Modeling Emergence:
Playing with Bio-inspired X-motilitY Structural Systems

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Abstract

The workshop will be a discussion of both motions and forces in Nature with geometric models. We will be modeling a novel "X-motilitY" bio-inspired structural system that combines the internal and external forces to demonstrate the transfer of energy within the structures themselves.

Modeling Emergence

One goal of this workshop is to demonstrate the value of modeling as a vehicle for learning, observing, sensing and analyzing structure & function. The activities will illustrate how Nature builds up efficient, sustainable and resilient structures as interactive, adaptive systems.

Modeling often leads to discoveries, by first observing the emergent, unexpected behaviors as external forces act upon it to transform its geometric structure. The Clinton "I Wonder" process leads to "what if" (I try this …) questions which creates a continuous, interactive flow for exploring bio-inspired structures.

In the first half hour of the workshop, we will examine pre-made models and the behaviors of the structures. We will observe the motions caused by forces which are controlled by the geometric constraints and material properties of these models. In the last hour of the workshop, participants will build and play with their own X-motilitY structures to experience the propagation of the forces for themselves.

Scale invariant natural structures are resilient to inner and outer forces and behave as a whole system (Figure 1). In each of these biological levels, Nature uses structural and material strategies to gain resilience, resulting in dynamic equilibrium.

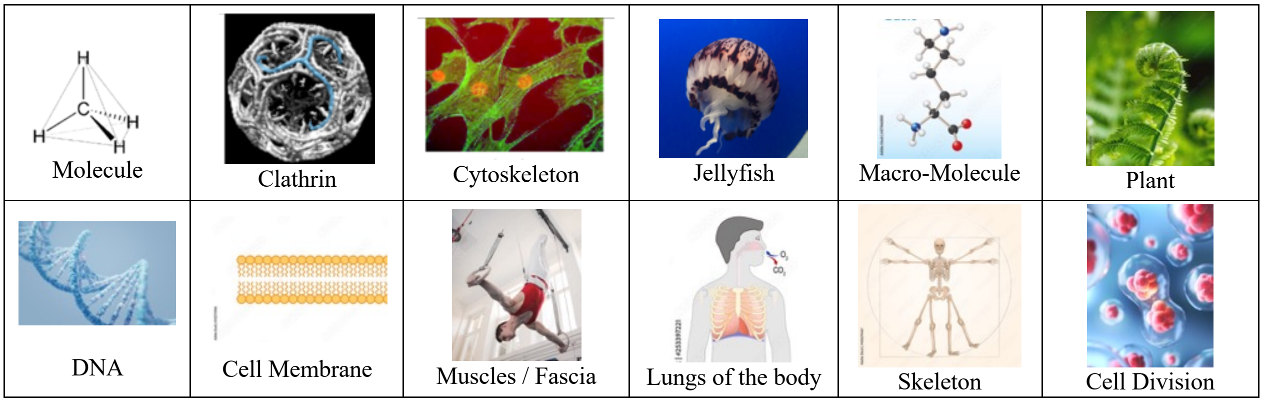

Molecule
Clathrin
Cytoskeleton
Jellyfish
Macro-Molecule
Plant
DNA
Cell Membrane
Muscles / Fascia
Lungs of the body
Skeleton
Cell Division

Figure 1: *Examples of natural whole systems at various scales*

In our physical world, every element, whether living or non-living, possesses structure. It is essential to understand the structural order, the sequence of elements, the system as a whole, and how structures react to internal and external forces. By delving into the interrelated nature of these components, including their natural state, we gain insight into Nature's dynamic, self-generated behaviors, resulting in motility.

Motility is the ability of an organism to move independently, such as bacterial flagella that generates the movement of the whole system. We named this novel structural system, X-motilitY. The behavior of whole systems emerges from the constraints defined by their structural and material properties. Motility structures take on different shapes, depending on the location and direction of the internal and external forces.

