Cognitive Challenges of Biologically Inspired Design

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(and William Hancock, Michael Helms, Swaroop Vattam, Bryan Wiltgen, Spencer Rugaber and Jeannette Yen)

NASA Summit, August 2016

Design & Intelligence Laboratory

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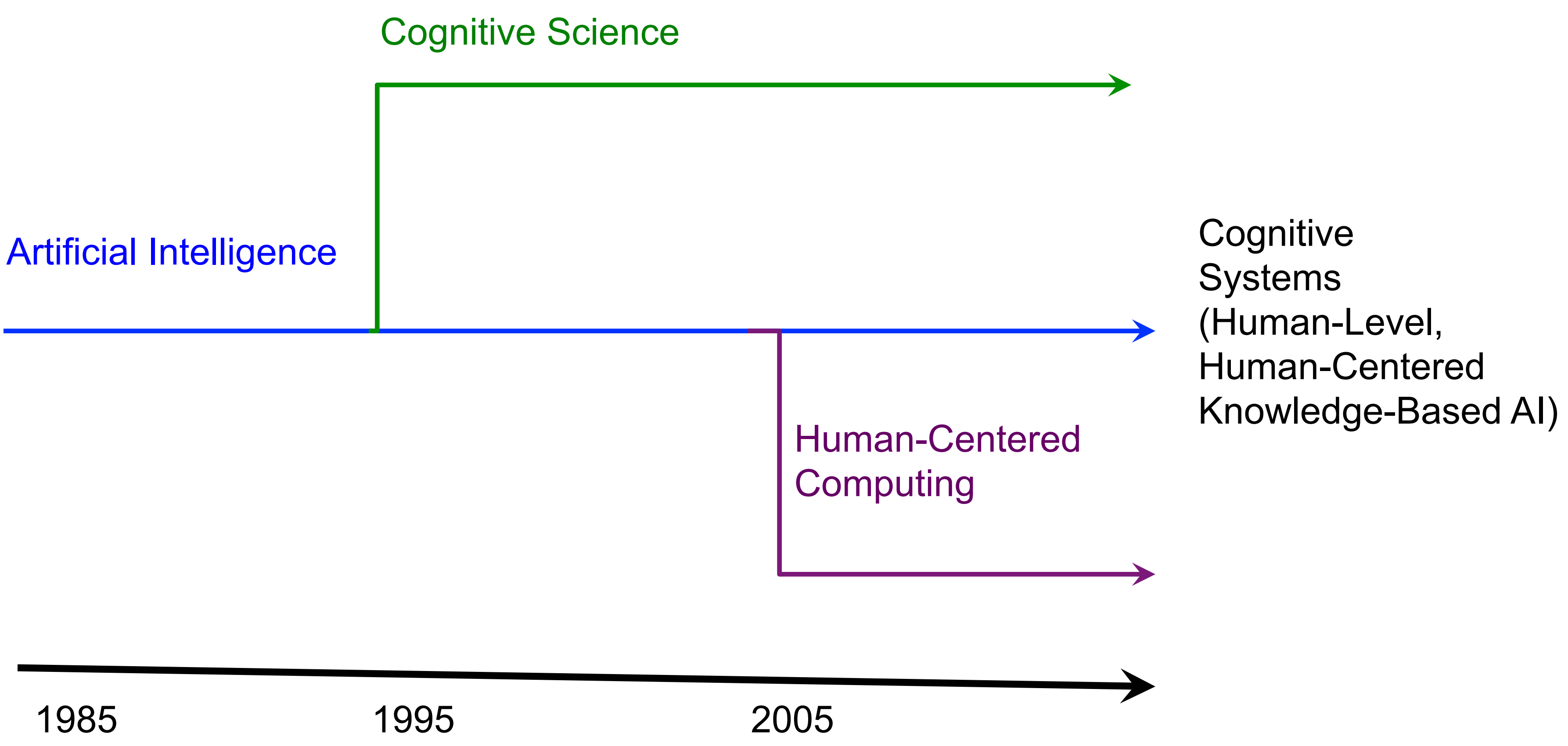

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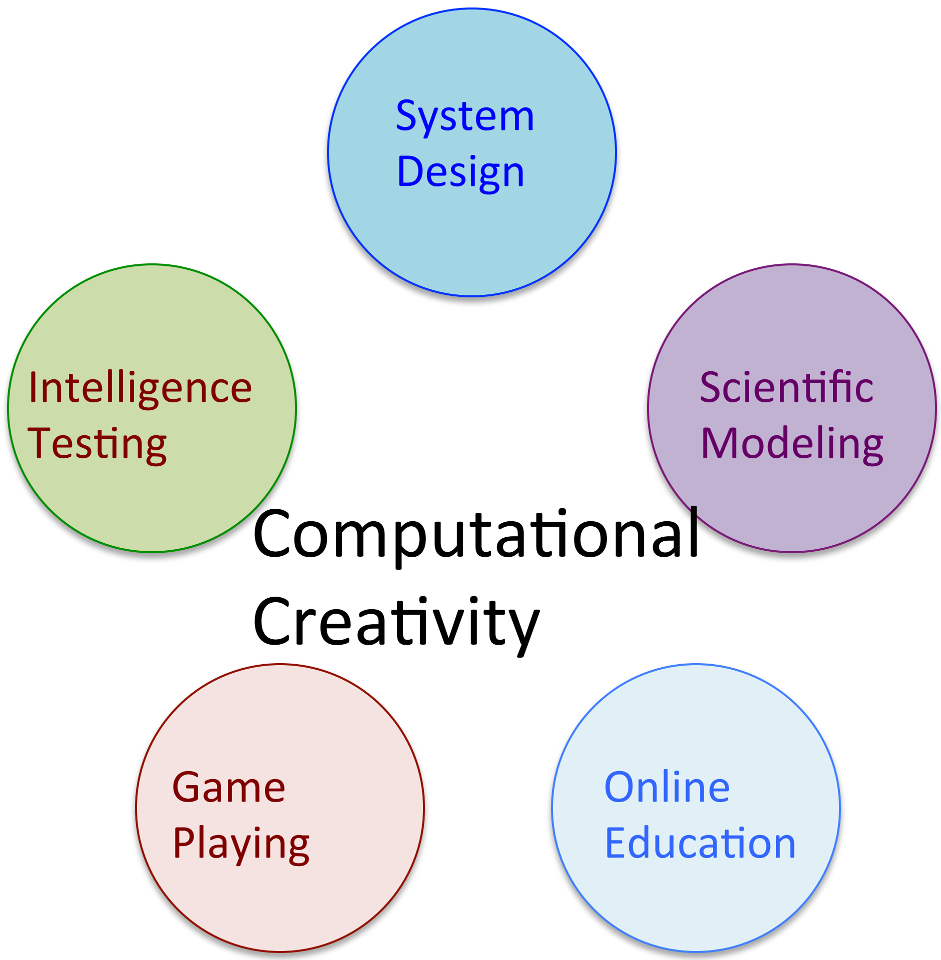

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Faculty

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Joyner

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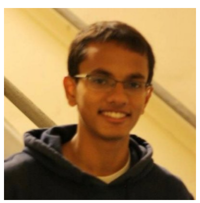
Rugaber

Ph.D. Students

Banerjee



Delgado

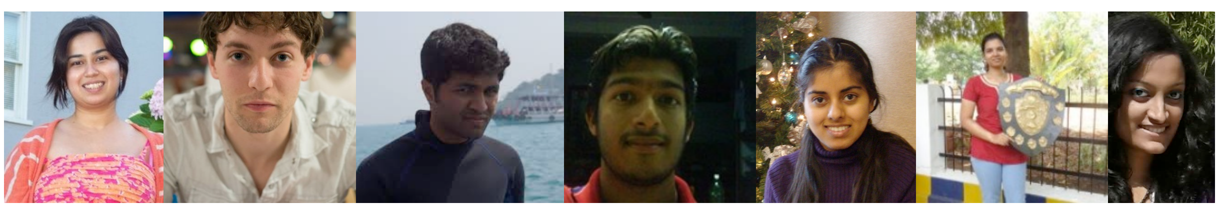
Ehsan

Fitzgerald

Wiltgen

M.S Students

AwasthyFrazerKulkarniKumbleKoushikSarathyShetty



UG Students

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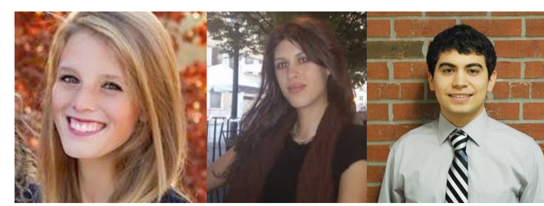


Biologically Inspired Design

(Biomimicry, Biomimetics, Bioinspiration)

1. View nature as a vast library of designs (products, processes, systems)

2. Generation of designs by analogy to nature.

3. Evaluation of designs using nature as the standard.

Biologically Inspired Design: ***A new movement in design***

- Creativity and innovation
- Major, rapid advances in biology
- The world is networked a lot more now.
- Critical, urgent and increasing needs of environmental sustainability

But for biologically inspired design to be successful, we need …

- Repeatability

  A design science, a theory

- Scalability

  A set of computational techniques and tools

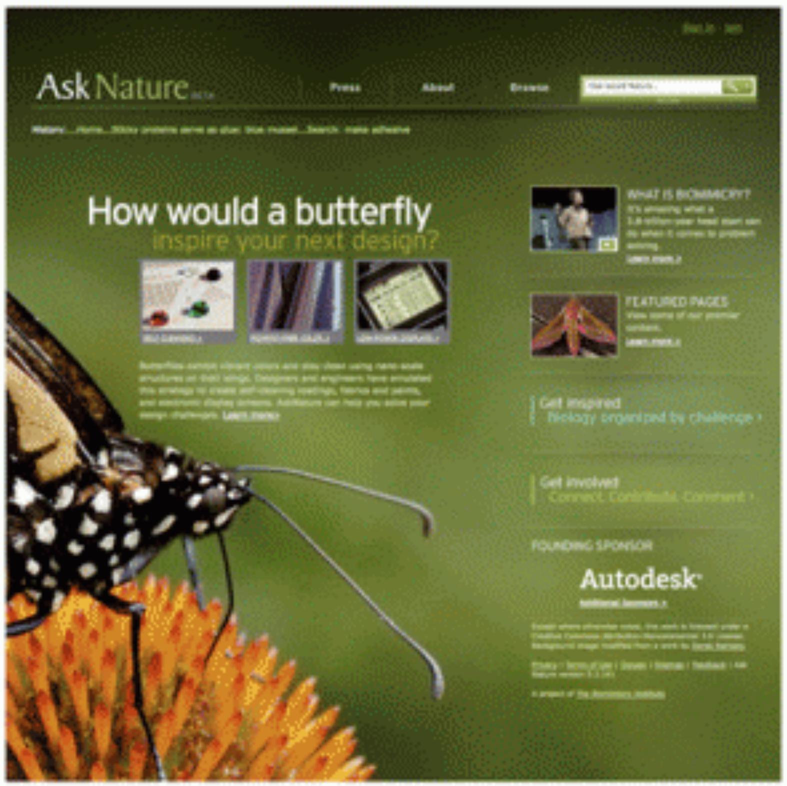
A thought experiment

Imagine we are in ~1956:

