Ants and Bits

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Abstract. Ants have always been helping people to solve various problems. Everybody remembers how they sorted seeds for Cinderella. For the IT community, ants have helped to show that Information Theory is not only an excellent mathematical theory but that many of its results can be considered laws of Nature. Reciprocally, we helped ants to be distinguished among other "intellectuals" such as counting primates, crows and parrots as one of the smartest species [1, 2]. Our long-term experimental study on ant "language" and intelligence were fully based on fundamental ideas of Information Theory, such as the Shannon entropy, the Kolmogorov complexity, and the Shannon's equation connecting the length of a message l and its frequency of occurrence p, i.e., $l = -\log p$. This approach enabled us to discover a developed symbolic "language" in highly social ant species based on their ability to transfer the abstract information about remote events and to estimate the rate of information transmission. We also succeeded to reveal important properties of ants' intelligence. These insects appeared to be able to grasp regularities and to use them for "compression" of data they communicate to each other. They can also transfer to each other the information about the number of objects and can even add and subtract small numbers in order to optimize their messages.

Introduction

From time immemorial, people have been dreaming about understanding animal "languages"- a dream with which many legends are associated. The title of the book of the famous ethologist Konrad Lorenz, King Solomon's Ring (1952), refers to the legend about King Solomon who possessed a magical ring that gave him the power of speaking with animals. However, decoding the function and meaning of animal communications is a notoriously difficult problem. A bottleneck here is the low repeatability of standard living situations, which could give keys for cracking animals' species-specific codes. Up to now, there are only two types of natural communication systems that have been partly deciphered: the fragments of honeybees' "dance language", and acoustic signalization in vervet monkeys and several other species (see [3] for a review). In both types of communications, expressive and distinctive signals correspond to repeatable and frequently occurring situations in the context of animals' life. The problem of cracking animals' codes have become especially attractive since the great "linguistic" potential was discovered in several highly social and intelligent species by means of intermediary artificial languages. Being applied to apes, dolphins and gray parrots, this method has revealed astonishing mental skills in the subjects [4, 5, 6]. However, surprisingly little is known yet about natural communication systems of those species that were involved in language-training experiments based on adopted human languages. Explorers of animal "languages" thus have met a complex problem of resolving the contradiction between their knowledge about significant "linguistic" and cognitive potential in some species and limitations in understanding their natural communications.

We have suggested to apply ideas of Information Theory for studying natural communications of animals, that is, not to decipher signals, but to investigate the very process of information transmission by measuring time duration which the animals spend on transmitting messages of different lengths and complexities.

Ants of highly social species are good candidates for studying general rules of cognitive communication. There are more than 12000 ant species on Earth, and the great majority of them use relatively simple forms of communication such as odor trails, tandem running, and so on. Only a few highly social species belong to the elite club of rare "cognitive specialists", and among them are several species of red wood ants (*Formica rufa* group), with their big anthills "boiling" with hundreds of thousands of active individuals.

To reveal the power of ants' "language" we used two main notions of Information Theory, that is, (1) the quantity of information, and (2) the duration of time spent by the agents for transmitting 1 bit. This approach based on the "binary tree" experimental paradigm [7] enabled us to estimate the rate of information transmission in ants and to reveal that these insects are able to grasp regularities and to use them to compress information. The other series of experiments was based on the Shannon's equation connecting the length of a message (l) and its frequency (p), i.e., $l = -\log p$, for rational communication systems. Applying this concept, we demonstrated that ants are able to transfer to each other the information about the number of objects, and they even can add and subtract small numbers in order to optimize their messages [2].

The first results of this long-term work were reported at the International Information Theory Symposium 1984 in Tashkent *(the binary tree experiments) and at the ISIT-1994 in Norway (the ability to add and subtract small numbers), and then the obtained data were discussed at many international conferences and published in biological and mathematical journals (see, for example, [1, 4, 5]).

How to ask ants to transmit some bits of information to each other

The experimental paradigm of our approach is simple. All we need to do is to establish a situation where ants must transfer a specific amount of information to each other. The crucial idea of the first scheme of experiments is that we know exactly the quantity of information to be transferred and the time needed to do it. To organize the process of information transmission between ants, a special maze has been used, called a "binary tree" , where the number and sequence of turns towards the goal correspond to the amount of information to be transferred (Fig. 1).

