Bioinspiration as a method of problem-based STEM education:

a case study with the COVID-19 crisis

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ABSTRACT

Bioinspiration is a promising lens for biology instruction as it allows the instructor to focus on current pressing problems, such as the COVID-19 pandemic. From social distancing to oxygen stress, organisms have been tackling pandemic-related problems for millions of years. What can we learn from such diverse adaptations in our own applications? We use a seminar course on the COVID-19 crisis to illustrate bioinspiration as an approach to teaching biology content. We highlight three focal areas of the COVID crisis explored in the course (air filtration, medical interventions, and behavioral crises), each of which relates to core content from across biological disciplines (e.g., morphology, physiology, behavior). We also highlight several promising ideas, such as the nanostructure of butterfly wings informing the design of transparent masks. We conclude by stressing that for bio-inspired approaches to succeed, we must invest in basic research and systems that connect scientists across disparate fields.

Keywords: biomimetics, SARS-CoV-2, problem-based learning, creativity

Introduction

Over the last two decades, there have been increasing calls for science education to use problem- and inquiry-based approaches (Hmelo-Silver 2004, Norman and Schmidt 1992, Schmidt H. G. et al. 2011), while also integrating across the many scientific disciplines that are often so siloed (Brewer and Smith 2011, Kelley and Knowles 2016, Stohlmann et al. 2012). These educational approaches more effectively motivate students to learn science concepts, relative to historical “content-for-content sake” approaches. In addition, such active learning approaches tend to more effectively train students in critical thinking and science process skills such as literature review and information synthesis (Coil et al. 2010, McConnell et al. 2003, Setiawaty et al. 2018, Walker 2003). However, we are still exploring a range of ways to implement problem-, inquiry-, and integration-based approaches, as teaching core content is often more straightforward. In this manuscript, we illustrate how “bioinspiration” can be used as a general approach to accomplish all of these goals in one class centered on topical problems for a given audience.

Bioinspiration (or biomimetics) is a problem-solving approach that looks to diverse biological traits for inspiration in our own applications; organisms have been “solving” problems analogous to ours over evolutionary time (Bar-Cohen 2005, Bhushan 2009). Bioinspired approaches are increasingly common in engineering, chemistry, and architecture, and are potentially applicable to any field or problem (Snell-Rood 2016, Wanieck K. et al. 2017). Biomimetic approaches greatly expand the space of potential solutions explored when problem solving (Graeff Eliot et al. 2018, Graeff E. et al. 2019, Vincent et al. 2006) and design solutions are often improved by taking inspiration from biological traits (Jacobs et al. 2014, Kennedy and Marting 2016). The nature of a biomimetic approach also makes it a useful way to frame biology courses, as it is a problem-based approach to biology content (Gardner 2012, Stevens et al. 2019). Educators can use a biomimetic approach to structure inquiry and content around the most pressing issue of the day. Problems are abstracted into functional concerns, and students

explore biological traits and systems that have explored similar functional space over evolutionary time (Fayemi et al. 2017).

This review illustrates the bioinspired approach to structuring a course using a summer 2020 class centered on one of the most pressing current issues -- the COVID-19/SARS-CoV-2 pandemic. Our class “Biomimetic approaches to pandemics” explored how bioinspiration approaches could broaden the solution space explored when solving problems related to COVID-19. This review presents highlights of our process to demonstrate the utility of a biomimetics approach to structuring a biology class. The basic format of the class (see Supplementary Material for syllabus and sample class structure) also worked very well in an online format. In this manuscript, we first give a broad overview of the COVID-19 crisis, before walking through three different focal problem areas, and a number of relevant biological systems we explored in class. This level of detail is primarily meant to illustrate how the content in the class was structured and the types of explorations we took into different areas of biology (physiology, behavior, morphology, evolution). While we are not virologists or epidemiologists, we also hope that some of these ideas could serve as inspiration for creative approaches to solving pandemic-related problems during this or future outbreaks. We conclude review by discussing some of the broader take-home messages in terms of when biomimetic approaches may be more likely to lead to innovative technologies and real solutions to problems.

Mapping the problem space of the COVID-19 pandemic

SARS-CoV-2 is the coronavirus responsible for the COVID-19 pandemic. While the problem stems from a single-stranded RNA virus, it extends into most every space of science, technology, and society. We started our class by “mind-mapping” the COVID-19 pandemic (Davies M. 2011, Edwards and Cooper 2010), with each student taking a visual approach to exploring how the central problem of the class connects to dozens of other problems (Figure 1). This problem space is vast, which represents an opportunity for students to choose problems of

individual interest, and for problems to be structured in the syllabus matched to relevant content (see Supplementary Material). The COVID-19 pandemic encompasses problems related to addressing the disease in patients, including ventilators, antiviral medicines, and those related to disease spread, such as disinfectants, and social distancing. There are problems related to supply chain disruptions in the face of lock-down, economic collapse in response to job loss and future unknowns, and problems related to childcare, mental health, and anxiety (Figure 1).

Figure 1. Sample mind mapping of the COVID-19 problem. Sample “mind map” of the COVID-19 problem. Individual lines connect ideas in a free-flowing brainstorming session (e.g., “X makes me think of Y”), rather than any particular causal structure. This mind mapping helps to identify the many sub-problems within a larger problem. In comparing the problem maps from different students, we also see how individual experiences shape the perception of high priority problems.

Each individual in the class mapped the COVID-19 problem space separately and then compared notes. This experience revealed how individual experiences bias different parts of the problem space, for instance those with small kids in their immediate social network highlighted many of the challenges of childcare and working from home, while those who had to continue in-person work highlighted problems with mask conformity in public spaces. This exercise also showed how each individual problem could be further “mapped” to individual components that

might be more amenable to problem-solving. For instance, “toilet paper shortages” was mapped further to liquid absorption, supply chain issues, hoarding and reselling, alternate materials, and questions about why we use toilet paper in the first place. Sequential mind-mapping illustrates the broader importance of problem analysis in bioinspired approaches, both to determine possible intervention points, and to find a range of possible biological analogs (Fayemi et al. 2017, Wanieck K. et al. 2017).

Our class analysis of the COVID-19 pandemic challenge space was followed by a walk-through of six particular issues (see Supplementary Material: A). In this review, we have chosen three of these areas as examples to illustrate the structure of a bio-inspired problem solving approach. For each topic, we first learned more about the challenge before selecting relevant “functions” to guide our exploration of the biological solutions space (e.g., through use of the asknature database, (Deldin and Schuknecht 2014)). Learning about a number of relevant organisms and their adaptations created the opportunity to review fundamental biology content (see Supplemental Material: B) before returning to the COVID-19 problem.

Masks and air filters: exploring morphological adaptations

The first portion of our course explored “form and function” in biology by focusing on the materials and design of masks and air filtration as a focal COVID-19 subproblem. Airborne transmission is a key component of the rapid spread of SARS-CoV-2 (Prather et al. 2020). Viral particles suspended in respiratory droplets result in increased rates of transmission in indoor spaces (Allen and Marr 2020). Thus, wearing masks and increasing ventilation are often highly effective control measures (Cheng et al. 2020, Wang Yu et al. 2020a). Coronaviruses are very small (on the order of 0.1 μm in diameter), and many materials that effectively block individual viral particles also reduce air flow, limiting their utility in masks (Davies A. et al. 2013, Zangmeister et al. 2020). However, many materials can block larger respiratory droplets (5-10 μm), which can reduce disease spread (Bourouiba 2020, Stadnytskyi et al. 2020). Thus, cloth

120 masks are recommended for broad use when more effective N95 masks are not available.
121 Filtration systems that purify indoor air (e.g., stand-alone or HVAC HEPA filters) can filter out
122 viral particles using a wider range of materials that are not necessarily breathable (Zhao et al.
123 2020). For instance, the use of HEPA filtration in hospitals can cleanse air of SARS-CoV-2
124 particles (McDonald 2020, Phu et al. 2020). Can bioinspiration give ideas for the design of more
125 effective, efficient, or easy-to-use masks or air filtration systems?

126 ***Filtration systems.*** We explored a range of ways in which “filtration” applies to
127 biological systems and traits. Many animals use filter-feeding to separate food particles from the
128 surrounding air or water. In other cases, biological materials that have evolved in one context
129 (e.g., plant fibers) can be used as filters in human applications – in other words, filtration is a
130 function in human applications rather than the evolved function of that trait (“bioutilization”
131 (HOYOS and Fiorentino 2016)). We highlight some of the filter feeding systems we explored,
132 and how this biology could potentially inspire new directions in design of masks or air purifiers.

133 Marine organisms show an incredible diversity of filter feeding mechanisms that span all
134 of the primary mechanisms of filtration shown in human engineered filters. Filter feeding
135 organisms vary in size from microscopic to the largest animals on earth (baleen whales). Animal
136 filtration systems selectively exclude or include particles down to the micron-level, meaning
137 there are potential applications for blocking the aerosol particles relevant in COVID-19
138 transmission, in addition to potentially the viral particles themselves. How are they filtering
139 particles? Many species that have been assumed to use sieve-based filtration actually rely on a
140 combination of filtration mechanisms, including crossflow filtration (i.e., fluid flow parallel to the
141 filter (Conley et al. 2018c)). Some marine tunicates (appendicularians) have a two-stage
142 filtration system that relies on morphological shape, behavior, and properties of the mucous
143 mesh to filter and concentrate particles as small as viruses, that are important components of
144 their diet (Conley et al. 2018a, Lawrence et al. 2018). Tunicates vary tremendously in the
145 structure and morphology of their filtration systems and mucous nets with functional implications

for filtration rate, particle size (Conley et al. 2018a, Sutherland et al. 2010), and even particle shape (Conley and Sutherland 2017). While some of the filtration mechanisms overlap with those used in industrial filters, in many cases, aspects of the biological filters are unique; for instance, filter movements can result in selective removal of some particles, a form of filter self-cleaning (Conley et al. 2018b). Outside of tunicates, other marine organisms also filter in unexpected ways. Manta rays exhibit a novel mechanism termed “ricochet separation” that separates particles based on size and prevents filter clogging (Divi et al. 2018), a discovery which has inspired novel industrial filters capable of separating nanoparticles (Wang Z. B. et al. 2020c). The diversity of marine filtration systems could potentially inspire creative new directions in the design of more effective or longer lasting facemasks or air purifiers.

