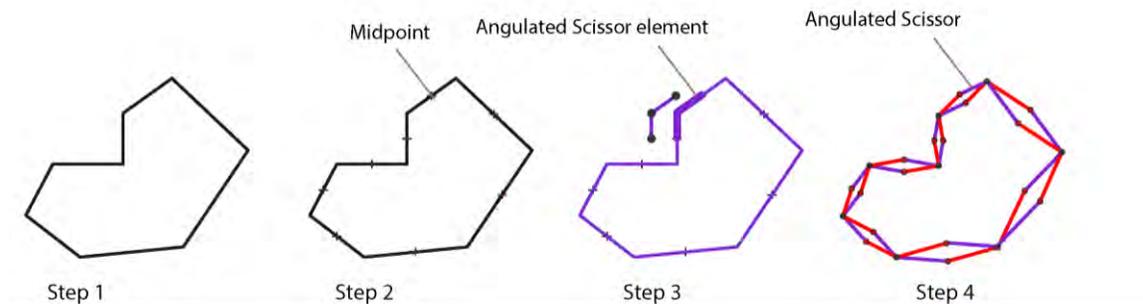
- 1- Draw a polygon with any number of sides;
- 2- Define the midpoints of all sides;
- 3- Draw an angulated polyline between every vertex and two neighboring midpoints.

This polyline is an angulated scissor element; and

- 4- Pair each angulated scissor element with the same element and connect them together.



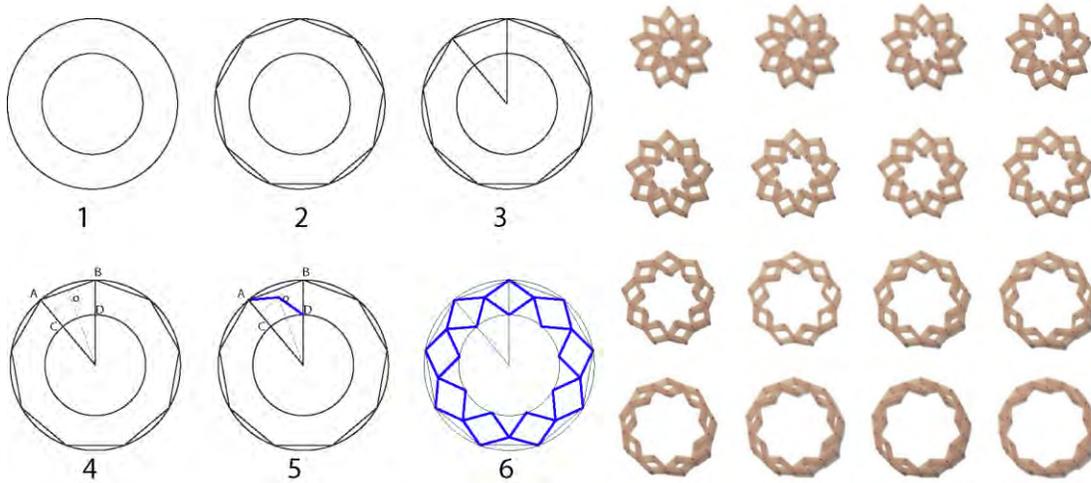
**Figure 6:** Design process for a regular kinetic polygon.