In Nature, we observe various types of motion across different scales and levels. Natural structures respond to the direction of the external forces by absorbing, storing, and redistributing them, while internal forces contribute to kinetic or motile behavior (Figure 2).

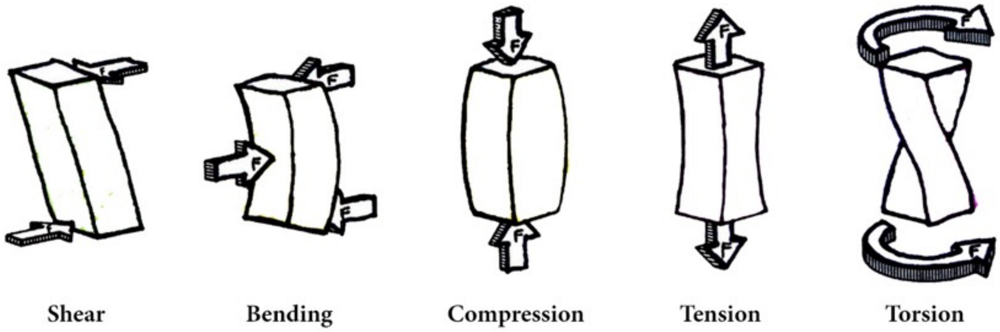


Figure 2: *The direction of forces that are impacted by the material properties*

In Table 1, we classify six different structural systems with unique characteristics: rigid, semi-rigid, tensile, transformable, kinetic and motile. We will present and play with models that represent the structural and material properties with the forces applied.

Table 1: *Properties of dynamic structures from the jitterbug to X-motilitY structures*

Rigid	Semi-Rigid	Tensile	Transformable	Kinetic	Motile
					
Shear, compression	Shear, Bending, twisting	Tension, torsion Harmonic Resonance	Torsion, twist	Shear, twist	All

We will present a series of dynamic models, including Buckminster Fuller's "jitterbug." As external forces are applied to the pre-made models, inspired by various artists and outlined in Table 1, participants will perceive the transformative behavior of the entire systems. Through bio-inspired play, we will observe different geometric states and receive tactile feedback corresponding to forces constrained by the five material properties (compression, tension, bending, torsion, and shear). These properties direct the propagation and balance of forces within the systems themselves. During the workshop, participants will experience "Aha" moments as they sense forces along face, edge, vertex, or vector directions. This imparts a visceral understanding of forces such as shear, bend, torsion, compression, and harmonic resonance, stemming from the three-dimensional properties of the models.

Structure is a dynamic form that adjusts in response to the larger whole, contributing to the overall information of the system. Joseph D. Clinton`s statement, “structure generates form and form has structure” underscores Nature's lessons in structural efficiency. In Nature, the correlation between form and function is a fundamental principle, with various functions giving rise to different forms and geometries.

In order to understand the complex behaviors of Nature in a concrete-to-abstract way, we need to experience structural processes through modeling that engage all of our senses in order to analyze the structural system constraints and material properties. We will ask "how and why" Nature uses strategies such as symmetry transformations, structural order, spherical configurations, close-packing, expansion, contraction and resilience for efficient outcomes.

The Bio-inspired X-motilitY System

The X-motilitY system is based on spherical and rotational movement of its components relative to the axes of edges, faces, vertices and vector directions. The system reacts to internal and external forces and the vertices act as the energy centers [1] that enable the structure to transform. The emergent behavior of the system is maintained by the geometric constraints which still remains a subject of on-going research and exploration, included in this workshop. The unique emergent behavior of the system is a result of the material properties and structural composition.

In the language of physics, points, lines, planes and solids cannot share a common position in space without interference with each other. They must accommodate one another. For the structural system, the components need to have three dimensional definitions. We will define the point as a sphere and the line as an extended cylinder as the physical geometrical elements (Figure 3(a)). The basic unit of this cube is an extended cylinder with spherical endings. There are the two rotational constants for the structure. One is when two extended cylinders are tangent to each other with a rotational motion at their middle points. The other is when the spherical endings of the cylinders remain tangent throughout their rotations around each other (Figure 3(c)).

