How Is This Similar to That?

The skill of recognizing parallel dynamic structures on center stage

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Author's note:
While making my way through Harvard's doctoral program in education, I found myself endlessly explaining what was this thing called "systems thinking." Like Sisyphus pushing the boulder uphill, I had a burden to carry and a lesson to learn. By the time I graduated (seven years later), I had learned to place systems thinking skills in the context of more conventional educational thinking skills, in order to communicate with my academic colleagues. This article is intended to put systems educators' daily work in context for educational researchers and to highlight a central skill for schools seeking to teach students to see, understand, and ultimately affect the systems around them.

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In a handful of classrooms across the country, middle and high school students are learning about the dynamics of systems by experimenting with a rain barrel. In the activity, one scenario has water flowing into the barrel at a greater rate than it is flowing out. Students are asked to consider what happens to the level of the water in the barrel. Now the scenario changes: the water flowing out of the barrel is at a greater rate than the water flowing in. What happens to the water level then? After using this hands-on model, students are asked to recognize the same *structural dynamic* [i] in other situations having nothing explicitly to do with rain barrels, such as: (a) intravenous drug infusions (or multiple injections, equivalent to buckets being poured into the rain barrel); (b) the flushing of pesticides from a river/reservoir system; (c) the cooling process in a cup of coffee (i.e. Newton's Law of Cooling); or (d) the influence of carbon emissions on global climate change[ii] What do we call this type of reasoning and why is it important?

The cognitive process on center stage here is the recognition of recurrent patterns of behaviors in different domains and situations. In the lists of systems thinking skills and habits, this skill tends to be assumed, but not frequently named. We're called to use this type of reasoning when we encounter natural or social systems that share certain characteristics or behaviors. We intuitively understand, for example, that competing street gangs and the advertising campaigns for Coke and Pepsi share a similar, underlying structural dynamic, i.e., escalation. When we are unaware of these dynamic structures, we are more likely to *react* to behaviors produced by them, rather than to understand and potentially take actions to *change* the structures. If we are able to see recurring dynamic structures around us, we begin, as Peter Senge suggests, in his book *The Fifth Discipline* (1990), "a process of freeing ourselves from previously unseen forces and ultimately mastering the ability to work with them and change them." From an educator's perspective, the ability to see similar patterns of behavior across disciplines translates into increased retention and transfer for students, as well as the potential for improved coherence across curriculum.

Sounds good, right? But what do we call this reasoning skill? And how does one develop it? This is where homologies and the use of homologous reasoning come in.[iii]

Buckle your seatbelts for a moment as we take a brief ride into abstract space. I promise we will land on the ground in a paragraph or two.

In his theory of general systems, Viennese biologist Ludwig von Bertalanffy (1968) offered general principles that apply to systems, irrespective of their nature. Arguing for more precision in describing complex system phenomena, he suggested that analogies were of no help. In his own words, analogies are "superficial similarities of phenomena which correspond neither in their causal factors nor in their relevant laws."[iv] Homologies, however, were particularly important "to describe formal correspondence between systems of any kind." (p. 84)

Said more simply, where an *analogy* refers to a "correspondence in function" a *homology* is "a likeness in structure" (or pattern of interrelationships). Using an analogy, one might suggest that wolves/rabbits and lynx/hares pairs are similar because they are all mammals; using a homology, one might note that these pairs are similar because they are part of predator-prey relationships.

We can think of homologous structures, such as coupled reinforcing and balancing feedback loops, as David Lane has suggested, "as devices which seek to provoke the user into thinking in certain loose categories and comparing real world phenomena with the ideal type in order to generate explanatory insights." Homologies can also be thought of as "explanatory schemas" that enable one to put one's stock of knowledge into action. What is the advantage of such abstract schemas? As educational researcher Stellan Ohlsson explains, "content-full schemas, no matter how general, are limited to their respective domains, whereas an abstract schema is, in principle, transferable across domains (with what success is always an empirical question). This allows the formal thinker to think productively when faced with discourse from an unfamiliar domain."[v]

Let's have a bit of fun with this idea and imagine we overhear the following conversation:

> As Schimogens' appeal relies more on Wooser's efforts, the emphasis given to Wooser's efforts increases. This leads to more Wooser efforts and less effort given to developing new types of Schimogens. This further exacerbates the problem of the Schimogens' poor overall performance.

