Biologically Inspired Design for Industry: An Evolving Practice

Marsha Forthofer, Kimberly-Clark Corporation

Dr. Michael Helms, Georgia Institute of Technology

Image source: Stu Porter
Introductions

Marsha Forthofer
• Senior Scientist – Materials at Kimberly-Clark Corporation (K-C)
• B.S. in Chemical Engineering
• M.S. in Biomimicry
• Certified Biomimicry Professional from Biomimicry 3.8

Dr. Michael Helms
• Research Scientist, Georgia Institute of Technology (GT)
• Ph.D. in Cognitive Science
• Founder, PatternFox Consulting
Biologically Inspired Design (aka Biomimicry, Biomimetics, Bionics, etc.): the understanding and applying of deep design principles found in biology.

I believe the primary goal of biologically inspired design is to:

1. Generate more sustainable designs, or
2. Increase radical design innovation, or
3. Change the relationship between humans and nature, or
4. Generate interest and investment for biological research
K-C is leading the world in “Essentials for a Better Life”

Formed in 1872

43,000 employees worldwide

$18.6 Billion in Net Sales in 2015

#1 or #2 share position in 80 countries

Nearly one-quarter of the world’s population use our products daily
K-C learns from nature to develop new material innovations

The mission of K-C’s Nature-inspired Materials platform is to develop new materials to enable K-C business plans and sustainability goals by discovering and translating nature’s strategies.
We explored a “single-solution” approach

Relevant Problem:

Moving liquid unidirectionally

Known System
Source: Ben Goodwyn
We explored a “problem-based” inspirational approach

Known Problem:
High humidity in the products leads to discomfort and skin health issues

Relevant Systems

Sources: Shutterstock
From our work, we identified key challenges and interests

• Key challenge: How do we translate a set of partially understood biological solutions to a product prototype?

• Other interests:
  • Gain exposure to other BID-related tools
  • Improve facilitation of the BID process
  • Understand key biological mechanisms

• We engaged with Georgia Tech’s Center for Biologically Inspired Design in 2014 to address the key challenge and other interests.
Center for Biologically Inspired Design
At Georgia Institute of Technology

Dr. Jeannette Yen
Prof. Biology
Director CBID

www.cbid.gatech.edu
The biologically inspired design process

Four key processes:

1. **Define** the problem
2. **Search** for biological solutions
3. **Evaluate** the match
4. **Transfer** principles to design
Retention and Distribution Project: Kimberly-Clark Corporation desires to increase fluid distribution and retention in diapers and adult incontinence products. The functions of distribution and retention involve competing forces (capillary forces and permeability).

Humidity Management Project: Kimberly-Clark Corporation desires to use specific material features to reduce humidity at the skin-product interface layer to increase comfort and reduce irritation/rash.
**Functional decomposition & 4-box problem specification**

### Operational Environment
- ~xx insults per use
  - Each insult xx-yy mL/s up to xx mL
  - Insult duration ~xx sec +/- yy sec
  - ~xx minutes between insults
- Urine
  - ~xx% Water
  - ~xx% urea,
  - ~xx% chloride, sodium, potassium
  - Some differences between adults/infants
  - pH xx – yy (avg. ~zz)
- In use warm (~xx °F)
- During transportation (xx °C – xx °C)
- Varying body positions, shapes, sizes, & movements
- Varying applied pressures

### Functions
- Absorb urine
- Absorb surge
- Absorb urine (over time/multiple insults)
- Distribute (free and loosely held) urine to retention points
- Retain (tightly held/locked-up) urine
- Maintain void volume under pressure
- Dispose of urine
- Prevent leakage/leak
- Maintain freedom of movement
- Maintain comfort
- Maintain discretion (adults)
- Minimize bulge
- Minimize overall profile
- Prevent/reduce odor
- Protect skin from urine (prevent exposure)
- Prevent urine from (prolonged) skin contact

### Specifications/Materials
- Wearable undergarment
  - Child & Adult sizes (up to xx cm vertical distance)
  - Comfortable against skin
  - Compliant materials
  - Non-toxic/non-allergenic
  - Polymer/textile based
  - Specialized surface modifications
  - Specialized hierarchical structures (fiber organization)
  - Fiber resiliency to maintain void volume
  - Resource efficient, lightweight materials
  - Low cost materials < $xx/per
  - Layered manufacturing

### Performance Criteria
- Leak proof (xx%) over multiple (xx+) insults
- Absorb surge within ~xx seconds
  - >xx mL/cm²/s
  - xx-yx Darcy
- Absorb & retain multiple insults (xx+)
  - xx mL/cm²
  - SAM xx g/g; fluff xx g/g
  - SAM/fluff xx-yy Darcy
- Retain over pressures (xx-yy kPa)
- Vertical distribution: distance xx-yy cm
- Vertical distribution: pressure xx-yy kPa
- Surface wetness measures [challenging]
- Aesthetically pleasing/attractive
Problem Definition

**Key Benefit:**
Re-representing the design problem to facilitate search and evaluation specifically for biologically inspired design.