Mask transparency. In addition to exploring the primary function of masks (filtration), we also identified other challenges associated with masks, such as transparency. People with hearing loss and social communication disorders can have difficulties communicating when they cannot not see the mouth movements of the others in the conversation (Chodosh et al. 2020, Corey et al. 2020). Creating transparent masks is challenging because most existing transparent materials, such as glass and plastic, are not breathable and often fog. We considered whether bio-inspired approaches could be used to develop novel transparent textiles, specifically a breathable, transparent material that is also an effective filter.

Butterflies, and insects more generally, have evolved transparent wings independently multiple times, often with diverse underlying mechanisms (e.g., (Dushkina et al. 2017, Watson et al. 2017)). The wings of most butterflies and moths are semi-translucent when wing scales are removed, but in some cases, there has been selection on transparency to facilitate effective camouflage (Figure 2A (Gomez et al. 2020, Johnsen 2001, McClure et al. 2019)). Many of these wing structures are additionally hydrophobic, another desired characteristic in mask design (El-Atab et al. 2020, Wanasekara and Chalivendra 2011). Our research honed in on one butterfly species in particular. The wings of the glasswing butterfly are both antireflective and translucent

because of randomly dispersed pillar-shaped nanostructures (about 4 μm in width) on the wing surface (Figure 2C, (Pomerantz et al. 2020, Siddique et al. 2015)). Creating similarly sized and shaped structures on glass reduces reflectivity and increases transparency (Diao et al. 2016, Sourakov and Al-Obeidi 2019), but is it possible to use an analogous design to make a breathable fabric more opaque? “Electrospinning” can be used to create fibers as small as 2 μm in width and has been applied to breathable fibrous materials (Frey 2008, Xue et al. 2019). Indeed, electrospinning has been used to create translucent air filtering materials (Figure 2D, (He et al. 2020, Xu et al. 2016)), suggesting inspiration from butterflies could improve on existing designs to create bio-inspired transparent face masks (Eadie and Ghosh 2011).

Figure 2. The glasswing butterfly as inspiration for transparent face masks. A) The glasswing butterfly (*Greta oto*) relies on transparent wings for camouflage in rainforests of Central and South America. This transparency stems from antireflective surfaces on their wing cuticle characterized by small

185 *hairs (B) interspersed with densely packed nanopillars (C). Electrospinning, which has already been used*
186 *to synthesize semi-transparent filters (D), could potentially be used to develop transparent face masks.*
187 *Image credits: (A) Image courtesy of Andrei Sourakov; (B & C) SEMs courtesy of Radwan Siddique; (D)*
188 *reprinted (adapted) with permission from (Xu et al 2016 Nano Lett (Xu et al. 2016)). Copyright (2016)*
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191 **Medical interventions: exploring physiology**

192 In the middle portion of our class, we covered biology content related to physiology in
193 the context of medical interventions related to COVID-19. We explored a number of possible
194 medical intervention points, including coping with oxygen stress, and beating back the virus
195 through the body's immune response or through antiviral medications. The SARS-CoV-2 virus
196 invades the human body by binding to ACE-2 receptors in respiratory airways, and then
197 hijacking the cell's machinery to replicate itself (Matheson and Lehner 2020, Wadman et al.
198 2020). Antiviral medications can inhibit SARS-CoV-2 at the start of infection by interfering with
199 viral binding or replication (e.g., Remdesivir, (Eastman et al. 2020, Wang Y. M. et al. 2020b)).
200 Downstream of this point, infection causes issues with low blood oxygen, inflammation, blood
201 clotting and resulting tissue damage (Ciceri et al. 2020, Wadman et al. 2020). Can we improve
202 existing medical interventions by learning from diverse adaptations across organisms in
203 response to similar physiological challenges?

204 ***Dealing with low oxygen.*** One of the primary medical concerns of SARS-CoV-2
205 infection is low blood oxygen, sometimes presenting without behavioral indicators of oxygen
206 stress ("silent hypoxemia or hypoxia" (Tobin et al. 2020a, Wilkerson et al. 2020)). Infection can
207 degenerate into Acute Respiratory Distress Syndrome, requiring mechanical ventilation (Rello et
208 al. 2020). However, ventilator use is associated with poor health outcomes for COVID-19
209 infection, possibly more so than other respiratory infectious diseases (Fan et al. 2020,
210 Richardson et al. 2020, Tobin et al. 2020b). Over the course of the pandemic, medical attention
211 has increasingly shifted to the disease's role in complications in the vasculature associated with
212 a "storm" of molecules (cytokines) that signal inflammation (Ackermann et al. 2020a, Ciceri et al.

2020, Low et al. 2020, Nishiga et al. 2020). We must act before the rapid deterioration that can lead to systemic inflammation, organ damage and potentially death (Ackermann et al. 2020b, Wadman et al. 2020); monitoring and intervention during the mild hypoxia stage is key.

We explored possible lessons from diverse organismal adaptations to cope with low oxygen conditions, whether due to variation in elevation, water temperature, or physiological changes such as hibernation. With respect to hibernation, many mammals reduce oxygen needs during winter through lowering body temperature and metabolism (Carey et al. 2003, Drew et al. 2004), physiological changes which could inspire ways to improve tissue survival under blood loss in humans (Rodriguez et al. 2017). With respect to low oxygen in the surrounding environment, many animals cope through evolutionary and physiological changes that affect how hemoglobin in red blood cells captures oxygen. For example some fish survive low oxygen conditions with increased hemoglobin binding efficiency (Nilsson and Renshaw 2004), with a greater diversity of hemoglobins in species in more variable environments (Baalsrud et al. 2017). Some companies are in the early stages of blood transfusion treatments using such unusual hemoglobins to treat COVID-19 (e.g., from a marine worm (Garraud 2020, Le Gall et al. 2014)), similar to related treatments that pack red blood cells or saturate cells with oxygen (Geier and Geier 2020). It turns out there is a huge diversity of hemoglobins across birds as well, representing independent adaptation to high elevation through increased oxygen binding ((Storz 2016), although applications of such proteins as a treatment for hypoxia are likely limited by the ability of these hemoglobins to then release of oxygen to stressed tissues). Interestingly, human populations at high elevations also exhibit diverse adaptations to low oxygen conditions (Beall 2007, Storz 2010) and have decreased susceptibility to SARS-CoV-2 (Arias-Reyes et al. 2020). These populations could inspire other COVID-19 treatments, such as physiological acclimation to low oxygen conditions (e.g., altitude training, (Mairbaur et al. 1986, Saunders et al. 2009, Subudhi et al. 2014)) or use of phytochemical drugs following clinical trials ((Biondich and Joslin 2015, Chiang et al. 2015) and legalization).

Animals in underground burrows also frequently experience low oxygen. Subterranean rodents such as naked and blind mole rats can survive in 5% oxygen conditions for hours, through a number of adaptations, from reductions in metabolism and shifts to anaerobic glycolysis, to induction of unconsciousness (Figure 3A, (Park et al. 2017)). Another key adaptation in these species involves changes to the Nrf2-signaling pathway, which is a key regulator of stress responses in mammals (Figure 3B). Naked mole rats and other relatively longer-lived species have higher Nrf2-signaling, generally achieved through reduced degradation of Nrf2 (Lewis et al. 2015, Schmidt H. et al. 2016). What, if anything, do such observations suggest for SARS-CoV-2 interventions? Targeting the upregulation of this pathway could be feasible, and, indeed, has already been suggested as a potential therapeutic target (McCord et al. 2020). A number of plant chemicals are known stimulators of Nrf2 signaling, with beneficial effects when taken at low doses (Hybertson et al. 2019, Juge et al. 2007, Mattson and Cheng 2006); some act through reduced degradation of Nrf2, analogous to adaptations in naked mole rats (Zhang H. H. et al. 2019). Diverse adaptations of organisms to deal with low oxygen can inspire new hypotheses for medical intervention points.

Figure 3. Naked mole rats as inspiration for medical interventions. (A) Naked mole rats (*Heterocephalus glaber*) cope with low oxygen in their underground burrows in part through changes in (B) Nrf2-signaling. Nrf2 is normally activated by a range of stressors, resulting in enhanced cryoprotection, but in naked mole rats, higher constitutive expression is achieved through reduced Nrf2 degradation. (C) Changes in Nrf2 signaling have been hypothesized as an intervention point to dampen the cytokine storms associated with negative outcomes of SARS-CoV-2 infection. (D) Bioactive phytochemicals in some plant extracts (e.g., shown *Withania somnifera*) have been shown to activate Nrf2 (Hybertson et al. 2019) and are being explored as a COVID-19 treatment. (Disclaimer: this is not a clinical endorsement of any potential treatment). Image permissions: (A) and (D) from Wikimedia commons (Ltshears; Sibthorp and Smith 1819) (B) Reprinted with permission from PNAS (Lewis et al. 2015) (C) reprinted from (McCord et al. 2020) under an creative commons license.

Dealing with viral infections: immunity and chemical defenses.

We next turned to biological traits that could themselves combat viruses. Could we learn something from amazing immune systems in some species or chemical defenses in others? We first focused on bats, which tend to harbor many coronaviruses ((Banerjee et al. 2019) but not more viruses overall (Mollentze and Streicker 2020)), and rarely show external symptoms in response to these diseases (Baker et al. 2013, Hayman 2019, Mandl et al. 2018). Genomic analyses suggest bats

have a number of genes that may have been a target of selection related to disease, including MHC genes and those involved in innate immunity (Pavlovich et al. 2018, Zhang G. J. et al. 2013). With respect to coronaviruses, it appears the bat immune system tends to have a constitutively expressed innate immune response (the interferon pathway, (Banerjee et al. 2020, Brook et al. 2020)). To avoid the costs of a concomitant sustained inflammation response, bats tend to have a suppressed inflammation response (Ahn et al. 2019). This exploration into bat immunity points independently to the importance of depressing the inflammation response in treating COVID-19 (Tay et al. 2020). Indeed, some of the most promising treatments target specific pro-inflammatory cytokines that are also differentially regulated in bats (Banerjee et al. 2020, Leyfman et al. 2020, Schett et al. 2020).

