**Projects and source material**

**Reference Papers**

The first two references are used in the slide show. The third one is a general review of the trade-off as used in this workshop.

Conn A, Pedmale UV, Chory J, Navlakha S. High-Resolution Laser Scanning Reveals Plant Architectures that Reflect Universal Network Design Principles. Cell Syst. 2017;5(1):53-62 e3.

Suen JY, Navlakha S. Travel in city road networks follows similar transport trade-off principles to neural and plant arbors. J R Soc Interface. 2019;16(154):20190041.

Vincent JFV. The trade-off: a central concept for biomimetics. Bioinspired, Biomimetic and Nanobiomaterials. 2017;6(2):67-76.

**Adaptive shape-changing**

There are many examples in the modern world of robotics where novel problems require novel answers. But we don't, by definition, know what the problems will be and therefore have to design a system that can adapt to unforeseen circumstances. An example would be a robot exploring a variety of terrains. What transport system might be required to cope with rocks, mud, flat surfaces and slippery surfaces? How can you be sure that the appropriate system is activated?

Define the parameters of the trade-off(s) that this problem represents, then see how the examples provided can resolve such trade-offs for you.

Green PB. Pattern formation in shoots - a likely role for minimal energy configurations of the tunica. International Journal of Plant Sciences. 1992;153:59-75.

Longo L, Lee J, Blaber M. Experimental support for the foldability-function tradeoff hypothesis: segregation of the folding nucleus and functional regions in fibroblast growth factor-1. Protein science : a publication of the Protein Society. 2012;21(12):1911-20.

Reid CR, Lutz MJ, Powell S, Kao AB, Couzin ID, Garnier S. Army ants dynamically adjust living bridges in response to a cost-benefit trade-off. Proc Natl Acad Sci U S A. 2015;112(49):15113-8.

Weihs D. Stability versus maneuverability in aquatic locomotion. Integrative and Comparative Biology. 2002;42(1):127-34.

Another example would be a robot in a factory, sorting items for use in assembly of a larger system. Assuming the robot can distinguish the different objects and decide where they should be moved to, how does it manipulate them?

Define the parameters of the trade-off(s) that this problem represents, then see how the examples provided can resolve such trade-offs for you.

Carruthers AC, Thomas ALR, Taylor GK. Automatic aeroelastic devices in the wings of a steppe eagle Aquila nipalensis. Journal of Experimental Biology. 2007;210(23):4136-49.

Combes SA, Daniel TL. Flexural stiffness in insect wings II. Spatial distribution and dynamic wing bending. Journal of Experimental Biology. 2003;206:2989-97.

Marsh RL. How muscles deal with real-world loads: the influence of length trajectory on muscle performance. Journal of Experimental Biology. 1999;202:3377-85.

Gosavi S. Understanding the folding-function tradeoff in proteins. PloS one. 2013;8(4):e61222.

**Deployable structures**

As we explore the further reaches of space, we need to have more equipment packed into a smaller space in the exploration vehicle. The trade-off is simple - we need objects that can be small but large. How can we resolve this? Decide on the trade-off parameters of the examples given, and extract the principles that resolve them. What design suggestions can you make? How might you implement them?

Ferguson GP, Messenger JB. A countershading reflex in cephalopods. Proceedings of the Royal Society B. 1991;243:63-7.

Haas F, Gorb S, Wootton RJ. Elastic joints in dermapteran hind wings: materials and wing folding. Arthropod Structure & Development. 2000;29:137-46.

Longo L, Lee J, Blaber M. Experimental support for the foldability-function tradeoff hypothesis: segregation of the folding nucleus and functional regions in fibroblast growth factor-1. Protein science : a publication of the Protein Society. 2012;21(12):1911-20.

Glaser AE, Vincent JFV. The autonomous inflation of insect wings. Journal of Insect Physiology. 1979;25:315-8.

Eylers JP. Aspects of skeletal mechanics of the starfish *Asterias forbesii*. Journal of Morphology. 1976;149:353-67.

**Eat or be Eaten**

This is a common problem in biology - it is necessary to go into a zone of possible danger in order to access food. But there may be a risk involved. This is like a cost-benefit trade-off.

Analyse the examples given, first by deciding the two parameters of the trade-off, then by extracting the principles that allow the trade-off to be manipulated. Propose a cost-benefit trade-off from within your experience, research or work, and apply the principles to this trade-off. Try to use the principles suggested by the biology rather than simply fall back on the principles you might use at present.