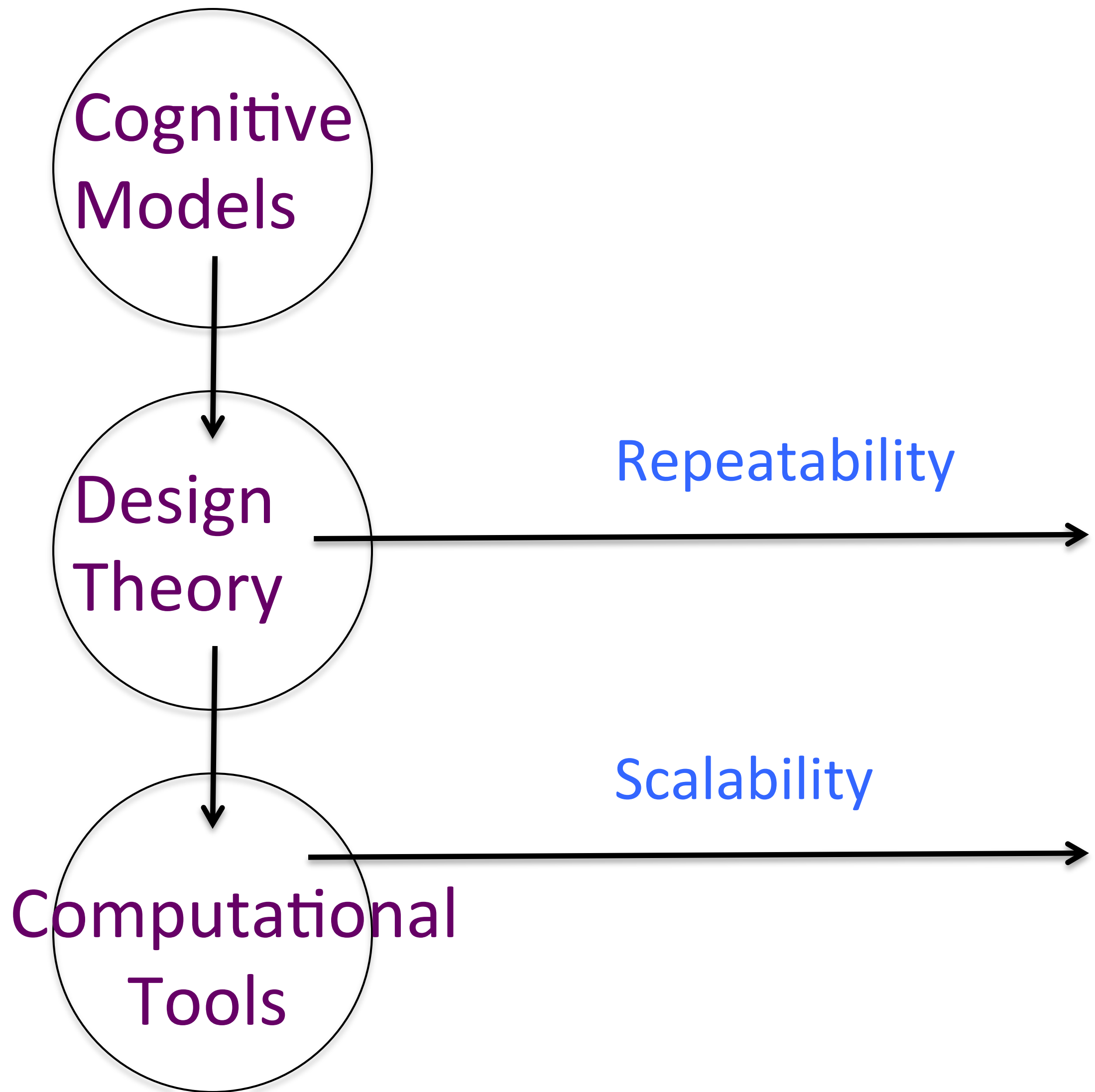
Why and how did computer science succeed?

BioTRIZ as a Design Theory

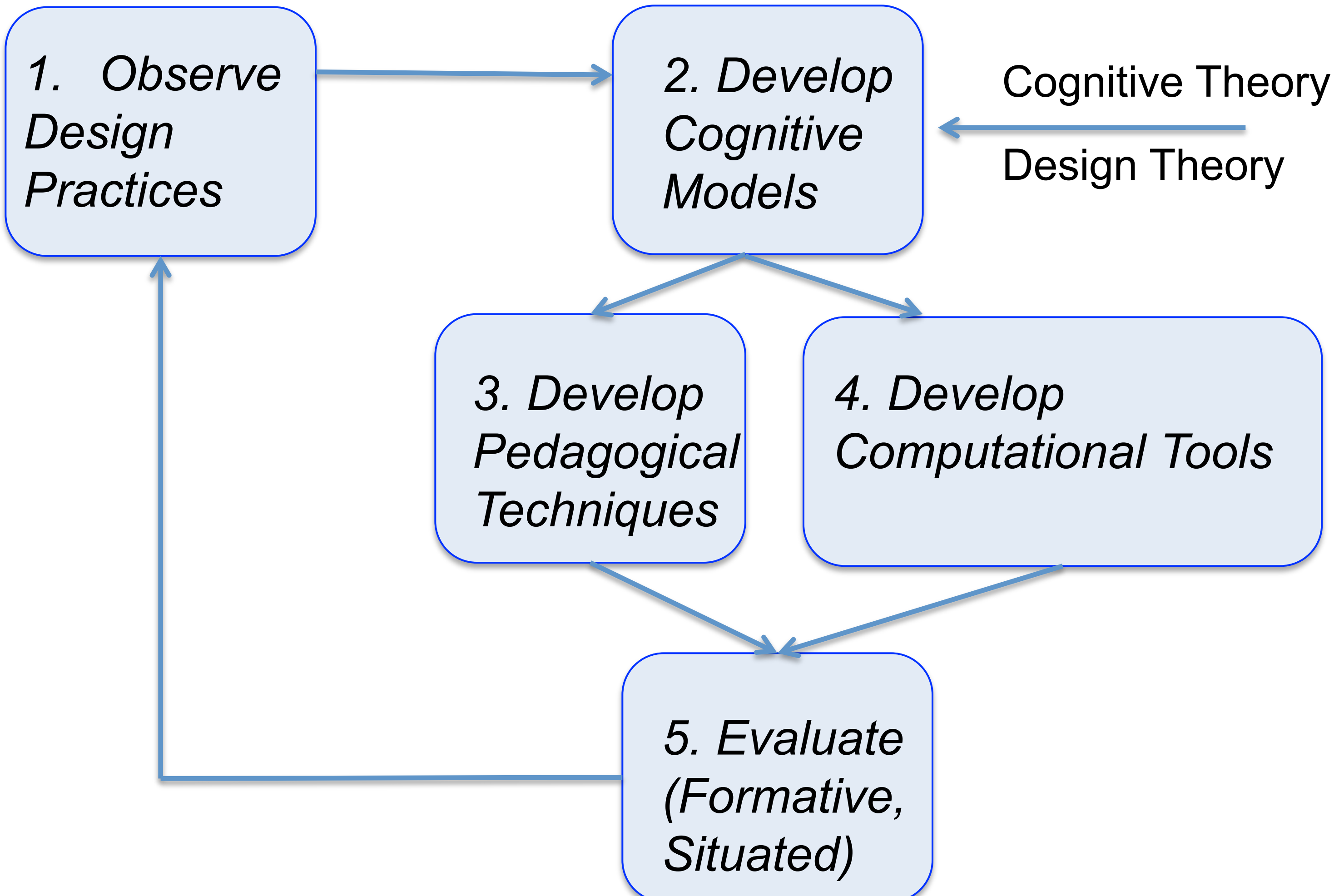
AskNature as a Computational Tool



We ground design theory and computational tools in cognitive models



DILab Research Methodology for Studying Biologically Inspired Design



Georgia Tech Biol/ME/ISyE/PTE 4740: Biologically Inspired Design

Jeannette Yen

Yearly
Senior level
Interdisciplinary
Project-based

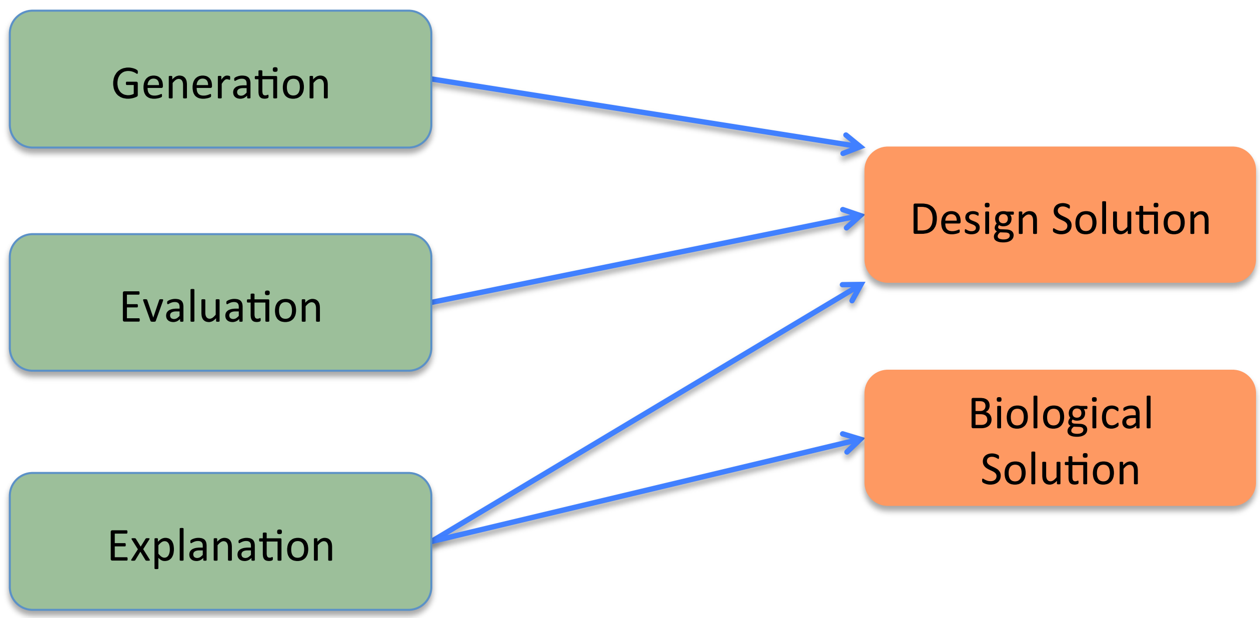
2006-2013
(Yen et al. 2011, 2014)

Interdisciplinary team projects in DILab
Prototyping

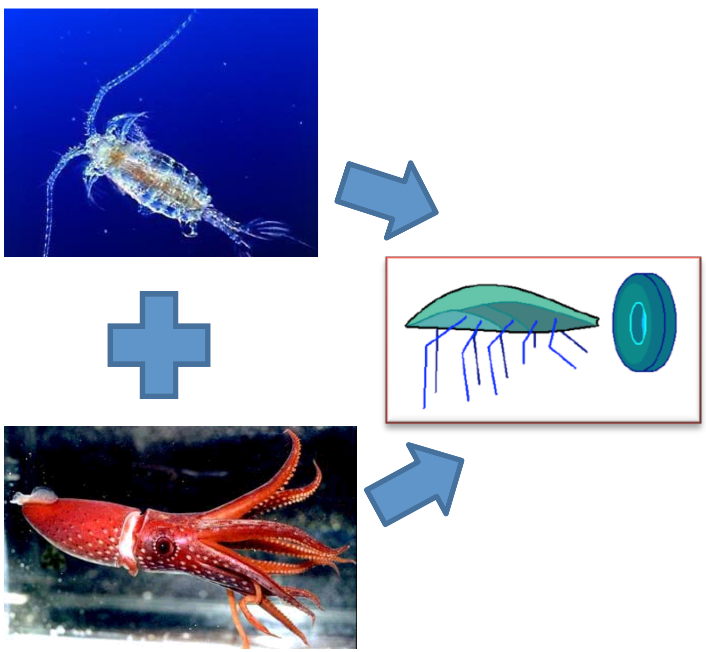
(Weiler & Goel 2015)