What is this conversation about? Is this a conversation between two Jedi knights in the midst of an intergalactic battle? Perhaps, but we don't need to know more about the Schimogens and Woosers to begin to understand the dynamics at play here. As we trace the changes over time and unintended consequences in this conversation, we might begin to recognize a common homologous pattern in which a fix – in this case, more emphasis on the Wooser's efforts – is doing more harm than good and is actually making the original problem worse. This homologous structure, or archetype, is often labeled "fixes that fail."

Many researchers and practitioners have recognized that homologies, or structural similarities, exist within and among a variety of systems.[vi] These structures have been described in various literatures, and range from the almost folkloric "tragedy of the commons" to the more specific system dynamic "molecules."[vii] For example, Jay Forrester, founder of the field of system dynamics, offers this example of homologous structures:

> The dynamic structure that causes a pendulum to swing is the same as the core structure that causes employment and inventories to fluctuate in a product-distribution system and

> in economic business cycles. Humanities are taught without relating the dynamic sweep of history to similar behaviors on a shorter time scale that a student can experience in a week or a year.[viii]

In alignment with Forrester are numerous psychologists, ecologists, scientists and other system dynamicists who have long argued that recognizing these similarities improves one's ability to transfer problem solving insights from one context to another.[ix] Turning to K-12 education, Forrester has argued that the "transferability of structure and behavior should create a bridge between science and the humanities. Feedback loop structures are common to both. An understanding of systems creates a common language. Science, economics, and human behavior rest on the same kinds of dynamic structures." Forrester provides this example:

> A student in an eighth grade class grew bacteria in a culture dish, then looked at the same pattern of environmentally limited growth through computer simulation. From the computer, the student looked up and observed: "This is the world population problem, isn't it?" Such transfer of insights from one setting to another will help to break down barriers between disciplines. It means that learning in one field becomes applicable to other fields. [x]

How is homological reasoning being fostered in K-12 education today? Before we dive into this question, let us take a look at what is known about the development of this reasoning skill.

The Development of Homologous Reasoning

We know that adults, with advanced skills in the field of system dynamics, for instance, develop a mental library of recurring patterns of behavior and can recognize these generic structures[xi] in widely different domains. Typically, this occurs over time, through graduate level classes and extensive research or client work.

Although there is a great deal of empirical research about the development of related skills, such as analogical reasoning,[xii] there is not yet a cogent body of research on the development of homologous reasoning in children and adults. In a review of the analogical reasoning literature, I found that (a) analogical reasoning is considered an achievable skill for children as young as four[xiii]; (b) the development of analogical reasoning skills is influenced by the learning environment; (c) students make better analogies when they have more knowledge; and d) familiarity and practice with analogies facilitates students ability to reason by analogy.

This research has shown that children can progress from merely noticing the occurrence of analogies to productive use of analogies to solve problems.[xiv] There is also a similar progression from focusing on surface similarities to a reliance on deeper structural analogies. For example, during their three-year research effort to develop a "community of learners" among fifth and sixth grade students and their teachers, educational researchers Anne Brown and Joseph Campione found that "children initially make surface analogies, such as between human eyes and the headlights of a car (surface), while later they make the analogy between a car's engine and the human heart (deep)." Brown and Campione found that increased knowledge in and across domains facilitates a child's shift from accepting "superficial analogy" to using "deep analogy" to explain behaviors and mechanisms. As Brown and Campione explain:

> Although in the laboratory, this development from noticing to using, and from surface to deep, was thought to be age-dependent, the classroom work suggests that the shift is

knowledge-based, occurring micro-genetically within a year as readily as cross-sectionally across several years.[xv]

This finding provides strong support for something many systems educators already know: an integrated, interdisciplinary curriculum fosters students' abilities to recognize systems patterns in one domain and apply them in another.

