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The Art and Science of Biomimicry – *Abstracting Design Principles from Nature*

Laura Stevens (1&2), Deborah Bidwell (3), Michelle Fehler (4), Asha Singhal (5)

1: The Hague University of Applied Sciences, Netherlands;
2: Delft University of Technology, Netherlands;
3: College of Charleston, USA;
4: Arizona State University, USA;
5. Biomimicry Frontiers, Canada

corresponding author: laura.l.stevens@gmail.com
bidwelld@cofc.edu
mfehler@asu.edu
ashaksinghal@gmail.com

ABSTRACT

Biomimicry is an emerging discipline that seeks nature's advice and brings diverse stakeholders together to create designs that emulate the way nature functions, not just the way it looks. The field itself is a multidisciplinary endeavor, yet biomimicry educators frequently work alone. Pedagogical methods based on trial and error may waste precious time. In this study, a set of four biomimicry experts from diverse disciplines and different areas around the globe collaborated to compare pedagogy and analyze student work to illuminate best principles for teaching students to translate biology into design solutions, a key step in the biomimicry design process. A total of 313 assignments created by 179 different students were evaluated. The results showed that the inclusion of Art in the learning of science, namely the hand-drawing of the biological mechanism can lead to higher quality of abstracted design principles.

Keywords
Biomimicry, Abstracted design principle, Pedagogy, Science education and aesthetics, Analogical thinking, Art and Nature, Drawing to learn, Biology

"Come forth into the light of things, let nature be your teacher." ~ William Wordsworth

INTRODUCTION

Biomimicry is an emerging approach to innovative problem-solving that looks to nature for resilient and sustainable solutions to human problems. The foundation of biomimicry lies within biology and is simultaneously ancient, but merges with engineering, design and other disciplines such as chemistry, social innovation and business. The adaptations and deep patterns present within the millions of species living on earth today represent 3.8 billion years' worth of time tested, sustainable solutions to the same challenges that humans now face. Humans are (re)learning to apply these functional biology design lessons through the process of Biomimicry Design Thinking. Practitioners of biomimicry don't just learn about nature, they learn from nature. Biomimicry aims to realign human actions with nature's principles, to promote a viable, equitable, and livable world (The Biomimicry Institute 2009).

The demand for nature-oriented design education and improvement of 21st century teaching has grown exponentially in recent years. The scope of biomimicry has been explored in depth by pioneers such as Janine Benyus in her book *Biomimicry - Innovation Inspired by Nature*, and by Dayna Baumeister in her book *Biomimicry Resource Handbook*. Yet, engaging in the process of Biomimicry thinking takes practice and an initial investment of time. Over the past 10 years, Biomimicry has found its way into kindergarten workshops, K-12 programs around the globe to an entire Master of Science in Biomimicry program, initiated by Baumeister in 2015 (Biomimicry 3.8 2020). On the other hand, nature-driven designs didactics have only just begun to take root.

Biomimicry can be distinguished from bio-inspired design in that biomimetic designs are held to a rigorous scientific standard. Living systems are made up of complex, ever-changing networks of interdependent organisms surviving within this complexity. When biomimics look for biological models, we look for adaptations that have been honed to solve for specific problems. Biomimicry asks nature's advice by focusing on what we need our design to do in a specific context and matching that function and context to natural mentors that have solved the same functional challenge in beautiful, elegant, efficient, regenerative and resilient ways. What may be most striking about biomimetic design is the aesthetic beauty with which design challenges are solved and just as in nature, aesthetics can be highly adaptive in design.

What is the art behind the science of biomimicry? How are the biological strategies and mechanisms from adaptations in nature translated into abstracted design principles for biomimicry practitioners, innovators, architects and designers? This chapter reviews the steps necessary to teach that translation, highlights the importance of drawing to learn, and showcases artful illustrations made by student biomimicry practitioners during this process. Preliminary research showed that when teaching biomimicry students how to bridge the gap between biology and design through abstracting design principles, the lack of scientific research on pedagogical methodologies leaves teachers and students exploring the design process together through trial and error. Observations and student survey responses in the study 'Analogies in Biomimicry' (Stevens et al. 2020) showed that students continually struggle with understanding how to transfer biology to design. However, in this same study, Stevens found that first drawing the biology and subsequently drawing the abstraction of how that biology is functioning, aided in her students understanding the design principles and implementing these into design solutions. Is this true elsewhere? Biomimicry is a team effort and successful biomimics rarely work alone. Yet biomimicry educators frequently do. This chapter brings four biomimicry educators (three professors and a biomimicry practitioner) together to examine and share best teaching principles in the field for the translation phase between biology and design, evaluating this phase through the work of 205 students. The authors share a background of learning biomimicry from the same Master of Science program at Arizona State University (ASU).

FRAMEWORK

Biomimicry Thinking

Biomimicry Design Thinking is the methodology which merges Biomimicry Thinking and Design Thinking, following the design phases of scoping the challenge, discovering existing solutions, creating ideas and evaluating them to create innovative design solutions (Stevens et al, 2020). Within biomimicry, each phase is focused on what we, as designers, can learn from nature. In the scoping phase biomimics ask what we want our design to *do,* identifying its function and biologizing that function so that we can ask nature's advice about how to solve it. Just as a well-adapted organism thrives in natural systems by optimizing its fitness and adapting to an ever-changing context within its unique niche, a well-adapted human design must meet the functional needs of the design challenge within the context it operates in order to optimize its success (Baumeister 2014). When biologizing the design question, biomimics ask, 'How might nature do ____?' (Rowland

2017). For example, how might nature regulate temperature? The discovering phase of biomimicry then looks to natural organisms, processes, or ecosystems that have evolved adaptations for solving the same functional design problem and context we face, as opposed to looking for inspiration from previous designs made by other human designers, which is often the norm in ideating phases of the Design Thinking process (Harris and Ambrose 2009). The goal of biomimetic design is to learn from the research and development throughout which life has survived, applying scientific principles to create resilient human innovations that are vetted by science and sustainable by design.

Researching the *Function, Strategy, and Mechanism* of adaptations is key for translating those from nature into human design (ASU 2017). For example, a cactus excels at 'regulating temperature.' Biomimics explain the natural strategy, or 'how the cactus regulates temperature'. The strategy of the cactus might be described as 'by creating shadow and air flows'. The next step is to consult scientific literature to determine how the natural mechanism of this strategy works. For example, research articles describe detailed mechanisms regarding how much shade is provided by ribs and spines and more specifically how the shadows and air flows are created (figure 1).

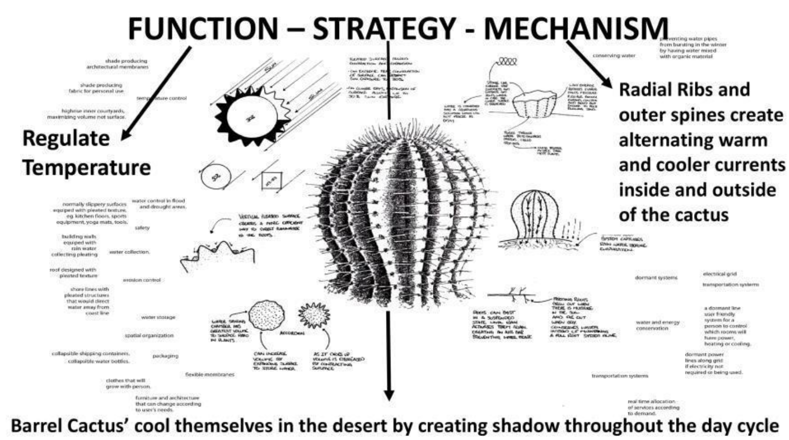


Fig. 1. Example of function-strategy-mechanism presentation published with permission by Rui Felix (adjusted with biomimicry terms).

During desktop research to find organisms fitting their design need, biomimicry design students iterate to become adept with the function-strategy-mechanism paradigm. In the discovery design step, student teams explore dozens of possible natural mentors to describe their function and strategies before honing in on those which seem to carry out the function best.

A deep dive into scientific articles locates primary research to reveal detailed mechanisms behind nature's elegant solutions. Each organism is recorded in a "biobrainstorm" collection spreadsheet. This includes, the function, organism common and scientific name, it's strategy and mechanism fulfilling the function, quoted literature citations and cited references.

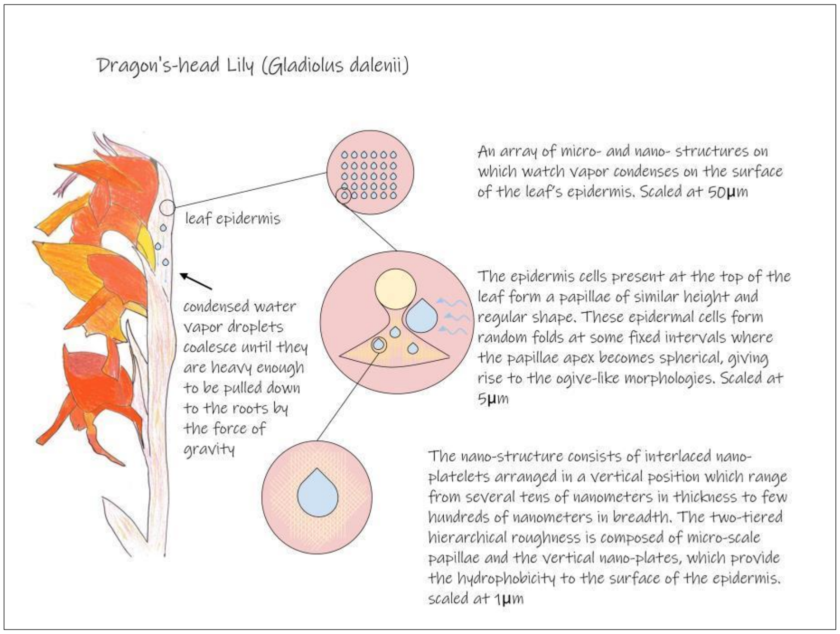


Fig. 2: Biological Design Principle and diagram of *Gladiolus dalenii,* C.M. Langford

Subsequently, biomimicry students hone in on and summarize promising mechanisms as Biological Design Principles (figure 2) describing both in text and visually how the biological function is carried out. Finally, they reach the crucial and most difficult step, writing an Abstracted Design Principle in which biological terms are eliminated and exchanged for non-biological terms to make this natural design lesson accessible to designers and engineers (figure 3).

ABSTRACTED DESIGN PRINCIPLE

An erected unit coated in micro-protrusions that fold at fixed intervals form spherical apexes with concave bases at heights of 10.2 ± 1.5 μm, diameters of 5.5 ± 0.4 μm and cavity depths of 6.2 ± 0.5 μm. The apexes are hierarchically arranged to form rows and columns with longitudinal spacing of 18.3 ± 2.5 μm and transversal spacing of 36.6 ± 2.9 μm. The fleshy protrusions have vertically positioned, interlaced platelet nano-structures on their surfaces. The micro and nano-structures have surface contact angles of 135° ± 0.4°. the coating condenses water vapor at the protrusions base, with secondary condensation sites on the surface nano-structures. Droplets grow in size and eventually gravity pulls the droplets downward.

ABSTRACTED DESIGN PRINCIPLE ILLUSTRATION

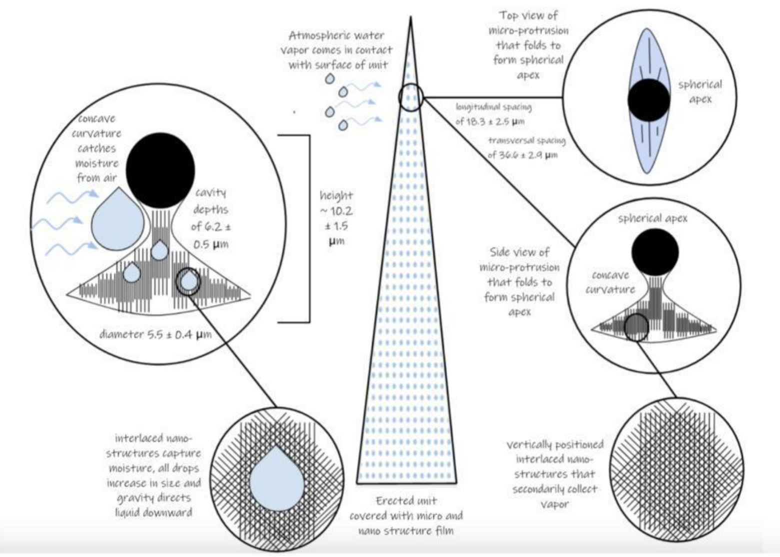


Fig. 3. Abstracted Design Principle and diagram of *Gladiolus dalenii*, C.M. Langford

Abstracted Design Principles (ADPs) are illustrated, demonstrating how the mechanism works including the scale, texture, subcomponents, behavior or interconnecting functions. The goal is to use the ADP diagrams as a starting point for design ideation (Baumeister 2014). A Nature's Technology Summary (NTS) is the template we assign for capturing and summarizing the research and ADPs for each of the biological mentors that make the final cut.

