

# AI-Inspired Biology: Does AI Have Something to Contribute to Biology?

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## Abstract.

Biology, and particularly the study of ‘natural intelligence’, has long provided diverse forms of inspiration for AI and robotics researchers. However, instances of biologists gaining inspiration from AI have been less common. In this paper (written as an introduction to the AI-Inspired Biology Symposium), we argue that there are many ways in which biologists interested in natural intelligence can learn from AI, and outline the different kinds of contributions that AI can make. We describe some of the open, unsolved problems in animal cognition — including more detailed case studies of two problems we are particularly interested in: orangutan locomotion and New Caledonian crow tool use — and highlight the ways in which we believe AI can contribute to understanding and eventually solving these problems. Finally, we discuss the potential barriers to collaboration between the two fields, and ways in which we can make progress and collaborate to our mutual benefit.

## 1 INTRODUCTION

Imagine watching an orangutan (*Pongo abelii*) slowly making his way through the tangled canopy of a Sumatran rainforest. He arrives at a gap which contains an isolated young tree with a relatively thin, flexible trunk, then reaches out to grasp the trunk. As he pulls himself into this tree, he shifts his body weight — somewhat like a child on a swing — to oscillate the tree until its sway brings him within grasping distance of the branches on the far side of the gap.

A female elephant (*Loxodonta africana*) and her calf are bathing and drinking in a muddy waterhole with the rest of their social group. When it is time to leave, the adults can step over the muddy banks easily, but the small calf keeps slipping back into the water as she tries to climb out. Observing her offspring’s difficulty, the mother uses her powerful trunk and tusks to break down the mud bank to form a gentle gradient, which her calf then climbs with ease.

A New Caledonian crow (*Corvus moneduloides*) breaks a twig off a tree, carefully trims all leaves and side branches from the twig, then hops over to a rotting log. It selects a hole in the log and inserts the stick, jiggling it rapidly up and down. Inside the hole a Cerambycid larva mounts a defence of the burrow, trying to bite the stick with its large mandibles. Like a fisherman, the crow needs to move the stick to incite the larva to bite it, but if it pulls the stick away too violently, the larva will release its grip and drop back into the hole. When the crow detects that the larva has bitten on to the stick, it pulls both rapidly out of the hole and eats the larva.

Such examples of animals<sup>2</sup> solving problems posed by their environments are numerous, and more are being discovered as the detail with which we are able to observe animal behaviour in natural environments improves. ‘Natural intelligence’ (henceforth NI) tends to be characterised by complexity, flexibility, robustness and richness. In the examples above, the animals had to adjust their behaviour depending on the current context, plan a complex sequence of actions, and perhaps imagine the effect of their planned action on the environment. However, the extent and type of complexity involved differs. For example, the orangutan has to understand itself as a causative agent in physically altering its physical environment. In contrast, the New Caledonian crow faces somewhat less complexity, and yet it must still adjust its actions in a very sensitive way, depending on the behaviour, orientation and location of the larva. In the case of the elephant, she needed to adjust her behaviour by appreciating the difference between her own motor competences and those of her offspring. Some of these examples involve ‘online’ intelligent control of processes in the environment as they are happening. Others seem to involve ‘offline’ intelligent consideration of possible processes that are not occurring, but might occur and produce effects. In the former, the detailed morphology and fine tuning of sensory motor signals of the animal are directly involved. In the latter more abstract (possibly symbolic) information processing is required. In contrast the products of artificial intelligence research (AI) in robotics, — despite decades of research — tend to be comparatively simple and restricted, and do not cope well with novel situations, or where the parameters of the task are not known in advance [27]. This is certainly not a reflection of the quality of the field of AI or its researchers, but demonstrates the enormity of the task of replicating even a tiny subset of the capabilities of animals. After all, evolution has had a head start of millions of years.

While biologists now have quite a good understanding of the range and complexity of behaviours shown by animals, we are a long way from being able to explain *how* the information processing systems underlying such behaviour function, or even to describe the structure of such systems. In contrast, concepts in AI developed to understand complex systems might provide precisely the tools we need (or at least important steps towards such tools) to make progress in this area. In this paper, we will discuss the reasons why we are arguing that AI can inspire biology, and propose some examples from our own work. Our main focus is on the role for AI’s conceptual and analytical tools, but attempting to build systems (or parts of systems) as physical robots or simulations probably will also have a role.