As part of the studies conducted by Brown and Campione, they also found that "practice creates a mind-set to reason by analogy" (p. 250). This finding is supported by several action research projects conducted by members of the Waters Foundation. In one such project, an interdisciplinary team[i] of teachers and Waters Foundation mentors wanted to know if the use of systems thinking skills would facilitate the ability of 7th grade students to see similarities between different systems. Specifically, they asked whether students would be able to recognize and transfer the generic structure of exponential growth in scenarios involving a bank account, Fibonacci rabbits, world population and bacterial populations.

In math class, students used a model called Fibonacci Rabbits. In science class, students grew bacteria and used a model of bacterial growth in the context of potato salad spoiling at a school picnic. In social studies class, students used a computer model that simulated world population growth and the dependence on oil for energy. During the course of these activities, students were also exposed to other exponential patterns (a bank account and the *One Grain of Rice* story) in a series of lessons in computer technology class. It was in this context that time was afforded for practice of homologous reasoning. According to Larry Weathers, "we read (in the learning transfer literature) that students would not significantly develop the skills of picking up transfer of knowledge to other situations unless they had the exposure to the process and the opportunity to practice it in a guided way."

How well did the students do? According to the team report: "Students improved in their ability to anticipate the feedback relationship that caused the exponential growth pattern and to successfully explain it. The percent of students receiving the highest rubric grade when asked to explain the cause of the exponential growth pattern improved from 13% of students to 55%. Students also improved in their ability to come up with an example of exponential growth from prior experience, with 38% of students answering this question in the pre-test compared to 61% of students in the post test."

In my own doctoral research, I investigated middle school students' and their teachers' naïve conceptions of dynamic systems. As part of this study, participants provided their intuitive understanding of six systemic scenarios (involving predator-prey relationships, birth rate and population trends, room clean-up dynamics, and so on), and were then asked to describe a similar situation, but from a different domain. For example, after describing how wolves and rabbits are interrelated, participants were then asked to describe another situation that seemed similar, but was not an example from the animal kingdom. Without previous formal experience with generic systems structures, a surprising number of students (21%) and teachers (53%) described homologies that were structurally similar yet distinct in terms of the domain. Here is a sample response from a student I will call "Toby." When asked to think of a similar situation to the wolf-rabbit story he just told, Toby responded:

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[i] This team included Scott Hoffman, Barbara Bowden, Mike Desarro, Robin Goldstein, Dick Maki and Larry Weathers of the Bromfield School, Harvard, Massachusetts.

> There's something sort of like that with environmentalists. When there's really low enough attention paid to the environment that they're supporting, then they just get frantic. It boosts the numbers of people, then they get more secure. Then once the area they're concentrating on is back to around normal, they just ignore it, and slowly the numbers just go down until it's back to, "oh my God!" They wait until the last possible minute to react. And it goes on like that.

A Waters Foundation action research project with middle level schools in Tucson, surfaced similar homologous reasoning skills by middle school students. Here, Tracy Benson, a Waters Foundation mentor, shares this student-generated example of a "Fixes that Fail" archetype:

> My Mom nags me to clean my room, I stuff things in my closet and under the bed (quick fix), and at first she doesn't see it, but then I get her even more mad when she discovers that I still have a mess, even though it is kind of hidden. In addition, it ends up taking me more time in the long run to clean because I have to pull everything out from hiding and put things in their right places. This is also like the problem I have when I have a test or big paper due. I sometimes decide to copy or cheat and sometimes I get away with it. But sometimes the teacher finds out, and I have to rewrite or do extra credit because I get zeros. It then takes me even more time to do homework or study. It is reminds me of when I went to a new school and wanted to make friends. I tried acting "cool" and not like myself (quick fix). I ended up getting attention from the wrong crowd which prevented me from making friends who were more like the ones I had at my old house.[ii]

