What Counts

How Every Brain Is Hardwired for Math

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Back to the Beginning: Our Animal Ancestors

An innate capacity for numbers coded in our genome implies that we have inherited that coding from our parents, and they from their parents. How far back in our evolutionary history can we trace it? We have seen that the earliest *Homo sapiens* appeared to possess the capacity, and possibly our Neanderthal cousins too. We have no direct evidence that our common ancestor, *Homo erectus*, could count, since the surviving artefacts offer no clues. It is, however, possible to test descendants of our more distant ancestors, the chimpanzees, who split off from the human lineage about 6 million years ago.[44] If we can find evidence that chimpanzees categorize the world in terms of numerosities, then this opens up the possibility that the genetic endowment goes back to at least the ancestor of both humans and chimps. Of course, other animals may have this number sense too, in which case it originates much further back in the evolution of life.

But there is one crucial caveat to this line of reasoning. To show that an ability has been inherited from an ancestral animal, the mere fact that we can both do the same thing is not enough. Bees and birds can both fly, but the flying apparatus of birds is completely unrelated genetically to that of bees. For more abstract abilities it is necessary to show that doing the same thing is the result of the activity of genetically related brain structures. In chimps' brains, which are very like ours though smaller, I would be happy only if equivalent brain structures are implicated. Of course, if chimps cannot use numerosities then the whole issue will not arise, and we may assume that these abilities originated no earlier than the first hominids, perhaps even just with *Homo sapiens*.

So how can we find out whether animals possess a concept of numerosity, given that animals do not count aloud? There are two basic methods. First, we can see if it is possible to train an animal to respond to numerosity, and just the numerosity. Second, we can see whether an animal's behaviour is governed by numerosity without training. For example, we may be able to use the same methods used to study equally speechless infants. Naturally, for a capacity to have survived millions of years of evolution, it is likely to have been of use to individual animals in improving their reproductive success, or at least to have been closely linked to some other capacity that has improved their reproductive success.

Since animals cannot use number words (apart from Alex, an African Grey parrot (see p. 138), we should avoid the word 'count', which is closely associated with the use of number names. Let us talk instead of 'enumerating'. The great German student of animal behaviour, Otto Koehler, called genuine examples of animal enumeration 'thinking unnamed numbers', where the animal uses 'inner marks' to keep track of numerosities.

Trained to Enumerate

Let me start with an example of an animal who, despite appearances, did not count: the horse Clever Hans. Clever Hans, who flourished at the turn of the century, was able to produce answers to arithmetical problems by tapping his foreleg. Some of these arithmetical problems would be too difficult for many US high-school graduates[45]: he was, for example, able to add fractions such as ⅖ and ½, and gave the answer by tapping out the numerator, 9, and the denominator, 10, separately. He could find factors, and tapped out correctly, 1, 2, 4, 7, 14, and 28 when asked to find the factors of 28. He could give square roots and cube roots. His owner, Van Osten, a mathematics teacher and horse trainer, was entirely convinced that these talents were genuine, and allowed a panel of experts, which included a psychologist, an animal trainer, a circus manager, and the director of the Berlin zoo, to carry out extensive tests. They were puzzled and could see no evidence that the trainer was cueing Clever Hans. The chairman of the panel, the psychologist Carl Stumpf, wrote, 'I could not believe that a horse could perceive movements which escaped the sharp eyes of a circus manager . . . One would hardly expect this feat on the part of an animal who was so deficient in keenness of vision.' Stumpf was, in keeping with the post-Darwinian zeitgeist of 1904, willing to believe in the essential similarity between the human and the animal mind. He noted that even 'educators were disposed to be convinced because of the clever systematic method of instruction [but] which had not, until then, been applied to the education of a horse'.

Of course, the horse had been extensively trained, and rewarded whenever he produced the correct answer. But his arithmetical skills were not due to training. One man, Oskar Pfungst, was not stumped by this. He discovered the explanation by careful experimentation with Hans and other horses. Hans was cued to stop tapping his foot by the movements of the questioner's head, eyebrows, or dilation of his nostrils. Van Osten, quite inadvertently, began to produce these cues near the answer, which Hans, who was indeed a clever horse, picked up, and was then rewarded for doing so. Hank Davis, a leading expert on animal counting from the University of Guelph in Ontario, noted that

> Pfungst determined that it was not even necessary that such cues be sent by Van Osten. Hans was 'clever' enough to learn the signaling systems of other interrogators. As long as the questioner knew the correct answer, Hans was also likely to succeed . . . The inadvertent delivery of cues resulted from the normal buildup of tension in the questioner as Hans approached the correct answer. Perhaps most telling was the fact that Pfungst, himself, could not stop Hans even after he knew the nature of the signaling system and had attempted to suppress it.[46]

Scientists today take extraordinary precautions to avoid a repeat of the Clever Hans phenomenon. For example, any experimenters in view of the animal must not know what the correct response should be, so they could not cue the animal correctly even if they wanted to.