In the laboratory we used fragments of ant colonies of about 2000 specimens each, and all active ants were labeled with color marks. Ants were housed in transparent artificial nests, so that their movements and contacts were observable. The laboratory colonies were

*A well-known Russian Information Theorist Yuri L. Sagalovitch related that year, he bought one of famous Tashkent big melons, and decided to have a rest on a bench, looking through the Symposium Proceedings. While reading about ants, he got carried away, and his melon was stolen.

found to include teams of constant membership which consisted of one scout and three to eight recruits (foragers): the scout mobilized only members of its team to the food. The composition of the teams was revealed during special run-up experiments. During the main course of experiments, in each trial one of the scouts was placed on a certain leaf of the binary tree that contained a trough with the food, and then it returned to the nest by itself. Returning to the group of foragers, the scout contacted one to four foragers in turn (Fig. 2). The duration of the contacts was measured every time.

All experiments were so devised as to eliminate all possible cues that could help the ants to find the food, except their information contact with the scout. To avoid the use of an odor track, the experimental set-up was replaced by an identical one when the scout was in the nest or on the arena contacting its group (see Fig. 3). All troughs in the fresh maze contained only water to avoid the possible influence of the smell of syrup. If the group reached the correct point, they were immediately presented with the food. The scout had to make up to four trips before it was able to mobilize its group of foragers. After the scout had contacted its team, it was isolated in a separate container for a while, and the foragers had to search for the food by themselves.

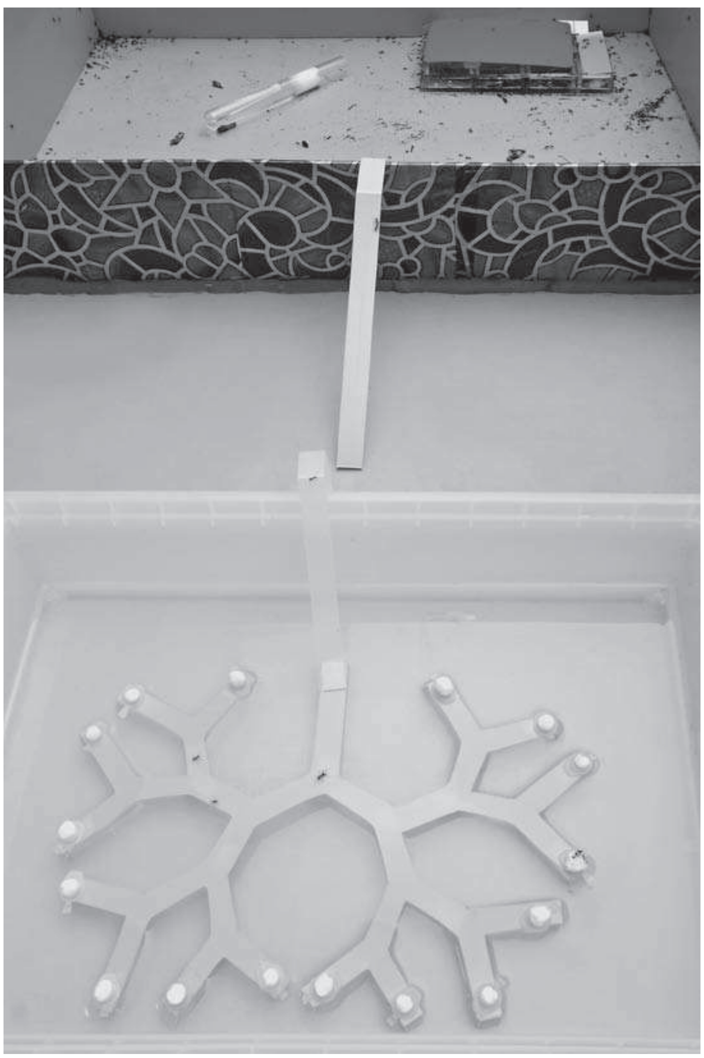

Fig. 1. A laboratory arena deviled into two parts, containing an artificial ant nest and a binary tree maze placed in a bath with water. Photo by Nail Bikbaev.

The experiments based on Shannon entropy present a situation in which, in order to obtain food, the ants have to transmit certain information which is quantitatively known to the researcher. This information concerns the sequence of turns towards a trough with syrup. The laboratory maze "binary tree" is used where each "leaf" of the tree ends with an empty trough with the exception of one filled with syrup. The leaf on which to place the filled trough was chosen randomly by tossing a coin for each fork in the path. The simplest design is a tree with one fork and two leaves, that is, a Y-shaped maze. It represents one binary choice which corresponds to one bit of information. In this situation a scouting animal should transmit one bit of information to other individuals: to go to the right (R) or to the left (L). In other experiments the number of forks of the binary tree increased to six. Hence, the number of bits necessary to choose the correct way is equal to the number of forks, that is, turns to be taken (Figure 1 shows a labyrinth with 3 forks). In total, 335 scouts along with their teams were used in all experiments with the binary tree, and each scout took part in tens of trials.