How is this similar to that? Fostering a habit of mind

Educators, organizational leaders, and academics alike will attest that developing a mental stock of generic structures can be a powerful means of accelerating learning and generating insight in people of any age. How do we help young people to become aware of these recurring structures in our personal and professional lives?

Use systems archetypes as thought organizers
Educators and parents can create opportunities for familiarity and practice, just as the Waters Foundation team did with the group of seventh grade students in Harvard, Massachusetts. A means of raising awareness of homologous structures is to use the systems archetypes as "thought organizers." In several Tucson schools, systems archetypes such as "Fixes that Fail, " "Escalation," "Shifting the Burden,"and "Tragedy of the Commons"[xvi] are commonly used by reading, writing, and social studies teachers at the middle level primarily but also in a kindergarten through second grade school whose teachers use systems archetypes with reading comprehension. Students use the archetypes to organize their thoughts prior to writing to help them compose dynamic, fluent stories or expository essays. According to Tracy Benson, "Two different action research projects this year gleaned the motivational pay-off of using archetypes with students. When students are asked to make connections between what they are reading and/or studying and their own lives, their engagement increases, along with the quality of their oral and written explanations."

Making the link to curriculum standards

It is useful, perhaps even critical in some school settings, to know how homologous reasoning aligns with the state's curriculum standards. Generally, homologous reasoning is most closely aligned with "Complex Thinking Standards," one of five dimensions of learning linked to assessment standards. Marazano and colleauges.[xvii] identify thirteen of the most commonly recognized complex reasoning skills (p. 19):

- Comparing
- Classifying
- Induction
- Deduction
- Error Analysis
- Constructing support
- Abstracting
- Analyzing Perspectives
- Decision Making
- Investigation
- Experimental Inquiry
- Problem Solving
- Invention

To meet the "Complex Thinking Standards," students must be able to effectively use the above complex reasoning strategies. Homologous reasoning is aligned with several of the strategies listed above, including "abstracting." Abstracting is defined as: "Identifying and explaining how the abstract pattern in one situation or set of information is similar to or different from the abstract pattern in another situation or set of information"(p. 74). Questions related to abstracting include: "What's the general pattern of information here? Where else does this apply? How can the information be represented in another way, for example, graphically or symbolically?

Look for opportunities within and across current curriculum units

When teachers and school administrators value homologous reasoning as a necessary skill, teachers are encouraged to look outside their own disciplines and to see interconnections between such topics as math and humanities. Teachers may also be drawn to co-teaching subjects in the same room. However, our current educational climate, with its emphasis on the disciplines and standardized tests, may not allow for such interdisciplinary teaching.

Another opportunity then lies within the middle school and high school curricula. A good example of this is a series of curriculum modules designed by Harvard's Tina Grotzer and colleagues to infuse models of causality into topics such as pressure, electrical circuits and ecosystems[xviii]. Grotzer argues that understanding about ecosystems, for example, involves reasoning about forms of causality that are unfamiliar to many students. Using the ecosystem module, teachers infuse models of causality found in ecosystem units to deepen students' understanding. For example, students are taught to understand the inherent temporal delays in decaying processes and the importance of "balance and flux" processes in ecosystem populations through case studies, self-generated causal maps and StarLogo models. By asking cross-domain questions such as, "How are these dynamics similar to situations you see at home, at school or in the newspaper?" teachers may foster students' homological reasoning skills as well. In this way, students learn important disciplinary knowledge but are also encouraged to detect interrelationships and dynamics across disciplines as well. As educators and parents alike, we can make stronger links between the disciplines (multi-disciplinary study) and across disciplinary subjects (interdisciplinary study). Issues such as hunger and climate change are matters not only of science, or geography, or economics, or philosophy. They cut across several disciplines and are understood only to the extent that these domains are addressed together.[xix]

