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The Behavior of Organisms and how the Response is Directed

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Abstract

The behavior of bacteria and the behavior of eukaryotes are compared. The role of The Boss in behavior is presented.

Keywords: Organisms; Eukaryote Drosophila: Bacteria; Chemotaxis in Bacteria; Biology; Metabolism; Genetics; Neurobiology; Psychology; Biochemistry; Neuroscience

Introduction

My great love in life is Nature. When all else fails and life seems to offer no more, I return to Nature and rediscover this love which makes life for me glorious. I have made many mistakes and failed much, but my love of Nature has been unerring. The few great thoughts and the few great ideas I have come up with had their origins in this. Science to me is an attempt to understand Nature. When ego and competition enter, this great inspiration fades. But a return to Nature makes the inspiration return and drives all other motivations away. For me science and life are not worthwhile unless they encompass a love of Nature.

When I was a boy, I was interested in butterflies. Soon this expanded into birds and flowers. To learn how these all work, I studied biochemistry at college and in graduate school, then I pursued genetics. I did research on the behavior of bacteria and on the behavior of fruit flies: I was interested in the diversity of nature. Examples of that diversity written by me are Chemotaxis in Bacteria [1-3].

On the Behavior of Bacteria

In figure 1 I present figure from my original summary of the mechanism of behavior of bacteria, on which is based all subsequent reports by all others working on behavior of bacteria [4].

Sandy Parkinson wrote about this, “Adler’s initial paper set the stage for subsequent work by thousands of bacterial behaviorists that has made the *E. coli* chemotaxis machinery the best understood signal transduction system in all of biology” [5] (Figure 2).

Theodor Engelmann discovered in 1881 that bacteria are attracted to light, this is known as phototaxis. The role of microbial rhodopsin in phototaxis has now been described by John Spudich [6]. Wilhelm Pfeffer discovered in 1883 that bacteria are attracted and repelled by various chemicals, this is known as chemotaxis. A biochemical mechanism for chemotaxis in bacteria has been summarized by Julius Adler [2], Gerald Hazelbauer [7].

The bacteria have sensory receptors that detect stimuli: these are sensory methyl-accepting chemotaxis proteins that can be methylated or demethylated depending on presence or absence of stimuli. Then these sensing receptors tell intermediate proteins to tell the flagella to rotate counterclockwise, which results in running by the bacteria to attractants, or clockwise, which results in tumbling by the bacteria for repellents . Bacteria sense stimuli by means of tans-membrane methyl-accepting chemotaxis proteins. In *E. coli* these are Tsr, Tar, Tap, Trg, and Aer, see Sandy Parkinson, 2004. Then there are inside proteins that analyze these outside data. In E. coli these are CheA, CheB, CheR, CheW, CheY, and CheZ [8]. These inside proteins act on the flagella to produce a behavioral response.

Attraction of *E. coli* bacteria is shown in figures 3 & 4, repulsion of bacteria is shown in Figure 5. Figure 6 shows that chemoreceptors are in the “head” of bacterium, see Janine Maddock and Lucy Shapiro, 1993, and Figure 3 of Parkinson [8].

When the medium is liquid, bacteria do what is shown in figures 3-5. It is called “swimming”, but when the medium is more solid bacteria become longer and have more flagella and spread out further, this is called “swarming” [9].

Figure 1: Behavior is the response to sensing stimuli.

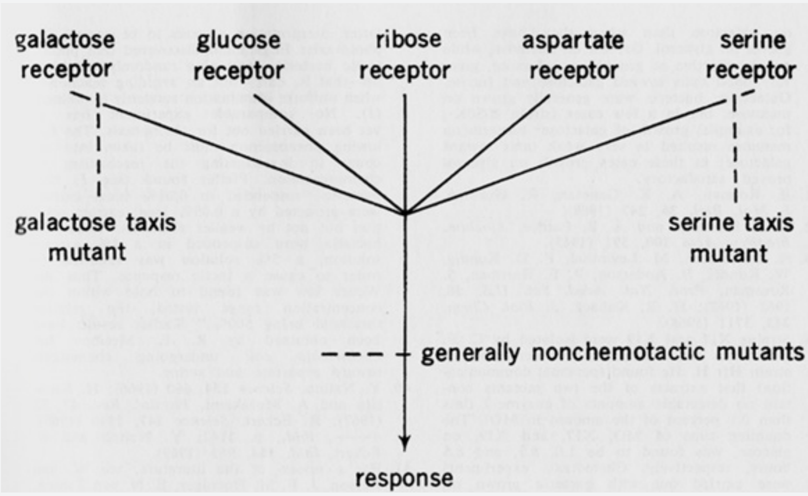

Figure 2: Mechanism of behavior in bacteria.