It might seem to us that the obvious creatures to test would be our nearest relatives, the ones with brains most like our own—chimpanzees. Chimpanzees we now know are highly intelligent, social animals, who in the wild make and use tools and even, to some extent, create a culture. They can be trained to communicate very effectively with humans, and with each other, using the sign language of the deaf.[47] There is a good chance, therefore, that chimps might show some ability to enumerate. However, studies of chimp enumeration have been held back because Behaviourism, the dominant philosophy in most US animal labs until recently, worked on the assumption that animals lacked any kind of cognitive concept, including number concepts, and indeed many Behaviourists believed that concepts were superfluous to the explanation of *human* behaviour. What was critical to the Behaviourist was the establishment of simple links between a stimulus and a response, and it really didn't matter what 'organism' was used, provided they could register the stimulus and physically produce the response. Why, then, use chimps, which are rare, expensive, large, strong, and dangerous, when they could use rats, which are small, cheap, and safe?

There is another tradition, going back to Darwin, which doesn't shrink from attributing concepts to animals. One of Darwin's students, George Romanes, was the first to try to train a chimp to use numbers. He reported in 1898 how he taught a chimpanzee to give the right number of straws on a verbal command, up to five.[48] Interestingly, two chimps trained by a strict Behaviourist took half a million trials to match numerals 1 to 7 to numbers of objects, and naturally no numerical concepts were invoked to explain this performance.[49]

It is only recently that chimpanzee enumeration has come under scientific scrutiny. The Japanese researcher Tetsuro Matsuzawa trained a chimpanzee called Ai to select Arabic numerals that corresponded to the number of items in a display, such as pencils, gloves, and spoons, up to six.[50] Even more impressive numerical abilities have been elicited by scientists at the Yerkes Primate Research Center in Georgia.

Sarah Boysen[51] trained Sheba, a three-year-old female chimpanzee, to use Arabic numerals up to 4 in a range of standard number tasks that a three-year-old child might find difficult. The training was long and complicated, and proceeded in four stages, each with several steps.

Stage I: Sheba Is Trained to Use One-to-One Correspondence

In this stage Sheba has to learn to match a small collection of marks on a card with one of three collections of gumdrops in circular 'wells'. When she is correct she is rewarded with gumdrops, a tasty treat.

Step 1. Sheba learns to point to the location of a gumdrop, indicated on a card in front of her, in one of the three wells (Figure 3.3a).

Step 2. Sheba learns to pick out the number of gumdrops corresponding to the cards, but with one distractor (2 *v.* 1, Figure 3.3b). Here she is discriminating between two numerosities.

Step 3. Sheba learns to pick out the number of gumdrops corresponding to the card, with two distractors (1 *v.* 3 *v.* 2, Figure 3.3c). Now she is discriminating among three numerosities.

Mastery of this task enables her to go on to learn how to use numerals instead of collections of gumdrops. But again she is rewarded when she picks the correct number.

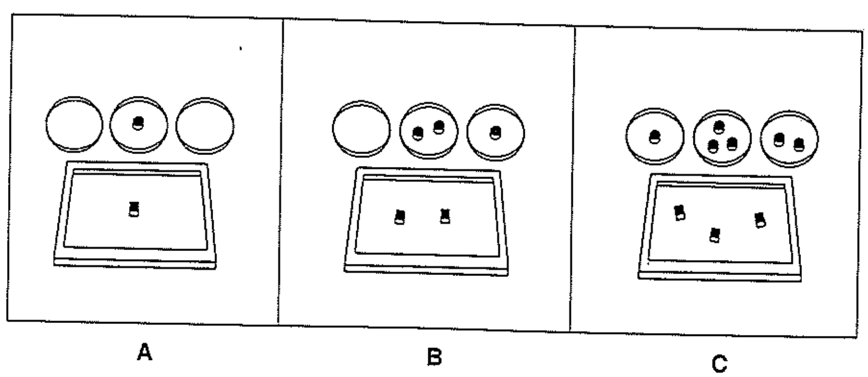

Figure 3.3 Sheba the chimp learns to match numerosities. She is rewarded for matching the numerosity of the marks on the rectangular card with gumdrops placed in circular wells. This is the first stage in training her to understand Arabic numerals. (From Boysen[52])

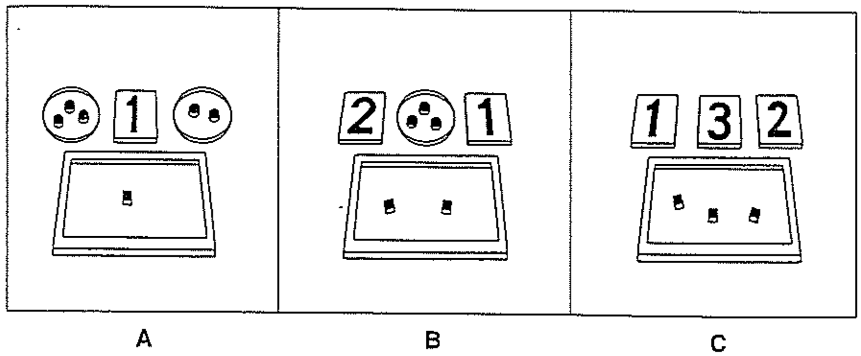

Figure 3.4. Sheba learns Arabic numerals. She is rewarded for picking the numeral that corresponds to the numerosity on the card. She starts with one numeral, then goes on to two, and finally has to pick one of three numerals corresponding to the numerosity. (From Boysen[53])

Stage II: Sheba Learns Arabic Numerals

Step 1. Sheba learns to pick the numeral from three wells (Figure 3.4a); she already knows that one gumdrop on the card does not correspond to the gumdrops in the two wells. In this way she begins to learn the meaning of '1', '2', and '3'.