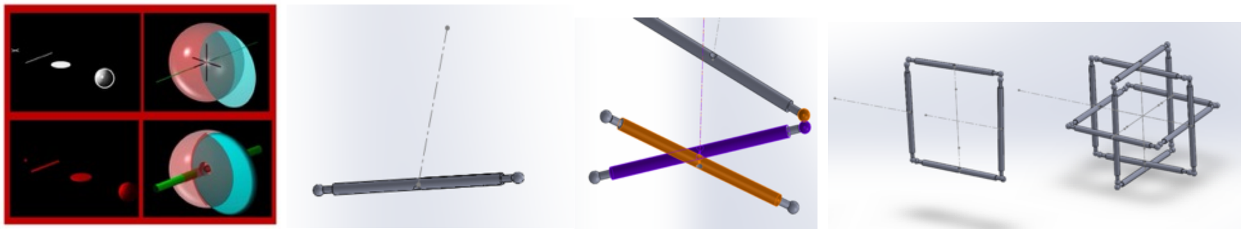
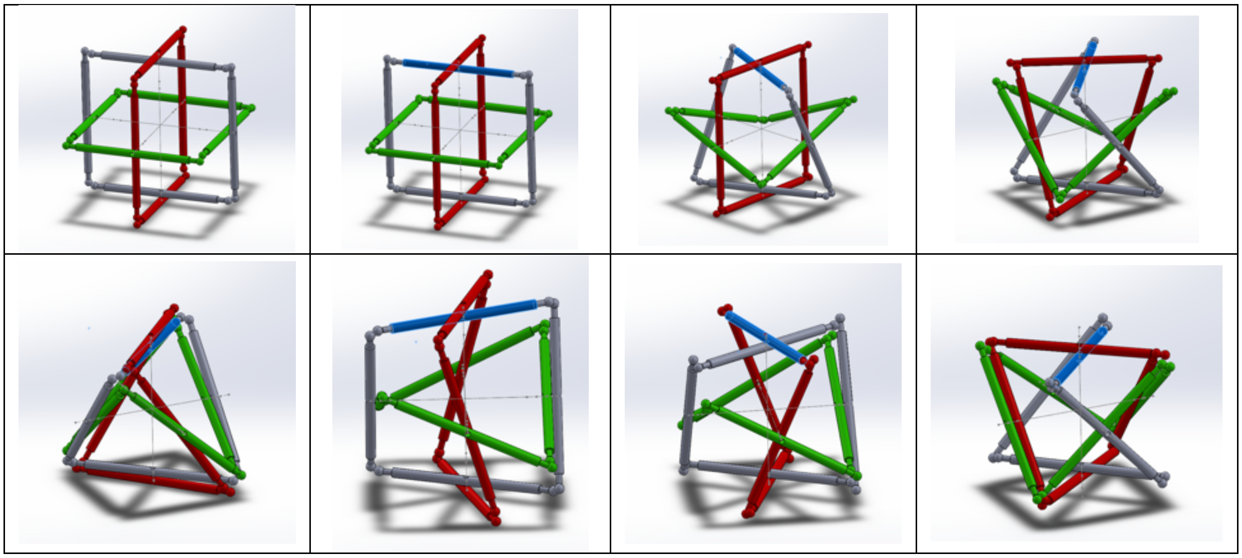

(a) (b) (c) (d) (e)

Figure 3: *(a) Mathematical and physical languages illustration, (b) point: (dynamic vertices, joints, spheres), the basic unit, line, (edges, rods, extended cylinders), (c) the relation of the basic units, (d) plane (sur/faces, shapes, vectors), (e) spheres, volumes, geometric states*

Melodi`s Cube is the basic structure that illustrates the X-motilitY system with its configurable geometric constraints. Mainly, the structural system is built with 12 identical basic units, six rotational axes and twelve dynamic points (the point of the intersection of two spheres) at the end of the units (Figure 3(c)). The midpoint of the basic units are their rotation axis, and the two units merge together in a relation of under and over. When the 12 basic units are woven as shown in Table 2, the system emerges with a 3-dimensional behavior that affects the motion of the whole structure. As a unique case of the structure, when all the rotational axis are aligned exactly at XYZ coordinate system, Table 2 shows the states of the structure under force. When the blue unit is rotating along its rotation axis, the force is distributed to all parts and the system transforms from a cube to a double-tetrahedron or as a single tetrahedron with one degree of freedom.