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<sup>2</sup> Unless we distinguish explicitly between human and non-human animals, we include humans when referring to ‘animals’.

## 1.1 What problems do biologists need help with?

As biologists, there are a number of different levels at which we must consider cognitive systems in NI. At the evolutionary level, we need to understand the selection pressures promoting NI, and any evolutionary trade-offs involved [4]. Since the animal's environment<sup>3</sup> poses the problems that evolution must solve in order for the animal to reproduce, understanding the scope and nature of those problems is key to understanding a species' evolution. At the next level, we need to understand the structure of the information processing system in particular species: for example, in what ways can animals process, store and reuse information in new contexts? Finally, at the level of the individual animal, we need to understand how the system is constructed, shaped and fine-tuned by both development and learning. This includes both:

- how the genome together with epigenetic processes control the construction of the organism as an extremely complex physical machine, including self-maintaining and self-repairing mechanisms
- how the genome together with epigenetic processes control the development of increasingly complex information processing systems whose relationship to the physical machinery may be very obscure (as it is in complex computer-based systems).

At all the levels described above, the central problem with understanding NI is that cognition is a 'black box' system: we know (in most cases, but see section 2.4) what information passes in to the system, and we can record the animal's subsequent behaviour, but the information processing system is largely hidden. The parts of this system also operate in parallel and concurrently, with complex interactions between parts. Some changes to the system may only alter the behaviour or interaction between internal systems or virtual machines [24, 8], with no obvious external change. As a simple example, this can occur when an animal has learned something about the temporal relationship between a stimulus and a reinforcement event, but because the stimulus occurs *after* the event, there is no benefit in making a response. This has been demonstrated in rats, which can be shown to have learned about the temporal relationship between a light cue and an electric shock (where the shock precedes the light), even though they do not show any response until given the opportunity to respond to a second stimulus (a tone), preceding both the light and the shock [1]. The experiment shows that — even though they had never experienced the tone and shock paired together — they knew about the temporal relationship between the two.

Our understanding is also limited by the fact that our own cognitive processes differ from those of other animals, which can sometimes lead us to make unwarranted assumptions [19]. In addition, biological explanations for the evolution of cognitive abilities in animals tend to be rather specific to particular species or higher taxonomic grouping. While this practice can be justified because evolution shapes cognitive systems (and morphology) according to animals' precise ecological circumstances and phylogeny, it does not allow us an overview of how evolution has shaped cognitive systems in a range of species, or why other possible 'solutions' were not adopted by evolution. Finally biologists (and psychologists) often neglect individual variation, treating it only as a statistical inconvenience, rather than a valuable source of information about the ways in which ontogeny and learning can shape NI (see also section

<sup>3</sup> When we refer to 'environment' we include not only the physical habitat of the animal, but also members of its own species, its prey, predators and so on.

2.5 for a related problem). If one individual solves a particular problem, while the others fail, it is important to examine the strategies of each of the subjects in detail and look for relevant differences. For example, imagine you have presented subjects with the problem of removing the lid of an opaque box, which is fixed to the body of the box with a number of bolts, only some of which are functional. 'Distractor' bolts are in fact two separate bolts, aligned vertically, but not connected inside the box. The successful subject might have avoided trying to remove the distractor bolts (thus solving the problem) because it noticed that when the bottom of the bolt was rotated, the top part did not also rotate, suggesting that they were not connected. Careful observations such as differences between subjects can potentially provide important information about the way in which relevant information is collected and processed by individuals.

## 1.2 Examples of open problems in animal cognition

In addition to the broad problems outlined in section 1.1, there are a number of other more specific unsolved problems in animal cognition, all of which would — in our opinion — benefit from insights derived from the field of AI.