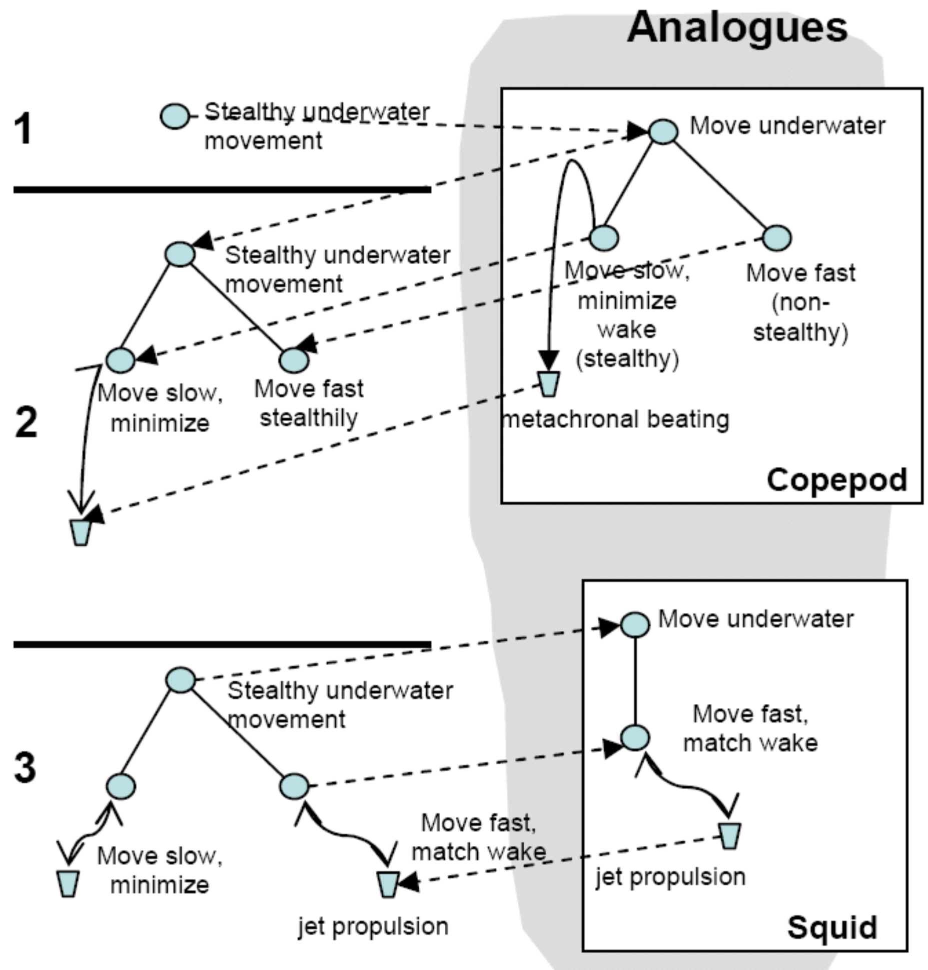
First Finding:
Analogies are all over the place