Analogical thinking or reasoning, is the theory of using what is learned in one context (such as biology) and applying it to a second context, such as design (Casakin and Goldschmidt 1999). Within the field of biomimicry, three distinct levels of hierarchy in this analogical thinking are described from the most simple to the most intricate: 1) form-analogies, or those emulating the functional shape or structure of an organism; 2) process-analogies, or those emulating the functional behavior or biochemistry of an organism; and 3) System-analogies, when an entire ecosystem's function is emulated (Baumeister 2014). Mimicking systems is considered the highest level of analogical thinking within biomimicry design.

In this study we illustrate, describe and analyze biomimicry students' attempts to write and illustrate ADPs within their NTS's to evaluate effective and ineffective methodology to illuminate current best pedagogical principles.

Drawing in Science

One method for improving understanding of complex ideas is through drawing scientific visualizations which are important learning aids in science education (Landin 2015). Developmentally, drawing is motivational and engaging for children and drawing to show understanding in the higher education classroom also captivates student interest and may amplify creative thinking by stimulating interactions between brain hemispheres (Ainsworth et al. 2011; Deietrich and Kanso 2010). Cognitive functions such as observation, problem solving, explanation and communication, which form the foundations of scientific thinking, interrelate with the basic mechanisms of illustrating (Fan 2015). Drawings are fundamentally critical portrayals that incorporate a few subtleties and preclude others; subsequently, every impression a student makes in a drawing might be reflective of what students are and are not learning (Dove et al. 1999). Drawing enables students to synthesize ideas, training them to identify any gaps in their understanding (Quillen and Thomas 2015; Van Meter et al. 2006; Zhang and Linn 2010). Biomimics must accurately understand biological adaptations to create designs that function the same way that nature does. Although it is important for biomimicry students to be explicit in the visual representation of the natural adaptive mechanism, only basic visual communication skills are required to promote understanding, the process is more important to the learning than the outcome (Kang et al. 2014; Rovalo 2019). Drawing also facilitates communication of the mechanism to other audiences, assisting with the translation of the functional mechanism found in nature into engineering lexicon. Drawing with accuracy enhances observation skills and learning. There is a feedback mechanism involved, the act of drawing both requires and enhances understanding (Pyle 2000).

Drawing in science serves various purposes in student learning. When looking through the lens of abstracting design principles in biomimicry, drawings serve multiple pedagogical goals: drawing as a mode of internalizing science, drawing to enhance observation, drawing to enhance model-based reasoning, drawing for problem solving, drawing to connect concepts/ideas, drawing to learn, drawing to reveal student's mental models and drawing to communicate (Quillin and Thomas 2015). Drawing can help make the "unseen seen". To understand forms, processes and systems in nature, drawing requires a deep understanding of the details. It allows an external process to internalize information (Quillin and Thomas 2015) and can visually pinpoint where a gap is in understanding. Biomimicry can only emulate nature successfully if it follows what nature does in an authentic way. This forces the biomimic to look closely, investigate the natural model from different perspectives, and explore specifically how the adaptation functions (Leslie and Roth 2000). Even biologists are asked to draw abstract visual models to support reasoning while solving problems based on complex concepts (Quillin and Thomas 2015).

Student drawings in biology can range across broad spectra. They can vary across scales from atomic to ecological; they can differ in their incorporation of text, eg: flowcharts are created predominantly with words, indicating relationships. On the other end of the spectrum, drawings depicting species morphology might contain few to no labels and can range from detailed to abstract depending upon the context. While a thoroughly detailed drawing might be useful for understanding bird behavior, only a simple shape with the word bird inside it will be sufficient for an ecosystemic concept map outlining interspecific relationships (Quillin and Thomas 2015).

RESEARCH QUESTION

Although biomimicry education is expanding exponentially, teachers and students still struggle with getting the science accurately and visually communicated into design principles that can be used for innovative ideas. The authors have the same foundational biomimicry education, but teaching at different schools to different student audiences results in variations on our desired outcome. What are these differences and how can we rigorously funnel what we've learned through iterative curriculum development into recommended pedagogical principles? Our research question is: Which characteristics, methods, factors, descriptors, learning outcomes, or techniques, are most often present in biomimicry student work that correlates to the highest quality adapted design principles?

Pinpointed Sub-questions:

- What subcomponents of the biomimicry thinking methodology are most vital for students to achieve high quality abstracted design principles?

- What curricular or pedagogical factors influence whether students achieve systems level abstracted design principles?

- What is the art behind the science of biomimicry? Does drawing to learn improve the learning outcomes of multi-disciplinary novice biomimicry practitioners? If so, how is it correlated with achieving high quality abstracted design principles?

Our research focused on the quality of the Nature's Technology Summary (NTS) to normalize our diverse set of data. We want to find out how each of the methods from our classrooms improves the communicative starting point for biomimicry design for interdisciplinary design teams, namely the Abstracted (biological) Design Principle. Does the primary research offer explanatory diagrams with scaled measurements? Are there visuals of how a mechanism moves? Have students observed details while drawing what they see in nature? These are a few predictions of what may arise from this research. By exploring these factors, we aim to identify which methodological steps are essential to reach a comprehensive and useful visual translation. And, when these factors are defined, how to introduce more complex translations to apply to design.

METHOD

Context and participants

In this study, we analyze a single biomimicry assignment, the NTS, given across four separate university student cohorts over a two-year period using both quantitative and qualitative approaches to improve our result validity (Khakpour 2012). We identify recommended pedagogical principles for teaching and learning the crucial and most challenging step of the biomimicry design process: abstracting the design principle. Student populations varied between undergraduate and graduate levels, and ranged across a variety of disciplines, allowing for the comparison between design students and interdisciplinary students lacking design backgrounds, and between novice first year undergraduates (a control group) and experienced upper-level undergraduate and graduate student populations. Universities included in the study are The Hague University of Applied Sciences (THUAS), Arizona State University (ASU), and the College of Charleston (CofC). A total of 313 NTS assignments created by 179 different students were evaluated. Our preliminary recommended pedagogical principles findings were applied to the most recent test group (ASU, summer 2020). See Table 1.

Table 1: Research context, participants and other details * Summer cohort ASU = special test group with preliminary ‘recommended pedagogical principles’ findings integrated in instruction.

Institution	The Hague University of Applied Sciences (THUAS)	Arizona State University (ASU)	College of Charleston (CofC)
Location	The Hague, Netherlands	Tempe, Arizona, USA	Charleston, South Carolina, USA
Audience	Design, Engineering, other miscellaneous technical fields	Architecture, Industrial design, Interior Arch., Landscape Arch., Visual Communication Design, Sustainability	Biology, Entrepreneurship, Urban Studies, Environmental and Sustainability Science, First Year Experience
Level	Undergraduate	Undergraduate & Graduate	Undergraduate
Cohort dates:	Spring 2019 Spring 2020	Fall 2019 *Summer 2020	Spring 2019 Fall 2019 Spring 2020
Number of participants & number of NTS’ made	2019 n=22 (16 NTS) 2020 n=23 (35 NTS)	2019 n=15 (30 NTS) *2020 n=12 (12 NTS)	Sp2019 n=40 (112 NTS) F2019 n=20 (19 NTS) Sp2020 n=47 (89 NTS)
Student Background	Minor for exchange students (motivation letter) or 4th semester for IDE students	Graduate students from various design disciplines (ARCH, IND, INT, ALA, VCD) as well as students from sustainability.	Variable. No prior design experience. Upper level tends to have more biology, sustainability and environmental science background.
Course name(s)	Design with Nature, Industrial Design Engineering semester	Biomimicry in Design	Special Topics: Biomimicry Thinking and Biomimicry, Nature as Mentor.

DESCRIPTION OF COMMON ASSIGNMENT

The common assignment for all cohort participants, the Nature’s Technology Summary (NTS), is described in detail below. Students at THUAS, ASU, and CofC all completed the NTS assignment as a major element in the semester. A NTS template was provided to all student populations. Students followed the same 6 step process. To prepare for the NTS assignment and engage in observations of biology throughout the courses, a variety of preliminary observational, research, and drawing tasks were assigned (figure 4a–c).

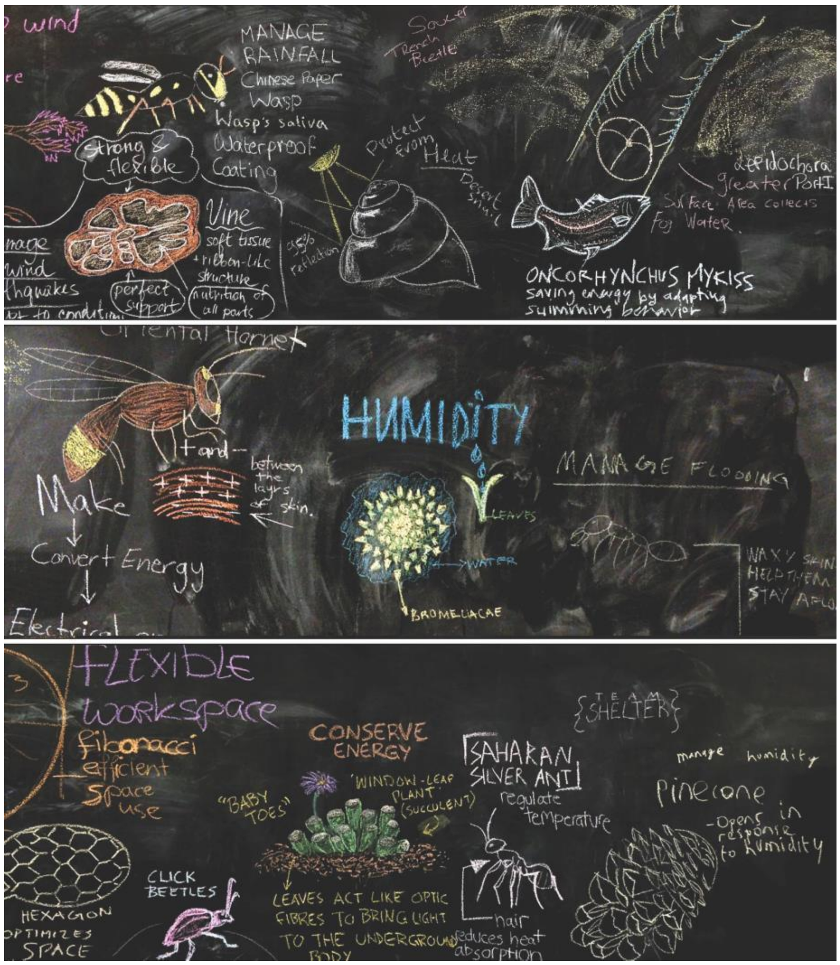


Fig. 4a: Pre-NTS bio brainstorming and drawing to learn, THUAS students spring 2020.

Pricklypear (Opuntia basilaris)
5.23.20
3:47 pm
Millett Ranch
Its 90 feels 85 degrees with little to no clouds with little wind that is blowing northwest.
The sun is bright but not too hot for being outside. The birds are singing loud today, and I wish I could capture the purple in the prickly pear cactus.