1. It is generally agreed that there is a large difference between the cognitive capabilities of human and non-human animals. However, it is not clear whether the difference is a mainly quantitative one (humans are better at a greater number of tasks than non-human animals) or a qualitative one (cognitive systems in humans and non-humans are of fundamentally different kinds), or a mixture. Whatever the nature of the difference turns out to be, why and how did it evolve? What kinds of selective pressures promote advanced cognition, and are they the same in all animals? Is the real difference between our cognitive abilities and those of other animals flexible, extensible, domain-general abilities, rather than domain-specific adaptations for problem solving in a particular domain? How do we distinguish between examples of domain-general intelligence and those of domain-specific intelligence?
2. How do some organisms acquire complex cognitive capabilities so quickly [26, 8, 25]? What is the structure of such a cognitive architecture [16]? The provision of 'innate modules' (requiring little or no environmental input) would provide rapid acquisition of skills though without much flexibility, but learning from a "blank slate" state (which would provide more flexibility) is both computationally and biologically implausible [18]. Is there a process which could provide the best of both worlds [8], by structuring learning in such a way that existing competences could be combined in a manner that is specifically influenced by the environment, to form qualitatively new abilities? As biologists, it seems implausible to us that evolution would have neglected to make use of the unchanging properties of the environment, which remain stable from generation to generation, and bias animals' learning with certain 'expectations' about these properties. We know from research on children that they have certain expectations about solidity and continuity of surfaces [28], and it would be surprising if some non-human animals did not share some of these expectations, along with others concerning geometry and topology of objects, connection, contact and so on. If there is any truth in Chomsky's well-known (and much disputed) claim that humans have an innate language learning mechanism, then it may turn out to be a special case of the class of mechanisms supporting "meta-configured" competences described in [8].
3. If having a big brain and complex cognition is so evolutionarily advantageous, why don't more animals have a large brain and

complex cognition? We need to investigate what selective advantages advanced cognition brings, and what the constraints on evolving such abilities are (see [4, 11] for two opposing views on this topic).

## 2 HOW CAN AI HELP?

### 2.1 The ‘designer stance’

In NI, evolution is the ‘designer’, though it is not (of course) working towards a predetermined final design. As biologists, we tend to observe the behaviour of the animal, and then think about how the animal’s environment and phylogenetic history might have selected for that behaviour. In contrast, when taking a ‘designer stance’ [12, 18, 23], we can reverse this process and attempt to determine the ‘requirements’ of the environment. In other words, we can evaluate the design problems posed by the animal’s environment, and then consider the range of designs which could fulfil these requirements, comparing our findings the actual designs revealed by observations and experiments on animals (see [18]). It can also be instructive to consider the opportunities *not* taken by evolution. For example, in an analogous exercise, Raup [20] developed a model to explore the morphological diversity of mollusc shells, varying parameters of shell geometry to produce a complete theoretical ‘morphospace’ for all possible mollusc shells. While there are living or fossil examples representing many of the regions of the morphospace, some parts are empty, raising interesting questions about why those designs were not exploited by evolution. This model considered only the range of designs possible, not the requirements imposed by the environment which determine functional shell designs, but considering requirements and designs in tandem would be instructive.

### 2.2 The value of construction

A benefit that was not obvious to us before we started to interact with AI researchers is the value of constructing a model (real or simulated) over attempted deduction of mechanisms from behaviour. As biologists, we are used to working with fully competent animals, so it is very easy to overlook subtle but important details and processes when thinking about the mechanisms involved in a particular behaviour. However, thinking about how to construct a complete or partial working system quickly reveals the gaps in one’s knowledge. For example, one has to consider the entire process, from defining what sensory information is collected and stored by the animal, through to the motor actions the animal takes on the environment (see also section 2.4), and this can reveal hitherto unnoticed gaps in understanding. We have personally found that — even as a thought experiment — it is very illuminating to think through the process of how you would implement a particular behaviour, guided and prompted by AI researchers. However, attempting to construct a physical robot or simulation is even more revealing. For example, when building a robot which interacts with the world, AI researchers have to consider how to filter the incoming information and attend preferentially to the ‘important’ information. Since we do not normally need to be concerned with attention as biologists<sup>4</sup>, we often neglect to think about how animals filter sensory information and direct their attention, nor do we generally consider what kinds of information can be considered ‘important’ to the animal.

<sup>4</sup> Psychologists do consider many aspects of attention, but usually in a laboratory, not a ‘field’ environment.

### 2.3 Generating hypotheses

Interacting closely with AI researchers gives us a way of evaluating alternative theories. Of course, the domains of NI and AI are radically different (at least at present), so results of experiments in either domain cannot be compared directly. However, we can capitalise on the complementary strengths and weaknesses of NI and AI to help generate new hypotheses for both systems. NI systems are rich and complex, but we know very little about the mechanisms involved, while AI systems are poorer and less complex, but because we have constructed the system ourselves, we know about the mechanisms involved in great detail. In addition, we can perform experiments with AI systems (such as removing parts of the mechanism, depriving the system of particular information and so forth) which are impractical or unethical to do with animals. Information about the results of such experiments, the kinds of tasks on which the AI systems succeed or fail, and the nature of such successes and failures, can all help us to generate new hypotheses about NI systems.