Designers make analogies for…



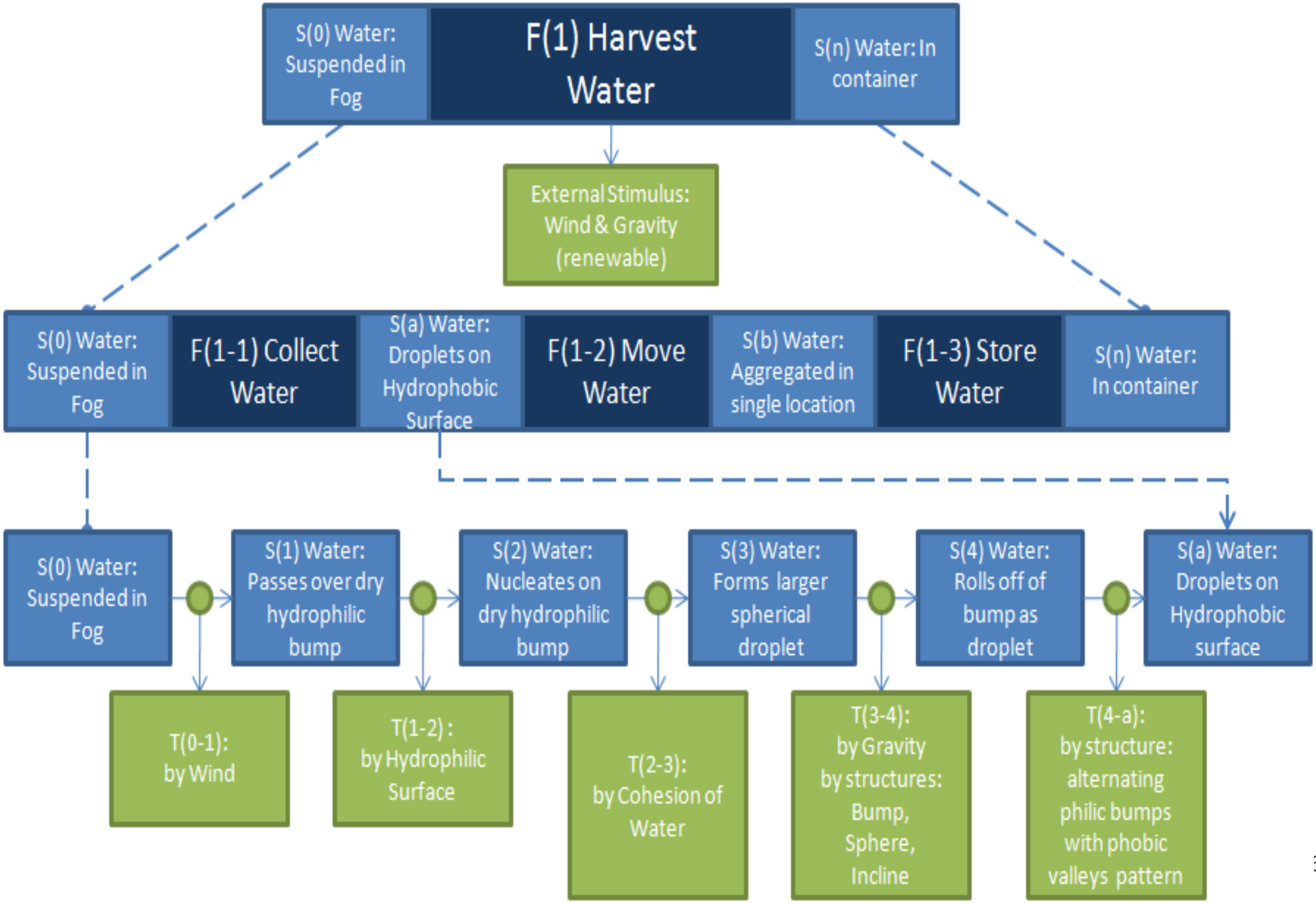
Second Finding: Compound Analogies



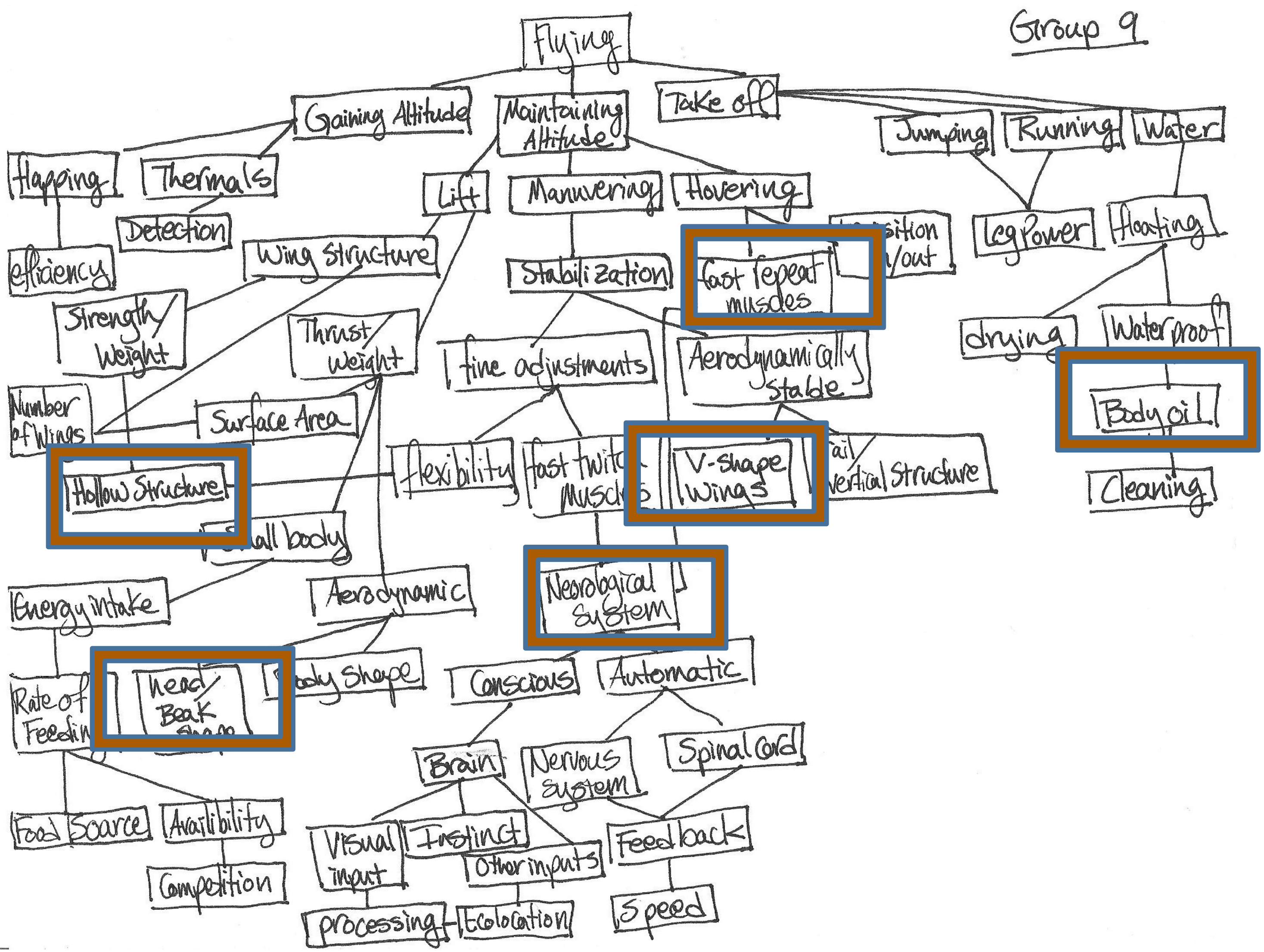


Third Finding: Analogical Transfer of Causal Mechanisms

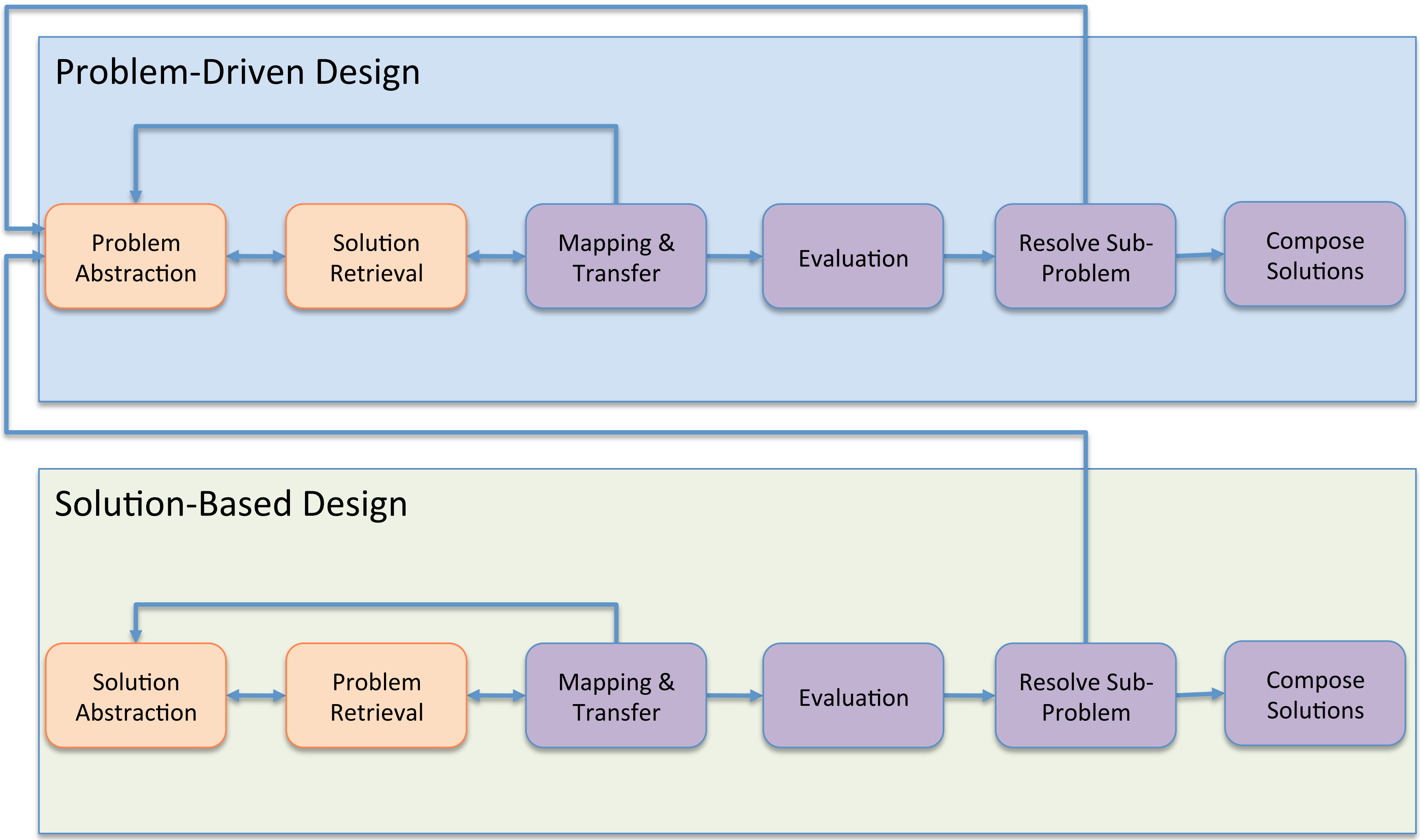
Example: The Fog Harvesting Pattern



Fourth Finding: Analogical Transfer of Problem Decompositions



Fifth Finding: Problem-Driven and Solution-Based Processes of Design

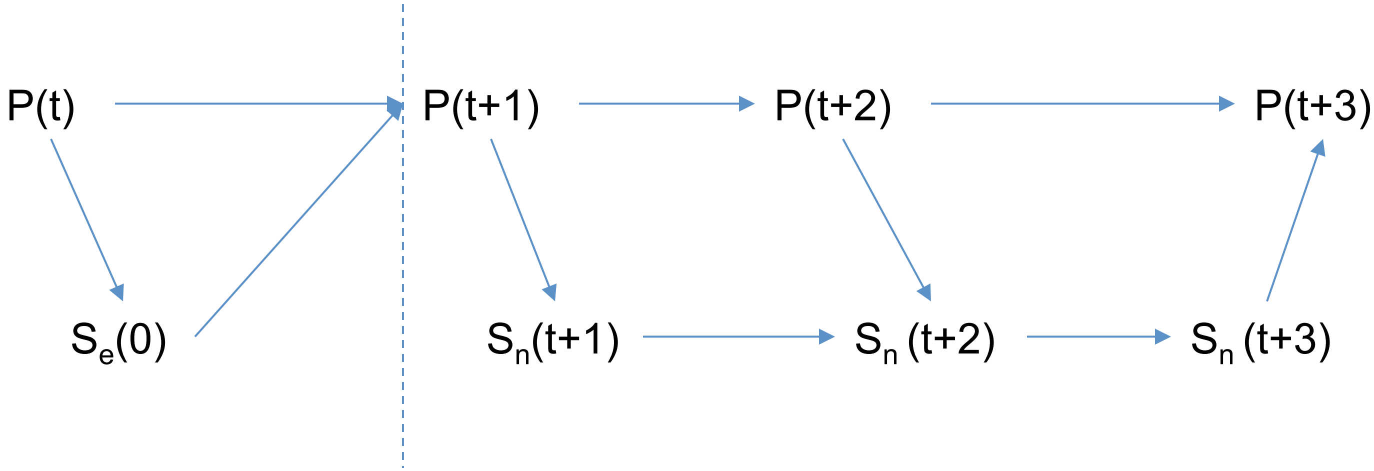


Solution-Based Design

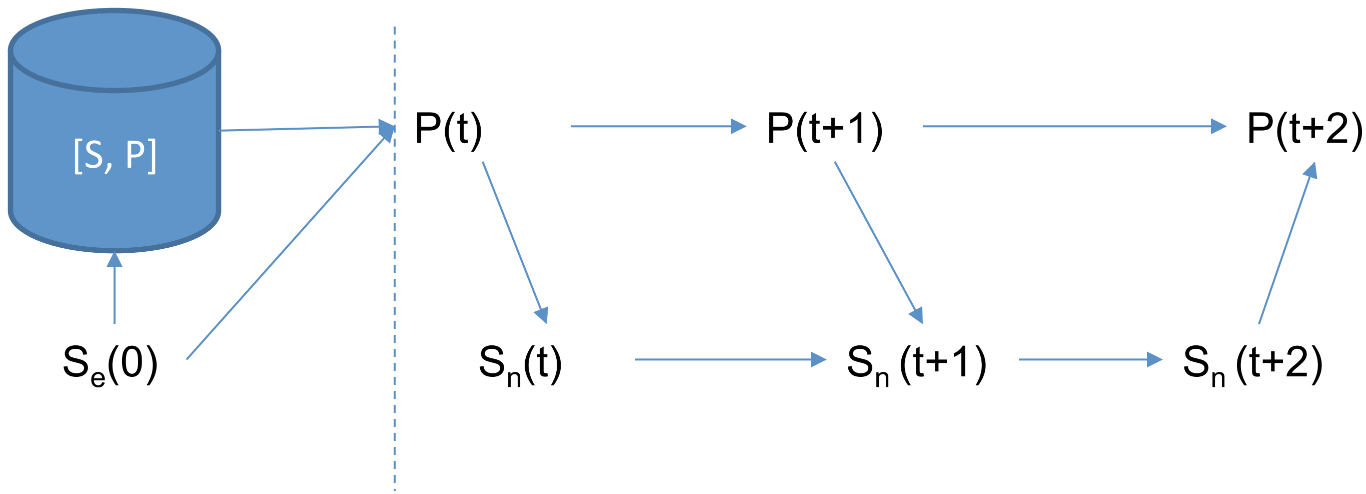
Example: Design of windmill turbines mimicking the tubercles on the pectoral flippers of humpback whales