Step 2. Sheba learns to pick one numeral from a choice of two numerals, reinforcing the training of Step 1 (Figure 3.4b).

Step 3. Sheba learns to pick the correct numeral from a choice of three (Figure 3.4c).

Stage III: Sheba's Understanding of 1, 2, and 3 Is Tested in a New Task

Sheba is shown a numeral on a computer screen and has to point to the well with that number of objects (Figure 3.5). She is rewarded with gumdrops when she is correct.

Stage IV: Transfer of This Knowledge to Simple Addition

Finally, Sheba showed that all this training could result in two remarkable achievements—adding objects and indicating the sum in numerals; and adding numbers denoted by numerals.

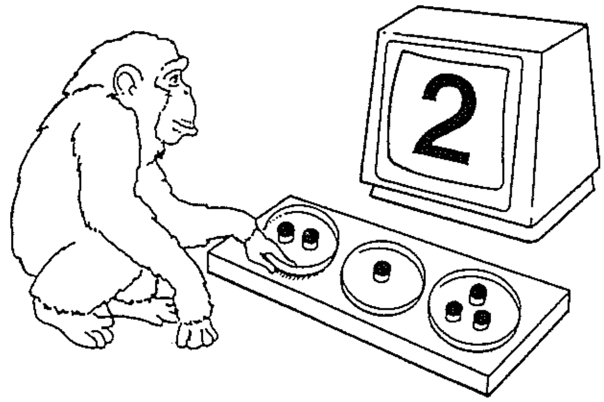

Figure 3.5 Sheba learns the numerical value of the numerals. In this stage of the learning she must pick the well with the numerosity corresponding to the numeral on the computer screen. (From Boysen[54])

Step 1. Oranges were hidden at two of three locations in Sheba's work area: a tree stump, a food bin, and a plastic dishpan (Figure 3.6). Sheba found the oranges and then pointed to one of the numerals to indicate the sum of the two.

Extraordinarily, she did this on the very first trial of the session, without any training at all, and maintained this performance for two weeks.

Here, Sheba may be showing us that she can add together the numbers of oranges she found in two of the three hiding places. Alternatively, she may have been counting them as she found them, perhaps as three- or four-year-old children add by counting on. When they are adding 3 and 2 they may go, 'one, two, three' for the first number, and then 'four, five' to add the second.

Step 2. Arabic numerals, rather than oranges, were hidden at two of the locations, and she had to add together the numbers she found. She learned this task very quickly.

Sheba thus learned to use abstract representations—Arabic numerals—for small numbers. Human children can use their emerging knowledge of numbers in a range of tasks. David Geary, as we have

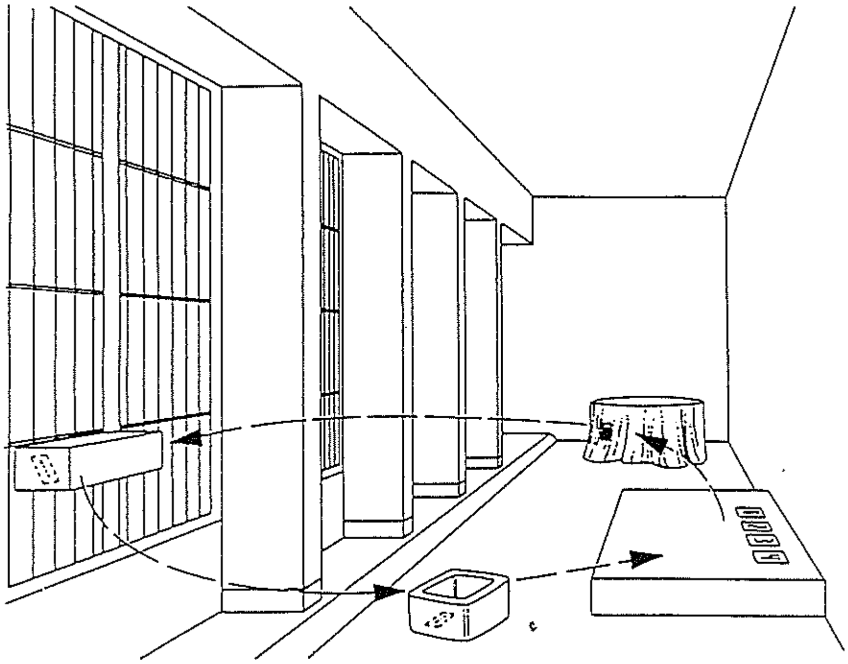

Figure 3.6 Sheba shows that she can add. In the first version of the task, oranges are hidden in three locations in Sheba's work area. She has to find the oranges and then pick the numeral corresponding to the sum. Having already learned the meaning of the numerals, she was successful on her very first trial. Having mastered this task, the numerals were substituted for oranges at these locations (as shown here), and again Sheba was successful at selecting the numeral in the tray corresponding to the sum. (From Boysen[55])

seen, postulated three 'biologically primary abilities'—discriminating numerosities, counting, and simple arithmetic. To these, I would add ordering numbers by size, or at least being able to select the larger of two numbers. So important and basic is this ability, that I devote the whole of Chapter 6 to it. Can Sheba use her knowledge of numbers in these four skills?