### 2.4 A systems approach

Designers of robots need to think about the entire set of interconnected, interacting processes involved in obtaining information from the environment, processing it, acting on it, and perceiving the resultant change in the world: they are responsible for constructing those systems and getting them to interact. Biologists, with the luxury of studying fully-formed, fully-capable animals, tend to specialise in studying one part of the system. This is changing gradually with collaborations between biologists, psychologists and physiologists, but collaborating with AI researchers can help us to think about the processes in a more abstract way, later applying that abstract knowledge to what we already know about NI systems, and helping to identify gaps in our knowledge.

### 2.5 A qualitative approach

Experiments in animal cognition tend to focus on establishing that species *A* has capability *X* but species *B* does not, while experiments in developmental psychology sometimes focus on the age at which children transition from not having to having capability *X*. We argue that while it is important to establish differences between species and developmental transitions within a species, it is equally vital to learn about the details of the ways in which that capability is built (what are the necessary conditions, how does it vary with developmental conditions), under what conditions it fails and so on. In other words, we need to develop the kinds of processes and logic used by AI researchers when debugging faulty programs.

## 3 EXAMPLES

### 3.1 Orangutan locomotion

To return to the orangutan who slowly meandered through the canopy of the Sumatran rainforest at the start of our paper: how can AI help us to understand his biology? He belongs to the largest mammalian species to live a habitually arboreal lifestyle; adult male orangutans may weigh up to 100kg, adult females about 40kg, and juveniles about 25kg. How do they move such a large body mass through the canopy safely to feed and to reproduce? How do orangutans deal with the problems of arboreal living compared to other species? Is this environment cognitively challenging and if so, what, if anything, can we learn about NI in orangutans; the selective pressures behind its

development and the evolutionary tradeoffs that have occurred and have thus allowed the continuation of the species.

The most challenging components of life in the forest canopy for a large-bodied habitually- arboreal species are the compliance of the branches and lianas they must use to support their body mass and the gaps in the canopy that they must traverse without descending to the ground, both to avoid ground dwelling predators such as the Sumatran tiger and to avoid the enormous energetic cost of repeatedly descending to the ground and opposing gravity to climb back up into the next tree [31]. Even the narrowest gaps between trees lie between very flexible terminal branches, which bend substantially under the animal's weight, and vary enormously in their properties.

Orangutans deal with the mechanics of crossing gaps and moving on compliant branches in a number of ways. Unlike all other arboreal primates and marsupials that deal with branch instability by walking on all fours on top of the branch but with very bent elbows and knees to bring their centre of mass close to the support and therefore reduce branch vibrations, orangutans employ an upright, mostly suspensory clambering type behaviour [17, 21] in which they use all their limbs to support the body at any angle [29, 32, 33]. In this technique they increase stability because they have, in effect, already fallen off the support and their centre of mass is thus directly under the branch bearing their weight. Balance and increased stability are further achieved through long contact times between multiple limbs and multiple supports and locomotor behaviours that lack regular limb sequences, which serves to avoid the risk of resonance in branch-sway caused by high-frequency, patterned gait [33]. For crossing large gaps, orangutans use tree sway, the behaviour we described earlier, where they oscillate flexible tree trunks with increasing magnitude until they can reach across gaps in the canopy to transfer into the next tree [5, 29, 30].

Thus, we now know a great deal about the biomechanics of how orangutans interact with their habitat [6, 29, 30, 30, 31, 33], but this tells us very little about how orangutans understand the affordances of this physically highly complex habitat and/or make decisions about how they will interact with it. Nor does it take into account the requirements posed by the animals' environment in its wider sense. This includes social constraints: even for a relatively solitary animal like the orangutan, access to preferred food resources is still dictated by a dominance hierarchy and the individual's social status and is therefore still likely to influence the way in which the animal can interact with its habitat. Other environmental considerations are infant care during arboreal travel (which increases both the cognitive and physical demands on the mother, and also provides complex learning opportunities for infants), the presence of ground dwelling predators, and ontogeny since both physical size and cognitive ability change dramatically through ontogeny but the animal must still be able to move safely through the forest to feed. Adopting the designer stance and other AI methodologies — both in theoretical analysis of problems and in attempting to design working robots or simulations — can suggest new experimental approaches that might be useful to test which aspects of a habitat are problematic, and to compare and evaluate the solutions that are used versus the solutions that are possible but have not been adopted.