Next, we considered chemical defenses that many species use to battle viruses, bacteria, parasites and herbivores (e.g., (Naithani et al. 2008, Perez 2003, Zasloff 2002)). Many natural products that initially evolved in one context (cell communication, defense, venom), can also inhibit the replication of microbes. Indeed, >75% of our medications originate from biological organisms (and >50% from plants), but applied to new human contexts (Dias et al. 2012, Kapoor et al. 2017, Mishra et al. 2013). The question becomes how we discover which biological compounds have antiviral functions against novel pathogens such as SARS-CoV-2 (Lachance et al. 2012). Is it most efficient to screen large libraries against an application of interest, perhaps combined with pre-screening modeling approaches (Duffy and Avery 2012, Lipinski and Hopkins 2004, ul Qamar et al. 2020)? Given that existing libraries likely represent <1% of existing biological chemical diversity, such an approach suggests we may be missing many new possible drugs (Farnsworth 1988). Can we use ecological and evolutionary knowledge to direct this search and discovery? Perhaps lineages that are sessile (Granato et al. 2019), or involved in intense coevolutionary arms races with herbivores, are likely to evolve broad-spectrum defenses that combat a diversity of threats (Becerra et al. 2009, Sohail et al. 2011). Or perhaps lineages that suffer from more viral attacks (e.g., (Lefeuvre et al. 2019)), or

live in denser aggregations, are more likely to harbor anti-microbial chemicals. For instance, it is possible that the high incidence of anti-microbial peptides found in amphibians comes from their vulnerability to microbial attack (Lazzaro et al. 2020). Effectively exploring this chemical “bio-space” is one of the most exciting next frontiers in bio-inspired approaches.

Cooperation and anxiety: exploring behavioral ecology and evolution

In the final portion of our class, we focused on two behavioral crises of the COVID-19 pandemic to explore biology content related to behavioral ecology and evolution. We focused on mental health and cooperation with public health measures to highlight biomimetic approaches to solving behavioral challenges. “Behavior” broadly defined refers to a system’s response to signals from the external environment. Interventions to facilitate behavioral change can come through altering the triggers of a behavior or targeting the outcome of a behavior. Such behavioral interventions often come with ethical considerations, which was a frequent discussion point when exploring different systems.

Mental health in the face of stressful unknowns. The COVID-19 pandemic has resulted in increased rates of anxiety, depression, and substance abuse stemming from a range of factors, including unemployment, balancing working from home with dependent care, social isolation during lockdown and school closure, and the stressful unknowns of a new, deadly disease (Holmes et al. 2020, Rajkumar 2020, Torales et al. 2020). We focused primarily on the latter area in our biomimetic explorations. During the COVID-19 crisis, humanity is navigating a huge novel risk – how do we safely alter our behavior in this new reality? There are many examples of animals evaluating novel, unknown, and stressful environments. Some species adeptly adjust their behavior to completely new conditions like cities or novel resources (Bonier et al. 2007, Graves and Shapiro 2003, Moller 2009). Can we learn anything by contrasting diverse responses of animals to new conditions? Animals are often fearful of new or unknown situations, showing hesitance, avoidance, or anxious behaviors in new, open environments, or

in response to new objects in their cage (“neophobia,” (Greenberg and Mettke-Hofmann 2001)). Animals pay careful attention to cues of risky and dangerous situations, including signs of death, disease, and predators, and adjust their activity accordingly, creating “landscapes” of fear and disgust (Buck et al. 2018, Curtis 2014, Kohl et al. 2018, Madin et al. 2011, Weinstein et al. 2018). However, animals also habituate to new conditions, and gradually relax initial fear responses as they learn the true dangers and associated ways to mitigate these dangers (e.g., (Martin and Reale 2008, Rodriguez-Prieto et al. 2009)). Such behavioral adjustments to potential risks takes time, information gathering, and risk assessment, often in social groups, which helps to mitigate risk in new conditions (Lima and Dill 1990, Morrell and Romey 2008, Stankowich and Blumstein 2005). For example, guppies approach and inspect new predators; the risk of gathering this information can be somewhat offset by doing so with other fish (Dugatkin and Godin 1992, Magurran and Seghers 1994). Similarly, crows may benefit from social groups to mitigate risk of novel food inspection (Greggor Alison 2016, Greggor A. L. et al. 2016a, Greggor A. L. et al. 2016b). Thus, animals are constantly updating their assessment of risk, based on past information and current cues (“Bayesian updating” (Stamps and Frankenhuis 2016, Valone 2006)), but social support can affect how such risk translates into fear and anxiety (Figure 4).

These observations offer two potential insights with respect to the pandemic. First, it offers an important perspective on the observation that COVID-19 related anxiety and depression is strongly linked to social media use (Gao et al. 2020, Garfin et al. 2020, Ni et al. 2020, Zhong et al. 2020). Exposure to social media (and media in general) can create an inflated sense of local risk as the media tends to highlight the most impacted locations at a given point in time. Animals are highly sensitive to environmental cues, and the media has in many ways warped how we assess current conditions (e.g., (Collimore et al. 2008, Nellis and Savage 2012, Patton et al. 2014)) relative to the world in which we evolved. Second, given that many animals evaluate novel, risky situations in social settings highlights how risk assessment

in social isolation is likely to be particularly stressful. This points to the importance of social support in navigating new, risky situations, suggesting pandemic-appropriate interventions such as social pods (Leng et al. 2020) or social support animals, especially those that are as socially responsive as people (e.g., dogs (Friedmann et al. 2011, Nimer and Lundahl 2007)). Both of these responses highlight ways in which people could manipulate the context eliciting anxiety or depression by reducing social media use or the use of social support animals. This approach is similar to cognitive behavioral therapy approaches to mental health where patients identify cognitive biases and their own triggers of stress and consciously work to rewire those responses or alter the inputs (Butler et al. 2006, Ho et al. 2020).

Figure 4. Triggers of risk and fear in novel situations. Animals assess the risk level of their environment as a function of cues of risk, updating prior risk assessments with new evidence (“Bayesian updating” left, (Stamps and Frankenhuis 2016, Valone 2006)). Cues from social media feeds may create a false sense of local risk, triggering fear and anxiety (Tovote et al. 2015), especially in social isolation.

Encouraging cooperation with public health policies. Many public health measures during pandemics require some degree of self-sacrifice for the greater social good. For instance, wearing masks comes with some personal discomfort, but we need a critical mass of the public to be wearing them (e.g., cloth masks with 60% efficacy require 60% of the public to wear masks to contain the virus (Tian et al. 2020)). How do we encourage cooperation with these policies? Classic game theory highlights the evolutionary challenges of altruistic strategies: the temptation to be selfish or “defect” results in “cheaters” that benefit when they are rare, but the entire system begins to suffer as they increase in frequency (Doebeli and Hauert

2005, Fehr and Rockenbach 2004, Perc and Szolnoki 2010, Smith 1979). The “payoff matrix” affects the relative costs and benefits of cooperation versus more selfish strategies (e.g., (Doebeli and Hauert 2005)), but dynamics change as players in a game meet multiple times and make choices about where to settle (Archetti et al. 2011, Perc and Szolnoki 2010). We used this broad approach to explore whether studies of the ecology and evolution of cooperation and mutualism (West et al. 2007) could offer novel insights for human cooperation with public health measures.

We turned our attention to exploring examples of cooperation and mutualism where unrelated individuals cooperate; such examples are more analogous to our focal problem than say eusocial ants or termites rallying around their queen. We explored in more detail one particular example, the mutualistic relationship between cleaner fish and its reef fish clients. Cleaner fish pick ectoparasites off of client fish, but actually prefer to eat client scales or mucous, which is costly to clients (Grutter and Bshary 2003). Clients encourage cooperative behavior by altering both the associated benefits and costs, for instance ending interactions early with uncooperative cleaners, often aggressively chasing them away (a cost or punishment (Bshary and Grutter 2002)). Clients will also stay longer for more cooperative cleaner fish (a reward or benefit (Gingins and Bshary 2015)). Interestingly, theory suggests that rewards for cooperation may have been more important in the evolution of cooperation than often appreciated (Gingins and Bshary 2015, Weyl et al. 2010), suggesting that a focus on punishing cheaters (Douglas 2008, Raihani et al. 2012) may be less effective in applications to promote cooperation. These studies led to discussions how we might increase rewards for mask-wearing, such as government incentives to reward masks in stores (e.g., game theory and incentives in vaccinations (Chapman et al. 2012)), or promoting masks as fashionable self-expressions (e.g., fitness benefits of “trends” (Kokko et al. 2007)). These interventions illustrate one approach to encouraging cooperation: altering the costs and benefits of the payoff matrix for one interaction between participants.