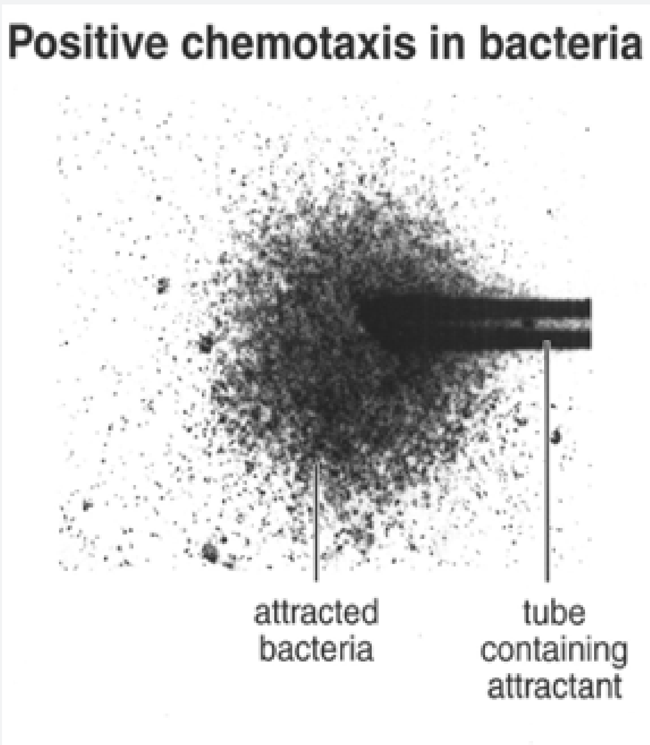

Figure 3: Bacteria attracted by chemical.

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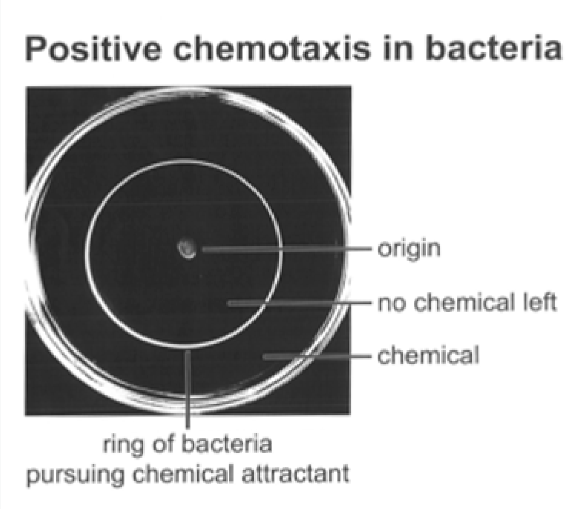

Figure 4: Bacteria repelled by chemical.

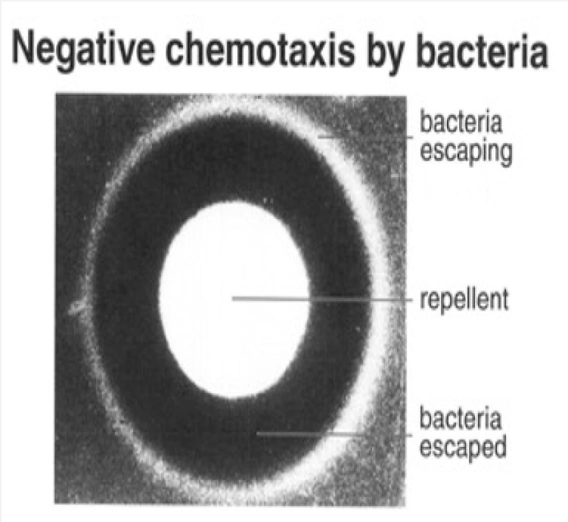

Figure 5: Bacteria attracted by chemical.