Notes: This cactus may consist of hundreds of pads that are green, and blue-gray color, and can grow five inches long. During summer, the pads shrivel up because they pump out the water they stored during winter.

https://calscape.org/loc-california/Opuntia%20basilaris()

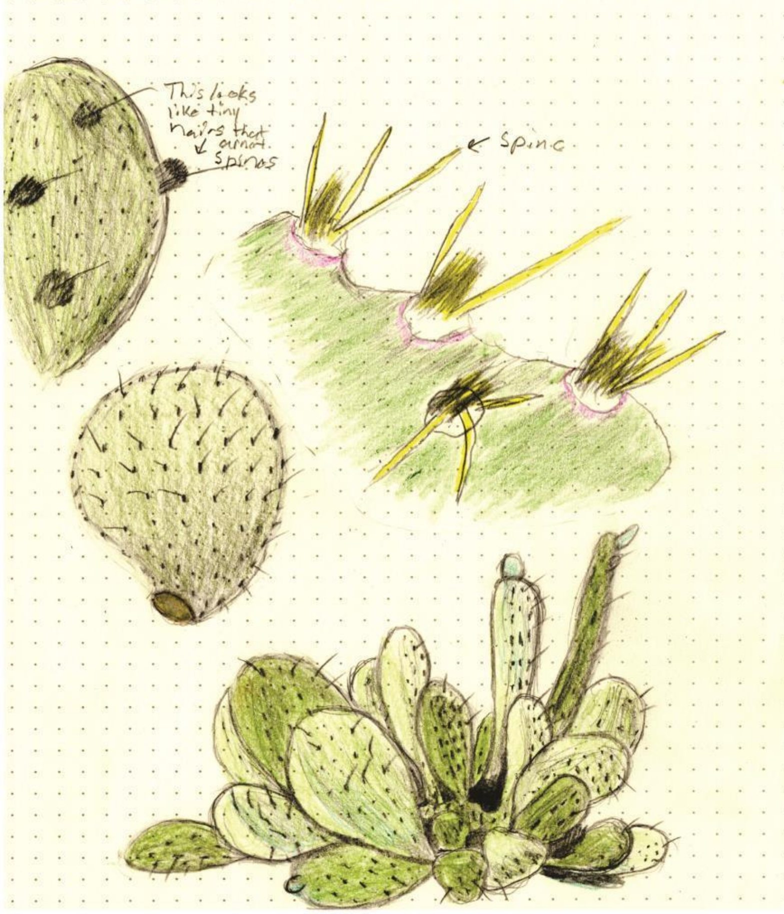


Fig. 4b: iSites drawing to learn how to observe and see, H. Carter, ASU student summer 2020.

Fig. 4c: iSites drawing to (re)connect with local flora, describe biological adaptations, and learn how to observe and see, E. Peters, CofC student spring 2019.

Assignment Steps:

Step 1: *BioBrainstorm*: this pre-NTS step includes seeking organisms that are successfully solving the same challenge in the same context as the human design challenge. Students conduct preliminary research including a broad spectrum of potential organisms from wide ranging taxa and scales, representing diverse strategies. Honing on in their top choices, students go deeper to thoroughly investigate the primary literature. The research on these top choice organisms is summarized using the NTS template (figure 5a–c).

NATURE'S TECHNOLOGY SUMMARY | (DESIGN BRIEF APPENDIX)

Contact: Agostina Feltrinelli

Natural History:

The western honey bee is native to Europe, the Middle East, and Africa, and, though none of its at least 20 recognized subspecies naturally occur in the Americas, these have been extended beyond their natural range due to the economic benefits brought about by they pollination and honey production. Because of this, honey bees are now naturalized on all continents apart from Antarctica.

The non-reproductive females, the worker honey bees, are the smallest in size, with their bodies specialised for pollen and nectar collection, as their hind legs have a corbicula (pollen basket) which is specially designed to carry large quantities of pollen back to the colony. They also produce wax scaled on the underside of their abdomen, which are used to construct the wax comb within the colony, and have a barbed stinger with a poison sac which is torn from the end of their abdomen when they sting a tough-skinned victim such as a human. The act of stinging, a defensive behaviour worker bees use to protect the colony, results in the bee's death.

Honey bees have a highly social life history and their colonies could be considered to be superorganisms, with the entire colony being viewed as a biological unit. Their reproductive process, or swarming, is based on the premise of producing more colonies rather than individual bees.

Honey bees typically swarm in spring and early summer, when pollen and nectar are plentiful (Mortensen, Schmehl, and Ellis, 2013).

Function:	Modify chemical/electrical state, electric charge; Maintain community, provide ecosystem services through pollination; Get, store or distribute resources, capture solids; Get, store or distribute resources, distribute solids.
Strategy:	Honey bees collect and release pollen through the hairs on their bodies, whose static charge varies from that of the pollen.
Champion:	Honey Bee *Apis Mellifera*

Description Text:

Under clear, fair-day conditions, plants generally have small negative surface charges and are therefore surrounded by low intensity electric fields. The magnitude of their electric fields depends on the chemical composition of the plants, its height, and the environment, as, under unstable weather conditions, these fields can change polarity, with their surface charges becoming positive. The distribution of its electric field, on the other hand, varies with its shape, with sharp points such as flowers exhibiting greater electrical fields.

In contrast, foraging bees, such as honey bees, usually have electrically positive surface charges which occur when they fly through the air. In this manner, when a bee flies through the air, it is confronted with electrical currents and its body is electrostatically charged with frictional electricity. Research has suggested that pollen seeking insects' ability to accumulate pollen on their surface and later distribute it is enhanced by the forces of attraction between the insect's

1

Fig. 5a: example step 1 & 2 NTS (Organism, function & context), A. Feltrinelli, THUAS, spring 2019.

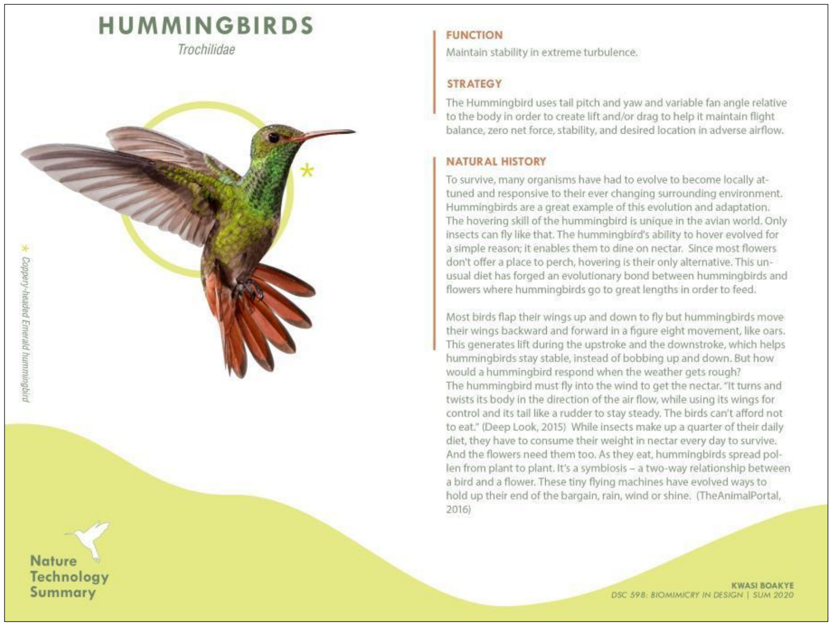
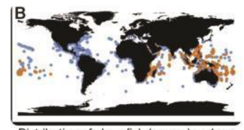


Fig. 5b: example step 1 & 2 NTS (Organism, function & context), K. Boakye, ASU, summer 2020.

NATURES TECHNOLOGY SUMMARY (NTS)

Your Name: Mylene Gonzales



Distribution of clownfish (orange) and sea anemone (blue) across the globe (Litsios et al., 2012)

SUMMARY

Champion Mentor (common & Latin name)	Clown anemonefish (*Amphiprion ocellaris*) and Sea Anemone (*Actiniara*)
Organisms natural history context (habitat & conditions driving the evolution of its strategy)	Clown anemonefish are a species of damselfish that live in the warm waters of the Indian and Pacific oceans (users.on.net). Similarly, sea anemone are found in the tropical seas of the Pacific, but can also be found in coastal and temperate waters. (Tolweb.org). Mutualism between clownfish and sea anemone is well-known and is one of many mutualistic relationships that have evolved in coral reef ecosystems. Because clownfish are poor swimmers, they must hide in the tentacles of sea anemones (which have stinging nematocysts) in order to escape from their predators like larger fish, eel, and/or sharks (Mebs, 2009). Sea anemone's also benefit from this interaction because the clownfish scare away predators that usually eat anemone (Godwin and Fautin, 1992) and the excretory waste of clownfish also provide the anemone's zooxanthellae with nutrients.
Function (What does the technology do? Pasted from the FBS template)	The mutualistic relationship is an example of maintain community, cooperate between different species from the biomimicry taxonomy. Mutualism also increases the fitness of both individuals (Porat and Chadwick-Forman, 2004)
Mechanism (how the strategy works pasted from FBS worksheet)	The clownfish coats itself in the mucus of the anemone in order to protect itself from the stinging nematocysts. Clownfish is able to inhabit the anemone and is protected from other fish that may try to eat it through the stinging tentacles (Mebs, 2009). The sea anemone gets protection from its own predators by the territorial aggression of the clownfish that fight off other fish that may swim close to the anemone (Godwin and Fautin, 1992). It also gets nutrients from the clownfish when the clownfish excretes undigested waste and it falls onto the symbiotic dinoflagellates of the anemones that live in its tentacles.
Design Principle (idea that can be emulated in design, pasted from the FBS worksheet)	Daily close-knit interactions between two dissimilar individuals can foster meaningful relationships. Overtime, both individuals gain each other's trust, support, and other benefits that allow each individual to achieve positive personal growth.
Lifes Principles (use both headings and subheadings from the LP sheet and pick 2-4 that best fit)	Evolve to survive- replicate strategies that work Be locally attuned and responsive- cultivate cooperative relationships Be resource efficient- recycle all materials

Fig. 5c: example step 1 & 2 NTS (Organism, function & context), M. Gonzales, CofC, spring 2020.

Step 2: *Function-Strategy-Mechanism*: Students write a short natural history, define one biological function, write out the strategy that allows the organism to meet this function and then write a longer piece about the specific biological mechanism that achieves this strategy. Direct primary literature citations should be included, complete with in-text and final references (also shown in figure 5a–c).

Step 3: *Drawing to Learn*: Students (hand) draw the biological function, strategy, and mechanism as is described in the scientific research and describe the principle of what is happening in a succinct manner. This 'drawing to learn' process creates a Biological Mechanism Drawing that visually communicates how the organism achieves its function (figure 6a–c).

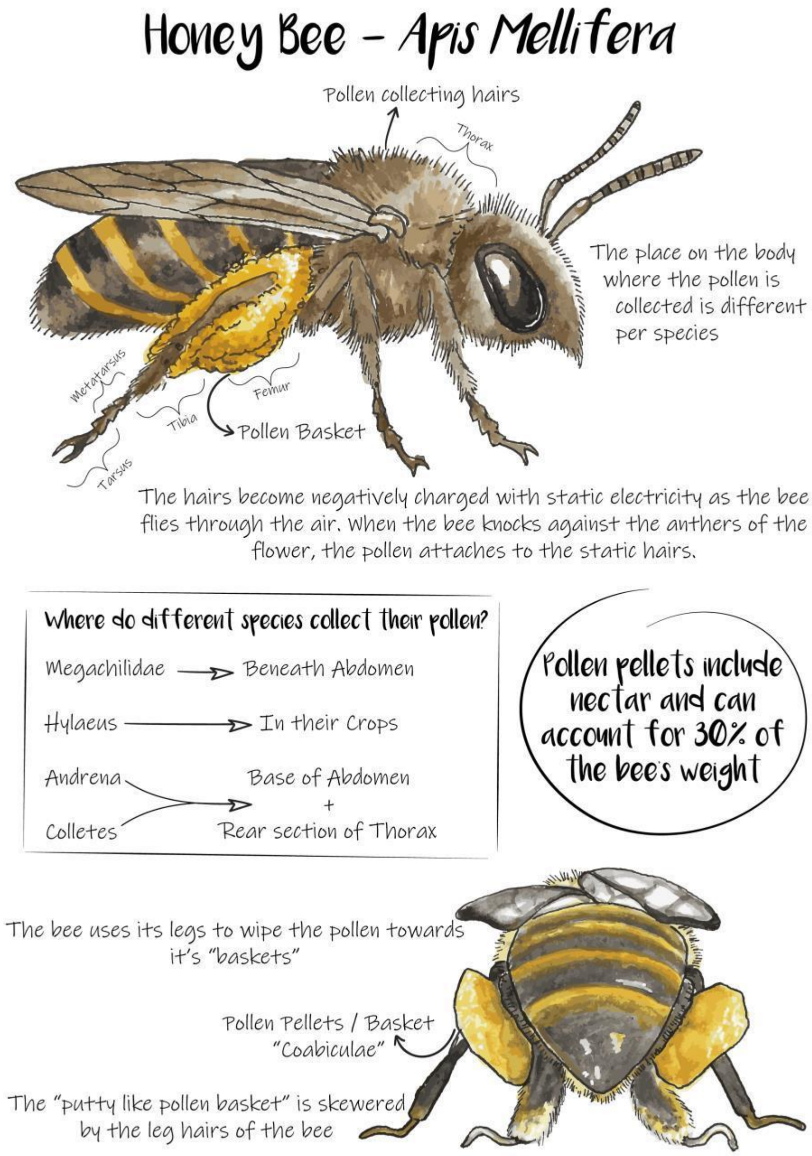


Fig. 6a: Step 3 NTS (BDP), A. Feltrinelli, THUAS.