The system transforms into various geometric states: a one-rod length linear structure, a two rod length linear structure, XYZ axes constrained structures (Table 2) and/or other unique structures.

Table 2: *A unique case of the X-motilitY system*



We will explore the whole-to-parts relationships through modeling to observe and analyze how the properties of structure (joints, proportions) and materials affect the behaviors of the whole system. Geometric constraints dictate the dynamic equilibrium that emerges within the structure, defining its natural states and sequences as it transforms into different geometrical configurations. We use 20cm bamboo straws for the rods, three 85cm elastic threads for the flexible joints and 2mm nuts and bolts for the rotational joints in order to build up the model as shown in Figure 4.

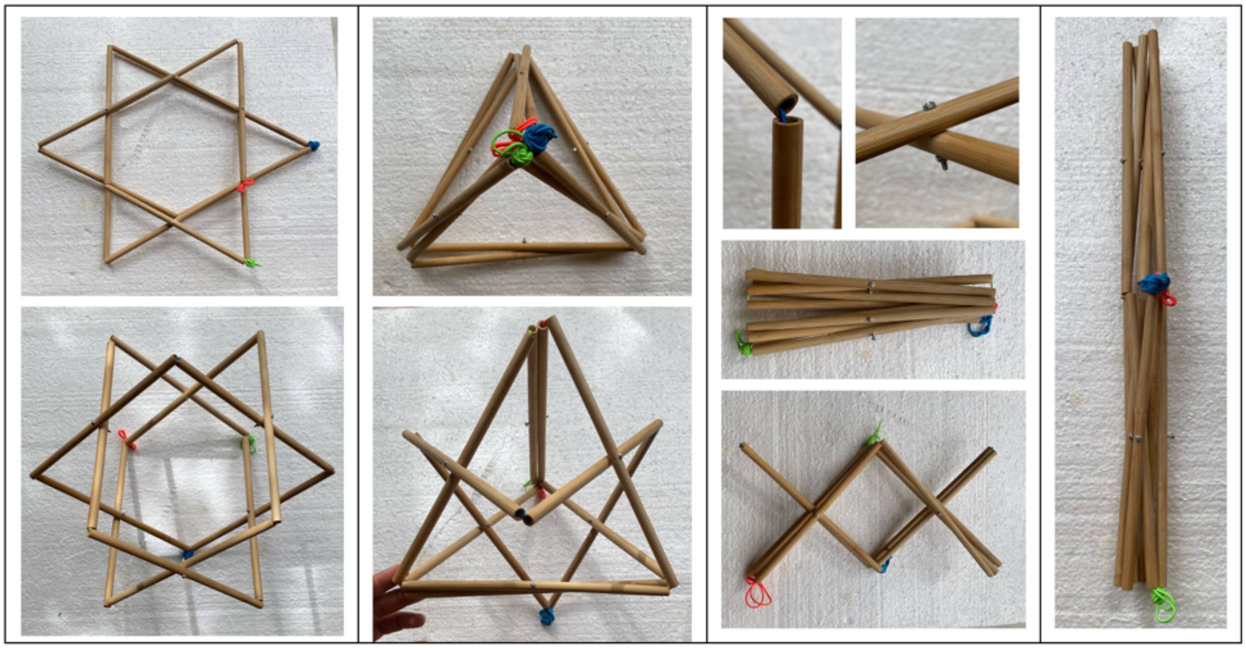


Figure 4: *The model with the identical 12 bamboos, 6 small nuts and bolts, 3 elastic threads.*

We can analyze the same behaviors using a computer simulation. Sequential changes to the geometric constraints can be controlled through algorithmic methods, demonstrated by Gary Doskas`s Structural Simulator. This may also unveil some of the behavior of adaptive systems.