Sixth Finding: Problem Evolution and Inception

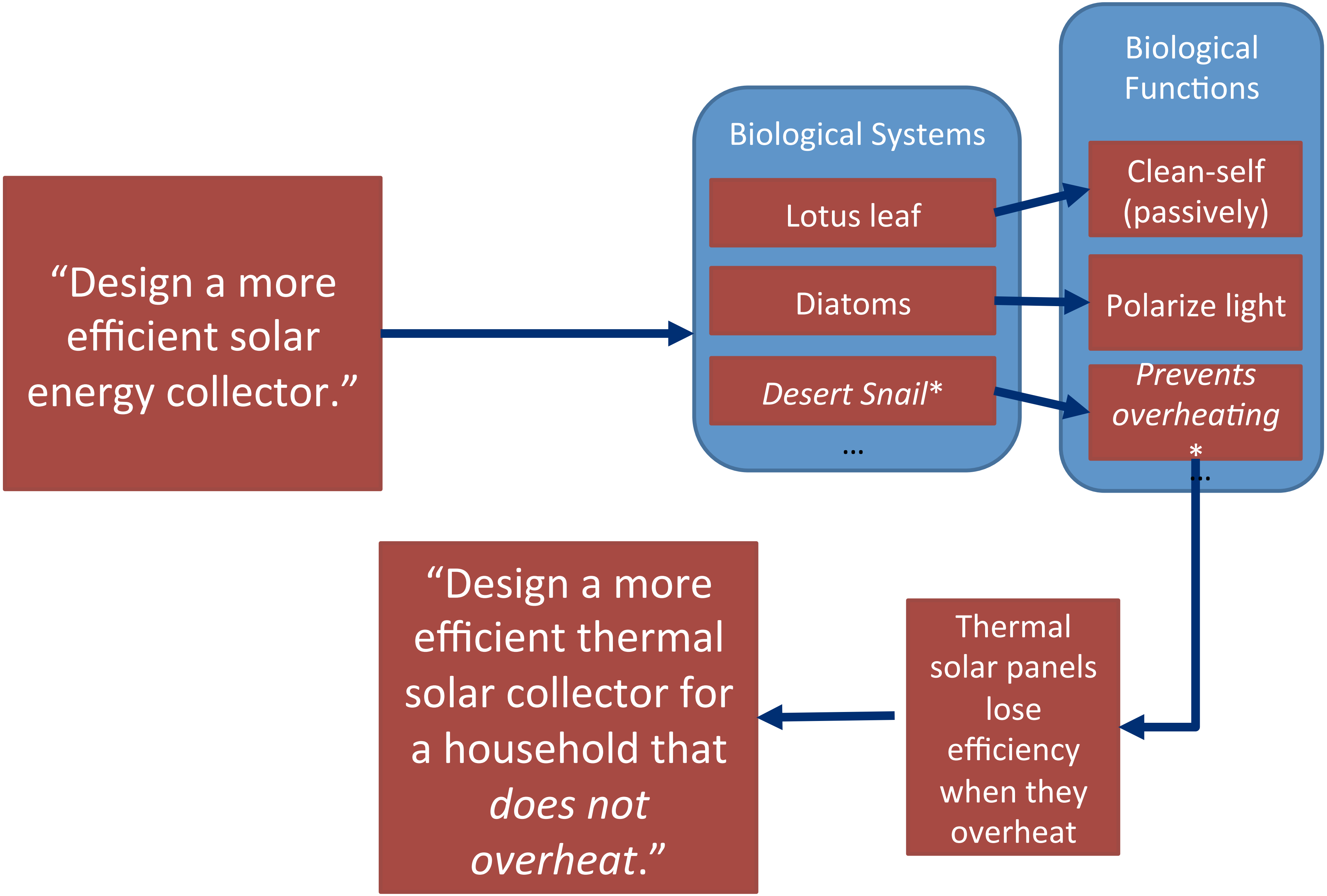
Solution-based Problem Evolution



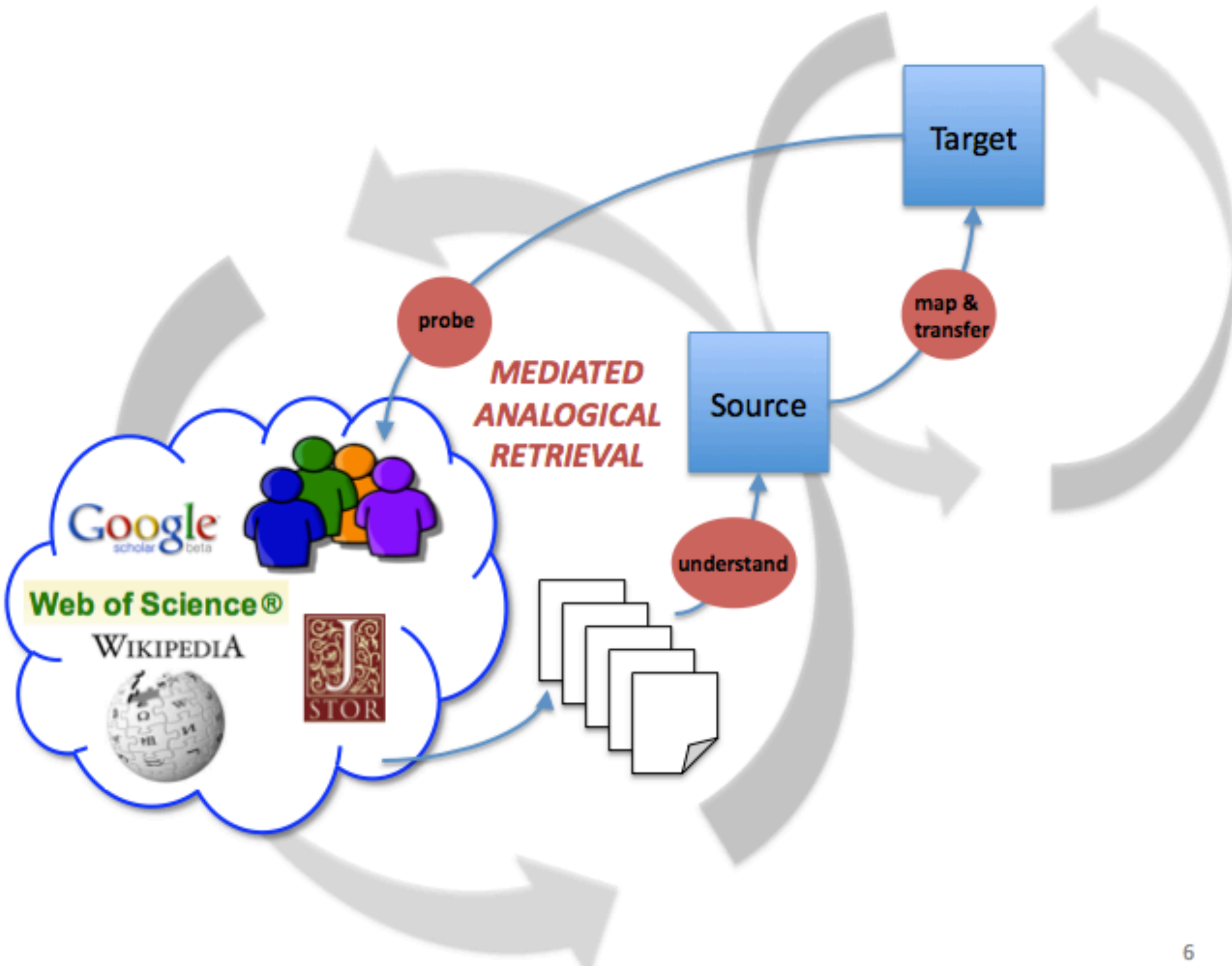
Solution-based Problem Inception



Analogical Problem Evolution Example



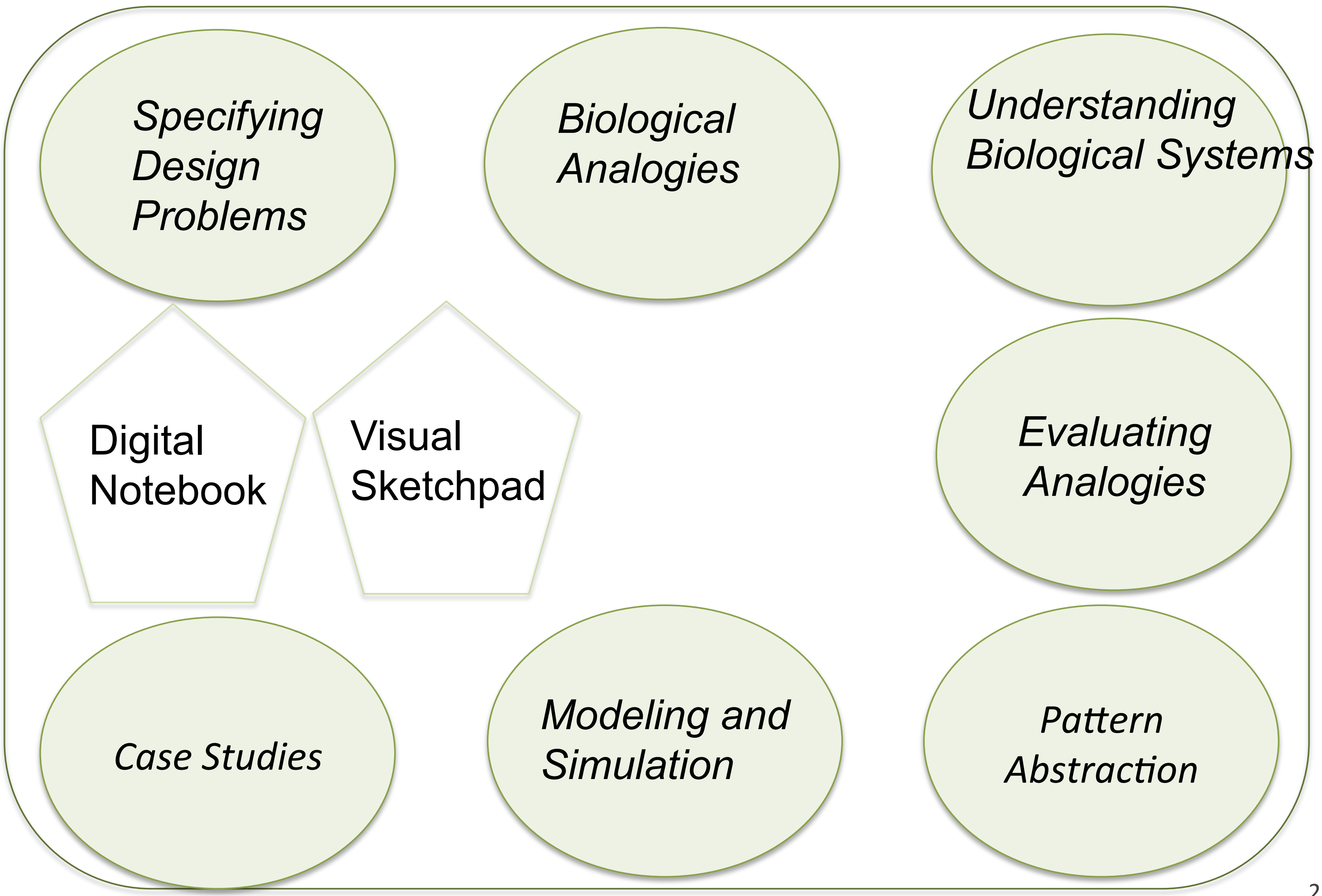
Seventh Finding: Situated Analogy



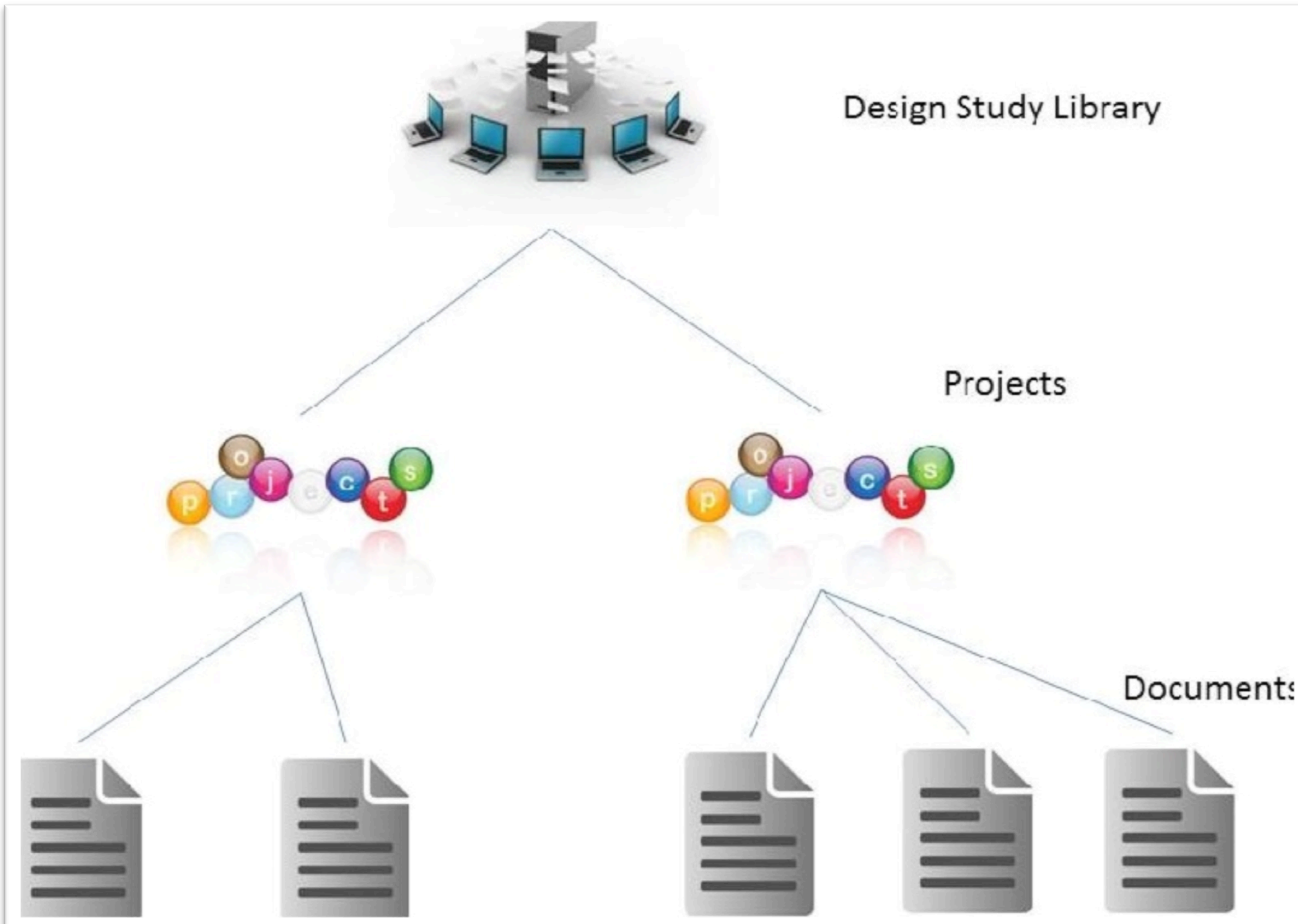
Eight Cognitive Challenges of Biologically Inspired Design
1. Communication across disciplines
2. Understanding biological and technological systems
3. Understanding the design processes
4. Specifying problems
5. Searching for biological analogies
6. Evaluating biological analogies
7. Analogical transfer
8. Evaluating design solutions

Cognitive Challenge	Our Solution
1. Communicating across disciplines	Shared language (SBF)
2. Understanding systems	Library of models (DANE)
3. Understanding design processes	Library of case studies (DSL)
4. Specifying problems	Problem schema (Four Box)
5. Searching for analogies	Search engine for the web (IBID, Watson+)
6. Evaluating biological analogies	Matching (T square)
7. Analogical transfer	Design patterns
8. Evaluating design solutions	Mapping, Simulation (AEMS)

BIDE: Interactive Design Environment



Design Study Library (DSL)



Case Study Sample

- Identify a problem:
  - lawn mower generates noise
  - between 85 to 90 dB
  - a source of annoyance
  - cause hearing damage

Case Study Sample

- "Quiet" nature systems:
  - Owl Feathers
  - Whale Tubercles
  - Cat's Paws
  - Maple Seed
  - Leopard
  - Frog
  - ……17 systems collected

Case Study Sample

- Biology v.s. Technical:

Problem Target (lawnmower blade)		Biological Source (Eagle Owl feathers)
Operational Environment		Operational Environment
Urban areas	Different	Rural areas
Residential lawns	Different	Wooded and open land
Wear due to soil and foliage	Similar	Wear due to flight mechanics
In the air	Same	In the air
Broad temperature/humidity range	Same	Broad temperature/humidity range