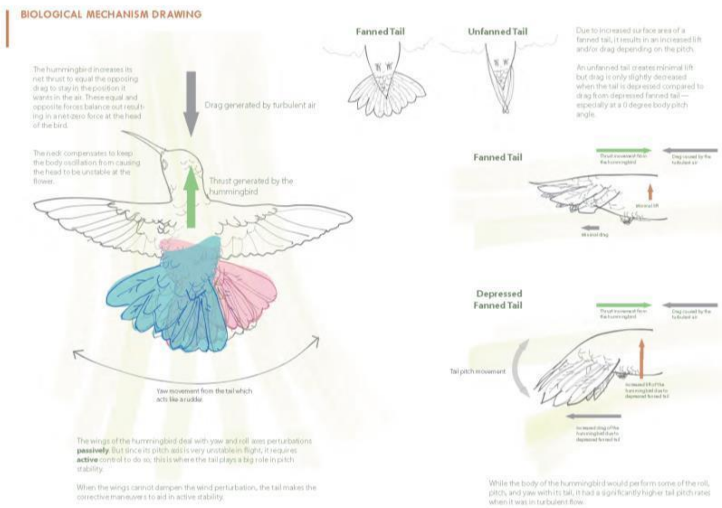


Fig. 6b: Step 3 NTS (BDP), K. Boakye, ASU.

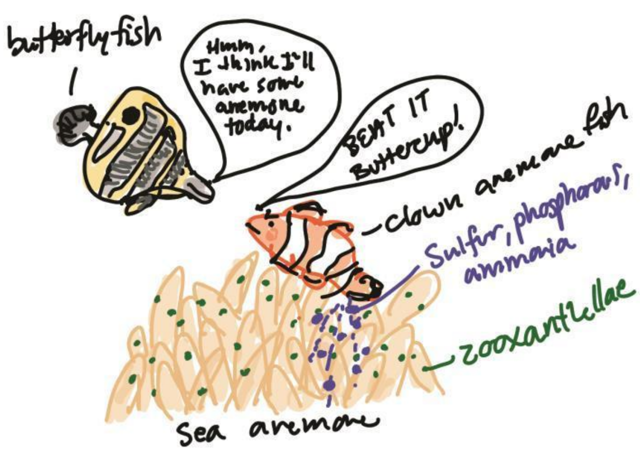


Fig. 2. Sea anemone gets benefits of this mutualism by 1) clownfish defending the anemone from its own predators like butterflyfish 2) clownfish secretes undigested waste (sulfur, phosphorous, ammonia) that become food for symbiotic zooxanthellae living inside the cells of sea anemone (Mebs, 2009)

Fig. 6c: Step 3 NTS (BDP), M. Gonzales, CofC.

Step 4: *Abstracting the Design Principle (ADP)*: Students synthesize and describe the causal mechanism replacing the biological terms with non-biological (i.e. engineering) terms to identify the lesson that natural organisms have for human designers, the Abstracted Design Principle (ADP) (figure 7).

"Fibres develop a positive static charge due to external factors such as motion, whereas separate modules have a negative charge, making them ideal to stick to these fibres. Due to their opposite charges, when the modules come into contact with the fibres, the modules stick to the fibres.". a) ADP Honey bee (*Apis Mellifera*), A. Feltrinelli, THUAS spring 2019
"The design uses an expandable flap that can pitch, roll, and yaw opposite the direction of adverse airflow to generate an increase/decrease in lift and/or drag in order to help reduce energy use, increase stability, and/ or support continuous maneuverability in turbulent airflow to stay in desired location". b) ADP Hummingbird *(Trochilidae), K. Boakye, ASU summer 2020*
"Daily close-knit interactions between two dissimilar individuals can foster meaningful relationships. Overtime, both individuals gain each other's trust, support, and other benefits that allow each individual to achieve positive personal growth" c) ADP Clown anemonefish *(Amphiprion ocellaris)* & Anemone *(Actiniara), M. Gonzales CofC spring 2020*

Fig. 7: Step 4 of NTS (ADP text): THUAS (a), ASU (b) & CofC (c)

Step 5: *Drawing to Communicate*: Students visually communicate the Adapted Design Principle to designers and engineers Note, CofC students lack design experience, and although hand drawing was strongly emphasized as a teaching and learning tool, they were given the option to include either hand drawings or well-chosen images from the primary literature in their final NTS submissions. (Figure 8a–c).

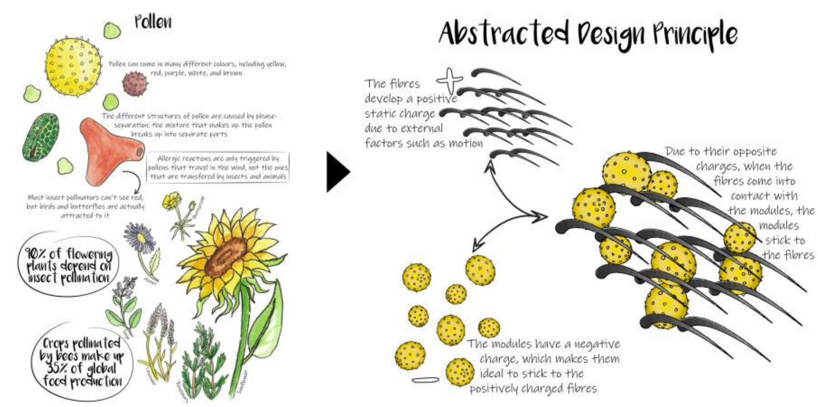


Fig. 8a: NTS Step 5 ADP's from Honey bee (Apis Mellifera), A. Feltrinelli, THUAS.

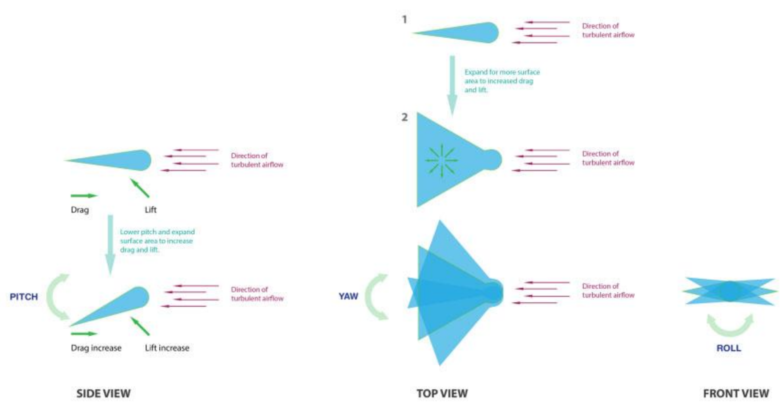


Fig. 8b: NTS Step 5 ADP's from Hummingbird (*Trochilidae*), K. Boakye, ASU.

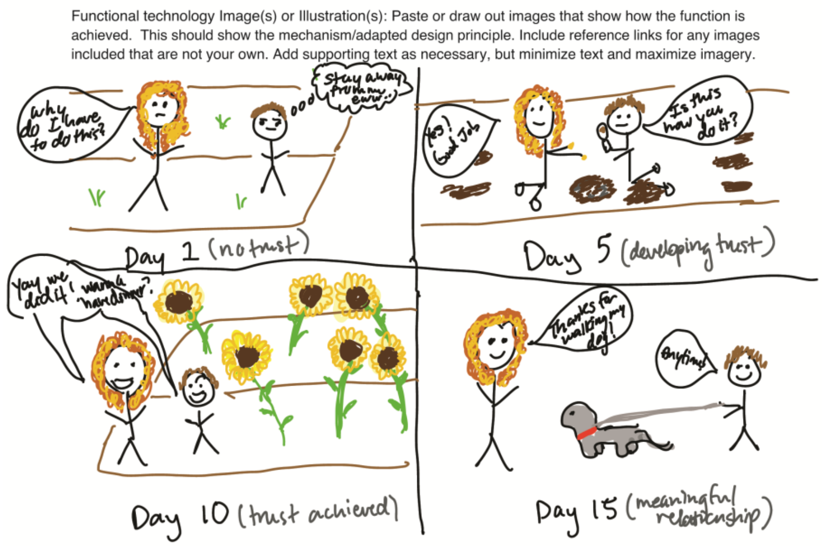


Fig. 8c: NTS Step 5 ADP's from Clown anemonefish (*Amphiprion ocellaris*) and Anemone (*Actiniara*), M. Gonzales CofC.

Step 6: *Brainstorming and emulation*: The design phase where students ideate and iterate biomimetic design ideas is not part of this study, but is shown here (Figure 9a–c) to aid the reader's understanding of how ADP's are used.

Fig. 9a: *Step 6 of NTS,* Sweater from Honey bee (*Apis mellifera*), A. Feltrinelli, THUAS.

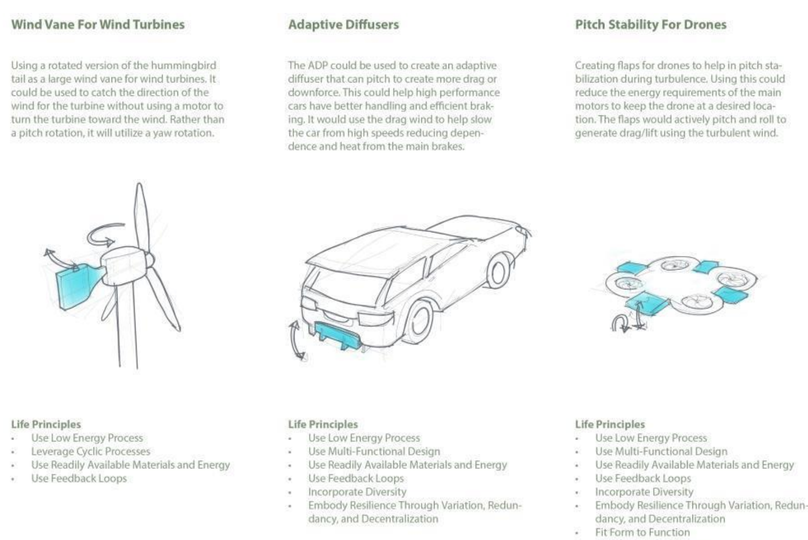


Fig. 9b: Step 6 of NTS, Hummingbird *(Trochilidae)*, K. Boakye, ASU.

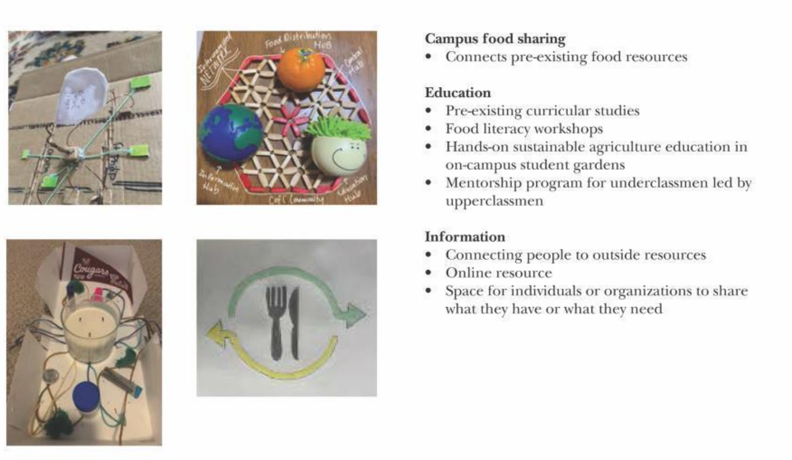


Fig. 9c: Step 6 of NTS Anemone and clownfish M. Gonzales, CofC.