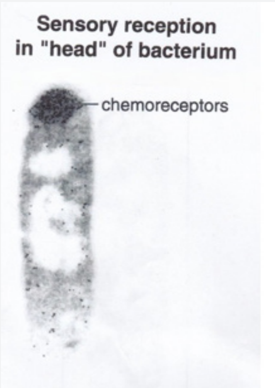

Figure 6: Chemoreceptors are located at the end of bacterium.

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Many other examples of behavior of bacteria: George Ordal pursues chemotactic behavior in *Bacillus subtilis* [10]. Gliding motility and multicellular swarming have been studied by Dale Kaiser, 1993, and by Beiyan Nan and David Zusman [11], both in *Myxococcus Xanthus*. Extension and retraction of type IV pili was pursued by Jeffrey Skerker & Howard Berg [12]. Surface sensing and attachment in *Caulobacter cresentus,* was studied by Kelly Hughes & Howard Berg [13]. Genes governing swarming in *B. subtilis* have been investigated by Daniel Kearns, Francis Chu, Rivka Rudner, and Richard Losick, 2004. How bacteria sense flow, which is called rheosensing, is described in *Pseudomonas aeruginosa* by Joseph Sanfilippo, Alexander Lorestani, Mattias Kohch.

On the Behavior of Eukaryotes

Eukaryotes also sense stimuli by means of transmembrane proteins, which are also anchored in the cell membrane and are also turned on by stimuli. After that initial event of stimulus detection the sensed information is sent to brain proteins that act to produce a behavioral response. This was discovered by Linda Buck [14] & Richard Axel [15]. Then it was explored further for other sensory systems of animals like light, taste, etc.: Charles Zucker and coworkers, 2001, Robert Margolski and coworkers, 2002; and others.

How Response is Directed

How response is directed in eukaryotes

Is there something that directs each organism? To me one of the most interesting questions of behavior is how an organism can make a decision about what to do when it encounters conflicting stimuli. A study of this would lead to the mechanism that is in control of the organism.

It was proposed by me that organisms have something in charge of them. This is called "The Boss". It is a novel idea. The Boss directs both the interior and the outside of the organism. The Boss is to be found in people, animals, plants, and microorganisms. How does The Boss lead? The control by The Boss is not always direct: many aspects are delegated to managers, who delegate to foremen, who delegate to workers. So far it is largely the workers that have been studied, and sometimes the foremen are revealed, and rarely the managers, but The Boss has remained largely hidden.

Sometimes there is a conflict between several attractants, or between several repellents, or between an attractant and a repellent. In the case of attractant together with repellent, there are reports of such conflicting behavior, for example in people (Fabien Grabenhost et al., 2008, Edmund Rolls et al., 2009), insects (Vincent Dethier, 1955), Drosophila fruit flies [16] (Chung-Hui Yang et al. 2008; Ryan Joseph et al. 2009), and bacteria [17,18]. Mutants of some of these are being studied and are proving valuable for learning how The Boss may act in behavior.

To try to find evidence that might reveal existence of The Boss, we looked for mutants missing The Boss in fruit flies. These are mutants that are motile but can't decide what to do, they don't respond to outside and inside attractants and repellents or to inside stimuli like hunger, thirst, and sleep. So all responses are shut off for these motile mutants. Thus they are defective in the response mechanism, which I regard to be The Boss. A summary of such mutants found is presented next.

We isolated motile mutants of fruit flies that lack all behavioral responses at an elevated temperature presumably by lacking The Boss there, but they do have the responses at room temperature where The Boss still exists [19].

In addition, we isolated motile mutants of fruit flies that lack all behavioral responses at both elevated temperature and room temperature by presumably lacking The Boss, as reported in Vang and Adler, 2018 *bioRxiv*. (Then there must be some alternative way to allow survival.) In those mutants the defect is found to be in RNA splicing. It is known that first the DNA is converted to RNA, then this newly made RNA undergoes RNA splicing to transform it into a messenger RNA needed for protein synthesis. Thus, the defect in these mutants is considered to be in RNA splicing.