One of the most interesting aspects of gap crossing in orangutans is that the geographical separation between the tree they are in and the tree they want to be in on the other side of the gap is usually too large for them to be able to experiment with the supports' responses to loading in the destination tree. Gap crossing decisions can therefore only be made by prior learning of how different gaps transform during locomotion or by using more abstract knowledge of support

mechanics and their affordances to predict how the gap will transform, before loading the supports. We propose that the combinatorial diversity of 3-D configurations of gaps (with varying gaps, numbers of possible supports, diameters, orientations, etc.), and the high costs of failed attempts (falls are much more likely to be fatal for animals of large body mass), rule out associative learning (e.g. that based on repeated retinal patterns), as the sole learning mechanism.

AI can offer a great deal here. The complexity of this system may mean that constructing an AI model is perhaps some way down the line, but again the designer stance could greatly help us understand the problems from the animals' perspective without falling into the trap of assuming there is only one way of perceiving the problems of gap crossing and deciding the most appropriate approach — the human way [23]. Indeed, the problems associated with human bias are even more severe in this scenario because orangutans travel 20-30m up in the forest canopy which means that few researchers can ever have even seen the problem from the same physical perspective as the animal, let alone from the same cognitive perspective.

A key question is if orangutans can contemplate the consequences of their locomotor actions and support behaviour in advance, then how far in advance are they able to do so? The distinction in the AI literature between reactive and deliberative planning [3] is relevant here. In reactive planning, the planner chooses only the most appropriate next action to get closer to achieving the goal. If orangutans follow the same geographical travel routes between major food resources, they might only need to make small adjustments for which reactive planning would be sufficient. However, the canopy of tropical rainforest is subject to frequent structural changes as trees and lianas grow, break or fall. These can result in large gaps in the canopy that arboreal animals must circumvent and in the loss of key feeding trees, thus changing routes travelled fundamentally. Since Sumatran orangutans rarely seem to encounter arboreal 'dead-ends' (Thorpe, pers. obs.), it is likely that they employ some level of deliberative planning, where they perceive a desired goal/sub-goal and construct a series of steps (before action is taken) to achieve it. Unless this sequence has been previously learned or is genetically encoded, deliberative planning implies that orangutans reason about the outcomes of alternative possible sequences of planned actions, and use these predictions to evaluate the best course of action.

But recent developments in AI enable us to take this process even further. There tends to be a natural inclination in biology and many other disciplines to try to divide natural phenomena into clear-cut, binary alternatives. The innate *versus* learned distinction is one such false dichotomy in biology, and the division between reactive and deliberative planning can be seen as another. In reality, when we consider the problem using the designer stance, it is likely that there are many different kinds of behaviour, which can be classified in a number of different ways, forming different kinds of organisational structure. There is an extended discussion of this topic in the paper by Sloman in these Proceedings.

We suggest that, rather than trying to divide up competences into inappropriate binary divisions, we should consider asking questions about how they evolved and the evolutionary selection pressures involved, what kinds of information and neural mechanisms are involved in their expression, and what kinds of architectures could support such types of competence. In addition, we need to think about variation between individuals and species, and how this relates to our taxonomy of the phenomenon. This approach is potentially a much more powerful method to understand not only the nature and extent of deliberative planning in orangutans (and other species), but also in addressing whether their solutions to arboreal living really differ as

much as their differences in morphology from other species would suggest.

### 3.2 Tool use in New Caledonian crows

New Caledonian crows (*Corvus moneduloides*) are highly unusual among birds because they make and use tools in rather sophisticated ways. Not only do they use sticks to extract larvae from rotten logs as described earlier [13], but they also make and use a variety of other tools [15, 34], including a multi-step process involving cutting and tearing of *Pandanus spp.* leaves to form stepped tools [14]. Tools are an integral part of their foraging behaviour, and are used frequently [2]. However, there is substantial variation in both the amount of time that individuals spend using tools, and their subsequent foraging success [2]: why do crows differ in their ability to use tools, and what factors might influence this during development and learning?