Sheba was able to learn to pick the larger of two numbers—the basis for ordering by size. She learned pairs that differed by 1, such 1 *v.* 2, 2 *v.* 3, 3 *v.* 4, and in each trial she was rewarded when she picked the larger number. When she was proficient at this, she was presented with a pair of numbers that she hadn't seen as a pair before, such as 2 *v.* 4, which she was able to manage well.

Another very basic human skill, as we have seen, is counting. The child learns to map each member of a collection of objects to a sequence of words. Since chimps do not know spoken words, and cannot learn them, I have been careful not to talk about 'counting', but about 'enumeration'. But can chimps do something that is equivalent? Can they put objects in one-to-one correspondence with mental tags of some sort? We cannot show that any of Sheba's achievements depended on being able to count in this sense. One experiment by colleagues at the Yerkes Primate Research Center in Georgia shows that counting is possible. Yerkes was famous in the 1980s for teaching chimpanzees to communicate in a symbolic language. The most famous of these chimpanzees was Lana, trained by Duane Rumbaugh and his colleagues. Rumbaugh and David Washburn set out to see if Lana, by now a seventeen-year-old, could count.[56]

They now wanted to use a method which would force Lana to use mental tags, and which therefore had to exclude the possibility of her using other cues, such as the spatial arrangement of the collection to be counted. They devised a method that depended on making the right number of objects disappear from a computer screen. To do this, Lana had to remember how many objects she had made disappear. She was already skilled at using a joystick to control the position of a cursor on a computer screen, but she needed to understand the new task. In the training phase, she was shown a numeral, 1, 2, or 3, had to select boxes until she had reached that number, and then demonstrate her understanding by moving the joystick back to the numeral.

In a typical early trial, Lana saw the numeral 3, and at the bottom of the screen a line of rectangular boxes. As Lana removed two boxes by moving the cursor into them, the numerals 1 and 2 appeared in their place and two 'feedback boxes' that turned blue. This was designed to give Lana assurance that she was proceeding correctly. To complete this trial successfully, Lana had to remove a third box and return the cursor to the target numeral, 3. When she was successful she got a reward, but if she returned the cursor too early (after 2, for example) or too late, then the computer would emit a raucous tone.

Once Lana had mastered the training, she went on to the experiment proper. Now the boxes were arranged differently for each trial, and there was no feedback, either from the feedback boxes or in the form of numerals appearing in place of the selection boxes. Lana showed that she could manage all the numerals from 1 to 4 very efficiently. Something very like human counting must have been involved, because she had to keep a *mental* tally of the *number* of boxes she had removed from the screen. There were no external cues she could have relied on in the final test sessions.

Sheba's ability to add small numbers was matched by Sherman and Austin, two language-trained chimpanzees in Rumbaugh and Washburn's lab.[57] Not only could they add two numbers together, they could accurately compare the size of the sum with the result of a second addition. The way they did this was simple and elegant, and actually required very little training. Sherman and Austin would see two trays, and quickly learned to choose the tray with more chocolates on it (Figure 3.7). Not surprising, you may think, but there was a catch. In each tray were two wells with pieces of chocolate in them. To decide which tray had the most chocolates, Sherman and Austin had to add the contents of the two wells, and then select the larger of the two sums. This is a task then that demands the use of three primary abilities: recognizing the numerosities (of the wells and the sums), adding, and ordering.

Of course, these two chimps may not have been adding so much as applying a 'counting all' strategy to the two wells. Nevertheless, if children added the pieces of chocolate together this way, we would be quite happy to say that they were adding, but using a particular technique to do it.

Higher Maths in 'Lower' Animals

Can we find any of these biologically primary skills in ancestors of both chimpanzees and humans, or indeed in any other animals? The seminal demonstration comes not from mammals but from birds. It has long been thought that birds can count the number of eggs in a nest. Whether they can or not, Otto Koehler showed in a series of classic experiments between the late 1930s and the 1950s that birds can use numerosities to guide behaviour, and perhaps even use mental tags to count. Koehler put forward a new and important hypothesis which, like much of his work, has been largely ignored, one suspects because