Asking different questions

Finally, one simple way parents and educators can help young people become aware of recurring dynamic structures is by asking different questions. As young people encounter a particular challenging or chronic situation, parents and educators can help the young person to pause before leaping to a conclusion, and instead ask questions such as: "What happens next?" or "Where else have you seen, or, might you, see this pattern?" or "How is this situation like that?" I offer here an anecdote from my own parenting experience. Not long ago I read the following tale of Hercules and Pallas (one of Aesop's Fables) to my sons:

> Hercules, once journeying along a narrow roadway, came across a strange-looking animal that reared its head and threatened him. Nothing daunted, the hero gave him a few lusty blows with his club, and thought to have gone on his way. The monster, however, much to the astonishment of Hercules, was now three times as big as it was before, and of a still more threatening aspect. He thereupon redoubled his blows and laid about him fast and furiously; but the harder and quicker the strokes of the club, the bigger and more frightful grew the monster, and now completely filled up the road. Pallas then appeared upon the scene. "Stop, Hercules," said she. "Cease your blows. The monster's name is Strife. Let it alone, and it will soon become as little as it was at first."

The moral? "Strife feeds on conflict."

After the story, I asked my son where else he saw this same kind of situation. Sheepishly, he pointed to his brother. He then went on to explain how sometimes one tease leads to a poke, which leads to a push, and so on. (You know the scenario.) In my son's explanation, I heard the dynamic of escalation. One party does something that is seen as a threat by another party so the other party responds in kind, increasing the threat to the first party. This results in even more threatening actions by the first party and the cycle continues. I then asked what I think of as the "policy level" question: What could you do differently? My son suggested that walking away and leaving his brother alone for a while would work. I did too.[xx]

In Closing

Thanks to the many educators, practitioners and academics within and around the system dynamics community, we have seen that fostering homologous reasoning has many potential benefits. These include:

- *Increased student engagement*. As students are encouraged to make connections between what they are reading and/or studying and their own lives, they become more engaged and personally involved in what they are learning.

- *Improved transfer and problem solving skills*. Academic researchers have long argued that recognizing similarities improves one's ability to transfer problem solving insights from one context to another. The experience of systems educators is showing that knowledge of underlying structural similarities can enable students of any age to think productively when faced with unfamiliar terminology or scenarios.

- *Increased retention.* In one of his many penetrating insights, educational researcher Jerome Bruner observed that human memory is greatly facilitated when "detail is placed in a structured pattern." Without a structured pattern, Bruner argued, "detail is rapidly forgotten." Encouraging homologous reasoning in students can improve retention and transfer of materials by helping students access and refine schemas of the concepts they need to acquire.

- *Increased student empowerment.* The ability to recognize patterns of behavior within what may appear to be what Russ Ackoff has called a "wicked mess" is empowering. Armed with this understanding, young people have a greater ability to analyze and act in informed ways, without jumping to blame a single cause for the challenges they will encounter.

- *Improved coherence across the curriculum.* Emphasis on homologies can also create a bridge between and among disciplines, for example, between science and the humanities, and so improves coherence across curricular units.

There is no one pedagogy, book or computer program that will help students develop homologous reasoning skills. Instead, we must take every opportunity – scanning our every day artifacts such as newspapers, text books, games, museum displays and the media – to help our young people develop habit of mind that looks across disciplines and appreciates similar system dynamics. With consistent efforts to develop homologous reasoning – as of yet seen as an unusual, even revolutionary way of thinking – we may see it transform into what Art Costa has called natural habit of mind. As Toulmin and Goodfield[xxi] once observed: "One century's common sense is an earlier century's revolutionary discovery that has since been absorbed into the natural habits of thought."