Our knowledge of how DNA, RNA, and protein is made, and how this is controlled, is now extensive for DNA synthesis (Kaguni, 2006; Zakrzewska-Czerwinska et al., 2007; Katayama et al., 2010; and Masai et al., 2010), for RNA synthesis (Jackson et al., 2010; Malys and McCarthy, 2010; and Nakagawa et al., 2010), and for protein synthesis (Thomas and Chiang, 2006; Passalacqua et al. , 2009; Jiang and Pugh, 2009; Sorek and Cossart, 2010; and Kim and Park, 2011). As an example, there is a time during the cell cycle when DNA synthesis is turned on and a time when it is turned off. The proposal here is that there is a master control, The Boss, that dictates what shall be the state of synthesis of DNA, RNA, and protein.

In summary: The Boss is the thing in every organism that is in charge of the organism. The Boss is functionally similar in every organism. The Boss directs the synthesis and activity of DNA, RNA, and proteins, and thereby is in charge of behavior, metabolism, development, immunological response, and reproduction (Figure 7).

How response is directed in bacteria compared to eukaryotes

Bacteria swim by running and tumbling (Figure 8). Running allows them move toward an attractant, tumbling makes them avoid a repellent. This is in accord with older reference cited by Adler [20] [21-23]. Does The Boss exist in bacteria? I think so. When an attractant and a repellent are present together, bacteria employ a data-processing system that collects this information,

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chooses what to use, and then sends the decision on to the flagella for action [24]. In such an experiment, Nora Tsang, Robert Macnab, and Daniel Koshland have concluded that "repellents and attractants utilize a common memory mechanism for taxis" [17]. This data-processing system, or perhaps its previous step, would be the bacterial equivalent of The Boss of more complex organisms. The data-processing system is being studied more recently [25] by use of physics.

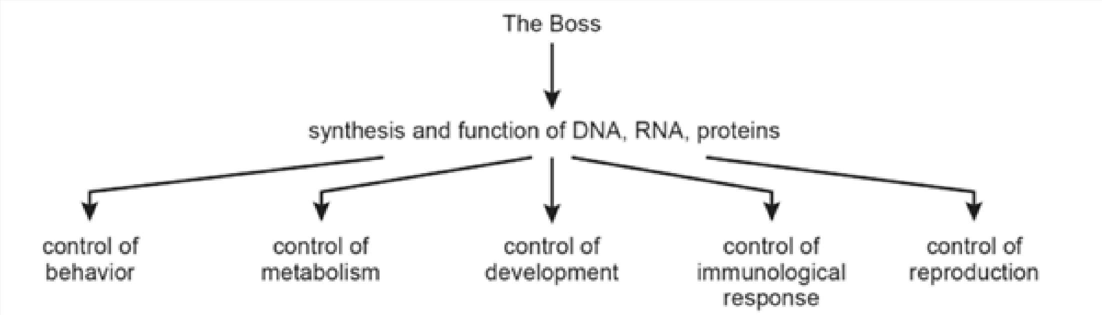

Figure 7: Summary of the role of The Boss.

