Computational Imagination and Scientific Creativity

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Imagination

Albert Einstein:
Imagination is more important than knowledge.

A central conundrum in creativity:
Since any solution to a problem must begin from what the agent already knows, how can the agent create novel solutions?

We are exploring imagination as one possible answer to this question.
Methodology:

1. Conduct a cognitive study of creative design or scientific problem solving.

2. Develop a computational model and implement it in a computer program.

3. Analyze computational models for patterns of knowledge and patterns of reasoning – (building blocks)

4. Develop and evaluate interactive tools for supporting human problem solving/learning
Our Message:

1. Knowledge is multi-layered and multi-modal; Organization of knowledge enables dynamic, opportunistic shifts among different layers of abstraction and modalities of representation.

2. Analogical retrieval, mapping and transfer occur at multiple abstraction levels and representation modalities; Analogical reasoning is not only model based but also constructive and compositional.
Outline:

1. A Study of Physics Problem Solving – Computational Model

2. A Study of Biologically Inspired Design - Cognitive Study

3. A Computational Tool for Model Construction, Simulation and Visualization
1. A Study of Physics Problem Solving

John Clement (U. Mass) designed the experiment, and collected and analyzed the verbal protocols.

Nancy Nersessian (Georgia Tech) & Todd Griffith reanalyzed the protocols in terms of constructs she had found in her analysis of historical case studies of scientific discoveries.

Griffith and I developed a computational model using building blocks my group had developed for creative design.

Griffith implemented the model in a computer program.
The two springs are identical except that the diameter of the coil in the second is twice the coil diameter of the first.

If the first spring stretches by amount $x$ when a mass $m$ is applied to it, by what amount $y$ will the second spring stretch when the same mass is applied to it?
All 14 subjects (graduate students in physics and Engineering) had knowledge of spring systems, of linear harmonic oscillators.

However, the relationship between the coil diameter, the applied mass, and the amount of stretching is hidden in the constant $k$ in Hooke’s Law ($F = kx$).

Thus, their mental models of spring systems failed to provide an answer.
After much additional reasoning, 4 of the 14 subjects gave the correct answer.

All subjects who correctly addressed the problem appeared to follow a common trajectory of reasoning.

Our computer program, called TORQUE, mimics their reasoning trajectory.
TORQUE’s (High Level) Task Structure

Problem

Model-Based Search

Problem Transformation

Model Construction

Model Transformation

Reminding / Mapping

Transfer
TORQUE *imagines* springs of various forms.

As TORQUE *imagines* springs of various forms, it is reminded of a beam attached to a wall at one end and bent because of a mass applied to it at the other.

This reminding is based on the similarity between the shapes of a full stretched spring and the bending beam.
FUNCTION

BEHAVIOR:

STRUCTURE:
Components, Relations

SHAPES:
Spatial Relations

DRAWING

DSSBF: A Layered, Multimodal Knowledge Schemata
A Partial Taxonomy of Generic Transformations:

Behavior-Level Transformations:
Repetition, Flow of Causality

Structure-Level Transformations:
Components (e.g., number of coils)
Connections

Shape-Level Transformations:
Shapes (e.g., shape of a coil),
Sizes (e.g., the diameter of the coil),
Spatial relations,
Continuity
Snapshots of TORQUE’s Working Memory
As TORQUE is reminded of other physical systems, it inspects their (functional, causal) models for any knowledge that might be potentially useful for the spring problem.

When TORQUE inspects its model of bending beams, it finds that the amount of bending is proportional to the length of the beam.

Next, it maps the length of the beam to the length of the spring, and the function of bending of beams to the function of stretching of springs.
Then, it transfers the above mathematical relationship to the spring problem, and hypothesizes that the amount of stretching in a spring might be proportional to the length of the spring coil.

This is an abductive hypothesis, not a deductive assertion: analogies in general provide no guarantee of deductive soundness or completeness.

This is idea generation.
TORQUE calculates that the length of the coil of the second spring is twice the length of the first.

It thus discovers that the amount of stretching in the second coil would twice as much as that of the first \((y=2x)\).

We evaluated the TORQUE program by showing that it could mimic the reasoning trajectory of the 4 successful subjects simply by changing the initial knowledge in the program (but keeping the knowledge schemata, the taxonomy of transformations, the analogical reasoning processes, and the task structure constant).
Note the multi-modal representation of knowledge and the multi-layered organization of multi-modal knowledge.

Note also that while analogical reminding between springs and beams is based on their visual representations, analogical mapping uses both visual and conceptual knowledge, and the unit of analogical transfer is a mathematical relationship.
2. A Study of Biologically Inspired Design

Georgia Tech’s Center for Biologically Inspired Design teaches interdisciplinary courses.

Both faculty and students from biology, chemistry, engineering, architecture, etc.

The courses typically are project oriented: students work in small interdisciplinary groups, often outside the classroom.