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[i] The rain barrel represents a stock/flow structure: the amount of water in the barrel is the "stock"; the water flowing into and out of the barrel are "flows." At the core of system dynamics lies the premise that the structure of a system (comprised of, for example, stock/flow relationships and feedback loops) generates the behaviors we observe over time. In any stock/flow structure—whether it be the national debt (stock) and the national deficit (flow), or the number of trees (stock) and the rate of harvesting/planting (flows) —when the inflow into a stock is greater than the outflow, the level of the stock is rising. When the outflow is greater than the inflow, the level of the stock is falling. When the inflow is equal to the outflow, the level of the stock remains steady.

[ii] In global climate change, for example, we can imagine the concentration of greenhouse gases (GHG's) as a bathtub or stock. Flowing from the faucet into the stock of GHG's are human-generated GHG emissions. The drain or flow out of the bathtub is the rate at which CO_2 is removed from the atmosphere (via net uptake by biomass, the ocean, and other sinks). Most climatologists agree that due to deforestation and saturation of other carbon sinks, human GHG emissions are almost twice the rate of removal. The bathtub is filling twice as fast as it is draining.

[iii] In my own doctoral research, I've come to call this process *homologous reasoning.* I choose "homologous reasoning" here over "archetypal reasoning" because of its specificity regarding underlying structures, its inclusiveness of generic causal patterns (represented by influence diagrams, causal loop diagrams or stock/flow diagrams) and its closer connection to the cognitive science and human development literatures/communities.

[iv] Homologies as a concept can be traced back to Aristotle but the term was first coined in 1843 by anatomist Richard Owen. For Ludwig Von Bertalanffy's view of homologies, see his book *General System Theory: Foundations, Development, Applications* (1968).

[v] For more on "abstract schemas" see Ohlsson's article in the journal *Educational Psychologist, (1993*), volume 28.

[vi] The list of those who have described structural similarities within physical, biological, economic and social systems is of course too long to include here. Some of those works that have most influenced my own thinking include: W.B. Cannon's *The Wisdom of the Body* (1939), Jay Forrester's *Counterintuitive Behavior of Social Systems* (1971), Gregory Bateston's *Steps to an Ecology of Mind* (1972*),* Donella Meadows' *Whole Earth Models & Systems (*1982). Peter Senge's *The Fifth Discipline* (1990), Daniel Kim's *Systems Archetypes I* (1992) and David Lane and C. Smart's 1996 article in the System Dynamics Review*: Reinterpreting Generic Structure: evolution, application and limitations of a concept.*

[vii] In a 1968 issue of *Science* magazine, Garrett Hardin first described "Tragedy of the Commons" in this way: "Much of man's world is treated as a 'commons' wherein individuals have the right to freely consume its resources and return their wastes. The 'logic of the commons' ultimately produces its ruin as well as the demise of those who depend upon it for survival" (volume 62, p. 1243). For more on systemic "molecules", see Hines, J., Eberlein, B., Richardson, G., Johnson, D., Richmond, B., & Melhuish, J. (1996-2000). Modeling with Molecules 1.4 (Version 1.4) [Vensim]. Harvard, MA.: LeapTec and Ventana Systems, Inc.

[viii] This quotation is drawn from Jay Forrester's 1992 talk, *System Dynamics and Learner-Centered-Learning in Kindergarten through 12th Grade Education*.—a highly recommended read. The full text can be found on the CLE website (see: www.clexchange.org).

[ix] Particularly strong arguments related to the link between recognizing structural similarities and improved transferability of problem solving insights have been made by Robert Nisbett, G. Fong et al. (see their 1987 article: Teaching Reasoning in *Science* (238), 625-631) and Jim Doyle (see his 1997 article: The cognitive psychology of systems thinking, *System Dynamics Review*).