The binary tree and ants' language

Before analyzing ants' "linguistic potential" we considered the evidence of information transmission from the scouts to the foragers. The statistical analysis of the number of faultless findings of the goal was carried out by comparing the hypothesis H_0 (ants find the leaf containing the food by chance) with the hypothesis H_1 (they find the goal thanks to the information obtained), proceeding from the fact that the probability of finding the correct way by chance when the number of forks is i is $(1/2)^i$. We analyzed different series of experiments (338 trials in sum), separately for 2, 3, 4, 5, and 6 forks. In all cases H_0 was rejected in favor of H_1; $P < 0.001$, thus unambiguously demonstrating information transmission from scouts to foragers (see details in [1]).

In order to evaluate the rate of information transmission in ants, let us note that the quantity of information (in bits) necessary to choose the correct route in the maze equals i, the depth of the tree (the number of turns to be taken), that is, $\log 2\ n$ where n is the number of leaves. The obtained results have shown that the duration of the contacts between the scouts and foragers (t) is $ai + b$, where i is the number of turns (the depth of the tree), a is the time duration required for transmitting one bit of information, and b is an introduced constant, reflecting the fact that ants can transmit information not related directly to the task, for example, the simple signal "food". Besides, it is not ruled out that a scout ant transmits, in some way, the information on its route to the nest,

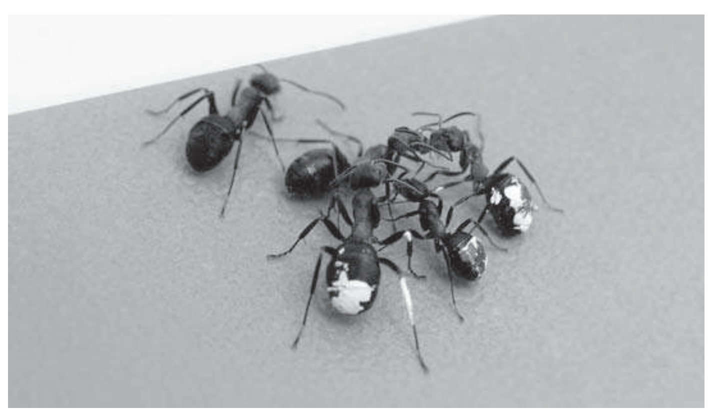

Fig. 2. A scouting ant contacting with members of its team. Photo by Nail Bikbaev.

using acoustic or some other means of communication. The rate of information transmission (a) derived from the equation $t = ai + b$ was about 1 minute per bit in three ant species, which is at least 10 times smaller than in humans.

Another series of experiments with the binary tree was inspired by the concept of Kolmogorov complexity and was designed to check whether ants possess such an important property of intelligent communications as the ability to grasp regularities and to use them for encoding and "compressing" information. This concept is applied to words (or text) composed of the letters of any alphabet, for example, of an alphabet consisting of two letters: L and R. We interpret a word as a sequence of left (L) and right (R) turns in a maze. Informally, the Kolmogorov complexity of a word (and its uncertainty) equates to its most concise description. For example, the word "LLLLLLLL" can be represented as "8 L", the word "LRLRLRLR" as "4LR", while the "random" word of shorter length "LRRLRL" probably cannot be expressed more concisely, and this is the most complex of the three.

We analyzed the question of whether ants can use simple regularities of a "word" to compress it. It is known that Kolmogorov complexity is not algorithmically computable. Therefore, strictly speaking, we can only check whether ants have a "notion" of simple and complex sequences. In our binary tree maze, in human perception, different routes have different complexities. We applied a statistical test in order to examine whether the time for transmission of information by ants depends on its complexity. We considered two hypotheses. The main hypothesis is H_0, that is, the time for transmission of information does not depend on the complexity of the "text". The alternative hypothesis is H1 that this time actually depends on the complexity of the "text". The hypothesis H_0 was rejected ($P = 0.01$), thus showing that the more time ants spent on the information transmission, the more complex - in the sense of Kolmogorov complexity - was the message (see details in [1]). It is worth to note that ants began using regularities to compress only quite large "texts". They spent from 120 to 220 sec. to transmit information about random turn patterns on the maze with 5 and 6 forks and from 78 to 135 sec. when turn patterns were regular. There was no essential difference when the length of sequences was less than 4.

