The purpose of this paper is to demonstrate a systems modeling and design approach based on universal geometry. Systems modeling and design can be enhanced with a structural representation of system requirements (which are often written), and system models (which are often mathematical). Written and mathematical approaches show system structure, boundary, and feedback either in words or equations. In contrast, this paper illustrates systems mapping onto simple three-dimensional geometric models (e.g. the tetrahedron and the octahedron). Using this methodology ensures structural integrity of the system representation or design. Loops and feedback are made explicit, and the models encourage describing all connections between parts of the system. The techniques described here are aligned with the thinking of Buckminster Fuller, who coined the term design science to describe an integrated approach to problem solving and design of the future. Geometric systems design is one technique from the field of design science. There is an expanded version of this paper online at [http://www.tc.umn.edu/~ahler002/gsd2.htm](http://www.tc.umn.edu/~ahler002/gsd2.htm)

**Keywords**: systems, modeling, design, geometric, Fuller

### 1. The Nature of Systems

Systems science confirms that every design problem or opportunity is a system. For the purposes of this paper, a part of the world is a system if it displays the following characteristics:

- a boundary
- internal Connections or structure
- storage of material, energy, or information
- material, information or energy flows

These system attributes and their interaction give rise to system behavior. Two types of behaviors are:

- Consistency of a variable: maintaining a set-point, moving towards a goal, or cycling/looping in time
- Consistency of structure, or pattern integrity: maintaining structure despite environmental changes

The set of system characteristics can be modeled graphically by a tetrahedron as follows:

![Figure 1](#)
2. The Structure of Nature

When a systems model is made, portions of the system are abstracted from the real world, and a representation is made of those parts. There are many ways to do this -- descriptions or specifications can be written, or mathematical equations can be defined to predict system behavior. In all cases, those parts of the system which are important are described. This is similar to the seven blind men describing an elephant (the first blind man grasped a leg and thought the elephant like a tree, another grasped the tail and thought the elephant like a rope, etc.)

In many cases, only a few system variables are picked, and a loop is described. These are the properties of interest, and the model concentrates in this area. However, even the simplest system may have several loops and behaviors. As a result, system models and designs can be ineffective. For example, an intervention in one area may be counteracted by system behavior arising in another area.

So how can system models be improved? One approach is to examine the research on the organizing principles of nature. It would make sense if system models use the same structure that nature uses.

From examinations of natural or universal geometry, Fuller (Fuller, Sect. 620.05) determined that nature’s minimum structure is the tetrahedron. Why is this the simplest geometric model? To review basic geometry: one point is singular, two points define a line, three points define a plane. Four points are the fewest required to define an object in three dimensional space. Four points arranged equidistant to one another define a tetrahedron.

The universal geometry described by Fuller starts with that simplest object -- the tetrahedron of Figure 1, and proceeds to the octahedron, icosahedron, and dodecahedron (Fuller, Sect. 610.2.)

Along with being simple, universal geometry is economical. Nature (in the form of evolution) favors those systems that need the least energy to maintain, and are the strongest in the face of external changes. For example, in a tetrahedron each node is connected to all neighboring nodes, so force applied to one node is evenly distributed around the structure.

Fuller directly mapped system onto structure (Fuller, Sect. 400). His idea can be utilized in system modeling by mapping each relevant part of a system onto a node. Note that Fig. 1 maps system characteristics onto a tetrahedron, showing all possible connections. In addition, all possible loops can be defined as paths over its edges. This is a simple yet powerful model.

Figure 2 shows the combination of system attributes and behaviors. Note that in the octahedron, each node is connected to only four others. There are six nodes in the octahedron, so there are some connections implicit (internal to the structure) to tie each node to the fifth one.

This approach of mapping system to structure has been discussed by other authors. For example, Fuller’s ideas on the correspondence of structure to system has been re-stated by Urner; the idea of tetrahedron as system is used in the Tetworld Game (Siegmund); and tetrahedral modeling has been used for management issues by Prasad Kaipa (Mithya.)
3. Making a Geometric Model

So how can a system in the real world be mapped into/onto a geometric object? First, remember that systems exist because they "stick together" in an organized fashion. To make a geometric model of a system, the first step is to:

1) Figure out what parts of the world fit within the system boundary and how they are connected. A related question: What keeps these things "stuck together" in the current state?