The cleaner fish system also highlights another mechanism of cooperation: reciprocal altruism, which emerges when identifiable individuals have repeated interactions. Reciprocal altruism has strong support across theory and many plant and animal systems (Kiers et al. 2011, Raihani and Bshary 2011, West et al. 2007). In client fish, this plays out both directly and indirectly. Client fish are more likely to return to a cleaning location with cooperative cleaner fish, but are more likely to change cleaners if they had previously been cheated or ignored (Bshary and Schaffer 2002). This cleaner fish system also shows evidence of “indirect” reciprocity, where individuals are more likely to cooperate with individuals with a cooperative reputation, and individuals are thus sensitive to how a current action affects their reputation: cleaner fish are more likely to cooperate when there is an audience (Pinto et al. 2011) and adjust cheating depending on social context, “managing” their reputation. These studies led us down several discussions of what kinds of social behavior manipulation are truly ethical: if individuals are more likely to be cooperative if their identity is known, do we start requiring individual identification to be displayed in public spaces? (Probably not!) Do we build on studies showing increased cooperation when individuals feel they are being watched, by affixing staring eyes to grocery store walls (Bateson et al. 2006)? (Again, probably not!) However, this discussion brings up complex debates about the ethics of subtle behavioral manipulations through cognitive biases which often seem ethical in the health realm (“nudges,” (Marteau et al. 2012)) but less so in the advertising realm, even if they are frequently used in marketing (Jolls et al. 1998, Kahneman 2003, Wilkinson 2013). Although these latter examples might not be ethical or feasible, this line of questioning highlights how exploring a human challenge through a biological lens can prompt novel thinking.

Next steps for bioinspiration in teaching and research

Over the last several decades, there have been increasing calls to revise undergraduate science education to be integrated across disciplines and focused around inquiry and problem-

solving (Aikens 2020, Brewer and Smith 2011, Norman and Schmidt 1992, Suwono et al. 2018). In this paper, we illustrate one such approach – using biomimetics to tackle whatever problem is currently the most pressing to society. This approach is engaging because everyone (including the instructor) is often consumed with this problem. At the same time, this approach makes very specific content from diverse fields, from fluid dynamics to molecular biology, immediately relevant. We close by highlighting three more general lessons for biomimetic approaches in both teaching and research.

First, how does one build a course structured around biomimetics? There are a number of different curricula structured around biomimicry (Stevens et al. 2019, Urmann 2016, Wanieck Kristina et al. 2020), but this particular course was structured more around the biology relevant to biomimetic approaches (see Supplementary Material). After zeroing in on a problem of interest, from health concerns to climate change, possibly one of the most useful tools we employed was mind-mapping (Davies M. 2011, Edwards and Cooper 2010) – a visual approach to diagramming and exploring connections between sub-problems related to the focal problem. We then parsed individual problems to subfields in biology that were particularly relevant. For instance, thinking about function of morphological traits maps onto discussions of adaptation and evolution, while medical applications mapped onto aspects of physiology and developmental genetics. We also touched on ecology in the context of networks of interactions and selective environments, and behavior in the context of manipulating responses to the environment. In navigating these topics, we also discussed designing biological experiments, reading primary literature, interpreting phylogenetic relationships and a number of other topics. An instructor can structure content depending on the interests of students in the course and the specific focal problem tackled by the class.

Second, how do we build interactions to promote creative exploration of a wide range of ideas? We began the course by encouraging any ideas, even ones that might initially seem unfeasible or bizarre. Each week we explored a wide range of biological systems that came to

mind (only a small subset highlighted here). While we could navigate the biology ourselves, we quickly learned that the primary limitation in moving these ideas into applications was relevant expertise from designers, engineers, doctors, and other disciplines that would affect the next steps of moving an idea to an application. Future iterations of such a course would be improved by building teams of biologists and engineers (Graeff Eliot et al. 2018, Graeff E. et al. 2019, Vincent et al. 2006), although guest appearances or email consultation by relevant experts sufficed for our 8-week course.

Finally, exercises from this course illustrate constraints of a biomimetic approach to solving problems during a crisis. Taking products to market takes time (Chirazi et al. 2019), and a biomimetic approach involves additional time associated with exploring biological systems and understanding biological traits. For this process to be effective, much of the basic research to understand a trait likely needs to be in place. Existing collaborations between biologists and engineers would also increase the chances of a quick, effective bio-inspired approach. Public health emergencies (or any pressing societal problem) also creates opportunities for conflicts-of-interest to bias outcomes in science in perverse and unhealthy ways. For instance, health-related research sponsored by industry is more likely to be interpreted in industry-favorable ways (Als-Nielsen et al. 2003, Kelly et al. 2006, Lexchin et al. 2003). All of these points underscore the importance of societal investment in basic science (Rosenberg 1990, Salter and Martin 2001, Toole 2012). Challenge-based approaches in biology education can be incredibly effective, and biomimetics can greatly expand the range of possible solutions in problem solving. However, the underlying basic research that forms the basis of this problem solving must be there if a problem-solving team needs to solve a problem immediately.

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Literature Cited

- Ackermann M, Mentzer SJ, Kolb M, Jonigk D. 2020a. Inflammation and Intussusceptive Angiogenesis in COVID-19: everything in and out of Flow: Eur Respiratory Soc.
- Ackermann M, Verleden SE, Kuehnel M, Haverich A, Welte T, Laenger F, Vanstapel A, Werlein C, Stark H, Tzankov A. 2020b. Pulmonary vascular endothelialitis, thrombosis, and angiogenesis in Covid-19. New England Journal of Medicine.
- Ahn M, et al. 2019. Dampened NLRP3-mediated inflammation in bats and implications for a special viral reservoir host. Nature Microbiology 4: 789-799.
- Aikens ML. 2020. Meeting the Needs of A Changing Landscape: Advances and Challenges in Undergraduate Biology Education. Bulletin of Mathematical Biology 82.
- Allen JG, Marr LC. 2020. Recognizing and controlling airborne transmission of SARS-CoV-2 in indoor environments. Indoor Air 30: 557-558.
- Als-Nielsen B, Chen WD, Gluud C, Kjaergard LL. 2003. Association of funding and conclusions in randomized drug trials - A reflection of treatment effect or adverse events? Jama-Journal of the American Medical Association 290: 921-928.
- Archetti M, Scheuring I, Hoffman M, Frederickson ME, Pierce NE, Yu DW. 2011. Economic game theory for mutualism and cooperation. Ecology Letters 14: 1300-1312.
- Arias-Reyes C, Zubieta-DeUrioste N, Poma-Machicao L, Aliaga-Raudan F, Carvajal-Rodriguez F, Dutschmann M, Schneider-Gasser E, Zubieta-Calleja G, Soliz J. 2020. Does the pathogenesis of SARS-CoV-2 virus decrease at high-altitude? Respiratory Physiology & Neurobiology 277.
- Baalsrud HT, Voje KL, Torresen OK, Solbakken MH, Matschiner M, Malmstrom M, Hanel R, Salzburger W, Jakobsen KS, Jentoft S. 2017. Evolution of Hemoglobin Genes in Codfishes Influenced by Ocean Depth. Scientific Reports 7.
- Baker ML, Schountz T, Wang LF. 2013. Antiviral Immune Responses of Bats: A Review. Zoonoses and Public Health 60: 104-116.
- Banerjee A, Kulcsar K, Misra V, Frieman M, Mossman K. 2019. Bats and Coronaviruses. Viruses-Basel 11.

- Banerjee A, Baker ML, Kulcsar K, Misra V, Plowright R, Mossman K. 2020. Novel Insights Into Immune Systems of Bats. *Frontiers in Immunology* 11.
- Bar-Cohen Y. 2005. *Biomimetics: biologically inspired technologies*: CRC Press.
- Bateson M, Nettle D, Roberts G. 2006. Cues of being watched enhance cooperation in a real-world setting. *Biology Letters* 2: 412-414.
- Beall CM. 2007. Two routes to functional adaptation: Tibetan and Andean high-altitude natives. *Proceedings of the National Academy of Sciences of the United States of America* 104: 8655-8660.
- Becerra JX, Noge K, Venable DL. 2009. Macroevoolutionary chemical escalation in an ancient plant-herbivore arms race. *Proceedings of the National Academy of Sciences of the United States of America* 106: 18062-18066.
- Bhushan B. 2009. Biomimetics: lessons from nature - an overview. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 367: 1445-1486.
- Biondich AS, Joslin JD. 2015. Coca: High Altitude Remedy of the Ancient Incas. *Wilderness & Environmental Medicine* 26: 567-571.
- Bonier F, Martin PR, Wingfield JC. 2007. Urban birds have broader environmental tolerance. *Biology Letters* 3: 670-673.
- Bourouiba L. 2020. Turbulent Gas Clouds and Respiratory Pathogen Emissions Potential Implications for Reducing Transmission of COVID-19. *Jama-Journal of the American Medical Association* 323: 1837-1838.
- Brewer C, Smith D, eds. 2011. *Vision and change in undergraduate biology education: a call to action* Washington DC: American Association for the Advancement of Science.
- Brook CE, et al. 2020. Accelerated viral dynamics in bat cell lines, with implications for zoonotic emergence. *Elife* 9.
- Bshary R, Schaffer D. 2002. Choosy reef fish select cleaner fish that provide high-quality service. *Animal Behaviour* 63: 557-564.
- Bshary R, Grutter AS. 2002. Asymmetric cheating opportunities and partner control in a cleaner fish mutualism. *Animal Behaviour* 63: 547-555.
- Buck JC, Weinstein SB, Young HS. 2018. Ecological and Evolutionary Consequences of Parasite Avoidance. *Trends in Ecology & Evolution* 33: 619-632.
- Butler AC, Chapman JE, Forman EM, Beck AT. 2006. The empirical status of cognitive-behavioral therapy: A review of meta-analyses. *Clinical Psychology Review* 26: 17-31.
- Carey HV, Andrews MT, Martin SL. 2003. Mammalian hibernation: Cellular and molecular responses to depressed metabolism and low temperature. *Physiological Reviews* 83: 1153-1181.