Ideas of information theory and numerical competence in ants

Numerical competence is one of the main intriguing domains of animal intelligence. Recent studies have demonstrated some species as being able to judge about numbers of stimuli, including things, and sounds, and maybe smells (see [2] for a review). For example, lions can count roaring that comes from individuals who are not members of the pride; honey bees are able to use the number of landmarks as one of the criteria in searching for food sources. There are many other examples that come from different animal species, from mealy beetles to elephants; however, we are still lacking an adequate "language" for comparative analysis. The main difficulty in comparing numerical abilities in humans and other species is that our numerical competence is closely connected with abilities for language usage and for symbolic representation.

We suggested a new experimental paradigm which is based on ideas of information theory and is the first one to exploit natural communicative systems of animals. In our experiments ant scouts were required to transfer to foragers in a laboratory nest the information about which branch of a special "counting maze" they had to go to in order to obtain syrup. "Counting maze" is a collective name for several variants of set-ups (Fig. 4). The experiments were based on a procedure similar to the binary tree study. The main idea of this experimental paradigm is that experimenters can judge how ants represent numbers by estimating how much time individual ants spend on "pronouncing" numbers, that is, on transferring information about index numbers of branches.

Fig. 3. Dr. Natalia Azarkina (our guest from Moscow University) is marking ants by paint. One can see several extra mazes near the arena. Photo by Zhanna Reznikova.

The findings concerning number-related skills in ants are based on comparisons of duration of information contacts between scouts and foragers which preceded successful trips by the foraging teams. In total, 32 scout-foragers teams worked in three kinds of set-ups. It turned out that the relation between the index number of the branch (j) and the duration of the contact between the scout and the foragers (t) is well described by the equation $t = c\,j + d$ for different set-ups which are characterized by different shapes, distances between the branches and lengths of the branches. The values of parameters c and d are close and do not depend either on the lengths of the branches or on other parameters.

It is interesting that quantitative characteristics of the ants' "number system" seem to be close, at least outwardly, to some archaic human languages: the length of the code of a given number is proportional to its value. For example, the word "finger" corresponds to 1, "finger, finger" to the number 2, "finger, finger, finger" to the number 3 and so on. In modern human languages the length of the code word of a number j is approximately proportional to $\log j$ (for large j's), and the modern numeration system is the result of a long and complicated development.

An experimental scheme for studying ants' "arithmetic" skills based on a fundamental idea of information theory, which is that in a "reasonable" communication system the frequency of usage of a message and its length must correlate. The informal pattern is quite simple: the more frequently a message is used in a language, the shorter is the word or the phrase coding it. This phenomenon is manifested in all known human languages.

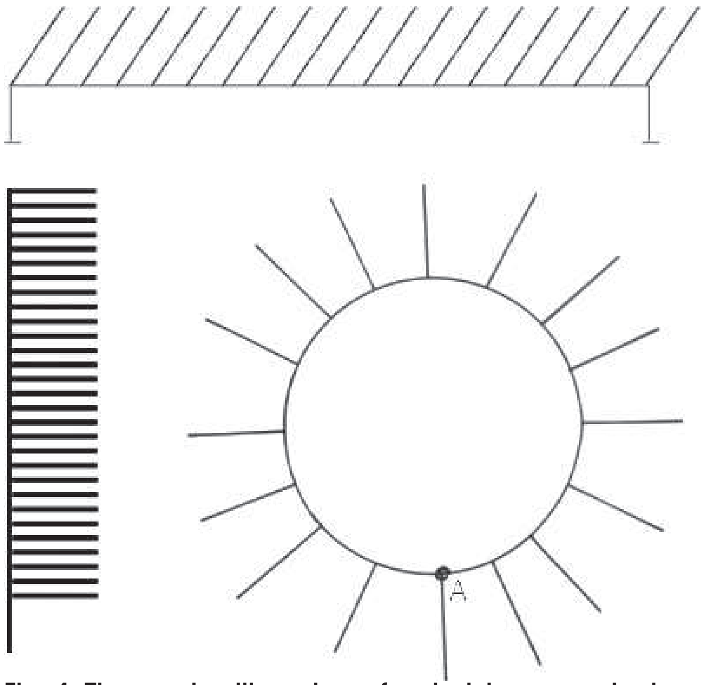

Fig. 4. The comb – like set-ups for studying numerical competence in ants: a horizontal trunk, a vertical trunk and a circle.