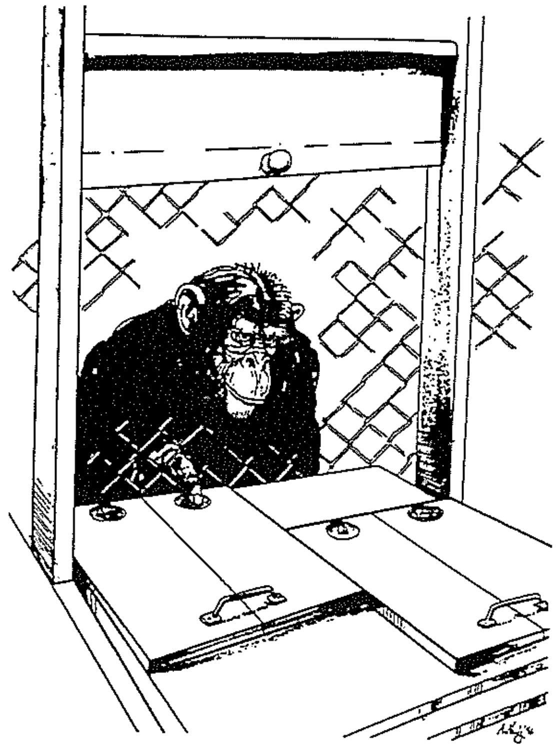

Figure 3.7 Austin has learned to select the tray with more pieces of chocolate on it. Since each tray has two wells with pieces of chocolate in them, he must add the numbers together and select the larger sum. (From Rumbaugh & Washburn[58])

he published almost exclusively in German, and around the time of the Second World War.[59] What he proposed was that humans would never have started counting without two pre-linguistic abilities: the ability to compare two numerosities presented simultaneously, and the ability to remember numbers of objects *presented sucessively in time*. Both these abilities, he showed, we share with birds.

In one experiment, a raven called Jakob was rewarded when he tried to open a box with the same number of spots on its lid as there were on a large 'key' card (Figure 3.8). The arrangement of spots was always different on the lid and the key card. The wrong lid always differed by just one spot. Jakob solved the task by finding the lids with same numbers as key cards, and learned eventually to distinguish 2, 3, 4, 5, and 6 spots.

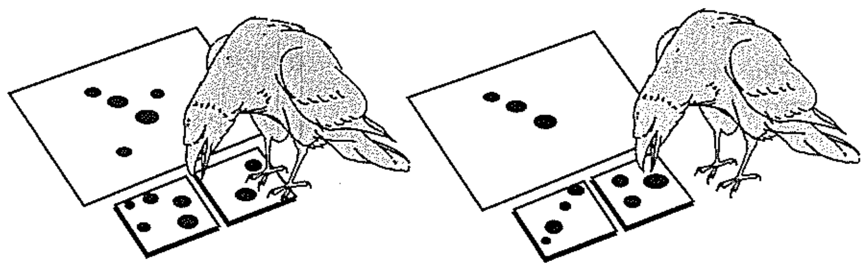

Figure 3.8 A raven matches numerosities. The great German ethologist Otto Koehler trained his raven Jakob to pick one of two small boxes that had the same number of blobs on its lid as there were on a big card. Notice that the pattern on the correct lid is quite different from the pattern on the card: This is one of a classic series of experiments with birds that demonstrated their numerical ability. (after Thorpe[60])

Koehler next showed that animals could 'act upon' a number. So jackdaws were trained to open the lids of a row of boxes until they had taken from them a given number of pieces of food, say 5, and then stop. To do this, they, like Lana, had to keep track of the pieces of food they had taken. They had to create what Koehler called 'inner marks', mental tags, similar to (though of course not the same as) our silent counting using number words. Jackdaws did this very successfully.

This was demonstrated in an experiment with a jackdaw, given the task of raising lids on a row of boxes until he had taken 5 pieces of food. One trial in the many that made up the experiment was remarkable. The pieces were distributed in the first five boxes 1, 2, 1, 0, 1. The jackdaw opened only the first three lids, and so had taken only 4 pieces of food. Koehler, a meticulous experimenter, was just about to record 'one too few, incorrect solution', when the jackdaw came back to the row of boxes. The great British pioneer in bird behaviour, W. H. Thorpe, described what happened next.

> The bird went through a most remarkable performance: it bowed its head once before the first box it had emptied, made two bows in front of the second box, and one before the third, then went farther along the line, opened the fourth lid (no bait) and the fifth and took out the last (fifth) bait. Having done this, it left the rest of the line of boxes and went home with an air of finality. This 'intention' bowing, repeated the same number of times before

> each open box as on the first occasion when it found baits in them, seems to prove that the bird remembered its previous actions.[61]

Koehler, who was always extremely cautious in putting forward interpretations of animal behaviour, thought that the bird must have created 5 inner marks, unnamed numbers, which it used to compare its own actions with those required by the task.

To what extent are these inner marks like our numbers? Koehler thought that they were 'equal marks', rather like our using one nod of the head for one, two nods for two, and so on. Each nod is to equal the others, and they are the *mental equivalent of tallies*. He called the creation of a collection of these inner marks 'thinking unnamed numbers'. Our numbers are unequal in this sense. 'Three' is qualitatively different from 'two', and in a fixed order in relation to it. Koehler did not rule out the possibility that animals may have mental marks like ours, but they were not necessary to explain his experimental results.

One particularly striking example of bird counting comes from Alex, an African Grey parrot trained by Irene Pepperberg at the University of Arizona. When Alex is asked how many objects there are on a tray, or even how many red objects there are, he will actually say the number. Of course, this has taken many, many years of training, but it is impressive because he has learned not just to associate the right number name (more correctly, the right vocal response) with the numerosity of the array, but also because he is able to apply the name to a collection of objects he has not been trained with. This is important because it shows that Alex's representation of numerosity is not tied to a particular collection of objects, but is more abstract than that.[62]

Since Koehler's time, many researchers have found evidence both for the ability to compare and select from simultaneously presented numbers, and for 'acting upon' a number, in a wide range of species. Rats, for example, can learn to count shocks, or learn the number of doors to ignore before entering the arm of a maze which contains food.