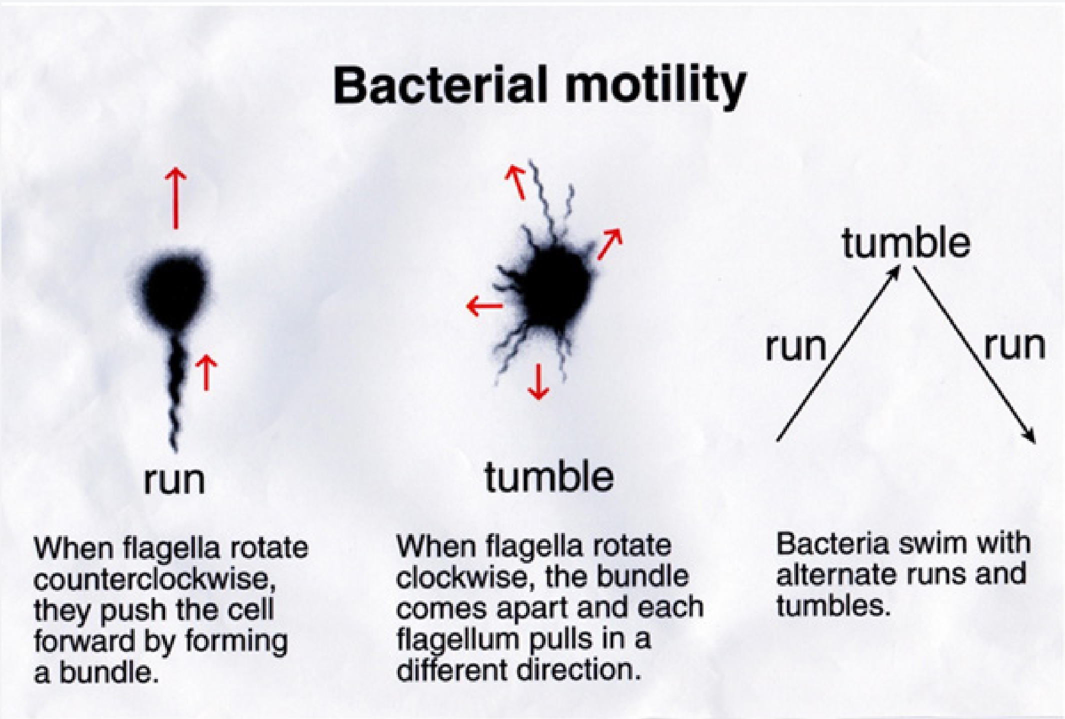

Figure 8: Running and tumbling.

Daniel Koshland has reported the following on pages 68 to 72 of his [26]. Conclusions and Extrapolations, Integration in the Processing System. The bacterial processing system not only can give additive responses to combinations of like stimuli, but it can integrate the effects of several different stimuli in an algebraic manner. Clearly such a property is similar to that of a neuron, which receives excitatory and inhibitory signals and must have the ability to integrate this information. The sensory system of a bacterium is a relatively simple input-output system with a processing capability that is moderately simple. It is in no way as complex as the human brain, and it could be argued that it is appreciably simpler than an individual neuron. A particularly

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interesting feature of the bacterium is that it encompasses many of the principles of higher behavioral systems within a single cell. It has specialized response systems that ultimately lead into a centralized system."

Here is another approach for getting at The Boss in bacteria. *E. coli* is responsive not only to chemicals but also to blue light, cold and warmth, anode and cathode, and osmolarity [2]. These all go to the flagella for action, so the earliest step for each must encompass data processing, which may be on the pathway from The Boss. Further, *E. coli* has a mechanism that overrules all other mechanisms: Zachary Burton, Carol Gross, Kathleen Watanabe, & Richard Burgess [27] and James Lupski, Bob Smiley & Nigel Godson [28] discovered that *E. coli* has an operon that controls all three of the most basic processes – DNA synthesis, RNA synthesis, and protein synthesis. How is that operon turned on and off? It may well be by The Boss [2] (Table 1).

Table 1: The size of the genome.

Size of Genome (number of DNA basepairs)	
bacterium	4,639,221
yeast	12,495,682
nematode	100,258,171
fruit fly	122,653,977
zebrafish	1,500,000,000
mouse	2,800,000,000
human	3,300,000,000
mustard	135,000,000
corn	2,300,000,000

How it all Happens: DNA

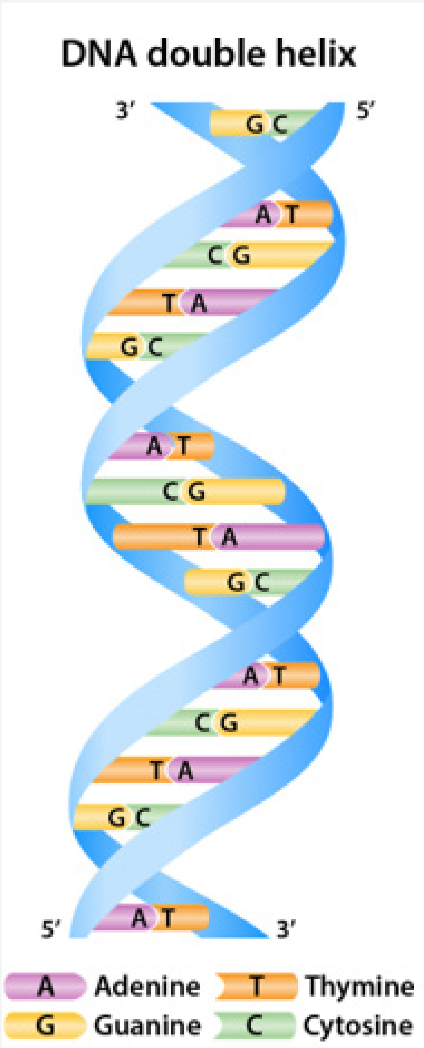

Figure 9: DNA has AT base-pairs and GC base-pairs.