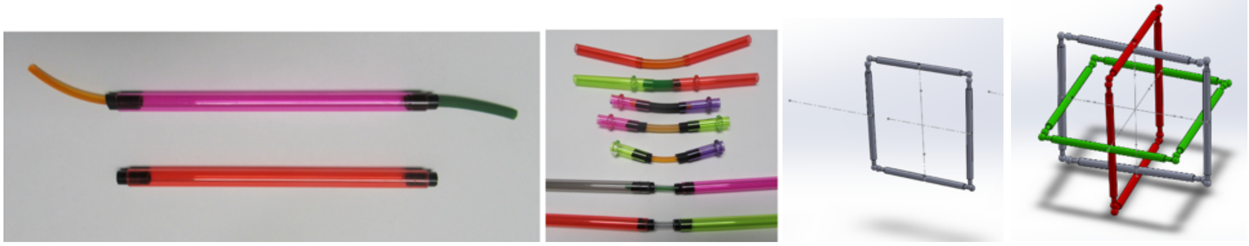
Tensegrity balances the forces of tension and compression. Motility structures employ a balance between torsional bending and twisting through a configurable geometric memory. But unlike tensegrity, when an external force is applied to the resilient structural system, it will transform itself, similar to a deployable structure. The X-motilitY structural system relies on the torsional equilibrium of its material and structural properties. It exhibits the ability to transform external forces into directed motion.

Modeling of the X-motilitY Structural System

In the following hour, we will explore modeling the X-motilitY Structure by playing with various materials and structural constraints. After making the models each participant will be given a selection of materials to choose from to customize the behaviors through "what if" experiments that allow them to tailor its behavior for different applications. These may include considerations such as weight bearing, weight sensitivity, jumping ability, agility, and efficient material usage. Ample materials will be provided to ensure that each participant can create at least one basic X-motilitY Structure. The materials used in the construction of X-motilitY Structures are: rigid straws, flexible rubber tubing and elastic bands.

First Play:

- Distribute the materials: 4 identical rigid straws, 4 identical rubber tubing will be provided for each participant (Figure 5(a)).
- Tools to prepare the materials will be provided; scissors or cutters.
- Insert flexible rubber tubing into the one end of each one of the rigid straws as in Figure 5(a).
- Connect 4 straws in a closed loop to make the green plane in Figure 5(c).
- Play with the plane.



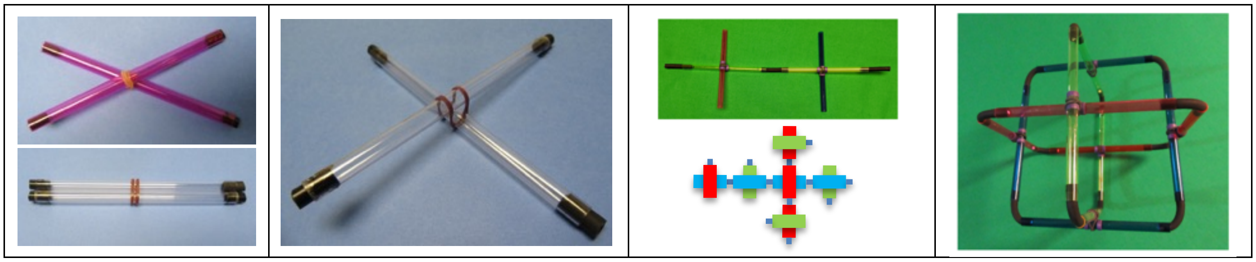
(a) (b) (c) (d)