**Key Insight:**
Functional decomposition provides a visual representation of the problem space. It allows us to identify explicit trade offs, and focus exploration.
Systematic search results in patterns of key principles

Relative Humidity (Aeration)

Temperature Gradient (Temp. Gradient)

Laplace Pressure (LP)

Partial Vapor Pressure (PVP)

Biological Discovery 1(Disc1)

Biological Discovery 2(Disc2)
Key Benefit:
Systematic search results in an exhaustive exploration of the problem domain, resulting in deep and broad problem insight.

Key Insight
Understanding what you find in search requires integrating other disciplines into the work – it’s not just about the biologists perspective. You need to apply scientific rigor to understand the biology deeply.
We systematize and quantify evaluation using 4-box criteria

<table>
<thead>
<tr>
<th>Organism</th>
<th>Total Score</th>
<th>Func.</th>
<th>Env.</th>
<th>Mat.</th>
<th>Size</th>
<th>Perf.</th>
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<tr>
<td>Organism 1</td>
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<td>2</td>
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<td>3</td>
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<td>Organism 10</td>
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<tr>
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<tr>
<td>Organism 13</td>
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<td>4</td>
<td>3</td>
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<td>3</td>
</tr>
</tbody>
</table>

**Functions**
- Absorb urine
- Absorb surge
- Absorb urine (over time/multiple insults)
- Distribute (free and loosely held) urine to retention points
- Retain (tightly held/locked-up) urine
- Maintain void volume under pressure
- Dispose of urine

**Specific theoretical result**
- \( q_{contact} = p_3 a = p_3 b = p_{12} \)
- \( r_{min} = 1.8 \times 10^{-6} \text{ m} \)
- Minimum squeeze resistance of 20 kPa
- Maximum squeeze resistance of 60 kPa
- \( r_{max} \geq 1.90r_{min} \) let \( r_{max} = 4r_{min} \)
- \( r_{max} = 0.131r_{max} = 0.524r_{min} \)
- \( \approx (r_{max} r_{min})(4.31) = 12.9r_{min} \)
- \( V_{tot} = 4.00 \times 10^{-5} \sqrt{t} \text{ m}^3 = 4.00 \cdot 10^{-2} \sqrt{t} \text{ L} \)
- \( t \approx 625 \left( \frac{V_{tot}}{L} \right)^2 \text{ s} \)
- \( \rightarrow 0.3 \text{ L in 56 s and 0.9 L in 506 s (8.5 min)} \)
**Key Benefit**: A quantified set of design principles considered systematically in the design context.

**Key Insight**

The matrix provides a systematic way to analyze analogies. Instead of “this looks interesting,” it provides a framework for decision making.
We develop recommendations for transfer based on the “biological readiness level” (BRL).

- Discovering the underlying physical structures of the mechanism
- Discovering the underlying principles of the mechanism
- Identifying how different variations and patterns of underlying structures yield results
- Learning how to produce at scale and cost, within existing manufacturing constraints
- Applying patterns and variations to instantiate a product optimized for context
## Research call for proposal (CFP)

<table>
<thead>
<tr>
<th>CFP Components</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Background</strong></td>
<td>Problem definition</td>
</tr>
<tr>
<td></td>
<td>Biology background</td>
</tr>
<tr>
<td><strong>Research</strong></td>
<td>Understanding structure and mechanism</td>
</tr>
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<td></td>
<td>Computational and theoretical modeling of phenomena</td>
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<tr>
<td></td>
<td>Small scale manufacturing techniques</td>
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<tr>
<td></td>
<td>Bench testing against predicted results</td>
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</tbody>
</table>
Key Benefit: Provides a current assessment and path forward.

Key Insight
The CFP crystalizes your understanding of the key biological principles & provides a translation of the output of the BID process into a format that others can use.
Kimberly-Clark Current Results

• Most mature BID project is moving into year 5, and has achieved some internal momentum.