The scheme was as follows. Ants were offered a horizontal trunk with 30 branches. The experiments were divided into three stages, and at each of them the regularity of placing the trough with syrup on branches with different numbers was changed. At the first stage, the branch containing the trough with syrup was selected randomly, with equal probabilities for all branches. So the probability of the trough with syrup being placed on a particular branch was 1/30. At the second stage we chose two "special" branches A and B (N 7 and N 14; N 10 and N 20; and N 10 and N 19 in different years) on which the trough with syrup occurred during the experiments much more frequently than on the rest - with a probability of 1/3 for "A" and "B", and 1 /84 for each of the other 28 branches. In this way, two "messages" -"the trough is on branch A" and "the trough is on branch B"- had a much higher probability than the remaining 28 messages. In one series of trials we used only one "special" point A (the branch N 15). On this branch the food appeared with the probability of 1/2, and 1/58 for each of the other 29 branches. At the third stage of the experiment, the number of the branch with the trough was chosen at random again.

The obtained data demonstrated that ants appeared to be forced to develop a new code in order to optimize their messages, and the usage of this new code has to be based on simple arithmetic operations. The patterns of dependence of the information transmission time on the number of the food-containing branch at the first and third stages of experiments were considerably different. In the vicinities of the "special" branches, the time taken for transmission of the information about the number of the branch with the trough was, on the average, shorter. For example, in the first series, at the first stage of the experiments the ants took 70–82 seconds to transmit the information about the fact that the trough with syrup was on branch N 11, and 8–12 seconds to transmit the information about branch N 1. At the third stage it took 5–15 seconds to transmit the information about branch N 11. Analysis of the time duration of information transmission by the ants raises the possibility that at the third stage of the experiment the scouts' messages consisted of two parts: the information about which of the "special" branches was the nearest to the branch with the trough, and the information about how many branches away is the branch with the trough from a certain "special" branch. In other words, the ants, presumably, passed the "name" of the "special" branch nearest to the branch with the trough, and then the number which had to be added or subtracted in order to find the branch with the trough. That ant teams went directly to the "correct" branch enables us to suggest that they performed correctly whatever "mental" operation (subtraction or addition) was to be made (see details in [2]). It is likely that at the third stage of the experiment the ants used simple additions and subtractions, achieving economy in a manner reminiscent of the Roman numeral system when the numbers 10 and 20, 10 and 19 in different series of the experiments, played a role similar to that of the Roman numbers V and X. This also indicates that these insects have a communication system with a great degree of flexibility. Until the frequencies with which the food was placed on different branches started exhibiting regularities, the ants were "encoding" each number (j) of a branch with a message of length proportional to j, which suggests unitary coding. Subsequent changes of code in response to special regularities in the frequencies are in line with a basic information-theoretic principle that in an efficient communication system the frequency of use of a message and the length of that message are related.

In conclusion, we have demonstrated that ants of highly social species can (1) transfer information, (2) compress information, (3) change the way they represent information; (4) add and subtract small numbers. The obtained results are important not only for biology, but also for cognitive science, linguistics, cybernetics and robotics. Generally speaking, we can say that the methods and ideas of Information Theory enabled us to reveal some important laws of Nature.

References

[1] B. Ya. Ryabko and Zh.I. Reznikova, "Using Shannon Entropy and Kolmogorov Complexity to study the communicative system and cognitive capacities in ants", *Complexity*, vol. 2, no.2, pp. 37–42, 1996.

[2] Zh. I. Reznikova, B.Ya. Ryabko, " Numerical competence in animals, with an insight from ants", *Behaviour*, vol. 148, no 4, pp. 405–434, 2011.

[3] Zh. I. Reznikova, *Animal intelligence: From individual to social cognition*, Cambridge University Press, Cambridge, UK, 2007.

[4] E. S. Savage-Rumbaugh, S. G. Shanker, T. J. Taylor, *Apes, Language and the Human Mind*, Oxford University Press, Oxford, UK, 1998.

[5] L. M. Herman, S. L. Abichandani, A. N. Elhajj, E. Y. K. Herman, J. L. Sanchez, A. A. Pack, "Dolphins (*Tursiops truncatus*) comprehend the referential character of the human pointing gesture", *J. Comp. Psychol.*, vol, 113, no. 1–18, 1999.

[6] I. M. Pepperberg, *The Alex Studies*, Harvard University Press, Cambridge, MA, USA, 1999.

[7] B. Ya. Ryabko, Zh. I. Reznikova, "The use of ideas of Information Theory for studying language and "intelligence" in ants", *Entropy*, vol. 11, no 4, pp. 836–853, 2009.