Case Study Sample

- Re-design blade shape:

Enables deep analysis

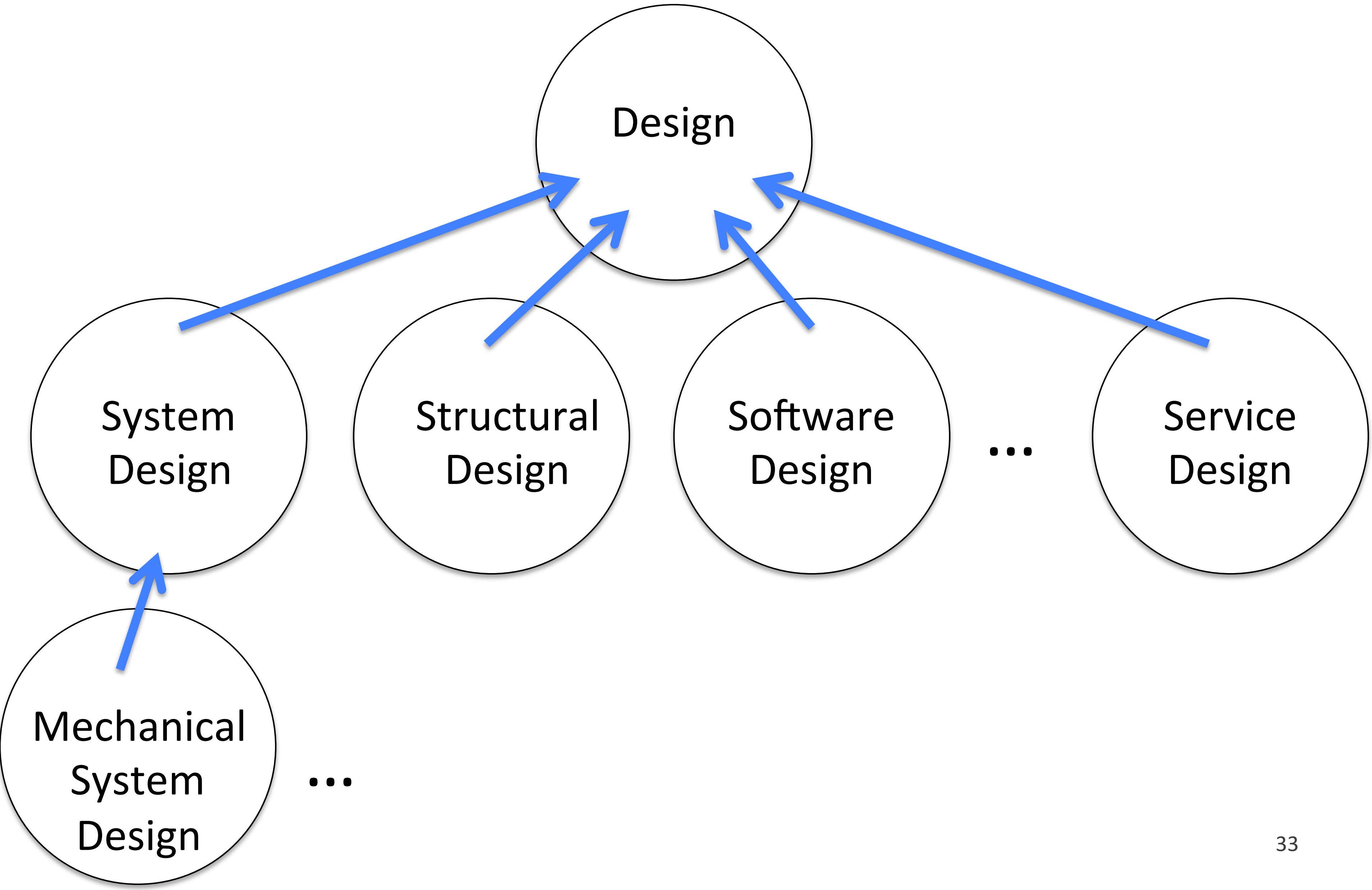
- Are the processes biologically inspired design domain-independent?

- Are the processes biologically inspired design scale-independent?

A fundamental conundrum:

bioinspiration ranges across many domains and scales, BUT ALL our theories, techniques and tools are domain and scale independent!

Domain Independence of Design?



Six Patterns

P1. Compound analogy is rare with solution-based design.

P2. Problem decomposition is likely to be found when problem-driven design too is found.

P3. Solution-based design is commonly found in physiology, and not as much in other domains.

Six Patterns

P4. Sensing commonly uses problem-driven design, not solution-based design.

P5. Materials and sensing rarely occur together.

P6. Environmental impact analysis is seldom done with solution-based design.

Conclusion

Biologically inspired design is domain specific!

Conjecture

Biologically inspired design is scale independent!

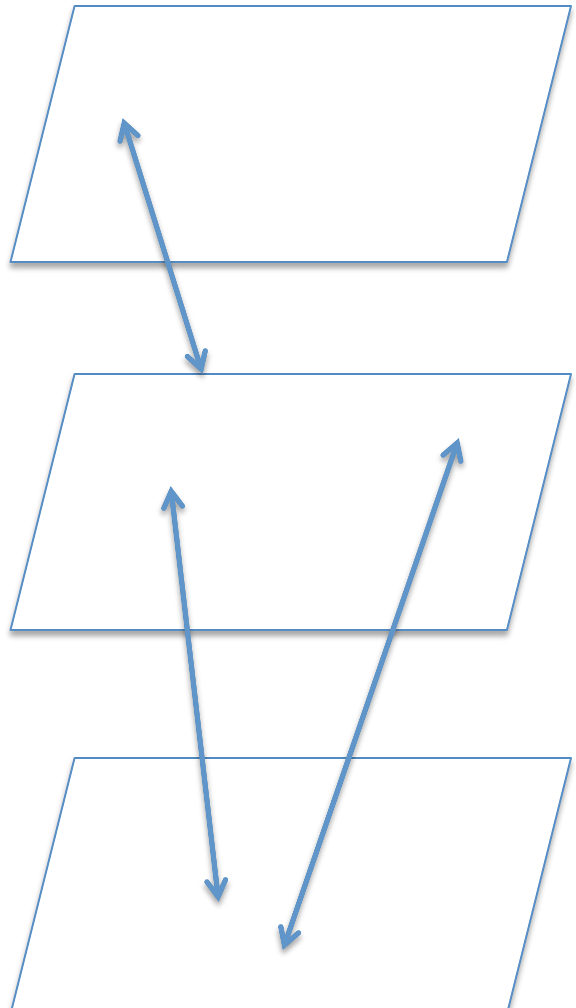
Finding biological analogues: Challenges

- Findability
- Recognizability
- Understandability

Structure, Behavior, Function - First Idea: Abstraction

Function
(Outcome, Result)
Observable, Measurable)

Schema



Behavior
(Mechanism, Causal)
Composition, Explanation)

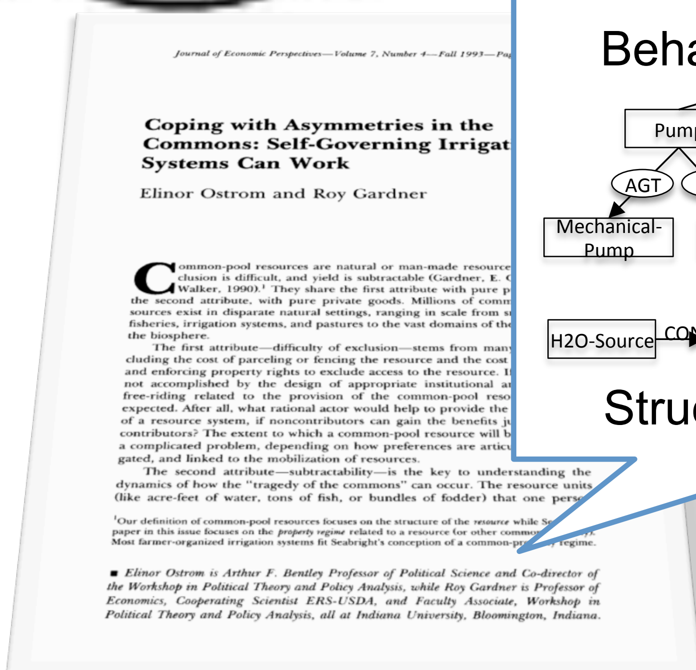
Graphs,
Equations

Structure
(Physical, Analog,
Visible)

Physical structure,
Replica
Photograph,
Diagram

(Goel, Rugaber & Vattam 2009)

for BID



Journal of Economic Perspectives—Volume 7, Number 4—Fall 1993—Pa

Coping with Asymmetries in the Commons: Self-Governing Irrigat Systems Can Work

Elinor Ostrom and Roy Gardner

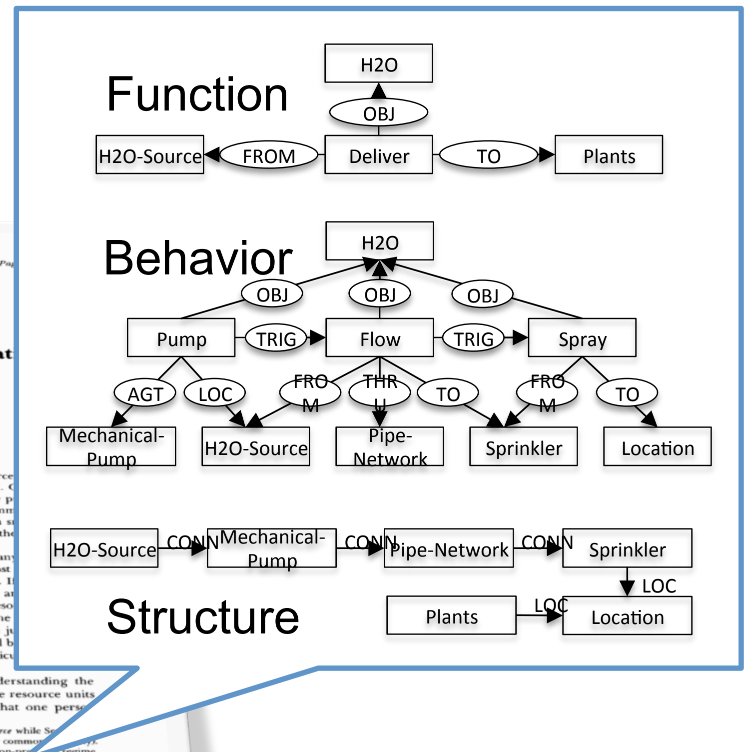
Common-pool resources are natural or man-made resource clusion is difficult, and yield is subtractable (Gardner, E. C Walker, 1990).[1] They share the first attribute with pure p the second attribute, with pure private goods. Millions of comm sources exist in disparate natural settings, ranging in scale from s fisheries, irrigation systems, and pastures to the vast domains of the the biosphere.

The first attribute—difficulty of exclusion—stems from many cluding the cost of parceling or fencing the resource and the cost and enforcing property rights to exclude access to the resource. I not accomplished by the design of appropriate institutional ar free-riding related to the provision of the common-pool reso expected. After all, what rational actor would help to provide the of a resource system, if noncontributors can gain the benefits ju contributors? The extent to which a common-pool resource will b a complicated problem, depending on how preferences are artic gated, and linked to the mobilization of resources.

The second attribute—subtractability—is the key to understanding the dynamics of how the "tragedy of the commons" can occur. The resource units (like acre-feet of water, tons of fish, or bundles of fodder) that one pers

[1]Our definition of common-pool resources focuses on the structure of the *resource* while Se paper in this issue focuses on the *property regime* related to a resource (or other common Most farmer-organized irrigation systems fit Seabright's conception of a common-pr regime.