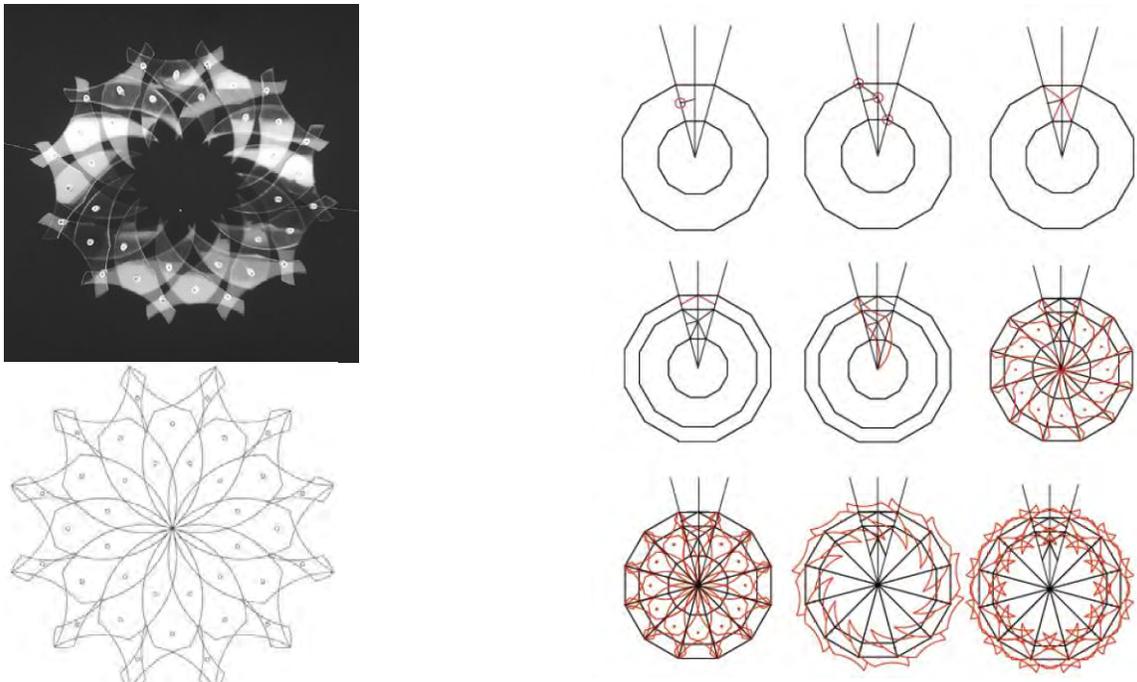
**Figure 7:** Design process for an irregular kinetic polygon.

There are different methods for designing kinetic polygons. Figure 8, Figure 9, and Figure 10 present additional approaches (geometric and algebraic) to designing angulated scissors for kinetic polygons. However, in the author's opinion, the following method is the simplest.

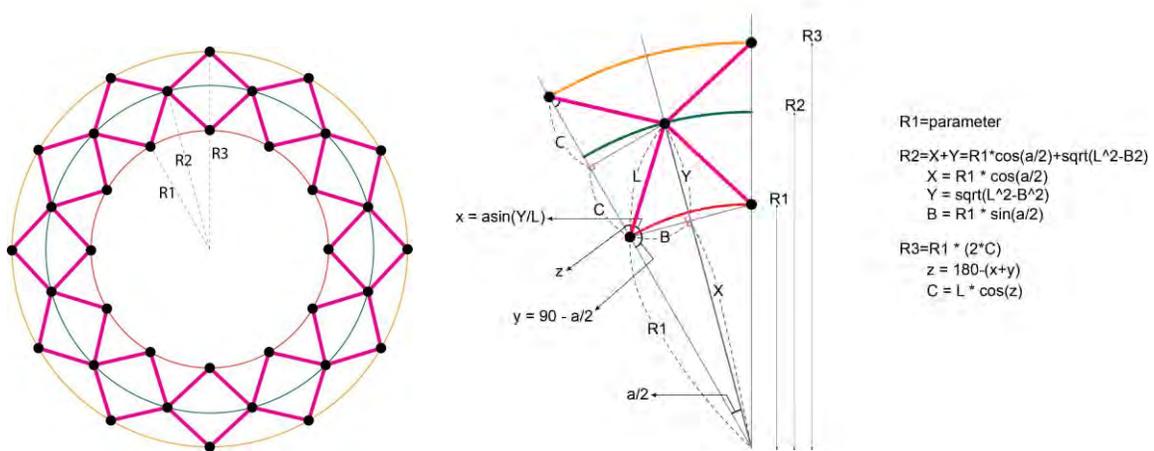
- 1- Draw two circles, same center.
- 2- Draw an inscribed polygon inside the larger circle.
- 3- Draw two adjacent radii to define a section of the polygon.
- 4- Draw two perpendicular lines at the midpoints of Segments AB and AC, the intersection of these two lines defines the location of point O.
- 5- Draw an angulated polyline between points A, O, and D.
- 6- Mirror the angulated element (AOD), and then array the points to design the kinetic polygon.