Birds and rats have small brains, even taking into account their much smaller bodies. The animals with the largest brains for their body size are, of course, humans. But the next-largest brains are not in our closes relatives, the chimpanzees, but in dolphins. There has been almost no research on dolphin numerical abilities, and none at all on the kinds of ability they may share with chimpanzees, rats, and birds.[63]

The Evolution of the Number Module

Laboratory experiments show that animals have a latent capacity to do simple numerical tasks. As well as in the recently evolved apes, it is found in birds, which evolved after the dinosaurs. For this capacity to be preserved for millions of years, it must surely have offered some advantage to those species that possessed it. But what could this be? The life of the individual animal—the *phenotype*—depends on feeding and safety from predation. Securing these helps all members of a species similarly endowed—the *genotype*—to survive and reproduce better and, other things being equal, to reproduce more offspring than species members without the endowment. In this way, the valuable capacity to carry out these simple numerical tasks will remain in the gene pool. However, the genotypic capacity may persist even though it offers the phenotype no advantage.[64]

Squirrels will have more nuts for winter if they consistently choose branches with three nuts rather than two, and in general foraging will be more effective if the animal can decide which patch has the most food. It is certainly true that animals make more trips to patches where there is more food. If there are two patches, A and B, so that A has twice as much food as B, then animals tend to go twice as often to A as to B, and make the ratio of trips match the ratio of food. Why they do not spend all their time at the patch with the most food, which would seem to be the optimal strategy, is a problem we cannot go into here. The main point for us is this: animals can estimate and compare two quantities. Many researchers have suggested that this is precisely what constitutes the adaptive advantage of number capacity.[65] But squirrels may not be counting nuts; they may be relying on a concept of quantity that is not numerousness—the amount of nut-stuff on the two branches. This is how we estimate the volumes of milk or granulated sugar, for example. Foraging success critically depends on making quantitative estimates without using numbers. Even invertebrates do this. Worker bees, for example, when they have found an abundant source of pollen or nectar, return to the hive and 'dance' a message to the other bees indicating the direction and the distance of the food source. When the quantity of food decreases below a certain threshold, the bees may still visit the patch but will not dance on their return. They thus make estimates of relative quantity.[66]

Evolutionary explanations of behaviour can easily become Just-So stories, whose acceptability depends too often on the imagination of the teller and the gullibility of the audience. What is needed are documented examples of behaviours in the wild that cannot depend on quantity estimates, but must depend on numerosities. These examples are almost impossible to discover, since numerosity in nature almost always varies with quantity. This may of course be why a sense of numerosity is adaptive.

As we have seen, birds can be trained to make use of a number sense which, in exceptional individuals, can go up to 7. Do they use this in the wild? Bird-nesting children have always wondered whether birds can count the number of eggs or chicks in the nest. There would seem to be a good reason for being able to do so. In normal circumstances, egg-laying continues until incubation behaviour is triggered. Too many eggs could mean that the parents will be unable to feed all their chicks, which may be detrimental to *all* the chicks in the nest; too few would reduce the chance of the genes surviving. If eggs are taken during laying, birds will usually lay extra eggs; and if eggs are added, they will stop laying, perhaps even reabsorbing eggs that have formed inside their body. Even after the birth of the chicks, the female may cannibalize some offspring if she cannot feed all of them.[67] But does this mean that birds count their eggs and their chicks? Does it mean they have a sense of their absolute numerosity, of 'fiveness', say? Does the female think to herself, in effect, 'I can only support five chicks, so I'd better eat the sixth?' Birds probably do have a real sense of numerosity, but one can imagine other ways of reaching the same decision. They could be using some perceptual cue, such as the visible ratio of eggs to nest, or of chicks to nest, as judged simply in terms of the proportion of light (eggs, chicks) to dark (nest).[68] This behaviour is certainly consistent with its being controlled by a Number Module, but it is also consistent with its being controlled by a mechanism sensitive to relative quantity more generally.

There is another activity in which birds seem to count, and that is in singing. Songbirds such as the chaffinch, lark, or canary are genetically programmed to sing their own species-special song, but it has been known since at least the eighteenth century that the birds also learn. Canary-fanciers prize 'schoolmaster canaries', particularly good singers from whom other canaries learn. In fact, there are local 'dialects' of birdsongs.[69] A dialect can be the exact number of repetitions of a note—seven in this forest, but eight in the distant meadow. This means that the offspring learn the number of repetitions of the note from the parent, and countersinging adult neighbours copy this number of repetitions. The German ethologist Uta Seibt argues that this is really a very abstract concept of number: the perceived number of notes is transformed into the performed number of notes.[70]

One extraordinary recent demonstration shows that rhesus monkeys can use numerosities in the wild. In a monkey colony on the island of Cayo Santiago in Puerto Rico, Marc Hauser and his colleagues from Harvard University carried out the same Mickey Mouse experiments as Karen Wynn had with infants. Since the monkeys were wild, and could not be confined to their mothers' laps, like Wynn's babies, the experimenters had to wait until a monkey took an interest in their apparatus, which was a field version of Wynn's Mickey Mouse experiment using pieces of aubergine instead of dolls. Just like the infants, the monkeys showed surprise when 1 piece + 1 piece did not yield 2 pieces of aubergine; and when 2 pieces – 1 piece did not yield 1 piece.[71] This shows that they are able to use numerosity representations to estimate food supply, but it still does not show that they will do so when not prompted by an experiment.