If the situation requires fixing a problem, or designing for an opportunity the next step is:

2a) Design a new way to change the behavior of the structure or
2b) Stick the pieces together in a new way

Once this is defined the final step is:

3) Plan a path to get from here to there.

The examples illustrated by Fig. 1 and 2 are system models at an abstract level. This high level representation shows how system properties interact. The system boundary determines structure (in part) while the connections enable flow. Each system attribute interacts with each other one.

This same modeling method can be used to document any given system. At each node, a major component of the situation is placed, instead of a high-level idea. For these models, the nodes can be visualized as
the stuff of the "real world" -- that which would remain if time were stopped. If a quantity of something can be measured in this moment, then that something should be placed at a node. In the language of systems dynamics, the node represents a stock or an accumulation.

If something has accumulated, it must have come from somewhere! In geometric modeling, the increases and decreases at a node occur via the edges or connections that join the nodes. Once the nodes are defined, the flows that increase or decrease the quantity can be identified. The edges can also be visualized as pathways for energy or information (particularly if the nodes store energy or information.) The process can be continued to define material, energy, or information loops between nodes.

The basic procedure will be to identify system components, place them in a regular structure, and then examine how the components are "stuck together".

4. Stopping Time

To make a model, the pieces that make up a system need to be defined. There are many ways to accomplish this. A group of people can get together and brainstorm, or experts may be called in to discuss their knowledge. This paper shows one simple technique that allows anyone to define a systems model -- "slowing the system down" so an image can be made of it.

When time is stopped, a "snapshot" can be taken of the current state. There are several ways to accomplish this. First, get a helper. With a new roll of film or disposable camera, roam around the system of interest. Act as journalists, uninvolved in the current situation. Take pictures of every "thing" that seems to be part of the system. As pictures are taken, feel where the boundaries of the system are. Boundaries can be found that are physical (geographical), energetic (monetary?), and informational. These boundaries often regulate flow between systems, or parts of a system. At boundaries of human activity systems, gatekeepers can be found (i.e. monetary exchange rates, customs or duties, or immigration quotas.) Record and title the pictures.

A second way to stop time is to look at numbers. If the system of interest is a neighborhood, look up data on number and age of houses and owners, size of lots, percentage of residential and commercial property, number of trees, location of playgrounds and parks.

Time can also be stopped mentally. Visualize the system, and then stop time using either of the first two techniques. This is the easiest method but the one most likely to miss system components. To enhance this method, have a helper do the same exercise independently and combine results.

5. Mapping onto a structure

Now we need to combine the parts into a structure. Get colored paper or a geometric modeling set (e.g. Zometool or Roger's Connections; see reference section) or sticks and modeling clay.

Starting with paper, cut out pieces and label each one with the name of something in the system. Each one can be a "cloud" floating around. Place the pieces on a large sheet of paper, and draw in connections between them. Take adequate time and move pieces around and re-draw the connections until it feels right. As the parts are re-arranged, think of the simplest geometric structures -- the tetrahedron (Fig. 1) and the octahedron (Fig. 2). Since these are the simplest models that have structural integrity, try and fit the map to one of them. If there are more nodes than 4 (for the tetrahedron) or 6 (for the octahedron), try and combine or limit them. Similarly, if there are less than 4 or 6 nodes there may be some parts of the system missing. Look back at the system of interest, paying particular attention to the boundaries. There may be some elements outside the boundary that should be put back in, or some inside that should be put
back out. If there are still more nodes than four or six, consider modeling the system as interacting geometric structures (for example, two tetrahedrons that connect together, as Fig 3b.)

If geometric modeling tools are used, pick a vertex and name it (use a piece of masking tape). Then pick the one that seems most closely connected to the first and connect them. Find a third and connect that in as well. Continue in this fashion, re-arranging the vertices and connections as needed. Once again, try and fit the model to the tetrahedron or octahedron. Note that in the tetrahedral model, each node has connections to three others, while in the octahedral model each node connects to four.