**Figure 8:** A geometric approach to designing the angulated scissor structure used in a polygon.



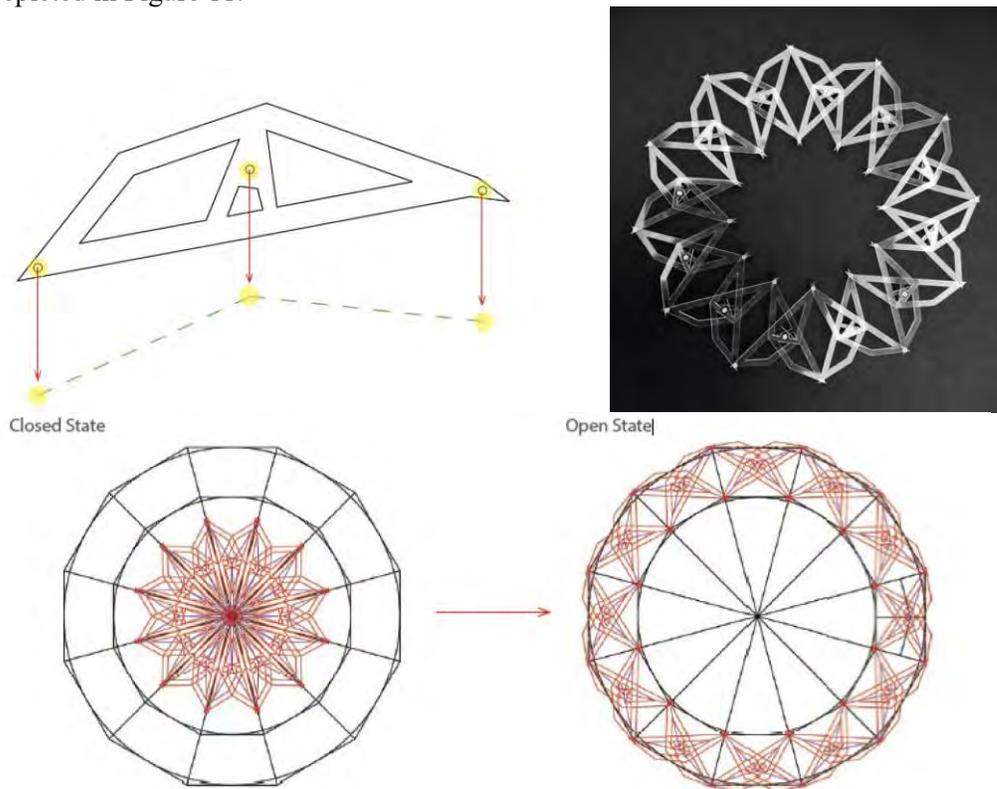
**Figure 9:** An overlaid pattern applied after designing the underlying geometry. The acrylic model of the kinetic pattern (left). The process of designing the overlaid pattern (right).



**Figure 10:** An algebraic approach to defining the angle of an angulated scissor.

As discussed above, the underlying geometry is the key to movement. After finding the underlying geometry, a designer can design an unlimited number of overlaying patterns. Although there are limitless possibilities, collision is one constraint that must be checked.

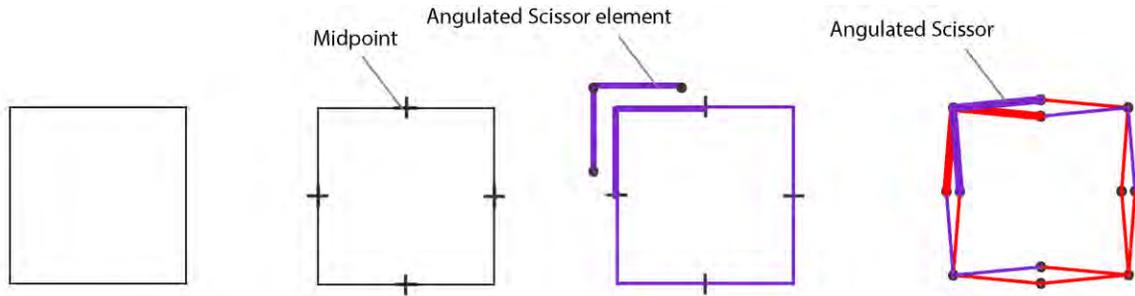
In order to make sure that a specific shape will work with the tessellation, the geometry should be rotated from a closed position to an open one. This is shown in the technical drawings depicted in Figure 11.



**Figure 11:** To avoid collisions, the geometry should be rotated from a closed position to an open one.

## Reconfigurable Kinetic Tessellations

The full depth of the motion design process cannot be understood by theory alone. Therefore, to achieve a better understanding of the design process and the internal and external factors that craft a motion composition, we designed and fabricated a series of Reconfigurable Kinetic Tessellations named L8 that offer a variety of kinetic compositions. L8 is a series of magnetic-kinetic simulators comprised of eight pieces that can be assembled in multiple configurations. L8 is generated from a four-sided polygon (see Figure 12).