■ *Elinor Ostrom is Arthur F. Bentley Professor of Political Science and Co-director of the Workshop in Political Theory and Policy Analysis, while Roy Gardner is Professor of Economics, Cooperating Scientist ERS-USDA, and Faculty Associate, Workshop in Political Theory and Policy Analysis, all at Indiana University, Bloomington, Indiana.*



Data: Natural Language Documents

“The mechanism by which fog water forms into large droplets on a beaded surface has been described from the study of the elytra of beetles from the genus Stenocara. The structures behind this process are believed to be hydrophilic peaks surrounded by hydrophobic areas; water carried by the fog settles on the hydrophilic peaks of the smooth bumps on the elytra of the beetle and form fast-growing droplets that - once large enough to move against the wind - roll down towards the head. ”

Thomas Nørgaard and Marie Dacke (2010) Namib Desert Darkling Beetles. Frontiers in Zoology 7: 23.

Knowledge: Structure, Behavior, Function

Structure:

- Name: Elytra
- Properties: hydrophobic, hydrophilic, smooth
- Parts: grooves

Knowledge: Structure, Behavior, Function

Causal Behavior:

- Predicate – Move
- Cause - “water carried by the fog settles on the hydrophilic peaks of the smooth bumps on the elytra of the beetle and form fast-growing droplets that - once large enough“
- Effect - “roll down towards the head”

Input: A Function/Goal/Task or a Structure/Component/Entity

Function

- Move

Structure:

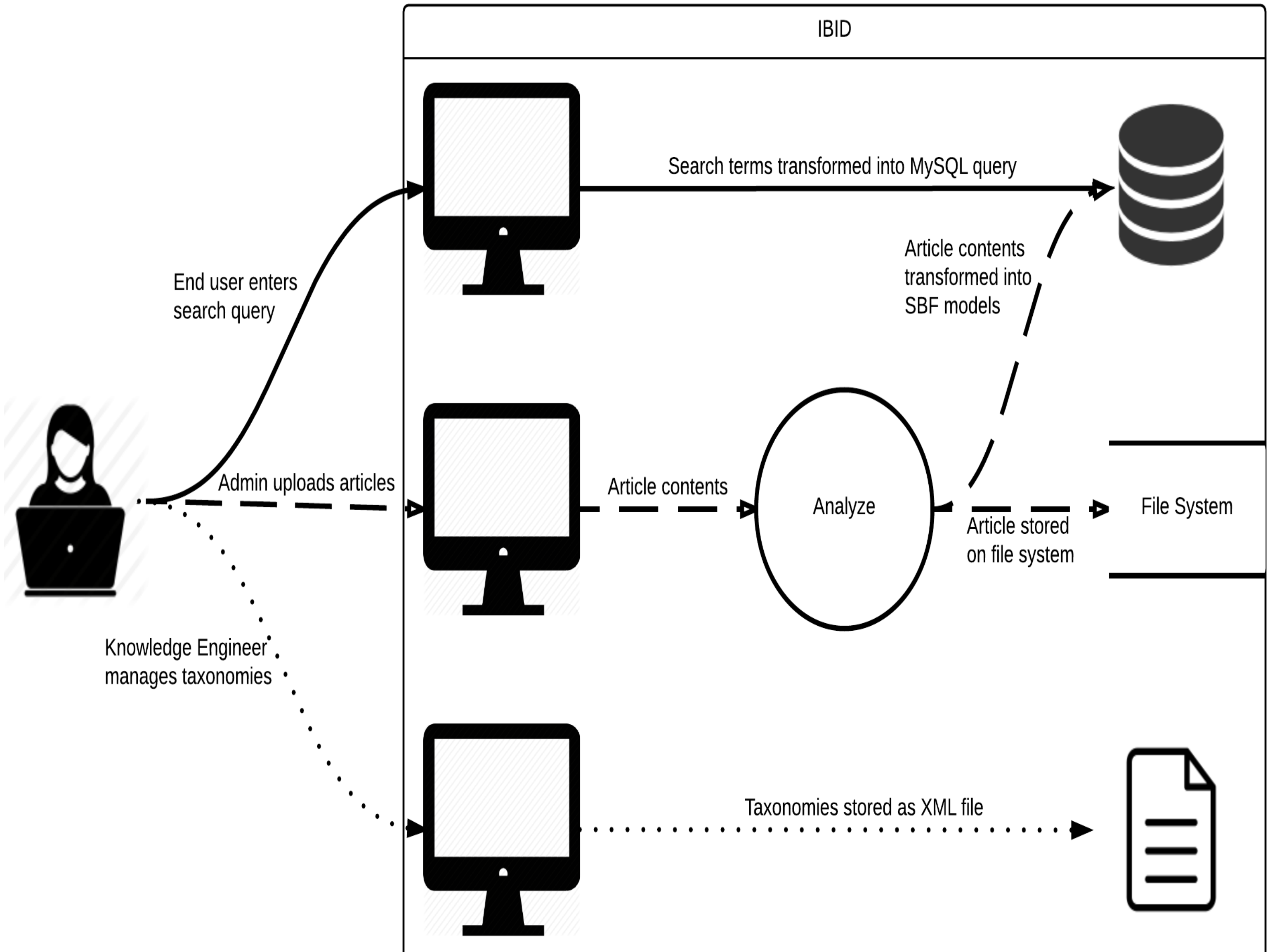
- Name: Elytra

Output: Natural Language Documents

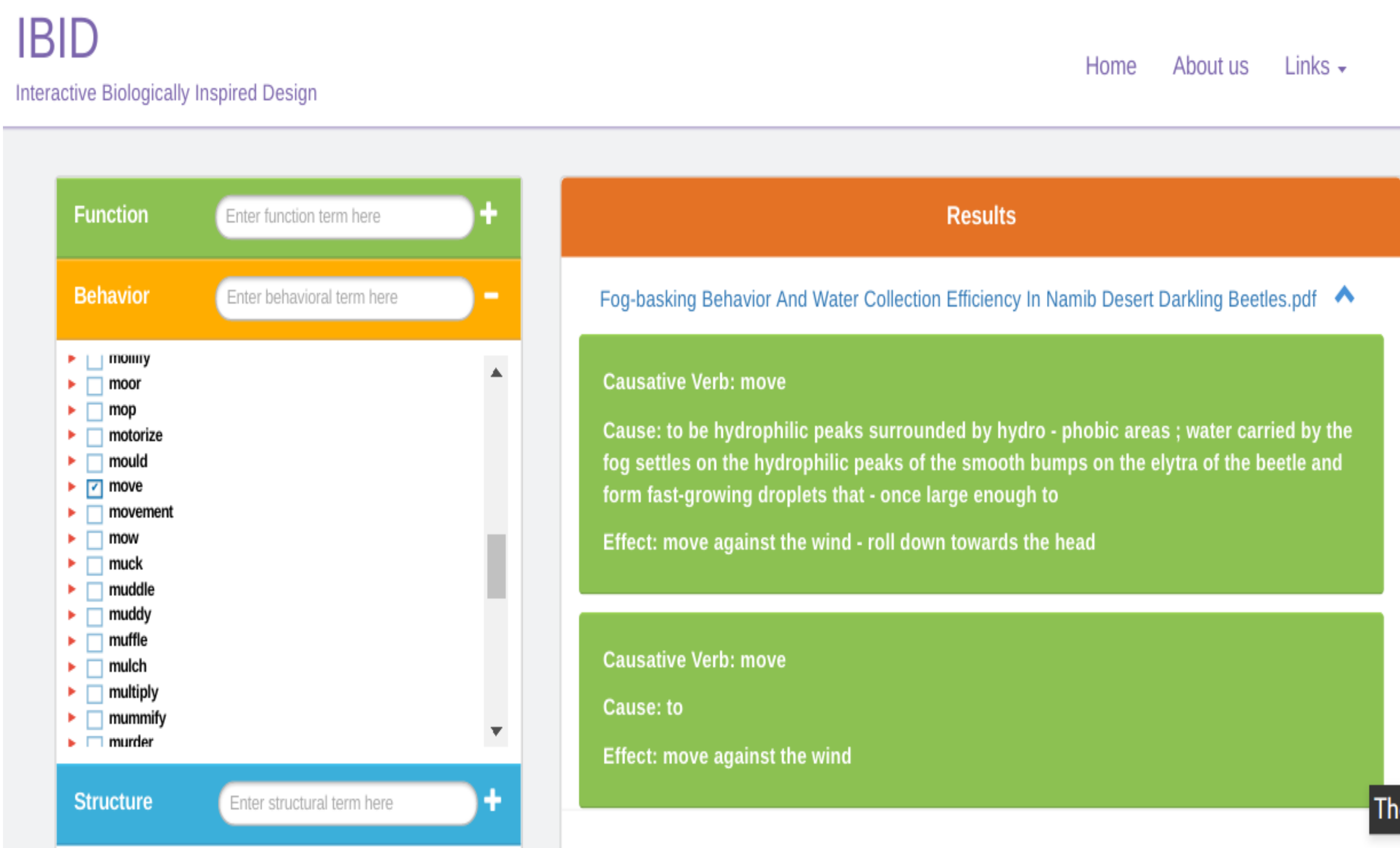
"The mechanism by which fog water forms into large droplets on a beaded surface has been described from the study of the elytra of beetles from the genus Stenocara. The structures behind this process are believed to be hydrophilic peaks surrounded by hydrophobic areas; water carried by the fog settles on the hydrophilic peaks of the smooth bumps on the elytra of the beetle and form fast-growing droplets that - once large enough to move against the wind - roll down towards the head. "

PLUS the semantic annotations..