Figure 5: *The X-motilitY Structure elements (a) the rigid straws, (b) the variable flexible rubber tubing, (c) the plane with four-arm linkage, (d) X-motilitY geometric constraints*

Second Play:

- Distribute the materials: 12 identical rigid straws, a length of flexible rubber tubing and elastic bands in various sizes will be provided (Figure 6(a)).
- Form the X component by binding 2 rigid straws together with elastic bands. This sets the rotation position to 90 degrees in the first X component (Figure 6(b)).
- Proceed to make six X components.
- Cut the flexible rubber tubing into 12 pieces with the same length (approximately 4 to 6 cm).
- Weave as shown in the net diagram (Figure 6(c)), in an under-over relation. Connect the whole structure by inserting the flexible tubing at each end of the connections (Figure 5(d) and 6(d)). Pay special attention to the woven nature of the interleaved square loops regarding the rigid straws inner or outer location within the X component.
- Now, time to play with the first X-motilitY model (Figure 6(d)).

Questions: What are the behaviors of the structure that you experience during this bio-inspired play? Do you see these kinds of behaviors in Nature (such as the jumping of a frog, the movements of a fish`s mouth or the beak of the bird)?



(a) (b) (c) (d)

Figure 6: *The X-motilitY Structure (a) the X component with elastic band at 0 and 30 degrees, (b) the X component with elastic band at 90 degrees, (c) the net and the model showing the under-over weaving, (d) the X-motilitY neutral state with 90 degree X components.*

Third Play:

We will experiment with the changes in the joints that have different torsion properties. These changes will result in the new emergent behavior of the X-motilitY Structures.

- In this play we will make experiments based on the following suggestions to explore three different torsion properties of the flexible rubber tubing, different size elastic bands and binding techniques of the X component (Figure 5(b) and 6(a)).
- Choose one of the following suggestions:
  1. Change the rubber tubing materials with different elasticity that connect the X components together.
  2. Change the strength and the size of the elastic bands, the number of twists or sizes of the elastics on the X components by doubling or tripling the elastic bands.
  3. Change the binding techniques to change the rotation angle of the X component.
- Take notes for follow up discussion regarding the changes made and the resulting behaviors.
- Play with your new versions of the X-motilitY Structures.

Questions: Do you observe the accommodation of motility in Nature (such as the muscles when you move your body or the molecular movements within DNA)?

Once fully assembled and played with, the participants can then experience the tactile dynamic motion of the skeletal framework of the X-motilitY system. The question "what if" may lead to the use of other torsion properties for each joint. This will influence a unique equilibrium position. For example, a soft metal could be inserted into the elbow joint to give it some rotational memory and the ability to lock the joints at one position.

Demonstration:

In this part of the workshop, we will demonstrate the use of a computer-based structural simulator to explore some of the behaviors of X-motilitY in a weightless environment. If desired, the components of X-motilitY structure will be allowed to pass through each other and angular drag and friction can be eliminated. This will display a continuous harmonic transformation of geometric states as torsion forces propagate through the joints of its structure and reaches a state of equilibrium.

The X-motilitY structure has numerous rotational states of symmetry and/or equilibrium. Two methods will be used in the simulator to describe the unique geometric states of X-motilitY (X method, E method). In the X-method, a sequence of six angles are used which represent the rotational position of the straws of the six X components. For example, the cubic equilibrium state seen in Figure 7(a) can be defined as X:90:90:90:90:90:90. An alternate E-method is based on three pairs of angles. Each pair consists of two adjacent angles from each square loop. For example, the tetrahedral state illustrated in Figure 7(b) can be defined as E:60:60:60:60:60:60. A few other geometric states of X-motilitY can be seen in Figure 8 with their associated sequence definitions.