Modeling clay and sticks can be used in the same fashion as the geometric modeling tools. If the modeling clay is colored, different colors can be used to represent different nodes or types of material. As above, try to fit the model to the tetrahedron or octahedron.

6. Defining the connections

Once a preliminary structure has been determined, set it aside and think back to the connections between the nodes. What do these connections represent?

Since each node represents a quantity of something, that quantity must be capable of changing over time. So, the connections can carry material -- for example if the system were a farm and the node were corn, the connections could be soil, sun, air and water (see Fig. 3). As each of these varied over time, the quantity of corn would cycle. The geographic limits will in turn drive the quantities of the constituents (air, soil, sun, water), which will then determine the quantity of corn.

Note that in the above example, the four nodes of air, earth, sun and water are modeled as a tetrahedron. This is a fundamental (or generative) tetrahedron which provides an environment for many plants. The corn seed (which later becomes a plant) is a fifth node, modeled as a second tetrahedron linked up to the first (see Figure 3). If there were another element required for corn to grow, the system could be modeled as an octahedron (six nodes).

Each connection can therefore support a flow, as well as maintain the structure. What forces or flows hold the nodes together? What forces them apart? In a mechanical system, each edge would be a combination of tension (pushing apart) and compression (pulling together). Think about the example of molecules in which the attraction of electrons to protons holds them in a shell while the repulsion between electrons distributes them across the shell, and different atoms form molecules due to sharing of electrons between shells of different atoms.

While the forces that hold a system together may seem static -- attraction and repulsion with constant values -- the loops that flow between nodes are clearly dynamic. What insights does the static structure give to the dynamic loops that the system supports?
6.1 Inputs and outputs

In the corn example, it is easy to see that the end-product comes from the constituents (corn comes from soil, sun, air and water). It is also clear where soil comes from -- over time, the cycles of sun, corn, air and water have resulted in soil (although this is a larger scale model). But where does the sun come from? Since it is clear that the sun is an input to this system and not dependent on it, the sun is an input node to our model. The solar output is modeled as an input to the corn model. This node is part of another geometric model that connects to the corn model at the sun node. The sun geometric model has many parts, including nuclear fusion and radiation.

Similarly, the corn node may need to be connected as an output. If corn is grown as an intentional practice, typically it is stored to be sold or eaten at a later time. Once again, this node can be shown connecting to another geometric model -- perhaps one representing a roadside stand.

Note that there are several loops in the corn model. Water flows from the soil into the corn, thence into the air and then back to the plant. Fertilizer (if modeled) flows from the soil into the corn and then back into the soil as the corn plant decays.

6.2 Energy flows and storage

In the corn example above, energy flows into the model from the sun. Energy is stored as corn at that node (embodied energy or emergy, Odum). Does energy flow from the soil (nutrients and fertilizer) to the corn plant? “Walk around” the model and define what energy flows in the connections between the parts. Find at least two loops in your model. Arrows can be used to show attraction, repulsion, or flow.
6.3 Information flows and feedback

Since this model can be used to represent information or knowledge, the edges can also carry information. Previously, information has been talked about as if it were a flow (like a river, carrying water from one place to another). Of course, that water had to come from somewhere -- in fact, it came from rain and snow that came from clouds. So, the visible river is one aspect of a water loop.

In the same way, the visible flow of information is one part of a larger loop. This larger loop creates the environment (source and potential) that then creates the visible flow. In the case of the river, it empties into the sea or lake and thence evaporates, once again driving the loop. So it is with information. The sea of written material -- the stuff of culture -- pervades human consciousness and provides fertile grounds for the creation of new materials. Each flow is part of a loop that supports it. When the information flows are mapped, the loops and their support in the system should be mapped as well.

Look back at the model and define what information flows in the connections between the nodes. Examine the model to see which nodes and connections define a loop where information is used as feedback. Use arrows to show attraction, repulsion, or flow.

7. Boundary

Now that there is a preliminary model, think back to the connections between the system being modeled and the outside world. These connections define the boundary in one of the ways discussed above (space, energy, information, or time). What differences are defined by the boundary/connections between the problem/opportunity and the system it is embedded in?