**Figure 12:** The underlying geometry of L8, generated from a four-sided polygon.

One of L8's innovations is the use of magnets as pivot points for the kinetic patterns. Generally, when fabricating kinetic models, we use screws and nuts to connect the linkages together.

In contrast, L8 has a strong permanent magnet housed internally within each of the three vertices of the block, all at approximate right angles to one another. These internal magnets are not directly accessible to the user, but they allow the magnetic connections to pivot with similar blocks or other magnetic parts. One of L8's most critical aspects is that the internal magnets act as pivoting hinges for different kinetic patterns. The use of internal magnets provides a relatively simple and cost-effective method for attaching multiple components when using materials that can be produced through extrusion or molding operations.

We explored different methods of fabricating elements, including a laser cutter, lamination, 3D printing, and injection molding. Interestingly, L8 was designed for a specific kinetic pattern (see Figure 13); however, because of the embedded magnets, we discovered that countless kinetic patterns were possible by assembling and disassembling the blocks for different compositions (see Table 1).

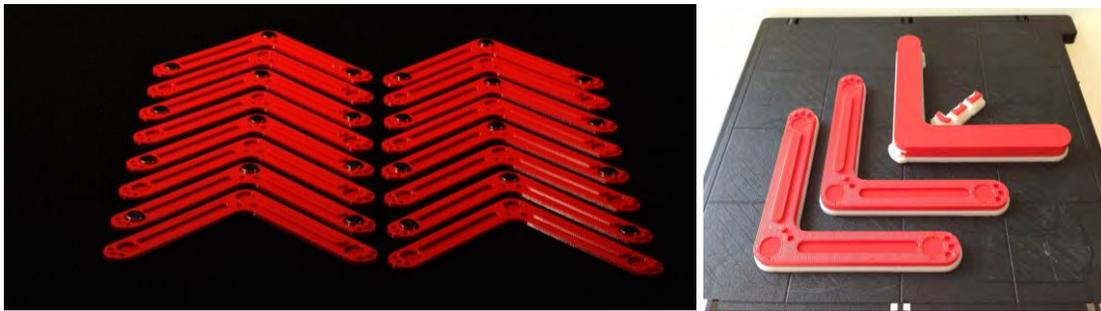


**Figure 13:** Basic L8 based on the pure underlying geometry. Here, the linkages are not purely 2D. The links occur in at least TWO different layers.

The magnets allow for universal magnetic connections to be made with similar members or other magnetic elements. The spacing of the magnets permits a variety of shapes to be made and substantial flexibility when multiple members are connected. Thus, the magnets act similarly to joints, connecting all of the members. The poles of these magnets in every L block are of same polarity. Therefore, you can stack all L blocks from one side. Figure 14, 15, and 16 show different fabrication methods of embedding magnets inside the blocks.



**Figure 14:** This block is made of wood and has smooth surfaces. Each block is .62 inches wide, 3.6 inches long on each side, and .15 inches thick. Each module consists of three layers (two thin veneer layers on top and bottom and one 1/16 inch thick piece of plywood as the middle layer). All layers were laser cut and laminated together to hold three magnets inside the module.