Johnsen S, Sosik HM. Cryptic coloration and mirrored sides as camouflage strategies in near-surface pelagic habitats: Implications for foraging and predator avoidance. Limnology and Oceanography. 2003;48:1277-88.

Dammhahn M, Almeling L. Is risk taking during foraging a personality trait? A field test for cross-context consistency in boldness. Anim Behav. 2012;84(5):1131-9.

Abrams PA. Adaptive changes in prey vulnerability shape the response of predator populations to mortality. Journal of Theoretical Biology. 2009;261(2):294-304.

Bennett AM, Pereira D, Murray DL. Investment into defensive traits by anuran prey (Lithobates pipiens) is mediated by the starvation-predation risk trade-off. PloS one. 2013;8(12):e82344.

Langerhans RB. Trade-off between steady and unsteady swimming underlies predator-driven divergence in Gambusia affinis. J Evol Biol. 2009;22(5):1057-75.

Thaler JS, McArt SH, Kaplan I. Compensatory mechanisms for ameliorating the fundamental trade-off between predator avoidance and foraging. Proc Natl Acad Sci U S A. 2012;109(30):12075-80.

**Better data capture**

The problem of signal-to-noise ratio is always with us. We need to transmit, receive and process the maximum amount of information for the least amount of energy, and the information has to be reliable.

There are techniques available in technology, but does biology use the same techniques to solve the same problems.

In the papers with which you are provided there are several trade-offs analysed ranging from reception to processing. Extract from the papers what are the parameters of the trade-offs and the principles used to resolve the trade-off. Are these principles and recommendations different from the technology with which you are familiar.

Göpfert MC, Robert D. The mechanical basis of *Drosophila* audition. Journal of Experimental Biology. 2002;205:1199–208.

Sandeman DC, Tautz J, Lindauer M. Transmission of vibration across honeycombs and its detection by bee leg receptors. Journal of Experimental Biology. 1996;199:2585-94.

Ala-Laurila P, Rieke F. Coincidence detection of single-photon responses in the inner retina at the sensitivity limit of vision. Curr Biol. 2014;24(24):2888-98.

Latash ML, Sun Y, Latash EM, Mikaelian IL. Speed-difficulty trade-off in speech: Chinese versus English. Exp Brain Res. 2011;211(2):193-205.

Chou CS, Bardwell L, Nie Q, Yi TM. Noise filtering tradeoffs in spatial gradient sensing and cell polarization response. BMC systems biology. 2011;5:196.

**Friendly fire**

In every armed combat there are examples of people killing others who are on the same side of the battle. This is called "friendly fire".

Animals manage to avoid this sort of problem.

From the papers with which you are provided, define the trade-off parameters and the principles that manipulate the trade-off.

Determine the trade-off that defines "friendly fire"

Hence see what methods or changes might be available to reduce the risk of "friendly fire'.

Johnsen S, Sosik HM. Cryptic coloration and mirrored sides as camouflage strategies in near-surface pelagic habitats: Implications for foraging and predator avoidance. Limnology and Oceanography. 2003;48:1277-88.

Merilaita S, Lind J. Background-matching and disruptive coloration, and the evolution of cryptic coloration. Proc Biol Sci. 2005;272(1563):665-70.

Parker AR, Mckenzie DR, Ahyong ST. A unique form of light reflector and the evolution of signalling in *Ovalipes*

(Crustacea: Decapoda: Portunidae). Proceedings of the Royal Society B. 1998;265:861-7.

Garcia JE, Rohr D, Dyer AG. Trade-off between camouflage and sexual dimorphism revealed by UV digital imaging: the case of Australian Mallee dragons (*Ctenophorus fordi*). J Exp Biol. 2013;216(Pt 22):4290-8.

**Quickly or accurately?**

The conflict between doing something quickly and making a mistake, or alternatively being careful but late with the decision, is very common.

Analyse the papers provided for the particular example of the speed-accuracy trade-off and enter the results into the ontology, expressed as two trade-off parameters and the principles which allow manipulation of the trade-off.

Consider a number of instances (two will do) where a quick decision is needed, such as correcting a mistake while climbing a cliff, avoiding a car accident, or playing a musical instrument.