[x] Forrester, J. (1992). *System Dynamics and Learner-Centered-Learning in, Kindergarten through 12th Grade Education*. Acton, Massachusetts: Creative Learning Exchange (www.clexchange.org)

[xi] Other terms one might hear used for generic structures (a term coined by Mark Paich) include "systems archetypes" and "kernel structures"(a term used by Dennis Meadows).

[xii] Analogical reasoning research has explored people's ability to recognize either superficial or deep structural similarities in a well-known domain and apply it to another domain. However, very few studies discuss children's and adult's ability to recognize homologous structures *across* natural and social systems. Several studies do look at children's or adult's ability to recognize and utilize homologous structures within the same domain (for example, within ecosystems or within management-related systems). For a review of the analogical reasoning literature as it relates to the development of systems thinking skills in general, see "Thinking about everyday systems: An empirical investigation of middle school students' and their teachers' understanding of natural and social systems" (2004), Harvard Graduate School of Education, unpublished manuscript.

[xiii] I have heard numerous examples of children as young as four or five demonstrate rudimentary homologous reasoning skills. Here is a brief example from my own personal experience:
While driving around a crowded rotary with my two sons, my then four-year old noticed the congested traffic ahead. People in cars and trucks were honking impatiently as they tried to navigate their way through the orange cones set up by a road construction crew. Pointing to the cars darting in and out, my son asked:

"Mommy, what happens when everyone says 'me first'?"

Humbled by the wisdom of his simple question, I responded:

"What do you think would happen if everyone said 'me first!'?
He suggested there might be a few accidents or even "a big, huge crash!" I then asked:
"Are there other situations you can think of when everyone says me first?"
To my great surprise (and delight) he responded:
"Mommy, you know how you said it's not good to let the water run when we brush our teeth because if everyone did that the reservoir would go down? Well, it's kinda like that."
At his tender age, he was making the connection to the "tragedy of the commons" archetype, a common pattern of behavior that emerges around the "commons" – e.g., over-crowded community pools, over-used water supplies, and so on.

[xiv] Much of this research has been conducted by Diedre Gentner. I found Gentner and Stevens' *Mental Models* book (1983, Lawrence Erlbaum) to be particularly helpful.

[xv] For the complete study, see: Brown, A., & Campione, J. (1994). Guided Discovery in a Community of Learners. In K. McGilley (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* . Cambridge, MA: MIT Press.

[xvi] Kim, D. (1992). *Systems Archetypes I*. Waltham, Massachusetts: Pegasus Communications (www.pegasuscom.com)

[xvii] See Marzano, R. J., Pickering, D. J., & McTighe, J. (1993). *Assessing Student Outcomes: Performance Assessment Using the Dimensions of Learning Model*. Alexandria, Virginia: Association for Supervision and Curriculum Development.

The curriculum module —*Causal Patterns Ecosystems: Lessons to Infuse into Ecosystems Units to Enable Deeper Understanding* —was created by Tina Grotzer and colleagues K. Donis, D. MacGillvray, S. Mittlefehldt, R. Lincoln and R. Gould (2003). It is available on-line through the Project Zero website (www.pz.harvard.edu/).

When should we begin to teach our students to recognize, understand, and ultimately to affect these systems? I have been personally astounded by glimpses of systemic reasoning in three- to four-year olds and so, resonate with Bruner, when he observes in *The Process of Education* (1960/1977) "any subject can be taught to any child at any age in some form that is honest."

This anecdote also points to the potential of children's stories as a means of fostering homologous reasoning skills. For a sampling of such "systemic" stories, see *When A Butterfly Sneezes: A Guide for Helping Children Explore Interconnections in Our World Through Favorite Stories* (2001, Pegasus Communications). Additional stories can be found on the Waters Foundation website. (See www.watersfoundation.org; click on "literature connections.")

[xxi] Toulmin, S., & Goodfield, J. (1961). *The Fabric of the Heavens*. London: Hutchinson.