The final design project is critiqued publicly.
For two years, Michael Helms and Swaroop Vattam from my research group have been observing all classroom interactions as well as the work of a few interdisciplinary design teams outside the classroom.

Helms and Vattam observed the design trajectory of a team of biologists and engineers asked to design an underwater microbot with a locomotion modality that would ensure stealth.

In general,

Biologists tend to talk in terms of structures and causal mechanisms (but not functions);

Engineers tend to talk in terms of functions (and a lot less in terms of structures and causal processes).

They achieve a shared vocabulary once they start making drawing (external representations).
The design team’s initial exploration for the microbot design focused on the locomotion of the copepod as a source for the design concept.

In exploring this concept, the team became aware that the copepod uses two rhythms (of leg-like appendage movement) for achieving underwater motion: A slow and stealthy rhythm during foraging for food, and a quick but non-stealthy rhythm for escaping from predators.

This led the team to decompose their original problem into two subfunctions, one for slow and stealthy movement, and one for rapid, yet stealthy movement.
Next, the team used the squid locomotion as a source for the design concept for addressing the second subfunction (stealthy, fast motion).

Some squids implement a single orifice, interrupted, jet propulsion for forward motion. This locomotion is stealthy because its wake matches the external disturbances that naturally occur in the surrounding water.

The mechanism for stealth in squid locomotion (wake matching) is significantly different from the way stealth is achieved in copepod motion (wake minimizing).
Note the complex interplay between the mechanisms of problem decomposition and analogical reasoning, leading to compound analogies and resulting in a combination of multiple design ideas.
Move slow, minimize wake
Move underwater stealthily
Move fast, match wake

(1) Have leg-like appendages
(2) Rhythmically move those appendages according to “metachronal beating pattern”

Include a single orifice interrupted jet engine

Copepod locomotion

Squid locomotion

The Design Trajectory
FUNCTION:
Filtration System to capture Indoor allergens of sizes varying from 0.01 to 100 micron

BEHAVIOR:
Mechanical capturing of particles and allergens through small and tightly packed pores

STRUCTURE:
A layer of diatom pores packed to act as a filter medium.

SHAPEs:
2 layers of diatom pores packed to maximise capture size.

FUNCTION:
Pores ~20-200nm can catch most of the microscopic particles

BEHAVIOR:
Mechanical capturing of particles through small and tightly packed pores

DRAWING:
Diatoms incorporated in the overall solution

A Drawing made by one of the Design Teams
Note the multiple levels of abstraction and the multimodal representations.

Note also that analogical mapping and transfer occur at multiple abstraction levels.
3. A Computational Tool for Model Construction, Simulation and Visualization

Cindy Hmelo-Silver (Rutgers) has found that while Experts think about complex systems in terms of their structure, functions and behaviors, novices (e.g., middle school children) think in terms of structure, show minimal understanding of function, and almost no understanding of behaviors.

Rebecca Jordan (Rutgers) is an ecologist. Spencer Rugaber (Georgia Tech) is an HCI expert.
ACT (for Aquarium Construction Toolkit) has several components:

1. The physical aquarium.
2. An SBF modeling tool
3. A simulation and visualization tool (based on Wilsenky’s NetLogo)
4. An electronic notebook
5. Interfaces to WWW, Excel, PDF
6. Facility for replay of work
**Bh: Nitrogen cycle**

- **Initial State:** Ammonia level: zero, Nitrite level: zero, Nitrate level: zero
- **State 1:** Ammonia level: low, Nitrite level: low, Nitrate level: low
- **State 2:** Ammonia level: low, Nitrite level: zero, Nitrate level: zero
- **State 3:** Ammonia level: high, Nitrite level: low, Nitrate level: zero
- **State 4:** Ammonia level: high, Nitrite level: low, Nitrate level: low
- **State 5:** Ammonia level: high, Nitrite level: high, Nitrate level: high

- **Fn: Remove ammonia**

**Bh: Maintain fish**

- **Initial State:** Fish (number): 2, Fish (health): healthy
- **Maintain State:** Fish (number): 2 + ∆, Fish (health): healthy

- **Fn: Clean water**
- **Fn: Provide oxygen**
- **Fn: Regulate heat**
- **Fn: Remove ammonia**

**Str: Fish tank**

- Plants
- Air pump
- Heater
- Thermostat
- Food

**Str: Nitrogen cycle**

- Nitrosomonas
- Nitrobacter
- Nitrate
- Nitrite
- Fish
- Water
- Ammonia
ACT has just been introduced into middle schools.

We are analyzing preliminary data.

But note the various notions of a model:
1. Conceptual
2. Simulation
3. Visualization
1. Knowledge is multi-layered and multi-modal; Organization of knowledge enables dynamic, opportunistic shifts among different layers of abstraction and modalities of representation.

2. Analogical retrieval, mapping and transfer occur at multiple abstraction levels and representation modalities; Analogical reasoning is not only model based but also constructive and compositional.
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