The best examples so far of number use in the wild do not come from foraging. In the Serengeti National Park in Tanzania, a lioness is returning at dusk to her pride. Eighteen females, one adult male, and seven cubs are waiting over a kilometre away. She hears a roar, one she does not recognize. It must be an intruder into her territory. Her cubs are safely with her sisters, and she is all alone. She hears the roar again, it's the same lion. Should she try to drive off the intruder? It would be an even match—her against one intruder—and it could turn into a real fight. With lions, that could be fatal. Dusk turns to the inky black of night, and she returns silently to the pride.

The following week, again at dusk, she hears roaring 500 metres away. She hears one unfamiliar voice, then a chorus of roars, one overlapping the next, and none of them the familiar voices: three intruders. This time she is with four of her sisters from the pride. Three of them, five of us. Their ears prick. The roaring is coming from a stand of trees over to their left. They wait, they peer into the night and at each other. One of them, the leader, approaches the roaring cautiously at first, as the others join her, more quickly until they are charging headlong into the trees.

By the time they reach the trees, the roaring has stopped and there is no sign of the intruding lions. This is not surprising. The roaring was actually coming from a loudspeaker set up by Karen McComb and her colleagues at the University of Sussex.[72] She was testing a theory about the way lions make a numerical assessment of the threat from intruders and the strength of the defence forces. The theory predicts that lions (like many other animals, fighting among which would be costly) will contest resources only when they are very likely to win; otherwise they will withdraw. The one exception is when a lioness is with her cub: then she will always attack an intruder. The lions' decision to attack depends on the number of intruders—in this experiment one or three—and how many adult defenders there are. The lioness leader identifies roaring as coming from individuals who are not members of the pride; she will also represent the defenders as known individuals. The best explanation of her decision is that she enumerates the number of distinguishable roarers and the number of her sisters, and the compares the two numbers. Only when the number of defenders is greater than the number of intruders will she launch an attack. This is remarkable because the number of intruders comes from the sound they make (they are not visible), while the number of defenders comes from another sense or other senses, vision probably, and is stored in the lioness's memory. Thus she has to abstract the numerosity of the two collections—intruders and defenders—away from the sense in which they were experienced and then compare these abstracted numerosities.

Chimpanzees are social animals like lions, but unlike lions they use tools. West African chimpanzees use stones to crack nuts, with a large stone as an anvil and a smaller stone as a hammer, while East African chimpanzees do not do this.[73] This has led to suggestions that chimpanzees have cultures that are passed from generation to generation by social learning, just as human cultures are. Indeed, when an individual who knows how to crack a nut with a stone is introduced into a culture which doesn't do this, members pretty soon learn how to do it, particularly the younger adults. The key question for us is this: can the use of numerical skills be part of a chimpanzee culture? Can a wild chimpanzee community learn to use their latent numerical ability in a way that is particular to them?

The story of Brutus, an alpha male, is an extraordinary and unique example of just this. He was observed by Swiss zoologist Christophe Boesch in the forests of the Taï National Park in Côte d'Ivoire. Brutus was the leader of a community of eighty chimpanzees. Like other communities, parties of around ten would go off in search of food, often travelling in one direction for hours in silence. These travelling parties would keep in touch by pant-hooting and by drumming on trees with buttresses, which are very resonant and can be heard for thousands of metres through the forest. Boesch noticed that sometimes after he had heard drumming, all the parties in the community would change direction. Many months of patiently following the community made Boesch realize that it was only when Brutus was drumming that the community changed direction. Analysis of the drumming and the reactions to it led Boesch, a famously careful researcher, to the astonishing conclusion that Brutus was signalling to his community in a 'symbolic drumming code' based on the *number* of drumbeats. Brutus conveyed three completely specific messages:

1. Drumming *once* at two different trees indicated the direction he was proposing, which was the direction followed by Brutus when moving between the two drummed trees.

2. Drumming *twice* at the same tree meant rest for an hour. The community activity stopped for an average of 60 minutes. In twelve observed instances, the rest was never less than 55 minutes and never more than 65 minutes. Once Boesch observed Brutus drumming four times on the same tree, and the party rested for 2 hours!

3. Drumming *once* at one tree and *twice* on another tree meant change direction to the one proposed, and then rest for an hour.[74]

For this form of communication to work, Brutus and other members must be able to use their numerical capacity to distinguish 1, 1 from 2 from 1, 2. It is only found in this one community in the Taï Forest: it was part of their culture and no one else's. I say 'was' because Brutus has now stopped using the code. Poaching, the greatest threat to chimpanzee survival, has killed or kidnapped so many prime males that the number of travel parties has since declined dramatically.