Distinction between student cohorts:

THUAS

Students from The Hague University of Applied Science conducted a Challenge to Biology (C2b) design solution project using the biomimicry design methods (Baumeister 2014) combined with Design Thinking, from scoping through evaluation to incorporate methodologies into a design-based-learning (DBL) project. The non-obligatory NTS assignment at THUAS culminated the discovery phase and prepared students for the creative brainstorming process. Sharing iterative Drawing-to-Learn exercises by hand were a main factor as well as technical drawings of how the mechanisms worked within a final prototype.

ASU

Students from the ASU Summer 2020 course built their NTS based on a Biology to Design (B2d) process rather than the more common challenge to Biology (C2B) process because of the shorter 5-week period. Starting with the organism, process or system of choice, they dove deep to discover just one strategy to translate into a design principle, focussing on one function. The ASU NTS template also asks students to specify at least 4 Life's Principles that the organism is exhibiting to recognize the deep patterns and connections in nature. *This test group integrated our preliminary 'recommended pedagogical principles' findings into the NTS instructions.

CofC

Students from the College of Charleston (CofC) First Year Seminar (FYSE) and upper level courses conducted a month-long Challenge to Biology (C2B) design project using the biomimicry design method (Baumeister 2014) from scoping through evaluation. The NTS assignment at CofC concluded the discovery phase and prepared students for the creative brainstorming process. While it was emphasized and strongly encouraged to hand draw both the biological and functional technology mechanisms employing 'drawing to learn' methodology to formulate abstracted design principles, hand drawn visuals were not mandatory for the final NTS submission. Students in the CofC cohorts came from a diverse spectrum of disciplines including biology, entrepreneurship, urban studies, and environmental and sustainability studies, and had little to no prior design experience. Learning outcomes for the first-year experience students emphasized research methods, creativity, growth mindset, and communication skills. Upper level students (spring) were almost exclusively junior and seniors (3rd and 4th year), as such, learning outcomes and expectations were elevated.

DATA COLLECTION AND ANALYSIS

Phase 1: Assignment cues comparison

Syllabi, assignments, and lesson plans were shared between author faculty at three participating universities (THUAS, ASU and CofC). We compared our teaching methodology. For this study, student Nature Technology Summaries (NTS's) deliverables were collected and shared between the authors after Institutional Review Board (IRB) approval and/or student consent for publication. The same external assessor scored each of the student NTS assignments with an identical rubric recording categorical Y/N data about the clarity and depth of student work.

			Rubric											
S.No	Organism	Function	References	Latin Name	Context	Function	Mechanism	BDP / Context illustration	ADP text	Functional Tech illustration ADP diagram (no biology or = no)		Life's Principles	Description	Form, Process or System analogy used
			3+ ref (must have at least 3 references)	correct, (cap, italics but still a "Yes"if it is in there (?)	complete + biome (characteristics where it exists in Nature)	BM taxonomy (from the sheet diagram)	Thorough description of how the organism achieves its function	organism (correct species) performing the function in context. citation + web address	No biology, engineering/architecturally oriented, well done.	diagram from literature with citation/web address	Hand Drawn	well correlated and matched, three or more LP's included	explains the context, function, strategy, and mechanism, includes in-text citations	
			Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	F / P / S

Fig. 10: NTS Rubric.

Phase 2: Rubric analysis of NTS's

A scoring of Yes=green and No=red, made visible whether an NTS element was included or lacking (figures 10 & 11). These empirical data made statistical comparisons possible. We investigated which elements aid in reaching accurate abstracted design principles (ADPs) that are both true to nature and beneficial to designers as they start the ideation phase. We also recorded whether ADPs were form, process or system based. Systems level analogies were emphasized within THUAS and CofC courses in 2020. To rank as a high-quality mechanism (Y) students were required to write a thorough description of how the biological organism or system achieves its function including as much detail as is scientifically known to describe the structural, process, or systems level workings. To rank as a high-quality ADP (Y) students were required to write a broadly translatable, engineering/architecturally oriented, scientifically accurate design principle that was devoid of biological terminology.

Phase 3: Statistical Analysis
We utilized 2 x 2 contingency table statistical testing (Fisher 1934) in R to test for a) independence between the quality of written ADPs and the quality of written mechanisms and b) independence between quality of written ADP and evidence of hand drawing by students during their NTS process.

Phase 4: Qualitative Analysis
Our weekly roundtable discussions during the co-creation of this manuscript regarding where our students struggled and where they thrived led to qualitative findings and recommendations for optimal biomimicry teaching principles.

RESULTS

Phase 1: Assignment cues comparison
We found a large degree of synchrony and overlap in how we facilitated the Nature's Technology Summary (NTS) assignment (table 2). The background material and learning objectives were alike. Similar exercises and instructional cues were given. The bio brainstorm research procedures were assigned in an indistinguishable manner, as were the instructions and learning objectives for completing a NTS. All students were assigned the same NTS template listing the organism/ecosystem, the abiotic context in which the biological organism/system evolved, the biological function(s) it is capable of, references from primary resources, a description and diagram of how the organism carries out the biological function, and a description and diagram of the design/engineering abstracted design principle. The slight

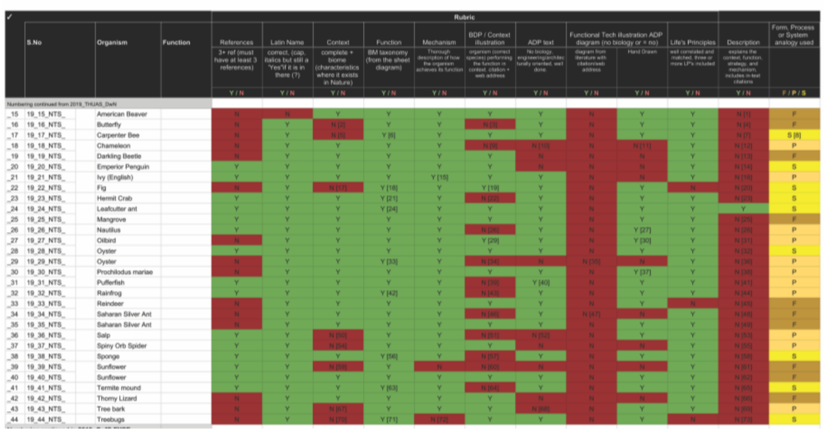
nuances found in the NTS assignments between institutions were the omission of Life's Principles at THUAS and the omission of mandatory hand drawn work at CofC.

Table 2: synchronizing NTS cues

NTS template elements		
THUAS *BS IDE* *Laura Stevens*	*ASU* *BS MS* *Michelle Fehler*	*C of C* *BS BA* *Deborah Bidwell*
organism (common and Latin name)	x	x
function	x	x
primary references (minimum 1)	x (minimum 3)	x (minimum 3)
context	x	x
biological strategy & mechanism	x	x
diagram of biological design principle	x	x
(hand drawn)	x	*optional*
Abstracted Design Principle text	x	x
ADP diagram	x	x
(hand drawn)	x	*optional*
	Life's Principles	x

x: same as THUAS, BS, MS and BA (Bachelor of Science, Master of Science, Bachelor of Arts)

Phase 2: Rubric analysis results of NTS's



✓	S.No	Organism	Function	Rubric: References	Latin Name	Context	Function	Mechanism	BDP / Context illustration	ADP text	Functional Tech illustration ADP diagram (no biology or = no)		Life's Principles	Description	Form, Process or System analogy used
				3+ ref (must have at least 3 references)	correct, (cap, italics but still a 'Yes' if it is in there (?)	complete + biome (characteristics where it exists in Nature)	BM taxonomy (from the sheet diagram)	Thorough description of how the organism achieves its function	organism (correct species) performing the function in context, citation + web address	No biology, engineering/architecturally oriented, well done	diagram from literature with citation/web address	Hand Drawn	well correlated and matched, three or more LP's included	explains the context, function, strategy, and mechanism, includes in-text citations	
				Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	F / P / S
Numbering continued from 2019_THUAS_DwN															
_15	19_15_NTS_	American Beaver		N	N	Y	Y	Y	Y	Y	N	Y	Y	N [1]	F
_16	19_16_NTS_	Butterfly		N	Y	N [2]	Y	Y	N [3]	Y	N	Y	Y	N [4]	F
_17	19_17_NTS_	Carpenter Bee		N	Y	N [5]	Y [6]	Y	Y	Y	N	Y	Y	N [7]	S [8]
_18	19_18_NTS_	Chameleon		N	Y	Y	Y	Y	N [9]	N [10]	N	N [11]	Y	N [12]	P
_19	19_19_NTS_	Darkling Beetle		N	Y	Y	Y	Y	Y	N	N	N	Y	N [13]	F
_20	19_20_NTS_	Emperior Penguin		Y	Y	Y	Y	Y	Y	N	N	N	Y	N [14]	S
_21	19_21_NTS_	Ivy (English)		Y	Y	Y	Y	Y [15]	Y	Y	N	N	Y	N [16]	P
_22	19_22_NTS_	Fig		N	Y	N [17]	Y [18]	Y	Y [19]	Y	N	Y	N	N [20]	S
_23	19_23_NTS_	Hermit Crab		Y	Y	Y	Y [21]	Y	N [22]	Y	N	Y	Y	N [23]	S
_24	19_24_NTS_	Leafcutter ant		Y	Y	Y	Y [24]	Y	Y	Y	N	Y	Y	Y	S
_25	19_25_NTS_	Mangrove		Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N [25]	F
_26	19_26_NTS_	Nautilus		Y	Y	Y	Y	Y	N [26]	Y	N	Y [27]	Y	N [28]	P
_27	19_27_NTS_	Oilbird		N	Y	Y	Y	Y	Y [29]	Y	N	Y [30]	Y	N [31]	P
_28	19_28_NTS_	Oyster		Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N [32]	S
_29	19_29_NTS_	Oyster		N	Y	Y	Y [33]	Y	N [34]	N	N [35]	N	Y	N [36]	P
_30	19_30_NTS_	Prochilodus mariae		N	Y	Y	Y	Y	Y	Y	N	Y [37]	Y	N [38]	P
_31	19_31_NTS_	Pufferfish		Y	Y	Y	Y	Y	N [39]	Y [40]	N	Y	Y	N [41]	P
_32	19_32_NTS_	Rainfrog		Y	Y	Y	Y [42]	Y	N [43]	Y	N	Y	Y	N [44]	P
_33	19_33_NTS_	Reindeer		N	Y	Y	Y	Y	Y	Y	N	Y	N	N [45]	F
_34	19_34_NTS_	Saharan Silver Ant		N	Y	Y	Y	Y	N [46]	Y	N [47]	N	Y	N [48]	F
_35	19_35_NTS_	Saharan Silver Ant		N	Y	Y	Y	Y	Y	Y	N	Y	Y	N [49]	F
_36	19_36_NTS_	Salp		Y	Y	N [50]	Y	Y	N [51]	N [52]	N	Y	Y	N [53]	P
_37	19_37_NTS_	Spiny Orb Spider		Y	Y	N [54]	Y	Y	Y	N	N	N	Y	N [55]	P
_38	19_38_NTS_	Sponge		Y	Y	Y	Y [56]	Y	N [57]	Y	N	Y	Y	N [58]	S
_39	19_39_NTS_	Sunflower		Y	Y	N [59]	Y	N	N [60]	N	N	N	Y	N [61]	F
_40	19_40_NTS_	Sunflower		Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N [62]	F
_41	19_41_NTS_	Termite mound		Y	Y	Y	Y [63]	Y	N [64]	Y	N	Y	Y	N [65]	S
_42	19_42_NTS_	Thorny Lizard		N	Y	Y	Y	Y	Y	N	N	N	Y	N [66]	F
_43	19_43_NTS_	Tree bark		N	Y	N [67]	Y	Y	Y	N [68]	N	Y	Y	N [69]	P
_44	19_44_NTS_	Treebugs		N	Y	N [70]	Y [71]	N [72]	Y	Y	N	Y	N	N [73]	S

Fig 11: Sample NTS rubric scoring of one cohort (by external assessor).