List the spatial boundary (edge of a pond), the informational boundary (how the system looks from the outside as compared to the inside) the energetic boundary (what flows in and out), and the temporal boundary (over what range of time is the model valid, what is the period of the behavior modeled).

8. Maintaining a set-point, moving towards a goal, or cycling/looping

The model now represents the major components of the system, and has clear connections between itself and the outside world. One may visualize the time-based behavior that the system will exhibit. Alternatively, there may also be knowledge of system behavior over time, giving some idea of the past states. Look at the model to see what connections and flows could support this behavior. Sometimes this type of intuitive behavior is more revealing than a mathematical model, although making a mathematical model gives great ability to see what changes in nodes and connections will effect system behavior. There are modeling systems from Vensim (Ventana Systems), Stella/I-Think (High Performance Systems) or Extend (Imagine That) that work well for systems models. Obtain a copy of one of these programs and put the model into it (there may be demo versions available.)

When system behavior is examined, decide whether the system maintains a fixed level (for example body temperature) or cycles in time (for example sleep and wake cycles.)

Note that at a lower level, some nodes are storages or accumulations (of energy, information or material) that have fixed levels. Since systemic behavior is typically required to maintain a fixed level, this node may represent a lower level system that effects the system under study. Some of these storages may also oscillate or move around a set-point.
Another systemic behavior is goal-seeking -- following or moving towards something over time. For this to occur, there needs to be feedback loops involved that sense the world, comparing an external value with an internal level. Can a loop that drives such behavior be located?

9. Systems Design

Once the model of the current situation is complete, alternatives can be imagined or envisioned. Referring back to the model, think of the loops that control the set-point or cycle. If the level of a set-point needs to be changed, find the node that is being controlled, and the mechanism that is controlling it. The control mechanism will have a comparison function in which the value of a node is compared to some ideal value. Is there a way to change the ideal value that the system is using? Could other loops be designed that would produce desirable changes? What would the side-effects of the changes be? From a set of questions like these, structural changes can be defined that will drive the behavior. Create a new model based on the desired state. Consider using tools like brainstorming (multi-brain), mind mapping (Buzan), clustering or lateral thinking (de Bono) to generate alternatives. Once alternatives are generated, they will need to be evaluated and documented. Since each alternative is a new system, it will be embedded in the real world like the current problem or opportunity. Therefore, the same modeling techniques can be used again, but focused on future alternatives.

As modeling proceeds, refer back to the tetrahedral/octahedral systems model and think about how those system attributes are included in the model and the alternatives. Documenting the alternative designs will often make clear which one is the best.

It is often recommended that designers use criteria to evaluate alternatives. In his design to save Spaceship Earth, Fuller used the following mission criteria:

Reform the environment, not humanity
Up performance (higher efficiency)
Do not resort to politics
General systems perspective (beginning with the whole before proceeding to the parts)
Success (plenitude) for all.

What criteria can be defined for this system design? Do the criteria have structural integrity?

With the alternative future defined as a system, the design process can move towards implementation. There will be a model of the future alongside one of the present, and the differences between these models highlight the changes to be made. Since modelers are not necessarily in positions of power, strategies to move the system towards the desired state will need to be found. This process is what Fuller referred to as "turning the trimtab."

*trimtab*: A large ship is steered by means of a rudder. The rudder is small compared to the ship, but can still be a large object and therefore difficult to turn. A trimtab can be placed on the rudder (sort of like a rudder for the rudder) allowing the larger rudder and thence the ship to be turned. The success of the modelers will depend on the pattern integrity of the model, and their ability to find trimtabs.

Since systems are stable due to their structural nature and feedback loops, change will be resisted. Along with techniques like finding trimtabs, changes will need to be implemented in a systemic way. For example, if a new loop is to be implemented, a system will need to start up the operation of that loop and maintain it until it replaces the original loop. In a human activity system, people will need to be educated about the nature of the new design so that they help support the new system. From a practical perspective, systemic change is likely to fail unless the participants are involved.
9.1 Checklist for design of the future
A) Create a model of the present.
B) Define the desired future. For example, if the level of something (like affordable housing) is low, define what the new level should be.
C) Define criteria, and rank the alternatives using them.
D) Build a model of the future. If new structures or connections are needed, how will they be created? How will they be maintained?
E) Summarize the connections, structure, and "stickiness" that holds the current system together.
F) Now look at what structures and connections need to change from the present to the desired future.
G) Design the system to change the present into the future.
H) Create a pathway to move the current system to the new structures and connections (and keep it there!). Use brainstorming, mind mapping, clustering, or lateral thinking techniques (de Bono) to generate alternative designs and structures.
I) Document the new system (using a geometric model.)
J) Test your models by getting other people to critique them.