- Chapman GB, Li M, Vietri J, Ibuka Y, Thomas D, Yoon H, Galvani AP. 2012. Using Game Theory to Examine Incentives in Influenza Vaccination Behavior. *Psychological Science* 23: 1008-1015.
- Cheng VCC, et al. 2020. The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. *Journal of Infection* 81: 107-114.
- Chiang HM, Chen HC, Wu CS, Wu PY, Wen KC. 2015. *Rhodiola* plants: Chemistry and biological activity. *Journal of Food and Drug Analysis* 23: 359-369.
- Chirazi J, Wanieck K, Fayemi PE, Zollfrank C, Jacobs S. 2019. What Do We Learn from Good Practices of Biologically Inspired Design in Innovation? *Applied Sciences-Basel* 9.
- Chodosh J, Weinstein BE, Blustein J. 2020. Face masks can be devastating for people with hearing loss Innovation is urgently needed to ensure clear communication in medical settings. *Bmj-British Medical Journal* 370.
- Ciceri F, Beretta L, Scandroglio AM, Colombo S, Landoni G, Ruggeri A, Peccatori J, D'Angelo A, De Cobelli F, Rovere-Querini P. 2020. Microvascular COVID-19 lung vessels obstructive thromboinflammatory syndrome (MicroCLOTS): an atypical acute respiratory distress syndrome working hypothesis. *Crit Care Resusc* 15.
- Coil D, Wenderoth MP, Cunningham M, Dirks C. 2010. Teaching the process of science: faculty perceptions and an effective methodology. *CBE—Life Sciences Education* 9: 524-535.
- Collimore KC, McCabe RE, Carleton RN, Asmundson GJG. 2008. Media exposure and dimensions of anxiety sensitivity: Differential associations with PTSD symptom clusters. *Journal of Anxiety Disorders* 22: 1021-1028.
- Conley KR, Sutherland KR. 2017. Particle shape impacts export and fate in the ocean through interactions with the globally abundant appendicularian *Oikopleura dioica*. *Plos One* 12.
- Conley KR, Lombard F, Sutherland KR. 2018a. Mammoth grazers on the ocean's minuteness: a review of selective feeding using mucous meshes. *Proceedings of the Royal Society B-Biological Sciences* 285.
- Conley KR, Gemmell BJ, Bouquet JM, Thompson EM, Sutherland KR. 2018b. A self-cleaning biological filter: How appendicularians mechanically control particle adhesion and removal. *Limnology and Oceanography* 63: 927-938.
- Conley KR, Ben-Tal A, Jacobi Y, Yahel G, Sutherland KR. 2018c. Not-so-simple sieving by ascidians: re-examining particle capture at the mesh and organismal scales. *Marine Biology* 165.
- Corey RM, Jones U, Singer AC. 2020. Acoustic effects of medical, cloth, and transparent face masks on speech signals. *arXiv preprint arXiv:2008.04521*.
- Curtis VA. 2014. Infection-avoidance behaviour in humans and other animals. *Trends in Immunology* 35: 457-464.

- Davies A, Thompson KA, Giri K, Kafatos G, Walker J, Bennett A. 2013. Testing the Efficacy of Homemade Masks: Would They Protect in an Influenza Pandemic? *Disaster Medicine and Public Health Preparedness* 7: 413-418.
- Davies M. 2011. Concept mapping, mind mapping and argument mapping: what are the differences and do they matter? *Higher Education* 62: 279-301.
- Deldin J-M, Schuknecht M. 2014. The AskNature database: enabling solutions in biomimetic design. Pages 17-27. *Biologically inspired design*, Springer.
- Diao Z, Kraus M, Brunner R, Dirks JH, Spatz JP. 2016. Nanostructured Stealth Surfaces for Visible and Near-Infrared Light. *Nano Letters* 16: 6610-6616.
- Dias DA, Urban S, Roessner U. 2012. A historical overview of natural products in drug discovery. *Metabolites* 2: 303-336.
- Divi RV, Strother JA, Paig-Tran EWM. 2018. Manta rays feed using ricochet separation, a novel nonclogging filtration mechanism. *Science Advances* 4.
- Doebeli M, Hauert C. 2005. Models of cooperation based on the Prisoner's Dilemma and the Snowdrift game. *Ecology Letters* 8: 748-766.
- Douglas AE. 2008. Conflict, cheats and the persistence of symbioses. *New Phytologist* 177: 849-858.
- Drew KL, Harris MB, LaManna JC, Smith MA, Zhu XW, Ma YL. 2004. Hypoxia tolerance in mammalian heterotherms. *Journal of Experimental Biology* 207: 3155-3162.
- Duffy S, Avery VM. 2012. Development and Optimization of a Novel 384-Well Anti-Malarial Imaging Assay Validated for High-Throughput Screening. *American Journal of Tropical Medicine and Hygiene* 86: 84-92.
- Dugatkin LA, Godin JGJ. 1992. PREDATOR INSPECTION, SHOALING AND FORAGING UNDER PREDATION HAZARD IN THE TRINIDADIAN GUPPY, *POECILIA-RETICULATA*. *Environmental Biology of Fishes* 34: 265-276.
- Dushkina N, Erten S, Lakhtakia A. 2017. COLORATION AND STRUCTURE OF THE WINGS OF *CHORINEA SYLPHINA* BATES. *Journal of the Lepidopterists Society* 71: 1-11.
- Eadie L, Ghosh TK. 2011. Biomimicry in textiles: past, present and potential. An overview. *Journal of the Royal Society Interface* 8: 761-775.
- Eastman RT, Roth JS, Brimacombe KR, Simeonov A, Shen M, Patnaik S, Hall MD. 2020. Remdesivir: A Review of Its Discovery and Development Leading to Emergency Use Authorization for Treatment of COVID-19. *Acs Central Science* 6: 672-683.
- Edwards S, Cooper N. 2010. Mind mapping as a teaching resource. *The clinical teacher* 7: 236-239.

673 El-Atab N, Qaiser N, Badghaish HS, Shaikh SF, Hussain MM. 2020. A Flexible Nanoporous
674 Template for the Design and Development of Reusable Anti-COVID-19 Hydrophobic Face
675 Masks. *ACS nano*.
676
677 Fan E, Beitler JR, Brochard L, Calfee CS, Ferguson ND, Slutsky AS, Brodie D. 2020. COVID-
678 19-associated acute respiratory distress syndrome: is a different approach to management
679 warranted? *Lancet Respiratory Medicine* 8: 816-821.
680
681 Farnsworth NR. 1988. Screening plants for new medicines. *Biodiversity* 15: 81-99.
682
683 Fayemi PE, Wanieck K, Zollfrank C, Maranzana N, Aoussat A. 2017. Biomimetics: process,
684 tools and practice. *Bioinspiration & Biomimetics* 12.
685
686 Fehr E, Rockenbach B. 2004. Human altruism: economic, neural, and evolutionary
687 perspectives. *Current Opinion in Neurobiology* 14: 784-790.
688
689 Frey MW. 2008. Electrospinning cellulose and cellulose derivatives. *Polymer Reviews* 48: 378-
690 391.
691
692 Friedmann E, Barker SB, Allen KM. 2011. Physiological correlates of health benefits from pets.
693
694 Gao JL, Zheng PP, Jia YN, Chen H, Mao YM, Chen SH, Wang Y, Fu H, Dai JM. 2020. Mental
695 health problems and social media exposure during COVID-19 outbreak. *Plos One* 15.
696
697 Gardner GE. 2012. Using Biomimicry to Engage Students in a Design-Based Learning Activity.
698 *American Biology Teacher* 74: 182-184.
699
700 Garfin DR, Silver RC, Holman EA. 2020. The Novel Coronavirus (COVID-2019) Outbreak:
701 Amplification of Public Health Consequences by Media Exposure. *Health Psychology* 39: 355-
702 357.
703
704 Garraud O. 2020. How do I see the production of engineered blood cells available for
705 transfusion? *Transfusion and Apheresis Science* 59.
706
707 Geier MR, Geier DA. 2020. Respiratory conditions in coronavirus disease 2019 (COVID-19):
708 Important considerations regarding novel treatment strategies to reduce mortality. *Medical*
709 *Hypotheses* 140.
710
711 Gingins S, Bshary R. 2015. Pairs of cleaner fish prolong interaction duration with client reef fish
712 by increasing service quality. *Behavioral Ecology* 26: 350-358.
713
714 Gomez D, Pinna C, Pairraire J, Arias M, Barbut J, Pomerantz A, Nous C, de Marcillac WD,
715 Berthier S, Patel N. 2020. Transparency in butterflies and moths: structural diversity, optical
716 properties and ecological relevance. *bioRxiv*.
717
718 Graeff E, Maranzana N, Aoussat A. 2018. Role of biologists in biomimetic design processes:
719 preliminary results. Pages 1149-1160. *DS 92: Proceedings of the DESIGN 2018 15th*
720 *International Design Conference*.
721
722 Graeff E, Maranzana N, Aoussat A. 2019. Biomimetics, where are the biologists? *Journal of*
723 *Engineering Design* 30: 289-310.

- Granato ET, Meiller-Legrand TA, Foster KR. 2019. The Evolution and Ecology of Bacterial Warfare. *Current Biology* 29: R521-R537.
- Graves SD, Shapiro AM. 2003. Exotics as host plants of the California butterfly fauna. *Biological Conservation* 110: 413-433.
- Greenberg R, Mettke-Hofmann C. 2001. Ecological aspects of neophobia and neophilia in birds. Pages 119-178. *Current ornithology*, Springer.
- Greggor A. 2016. A critical evaluation of neophobia in corvids: causes, consequences and conservation implications. Department of Psychology, University of Cambridge.
- Greggor AL, McIvor GE, Clayton NS, Thornton A. 2016a. Contagious risk taking: social information and context influence wild jackdaws' responses to novelty and risk. *Scientific Reports* 6.
- Greggor AL, Clayton NS, Fulford AJC, Thornton A. 2016b. Street smart: faster approach towards litter in urban areas by highly neophobic corvids and less fearful birds. *Animal Behaviour* 117: 123-133.
- Grutter AS, Bshary R. 2003. Cleaner wrasse prefer client mucus: support for partner control mechanisms in cleaning interactions. *Proceedings of the Royal Society B-Biological Sciences* 270: S242-S244.
- Hayman DTS. 2019. Bat tolerance to viral infections. *Nature Microbiology* 4: 728-729.
- He H, Gao M, Illés B, Molnar K. 2020. 3D printed and electrospun, transparent, hierarchical polylactic acid mask nanoporous filter. *Int. J. Bioprint* 6.
- Hmelo-Silver CE. 2004. Problem-based learning: What and how do students learn? *Educational Psychology Review* 16: 235-266.
- Ho CSH, Chee CYI, Ho RCM. 2020. Mental Health Strategies to Combat the Psychological Impact of Coronavirus Disease 2019 (COVID-19) Beyond Paranoia and Panic. *Annals Academy of Medicine Singapore* 49: 155-160.
- Holmes EA, et al. 2020. Multidisciplinary research priorities for the COVID-19 pandemic: a call for action for mental health science. *Lancet Psychiatry* 7: 547-560.
- HOYOS CM, Fiorentino C. 2016. Bio-utilization, bio-inspiration, and bio-affiliation in design for sustainability: Biotechnology, biomimicry, and biophilic design. *The International Journal of Designed Objects* 10: 1-18.
- Hybertson BM, Gao BF, Bose S, McCord JM. 2019. Phytochemical Combination PB125 Activates the Nrf2 Pathway and Induces Cellular Protection against Oxidative Injury. *Antioxidants* 8.
- Jacobs SR, Nichol EC, Helms ME. 2014. "Where Are We Now and Where Are We Going?" The BioM Innovation Database. *Journal of Mechanical Design* 136.