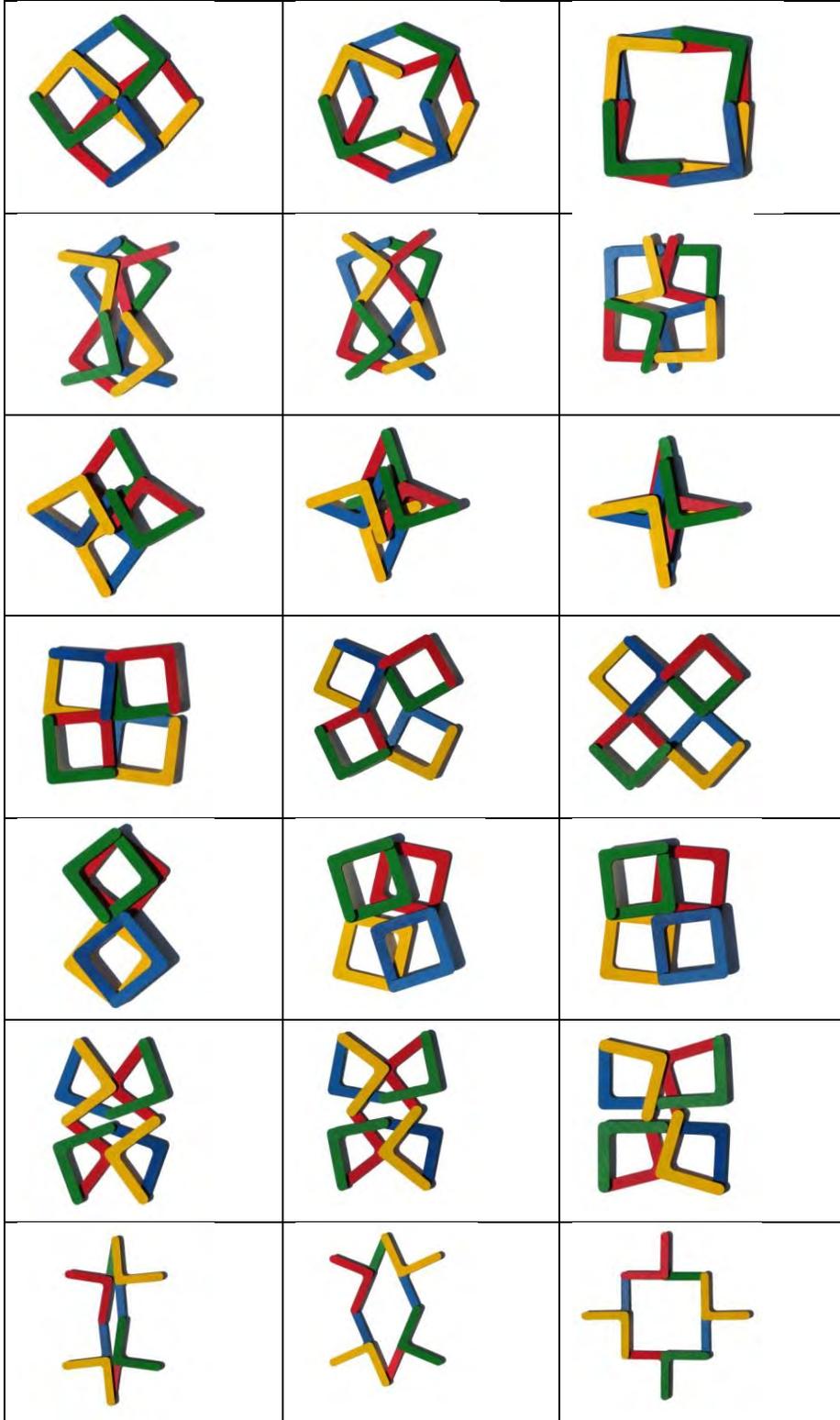


**Figure 15:** 3D-printed L8 modules.

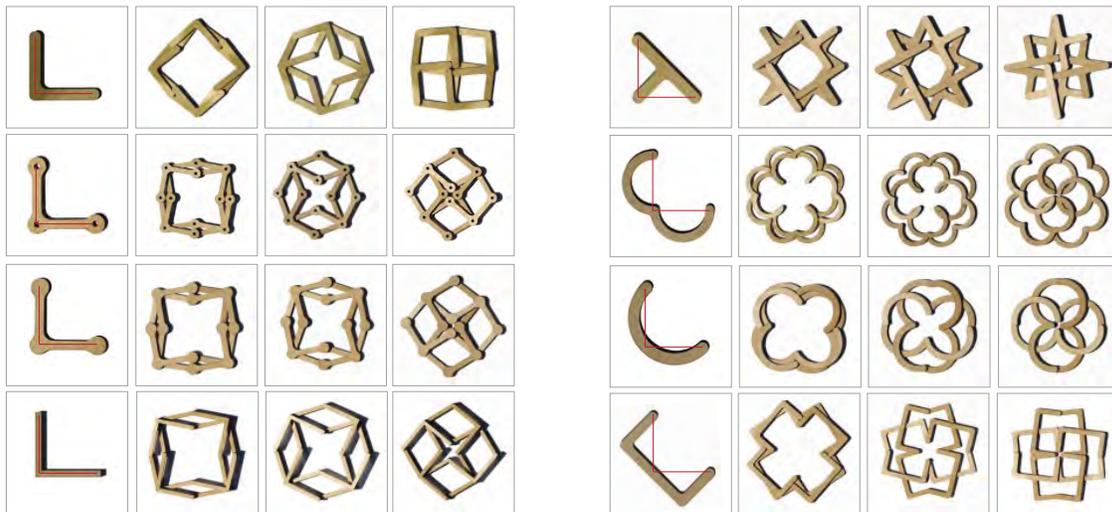


**Figure 16:** Injection-molded parts for mass production. The two caps are the same modules. This was done to decrease the cost of fabrication. After embedding the magnets, the plastic parts were welded together.