• Currently funding two new lines of research with academic partner institutions as a result of this work.
  • Targeted/prototype research

• Investigating means of “seed funding” for a third line of research.
  • Basic/biological research
The Evolution of Industry Application

1. Improving processes

2. Shifting challenge point

3. Evolving culture
Thank you.

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Dr. Michael Helms
Georgia Institute of Technology
PatternFox Consulting
(mhelms3@gatech.edu)
<table>
<thead>
<tr>
<th>Problem Definition</th>
<th>Search &amp; Indexing</th>
<th>Evaluation</th>
<th>Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem specification</td>
<td>Biology knowledge and experience</td>
<td>State-of-the-art manufacturing knowledge</td>
<td>Pattern identification</td>
</tr>
<tr>
<td>Problem decomposition</td>
<td>Engineering-to-biology translation</td>
<td>Deep science - physics, chemistry, etc.</td>
<td>Biological research techniques and capabilities</td>
</tr>
<tr>
<td>Problem abstraction</td>
<td>Biological literature review</td>
<td>Conceptual design</td>
<td>Theoretical and computational modeling</td>
</tr>
<tr>
<td>Technical engineering &amp; manufacturing</td>
<td>Biological science, physics, chemistry, etc.</td>
<td>Quantitative analysis</td>
<td>Prototyping</td>
</tr>
<tr>
<td>knowledge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Customer &amp; market knowledge</td>
<td>Relationship/network management</td>
<td>Dealing with ambiguity</td>
<td>Research for design</td>
</tr>
<tr>
<td></td>
<td>Flexibility</td>
<td></td>
<td>Research management</td>
</tr>
</tbody>
</table>
## Operational Environment

- ~**xx** insults per use
  - Each insult **xx-yy mL/s** up to **xx mL**
  - Insult duration ~**xx** sec (+/- **yy** sec)
- ~**xx** minutes between insults

### Urine
- ~**xx**% Water
- ~**xx**% urea,
- ~**xx**% chloride, sodium, potassium
- Some differences between adults/infants
- pH **xx-yy** (avg. ~**zz**)  
- In use warm (~**xx **°F)
- During transportation (**xx**°C – **xx**°C)
- Varying body positions, shapes, sizes, & movements
  - Varying applied pressures

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- Protect skin from urine (prevent exposure)
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## Specifications/Materials

- Wearable undergarment
  - Child & Adult sizes (up to **xx cm** vertical distance)
- Comfortable against skin
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- Non-toxic/non-allergenic
- Polymer/textile based
- Specialized surface modifications
- Specialized hierarchical structures (fiber organization)
- Fiber resiliency to maintain void volume
- Resource efficient, lightweight materials
- Low cost materials < $**xx*/per
- Layered manufacturing
- Disposable materials

## Performance Criteria

- Leak proof (**xx%**) over multiple (**xx+**) insults
- Absorb surge within ~**xx** seconds
  - >**xx** ml/cm²s
  - **xx-yy** Darcy
- Absorb & retain multiple insults (**xx+**)
  - **xx** mL/cm³
  - SAM **xx** g/g; fluff **xx** g/g
  - SAM/fluff **xx-yy** Darcy
- Retain over pressures [**xx-yy** kPa]
- Vertical distribution: distance **xx-yy** cm
- Vertical distribution: pressure **xx-yy** kPa
- Surface wetness measures [challenging]
- Aesthetically pleasing/attractive
We evaluate system match to problem specification

<table>
<thead>
<tr>
<th>4-Box Criterion</th>
<th>Very High (5)</th>
<th>Very Low (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>Matches one or more core functions, and one or more sub-functions (deep tree)</td>
<td>Does not match functions</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Exactly matches more than one key condition, and closely matches multiple others</td>
<td>Does not match any key conditions</td>
</tr>
<tr>
<td><strong>Specification: Materials</strong></td>
<td>Material/system can be manufactured now, cheaply</td>
<td>Materials cannot be manufactured with existing methods</td>
</tr>
<tr>
<td><strong>Specification: Size</strong></td>
<td>Physical size is same order of magnitude</td>
<td>Physical size is two or more orders of magnitude difference or effect will not transfer at scale</td>
</tr>
<tr>
<td><strong>Performance: Scale</strong></td>
<td>Performance is better than or at same scale for key function</td>
<td>Performance two or more OOM greater or cannot possibly improve current performance</td>
</tr>
</tbody>
</table>
Management Expectations, BID materials design project

Team composition
1. Product designers & engineers
2. Biologists
3. Research scientists
4. Strong networking & communication skills

Timelines
1. 3-6 months for described process
2. 2-6 years of research, depending on bullseye

Investment cost
1. Described process: $25k-$200k
2. Academic research partnerships (post-doc): $150-$250k/year
3. Total development cost through prototype: $350k - $2M

This will vary by research domain and BRL.