(a) (b)

Figure 7: *The X-motilitY Structure natural geometric states, (a) the X component with elastic band at 90 degree forming a hexahedron, X-motilitY neutral state (b) X-motilitY in tetrahedral state.*

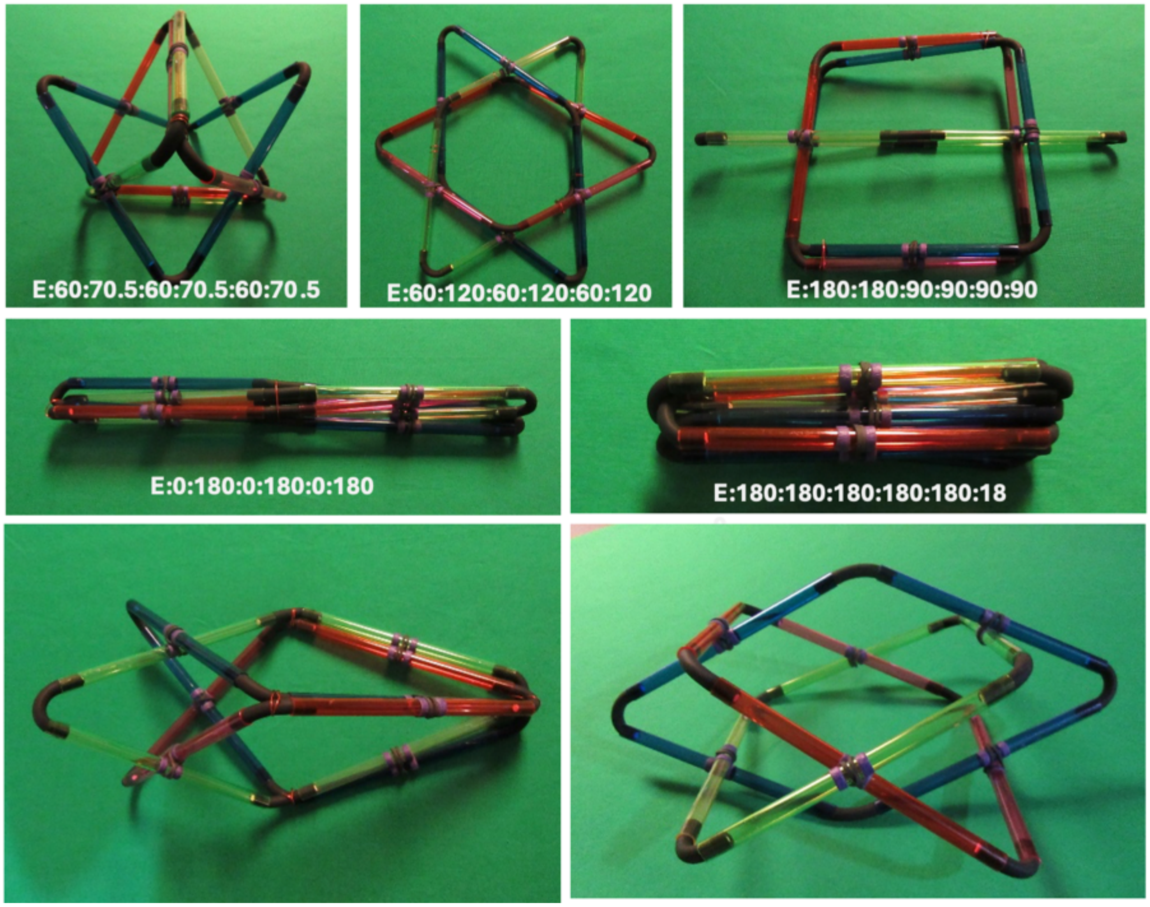
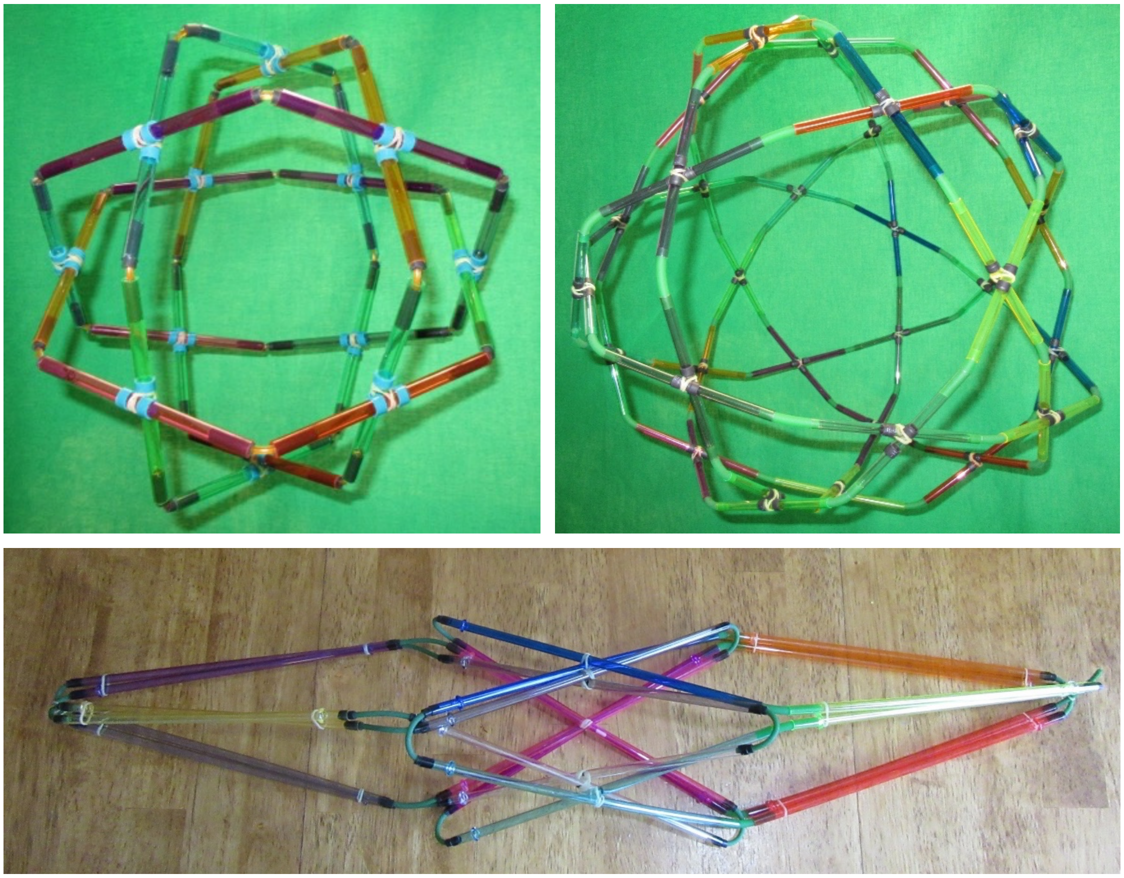


Figure 8: *Examples of X-motilitY's geometric states using the E-method.*

The joints in X-motilitY can also be motorized in the simulator, and articulation sequences can be defined to perform various structural transformations between its geometric states.

In the last stage of the workshop, we will encourage the teams to combine their structures together to form more complex structures such as the cuboctahedron, icosidodecahedron (Figure 9).



(a) (b)

(c)

Figure 9: *The Geometric States with more X components, (a) The cuboctahedral State of X-motilitY, (b) The icosadodecahedral state of X-motilitY, (c) Combination of two cubic X-motilitY.*

Summary

Through praxis and play, participants will experience the bio-inspired X-motilitY System of modeling. By engaging all of the senses, we will appreciate how these systems emulate the forces, motions and behaviors of Nature. The “I Wonder” process followed by “what if” questions will generate many more “Aha” moments. We will encourage everyone to share their Aha moments.

We will be in a state of what Albert Einstein declared “Play is the highest form of research” during the workshop.

References

[1] R. Buckminster Fuller “Synergetics Explorations in the Geometry of Thinking. ” Macmillan Publishing Co., Inc., 1975, USA.