**Table 1:** Eight different kinetic L8 compositions. Rows 1,2,3 and 6 have 8 actively turning pivots, while others rows have only 4 actively turning pivots (rows 4, 5, and 7).



The three vertices of the “L” act as a foundation for numerous other shapes, such as circular, elliptical, polygonal, and the like. As discussed as it relates to underlying geometry, in L8, the three points are the most crucial parts of the tessellation. As long as these points remain precisely in the correct positions, most shapes can be overlaid to create a variety of compositions. We implemented this rule to facilitate the design of different overlaid patterns such as circular, “T”, and “U” shapes. Although they look different, all of these shapes have three magnets in the same locations. Each group of magnetic members generates various forms of the same kinetic geometric composition. Since the location of the magnets remains the same, each set can be mixed with other sets to make interesting compositions (see Figure 18).



**Figure 17:** Different overlaid patterns from the L8 design.



**Figure 18:** In L8, the locations of the magnets are the same; therefore, each set can be mixed with other sets to make interesting compositions.

One of the purposes of designing the kinetic simulator we call L8 was for its educational value; it allows users to play with geometry without having to understand important underlying principles. The units are color coded to make variously colored geometric patterns and simplify the process of assembly (Figure 19).

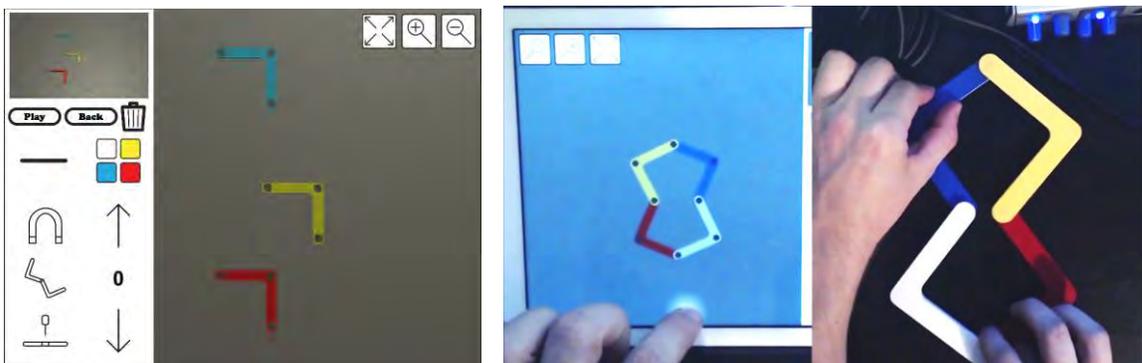


**Figure 19:** L8 as an educational toy.

### Future Work

We are collaborating with the computer science department<sup>2</sup> at Texas A&M University to digitize the physical mechanism in L8; this will help future users to learn about linkages, joints, kinematics, degrees of freedom, and the geometry of motion. Exploring these functions will also assist designers in understanding kinematics and developing ideas regarding the physics of how objects move and act in a system.

Our prototype was built in Unity3D for iPads running iOS 10 or later. We simulated the kinematics by using a combination of Unity Fixed and Hinge Joints; the user can interact with these joints by touching and dragging with one or two fingers on the iPad. The final result will be an application that behaves like the physical version but in a way that is more precise, because the prototype will remove the possibility of pieces connecting that aren't adjacent to one another and eliminate the limitation of repelling magnetic poles (see Figure 20).



**Figure 20:** L8 application prototype: a kinetic application for iPads developed by Kyle Purser, Conner Flatt, and Kyle Rowland.

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<sup>2</sup> Dr. Dylan Shell from the Department of Computer Science at Texas A&M worked with the authors.

## Conclusion

In this research, we introduced three methods for designing kinetic polygons that can be applied to any type of closed 2D geometry, such as regular/irregular or convex/concave polygons. We also presented a series of reconfigurable kinetic tessellations called “L8” that was designed and fabricated to explore the possibilities of kinetic motion compositions. Finally, we introduced an application still in development that digitizes L8’s physical mechanism. We believe it will help others learn about linkages, joints, kinematics, degrees of freedom, and the geometry of motion.

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