What, if anything, do New Caledonian crows (hereafter, ‘crows’) understand about the process of making and using tools, and the physical laws and causal regularities that underlie such behaviour? As discussed in sections 1.1 and 2.5, rather than attempting to demonstrate that crows either have or do not have a specified form of ‘understanding’ of the problem, we need to investigate details of the way in which they process information, including probing the kinds of tasks they tend to either succeed or fail on, the kinds of errors they make under which circumstances, and the kinds of representations of the problems that they might form [9].

Since crows use a variety of tools, one might assume that — like humans — they use each type of tool for a particular purpose, and that they select tools according to the kind of task they are faced with. One basic aspect of selectivity is that crows may choose tools with appropriate dimensions for the task facing them. Since they tend to probe for invertebrates and other food items in holes in logs, the length and diameter of tools might both be important for their function. We tested this by providing a tool using opportunity in captivity, in which the provided tools varied in length, and the distance of a food reward from the open end of a tube varied unpredictably [10]. This meant that on any one trial, some of the tools would match or exceed the distance to food (and thus be functional), while others would be too short. Both crows tested showed some evidence for selectivity, choosing tools which either matched the distance to food, or were the longest tool, significantly more often than would be expected by chance [10]. In another experiment, we probed selectivity during manufacture of tools by providing branches of oak in full leaf as the raw material for tools with which to push food out of a tube, where the aperture varied in diameter from trial to trial [7]. Again, both crows varied the maximum diameter of the tool they made in accordance with the diameter of the tube, making broader tools when the diameter of the aperture was larger [7]. Recent evidence from the field has shown that selectivity is not restricted to captivity. Crows do not appear to choose their tools randomly from the pool of available material, and longer tools tend to be found left in deeper holes [2].

Faced with such situations, why do crows not use or manufacture the longest/narrowest tool possible, since that strategy should always result in success? In trying to understand their choices, we face similar problems to those discussed earlier in relation to orangutan locomotion (section 3.1): we tend to view the problem from a human perspective, neglecting differences in both information processing and the ergonomics of tool use for crows. However, we can speculate about the possible disadvantages of using such a heuristic when selecting tools. Longer tools are inevitably heavier, and may be unwieldy to use precisely, particularly when one considers the length

of the tool relative to the bird’s body length, and that it is held in the beak, not the hand or foot. Similarly, narrower tools might be more difficult or time-consuming to make, and may break more easily.

We also know that crows show a form of creativity, making tools from materials with unfamiliar properties and using different manufacturing processes than they ordinarily use. One crow spontaneously bent a piece of straight wire into a hook to retrieve a bucket containing food from a vertical tube [35], despite the lack of similar pliable materials in the wild. Furthermore, she was able to *unbend* metal strips to retrieve food, showing a number of different techniques to achieve this [36]. Nevertheless, such experiments can sometimes reveal conflicting evidence for ‘understanding’, reinforcing the point that we need to study the details of the precise ways in which individuals attempt to solve such problems, in what circumstances this process fails, and how they gather information about possible solutions [36]. Only then will we be in a position to specify requirements for satisfactory AI models of their competences.

Returning to the vignette of New Caledonian crow tool use we presented in section 1, we have recently investigated the detail of crows’ use of tools while fishing for larvae (Troscianko, Rutz, Bluff, Kacelnik and Chappell in prep.). Since the larva moves independently, the crow must alter its probing behaviour with the tool depending upon the precise behaviour of the larva. Furthermore, the constraints of the task are such that it must combine restricted visual information with tactile cues (felt through the tool tip) to inform it about the larva’s depth in the hole and activity, and determine the most appropriate mode of manipulation of the tool. As usual, such work prompts more questions than it answers. We would like to know, for example, how juvenile crows acquire this behaviour and whether individuals differ in their ‘fishing’ tactics.

There are clearly still many open questions about tool use and manufacture in crows, and it offers a rich domain for collaborations with AI researchers. There are a number of areas in which such collaborations could offer valuable new insights, and we will elaborate on a selection of those areas below.