- Johnsen S. 2001. Hidden in plain sight: The ecology and physiology of organismal transparency. *Biological Bulletin* 201: 301-318.
- Jolls C, Sunstein CR, Thaler R. 1998. A behavioral approach to law and economics. *Stanford Law Review* 50: 1471-1550.
- Juge N, Mithen RF, Traka M. 2007. Molecular basis for chemoprevention by sulforaphane: a comprehensive review. *Cellular and Molecular Life Sciences* 64: 1105-1127.
- Kahneman D. 2003. Maps of bounded rationality: Psychology for behavioral economics. *American Economic Review* 93: 1449-1475.
- Kapoor R, Sharma B, Kanwar S. 2017. Antiviral phytochemicals: an overview. *Biochem. Physiol* 6: 7.
- Kelley TR, Knowles JG. 2016. A conceptual framework for integrated STEM education. *International Journal of Stem Education* 3.
- Kelly RE, Cohen LJ, Semple RJ, Bialer P, Lau A, Bodenheimer A, Neustadter E, Barenboim A, Galynker, II. 2006. Relationship between drug company funding and outcomes of clinical psychiatric research. *Psychological Medicine* 36: 1647-1656.
- Kennedy EB, Marting TA. 2016. Biomimicry Streamlining the Front End of Innovation for Environmentally Sustainable Products. *Research-Technology Management* 59: 40-47.
- Kiers ET, et al. 2011. Reciprocal Rewards Stabilize Cooperation in the Mycorrhizal Symbiosis. *Science* 333: 880-882.
- Kohl MT, Stahler DR, Metz MC, Forester JD, Kauffman MJ, Varley N, White PJ, Smith DW, MacNulty DR. 2018. Diel predator activity drives a dynamic landscape of fear. *Ecological Monographs* 88: 638-652.
- Kokko H, Jennions MD, Houde A. 2007. Evolution of frequency-dependent mate choice: keeping up with fashion trends. *Proceedings of the Royal Society B-Biological Sciences* 274: 1317-1324.
- Lachance H, Wetzel S, Kumar K, Waldmann H. 2012. Charting, Navigating, and Populating Natural Product Chemical Space for Drug Discovery. *Journal of Medicinal Chemistry* 55: 5989-6001.
- Lawrence J, Topper J, Petelenz-Kurdziel E, Bratbak G, Larsen A, Thompson E, Troedsson C, Ray JL. 2018. Viruses on the menu: The appendicularian *Oikopleura dioica* efficiently removes viruses from seawater. *Limnology and Oceanography* 63: S244-S253.
- Lazzaro BP, Zasloff M, Rolff J. 2020. Antimicrobial peptides: Application informed by evolution. *Science* 368: 487-+.
- Le Gall T, et al. 2014. In vivo biodistribution and oxygenation potential of a new generation of oxygen carrier. *Journal of Biotechnology* 187: 1-9.

Lefevre P, Martin DP, Elena SF, Shepherd DN, Roumagnac P, Varsani A. 2019. Evolution and ecology of plant viruses. *Nature Reviews Microbiology* 17: 632-644.

Leng T, Whie C, Hilton J, Kucharski AJ, Pellis LJ, Stage H, Davies NG, Keeling MJ, Flasche S. 2020. The effectiveness of social bubbles as part of a Covid-19 lockdown exit strategy, a modelling study. *medRxiv*.

Lewis KN, Wason E, Edrey YH, Kristan DM, Nevo E, Buffenstein R. 2015. Regulation of Nrf2 signaling and longevity in naturally long-lived rodents. *Proceedings of the National Academy of Sciences of the United States of America* 112: 3722-3727.

Lexchin J, Bero LA, Djulbegovic B, Clark O. 2003. Pharmaceutical industry sponsorship and research outcome and quality: systematic review. *Bmj-British Medical Journal* 326: 1167-1170B.

Leyfman Y, Erick TK, Reddy SS, Galwankar S, Nanayakkara PW, Di Somma S, Sharma P, Stawicki SP, Chaudry IH. 2020. Potential immunotherapeutic targets for hypoxia due to COVID-19. *Shock* 54: 438-450.

Lima SL, Dill LM. 1990. BEHAVIORAL DECISIONS MADE UNDER THE RISK OF PREDATION - A REVIEW AND PROSPECTUS. *Canadian Journal of Zoology* 68: 619-640.

Lipinski C, Hopkins A. 2004. Navigating chemical space for biology and medicine. *Nature* 432: 855-861.

Low TT, Cherian R, Lim SL, Chandra B, Tung ML, Kumar SK, Lye P, Yi ACX, Teo L, Tay ELW. 2020. Rethinking COVID-19 'pneumonia' - is this primarily a vaso-occlusive disease, and can early anticoagulation save the ventilator famine? *Pulmonary Circulation* 10.

Madin EMP, Madin JS, Booth DJ. 2011. Landscape of fear visible from space. *Scientific Reports* 1.

Magurran AE, Seghers BH. 1994. PREDATOR INSPECTION BEHAVIOR COVARIES WITH SCHOOLING TENDENCY AMONGST WILD GUPPY, POECILIA-RETICULATA, POPULATIONS IN TRINIDAD. Pages 121-134.

Mairbaur H, Schobersberger W, Humpeler E, Hasibeder W, Fischer W, Raas E. 1986. BENEFICIAL-EFFECTS OF EXERCISING AT MODERATE ALTITUDE ON RED-CELL OXYGEN-TRANSPORT AND ON EXERCISE PERFORMANCE. *Pflugers Archiv-European Journal of Physiology* 406: 594-599.

Mandl JN, Schneider C, Schneider DS, Baker ML. 2018. Going to Bat(s) for Studies of Disease Tolerance. *Frontiers in Immunology* 9.

Marteau TM, Hollands GJ, Fletcher PC. 2012. Changing Human Behavior to Prevent Disease: The Importance of Targeting Automatic Processes. *Science* 337: 1492-1495.

Martin JGA, Reale D. 2008. Temperament, risk assessment and habituation to novelty in eastern chipmunks, *Tamias striatus*. *Animal Behaviour* 75: 309-318.

Matheson NJ, Lehner PJ. 2020. How does SARS-CoV-2 cause COVID-19? *Science* 369: 510-511.

- Mattson MP, Cheng A. 2006. Neurohormetic phytochemicals: low-dose toxins that induce adaptive neuronal stress responses. *Trends in Neurosciences* 29: 632-639.
- McClure M, et al. 2019. Why has transparency evolved in aposematic butterflies? Insights from the largest radiation of aposematic butterflies, the Ithomiini. *Proceedings of the Royal Society B-Biological Sciences* 286.
- McConnell DA, Steer DN, Owens KD. 2003. Assessment and active learning strategies for introductory geology courses. *Journal of Geoscience Education* 51: 205-216.
- McCord JM, Hybertson BM, Cota-Gomez A, Geraci KP, Gao B. 2020. Nrf2 activator PB125® as a potential therapeutic agent against COVID-19. *Antioxidants* 9: 518.
- McDonald CJ. 2020. Protections against the Risk of Airborne SARS-CoV-2 Infection. *Msystems* 5.
- Mishra K, Sharma N, Diwaker D, Ganju L, Singh S. 2013. Plant derived antivirals: a potential source of drug development. *J. Virol. Antivir. Res* 2: 2-9.
- Mollentze N, Streicker DG. 2020. Viral zoonotic risk is homogenous among taxonomic orders of mammalian and avian reservoir hosts. *Proceedings of the National Academy of Sciences of the United States of America* 117: 9423-9430.
- Moller AP. 2009. Successful city dwellers: a comparative study of the ecological characteristics of urban birds in the Western Palearctic. *Oecologia* 159: 849-858.
- Morrell LJ, Romey WL. 2008. Optimal individual positions within animal groups. *Behavioral Ecology* 19: 909-919.
- Naithani R, Huma LC, Holland LE, Shukla D, McCormick DL, Mehta RG, Moriarty RM. 2008. Antiviral Activity of Phytochemicals: A Comprehensive Review. *Mini-Reviews in Medicinal Chemistry* 8: 1106-1133.
- Nellis AM, Savage J. 2012. Does Watching the News Affect Fear of Terrorism? The Importance of Media Exposure on Terrorism Fear. *Crime & Delinquency* 58: 748-768.
- Ni MY, Yang L, Leung CMC, Li N, Yao XI, Wang YS, Leung GM, Cowling BJ, Liao QY. 2020. Mental Health, Risk Factors, and Social Media Use During the COVID-19 Epidemic and Cordon Sanitaire Among the Community and Health Professionals in Wuhan, China: Cross-Sectional Survey. *Jmir Mental Health* 7.
- Nilsson GE, Renshaw GMC. 2004. Hypoxic survival strategies in two fishes: extreme anoxia tolerance in the North European crucian carp and natural hypoxic preconditioning in a coral-reef shark. *Journal of Experimental Biology* 207: 3131-3139.
- Nimer J, Lundahl B. 2007. Animal-assisted therapy: A meta-analysis. *Anthrozoos* 20: 225-238.
- Nishiga M, Wang DW, Han YL, Lewis DB, Wu JC. 2020. COVID-19 and cardiovascular disease: from basic mechanisms to clinical perspectives. *Nature Reviews Cardiology* 17: 543-558.