10. Application to Requirements and Models
This same methodology may be applied to written system requirements or mathematical models. If a set of system requirements is to be modeled, the major pieces (nodes) need to be extracted from the description. This can be done with the same methods as described in earlier sections (identify key concepts, constraints, boundaries, and connections). Proceed as above, making a geometric model and defining the connections and loops. It may be necessary to bring in additional (implicit) information to complete the model. Similarly, a systems dynamics or differential equation based mathematical model will have storages or accumulations, coupled to each other by rates of change. Map these equations onto a geometric model and see what other connections exist, and what boundaries are implicit in the model. The same approach may be applied to other types of mathematical models.

11. Alternative Geometric Models
The process described employs model-making based on nodes and interconnections. However, a tetrahedron also has six edges that connect the four nodes. This leads to the idea that models can be based on edges. In this case, the nodes are points that connect four edges, and can be viewed as switching stations that connect edges together. As discussed earlier, each edge may have a tension and a compression component.

Another approach is to visualize the parts of the system as the four faces of the tetrahedron. In this case, each element can be visualized as a dimension, distinct from each other element. Edges now represent the connection between elements, but each edge only connects two elements. Nodes become the place where three elements connect.

12. Summary
The simplest structural models from universal geometry have been applied to systems modeling and design. The advantages of this are models that have structural integrity (all connections are explicit and necessary), and clearly delineate all connections between parts. Several methods have been described to
create such models, and the relation between a model of the present and a design for the future has been discussed. Finally, alternative modeling schemes based on the same approach have been suggested.
13. References

Web: You can see an example mind map at:
http://www.sharedvisions.com/explore/literature/mindmap.htm

Web: The official de Bono page is at: http://www.edwdebono.com/debono/home.htm

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Web: Synergetics text is on the web at
Other resources on synergetic geometry can be found at

High Performance Systems, Inc. 45 Lyme Road, Suite 200, Hanover, NH 03755
Phone: 1-800-332-1202 or (603) 643-9636 Fax: (603) 643-9502
E-mail: support@hps-inc.com. Web: http://www.hps-inc.com

Imagine That, Inc. - 6830 Via Del Oro, Suite 230 - San Jose, CA 95119 - USA
408-365-0305 - 408-629-1251 fax extend@imaginethatinc.com
Web: http://www.imaginethatinc.com

Mithya. The Mithya Institute for Learning and Knowledge Architecture:
268 E. Hamilton Avenue, Suite D Campbell, CA 95008-0239
Phone: (408) 871-0462 E-mail: info@mithya.com
Web: http://www.mithya.com/pyramids/pyramidscontract.html

Web: A brief exposition on emergy can be found at:
http://www.enveng.ufl.edu/homepp/brown/syseco/emergy.htm

Roger's Connection  P.O. Box 871 Fairfield, IA 52556 U.S.A.
1-888-RogersC (1-888-764-3772) Elsewhere: (515) 469-3000
Fax: (515) 469-3034 e-mail: connect@RogersConnection.com
Web: http://www.rogersconnection.com

Web: A paper on the game can be found at: http://www.vxm.com/link.siegmund.html
The game itself is at: http://members.tripod.com/~Tetworld/+index.html

Web: http://www.teleport.com/~pdx4d/system.htm

Ventana Systems, Inc. 60 Jacob Gates Road Harvard, MA 01451
Phone: 617 489 5249 Fax: 617 489 5316
Web: http://www.vensim.com

Zometool, Inc. 1526 South Pearl Street Denver, CO 80210 USA
Toll-free: 888-966-3386 Phone: 303-733-2880
Fax: 303-733-3116 email: sales@zometool.com
Web: http://www.zometool.com