Decide on the trade-off parameters for each, then derive the principles which will enable you to resolve the trade-off. What are the general rules?

Lambert EP, Motta PJ, Lowry D. Modulation in the feeding prey capture of the ant-lion, *Myrmeleon crudelis*. Journal of Experimental Zoology Part A, Ecological genetics and physiology. 2011;315(10):602-9.

Ings TC, Chittka L. Speed-accuracy tradeoffs and false alarms in bee responses to cryptic predators. Current biology : CB. 2008;18(19):1520-4.

Goldfarb S, Wong-Lin K, Schwemmer M, Leonard NE, Holmes P. Can post-error dynamics explain sequential reaction time patterns? Frontiers in Psychology. 2012;3:213.

Heitz RP, Schall JD. Neural mechanisms of speed-accuracy tradeoff. Neuron. 2012;76(3):616-28.

Malcom JW. Evolution of competitive ability: an adaptation speed vs. accuracy tradeoff rooted in gene network size. PloS one. 2011;6(4):e14799.

Marshall JA, Dornhaus A, Franks NR, Kovacs T. Noise, cost and speed-accuracy trade-offs: decision-making in a decentralized system. J R Soc Interface. 2006;3(7):243-54.

**Stable or maneuverable?**

There are many instances where a system has to be stable, giving predictable performance, or maneuverable, giving the opportunity to escape from danger. Analyse the research papers, extracting the parameters of the trade-offs and the principles used to manipulate or resolve the trade-offs.

Use this information in the design of a flying robot ("drone") which is making a 3D scanning (lidar) survey of strips of territory while under enemy fire, which it can detect and must avoid.

Bartol IK, Gharib M, Webb PW, Weihs D, Gordon MS. Body-induced vortical flows: a common mechanism for self-corrective trimming control in boxfishes. Journal of Experimental Biology. 2005;208:327-44.

Weihs D. Stability versus maneuverability in aquatic locomotion. Integrative and Comparative Biology. 2002;42(1):127-34.

Studer RA, Christin PA, Williams MA, Orengo CA. Stability-activity tradeoffs constrain the adaptive evolution of RubisCO. Proc Natl Acad Sci U S A. 2014;111(6):2223-8.

**Life or death?**

As climate change takes hold we may find we have to develop ways of avoiding the worst weather conditions while still living in such an area because of pressure of population, or because the area still provides a valuable resource.

Animals have evolved techniques to deal with such a trade-off; avoiding predation whilst gaining advantage from a resource.

Analyse the research papers provided for the parameters of the trade-off and the principles evolved to deal with them. Then apply those principles to humans living in a hostile climate.

Brierley AS, Cox MJ. Shapes of krill swarms and fish schools emerge as aggregation members avoid predators and access oxygen. Current biology : CB. 2010;20(19):1758-62.

Morgan SG, Anastasia JR. Behavioral tradeoff in estuarine larvae favors seaward migration over minimizing visibility to predators. Proceedings of the National Academy Of Sciences of the United States of America. 2008;105(1):222-7.

Abrams PA. Adaptive changes in prey vulnerability shape the response of predator populations to mortality. Journal of Theoretical Biology. 2009;261(2):294-304.

Bennett AM, Pereira D, Murray DL. Investment into defensive traits by anuran prey (Lithobates pipiens) is mediated by the starvation-predation risk trade-off. PloS one. 2013;8(12):e82344.

**Tough materials**

One of the remarkable properties of biological materials is their resistance to permanent damage. This is a combination of fracture toughness and repair mechanisms.

Review the research papers for the parameters of the trade-offs and the principles that resolve those trade-offs. Use this information to design a space suit that is light and resists permanent damage.

De Blasio FV. Thriving at high hydrostatic pressure: the example of ammonoids (extinct cephalopods). Bioinspiration & Biomimetics. 2006;1(3):L1.

Currey JD. The many adaptations of bone. J Biomech. 2003;36:1487–95.

Koh CT, Oyen ML. Branching toughens fibrous networks. Journal of the Mechanical Behavior of Biomedical Materials. 2012;12(0):74-82.

Chiang MY, Yangben Y, Lin NJ, Zhong JL, Yang L. Relationships among cell morphology, intrinsic cell stiffness and cell-substrate interactions. Biomaterials. 2013;34(38):9754-62.