- Norman GR, Schmidt HG. 1992. THE PSYCHOLOGICAL BASIS OF PROBLEM-BASED LEARNING - A REVIEW OF THE EVIDENCE. *Academic Medicine* 67: 557-565.
- Park TJ, et al. 2017. Fructose-driven glycolysis supports anoxia resistance in the naked mole-rat. *Science* 356: 305-308.
- Patton SC, Beaujean AA, Benedict HE. 2014. Parental Bonds, Attachment Anxiety, Media Susceptibility, and Body Dissatisfaction: A Mediation Model. *Developmental Psychology* 50: 2124-2133.
- Pavlovich SS, et al. 2018. The Egyptian Rousette Genome Reveals Unexpected Features of Bat Antiviral Immunity. *Cell* 173: 1098-+.
- Perc M, Szolnoki A. 2010. Coevolutionary games-A mini review. *Biosystems* 99: 109-125.
- Perez RM. 2003. Antiviral activity of compounds isolated from plants. *Pharmaceutical Biology* 41: 107-157.
- Phu H-T, Park Y, Andrews AJ, Marabella I, Abraham A, Mimmack R, Olson BA, Chaika J, Floersch E, Konia M. 2020. Design and evaluation of a portable negative pressure hood with HEPA filtration to protect health care workers treating patients with transmissible respiratory infections. *American journal of infection control*.
- Pinto A, Oates J, Grutter A, Bshary R. 2011. Cleaner Wrasses *Labroides dimidiatus* Are More Cooperative in the Presence of an Audience. *Current Biology* 21: 1140-1144.
- Pomerantz AF, Siddique RH, Cash EI, Kishi Y, Pinna C, Hammar K, Gomez D, Elias M, Patel NH. 2020. Developmental, cellular, and biochemical basis of transparency in the glasswing butterfly *Greta oto*. *bioRxiv*.
- Prather KA, Wang CC, Schooley RT. 2020. Reducing transmission of SARS-CoV-2 Masks and testing are necessary to combat asymptomatic spread in aerosols and droplets. *Science* 368: 1422-1424.
- Raihani NJ, Bshary R. 2011. Resolving the iterated prisoner's dilemma: theory and reality. *Journal of Evolutionary Biology* 24: 1628-1639.
- Raihani NJ, Thornton A, Bshary R. 2012. Punishment and cooperation in nature. *Trends in Ecology & Evolution* 27: 288-295.
- Rajkumar RP. 2020. COVID-19 and mental health: A review of the existing literature. *Asian journal of psychiatry*: 102066.
- Rello J, Storti E, Belliato M, Serrano R. 2020. Clinical phenotypes of SARS-CoV-2: implications for clinicians and researchers. *European Respiratory Journal* 55.
- Richardson S, Hirsch JS, Narasimhan M, Crawford JM, McGinn T, Davidson KW, Northwell C-RC. 2020. Presenting Characteristics, Comorbidities, and Outcomes Among 5700 Patients Hospitalized With COVID-19 in the New York City Area. *Jama-Journal of the American Medical Association* 323: 2052-2059.

- Rodriguez-Prieto I, Fernandez-Juricic E, Martin J, Regis Y. 2009. Antipredator behavior in blackbirds: habituation complements risk allocation. *Behavioral Ecology* 20: 371-377.
- Rodriguez C, Drewes LR, Andrews MT. 2017. Hibernation-based blood loss therapy increases survivability of lethal hemorrhagic shock in rats. *Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology* 187: 769-778.
- Rosenberg N. 1990. WHY DO FIRMS DO BASIC RESEARCH WITH THEIR OWN MONEY. *Research Policy* 19: 165-174.
- Salter AJ, Martin BR. 2001. The economic benefits of publicly funded basic research: a critical review. *Research Policy* 30: 509-532.
- Saunders PU, Pyne DB, Gore CJ. 2009. Endurance Training at Altitude. *High Altitude Medicine & Biology* 10: 135-148.
- Schett G, Sticherling M, Neurath MF. 2020. COVID-19: risk for cytokine targeting in chronic inflammatory diseases? *Nature Reviews Immunology* 20: 271-272.
- Schmidt H, Hangmann J, Shams I, Avivi A, Hankeln T. 2016. Molecular evolution of antioxidant and hypoxia response in long-lived, cancer-resistant blind mole rats: The Nrf2-Keap1 pathway. *Gene* 577: 293-298.
- Schmidt HG, Rotgans JI, Yew EHJ. 2011. The process of problem-based learning: what works and why. *Medical Education* 45: 792-806.
- Setiawaty S, Fatmi N, Rahmi A, Unaida R, Hadiya I, Muhammad I, Sari RP. 2018. Science, technology, engineering, and mathematics (STEM) learning on student's science process skills and science attitudes. *Proceedings of MCoMS 2017*, Emerald Publishing Limited.
- Siddique RH, Gomard G, Holscher H. 2015. The role of random nanostructures for the omnidirectional anti-reflection properties of the glasswing butterfly. *Nature Communications* 6.
- Smith JM. 1979. GAME THEORY AND THE EVOLUTION OF BEHAVIOR. *Proceedings of the Royal Society of London Series B-Biological Sciences* 205: 475-488.
- Snell-Rood E. 2016. Bring biologists into biomimetics. *Nature* 529: 277-278.
- Sohail MN, Rasul F, Karim A, Kanwal U, Attitalla IH. 2011. Plant as a Source of Natural Antiviral Agents. *Asian Journal of Animal and Veterinary Advances* 6: 1125-1152.
- Sourakov AA, Al-Obeidi A. 2019. Biomimetic non-uniform nanostructures reduce broadband reflectivity in transparent substrates. *Mrs Communications* 9: 637-643.
- Stadnytskyi V, Bax CE, Bax A, Anfinrud P. 2020. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. *Proceedings of the National Academy of Sciences of the United States of America* 117: 11875-11877.
- Stamps JA, Frankenhuys WE. 2016. Bayesian Models of Development. *Trends in Ecology & Evolution* 31: 260-268.

- Stankowich T, Blumstein DT. 2005. Fear in animals: a meta-analysis and review of risk assessment. *Proceedings of the Royal Society B-Biological Sciences* 272: 2627-2634.
- Stevens L, De Vries MM, Bos MM, Kopnina H. 2019. Biomimicry design education essentials. Pages 459-468. *Proceedings of the Design Society: International Conference on Engineering Design*: Cambridge University Press.
- Stohlmann M, Moore T, Roehrig G. 2012. Considerations for teaching integrated STEM education. *Journal of Pre-College Engineering Education Research* 2: 28-34.
- Storz JF. 2010. Genes for High Altitudes. *Science* 329: 40-41.
- . 2016. Hemoglobin-oxygen affinity in high-altitude vertebrates: is there evidence for an adaptive trend? *Journal of Experimental Biology* 219: 3190-3203.
- Subudhi AW, et al. 2014. AltitudeOmics: The Integrative Physiology of Human Acclimatization to Hypobaric Hypoxia and Its Retention upon Reascent. *Plos One* 9.
- Sutherland KR, Madin LP, Stocker R. 2010. Filtration of submicrometer particles by pelagic tunicates. *Proceedings of the National Academy of Sciences of the United States of America* 107: 15129-15134.
- Suwono H, Saefi M, Susilo H. 2018. Challenge Based Learning to Improve Scientific Literacy of Undergraduate Biology Students. 6th International Conference of Science Educators and Teachers (ISET). Srinakharinwirot Univ, Bangkok, THAILAND.
- Tay MZ, Poh CM, Renia L, MacAry PA, Ng LFP. 2020. The trinity of COVID-19: immunity, inflammation and intervention. *Nature Reviews Immunology* 20: 363-374.
- Tian L, Li X, Qi F, Tang Q-Y, Tang V, Liu J, Li Z, Cheng X, Li X, Shi Y. 2020. Calibrated intervention and containment of the COVID-19 pandemic. *arXiv preprint arXiv:2003.07353*.
- Tobin MJ, Laghi F, Jubran A. 2020a. Why COVID-19 Silent Hypoxemia Is Baffling to Physicians. *American Journal of Respiratory and Critical Care Medicine* 202: 356-360.
- . 2020b. Caution about early intubation and mechanical ventilation in COVID-19. *Annals of Intensive Care* 10.
- Toole AA. 2012. The impact of public basic research on industrial innovation: Evidence from the pharmaceutical industry. *Research Policy* 41: 1-12.
- Torales J, O'Higgins M, Castaldelli-Maia JM, Ventriglio A. 2020. The outbreak of COVID-19 coronavirus and its impact on global mental health. *International Journal of Social Psychiatry* 66: 317-320.
- Tovote P, Fadok JP, Luthi A. 2015. Neuronal circuits for fear and anxiety. *Nature Reviews Neuroscience* 16: 317-331.
- ul Qamar MT, Alqahtani SM, Alamri MA, Chen L-L. 2020. Structural basis of SARS-CoV-2 3CLpro and anti-COVID-19 drug discovery from medicinal plants. *Journal of pharmaceutical analysis*.