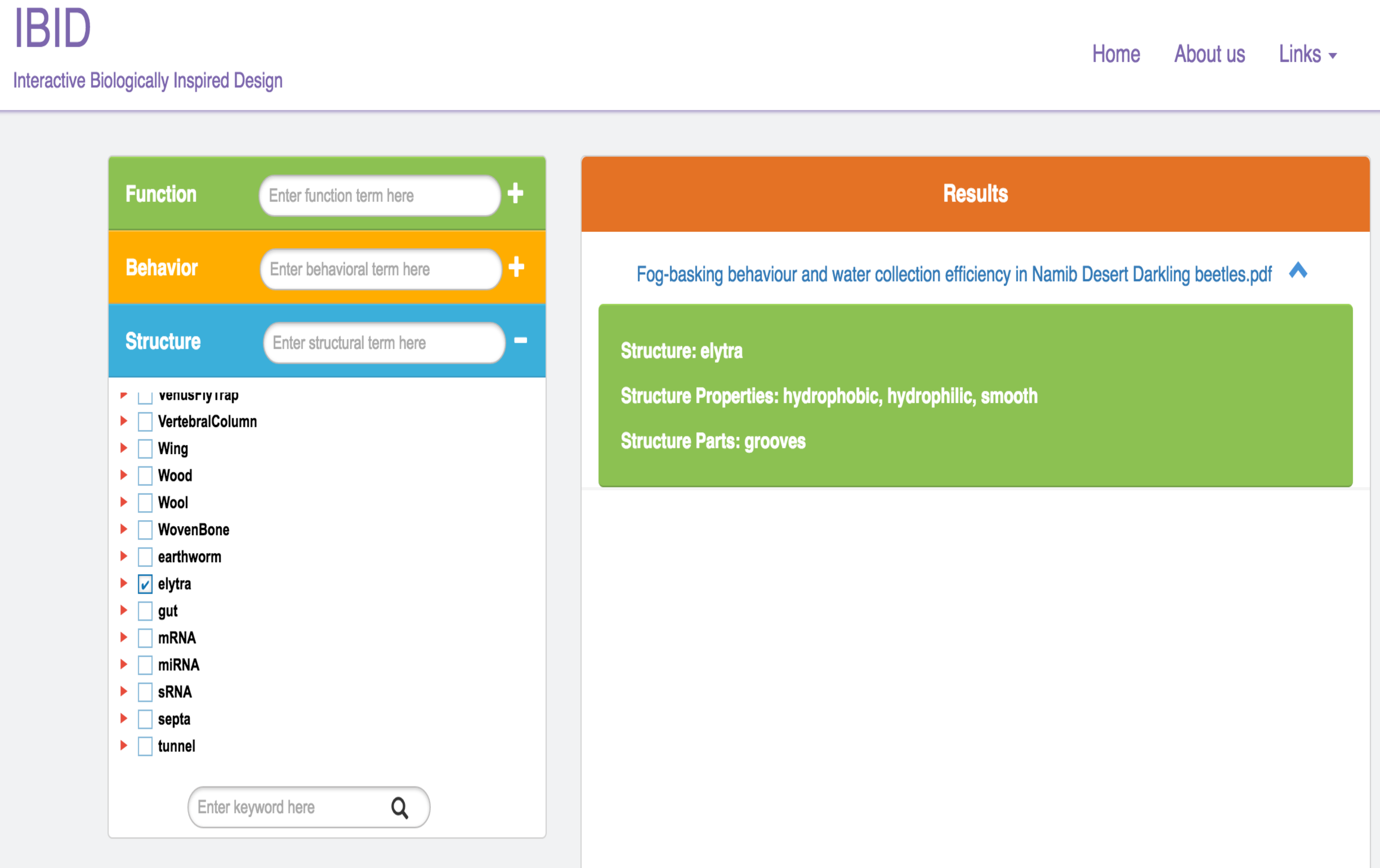
Computational Architecture



Interface


IBID
Interactive Biologically Inspired Design
Home
About us
Links
Function
Enter function term here
Behavior
Enter behavioral term here
moor
mop
motorize
mould
move
movement
mow
muck
muddle
muddy
muffle
mulch
multiply
mummify
murder
Structure
Enter structural term here
Results
Fog-basking Behavior And Water Collection Efficiency In Namib Desert Darkling Beetles.pdf
Causative Verb: move
Cause: to be hydrophilic peaks surrounded by hydro - phobic areas ; water carried by the fog settles on the hydrophilic peaks of the smooth bumps on the elytra of the beetle and form fast-growing droplets that - once large enough to
Effect: move against the wind - roll down towards the head
Causative Verb: move
Cause: to
Effect: move against the wind

Interface


IBID
Interactive Biologically Inspired Design
Home
About us
Links
Function
Enter function term here
Behavior
Enter behavioral term here
Structure
Enter structural term here
VertebralColumn
Wing
Wood
Wool
WovenBone
earthworm
elytra
gut
mRNA
miRNA
sRNA
septa
tunnel
Enter keyword here
Results
Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles.pdf
Structure: elytra
Structure Properties: hydrophobic, hydrophilic, smooth
Structure Parts: grooves

Administrator's Interface

IBID

Interactive Biologically Inspired Design

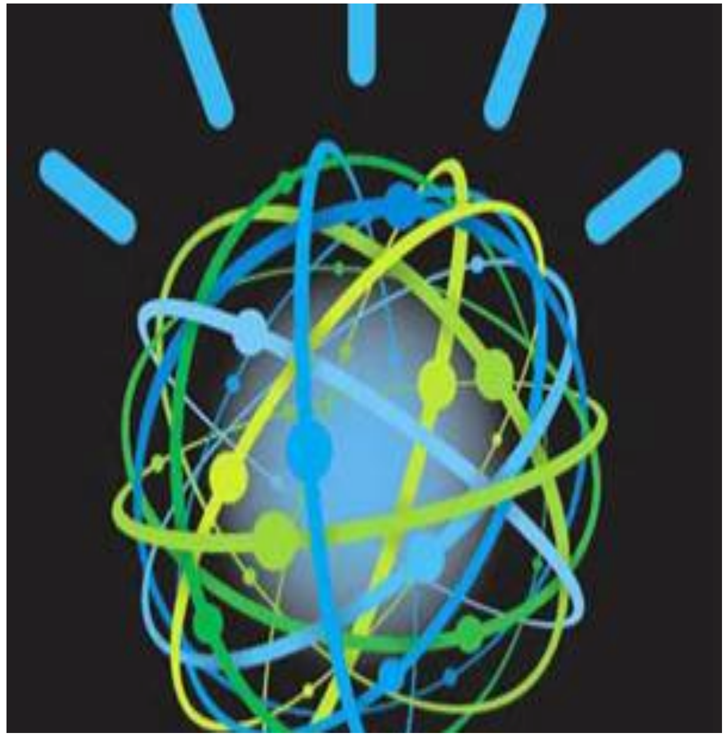
IBID   Ontology Manager

ADMINISTRATOR INTERFACE

Select File to Upload | Start Upload All | Cancel Upload All

Sl no.		File Download URL	Metadata	
1		02 paper 108 Millen et al_1287016861543.pdf	+	
2		02-ecai_1286355893397.pdf	+	
3		05Sosa and GeroAIEDAM_1286898202612.pdf	+	
4		3chamber method_1305674169636.pdf	+	
5		3chamber1_1288486029772.pdf	+	
6		African Wild Dog Communication_1288168124623.pdf	+	

IBM's Watson



A Tool for Constructing Cognitive Systems for Question Answering?

GT Watson+
Human-Computer Co-Creativity

GT Watson+ is a set of cognitive systems that add semantics and context to user interactions

Hypothesis 1: GT Watson+ can save human effort at question answering, for example, in education and training.

Hypothesis 2: Interactions with GT Watson+ may aid human creativity.

IBM's Watson
Engagement Advisor

CS 4803/8803:
Computational Creativity

Computational Biomimicry Applications

Human-Computer Co-Creativity

Spring ‘15 - CS 4803/8803: Computational Creativity

Ask Jill

SustArch

Watson BioMaterial

Watsabi

Twenty Questions

Erasmus

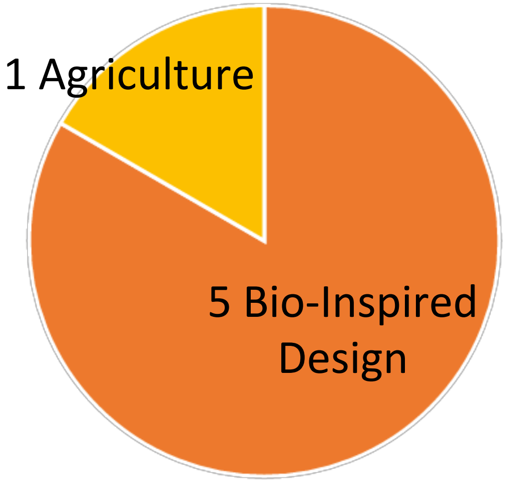
Goal

Deeply address a problem in computational creativity, specifically in the domain of biologically inspired design.

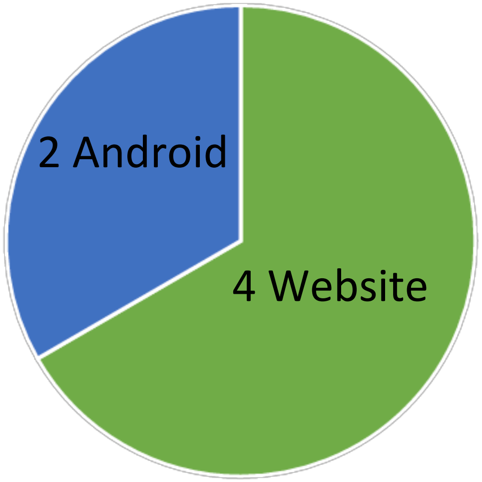
IBM’s Watson should be a part of your app

Spring '15 - Project Results

Project Topics



Project Platforms



Project Interactivity

- All enabled human-computer interaction.
- 2 additionally enabled human-human interaction.

- Human-computer Co-creativity
- Best Practices
    - Training Watson
    - Well structured / annotated data is needed and time consuming to produce.

Erasmus Example -1

- *Q1: How do sea birds drink water?*
- A1: Marine birds can drink seawater because their cephalic 'salt' glands secrete a sodium chloride (NaCl) solution more concentrated than seawater. Salt gland secretion generates osmotically free water that sustains their other physiological processes. Acclimation to saline induces interstitial water and Na move into cells.

Erasmus Example -2

- *Q2: What are salt glands?*
- A2: The salt glands of marine (and some falconiform and desert birds) secrete excess NaCl via the salt glands in less water imbibed with it, thus generating free water needed to return Osm to its preload value. However, salt gland secretion is the culmination of a series of highly integrated interactions among the gut, kidneys, hindgut, salt glands, and supporting organs. Some aspects of these organs in Pekin ducks have been reviewed by Simon (1982)….

Erasmus Example -3

- *Q3: What is osmosis?*
- A3: Reverse osmosis (RO) is a water purification technology that uses a semipermeable membrane to remove larger particles from drinking water. This membrane technology is not considered a proper filtration method. In reverse osmosis, an applied pressure is used to overcome osmotic pressure, a colligative property, that is driven by chemical potential, a thermodynamic parameter. Reverse osmosis can remove many types of molecules and ions from solutions, including bacteria, and is used in both industrial processes and the production of potable water.

20 Questions Example -1

- *Q1: What is solar energy?*
- A1: An array of flat-plate collector modules, connected in parallel was employed to absorb sun rays. The solar collec-tors heated the circulating fluid, which was a mixture of water and ethylene-glycol of about 40% by weight. This mixture was selected in order to avoid possible freezing when ambient temperatures fell below zero. The solar col-lectors were coated with an absorptive surface, oriented to the south, and inclined at a preselected optimum angle. The design characteristics of the collectors (i.e., the net absorp-tion surface of a single module, the energy loss product, and the energy absorption product) were obtained from various manufacturers catalogues. A counter-flow heat exchanger unit was located next to the storage tank so that heat from the circulating fluid was easily transferred to the water of the storage tank.

20 Questions Example -2

- *Q2: How does thermoregulation occur in nature?*
- A2: The flowers of several families of seed plants warm themselves when they bloom. In some species, thermogenesis is regulated, increasing the rate of respiration at lower ambient temperature (Ta) to maintain a somewhat stable floral temperature (Tf). The precision of this regulation is usually measured by plotting Tf over Ta. However, such measurements are influenced by environmental conditions, including wind speed, humidity, radiation, etc. This study eliminates environmental effects by experimentally 'clamping' Tf at constant, selected levels and then measuring stabilized respiration rate....

20 Questions Example -3

- *Q3: What is role of air gaps in the process of thermoregulation?*
- A3: For the ventilation of enclosed mounds, L4scher (1955, 1961) postulated a thermosiphon mechanism with air rising inside the central shaft and falling in the ridges, driven by convection currents. This mechanism became a classical textbook example of elaborate ventilation of animal structures (e.g. Heinrich 1993), although critical studies were lacking. The results for M. bellicosus in the CNP indicate that this mechanism only plays a minor role in enclosed cathedral-shaped mounds in the savannah, i.e. under the conditions that L4scher proposed (L4scher 1955, 1961)…

Current Status

- IBM encouraged us to spawn a startup and admitted us to its industrial ecosystem
- We are conducting customer discovery
- Initial interviews suggest enormous interest
- But still need to find a paying customer
- Problems: Quality? Repeatability? Scalability?

Biologically Inspired Design:
A new movement

Charles Vest (2009): ""We're going to see in surprisingly short order that biological inspiration and biological processes will become central to engineering real systems. It's going to lead to a new era in engineering."

Steve Jobs (2011): "I think the biggest innovations of the twenty-first century will be the intersection of biology and technology. A new era is beginning, just like the digital one …"

Towards a Design Science and Computational Technology of Biologically Inspired Design

- Repeatability - Design Science, Theory
- Scalability – Computational Techniques, Tools
- Grounding – Cognitive Models

Towards a Design Science and Computational Technology of Biologically Inspired Design

- Identify cognitive challenges (eight major challenges)
- Develop interactive tools for addressing specific challenges (Four Box, T square, DSL, Biologue, IBID, GT Watson+)

Acknowledgements

design intelligence lab

center for biologically inspired design

BIOMIMICRY 3.8
two organizations. one vision.

GVU
GEORGIA TECH

Georgia Tech
College of Computing
School of Interactive Computing

NSF

IBM