After each NTS was scored, the percentage of students successful for each element of the NTS could be determined (table 3). Within most of the assignments from the three universities, there were small, overlooked aspects which were common, such as not including in-text citations and not having three or more references (though in most cases this is not specified within the template). This appears to have had no impact on the overall quality of the NTSs or ADP within the NTS.

Table 3: included NTS elements

NTS template elements included correctly (Y) in assignment (% included successfully)

THUAS BS IDE	*15 week 2019 DwN*	*15 week 2020 DwN*	*ASU MS*	*16 week 2019 DSC*	**5 week 2020 DSC*	*CofC BS BA*	*14 week 2019 FYSE*	*14 week 2019 Up-per*	*14 week 2020 Up-per*
organism	88%	100%		97%	100%		100%	92%	93%
function	81%	86%		100%	92%		100%	97%	96%
references	50%	49%		50%	100%		79%	65%	63%
context	69%	50%		73%	83%		74%	83%	67%
mechanism	100%	89%		93%	100%		100%	88%	88%
diagram of BDP	94%	69%		60%	100%		65%	77%	83%
(hand drawn)	94%	69%		60%	100%		N/A	N/A	N/A
ADP text	94%	63%		70%	100%		21%	40%	57%
ADP diagram	94%	66%		70%	92%		11%	21%	28%
(hand drawn)	94%	63%		70%	92%		5%	12%	18%
Life's Principles	0%	0%		90%	77%		37%	53%	52%
**Systems	1%	14%		30%	0%	**	11%	21%	42%

x: hand drawn was optional at CofC
** short 5-week semester*
*** THUAS emphasized systems and CofC and THUAS emphasized SDG's in the challenges in 2020*

Phase 3 Statistical results

Table 4: Summary of statistical results testing association between quality ADP (Y) scores, hand drawing ADP (Y), and quality mechanism scores (Y) by school and cohort.

Results of Fisher's exact tests of association between quality ADP text (Y) with quality mechanism (Y) and hand drawing ADP (Y) pooled by university cohort with CofC FYSE representing control group. Significant results, a = 0.05 p values in bold. Odds ratios in parentheses.

	THUAS pooled n = 51 NTS	ASU pooled n = 42 NTS	CofC upper pooled n = 201 NTS	CofC FYSE n = 19 NTS
Hand drawn (Y)	**p=0.0007284**	**p = 0.0001367**	**p = 0.000005278**	p=1
	(10.76884)	**(29.80795)**	**(8.804148)**	(0)
Mechanism (Y)	p=1	p = 0.3868	p = 0.05253	p=1
	(0.8740843)	(3.2829709)	(2.618477)	(0)

Table 5: Summary of statistical results testing association between quality ADP (Y) scores, hand drawing of ADP (Y), and quality mechanism scores (Y) pooled THUAS, ASU, CofC upper level.

Results of Fisher's exact tests of association between quality ADP text (Y) with quality mechanism (Y) and hand drawing ADP (Y) pooled THUAS, ASU, CofC upper. Significant results a = 0.05 p values in bold. Odds ratios in parentheses.

	Pooled THUAS, ASU, CofC upper. n = 313 NTS
Hand drawn (Y)	**$p < 2.2 \times 10^{-16}$**
	(11.35)
Mechanism (Y)	**p = 0.0357**
	(2.343932)

Results indicate that CofC first year experience students performed differently than all other student cohorts and struggled specifically with the ADP step (Table 4). Fisher's exact tests showed no significant differences between upper level students in 2019 and 2020 cohorts within any university ($p > 0.05$), so data were pooled within schools. Fisher's exact tests show a significant correlation between hand drawing of ADPs and the quality of the ADP text ($p < 0.001$) for all university groups excluding CofC FYSE (Table 4). If there is not a good ADP, it is likely that there was no hand drawing (Figure 12). There is a trend toward quality mechanisms being associated with quality ADPs in the larger CofC upper level cohort ($p = 0.05253$), (Table 4). Pooling data across universities (excluding CofC FYSE) and applying Fisher's exact testing resulted in a highly significant correlation between quality of ADP text and hand drawing of ADP $p < 2.2 \times 10^{-16}$ (Table 5). Pooling across universities (excluding CofC FYSE) also revealed a significant correlation between quality of mechanism and quality of ADP text (p = 0.0357), (Table 5). If there was a quality mechanism, a quality ADP text was more likely (Figure 13).

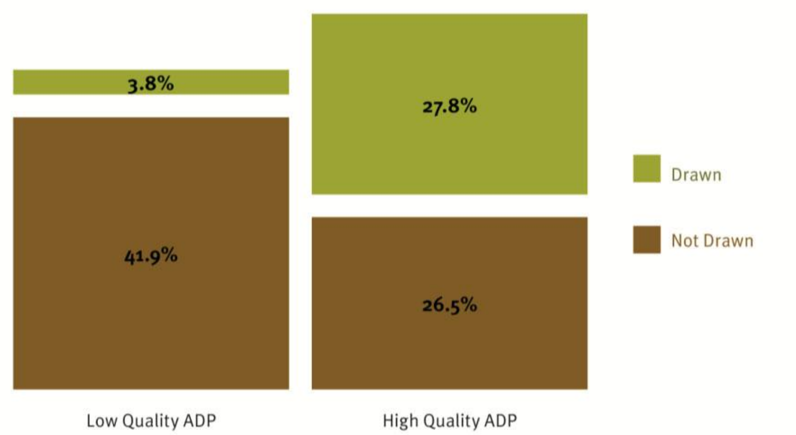


Fig. 12: Summary plot of pooled THUAS, ASU, and CofC upperclassmen data showing significant correlation between hand drawing of ADP diagrams and quality of ADP text. Fisher's exact test $p < 2.2 \times 10^{-16}$ Odds ratio = 11.35. n = 313 NTS.

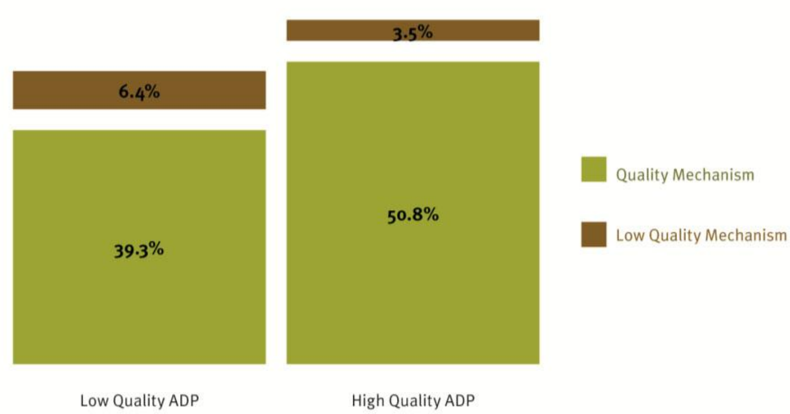


Fig. 13: Summary plot of pooled THUAS, ASU, and CofC upperclassmen data showing significant correlation between quality of mechanism and quality of ADP text. Fisher's exact test p = 0.0357 Odds ratio = 2.34. n = 313 NTS.

Phase 4: Qualitative analysis results

Table 6. Findings table elements influential in high quality BMY Design Principles

Elements influential in achieving high quality NTS'

THUAS and CofC 2019–2020, ASU 2019		*ASU 2020 Test group +*	
Key insights comparison Phase 1	- Life's Principles THUAS - no required 3 references THUAS - hand drawing CofC - not all students did same # NTS'	Influence additions	LPs were added to help understand the deeper patterns in nature
Key insights from NTS assignment results similarities/ differences Good / bad Phase 2	- ADP texts speculative and vague CofC (partially all) - some ADP diagrams include biological elements (which they should not) - jumping to design solutions - content missing THUAS - NTS sections often missing THUAS where biological drawings explaining how mechanism works (jumping to design) - speculative desired characteristic mechanics -CofC FYSE students struggled with ADPs	Proposed improvements	- ADP iterations in class - Partial NTS assignments, iterative, short feedback loops prior to next step -underlying theme of function, strategy, mechanism throughout - assign biomechanical drawing as separate assignment for emphasis - peer feedback to introduce repeating exposure to observations in nature and drawn translations - require the drawing of biology by hand, rather than finding an illustration - narrow focus of NTS to one organism, process or system
Key insights systems Phase 2	- Fewer systems in 2019 (not requested) - THUAS and CofC stressed attempting systems in 2020 class	Proposed improvements from phase 1 course elements	-progress from form, to process, to systems as course proceeds -iterations system mapping of challenge - NTS examples of systems relationships - explain text and hand draw BDP diagrams with exactness from scientific research - Future proposal to start with form, transgressing to process and then system analogies
Key insights Phase 3	- direct correlation between high % hand drawing and achieving 'good' ADPs -direct correlation between good mechanism and achieving 'good' ADPs - correlation high % correct organism, function, context etc. to achieving systems when 'organism' chosen is a system.	Proposed improvements	- *multiple* ADP's / NTS's - require hand drawing - require feedback on mechanism before ideation

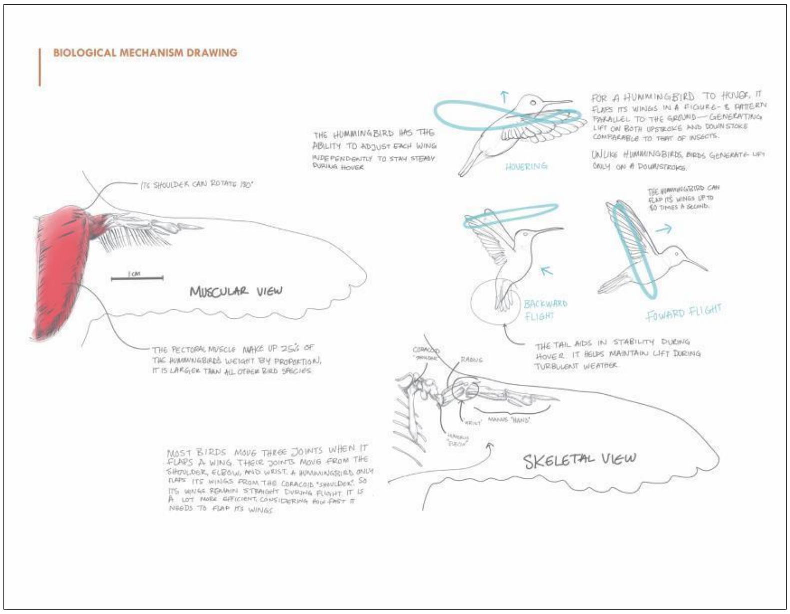
Main suggestions for improving ADP in NTS in biomimicry methodology
- Develop NTS in rounds: 1) learn biology 2) draw BDP 3) ADP text (feedback to refine) 4) draw ADP diagram 5) all fields added
- setup timeline for multiple short feedback loops

- choose drawing assignments studying form, process and systems to mimic, fitting design function - select only 1 strategy from 1 organism, behavior, system function per NTS - hand draw BDP's showing exact mechanism referred to from literature - possibly move from emulation of form to process to systems as course progresses - Add/keep LP's and min. 3 references

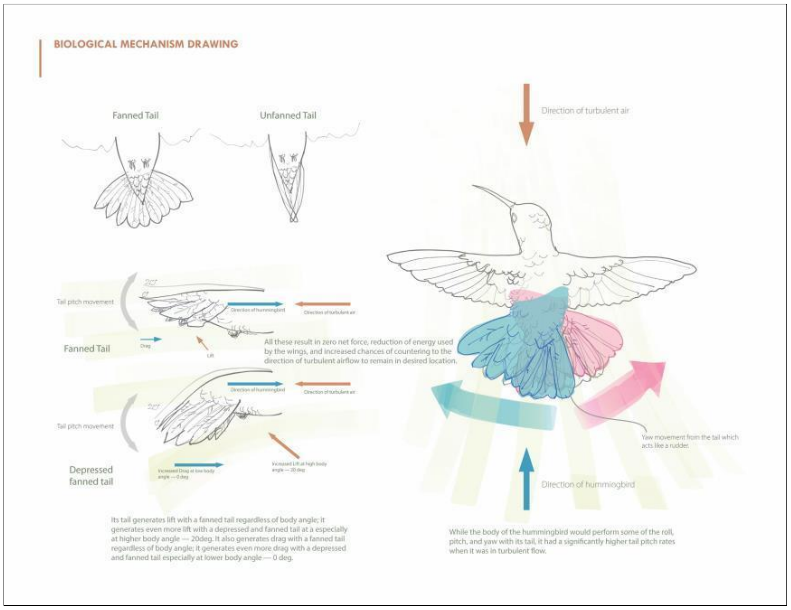
Influential course/NTS elements: With THUAS students, none of the NTS submissions included Life's Principles, though this is due to these not being included as a section, as was the case with non-mandatory in-text citations. Although the assignment was not mandatory and not assessed as such, more than half of the students delivered. Here, the "Context" section lacked, and many opted for background information only, obviating the need to describe the habitat and environmental conditions these champions face daily. Students choose to draw the biological organism more often than the abstracted principles, frequently jumping to the design phase before this knowledge was internalized. Charleston students' contexts were generally clear and complete, providing an understanding of the conditions, however, they were not required to hand draw the biology or abstractions themselves and often had biological explanations where an abstraction was required.