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The genome has protein-coding DNA genes, see next, and non-protein-coding DNA genes, see below that.

Protein-Coding DNA Genes

DNA has protein-coding genes. These make messenger RNA, which is used by the ribosomes to synthesize all the various proteins needed by the organism. RNA is made up of four kinds of ribonucleotides: adenine ribonucleotide, uracil ribonucleotide, guanine ribonucleotides, and cytosine ribonucleotide. The number of different protein-coding genes is constant in each organism (Table 2). There are about 500 to 5,000 genes in different kind of bacteria, about 6,000 in yeast, and very roughly speaking a similar number (16,000 - 32,000) in the eukaryotes. That similarity suggests that the organisms might have common components.

Table 2: Protein-coding genes.

Number of Genes for Making Proteins	
bacterium	4,290
yeast	5,770
nematode	21,733
fruit fly	15,682
zebrafish	26,206
mouse	20,000
human	21,000
mustard	25,498
corn	32,000

Various organisms are compared in table 2 for how many protein-making genes they have. In 1941 George Beadle and Edward Tatum showed, using the bread mold Neurospora, that a single gene makes a single protein. It was said in 1954 by the molecular biologist Jacques Monod, "What is true for *E. coli* is true for the elephant", and that was similarly said in 1926 by the Dutch microbiologist Albert Kluyver. Now we know that those sayings are only partly true: In the "lower" organisms (like bacteria) each protein-coding gene does make one protein but in "higher" organisms each protein-coding gene can make many different proteins by combining a variety of different parts of each gene. Thus for example in people about 500,000 different proteins get made from its 21,000 protein-coding genes.

Many of the proteins are similar in all the different organisms. This high level of similarity suggests that the organisms are related. For example about 60% of genes are conserved between the fruit fly and the human genome. A further example of similarity is between yeast and humans: about 30% of yeast's genes are related to those of humans. These similarities are so close that the human versions of many genes can be interchanged in yeast with little or no effect on cell function.

Non-protein-coding DNA genes

Some of the DNA does not encode proteins. These genes make RNA that is not translated into proteins.

In bacteria most but not all of the DNA is genes that code for proteins. But in more complex organisms the genes for coding proteins are only a smaller part of the DNA, for example in yeast it is about 65%, in worms about 20%, and in humans only about 2% (Figure 10) the rest of the DNA is due to the non-protein-coding genes. So the non-protein-coding genes occur infrequently in simple organisms like bacteria, while they occur prominently in more complex organisms.

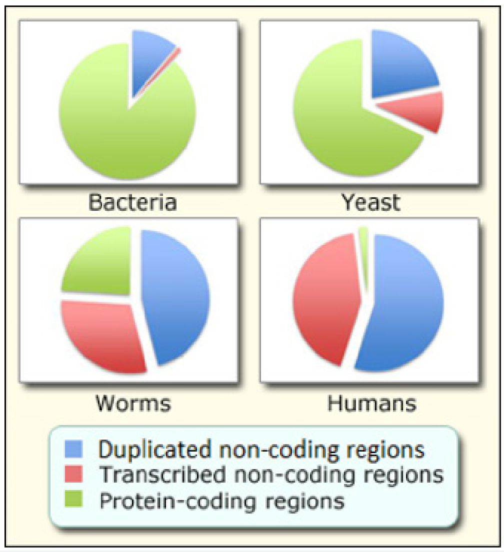

Figure 10: The non-protein-coding regions of the genome have undergone an expansion throughout evolution, supporting their potential importance in organismal complexity.

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Thus, a large part of the eukaryotic DNA produces RNAs which do not make proteins. So the biological complexity of organisms is not due merely to the number of protein-encoding genes but also to the number of non-protein-encoding genes. For example, when those proteins are not needed there are non-coding RNAs that can bind to messenger RNA to prevent it from being translated into proteins [29-41].

Nerves and Behavioral Genetics

The number of nerve cells in a variety of organisms is shown here (Table 3):

Table 3: How many nerve cells there are.

Number of Nerve Cells	
bacterium	1?
yeast	1?
nematode	302
fruit fly	250,000
zebrafish	10,000,000
mouse	71,000,000
human	86,000,000

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