- Urmann L. 2016. Integrating Biomimicry into Higher Education: Designing and Developing a Biomimicry Minor at the University of California, Santa Cruz.
- Valone TJ. 2006. Are animals capable of Bayesian updating? An empirical review. *Oikos* 112: 252-259.
- Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl AK. 2006. Biomimetics: its practice and theory. *Journal of the Royal Society Interface* 3: 471-482.
- Wadman M, Couzin-Frankel J, Kaiser J, Maticic C. 2020. A RAMPAGE THROUGH THE BODY. *Science* 368: 356-360.
- Walker SE. 2003. Active learning strategies to promote critical thinking. *Journal of athletic training* 38: 263.
- Wanasekara ND, Chalivendra VB. 2011. Role of surface roughness on wettability and coefficient of restitution in butterfly wings. *Soft Matter* 7: 373-379.
- Wang Y, Tian H, Zhang L, Zhang M, Guo D, Wu W, Zhang X, Kan GL, Jia L, Huo D. 2020a. Reduction of secondary transmission of SARS-CoV-2 in households by face mask use, disinfection and social distancing: a cohort study in Beijing, China. *BMJ Global Health* 5: e002794.
- Wang YM, et al. 2020b. Remdesivir in adults with severe COVID-19: a randomised, double-blind, placebo-controlled, multicentre trial. *Lancet* 395: 1569-1578.
- Wang ZB, Xu J, Wang PG, Zhang Y, You J, Li CX. 2020c. Noncloggingly Sieving Sub-6 nm Nanoparticles of Noble Metals into Conductive Mesoporous Foams with Biological Nanofibrils. *Acs Nano* 14: 828-834.
- Wanieck K, Ritzinger D, Zollfrank C, Jacobs S. 2020. Biomimetics: teaching the tools of the trade. *FEBS Open Bio*.
- Wanieck K, Fayemi PE, Maranzana N, Zollfrank C, Jacobs S. 2017. Biomimetics and its tools. *Bioinspired Biomimetic and Nanobiomaterials* 6: 53-66.
- Watson GS, Watson JA, Cribb BW. 2017. Diversity of Cuticular Micro- and Nanostructures on Insects: Properties, Functions, and Potential Applications. *Annual Review of Entomology*, Vol 62: 185-205.
- Weinstein SB, Buck JC, Young HS. 2018. A landscape of disgust. *Science* 359: 1213-1214.
- West SA, Griffin AS, Gardner A. 2007. Social semantics: altruism, cooperation, mutualism, strong reciprocity and group selection. *Journal of Evolutionary Biology* 20: 415-432.
- Weyl EG, Frederickson ME, Yu DW, Pierce NE. 2010. Economic contract theory tests models of mutualism. *Proceedings of the National Academy of Sciences of the United States of America* 107: 15712-15716.
- Wilkerson RG, Adler JD, Shah NG, Brown R. 2020. Silent hypoxia: A harbinger of clinical deterioration in patients with COVID-19. *The American Journal of Emergency Medicine*.

1131
 1132 Wilkinson TM. 2013. Nudging and Manipulation. *Political Studies* 61: 341-355.
 1133
 1134 Xu JW, Liu C, Hsu PC, Liu K, Zhang RF, Liu YY, Cui Y. 2016. Roll-to-Roll Transfer of
 1135 Electrospun Nanofiber Film for High-Efficiency Transparent Air Filter. *Nano Letters* 16: 1270-
 1136 1275.
 1137
 1138 Xue JJ, Wu T, Dai YQ, Xia YN. 2019. Electrospinning and Electrospun Nanofibers: Methods,
 1139 Materials, and Applications. *Chemical Reviews* 119: 5298-5415.
 1140
 1141 Zangmeister CD, Radney JG, Vicenzi EP, Weaver JL. 2020. Filtration Efficiencies of Nanoscale
 1142 Aerosol by Cloth Mask Materials Used to Slow the Spread of SARS CoV-2. *ACS nano*.
 1143
 1144 Zasloff M. 2002. Antimicrobial peptides of multicellular organisms. *Nature* 415: 389-395.
 1145
 1146 Zhang GJ, et al. 2013. Comparative Analysis of Bat Genomes Provides Insight into the
 1147 Evolution of Flight and Immunity. *Science* 339: 456-460.
 1148
 1149 Zhang HH, Zheng W, Feng XL, Yang F, Qin H, Wu SS, Hou DX, Chen JH. 2019. Nrf2-ARE
 1150 Signaling Acts as Master Pathway for the Cellular Antioxidant Activity of Fisetin. *Molecules* 24.
 1151
 1152 Zhao B, Liu YM, Chen C. 2020. Air purifiers: A supplementary measure to remove airborne
 1153 SARS-CoV-2. *Building and Environment* 177.
 1154
 1155 Zhong B, Huang Y, Liu Q. 2020. Mental health toll from the coronavirus: Social media usage
 1156 reveals Wuhan residents' depression and secondary trauma in the COVID-19 outbreak.
 1157 *Computers in human behavior* 114: 106524.
 1158

1159 **Supplementary Material**

1160 **A. Overall class schedule**

Date	Topic
June-9	Motivation for class & intro to course structure
June-11	Dissecting problems – problem map for covid-19
June-16	Form and function in biology <i>Focal problem: filtration</i>
June-18	Studying function and organismal biology <i>(filtration continued)</i>
June-23	Selective environments: ecology <i>Focal problem: toilet paper and absorption</i>
June-25	Evaluating feasibility in creative, collaborative explorations <i>(toilet paper continued)</i>
June-30	Macroevolution of traits and convergence of function <i>Focal problem: oxygen stress</i>
July-2	<i>Projects</i>
July-7	Exploring the unknown in biological space <i>Focal problem: antiviral medication</i>
July-9	Diversification of physiological responses <i>Focal problem: immunity and inflammation</i>
July-14	Cue-response systems and the evolution of behavior <i>Focal problem: mental health and anxiety</i>
July-16	<i>Projects</i>
July-21	Social interactions and game theory <i>Focal problem: altruism and cooperation for public good</i>
July-23	<i>Projects – interview with experts in engineering and fluid mechanics</i>
July-28	Ecosystems and networks of interactions <i>Focal problem: economic collapse</i>
July-30	<i>Projects and next steps</i>

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1162 **B. Example Class structure: (from Class 5, June 23)**

1163 **Objectives and key concepts to take away from class**

- 1164 • Learn about ecological environments that shape the evolution of biological traits
- 1165 • Introduction to targets of selection versus functions as a product
- 1166 • Understand abiotic variation – primary and secondary – and emergence of biomes
- 1167 • Understand biotic variables and the importance of behavior influences microhabitat

1168 **Background:** We are focusing on “toilet paper” and the function of “absorption” from our overall

1169 mind map. This lesson plan corresponds to the 5th (of 16) classes. Starting early in the class

1170 with problems with “material” solutions (e.g., building a filtration system) are often a

1171 straightforward place to start in terms of exploring adaptations. Behavior, and system-related

1172 problems are easier to tackle later in the class after more basic concepts about evolution,

1173 ecology, and organismal biology have been worked through.

1174 **Reading:** MacLean 1983 BioScience *Water transport by sandgrouse*

Activities and structure

1. Pre-class assignments:

- a. Make a mini-mind map for “toilet paper” – what additional problems or ideas come to mind around “toilet paper shortage”
- b. Brainstorm biological systems related to one focal function – in this case, the “absorption” capacity of toilet paper. List as many biological systems or traits that come to mind.

2. Group discussion: Review functions and sub-problems that come to mind around toilet paper shortages. Discuss a few additional ideas that came up on a google search (e.g., people used to use corn cobs!)

3. Content: clarify what we mean by “absorption” of liquid (capillary action, sorptivity of materials, other notes from fluids/physics)

4. Discussion: what biological systems or traits do you think of around “absorption.”

- a. Note that some of these are traits and properties of individual species (sponges), and some are byproducts of ecosystems (wetlands) or biological materials in new situations (cellulose fibers in paper towels). Absorption as a byproduct versus a target of natural selection.

5. Discussion: What environments do you think of when you think of selection on absorption as a trait? Environments with not enough water... and those with lots of water...

6. Paper review and discussion around a favorite example (sandgrouse feathers). Watch a few videos of sandgrouse behavior, review a few key figures from paper and go around and get individual student reactions from the reading.

7. Content: Ecology content... framed around how we can more thoroughly explore the types of environments that select for a particular function

- a. Review difference between abiotic and biotic factors
- b. Review geographic variation in primary abiotic factors (temperature, precip) and how this translates into biomes (see wikipedia article on biomes)
- c. Note minor abiotic variables may also matter (e.g., wind speed map)

8. Discuss how this knowledge might change how you are thinking about looking for biological systems for absorption – new ideas for terms in a literature search?

9. Content: Ecoregions (867 of them!) across 14 biomes:

[https://en.wikipedia.org/wiki/List_of_terrestrial_ecoregions_\(WWF\)](https://en.wikipedia.org/wiki/List_of_terrestrial_ecoregions_(WWF))

- a. Activity: navigate to one of these 867 ecoregions
- b. Discuss: why might you want to look at different geographic areas within an ecoregion?

10. Content: biotic variables

- a. Example: plants are also playing a role in water uptake
- b. Can we make geographic generalizations about biotic variables (E.g., variation in biodiversity worldwide?)
- c. Behavior and physiology structures how individuals experience variation

11. Discuss: where would you look for absorption based on discussion of these biotic axes? Would different deserts be complementary?

12. Back to the problem and bio-inspiration

- a. An example of bio-inspired fog harvesters (absorption from gas to liquid)
- b. Return to toilet paper and absorption

1221 c. **Activity:** go back to list of examples you came to class with...how would this
1222 change? How would your subsequent search and research change?

1223 **C. Class project overview**

1224 Students in this course also engage in a class project around a problem of their choice. This
1225 offers them a chance to dig deeper into a problem and potential solution of interest. In exploring
1226 this problem, the students gain more experience with literature searches, reading the primary
1227 literature, and considering the types of experiments and additional research that would be
1228 necessary to explore this idea. Possible project products include a design diagram for a bio-
1229 inspired product or a research proposal for next R&D steps. In the case of this class, we worked
1230 jointly on writing sections for this paper, moving between presenting our findings to each other,
1231 and working on written sections of the paper. We also invited engineers from several fields (fluid
1232 dynamics and mechanical engineering) to come to one of our classes and critique our ideas
1233 (similar to a design review used in other fields).

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