All students demonstrated a struggle with both the Abstracted Design Principle texts as well as the diagrams depicting these. ADP texts in many cases were vague and either referenced the biological mechanism or the champion, failing to give insight into how the mechanism functions, while others jumped ahead to begin thinking of design solutions within the ADP rather than the more open-ended statements which would aid in the development of multiple design ideas. CofC students tended to speculate in the ADP on the desired characteristics that the champion displayed for use in their solution, or simply mentioned that an aspect should be considered. ADP's of both THUAS and ASU students in design oriented semesters, seemed to do quite well, while fewer Charleston students had success. In many cases CofC students added a depiction of the biological champion achieving the mechanism rather than something "abstracted" from biology or nature to the ADP. CofC students had the majority of systems-level ADP's ready to start the ideation/emulating phase of design thinking (Table 3).

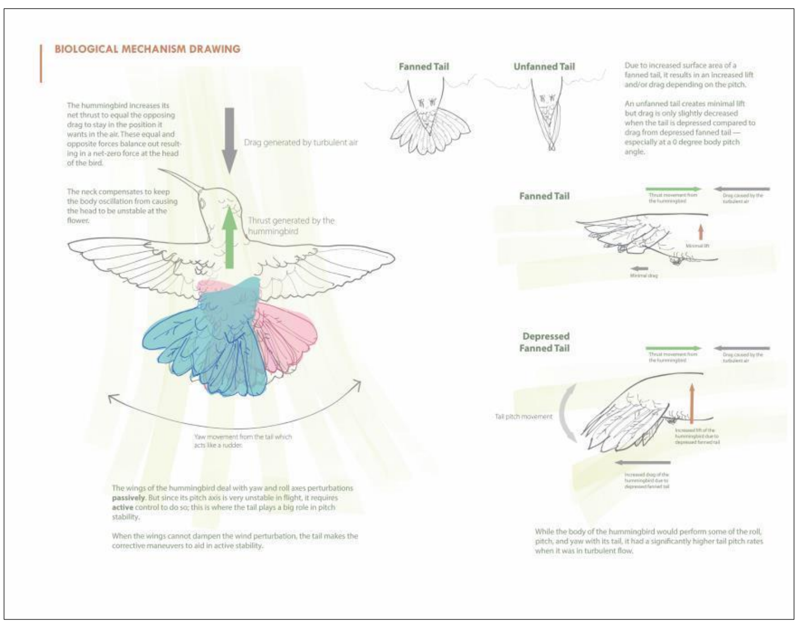
Note that the ASU 2020 cohort had the benefit of what was being learned during this study and was added last to test our 'recommended pedagogical principles' at an early stage. Our analysis shows that the highest overall scores were achieved for this cohort (except for the number of system analogies which were not requested by the instructor) (Table 3). The ASU summer cohort, being a short 5 week class, wasn't exposed to the full breadth of the BMY thinking process. A Biology to Design approach was chosen, where the students picked an organism of choice based on fascination or curiosity, which then inspired their NTS focus. Evidence for effective learning through multiple iterations of biological mechanism drawings with frequent instructor and expert feedback can be seen in Figure 14.



a)



b)



c)

Figure 14a–c: Example of the evolution of the Biological Mechanism Drawing for the Hummingbird NTS Biomechanical drawing process between feedback loops. K. Boakye, ASU summer 2020. Continued feedback and research allowed the student to iterate, refine, and deepen his understanding of the mechanism. This allowed him to arrive at a stronger ADP.

a) first Biomechanical drawing, focused on the wings of the hummingbird. At this phase, the student continued to learn about the mechanism of the stabilization of the bird.
b) once the student discovered that the tail was a more important strategy in stabilizing, he drew a new biological mechanism drawing
c) After more research, feedback and two interviews with experts, the student updated the drawing to be more specific about how the mechanism worked. This deeper understanding led to a stronger ADP.

DISCUSSION

This study examines characteristics, methods, factors, descriptors, learning outcomes, and techniques which are most often present in biomimicry student work that correlates to the highest quality abstracted design principles for the creating phase of Biomimicry Design Thinking.

RQ1

In this study, we looked at what subcomponents of the biomimicry thinking methodology are most vital for students to achieve high quality abstracted design principles. We found that each element of the NTS template appears to be valuable. Identifying natural history, context and function, align with the scoping phase. Strategy and mechanism are vital to translating nature to design during discovery and key to accurate emulation during brainstorming. Including Life's Principles and requiring references from the scientific literature may help students accurately describe the biological mechanisms, and accurate biological mechanisms are correlated with stronger ADPs (Table 3, Table 5 and Figure 13).

First year experience (FYSE) students can be thought of as a control group, a novice population. First semester US college students are in transition from high school to university level academics and typically lack the foundational knowledge and skills for excelling at the same higher order thinking level as their upperclassmen counterparts (Chaffin et al. 2019; Bloom 1956). The NTS assignment for the FYSE cohort emphasized achieving a quality mechanism through an introduction to primary literature research more so than emphasizing achieving a high-quality ADP. Although taught how to generate ADP's in an identical manner as CofC upperclassmen, the FYSE cohort's ADPs were not adequate. Although the

FYSE cohort excelled at achieving quality mechanisms (Table 3), they were largely unsuccessful at ADP writing. Understanding the biology alone appears inadequate for translating it into design principles. While our best learning comes when we are stretched and challenged, quality long term learning requires frequent low stakes opportunities that provide retrieval practice, repetition and interleaving (Brown et al. 2014). Our results support the growing body of pedagogical knowledge suggesting that students need iterative practice and frequent feedback when developing new skills such as defining biological functions using the biomimicry taxonomy, writing a succinct biological strategy, or researching and interpreting the biological mechanism underlying a form, process, or system in nature (Roediger and Pyc 2012; Biwer et al. 2020). The influence of class size on pedagogy is an important consideration. In larger classes, utilizing guided peer review in lieu of more time-consuming instructor-only feedback may be a valuable tool for providing rapid, iterative assessment of early NTS steps in both online and face to face courses (Allen and Tanner 2005).

It is worth reminding our readers that during the spring semester of 2020 we experienced a global pandemic caused by a novel coronavirus. College campuses around the globe abruptly shifted from face to face to online learning during this COVID-19 outbreak. The ASU biomimicry summer 2020 class was online by design, but THUAS and CofC courses in spring 2020 experienced a disruptive shift from face to face to online learning, in the middle of the team based challenge to biology design project.

During this study, we could apply what we discovered from our early findings to integrate research and action, adapting our pedagogy in real time (Salafsky et al. 2002). Challenges identified in facilitating the NTS template in 2019 and early 2020 courses were addressed in the ASU Summer 2020 cohort test group. We found that presenting the NTS assignment in four steps with multiple (peer) feedback moments on each, was linked with improving the Abstracted Design Principle quality to 100% (Table 3).

RQ2

We also wanted to discover what curricular or pedagogical factors influence whether students achieve systems level abstracted design principles. THUAS, ASU and CofC emphasized challenges that encouraged students to attempt system analogies, while the five-week semester at ASU could not do this in 2020 because of time constraints. It is possible that a higher percentage of systems level ADP's was achieved by the 2020 CofC class because the challenges centered on UN Sustainable development goals

(SDG's), which are wicked problems and triggered more systems level approaches to ideation. On the other hand, THUAS also focused on challenges concerning the SDG's in both years, but had a lower percentage of students who were successful in systems thinking. We noted that several CofC students included mutualistic, symbiotic relationships within their NTS submissions. Encouraging students to seek out organisms that exhibit mutualism is likely to be a good pedagogical strategy for achieving systems level NTS's in future cohorts. Systems level biomimetic emulation will be vital for becoming a regenerative species. "The first step is to imagine it, to envision this symbiotic world, a world in which we are a welcome species – a nature contributor" (Benyus 2020). We are interested in exploring the possible pedagogical benefits of beginning students with function, strategy and mechanism explorations based first on forms, then expanding to processes and then to systems in progression over the course of the semester.

RQ3

We finally asked, what is the art behind the science of biomimicry. Does drawing to learn improve the learning outcomes of multi-disciplinary novice biomimicry practitioners? If so, how is it correlated with achieving high quality abstracted design principles? The Biomimicry thinking process has been explained in detail in the Biomimicry Resource Handbook (Baumeister 2014) as well as in Biomimicry step-by-step (Rowland 2017). They both mention sketching or hand-drawing as part of iSites, which are guided nature journaling observations. Sketching is usually taught as part of a biomimic's practice (Rovalo 2019), and it could be implied that sketching does help with understanding nature's strategies. However, hand-drawing had not previously been specifically highlighted as part of the process to arrive at a high-quality ADP. Our study shows that it should be. We discovered that the use of hand drawing to depict the visuals in the NTS is highly correlated with high quality Abstracted Design Principles.

The vital step of hand-drawing the biological mechanism is a discovery we feel is a contribution to biomimicry pedagogy and was not entirely expected. Drawing helps to peak curiosity while allowing the biological information to be internalized by the learner (Quillin & Thomas 2015). Emphasizing the intended purpose of drawing as an inquisitive learning tool and process can help students overcome their fear of drawing. 'Artistry is not a prerequisite for most uses of drawing as a tool.' (Quillin & Thomas 2015). We also want to highlight the importance of repeated low stakes practice with prompt feedback and opportunities for iteration while discovering and sketching the biological mechanism (Figure 14).

The correlation between a quality mechanism and a quality ADP, though weaker, should not be overlooked. We note that many students could achieve quality ADPs without including hand drawings in their final NTS files. These students likely did draw to learn the mechanism (which was emphasized by the Instructor) but did not feel the quality of their drawings merited inclusion in the final draft of the CofC NTS. It should also be considered that students have diverse learning strategies and while drawing to learn may work for the majority, accommodating other ways of knowing and learning is advisable. Reaching a high-level understanding of the biological mechanism is the target, and drawing to learn is correlated with high level achievement of this learning outcome. However, our recommendations are not prescriptive best practices, but flexible and adaptive suggestions for effective pedagogical principles.

To better emphasize the biological mechanism drawing, it became its own assignment (instead of it being part of the NTS) for summer 2020 ASU students who were required to submit their hand drawn assignments as letter sized pdf documents to increase the focus on understanding of detail, scale and perspective. Low stakes peer feedback on visuals allowed rapid proof of understanding if the drawing clearly explained the function, strategy and mechanism with a sufficient level of detail, and what improvements were needed. Additional feedback was provided by the Instructor and students revised their drawings for NTS part 3. The Biological Mechanism drawing clearly assisted students in their learning process (Figure 14), but also turned out to be one of the most important steps for the Instructor to gauge the level of students' understanding of the organism and is highly recommended as an optimal pedagogical principle. Given a compressed schedule, the B2D process served as an effective way for learning how to abstract design principles for the first time. Future research could explore the difference in learning the Biomimicry thinking process through a comparison of students who research form-based, process-based, and systems based biological mechanisms. This may help determine whether instructors should intentionally move students along this paradigm from form to process to systems in their pedagogy.