These examples suggest that animals can and do use numerosity skills in the wild. This seems to help them to resist predation and communicate while foraging. According to Hank Davis, an expert in the numerical abilities of rats, 'I believe that *absolute numerosity* is a distinctly human invention. No nonhuman animal needs this form of numerical competence in order to lead a successful, totally normal life.'[75] What animals use, he says, is just *relative numerosity*. They do not need to understand that each time they see a collection of 3 things, it has the same numerosity, only that in the course of comparing it with other collections, they can tell which has more, that is, it has more than 2 and less than 4 things. We have seen lions compare the numbers of intruders and defenders. In these circumstances, knowing the absolute number of defenders, or of attackers, may not be necessary. Brutus's chimpanzee companions may have relied on 2 being more than 1, and 2, 2 being more than 2, or 1, 2. However, the basis of the comparison could still be the ability to extract from the surroundings the absolute number of things in a collection and remember this for comparison with the numerosity of other collections. The lioness counts three intruders, remembers this (as did Koehler's jackdaw), and compares it with the number of defenders, including herself, before making a decision to attack or withdraw. The chimpanzees may similarly have remembered that two beats on the same tree means 'rest', while two beats on different trees means 'change direction'. At the moment we do not know which is the best account of the numerical capacities of our ancestors.

Are There Genes for Building the Number Module?

For us to have inherited a capacity for numerosity, this capacity must be encoded in the genome—the genetic instructions that control the building of our body. The human genome consists of 46 chromosomes, arranged in pairs, which we inherit from our mother and father. These chromosomes contain, we now believe, about 100,000 genes, about half of which go into building the brain.

How can we find out which genes are for numbers? In principle, it is very easy. We find people who are bad at numbers and work out where their genome is defective. Of course, there are many reasons for being bad at numbers—inadequate teaching for a start. So the first job is to find a group of people who are bad at numbers for reasons that are independent of environmental causes. The next job is identifying the part of each person's genome to see which ones are defective (and hoping that all members of the group show the same genetic defect). This means checking an enormous number of locations along each chromosome. We do now have some ideas about which regions on which chromosome are unlikely to be involved, but it still makes looking for a needle in a haystack seem easy.

There is another problem. No one has yet been able to identify genes responsible for any single cognitive function. No one has found the genes for language, for example. David Skuse and his colleagues at the Institute of Child Health in London have come nearer than anyone else to finding genes for a cognitive function, what they call 'social cognition'. This seems to consist of a range of social skills that might all depend on seeing another person's point of view.[76]

Skuse studied a population of females with Turner's syndrome. This is a chromosomal disorder in which one member of a pair of X chromosomes (45; 46) is missing or damaged. Normally, each member of the pair will be 'imprinted' according to whether it comes from the mother, called Xm, or from the father, Xp. In boys, who will have an X and a Y, the X will come from the mother. So in girls with Turner's syndrome, those with just the Xm will be much more like boys, and these are the ones with poor social cognition.

The other striking feature about Turner's syndrome compared with control subjects matched for age is that they are worse at mathematics but not at reading or spelling. On the whole they seem to be about two years behind. It is not clear from the one detailed study that exists, by Joanne Rovet and her colleagues at the Hospital for Sick Children in Toronto,[77] where or why these children are worse.

Do they fail to acquire more advanced skills? Do they lack some 'biologically basic abilities'? It remains to be discovered.

In collaboration with David Skuse and his team, I have started to carry out tests on females with Turner's syndrome. If there is a set of genes that build the brain circuits for the Number Module, then we may be able to track them down over the next three or four years. If there are not . . .

Laboratory experiments demonstrate that many species of mammals and birds can be trained to carry out simple tasks that depend on numerosity. With ingenuity, experimenters have been able to ensure that the animals are responding to the numerosity of a display rather than to the quantity of stuff in the display. The capacity to use numerosity information may offer its possessors an adaptive advantage, though it is very difficult to separate out the advantage of being able to use quantity information from being able to use numerosity information. Two examples from mammals in the wild support a specifically numerical interpretation—a lioness repelling intruders and a chimp leader directing his troop. These animals no doubt use quantitative information in other circumstances as well.

Are these animals using the predecessor of our Number Module? The answer is, we do not know. To establish this claim it is not enough to show that we and they both respond to the same numerosity properties of our environments. We also have to show that we have inherited their bodily mechanisms for doing it—not just eyes and ears, which we have indeed inherited from our simian ancestors, but brain circuits too. Unfortunately, as I write, we have absolutely no evidence as to which brain areas chimps, lions, or birds use to carry out numerical tasks. It is possible that they use different brain areas from one another, and from us. The evidence for a deep evolutionary source for the Number Module is tempting, compatible but incomplete.

Nevertheless, it now abundantly clear that infants are born with a capacity to recognize distinct numerosities up to about 4, and to respond to changes in numerosity. They also possess arithmetical expectations: if you take 1 doll away from 2, they expect to find 1 doll remaining; and if you add 1 doll to 1 doll, they expect to see

2 dolls as a result. These laboratory findings suggest that infants can compare numerosities and select the larger of two small numbers. These three abilities—to recognize numerosities, to detect changes in numerosity caused by adding or taking away from a collection, and to order numbers by size—are the biologically basic numerical capacities, the ones that are embedded in our innate Number Module.