1. A thorough analysis of the requirements of the crows’ environment (section 2.1) would provide a framework in which we could evaluate crows’ tool-related behaviour. For example, can we categorise the variety of problems (related to tools) that the environment poses? Do the relevant parameters of these tasks vary dynamically in space and time? Which of these influence the crows’ evolutionary fitness, and which are irrelevant to its survival? If one was designing an agent to address the requirements of the environment (or the subset identified as important to evolutionary fitness), what kinds of representations would the agent require, and how would it process information, develop and learn? If the design space resulting from this process differs strikingly from the kinds of behaviours we know to exist in real crows, can we speculate about why evolution did not proceed down that path?
2. If the range of designs generated by the requirements analysis differs from range of behaviours shown by the crows, it might prompt us to investigate hitherto unnoticed competences, thus generating new hypotheses (see section 2.3). For example, given the difficulty of understanding the world from the perspective of a crow, it is possible that we have overlooked some subtle but important detail. Equally, if we test the generated hypotheses to the best of our ability and find that crows truly lack that competence (or form of representation, ability to apply knowledge in new contexts, etc.), then we have to attempt to explain its absence.
3. Adopting an integrated, systems approach (section 2.4) may help

us to make sense of how the varied components of the crow's cognitive system interact. For example, we currently make a number of possibly unwarranted assumptions about the information available to the animal, on which it might base decisions about how to solve a problem, because we do not have detailed knowledge of the sensory information available to the animal while it is manipulating a tool in a hole. Neither do we know what sort of ontology is available to the crow's perceptual mechanisms in interpreting that sensory information [22]. We need to consider the sensory, motor and information processing systems as a richly interconnected, overlapping and interacting set of processes which relate to, inform and modify one another.

#### 4 MAKING PROGRESS

While there are ongoing collaborations between groups of biologists and AI researchers, conferences, workshops and symposia, such as the current one, are important in broadening participation, and providing a forum for discussion of the problems and their possible solutions. One important issue that we are aware of is that the two fields tend not to read the journals in which the other publishes. In addition, publishing in journals on the other side of the disciplinary boundary is also rare. As a consequence, researchers in each field are often unaware of advances made in the other, so opportunities to make advances are lost. Along with research collaborations, journals need to be more open to publishing papers from related fields, so that more people are exposed to new ideas which might spark collaborations. This might be a more fruitful route than attempting to get researchers to read new journals, since it is already a difficult task to keep up with the literature in one's own field.

One potential barrier to this process is the lack of a common set of terminology. In both fields, there are examples of different terms for the same concept or process, and examples where the same term is used in different ways in each field (for example, the term 'learning' has subtly different meanings in biology and AI, and there are probably more categories of 'learning' in biology). This is obviously a potential source of confusion and wasted effort, as researchers can end up talking at cross-purposes and misunderstanding one another's arguments. On a more optimistic note, such misunderstandings can provide a good opportunity to refine and clarify concepts, because explaining them to someone outside the field often reveals inconsistencies or previously overlooked gaps.

Finally to make progress with integrating AI and biology, we need to keep an open mind, and maintain realistic expectations about what can and cannot be achieved.

#### 5 CONCLUSION

In this paper, we have attempted to explain the reasons why we think — from our perspective as biologists — that AI has the potential to make a significant contribution to the study of NI, by providing new conceptual frameworks and analytical tools. However, we would not propose such an interaction unless we believed that it would also involve benefits and scientifically interesting questions for AI researchers. After all, true altruism towards unrelated individuals is rare in nature — reciprocal altruism is more popular in social species! One such benefit involves the current role biology plays in AI, namely providing more detail of the competences of natural systems, and inspiration for artificial systems. In addition, studying the full range of NI in detail can clarify goals and assumptions in AI. For example, if you find species that can interact with the world in

a very flexible and sophisticated way, but lack language, does your autonomous robot necessarily need the ability to understand and produce language? If some animals lack trichromatic colour vision or binocularity, does a robot necessarily need either capability? The answer will depend on the intended 'niche' of the robot (and reveal another way that biologists can help), but thinking about these issues in relation to real animals may help to clarify existing assumptions.

Biology can also provide a new perspective on debates, such as those surrounding the importance and varieties of embodiment (see [37] for a recent review). The sensory and motor apparatus through which an animal interacts with the world has undeniably important effects on its cognition, as does the social or cultural environment in which it lives. However, convergent evolution has happened many times and ensures that — though two species may have radically different sensory, motor and information processing 'hardware' (think orangutans and octopuses) — they can emerge with striking similarities in their cognitive abilities ('software'). So while embodiment is important for the richness of the problem that it sets evolution, there are many possible solutions to the problem.

We hope that by interacting with AI researchers, we can also find a variety of new solutions to our various mutual problems.

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