Providing iterative feedback on the components of the NTS has been shown to be beneficial. Our results indicate it would be wise to add an additional step (step 5) between writing the ADP and drawing the ADP. We believe it to be important that the ADP is written well first, then the drawing can become a test of the writing. We recommend students team up in small groups to share their written ADP drafts with their peers who then make a first attempt to draw them. This low-stakes interactive process was tested with a team of four CofC spring 2020 students during an online check in, and shown to help identify any gaps that are lost in translation and allow for rapid ADP text prototyping based on peer feedback. When a written ADP draft passes the peer "draw-it" test, it is likely well written enough to be useful to designers and engineers during the creative innovation phase. After iterating the written ADP with peers, students can then draw better ADP diagrams. More testing is needed to determine if these higher quality ADP's will translate into improved design outcomes.

CONCLUDING REMARKS

Our research aimed to discover which characteristics, methods, factors, descriptors, learning outcomes, and/or techniques, are most often present in biomimicry student work and correlate to the highest quality design principles. We have come to understand the greater importance of the Nature Technology Summary as an essential tool for biomimicry designers and the crucial aspect of dividing it up in sections to be handled separately. In attempts to follow the biomimicry thinking design cycle completely, some students may have rushed through this assignment. It has become clear, this may not be rushed and the NTS needs a more prominent place in the curriculum before the design phase can begin. While we have seen students struggle with moving from this exercise to the start of the design phase before (Stevens et al. 2020), taking the time and getting feedback in several rounds has been a major discovery. We have also learned that just asking students to focus on systems analogies between biology and design helps, but asking specifically for symbiotic relationships helps this far more. We think that requiring students to focus on Forms, Process, and Systems in a consecutive order, may help. Each comes with different challenges. Forms are easier to see, but require a lot of detail to understand the mechanics. Processes may require deep dives into biochemistry which can be overwhelming for students lacking STEM backgrounds. The system is very complex to understand, but the design principles are metaphorical which require less detail/resolution of mechanisms. We can conclude that hand drawing both the biology and the abstracted design principles, triggers a deeper connection to the researched organism or system, and will continue to test these pedagogical principles in the future.

- Biomimicry students struggle with the translating phase of biological mechanisms to design principles, which are necessary for biomimicry design solutions.
- To help students overcome obstacles of this translation, the Nature's Technology Summary exercise is most optimal when divided in sections with intermediate feedback sessions.

- Hand drawing improves the translation phase and helps students internalize the science.
- Consecutively addressing forms, processes and system analogies in biomimicry design, may help students understand the differences between each, but more testing is needed in this field.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare no conflict of interests. The Hague University of Applied Sciences and Delft University of Technology - Netherlands Code of Conduct for Research Integrity (2018). College of Charleston IRB-2020-06-04-183355 - Protocol Exemption Integrated Science Volume 1 Chapter Art and Science of Biomimicry. Arizona State University HRB 503A Social Behavior Protocol Integrated Sciences vol. 1.

REFERENCES

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. Science, 333(6046), 1096–1097. https://doi.org/10.1126/science.1204153

Allen, D. & Tanner, K. (2005). Infusing active learning into the large-enrollment biology class: seven strategies, from the simple to complex. Cell Biol. Educ., 4(4), 262–268.

Baumeister, D. (2014). Biomimicry Resource Handbook. Biomimicry3.8.

Benyus, J.M. (1997). Biomimicry - Innovation Inspired by Nature. New York, NY, USA: HarperCollins.

Benyus, J.M. (Speaker). (2020). Biomimicry Institute Fireside Chat. Retrieved 27 June 2020, from https://youtu.be/RszoSf1JkL8.

Biwer, F., oude Egbrink, M.G., Aalten, P. & de Bruin, A.B. (2020). Fostering Effective Learning Strategies in Higher Education—A Mixed-Methods Study. J. Appl. Res. Mem. Cogn.

Biomimicry 3.8. (2020). Biomimicry 38. Retrieved 17 May, 2020, from https://biomimicry.net/never-say-never-how-biomimicry-enticed-two-professionals-back-into-the-virtual-classroom/

The Biomimicry Institute (2009). Workshop material Naturalis Biodiversity Center, Leiden, NL.

Bloom, B.S. (1956). Taxonomy of educational objectives: The classification of educational goals. New York, NY: Longmans, Green.

Brown, P.C., Roediger III, H.L. & McDaniel, M.A. (2014). Make it stick. Harvard University Press.

Casakin, H., & Goldschmidt, G. (1999). Expertise and the use of visual analogy: implications for design education. Design Studies, 20(2), 153e175. doi.org/10.1016/S0142-694X(98)00032-5

Chaffin, L., Korey, C.A., Warnick, C. & Wood, L. (2019). Life So Far: A Grounded Theory Analysis of College Student Transitions Through the Sophomore Year. Journal of The First-Year Experience & Students in Transition, 31(2), pp.79–93.

Dietrich, A. & Kanso, R. (2010). A Review of EEG, ERP, and Neuroimaging Studies of Creativity and Insight. Psychol. Bull. 136(5): 822–848 DOI: 10.1037/a0019749

Dove, J. E., Everett, L. A., & Preece, P. F. (1999). Exploring a hydrological concept through children's drawings. Int. J. Sci. Educ., *21*(5), 485–497. doi:10.1080/095006999290534

Fan, J. E. (2015). Drawing to learn: How producing graphical representations enhances scientific thinking. Transl Issues Psychol Sci, *1*(2), 170–181. doi:10.1037/tps0000037

Fisher RA (1934) Statistical methods for research workers, 5th edn. Oliver & Boyd, Edinburgh

Harris, P., Ambrose, G. (2009). Basics Design 08: Design Thinking. Switzerland: Bloomsbury Publishing.

Kang, H., Thompson, J., & Windschitl, M. (2014). Creating opportunities for students to show what they know: The role of scaffolding in assessment tasks. Sci. Educ., 98(4), 674–704.

Khakpour, A. (2012). Methodology of comparative studies in education. Contemp. Educ. Res. J., 1(000), 000. Retrieved 9 June, 2020, from https://www.researchgate.net/publication/272492215_Methodology_of_comparative_studies_in_education

Landin, J. (2015, September 4). Rediscovering the Forgotten Benefits of Drawing. Symbiartic. https://blogs.scientificamerican.com/symbiartic/rediscovering-the-forgotten-benefits-of-drawing/

Leslie, C. W. & Roth, C. E. (2003). Keeping a Nature Journal: Discover a Whole New Way of Seeing the World Around You. United States: Storey Publishing, LLC.

Pyle, C.M., 2000. Art as science: scientific illustration, 1490–1670 in drawing, woodcut and copper plate. Endeavour, 24(2), pp. 69–75

Quillin, K., Thomas, S., & Quillin, K. (2015). Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. CBE Life Sciences Education, 14(1), es2–es2. https://doi.org/10.1187/cbe.14-08-0128

Roediger III, H.L. and Pyc, M.A. (2012). Inexpensive techniques to improve education: Applying cognitive psychology to enhance educational practice. *J. Appl. Res. Mem. Cogn.*, 1(4), 242–248.

Rowland, R. (2017) Biomimicry step-by-step. BIOINSPIR BIOMIM NAN, http://dx.doi.org/10.1680/jbibn.16.00019

Rovalo, E. (2019) iSites Nature Journaling for Biomimicry. Biomimicry 3.8. Missoula, Montana.

Salafsky, N. Margoluis, R. Redford, K. H. & Robinson, J. G. (2002). Improving the Practice of Conservation: a Conceptual Framework and Research Agenda for Conservation Science. Conservation Biology, 16(6), 1469–1479.

Stevens, L., Kopnina, H., Mulder, K., De Vries, M. (2020) Analogies in Biomimicry. International Technology Studies (*in press*).

Van Meter, P., Aleksic, M., Schwartz, A., Garner, J. (2006) Learner-generated drawing as a strategy for learning from content area text. Contemp. Educ. Psychol. (31) 142–166. DOI: 10.1016/j.cedpsych.2005.04.001

Zhang, H. Z., Linn, M. (2010) Proceedings of the 9th International Conference of the Learning Sciences, Chicago, 29 June to 2 July 2010 (International Conference of the Learning Sciences, Chicago, 2010), vol. 2, pp. 165–166.

Tables legend

Figures legend

Fig. 9c: Step 6 of NTS Anemone and clownfish M. Gonzales, CofC.
Fig. 10: NTS Rubric.
Fig 11: Sample NTS rubric scoring of one cohort (by external assessor).
Fig. 12: Summary plot of pooled THUAS, ASU, and CofC upperclassmen data showing significant correlation between hand drawing of ADP diagrams and quality of ADP text. Fisher's exact test $p < 2.2 \times 10^{-16}$ Odds ratio = 11.35. n = 313 NTS.
Fig. 13: Summary plot of pooled THUAS, ASU, and CofC upperclassmen data showing significant correlation between quality of mechanism and quality of ADP text. Fisher's exact test $p = 0.0357$ Odds ratio = 2.34. n = 313 NTS.
Figure 14a–c: Example of the evolution of the Biological Mechanism Drawing for the Hummingbird NTS Biomechanical drawing process between feedback loops. K. Boakye, ASU summer 2020. Continued feedback and research allowed the student to iterate, refine, and deepen his understanding of the mechanism. This allowed him to arrive at a stronger ADP.

Expert opinion Integrated Science Thinking 2050

In 2050, the Age of Biology has emerged and the field of biomimicry is integrated into higher education around the world as a major program to educate professionals how to incorporate the knowledge found in nature into design solutions of all scales. The climate crisis has been overcome, human poverty is non-existent and energy, food and material resources are readily available, mainly because of our ability to translate biological strategies into systematic, regenerative design solutions that supply ecosystem services. Businesses are eager for biomimicry professionals to enter their workforce to educate others how to improve their eco-systems thinking in a manner that is inspiring, beautiful and iteratively circular, helping others to find their own potential within the system they exist in. Social innovation is thriving because of the shared knowledge and skills; humans are finally considered a valuable Earth organism, fully integrated within their place in nature. 'Co-operation' is the fashionable, fundamental favored movement, becoming the norm. And finally, there is no need for labels such as fair trade, organic, biomimetic or sustainable because in 2050, we understand how the planet works and at that point, it will be what and how we do things naturally.

Corresponding author, Laura Stevens (Laura.L.Stevens@gmail.com) holds two MS degrees in the fields of Architecture from Delft University of Technology and Biomimicry from Arizona State University. She is a biomimicry

design educator in her role as a professor in the Industrial Design Engineering program at The Hague University of Applied Sciences in the Netherlands. A sustainable Design instructor since 2007, she is presently working on her PhD in Delft, where she is writing a series of peer-reviewed articles and book chapters on the topic of Biomimicry Design Thinking as a methodology to enhance circular, systems-thinking solutions in design by learning from time-tested biological strategies and mechanisms found in nature. *Many thanks to the co-authors, Michelle Fehler, Deborah Bidwell and Asha Singhal, all of whom dedicated their knowledge and experience as professionals in the field. The chapter is an example of beneficial mutualism, and would have been impossible without them.*

Deborah Bidwell (bidwelld@cofdc.edu) is a Senior Instructor in the College of Charleston's department of biology. A professional Biomimic and Educator, Deb holds two MS degrees, one in Zoology (marine finfish aquaculture) from the University of New Hampshire and other in Biomimicry from Arizona State University. She is a Certified Biomimicry Professional candidate, graduating in 2021. A lifelong-learner, naturalist, optimist, leader, and explorer, Deb has been passionately teaching innovative biology and sustainability-related courses for more than twenty-five years.

Michelle Fehler (mfehler@asu.edu) is a Clinical Assistant Professor with a MSD in Design, an MS in Biomimicry and certification as a Biomimicry professional. She teaches Visual Communication Design and Biomimicry courses at the Design School at Arizona State University. Her research focuses on defining a life-centered design thinking methodology by infusing biomimicry thinking into the human-centered design process for which she

is exploring various tools and processes that make the biomimetic approach more accessible to designers from various disciplines.

Asha K. Singhal (ashaksinghal@gmail.com) is the Executive Design Lead and the head of European Projects at Biomimicry Frontiers. She graduated with a Master of Science in Biomimicry from Arizona State University (ASU) building upon her experience as an Architect. Her vision with her work is to create pragmatic narratives of hope inspired by nature to bridge the gap between the built and natural environments. She conducts research at the intersection of biology, architecture, art and emergent technologies, and applies that knowledge to the development of regenerative built environments at all scales. She has international experience working on projects in Canada, Germany, US & India.